**Measurement of the
Electroweak Top Quark Production Cross Section
and the CKM Matrix Element V_{tb}
with the DØ Experiment**

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Zusammenfassung

In der vorliegenden Analyse wird in einem etwa 1 fb^{-1} an integrierter Luminosität umfassenden Datensatz des DØ-Experiments nach der Produktion einzelner Top-Quarks mittels elektroschwacher Wechselwirkung gesucht. Die Ereignisse wurden am Tevatron-Beschleuniger des Fermi National Accelerator Laboratory, angesiedelt in Batavia, IL, USA, in Proton-Antiproton-Kollisionen bei einer Schwerpunktsenergie von $\sqrt{s} = 1.96 \text{ TeV}$ aufgezeichnet. Die Analyse konzentriert sich dabei auf die Messung des kombinierten Wirkungsquerschnitts des s- (tb) und des t-Kanal- (tqb) Produktionsmechanismus:

$$p\bar{p} \rightarrow tb + X, tqb + X.$$

Betrachtet werden hierbei Endzustände in denen das W Boson, welches beim Zerfall des Top-Quarks entsteht, im Weiteren in ein Elektron oder ein Myon sowie ein entsprechendes Neutrino zerfällt. Dieser Wirkungsquerschnitt ist direkt proportional zum Quadrat des CKM-Matrixelements $|V_{tb}|$ und erlaubt somit dessen Messung ohne zusätzliche Annahmen über die Unitarität der CKM-Matrix oder die Anzahl der Fermion-Generationen im Standardmodell der Elementarteilchenphysik. Eine Messung des Produktionswirkungsquerschnittes einzelner Top-Quarks ermöglicht somit einen direkten Test der V-A-Struktur der elektroschwachen Wechselwirkung.

Die Ereignisse werden zunächst in einer sogenannten *Multi-Process Factory* auf unterschiedliche Signal- und Untergrundhypothesen hin überprüft. Dabei werden durch Permutation der rekonstruierten Objekte alle auf Grund von Vieldeutigkeiten möglichen Zerfallsbäume erstellt und auf ihre Signalartigkeit hin überprüft. Vom wahrscheinlichsten Zerfallsbaum jeder Signal- bzw. Untergrundhypothese werden daraufhin Observablen gewonnen, die im Weiteren in einer multivariaten Analyseverfahren, sogenannten Boosted Decision Trees, zur Separation der erwarteten Signale von den Untergrundereignissen herangezogen werden. Anhand eines Bayes'schen Verfahrens wird schließlich in einer gleichzeitigen Parameteranpassung der 12 beteiligten Analysekanäle aufgrund der aus den Boosted Decision Trees erhaltenen Diskriminanten-Verteilungen der Wirkungsquerschnitt abgeleitet. Ausgehend von einer Masse des Top-Quarks von 175 GeV liefert die Messung einen Wirkungsquerschnitt von

$$\sigma(p\bar{p} \rightarrow tb + X, tqb + X) = 5,51^{+1,62}_{-1,31} \text{ pb.}$$

Die Signifikanz der Wirkungsquerschnittsmessung beträgt 4,2 Standardabweichungen.

Die Stärke der V-A-Kopplung am W_{tb} -Vertex kann daraus zu

$$|V_{tb} \times f_1^L| = 1,42^{+0,21}_{-0,20}$$

bestimmt werden. Sowohl die Messung des Wirkungsquerschnittes als auch die der Kopplungsstärke liegen etwa zwei Standardabweichungen über der Erwartung des Standardmodells.

Sie sind jedoch innerhalb der Fehlergrenzen mit anderen Messungen der DØ-Kollaboration auf demselben Datensatz verträglich. Unter der Einschränkung, dass die Kopplung f_1^L dem Standardmodellwert 1 genügt, wurde zusätzlich eine Messung von $|V_{tb}|$ sowie eine untere Grenze auf $|V_{tb}|$ bei einem 95% Vertrauensniveau abgeleitet:

$$|V_{tb}| = 1,00^{+0,00}_{-0,08} \quad \text{sowie} \quad |V_{tb}| > 0,79 @ 95\% \text{ C.L.}$$

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1 Introduction

To understand the composition of matter and the fundamental forces of nature is an aim that has been driving human kind for centuries. On large scales the theory of general relativity [1] describes the clustering of galaxies and the movement of planets around the sun due to gravity. The theory of general relativity extends the Newtonian gravity [2] that is able to explain the falling of apples from trees. On small scales, scattering experiments are performed to find the elementary particles matter is built of. It has been shown that atoms consist of electrons and nucleons [3], and that even the nucleons are not elementary. Their basic constituents are called quarks [4]. The quark model led to the development of Quantum ChromoDynamics (QCD), explaining the behaviour of the strong force. Furthermore, the weak and the electromagnetic forces could be unified in the Glashow-Weinberg-Salam (GWS) model. Building upon much earlier work, in the 1960s and 1970s the Standard Model of elementary particle physics was developed, a quantum field theory describing the interactions at very small scales, including all fundamental forces except for gravity.

At particle accelerators the Standard Model has been tested and will be tested further to a great precision [5]. The data analyzed in this thesis have been collected at the world's highest energetic-collider, the Tevatron, located at the Fermi National Accelerator Laboratory (FNAL) in the vicinity of Chicago, IL, USA. There, protons and antiprotons are collided at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV. The discovery of the top quark [6,7] was one of the remarkable results not only for the CDF and DØ experiments at the Tevatron collider, but also for the Standard Model, which had predicted the existence of the top quark because of symmetry arguments long before already. Still, the Tevatron is the only facility able to produce top quarks. The predominant production mechanism of top quarks is the production of a top-antitop quark pair via the strong force. However, the Standard Model also allows the production of single top quarks via the electroweak interaction. This process features the unique opportunity to measure the $|V_{tb}|$ matrix element of the Cabbibo-Kobayashi-Maskawa (CKM) matrix [8] directly, without assuming unitarity of the matrix or assuming that the number of quark generations is three. Hence, the measurement of the cross section of electroweak top quark production is more than the technical challenge to extract a physics process that only occurs one out of ten billion collisions. It is also an important test of the V-A structure of the electroweak interaction and a potential window to physics beyond the Standard Model in the case where the measurement of $|V_{tb}|$ would result in a value significantly different from 1, the value predicted by the Standard Model.

At the Tevatron two production processes contribute significantly to the production of single top quarks: the production via the t-channel, also called W-gluon fusion, and the production via the s-channel, known as well as W^* process. This analysis searches for the

combined s+t channel production cross section, assuming the ratio of s-channel production over t-channel production is realized in nature as predicted by the Standard Model. A data set of approximately 1 fb^{-1} is analyzed, the data set used by the DØ collaboration to claim evidence for single top quark production [9,10]. Events with two, three, and four jets are used in the analysis if they contain one or two jets that were tagged as originating from the decay of a b hadron, an isolated muon or electron, and a significant amount of missing transverse energy. This selection of events follows the signature that the single top quark events are expected to show in the detector. In the meantime, both collaborations DØ [11] and CDF [12] have analyzed a larger data set and have celebrated the joint observation of single top quark production [13].

The novelty of the analysis presented here is the way discriminating observables are determined. A so-called *Multi-Process Factory* evaluates each event under several hypotheses. A common analysis technique for example in top quark properties studies is to reconstruct the intermediate particles in the decay chain of the signal process from the final state objects measured in the various subdetectors. An essential part of such a method is to resolve the ambiguities that arise in the assignment of the final state objects to the partons of the decay chain. In a Multi-Process Factory this approach is extended and not only the decay chain of the signal process is reconstructed, but also the decay chains of the most important background processes. From the numerous possible event configurations for each of the signal and background decay chains the most probable configuration is selected based on a likelihood measure. Properties of this configuration, such as mass of the reconstructed top quark, are then used in a multivariate analysis technique to separate the expected signal contribution from the background processes. The technique which is used is called *Boosted Decision Trees* and has only recently been introduced in high energy physics analyses [14]. A *Bayesian approach* is used to finally extract the cross section from the discriminant output of Boosted Decision Trees.

The outline of this thesis is as follows. The next chapter starts with a theoretical introduction to the Standard Model of Elementary Particles in general, followed by an introduction to physics with top quarks. The latter part concentrates on the electroweak production of single top quarks and the connection to the CKM matrix element $|V_{tb}|$. The experimental apparatus is discussed in chapter 3. The collider complex at the Fermi National Accelerator Laboratory will be introduced and details of the DØ detector will be presented that are crucial to record all the information needed to perform the analysis. How the information recorded by the numerous subsystems of the DØ detector is processed in order to provide the data analyzers standardized physics objects such as tracks, electrons, or jets is described in chapter 4. In chapter 5 the event selection is described. The data set used in this analysis is introduced as well as the generators used to produce the Monte Carlo samples that are used to model the background and to optimize the multivariate analysis techniques. The analysis strategy is presented in chapter 6. Details on the implementation of a *Multi-Process Factory* and *Boosted Decision Trees* are given and the special features of the software toolkits are introduced that are needed to control these complex algorithms to run them with a high performance. In chapter 7 the application of a Multi-Process Factory in the search for electroweak top quark production is described in detail for the three jet multiplicity bins that are considered in the analysis. The optimization of the individual process templates that are reconstructed in the Multi-Process Factory is presented and the comparison

of observed data events with the background expectation is shown for the observables that are then used with the Boosted Decision Trees. Their optimization, the systematic uncertainties that are considered in this analysis, and the extraction of the signal cross section from the discriminant output distribution using a Bayesian approach are explained in chapter 8. The results of the cross section measurement and the determination of the CKM matrix element $|V_{tb}|$ are then given in chapter 9. Finally, chapter 10 gives a summary and ends with an outlook on future prospects of the analysis.

2 Top Quarks within the Standard Model

2.1 The Standard Model of Elementary Particle Physics

The Standard Model of elementary particle physics is a quantum field theory that describes the fundamental particles and the interactions between them. It includes the strong, weak, and electromagnetic force. Gravity is not included in the Standard Model, although attempts are made to include it. The theory of general relativity describes the gravitational interactions between massive objects. There are two types of elementary particles. Fermions are particles with spin $s=1/2$ and bosons are particles with spin $s=1$.

Matter is composed of fermions. Quantum numbers such as the electromagnetic charge or the spin projection are used to describe the state of these particles. Two fermions cannot share the same quantum state at the same time. They obey the Pauli exclusion principle. In the Standard Model twelve different types of fermions are arranged in three families. Table 2.1.1 summarizes some of their properties.

From the three families only fermions of the first family contribute to ordinary matter. The fermions from higher families can only be observed in high energy interactions. In these interactions they decay into particles of the first generation.

There are two different kinds of fermions: quarks and leptons. Quarks cannot be observed as free particles. They form bound states, so-called hadrons. If a hadron consists of a quark-antiquark pair, it is called a meson. It is called a baryon if it consists of three quarks. To obey the Pauli exclusion principle, quarks have to carry an additional quantum number, the so-called charge [17,18]. Leptons do not carry color charge. To each elementary particle there is a corresponding anti-particle which carries opposite quantum numbers.

In the Standard Model neutrinos are assumed to be massless. However, recent measurements of neutrino flavor oscillations have shown that neutrinos have mass [19–22] and therefore the Standard Model has to be extended to incorporate this fact. The neutrino mass values cited in table 2.1.1 are limits obtained from direct measurements. The sum of the masses of the three neutrinos is of the order of a few eV due to cosmological constraints [15]. This knowledge can be used to obtain stricter limits on the masses of ν_μ and ν_τ .

Name	Type	Symbol	Electric charge [e]	Mass [MeV/c ²]
electron	lepton	e	-1	0.51
electron neutrino	lepton	ν_e	0	$\leq 2 \cdot 10^{-6}$
up quark	quark	u	$+\frac{2}{3}$	1.5 – 3.3
down quark	quark	d	$-\frac{1}{3}$	3.5 – 6.0
muon	lepton	μ	-1	105.66
muon neutrino	lepton	ν_μ	0	≤ 0.19
charm quark	quark	c	$+\frac{2}{3}$	$(1.27^{+0.07}_{-0.11}) \cdot 10^3$
strange quark	quark	s	$-\frac{1}{3}$	104^{+26}_{-34}
tau	lepton	τ	-1	1776.8
tau neutrino	lepton	ν_τ	0	≤ 18.2
top quark	quark	t	$+\frac{2}{3}$	$(173.1 \pm 0.6 \pm 1.1) \cdot 10^3$
bottom quark	quark	b	$-\frac{1}{3}$	$(4.20^{+0.17}_{-0.07}) \cdot 10^3$

Table 2.1.1: Summary of the elementary fermions in the Standard Model with their electric charge and their mass [15]. The mass of the top quark is based on published results [16].

Mathematically the three forces included in the Standard Model are described by gauge theories. The basic idea behind gauge theories is that symmetry transformations can be performed locally as well as globally. The Lagrangian of the physical system described by a gauge theory is invariant under gauge transformations, i.e. invariant under local change of variables. However, to compensate for this change of variables additional fields have to be introduced, the gauge fields. The excitations of the gauge fields represent the particles that transmit the forces, the gauge bosons. Table 2.1.2 lists the gauge bosons and some of their properties.

Name	Symbol	Mediated force	Electric charge [e]	mass [MeV/c ²]
photon	γ	electromagnetic	$< 5 \cdot 10^{-30}$	$< 1.8 \cdot 10^{-24}$
gluon	g	strong	0	0
Z boson	Z^0	weak	0	$(91.1876 \pm 0.0021) \cdot 10^3$
W bosons	$W^\pm$	weak	± 1	$(80.398 \pm 0.025) \cdot 10^3$

Table 2.1.2: Summary of the gauge bosons in the Standard Model. The values of the electric charge and the mass the bosons are taken from reference [15].

According to the Noether theorem [23] a symmetry of the physical system can be related to

a conserved current, eventually corresponding to charge conservation. Only those particles that carry the charge of a certain force can interact via this specific force (e.g. an electron cannot interact via the strong force, because it carries no color charge).

The Quantum ElectroDynamics (QED) describes interactions of the electromagnetic force. The corresponding gauge boson is the photon. It preserves the invariance under redefinition of the electrostatic potential. The photon is a massless boson that couples to the electric charge, carrying no electric charge itself. Because the photon is massless, the range of the electromagnetic force is infinite.

The gluon is the gauge boson that mediates the strong force. Interactions via the strong force are described by Quantum ChromoDynamics (QCD) [24–26]. The gluon is massless, couples to color charge and even carries color charge itself. This leads to gluon self-interactions. Because of these self-interactions the strength of the strong force decreases at short distances. This feature of the strong force is called asymptotic freedom. At large distances, the so-called confinement takes place. The strength of the strong force increases and quarks are forced to create colorless bound hadrons. Due to the fact that gluons carry both charge and anti-charge the number of possible color combinations would lead to nine gluons. However, the color singlet is not physically significant and the number of gluons mediating the strong force is thus reduced to eight.

To understand the weak interaction it is important to introduce the concept of chirality. Something is chiral if it cannot be superimposed on its mirror image. Chirality must not be confused with helicity, which is the projection of a particles spin to the direction of its motion. Only for massless particles helicity is a Lorentz invariant observable. The wave function Ψ of a massive particle has both a right-handed (Ψ_R) and a left-handed (Ψ_L) chiral component: $\Psi = \Psi_R + \Psi_L$. A massive particle with positive helicity still has a left-handed component. In the case of ultrarelativistic particles chirality approximates helicity, because there is no frame of reference in which their helicity would change. For massless particles chirality equals helicity.

The weak interactions transmit via massive bosons. There is one electrically neutral boson, the Z boson, and there are electrically charged bosons, the W^+ and the W^- boson. The latter only couple to the left-handed chiral component of the fermion wave function. For anti-fermions, they couple to the right-handed chiral component of the wave function, respectively. The Z boson couples to both components, even though with different strengths. The weak force is the only Standard Model force that affects neutrinos. Another feature of the weak force is that it allows flavor changes. This is possible in interactions where a W boson is exchanged. The flavor change is possible because the eigenstates of the quarks that take part in the weak interaction differ from the mass eigenstates. The Cabibbo-Kobayashi-Maskawa matrix (CKM matrix) is the matrix that describes the transformation from mass eigenstates (d , s , and b) to eigenstates

d' , s' , and b' of the weak interaction [8,27]. Equation 2.1.1 demonstrates this transformation.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \quad (2.1.1)$$

The CKM matrix is unitary with dimension $n_{gen} \times n_{gen}$, or 3×3 given three generations. It does not have to be real. Interference caused by imaginary phases can lead to CP violation as observed in, for example, K-mesons. In fact, CP violation was the original motivation of Kobayashi and Mahawa for expanding the original 2×2 Cabbibo matrix. This was done even before there was evidence for a third fermion family.

The matrix element $V_{q_1 q_2}$ determines the strength of the coupling of two quarks q_1 and q_2 to a W boson. The strength of the coupling is proportional to $V_{q_1 q_2}$. The individual matrix elements $V_{q_1 q_2}$ have to be determined experimentally. Under the assumption of a unitary matrix and three fermion families, a global fit of all available measurements of matrix elements can be performed [15]. The result of the fit yields the following magnitudes for the nine CKM matrix elements:

$$V_{CKM} = \begin{pmatrix} 0.9741 \pm 0.00022 & 0.2257 \pm 0.0010 & (3.59 \pm 0.16) \cdot 10^{-3} \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & (41.5^{+1.0}_{-1.1}) \cdot 10^{-3} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}. \quad (2.1.2)$$

The electroweak theory by Glashow, Salam, and Weinberg [28–30] managed to unify the electromagnetic interaction with the weak interaction. Although the two forces appear different at low energies, the electroweak theory models them as two different aspects of the same electroweak force. This unification happens above the unification energy. Electroweak symmetry breaking is responsible for the differences between the electromagnetic and the weak force. The Higgs mechanism is the most favored description of the symmetry breaking [31–34]. A scalar quantum field, the Higgs field, is introduced to the Standard Model. Its quantum excitation, the Higgs boson, has not yet been observed. But, both the LEP experiments and the Tevatron experiments could exclude some mass ranges for the Higgs boson. The status as of spring 2009 [35] is summarized in figure 2.1.1. The hatched areas show the mass regions excluded by direct searches. The lines with the error bands show the combined sensitivity of the analyses performed at the two Tevatron experiments CDF and DØ. By coupling to the Higgs field the originally massless gauge bosons, the leptons, and the quarks acquire mass.

Feynman diagrams are used to visualize the interaction of two charged elementary particles via the exchange of a gauge boson. Figure 2.1.2 shows an example of a Feynman diagram for electron-electron scattering via the exchange of a virtual photon. The individual parts of a Feynman diagram can be used as a rule to translate the diagram into a mathematical expression for the transition amplitude M . The solid lines represent the propagation of a particle or an anti-particle in space-time. The coupling of the particles to gauge bosons is visualized by vertices, drawn as dots. The cross section of a process can be calculated from the transition amplitude by integrating over the whole phase space, i.e. over all initial and final state particles.

Figure 2.1.1: Status of the searches for the Higgs boson as of spring 2009 [35]. The hatched areas are the excluded mass ranges from direct searches by LEP (left) and the Tevatron (right). The solid line shows the current sensitivity of the analyses performed at the Tevatron experiments.

Figure 2.1.2: Example of a Feynman diagram. The incoming electrons are represented by the lines on the left hand side. The lines on the right hand side represent the outgoing electrons. The vertical line visualizes the photon that is exchanged. The dots represent the couplings of the electrons to the photon.

The cross section is a measure for the probability that an interaction occurs.

At the Tevatron accelerator protons and antiprotons collide. The fact that these particles are not elementary but baryons complicates the calculation of a cross section. The momentum of the proton is shared among its constituents. Each parton carries only a fraction of the proton momentum. A proton consists of two up quarks and one down quark, an anti-proton consists of the corresponding anti-quarks. These valence quarks are bound together by virtual gluons. These gluons can split into quark-antiquark pairs, the so-called sea-quarks. It is crucial to know

the momenta of these individual partons because the Feynman rules only apply to elementary particles. The momentum fraction of the proton carried by the partons is described by the Parton Distribution Function (PDF) $f_{i,p}(x_i, Q)$. This function depends on the scale Q that describes the typical energy scale of the interaction. Figure 2.1.3 shows the CTEQ6M PDF for a low momentum transfer of 2 GeV on the left side and for a momentum transfer of 100 GeV on the right side [36].

Figure 2.1.3: CTEQ6M parton distribution functions for gluons and the different quark flavors. The x -axis shows the proton momentum fraction of the parton, the y -axis the parton density. The left plot visualizes the distributions for a small momentum transfer, the right plot shows a larger momentum transfer [36].

In order to calculate a cross section that can be measured in proton-antiproton collisions, the PDFs have to be folded with the partonic cross section.

2.2 Top Quarks

The top quark is the heaviest of the known elementary particles. It was discovered in 1995 in proton-antiproton collisions at the Tevatron [6,7]. Due to its high mass it plays a special role among the quarks. The latest combination of top quark mass measurements from the CDF and the DØ experiment results in a value

$$m_{\text{top}} = 171.3 \pm 0.6(\text{stat.}) \pm 1.1(\text{syst.}) \text{ GeV} \quad (2.2.1)$$

for the mass of the top quark [16]. Figure 2.2.1 shows both the individual analyses that contribute to this combination and the fitted combined value. It is remarkable that the uncertainty on the top quark mass measurement is now limited by the systematic uncertainties.

As a quark, the top quark participates both in strong and in electroweak interactions. However, its predicted lifetime of $\tau \approx 0.5^{-24} \text{ s}$ is shorter than the hadronization scale, i.e. the top quark decays via the weak force before top-flavored hadrons can form. This short lifetime allows to study a bare quark. The top quark passes all its properties to its decay products.

Figure 2.2.1: Current world average of the top quark mass, fitted from the combination of several analyses performed by the CDF and the DØ experiment [16].

Because $|V_{tb}|$ is approximately 1 (see current limits on $|V_{tb}|$ in equation 2.1.2), the decay products are in almost 100% a W boson and a b quark.

The mass of the top quark plays also an important role in the mechanism of electroweak symmetry breaking. It can be used to constrain the mass of the Higgs boson through its radiative corrections on the mass of the W boson:

$$M_W^2 = \frac{\pi \alpha(M_Z^2)}{\sqrt{2} G_F} \times \frac{1}{\left(1 - \left(\frac{M_W^2}{M_Z^2}\right)\right)} \times \frac{1}{1 - \Delta r}. \quad (2.2.2)$$

The term Δr contains the radiative corrections. It has a quadratic dependency on the mass of the top quark and is logarithmically depending on the mass of the Higgs boson. These higher order contributions are illustrated in figure 2.2.2(a) for the dependency on the top quark mass and in figure 2.2.2(b) for the mass of the Higgs boson.

With precise measurements of the top quark mass and the W boson mass (the latter contains measurements from both the LEP experiments and the Tevatron experiments), it is thus possible to constrain the mass of the Higgs boson. Figure 2.2.3 shows the 68% confidence intervals of the W boson mass m_W and the top quark mass m_t in the m_W - m_t -plane. The region where the two ellipses and the green band, displaying possible values of the Higgs boson mass, overlap, is the favored value for the Higgs boson mass [5].

The measurements of the top quark mass shown in figure 2.2.1 have been performed in interactions where top quark pairs are produced via the strong interaction. These interactions will be

Figure 2.2.2: Contributions to the radiative corrections on the mass of the W boson due to loops containing a top quark arise from diagrams like the one in figure 2.2.2(a). Diagrams like figure 2.2.2(b) illustrate the contributions due to loops that contain a Higgs boson.

Figure 2.2.3: Constraints on the Higgs mass due to radiative corrections of the W boson mass. The uncertainties on the top quark mass and the W boson mass restrict the favored value for the mass of the Higgs boson to the overlap of the two ellipses and the green band [5] at a 68% confidence level.

discussed briefly in the next section 2.2.1. The production of single top quarks via electroweak interactions will then be topic of section 2.2.2. Detailed reviews on top-quark physics in hadron collisions can be found in references [37–40].

2.2.1 Production of Top Quarks via Strong Interaction

The production of top quark pairs via strong interaction is the dominant production mechanism for top quarks in hadron collisions. At the Tevatron the two dominant production processes are quark-antiquark annihilation and gluon fusion. In NLO calculations for the Tevatron

proton-antiproton collisions at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV, the quark-antiquark annihilation contributes about 85% to the total cross section. The production via gluon fusion contributes about 15%. Figure 2.2.4 shows the LO Feynman diagrams of the two production processes.

Figure 2.2.4: Leading-order Feynman diagrams of top quark pair production: (a) shows the production via quark-antiquark annihilation and (b) the production via gluon fusion.

Assuming a top mass of 175 GeV the production cross section at the Tevatron is calculated to be $\sigma_{t\bar{t}} = 6.90^{+0.46}_{-0.64}$ pb including soft gluon resummation at next-to-next-to-leading logarithmic accuracy [41].

2.2.2 Production of Top Quarks via Electroweak Interaction

The production of top quarks via the electroweak interaction, often referred to as single top quark production, is a probe of electroweak charged-current interactions. In top quark pair events the charged-current interaction can only be studied in the decays of the top quarks. Therefore, single top quark production was subject to many studies [42–53]. A review is provided in reference [54].

There are three types of single top quark production:

- **s-channel:**

The s-channel production of single top quarks is characterized by the exchange of a time-like W boson with $Q_W^2 > (m_t + m_b)^2$. Here, Q_W is the fourvector squared of the W boson. The left diagram in figure 2.2.5 represents a representative leading-order Feynman diagram.

- **t-channel:**

The t-channel process of single top quark production involves the exchange of a space-like W boson with $Q_W^2 < 0$. The right hand plot of figure 2.2.5 shows a representative leading-order Feynman diagram.

Figure 2.2.5: Leading-order Feynman diagram for single top quark production via the s-channel process (left) and via the t-channel process (right).

Figure 2.2.6: Leading-order Feynman diagrams for the production of a top quark associated with an on-shell W boson.

- **tW associated production:**

In this production process the top quark is produced in association with an on-shell W boson. Figure 2.2.6 shows representative leading-order Feynman diagrams for this process.

The cross sections have been calculated at the tree level [49] and at next-to-leading order [55–66]. Many of the next-to-leading order calculations are differential calculations, providing event kinematics. The cross sections summarized in table 2.2.1 are taken from references [67] and [68]. The calculations use a value of 171.4 ± 2.1 GeV for the mass of the top quark. They include NLO plus NNLO and NNNLO threshold soft-gluon corrections. The cross sections are given both for the Run II energy of the Tevatron collider (i.e. 1.96 TeV) and for the LHC (assuming a center-of-mass energy of 14 TeV). The values stated for the Tevatron are twice as high as the numbers given in the paper. This factor of 2 reflects the symmetry of the production of top and anti-top quarks at the proton-antiproton collisions at the Tevatron. The cross section of the associated production process is small at the Tevatron because of its massive final state. Therefore, the analysis presented in this thesis only searches for s- and t-channel production. Due to the high momentum fraction of the proton carried by gluons at the LHC (see figure 2.1.3), the cross section for associated production will become comparably large. The cross section for s-channel production however will remain rather small. The reason is that for the s-channel production an antiquark is needed. At the LHC this antiquark will have to come

from the sea.

Single Top Process	Cross Section [pb]		
	Tevatron Run II $t + \bar{t}$	LHC t	LHC $\bar{t}$
s-channel	1.08 ± 0.08	$7.80^{+0.70}_{-0.60}$	4.35 ± 0.26
t-channel	2.30 ± 0.14	150 ± 6	92 ± 4
tW associated	0.28 ± 0.06	43.5 ± 4.8	43.5 ± 4.8

Table 2.2.1: The cross sections for single top and anti-top production. Due to the proton-antiproton collisions at the Tevatron the cross sections for top and anti-top production are identical. The values are for a top mass of 171.4 GeV at NLO plus NNLO and NNNLO threshold soft-gluon corrections [67,68]. For the LHC values a center-of-mass energy of 14 TeV is assumed.

The event signature that this analysis is searching for is visualized in figure 2.2.7 for the leading-order s-channel Feynman diagram. Because of the small values of $|V_{td}|$ and $|V_{ts}|$ (see

Figure 2.2.7: Leading-order s-channel diagram for single top quark production followed by a leptonic decay of the W boson.

equation 2.1.2 and reference [15]), the top quark is expected to decay almost exclusively into a b-quark and a W-boson. Hadronic decays of the W boson are not analyzed. They suffer from a large QCD multijet background. This analysis concentrates on the leptonic decay of the W boson into an electron or a muon and a neutrino. This neutrino cannot be measured directly with the detector, it escapes detection. However, a significant amount of missing transverse energy hints to the presence of a neutrino. From the LO Feynman diagram two jets originating from the hadronization of the b-quarks are expected. The NLO Feynman diagrams for single top quark production contain diagrams with real emission. This emission can then produce a third jet in the event. Examples of these Feynman diagrams for the s-channel production process are shown in figure 2.2.8.

For the t-channel production of single top quarks, the LO Feynman diagram including the decay studied in this analysis is shown in figure 2.2.9. The final state objects are a b quark

Figure 2.2.8: Representative diagrams of real emission correction for single top quark production via the s-channel process [65].

Figure 2.2.9: Leading-order t-channel diagram for single top quark production followed by a leptonic decay of the W boson.

originating from the decay of the top quark, a charged lepton and a neutrino originating from the decay of the W boson, and the ‘spectator’ quark. The partner of the initial state b-quark remains in the proton remnant and cannot be detected. Both in the s- and in the t-channel signal processes decays of the W boson into tau leptons are included as signal process to this analysis if the tau subsequently decays into either an electron or a muon.

Figure 2.2.10 shows representative diagrams of NLO t-channel single top quark production with real emission corrections. They include the W-gluon fusion diagrams as graphs (k)-(n). These diagrams contain a b-quark in the final state that can be reconstructed as another b-jet in the event. Thus, in addition to the gluon and light quark jets also additional b-jets can be produced at next-to-leading order.

Even before the discovery of the top quark in 1995 it was concluded that due to its high mass its lifetime would be too short to form bound states [69]. According to the Standard Model, unlike other quarks the top quark does not form mesons or baryons. This fact can be used to study the properties of a bare quark. Due to the V-A structure of the interaction, the top quarks are produced highly polarized [49,63,64,70–73]. This polarization results in angular correlations between the top quarks decay products. These angular correlations can be used to increase the separation between the single top quark signal and the Standard Model background

Figure 2.2.10: Representative diagrams of real emission correction for single top quark production via the t-channel process [65].

processes in multivariate analysis techniques [52,54]. Variables exploiting angular correlations have (among others) successfully been used at various stages in the history of searches for single top quark production: to set limits on the single top quark production cross section [74], to find evidence for single top quark production [9,10,75], and finally in the observation of single top quark production [11,12]. Also this thesis in which the data set is analyzed that was used to find evidence for single top quark production takes advantage of these variables. Details of the analyses from CDF and DØ that led to the observation of single top quarks are summarized in table 2.2.2. For both measurements the significance to measure a the cross section at this value or higher in the absence of signal is 5.0 standard deviations.

The measurements of the single top quark production cross section are still statistically limited. Once more integrated luminosity is used in the analyses, it will be possible to study the V-A structure of the weak interaction more precisely. Deviations of the angular correlations from the Standard Model expectation could then hint to scenarios beyond the Standard Model, e.g. charged technipions [76].

The polarization of the top quark in electroweak top quark production can be understood by looking at the decays of a polarized top quark in its rest frame. The W boson as a heavy spin-1

	CDF	DØ
Integrated luminosity	3.2 fb^{-1}	2.3 fb^{-1}
Assumed mass of the top quark	175 GeV	170 GeV
Measured cross section	$2.3^{+0.6}_{-0.5} \text{ pb}$	$3.94 \pm 0.88 \text{ pb}$
Significance (p-value)	$3 \cdot 10^{-7}$	$2.5 \cdot 10^{-7}$

Table 2.2.2: Details on the analyses from CDF and DØ that led to the observation of single top quark production [11,12].

particle has three possible helicity states. It can be right-handed, longitudinal, or left-handed. Because of the small mass of the b-quark (compared to the mass of the W boson and the top quark) the right-handed polarization of the W boson in the top quark rest frame is heavily suppressed and can be ignored [77]. Thus, the (anti-)b-quark from the (anti-)top quark decay is always left-handed (right-handed) in this approximation.

The decay of a top quark into a longitudinally polarized W^+ boson is visualized in figure 2.2.11(a). The left-handed b-quark needs to go in the opposite direction to the spin of the

Figure 2.2.11: The correlation between the spin of the top quark and the direction of the charged lepton in the top quark rest frame are visualized. On the left side, the top quark decays into a W boson with longitudinal polarization. On the right side, the W boson has a left-handed polarization [76].

top quark in order to conserve angular momentum. The W boson thus goes in the direction of the top quark spin. The spin of the positron that originates from the decay of the W boson has its spin aligned with the top quark. It moves in the same direction as the spin of the top quark. The decay of a top quark into a left-handed W^+ boson and a b-quark is shown in figure 2.2.11(b). Due to conservation of angular momentum the left-handed b-quark needs to go in the direction of the spin of the top quark. The W boson goes in the opposite direction. Again, the positron has its spin aligned with the top quark and moves in the same direction as the top quark spin. Thus, the charged lepton from the decay of the W boson is the parton that has the highest correlation with the original spin of the top quark. An analogous correlation can be found between anti-top quarks and electrons. The spin of the electron is then aligned with the spin of the anti-top quark, but its direction is against the spin of the anti-top quark. The maximum analyzing

power is found in the angle $\theta_{l\vec{s}}$ between the the charged lepton l originating from the decay of the W boson and the top-quark spin axis $\vec{s}$ [78]. The angular distribution is then given by

$$\frac{dN}{d(\cos\theta_{l\vec{s}})} = \frac{1}{2} \times (1 + A_{\uparrow\downarrow} \cos\theta_{l\vec{s}}), \quad (2.2.3)$$

where $A_{\uparrow\downarrow}$ is the spin asymmetry originating from the fact that top quarks are not produced as ultrarelativistic particles, i.e. their helicity eigenstates are not identical with their chirality eigenstates. $A_{\uparrow\downarrow}$ is given by

$$A_{\uparrow\downarrow} = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}}. \quad (2.2.4)$$

Because the neutrino in figure 2.2.11(b) needs to have enough transverse momentum to balance both the positron and the b-quark, its transverse momentum is on average higher than the transverse momentum of the charged lepton. This is a consequence of the V-A structure of the interaction.

The direction of the d-type quark provides the most effective spin axis for all single top production processes. This is shown in reference [71]. However, the direction of the d-type quark is experimentally not known. It has to be chosen by taking into account the Feynman diagrams as shown in figure 2.2.5.

For the s-channel production of single top quarks it is obvious that the d-type quark is in the initial state. Thus, it either comes from the proton or the antiproton. This makes the beam axis an ideal base for the analysis of spin polarization in single top s-channel events. In events where an antitop-quark is created, the initial state contains a d-quark, provided by the proton in most cases. In events where a top-quark is created the initial $\bar{d}$ quark is contained in the antiproton. Therefore the spin of the top quark in the top quark rest frame is aligned with the antiproton beam in 98% of the time.

The situation changes for t-channel production of single top quarks. There, the d-type quark can be found in the initial state in 23%, and in the final state in 77% of the events [47,71]. Since the final state u-type quark tends to move in the same direction as the initial state d-type quark, the observed light quark jet can be used as a basis to analyze the top-quark spin in both cases. In this basis the polarization of the top quark is 95%.

2.2.3 The CKM Matrix Element $|V_{tb}|$

The single top quark production cross section is directly proportional to the square of the CKM matrix element $|V_{tb}|$. Thus, with a measurement of the single top cross section it is possible to measure $|V_{tb}|$ without assuming unitarity of the CKM matrix or three fermion generations [54]. The value of $|V_{tb}|$ given in equation 2.1.2 and published by the Particle Data Group [15] is derived assuming both unitarity of the CKM matrix and three families. Three experimental facts support the assumption of unitarity:

1. The first two rows of the CKM matrix are consistent with the unitarity condition.
2. The measurement of the B_s -mixing frequency constrains the ratio $|V_{td}/V_{ts}|$.
3. The measurements of

$$R = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}, \quad (2.2.5)$$

performed by both CDF [79] and DØ [80] imply a strong hierarchy between $|V_{tb}|$ and the other two CKM matrix elements in the third row.

The measurement of R can also be used to set a limit on $|V_{tb}|$ under the assumption of unitarity, i.e. $\sum_i |V_{ti}| = 1$. Both analyses set the same limit $|V_{tb}| > 0.78$ at 95% confidence level.

An indirect measurement of $|V_{tb}|$ that does not require the assumption of unitarity has been performed on electroweak data from LEP, SLC, the Tevatron, and neutrino experiments [81]. The result mostly comes from electroweak corrections to Z boson decays, especially in $Z \rightarrow b\bar{b}$ interactions. Corrections in $Z \rightarrow b\bar{b}$ events containing a top quark are shown in figure 2.2.12. The result of this measurement is $|V_{tb}| = 0.77^{+0.18}_{-0.24}$.

Figure 2.2.12: Vertex corrections on $Z \rightarrow b\bar{b}$ containing top quarks.

From the cross sections for single top quark production measured by CDF [12] and DØ [11] direct measurements of the CKM matrix element $|V_{tb}|$ are obtained. The CDF analysis results in

$$|V_{tb}| = 0.91 \pm 0.11 \text{ (stat. + syst.)} \pm 0.07 \text{ (theory)} \quad (2.2.6)$$

and in a lower limit on $|V_{tb}|$ of

$$|V_{tb}| > 0.71 \text{ @ 95\% C.L.} \quad (2.2.7)$$

DØ sets a lower limit of

$$|V_{tb}| > 0.78 \text{ @ 95\% C.L.} \quad (2.2.8)$$

assuming $|V_{tb}|^2$ in the interval of $[0,1]$. When the upper constraint on $|V_{tb}|^2$ is removed the measurement results in

$$|V_{tb} \times f_1^L|^2 = 1.07 \pm 0.12, \quad (2.2.9)$$

where f_1^L is the strength of the left-handed Wtb -coupling.

2.2.4 Single Top Quark Production as a Window to New Physics

Beyond-the-Standard Model interactions can affect the production cross section for single top quarks and would thus lead to deviations from $|V_{tb}| = 1$ [82]. As discussed in reference [76], the three production mechanisms are sensitive to different new effects.

The s-channel process is sensitive to new charged bosons. The Feynman diagrams (figure 2.2.13 shows two examples) are similar the Standard Model diagrams. Only the W boson is replaced by a new particle. New gauge bosons, like a heavy W' boson are predicted by

Figure 2.2.13: Feynman diagrams for anomalous single top quark production via s-channel processes. The left plot shows a W' vector boson, the right plot a top-pion as predicted by topcolor.

topflavor theories [83–85]. New scalar bosons, such as a top-pion that couples to top and bottom quarks are predicted by topcolor theories [86–90]. A charged Higgs boson from the MSSM could also play a similar role. Typically, because of the additional diagrams, this would lead to an enhancement of the s-channel cross section, especially if it is possible to produce the boson on-shell. The effects of some of those theories on the s-channel cross section are shown in figure 2.2.14 for both the Tevatron (left plot) and the LHC collider (right plot). Because of the large mass of the gauge boson, the topflavor model is barely distinguishable from the SM for the Tevatron. At the LHC however, the large mass is no problem due to the higher center-of-mass energy. Contributions of additional bosons would be suppressed in the t-channel by $1/M_B^2$, where M_B is the mass of the boson.

The t-channel cross section is very sensitive to additional new interactions. Flavor changing neutral current (FCNC) interactions are one example. Feynman diagrams for such interactions are shown in figure 2.2.15. The t-channel cross section would be increased because additional diagrams of type $qc \rightarrow qt$ would contribute. Although the interaction is presumably weaker, the higher c-quark parton density in the proton (compared to the b-quark parton density) would compensate this effect and lead to an overall rise of the cross section. The s-channel cross section would also be enhanced. However, the effect would probably be small due to the weakness of the FCNC interaction. If the CKM matrix element $|V_{ts}|$ would be larger than predicted, this could also lead to an enhancement of the t-channel cross section, due to the parton density functions. Examples of the effects that affect the t-channel cross section are also shown in figure 2.2.14.

Figure 2.2.14: Examples of how BSM processes would affect the single top quark cross section at the Tevatron collider (left) and at the LHC (right). The black dot represents the SM values of the single top quark cross section. The oval lines indicate the 3σ theoretical uncertainties. A top-flavor model with a Z' of mass 1 TeV and $\sin^2 \Phi = 0.05$ is indicated by the purple X. The effect of a charged top-pion with mass 250 GeV (left) and 450 GeV (right) is represented by the blue cross, assuming $t_R - c_R$ mixing of 20%. The green circle shows the effect of a FCNC Ztc -vertex and the red star shows the effect of a fourth quark generation. The figure is taken from reference [76].

Figure 2.2.15: Feynman diagrams for flavor changing neutral current interactions producing a single top quark via the s-channel (a) and the t-channel process (b).

3 The Tevatron Collider and the DØ Detector

The data analyzed in this thesis was produced by high energy proton-antiproton collisions at the Tevatron accelerator and recorded by the DØ detector. The Tevatron accelerator is located at the Fermi National Accelerator Laboratory (FNAL, also known as Fermilab, [91]) in Batavia, IL, USA. Fermilab was established in 1967. It is part of the U.S. Department of Energy [92] (DOE). Besides the Tevatron collider complex it also hosts other facilities, e.g. the MiniBooNE or the Minos experiments. The center-of-mass energy of $\sqrt{s} = 1.96$ TeV of the Tevatron collider makes it the only place world-wide to directly produce top quarks in relative abundance. Section 3.1 explains the chain of accelerators used in order to accelerate the protons and antiprotons to an energy of 980 GeV. Furthermore, the production of antiprotons is explained. Section 3.2 describes the DØ detector that is used to record information about the particles that are created in the $p\bar{p}$ collisions.

3.1 Fermilab Accelerator Facilities

The Fermilab accelerator complex consists of a chain of accelerators. Their goal is to produce and collide protons and antiprotons and to accelerate them up to an energy of 980 GeV. The five accelerators that are involved in these tasks are the Cockcroft-Walton, the LINAC, the Booster, the Main Injector and the Tevatron. The individual accelerators are briefly outlined in the following. More information can be found in [93,94]. In figure 3.1.1 these accelerators are shown schematically.

Cockcroft-Walton

The starting point of the acceleration chain is a bottle of hydrogen gas (H_2). In a magnetron surface-plasma source [96–98], the hydrogen molecules are split and additional electrons are bond to the atoms. The magnetron source consists of an oval cathode. This cathode is surrounded by an anode inside a magnetic field of 0.1-0.15 T and coated with Cesium. This helps to increase the rate at which the H^- ions are created by reducing the work function for removing an extra electron. The ions leave the source through an aperture in the cathode, pulsed with a frequency of 15 Hz. At that point, they have an energy of 18 keV. Figure 3.1.2 shows a sketch of the ion source.

Figure 3.1.1: Fermilab's accelerator chain [95].

Figure 3.1.2: Sketch of the magnetron, the source of H^- ions [93].

The negatively charged ions are then accelerated by the Cockcroft-Walton accelerator, which is located next to the magnetron source. The Cockcroft-Walton generator [96,99] uses a 75 keV AC input voltage to charge capacitors in parallel. The voltage from the capacitors is applied in series. This leads to a multiplication of the voltage value and the H^- ions can thus be accelerated to an energy of 750 keV.

LINAC

The task of the LINAC (LINEar ACcelerator) [97,99,100] is to accelerate the 750 keV H^- ions up to an energy of 400 MeV. This is achieved in two steps. First, the ions are accelerated to an energy of 116 MeV in an Alvarez drift-tube accelerator, built in 1971. In a second step, a more modern (built in 1993), side-coupled accelerator accelerates the ions up to 400 MeV. Overall, the LINAC is 130 m long and consists of an alternating series of metallic drift tubes and vacuum gaps (visualized in figure 3.1.3). At its end, the proton bunches are separated by 5 ns.

Figure 3.1.3: Visualization of the alternating series of gaps and drift tubes used in the linear accelerator [101].

Booster

The Booster is the first circular accelerator in the chain of accelerators. It is a synchrotron with a radius of 75 m. The beam of H^- ions from the LINAC is passed through a thin carbon foil when the particle bunches are injected into the Booster [102,103]. The carbon foil strips off the orbital electrons, leaving behind the positively charged protons. These protons are then accelerated with RF cavities to an energy of 8 GeV. This process takes 33 ms and 16,000 turns per proton bunch.

Main Injector, Debuncher and Accumulator

The Main Injector [104] is the next accelerator in the chain after the Booster. It is also a synchrotron, but with a circumference of 3320 m, it is much larger than the Booster. Commissioned in 1998 it replaced the Main Ring. The Main Injector has two duties. Its first task is to accelerate protons up to 120 GeV and to send them to the Antiproton Source [96,105,106]. The second task is to accelerate protons and antiprotons to an energy of 150 GeV and to inject them in the Tevatron.

To produce antiprotons, 8 GeV protons from the Booster are accelerated to an energy of 120 GeV and sent to a 7 cm thick nickel target. A lithium lens focuses the secondary particles. After the lens a dipole magnet acts as a charge-momentum separator and filters antiprotons with an energy of 8 GeV from the beam. The whole procedure is visualized in figure 3.1.4. In order to establish a manageable beam, the antiprotons are fed into the Debuncher and the

Figure 3.1.4: Visualization of the antiproton source [106].

Accumulator.

The Debuncher is another synchrotron. It is triangular-shaped with a mean radius of 90 m. Its task is to capture the antiprotons that arrive with a high momentum spread and to minimize the momentum spread. The protons are not accelerated in the Debuncher. They are kept at an energy of 8 GeV. The Debuncher exchanges the high energy spread of the protons for a large time spread, a process known as *bunch rotation*. The exchange bases on the fact that more energetic protons see a different phase of the radio frequency than the low energetic ones. From the Debuncher, the prepared antiprotons are ‘stacked’ in the Accumulator, another 8 GeV synchrotron. The Accumulator is also triangular-shaped and has a mean radius of 75 m. Both Debuncher and Accumulator make use of *stochastic cooling*, i.e. the reduction of the random motion of the beam [107]. The whole Antiproton Source, i.e. the complex of target, Debuncher and Accumulator, is able to produce $2 \cdot 10^{11}$ antiprotons per hour.

Recycler

The synchrotron called Recycler uses permanent magnets to store antiprotons at an energy of 8 GeV [108]. Originally, it should ‘recycle’ antiprotons from a Tevatron store, cool them and store them. This project was abandoned due to early problems in Run II. Now, the Recycler is used to store antiprotons from the Accumulator. When the Accumulator becomes full, the stacking efficiency decreases. Transferring the antiprotons to the Recycler thus improves the stacking efficiency. In the Recycler not only stochastic cooling is utilized. The antiproton beam and subsequently the luminosity could be significantly improved by applying *electron cooling* in the Recycler [109]. Electron cooling was introduced because stochastic cooling alone starts losing effectiveness with too many antiprotons stored in the ring.

Tevatron

The Tevatron accelerator is the largest of the accelerators installed at Fermilab. It is a collider and storage ring with a circumference of 6.28 km. Protons and antiprotons are injected with an energy of 150 GeV and accelerated up to an energy of 980 GeV. The Tevatron is

the only accelerator at Fermilab that uses superconducting magnets and thus the whole ring has to be kept at a temperature of about 4.3 K. The nearly 1,000 magnets are made up of a niobium/titanium alloy and produce a magnetic field strength of 4.2 T that bends the two circulating beams. Once this energy is reached, collisions can be initialized and the two beams are allowed to collide for many hours, a so-called *store*.

The beam structure of the particles circulating through the Tevatron is shown in figure 3.1.5. Protons and antiprotons are arranged in *bunches*. The length of a bunch is about 37 cm. The

Figure 3.1.5: The beam structure of the Tevatron in Run II [93,110].

gap between two bunches is 132 ns and also referred to as one *tick*. The bunches are organized in three *superbunches* or *trains*. This reflects the threefold symmetry of the collider ring with the injection at the $F0$ coordinate, the CDF experiment at $B0$, and the $D0$ experiment. Each of the superbunches consists of twelve bunches, i.e. a total number of 36 bunches circulate around the ring. The time between two bunches is 396 ns, implying a collisions a rate of 2.5 MHz. However, not all ticks are filled to leave a time window for the beam abort system. Therefore, an effective collision rate of 1.7 MHz is usually quoted. The beam structure is similar for the proton and the antiproton beam. The crossing angle of the counterrotating beams is zero at the nominal interaction points.

3.1.1 Proton-Antiproton Collisions and Luminosity

When both the proton and the antiproton beam have reached the nominal energy of 980 GeV, collisions are initiated at two points around the accelerator ring: $B0$ (the CDF experiment) and $D0$ (the $D0$ experiment). The coordinate system of the Tevatron accelerator can be seen in figure 3.1.6. The interaction regions are also referred to as *low beta regions*, where ‘low beta’ is connected with the *beta function* that describes the properties of the beams at each point of the collider. At the interaction point, the nominal value of the beta function β^* is 35 cm [112].

Figure 3.1.6: Schematic view and naming scheme of the Tevatron collider [111]. The name of the DØ detector refers to its position D0 at the ring. The CDF detector is located at point B0 and the Main Injector is connected to the Tevatron at point F0.

The rate for a particular process $\dot{N}$ to occur at a proton-antiproton collision depends on its cross section σ and the luminosity:

$$\dot{N} = \frac{dN}{dt} = \sigma \cdot \mathcal{L}(t) \quad (3.1.1)$$

Figure 3.1.7 shows cross sections and event rates for selected physics processes as a function of the center-of-mass energy. The total number of events produced in proton-antiproton collisions N is proportional to the *integrated luminosity*:

$$N = \sigma \cdot \int \mathcal{L}(t) dt. \quad (3.1.2)$$

The integrated luminosity $\int \mathcal{L}(t) dt$ is measured in units of inverse barns. The integrated luminosity delivered by the Tevatron during the whole Run II period can be seen in figure 3.1.8. In equation 3.1.2 the expression $\mathcal{L}(t)$ is the *instantaneous luminosity*. It has the unit of $(b \cdot s)^{-1}$ and can be derived from properties of the colliding beams:

$$\mathcal{L}(t) = \frac{f_{RF} \cdot N_p \cdot N_{\bar{p}} \cdot B}{2\pi \cdot (\sigma_p^2 + \sigma_{\bar{p}}^2)} \cdot \left(\frac{\sigma_l}{\beta^*} \right). \quad (3.1.3)$$

The parameters in this equation are the Tevatron radio frequency f_{RF} ($f_{RF} = 53.104$ MHz), the number of bunches B per beam ($B = 36$), the number of (anti)protons ($N_{\bar{p}}$) N_p in a bunch, the width of these bunches σ_p and $\sigma_{\bar{p}}$ and a form factor F . The form factor is a function of the longitudinal length of the bunch σ_l and the value of the beta function at the interaction point β^* .

Figure 3.1.7: Event rates and cross sections for selected physics processes as a function of the center-of-mass energy of the collision $\sqrt{s}$ [113].

Figure 3.1.8: Integrated luminosity delivered by the Tevatron in Run II [114].

Figure 3.1.9 shows the maximal instantaneous luminosity for the Tevatron stores in Run II.

To measure the luminosity the number of inelastic proton-antiproton collisions is counted at the DØ experiment [115–117]. This procedure is chosen because it is difficult to determine the beam characteristics at the interaction point with enough precision. Therefore, inelastic

Figure 3.1.9: Peak luminosities of the Tevatron collider in Run II [114].

proton-antiproton scattering is chosen as a reference process with a known cross section σ_{inel} of 60.7 ± 2.34 mb. The instantaneous luminosity can then be defined as

$$\mathcal{L}(t) = \frac{1}{\sigma_{inel}} \cdot \frac{dN}{dt}. \quad (3.1.4)$$

However, considering the high number of particles in each bunch, it happens that more than one hard scatter interaction occurs during one bunch crossing. Instead of counting the number of collisions, the number of bunch crossings without a hard interaction is counted. Since the number of interactions per bunch crossing follows a Poisson distribution $P(n)$ with

$$P(n) = \frac{\mu^n}{n!} \cdot e^{-\mu}, \quad (3.1.5)$$

where n corresponds to the number of interactions and μ to the average number of interactions per bunch crossing, the instantaneous luminosity can be rewritten as

$$\mathcal{L}(t) = \frac{1}{\sigma_{inel}} \cdot \mu \cdot f_{RF} = -\frac{f_{RF}}{\sigma_{inel}} \times \ln(P(n=0)). \quad (3.1.6)$$

Here, $P(n=0)$ is the probability for a bunch crossing without a hard scatter interaction. Figure 3.1.10 shows the probability density distributions $P(n)$ for different instantaneous luminosities.

Figure 3.1.10: Number of interactions per bunch crossing for different instantaneous luminosities [115–117].

3.2 The DØ Detector

The DØ detector is a typical multipurpose detector for high energy physics experiments, designed to study $p\bar{p}$ collisions with an emphasis on high-mass objects and physics processes with high transverse momenta. Commissioned in 1992 the detector has already been taking data during the Run I period of the Tevatron. The Run II version of the DØ detector [118] was modified compared to the Run I version [119]. Only the Run II version of the DØ detector will be discussed here.

A spherical coordinate system (r, θ, ϕ) is used to describe positions in the detector. Its origin is located at the center of the detector, the nominal interaction point. The polar angle θ is measured with respect to the beam axis. The angle $\theta = 0^\circ$ is aligned with the proton beam direction and $\theta = 180^\circ$ with the antiproton beam direction, respectively. In figure 3.2.1 the definition of the azimuthal angle ϕ is shown. The z -axis of the detector is defined to be parallel to the beam axis. Positive values in z correspond to $\theta = 0^\circ$, negative values correspond to $\theta = 180^\circ$.

Figure 3.2.1: Coordinate system of the DØ detector with respect to the Tevatron ring and the circulating proton and antiproton beams [120].

Instead of the polar angle θ a quantity called pseudorapidity (abbreviated with the letter η) is used. It is defined as

$$\eta = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right]. \quad (3.2.1)$$

In the limit of massless particles, pseudorapidity is identical to the true rapidity y :

$$y = \frac{1}{2} \log \left[\frac{E + p_z}{E - p_z} \right]. \quad (3.2.2)$$

The rapidity y is invariant under a Lorentz boost along the z -direction. Proton-antiproton collisions at the Tevatron usually occur with such a boost. The reason for this boost are the different momenta of the initial state partons of the interaction. Each parton carries a different fraction of the proton momentum. The pseudorapidity for a particle with polar angle $\theta = 90^\circ$ is 0 and approaches ∞ in the limit $\theta \rightarrow 0^\circ$. Throughout this chapter the pseudorapidity is

calculated with respect to the origin of the detector, often referred to as η^{det} .

Distances between two objects in the detector or the size of an object in the detector are often expressed as a solid angle ΔR , with

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}, \quad (3.2.3)$$

where $\Delta\phi = \phi_1 - \phi_2$ and $\Delta\eta = \eta_1 - \eta_2$ for two objects 1 and 2.

The DØ detector has a length of 20 m and is 13 m high. It is hermetic with a solid angle coverage of almost 4π . Several layers of sub-detectors allow the identification of different particles and the measurement of their energies and directions. The inner-most detectors close to the beam pipe are the tracking detectors. They allow the reconstruction of the path of charged particles as they traverse the detectors. Section 3.2.1.1 describes the Silicon Microstrip Tracker (SMT) which is the first sub-detector after the beam-pipe. It is followed by the Central Fiber Tracker (CFT). Its properties are presented in section 3.2.1.2. The calorimeter consists of two layers itself. The first layer allows the measurement of the energies of electromagnetic particles such as electrons or photons. The second layer measures strongly interacting particles such as pions or neutrons. Section 3.2.2 describes the calorimeter system. Muons are not stopped by the calorimeter. Their presence in an event is detected by hits in the muon system. An overview over the muon system is given in section 3.2.3. In order to select the interesting hard interactions and to reject minimum bias interactions, a three level trigger system is used to identify those events and to reduce the rate of events that are written to tape. The trigger system is introduced in section 3.2.4, followed by a section about the luminosity monitor (section 3.2.5).

3.2.1 The Tracking Systems

Two subdetectors are installed in the Run II DØ detector to measure the trajectory of charged particles near the interaction region. With reconstructed tracks, both charge and transverse momentum of the corresponding particles can be accessed. Furthermore the tracks can be used to find vertices or to implement algorithms for the identification of jets originating from the decay of long-lived b hadrons. Both the *Silicon Microstrip Tracker* (SMT) [121] and the *Central Fiber Tracker* (CFT) [122] are inside a 2 T superconducting solenoidal magnet [123]. Figure 3.2.2 shows the location of these components. More details about the SMT system will be given in section 3.2.1.1. The CFT system will be explained in more detail in section 3.2.1.2.

3.2.1.1 SMT

The SMT detectors are the innermost subsystem of the DØ detector. They surround the beam pipe, which is made of beryllium and has an outer diameter of 38.1 mm, a length of 2.37 m and a wall thickness of 0.508 mm. Silicon microstrip sensors are used to provide precise tracking close to the beam pipe and to obtain a good performance for vertex finding and b-tagging. The basic idea behind silicon microstrip sensors is that charged particles traversing the sensors ionize the material and create electron-hole pairs. An electric field that is applied to the depletion

Figure 3.2.2: Schematic of the innermost region of the DØ detector [118].

zone of the sensor - an area depleted of free charge carriers such as electrons and holes - deflects them into opposite directions. The charge that is thus created is collected by narrow strips, so-called *microstrips*, and can be read out from the electrodes. The location of the microstrip indicates the spatial position the ionizing particle passes by.

To cover almost the full η range, the SMT detector consists of barrel and disk modules as shown in figure 3.2.3. In the central region, barrel modules are interspersed by disk modules. In the forward region, only disk modules are used. The barrel section ranges from -38.2 cm to 38.2 cm

Figure 3.2.3: The Silicon Microstrip Tracker is made up of disks and barrels [118].

in the z coordinate around the nominal interaction point. This length is chosen to cover the interaction region of proton-antiproton collisions with a width of $\sigma_z = 26$ cm. The barrel detectors primarily measure the $r - \phi$ coordinate. There are six barrel detectors with centers at $|z| = 6.2$ cm, 19.0 cm, and 31.8 cm. In radial direction, the barrel detectors extend from 2.7 cm to 7.6 cm. A cross sectional view of the barrel detector is shown in figure 3.2.4.

Figure 3.2.4: A cross sectional view of the SMT barrel detector [124].

As shown in figure 3.2.3, there are twelve F-disk modules. They are located at $|z| = 12.5$ cm, 25.3 cm, 38.2 cm, 43.1 cm, 48.1 cm, and 53.1 cm. In radial direction, they extend from 2.6 cm to 10 cm. The H-disk modules in the high- η region are installed at $|z| = 100.4$ cm and 121.0 cm. In radial direction, the H-disks extend from 9.5 cm to 26.0 cm. The disks primarily measure $r - z$, but also $r - \phi$.

Table 3.2.1.1 summarizes the specifications of the various sensors that are used in the SMT system. There are single sided (SS) sensors with microstrips on one side only and double sided (DS) sensors, with microstrips on both sides. For double sided sensors, the microstrips are arranged at an angle relative to each other, allowing to reconstruct a two dimensional information of the traversing particle.

In total there are 793k channels in the SMT. They are read out using 128-channel SVXIIe chips [125], that include a preamplifier, a 32-cell analog pipeline, and an analog-to-digital converter (ADC) with a sparse readout. The SVXIIe chips produce heat that could lead to type conversion and increase the depletion voltage of the silicon sensors. Therefore, the detector is cooled with a coolant of -10°C . This helps to keep the silicon sensors at a temperature below 10°C . Cooling also helps to reduce radiation damage to the silicon.

Trigger:

Due to the high number of channels, the SMT is not used in the Level 1 trigger stage. It would take too long to read all of the channels out. At Level 2, the *Silicon Track Trigger* (STT) uses information from the SMT system. It can measure the impact parameter of tracks and can thus be used to trigger events that are likely to contain a b-quark.

Module	Type	Layer	Pitch (μm)	Angle ($^\circ$)	Length (cm)
F-disk	DS	-	p: 50, n: 63.5	30	7.93
H-disk	SS	-	40, 80 readout	15 ^a	7.63 inner
		-			6.33 outer
Central barrels (4)	DSDM ^b	1,3	p: 50, n: 153.5	90	12.0
	DS	2,4	p: 50, n: 62.5	2	6.0×2^c
Outer barrels (2)	SS	1,3	50	-	6.0×2
	DS	2,4	p: 50, n: 62.5	2	6.0×2

Table 3.2.1: SMT sensor specifications.

^atwo SS detectors mounted back to back^bDouble Sided, Double Metal^ctwo 6 cm sensors bonded together

3.2.1.2 CFT

The CFT is the second tracking device, following the SMT detector. It occupies the radial distance of 20 cm to 52 cm from the beam pipe. It is made up of scintillating fibers that are mounted on eight concentric cylinders. The length of the fibers is 2.52 m, except for the two inner cylinders. They have a length of only 1.66 m. Each cylinder is instrumented with two doublet layers of fiber. The first layer points in the radial direction. The second one points at a stereo angle of $\pm 3^\circ$, where the signs alternate between the cylinders. In total, there are 76,800 fibers. Each doublet on the innermost cylinder has 2,560 fibers and the doublet on the outermost cylinder have 6,500 fibers each. The outer layer covers an η region of $|\eta| < 1.7$. The diameter of a fiber is only $835 \mu\text{m}$, resulting in an inherent doublet resolution of about $100 \mu\text{m}$. Table 3.2.2 summarizes the properties of the fibers in the different cylinders.

The fibers are made of polystyrene (PS). The PS is doped 1% by weight with the organic fluorescent dye paraterphenyl (pT). An ionizing particle excites the PS. This excitation is transferred to the pT. Within a few nanoseconds, the pT has a fluorescent decay, resulting in light with a wavelength of 340 nm. To increase the mean free path of the light, 3-hydroxyflavone (3HF) is used at 1,500 ppm as a wavelength shifter, resulting in a final radiation with a wavelength of 530 nm. The fibers have two claddings to increase the attenuation length. While one end of the fiber is mirrored, the other end is connected to a clear fiber optical waveguide. The length of the waveguides varies from 7.8 m to 11.9 m. The waveguides take the signal to the *Visible Light Photon Counters* (VLPCs) [126,127]. The VLPCs are impurity-band silicon avalanche photodetectors that operate at 9 K and have an excellent quantum efficiency greater than 75%. They are capable of detecting single photons and have a gain of 22,000 to 65,000. Figure 3.2.5 shows an endview schematic of the CFT layers and their associated waveguides.

The VLPC cassettes also accommodate the readout electronics on *Analog Front End* (AFE) boards. The cassettes are mounted in cryostat slots. The VLPCs are located at the lower end,

Cylinder	Stereo Angle	Radius (cm)	Fibers per Cylinder	Length (m)
1	+3°	20	$2 \times 2 \times 1280$	1.66
2	-3°	25	$2 \times 2 \times 1600$	1.66
3	+3°	30	$2 \times 2 \times 1920$	2.52
4	-3°	35	$2 \times 2 \times 2240$	2.52
5	+3°	40	$2 \times 2 \times 2560$	2.52
6	-3°	45	$2 \times 2 \times 2880$	2.52
7	+3°	50	$2 \times 2 \times 3200$	2.52
8	-3°	52	$2 \times 2 \times 3520$	2.52

Table 3.2.2: Characteristics of the CFT system.

Figure 3.2.5: Schematic endview of the CFT with corresponding waveguides [118].

i.e. the cold end, of the cassette.

Trigger:

The fast readout of the CFT system allows the use of signal from the axial doublets for Level 1 triggering in the *Central Track Trigger* (CTT). Tracks found in the L1CTT are also sent to the Level 1 muon trigger system (L1MUO) for the matching with a muon candidate. Furthermore,

information from L1CTT is used together with the STT in Level 2 for track finding with the SMT system.

3.2.2 The Calorimeter Systems

Calorimeters measure the energy of a particle by total absorption. Electrons and photons produce an electromagnetic shower. Due to the interaction with matter, electrons emit photons (bremsstrahlung) and photons produce electron-positron pairs. Showering continues until a critical energy is reached, at which the electron starts losing more energy by collisions than by bremsstrahlung. At the critical energy photons are no longer able to produce electron-positron pairs. A unit typically used in calorimetry is the *radiation length* X_0 . The thickness of the calorimeter is often expressed in terms of X_0 . X_0 is defined as the length needed for an electron's energy to be reduced to $1/e$ of its original energy by radiation losses. Furthermore, the mean free path photons travel before they produce an electron-positron pair can be expressed in terms of X_0 : it is approximately $\frac{9}{7}X_0$ [128].

The interaction of hadronic particles with matter is more complex [129], though they also produce showers. In this case, a typical scale is the *interaction length* λ_A , i.e. the mean free path between interactions that are neither elastic nor diffractive. The depth of a hadronic shower depends on the atomic number (Z) of the material that is used.

The calorimeters in the DØ detector stop all particles except for muons and neutrinos. The muons lose energy in the calorimeters but traverse it and are finally detected in the muon chambers (see section 3.2.3). The neutrino can only be observed implicitly assuming conservation of momentum (see section 4.7 for details of the reconstruction of missing transverse energy).

The calorimeters are *sampling calorimeters* with uranium plates and liquid argon (LAr) as active medium. A schematic of a calorimeter cell can be seen in figure 3.2.6. It consists of alternating layers of absorber and signal boards. In the absorber plates, the radiation length is short, i.e. particles can be stopped after a short distance. However, it is not possible to read out a signal from them. Therefore, the gaps between absorber plates are filled with LAr. In these gaps, the shower is sampled. Charged particles passing through the gap ionize the LAr. A voltage of +2 kV is impressed upon the resistive surface of the signal boards. This leads to an electron drift time of 450 ns across the 2.3 mm LAr gap. The charges collected by the signal boards are then used to measure the total energy of the incident particle or jet. In figure 3.2.7 the readout chain of the calorimeter starting from an individual LAr cell is displayed.

Three separate cryostats are instrumented with calorimeter cells in the DØ detector. One in the central region (CC) and two in the forward regions (EC). The term EC combines the two end calorimeters ECS and ECN located at the 'south' and the 'north' of the experiment. The cryostats cool the active material and keep it at a temperature of 90 K. Figure 3.2.8 shows an isometric view of the calorimeter with all its subsystems. The electromagnetic (EM) sections of the calorimeters are closest to the interaction point. Their purpose is the measurement of the energy of electrons and photons. Nearly pure depleted uranium plates with a thickness of

Figure 3.2.6: Schematic view of a calorimeter unit cell [118].

Figure 3.2.7: Readout chain of the DØ calorimeter [118].

3 mm (CC) and 4 mm (EC) are used. The EM modules are divided into four layers, known as *floors*. They are labeled EM1, EM2, EM3, and EM4. The *fine hadronic* (FH) sections are next in depth and divided into three floors (FH1, FH2, and FH3) in the CC and in four floors in the EC (where an additional FH4 is installed). The EC is subdivided into three different hadronic regions with different interaction lengths, called ‘inner hadronic’, ‘middle hadronic’, and ‘outer hadronic’ region. The FH sections use 6 mm thick uranium-niobium (2%) alloy plates. The *coarse hadronic* (CH) sections are the last in depth. In the CC 46.5 mm thick plates of copper are used, the EC uses stainless steel. In the CC and in the ‘inner hadronic’ and ‘middle hadronic’ modules of the EC, there is only one CH floor. In the ‘outer hadronic’ module there are three CH floors. Table 3.2.3 summarizes the interaction lengths of each of the modules. The value for the first EM layer also includes the material in the cryostat wall.

Besides the measurement of the energy of particles, the calorimeter has another task to fulfill: to measure the location of the shower. For this purpose, the floors are segmented into calorimeter cells of $\Delta\eta = 0.1$ and $\Delta\phi = 2\pi/64 \approx 0.1$. For a precise measurement of the position of electromagnetic showers, the segmentation in EM3 is $\Delta\eta = 0.05$ and $\Delta\phi = 2\pi/128 \approx 0.05$. This is a result of the measurement of electromagnetic showers from

Figure 3.2.8: Isometric view of the calorimeter [118].

Electromagnetic Calorimeter [X_0]			Hadronic Calorimeter [λ_A]				
Layer	CC	EC	Layer	CC	EC		
					inner	middle	outer
EM1	1.4	1.6	FH1	1.3	1.1	0.9	-
EM2	2.0	2.6	FH2	1.0	1.1	0.9	-
EM3	6.8	7.9	FH3	0.76	1.1	0.9	-
EM4	9.8	9.3	FH4	-	1.1	0.9	-
			CH	3.2	4.1	4.4	6.0
EM	20.0	21.4	HAD	6.26	8.5	8.0	6.0

Table 3.2.3: Characteristics of the different calorimeter floors and total depth of EM and hadronic calorimeter.

the Run I period, where the peak of these showers was found in EM3. Due to the additional material in front of the calorimeter in Run II (in particular the solenoidal magnet), the shower maximum is reached earlier, now. Figure 3.2.9 shows the arrangement of the calorimeter cells in *pseudo-projective* towers. Pseudo-projective indicates, that the centers of the towers point to the nominal interaction point. However, the cell boundaries are arranged perpendicular to the absorber plates and thus do not point towards the center of the detector. The calorimeter covers a region up to about $|\eta| = 4$.

Figure 3.2.9: This schematic view demonstrates the segmentation of the calorimeter into pseudo-projective towers [118].

The performance of the calorimeter can be quantified in terms of its energy resolution $\Delta E/E$. There are three contributions to the energy resolution:

$$\frac{\Delta E}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C \implies \left(\frac{\Delta E}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2. \quad (3.2.4)$$

These contributions are:

- **Sampling term:** $\Delta E/E \propto 1/\sqrt{E}$
Showers are *statistical* processes. This term describes the fluctuations in the energy depositions due to this statistical behaviour. Although intrinsically limited, the accuracy of a calorimeter improves with energy.
- **Noise term:** $\Delta E/E \propto N/E$
This term does not depend on the energy. It describes *instrumental* effects like uranium noise or pedestal subtraction. The lower the energy, the more important is its contribution.
- **Constant term:** $\Delta E/E \propto C$
This term limits the resolution at high energies. It is also-called *systematic term*, because it takes the uncertainties from the calibration and non-uniformities of the calorimeter devices into account.

The parameters of the energy resolution of the calorimeter as introduced in equation 3.2.4 are summarized in table 3.2.4 for the central calorimeter. They are measured from data for the

electromagnetic calorimeter [130] and the hadronic calorimeter [131]. Furthermore, resolutions for EM objects (electrons, photons) and jets are shown for 50 GeV and 100 GeV objects.

	S	N	C	ΔE [GeV]	
				$E = 50 \text{ GeV}$	$E = 100 \text{ GeV}$
Electromagnetic objects	0.15	0.29	0.041	2.3 (4.6%)	4.3 (4.3%)
Jets	1.05	2.13	0.036	7.9 (16%)	11 (11%)

Table 3.2.4: Energy resolution parameters for the central calorimeter region. The values are derived from data [130,131].

Trigger:

Triggering on calorimeter information is important for all analyses with jets and electrons in the final state. In the first two trigger stages Level 1 and Level 2, a fast readout of the energy deposits in the calorimeter is used. A lateral segmentation of $\Delta\eta \times \Delta\phi \approx 0.2 \times 0.2$ is considered in the EM and FH layers. These 0.2×0.2 towers are called *trigger towers*. To trigger an event at Level 1, the decision is made based on the number of trigger towers above certain thresholds in transverse energy. These thresholds are either defined in the EM layer only (for the triggering of electromagnetic objects) or in the full trigger tower, including EM and FH layers (for the triggering of jets). At Level 2 EM objects and jets are defined based on some clustering of trigger towers [132]. The seed for the clustering is provided by the Level 1 trigger information.

3.2.3 The Muon System

The muon system [133] lies outside the calorimeter. Inside the calorimeter, muons lose about 1.6 GeV of their energy, acting as a minimum ionizing particle. However, muons are not stopped by the calorimeter. Therefore, it is the muon system duty to identify them and to measure their location and transverse momentum. Their transverse momentum is usually measured with the central tracking systems. The solenoidal magnetic field (shown in figure 3.2.10 in the case that the toroids are off) and the number of hits in the SMT and CFT detectors allow a more accurate measurement than the muon system alone. However, the ability to measure the transverse momentum of muons with the muon system alone is essential for muons with $|\eta| > 1.6$. In this region, the central tracking system has a lower efficiency.

To fulfill these tasks, the muon system consists of a toroidal magnet, three layers of wire chambers and scintillators. The arrangement of the wire chambers is shown in figure 3.2.11. Figure 3.2.12 shows the arrangement of the scintillators of the muon system. The toroidal magnet is needed for the momentum measurement in the muon system. The magnetic field in the central (CF) and end (EF) toroidal magnets is shown in figures 3.2.13(a) and 3.2.13(b). The wire chambers are needed for the determination of the position of the muons and for triggering. The scintillators have a fast readout. With this precise timing information it is possible to reject muons produced in air showers initiated by cosmic particles, so-called *cosmic muons* or

Figure 3.2.10: The magnetic field of the solenoidal magnet [133].

Figure 3.2.11: Exploded view of the muon system wire chambers [118].

cosmics. The timing information is also used to match the hits recorded in the wire chambers with bunch crossings. In general, there are three layers of sensors: the A layer is the first one, closest to the interaction region. It is placed in front of the magnet. Layers B and C follow after the magnet and allow the measurement of the outgoing direction of the muons. The average energy loss of the muons across the toroidal magnet is 1.7 GeV.

The central muon system covers a range of $|\eta| < 1$. This coverage is extended by the forward

Figure 3.2.12: Exploded view of the muon system scintillators [118].

Figure 3.2.13: The magnetic field in the central (figure 3.2.13(a)) and end (figure 3.2.13(b)) toroidal magnets [133].

muon system up to $|\eta| < 2$. The central muon system uses *Proportional Drift Tubes* (PDTs). These tubes are filled with a gas mixture of 84% argone, 8% methane, and 8% CF_4 . With this gas mixture, the maximum drift time at a drift velocity of $10 \text{ cm}/\mu\text{s}$ is 500 ns. The drift distance can be measured with a resolution of 1 mm. The dimension of the drift chambers is $2.8 \times 5.6 \text{ m}^2$. They are made of aluminum tubes. The B and C layers each have three rows, or ‘decks’, of cells. The A layer has four decks, except for the bottom A layer with

only three decks. One deck is built by 24 large rectangular cells with a length of 10.1 cm. Roughly 90% of the central detector is covered by at least two layers of PDTs. 55% is covered by three layers. The wires are arranged parallel to the magnetic field. Thus, the PDTs on the sides are oriented in y direction, the ones at the top and the bottom are oriented in x direction.

Each cell consists of vernier cathode pads at the top and bottom (+2.3 kV) and an anode wire (+4.7 kV). The anodes are read out in pairs. The wires of adjacent cells are ganged together on one side. The position of the hit along the length of the wire is provided by the time difference between the readouts from the two wires. Depending on the location of the hit, a resolution between 10 cm and 50 cm can be achieved.

The central muon system has two layers of scintillators: the $A\phi$ system at the A layer and the *cosmic cap* outside the toroid. The cosmic cap on the top and upper sides of the PDT C layer consists of a total of 240 counters. The *cosmic bottom* is only instrumented with 132 counters, due to the support structure of the calorimeter. The $A\phi$ scintillators are oriented in an angle of 4.5° with respect to ϕ to match the CFT sectors and to make track matching easier. The scintillators are read out by photomultipliers. Depending on the distance of the hit from the phototube, 18 to 30 photoelectrons are recorded per hit. The time resolution of the $A\phi$ scintillators is about 2.5 ns for all counters combined. This value is not adjusted for differences in time-of-flight, light propagation in the counters, or cable length.

The forward muon system ($1 < |\eta| < 2$) uses three layers of *Mini Drift Tubes* (MDTs), filled with 90% CF_4 and 10% CH_4 and scintillating counters. With a cross section of $0.94 \times 0.94 \text{ cm}^2$ the MDTs are much smaller than the wire chambers in the central muon system. This results in shorter drift times. A drift time of less than 60 ns can be achieved. The A layer consists of four planes of tubes that are mounted along the field lines. In layers B and C only three planes of tubes are used. The maximum tube length is 5.83 m for the outer tubes in the C layer. A voltage of -3.2 kV is applied to the cathode. The anode wire is grounded. A total number of 48,640 wires is read out and a coordinate resolution of 0.7 mm per hit is achieved. The muon hit detection efficiency per plane is $(95 \pm 2)\%$. For muons with a transverse momentum lower than 20 GeV, the momentum resolution from the forward muon system alone is approximately 20%.

Three layers of trapezoidal scintillators are installed at the forward muon system. They are arranged in $r - \phi$ geometry. One of the layers is installed in front of the magnet and two outside. Each layer is divided into octants and contains 96 counters. The largest counters have a size of $60 \times 110 \text{ cm}^2$ and are located in the outer rows of the C layer. There are twelve concentric zones. In the nine inner zones, the η segmentation is 0.12, in the three outer zones 0.07. The ϕ segmentation is 4.5° . The time resolution for all counters combined for hits from reconstructed muon tracks is 2.2 ns.

Trigger:

The muon system is included in all levels of trigger decisions. There are two systems for trig-

gering at Level 1 [134,135]. The first one is based on the wire chambers and the scintillators. There, the scintillators are used to associate a signal in the wire chambers with a bunch crossing. The second muon trigger system attempts to match wire hits with tracks from the *Central Track Trigger* (CTT). With the track match, it is even possible to have a cut on the transverse momentum of the muon at Level 1, using the CTT track.

At Level 2 [136], the muon system receives information from the Level 1 trigger and additional information gained from a fast calibration performed straight from the muon system. The rejection power at Level 2 is improved by using better timing information from the scintillators and finer tracking.

3.2.4 The Trigger Systems

The collision rate at the DØ detector is 1.7 MHz. However, the total rate of data that one can reliably store to tape is limited to 30 MB/s. A trigger system with three layers is thus used to reduce the rate to tape to about 50 Hz. The goal of the trigger system is to select events with an interesting signature and to reject small angle inelastic collisions. The three stages of the trigger system are independent and called Level 1, Level 2, and Level 3. Figure 3.2.14 shows a schematic of the combined trigger system and the data acquisition (DAQ) system.

Figure 3.2.14: Schematic of the DØ trigger system and the DAQ system [118].

The requirement for the Level 1 trigger system is to reduce the incoming rate of 1.7 MHz to 2 kHz. A maximal processing time per event of $3.3 \mu\text{s}$ is allowed. Because of the short time that is available to either accept or reject an event at Level 1, the number of tools available for selecting interesting events is limited: Calorimeter trigger towers (i.e. layers of calorimeter cell energies within a $\delta\eta \times \delta\phi = 0.2 \times 0.2$ space) are used in the L1CAL, signals in the muon drift chambers or scintillators in L1MUO and track patterns in the CFT in the L1CTT. For a fast response, the Level 1 trigger consists of hardware and firmware trigger elements. The *Trigger Framework* (TFW) collects the information of the individual trigger systems and then decides to accept or reject the event. In addition, the TFW communicates with the front-end electronics and the trigger control computer (as can be seen in figure 3.2.14). The TFW is also responsible for the *prescaling* of triggers. Prescales are used to reduce the rate of a trigger without switching it off completely. If a trigger has a prescale set to n , only one out of n events

is accepted, while the other $n - 1$ events will be rejected.

The flow of events from the detector to the Level 1 and the Level 2 trigger is shown in figure 3.2.15. The Level 2 trigger acts on all events that pass the Level 1 trigger. It is designed to

Figure 3.2.15: Flow of trigger related data between the detector, Level 1 trigger, Level 2 trigger, and the trigger framework [118].

reduce the Level 1 output event rate of 2 kHz to 700 Hz. In addition to the information from the Level 1 trigger system, hardware engines and embedded microprocessors (*preprocessors*) are used to analyze signals from the front-end electronics of the individual detector subsystems. Physics objects are formed from the calorimeter (L2CAL), the preshower detectors (L2PS), the muon system (L2MUO), and the CFT (L2CTT). At Level 2 there is enough time to include information from the SMT system (L2STT). A global Level 2 processor uses the output of the preprocessors as input and checks for correlations in combinations of physics objects.

The Level 3 trigger is a software-based collection of algorithms. They are executed on a collection of computer farm nodes on the events accepted by the Level 2 trigger. The goal is to reduce the event rate to 50 Hz. The algorithms executed on the more than 300 farm nodes are similar to the offline algorithms. The trigger has access to the full detector readout, thus all subdetector data must be transmitted to the farm nodes. Between two and four Level 3 trigger processes examine an event and check if it satisfies at least one of the trigger criteria. Since the major part of the processing time is spent in the tools that reconstruct physics objects, the results of these tools are cached and shared between the trigger processes. Events that pass the Level 3 trigger are temporarily stored on a machine called the *Collector*. Once a certain number

of events is stored there, they are transferred to another machine called *Datalogger* before they are finally sent to the tape storage at the Feynman Computing Center.

3.2.5 The Luminosity Monitor

The luminosity monitor is located directly in front of the end-cap calorimeters at $|z| = 140$ cm (see figure 3.2.16). It covers a range of $2.7 < |\eta| < 4.4$, and its main task is to collect information about inelastic $p\bar{p}$ collisions in each bunch crossing. Consisting of a set of 24 plastic

Figure 3.2.16: Schematic of the DØ luminosity monitor. Its position is shown in relation to the beam pipe, the SMT system, and the endcap calorimeter [118].

scintillators, it detects fragments from the break-up of the protons from the scattering process. These fragments carry charge and thus produce light in the scintillators. This light is then recorded by photomultiplier tubes. The location of these tubes in the geometry of the monitor is visualized by the red dots in figure 3.2.17. Each monitor has a diameter of 371 mm and each counter is 15 cm long.

The information about the inelastic collisions is very important in order to properly normalize all data collected with the DØ detector. The inelastic $p\bar{p}$ cross section is known from measurements by previous experiments. Thus, measuring this cross section with the luminosity monitor allows the measurement of the total integrated luminosity to which the DØ detector has been exposed [137,138].

Besides the inelastic $p\bar{p}$ cross section, the luminosity monitor can be used to measure the beam halo rates. For the measurement of the cross section, these events are the dominant background source. However, with a time-of-flight resolution of 0.3 ns for the luminosity detector, it is possible to separate the two processes. This precise timing information furthermore allows to use the luminosity monitor as a fast vertex finder. The relative difference of coincidence counts in the North and South detectors can be used to determine the z position of the vertex according to

$$z = \frac{c}{2}(t_+ - t_-). \quad (3.2.5)$$

Figure 3.2.17: Schematic displaying the geometry of the DØ luminosity monitor. The red dots indicate the location of the photomultipliers [118].

In this equation, $t_{\pm}$ denotes the time measured by the North (+) and South (-) detectors, respectively. For a collision to count as a proton-antiproton collision, the vertex has to fulfill $|z| < 100$ cm. This cut corresponds to approximately four times the length of the interaction region $\sigma_z = 26$ cm.

4 Reconstruction of Physics Objects

The purpose of this chapter is to introduce the steps that are necessary to translate the output of the detector (hits in the silicon sensors, energy deposits in the calorimeter,...) into physics objects such as muons, electrons, or jets. Sophisticated algorithms have been developed to fulfill this task. The event signature of s- and t-channel electroweak top quark production as discussed in this analysis is challenging because it requires the interaction of all detector components and a good understanding of the resulting physics objects. Tracks (see section 4.1) need to be reconstructed from information of the SMT and the CFT system. The tracks are used to identify the primary vertex of the interaction (section 4.2) and to identify secondary vertices from long-lived hadrons, and are matched to muons (section 4.3) and electrons (section 4.4). Information gained from calorimetry is important to be able to reconstruct jets (section 4.5), the signature of final state quark decays. Jets that originate from a b quark can be identified by so-called b-tagging algorithms. In both s- and t-channel single top quark production two b quarks are produced. Thus, b-tagging is a powerful tool to identify single top quark events and to suppress background events that mimic the signal signature. Section 4.6 presents the b-tagging algorithm used in this analysis. Finally, section 4.7 explains the reconstruction of the missing transverse energy. This is needed as a starting point for the reconstruction of the neutrino which is created in the leptonic decay of the W boson from the W-t-b-vertex. The neutrino escapes detection because it is only weakly interacting and thus gives rise to missing energy in the transverse plane with respect to the proton-antiproton beam. Since in this analysis only decays of the W boson into electrons and muons are considered, the identification of tau leptons will not be discussed. Details covering this topic can be found in [139].

4.1 Tracks

A charged particle that moves inside the detector volume is bent by the magnetic field. Its helical, three-dimensional trajectory is called a track and can be described by five parameters. It is the task of track-finding algorithms to determine these five parameters for all charged particles in an event. Starting points are hits in the SMT and CFT detectors (see section 3.2.1), originating from energy deposits left from ionizing particles. In case of the SMT, a hit corresponds to charge gathered by the microstrips. The collected charge must be above a certain threshold to reduce noise hits. The center of the hit is the weighted average over all neighbored strips that have registered a hit. The drift of the electron-positron pairs created in the silicon due to the magnetic field is taken into account. The drift angle of the electron-positron pair with respect to the electric field line is known as the Lorentz angle. For the CFT system, a hit corresponds to the light collected from two fibers in each superlayer. Because the fibers are shifted by an angle of 3° , the x- and y-coordinates of the hit can be calculated from the timing

information at the intersection of two scintillating fibers. Thus, a track is a sequence of hits in the tracking detectors that can be associated with one charged particle.

Two track finding algorithms are used: the *Histogram Track Finding* algorithm (HTF) [140] and the *Alternative Algorithm* (AA) [141]. The HTF method performs a Hough transformation [142] of the hits in the transverse (x,y) space into a space that is defined by the curvature ρ and the azimuthal angle ϕ . The idea behind this transformation is, that a particle with many hits in the x-y plane can be identified by a unique curvature and azimuthal angle. While random hits will show a uniform distribution in the ρ - ϕ space, hits belonging to one charged particle will produce a peak. The hits in the ρ - ϕ space are filled into a histogram. Bins in the histogram that only contain few entries are removed. Then, the histogram is processed through a two dimensional Kalman filter [143,144] where each bin of the histogram is considered to be a track template. This Kalman filter incorporates the detector geometry and the material density and removes tracks with very large errors. Tracks passing the filter are refitted and smaller track errors are obtained. A second Hough transformation is needed to determine the longitudinal coordinate information. Here, hits in r-z space are transformed into the parameter space (z_0, C), where z_0 is the intersection of the track along the beam axis and C is the track inclination

$$C = \frac{dz}{dr}. \quad (4.1.1)$$

Again, histograms are created, this time in the z_0 - C space, cleaned and processed through a Kalman filter. If the track finding started in the SMT (CFT) system, the newly formed tracks are then extrapolated outwards (inwards).

The AA method works in two dimensions and requires three SMT or CFT hits. In the following, the concept is explained for SMT hits. It works similarly when starting with CFT hits. Taking the innermost of the three SMT hits, the next hit must be on the following layer within $\Delta\phi < 0.08$. The requirement for the next hit on a following layer is that it is found on a circle with a radius greater than 30 cm and an axial impact parameter with the beam spot of less than 2.5 cm. The cut on the radius of the curvature of the extrapolated track indicates that the transverse momentum of the track is at least 180 MeV. Another criterion for a track hypothesis to be considered is that the χ^2 of the overall fit is lower than 16. Each track hypothesis is extrapolated to the next layer in the SMT or CFT system. In those cases where multiple hits fulfill the requirements, for each hit, a new track hypothesis is created. To increase the efficiency of the algorithm, a certain number of layers without hits is allowed for each hypothesis. The hypotheses are ordered by number of hits, number of misses and by the χ^2 of the fit. As long as the hypotheses do not share too many hits with already selected tracks, the hypotheses become tracks according to this order. If there are less than three SMT hits the AA method allows for ‘CFT-only’ tracks, using CFT hits as seed.

Both track collections, the one gained from the HTF method and the one obtained from the AA method, are combined, refitted and smoothed using a Kalman filter. This procedure is explained in detail in [143].

4.2 Primary Vertices

Within one bunch crossing inside the detector, many $p\bar{p}$ collisions occur, most of them low energy inelastic scattering processes. To distinguish these interactions from the hard scatter interaction and to associate the reconstructed physics objects to the right interaction, it is important to identify the primary vertex, i.e. the three-dimensional location of the hard scatter interaction inside the beam pipe. The main task is thus to identify those tracks that come from the primary vertex and to reject tracks from minimum bias interactions nearby or secondary vertices due to heavy quark decays. The algorithm used to fulfill this task is the *adaptive primary vertex algorithm* [145].

In a first step, this algorithm selects all tracks with at least two SMT hits and a transverse momentum larger than 0.5 GeV. The tracks are divided into several interaction areas, where each area has a width of 2 cm along the z axis. The algorithm fits a vertex to each of these track collections. A Kalman filter is applied to remove tracks with the highest χ^2 contributions to the vertex fit. The removal of tracks stops, once the vertex fit has a $\chi^2/n_{\text{dof}} < 10$, where n_{dof} is the number of degrees of freedom in the fit. From now on, only tracks are taken into account, that fulfill $dca/\sigma_{dca} < 5$, dca is the distance of closest approach of the track to the beam position and σ_{dca} is the standard deviation of the dca distribution. The next step is the actual adaptive primary vertex algorithm. It is an iterative procedure that assigns a weight ω_i (according to equation 4.2.1) to each track i . The first fit is made with all $\omega_i = 1$.

$$\omega_i = \frac{1}{1 + \exp((\chi_i^2 - \chi_{\text{cutoff}}^2)/2T)}. \quad (4.2.1)$$

The χ^2 of the previous track fit is used as input to the next iteration. χ_{cutoff}^2 and T are parameters that can be tuned. The values currently used are $\chi_{\text{cutoff}}^2 = 4$ and $T = 1$. After reweighting, a Kalman filter is used again to determine the primary vertex. The weights ω_i of the tracks are updated using the result of the new fit. Once a weight ω_i is lower than 10^{-6} , the weight of this track is set to zero. The iteration stops if the weights for all tracks change by less than 10^{-4} or a maximum number of iterations has been performed already. An example of the weights of the tracks associated with a vertex is shown in figure 4.2.1. In figure 4.2.1(a) the track weights in $Z \rightarrow q\bar{q}$ and $Z \rightarrow b\bar{b}$ events are shown. For comparison, figure 4.2.1(b) shows the same distribution in data events requiring one muon with transverse momentum of at least 4 GeV and at least two back-to-back jets. The data sample is splitted according to the number of b-tagged jets. In this figure, events with no b-tagged jet and with two b-tagged jets are shown.

The result of this adaptive vertex algorithm is a list of primary vertices. To figure out which vertex is the one from the hard scatter interaction, each vertex is assigned a probability to originate from a minimum bias event, i.e. to be not the vertex of the hard scatter interaction. The transverse momentum of tracks is low in minimum bias interactions. Therefore, based on the transverse momentum of the track, a probability can be determined whether this track originates from such an inelastic $p\bar{p}$ collision [146]. From the individual probability for each track, a probability for each vertex can be derived to be a vertex of a minimum bias interaction. The vertex with the lowest probability is selected to be the primary vertex of the hard scatter interaction. Distributions of the minimum bias probability of vertices in simulated events are

Figure 4.2.1: Comparison of track weights in simulated $Z \rightarrow q\bar{q}$ and $Z \rightarrow b\bar{b}$ events (figure 4.2.1(a)) with a data sample containing at least two back-to-back jets, with either zero or two jets tagged as originating from the decay of a b hadron (figure 4.2.1(b)) [145].

shown in figure 4.2.2 for the primary vertex of the hard scatter interaction (figure 4.2.2(a)) and for minimum bias vertices (figure 4.2.2(b)).

Figure 4.2.2: Minimum bias probability for vertices in simulated events. Figure 4.2.2(a) shows the distribution for the selected primary vertex of the hard scatter interaction. In figure 4.2.2(b) the distribution for minimum bias vertices is shown [146].

4.3 Muons

The reconstruction of muons starts with the reconstruction of hits from both the scintillators and wire chambers in the three layers of the muon system [147,148]. The next step is to reconstruct

straight line segments from the hits in each individual layer [149]. Because there is no magnetic field between layers B and C, the tracks reconstructed in these two layers can be matched. A so-called local muon track is then reconstructed by extrapolating the muon segment through the toroidal magnet [150]. The energy loss of the muons by traversing the magnet is taken into account in the algorithm. Error matrix propagation is used to combine the local muon track with a track from the central tracker. This combination improves the resolution of the muon transverse momentum because the measurement of this quantity based on the curvature of the local muon track in the toroidal magnetic field alone is rather poor. In the combination procedure the influences of the magnetic field of the toroid and the solenoid are taken into account as well as the energy loss in the calorimeters and the toroid and multiple scattering. To reduce the contribution of muons that originate from cosmic rays, timing information is used. The muon candidate is required to hit all three layers of the muon system within 10 ns after the bunch crossing. As a second requirement to remove muons from cosmic rays, the muon tracks are required to come from the primary vertex of the interaction. A relative longitudinal distance of 1 cm is allowed. The cut on the transverse distance depends on the number of SMT hits that are associated with the track. If there is no SMT hit, a cut on the distance of closest approach (dca) of $|dca| < 0.2$ cm is applied. If there is at least one SMT hit associated with the track, this criterion is tightened to fulfill $|dca| < 0.02$ cm.

In the analysis, muons of quality ‘ $|nseg| = 3$ medium’ are used. This is one of the certified muon identification qualities [148]. ‘Medium $|nseg| = 3$ ’ means that the muon has:

- at least two A layer wire hits,
- at least one A layer scintillator hit,
- at least two BC layer wire hits, and
- at least one BC scintillator hit.

Figure 4.3.1 shows the reconstruction efficiency for muons of this type as a function of pseudo-rapidity η and azimuth angle ϕ . The inefficiency at the less instrumented bottom of the detector, the so-called ‘muon hole’, is clearly visible.

The muon is required to match a central track. The track quality is required to be medium, i.e. a $\chi^2/\text{ndof} < 4$ for the matching of local muon track and the track from the central tracker is required in addition to the criteria listed above. If a muon fulfills all these requirements, it is called a *loose* muon.

To satisfy the criteria of a *tight* muon, the muon has to fulfill additional isolation requirements. These criteria depend on the transverse momentum of the muon. The first one, I_{tr} , is shown in equation 4.3.1. It adds up the transverse momenta of all tracks in a cone of radius $R < 0.5$ around the direction of the muon, omitting the track associated with the muon itself,

$$I_{\text{tr}} = \frac{1}{p_{T,\mu}} \times \sum_{\text{tracks}} p_{T,\text{track}}. \quad (4.3.1)$$

The second isolation criterion, I_{cal} , is similar, but for energy deposits in calorimeter towers around the muon track. The functional form can be seen in equation 4.3.2. Only calorimeter

Figure 4.3.1: Muon reconstruction efficiency for muons of type ‘medium $|nseg| = 3$ ’ as a function of η and ϕ [148].

towers are taken into account that are in a cone around the muon direction of $0.1 < \Delta R < 0.4$. The lower value cuts out a cone of potential energy deposits from the muon itself due to its nature as a minimum ionizing particle traversing the calorimeter material,

$$I_{\text{cal}} = \frac{1}{p_{T,\mu}} \times \sum_{\text{cal. towers}} E_{T,\text{cal. tower}}. \quad (4.3.2)$$

To be counted as a tight muon, values smaller than 0.2 have to be achieved for both I_{tr} and I_{cal} . The combination of these two isolation criteria is also known as *TopScaledLoose*. Figure 4.3.2 shows the isolation efficiency for this and other isolation criteria as a function of transverse muon momentum measured in a $Z \rightarrow \mu\mu$ data sample.

4.4 Electrons

Goal of the electron identification is to select real electrons and to reject fake electrons. Electrons can be faked by jets with a high electromagnetic component, photons that convert to e^+e^- pairs, π^0 mesons where a track points in the direction of the shower, or η mesons [151].

The first step in the identification of electrons is to run a simple cone jet algorithm over the energy deposits in the calorimeters that results in a collection of EM clusters [152,153]. The threshold for the seed tower is 500 MeV of transverse momentum. Energy is clustered around this tower within a cone of radius $R < 0.4$ in the η - ϕ -plane. An electron candidate has to satisfy the following four criteria:

1. Its transverse momentum must be higher than 1.5 GeV,
2. The fraction f_{em} of energy deposits in the electromagnetic calorimeter E_{EM} has to be at least 90% compared to the total energy of the cluster E_{tot} :

$$f_{EM} \equiv \frac{E_{EM}}{E_{tot}} > 0.9. \quad (4.4.1)$$

Figure 4.3.2: Isolation efficiency vs. transverse momentum for muons that pass different isolation criteria. The TopScaledLoose isolation criterion (visualized by the blue triangles) is used in this analysis [148].

3. An isolation requirement f_{iso} that requires that the energy deposits in a ring with radii $0.2 < R < 0.4$ are less than 20% of the total energy of the cluster E_{tot} :

$$f_{iso} \equiv \frac{E_{tot}(R < 0.4) - E_{EM}(R < 0.2)}{E_{tot}(R < 0.4)} < 0.2. \quad (4.4.2)$$

4. The most energetic calorimeter tower in the cluster has to contain an energy fraction of at least $0.4 \cdot E_{tot}$.

To satisfy the electron quality called *d0correct*, the isolation criterion of equation 4.4.2 is tightened to $f_{iso} < 0.15$. By doing so, especially the jet background is further reduced. Up to now, the algorithm detects both electrons and photons with a high efficiency because no track match has been required so far. Electrons of quality ‘d0correct’ are important because they will be used for the electromagnetic corrections to the missing transverse energy (see section 4.7) if they have a transverse momentum higher than 5 GeV and are within $|\eta| < 2.5$.

There are two more electron qualities used in this analysis, *top_loose* and *top_tight*. To understand the additional criteria that are applied for these qualities, three more variables need to be introduced: the H-Matrix [154], the χ^2 of the track match, and the electron Likelihood [151].

H-Matrix

With the input of the following seven variables, the H-matrix tries to measure the compatibility of the energy deposits in the calorimeter with an electron shower:

- Energy fraction in the four EM layers,

- the $r\phi$ width of the shower in the third EM layer,
- logarithm of the total energy: $\log_{10}(E)$, and
- the ratio of the z position of the primary vertex over the uncertainty: z_{vtx}/σ_{vtx} .

These variables are used to calculate the covariance matrix M_{ij} for N electrons,

$$M_{ij} = \frac{1}{N} \sum_{n=1}^N \left(x_i^{(n)} - \bar{x}_i \right) H_{ij} \left(x_j^{(n)} - \bar{x}_j \right), \quad (4.4.3)$$

where $\bar{x}_i$ and $\bar{x}_j$ are the means of the shower variables x_i and x_j . They are derived from electrons in Monte Carlo events. The H-matrix is then defined as the inverse covariance matrix, i.e. $H = M^{-1}$. It is now possible to calculate a χ^2 for each electron k . This value tells how the shower of the electron candidate matches the shower of an electron:

$$\chi_{hm}^2 = \sum_{i,j=1}^7 \left(x_i^{(k)} - \bar{x}_i \right) H_{ij} \left(x_j^{(k)} - \bar{x}_j \right) \quad (4.4.4)$$

Track Match

To distinguish electrons from neutral particles such as photons or π^0 mesons, the presence of a track reconstructed in the central tracking detectors pointing to the electromagnetic energy cluster can be required. The quality of the track match is another way to separate electrons from neutral particles that have an overlapping track by chance. An electron is required to have a track matched in z and ϕ direction. Two χ^2 values are calculated to determine the matching quality:

- χ_{spatial}^2 only matches the z and ϕ directions:

$$\chi_{\text{spatial}}^2 = \left(\frac{\delta\phi}{\sigma\phi} \right)^2 + \left(\frac{\delta z}{\sigma z} \right)^2 \quad (4.4.5)$$

$\delta\phi$ (with $\delta\phi = \phi_{\text{track}} - \phi_{\text{EM cluster}}$) and δz (with $\delta z = z_{\text{track}} - z_{\text{EM cluster}}$) are measured at the third EM layer. The expected widths σ_ϕ and σ_z are determined from electrons in Monte Carlo events.

- $\chi_{E/p}^2$ also takes the difference in the transverse momentum p_T of the track and the transverse energy E_T of the electromagnetic cluster into account. This ratio E_T/p_T is close to one for electrons and differs for tracks that are randomly associated with the electromagnetic cluster. σ_{E_T/p_T} is the expected width of this ratio for an electron, determined from Monte Carlo events.

$$\chi_{E/p}^2 = \chi_{\text{spatial}}^2 + \left(\frac{E_T/p_T - 1}{\sigma_{E_T/p_T}} \right)^2. \quad (4.4.6)$$

Electron Likelihood

A set of seven variables x is used to define a likelihood measure to determine if an electron candidate with a track match really is an electron. The functional form of the likelihood measure L is:

$$L = \frac{P_{\text{sig}}(x)}{P_{\text{sig}}(x) + P_{\text{bkg}}(x)} \quad (4.4.7)$$

The signal probability P_{sig} and the background probability P_{bkg} are the products of the probabilities of the individual variables, i.e. $P_{\text{sig}} = \prod_{i=1}^7 P_{\text{sig},i}$ and $P_{\text{bkg}} = \prod_{i=1}^7 P_{\text{bkg},i}$. The track associated with the electromagnetic cluster is the one with the probability $P(\chi_{\text{spatial}}^2)$ that fulfills the distance requirements of $\delta\phi < 0.05$ and $\delta\eta < 0.05$. The variables used in the likelihood are:

- The spatial track match probability $P(\chi_{\text{spatial}}^2)$.
- E_T/p_T .
- The distance of closest approach of the track to the primary vertex of the hard scatter interaction.
- The χ_{hm}^2 value obtained by the H-matrix. A loose cut on $\chi_{hm}^2 < 50$ is already applied before the likelihood method is used.
- The fraction of electromagnetic energy in the cluster f_{EM} .
- The number of other tracks in a cone in the η - ϕ plane with radius $R = 0.05$ around the track that is associated with the electromagnetic cluster. An electron should have a single track pointing to the electromagnetic cluster. Electrons from photon conversions would have two tracks, and jets that fake an electron could have even more tracks.
- The scalar sum of the transverse momenta of all tracks except the associated track within a cone in the η - ϕ -plane of radius $R = 0.4$.

With the three variables presented above, the tighter electron quality criteria can be explained. For an electron to pass the *top_loose* quality cuts, the following criteria must be satisfied on top of the ‘d0correct’ quality cuts: The track associated to the electromagnetic cluster must fulfill $\delta\eta < 0.05$, $\delta\phi < 0.05$, $P(\chi_{E/p}^2) > 0$, and have a transverse momentum higher than 5 GeV.

The electron quality called *top_tight* finally also adds a cut on the result of the likelihood output. Electrons of the quality ‘top_tight’ are required to have a likelihood measure $L > 0.85$.

Figure 4.4.1 visualizes the reconstruction efficiencies for ‘top_loose’ and ‘top_tight’ electrons as a function of η^{det} [155]. The efficiencies have been determined using a ‘tag and probe’ method on both simulated $Z \rightarrow e^+e^-$ events and a $Z \rightarrow e^+e^-$ data sample. The differences in the reconstruction efficiencies around $\eta^{\text{det}} = 0$ are due to incomplete modeling of tracking efficiencies in simulated events.

In this analysis, only central electrons (so-called CC electrons) are used, i.e. electrons with $|\eta^{\text{det}}| < 1.1$.

Figure 4.4.1: Electron reconstruction efficiencies for the ‘top_loose’ (figure 4.4.1(a)) and the ‘top_tight’ (figure 4.4.1(b)) electron quality as a function of pseudorapidity η^{det} [155].

4.5 Jets

Quarks and gluons in the final state of a scatter process cannot be detected directly, because they hadronize. The energy deposits of the hadronization products can be measured in the layers of the electromagnetic and hadronic calorimeters of the DØ detector. A jet algorithm clusters these individual energy deposits and combines them into one object, a jet. The direction, the measured energy, and the momentum of the jet can then be related to the original quark or gluon [156]. Before a jet algorithm can be applied to the detected energy deposits of the calorimeter, the data of the calorimeter is preprocessed to remove noise. This step is explained in the next section (section 4.5.1). Section 4.5.2 will then explain the actual jet reconstruction.

4.5.1 Calorimeter Preprocessing

The preprocessing of data recorded by the calorimeter is performed, before any physics object is reconstructed from it. The goal of this procedure is to remove noise. An example for noise in the calorimeter are ‘hot’ cells. Due to hardware problems during data taking, individual calorimeter cells can then report high energy deposits. These cells can be suppressed to not affect the ongoing data taking. To further suppress hot cells and transient spikes in energy, the NADA algorithm is applied. NADA is an acronym for *New Anomalous Deposits Algorithm* and is applied at the Level3 trigger stage and during the offline processing of the event [157–159]. The NADA algorithm sets the energy of a cell to a value of 1 MeV if its energy deposit is identified as unphysical. This means that the cell itself has an energy $E_{cell} > 1 \text{ GeV}$, and the sum of the energies of the 26 neighboring cells E_i (with $1 \leq i \leq 26$) in the η - ϕ -plane E_{cube} is lower than a given cut value E_{cube}^{cut} and the energy of each cell is above a certain threshold E_i^{cut} , i.e. $E_i < E_i^{cut}$. Figure 4.5.1 sketches the candidate cell (black square) and its 26 neighbors (white squares).

To remove other sources of noise, such as uranium decays, pile-up from previous bunch-crossings, or noise introduced by the electronics, another algorithm is applied. It is called T42 algorithm [160–162]. It removes cells with a negative energy and cells that have an energy

Figure 4.5.1: Sketch of the neighboring calorimeter cells (white squares) around the candidate cell (black square) that are taken into account in the NADA algorithm [157].

between 2.5σ and 4σ over the pedestal value. In order not to remove cells that contain signal-like information, the latter cut is only applied if there is no neighboring cell next to the candidate that also measures an energy deposit with 4σ over the pedestal value. Neighbors are defined in the same way as for the NADA method. The T42 algorithm is applied on top of zero suppression. There, all cells with an energy less than 2.5σ above the pedestal value are removed to reduce noise.

4.5.2 Jet Reconstruction

An optimal jet algorithm that allows the reconstruction of the kinematics and direction of final state quarks or gluons should fulfill certain requirements [156,163]. It has to be *infrared safe*, i.e. insensitive against additional, soft radiation. This requirement is visualized in figure 4.5.2, where the jet algorithm should find two jets but only reconstructs one jet due to soft radiation.

Furthermore, a jet algorithm should be *collinear safe*. This requirement is visualized in figure 4.5.3. In this example it is shown how a jet algorithm can be sensitive to the ordering of particles according to their transverse energy that act as seed for the algorithm.

The following situation is another example for the requirement that a jet finding algorithm should be collinear safe: If a strongly interacting particle deposits its energy into several calorimeter towers instead of just one tower, the jet finding algorithm might not recognize these energy deposits as a seed, because the energy deposit within each tower is lower than the threshold of the algorithm. At hadron colliders, the center-of-mass of the hard scatter interaction is typically boosted with respect to the $p\bar{p}$ center-of-mass. A jet algorithm should

Figure 4.5.2: One requirement for a jet algorithm is infrared safety. An example for a situation where a jet algorithm is sensitive to soft radiation is shown here. While the algorithm finds two jets in the left diagram, it only finds one jet in the right one. The soft radiation misguides the algorithm to merge the two jets into one [156].

Figure 4.5.3: This diagram illustrates possible sensitivity of a jet algorithm to collinear radiation. Here, the sensitivity occurs due to the ordering in transverse energy of the particles used as seed [156].

find the same jets independent of the boost of the system. *Invariance under boosts* is thus another requirement. Furthermore, a jet finding algorithm must not be sensitive to the details of the final state and the kinematic quantities of the jet must obey some boundaries, e.g. that the transverse energy of a massless jet is lower than $\sqrt{s}/2$. This criterion is called *boundary stability*. The application of the algorithm should be generally possible and find the same jets on parton-, particle-, and calorimeter level (*order independence*). Finally, the algorithm should be easy to implement, easy to calibrate, stable with luminosity, unbiased, and efficient in the use of computing resources.

The algorithm to reconstruct jets in the DØ calorimeter is the *Run II Cone Algorithm*, also known as the *Improved Legacy Cone Algorithm* (ILCA) [156,163]. It is a seed-based algorithm. However, it does not use individual calorimeter towers as seeds. To improve its collinear safety, it starts with a *simple cone* algorithm that reconstructs calorimeter clusters that are then used as a seed. A first cluster, a so-called precluster, is made once a calorimeter tower has a transverse energy $E_T > 0.5 \text{ GeV}$. All other calorimeter towers within a cone of radius $R = 0.3$ (with $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$) and transverse energy $E_T > 1 \text{ MeV}$ are added to the precluster.

Towers added to the precluster are removed from the list of available towers. This list is an E_T -ordered list of calorimeter towers that the algorithm loops over, starting with the tower with the maximal E_T . Once one precluster is created, the algorithm continues with the next calorimeter tower with $E_T > 0.5$ GeV. The algorithm stops once all preclusters are created.

In the next step, a list of E_T ordered preclusters replaces the list of calorimeter towers. In this step, proto-jets are built from the precluster objects. The algorithm loops over all preclusters and checks, if the precluster is near an already existing proto-jet, using a criterion of $\Delta R < 0.25$, where $\Delta R = \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$ (where y represents the rapidity of the objects under consideration). If the ΔR criterion is not fulfilled, the precluster is used as a new seed for a proto-jet. Otherwise, the precluster is skipped and the next precluster is analyzed. Now, calorimeter towers are added to the new proto-jet candidate seed. All towers with $\Delta R < 0.5$ are added to the seed proto-jet candidate JC . After all towers are added, JC becomes a new proto-jet candidate JC' . If JC' has a transverse energy $E_T < 3$ GeV, the next precluster is analyzed. Otherwise, the proto-jet candidate becomes a proto-jet if $\Delta R(JC, JC') < 10^{-3}$ and JC' is no duplicate of another proto-jet that already exists.

As a method to minimize the sensitivity of the algorithm to soft radiation, the algorithm attempts to add additional proto-jets by using the midpoint of any pair of two proto-jets as a new seed. The iteration then works in the same way as described above, except for the $\Delta R < 0.25$ check or the check for duplicate proto-jets.

In the next step, a list of E_T -ordered proto-jets replaces the list of preclusters. Again, the algorithm iterates over the list. Now, the algorithm checks, if the proto-jet overlaps with any other proto-jet in the list, i.e. shares calorimeter towers. If not, the proto-jet is promoted to a jet and removed from the proto-jet list. Otherwise, a check is performed if the sum of the transverse energies of the overlapping towers is more than 50% of the total transverse energy of one of the two proto-jets. If this happens, the two proto-jets are merged into a new proto-jet object. This object is added to the list of proto-jets, and the individual proto-jets are removed from it. If the overlap is less than 50%, the two proto-jets are split into two distinct proto-jets whose total transverse energy and direction are recomputed. The towers in the overlap region are assigned to the proto-jet that is closest in ΔR . The two proto-jets are then put back into the list, the list of proto-jets is resorted and the iteration starts again. Once the algorithm stops iterating over proto-jets, the list of jets is complete and a set of quality criteria is applied to the jets [164]. Only jets satisfying all of these criteria are considered a good quality jet.

- In a first cleaning step, all jets with transverse energy $E_T < 6$ GeV are removed from the list.
- Cuts on the fraction f_{CH} of the jet E_T deposited in the coarse hadronic CH layers of the calorimeter:

- $f_{CH} < 0.4$, or
- $f_{CH} < 0.44$ and $|\eta^{det}| < 0.8$,

- or $f_{CH} < 0.65$ and $0.85 < |\eta^{det}| < 1.25$, and $n_{90} < 20$ (where n_{90} is the minimum number of towers that is needed to contain 90% of the jets transverse energy),
- or $f_{CH} < 0.46$ and $1.5 < |\eta^{det}| < 2.5$.
- Cuts on the electromagnetic fraction f_{EM} and other electromagnetic properties:
 - $f_{EM} > 0.05$, or
 - $f_{EM} > 0.04$ and $|\eta^{det}| > 2.5$, or
 - $f_{EM} > 0.03$ and $1.1 < |\eta^{det}| < 1.4$.
 - Jets with $f_{EM} > 0.95$ are removed.
 - Jets that overlap with an electron of quality ‘top_loose’ (as defined in section 4.4) are also removed.
- The jet has to pass the Level 1 trigger tower confirmation:
 - $L1SET > 55 \text{ GeV}$, or
 - $f_{90} < 0.5$ or $f_{CH} < 0.15$ if the jet is outside the Level 1 coverage, where f_{90} is the fraction of the number of towers within the jet that is needed to contain 90% of the jet’s transverse energy.
 - If the jet is reconstructed within the Level 1 trigger coverage, one of the following criteria must be fulfilled:
 - * $L1_{ratio} > 0.5$, or
 - * $L1_{ratio} > 0.35$ for $E_T < 15 \text{ GeV}$ and $|\eta^{det}| < 1.4$, or
 - * $L1_{ratio} > 0.1$ for $E_T < 15 \text{ GeV}$, and $|\eta^{det}| > 3$, or
 - * $L1_{ratio} > 0.1$ for $E_T \geq 15 \text{ GeV}$, and $|\eta^{det}| > 3$.

These quality criteria are derived with the goal to have a high efficiency for real jets and a high rejection power for unphysical background.

Up to now, no correction of the jet energy has been performed. However, corrections of the jet energy scale have to be applied to match the energies measured with the calorimeter with the energies of the final state quarks and gluons. The functional form of the correction is given in equation 4.5.1 and the individual terms are explained below,

$$E_{jet} = \frac{E_{jet}^{uncorrected} - O}{F_{\eta} \times R \times S}. \quad (4.5.1)$$

- $E_{jet}^{uncorrected}$ is the uncorrected jet energy, i.e. the energy of the jet as reconstructed from the jet finding algorithm.
- O is the offset correction. It represents energy that does not originate from the hard scatter interaction, e.g. additional minimum bias events or pile-up from previous bunch-crossings. The offset correction is measured in minimum bias interactions. The energy of calorimeter towers is summed up within a jet cone radius. Figure 4.5.4 shows the offset correction as a function of η^{det} for different primary vertex multiplicities.

Figure 4.5.4: Offset energy correction as a function of η^{det} . The corrections are shown for a cone size of $R = 0.5$ and different primary vertex multiplicities [165].

- F_η corrects for differences in the calorimeter response in different η regions. The relative response is measured with γ +jets events in the so-called *missing E_T projection fraction method*. Events with one photon and one jet flying back-to-back are analyzed. The energy of the photon is assumed to be perfectly well measured. Thus, any imbalance in transverse energy is an effect of the detector response. The response is corrected relative to the response to $\eta^{det} = 0$. The size of the effect is shown in figure 4.5.5 before the jet energy scale is corrected (figure 4.5.5(a)) and after the full jet energy correction has been applied (closure test, figure 4.5.5(b)).

Figure 4.5.5: The relative energy correction as a function of η^{det} is shown for uncorrected jets (figure 4.5.5(a)) and for fully jet energy scale corrected jets (closure test, figure 4.5.5(b)) [165].

- R corrects for the absolute energy response of the calorimeter. It is also measured using back-to-back photon+jet events, but after the η -dependent correction has been applied. This factor also corrects for energy losses in uninstrumented regions of the detector or

for the differences in the response of the calorimeter to low energetic hadrons compared to electrons or photons. Figure 4.5.6 shows the absolute energy response as a function of the partly-corrected jet energy scale and for different η regions of the detector.

Figure 4.5.6: Absolute energy response in different η^{det} regions after offset and relative response corrections for jets reconstructed with a cone size of $R = 0.7$ [165].

- The absolute response is obtained by a fit through all points shown in the graph. The uniform response in the different η^{det} regions proves the success of the relative response corrections.
- The showering correction, S , corrects for the part of the shower that is not included in the cone of the jet. It also corrects for energies that do not belong to the jet, but leak into its cone. The shower corrections are determined from Monte Carlo events. The size of the corrections is shown in figure 4.5.7 as a function of the corrected transverse jet energy and for three different η^{det} regions.
- If a jet contains a muon within $\Delta R < 0.5$, the jets are in addition corrected for the transverse momentum the muon and its neutrino carry away. This correction is important for jets originating from heavy quark flavors.

4.6 Identification of Jets Originating from b-Hadrons

B quarks can be found in the final state of many interesting physics processes such as single top quark production or top quark pair production. To identify these processes and to suppress the background of physics processes without final state b quarks, it is desirable to identify jets that originate from b quarks. The first way to identify b-jets, i.e. jets originating from a b quark, exploits the fact that about 20% of the b-jets are associated with a muon. The branching ratio for b quarks to decay into a muon is $BR(b \rightarrow \mu X) = 10.95\%$. Since almost

Figure 4.5.7: The showering correction for jets in data events, reconstructed with a cone size of $R = 0.5$, is shown as a function of corrected (up to absolute response) jet transverse energy for different pseudorapidity values [165].

100% of the b hadrons decay into hadrons that contain a c quark and the branching ratio for those charm hadrons to contain a muon in the final state is $BR(c \rightarrow \mu X) = 9.58\%$, these two numbers add up to the 20% mentioned above. The *Soft Lepton Tag* (SLT) algorithm is optimized to identify this kind of jets [166].

The long lifetime of b hadrons (compared to hadrons formed by light partons) enables to define another set of algorithms that distinguish b -jets from light flavor jets. These algorithms search for signs of the decay of a b hadron that can occur up to a few millimeters away from the primary vertex of the interaction [167]. Signs for the decay of a b hadron can either be the identification of a displaced decay vertex, a so-called *secondary vertex*, or tracks with a large impact parameter, i.e. with an offset from the primary vertex of the interaction.

This second type of algorithms (they are commonly known as *b-tagging algorithms*) require the identification of the primary vertex and so-called *track-jets* [167]. Track-jets are jet objects that are based on track information instead of calorimeter information. The algorithm that is used to identify track-jets is the same simple cone algorithm that is used for the preclustering of calorimeter towers in the jet reconstruction (see section 4.5). As seed, a track with transverse momentum $p_T > 1$ GeV is used. The cone size of the track-jets is $R = 0.5$ in the $\eta - \phi$ -plane. The tracks are ordered with decreasing transverse momentum and grouped into clusters with a width of 2 cm along the z -axis. Some selection requirements are applied to the tracks used as input to the jet algorithm:

- At least one SMT hit,
- transverse momentum of at least 500 MeV,

- $|b_{tr}| < 0.15$ cm, and
- $b_z < 0.4$ cm,

where $|b_{tr}|$ is the distance of closest approach in the x - y plane between a track and the closest primary vertex and b_z is the distance of closest approach in z direction. The requirements on these two variables are chosen to reject long-lived particles such as kaons or Λ hadrons. Once all track-jets are reconstructed, they are matched with the reconstructed calorimeter jets. A good match is defined by a maximal distance between the two jet objects of $\Delta R < 0.5$.

There are two algorithms that rely on the impact parameter of tracks. The *Counting Signed Impact Parameter* algorithm (CSIP) [168] and the *Jet Lifetime Probability* algorithm (JLIP) [169]. The CSIP algorithm marks a jet as b-tagged in two cases:

1. The impact parameter significance $S_{IP} = IP/\sigma_{IP}$ of two tracks is greater than three.
2. The signed impact parameter significance of three tracks is greater than two. A positive sign is assigned if the projection of the impact parameter onto the jet axis falls between the primary vertex and the jet. A negative sign is assigned if the projection is on the other side of the vertex.

The JLIP algorithm builds a probability based on all impact parameters of the jets.

The *Secondary Vertex Tagger* (SVT) [167] tags jets as b-jets based on a secondary vertex. Starting with tracks from the track-jet with an impact parameter significance $S_{IP} > 3$, vertex seeds with two tracks are built. With a Kalman filter algorithm secondary vertices are reconstructed by adding additional tracks. The track with the lowest contribution to the total χ^2 of the vertex fit is chosen as long as its contribution is lower than 15 and the total χ^2 is lower than 100. A secondary vertex has at least three tracks associated to it. For each secondary vertex a signed decay length $|L_{xy}|$ is defined as the distance between this secondary vertex and the primary vertex. The sign is defined in the same way as for the CLIP algorithm. Operating points of the SVT algorithm are defined and certified based on the decay length significance $S_{DL} = |L_{xy}|/\sigma(L_{xy})$, the transverse momentum of the jet, the number of SMT hits, the χ^2 of the vertex fit and many more parameters.

The algorithm that is used in the search for electroweak top quark production uses the results of the taggers introduced before (except for the SLT algorithm) and combines them in a neural network (NN). The SLT algorithm is orthogonal to the other taggers and therefore used to measure the efficiency of the neural network tagger. Seven variables are used as input to the NN tagger. Five of them come from the super-loose operating point of the SVT algorithm, the remaining two variables are the result from both the CSIP and JLIP algorithm. The variables are summarized in table 4.6.1.

For the NN tagger, several operating points are certified by the b-ID group [171]. In this analysis, the *tight* operating point has been chosen. Tight means a jet is called a b jet, if its NN

1	S_{DL} of the displaced vertex
2	Weighted combination of the input tracks' parameter significance
3	Probability that the jet originates from the primary vertex
4	χ^2/N_{dof} of the secondary vertex fit
5	Number of tracks used to reconstruct the secondary vertex
6	Mass of the secondary vertex
7	Number of secondary vertices found in the jet

Table 4.6.1: Summary of the seven variables used as input to the NN tagger. The variable list is ordered according to the relative importance of the variables determined in the training [170].

Figure 4.6.1: B-tagging efficiency for the tight operating point of the NN tagger. The efficiency on data is shown in green. The red line shows the performance of the tagger on Monte Carlo events, and the blue line shows the ratio between the data efficiency and the Monte Carlo efficiency [170]. However, in this analysis, the tagger has not been applied to Monte Carlo events.

output value is greater than 0.775. This operating point has an average efficiency to identify b -jets of 47% for jets up to $|\eta| = 2.5$. The efficiency of the tight operating point is shown in figure 4.6.1 as a function of transverse momentum p_T and pseudorapidity η . The average fake rate for the tight operating point is 0.47%. Figure 4.6.2 shows the fake rate as a function of transverse jet momentum.

B-Tagging in Monte Carlo Events

In Monte Carlo events, the b -tagging algorithm is not applied directly. This would lead to a too high b -tag efficiency because there are large differences in tracking-related quantities the b -tagging algorithm relies on between data events and simulated events. Instead, a parametrization of the b -tagging performance is used, so-called *tag-rate functions* (TRF) [170]. This parametrization takes into account the jet flavor and the kinematic quantities of the jet.

The matching of track-jets with calorimeter jets that is applied in data events is also known as *taggability*. In Monte Carlo events, this requirement is replaced by the application of a

Figure 4.6.2: Probability to identify a light flavor jet as a b-jet for the tight operating point of the NN tagger in different detector regions [170].

taggability rate function. This is a parametrization of the efficiency for a jet to be taggable. The taggability rate function is a function of the pseudorapidity η and the transverse momentum p_T of the jet, and the z coordinate of the primary vertex in the event. A ‘loose’ data sample, i.e. events that pass the ‘loose’ lepton selection requirements of section 4.3 and 4.4, but not the ‘tight’ requirements, is used to derive the parametrization. Except for the isolation cuts, the events used pass all selection criteria of section 5.3. The applicability of the result in the data sample with the ‘tight’ isolation criterion has been verified. Figure 4.6.3 shows the result of the application to the ‘tight’ data sample in the muon channel, figure 4.6.4 shows the result in the electron channel.

After the taggability criteria are applied, the probability that a jet in an event is tagged is based on the TRFs. The semileptonic Monte Carlo efficiency $\epsilon_{b \rightarrow \mu}^{MC}$ is obtained by applying the NN tagger to an admixture of $Z \rightarrow b\bar{b}$ and $t\bar{t}$ Monte Carlo events. In these events, the b-jet is required to contain a muon inside its cone. In data events, the semileptonic efficiency $\epsilon_{b \rightarrow \mu}^{data}$ is derived from a subset of a muon-in-jet data sample in which one jet is tagged with the JLIP tagger. A scale factor SF_b can then be derived as a function of pseudorapidity η and transverse momentum p_T of the jets:

$$SF_b = \frac{\epsilon_{b \rightarrow \mu}^{data}}{\epsilon_{b \rightarrow \mu}^{MC}}. \quad (4.6.1)$$

Now, it is assumed that the efficiency to tag a b-jet in a Monte Carlo sample is independent of the semileptonic decay of the b, and thus:

$$\epsilon_b^{MC} \equiv \epsilon_{b \rightarrow \mu}^{MC}. \quad (4.6.2)$$

The inclusive b-decay efficiency ϵ_b is then given by:

$$\epsilon_b = \epsilon_b^{MC} \times SF_b. \quad (4.6.3)$$

One of the main background in the search for electroweak top quark production comes from $Wb\bar{b}$ events. In these events the b-quarks are produced from gluon splitting and thus have

Figure 4.6.3: The ratio of the predicted taggability rate function over the observed taggability in the muon channel [172].

Figure 4.6.4: The ratio of the predicted taggability rate function over the observed taggability in the electron channel [172].

different kinematics than the b -quarks in the $t\bar{t}$ and $Z \rightarrow b\bar{b}$ events. Therefore, the uncertainty on ϵ_b is set large enough to cover these kinematic differences.

The inclusive c-quark efficiency ϵ_c is calculated in a similar way as ϵ_b :

$$\epsilon_c = \epsilon_c^{MC} \times SF_c. \quad (4.6.4)$$

The assumption is made that the two scale factors for b- and c-quarks are identical, i.e.

$$SF_b \equiv SF_c. \quad (4.6.5)$$

The efficiency ϵ_c^{MC} is measured in a Monte Carlo sample containing Z events, QCD events, and $t\bar{t}$ decays to c-quarks. Figure 4.6.5 shows ϵ_b and ϵ_c for the tight working point of the NN tagger as a function of transverse momentum p_T and pseudorapidity η^{det} .

Figure 4.6.5: Efficiencies for the tight working point of the NN tagger for b-jets (figures 4.6.5(a) and 4.6.5(b)) and for c-jets (figures 4.6.5(c) and 4.6.5(d)) as a function of transverse momentum p_T and pseudorapidity η^{det} in the inclusive b and c Monte Carlo samples. The corresponding data tag-rate functions are also displayed [172].

The next step is to measure the mistag rate ϵ_{light} , i.e. the probability that a light flavor jet is misidentified as a b-jet. This is done by measuring the negative tag rate, ϵ_{data}^- , in EM and QCD data skims. A negative tag is defined as the output of NN when the three taggers used as input to the NN tagger yield a negative tag according to their definition of a negative tag. Two scale factors SF_{hf} and SF_l derived in Monte Carlo events are introduced to correct for the residual presence of b- and c-quark jets in the events with negative tags and the asymmetry between

positive and negative tags:

$$SH_{hf} = \frac{\epsilon_{\text{QCD light}}^-}{\epsilon_{\text{QCD all}}^-}, \quad (4.6.6)$$

$$SH_{ll} = \frac{\epsilon_{\text{QCD light}}^+}{\epsilon_{\text{QCD light}}^-}, \quad (4.6.7)$$

where $\epsilon_{\text{QCD light}}^\pm$ is the efficiency of positive (+) or negative (-) tags for light flavor jets in the QCD Monte Carlo sample, and $\epsilon_{\text{QCD all}}^-$ is the efficiency of a negative tag in complete sample. The misstag rate ϵ_{light} can then be written as:

$$\epsilon_{\text{light}} = \epsilon_{\text{data}}^- \times SF_{hf} \times SF_{ll}. \quad (4.6.8)$$

With the ingredients collected above, it is now possible to calculate the probability to tag a jet of flavor α (where α is either b, c, or light flavor) as a function of its transverse momentum p_T and its pseudorapidity η . This is done by multiplying the taggability and the tagging efficiency:

$$\mathcal{P}_\alpha(p_T, \eta) = P^{\text{taggable}}(p_T, \eta) \times \varepsilon_\alpha(p_T, \eta). \quad (4.6.9)$$

With the jet-wise probability of equation 4.6.9 it is possible to deduce the probability for an event to contain zero, one or two tags:

$$\begin{aligned} P_{\text{event}}(0 \text{ tag}) &= \prod_{j=1}^{N_{\text{jets}}} (1 - \mathcal{P}_{\alpha_j}(p_{Tj}, \eta_j)), \\ P_{\text{event}}(1 \text{ tag}) &= \sum_{j=1}^{N_{\text{jets}}} \mathcal{P}_{\alpha_j}(p_{Tj}, \eta_j) \prod_{i \neq j} (1 - \mathcal{P}_{\alpha_i}(p_{Ti}, \eta_i)), \\ P_{\text{event}}(2 \text{ tags}) &= \sum_{j=1}^{N_{\text{jets}}} \mathcal{P}_{\alpha_j}(p_{Tj}, \eta_j) \prod_{i \neq j} \mathcal{P}_{\alpha_i}(p_{Ti}, \eta_i) \prod_{k \neq j \neq i} (1 - \mathcal{P}_{\alpha_k}(p_{Tk}, \eta_k)). \end{aligned}$$

The Monte Carlo events are now split according to the number of jets and the number of possible tags and a weight is assigned to each permutation of the event. Each event thus enters the analysis numerous times, but each time with a different weight. It is taken care that the sum over the permuted weights is identical to the original weight of the event to be tagged zero, one, or two times. This method allows to have a high Monte Carlo statistic in all analysis bins and is thus important for a proper optimization of the multivariate analysis techniques.

4.7 Missing Transverse Energy

Both the signal processes of electroweak top quark production and the dominant background processes of top quark pair production and the production of W bosons associated by jets have at least one neutrino in the final state that escapes detection in the DØ detector. However, there is a correlation between the missing energy of an event in the transverse plane with respect to the beam axis and the x - and y -components of the momentum vector of the neutrino. The missing

transverse energy can only be calculated in the x - y -plane because only there the net momentum is known for the moment, in which the interaction happens. The net momentum in the transverse plane is zero in this moment, the net momentum in the z direction is unknown – but different from zero – because the initial state partons carry a different fraction of their proton or anti-proton momentum. The calculation of the missing transverse energy $\cancel{E}_T$ can be performed as the negative vectorial sum of transverse momenta of particles observed in the detector. In practice, this approach is replaced by adding up vectorially the transverse energies in all calorimeter cells in the EM and FH layers of the calorimeter [173] as a first step. The CH calorimeter cells are too noisy to be introduced in the vector sum. Once all physics objects are reconstructed, the obtained value is corrected for the individual energy scales of these objects. The dominant corrections are introduced by the energy scale of reconstructed jets. This correction also covers muons that are reconstructed inside a jet. However, for isolated muons satisfying the loose quality criteria, the energy deposits of the muon inside the calorimeter is subtracted from the $\cancel{E}_T$ measurement. Instead, the transverse momentum of the muon is added. As mentioned in section 4.4, electrons and photons of quality ‘d0reco’ are used for the correction if their transverse momentum is above 5 GeV and if they are reconstructed within $|\eta| < 2.5$.

5 Event Selection

In this chapter the data sample collected by the DØ detector that is used in this analysis is presented (section 5.1). The signal and background samples that are used in the analysis to derive the preselection criteria and to optimize the multivariate classifiers are presented in section 5.2. Based on the reconstructed objects introduced in chapter 4, the event selection is performed. This is done in a group wide effort of the DØ single top quark analysis group. The event selection is described in detail in [172]. The selection cuts, their motivation and the resulting event yields are presented in section 5.3.

5.1 Data Samples

The data samples used in this analysis corresponds to an integrated luminosity of approximately 0.9 fb^{-1} for both the electron and the muon channel, taking into account the latest correction factors [137,138]. The exact integrated luminosity values will be outlined below. The events were collected between August 2002 and December 2005, including run numbers from 151817 to 213063. Version p17.09.03 of the DØ production code was used to reconstruct the events. The trigger requirements are selected according to the signal event signature. Thus, lepton+jet triggers are used. In section 5.1.1 the specific triggers for the muon channel are presented, section 5.1.2 summarizes the triggers used in the electron channel. Additional information about the triggers used in the analysis can be found in references [174–176].

5.1.1 Muon Channel

Events with at least one muon and one jet are selected for the muon channel analysis. Since the triggers have changed several times during the entire run period, a summary of the triggers used to collect single top quark events in the muon channel is shown in table 5.1.1. In addition, the integrated luminosity recorded with each of these triggers is stated.

The Level 1 trigger condition is the same for all seven triggers. A muon with scintillator and wire hits is required together with one calorimeter tower with total (i.e. electromagnetic and hadronic) transverse energy $E_T > 5 \text{ GeV}$ ($E_T > 3 \text{ GeV}$ for the period of v13.0 - v13.2). The different Level 2 and Level 3 conditions are listed below:

- MU_JT20_L2M0
 - Level 2: One muon object.
 - Level 3: One jet object with $E_T > 20 \text{ GeV}$.

Trigger Version	Trigger Name	Integrated Luminosity [pb^{-1}]		
		Delivered	Recorded	Good Quality
v8.0 - v9.0	MU_JT20_L2M0	7	6	6
v9.0 - v10.0	MU_JT20_L2M0	48	42	25
v10.0 - v11.0	MU_JT20_L2M0	21	19	11
v11.0 - v12.0	MU_JT20_L2M0	79	74	65
v12.0 - v13.0	MU_JT25_L2M0	277	255	231
v13.0 - v13.2	MUJ2_JT25	56	39	31
v13.2 - v13.3	MUJ2_JT25_LM3	26	22	16
v13.3 - v14.0	MUJ2_JT30_LM3	382	277	252
v14.0 - v14.2	MUJ1_JT25_LM3	0	0	0
v14.2 - v14.3	MUJ1_JT25_ILM3	25	23	21
v14.3 - v15.0	MUJ1_JT35_LM3	265	248	214
Total Integrated Luminosity		1,187	1,006	871

Table 5.1.1: Triggers and their corresponding integrated luminosities by trigger version for the muon channel.

- MU_JT25_L2M0
 - Level 2: One muon object.
 - Level 3: One jet object with $E_T > 25 \text{ GeV}$.
- MUJ2_JT25
 - Level 2: One muon object and a jet object with $E_T > 8 \text{ GeV}$.
 - Level 3: One jet object with $E_T > 25 \text{ GeV}$.
- MUJ2_JT25_LM3
 - Level 2: One muon object and a jet object with $E_T > 8 \text{ GeV}$.
 - Level 3: One muon object with $p_T > 3 \text{ GeV}$ and one jet object with $E_T > 25 \text{ GeV}$.
- MUJ2_JT30_LM3
 - Level 2: One muon object and a jet object with $E_T > 8 \text{ GeV}$.
 - Level 3: One muon object with $p_T > 3 \text{ GeV}$ and one jet object with $E_T > 30 \text{ GeV}$.
- MUJ1_JT25_ILM3
 - Level 2: One muon object and a jet object with $E_T > 8 \text{ GeV}$.
 - Level 3: One isolated muon object with $p_T > 3 \text{ GeV}$ and one jet object with $E_T > 25 \text{ GeV}$.
- MUJ1_JT35_LM3
 - Level 2: One muon object and a jet object with $E_T > 8 \text{ GeV}$.

- Level 3: One muon object with $p_T > 3$ GeV and one jet object with $E_T > 35$ GeV.

The average trigger efficiency for the signal samples is determined based on the trigger simulation. The efficiencies for each trigger period are shown in table 5.1.2. The overall efficiency is 87% for s-channel events and 82% for t-channel events. With increasing luminosity, the threshold for jets has had to be raised, resulting in a decrease in efficiency.

Trigger Version	s-channel	t-channel
v8.0 – v9.0	96%	94%
v9.0 – v10.0	93%	90%
v10.0 – v11.0	91%	88%
v11.0 – v12.0	92%	88%
v12.0 – v13.0	91%	88%
v13.0 – v13.2	91%	87%
v13.2 – v13.3	91%	87%
v13.3 – v14.0	86%	81%
v14.0 – v14.2	92%	89%
v14.2 – v14.3	92%	89%
v14.3 – v15.0	80%	72%
Overall average	87%	82%

Table 5.1.2: Average muon-channel trigger efficiencies for s- and t-channel single top events after selection.

5.1.2 Electron Channel

The triggers for the electron channel are calorimeter-based. Events with at least one electron and at least two jets are selected. The requirement of two jets is due to the fact that electrons are treated as jets at the trigger level. They are identified as energy deposits in the calorimeter, just like jets. The triggers to select electron single top events underwent changes during the entire run period. The triggers are summarized in table 5.1.3 together with the integrated luminosity that was recorded with each of them.

The Level 1, Level 2, and Level 3 trigger conditions for each of the four different triggers is summarized shortly:

- EM15_2JT15
 - Level 1: One EM calorimeter tower with $E_T > 10$ GeV and two jet calorimeter towers with $E_T > 5$ GeV.
 - Level 2: One EM object with $E_T > 10$ GeV and electromagnetic fraction $> 85\%$. In addition, two jet objects with $E_T > 10$ GeV are required.
 - Level 3: One EM object with $E_T > 15$ GeV, passing the shower shape criteria for an EM object. In addition, two jet objects with $E_T > 15$ GeV are required.

Trigger Version	Trigger Name	Electron Channel Integrated Luminosity [pb^{-1}]		
		Delivered	Recorded	Good Quality
v8.0 – v9.0	EM15_2JT15	6	5	5
v9.0 – v10.0	EM15_2JT15	48	42	25
v10.0 – v11.0	EM15_2JT15	20	18	10
v11.0 – v12.0	EM15_2JT15	79	72	63
v12.0 – v13.0	E1_SHT15_2J20	273	251	227
v13.0 – v13.3	E1_SHT15_2J25	80	73	55
v13.3 – v14.0	E1_SHT15_2J30	354	325	294
v14.0 – v15.0	E1_SHT15_2J25	290	271	234
Total Integrated Luminosity		1,150	1,056	913

Table 5.1.3: Integrated luminosities by trigger version for the electron channel. Both the individual integrated luminosities recorded with each trigger and the total integrated luminosity are shown.

- E1_SHT15_2J20
 - Level 1: One EM calorimeter tower with $E_T > 11$ GeV.
 - Level 2: No requirement.
 - Level 3: One EM object with $E_T > 15$ GeV, passing the shower shape criteria for an EM object. In addition, two jet objects with $E_T > 20$ GeV are required.
- E1_SHT15_2J25
 - Level 1: One EM calorimeter tower with $E_T > 11$ GeV.
 - Level 2: No requirement.
 - Level 3: One EM object with $E_T > 15$ GeV, passing the shower shape criteria for an EM object. In addition, two jet objects with $E_T > 20$ GeV are required. One of the jet objects should fulfill $E_T > 25$ GeV.
- E1_SHT15_2J30
 - Level 1: One EM calorimeter tower with $E_T > 11$ GeV.
 - Level 2: No requirement.
 - Level 3: One EM object with $E_T > 15$ GeV, passing the shower shape criteria for an EM object. In addition, two jet objects with $E_T > 20$ GeV are required. One of the jet objects should fulfill $E_T > 30$ GeV.

The average trigger efficiency for the signal samples is determined based on the trigger simulation. The efficiencies for each trigger period are shown in table 5.1.4. The overall efficiency is 87% for s-channel events and 86% for t-channel events. A similar effect as for the muon channel can be seen: the threshold for jets has had to be raised with increasing instantaneous luminosities.

Trigger Version	s-channel	t-channel
v8.0 – v9.0	92%	92%
v9.0 – v10.0	91%	91%
v10.0 – v11.0	91%	91%
v11.0 – v12.0	91%	91%
v12.0 – v13.0	86%	85%
v13.0 – v13.3	87%	86%
v13.3 – v14.0	86%	85%
v14.0 – v15.0	88%	87%
Overall average	87%	86%

Table 5.1.4: Average electron-channel trigger efficiencies for the s- and t-channel single top events after selection.

5.2 Signal and Background Modeling

The generation of Monte Carlo events is important in today's high energy physics analyses. Simulated signal events are used to understand the signature and the kinematic properties of the signal process. The efficiency of the preselection is quantified with these events and the acceptance for this process is measured. Furthermore, it allows to extract expected results based on a cross section estimate provided by the generators. Generated events of the background processes that show a similar signature in the detector as the signal events, are needed in order to optimize the selection cuts. A large number of simulated signal and background events allows the application of advanced multivariate analysis techniques like Boosted Decision Trees or Artificial Neural Networks. In searches, like this analysis, the correct modeling of the background processes is even more important, because the goal of the analysis is to find deviations of the observed data from the background model. In Section 5.2.1 the Monte Carlo event generator used to produce the s- and t-channel single top quark samples is introduced. The Monte Carlo event generators that were used to generate the background processes are presented in section 5.2.2. An overview of the chain of tools used in the DØ software framework to produce simulated Monte Carlo events is given in section 5.2.3. In order to minimize the differences between simulated and recorded events, additional correction factors are applied on the simulated Monte Carlo events (see section 5.2.4). Finally, an overall normalization of the simulated background events with the observed data has to be achieved. The methods used to achieve this are presented in section 5.2.5.

5.2.1 Generated Signal Samples

The CompHEP based SingleTop Monte Carlo event generator has been used to generate s- and t-channel single top quark samples [54,177]. It was shown that for s-channel single top quark production the LO distributions multiplied with a k -factor match the NLO distributions [61]. Therefore, the SingleTop generator uses the LO diagrams and applies a k -factor of 1.3. The mass of the top quark is a parameter in the event generation that has to be set by the user.

Throughout the analysis, a value of $m_t = 175$ GeV was used. The scales were set to $Q^2 = m_t^2$ for the s-channel and to $Q^2 = (m_t/2)^2$ for the t-channel. All events were generated using version CTEQ6L1 of the parton density functions provided by the CTEQ collaboration [36]. To ensure the correct transfer of the spins, both the top quarks and the W bosons from the top quark decays are decayed in the SingleTop generator.

It is more difficult to properly generate the kinematics for t-channel Monte Carlo events than for s-channel events. It is not sufficient to use the LO diagrams ($qb \rightarrow q't$) only. The contributions to the effective cross section of higher order Feynman diagrams ($qg \rightarrow q'tb$) are of the same order. Unfortunately, it is not possible to just add the different contributions because there are regions of phase space where the two matrix elements overlap. The overlap occurs because the gluon splitting kernel is part of the parton density distribution of the b-quark, that is used in the LO diagram. To avoid the double counting of these regions, a proper combination of the processes is required.

Two distinct regions of phase space are defined. In the first region, where the transverse momentum of the b-jet is less than $p_T^{cut} = 10$ GeV, the LO matrix element is used in the generation of events. Here, the b-quarks emerge from gluon splitting inside the proton. This process is modeled well by initial state radiation from the PYTHIA event generator [178]. For higher transverse momenta, the b-jet distributions are no longer well-modeled using this approach. Therefore, for transverse momenta above $p_T^{cut} = 10$ GeV, the W-gluon fusion diagrams are used. To ensure a smooth transition from one region of phase space to the other, a k -factor of 1.21 is applied to the events in the low transverse momentum region. Figure 5.2.1 shows the transverse momentum and rapidity distributions of the b-quark for two different values of p_T^{cut} . For the plots on the left hand side, a value of $p_T^{cut} = 20$ GeV is applied, the plots on the right hand side show the distributions with a value of $p_T^{cut} = 10$ GeV, the value used in the generation of events for this analysis.

Figure 5.2.1: Transverse momentum and rapidity (y) distributions of the b-quark for two different values of p_T^{cut} . On the left hand side, a value of 20 GeV was used, on the right hand side a value of 10 GeV was used [54]. The contributions of the two processes and the resulting distributions are shown.

In summary, the effective NLO cross section used in the SingleTop generator can be written as:

$$\sigma_{\text{NLO}} = \underbrace{k \cdot \sigma_{\text{pythia}}}_{p_T^{\text{cut}} < 10 \text{ GeV}} + \underbrace{\sigma_{\text{singletop}}}_{p_T^{\text{cut}} > 10 \text{ GeV}} . \quad (5.2.1)$$

With this approach it is possible to obtain distributions that agree very well with many NLO differential distributions for t-channel single top quark production.

The first part of table 5.2.1 summarizes the initial number of events, the cross section, and the integrated luminosities for the generated signal samples.

5.2.2 Generated Background Samples

The signature of the signal events of electroweak top quark production determine possible background processes that mimic the signal event topology in the detector. This signature consists of one charged lepton, associated by missing transverse energy due to its origin from the leptonic decay of a W boson. Furthermore there are at least two jets with at least one of the jets being tagged as originating from the decay of a b hadron. The main background processes are:

- W+jets

The production of a W boson associated by two or more jets is the largest background process. Its cross section is several times higher than the predicted cross section for the electroweak production of top quarks [179]. Especially the contribution of $Wb\bar{b}$ events (about 1% of the total W+jets cross section) has the same final state as the s-channel production of single top quarks. To reduce this enormous background, the requirement that at least one of the jets should be tagged as originating from the decay of a b hadron is essential. Due to the higher b-tagging fake rates, the percentage of events from $Wc\bar{c}$ and Wc production is increased compared to the total W+jets sample after b-tagging.

- Z/γ^* +jets

The kinematics of Z boson production are similar to the production of W bosons. Therefore, they are considered as one single background called “W+jets” through the remainder of this analysis. For events with e^+e^- or $\mu^+\mu^-$ in the final state, one of the charged leptons needs to be lost in order to match the signal event signature. This can happen if the lepton fails an identification cut, overlaps with a jet in the calorimeter (electron), or it ends in a region where the detector is not or insufficiently instrumented, e.g. the missing layer muon chambers at the bottom of the detector. Hence, the main contribution to the total background from this physics process comes from events where Z/γ^* decays into $\tau^+\tau^-$ with one of the taus decaying leptonically and the other one hadronically.

- Diboson production

Events from WW , WZ , and ZZ production are only a small background. Their cross sections are of the order of a few picobarn each [180]. WW and WZ diboson events can appear in the selected events if one of the W bosons decays leptonically and the other vector boson decays into two quarks. The only chances of ZZ diboson events to pass the selection criteria are that one of the Z bosons decays into two quarks and the other one decays into two charged leptons. Then, one of the charged leptons has to be lost (in

case the Z boson decays into either e^+e^- or $\mu^+\mu^-$) or one of the two taus $\tau^+\tau^-$ decays leptonically and the other one hadronically. However, the latter process suffers from a low branching ratio. Because the expected contributions of this background to the total background in the analysis is small, it is incorporated in the W +jets background and no additional Monte Carlo event sample is generated.

- QCD Multijet events and heavy flavor production

Multijet background can be effectively suppressed by the requirement to have at least one jet tagged as a b-jet. In the electron channel, these events originate from the misidentification of jets as an electron. Due to the large jet cross section for events with more than three jets, this contribution is significant, although the misidentification rate is rather small. In the muon channel, these events can enter the data set when a muon is created by an in-flight decay of a pion or kaon. Another possibility is the punch-through of particles from a jet that enter the muon system. A tight muon isolation requirement suppresses these events.

In heavy flavour production, i.e. the production of $b\bar{b}$ and $c\bar{c}$ events, b-tagging is less sufficient to suppress these background processes. In the muon channel real muons can be reconstructed that come from the decay products of one of the b quarks.

- $t\bar{t}$ production

The background of top quark pair production via strong interaction is a significant contribution to the total background. Its NNLO cross section is 6.77 ± 0.42 pb for a top mass of 175 GeV and a scale of $Q^2 = m_t^2$ [181]. In events in the dilepton channel, one of the charged leptons in the final state must escape detection in order to have a similar event signature as the signal process. This channel is relevant for the analysis channel with two and three jets. In the analysis channels with three and four jets, the contributions of the semileptonic decay of top quark pairs becomes a dominant background source. To enter the analysis bin with three jets, one of the four jets must be lost.

The W +jets background and the background from the production of top quark pairs via strong interaction are modeled by events generated using the ALPGEN Monte Carlo event generator in version 2.05 [182]. For the parton shower, the implementation of PYTHIA version 6.323 is used [178]. To avoid double-counting of events, a matching scheme, the MLM prescription [183], is applied. With ALPGEN, Monte Carlo event samples for $W + m$ light partons (u,d, or s quarks or a gluon), $W + c\bar{c} + n$ light partons, and $W + b\bar{b} + n$ light partons are generated separately, where m goes from zero to five and n goes from zero to three. In the process of the parton showering it is possible that PYTHIA introduces additional gluons that split to quarks, leading to additional jets in the event. With the MLM matching scheme, events are removed that contain additional jets by clustering quarks and gluons using a UA1 cone jet algorithm [184]. Those jets are then matched to the partons of the hard process. In the end, each parton must correspond to one jet and vice versa. Otherwise the event is rejected and the process repeated. This is done for the samples with $m \leq 4$ and $n \leq 2$. Because $W + c\bar{c}$ and $W + b\bar{b}$ events were generated separately, those events were removed where PYTHIA added additional heavy flavor jets [185]. The combination of all samples with their correct weights [186] results in the total W +jets sample used in the analysis. In the generation of the W +jets events, the CTEQ6L1 set of parton density functions was used and the scale was set to $Q^2 = m_W^2 + p_T^2(W)$.

The same MLM matching procedure is also applied to the Monte Carlo event samples of top quark pair production. They were also generated using the ALPGEN generator, together with the PYTHIA parton shower. For both the semileptonic and the dilepton channel of top quark pair production, two exclusive event samples were generated, containing zero and one additional light partons. A third, inclusive sample contains at least two additional light partons. The parton density distributions were again CTEQ6L1 and the scale was set to $Q^2 = m_t^2 + \sum_{\text{jets}} p_T^2$.

Table 5.2.1 summarizes the initial number of generated Monte Carlo events for each signal and background sample, together with their cross sections, their branching ratios and the corresponding integrated luminosities. The cross sections for electroweak top quark production are taken from [61] and the ones for top quark pair production from [181]. These cross sections are used to weight the samples according to their branching ratios to the integrated luminosity of the data set. The $W + \text{jets}$ cross sections are not used in this analysis. The values in the table represent the values calculated by ALPGEN. Also, the relative weight between the W+light parton sample and the W+heavy parton samples has a large uncertainty [187,188]. Therefore, this weight is measured when b-tagging is applied. The procedure will be discussed in section 5.2.5.

Event Type	Cross Section [pb]	Branching Fraction	Number of Events	Int. Lum. [fb ⁻¹]
Signals				
$t\bar{b} \rightarrow e+\text{jets}$	0.88 ± 0.14	0.1111 ± 0.0022	92,620	947
$t\bar{b} \rightarrow \mu+\text{jets}$	0.88 ± 0.14	0.1111 ± 0.0022	122,346	1,251
$t\bar{b} \rightarrow \tau+\text{jets}$	0.88 ± 0.14	0.1111 ± 0.0022	76,433	782
$tqb \rightarrow e+\text{jets}$	1.98 ± 0.30	0.1111 ± 0.0022	130,068	591
$tqb \rightarrow \mu+\text{jets}$	1.98 ± 0.30	0.1111 ± 0.0022	137,824	626
$tqb \rightarrow \tau+\text{jets}$	1.98 ± 0.30	0.1111 ± 0.0022	117,079	532
Backgrounds				
$t\bar{t} \rightarrow \ell+\text{jets}$	6.8 ± 1.2	0.4444 ± 0.0089	474,405	157
$t\bar{t} \rightarrow \ell\ell$	6.8 ± 1.2	0.1111 ± 0.0089	468,126	620
$Wb\bar{b} \rightarrow \ell\nu b\bar{b}$	142	0.3333 ± 0.0066	1,335,146	28
$Wc\bar{c} \rightarrow \ell\nu c\bar{c}$	583	0.3333 ± 0.0066	1,522,767	8
$Wjj \rightarrow \ell\nu jj$	18,734	0.3333 ± 0.0066	8,201,446	1

Table 5.2.1: The cross sections, branching fractions, initial numbers of events, and integrated luminosities of the Monte Carlo event samples used in the analysis.

It is very difficult to properly model the QCD multijet background with Monte Carlo methods. Therefore, this background contribution is modeled with data, using an orthogonal sample of events than the ones selected for the analysis. The orthogonality is achieved by selecting events that pass all selection cuts except the isolation cut (for the muon channel) or the likelihood cut (for the electron channel). The scaling of this and the Monte Carlo modeled backgrounds is explained in detail in section 5.2.5.

5.2.3 Event Generation and Detector Simulation

Several steps are needed to get simulated Monte Carlo events of signal and background processes that can be used to optimize the selection cuts or to train the multivariate analysis technique. The first step is to generate the hard scatter collision of the contributing physics processes. This is typically done by ‘matrix-element’ generators. As explained in sections 5.2.1 and 5.2.2, in this analysis, the CompHEP based SingleTop generator is used for the production of s- and t-channel Monte Carlo events of electroweak top quark production. The ALPGEN generator is used for the production of W+jets events and for events of top quark pair production. Parton density functions need to be provided as input to the generation step to represent the initial conditions inside the proton and antiproton. For all samples, the CTEQ6L1 PDFs are used [36]. Figure 5.2.2 shows a plot of parton distributions functions from the CTEQ collaboration for two distinct momentum transfers. For some particles in the decay chain,

Figure 5.2.2: CTEQ6M parton distribution functions for gluons and the different quark flavors. The x -axis shows the proton momentum fraction of the parton, the y -axis the parton density. The left plot visualizes the distributions for a small momentum transfer, the right plot shows a larger momentum transfer.

special packages are used to describe their kinematics and decays with higher accuracy. The TAUOLA package [189] is used in version 2.5 for the decay of tau leptons. Version 00.00.17 of the EvtGen package is used for a proper simulation of the decay of B hadrons. For the hadronization of the final state partons version 6.323 of PYTHIA is used [178]. PYTHIA also simulates additional interactions between the final state particles and the proton remnant.

A GEANT [190–192] based simulation of the DØ detector is used to simulate the response of the detector to the generated particles. The package is called DØGSTAR [193]. DØGSTAR is capable of simulating the interactions between particles and the material in the detector such as electromagnetic showers in the calorimeter or multiple scattering of a charged particle in the silicon detectors.

In the next step the DØGSTAR output is used by the DØSIM package [194]. DØSIM overlays the simulated events with minimum bias events to account for additional inelastic $p\bar{p}$ collisions.

Those minimum bias events are randomly picked from a huge sample of recorded data events. The only trigger requirement for these events was the presence of at least one $p\bar{p}$ interaction. To properly take into account the growing number of minimum bias vertices with rising instantaneous luminosity, the overlay of minimum bias events is chosen to match the expected instantaneous luminosity profile of the recorded events. The peak instantaneous luminosities for the Run II data taking period until January 2009 is shown in figure 5.2.3. DØSIM fur-

Figure 5.2.3: Peak instantaneous luminosity profile since the start of the Run II data taking period [195].

thermore models the calorimeter pile-up from previous bunch crossings, calorimeter noise, and noise and inefficiencies in the tracking systems and the muon system. Finally, a raw data chunk is produced that is similar to the data raw data recorded by the detector. This allows the reconstruction of the simulated events using the same software and the same algorithms as described for data events in section 4.

5.2.4 Correction Factors on Monte Carlo Events

Although many attempts are made to simulate the detector and its response as accurately as possible, there are still differences between simulated and recorded events that need to be corrected for. For example, missing material in the GEANT simulation or unmodeled aging effects of the detector lead to these differences. The general procedure to account for the differences is to smear the reconstructed Monte Carlo objects in one variable. After smearing, the Monte Carlo objects have similar resolutions as the objects reconstructed from data. To apply further corrections to the Monte Carlo events, the relative differences between them and data events are measured and correction factors determined. The smearing and the correction factors for the different physics objects are discussed next.

5.2.4.1 Muon Corrections

The muon smearing and the correction factor are explained in detail in [148]. They are derived from $Z \rightarrow \mu\mu$ events that provide a clean and unbiased environment in both simulated events and observed data. The smearing of the muon is performed on the variable q/p_T , where q is the charge of the muon and p_T its transverse momentum. This variable is chosen because the muon momentum vector is taken from the track in the tracking detectors that is matched with the hits in the muon systems. The differences in the width and the position of the Z boson resonance in the invariant mass of the two muons between data and Monte Carlo events determines the amount to which the muon track must be smeared. The smearing is performed according to:

$$\left(\frac{q}{p_T}\right)' = \frac{q}{p_T} + \left(A + \frac{B}{p_T}\right) \cdot G. \quad (5.2.2)$$

A and B are parameters that are measured separately for muons in $|\eta| < 1.6$ and $|\eta| > 1.6$ for muons with a SMT track hit. For muons without a SMT track hit, the parameters are measured over the whole η region. The parameter G is a random number, drawn from a Gaussian distribution with width 1 and a mean value of 0. A summary of the smearing parameters is given in table 5.2.2. The splitting in two different periods of data taking is necessary because after a shutdown the muon resolution became 15% worse. The samples are smeared in such a way that the Monte Carlo events have the same ratio of pre- to post-shutdown events as the data.

Muon type	before Dec. 2004		after Dec. 2004	
	A [1/GeV]	B	A [1/GeV]	B
with SMT hit and $ \eta < 1.6$	0.00313	-0.0563	0.00308	-0.0370
with SMT hit and $ \eta > 1.6$	0.00273	-0.0491	0.00458	-0.0550
without SMT hit	0.00509	-0.0916	0.00424	-0.0509

Table 5.2.2: Smearing parameters A and B of equation 5.2.2 for two different run periods and three different muon samples [148].

After smearing is applied to the Monte Carlo events, a correction factor is defined that accounts for the differences in the muon identification efficiency. It consists of three parts: the muon type and quality, the track match efficiency and the isolation efficiency. The correction factor cf_μ is then

$$cf_\mu = \frac{\epsilon_{\text{Reco}}^{\text{Data}}}{\epsilon_{\text{Reco}}^{\text{MC}}} \times \frac{\epsilon_{\text{Track Match}}^{\text{Data}}}{\epsilon_{\text{Track Match}}^{\text{MC}}} \times \frac{\epsilon_{\text{Track Isolation}}^{\text{Data}}}{\epsilon_{\text{Track Isolation}}^{\text{MC}}}. \quad (5.2.3)$$

The correction factor for the muon reconstruction efficiency only depends on pseudorapidity η . In ϕ both Monte Carlo events and data show the same dependence. In data, the average reconstruction efficiency measured on a sample of $Z \rightarrow \mu\mu$ candidate events is 80.2%. The average correction factor for the Monte Carlo events is 0.97.

The track match efficiency depends on two track related parameters: the pseudorapidity η of the track and the longitudinal vertex position of the primary interaction. In data, the average track match efficiency is 91.0%. A correction factor of 0.93 is applied to Monte Carlo events.

The dominant dependence of the muon isolation efficiency is the number of reconstructed jets

in an event. With higher jet multiplicities, more regions of the detector are occupied with energy deposits, making it more difficult for a muon to be isolated. The correction factor for Monte Carlo events with two or three jets is 0.98. The average efficiency is 94%.

5.2.4.2 Electron Corrections

The resolution of Monte Carlo simulated electrons is well modeled. Thus, no additional smearing needs to be applied. However, a correction factor cf_e for the reconstruction efficiency is applied to Monte Carlo electrons,

$$cf_e = \frac{\epsilon_{\text{Reco}}^{\text{Data}}}{\epsilon_{\text{Reco}}^{\text{MC}}} \times \frac{\epsilon_{\text{Track match+Likelihood}}^{\text{Data}}}{\epsilon_{\text{Track match+Likelihood}}^{\text{MC}}}. \quad (5.2.4)$$

Both contributions are measured in $Z \rightarrow ee$ samples in both data and simulated events [155]. The electron reconstruction efficiency for data and Monte Carlo events and the Monte Carlo correction factor are shown in figure 5.2.4. Both show a dependency on the transverse momentum of the electron.

Figure 5.2.4: Figure 5.2.4(a) shows the reconstruction efficiency for electrons in $Z \rightarrow ee$ data (red) and Monte Carlo events (blue) as a function of transverse momentum of the electrons. The Monte Carlo correction factor as a function of transverse momentum is shown in figure 5.2.4(b) [155].

The efficiency of the electron likelihood and the track matching is shown in figure 5.2.5(a) for data and Monte Carlo events. Both the efficiency and the resulting Monte Carlo correction factor (see figure 5.2.5(b)) depend on η^{det} . In this analysis, only central electrons with $|\eta^{\text{det}}| < 1.1$ are considered.

5.2.4.3 Jet Corrections

For jets reconstructed from Monte Carlo events no correction factor for the reconstruction efficiency is needed. However, a procedure called SSR (Smearing, Shifting, and Removal) is applied to these jets [196]. This procedure fixes the differences between the simulated and observed jets in terms of energy resolution, energy scale and reconstruction efficiency. The input to this procedure comes from the comparison of back-to-back photon+jets events in data and

Figure 5.2.5: Figure 5.2.5(a) shows the reconstruction efficiency of electrons for data (red) and Monte Carlo events (blue) in $Z \rightarrow ee$ events as a function of η . The Monte Carlo correction factor as a function of η is shown in figure 5.2.5(b) [155].

Monte Carlo events. The jet energy resolution is corrected by smearing the transverse momentum of the simulated jets with a Gaussian distribution. The width of the distribution σ_{smear} is calculated as:

$$\sigma_{\text{smear}} = \sqrt{\sigma_{\text{Data}}^2 + \sigma_{\text{MC}}^2} \quad (5.2.5)$$

Monte Carlo jets with a transverse momentum lower than 15 GeV after smearing are removed from the event. After smearing, no further correction for the relative differences in jet energy scale between Monte Carlo events and data are necessary. First, the SSR procedure has to be applied, then selection cuts for the jets can be optimized.

5.2.4.4 Trigger Simulation

Distributions of Monte Carlo events can only match the corresponding distributions in data if also trigger effects are modeled properly. Each Monte Carlo event is assigned an event-wide trigger probability [174,197]. This probability tells how likely an event would have been triggered by the DØ trigger framework 3.2.4. It can be calculated as the product of the condition probabilities to pass each of the three trigger levels, given it has passed the previous trigger level. Thus, the probability P_{Trig} for an event x can be written as:

$$P_{\text{Trig}}(x) = \left(\prod_{\text{Trig. terms}} P_{L1}(x) \right) \times \left(\prod_{\text{Trig. terms}} P_{L2|L1}(x) \right) \times \left(\prod_{\text{Trig. terms}} P_{L3|L2}(x) \right). \quad (5.2.6)$$

The probability for a given trigger level i P_{Li} (with $i=1,2$, or 3) is given by:

$$P_{Li}(x) = \prod_{k=1}^{\text{N objects}} P_{Li, \text{Object}}(x_k). \quad (5.2.7)$$

In equation 5.2.7, $P_{Li, \text{Object}}(x_k)$ is the probability for one of the reconstructed objects in the event to pass the object specific triggers (i.e. a muon to pass a single muon trigger term). The ‘N objects’ individual probabilities for each object are summed up and give $P_{Li}(x)$. $P_{Li, \text{Object}}(x_k)$ can be written as

$$P_{Li, \text{Object}}(x_k) = 1 - \prod_{l=1}^{\text{N objects}} (1 - \epsilon_{Li}(x_{\text{Object}, l})). \quad (5.2.8)$$

This is the probability of an object to pass a certain trigger level expressed as one minus the probability of all objects to fire the trigger. $\epsilon_{Li}(x_{\text{Object},l})$ is the efficiency of the trigger term for the reconstructed object that is analyzed.

Finally, the trigger simulation has to take the changes in the trigger terms into account. Therefore, the trigger probabilities are weighted according to the integrated luminosity that was recorded while these triggers were activated. This averaging is shown in equation 5.2.9 with the final trigger probability $P(x)$,

$$P(x) = \frac{\sum_{\text{version}} (\mathcal{L}_{\text{version}} \times P_{\text{version}}(x))}{\sum_{\text{version}} \mathcal{L}_{\text{version}}} \quad (5.2.9)$$

The trigger efficiencies for electron and muon trigger terms are measured in data. Clean samples of $Z \rightarrow ee$ or $Z \rightarrow \mu\mu$ events are selected that contain hardly any background events. With the two charged leptons in the event, it is possible to apply the ‘tag and probe’ method. One of the leptons is required to trigger the event (the ‘tag’ lepton). The other lepton, the ‘probe’ lepton, can then be used to measure the trigger efficiency. The efficiency $\epsilon_{\text{Trigger}}$ is then defined as:

$$\epsilon_{\text{Trigger}} = \frac{\text{Number of probe leptons passing the trigger term}}{\text{Total number of events}}. \quad (5.2.10)$$

The efficiencies are parameterized in terms of transverse momentum p_T , pseudorapidity η , or ϕ . Figure 5.2.6 shows one example for the efficiency of an electron trigger term and one example for the efficiency of a muon trigger term that are used in the analysis.

To derive the jet trigger efficiencies, a sample of muon+jets events was selected, where the

Figure 5.2.6: An example turn-on curve for an electron trigger (left) measured as a function of electron E_T . On the right, an example muon turn-on curve is shown. Here, the curve is parameterized as a function of η^{det} . The points are trigger efficiencies derived from data, the error bars show the uncertainties for each point and the solid line the result of a fit [172].

muon passed its muon trigger term. The jet trigger efficiency is then calculated as the ratio of jets that pass the trigger requirement with respect to the total number of jets. The efficiencies are parameterized in transverse momentum p_T and pseudorapidity η^{det} .

5.2.5 Background Normalization and Multijet Background

For the background of top quark pair production, the production cross section is known up to NNLO [181]. Therefore, the Monte Carlo event sample for $t\bar{t}$ production is normalized using

the calculated cross section, the known branching ratios and the integrated luminosity. The expected number of $t\bar{t}$ events $N_{t\bar{t}}$ is thus given by:

$$N_{t\bar{t}} = \sigma_{t\bar{t}} \times \text{BR} \times \int \mathcal{L} dt \quad (5.2.11)$$

To correct for the leading order cross section implemented in ALPGEN, a weight is assigned to each simulated $t\bar{t}$ event. This weight $\omega_{t\bar{t}}$ also contains correction factors for the trigger simulation, the corrections factors for the Monte Carlo object reconstruction and for the b-tagging:

$$\omega_{t\bar{t}} = \frac{N_{t\bar{t}}}{\sum_{\text{selected events}} (\epsilon_{\text{Trigger}} \times \epsilon_{\text{MC corrections}} \times \epsilon_{\text{TRF}})} \quad (5.2.12)$$

The normalization of the W+jets background and the QCD multijet background is achieved by a procedure known as the matrix method [198]. As described in section 5.2.2, the W+jets events are simulated with ALPGEN, while the multijet background is modeled from a data set where the events passed all selection cuts except the isolation cut (in the muon channel) or the likelihood cut (in the electron channel). The matrix method is applied before the b-tagging algorithm is run over the data. It gives an estimate of the fractions of events in the selected sample that contain a fake lepton from multijet production or a real isolated lepton from W+jets events or top quark pair production. To achieve this, two data samples are defined. The first one, called the *tight* sample, contains the events that are used to measure the cross section, i.e. events, that pass all selection criteria. The second sample, the so-called *loose* sample contains the tight sample as a subset. Events in the loose sample have also passed all selection cuts, except for the isolation requirement. Instead of the tight isolation requirement these events only fulfill the loose requirement (see sections 4.4 and 4.3). The numbers of events in the loose and the tight sample are thus:

$$N_{\text{loose}} = N_{\text{multijet}} + N_{\text{W+jets}} + N_{t\bar{t}} \quad (5.2.13)$$

$$N_{\text{tight}} = \epsilon_{\text{multijet}} \times N_{\text{multijet}} + \epsilon_{\text{W+jets}} \times (N_{\text{W+jets}} + N_{t\bar{t}}) \quad (5.2.14)$$

The two parameters $\epsilon_{\text{multijet}}$ and $\epsilon_{\text{W+jets}}$ can be interpreted as the efficiency that an event that passes the loose selection requirement also passes the tight requirement. Once the efficiencies are available, they can be used to invert the system of two equations and to calculate the expected number of multijet events and the expected number of W+jets events (as formulated in equations 5.2.15 and 5.2.16).

$$N_{\text{multijet}} = \frac{\epsilon_{\text{W+jets}} \times N_{\text{loose}} - N_{\text{tight}}}{\epsilon_{\text{W+jets}} - \epsilon_{\text{multijet}}}, \quad (5.2.15)$$

$$N_{\text{W+jets}} = \frac{N_{\text{tight}} - \epsilon_{\text{multijet}} \times N_{\text{loose}}}{\epsilon_{\text{W+jets}} - \epsilon_{\text{multijet}}} - N_{t\bar{t}}. \quad (5.2.16)$$

The efficiency $\epsilon_{\text{W+jets}}$ is measured in $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ events, using the ‘tag and probe’ method that has already been introduced in section 5.2.4.4. Once one of the two leptons is tagged as ‘tight’, $\epsilon_{\text{W+jets}}$ can be determined by the fraction of events where the other lepton, the ‘probe’ lepton, also passes the ‘tight’ criterion. In the electron channel this efficiency depends on the transverse momentum of the electron and its pseudorapidity η^{det} . This is visualized in figure 5.2.7. In the muon channel, the measurement of $\epsilon_{\text{W+jets}}$ shows a dependency on the transverse momentum of the muon and the number of reconstructed jets in the event. Both effects are shown in figure 5.2.8.

Figure 5.2.7: The efficiency ϵ_{W+jets} (called ϵ_{real-e} here) depends on the transverse momentum of the electron (figure 5.2.7(a)) and its pseudorapidity η^{det} (see figure 5.2.7(b)) [172].

Figure 5.2.8: The efficiency ϵ_{W+jets} (called $\epsilon_{real-\mu}$ here) depends on the transverse momentum of the muon (figure 5.2.8(a)) and the jet multiplicity (see figure 5.2.8(b)) [172]

Table 5.2.3 summarizes the measured values of ϵ_{W+jets} in both the muon and the electron channel for different jet multiplicities.

Number of jets	ϵ_{W+jets} (electron channel)	ϵ_{W+jets} (muon channel)
1	$(87.3 \pm 2.1)\%$	$(99.1 \pm 2.2)\%$
2	$(87.4 \pm 2.1)\%$	$(98.9 \pm 2.2)\%$
3	$(87.4 \pm 2.1)\%$	$(98.7 \pm 2.2)\%$
4	$(87.5 \pm 2.1)\%$	$(96.1 \pm 2.1)\%$

Table 5.2.3: Average values for ϵ_{W+jets} for the electron and the muon channel for different jet multiplicities [172].

The measurement of $\epsilon_{multijet}$ is performed in a data sample that is assumed to contain dominantly multijet events. It can be interpreted as the probability that a fake lepton passes the isolation criteria of the event selection. Events are selected that pass all selection criteria except the one for missing transverse energy. The cut on missing transverse energy is changed to less than 10 GeV. Now, $\epsilon_{multijet}$ is determined as the number of events that pass the ‘tight’ criteria over the number of events that pass the ‘loose’ criteria in this sample. In the electron channel,

$\epsilon_{\text{multijet}}$ depends on the number of reconstructed jets in an event (see figure 5.2.9) and on the trigger version. The latter effect is due to changes in the isolation criteria in the different trigger versions (see table 5.2.4). In the muon channel, there is a small dependency of $\epsilon_{\text{multijet}}$ on the

Figure 5.2.9: The dependence on the jet multiplicity for $\epsilon_{\text{multijet}}$ (named $\epsilon_{\text{fake-e}}$ here) in the electron channel is shown [172].

pseudorapidity of the muon in the detector system η^{det} . This is shown in figure 5.2.10 for a different number of reconstructed jets per event. The average efficiency $\epsilon_{\text{multijet}}$ is shown in table 5.2.5.

Figure 5.2.10: In the muon channel, $\epsilon_{\text{multijet}}$ (named $\epsilon_{\text{fake-}\mu}$ here) depends on the pseudorapidity η^{det} . This dependency is shown for different jet multiplicities [172].

No. of jets	$\epsilon_{\text{multijet}}$ (electron channel) for trigger version				
	v8–v11	v12	v13a	v13b	v14
1	$(11.2 \pm 0.5)\%$	$(17.9 \pm 0.6)\%$	$(18.7 \pm 1.2)\%$	$(19.1 \pm 0.6)\%$	$(18.5 \pm 0.6)\%$
2	$(12.8 \pm 1.0)\%$	$(19.2 \pm 1.0)\%$	$(18.8 \pm 2.2)\%$	$(19.4 \pm 1.1)\%$	$(22.0 \pm 1.2)\%$
3	$(13.6 \pm 1.5)\%$	$(19.5 \pm 1.6)\%$	$(19.8 \pm 3.4)\%$	$(19.2 \pm 1.6)\%$	$(19.4 \pm 1.7)\%$
4	$(10.0 \pm 2.8)\%$	$(15.5 \pm 2.9)\%$	$(20.9 \pm 8.6)\%$	$(17.7 \pm 3.3)\%$	$(20.7 \pm 3.7)\%$

Table 5.2.4: $\epsilon_{\text{multijet}}$ for the electron channel divided into different trigger periods [172].

The Monte Carlo events in the W +jets sample can now be reweighted by a weight $\omega_{W+\text{jets}}$ in a similar way as the Monte Carlo events of top quark pair production,

$$\omega_{W+\text{jets}} = \frac{\epsilon_{W+\text{jets}} \times N_{W+\text{jets}}}{\sum_{\text{selected events}} (\epsilon_{\text{Trigger}} \times \epsilon_{\text{MC corrections}} \times \epsilon_{\text{TRF}})}. \quad (5.2.17)$$

The multijet events are also reweighted by a weight ω_{multijet} :

$$\omega_{\text{multijet}} = \frac{\epsilon_{\text{multijet}} \times N_{\text{multijet}}}{N_{\text{Data events}}}. \quad (5.2.18)$$

No. of jets	$\epsilon_{\text{multijet}}$
1	40.8%
2	35.8%
3	34.2%
4	30.9%

Table 5.2.5: $\epsilon_{\text{multijet}}$ for the muon channel. The values are averaged over the whole η^{det} range [172].

	Electron Channel			Muon Channel		
	2 jets	3 jets	4 jets	2 jets	3 jets	4 jets
N_{loose}	15,213	7,118	2,191	7,092	3,054	878
N_{tight}	8,220	3,075	874	6,432	2,590	727
$\epsilon_{\text{multijet}} \times N_{\text{multijet}}$	1,433	860	256	329	223	56
$\epsilon_{\text{W+jets}} \times N_{\text{W+jets}}$	6,787	2,215	618	6,105	2,369	669

Table 5.2.6: Selected number of loose and tight data events (first two rows) and expected number of W+jets and multijet events in the tight sample after applying the matrix method (bottom two rows) [172].

After the yield of the total sample of Monte Carlo W+jets is scaled to data with the matrix method, the relative fraction of heavy flavor production ($Wb\bar{b}$ and $Wc\bar{c}$ Monte Carlo samples) is determined. In the production of these samples, the ALPGEN Monte Carlo event generator is used. However, the cross sections generated by ALPGEN are only leading order. Unfortunately, these cross sections are sensitive to NLO corrections, especially for the $Wb\bar{b}$ and $Wc\bar{c}$ processes [179,187,188]. The relative composition of these events with respect to the W+light parton events $N_{\text{W+lp}}$ can be expressed by a scale factor α as shown in equation 5.2.19. It is assumed that the same value of α applies for both the $Wb\bar{b}$ and the $Wc\bar{c}$ Monte Carlo events:

$$N_{\text{W+jets}} = \alpha \left(N_{Wb\bar{b}} + N_{Wc\bar{c}} \right) + N_{\text{W+lp}} \quad (5.2.19)$$

with the constraint

$$N_{\text{W+jets}} + N_{t\bar{t}} + N_{\text{multijet}} = N_{\text{Data}} \quad (5.2.20)$$

To avoid to perform this normalization in the signal region, which could lead to a bias in the single top quark analysis, the factor α is derived in a data sample without any b-tagged jet, i.e. a sample that is not used in the analysis, that has enough statistics, and a similar sensitivity to the heavy flavor ratio as the signal region. The values of α for the different jet multiplicity bins in the electron and muon channel for the zero-tag data sample are shown in figure 5.2.11. The eight values that are shown in this figure and used in the fit are summarized in table 5.2.7. For the analysis, a value $\alpha = 1.5$ is chosen, and a 30% uncertainty assigned to it.

Heavy flavour scale factor α measured in the zero tag bins

Figure 5.2.11: Values of the heavy flavor factor α measured in different jet multiplicity bins for the muon and the electron channel in the zero-tag sample [172].

	1 jet	2 jets	3 jets	4 jets
Electron Channel	1.53 ± 0.10	1.48 ± 0.10	1.50 ± 0.20	1.72 ± 0.40
Muon Channel	1.54 ± 0.10	1.50 ± 0.10	1.52 ± 0.10	1.38 ± 0.20

Table 5.2.7: Summary of the scale factors α for each jet multiplicity bin for events that contain no b-tagged jet in the electron and the muon channel. The uncertainties are statistical only.

5.3 Selection of Events

In the event selection, cuts on the reconstructed physics objects introduced in chapter 4 are applied. These cuts are chosen such that the signature of the signal process of electroweak top quark production is reflected. Furthermore, it is tried to remove events that mimic the single top quark signature or events that originate from detector effects such as noisy calorimeter cells. However, the goal is to apply loose selection cuts. This allows to train the multivariate analysis techniques with high statistics and to let them figure out correlations between the signal and background samples and to achieve a good discrimination between the two components.

Selection Requirements Common for Muon and Electron Channel

The requirements listed below, are common for both the muon and the electron channel. The specific selection cuts for the muon and the electron channel will be presented later.

Data Quality

All data events are checked if they pass the data quality criteria for tracking, calorimetry, and the muon system provided by the data quality group [199]. Version v02-01-01 of the `caf_dq` package was used together with version v2006-05-04 of the data quality definitions `dq_defs`.

Trigger Selection

An event must pass one of the triggers listed in section 5.1.2 for the electron channel or one of the triggers listed in section 5.1.1 for the muon channel. Furthermore, the electron and the muon objects reconstructed in the offline software must match the lepton object that has initially fired the trigger.

Vertex Selection

While the number of minimum bias vertices is not limited, only one vertex fulfilling the criteria described in section 4.2 is allowed. This vertex must have at least three tracks attached to it and its z coordinate is required to fulfill $|z_{PV}| < 60$ cm.

Jet Selection

The expected number of reconstructed jets in an event derived from the s- and t-channel Feynman diagrams for single top quark production is two or three. To also take into account effects from initial state or final state radiation, events with at least two and a maximum of four fully reconstructed jets are selected. All jets must be reconstructed within $|\eta^{det}| < 3.4$ and with a transverse momentum higher than 15 GeV. In addition, the leading jet, i.e. the jet object with the highest transverse momentum, is required to have a transverse momentum higher than 25 GeV and to be reconstructed within $|\eta^{det}| < 2.5$. A requirement on the transverse momentum of the second leading jet is made. Its transverse momentum must be higher than 20 GeV. To further reduce the contribution of noisy events, events that contain more than three objects that fail the standard jet ID requirements are rejected. A triangle cut between the missing transverse energy $\cancel{E}_T$ and the leading jet helps to remove events where $\cancel{E}_T$ is poorly measured. The cut is applied in the $|\Delta\phi(\text{leading jet}, \cancel{E}_T)|$ vs. $\cancel{E}_T$ plane. Events to the right of the line that goes through the points (1.5 rad, 0 GeV) and (π rad, 35 GeV) pass this cut.

Missing Transverse Energy Selection

In the decay of the W boson originating from the decay of the top quark, a neutrino is produced that escapes detection. This leads to a significant amount of missing transverse energy in the event. To suppress QCD multijet events, a minimum amount of $\cancel{E}_T$ of 15 GeV is required. An upper cut of 200 GeV removes mismeasured events, e.g. caused by a mismeasurement of the muon track momentum.

Additional Selection Requirements in the Muon Channel

The selection requirements described here are specific for the muon channel and are applied on top of the common selection cuts described above.

Events in the muon channel contain exactly one tight muon (as defined in section 4.3). The transverse momentum of this muon is required to be higher than 18 GeV and its pseudorapidity $|\eta^{det}| < 2.0$. With this cut, $Z \rightarrow \mu\mu$ events and $t\bar{t}$ dilepton events with two muons in the final state are removed.

The muon is required to come from the primary vertex of the interaction. Therefore, a cut $|\Delta z(\mu, PV)| < 1$ cm is applied on the distance in z direction between the muon and the primary vertex.

To keep the electron and muon channel orthogonal, events that contain an electron of quality *top_tight* with transverse energy higher than 15 GeV and pseudorapidity $|\eta^{det}| < 2.5$ are rejected. This cut also rejects $t\bar{t}$ dilepton events with one muon and one electron in the final state. To remove events with poorly measured missing transverse energy, three triangle cuts are applied in the $\Delta\phi(\mu, \cancel{E}_T)$ vs. $\cancel{E}_T$ plane. Events pass the selection if they are:

- below the line connected through the points (2.5 rad, 0 GeV) and (π rad, 30 GeV),
- above the line connected through the points (1.5 rad, 0 GeV) and (0 rad, 50 GeV), and
- above the line connected through the points (1.1 rad, 0 GeV) and (0 rad, 80 GeV) .

Additional Selection Requirements in the Electron Channel

On top of the common selection cuts, the following electron specific cuts are applied for events to pass the selection in the electron channel.

Exactly one electron of quality *top_tight* (see section 4.4) is allowed in each event. The kinematic of this electron is required to fulfill a transverse energy higher than 15 GeV and to be reconstructed in the central region of the detector, i.e. $|\eta^{det}| < 1.1$.

To guarantee that the electron comes from the hard interaction, a cut on the distance in z direction between the electron and the primary vertex PV of the event is required: $|\Delta z(e, PV)| < 1$ cm. An event is rejected if it contains any other electron of the quality *top_loose* with a transverse energy higher than 15 GeV. This cut removes $Z \rightarrow ee$ events and $t\bar{t}$ dilepton events, with two electrons in the final state.

To keep the electron and muon channel orthogonal, an event may not contain a tight muon with transverse momentum larger than 18 GeV and $|\eta^{det}| < 2.0$. This cut also helps to remove $t\bar{t}$ dilepton events with one electron and one muon in the final state.

To remove events with poorly measured missing transverse energy, three triangle cuts are applied in the $\Delta\phi(e, \cancel{E}_T)$ vs. $\cancel{E}_T$ plane. Events pass the selection if they are:

- below the line connected through the points (2.0 rad, 0 GeV) and (π rad, 24 GeV),
- above the line connected through the points (2.0 rad, 0 GeV) and (0 rad, 40 GeV), and
- above the line connected through the points (1.5 rad, 0 GeV) and (0 rad, 50 GeV).

Sample Splitting

The data set used in this analysis is divided into twelve orthogonal samples. They are analyzed separately and later combined in the procedure that extracts the cross section. The data set is split by lepton flavor (electron and muon channel), by the number of reconstructed jets in the event (two, three or four jets) and the number of b-tagged jets (one or two b-tagged jets). The division by lepton flavor is because of the different trigger requirements for each of the lepton types. Furthermore, electron and muon events have a different sensitivity for the different background sources. By splitting the data sample in this way, a proper modeling is possible in each lepton flavor. The same argumentation can be made for the splitting into different jet multiplicity bins. The division into different events with one and two b-tagged jets reflects the different sensitivities for s- and t-channel single top quark events with respect to b-tagging. While events with one b-tagged jet are sensitive to both s- and t-channel, the sensitivity for s-channel production is dominant in events with two b-tagged jets.

Signal Acceptances

With the branching fraction BR of the Monte Carlo sample and the initial number of Monte Carlo events N_{initial} (both values can be found in table 5.2.1), the number of events that pass the selection criteria N_{selected} and the correction factors for the triggers ($\epsilon_{\text{trigger}}$), for Monte Carlo events ($\epsilon_{\text{correction}}$, see section 5.2.4), and for the b-tagging (ϵ_{TRF} , see section 4.6), it is possible to determine the signal acceptance $\mathcal{A}$ as

$$\mathcal{A} = \frac{B}{N_{\text{initial}}} \sum_{N_{\text{selected}}} (\epsilon_{\text{trigger}} \times \epsilon_{\text{correction}} \times \epsilon_{\text{TRF}}) \quad (5.3.1)$$

Table 5.3.1 summarizes the signal acceptances for simulated s- and t-channel events separately. The acceptances are shown for both lepton types, the three jet multiplicity bins used in this analysis, for the whole sample before the b-tagging was applied, and divided into the subsamples with one or two b-tagged jets.

The yields, i.e. the predicted number of events for each signal or background channel, are shown in tables 5.3.2 to 5.3.4. Table 5.3.2 shows the yields and the number of data events for all events that pass the selection criteria before b-tagging is applied. Due to the normalization of the W +jets and multijet background with the ‘matrix method’ (as explained in section 5.2.5), the sum of the background events is exactly equal to the number of data events in this table. The numbers have been rounded to integer values for clarity, i.e. the sum of the components might differ from the values given for these sums.

Table 5.3.3 displays the yields for signal, background and data events with one b-tagged jet. Due to the application of b-tagging, the sum of background events no longer equals the number of observed events in data. For events with three or four reconstructed jets in the electron channel and for events with three reconstructed jets in the muon channel, the predicted number of events due to the background model is higher than the number of observed data events. For the other jet multiplicity bins, more events are recorded than predicted.

	Electron Channel			Muon Channel		
	2 jets	3 jets	4 jets	2 jets	3 jets	4 jets
Before b tagging						
s-channel	1.77%	0.83%	0.23%	1.36%	0.69%	0.19%
t-channel	1.49%	0.79%	0.25%	1.17%	0.64%	0.20%
One b -tagged jet						
s-channel	0.82%	0.39%	0.11%	0.64%	0.32%	0.09%
t-channel	0.61%	0.34%	0.11%	0.50%	0.28%	0.09%
Two b -tagged jets						
s-channel	0.29%	0.14%	0.04%	0.24%	0.12%	0.03%
t-channel	0.02%	0.05%	0.02%	0.01%	0.04%	0.02%

Table 5.3.1: Acceptances for the simulated s- and t-channel events of electroweak top quark production after all selection cuts are applied. The acceptances for the samples before b-tagging are also added for comparison.

	Electron Channel			Muon Channel		
	2 jets	3 jets	4 jets	2 jets	3 jets	4 jets
Signals						
tb	14	7	2	10	5	1
tqb	27	14	5	20	11	3
$tb+tqb$	41	21	6	31	16	5
Backgrounds						
$t\bar{t} \rightarrow ll$	35	28	10	27	22	8
$t\bar{t} \rightarrow l + \text{jets}$	26	103	128	14	71	99
$Wb\bar{b}$	358	149	42	312	161	47
$Wc\bar{c}$	931	389	93	1,028	523	131
Wjj	5,437	1,546	343	4,723	1,591	385
Multijets	1,433	860	256	329	223	58
Background Sum	8,220	3,075	874	6,434	2,592	727
Data	8,220	3,075	874	6,432	2,590	727

Table 5.3.2: Predicted number of events after selection and before b tagging is applied. Because of the normalization of W+jets and multijet events with the ‘matrix method’, the sum of background events equals the number of observed data events.

The yields for events with exactly two b-tagged jets are shown in table 5.3.4. The number of predicted events with four jets (electron channel) and two jets (muon channel) is higher than the number of observed events after b-tagging is applied.

Figure 5.3.1 summarizes the results of the event selection in terms of percentage of selected events and the signal over background ratio for the different analysis bins and separated by s-channel and t-channel Monte Carlo signal samples. Out of the twelve analysis bins that are used, the channel with two jets and one b-tagged jet has the highest percentage of selected s-channel

	Electron Channel			Muon Channel		
	2 jets	3 jets	4 jets	2 jets	3 jets	4 jets
Signals						
tb	7	3	1	5	2	1
tqb	11	6	2	9	5	2
$tb+tqb$	18	9	3	14	7	2
Backgrounds						
$t\bar{t} \rightarrow ll$	16	13	5	13	10	4
$t\bar{t} \rightarrow l+\text{jets}$	11	47	58	6	32	45
$Wb\bar{b}$	120	50	14	110	56	16
$Wc\bar{c}$	74	36	9	74	46	13
Wjj	61	20	5	58	23	6
Multijets	66	48	18	26	24	8
Background Sum	348	213	110	286	191	93
Data	357	207	97	287	179	100

Table 5.3.3: Predicted number of events after selection for events with exactly one b -tagged jet.

	Electron Channel			Muon Channel		
	2 jets	3 jets	4 jets	2 jets	3 jets	4 jets
Signals						
tb	2.3	1.1	0.3	1.9	0.9	0.3
tqb	0.3	0.8	0.4	0.2	0.7	0.4
$tb+tqb$	2.6	1.9	0.7	2.1	1.6	0.6
Backgrounds						
$t\bar{t} \rightarrow ll$	5.5	4.6	1.7	4.6	3.8	1.4
$t\bar{t} \rightarrow l+\text{jets}$	1.7	13.6	21.8	1.0	10.2	18.0
$Wb\bar{b}$	16.2	6.8	1.8	15.3	8.2	2.3
$Wc\bar{c}$	1.6	1.1	0.4	1.6	1.5	0.5
Wjj	0.1	0.1	0.0	0.1	0.1	0.0
Multijets	2.5	3.2	2.7	1.5	1.9	0.4
Background Sum	27.5	29.4	28.4	24.1	25.7	22.7
Data	30	37	22	23	32	27

Table 5.3.4: Predicted number of events after selection for events with exactly two b -tagged jets.

events, whereas the channel with two jets, both of them tagged as originating from the decay of a b hadron, has the best signal over background ratio. For simulated t -channel events, the analysis bin with two jets, one of them b -tagged, has the best performance in both percentage of selected events and signal over background ratio.

To give an impression of the good quality of the background model after the selection, figures 5.3.3 to 5.3.5 shows the data to Monte Carlo comparison in all channels used in the analysis for three different variables. In addition, the uncertainty on the background model is added as

shaded area. The color code that matches the colors in the histograms to the physics processes is given in figure 5.3.2.

The first variable shown in figure 5.3.3 (on page 103) is the transverse momentum distribution of the charged lepton in the event.

Figure 5.3.4 (on page 104) shows the reconstructed missing transverse energy in the event for the different analysis bins.

As an example for the quality of background model to describe jets, figure 5.3.5 (on page 105) shows the transverse momentum distribution for the leading jet in the event, i.e. the jet with the highest transverse momentum of all reconstructed jets.

Percentage of s-channel tb selected events and S:B ratio (white squares = no plans to analyze)					
Electron + Muon	1 jet	2 jets	3 jets	4 jets	≥ 5 jets
0 tags	8% 1 : 11,000	19% 1 : 1,600	9% 1 : 1,200	3% 1 : 1,100	1% 1 : 1,000
1 tag	6% 1 : 270	24% 1 : 55	12% 1 : 73	3% 1 : 130	1% 1 : 200
2 tags		9% 1 : 12	4% 1 : 27	1% 1 : 92	0% 1 : 110

Percentage of t-channel tqb selected events and S:B ratio (white squares = no plans to analyze)					
Electron + Muon	1 jet	2 jets	3 jets	4 jets	≥ 5 jets
0 tags	10% 1 : 4,400	27% 1 : 520	13% 1 : 400	4% 1 : 360	1% 1 : 300
1 tag	6% 1 : 150	20% 1 : 32	11% 1 : 37	4% 1 : 58	1% 1 : 72
2 tags		1% 1 : 100	2% 1 : 36	1% 1 : 65	0% 1 : 70

Figure 5.3.1: Percentages of the selected s-channel (upper table) and t-channel (lower table) signal events and signal-to-background ratios in each analysis channel.

Figure 5.3.2: Color scheme to identify the different physics processes in the following histograms.

Figure 5.3.3: The transverse momentum of the electron or muon for events with two jets (left column), three jets (center column), and four jets (right column). Electron events with one b-tagged jet are shown in the first row, muon events with one b-tagged jet in the second row. The third row displays electron events containing two b-tagged jets, the last row shows muon events with two b-tagged jets.

Figure 5.3.4: The missing transverse energy distribution is shown for events with two jets (left column), three jets (center column), and four jets (right column). Electron events with one b-tagged jet are shown in the first row, muon events with one b-tagged jet in the second row. The third row displays electron events containing two b-tagged jets, the last row shows muon events with two b-tagged jets.

Figure 5.3.5: The transverse momentum distribution of the jet with the highest transverse momentum of all reconstructed jets in an event is shown for events with two jets (left column), three jets (center column), and four jets (right column). Electron events with one b-tagged jet are shown in the first row, muon events with one b-tagged jet in the second row. The third row displays electron events containing two b-tagged jets, the last row shows muon events with two b-tagged jets.

6 Analysis Strategy and Software Algorithms

In this chapter the analysis strategy is explained and the software toolkits are introduced that are used to realize this strategy. Section 6.1 gives a short overview of the different steps that are sequentially performed in the analysis. In section 6.2 the concept of a Multi-Process Factory analysis is motivated and the advantages of the software toolkit PAX for the implementation of this strategy are explained in detail. As a multivariate classifier for the statistical analysis of the observables obtained by the Multi-Process Factory analysis, Boosted Decision Trees are used. Their properties are introduced in section 6.3 and their implementation in the TMVA software package is presented.

6.1 General Analysis Flow

A sketch of the analysis flow is shown in figure 6.1.1. It demonstrates the different steps of the analysis that follow the preselection of the events, as explained in section 5.3. First, the events are analyzed in the Multi-Process Factory and the result, i.e. the observables obtained by the analysis of the different processes, is stored as a `TTree` object in a `ROOT` file (version 5.20.00 of the `ROOT` data analysis framework is used [200]). The training and application of the Multi-Process Factory will be explained in the next section 6.2.1. The `ROOT` files are then used as input to the multivariate classifier of Boosted Decision Trees. This analysis technique is introduced in section 6.3. The optimization of the Boosted Decision Trees for the presented analysis of the measurement of the cross section of electroweak top quark production is explained in section 8.1. The results of the Boosted Decision Tree classifier are again stored in `ROOT` files. Those files are then used in the package `top_statistics` [201] of the $D\bar{O}$ top quark analysis group in order to perform the measurement of the cross section and to obtain the sensitivity of the analysis (see section 8.4).

6.2 A Multi-Process Factory Analysis

It is a common technique in high energy physics analyses to reconstruct the complete decay cascade for the decay of a heavy particle. Especially in analyses dealing with the production of top quark pairs this method is frequently used. When trying to measure properties of a heavy particle or characteristics of its decay, it is often necessary to reconstruct the whole decay chain (e.g. the first measurements of the top quark mass with the $D\bar{O}$ experiment already reconstructed all possible assignments of reconstructed objects with the partons from the top quark

Figure 6.1.1: Steps of the analysis following the preselection of events. First, the events are analyzed in the Multi-Process Factory. The observables gained in this step are stored in a ROOT file and used in the multivariate analysis with Boosted Decision Trees. The results of the evaluation of the Boosted Decision Trees are then again stored in a ROOT file and used in the statistical analysis, where the measurement of the cross section and the determination of the sensitivity takes place.

decay (see [202] and [203]). Another example is the measurement of the helicity fractions of W bosons from top quark decays [204]). A common feature of these analyses is that each event is evaluated under the signal hypothesis only. The ambiguities that arise in assignment of reconstructed objects to the partons of the decay are only resolved for the assumption that the events originate from the signal process. In a Multi-Process Factory analysis the reconstruction of the decay chain of the signal process is only one of many decay chains that are evaluated. Furthermore the decay chains of the most important background processes are also reconstructed for each event. Of course it is taken care of resolving the ambiguities also in these decay cascades. In the search for electroweak top quark production performed here, the signal contribution in the data is hidden in an overwhelming background. The ansatz of this analysis technique is to make a step towards active identification of both the contributing signal and background processes. By reconstructing an event not only under the hypothesis of the signal process, but also under the assumption to originate from a background process, access is gained to observables that are specific for these background processes and that can contribute to the separation power in the statistical analysis. In addition, having the complete decay chain reconstructed, one has access to angular correlations between different partons of the decay chain and can also exploit the differences in the resulting distributions for signal and background events. A summary of the

reconstructed decay chains for the three different jet multiplicity bins analyzed in this analysis is given in table 6.2.1.

	2 jets	3 jets	4 jets
electroweak top quark production (s-channel)	x	x	x
electroweak top quark production (t-channel)	x	x	x
top quark pair production (semileptonic)	-	x	x
top quark pair production (dilepton)	x	x	-
Production of W bosons associated by jets	x	x	x

Table 6.2.1: Summary of the different signal and background hypotheses. For each individual jet bin an event is analyzed with respect to the marked processes during the Multi-Process Factory analysis.

Looking at the column for events with three jets, it is obvious that the leading order Feynman diagrams for the two processes of top quark pair production have one more (less) jet in the case of the dilepton (semileptonic) decay channel than predicted. What is reconstructed in all these processes are not Feynman diagrams but so called Parton Picture Templates (PPT). They represent the experimentalists' view of the decay chain by taking into account theory information (by the use of generator information) and additional knowledge about the detector or knowledge gained by dedicated studies. Thus, the opportunities to gain information from signal and background processes is not limited to Feynman diagrams, but to any meaningful Parton Picture Template. For example in the case of the semileptonic decay of top quark pairs in events with three jets, even two Parton Picture Templates are reconstructed, after performing a study on Monte Carlo events where the reasons for the jet losses were identified (see [205] for details). The two Parton Picture Templates for this process are shown in figures 7.2.55 and 7.2.56, respectively.

In the next section 6.2.1 the training and the application of a Multi-Process Factory are explained in detail. The advantages the software toolkit PAX provides for the implementation of a Multi-Process Factory will then be discussed in section 6.2.2.

6.2.1 Application and Optimization of a Multi-Process Factory

In section 6.2.1.1 the application of a Multi-Process Factory is explained in a bottom-up approach: First, the sequence of procedures in one process is demonstrated. Afterwards, this concept is extended to a full Multi-Process Factory. The procedure to optimize each individual process is then explained in section 6.2.1.2. Examples on how to extract variables from the Multi-Process Factory for the use in a multivariate analysis technique are then presented in section 6.2.1.3.

6.2.1.1 From one Process to a Multi-Process Factory

The concept of a Multi-Process Factory is explained by starting with a Factory that has only one process to take care of, and is then extended. This Singleprocess Factory can thus be compared with a standard analysis that aims at the measurement of properties of the decay of a

heavy particle and tries to reconstruct the decay chain of the signal hypothesis as thoroughly as possible. Because the different steps an event takes in one of the processes are similar in all other processes, it is sufficient to present those steps for one process and to make generalizations afterwards. In figure 6.2.1 a Factory (represented by the grey area) for a single process is shown. For each event to be analyzed, a copy of the event is given by the Factory to the

Figure 6.2.1: The different steps of an event in the reconstruction of a process (blue colored area) are shown. The process receives a copy of the event information from the Factory (grey area). Based on this information, it reconstructs all possible configurations of the decay chain according to its Parton Picture Template. These configurations are evaluated and the most likely one identified. The Factory has access to the latter configuration and reads out the observables from it that will be used in the statistical analysis.

process (represented by the blue area). Thus it is guaranteed that the original instance of the event is not altered by a process and that each of the processes receives the same information as input. The task of the process is then to reconstruct all possible configurations of an event. The process carries a template of the decay chain to be reconstructed. This template is called Parton Picture Template (PPT). In figure 6.2.2 the Parton Picture Template of the process that reconstructs electroweak top quark production in the s-channel for events with two reconstructed jets is shown as an example. There, the Parton Picture Template is similar to the leading order

Figure 6.2.2: Parton Picture Template to be reconstructed by the process that evaluates an event with two reconstructed jets under the hypothesis of electroweak top quark production through a s-channel process. In this case, the Parton Picture Template is similar to the leading order Feynman diagram.

Feynman diagram of the physics process. But, as already mentioned before, this is not a general requirement and depends on the experimentalists' knowledge of the particular features of the event kinematics. For example, in this analysis a background to the electroweak production of top quarks in events with three jets is the production semileptonic decay of top quark pairs, produced via strong interaction. The leading order Feynman diagram to this physics process has already four quarks in the final state, i.e. four reconstructed jets are expected. After a Monte Carlo based study of those events with three jets [205] it is possible to define the PPT shown in figure 6.2.3. It represents the semileptonic decay of a pair of top quarks, produced via strong interaction, where one of the quarks from the hadronic decay branch (i.e. the branch, where the W boson from the top quark decay decays into two quarks) escapes detection. The two remaining jets of the hadronic decay branch are combined to a dijet four-vector. In the branch with the leptonic decay of the W boson the top quark can be reconstructed completely. In spite of not having enough reconstructed objects available to reconstruct the complete decay of two top quarks produced as a pair, this PPT enables the experimentalist to obtain information about at least one top quark. Furthermore, also observables gained from the dijet four-vector can be useful in the multivariate analysis.

The number of possible assignments of reconstructed objects (i.e. jets, charged leptons, and missing transverse energy) to the final state partons in the Parton Picture Template yields the number of configurations that are reconstructed in the process. During the reconstruction of these configurations, those that cannot be distinguished are neglected. For example, when reconstructing a W boson that decays hadronically into two quarks q and q' , two jets j_1 and j_2 would be associated with these quarks. The kinematic quantities of the resulting W bosons are independent of the correct assignment. Both possible assignments $j_1 \rightarrow q$ and $j_2 \rightarrow q'$ or $j_1 \rightarrow q'$ and $j_2 \rightarrow q$ lead to the same kinematics for the W boson. Therefore, one of the configurations can be neglected.

In this analysis, only one of the n possible configurations is taken into account, finally. Therefore, all reconstructed configurations are evaluated in a Likelihood measure. The goal of this Likelihood measure is to identify the one out of n configurations in the signal sample that matches the kinematic correct configuration. Here, signal sample corresponds to the physics process that stands as a model for the Parton Picture Template, i.e. it is not necessarily

Figure 6.2.3: Parton Picture Template for the reconstruction of events with three reconstructed jets under the hypothesis to originate from a semileptonic top quark pair decay. This is an example for a process in the Multi-Process Factory where the Parton Picture Template does not correspond to the leading order Feynman diagram of the physics process.

the electroweak production of top quarks. These correct configurations are used as input for the Likelihood method and are obtained by matching the reconstructed objects with the information of the generated partons. The way these configurations are reconstructed will be explained in detail in section 6.2.1.2. Observables of these correct configurations B are stored in histograms. Those histograms are then normalized to unit area of in order to fulfill the criteria for a probability density distribution.

The Likelihood measure $L(C)$ for each of the n different configurations C is then calculated as

$$L(C) = \prod_{i=1}^k P(x_i|B), \quad (6.2.1)$$

with k observables used in the calculation of the Likelihood measure. The term $P(x_i|B)$ in the Likelihood measure gives the probability to measure the value x of variable i under the assumption that the configuration C that is currently analyzed is the best configuration B (more details on the Likelihood measure $L(C)$ and the probability $P(x_i|B)$ can be found in appendix A). There are cases where $P(x_i|B) = 0$ because $f(x_i|B) \equiv 0$ in the interval $[x_{\min}, x_{\max}]$ (with $f(x_i|B)$ being the (binned) probability density function of observable i for the best configuration B). This happens when a background event (for a given process) lies in a different region of phase space than the signal events used for the optimization of this Likelihood measure, i.e. the filling of the histograms. In this case, a value of $1/10000$ is returned in order to avoid $L(C)$ to become 0 and to be able to separate the different configurations.

The number of observables used in the Likelihood measure is chosen equal or higher as the number of assignments that need to be made, in order to give a unique answer. For example, in the case of electroweak production of single top quarks in the s-channel in events with

two jets (see Parton Picture Template in figure 6.2.2) there are three ambiguities that need to be resolved: the z component of the neutrino momentum vector (since the reconstructed missing transverse energy only yields information about the x and y component) and the two reconstructed jets need to still be assigned to the partons b(prod) and b(lept). In this case, three variables are used in the Likelihood measure (see section 7.1.1.1).

Once all configurations are evaluated, the one configuration C^* with the highest Likelihood measure $L^*(C)$ is identified. The whole process of evaluating the configurations and identifying the most likely configuration C^* is called *Ambiguity Resolution*. The Factory has access to this configuration (see figure 6.2.1), reads out its properties that will be used in the statistical analysis and stores them in a ROOT file, as shown in figure 6.1.1.

Figure 6.2.4 generalizes the concept introduced so far by showing the flow of an event through the full Multi-Process Factory. An event containing the information of the reconstructed objects is given to the Factory. The Factory centrally checks for all participating processes if the preselection criteria are fulfilled and which processes should be started for a given event (depending on the number of reconstructed jets). Those processes (labeled A, B, C, and D for simplicity) receive a copy of the event information. In each process the procedure explained above for one individual process is performed, i.e. all possible event configurations are reconstructed and evaluated according to the different Parton Picture Templates of A, B, C, and D and their Ambiguity Resolution. The Factory then accesses the most likely configuration in each process, and reads out the properties of their decay chains. The obtained values are then written into a ROOT file and stored for the following statistical analysis.

6.2.1.2 Optimization of the Likelihood Measure

In order to optimize the Likelihood measures used in the Ambiguity Resolutions of the processes analyzed in the Multi-Process Factory, the best possible configuration of the reconstructed Parton Picture Template has to be identified by matching the information of the generator with the reconstructed objects in the event. Histograms of observables of this configuration are then used as input to the Likelihood measure. This procedure is depicted in figure 6.2.5. Events used in this matching procedure are taken from the Monte Carlo samples described in sections 5.2.1 and 5.2.2 and that correspond to the physics process the Parton Picture Template represents. The events have passed the preselection cuts for the muon channel analysis or the electron channel analysis as described in section 5.3. In addition to the reconstructed objects, the event container also carries information about the partons that were initially generated. The matching procedure now tries to match the reconstructed jets and leptons to the final state quarks and leptons from the generator. Therefore a χ^2 value is calculated for each possible assignment, i.e. reconstructed jets are assigned to quarks and reconstructed charged leptons to generated leptons. Input to the χ^2 are kinematic quantities. For the muons and the electrons the angles θ and φ and the transverse momentum P_T are used in the calculation of $\chi_{e,\mu}^2$:

$$\chi_{e,\mu}^2 = \left(\frac{\Delta\theta}{\sigma_\theta} \right)^2 + \left(\frac{\Delta\varphi}{\sigma_\varphi} \right)^2 + \left(\frac{\Delta P_T}{\sigma P_T} \right)^2. \quad (6.2.2)$$

Figure 6.2.4: Abstract representation of a Multi-Process Factory reconstructing four different Parton Picture Templates in the four processes labeled A, B, C, and D. After a consistency check, each process receives a copy of the event information, reconstructs all possible configurations of its Parton Picture Template and evaluates those using a Likelihood measure. The Factory collects the most likely configuration of each process and reads out their observables that are used in the statistical analysis (using Boosted Decision Trees in the analysis presented here). Those observables are then stored in a ROOT file.

For the matching of reconstructed jets to generated quarks, only spacial quantities are considered in the calculation of $\chi_{j,q}^2$. A term considering the transverse momentum is neglected because of the big uncertainties in the jet energy scale. Equation 6.2.3 thus shows the calculation of $\chi_{j,q}^2$:

$$\chi_{j,q}^2 = \left(\frac{\Delta\eta}{\sigma_\eta} \right)^2 + \left(\frac{\Delta\varphi}{\sigma_\varphi} \right)^2 \quad (6.2.3)$$

The resolutions σ are obtained by fitting a Gaussian over the differences Δ of the generated quantity and the reconstructed quantity in the signal sample of electroweak top quark production. This is done on the whole event sample that passes the preselection criteria, i.e. no cut on the number of reconstructed jets or the number of b-tagged jets is applied. However, the resolutions for the charged leptons are treated separately because of the differences in their identification processes. Analysis-wide, the resolutions obtained by this procedure are used, independent of the physics process represented by the Parton Picture Template. Table 6.2.2 summarizes the resolutions used as input to the χ^2 determination. The χ^2 values are calculated

Figure 6.2.5: Sketch of the different steps performed in the reconstruction of the best possible configuration of the Parton Picture Template. An event containing both generator information and reconstructed objects is fed to a matching algorithm. Having an assignment of the final state objects to the final state partons, it is possible to reconstruct the decay chain. Observables from this decay chain are then put into histograms and stored in a ROOT file. This file is then used in the Ambiguity Resolution in the application of the process in the Multi-Process Factory.

for all combinations of partons and reconstructed objects. Then, those combinations with a minimal value of χ^2 are chosen and the reconstructed objects and generated partons assigned to another as a good match. For each successful matching a matching quality criteria Q_M is derived. It is calculated as the sum over the spacial distances $\Delta R(\text{rec}, \text{gen})$ in the $\eta - \varphi$ -plane of the matched objects. Thus, Q_M is calculated as

$$Q_M = \sum_{i=1}^n \Delta R_i(\text{rec}, \text{gen}), \quad \text{with} \quad (6.2.4)$$

$$\Delta R(\text{rec}, \text{gen}) = \sqrt{(\Delta \eta(\text{rec}, \text{gen}))^2 + (\Delta \varphi(\text{rec}, \text{gen}))^2} \quad (6.2.5)$$

matching of leptons		
	muons	electrons
σ_θ	0.00035	0.0019
σ_φ	0.00025	0.0018
σ_{P_T}	2.05 GeV	8.48 GeV
matching of quarks and jets		
σ_η	0.023	
σ_φ	0.016	

Table 6.2.2: Resolutions of the different observables used in the calculation of the χ^2 matching criteria.

for n assignments of partons to reconstructed objects. A cut on Q_M is applied to select events where the reconstructed objects originate with high probability from the partons found in the generator information. Contributions from initial or final state radiation that lead to wrong configurations are thus minimized. The cut value is chosen such that the best 68% of the matched events pass the cut. The determination of the cut value on Q_M is performed for each process independently, i.e. it is dependent on the signal process that is represented by the Parton Picture Template and the number of reconstructed jets. Example distributions for the matching quality distribution are shown in figure 6.2.6 for events with two reconstructed jets in simulated events for electroweak top quark production in the s-channel.

Figure 6.2.6: 68% cutoff value for the matching quality Q_M between generated partons and reconstructed objects for muon 6.2.6(a) and electrons 6.2.6(b) event in the s-channel single top quark sample. Only quantities of events with good matching quality (grey area) are used as input to the Likelihood measure that is used to resolve the ambiguities in application of the process to assign reconstructed objects to the parton of the Parton Picture Template.

Having matched the reconstructed objects to final state particles in the generator decay, it is now possible to reconstruct the best possible configuration of the Parton Picture Template, by

adding the four-momentum vectors of two daughter particles to obtain the mother particle in the decay chain. If the mother particle is a W boson that decays leptonically into a charged lepton and a neutrino, there may be two more ambiguities that need to be resolved. Since the neutrino escapes detection its kinematics are reconstructed using the missing transverse energy in the event. However, the missing transverse energy only yields the x and y component of the momentum vector. The z component can be calculated using the mass of the W boson as a constraint and requiring conservation of momenta. A value of 80.4 GeV for the mass of the W boson was used in all processes [206]. The number of solutions and the details of the calculation of the z component of the neutrino is elaborated in appendix C.

A special procedure needs to be followed in case the electron or neutrino in the final state originates from the leptonic decay of a tau lepton. Due to the two additional neutrinos in those events, it is not sufficient to compare the missing transverse energy with the neutrino originating from the decay of the W boson. An effective neutrino is calculated by adding up the momenta of the three neutrinos. This value is added to the generator information and used in the comparison with the missing transverse energy. Due to the uncertainties in the calculation of the z component of the neutrino momentum and the uncertainties in the reconstruction of the missing transverse energy, for the best possible configuration the z component is chosen where the spacial distance ΔR between the (effective) generated neutrino and the reconstructed neutrino is minimal.

The goal in the optimization of the Ambiguity Resolution is to find a set of input variables so that the configuration C^* with the highest Likelihood measure is similar to the best possible configuration B as often as possible. In chapter 7 this is expressed in the documentation of the different processes with the two efficiencies ϵ_{68} and ϵ_{100} as defined in definition 6.2.1.

Definition 6.2.1 (Efficiencies ϵ_{68} and ϵ_{100} of the Ambiguity Resolution)

Two different efficiencies ϵ_{68} and ϵ_{100} are calculated for the Ambiguity Resolution in each process reconstructing a Parton Picture Template. The configuration C^ is selected in the Ambiguity Resolution and the configuration B is the best possible configuration. The two efficiencies can then be calculated as:*

$$\epsilon_{68} = \frac{\text{Number of events passing the 68\% matching quality cut where } C^* \text{ matches } B}{\text{Number of events passing the 68\% matching quality cut}}$$

$$\epsilon_{100} = \frac{\text{Number of events where } C^* \text{ matches } B}{\text{Number of matched events}}$$

The number of events uses the event weights to take e.g. the different trigger probabilities of the events into account. The set of variables used for the Ambiguity Resolution is optimized on ϵ_{100} in the muon channel and then used in the electron channel analysis as well. However, the efficiencies are determined individually for the muon channel and the electron channel analysis. For the calculation of these efficiencies a matched event is an event where the charged lepton and the jets could be matched to their corresponding partons. The ambiguity in the reconstruction of the neutrino is neglected in the matching because of the uncertainty on the number of solutions in the determination of the z component of the neutrino momentum vector.

The efficiency ϵ_{68} refers to the number of events that is used as input to the histograms used in the Ambiguity Resolution. ϵ_{100} refers to the full sample of signal events for the given Parton Picture Template and thus represents the efficiency of the Ambiguity Resolution to select the best possible configuration in the full analysis.

6.2.1.3 Extracting Observables

Once a process has reconstructed all possible versions of its Parton Picture Template and evaluated them in the Ambiguity Resolution, observables of this selected event configuration are stored in a `TTree` object of the `ROOT` toolkit (see figure 6.2.4). Taking the electroweak production of top quarks in the s-channel (see Parton Picture Template in figure 6.2.2) as an example process, the mass or transverse momentum of the reconstructed top quark $t(\text{lept})$ or the pseudorapidity η of one of the jets assigned to parton $b(\text{lept})$ or $b(\text{prod})$ could be candidates for such observables. Kinematic quantities of the reconstructed objects assigned to the partons of the Parton Picture Template or of the reconstructed, intermediate particles are good candidates for observables that are able to separate the signal events of electroweak top quark production from the background contributions. There is also the possibility to take advantage of angular correlations between different partons of a Parton Picture Template.

However, it is not always necessary to reconstruct a Parton Picture Template in order to determine observables. Event shape variables such as the scalar sum over the energies of jets in the event, called H , can be calculated without any assignment between reconstructed objects and parton and thus without the need to resolve any ambiguities. In the following, definitions of some of these observables used in the statistical analysis and thus appearing in the different analysis bins in chapter 7 are summarized.

Definition 6.2.2 (leading jet)

The reconstructed jets can be sorted according to their transverse momentum. The one with the highest transverse momentum is called ‘leading jet’ or ‘jet1’. The other jets are labeled as ‘jet2’, ‘jet3’, and ‘jet4’ accordingly. In the analysis bins where two jets are tagged as originating from the decay of a b hadron, these two jets are sorted after their transverse momentum and the names ‘leading b -tagged jet’ and ‘second leading b -tagged jet’ are assigned. Similar names are used for those jets that are not b -tagged. They are labeled ‘leading untagged jet’ or ‘second leading untagged jet’ accordingly.

In the generator used to produce the simulated signal samples of electroweak top quark production, the mass of the top quark is set to 175 GeV (see section 5.2.1). This allows to define a ‘best jet’:

Definition 6.2.3 (best jet)

The ‘best jet’ is defined as the one reconstructed jet in the event for which the invariant mass $M(W, \text{jet})$ is closest to $m_{\text{top}} = 175 \text{ GeV}$. Jets can be sorted after this criterion and are labeled as ‘best jet’, ‘second best jet’, etc.

Definition 6.2.4 (b-tagged jet)

In the case where only one jet in the event is identified as originating from the decay of a b hadron, the label ‘ b -tagged jet’ is assigned to this jet. For events with two b -tagged jets the jet with the higher transverse momentum carries the label ‘ b -tagged jet’.

The definitions 6.2.5 and 6.2.6 define two possibilities to have access to the decay chain of a top quark by assuming that the reconstructed value of the top quark mass should be as close as possible to the value used in the generator, i.e. 175 GeV.

Definition 6.2.5 (best top quark)

The ‘best top quark’ is the four-momentum vector of the sum of the four-momentum vectors of the reconstructed W boson and the best jet, according to definition 6.2.3.

Definition 6.2.6 (b-tagged top quark)

The ‘b-tagged top quark’ is the four-momentum vector of the sum of the four-momentum vectors of the reconstructed W boson and the one of the b-tagged jets that yields an invariant mass $M(W, \text{jet})$ closest to 175 GeV.

A variable widely known as ‘ q times η ’ is a characteristic variable for the t-channel production of single top quarks at the Tevatron proton-antiproton collider. The sign of the charge of the charged lepton from the decay of the W boson is multiplied with the pseudorapidity η of the (anti-)quark that appears, after a valence (anti-)quark has emitted the timelike W boson. This (anti-)quark usually follows the direction of the (anti-)proton beam it originates from. With the timelike W boson the charge of the charged lepton is already fixed. The product ‘ q times η ’ has an asymmetry for the t-channel production of single top quarks. Events initiated by the transition of $u \rightarrow d$ or $\bar{u} \rightarrow \bar{d}$ occur approximately twice as often as events initiated by the transition of $d \rightarrow u$ or $\bar{d} \rightarrow \bar{u}$ because of the uud ($\bar{u}\bar{u}\bar{d}$) valence quarks of the (anti-)proton. Since the charge of the charged lepton has just the opposite sign in $u \rightarrow d$ than in $\bar{u} \rightarrow \bar{d}$ reactions and the two beams are circulating in opposite directions, these two effects cancel in the calculation of ‘ q times η ’. Therefore approximately 2/3 of the events are found on positive values of ‘ q times η ’ and only 1/3 of the events have negative values in these observables (taking also into account the coordinate system of the in the DØ detector). Instead of reconstructing the complete decay chain of the t-channel process and thus identifying the jet corresponding to the scattered parton, definition 6.2.7 is often used:

Definition 6.2.7 q times η

The so-called ‘ q times η ’ variable is calculated as the sign of the charge of the charged lepton reconstructed in the event, multiplied by the pseudorapidity η of the ‘leading untagged jet’ (according to definition 6.2.2).

6.2.2 The PAX Toolkit

PAX (Physics Analysis Expert) [207,208] is a C++ toolkit [209] for the analysis of elementary particle interactions and uses containers of the Standard Template Library (STL) [210] for performance optimization. It provides an additional level of abstraction in particle physics analysis beyond detector reconstruction. With its approach to be independent of the details of the underlying experiment specific software, it enables physicsists to develop, exchange and share analysis code among different experiments easily. Thus, the specific analysis code remains untouched even when the underlying software of the detector reconstruction changes. Only the interface needs to be updated.

The idea of PAX is based on similar projects like H1PHAN [211] and ALPHA [212] of the H1 and the ALEPH experiment that have been developed in the past. They were used in experiments with e^+e^- and ep physics, i.e. in an environment without huge hadronic background. The

experiments for both the present and the near future in high energy physics are hadron colliders - either proton-antiproton collisions at Fermilab's Tevatron collider or proton-proton collisions at the Large Hadron Collider (LHC) - the challenge is to deal with many simultaneous events and large event sizes. PAX is developed to control the combinatorical tasks arising through the different possible interpretations for the same event. Furthermore, PAX reduces the amount of data to those relevant for the analysis.

The PAX toolkit has found users in different experiments, CMS, CDF, and DØ. In addition, interfaces to Monte Carlo generators exist and allow studies on parton level.

The place of PAX in a particle physics research project is between the database storing the reconstructed detector output and the physics result. To be able to present the results, it is still necessary to use ROOT or PAW [213] for histogramming and visualization. It is also no tool to perform detector reconstruction. This needs to be done beforehand to fill the reconstructed data into PAX.

6.2.2.1 The PAX Kernel

The basic unit in PAX is a class called `PaxEventInterpret`. Each `PaxEventInterpret` stores a distinct interpretation of the event currently analyzed. It contains three types of generalized physics objects (as depicted in figure 6.2.7):

- Particles (or reconstructed objects like tracks or jets) that can be represented by Lorentz-vectors, are stored in objects of the class `PaxFourVector`.
- Vertices are used to realize particle decays and are represented by the class `PaxVertex`.
- Collisions are represented by the class `PaxCollision` and can be used to separate multiple interactions in high-luminosity environments.

The relations between them are managed by the `PaxRelationManager`. An illustration of the different relations between the objects is shown in figure 6.2.8. The user can store additional information in an instance of a `PaxEventInterpretation`, `PaxFourVector`, `PaxCollision` or `PaxVertex` using the `PaxUserRecord` facility. It consists of a map with key string and mapped type double which can be searched correspondingly.

All the information about an interpretation of the event needs to be stored in a `PaxEventInterpret`. During the course of the analysis it can be necessary to make copies of an `PaxEventInterpret`. Copying a `PaxEventInterpret` means to make a physical copy in memory, i.e. all objects and all relations are duplicated and are independent of their origin. As a consequence, if the `PaxEventInterpret` they are stored in is deleted, all its registered objects will be deleted, too. It is the user's responsibility to book, fill or copy the event interpretation and it is his responsibility to delete it, too.

The `PaxFourVector` inherits either from the `HepLorentzVector` of the CLHEP [214] or from the class `TLorentzVector` of the ROOT package. Both of them provide similar functionality in their four-vector operations. In addition, a `PaxFourVector` provides methods and properties, e.g. relations to its begin- or end-vertex, its `PaxUserRecord`, a `PaxName`,

Figure 6.2.7: The basic unit in PAX, the `PaxEventInterpreter` contains maps for `PaxFourVectors`, `PaxVertices` and `PaxCollisions`. The relations between them are managed by the `PaxRelationManager`.

and so on.

The mechanism of the `PaxRelationsManager` bases on the ‘mediator’ design pattern [215]. It establishes the right connections automatically. For example, in a reconstructed event of the type $W^- \rightarrow e^- + \bar{\nu}_e$, the `PaxFourVector` of the electron will get a begin vertex relation to the `PaxFourVector` of the W boson, while the W boson gets an outgoing four-vector relation to the `PaxFourVector` of the electron.

The objects have also relations to themselves. If an object is copied, the relation manager stores a pointer to the original instance in the relations of the corresponding object. Thus it is possible to record both the decay tree and the history of the objects and to trace it back by iterating over the objects relations.

Another sophisticated feature PAX provides is its lock mechanism. It allows to exclude parts of an event interpretation from the analysis. This can be very useful in many areas. For example, if there are several collisions in one bunch crossing of a collider experiment (as expected for LHC and observed at the Tevatron), whole collisions can be excluded. This works because applying the `lock`-command to an object locks its whole decay tree. Or if the analyzed process contains jets and isolated leptons, one might lock this lepton from a jet finding algorithm.

Figure 6.2.8: The `PaxRelationManager` establishes decay trees, records histories and locks parts of an interpretation.

6.2.2.2 PaxProcess and PaxProcessFactory

In addition to the kernel functionality of the PAX toolkit, there is a collection of additional objects that can be used in the analysis of HEP events, the so-called `PaxAccessories` (presented at [216], available at [217]). The two classes needed for the implementation of a Multi-Process Factory are the `PaxProcess` and the `PaxProcessFactory`. The `PaxProcess` add another layer of abstraction on top of the `PaxEventInterpret`. Its distinct feature is its ability to hold several instances of `PaxEventInterpret` objects at a time. Thus, ambiguous interpretations when reconstructing a scattering process can be kept in parallel for further analysis.

An object of the class `PaxProcessFactory` enables to build collections of `PaxProcesses`. By implementing a `PaxProcess` for each scattering process, this is a way to perform a simultaneous analysis of one event under the assumption of various scattering processes. The `PaxProcess` objects can then be evaluated and their results compared, e.g. to find the most probable process. Besides their features mentioned above, both objects also have a `PaxUserRecord` that allows the user to store additional information, a `PaxName`, and other members that are common to the physics objects in the PAX toolkit.

6.2.2.3 Mapping a Physics Process to a PaxProcess

In the context of the Multi-Process Factory analysis, each Parton Picture Template corresponds to one `PaxProcess` object in a `PaxProcessFactory`. The development of the different configurations of an event happens in the `analyzeEvent` method. This is the place where the reconstructed objects are assigned to the final state partons of the Parton Picture Template and the decay chain is reconstructed. Here, the assignment and the steering of the reconstruction of the different configurations has to be coded for each Parton Picture Template a `PaxProcess` reconstructs. With improvements in the ongoing software development [218], this step will be automatized [219] and it will be possible to steer it – and the whole analysis – from a graphical user interface [220]. The `PaxProcessFactory` calls the `analyzeEvent` method for each `PaxProcess` it has the responsibility for. In the reconstruction of the configurations the ability of PAX to make a deep copy of the whole event container is important. Before a specific decay chain is reconstructed, a copy of the input `PaxEventInterpret` is made. Thus, each configuration carries the whole information about the reconstructed event, but ends up with a different assignment of reconstructed objects to final state partons of the Parton Picture Template.

The `PaxProcessFactory` has the master copy of the `PaxEventInterpret` belonging to the event that is currently analyzed. Each `PaxProcess` receives only a copy of this `PaxEventInterpret`. Hence it is guaranteed, that each `PaxProcess` has exactly the same information available as any other `PaxProcess`, independent on the number of `PaxProcess` objects that were run before or will be run afterwards.

6.3 Boosted Decision Trees as a Multivariate Classifier

Boosted Decision Trees are a multivariate classifier whose application only recently started to become popular in high energy physics analyses. The first major application of Boosted Decision Trees was reported in 2005 by the MiniBooNe experiment [14]. Two different concepts are combined in this classifier and are presented in the following sections. Section 6.3.1 introduces the concept of Decision Trees. They are a machine learning technique that has been widely used in the social sciences [221]. In simple cut-based analyses, events that fail to pass one cut are dismissed and are of no further use for the analysis. These events are neglected even if they would have passed all the other criteria, that are applied. A Decision Tree extends these consecutive cuts into a multivariate analysis technique, by continuing to analyze the events that fail a particular criterion.

The technique of boosting is powerful to improve the performance of a classifier [222]. Based on the training of a Decision Tree T_n , a Decision Tree T_{n+1} is trained by reweighting the misclassified events in Decision Tree T_n with some error function. By averaging over several Decision Trees the discrete characteristic of the discriminant output of a single Decision Tree is turned into a continuous observable. Details on the boosting algorithm will be presented in section 6.3.2.

In this analysis, the implementation provided by the TMVA toolkit [223] is used. However, Boosted Decision Trees are also available from other toolkits offering implementations of multivariate classifiers, such as the package `StatPatternRecognition` [224]. A short introduction to the TMVA toolkit will be given in section 6.3.3.

6.3.1 The Concept of Decision Trees

Decision Trees can be easily visualized by a two-dimensional tree structure. This is a nice feature because it allows the analyst to understand why a certain event was labeled signal or background event. Figure 6.3.1 shows a part of an example Decision Tree. Mathematically,

Figure 6.3.1: Example representation of parts of a Decision Tree. In the root node, an optimal decision $D1$ is made, yielding the best separation from signal and background. The subsample of events passing this decision is moved along the green arrow to node $D3$, those events failing the decision are moved to node $D2$. Both in $D2$ and $D3$ new decisions are made, optimal for the remaining subsample of events. Once the splitting stops, the terminal nodes are called leaves, e.g. those events passing decision $D2$ fall into *Leaf1*. The purity of this leaf is the classifier output of the Decision Tree for all events that end up in *Leaf1* in the evaluation step.

Decision Trees are *rooted binary trees*. The root node of the example Decision Tree is labeled $D1$. The special feature of the root node is that it has no parents. The training (or building) of a Decision Tree starts with the root node. A set of variables $\{x_i\}$ for each event in a sample of signal and background events¹ is given to it and an initial splitting of this sample is performed

¹In general, for the training of a multivariate classifier, the available samples of signal and background events are split into three subsamples taking care that all three subsamples cover the same region of phase space. The first subsample (called the training sample) is used for the training of the classifier. Together with the second subsample (the test sample), it is used iteratively to improve the performance of the classifier by varying its training parameters. The third subsample (the yield sample) is kept until the final decision on the parameters is made, in order to avoid a bias in the measurement through the training procedure.

based on a splitting criterion. This criterion determines the variable x_i and the cut value $c(x_i)$ that gives the best separation. Events passing (failing) this cut $c(x_i)$ follow the green (red) arrow in the example tree of figure 6.3.1 and are collected in a new node $D3$ ($D2$). The splitting algorithm is then applied recursively to the two child nodes, until the whole tree is built. At each new node, the splitting algorithm identifies the best variable x_i and the best cut value $c(x_i)$ taking into account the subsample of events that it has received as input. Once the splitting stops, the terminal node is called a leaf. The signal purity P_s of the leaf is then calculated as

$$P_s = \frac{s}{s+b} \quad (6.3.1)$$

and used as the discriminant output value for events in the evaluation step that end up in this node.

The goal of the node-splitting decision is to decrease the impurity of the tree. Therefore, an impurity measure (or *Separation Index* SI) is introduced, the so-called *Gini Index* GI (there are also other measures available in the TMVA toolkit that show a similar performance):

$$GI = 1 - \sum_{i=s,b} P_i^2 = 2 \cdot \frac{sb}{(s+b)^2}. \quad (6.3.2)$$

In equation 6.3.2 s and b are the weighted sum of the signal and background events in a node. P_s is the signal purity as defined in equation 6.3.1, and P_b is the equivalent term for background events, i.e. $P_b = b/(s+b)$. A function that qualifies as a Separation Index should fulfill certain features: Its value should be minimal for a perfect separation of events ($s \gg b$ or $b \gg s$, and maximal if no separation is achieved, i.e. $s \approx b$. Furthermore, it should be symmetric for signal and background contributions. In order to respect the different purities of nodes, the function should be strictly concave.

The best split S^* is the one split S that maximizes the decrease of impurity, i.e. that maximizes the *Separation Gain* SG . The Separation Gain is measured as the difference between the Separation Index of the parent node and the sum of the indices of the two daughter nodes,

$$SG = SI_p - f_l \cdot SI_l - f_r \cdot SI_r, \quad (6.3.3)$$

where SI_p is the Separation Index of the parent node and SI_l (SI_r) the Separation Index of the left (right) child node. f_l and f_r are the relative fractions of events in the left and the right child node, respectively.

There are two cases where a new node is not splitted any further. The first case is that this node only contains signal or background events and a further splitting thus would not lead to any additional separation. The second stop-criterion is introduced in order to avoid overtraining of a Decision Tree. In principle it is possible to build the tree until each leaf node would only contain one signal or background event. In order to have some statistical significance for the purities P_s that are used as discriminant output variable of a Decision Tree, a minimal number of events, `nEventsMin`, is required in a node. Once a new node contains fewer than $2 \cdot \text{nEventsMin}$ events, it will be automatically declared a leaf. A leaf is called a signal leaf, when its signal purity P_s is greater than some value, and background leaf otherwise.

An advantage in the use of Decision Tree is that they are insensitive to additional variables, as long as they are well-modeled. It is obvious that an extra variable that has not enough separation power to be the best variable x_i used for splitting in any of the nodes just increases the time it

takes to build the tree, but does not affect its performance. However, statistical fluctuations in the training sample can lead to different tree structures and thus to a different classifier response. The structure of the Decision Tree would also vary if one exchanges the training sample with the testing sample.

6.3.2 Boosting, Pruning and Evaluation of Decision Trees

The technique of boosting [222] helps to overcome the limitations of a single Decision Tree, such as its discrete discriminant output. Instead of building only one Decision Tree, a whole set of Decision Trees, a so-called *forest* is constructed. This procedure is sketched in figure 6.3.2. All trees in the forest are trained using the same set of input events from the trainings sample.

Figure 6.3.2: To overcome the discrete classifier output of a single Decision Tree and to stabilize the response of the Decision Trees with respect to fluctuations in the training sample, a boosting algorithm is applied. Instead of one Decision Tree the result is a forest of Decision Trees. The boosting algorithm reweights misclassified events so that the next Decision Tree can concentrate more on them during its creation.

However, with the boosting procedure, the weights of the events are modified after the construction of each tree. The basic idea is, to increase the weight of misclassified events and to train a new tree with these reweighted events. The training of the new Decision Tree should then be more sensitive to those events.

The boosting algorithm used here is known in the literature as AdaBoost algorithm [222]. In this algorithm, the misclassification rate of a tree is defined in terms of an error function. For the n -th tree T_n the error is computed as:

$$\text{err}_n = \frac{\sum_i (\omega_i \times I_n(i))}{\sum_i \omega_i}. \quad (6.3.4)$$

ω_i is the weight of the i -th event and $I_n(i) = 1$ if event i is misclassified in Decision Tree n and 0 otherwise. The weight α_n of tree n is then

$$\alpha_n = \beta \times \ln \left(\frac{1 - \text{err}_n}{\text{err}_n} \right). \quad (6.3.5)$$

The weight ω_i of each misclassified event is multiplied with α_n and the whole sample renormalized in order to keep the sum of weights in the tree constant. Both the *boost parameter* β and the number of boosting cycles *NTrees* are parameters that need to be optimized independently for each analysis.

Another way to reduce the overtraining of a tree due to statistically insignificant nodes is called *pruning*. The algorithm used in the analysis is called *cost complexity* [221] (a second algorithm is also implemented in the TMVA package, the *expected error pruning* [225]). After the Decision Tree has been built up to its maximum size and its error is computed, the tree is cut back from bottom up. The number of nodes in the subtree below a given node is set into relation to the gain that is achieved by the subtree (in terms of misclassified training events) compared to the case when no splitting is performed at the given node. The pruning continues until the *prune strength* PS (a parameter of the Decision Tree that needs to be optimized) is bigger than the cost complexity ρ of the node, with

$$\rho = \frac{R(\text{node}) - R(\text{subtree below that node})}{\# \text{nodes}(\text{subtree below that node}) - 1}. \quad (6.3.6)$$

R is the so-called *cost estimate* and calculated as the misclassification rate

$$R = 1 - \max(P_s, 1 - P_s). \quad (6.3.7)$$

The classifier output d of a forest of k Decision Trees for an event i is

$$d(i) = \sum_{k \in \text{forest}} \ln(\alpha_k) \cdot h_k(i), \quad (6.3.8)$$

where $h_k(i)$ is the purity of the leaf event i ends up in for the k -th Decision Tree (alternatively it is possible that $h_k(i) = 1$ if the event falls into a signal leaf and $h_k(i) = 0$ in case the leaf is a background leaf). The summation over the Decision Trees in the forest that differ due to the reweighting that has been applied through the boosting makes the discrete nature of the discriminant of a single Decision Tree disappear.

Decision Trees are often referred to the classifier that shows the best ‘out of the box’ performance. Due to the simplicity of the method, with only a little bit of tuning, good results can be achieved. Their performance is often compared to *Artificial Neural Networks* [226]. Especially in scenarios with complex correlations between the input variables, Boosted Decision Trees are often superior compared to other multivariate classifiers. Their insensitivity against poorly discriminating input variables is one of their advantages compared to Artificial Neural Networks: while the network has to find a way to deal with these variables, the splitting algorithm applied to a Decision Tree node just ignores them.

6.3.3 The TMVA Toolkit

The TMVA package [223] is an open source C++ toolkit for multivariate data analysis within the ROOT analysis framework [200]. It is available according to the terms listed in the BSD license. For the analysis presented in this thesis, version 3.9.5 of TMVA has been used together with version 5.20.00 of ROOT. The TMVA toolkit hosts a variety of multivariate classification algorithms, e.g. likelihood estimators, Artificial Neural Networks, Support Vector Machines, or the presented Boosted Decision Trees. Their implementation and the implementation of the tools that

are needed in addition (e.g. parameter fitting) follow an object-oriented approach and are coded in the C++ programming language [209]. The authors provide with their `TMVA::Factory` class an object that allows the simultaneous training, testing and performance evaluation of several classifiers using the same samples of trainings and test events. These events can be fed into the `TMVA::Factory` either by a `TTree` object stored in a ROOT file (commonly used in high energy physics analyses) or they can be read in by a simple text file. Furthermore, the `TMVA::Factory` object is able to perform a preprocessing of input variables (e.g. decorrelation) and provides a preliminary ranking of them. For classifiers that allow a classifier-specific ranking of variables (e.g. Boosted Decision Trees), the importance of the variables in the training process is calculated. This enables the analyst to get a quick overview of the separation power of his individual variables and to easily test several multivariate classifiers to figure out which one suits best for his problem. A graphical user interface is in place and allows to conveniently display the results of the training and testing procedure. These results are also stored in a ROOT file. The parameters of the classifiers (the ‘weights’) are stored in a human readable text file after the classifiers are trained. A `TMVA::Reader` class provides access to these configurations and can be included in any C++ executable. As an alternative, they can be used in a ROOT macro or in a python analysis job, using the PyROOT interface. The goal of packages like TMVA or `StatPatternRecognition` (another toolkit offering multivariate classifiers that is used in high energy physics [224]) is to reduce the amount of work a data analyzer has to invest into the programming of his implementation of the multivariate classifier he is interested in. The central developing and improving of the configuration possibilities and the understanding of these complex classifiers, a better performance can be achieved by discussing challenges and problems in a wider community and the user has more time left to think about the resulting distributions, i.e. to spend more time on the physics interpretation of his data.

7 Application of a Multi-Process Factory in the Search for Electroweak Production of Top Quarks

In this chapter the application of a PaxProcessFactory (as discussed in section 6.2.2.2) in the search for electroweak top quark production with the $D\bar{O}$ experiment at the Tevatron collider is presented. The following sections describe the contributing PaxProcesses for the three jet multiplicity bins which were considered in the analysis, i.e. events with two jets in section 7.1, events with three jets in section 7.2, and events with four jets in section 7.3. For each PaxProcess the Parton Picture Template (PPT, see section 6.2.2.3) which is reconstructed in this PaxProcess is motivated. If there are ambiguities in the assignment of reconstructed objects to the partons in the PPT, the input variables to the likelihood method that is used to resolve these ambiguities (as explained in section 6.2.1.2) are shown and the efficiencies for the correct assignment of the final state objects are given. For the statistical analysis with Boosted Decision Trees in chapter 8 only the configurations with the highest likelihood value are taken into account. Observables from these configurations are used as input variables for the Boosted Decision Trees. The selection of these observables follows different criteria:

1. The simulated background has to describe the observed data events within the statistical precision.
2. The observables are supposed to cover different regions of phase space. Therefore a mixture of observables derived from the reconstruction of Parton Picture Templates in the multiprocess factory and of event shape variables is chosen.
3. The variables should show separation power to discriminate single top events from background events. However, because of the multidimensional structure of the Boosted Decision Trees that are used for the statistical analysis (as explained in section 6.3), variables that do not show much separation power at first glance can turn out to be useful during the training of the Boosted Decision Trees.

The comparison of data with simulated background events of these observables is shown separately for each analysis bin, i.e. the sections are split into four paragraphs, one for each combination of charged lepton type (muon and electron) and number of b-tagged jets (one and two). The legend shown in figure 7.0.1 explains the color code used in the histograms where observed data events are compared to simulated background events. The solid line shows the shape of

Figure 7.0.1: Color scheme used in the histograms where data events are compared with the sum of the different expected background sources.

simulated signal events. For analysis channels with one b-tagged jet, the contribution of signal events is rescaled by a factor of 10. A factor of 5 is used for analysis channels that require two b-tagged jets in an event. The rescaling is intended to show the shape of the signal distributions more clearly.

7.1 Processes for Events with Two Jets

The analysis bin with two reconstructed jets in an event is the most sensitive one in the search for electroweak top quark production (cf section 5.3). Four different Parton Picture Templates are reconstructed in the ProcessFactory for events with two jets. Two Parton Picture Templates refer to the signal processes: s-channel production of single top quarks (see section 7.1.1) and t-channel production of single top quarks (see section 7.1.2). Section 7.1.3 deals with the background of top quark pair production, where both W bosons from the top quarks decay chains decay leptonically into a charged lepton and a neutrino. The dominant physics process background, the production of W bosons associated with jets is treated in section 7.1.4. Here, also event shape variables are explained. A summary of the variables that result from those PaxProcesses and are used in the statistical analysis with Boosted Decision Trees can then be found in section 7.1.5.

7.1.1 s-Channel Production of Top Quarks

The Parton Picture Template for the s-channel production of single top quarks in events with two jets (see figure 7.1.1) is similar to the leading order Feynman diagram.

A parton named CM is considered as the initial particle of the reconstruction procedure. It splits into a top quark named t(lept) and a b quark named b(prod). The supplement ‘lept’ in t(lept) indicates the leptonic decay of the W boson in the top quark decay chain, while the supplement ‘prod’ in b(prod) refers to the production of the b quark at the primary vertex. The top quark then decays into a W boson W(lept) and a b quark b(lept). The W boson decays leptonically into a charged lepton and a neutrino.

Figure 7.1.1: The Parton Picture Template for the s-channel production of electroweak top quarks in events with two jets shown here is similar to the leading order Feynman diagram. A particle labeled CM, representing the center-of-mass system, splits into a top quark (named t(lept)) and a b quark (named b(prod), because of its origin at the production vertex). The top quark decays into a W boson and another b quark, both partons are supplemented with (lept) to indicate their origin. The W boson then decays into a charged lepton and a neutrino.

68% matching quality cut for	
muons	electrons
0.22	0.19

Table 7.1.1: 68% matching quality cut in $\Sigma\Delta R$ for muon and electron s-channel single top events with two jets.

7.1.1.1 Ambiguity Resolution

There are four possible configurations in the assignment of reconstructed objects to the partons of this Parton Picture Template. All configurations are evaluated in a likelihood method in order to find the most likely one. The input variables to this likelihood method come from studies where parton information from the generator level is matched to reconstructed objects after full detector simulation. To ensure that the resulting distributions for s-channel single top quark production are not affected by initial state or final state radiation, a quality cut on $\Sigma\Delta R$, the sum over the spatial distances ΔR between the reconstructed objects and the generated parton they are matched to, is applied. Only quantities of the 68% best matched events are taken into account. Studying the muon and the electron channel independently, two different cutoff values are obtained. For the muon channel all matched events with $\Sigma\Delta R < 0.22$ are considered in the likelihood method, for the electron channel all matched events with $\Sigma\Delta R < 0.19$ are considered. The cutoff values in $\Sigma\Delta R$ are summarized in table 7.1.1 and visualized in figure 7.1.2(a) for the muon channel and in figure 7.1.2(b) for the electron channel, respectively.

Three variables are used in the likelihood method to resolve the ambiguities which arise from the matching of reconstructed objects to the partons in the Parton Picture Template. In order to assign the correct jet to the parton the transverse momenta distributions for both jets associated with b(lept) and b(prod) are used. Comparing the resulting distributions for in figure 7.1.3 b(lept) and for b(prod) in figure 7.1.4, the tendency of the jets matched to b(prod) to have a lower transverse momentum can be seen.

Figure 7.1.2: 68% cutoff value for the matching quality $\Sigma\Delta R$ between generated partons and reconstructed objects for muon 7.1.2(a) and electron 7.1.2(b) events in the s-channel single top quark sample. Only quantities of events with good matching quality (grey area) are used as input to the likelihood method that is used to resolve the ambiguities in the jet-parton-assignment.

Figure 7.1.3: Input distributions for the likelihood method to resolve ambiguities in the s-channel Parton Picture Template for events with two jets and one charged lepton. Here the transverse momentum distributions for jets matched to parton b (left) are displayed in the muon channel (figure 7.1.3(a)) and in the electron channel (figure 7.1.3(b)).

The cosine of the angle between the W boson boosted into the rest frame of the top quark and the lepton, boosted to the rest frame of the W boson is a handle to chose the correct solution for the z component of the neutrino momentum. This distribution is shown in figure 7.1.5(a) for the muon channel and in figure 7.1.5(b) for the electron channel.

The efficiency of the likelihood method is determined by comparing the configuration with the highest likelihood value with the configuration obtained from the matching of the reconstructed objects with the partons from the generator. The efficiencies ϵ_{68} and ϵ_{100} , as described in definition 6.2.1, are summarized in table 7.1.2 for both the muon channel analysis and the electron channel analysis. All four efficiencies are around 62%, i.e. higher than the 50% probability to assign the correct combination by chance.

Figure 7.1.4: Input distributions for the likelihood method to resolve ambiguities in the s-channel Parton Picture Template for events with two jets and one charged lepton. Here the transverse momentum distributions for jets matched to parton b(prod) are displayed in the muon channel (figure 7.1.4(a)) and in the electron channel (figure 7.1.4(b)).

Figure 7.1.5: Input distributions for the likelihood method to resolve ambiguities in the s-channel Parton Picture Template for events with two jets and one charged lepton. Cosine of the angle between the W boson, boosted to the top quark rest frame, and the charged lepton, boosted to the W boson rest frame for muon events (figure 7.1.5(a)) and for electron events (figure 7.1.5(b)).

7.1.1.2 Observables for Boosted Decision Trees

Of all four possible configurations, the configuration with the highest likelihood measure is used to obtain observables for the multivariate analysis. In the following paragraphs the comparisons

	muon channel	electron channel
$\epsilon_{68}[\%]$	62.2	62.1
$\epsilon_{100}[\%]$	61.7	61.7

Table 7.1.2: Efficiencies ϵ_{68} and ϵ_{100} of the likelihood method for the muon channel analysis and the electron channel analysis.

of data with simulated events for those variables entering the Boosted Decision Trees are shown for the different analysis bins.

Events with two jets, one b-tagged jet, and one muon

The variables used in the multivariate analysis for events with two jets, one b-tagged jet, and one muon are shown in figures 7.1.6 to 7.1.9. Overall, the agreement of the observed data with the background model is good.

Figure 7.1.6(a) shows the reconstructed mass of the parton $t(\text{lept})$. The signal distribution of electroweak top quark production peaks at 175 GeV, the mass used in the generator. The background peaks at a lower value of 150 GeV. Both distributions have a long tail towards high reconstructed masses, indicating the wrong choice of the jet associated with the parton $b(\text{lept})$. Besides its mass, also the transverse momentum of the reconstructed top quark (see figure 7.1.6(b)) and its pseudorapidity η (shown in figure 7.1.6(c)) are variables used in the Boosted Decision Trees. The transverse momentum distribution for the background model has its maximum at 30 GeV. The distribution for the signal sample has a flatter rising edge and peaks at 40 GeV. The top quarks are produced symmetrically around 0 in pseudorapidity η . Background events reconstructed under the single top s-channel hypothesis show a similar symmetric distribution. In the observed data sample, there is an excess in one bin at $\eta = -2$ compared to the background expectation. However, all other bins agree well within the statistical precision and thus this distribution can be used in the multivariate analysis.

Figure 7.1.6: Properties of the reconstructed top quark $t(\text{lept})$ are shown in this figure. The reconstructed mass is shown in figure 7.1.6(a), the transverse momentum in figure 7.1.6(b) and the pseudorapidity η distribution in figure 7.1.6(c) for events with two jets, one of them tagged as a b-jet and one muon.

The next two variables used in the multivariate analysis are kinematic quantities of jets assigned to the parton $b(\text{lept})$. Figure 7.1.7(a) displays their transverse momentum and figure 7.1.7(b) their pseudorapidity η . The transverse momentum distribution shows some separation power between the expected signal and the background. For the signal, it peaks at 65 GeV, a value expected for a b-jet from a top quark decay. The background distribution has its maximum at 55 GeV and differs from the signal distribution, especially at the rising edge. The pseudorapidity η distribution of the jets in the role of $b(\text{lept})$ is symmetric around $\eta = 0$ and has a plateau in the central region, i.e. for pseudorapidities $|\eta| < 1$.

Figure 7.1.7: Transverse momentum (figure 7.1.7(a)) and pseudorapidity η (figure 7.1.7(b)) for jets assigned to the parton b(left) in events with two jets, one b-tagged jet, and one muon.

The same quantities as for jets associated with the parton b(left) are selected for the statistical analysis for jets associated with the parton b(prod). The transverse momentum distribution appears to be composed of two contributions (see figure 7.1.8(a)): One responsible for the shape from 20 GeV to 60 GeV and the second one for the tail of the distribution starting at 60 GeV. For the region with low transverse momentum there is a steep slope in the distribution of the background model, while the simulated signal events show a flatter slope. Again, the distribution for the pseudorapidity η of jets matched to parton b(prod) is symmetric around $\eta = 0$. For the background distribution the slope on both the rising and the falling edge of the distribution is steeper than for the signal sample.

Figure 7.1.8: Transverse momentum (figure 7.1.8(a)) and pseudorapidity η (figure 7.1.8(b)) for jets assigned to the parton b(prod) in the Parton Picture Template. Shown are distributions for events with two jets, one b-tagged jet and one muon.

The distance ΔR between the two jets in the event is shown in figure 7.1.9(a). The shape between the background model and the simulated signal events differs in the region of $0.5 < \Delta R < 2.0$. The transverse momentum of the reconstructed W boson can be seen in figure 7.1.9(b). The observed data describe the background model well. The value of the likelihood measure for the one out of four configurations with the highest likelihood measure is shown in figure 7.1.9(c). A shift towards higher likelihood values for signal events is visible.

Figure 7.1.9: The distance ΔR between the two jets in the events is shown in figure 7.1.9(a). The transverse momentum of the reconstructed W boson can be seen in figure 7.1.9(b), the value of the likelihood method for the most probable configuration can be seen in figure 7.1.9(c). All distributions show events with two jets, one of them tagged as originating from a b hadron decay, and one muon.

Events with two jets, two b-tagged jets, and one muon

The variables used in the multivariate analysis for events with two jets, two b-tagged jets, and one muon are shown in figures 7.1.10, 7.1.11, 7.1.12, and 7.1.13. This analysis bin suffers from low statistics due to the b-tag requirements. Especially the multijet background is reduced very efficiently. Dilepton top quark pair production and $Wb\bar{b}$ production remain as dominant backgrounds. In spite of the low statistics, variables are found that agree well in the comparison of the simulated background expectation and the observed data events and can thus be used in the Boosted Decision Tree analysis.

The same observables of the reconstructed top quark are used in the statistical analysis for events with two b-tagged jets as for events with one b-tagged jet only. Figure 7.1.10(a) shows the mass of the reconstructed top quark. The background distribution is broader than the distribution for the expected signal. The latter has its maximum at 175 GeV, the value that was used in the generation of these samples. The transverse momentum of the reconstructed top quark $t(\text{lept})$ can be seen in figure 7.1.10(b). The rising edge of the distribution for the background events is much steeper than for the single top quark events. The majority of the $Wb\bar{b}$ events are clustered at lower transverse momenta. The distribution for the dilepton top quark pair production sample is very broad and shows no distinct peak structure, while the distribution for the expected signal reaches its maximum at 40 GeV. A distribution symmetric around 0 can be seen for the pseudorapidity η of the reconstructed top quark in figure 7.1.10(b). It is remarkable that all multijet events are located at $\eta > 1$, but this is probably just due to the small statistics of this particular background.

Kinematic distributions of jets assigned to the parton b(lept) are shown in figure 7.1.11. The transverse momentum of these jets (see figure 7.1.11(a)) and their pseudorapidity η (see figure 7.1.11(b)) are used as input to the multivariate analysis. The transverse momentum spectrum of the single top quark signal events is a bit harder than the spectrum for the expected background. The distribution of the pseudorapidity is symmetric around 0 again, apart from the statistical fluctuation in the background distribution between $-1 < \eta < 0$ that is due to the multijet background.

Figure 7.1.10: The mass of the reconstructed top quark $t(\text{lept})$ is shown in figure 7.1.10(a), the transverse momentum in figure 7.1.10(b), and the distribution of the pseudorapidity η can be seen in figure 7.1.10(c). All histograms show events with two jets, both tagged as originating from a b hadron decay, and one muon.

Figure 7.1.11: Kinematic distributions of jets assigned to play the role of parton $b(\text{lept})$ in the Parton Picture Template. Their transverse momentum is shown in figure 7.1.11(a) and their pseudorapidity distribution in figure 7.1.11(b). Both histograms contain events with two jets, both of them b-tagged, and one muon.

The transverse momentum distribution of jets assigned to the parton $b(\text{prod})$ shows the same distinctive feature in events with two b-tagged jets as in jets with only one b-tagged jet. The majority of events is between 20 GeV and 60 GeV. There, the falling slope of the distribution for the single top signal events is flatter than the one for the background distribution. In the region above 60 GeV, the shapes of both distributions are similar. The distribution of the pseudorapidity η of the jets assigned to the parton $b(\text{prod})$ is symmetric around $\eta = 0$ for both signal and background events. The multijet background events are all located at $\eta > 0$, which is probably just a statistical fluctuation due to the limited number of events.

The spatial distance ΔR between the two jets in the event shows a different shape in the region $0 < \Delta R < 2$ for signal and background events, as can be seen in figure 7.1.13(a). While for background events the distribution is rather flat, there are hardly any jets in the signal sample that are that close to one another, resulting in a rising distribution. The transverse momentum distribution for the reconstructed W boson $W(\text{lept})$ is displayed in figure 7.1.13(b). The distribution for the single top quark signal events rises from 0 GeV up to 50 GeV before it starts to decrease again. The background distribution is broader and rises faster. The likelihood

Figure 7.1.12: Figure 7.1.12(a) shows the transverse momentum distribution for jets assigned to the parton b(prod) in the Parton Picture Template. For the same jets, figure 7.1.12(b) displays the pseudorapidity distribution. Both histograms contain events with two jets, both of them tagged as b-jets, and one muon.

value for the most probable configuration of an event is shown in figure 7.1.13(c).

Figure 7.1.13: The spatial distance ΔR between the two jets in the event is shown in figure 7.1.13(a). Figure 7.1.13(b) shows the transverse momentum of the reconstructed W boson W(lept), and figure 7.1.13(c) displays the likelihood value for the most probable of the four possible configurations. All histograms show events with two jets, both tagged as originating from a b hadron decay, and one muon.

Events with two jets, one b-tagged jet, and one electron

The variables used in the multivariate analysis for events with two jets, one b-tagged jet, and one electron are shown in figures 7.1.14 to 7.1.17. Overall, the observed data agree very well with the simulated background model for the observables that are selected to enter the multivariate analysis.

Quantities of the reconstructed top quark t(lept) are shown in the first set of observables in figure 7.1.14. In figure 7.1.14(a) the mass of the reconstructed top quark can be seen. The maximum in the signal distribution is at 175 GeV, the mass value set in the generator. The background distribution is broader and peaks at a lower mass value of 150 GeV. Figure 7.1.14(b) shows the transverse momentum distribution of the reconstructed top quarks. On average the transverse momentum of the reconstructed top quarks in the signal sample is higher than for

the background events, forced into a s-channel single top hypothesis. The pseudorapidity η of the reconstructed top quarks can be seen in figure 7.1.14(c). It shows a symmetric distribution around $\eta = 0$. The background distribution shows a dip at $\eta = 0$, whereas the distribution for the signal events has a plateau in the region of $|\eta| < 1.0$.

Figure 7.1.14: The mass of the reconstructed top quark t (left) is shown in figure 7.1.14(a). Figure 7.1.14(b) shows the transverse momentum distribution and figure 7.1.14(c) the distribution of the pseudorapidity η . All histograms show events with two jets, both tagged as originating from a b hadron, and one electron.

Transverse momentum (see figure 7.1.15(a)) and pseudorapidity η (see figure 7.1.15(b)) are the quantities used from the jets assigned to the parton b (left) in the statistical analysis. For the single top signal events the transverse momentum distribution peaks at 60 GeV as one would expect from a jet from the top quark decay. However, the background distribution differs significantly. It rises steeply and reaches its maximum already at 40 GeV. The pseudorapidity distributions for both simulated background and simulated signal events are symmetric around $\eta = 0$.

Figure 7.1.15: Transverse momentum (figure 7.1.15(a)) and pseudorapidity η (figure 7.1.15(b)) for jets assigned to the parton b (left) of the Parton Picture Template for events with two jets, both tagged as b -jets and one central electron.

The same two quantities as for the jets matched to parton b (left) are taken into account in the statistical analysis for jets matched to parton b (prod) of the Parton Picture Template. The transverse momentum distribution in figure 7.1.16(a) shows the same structure as for the muon channel. From 0 GeV to 60 GeV a falling distribution can be seen, while for transverse

momenta above 60 GeV a second, broad component appears. However, the falling edge of the distribution up to 60 GeV is much steeper for the background events than for the events of electroweak top quark production. The pseudorapidity distribution shown in figure 7.1.16(b) is symmetric around $\eta = 0$ for background events, signal events and observed data events. The width of the distribution for signal events is broader than the distribution for the background expectation.

Figure 7.1.16: Transverse momentum (see figure 7.1.16(a)) and pseudorapidity η (see figure 7.1.16(b)) distribution for jets matched to parton b(prod) of the Parton Picture Template. Both histograms show events with two jets, both tagged as originating from a b hadron decay, and one central electron.

The spatial distance ΔR between the two jets in the event is shown in figure 7.1.17(a). The distribution shows that the probability for signal events to have two jets reconstructed close to another is much lower than for background events. The transverse momentum of the reconstructed W boson (see figure 7.1.17(b)) is on average higher for the single top events than for the background events. The signal distribution peaks at 55 GeV, whereas the background distribution has its maximum at 40 GeV. The result of the likelihood method for the one configuration with the highest value is shown in figure 7.1.17(c). The signal events are clearly shifted towards higher values.

Events with two jets, two b-tagged jets, and one electron

In figures 7.1.18 to 7.1.21 the variables used in the Boosted Decision Tree analysis are shown for events with two jets, both of them tagged as originating from a b hadron, and one electron. Due to the limited statistics in this analysis bin, the quality of the description of the observed data events by the simulated background model (mostly $Wb\bar{b}$ events) varies. Only those variables are selected that have a reasonable agreement within statistical uncertainty.

In figure 7.1.18 observables gained from the reconstructed top quark t(left) are shown. Its mass can be found in figure 7.1.18(a). The distribution of the simulated signal events peaks at the mass that was used in the generator, 175 GeV. For the background, the reconstructed mass is lower on average. The distribution has its maximum at 150 GeV. The transverse momentum of the reconstructed top quark t(left) is shown in figure 7.1.18(b). For the background, lower transverse momenta are reconstructed than for the sample of electroweak top quark production.

Figure 7.1.17: The distance ΔR between the two jets in the event is shown in figure 7.1.17(a). Figure 7.1.17(b) display the transverse momentum of the reconstructed W boson $W(\text{lept})$, and figure 7.1.17(c) shows the result of the likelihood method for the most likely configuration. All histograms are for events with two jets, both of them tagged as originating from a b hadron decay, and one central electron.

Both distributions have long tails towards high values. The main feature of the distribution of the top quark pseudorapidity η is its symmetry around $\eta = 0$.

Figure 7.1.18: The mass of the reconstructed top quark is shown in figure 7.1.18(a). The transverse momentum distribution can be seen in figure 7.1.18(b), and the distribution of their pseudorapidity in figure 7.1.18(c). All histograms show events with two jets, both of them b-tagged, and one central electron.

The transverse momentum and the pseudorapidity η for jets assigned to the parton b(lept) are further variables used in the statistical analysis. For the signal sample, the transverse momentum distribution as shown in figure 7.1.19(a) reaches its maximum at 60 GeV, approximately 10 GeV above the jets from the background events. In pseudorapidity η the distributions are symmetric around $\eta = 0$. The distribution for the single top signal events is a bit broader than the distribution for the simulated background events.

The same quantities as for jets assigned to the parton b(lept) are taken into account for the statistical analysis for those jets that are selected to play the role of parton b(prod). Their transverse momentum distribution in figure 7.1.20(a) shows the same feature that has already been described in the other analysis bins. Most of the jets have a small transverse momentum. Especially for the background events, the distribution falls with a large slope. For transverse momenta larger than 60 GeV, a second component shows up and results in a broad distribution.

Figure 7.1.19: Transverse momentum (figure 7.1.19(a)) and pseudorapidity (figure 7.1.19(b)) distributions for jets assigned to the parton b(left) in the Parton Picture Template. Shown are events with two jets, both of them tagged as b-jets, and one central electron.

Again, the distribution of the pseudorapidity η of the jets matched to b(prod) is symmetric around $\eta = 0$.

Figure 7.1.20: Figure 7.1.20(a) shows the transverse momentum distribution of jets assigned to the parton b(prod) and figure 7.1.20(b) shows their pseudorapidity for events with two jets, both tagged as originating from b hadron decays, and a central electron.

The spatial distance ΔR between the two jets in the event is displayed in figure 7.1.21(a). In background events it happens more often that two jets are very close to another, whereas for signal events the distribution shows a steady slope up to $\Delta R = 3$. The transverse momentum of the reconstructed W boson is on average slightly higher for single top events than for background events. This can be seen in figure 7.1.21(b). The likelihood value of the configuration with the highest likelihood value for this Parton Picture Template is shown in figure 7.1.21(c).

Figure 7.1.21: The distance ΔR between the two jets in the event is shown in figure 7.1.21(a). Figure 7.1.21(b) displays the transverse momentum of the reconstructed W boson, and figure 7.1.21(c) shows the likelihood value for the selected configuration. All histograms show events with two jets, both of them b-tagged and one central electron.

7.1.2 t-Channel Production of Top Quarks

The Parton Picture Template for the t-channel production of single top quarks in events with two jets can be seen in figure 7.1.22. A study with simulated events shows that in 90% of the cases where simulated t-channel events show up in the analysis bin with two jets, it is the scattered b quark of the $2 \rightarrow 3$ process (see section 2.2.2) that was not reconstructed. Therefore, the Parton Picture Template for the t-channel production of single top quarks (as shown in figure 7.1.22) neglects this parton and concentrates on the b quark originating at the top quark decay vertex b(lept) and the light quark jet from the scattering process, q(scst). The parton q(scst) and the reconstructed top quark t(lept) are connected to a parton CM, representing the center-of-mass system. The W boson from the top quark decay decays further into a charged lepton and a neutrino.

Figure 7.1.22: For events with two jets the Parton Picture Template for the t-channel production of electroweak top quarks starts from a particle CM, representing the center-of-mass system. Two quarks are connected to its decay vertex: the top quark (t(lept)) and a quark named q(scst). The supplement ‘scst’ indicates its origin from the scattering process. The top quark decays into a W boson, W(lept), and a b quark named b(lept), indicating the leptonic decay of the W boson into a charged lepton and a neutrino.

7.1.2.1 Ambiguity Resolution

There are four possible configurations in the assignment of reconstructed objects to the partons for this Parton Picture Template. All configurations are evaluated in a likelihood method. The input variables to this likelihood method come from studies where parton information from the generator level is matched to reconstructed objects after simulation. To ensure that the resulting distributions for t-channel single top quark production are not affected by initial state or final state radiation, a quality cut on $\Sigma\Delta R$, the sum over the distances between the reconstructed objects and the generated parton they are matched to, is applied. As for the analysis of the s-channel, only quantities of the 68% best matched events are taken into account. Studying the muon and the electron channel independently, two different cutoff values are obtained. For the muon channel all matched events with $\Sigma\Delta R < 0.27$ are considered in the likelihood method, for the electron channel all matched events with $\Sigma\Delta R < 0.28$ are considered. The cutoff values in $\Sigma\Delta R$ are summarized in table 7.1.3 and visualized in figure 7.1.23(a) for the muon channel and in figure 7.1.23(b) for the electron channel.

68% matching quality cut for	
muons	electrons
0.27	0.28

Table 7.1.3: 68% matching quality cut in $\Sigma\Delta R$ for simulated t-channel single top events with two jets where the charged lepton is either a muon or an electron.

Figure 7.1.23: 68% cutoff value for the matching quality $\Sigma\Delta R$ between generated partons and reconstructed objects for muon (figure 7.1.23(a)) and electron (figure 7.1.23(b)) events in the t-channel single top quark sample. Only quantities of events with good matching quality (grey area) are used as input to the likelihood method that is used to resolve the ambiguities in the jet-parton-assignment.

Four variables are used in the likelihood method to resolve the ambiguities that arise from the matching of reconstructed objects to the partons in the t-channel Parton Picture Template for events with two jets. The first variable shown is the pseudorapidity η of the jets matched to the parton b(lept). The distributions for the muon channel analysis and the electron channel analysis can be found in figures 7.1.24(a) and 7.1.24(b), respectively. Jets matched with parton b(lept) are very central, i.e. the majority of jets is accumulated within $|\eta| < 1$.

The cosine of the angle between the W boson boosted to the rest frame of the top quark and the lepton, boosted to the rest frame of the W boson, is a handle to choose the correct solution for the z component of the neutrino momentum. This distribution is shown in figure 7.1.25(a) for the muon channel and in figure 7.1.25(b) for the electron channel.

The probability of the jets matched to the parton q(scatter) to be tagged as originating from a b hadron are used in the likelihood method, too. The distributions are shown in figure 7.1.26. In only 3% of the matched events, a b-tagged jet is matched with the generated parton q(scatter). In most cases the jet remains untagged. This agrees with the model that the origin of this jet is a scattered valence quark of the proton.

Besides the b-tagging probability, also the transverse momentum distribution of the jets matched to q(scatter) is used to resolve the ambiguities in the t-channel Parton Picture Template for events with two jets. The resulting distributions can be seen in figure 7.1.27(a) for the muon channel and in figure 7.1.27(b) for the electron channel. The maximum of both distributions is at 50 GeV with a steeply falling edge towards higher transverse momenta.

Figure 7.1.24: Input distributions for the likelihood method to resolve ambiguities in the t-channel Parton Picture Template for events with two jets and one charged lepton. Figures 7.1.24(a) and 7.1.24(b) display the distribution of the pseudorapidity η for jets matched to the parton b(left) for events in the muon and electron analysis.

Figure 7.1.25: Input distributions for the likelihood method to resolve ambiguities in the t-channel Parton Picture Template for events with two jets and one charged lepton. These distributions show the cosine of the angle between the W boson in the top quark rest frame and the lepton, boosted into the rest frame of the W boson, for the muon channel (figure 7.1.25(a)) and the electron channel (figure 7.1.25(b)), respectively.

The efficiency of the likelihood method is determined by comparing the configuration with the highest likelihood value with the configuration obtained from the matching of the reconstructed objects with the partons from the generator. The efficiencies ϵ_{68} and ϵ_{100} , as described in definition 6.2.1, are summarized in table 7.1.4 for the muon channel analysis and the electron channel analysis. In both analysis channels the efficiencies are higher than 50%, the probability to find the correct configuration by chance.

7.1.2.2 Observables for Boosted Decision Trees

The configuration with the highest likelihood measure of all four possible configurations is used to obtain observables for the multivariate analysis. In the following paragraphs, the comparisons

Figure 7.1.26: Input distributions for the likelihood method to resolve ambiguities in the t -channel Parton Picture Template for events with two jets and one charged lepton. Figure 7.1.26(a) shows the probability of the jet matched to the parton $q(\text{sc})$ to be tagged as originating from a b hadron for muon channel events. Figure 7.1.26(b) shows the same quantity for events with a final state electron.

Figure 7.1.27: Input distributions for the likelihood method to resolve ambiguities in the t -channel Parton Picture Template for events with two jets and one charged lepton. The transverse momentum distribution for jets matched to the parton $q(\text{sc})$ is shown for jets matched to the parton $q(\text{sc})$ for muon events in figure 7.1.27(a) and for electron events in figure 7.1.27(b).

	muon channel	electron channel
$\epsilon_{68}[\%]$	82.9	68.2
$\epsilon_{100}[\%]$	80.9	68.1

Table 7.1.4: Efficiencies ϵ_{68} and ϵ_{100} of the likelihood method for the muon channel analysis and the electron channel analysis.

of data with simulated events for those variables entering the Boosted Decision Trees are shown for the four different analysis bins.

Events with two jets, one b-tagged jet, and one muon

For events with two jets, one of them tagged as originating from a b hadron decay, missing transverse energy and one muon, the agreement between observed data and simulated backgrounds for the variables chosen as input to the statistical analysis is good. These variables are shown in figures 7.1.28, 7.1.29, 7.1.30, and 7.1.31.

Figure 7.1.28 shows properties of the reconstructed top quark $t(\text{lept})$. The mass of these top quark candidates is shown in figure 7.1.28(a). The simulated signal events peak at a value of 175 GeV, the value that was used in the generator. The peak for the distribution of the background model peaks at a lower value. The transverse momentum of the reconstructed top quarks can be seen in figure 7.1.28(b). There is one bin at a value of 50 GeV where the observed data show an excess over the background model. But overall, the agreement is good considering the statistical precision. The distribution of the pseudorapidity η of the reconstructed top quarks is symmetric around 0 (see figure 7.1.28(c)). However, where the distribution for the background model has a dip in the central region, the distribution for signal events has a plateau for the region of $|\eta| < 1$.

Figure 7.1.28: The mass of the reconstructed top quarks $t(\text{lept})$ is shown in figure 7.1.28(a), their transverse momentum distribution in figure 7.1.28(b), and their pseudorapidity η in figure 7.1.28(c). All histograms display events with two jets, one of them b-tagged, and one muon.

Two kinematic quantities of jets assigned to the parton b(lept) in the Parton Picture Template are used in the Boosted Decision Tree analysis and shown in figure 7.1.29. Their transverse momentum distribution (see figure 7.1.29(a)) shows some discriminating power. The majority

of the jets from the background samples have low transverse momentum compared to the signal sample. The signal distribution peaks at 60 GeV, a value expected for a b-jet originating from a top quark decay. The pseudorapidity distribution in figure 7.1.29(b) is symmetric around $\eta = 0$.

Figure 7.1.29: Transverse momentum (figure 7.1.29(a)) and pseudorapidity η (figure 7.1.29(b)) for jets matched to the parton b(left) in the Parton Picture Template. Both distributions show events with two jets, one of them b-tagged and one muon.

The pseudorapidity distribution of the jets assigned to the parton q(scatter) is symmetric around $\eta = 0$ (see figure 7.1.30(a)). However, for $|\eta| < 1.5$ the signal distribution has a plateau, whereas the background model has a distinct peak structure. The distribution of the product of the charge of the charged lepton and the pseudorapidity of the jets assigned to the parton q(scatter) is only symmetric for the background events. For the single top events, especially for those from t-channel production, there is a significant asymmetry towards positive values that reflects the production process in a $p\bar{p}$ -collider.

Figure 7.1.30: Pseudorapidity η for jets assigned to the parton q(scatter) of the Parton Picture Template (see 7.1.30(a)). Figure 7.1.30(b) shows the same quantity, but multiplied by the charge of the charged lepton. Both distributions show events with two jets, one of them tagged as originating from a b hadron decay, and a muon.

The transverse momentum of the reconstructed W boson (see figure 7.1.31(a)) is on average higher for the single top signal events than for the events from the background model. It peaks at 55 GeV, whereas the background distributions reaches its maximum at 40 GeV. The likelihood

value for the best configuration is also used as input to the multivariate analysis and shown in figure 7.1.31(b).

Figure 7.1.31: Transverse momentum of the reconstructed W boson (figure 7.1.31(a)) and result of the likelihood method for the best configuration (figure 7.1.31(b)). Both distributions show events with two jets, one b-tagged jet and one muon.

Events with two jets, two b-tagged jets, and one muon

The analysis bin with two jets, both of them tagged as originating from a b hadron decay, and one muon suffers from low statistics due to the requirement to find two b-tagged jets. Several variables are sufficiently well described in the comparison of observed data and simulated background events that they can be used in the multivariate analysis. These comparisons are shown in figures 7.1.32, 7.1.33, 7.1.34, and 7.1.35. The plots show that the dominant background processes are $Wb\bar{b}$ production and decays of top quark pairs in the dilepton channel.

Figure 7.1.32 shows quantities of the reconstructed top quark t (left) for the most likely configuration of the Parton Picture Template. The distribution for the signal events peaks at the value that was used in the generator, 175 GeV. The background events peak at a lower value of 150 GeV and show, in general, a broader distribution (see figure 7.1.32(b)). For the transverse momentum distribution of the reconstructed top quarks, the signal events have a broader spectrum compared to the background model. On average, the transverse momentum is higher for the single top quark events. This transverse momentum spectrum can be seen in figure 7.1.32(b). Figure 7.1.32(c) shows the pseudorapidity η of the reconstructed top quarks. The distributions are symmetric around $\eta = 0$. The peak in the background distribution at $\eta = -2.0$ is a statistical fluctuation caused by the small number of multijet events that passed the selection requirements for these analysis bin.

The transverse momentum (see figure 7.1.33(a)) and the pseudorapidity η (see figure 7.1.33(b)) of the jets assigned to the parton b (left) are also used in the statistical analysis with Boosted Decision Trees. On average the single top quark signal sample has a higher transverse momentum for jets assigned to the parton b (left) than the background sample. The pseudorapidity distribution is symmetric around $\eta = 0$ for both samples.

Figure 7.1.32: The mass of the reconstructed top quark is shown in Figure 7.1.32(a), their transverse momentum spectrum in figure 7.1.32(b), and their pseudorapidity distribution in figure 7.1.32(c) for events with two jets, both tagged as b-jets and one muon.

Figure 7.1.33: Figure 7.1.33(a) shows the transverse momentum of jets assigned to the parton b(left) and figure 7.1.33(b) displays their pseudorapidity η . Both distributions show events with two jets, both tagged as b-jets, and one muon.

The pseudorapidity distribution for jets associated with parton $q(\text{scat})$ of the Parton Picture Template is shown in figure 7.1.34(a). It is symmetric around $\eta = 0$ for the observed data events, for the signal events of electroweak top quark production and the simulated background model. Multiplying the pseudorapidity η of the jets matched to the parton $q(\text{scat})$ with the charge of the charged lepton in the event results in the distribution shown in figure 7.1.34(b). Compared to the distribution in figure 7.1.34(b) for events with only one b-tagged jet, there is hardly any asymmetry. This can be explained with the fact that the parton $q(\text{scat})$ is expected to be a jet originating from a light quark, in particular the valence quark that had emitted the W boson. Both jets in the event are tagged as originating from a b hadron decay. Therefore, the effect of producing an asymmetry is no longer possible and the result is a symmetric distribution.

The transverse momentum distribution of the reconstructed W boson $W(\text{left})$ is shown in figure 7.1.35(a). On average, the transverse momentum of the W bosons reconstructed from the signal sample is higher than for the background sample, that has a broader distribution. The result of the likelihood method for the best configuration is shown in figure 7.1.35(b) and is also used as input to the Boosted Decision Tree analysis.

Figure 7.1.34: The distribution of the pseudorapidity of jets assigned to the parton $q(\text{scat})$ is shown in figure 7.1.34(a), the product of the pseudorapidity η with the charge of the charged lepton is shown in figure 7.1.34(b). Both histograms show events with two jets, both tagged as b-jets, and one muon.

Figure 7.1.35: Figure 7.1.35(a) shows the transverse momentum of the reconstructed W boson $W(\text{lept})$, figure 7.1.35(b) displays the result of the likelihood method for the best of the four possible configurations for events with two jets, both tagged as originating from a b hadron decay, and one muon.

Events with two jets, one b-tagged jet, and one electron

For events with two jets, one of them tagged as originating from a b hadron decay, missing transverse energy and one electron, the agreement between observed data and simulated background contributions for the variables chosen as input to the statistical analysis is good. Their comparisons can be found in figures 7.1.36 to 7.1.39.

Properties of the reconstructed top quark $t(\text{lept})$ are shown in the first of these four figures. Figure 7.1.36(a) shows the mass of the reconstructed top quark. The distribution of the single top quark signal events peaks at a value of 175 GeV, the value used in the generator for these samples. For background events the mass distribution of the reconstructed top quarks already reaches its maximum at 125 GeV. Furthermore, the distribution is broader than for the signal events. The transverse momentum spectrum of the reconstructed top quarks can be found in figure 7.1.36(b). For the background samples, the transverse momentum is slightly lower and

shows a narrower distribution. In pseudorapidity η the background distribution shows a dip at $\eta = 0$. However, the distribution of the signal events has a plateau for $|\eta| < 1.0$. The distribution for the observed data, the one for the signal samples and the distribution of the background samples is symmetric around $\eta = 0$.

Figure 7.1.36: The mass of the reconstructed top quark t (left) is shown in figure 7.1.36(a), their transverse momentum in figure 7.1.36(b), and their pseudorapidity η in figure 7.1.36(c) for events with two jets, one of them tagged as originating from a b hadron decay, and one central electron.

For jets assigned to the parton b (left) in the Parton Picture Template the transverse momentum spectrum can be seen in figure 7.1.37(a). For the signal events the distribution peaks at 60 GeV, whereas the background model prefers to assign jets with lower transverse momenta to the parton b (left). The distribution of these jets in pseudorapidity η is similar for signal and background events. Both distributions are symmetric around $\eta = 0$. They are shown in figure 7.1.37(b).

Figure 7.1.37: Figure 7.1.37(a) shows the transverse momentum distribution of jets assigned to the parton b (left) and figure 7.1.37(b) shows their pseudorapidity η . Both histograms show events with two jets, one of them tagged as b -jet, and one central electron.

The pseudorapidity η of jets assigned to the parton q (scat) is shown in figure 7.1.38(a). It is symmetric around $\eta = 0$ for both the signal and the background distribution. In the distribution of the observed data events, there are three consecutive bins below the expected background model in the region of $0 < \eta < 1$. However, within the statistical precision, this variable can

still be used in the multivariate analysis. Especially for the distribution of signal events, there is a plateau in the region of $|\eta| < 1.0$, but also the background distribution does not show a particular peak structure. Figure 7.1.38(b) shows the result of the product of the sign of the lepton charge of the charged lepton and the pseudorapidity η of the jets assigned to $q(\text{scat})$. The asymmetry that can be seen in signal events has already been explained for the events with a muon in the final state instead of an electron. The distribution for background events is symmetric around $q \times \eta = 0$.

Figure 7.1.38: Figure 7.1.38(a) shows the pseudorapidity η of jets assigned to the parton $q(\text{scat})$ in the Parton Picture Template. The same quantity, but multiplied with the sign of the charge of the charged lepton is shown in figure 7.1.38(b). Both distributions show events with two jets, one of them tagged as a b-jet, and one central electron.

The transverse momentum of the reconstructed W boson $W(\text{lept})$ is shown in figure 7.1.39(a). On average, the transverse momentum is higher for the signal events of electroweak top quark production. The result of the likelihood method for the configuration with the highest likelihood value is shown in figure 7.1.39(b).

Figure 7.1.39: Transverse momentum of the reconstructed W boson $W(\text{lept})$ (figure 7.1.39(a)) and result of the likelihood method for the most likely configuration (figure 7.1.39(b)) for events with two jets, one of them b-tagged, and one central electron.

Events with two jets, two b-tagged jets, and one electron

The analysis bin with two jets, both of them tagged as originating from a b hadron decay and one electron suffers from low statistics due to the requirement to identify two b-tagged jets. Within the statistical precision, the agreement of the background model and the observed data is good enough for some variables, so that they can be taken into account in the Boosted Decision Tree analysis. The histograms in figures 7.1.40 to 7.1.43 show that the dominant backgrounds are $Wb\bar{b}$ production and decays of top quark pairs in the dilepton channel.

From the reconstructed top quarks, three properties are used in the statistical analysis: the mass (see figure 7.1.40(a)), their transverse momentum (see figure 7.1.40(b)), and their pseudorapidity η (see figure 7.1.40(c)). The top quark mass peaks at the value used in the generator, i.e. 175 GeV. For the background model the mass distribution is broader and lower mass values are reconstructed more frequently. On average, the transverse momentum of the top quarks is higher for the signal sample of electroweak top quark production. The distribution reaches its maximum at 45 GeV, which is 10 GeV above the expected background events. The pseudorapidity distribution is symmetric around $\eta = 0$ for both signal and background distributions.

Figure 7.1.40: Properties of the reconstructed top quark t (left): mass (figure 7.1.40(a)), transverse momentum (figure 7.1.40(b)), and pseudorapidity η (figure 7.1.40(c)). The three histograms show events with two jets, both of them tagged as originating from a b hadron decay, and one central electron.

The shapes of the transverse momentum distributions of jets assigned to the parton b (left) are very different for signal and background processes, see figure 7.1.41(a). The signal peaks at 60 GeV, a value expected from a b -jet from a top quark decay, while the background events prefer to assign jets with lower transverse momentum to the parton b (left). For pseudorapidity, the distributions are similar and symmetric around $\eta = 0$.

Both the pseudorapidity η for jets assigned to the parton q (scat) and the product of this pseudorapidity value with the sign of the charge of the charged lepton are symmetric distributions around 0, see figures 7.1.42(a) and 7.1.42(b). A slight asymmetry can be seen in the signal distribution in figure 7.1.42(b), but it is not as striking as in the case with only one b-tagged jet. However, this is expected, because the parton q (scat) should represent the light quark from the proton that emitted the virtual W boson. Since there is no jet from a light quark decay in events where all jets are tagged as originating from a b hadron decay, the asymmetric feature is expected to disappear.

Figure 7.1.41: Transverse momentum (figure 7.1.41(a)) and pseudorapidity η (figure 7.1.41(b)) of jets assigned to the parton b(left) in the Parton Picture Template. Events with two jets, both tagged as b-jets, and one central electron are shown.

Figure 7.1.42: Figure 7.1.42(a) shows the pseudorapidity η distribution for jets assigned to the parton q(scatter). Figure 7.1.42(b) shows this pseudorapidity multiplied by the sign of the charge of the charged lepton. Both histograms contain events with two jets, both b-tagged, and one central electron.

The transverse momentum of the reconstructed W boson W (left) is shown in figure 7.1.43(a). W bosons in the signal sample of electroweak top quark production tend to have a slightly higher transverse momentum than the predicted background model. Figure 7.1.43(b) shows the result of the likelihood method for the event configuration that was selected to be used in the statistical analysis.

Figure 7.1.43: The transverse momentum of the reconstructed W boson $W(\text{lept})$ is shown in figure 7.1.43(a). The value of the likelihood method for the most likely event configuration can be seen in figure 7.1.43(b). The histograms show events with two jets, both b-tagged, and one central electron.

7.1.3 Decay of Top Quark Pairs in Dilepton Events

The Parton Picture Template for the reconstruction of dilepton top quark pair events for events with two jets and one charged lepton is shown in figure 7.1.44. In dilepton top quark pair events two charged leptons and two neutrinos are expected according to the leading order Feynman diagram (see section 2.2.1). Because of the event selection, there is only one charged lepton in the analyzed events. Therefore it is not possible to reconstruct the whole top quark pair decay chain in this PaxProcess. The aim of this PaxProcess is to reconstruct the one top quark the recorded charged lepton belongs to. This branch of the Parton Picture Template is labeled ‘found’, in reference to the found lepton. The top quark $t(\text{found})$ is connected to a primary vertex that has an incoming parton labeled CM (representing the center-of-mass system) as initial particle of the interaction. The top quark decays into a W boson $W(\text{found})$ and a b quark $b(\text{found})$. The W boson subsequently decays into a charged lepton and a neutrino. The second jet in the event is also connected to the primary vertex and is named $b(\text{lost})$. The supplement ‘lost’ indicates that it belongs to the branch where the charged lepton was not reconstructed and therefore it is not possible to reconstruct the whole top quark decay chain.

Figure 7.1.44: Parton Picture Template reconstructing a dilepton top quark pair decay in events with two jets, one charged lepton and missing transverse energy. Because of the missing second charged lepton it is not possible to reconstruct the whole top quark pair decay. Therefore, the decay of one top quark named $t(\text{found})$ is reconstructed. The supplement denotes the branch in the top quark pair decay to which the reconstructed charged lepton belongs to. The top quark decays into a W boson $W(\text{found})$ and a b quark named $b(\text{found})$. The W boson then decays further into a charged lepton and a neutrino. The second jet is associated to a b quark $b(\text{lost})$, where ‘lost’ indicates that this b quark originates from the top decay where the charged lepton of the subsequent decay of the W boson was not reconstructed. Both the top quark and the b quark $b(\text{lost})$ are connected to a primary vertex. The vector sum of these two objects results in the kinematics of the incoming parton to the primary vertex, named CM, representing the center-of-mass system of the interaction.

7.1.3.1 Ambiguity Resolution

There are four possible configurations in the assignment of reconstructed objects to the partons for this Parton Picture Template. All configurations are evaluated in a likelihood method. The

68% matching quality cut for	
muons	electrons
0.24	0.28

Table 7.1.5: 68% matching quality cut in $\Sigma\Delta R$ for muon and electron events of dilepton top quark pair production with two jets.

input variables to this likelihood method come from studies where parton information from the generator level is matched to reconstructed objects after simulation. To ensure that the resulting distributions for dilepton top-antitop production are not affected by initial state or final state radiation, a quality cut on $\Sigma\Delta R$, the sum over the distances between the reconstructed objects and the generated parton they are matched to is applied. Only quantities of the 68% best matched events are taken into account. Studying the muon and the electron channel independently, two different cutoff values are obtained. For the muon channel all matched events with $\Sigma\Delta R < 0.24$ are considered in the likelihood method, for the electron channel all matched events with $\Sigma\Delta R < 0.28$ are considered. The cutoff values in $\Sigma\Delta R$ are summarized in table 7.1.5 and visualized in figure 7.1.45(a) for the muon channel and in figure 7.1.45(b) for the electron channel.

Figure 7.1.45: 68% cutoff value for the matching quality $\Sigma\Delta R$ between generated partons and reconstructed objects for muon 7.1.45(a) and electron 7.1.45(b) events of the simulated dilepton top quark pair production. Only quantities of events with good matching quality (grey area) are used as input to the likelihood method that is used to resolve the ambiguities in the jet-parton-assignment.

The reconstruction of the decay chain with the best possible matching of reconstructed objects to generated partons has a pitfall for the dileptonic decay of top quark pairs in events with two jets, missing transverse energy and only one charged lepton. The reconstructed missing transverse momentum has its origin from two neutrinos. However, due to the missing charged lepton it is only possible to reconstruct one W boson using a mass constraint. Taking the whole missing transverse energy into account leads to wrong kinematics of the W boson. Therefore, the measured missing transverse energy is corrected before the W boson is reconstructed. The correction uses generator information of the W boson from the decay branch where the charged lepton was not detected. The values for the missing transverse energy ME_{x_f} and ME_{y_f} that

are used in the quadratic equation to be solved in order to get the z component of the neutrino momentum are calculated in the following way:

$$ME_{x_f} = ME_{x_r} - P_x(W(\text{lost})) \quad (7.1.1)$$

$$ME_{y_f} = ME_{y_r} - P_y(W(\text{lost})) \quad (7.1.2)$$

Here, ME_{x_r} and ME_{y_r} denote the reconstructed x and y components of the missing transverse energy. $P_x(W(\text{lost}))$ and $P_y(W(\text{lost}))$ denote the x and y component of the generated W boson that cannot be reconstructed due to the missing second charged lepton. The kinematics of the generated W boson is used instead of the momentum components of the generated neutrino, because in this way the contribution of the missing charged lepton to the reconstructed missing transverse energy is also taken into account.

Three variables are used in the likelihood method to resolve the ambiguities that arise from the matching of reconstructed objects to the partons in the Parton Picture Template for events with two jets and one charged lepton. The cosine of the angle between the W boson $W(\text{found})$, boosted into the rest frame of the top quark, and the charged lepton, boosted into the rest frame of $W(\text{found})$, is a handle to decide for the correct neutrino solution. The distribution of this variable can be found in figure 7.1.46(a) for the analysis where the charged lepton is a muon, and in figure 7.1.46(b) for the analysis where the charged lepton is an electron.

Figure 7.1.46: Input distributions for the likelihood method to resolve ambiguities in the Parton Picture Template for the reconstruction of dilepton top quark pair events with two jets and one charged lepton. The cosine of the angle between the W boson, boosted to the top quark rest frame, and the charged lepton, boosted to the W boson rest frame, is shown for muon events (figure 7.1.46(a)) and for electron events (figure 7.1.46(b)).

A variable that is used to assign the correct jet to the parton $b(\text{found})$ is the distance ΔR between $b(\text{found})$ and the charged lepton. Figure 7.1.47(a) shows this distribution for the 68% of the events passing both the matching quality cut and the selection cuts for the muon channel analysis. Figure 7.1.47(b) shows the same quantity for the electron channel analysis.

Figure 7.1.47: Input distributions for the likelihood method to resolve ambiguities in the Parton Picture Template for the reconstruction of dilepton top quark pair events with two jets and one charged lepton. The distance ΔR between the jet assigned to the parton b(found) and the charged lepton is shown for the muon channel (figure 7.1.47(a)) and the electron channel (figure 7.1.47(b)).

The pseudorapidity η of the reconstructed top quark t(found) is the third variable used to resolve ambiguities in the assignment of reconstructed objects and partons. Because the kinematic quantities of the reconstructed top quark are affected by both the reconstructed W boson (i.e. the choice of the z component of the neutrino momentum) and the jet assigned to b(found), the top quark pseudorapidity is a good variable to be used in the likelihood method. Both for muon events (figure 7.1.48(a)) and electron events (figure 7.1.48(b)) the pseudorapidity distribution of the top quarks from the matching of reconstructed objects to generated partons is symmetric with a maximum at 0.

Figure 7.1.48: Input distributions for the likelihood method to resolve ambiguities in the Parton Picture Template for the reconstruction of dilepton top quark pair events with two jets and one charged lepton. The pseudorapidity η distribution of the reconstructed top quark t(found) is shown for the muon channel (figure 7.1.48(a)) and for the electron channel (figure 7.1.48(b)).

The efficiency of the likelihood method is determined by comparing the configuration with the highest likelihood value with the configuration obtained from the matching of the recon-

	muon channel	electron channel
$\epsilon_{68}[\%]$	54.8	55.9
$\epsilon_{100}[\%]$	55.0	55.3

Table 7.1.6: Efficiencies ϵ_{68} and ϵ_{100} of the likelihood method for the muon channel analysis and the electron channel analysis.

structed objects with the partons from the generator. The efficiencies ϵ_{68} and ϵ_{100} , as described in definition 6.2.1, are summarized in table 7.1.6 for the muon channel analysis and the electron channel analysis. All four efficiencies are around 55%, i.e. higher than the 50% probability to assign the correct combination by chance.

7.1.3.2 Observables for Boosted Decision Trees

The challenge in the reconstruction of this Parton Picture Template is the reconstruction of the neutrino kinematics in order to be able to reconstruct the top quark $t(\text{found})$. In dilepton top quark pair events, at least two neutrinos contribute to the missing transverse energy of an event. In the case where one W boson decays into a tau, with a subsequent decay of the tau into another charged lepton, even more neutrinos contribute to the missing transverse energy. In those events discussed here, the second charged lepton escapes detection and thus also contributes to the measurement of missing transverse energy. Taking all these reasons into account, it is obvious that it is not sufficient to just split the missing transverse energy in two equal values. For the reconstruction of the events where generator information is matched with reconstructed objects, it is possible to approximate the neutrino kinematics from the missing transverse energy and the knowledge of the generator information of the W boson that is lost.

The method used to approximate the x (y) component p_x^ν (p_y^ν) of the neutrino momentum in the data analysis aims to minimize the fluctuations between the reconstructed neutrino momentum and the generated value (this method was introduced for events with three jets in [227]). Therefore, fractions d_x and d_y of the missing transverse energy components are optimized. They allow to calculate the difference Δp_i^ν according to

$$\Delta p_i^\nu = p_i - \frac{\text{ME}_i}{d_i} \quad (7.1.3)$$

with $i = x, y$ and p_i being the neutrino momentum components from the generator for the neutrino that is used to reconstruct the parton $W(\text{found})$ in the Parton Picture Template. The values d_i are scanned in small steps for values between 1 and 8. For all events fulfilling the matching criterion of table 7.1.5, these values Δp_i^ν are calculated and filled into a histogram.

Then, the RMS¹ and the mean of the histogram are calculated. The RMS for different values of d_x is shown in figure 7.1.49(a) for the p_x^ν component of the neutrino in the muon analysis, and in figure 7.1.49(b) for the electron analysis.

¹The `GetRMS` method of `ROOT` that was used, returns the Standard Deviation (σ) of a distribution, not the root mean square. The σ estimate is computed as $\sqrt{\frac{1}{N} \cdot \sum (x_i - x_{\text{mean}})^2}$. The name ‘RMS’ was introduced many years ago (Hbook/PAW times) and kept for continuity.

Figure 7.1.49: Root mean square of the histograms obtained by calculating $\Delta p_x^\nu = p_x - \frac{ME_x}{d_x}$ for events in the muon channel analysis (figure 7.1.49(a)) and the electron channel analysis (figure 7.1.49(b)) for different values of d_x .

Figure 7.1.50(a) shows the resulting distribution for Δp_y^ν by varying d_y for the muon channel, and figure 7.1.50(b) for the electron channel.

Figure 7.1.50: Root mean square of the histograms obtained by calculating $\Delta p_y^\nu = p_y - \frac{ME_y}{d_y}$ for events in the muon channel analysis (figure 7.1.50(a)) and the electron channel analysis (figure 7.1.50(b)) for different values of d_y .

The RMS distributions have a minimum in both analysis bins for both Δp_x^ν and Δp_y^ν . The histograms presenting the mean values of the Δp_i^ν distributions are shown figure 7.1.51 for x component of the neutrino momentum (figure 7.1.51(a) displays the muon channel, figure 7.1.51(b) the electron channel distribution) and in figure 7.1.52 for the y component of the neutrino momentum (with figure 7.1.52(a) showing the muon channel and figure 7.1.52(b) the electron channel distribution). In none of the four figures a mean value of 0 could be achieved.

For the analysis in the muon channel, the mean of the Δp_y^ν distribution is much more shifted than for the analysis in the electron channel. This is most likely a feature of the so-called ‘muon hole’ of the DØ detector, a region where the efficiency to detect a muon is lower because one layer of muon chambers is replaced by a support structure of the detector. Muons pointing in this detector region will thus contribute to the y component of missing transverse energy reconstruction.

Figure 7.1.51: Mean of the histograms obtained by calculating $\Delta p_x^\nu = p_x - \frac{ME_x}{d_x}$ for events in the muon channel analysis (figure 7.1.51(a)) and the electron channel analysis (figure 7.1.51(b)) for different values of d_x .

Figure 7.1.52: Mean of the histograms obtained by calculating $\Delta p_y^\nu = p_y - \frac{ME_y}{d_y}$ for events in the muon channel analysis (figure 7.1.52(a)) and the electron channel analysis (figure 7.1.52(b)) for different values of d_y .

The optimal values for d_x and d_y are those values where the RMS distribution has its minima. At these points, the fluctuations between the approximated p_i^ν momentum component and the true components are minimal. To also take the shifts in the mean value of the Δp_i^ν distribution into account, this mean value is drawn versus the RMS value of the distribution for each value of d_x and d_y . The shifts can then be identified as the value on the y -axis of the leftmost point in the distribution. The resulting distributions for the x components can be found in figure 7.1.53(a) for the muon channel and in figure 7.1.53(b) for the electron channel. The corresponding figures for the y component are shown in figure 7.1.54(a) for the analysis in the muon channel and in figure 7.1.54(b) for the analysis in the electron channel.

The results for the values of d_i and for the shifts of the mean value for the two analysis channels are presented in table 7.1.7.

In the reconstruction of the Parton Picture Template, p_x^ν and p_y^ν of the neutrino that is used

Figure 7.1.53: The mean values of the Δp_x^ν distributions for different values of d_x drawn versus the RMS of these distributions for the analysis in the muon channel (see figure 7.1.53(a)) and the analysis in the electron channel (see figure 7.1.53(b)).

Figure 7.1.54: The mean values of the Δp_y^ν distributions for different values of d_y drawn versus the RMS of these distributions for the analysis in the muon channel (see figure 7.1.54(a)) and the analysis in the electron channel (see figure 7.1.54(b)).

together with the charged lepton to form the W boson W(found) are approximated as

$$p_x^\nu = \frac{ME_x}{3.5} - 0.07 \text{ GeV} \quad (7.1.4)$$

$$p_y^\nu = \frac{ME_y}{3.3} - 4.17 \text{ GeV} \quad (7.1.5)$$

Muon channel		Electron channel	
d_x	d_y	d_x	d_y
3.5	3.3	3.3	3.5
Shift in x [GeV]	Shift y [GeV]	Shift in x [GeV]	Shift in y [GeV]
0.07	4.17	0.11	1.63

Table 7.1.7: This table summarizes the results of the optimization of the parameters d_x and d_y , and the shifts of the mean value in the Δp_i^ν ($i = x, y$) distributions for the two analysis channels.

in the analysis in the muon channel and as

$$p_x^\nu = \frac{ME_x}{3.3} - 0.11 \text{ GeV} \quad (7.1.6)$$

$$p_y^\nu = \frac{ME_y}{3.5} - 1.63 \text{ GeV}. \quad (7.1.7)$$

for the analysis in the electron channel.

Having found a way to approximate the x and y component of the neutrino in the Parton Picture Template of figure 7.1.44, it is now possible to create and evaluate four possible configurations of the event under the hypothesis to originate from the decay of top quark pairs in the dilepton channel. The configuration with the highest likelihood measure is then used to obtain observables for the multivariate analysis. In the following paragraphs the comparisons of data with simulated events for those variables entering the Boosted Decision Trees are shown for the four different analysis bins.

Events with two jets, one b-tagged jet, and one muon

For events with two jets, one of them tagged as originating from a b hadron decay, missing transverse energy and one muon, the agreement between observed data and simulated background processes is good. Variables obtained by the reconstruction of this Parton Picture Template and chosen as input to the statistical analysis are shown in figures 7.1.55, 7.1.56, and 7.1.57.

In figure 7.1.55(a) the mass of the reconstructed top quark $t(\text{found})$ is shown. For the signal events of electroweak top quark production this distribution peaks at 170 GeV, but the maximum in the distribution for background events is already reached at 140 GeV. Both distributions have long tails towards higher values of reconstructed top quark masses. The transverse momentum spectrum of these reconstructed top quarks is shown in figure 7.1.55(b). The distributions for signal and background contributions peak at the same value of 60 GeV, but the distribution for the single top quark sample is broader.

The transverse momentum and the pseudorapidity of the jets assigned to the parton $b(\text{found})$ are shown in figures 7.1.56(a) and 7.1.56(b). The transverse momentum distributions differ significantly in the region of low transverse momenta, up to a value of 60 GeV. The background distribution peaks at very low values of transverse energies, whereas the distribution for the single top quark signal events is rising up to 60 GeV. In pseudorapidity, both samples are symmetric around $\eta = 0$.

The transverse momentum distribution for jets assigned to the parton $b(\text{lost})$ is shown in figure 7.1.57(a). Apart from the spike in the background distribution in the first bin of the histogram, the distributions are more or less flat up to 60 GeV and then start to fall towards higher transverse momenta. The pseudorapidity distribution of the reconstructed W boson is symmetric around $\eta = 0$ (see figure 7.1.57(b)). The background model has a dip at $\eta = 0$, whereas the signal distribution remains flat in the region of $|\eta| < 1.0$.

Figure 7.1.55: Mass (figure 7.1.55(a)) and transverse momentum (figure 7.1.55(b)) for the reconstructed top quarks $t(\text{found})$ in events with two jets, one of them tagged as originating from a b hadron decay, and a muon.

Figure 7.1.56: The transverse momentum of jets assigned to the parton $b(\text{found})$ is shown in figure 7.1.56(a). Their pseudorapidity can be seen in figure 7.1.56(b). These histograms show events with two jets, one of them tagged as originating from a b hadron decay, and one muon.

Events with two jets, two b-tagged jets, and one muon

The analysis bin with two jets, both of them tagged as originating from a b hadron decay, and one muon suffers from low statistics due to the requirement that both jets should be tagged as b-jets. However, the agreement between observed data and expected background model for the six variables shown in figures 7.1.58 to 7.1.60 is reasonable. Thus, they can be taken into account in the multivariate analysis.

The mass of the reconstructed top quarks $t(\text{found})$ can be seen in figure 7.1.58(a). The signal distribution peaks at 160 GeV, the distribution of the simulated background events at 145 GeV. The reason that the reconstructed top quark mass in the signal samples differs from 175 GeV is the splitting of the missing transverse energy to calculate the neutrino solution. Figure 7.1.58(b) shows the transverse momentum spectrum for the reconstructed top quarks $t(\text{found})$. In background events the reconstructed top quarks prefer to have lower transverse momentum. For the single top quark signal events, the distribution reaches its maximum at

Figure 7.1.57: The transverse momentum distribution of jets assigned to the parton $b(\text{lost})$ is shown in figure 7.1.57(a), and the pseudorapidity η of the reconstructed W boson $W(\text{found})$ can be seen in figure 7.1.57(b) for events with two jets, one of them b -tagged, and one muon.

60 GeV, and almost no top quark is reconstructed with low transverse momentum.

Figure 7.1.58: Mass and transverse momentum of the reconstructed top quarks $t(\text{found})$ are shown in figures 7.1.58(a) and 7.1.58(b) for events with two jets, both tagged as b -jets, and a muon.

The transverse momentum distribution for jets assigned to the parton $b(\text{lost})$ is shown in figure 7.1.59(a). While the background events are preferably reconstructed with low transverse momenta, the signal events of electroweak production of single top quarks are on average reconstructed with higher transverse momenta. The distribution of the pseudorapidity η of these jets is symmetric around $\eta = 0$ for both the signal and the background model.

The transverse momentum of the jets assigned to the parton $b(\text{found})$ is also used in the statistical analysis and shown in figure 7.1.60(a). The distribution of signal events seems slightly shifted towards higher values compared to the distribution for the expected background events. Figure 7.1.60(b) shows the pseudorapidity η of the reconstructed W boson $W(\text{found})$. This is a symmetric distribution around $\eta = 0$ for both signal and background events.

Events with two jets, one b -tagged jet, and one electron

For the analysis bin with two jets, one of them tagged as originating from the decay of a

Figure 7.1.59: Transverse momentum of jets assigned to the parton b(lost) (see figure 7.1.59(a)) and their pseudorapidity η (see figure 7.1.59(b)) for events with two jets, both of them tagged as b-jets, and one muon.

Figure 7.1.60: The transverse momentum distribution of the jets assigned to the parton b(found) can be seen in figure 7.1.60(a). Figure 7.1.60(b) displays the pseudorapidity η of the reconstructed W boson W(found). Both histograms contain events with two jets, both tagged as b-jets, and one muon.

b hadron and one central electron, six variables are used for the statistical analysis from the reconstruction of this Parton Picture Template. These variables are shown in the comparison of their expected distribution from simulated events with the observed data events. Within the statistical precision of this analysis bin, the agreement is good.

For the background events, the mass distribution of the reconstructed top quarks peaks at 140 GeV. The distribution for the single top quark signal events however peaks at 170 GeV. Both distributions have long tails towards high mass values. The shape of the transverse momentum distribution for the reconstructed top quarks are very similar for signal and for background events. Both have their maximum at 60 GeV. The distribution of the signal events seems to be a bit broader.

A variable that should be powerful during the statistical analysis is the transverse momentum of jets associated with the parton b(found), shown in figure 7.1.62(a). For background events, this is a falling distribution with its maximum in the lowest bin of the histogram. For signal

Figure 7.1.61: Mass of the reconstructed top quark $t(\text{found})$ (see figure 7.1.61(a)) and their transverse momentum (see figure 7.1.61(b)) for events with two jets, one of them tagged as originating from a b hadron decay, and one central electron.

events, the distribution rises up to 60 GeV before starting to fall again. A symmetric distribution for both signal and background events can be seen in figure 7.1.62(b) for the pseudorapidity η of jets assigned to the parton $b(\text{found})$.

Figure 7.1.62: Transverse momentum and pseudorapidity η of jets associated with the parton $b(\text{found})$ are shown in figure 7.1.62(a) and figure 7.1.62(b), respectively. The figures show events with two jets, one of them tagged as a b -jet, and one central electron.

Jets associated with the parton $b(\text{lost})$ show a falling transverse momentum distribution for the simulated background events (see figure 7.1.63(a)). For the single top quark signal events, the distribution rises slowly up to 60 GeV and then starts to fall with a similar slope when compared to the background distribution. The pseudorapidity η of the reconstructed W boson $W(\text{found})$ is shown in figure 7.1.63(b).

Events with two jets, two b -tagged jets, and one electron

With the requirement of both jets being b -tagged, the analysis bin with events with two b -tagged jets, one central electron, and missing transverse energy suffers from low statistics. Nevertheless, the same six variables are used to train the multivariate analysis as for events with only one b -tagged jet. The agreement between the background expectation and the observed

Figure 7.1.63: The transverse momentum distribution of jets assigned to the parton b(lost) in the reconstruction of the Parton Picture Template is shown in figure 7.1.63(a). Figure 7.1.63(b) shows the pseudorapidity η of the reconstructed W bosons. Both figures show events with two jets, one of them tagged as a b-jet, and one central electron.

data is fair, considering the statistical precision and is shown in figure 7.1.64, figure 7.1.65, and figure 7.1.66. The dominant physics background processes are $Wb\bar{b}$ production and decays of top quark pairs in the dilepton channel.

The mass distribution of the reconstructed top quarks t(found) is shown in figure 7.1.64(a). For events in the $Wb\bar{b}$ background sample, lower mass values are reconstructed. The signal samples and the sample of top quark pair production in the dilepton channel – the channel, this Parton Picture Template was optimized for – peak at 160 GeV and 175 GeV, respectively. The transverse momentum distribution of those reconstructed top quarks can be seen in figure 7.1.64(b). It is shifted slightly towards higher transverse momenta for signal events than for background events.

Figure 7.1.64: Figure 7.1.64(a) shows the mass of the reconstructed top quarks, figure 7.1.64(b) their transverse momentum, for events with two jets, both tagged as b-jets and one central electron.

Transverse momentum and pseudorapidity of jets assigned to the parton b(lost) are shown in figures 7.1.65(a) and 7.1.65(b). For the background events jets are selected that have a lower

transverse momentum. Their distribution has its maximum at 40 GeV, where the distribution for the single top quark signal events is still on the rising edge. From 70 GeV on, both distributions have a similar shape of the falling edge. The pseudorapidity distribution is symmetric around $\eta = 0$ for the simulated events. However, in the selected data sample, there is a slight asymmetry and more jets with pseudorapidity $\eta > 0$ are selected to play the role of the parton b(lost).

Figure 7.1.65: Figure 7.1.65(a) shows the transverse momentum distribution for jets assigned to the parton b(lost) in the Parton Picture Template. Their pseudorapidity η is displayed in figure 7.1.65(b). Both figures contain events with two jets, both tagged as originating from a b hadron decay, and one central electron.

The transverse momentum of jets selected to play the role of the parton b(found) is shown in figure 7.1.66(a). The majority of $Wb\bar{b}$ events can be found at low values of transverse momentum, whereas the distribution for the single top quark signal events is still rising up to 50 GeV. The falling edge of the transverse momentum spectrum is similar from 70 GeV onwards. The pseudorapidity η of the reconstructed W boson W(found) is symmetric around $\eta = 0$ and shows a very good agreement between the observed data and the background model (see figure 7.1.66(b)).

Figure 7.1.66: Transverse momentum of jets assigned to the parton b(found) (figure 7.1.66(a)) and the transverse momentum of the reconstructed W boson W(found) (figure 7.1.66(b)) for events with two jets, both b-tagged, and one central electron.

7.1.4 Global Event Observables

In this section variables are studied that are calculated from the properties of the reconstructed final state objects in an event only. Hence, there are no ambiguities that need to be resolved as for the other PaxProcesses. However, a Parton Picture Template is used and reconstructed in order to have access to some of the observables. This Parton Picture Template is displayed in figure 7.1.67. There are two jets in the event. They are ordered by decreasing transverse momentum and labeled jet1 and jet2 (with jet1 being the jet with the higher transverse momentum). The vector sum of these two jets builds a new four-vector, the so-called *Hadronic Final State* (HFS). This HFS four-vector is then connected to the primary vertex of the event. The charged lepton and the reconstructed missing transverse energy of the event are used to reconstruct a W boson. This is done using a W boson mass constraint to get a z component for the neutrino momentum vector. The x and y component of this vector are taken from the reconstructed missing transverse energy components. From the two solutions for the z component of the neutrino momentum the more central solution is used, i.e. the solution with the smaller absolute value of pseudorapidity η .

Figure 7.1.67: Parton Picture Template for the PaxProcess calculating event shape variables.

Although there are no ambiguities to be resolved, a Parton Picture Template is reconstructed for each event. The two jets, jet1 and jet2 (sorted by decreasing transverse momentum), are combined to a dijet four-vector, that is connected to the primary vertex and named Hadronic Final State (HFS). For the reconstruction of the W boson the z component of the neutrino needs to be calculated. This is done using the quadratic equation one gets from a W boson mass constraint and selecting the solution with the smaller pseudorapidity η . The W boson is reconstructed from the charged lepton and the neutrino, and also connected to the primary vertex.

7.1.4.1 Observables for Boosted Decision Trees

In the following, the variables used in the statistical analysis with Boosted Decision Trees are presented for the four different analysis bins.

Events with two jets, one b-tagged jet, and one muon

Variables of this PaxProcess used in the statistical analysis are shown in figures 7.1.68 to 7.1.97. Variables are chosen based on their good agreement in the comparison of simulated background with observed data and their potential to separate the events from the electroweak top quark signal from the background events.

Figure 7.1.68 shows the angles between the HFS and the charged lepton (figure 7.1.68(a)) and the angle between the charged lepton and the leading jet (figure 7.1.68(b)). These angles were calculated after boosting the HFS, jet1 and the charged lepton into the center-of-mass reference frame. In both cases, the distribution for the signal events shows a more distinct peak structure, whereas the distribution for the background events rises almost up to angles of 3 rad. The signal distributions reach their maximum at 2.3 rad for the angle between the HFS and the charged lepton and at 2.0 rad for the angle between the charged lepton and jet1.

Figure 7.1.68: Angle between the HFS and the charged lepton (figure 7.1.68(a)) and angle between the charged lepton and jet1 (figure 7.1.68(b)). In both cases the particles are boosted into the center-of-mass system of the event. The distributions show events with two jets, one of them tagged as originating from a b hadron decay, and one muon.

The mass (see figure 7.1.69(a)) and the transverse momentum (see figure 7.1.69(b)) of the dijet system that forms the HFS are used in the Boosted Decision Tree analysis. On average, the masses reconstructed for the signal sample are higher than for the background samples. The maximum of the distribution is reached at 105 GeV for signal events and at 90 GeV for background events. The latter have a much steeper slope of both their rising and falling edges of the distribution. The transverse momentum distribution is similar for both signal and background events.

Figure 7.1.69: The mass (see figure 7.1.69(a)) and the transverse momentum (see figure 7.1.69(b)) of the HFS are displayed in this figure. Both distributions show events with two jets, one b-tagged jet and a muon.

Figure 7.1.70 shows the result for the ‘best top quark mass’ (as defined in definition 6.2.5) and the ‘b-tagged top quark mass’ (as defined in 6.2.6). The distribution for the ‘best top quark mass’ is shown in figure 7.1.70(a) and peaks at 175 GeV for both the signal and the background events. Using the information from the b-tagging algorithm leads to a separation in the reconstructed top quark masses for signal and background events, as can be seen in figure 7.1.70(b) for the distribution of the ‘b-tagged top quark mass’. The signal distribution still peaks at 170 GeV, but for the background events, especially those from the associated production of W bosons with jets, the maximum of the distribution moves to a lower value of 140 GeV.

Figure 7.1.70: Figure 7.1.70(a) shows the distribution of the ‘best top quark mass’, figure 7.1.70(b) the one for the ‘b-tagged top quark mass’ for events with two jets, one b-tagged jet, and one muon.

The transverse momentum distribution of the ‘best jet’ (as defined in definition 6.2.3) is shown in figure 7.1.71(a). The distribution for the ‘leading b-tagged jet’ (as defined in definition 6.2.2) is displayed in figure 7.1.71(b). In both cases the distributions for the signal events have their maximum at higher transverse momentum values than for the background events. The distribution for the ‘leading b-tagged jet’ peaks at 60 GeV, a typical value for a b-jet from a top quark decay.

The cosine of the angle between the ‘best jet’ and the charged lepton in the reference frame

Figure 7.1.71: The transverse momentum distribution for the ‘best jet’ is shown in figure 7.1.71(a), the one for the ‘leading b-tagged jet’ in figure 7.1.71(b). Both histograms show events with two jets, one of them tagged as a b-jet, and one muon.

of the ‘best top quark’ is shown in figure 7.1.72(a). A significant difference between the signal and the background distribution can be seen in the region between -1 and -0.7 . There, the background distribution shows a falling shape, whereas the distribution of the single top quark signal events is rising up to -0.7 . The same feature can be found in figure 7.1.72(b) that shows the cosine of the angle between the b-tagged jet and the lepton in the reference frame of the ‘b-tagged top quark’.

Figure 7.1.72: The cosine of the angle between the ‘best jet’ and the charged lepton in the reference frame of the ‘best top quark’ is shown in figure 7.1.72(a). Figure 7.1.72(b) shows the cosine of the angle between the b-tagged jet and the charged lepton in the reference frame of the ‘b-tagged top quark’. Both distributions show events with two jets, one b-tagged jet, and one muon.

The cosine of the angle between jet1 and the HFS in the reference frame of the HFS is shown in figure 7.1.73(a). The slopes of the distributions for signal and background events are different. The signal distribution rises slower, whereas the background distribution reaches a plateau between 0.3 and 0.8. For the cosine of the angle between the leading jet and the charged lepton in the reference frame of the ‘b-tagged top quark’ a significant difference in the shape between signal and background events can be seen in the region between -0.9 and -0.6 (see

figure 7.1.73(b)). Here, it is the distribution for the single top quark signal that shows a plateau, whereas the distribution for the background events is steeply falling.

Figure 7.1.73: Two angular correlations are shown in this figure. In figure 7.1.73(a) the cosine of the angle between jet1 and the HFS in the reference frame of the HFS is shown, and in figure 7.1.73(b) the cosine of the angle between jet1 and the lepton in the reference frame of the ‘b-tagged top quark’ is shown. Both distributions show events with two jets, one b-tagged jet and one muon.

The cosine of the angle between the ‘best top quark’ and the charged lepton in the center-of-mass frame of the ‘best top quark’ is shown in figure 7.1.74(a). While the distribution for the background events is rather flat, the distribution for the electroweak top quark signal is falling for values bigger than -0.5 . Figure 7.1.74(b) shows the $\Delta\varphi$ between the charged lepton and the reconstructed missing transverse energy. For $\Delta\varphi > 2.0$ the distribution for the signal events starts to fall, while the distribution for the background events is still rising.

Figure 7.1.74: Figure 7.1.74(a) displays the cosine of between the charged lepton and the ‘best top quark’ in the center-of-mass reference frame of the ‘best top quark’. Figure 7.1.74(b) shows $\Delta\varphi$ between the charged lepton and the missing transverse energy. Both distributions show events with two jets, one of them tagged as originating from the decay of a b hadron, and one muon.

The scalar sum of the transverse energies in the jets is called H_t and shown in figure 7.1.75(a). The distribution for the signal events reaches its maximum at a higher value of 110 GeV than

the background distribution, that peaks at 80 GeV. If one also adds transverse momentum information of the charged lepton and the missing transverse energy in the calculation of H_t , the resulting distribution is shown in figure 7.1.75(b). The signal distribution peaks at 200 GeV, 40 GeV higher than for the background events.

Figure 7.1.75: The H_t variable for the two jets in the events is shown in figure 7.1.75(a). Adding also information about the charged lepton and the missing transverse energy results in the distribution of figure 7.1.75(b). Both distributions contain events with two jets, one b-tagged jet, and one muon.

The sum of the scalar energies of the jets in an event is called H and shown in figure 7.1.76(a). The distribution for the signal events of electroweak top quark production is broader than for the expected background contributions and peaks at a higher value of 160 GeV. The mass $\hat{S}$ of the four-vector I_μ is calculated after summing up all jets and the reconstructed W boson in the event:

$$\begin{aligned}
 I_\mu &= \sum_{\text{jets, W}} P_\mu \\
 \hat{S} &= \text{mass}(I_\mu)
 \end{aligned}
 \tag{7.1.8}$$

The $\hat{S}$ distribution is shown in figure 7.1.76(b).

Figure 7.1.76: Distribution of the H variable (see figure 7.1.76(a)) and of the $\hat{S}$ variable (see figure 7.1.76(b)) for events with two jets, one b-tagged jet, and one muon.

Figure 7.1.77(a) shows the ‘ q times η ’ variable as defined in definition 6.2.7. The expected asymmetry for the signal events is clearly visible, whereas the distribution for the simulated background events is symmetric around zero. The transverse mass of the reconstructed W boson is shown in figure 7.1.77(b). This variable is a good candidate to be useful to separate the multijet background. It is accumulated at low transverse mass values.

Figure 7.1.77: The product of the charge of the charged lepton and the pseudorapidity η of the leading untagged jet is shown in figure 7.1.77(a). The transverse mass of the W boson is shown in figure 7.1.77(b). Both distributions contain events with two jets, one of them tagged as originating from a b hadron decay, and one muon.

The difference in transverse momentum between jet1 and jet2 is shown in figure 7.1.78(a). The maximum of the distribution for signal events is at a difference of 20 GeV followed by a steep falling edge. The spatial distance ΔR between the two jets shows a difference in the distribution between signal and background events for low values up to $\Delta R = 2$. The background distribution is flat, implying that there are events where the two jets are close in ΔR . For the simulated signal events there are only a few events, where both jets are close to one another. The distribution rises slowly up to $\Delta R = 3$.

Figure 7.1.78: The distribution of the difference of the transverse momentum between jet1 and jet2 is shown in figure 7.1.78(a) and their spatial distance ΔR can be seen in figure 7.1.78(b). Both histograms show events with two jets, one of them tagged as a b-jet, and one muon.

Kinematic properties of jet1 and jet2 are shown in figures 7.1.79 and 7.1.80. Figure 7.1.79(a)

shows the transverse momentum of the leading jet in the event. For events of electroweak top quark production the leading jet has on average a higher transverse momentum than the background distribution. The pseudorapidity η of the leading jet is shown in figure 7.1.79(b). This distribution is symmetric around $\eta = 0$.

Figure 7.1.79: Transverse momentum (see figure 7.1.79(a)) and pseudorapidity η (see figure 7.1.79(b)) of the leading jet in the event. The histograms contain events with two jets, one of them b-tagged, and one muon.

The same quantities as for jet1 are also used for jet2 and are displayed in figure 7.1.80(a) (transverse momentum) and figure 7.1.80(b) (pseudorapidity η). The transverse momentum spectrum is much softer for the expected background contributions. The distribution of the pseudorapidity η is again symmetric around $\eta = 0$.

Figure 7.1.80: Figure 7.1.80(a) shows the transverse momentum of jet2, figure 7.1.80(b) shows their pseudorapidity η for events with two jets, one b-jet, and one muon.

The sum over the transverse energies of the reconstructed jets and the charged lepton is called SEt :

$$SEt = \sum_{\text{jets, charged lepton}} E_T. \quad (7.1.9)$$

The distribution is shown in figure 7.1.81(a). SEt is on average higher for the simulated signal events than for the expected backgrounds. If one also adds the missing transverse energy, the distribution shown in figure 7.1.81(b) is the result. It shows the same feature as the SEt distri-

bution, i.e. the single top quark signal distribution peaks at a higher value than the background distribution.

Figure 7.1.81: The scalar sum of the transverse energies of the jets and the lepton in the event is shown in figure 7.1.81(a). Adding also the missing transverse energy, figure 7.1.81(b) results from the calculation. Both distributions show events with two jets, one b-tagged jet, and a muon.

For the calculation of the variables aplanarity and sphericity, the sphericity tensor $S^{\alpha\beta}$ is needed:

$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\mathbf{p}_i|^2} \quad \alpha, \beta = 1, 2, 3. \quad (7.1.10)$$

The index i runs over all reconstructed particles of the event, the p_i are the four-momentum vectors of those particles

$$p_i = (\mathbf{p}_i, E_i). \quad (7.1.11)$$

The three eigenvalues λ_1 , λ_2 , and λ_3 of $S^{\alpha\beta}$ are sorted and obey

$$\lambda_1 \geq \lambda_2 \geq \lambda_3 \quad (7.1.12)$$

with

$$\lambda_1 + \lambda_2 + \lambda_3 = 1. \quad (7.1.13)$$

The aplanarity A is then calculated as:

$$A = \frac{3}{2} \lambda_3 \quad \text{with } 0 \leq A \leq \frac{1}{2}. \quad (7.1.14)$$

The sphericity S can then be calculated as:

$$S = \frac{3}{2} (\lambda_2 + \lambda_3) \quad \text{with } 0 \leq S \leq 1. \quad (7.1.15)$$

In figure 7.1.82(a) the aplanarity A is shown for this analysis bin. Both signal and background have a similar shape. The sphericity distribution is shown in figure 7.1.82(b). The slope of the falling edge of the distribution is steeper for the simulated background events than for the single top quark signal.

The pseudorapidity distribution for the isolated charged lepton is shown in figure 7.1.83(a). It is symmetric around $\eta = 0$. The background distribution shows spikes at $|\eta| = 1.5$ that are

Figure 7.1.82: Aplanarity A is shown in figure 7.1.82(a) and sphericity S is shown in figure 7.1.82(b) for events with two jets, one b-tagged jet, and one muon.

less pronounced in the distribution of signal events. The missing transverse energy distribution displayed in figure 7.1.83(b) shows that on average the single top quark signal has more missing transverse energy than the background. This variable is especially useful to reject multijet background.

Figure 7.1.83: Figure 7.1.83(a) shows the pseudorapidity η distribution for the charged lepton and figure 7.1.83(b) the reconstructed missing transverse energy for events with two jets, one of them tagged as originating from a b hadron decay, and one muon.

Events with two jets, two b-tagged jets, and one muon

The analysis bin with two jets, both tagged as originating from a b hadron decay, missing transverse energy and one muon suffers from low statistics due to the requirement, that both jets should be b-tagged. This requirement removes most of the W +jets and the multijet background. The remaining dominant backgrounds are $Wb\bar{b}$ production and top quark pair production in the dilepton channel. Variables used in the multivariate analysis are shown in figures 7.1.84 to 7.1.97. In view of the low statistic, these variables agree well in the comparison of simulated background events and observed data events and can thus be used in the Boosted Decision Tree analysis.

Figure 7.1.84 shows the angles between the HFS and the charged lepton (figure 7.1.84(a)) and

the angle between the charged lepton and the leading jet (figure 7.1.84(b)). Those angles are calculated after boosting the HFS, jet1 and the charged lepton into the center-of-mass reference frame. In both cases the signal distribution peaks at lower angles, whereas the background events accumulate at higher angles.

Figure 7.1.84: Angle between the HFS and the charged lepton in the center-of-mass frame (figure 7.1.84(a)). In the same reference frame, figure 7.1.84(b) displays the angle between the charged lepton and the leading jet for events with two jets, both of them tagged as b-jets, and one muon.

The mass of the HFS and its transverse momentum are shown in figure 7.1.85. The mass distribution of the signal events peaks at 120 GeV, approximately 40 GeV above the distribution for the background events. In both cases there are long tails towards high masses (see figure 7.1.85(a)). The transverse momentum distributions similar. However, the contribution from top quark pair production (the red color in figure 7.1.85(b)) has larger reconstructed transverse momenta.

Figure 7.1.85: Figure 7.1.85(a) shows the mass of the HFS, and figure 7.1.85(b) its transverse momentum for events with two jets, both tagged as b-jets and one muon.

The mass of the ‘best top quark’, as introduced in definition 6.2.5, is shown in figure 7.1.86(a). For both the single top quark signal events and the background events the distribution peaks at 175 GeV. However, the combined background distribution is much broader. Figure 7.1.86(b) shows the mass of the ‘b-tagged top quark’ as introduced in definition 6.2.6. There, only the

single top quark signal events peak at 175 GeV. Even for the top quark pair production, the maximum of the individual shapes is at approximately 200 GeV.

Figure 7.1.86: Mass of the ‘best top quark’ (figure 7.1.86(a)) and mass of the ‘b-tagged top quark’ (figure 7.1.86(b)) for events with two jets, both b-tagged, and one muon.

The transverse momentum distribution for those jets identified as ‘best jets’ according to definition 6.2.3 is shown in figure 7.1.87(a). The spectra for the top quark pair events and the single top quark signal events are very similar, but the remaining $Wb\bar{b}$ events accumulate at lower transverse momenta. The transverse momentum distribution of the ‘leading b-tagged jet’ according to definition 6.2.2 is displayed in figure 7.1.87(b). Again, the spectra for those events containing top quarks are very similar, but the $Wb\bar{b}$ events tend to have a softer transverse momentum spectrum.

Figure 7.1.87: Transverse momentum of the ‘best jet’ (figure 7.1.87(a)) and the ‘leading b-tagged jet’ (figure 7.1.87(b)) for events with two jets, both tagged as originating from a b hadron decay, and one muon.

The cosine of the angle between the ‘best jet’ and the charged lepton in the reference frame of the ‘best top quark’ is shown in figure 7.1.88(a). Between -0.9 and -0.7 , the distribution for the single top quark signal events is rather flat, whereas the distribution for the background already has a falling slope. Figure 7.1.88(b) shows the cosine of the angle between leading jet and the HFS in the rest frame of the HFS.

The cosine of the angle between the charged lepton and the ‘best top quark’ in the center-of-mass frame of the ‘best top quark’ is shown in figure 7.1.89(a) and exhibits an almost flat

Figure 7.1.88: Figure 7.1.88(a) displays the cosine of the angle between the ‘best jet’ and the charged lepton in the reference frame of the ‘best top quark’ and figure 7.1.88(b) displays the cosine of the angle between jet1 and the HFS in the rest frame of the HFS. Both distributions contain events with two jets, both tagged as b-jets, and one muon.

distribution for the expected background. However, considering the signal events of electroweak top quark production, the distribution is steadily falling starting from -0.5 . The distance $\Delta\varphi$ between the charged lepton and the reconstructed missing transverse energy can be seen in figure 7.1.89(b). The distribution for the signal events has a flatter slope than the corresponding background distribution.

Figure 7.1.89: The cosine of the angle between the charged lepton and the ‘best top quark’ in the center-of-mass frame of the ‘best top quark’ is displayed in figure 7.1.89(a). $\Delta\varphi$ between the charged lepton and the missing transverse energy is shown in figure 7.1.89(b). Both distributions show events with two jets, both tagged as b-jets, and one muon.

Ht , the scalar sum of the transverse energies of the jets in the event, is shown in figure 7.1.90(a). The $Wb\bar{b}$ events can be found predominantly at lower values of Ht . The shapes of the signal distribution and the background from top quark pair production are similar. However, if one also takes the transverse energies of the charged lepton and the missing transverse energy into account, the $Wb\bar{b}$ events are further shifted towards lower values and the background from top quark pair production is shifted towards higher values of Ht compared to the

distribution for signal events. The latter feature can be explained with the additional neutrinos that contribute to the missing transverse energy for the top quark pair events in the dilepton channel.

Figure 7.1.90: The Ht distribution calculated from all jets is shown in figure 7.1.90(a) and in figure 7.1.90(b) for all jets, plus the charged lepton and the missing transverse energy. Both histograms show events with two jets, both b-tagged, and one muon.

Adding up the scalar energies of the jets instead of their transverse momenta results in the distribution of the variable H shown in figure 7.1.91(a). On average, the single top quark signal events have a higher value of H compared to the total background expectation. Figure 7.1.91(b) shows the variable $\hat{S}$ as introduced in equation 7.1.8. The distributions for signal and background events are very similar in this variable. The transverse mass of the W boson is a good variable to separate the remaining multijet background from the signal. The multijet background is accumulated at very low values of transverse masses.

Figure 7.1.91: Figure 7.1.91(a) shows the variable H calculated from the two jets in the event. The $\hat{S}$ distribution is shown in figure 7.1.91(b) and the distribution of the transverse mass of the W boson can be seen in figure 7.1.91(c). The histograms contain events with two jets, both tagged as originating from a b hadron decay, and one muon.

The difference between the transverse momenta of jet1 and jet2 can be found in figure 7.1.92(a). The distributions are very similar for the signal events of electroweak top quark production and the background events. Their spatial distance ΔR is shown in figure 7.1.92(b). Up to values of $\Delta R = 2$ the shape of background distribution is flat, whereas the shape of the

signal sample (and the individual shape of the background of top quark pair production in the dilepton channel) is rising, i.e. there are almost no events where the two jets are close to another.

Figure 7.1.92: The difference in transverse momentum between jet1 and jet2 is shown in figure 7.1.92(a). The spatial distance ΔR between the two jets can be seen in figure 7.1.92(b). Both histograms contain events with two jets, both of them tagged as b-jets, and one muon.

The transverse momentum distributions and pseudorapidity distributions for jet1 and jet2 are shown in figure 7.1.93 and figure 7.1.94, respectively. In figure 7.1.93(a) the transverse momentum distribution for the leading jet can be seen. The transverse momentum spectrum for the background from $Wb\bar{b}$ production is softer than for the event samples containing at least one top quark. The distribution for the signal sample of electroweak top quark production has its maximum at 65 GeV, a value expected for a b-jet originating from the decay of a top quark. The pseudorapidity distribution in figure 7.1.93(b) is symmetric around $\eta = 0$ for both signal and background events.

Figure 7.1.93: The transverse momentum distribution of jet1 is shown in figure 7.1.93(a) and its pseudorapidity distribution in figure 7.1.93(b) for events with two jets, both tagged as b-jets, and one muon.

The transverse momentum spectrum for jet2 (see figure 7.1.94(a)) is very soft for the $Wb\bar{b}$ background. The signal distribution has its maximum at 40 GeV, whereas the maximum of the background distribution can be found at 25 GeV. In pseudorapidity η , both distributions are again symmetric around $\eta = 0$.

Figure 7.1.94: The transverse momentum distribution of jet2 is shown in figure 7.1.94(a) and its pseudorapidity distribution in figure 7.1.94(b) for events with two jets, both of them tagged as b-jets, and one muon.

The SEt distribution (see equation 7.1.9) is shown in figure 7.1.95(a). SEt is on average higher for the simulated signal events than for the expected backgrounds. If one also adds the missing transverse energy, the distribution shown in figure 7.1.95(b) is the result. It shows the same feature as the SEt distribution, i.e. the single top quark signal distribution peaks at a higher value than the background distribution. Due to the two neutrinos that are produced in dilepton top quark pair events, the background from top quark pair production is shifted towards higher values here, compared with the SEt variable.

Figure 7.1.95: Figure 7.1.95(a) shows the distribution for the SEt variable based on jets and the charged lepton. In figure 7.1.95(b) also the missing transverse energy is taken into account. Both histograms show events with two jets, both tagged as originating from a b hadron decay, and one muon.

The definitions for the event shape variables aplanarity A and sphericity S are given in equation 7.1.14 and equation 7.1.15, respectively. Both distribution are very similar for background and signal events in this analysis bin.

The pseudorapidity distribution of the isolated charged lepton is shown in figure 7.1.97(a). It is symmetric around $\eta = 0$ for both signal and background events. The missing transverse energy distribution in figure 7.1.97(b) shows fluctuations within that are in agreement within the limited statistics. The background model shows two features: the multijet background can

Figure 7.1.96: Event shape variables aplanarity (figure 7.1.96(a)) and sphericity (figure 7.1.96(b)) for events with two jets, both b-tagged, and one muon.

be found at low values of missing transverse energy and the background from top quark pair production in the dilepton channel tends to have more missing transverse energy. The latter can again be explained with the at least two neutrinos that contribute to the missing transverse energy for these events.

Figure 7.1.97: Pseudorapidity η of the charged isolated lepton (see figure 7.1.97(a)) and missing transverse energy (see figure 7.1.97(b)), reconstructed in events with two jets, both tagged as b-jets, and one muon.

Events with two jets, one b-tagged jet, and one electron

Variables of this PaxProcess used in the statistical analysis for this analysis bin are shown in figures 7.1.98 to 7.1.127. Overall, the agreement between the observed data and the background model for these variables is good. They are chosen because of this agreement and their potential to separate the events from the electroweak top quark signal from the background events.

Figure 7.1.98 shows the angles between the HFS and the charged lepton (figure 7.1.98(a)) and the angle between the charged lepton and the leading jet (figure 7.1.98(b)). Those angles are calculated after boosting the HFS, jet1 and the charged lepton into the center-of-mass reference frame. In the first case, the distribution for the signal events peaks at 2.3 rad and starts falling

afterwards, whereas the distribution for background events rises up to 2.5 rad, remains flat until 2.9 rad and then falls steeply. For the angle between the charged lepton and jet1 the signal distribution peaks at 2.0 rad, whereas the background distribution rises up to 2.5 rad, before it starts to fall.

Figure 7.1.98: The angle between the HFS and the charged lepton is shown in figure 7.1.98(a). Figure 7.1.98(b) shows the angle between the charged lepton and jet1. All particles were boosted into the center-of-mass reference frame. The histograms show events with two jets, one of them tagged as originating from the decay of a b hadron, and one central electron.

The mass of the HFS and its transverse momentum are shown in figures 7.1.99(a) and 7.1.99(b). While the background distribution of the mass of the HFS has its maximum at 60 GeV, the distribution for the events of electroweak top quark production reaches its maximum at 100 GeV. Also the tails of the distribution are more distinct for the signal samples. On average, the transverse momentum of the HFS is also higher for the single top quark signal than for the combined background. The majority of the background events accumulates at values below 50 GeV, a value where the signal distribution has its maximum. The slope of the falling edge towards higher values of transverse energy is similar for both signal and background events.

Figure 7.1.99: Figure 7.1.99(a) shows the mass of the HFS, figure 7.1.99(b) displays its transverse momentum distribution. Both histograms show events with two jets, one of them b-tagged, and one central electron.

The mass of the ‘best top quark’, as introduced in definition 6.2.5, is shown in fig-

ure 7.1.100(a). The signal distribution has its maximum at 175 GeV, the value used in the generator for the production of these samples. The background distribution is broader and slightly shifted towards lower values. Using the b-jet instead of the ‘best jet’ for the reconstruction of the top quark, the resulting distribution can be found in figure 7.1.100(b). The single top quark signal distribution still peaks at 175 GeV, but the separation from the background is much clearer. The maximum of the background distribution is reached at already 130 GeV. However, compared to the mass of the ‘best top quark’, the mass distribution of the ‘b-tagged top quark’ has longer tails towards higher mass values.

Figure 7.1.100: The mass of the ‘best top quark’ is shown in figure 7.1.100(a), the mass of the ‘b-tagged top quark’ in figure 7.1.100(b). Both histograms contain only events with two jets, one b-tagged jet, and one central electron.

Figure 7.1.101(a) presents the transverse momentum of the ‘best jet’, according to definition 6.2.3. The transverse momentum distribution for the b-tagged jet is shown in figure 7.1.101(b). In both cases, the spectrum for the simulated signal events is harder than for the background events. The distribution of the background events peaks at 40 GeV, i.e. 20 GeV less than for the events of electroweak top quark production.

Figure 7.1.101: Transverse momentum of the ‘best jet’ (figure 7.1.101(a)) and the b-tagged jet (figure 7.1.101(b)) for events with two jets, one of them tagged as a b-jet, and one electron.

The cosine of the angle between the ‘best jet’ and the charged lepton in the reference frame of the ‘best top quark’ is shown in figure 7.1.102(a). A significant difference between the signal

and the background distribution can be seen in the region between -1 and -0.7 . There, the background distribution shows a falling shape, whereas the distribution of the single top quark signal events is rising up to -0.7 . The same feature can be found in figure 7.1.102(b) that shows the cosine of the angle between the b-tagged jet and the lepton in the reference frame of the ‘b-tagged top quark’.

Figure 7.1.102: The cosine of the angle between the ‘best jet’ and the charged lepton in the reference frame of the ‘best top quark’ is shown in figure 7.1.102(a). The cosine of the angle between the b-tagged jet and the charged lepton in the reference frame of the ‘b-tagged top quark’ is shown in figure 7.1.102(b). Both histograms contain events with two jets, one of them tagged as originating from the decay of a b hadron, and one central electron.

The cosine of the angle between jet1 and the HFS in the reference frame of the HFS is shown in figure 7.1.103(a). The slopes of the distributions for signal and background events are different. The signal distribution rises slower and reaches a plateau at 0.5, whereas the background distribution rises up to 0.5 and then starts to fall again. For the cosine of the angle between the leading jet and the charged lepton in the reference frame of the ‘b-tagged top quark’ a significant difference in the shape between signal and background events can be seen in the region between -0.9 and -0.6 (see figure 7.1.73(b)). Here, it is the distribution for the single top quark signal that shows a plateau, whereas the distribution for the background events is already on the falling edge.

The cosine of the angle between the charged lepton and the ‘best top quark’ in the center-of-mass frame of the ‘best top quark’ is shown in figure 7.1.104(a). While the distribution of the background events is rather flat over the whole range, the distribution of the single top quark signal events rises up to -0.7 and then starts falling. Figure 7.1.104(b) displays the difference $\Delta\varphi$ between the charged lepton and the missing transverse energy. While for the background distribution there are many events where the two objects point back-to-back, the distribution for the signal events has its maximum for $\Delta\varphi = 2.0$. Up to this value, the shapes for both the signal and the background distribution are very similar.

The scalar sum of the transverse energies of jets in the event, Ht , is shown in figure 7.1.105(a). The signal events of electroweak top quark production on average have higher values of Ht . While the slope of the falling edge of the distribution is similar for both signal and background events, the background events accumulate at lower values of Ht and their distribution peaks at 70 GeV, approximately 30 GeV lower than the distribution for the signal events.

(a)

(b)

Figure 7.1.103: The cosine of the angle between jet1 and the HFS in the reference frame of the HFS is shown in figure 7.1.103(a). The cosine of the angle between jet1 and the charged lepton in the reference frame of the ‘b-tagged top quark’ is shown in figure 7.1.103(b). Both distributions show events with two jets, one of them tagged as a b-jet and one central electron.

(a)

(b)

Figure 7.1.104: The cosine of the angle between the charged lepton and the ‘best top quark’ in the center-of-mass frame of the best top quark is shown in figure 7.1.104(a). Figure 7.1.104(b) displays the distance $\Delta\varphi$ between the charged lepton and the missing transverse energy in the event. Both distributions contain events with two jets, one of them tagged as a b-jet, and one central electron.

Adding up also the transverse momentum of the charged lepton and the missing transverse energy, the resulting distribution can be found in figure 7.1.105(b). This distribution shows similar

features as the Ht distribution described above.

Figure 7.1.105: The scalar sum of the transverse momenta of the jets, Ht , is shown in figure 7.1.105(a). Adding also the contributions of the charged lepton and the missing transverse energy results in the distribution shown in figure 7.1.105(b). Both histograms show events with two jets, one of them tagged as originating from a b hadron decay, and one central electron.

Summing up the scalar energies instead of the transverse momenta of the jets, H , figure 7.1.106(a) is obtained. The background distribution peaks at a value of 100 GeV, whereas the distribution of signal events peaks at 150 GeV. The variable $\hat{S}$, as introduced in equation 7.1.8, is displayed in figure 7.1.106(b). Again, the maximum of the distribution for the signal events is higher than the maximum of the distribution of the background sum. In this case the difference is approximately 40 GeV, the background maximum is at 180 GeV. The shape of the tail towards higher values of $\hat{S}$ is similar for both distributions.

Figure 7.1.106: The sum over all energies of jets in the event is shown in figure 7.1.106(a), the variable $\hat{S}$ in figure 7.1.106(b). Both distributions contain events with two jets, one of them tagged as a b-jet, and one central electron.

The ‘q times η ’ variable, as introduced in definition 6.2.7, is shown in figure 7.1.107(a). It shows the expected, asymmetric behaviour for the signal events of electroweak top quark production and a symmetric distribution for the background model, making this a good variable for the separation of the two components in the statistical analysis later. The transverse mass of

the W boson (shown in figure 7.1.107(b)) is a variable that can be used to separate the multijet background from the signal. The multijet events can all be found at low values of this variable.

Figure 7.1.107: The ‘q times η ’ variable (figure 7.1.107(a)) and the transverse mass of the W boson (figure 7.1.107(b)) for events with two jets, one b-tagged jet, and one central electron.

The difference in transverse momentum between jet1 and jet2 is shown in figure 7.1.108(a). For both signal and background events, the majority of events is found at a difference lower than 30 GeV. The spatial distance ΔR of the two jets differs between the signal events and the background events for low values of ΔR . In the sample of electroweak top quark events there are almost no events where the two jets are close to one another. The distribution rises up to $\Delta R = 3$ and then starts to fall rapidly.

Figure 7.1.108: The difference in transverse momentum between jet1 and jet2 is shown in figure 7.1.108(a). The spatial difference ΔR in figure 7.1.108(b). Both distributions contain events with two jets, one of them tagged as a b-jet, and one central electron.

Figure 7.1.109(a) shows the transverse momentum distribution for the leading jet in the event. There is a difference of 20 GeV between the maximum of the distribution for background events and the maximum of the distribution of events from electroweak top quark production. The leading jets in the signal events have on average a higher transverse momentum, with the peak of the distribution at 65 GeV. The distribution of the pseudorapidity of jet1 can be seen in figure 7.1.109(b). It is a symmetric distribution around $\eta = 0$ for both the single top quark signal

events and the background model.

Figure 7.1.109: Transverse momentum distribution for the leading jet (figure 7.1.109(a)) and its pseudorapidity η (figure 7.1.109(b)) in events with two jets, one b-tagged jet, and one central electron.

The same properties as for jet1 are shown for jet2 in figure 7.1.110. Its transverse momentum spectrum is presented in figure 7.1.110(a). While the background events have a steep falling spectrum, the spectrum for the single top quark signal events remains flat up to a value of 25 GeV. The shape of the tails towards higher transverse momenta is then similar for both signal and background events. The distribution of the pseudorapidity η of jet2 can be seen in figure 7.1.110(b). It is symmetric around $\eta = 0$ for both signal and background events.

Figure 7.1.110: The transverse momentum distribution for jet2 is shown in figure 7.1.110(a). Its pseudorapidity distribution is shown in figure 7.1.110(b). Both distributions contain events with two jets, one of them tagged as originating from the decay of a b hadron, and one central electron.

The variable SEt , as defined in equation 7.1.9, is shown in figure 7.1.111(a) for this analysis bin. The maximum of the distribution of signal events is at a value of 150 GeV, the maximum for the background events at a value of 120 GeV. The slope of the falling edge of the SEt distribution is the same for both signal and background events. Adding also the information about the missing transverse energy, figure 7.1.111(b) is obtained. This distribution shows the same features as the SEt distribution before.

Figure 7.1.111: Figure 7.1.111(a) shows the SEt distribution for events with two jets, one b-tagged jet, and one central electron. Figure 7.1.111(b) shows the distribution when the missing transverse energy is also taken into account.

The aplanarity A of an event was defined in equation 7.1.14, the sphericity S in equation 7.1.15. The distributions of those event shape variables in this analysis bin are shown in figure 7.1.112(a) and figure 7.1.112(b), respectively. For the aplanarity, both the signal and the background distributions are very similar. However, in the sphericity distribution, the distribution of the single top quark signal events starts to drop earlier, at 0.15.

Figure 7.1.112: The aplanarity A of the events with two jets, one b-tagged jet, and one central electron is shown in figure 7.1.112(a), their sphericity in figure 7.1.112(b).

The distribution of the pseudorapidity of the isolated electron in the event is shown in figure 7.1.113(a). It is symmetric around $\eta = 0$ for both the signal and the background distribution. However, at $\eta = 0$ the background distribution has a small dip that is not present in the simulated events of electroweak top quark production. The missing transverse energy is a good variable to separate the multijet background from the single top quark signal events. But also the total background distribution prefers smaller values of missing transverse energy and drops earlier than the signal distribution.

Events with two jets, two b-tagged jets, and one electron

The analysis bin with two jets, both tagged as originating from a b hadron decay, missing

Figure 7.1.113: The pseudorapidity η of the isolated electron in the event is shown in figure 7.1.113(a). The missing transverse energy distribution for this analysis bin with one electron, two jets, and one b-tagged jet can be seen in figure 7.1.113(b).

transverse energy and one isolated electron suffers from low statistics due to the requirement that both jets should be b-tagged. This requirement removes most of the W +jets and the multijet background. The remaining dominant backgrounds are $Wb\bar{b}$ production and top quark pair production in the dilepton channel. Variables used in the multivariate analysis are shown in figures 7.1.114 to 7.1.127. In spite of the low statistic, these variables agree well in the comparison of simulated background events and observed data events and can thus be used in the Boosted Decision Tree analysis.

Figure 7.1.114 shows the angle between the HFS and the charged lepton (figure 7.1.114(a)) and the angle between the charged lepton and the leading jet (figure 7.1.114(b)). The angles were calculated after boosting the HFS, jet1 and the charged lepton into the center-of-mass reference frame. In both cases the signal distribution peaks at lower angles, whereas the background events accumulate at higher angles. While the background distribution in the first angle is still rising, the distribution of the signal events reaches its maximum at 2.45 rad and then starts to fall for higher angles. The scenario is even enhanced for the angle between the electron and the leading jet. Here, the distribution for the single top quark signal events already peaks at 2.1 rad.

The mass of the HFS and its transverse momentum are shown in figure 7.1.115(a) and figure 7.1.115(b), respectively. Especially the remaining events of the $Wb\bar{b}$ background are reconstructed at low HFS masses. The shapes of the background from top quark pair production and from the signal events are similar. In the transverse momentum distribution, the shape of the single top quark signal events and the background events resemble.

The mass of the ‘best top quark’ according to definition 6.2.5 is shown in figure 7.1.116(a), the mass of the ‘b-tagged top quark’ as defined in definition 6.2.6 in figure 7.1.116(b). For the ‘best top quark’ mass, the distribution of the signal events shows a nice peak at 175 GeV. The sum of all backgrounds also peaks at 175 GeV, but shows a much broader distribution. For the mass of the ‘b-tagged top quark’ the maximum of the distribution for the single top quark signal events is also at 175 GeV, but with a long tail towards higher mass values. The distribution of

Figure 7.1.114: Angle between the HFS and the leading jet (figure 7.1.114(a)) and angle between the isolated electron and the leading jet (figure 7.1.114(b)) when all particles are boosted into the center-of-mass frame of the event. The distributions contain events with two jets, both tagged as b-jets, and one electron.

Figure 7.1.115: Mass and transverse momentum of the HFS are shown in figure 7.1.115(a) and figure 7.1.115(b) for events with two b-tagged jets and one isolated electron.

the background component of top quark pair production seems shifted towards higher values. The overall background shape is very broad and rather flat for masses between 120 GeV and 210 GeV.

The transverse momentum distribution of the ‘best jet’ in the events, according to definition 6.2.3, is shown in figure 7.1.117(a). The majority of $Wb\bar{b}$ and multijet events can be found at low transverse momenta, with a maximum of the total background distribution at 35 GeV. The distribution of the signal events of electroweak top quark production peaks at 60 GeV. That the ‘best jet’ and the leading b-tagged are not always the same of the two b-jets in the event can be seen by comparing the distribution of the transverse momentum of the ‘best jet’ with the distribution of the transverse momentum of the leading b-tagged jet in figure 7.1.117(b). The distribution for the leading b-tagged jet has a much longer tail. The spectrum for the jets from top quark pair production in the dilepton channel is harder than the spectrum of electroweak top quark production, because there, both b-jets come from the decay of a heavy top quark.

The cosine of the angle between the ‘best jet’ and the isolated electron in the reference frame of the ‘best top quark’ is shown in figure 7.1.118(a). The main difference between the signal

Figure 7.1.116: Mass of the ‘best top quark’ (figure 7.1.116(a)) and the ‘b-tagged top quark’ (figure 7.1.116(b)) for events with two b-tagged jets, and one isolated electron.

Figure 7.1.117: Transverse momentum of the ‘best jet’ in the event (figure 7.1.117(a)) and transverse momentum of the leading b-tagged jet in the event (figure 7.1.117(b)) for events with two b-jets, and one isolated electron.

and the background distribution can be found between -0.9 and -0.7 , where the background distribution is already on its falling edge, while the signal distribution still rises. The cosine of the angle between the leading jet and the HFS in the reference frame of the HFS can be seen in figure 7.1.118(b) and shows a smaller slope for the rising edge of the distribution for the signal events of electroweak top quark production.

Figure 7.1.119(a) displays the cosine of the angle between the electron and the ‘best top quark’ in the center-of-mass frame of the ‘best top quark’. The background distribution is flat in this variable, but the distribution of the single top quark signal events is rising up to -0.6 and then steadily falling. The difference $\Delta\varphi$ between the electron and the missing transverse energy can be seen in figure 7.1.119(b). While the background distribution rises up to 2.8, the distribution for the signal events reaches its maximum already at 2.0 and then turns into a falling distribution.

The Ht variable, the scalar sum of the transverse energies of the two jets, is shown in figure 7.1.120(a). Most of the events from $Wb\bar{b}$ production appear at low values of Ht , whereas events from top quark pair production in the dilepton channel can be found at higher Ht values.

Figure 7.1.118: The cosine of the angle between the ‘best jet’ and the isolated electron in the reference frame of the ‘best top quark’ is shown in figure 7.1.118(a). The cosine of the angle between jet1 and the HFS in the reference frame of the HFS is shown in figure 7.1.118(b). Both distributions contain events with two b-jets, and one isolated electron.

Figure 7.1.119: Figure 7.1.119(a) displays the cosine of the angle between the lepton and the ‘best top quark’ in the center-of-mass frame of the ‘best top quark’. In figure 7.1.119(b) the difference $\Delta\varphi$ between the electron and the reconstructed missing transverse energy is shown. Both distributions contain events with two b-tagged jets and one central, isolated electron.

The signal distribution peaks at 90 GeV and shows a flatter falling edge than the sum of the backgrounds towards higher values of Ht . Adding also the transverse momentum of the electron and the missing transverse energy, figure 7.1.120(b) is obtained. The accumulation of top quark pair events at high values is even more prominent there. This is because of the at least two neutrinos that contribute to the missing transverse energy. The $Wb\bar{b}$ events can again be found at lower values, and the expected signal distribution is in the middle of the two background components, with a maximum at 200 GeV.

By adding up the scalar energies of the jets instead of their transverse momenta, the variable H is calculated and the distribution shown in figure 7.1.121(a) is obtained. The distributions for the single top quark signal sample and the events from top quark pair production are very similar. But, the background from $Wb\bar{b}$ production accumulates at low values of H . $\hat{S}$, a variable described in equation 7.1.8, is displayed in figure 7.1.121(b). The events from top

Figure 7.1.120: Figure 7.1.120(a) shows the scalar sum of the transverse momenta of the two jets in the event. Figure 7.1.120(b) takes also the transverse momentum of the electron and the missing transverse energy into account. Both distributions show events with two b-tagged jets, and one isolated electron.

quark pair production have on average the highest value in this variable, followed by the signal events of electroweak top quark production and the events from the production of W bosons with jets. In figure 7.1.121(c) the transverse mass of the W boson is shown. Comparing the signal distribution with the total background distribution, they look similar. However, the individual contribution of the background from top quark pair production is very broad. The reason for this is again that these events contain at least two neutrinos that contribute to the missing transverse energy.

Figure 7.1.121: Figure 7.1.121(a) shows the variable H for all jets in the events. Variable $\hat{S}$ is shown in figure 7.1.121(b). The transverse mass of the W boson is displayed in figure 7.1.121(c). All distributions contain events with two jets that were tagged as originating from the decay of a b hadron and an isolated electron.

The difference in transverse momentum between jet1 and jet2 is shown in figure 7.1.122(a). The shape of the signal distribution is flat up to a difference of 15 GeV and then starts to drop. This decline is slower than for the combined backgrounds. The spatial distance ΔR of the two jets in the event is shown in figure 7.1.122(b). There is a significant difference between the background model and the simulated signal events for values of $\Delta R < 2.3$. There are almost no jet pairs in the signal events that are close in ΔR , whereas there is a flat distribution for the background events in this region. The ΔR distribution for signal events rises up to a value of

$\Delta R = 3$.

Figure 7.1.122: The difference in transverse momentum between jet1 and jet2 is shown in figure 7.1.122(a). The spatial difference ΔR of the two jets can be seen in figure 7.1.122(b). Both distributions contain events with b-tagged jets, and one isolated electron.

The transverse momentum distribution of the leading jet can be seen in figure 7.1.123(a). The background distribution is dominated in the region of low transverse momentum from jets from the W boson production, the region of high transverse momentum from the production of top quark pair events. The signal events' transverse momentum distribution peaks in the middle between the two beforementioned components, at 65 GeV. The distribution of the pseudorapidity of jet1 is shown in figure 7.1.123(b). It is symmetrical around $\eta = 0$. The majority of the jets can be found in the central region of the detector, i.e. $|\eta| < 1.0$.

Figure 7.1.123: The transverse momentum distribution of jet1 is shown in figure 7.1.123(a). Figure 7.1.123(b) shows the pseudorapidity distribution of the leading jet. Both histograms show events with two b-tagged jets, and one isolated electron.

The transverse momentum distribution for jet2 is similar for the background from top quark pair production and for the signal events of electroweak top quark production. These have a long tail towards higher transverse momenta and peak at 40 GeV. Events from $Wb\bar{b}$ production are found at lower transverse momentum values, showing a steeply falling spectrum. The pseudorapidity distribution in figure 7.1.124(b) is symmetric around $\eta = 0$ for all contributing processes.

Figure 7.1.124: Transverse momentum distribution of the second leading jet (figure 7.1.124(a)) and their pseudorapidity distribution (figure 7.1.124(b)) for events with two b-jets, and one isolated electron.

The scalar sum over the transverse energies of the jets and the electron, SEt , is shown in figure 7.1.125(a). The distribution for the electroweak production of single top quarks peaks at 150 GeV, the one for the background from top quark pair production at 190 GeV and the distribution for the production of a W boson with jets has its maximum already at 100 GeV. Taking also the missing transverse energy into account, the distribution shown in figure 7.1.125(b) is obtained. The difference between the different physics processes is even more distinct there, because of the additional neutrino that contributes to the background of top quark pair production, that is dominated from the dilepton channel.

Figure 7.1.125: The sum over the transverse energies of the jets and the electron is shown in figure 7.1.125(a). Taking also the missing transverse energy into account, the distribution shown in figure 7.1.125(b) is obtained. Both histograms show events with two b-jets, and one isolated central electron.

The event shape variables aplanarity A and sphericity S were introduced in equations 7.1.14 and 7.1.15. The resulting distributions in this analysis bin are shown for aplanarity in figure 7.1.126(a) and for sphericity in figure 7.1.126(b). For aplanarity, the distributions of signal and background processes are very similar. In the sphericity distribution, there is a small difference. The signal distribution rises up to a value of 0.18, whereas the background distribution has its maximum already at 0.13.

Figure 7.1.126: The event shape variables aplanarity (figure 7.1.126(a)) and sphericity (figure 7.1.126(b)) are shown for events with two jets, both of them tagged as originating from the decay of a b hadron, and one central electron.

The pseudorapidity distribution of the isolated electron is shown in figure 7.1.127(a). It is symmetric around $\eta = 0$ for all contributing physics processes. The missing transverse momentum distribution in figure 7.1.127(b) shows the events from the multijet background at low values, and the events from top quark pair production as the dominant background at high missing transverse energies. The signal distribution has a short rising edge, a peak at 40 GeV and a long falling distribution towards higher values of missing transverse energies.

Figure 7.1.127: The pseudorapidity distribution of the isolated electron is shown in figure 7.1.127(a), the distribution of the missing transverse energy for events with two b -tagged jets and one isolated electron is shown in figure 7.1.127(b).

7.1.5 Summary of Observables for Events with Two Jets

A summary of the variables used in the statistical analysis for the four different analysis bins can be found in the following tables:

- For the muon analysis with one b-tagged jet, the variables can be found in table 7.1.8 on page 207 and table 7.1.9 on page 208.
- For the muon analysis with two b-tagged jets, the variables can be found in table 7.1.10 on page 209 and table 7.1.11 on page 210.
- For the electron analysis with one b-tagged jet, the variables can be found in table 7.1.12 on page 211 and table 7.1.13 on page 212.
- For the electron analysis with two b-tagged jets, the variables can be found in table 7.1.14 on page 213 and table 7.1.15 on page 214.

The discriminant output distributions for the Boosted Decision Tree configuration that is finally used in the analysis are presented on page 414 for the muon channel. Figure 9.1.1(c) shows the distribution for events with two reconstructed jets and one b-tag. The distribution for events with two jets and two b-tags is shown in figure 9.1.1(d). The discriminant output distributions for the two electron channel analysis bins with two reconstructed jets are shown in figures 9.1.2(c) (events with one b-tag) and 9.1.2(d) (events with two b-tags) on page 415.

Variable	Figure
Variables from the reconstruction of the s-channel single top PPT (see figure 7.1.1)	
Mass of the reconstructed top quark	7.1.6(a)
Transverse momentum of the reconstructed top quark	7.1.6(b)
Pseudorapidity η of the reconstructed top quark	7.1.6(c)
Transverse momentum of b(lept)	7.1.7(a)
Pseudorapidity η of b(lept)	7.1.7(b)
Transverse momentum of b(prod)	7.1.8(a)
Pseudorapidity η of b(prod)	7.1.8(b)
ΔR between b(prod) and b(lept)	7.1.9(a)
Transverse momentum of the reconstructed W boson	7.1.9(b)
Likelihood measure	7.1.9(c)
Variables from the reconstruction of the t-channel single top PPT (see figure 7.1.22)	
Mass of the reconstructed top quark	7.1.28(a)
Transverse momentum of the reconstructed top quark	7.1.28(b)
Pseudorapidity η of the reconstructed top quark	7.1.28(c)
Transverse momentum of b(lept)	7.1.29(a)
Pseudorapidity η of b(lept)	7.1.29(b)
Pseudorapidity η of q(scst)	7.1.30(a)
Charge of lepton times pseudorapidity η of q(scst)	7.1.30(b)
Transverse momentum of the reconstructed W boson	7.1.31(a)
Likelihood measure	7.1.31(b)
Variables from the reconstruction of the dilepton top quark pair decay PPT (see figure 7.1.44)	
Mass of the reconstructed top quark	7.1.55(a)
Transverse momentum of the reconstructed top quark	7.1.55(b)
Transverse momentum of b(found)	7.1.56(a)
Pseudorapidity η of b(found)	7.1.56(b)
Transverse momentum of b(lost)	7.1.57(a)
Pseudorapidity η of W(found)	7.1.57(b)

Table 7.1.8: Observables gained by the reconstruction of Parton Picture Templates and used as input for the Boosted Decision Tree analysis for events with two jets, one jet tagged as originating from a b hadron decay and one muon.

Variable	Figure
Event shape variables and variables from the reconstruction of PPT (see figure 7.1.67)	
Angle between HFS and lepton in center-of-mass reference frame	7.1.68(a)
Angle between lepton and jet1 in center-of-mass reference frame	7.1.68(b)
Mass of HFS	7.1.69(a)
Transverse momentum of HFS	7.1.69(b)
Best top mass	7.1.70(a)
B-tagged top mass	7.1.70(b)
Transverse momentum of the best jet	7.1.71(a)
Transverse momentum of the leading b-tagged jet	7.1.71(b)
Cosine of angle between best jet and lepton in best top reference frame	7.1.72(a)
Cosine of the angle between the b-tagged jet and the charged lepton measured in the b-tagged top quark rest frame	7.1.72(b)
Cosine of angle between jet1 and the HFS in the HFS rest frame	7.1.73(a)
Cosine of the angle between the lepton and jet1 in the b-tagged top reference frame	7.1.73(b)
Cosine of the angle between the lepton in the best top reference frame and the best top in the center-of-mass frame	7.1.74(a)
$\Delta\varphi$ between the charged lepton and the missing transverse energy	7.1.74(b)
Ht of all jets	7.1.75(a)
Ht of jet1, jet2, the lepton and the missing transverse energy	7.1.75(b)
H of all jets	7.1.76(a)
$\hat{S}$	7.1.76(b)
Lepton charge times pseudorapidity of the leading untagged jet	7.1.77(a)
Transverse mass of the W boson	7.1.77(b)
Difference of transverse momenta of jet1 and jet2	7.1.78(a)
ΔR between jet1 and jet2	7.1.78(b)
Transverse momentum of jet1	7.1.79(a)
Pseudorapidity η of jet1	7.1.79(b)
Transverse momentum of jet2	7.1.80(a)
Pseudorapidity η of jet2	7.1.80(b)
SEt of all reconstructed objects	7.1.81(a)
Ht of all reconstructed objects	7.1.81(b)
Aplanarity of all reconstructed objects	7.1.82(a)
Sphericity of all reconstructed objects	7.1.82(b)
Pseudorapidity η of the charged lepton	7.1.83(a)
Missing transverse energy	7.1.83(b)

Table 7.1.9: Event shape observables used as input for the Boosted Decision Tree analysis for events with two jets, one jet tagged as originating from a b hadron decay, and one muon.

Variable	Figure
Variables from the reconstruction of the s-channel single top PPT (see figure 7.1.1)	
Mass of the reconstructed top quark	7.1.10(a)
Transverse momentum of the reconstructed top quark	7.1.10(b)
Pseudorapidity η of the reconstructed top quark	7.1.10(c)
Transverse momentum of b(lept)	7.1.11(a)
Pseudorapidity η of b(lept)	7.1.11(b)
Transverse momentum of b(prod)	7.1.12(a)
Pseudorapidity η of b(prod)	7.1.12(b)
ΔR between b(prod) and b(lept)	7.1.13(a)
Transverse momentum of the reconstructed W boson	7.1.13(b)
Likelihood measure	7.1.13(c)
Variables from the reconstruction of the t-channel single top PPT (see figure 7.1.22)	
Mass of the reconstructed top quark	7.1.32(a)
Transverse momentum of the reconstructed top quark	7.1.32(b)
Pseudorapidity η of the reconstructed top quark	7.1.32(c)
Transverse momentum of b(lept)	7.1.33(a)
Pseudorapidity η of b(lept)	7.1.33(b)
Pseudorapidity η of q(scst)	7.1.34(a)
Charge of lepton times pseudorapidity η of q(scst)	7.1.34(b)
Transverse momentum of the reconstructed W boson	7.1.35(a)
Likelihood measure	7.1.35(b)
Variables from the reconstruction of the dilepton top quark pair decay PPT (see figure 7.1.44)	
Mass of the reconstructed top quark	7.1.58(a)
Transverse momentum of the reconstructed top quark	7.1.58(b)
Transverse momentum of b(lost)	7.1.59(a)
Pseudorapidity η of b(lost)	7.1.59(b)
Transverse momentum of b(found)	7.1.60(a)
Pseudorapidity η of W(found)	7.1.60(b)

Table 7.1.10: Observables gained by the reconstruction of events according to Parton Picture Templates and used as input for the Boosted Decision Tree analysis for events with two jets, both jets tagged as originating from a b hadron decay, and one muon.

Variable	Figure
Event shape variables and variables from the reconstruction of PPT (see figure 7.1.67)	
Angle between HFS and lepton in center-of-mass reference frame	7.1.84(a)
Angle between lepton and jet1 in center-of-mass reference frame	7.1.84(b)
Mass of HFS	7.1.85(a)
Transverse momentum of HFS	7.1.85(b)
Best top mass	7.1.86(a)
B-tagged top mass	7.1.86(b)
Transverse momentum of the best jet	7.1.87(a)
Transverse momentum of the leading b-tagged jet	7.1.87(b)
Cosine of angle between best jet and lepton in best top reference frame	7.1.88(a)
Cosine of angle between jet1 and the HFS in the HFS rest frame	7.1.88(b)
Cosine of the angle between the lepton in the best top reference frame and the best top in the center-of-mass frame	7.1.89(a)
$\Delta\varphi$ between the charged lepton and the missing transverse energy	7.1.89(b)
Ht of all jets	7.1.90(a)
Ht of jet1, jet2, the lepton and the missing transverse energy	7.1.90(b)
H of all jets	7.1.91(a)
$\hat{S}$	7.1.91(b)
Transverse mass of the W boson	7.1.91(c)
Difference of transverse momenta of jet1 and jet2	7.1.92(a)
ΔR between jet1 and jet2	7.1.92(b)
Transverse momentum of jet1	7.1.93(a)
Pseudorapidity η of jet1	7.1.93(b)
Transverse momentum of jet2	7.1.94(a)
Pseudorapidity η of jet2	7.1.94(b)
SEt of all reconstructed objects	7.1.95(a)
Ht of all reconstructed objects	7.1.95(b)
Aplanarity of all reconstructed objects	7.1.96(a)
Sphericity of all reconstructed objects	7.1.96(b)
Pseudorapidity η of the charged lepton	7.1.97(a)
Missing transverse energy	7.1.97(b)

Table 7.1.11: Event shape observables used as input for the Boosted Decision Tree analysis for events with two jets, both jets tagged as originating from a b hadron decay and one muon.

Variable	Figure
Variables from the reconstruction of the s-channel single top PPT (see figure 7.1.1)	
Mass of the reconstructed top quark	7.1.14(a)
Transverse momentum of the reconstructed top quark	7.1.14(b)
Pseudorapidity η of the reconstructed top quark	7.1.14(c)
Transverse momentum of b(lept)	7.1.15(a)
Pseudorapidity η of b(lept)	7.1.15(b)
Transverse momentum of b(prod)	7.1.16(a)
Pseudorapidity η of b(prod)	7.1.16(b)
ΔR between b(prod) and b(lept)	7.1.17(a)
Transverse momentum of the reconstructed W boson	7.1.17(b)
Likelihood measure	7.1.17(c)
Variables from the reconstruction of the t-channel single top PPT (see figure 7.1.22)	
Mass of the reconstructed top quark	7.1.36(a)
Transverse momentum of the reconstructed top quark	7.1.36(b)
Pseudorapidity η of the reconstructed top quark	7.1.36(c)
Transverse momentum of b(lept)	7.1.37(a)
Pseudorapidity η of b(lept)	7.1.37(b)
Pseudorapidity η of q(scst)	7.1.38(a)
Charge of lepton times pseudorapidity η of q(scst)	7.1.38(b)
Transverse momentum of the reconstructed W boson	7.1.39(a)
Likelihood measure	7.1.39(b)
Variables from the reconstruction of the dilepton top quark pair decay PPT (see figure 7.1.44)	
Mass of the reconstructed top quark	7.1.61(a)
Transverse momentum of the reconstructed top quark	7.1.61(b)
Transverse momentum of b(found)	7.1.62(a)
Pseudorapidity η of b(found)	7.1.62(b)
Transverse momentum of b(lost)	7.1.63(a)
Pseudorapidity η of W(found)	7.1.63(b)

Table 7.1.12: Observables gained by the reconstruction of Parton Picture Templates and used as input for the Boosted Decision Tree analysis for events with two jets, one jet tagged as originating from a b hadron decay, and one electron.

Variable	Figure
Event shape variables and variables from the reconstruction of PPT (see figure 7.1.67)	
Angle between HFS and lepton in center-of-mass reference frame	7.1.98(a)
Angle between lepton and jet1 in center-of-mass reference frame	7.1.98(b)
Mass of HFS	7.1.99(a)
Transverse momentum of HFS	7.1.99(b)
Best top mass	7.1.100(a)
B-tagged top mass	7.1.100(b)
Transverse momentum of the best jet	7.1.101(a)
Transverse momentum of the leading b-tagged jet	7.1.101(b)
Cosine of angle between best jet and lepton in best top reference frame	7.1.102(a)
Cosine of the angle between the b-tagged jet and the lepton measured in the b-tagged top quarks rest frame	7.1.102(b)
Cosine of angle between jet1 and the HFS in the HFS rest frame	7.1.103(a)
Cosine of the angle between the lepton and jet1 in the b-tagged top reference frame	7.1.103(b)
Cosine of the angle between the lepton in the best top reference frame and the best top in the center-of-mass frame	7.1.104(a)
$\Delta\varphi$ between the charged lepton and the missing transverse energy	7.1.104(b)
Ht of all jets	7.1.105(a)
Ht of jet1, jet2, the lepton and the missing transverse energy	7.1.105(b)
H of all jets	7.1.106(a)
$\hat{S}$	7.1.106(b)
Lepton charge times pseudorapidity of the leading untagged jet	7.1.107(a)
Transverse mass of the W boson	7.1.107(b)
Difference of transverse momenta of jet1 and jet2	7.1.108(a)
ΔR between jet1 and jet2	7.1.108(b)
Transverse momentum of jet1	7.1.109(a)
Pseudorapidity η of jet1	7.1.109(b)
Transverse momentum of jet2	7.1.110(a)
Pseudorapidity η of jet2	7.1.110(b)
SEt of all reconstructed objects	7.1.111(a)
Ht of all reconstructed objects	7.1.111(b)
Aplanarity of all reconstructed objects	7.1.112(a)
Sphericity of all reconstructed objects	7.1.112(b)
Pseudorapidity η of the charged lepton	7.1.113(a)
Missing transverse energy	7.1.113(b)

Table 7.1.13: Event shape observables used as input for the Boosted Decision Tree analysis for events with two jets, one jet tagged as originating from a b hadron decay, and one electron.

Variable	Figure
Variables from the reconstruction of the s-channel single top PPT (see figure 7.1.1)	
Mass of the reconstructed top quark	7.1.18(a)
Transverse momentum of the reconstructed top quark	7.1.18(b)
Pseudorapidity η of the reconstructed top quark	7.1.18(c)
Transverse momentum of b(lept)	7.1.19(a)
Pseudorapidity η of b(lept)	7.1.19(b)
Transverse momentum of b(prod)	7.1.20(a)
Pseudorapidity η of b(prod)	7.1.20(b)
ΔR between b(prod) and b(lept)	7.1.21(a)
Transverse momentum of the reconstructed W boson	7.1.21(b)
Likelihood measure	7.1.21(c)
Variables from the reconstruction of the t-channel single top PPT (see figure 7.1.22)	
Mass of the reconstructed top quark	7.1.40(a)
Transverse momentum of the reconstructed top quark	7.1.40(b)
Pseudorapidity η of the reconstructed top quark	7.1.40(c)
Transverse momentum of b(lept)	7.1.41(a)
Pseudorapidity η of b(lept)	7.1.41(b)
Pseudorapidity η of q(scst)	7.1.42(a)
Charge of lepton times pseudorapidity η of q(scst)	7.1.42(b)
Transverse momentum of the reconstructed W boson	7.1.43(a)
Likelihood measure	7.1.43(b)
Variables from the reconstruction of the dilepton top quark pair decay PPT (see figure 7.1.44)	
Mass of the reconstructed top quark	7.1.64(a)
Transverse momentum of the reconstructed top quark	7.1.64(b)
Transverse momentum of b(lost)	7.1.65(a)
Pseudorapidity η of b(lost)	7.1.65(b)
Transverse momentum of b(found)	7.1.66(a)
Pseudorapidity η of W(found)	7.1.66(b)

Table 7.1.14: Observables gained by the reconstruction of Parton Picture Templates and used as input for the Boosted Decision Tree analysis for events with two jets, both jets tagged as originating from a b hadron decay, and one electron.

Variable	Figure
Event shape variables and variables from the reconstruction of PPT (see figure 7.1.67)	
Angle between HFS and lepton in center-of-mass reference frame	7.1.114(a)
Angle between lepton and jet1 in center-of-mass reference frame	7.1.114(b)
Mass of HFS	7.1.115(a)
Transverse momentum of HFS	7.1.115(b)
Best top mass	7.1.116(a)
B-tagged top mass	7.1.116(b)
Transverse momentum of the best jet	7.1.117(a)
Transverse momentum of the leading b-tagged jet	7.1.117(b)
Cosine of angle between best jet and lepton in best top reference frame	7.1.118(a)
Cosine of angle between jet1 and the HFS in the HFS rest frame	7.1.118(b)
Cosine of the angle between the lepton in the best top reference frame and the best top in the center-of-mass frame	7.1.119(a)
$\Delta\varphi$ between the charged lepton and the missing transverse energy	7.1.119(b)
Ht of all jets	7.1.120(a)
Ht of jet1, jet2, the lepton and the missing transverse energy	7.1.120(b)
H of all jets	7.1.121(a)
$\hat{S}$	7.1.121(b)
Transverse mass of the W boson	7.1.121(c)
Difference of transverse momenta of jet1 and jet2	7.1.122(a)
ΔR between jet1 and jet2	7.1.122(b)
Transverse momentum of jet1	7.1.123(a)
Pseudorapidity η of jet1	7.1.123(b)
Transverse momentum of jet2	7.1.124(a)
Pseudorapidity η of jet2	7.1.124(b)
SEt of all reconstructed objects	7.1.125(a)
Ht of all reconstructed objects	7.1.125(b)
Aplanarity of all reconstructed objects	7.1.126(a)
Sphericity of all reconstructed objects	7.1.126(b)
Pseudorapidity η of the charged lepton	7.1.127(a)
Missing transverse energy	7.1.127(b)

Table 7.1.15: Event shape observables used as input for the Boosted Decision Tree analysis for events with two jets, both jets tagged as originating from a b hadron decay, and one electron.

7.2 Processes for Events with Three Jets

After the analysis bin with two reconstructed jets, the one with three reconstructed jets per event is the second most sensitive one in the search for electroweak top quark production. Five different Parton Picture Templates are reconstructed in the ProcessFactory for events with three jets. Two Parton Picture Templates refer to the signal processes: s-channel production of single top quarks (see section 7.2.1) and t-channel production of single top quarks (see section 7.2.2). Two PaxProcesses are used in the ProcessFactory to reconstruct Parton Picture Templates for the background processes emerging from top quark pair production. Section 7.2.3 deals with the reconstruction of semileptonic top quark-antitop quark events and actually reconstructs two different Parton Picture Templates. The dilepton channel of top quark pair production is analyzed in section 7.2.4. The main background, the production of W bosons associated by jets, and event shape variables are treated in section 7.2.5. A summary of the variables that result from these PaxProcesses which are used in the statistical analysis with Boosted Decision Trees can then be found in section 7.2.6.

7.2.1 s-Channel Production of Top Quarks

In events with three jets there is one additional jet compared to the leading order Feynman diagram of s-channel production of single top quarks. This additional jet can originate from initial or final state radiation or from other scattering processes taking part during the same bunch crossing. The Parton Picture Template that is reconstructed for s-channel production of single top quarks in events with three jets can be found in figure 7.2.1. The reconstructed top quark named $t(\text{lept})$ decays into a W boson named $W(\text{lept})$ that subsequently decays into a charged lepton and a neutrino and a b quark, labeled $b(\text{lept})$. The supplement ‘lept’ in the name of the partons indicates the leptonic decay of the W boson. The second b quark is labeled $b(\text{prod})$ and is also connected to the primary vertex. Here, the supplement ‘prod’ indicates the origin of this parton from the electroweak production process. The parton representing the additional jet is named $q(\text{scat})$ and is connected to the primary vertex. The vector sum of the partons connected to the primary vertex results in a new parton named CM. It represents the center-of-mass system of the interaction.

7.2.1.1 Ambiguity Resolution

There are twelve possible configurations in the assignment of reconstructed objects to the partons for this Parton Picture Template. All configurations are evaluated in a likelihood method in the later analysis step. The input variables to this likelihood method come from studies where parton information from the generator level is matched to reconstructed objects after simulation, resulting in the best possible configuration. To ensure that the resulting distributions for s-channel single top quark production are not affected by initial state or final state radiation, a quality cut on $\Sigma\Delta R$, the sum over the distances between the reconstructed objects and the generated parton they are matched to, is applied. Only quantities of the 68% best matched events are taken into account. Studying the muon and the electron channel independently, two different

Figure 7.2.1: This is the Parton Picture Template for s-channel electroweak top quark production for events with three jets, one charged lepton and missing transverse energy. The top quark $t(\text{lept})$ decays into a W boson named $W(\text{lept})$ and a b quark named $b(\text{lept})$. The supplement ‘lept’ indicates the leptonic decay of the W boson into a charged lepton and a neutrino in the top quark decay chain. The second b quark is named $b(\text{prod})$ and originates from the production of the top quark at the W-t-b-vertex. The additional jet in the event compared to the leading order Feynman diagram is labeled $q(\text{scat})$ in this Parton Picture Template. The top quark $t(\text{lept})$, the b quark $b(\text{prod})$ and the jet $q(\text{scat})$ are connected to the primary vertex and the vector sum of these partons is another parton named CM, indicating the center-of-mass system of the interaction.

68% matching quality cut for	
muons	electrons
0.42	0.41

Table 7.2.1: 68% matching quality cut in $\Sigma\Delta R$ for muon and electron s-channel single top events with three jets.

cutoff values are obtained. For the muon channel all matched events with $\Sigma\Delta R < 0.42$ are considered in the likelihood method, for the electron channel all matched events with $\Sigma\Delta R < 0.41$ are considered. The cutoff values in $\Sigma\Delta R$ are summarized in table 7.2.1 and visualized in figure 7.2.2(a) for the muon channel and in figure 7.2.2(b) for the electron channel.

Five variables are used in the likelihood method to resolve the ambiguities that arise from the matching of reconstructed objects to the partons in the Parton Picture Template. Two of them use quantities of the jets matched to the parton $b(\text{lept})$. Figure 7.2.3(a) shows the probability distribution of a jet matched to the parton $b(\text{lept})$ to be tagged as originating from a b hadron for the s-channel single top events in the muon channel. The distribution for the electron channel can be found in figure 7.2.3(b). Both distributions show a 50% chance that the jet assigned to the parton $b(\text{lept})$ is tagged as a b-jet. This value reflects the efficiency of the algorithm used for the identification of jets that originate from b hadrons.

Besides the probability to be b-tagged, also the transverse momentum distributions for the jets matched to the parton $b(\text{lept})$ are used in the likelihood method. Both the distribution for

Figure 7.2.2: 68% cutoff value for the matching quality $\Sigma\Delta R$ between generated partons and reconstructed objects for muon 7.2.2(a) and electron 7.2.2(b) events in the s-channel single top quark sample. Only quantities of events with good matching quality (grey area) are used as input to the likelihood method that is used to resolve the ambiguities in the jet-parton-assignment.

Figure 7.2.3: Input distributions for the likelihood method to resolve ambiguities in the s-channel Parton Picture Template for events with three jets and one charged lepton. Figure 7.2.3(a) shows the probability of the jet matched to the parton b(lept) to be tagged as originating from a b hadron for the muon channel, figure 7.2.3(b) displays the same quantity for the electron channel.

the muon channel (see figure 7.2.4(a)) and the distribution for the electron channel shown in figure 7.2.4(b) reach their maximum at 60 GeV, a value that is expected for a b-tagged jet from the top quark decay.

The same two quantities as for jets matched to the parton b(lept) are considered in the likelihood method for jets matched to the parton q(scst). Here, the probability to be tagged as originating from a b hadron is very low. This can be seen in figure 7.2.5(a) for the muon channel and in figure 7.2.5(b) for the analysis in the electron channel. The low probability supports the assumption that these jets come from initial or final state radiation, and are thus jets originating from light quarks.

The transverse momentum spectrum for the jets matched to the parton q(scst) is very soft, as can be seen in figure 7.2.6(a) for the analysis in the muon channel and in figure 7.2.6(b) in the

Figure 7.2.4: Input distributions for the likelihood method to resolve ambiguities in the s-channel Parton Picture Template for events with three jets and one charged lepton. The transverse momentum distribution for the jets matched to the parton b(lept) is shown in figure 7.2.4(a) for the muon analysis and in figure 7.2.4(b) for the electron analysis.

Figure 7.2.5: Input distributions for the likelihood method to resolve ambiguities in the s-channel Parton Picture Template for events with three jets and one charged lepton. Figure 7.2.5(a) shows the probability of the jet matched to the parton q(scst) to be tagged as originating from a b hadron for the muon channel, figure 7.2.5(b) displays the same quantity for the electron channel.

electron channel. It reaches its maximum at 20 GeV and falls steeply towards higher transverse momenta. From the comparison of this spectrum with the spectrum shown in figure 7.2.4 for jets matched to the parton b(lept), it is evident that these variables can be useful to distinguish between correct and wrong jet-parton-assignments in the analysis.

The cosine of the angle between the W boson boosted to the rest frame of the top quark and the lepton boosted to the rest frame of the W boson is a handle to choose the correct solution for the z component of the neutrino momentum. This distribution is shown in figure 7.2.7(a) for the muon channel and in figure 7.2.7(b) for the electron channel.

The efficiency of the likelihood method is determined by comparing the configuration with the highest likelihood value with the configuration obtained from the matching of the reconstructed objects with the partons from the generator. The efficiencies ϵ_{68} and ϵ_{100} , as described

Figure 7.2.6: Input distributions for the likelihood method to resolve ambiguities in the s-channel Parton Picture Template for events with three jets and one charged lepton. The transverse momentum distribution for the jets matched to the parton $q(\text{scat})$ is shown in figure 7.2.6(a) for the muon analysis and in figure 7.2.6(b) for the electron analysis.

Figure 7.2.7: Input distributions for the likelihood method to resolve ambiguities in the s-channel Parton Picture Template for events with three jets and one charged lepton. Cosine of the angle between the W boson, boosted to the top quark rest frame, and the charged lepton, boosted to the W boson rest frame for muon events (figure 7.2.7(a)) and for electron events (figure 7.2.7(b)).

in definition 6.2.1, are summarized in table 7.2.2 for the muon channel analysis and the electron channel analysis. The probability to assign the correct combination by chance is 16.7%. The measured efficiencies are all above 40%, ϵ_{68} in the muon channel is even above 50%.

	muon channel	electron channel
$\epsilon_{68}[\%]$	52.0	46.5
$\epsilon_{100}[\%]$	47.4	43.2

Table 7.2.2: Efficiencies ϵ_{68} and ϵ_{100} of the likelihood method for the muon channel analysis and the electron channel analysis.

7.2.1.2 Observables for Boosted Decision Trees

The event configuration with the highest likelihood value is chosen. Variables from this configuration are then used as input to the Boosted Decision Tree analyses in the different analysis bins. The comparison of these variables between observed data and the background model is presented in the following paragraphs.

Events with three jets, one b-tagged jet, and one muon

The variables used in the multivariate analysis for events with three jets, one b-tagged jet, and one muon are shown in figure 7.2.8 to figure 7.2.13. Overall, the agreement of the observed data with the background model is good and the variables presented here can be used in the statistical analysis.

In figure 7.2.8 the pseudorapidity distribution (figure 7.2.8(a)) and the transverse momentum distribution (figure 7.2.8(b)) of jets assigned to the parton b(lept) in the Parton Picture Template are shown. In pseudorapidity η , both the signal distribution of electroweak top quark production and the background distribution are symmetric around $\eta = 0$. However, the background model has a more distinct peak structure, whereas the signal distribution is almost flat for $|\eta| < 1.0$. The shapes of the transverse momentum distributions for signal events and background events are similar. Except for the region of low transverse momenta. There, especially events from the background of the production of W bosons associated by jets can be found.

Figure 7.2.8: Figure 7.2.8(a) shows the pseudorapidity η of jets assigned to the parton b(lept) in the Parton Picture Template, and figure 7.2.8(b) shows their transverse momentum. Both histograms show events with three jets, one of them tagged as a b-jet, and one muon.

The transverse momentum distribution of jets assigned to the parton b(prod) in figure 7.2.9(a) shows two components. A first peak structure can be seen for jets with transverse momenta lower than 50 GeV, a second, much broader structure for transverse momenta higher than 50 GeV. The observed data events follow this structure. The first peak is dominated by events from the production of W bosons associated with jets. The events from top quark pair production can be found at higher values. The pseudorapidity distribution of those jets can be found in figure 7.2.9(b). The distribution is symmetric around $\eta = 0$ and broader for signal events than for background events.

Figure 7.2.9: Transverse momentum (figure 7.2.9(a)) and pseudorapidity η (figure 7.2.9(b)) for jets assigned to the parton b(prod) in events with three jets, one of them tagged as originating from a b hadron decay, and a muon.

The same two quantities that are used in the statistical analysis from the jets assigned to the parton b(prod) are also used from the jets assigned to the parton q(scatter). Figure 7.2.10(a) shows the transverse momentum distribution of the jets. The distribution peaks at 25 GeV and is similar for signal and background events. The distribution of the jet pseudorapidity is again symmetric around $\eta = 0$ and can be seen in figure 7.2.10(b).

Figure 7.2.10: Transverse momentum (figure 7.2.10(a)) and pseudorapidity η (figure 7.2.10(b)) of jets assigned to the parton q(scatter) in events with three jets, one of them b-tagged, and one muon.

The transverse momentum of the reconstructed top quark is shown in figure 7.2.11(a). The distribution reaches its maximum at 50 GeV. The slope of the distribution at the falling edge is slightly steeper for the background. The events from top quark pair production appear on average at higher values of transverse momentum. Figure 7.2.11(b) shows the transverse momentum distribution of the reconstructed W boson W(lepton). The events from the multijet background are accumulated at low transverse momenta. This influences the total shape of the background, where the distribution has its peak at 20 GeV, whereas the maximum of the distribution for the signal events is at 40 GeV.

A measure M_η is calculated from the pseudorapidities of the reconstructed top quark t(lepton)

Figure 7.2.11: The transverse momentum of the reconstructed top quark $t(\text{lept})$ is shown in figure 7.2.11(a) and the transverse momentum of the reconstructed W boson is shown in figure 7.2.11(b) for events with three jets, one tagged as a b -jet and one muon.

and the jet assigned to the parton $b(\text{prod})$ according to:

$$\begin{aligned} M_\eta &= \sqrt{(\Delta\eta)^2 + \left(\sum \eta\right)^2}, \text{ with} \\ \Delta\eta &= \eta(b(\text{prod})) - \eta(t(\text{lept})), \text{ and} \\ \sum \eta &= \eta(b(\text{prod})) + \eta(t(\text{lept})). \end{aligned} \quad (7.2.1)$$

The distribution obtained by calculating this measure can be found in figure 7.2.12(a). The background events from top quark pair production prefer lower values of M_η . Figure 7.2.12(b) displays the distribution of another measure, M_{Ht} , based on the transverse momenta p_T of the partons and their transverse energies E_T :

$$\begin{aligned} M_{Ht} &= \frac{\sqrt{[p_T(b(\text{prod})) + p_T(t(\text{lept}))]^2 + \text{mass}(t(\text{lept}))^2}}{H_t}, \text{ with} \\ H_t &= ME_t + E_T(\text{lepton}) + E_T(b(\text{lept})) + E_T(b(\text{prod})) \end{aligned} \quad (7.2.2)$$

In this variable the majority of multijet background events has values larger than 1, whereas at least half of the signal events has values of M_{Ht} lower than 1.

The pseudorapidity η of the reconstructed parton CM is shown in figure 7.2.13(a). This parton points into the forward direction with its distribution peaking at $|\eta| = 4$. The distribution is symmetric around $\eta = 0$. The result of the likelihood method for the selected event configuration is presented in figure 7.2.13(b). The background of top quark pair production tends to lower values, whereas the single top quark signal distribution has a slowly rising slope over a wide range.

Events with three jets, two b -tagged jets, and one muon

Variables used in the multivariate analysis for events with three jets, two of them tagged as originating from a b hadron decay, missing transverse energy and one isolated muon are shown in figures 7.2.14 to 7.2.19. In this analysis bin, the statistical precision is limited because of the requirement of two b -tagged jets. The important backgrounds are the production of W bosons,

Figure 7.2.12: Variable M_η as explained in equation 7.2.1 is shown in figure 7.2.12(a) and variable M_{Ht} as explained in equation 7.2.2 is displayed in figure 7.2.12(b) for events with three jets, one b-tagged jet, and one muon.

Figure 7.2.13: Pseudorapidity distribution of the reconstructed parton CM (figure 7.2.13(a)) and result of the likelihood method for the selected event configuration (figure 7.2.13(b)). Both histograms show events with three jets, one of them tagged as originating from a b hadron decay, and one muon.

associated by two b-quarks, and both top quark pair processes, i.e. top quark pair production in the semileptonic channel and in the dilepton channel. Despite the limited statistics, there are variables that show a reasonable agreement between the expected background model and the observed data distributions and can thus be used in the Boosted Decision Tree analysis.

The mass of the reconstructed top quark $t(\text{lept})$ is shown in figure 7.2.14(a). The distribution peaks at 170 GeV and shows a very similar shape for both signal events and the background contributions from top quark pair production. The transverse momentum of the reconstructed top quark $t(\text{lept})$ however is on average higher for the background from top quark pair production. The multijet events can be found at very low transverse momentum values. The maximum of both the signal and the total background distribution is at 60 GeV.

The transverse momentum distribution of the jets assigned to the parton $b(\text{lept})$ is shown in figure 7.2.15(a). Again, the distributions of the electroweak top quark signal and the ones for top quark pair production are very similar. Overall, the background processes have a lower trans-

Figure 7.2.14: The mass of the reconstructed top quark t (lept) is shown in figure 7.2.14(a) and its transverse momentum in figure 7.2.14(b) for events with three jets, two b-tagged jets, and one isolated muon.

verse momentum. The pseudorapidity distribution for these jets is shown in figure 7.2.15(b). It is symmetric around $\eta = 0$ and rather flat for $|\eta| < 1$.

Figure 7.2.15: Transverse momentum of jets assigned to the parton b (lept) (figure 7.2.15(a)) and pseudorapidity η for the same jets (figure 7.2.15(b)) in events with three jets, two tagged as b -jets, and one isolated muon.

The transverse momentum distribution of jets assigned to the parton b (prod) of the Parton Picture Template shows the same feature in this analysis bin as in the one with only one b -tagged jet. It has two contributions. The first is a narrow peak structure, with a maximum at 30 GeV. The second contribution is a broad structure with a maximum at 80 GeV. The background events from top quark pair production have their maximum at an even higher value of 90 GeV. The pseudorapidity distribution of these jets is a bit asymmetric for the signal sample, preferring positive pseudorapidity values.

Figure 7.2.17(a) displays the transverse momentum distribution of jets assigned to the parton q (scat). The events from $Wb\bar{b}$ production have lower transverse momenta, those from top quark pair production higher transverse momenta, with a maximum of the distribution at 35 GeV, compared to 25 GeV for the signal events of electroweak single top quark production.

The distribution of the variable M_η , as introduced in equation 7.2.1, for this analysis bin is shown in figure 7.2.18(a). The events from the multijet background can all be found at values

Figure 7.2.16: Transverse momentum (figure 7.2.16(a)) and pseudorapidity (figure 7.2.16(b)) of jets assigned to the parton b(prod) of the Parton Picture Template for events with three jets, two of them tagged as originating from a b hadron decay, and one isolated muon.

Figure 7.2.17: Transverse momentum of jets assigned to the parton q(scatter) in the Parton Picture Template (figure 7.2.17(a)) and their pseudorapidity η (figure 7.2.17(b)) for events with three jets, two of them tagged as b-jets, and one isolated muon.

$M_\eta > 3$. The variable M_{Ht} , calculated according to equation 7.2.2, is shown in figure 7.2.18(b). The shapes of the signal and background distributions are very similar. The five data events with values $M_{Ht} > 1.5$ are in a region where the background model predicts only few events.

For the transverse momentum of the reconstructed W boson $W(\text{left})$, shown in figure 7.2.19(a), the spectrum for the background is slightly harder than for the signal events of electroweak top quark production. The pseudorapidity η of the parton CM, reconstructed from the top quark $t(\text{left})$, the jet assigned to b(prod) and the jet assigned to q(scatter) is displayed in figure 7.2.19(b). These partons CM point to the very forward region. The distribution is symmetric around $\eta = 0$ and peaks at $|\eta| = 4$. Figure 7.2.19(c) shows the result of the likelihood method for the one configuration that is selected.

Events with three jets, one b-tagged jet, and one electron

Figure 7.2.18: The distribution of M_η is shown in figure 7.2.18(a), the distribution of M_{Ht} can be seen in figure 7.2.18(b). Both histograms contain events with three jets, both tagged as b-jets, and one isolated muon.

Figure 7.2.19: The transverse momentum distribution of the reconstructed W boson $W(\text{lept})$ is shown in figure 7.2.19(a). Figure 7.2.19(b) displays the pseudorapidity η for the reconstructed parton CM. The result of the likelihood method for the selected configuration can be seen in figure 7.2.19(c). All histograms contain events with three jets, both tagged as originating from a b hadron decay, and one isolated muon.

The variables used in the multivariate analysis for events with three jets, one b-tagged jet, missing transverse energy, and one isolated electron are shown in figures 7.2.20 to 7.2.25. Overall, the observed data agree very well with the simulated background model for the observables that are selected to enter the multivariate analysis.

Figure 7.2.20(a) shows the pseudorapidity η for jets assigned to the parton b(lept) in the Parton Picture Template. The distribution is symmetric around $\eta = 0$ for both signal and background events. There are two bins at $\eta = 1$ where the observed data distribution is higher than the background model. But this difference is acceptable within the statistical precision. The transverse momentum of the jets assigned to the parton b(lept) is shown in figure 7.2.20(b). The spectrum for events from the multijet background is the softest one. Compared with the total background, the single top quark events on average have a higher transverse momentum of these jets.

Figure 7.2.21(a) displays the transverse momentum of jets assigned to the parton b(prod).

Figure 7.2.20: Pseudorapidity η (figure 7.2.20(a)) and transverse momentum (figure 7.2.20(b)) of jets assigned to the parton b(left) in the Parton Picture Template. The histograms contain events with three jets, one b-tagged jet, and an isolated electron.

This distribution has two components. The first one shows a narrow peak structure with a maximum at 25 GeV. There, the majority of the events from W boson production associated by jets and of multijet events can be found. The second component of the distribution is broad, peaks at 90 GeV and contains predominantly top quark pair events. The pseudorapidity distribution for these jets can be found in figure 7.2.21(b). It is symmetric around $\eta = 0$ for both signal and background events.

Figure 7.2.21: Transverse momentum (figure 7.2.21(a)) and pseudorapidity η (figure 7.2.21(b)) of jets assigned to the parton b(prod) for events with three jets, one b-jet, and one isolated electron.

Also for jets assigned to the parton q(scatter) of the Parton Picture Template, the transverse momentum (see figure 7.2.22(a)) and the pseudorapidity (see figure 7.2.22(b)) are used in the statistical analysis. The shape of the transverse momentum distributions are similar for the signal events of electroweak top quark production and the background model. The observed data describe this distribution very good. The pseudorapidity distribution is symmetric around $\eta = 0$ for all contributing physics processes.

The transverse momentum distribution of the reconstructed top quark t(left) is shown in figure 7.2.23(a). On average, the transverse momentum is slightly higher for the single top quark signal than for the combined background model. For the reconstructed W boson, the transverse

Figure 7.2.22: Transverse momentum (figure 7.2.22(a)) and pseudorapidity η (figure 7.2.22(b)) of jets assigned to the parton $q(\text{scat})$ for events with three jets, one b-tagged jet, and one isolated electron.

momentum distribution can be found in figure 7.2.23(b). The multijet background is clearly accumulated at low transverse momenta. The distribution for the signal events of electroweak top quark production has its maximum at 55 GeV, 10 GeV higher than the background distribution.

Figure 7.2.23: The transverse momentum of the reconstructed top quark t (left) is shown in figure 7.2.23(a). For the reconstructed W boson W (left) the distribution can be seen in figure 7.2.23(b). Both histograms contain events with three jets, one b-tagged jet and one isolated electron.

The variable M_η was introduced in equation 7.2.1. Its distribution in this analysis bin can be seen in figure 7.2.24(a). Especially the background contribution from top quark pair production seems to be concentrated at rather low values in M_η . The signal shape reaches its maximum at slightly higher values than the combined background distribution. The distribution of the M_{Ht} variable, according to equation 7.2.2, is shown in figure 7.2.24(b). The majority of the multijet background is pushed towards values of $M_{Ht} > 1.0$, whereas the signal distribution has its maximum below $M_{Ht} = 1$.

The pseudorapidity η distribution of the reconstructed parton CM is shown in figure 7.2.25(a). They point to the forward direction of the detector, with a maxima of the distribution at $|\eta| = 4$, being otherwise symmetric around $\eta = 0$. The result of the likelihood method for the selected event configuration is shown in figure 7.2.25(b). Many events from top quark pair production

Figure 7.2.24: Distributions of variable M_η (figure 7.2.24(a)) and variable M_{Ht} (figure 7.2.24(b)) for events with three jets, one jet tagged as originating from a b hadron decay, and one isolated electron.

are found at very low values. The signal events of electroweak top quark production have a rising slope towards higher values of the likelihood result.

Figure 7.2.25: The pseudorapidity distribution of the reconstructed parton CM is shown in figure 7.2.25(a). The result of the likelihood method for the selected event configuration is shown in figure 7.2.25(b). Both histograms contain events with three jets, one tagged as a b-jet, and an isolated electron.

Events with three jets, two b-tagged jets, and one electron

In figures 7.2.26 to 7.2.31 the variables used in the Boosted Decision Tree analysis are shown for events with three jets, both of them tagged as originating from a b hadron, and one electron. Due to the limited statistics in this analysis bin, the description of the observed data events by the simulated background model (mostly $Wb\bar{b}$ events) varies. Only variables with a reasonable agreement within statistical uncertainty are selected for the multivariate analysis.

From the reconstructed top quark $t(\text{left})$ the mass (see figure 7.2.26(a)) and transverse momentum (see figure 7.2.26(b)) are used as input to the statistical analysis. The mass distribution peaks at 170 GeV. Due to the large number of background events from top quark pair production, the background distribution looks similar to the distribution of electroweak top quark

production. However, in the transverse momentum distribution there are differences. Here, the top quarks reconstructed from top quark pair production have on average a higher transverse momentum than those from the signal sample. In both distributions, the multijet background can be found at the lower end of the spectrum.

Figure 7.2.26: The mass of the reconstructed top quarks t (left) and their transverse momentum are shown in figures 7.2.26(a) and 7.2.26(b) for events with three jets, two of them tagged as originating from a b hadron decay, and one isolated electron.

For jets assigned to the parton b (left) of the Parton Picture Template the transverse momentum distribution can be found in figure 7.2.27(a). It is very similar for the single top quark signal and the background from top quark pair production. The $Wb\bar{b}$ background events however have a softer transverse momentum spectrum. The pseudorapidity distribution of these jets is symmetric around $\eta = 0$ and can be seen in figure 7.2.27(b).

Figure 7.2.27: Transverse momentum and pseudorapidity of jets assigned to the parton b (left) in the Parton Picture Template are shown in figure 7.2.27(a) and 7.2.27(b) for events with three jets, two of them tagged as a b -jet, and one isolated electron.

Two components can be found in the transverse momentum distribution for jets assigned to the parton b (prod) in figure 7.2.28(a). The first one, for transverse momenta lower than 50 GeV, accumulates most of the $Wb\bar{b}$ background. The second one, for transverse momenta higher than 50 GeV, the background of top quark pair production is dominant. The spectrum for these events is harder than for the single top quark signal events. The pseudorapidity η of those jets is symmetric around $\eta = 0$ and can be seen in figure 7.2.28(b).

Figure 7.2.28: Transverse momentum and pseudorapidity η of jets associated with the parton $b(\text{prod})$ of the Parton Picture Template are shown in figure 7.2.28(a) and figure 7.2.28(b), respectively. The distributions contain events with three jets, two of them b-jets, and one isolated electron.

Also for jets associated with the parton $q(\text{scat})$ the transverse momentum (see figure 7.2.29(a)) and the pseudorapidity η (see figure 7.2.29(b)) are used as input in the statistical analysis. Especially the jets from top quark pair production in the semileptonic channel have very high transverse momenta because most likely all three jets are decay products of heavy particles. The maximum of the distribution is at 35 GeV with long tails up to 150 GeV. In pseudorapidity, the distribution is symmetric around $\eta = 0$ for all contributing processes.

Figure 7.2.29: Transverse momentum and pseudorapidity η of jets assigned to the parton $q(\text{scat})$ in the Parton Picture Template are shown in figure 7.2.29(a) and figure 7.2.29(b), respectively.

The distributions of the variables M_η and M_{H_t} as introduced in equations 7.2.1 and 7.2.2 are shown in figure 7.2.30(a) and figure 7.2.30(b). For M_η the distributions for signal and background events are very similar. M_{H_t} manages to push the majority of entries of the multijet background to values of $M_{H_t} > 1$, whereas the signal distribution peaks at $M_{H_t} = 1$.

The transverse momentum of the reconstructed W boson $W(\text{lept})$ is shown in figure 7.2.31(a). On average, the transverse momenta for the multijet events are lower than for the other physics processes. They all look very similar. The pseudorapidity distribution for the reconstructed parton CM is symmetric around $\eta = 0$ and peaks at $|\eta| = 4$ with a dip in the distribution at

Figure 7.2.30: The variables M_{η} and M_{Ht} are shown in figures 7.2.30(a) and 7.2.30(b) for events with three jets, two of them tagged as originating from the decay of a b hadron, and one isolated electron.

$\eta = 0$. For signal events of single top quark production CM points even further into the forward direction. The result of the likelihood method for the selected event configuration can be found in figure 7.2.31(c). The variable manages to accumulate a big portion of the background events from top quark pair events in the first bin of the distribution.

Figure 7.2.31: The transverse momentum of the reconstructed W boson $W(\text{lept})$ is shown in figure 7.2.31(a). Figure 7.2.31(b) shows the pseudorapidity η of the reconstructed parton CM. In figure 7.2.31(c) the result of the likelihood method for the selected event configuration can be seen. All distributions contain events with three jets, two of them b-tagged, and one isolated central electron.

7.2.2 t-Channel Production of Top Quarks

The Parton Picture Template for the reconstruction of t-channel single top quark production in events with three jets, missing transverse energy and one charged lepton is similar to the $2 \rightarrow 3$ process Feynman diagram and shown in figure 7.2.32. A top quark named $t(\text{lept})$ decays into a b quark $b(\text{lept})$ and a W boson $W(\text{lept})$. The supplement ‘lept’ indicates the subsequent leptonic decay of the W boson into a charged lepton and a neutrino. The parton labeled $b(\text{scat})$ represents the second b quark from the $2 \rightarrow 3$ process of t-channel single top quark production. The scattered valence quark that emitted the virtual W boson is represented by the parton $q(\text{scat})$. The three partons $t(\text{lept})$, $b(\text{scat})$, and $q(\text{scat})$ are connected to a common primary vertex. Their vector sum results in the kinematic of the incoming parton named CM, representing the center-of-mass system of the interaction.

Figure 7.2.32: The Parton Picture Template for the electroweak top quark in the t-channel process has a parton for the top quark, named $t(\text{lept})$. It decays into a W boson $W(\text{lept})$ and a b quark $b(\text{lept})$, where ‘lept’ indicates the leptonic decay of the W boson into a charged lepton and a neutrino. The parton named $b(\text{scat})$ represents the second b quark from the $2 \rightarrow 3$ process. $q(\text{scat})$ represents the parton from the initial scattering process that emitted the virtual W boson. The top quark $t(\text{lept})$, the b quark $b(\text{scat})$, and the parton $q(\text{scat})$ are connected to a common primary vertex. Their vector sum results in the incoming parton named CM, representing the center-of-mass system of the interaction

7.2.2.1 Ambiguity Resolution

There are twelve possible configurations in the assignment of reconstructed objects to the partons for this Parton Picture Template. All configurations are evaluated in a likelihood method in the later analysis. The input variables to this likelihood method come from studies where parton information from the generator level is matched to reconstructed objects after simulation. To ensure that the resulting distributions for t-channel single top quark production are not affected by initial state or final state radiation, a quality cut on $\Sigma \Delta R$, the sum over the distances between the reconstructed objects and the generated parton they are matched to, is applied. Because of the mixture of $2 \rightarrow 2$ and $2 \rightarrow 3$ processes in the simulated t-channel events (see section 5.2.1),

matching quality cut for	
muons	electrons
1.5	1.5

Table 7.2.3: Matching quality cut in $\Sigma\Delta R$ for muon and electron t-channel single top events with three jets.

the resulting $\Sigma\Delta R$ distribution shows two components for events with three jets: In about 40% of the events where the reconstructed objects could be matched with the generated partons within $0 < \Sigma\Delta R < 1.5$ and show a falling distribution. Then, for $\Sigma\Delta R > 1.5$ the distribution starts to rise again, resulting in a second maximum at $\Sigma\Delta R = 4.0$ and a broad structure up to $\Sigma\Delta R = 9.0$. Although it was possible to match the reconstructed objects to the generated partons, the matching quality is poor for at least 60% of the matched events. Therefore, the matching quality cut is set to 1.5 for both the muon channel analysis and the electron channel analysis, not requiring the full 68% of matched events as for the other PaxProcesses. The cutoff values in $\Sigma\Delta R$ are summarized in table 7.2.3 and visualized in figure 7.2.33(a) for the muon channel and in figure 7.2.33(b) for the electron channel.

Figure 7.2.33: Cut off value for the matching quality $\Sigma\Delta R$ between generated partons and reconstructed objects for muon 7.2.33(a) and electron 7.2.33(b) events in the t-channel single top quark sample. Only quantities of events with good matching quality (grey area) are used as input to the likelihood method that is used to resolve the ambiguities in the jet-parton-assignment.

Five variables are used in the likelihood method to resolve the ambiguities that arise from the matching of reconstructed objects to the partons in the t-channel Parton Picture Template for events with three jets. The first two distributions shown in figures 7.2.34 and 7.2.35 are obtained from reconstructed jets matched to the parton b(left). Figure 7.2.34(a) displays the probability that a jet matched to the parton b(left) is tagged as originating from a b hadron for events in the muon channel analysis, while figure 7.2.34(b) shows the same quantity for the electron channel analysis. Both distributions show a probability of more than 50% that the b-tagging algorithm returned a positive result for these jets, in agreement with the efficiency of the algorithm.

The second observable used from jets matched to the parton b(left) is their pseudorapidity η distribution. It is displayed in figure 7.2.35(a) for the muon channel and in figure 7.2.35(b)

Figure 7.2.34: Input distributions for the likelihood method to resolve ambiguities in the t-channel Parton Picture Template for events with three jets and one charged lepton. The probability of a reconstructed jet matched to the parton b(scst) to be tagged as originating from a b hadron decay is shown for events in the muon analysis (figure 7.2.34(a)) and for events in the electron analysis (figure 7.2.34(b)), respectively.

for the electron channel. The majority of jets matched to b(lept) is reconstructed in the central region of the detector, i.e. pseudorapidity $|\eta| < 1.0$.

Figure 7.2.35: Input distributions for the likelihood method to resolve ambiguities in the t-channel Parton Picture Template for events with three jets and one charged lepton. The pseudorapidity distribution for jets matched to the parton b(lept) is shown in figure 7.2.35(a) for events in the muon analysis and in figure 7.2.35(b) for the electron analysis.

Variables three and four in the likelihood method are from jets matched to parton q(scst). Their probability to be tagged as originating from a b hadron is shown in figure 7.2.36(a) for events in the muon analysis and in figure 7.2.36(b) for events in the electron analysis. There are hardly any entries in second bin, indicating that indeed most of these jets origin from light quarks.

The transverse momentum of jets matched to the parton q(scst) for those events fulfilling the matching quality criteria is shown in figure 7.2.37(a) for events in the muon analysis and in

Figure 7.2.36: Input distributions for the likelihood method to resolve ambiguities in the t -channel Parton Picture Template for events with three jets and one charged lepton. The probability of a reconstructed jet matched to the parton $q(\text{scat})$ to be tagged as originating from a b hadron decay is shown for events in the muon analysis (figure 7.2.36(a)) and for events in the electron analysis (figure 7.2.36(b)), respectively.

figure 7.2.37(b) for events in the electron analysis. Both distributions peak at 30 GeV with only few events above 150 GeV.

Figure 7.2.37: Input distributions for the likelihood method to resolve ambiguities in the t -channel Parton Picture Template for events with three jets and one charged lepton. Figure 7.2.37(a) displays the transverse momentum distribution of jets matched to the parton $q(\text{scat})$ for the muon analysis, figure 7.2.37(b) shows the same quantity for the electron analysis.

The cosine of the angle between the W boson boosted to the rest frame of the top quark and the lepton, boosted to the rest frame of the W boson is a handle to chose the correct solution for the z component of the neutrino momentum. This distribution is shown in figure 7.2.38(a) for the muon channel and in figure 7.2.38(b) for the electron channel.

The efficiency of the likelihood method is determined by comparing the configuration with the highest likelihood value with the configuration obtained from the matching of the reconstructed objects with the partons from the generator. The efficiencies ϵ_{68} and ϵ_{100} , as described

Figure 7.2.38: Input distributions for the likelihood method to resolve ambiguities in the t-channel Parton Picture Template for events with three jets and one charged lepton. These distributions show the cosine of the angle between the W boson in the top quark rest frame and the lepton, boosted into the rest frame of the W boson for the muon channel (figure 7.2.38(a)) and the electron channel (figure 7.2.38(b)).

	muon channel	electron channel
$\epsilon_{68}[\%]$	48.5	35.8
$\epsilon_{100}[\%]$	49.9	40.1

Table 7.2.4: Efficiencies ϵ_{68} and ϵ_{100} of the likelihood method for the muon channel analysis and the electron channel analysis.

in definition 6.2.1, are summarized in table 7.2.4 for the muon channel analysis and the electron channel analysis. It should be noted that in this case the number of events for the calculation of ϵ_{68} does not refer to 68% of the events that pass the matching quality criteria. The cuts on the quality of the matching between reconstructed objects and generated partons were set to a value of $\Sigma\Delta R$ of 1.5, neglecting the 68% criterion (see table 7.2.3). The probability to find the correct event configuration by chance is 16.7%. The efficiencies of the likelihood methods for the reconstruction of this Parton Picture Template are two to three times higher, reaching up to almost 50% for ϵ_{100} in the muon channel analysis.

7.2.2.2 Observables for Boosted Decision Trees

The event configuration with the highest likelihood value is chosen. Variables from this configuration are then used as input to the Boosted Decision Tree analyses in the different analysis bins. The comparison of these variables between observed data and the background model is presented in the following paragraphs.

Events with three jets, one b-tagged jet, and one muon

The variables used in the multivariate analysis for events with three jets, one b-tagged jet, and one muon are shown in figure 7.2.39 to figure 7.2.42. Overall, the agreement of the observed data with the background model is good and those variables presented here can be used in the

statistical analysis.

Mass (figure 7.2.39(a)), transverse momentum (figure 7.2.39(b)), and pseudorapidity η (figure 7.2.39(c)) of the reconstructed top quark $t(\text{lept})$ are used as inputs to the Boosted Decision Trees. The mass of the reconstructed top quarks peaks at 175 GeV for the signal events, i.e. the value used in the generator. The background distribution is very broad. The multijet background accumulates at very low mass values. The transverse momentum distribution of the reconstructed top quarks has its maximum at 45 GeV for both signal and background events. For the latter, the slope of the falling edge of the distribution is steeper. The pseudorapidity distribution has maxima at $|\eta| = 1.5$.

Figure 7.2.39: Mass (figure 7.2.39(a)), transverse momentum (figure 7.2.39(b)) and pseudorapidity η (figure 7.2.39(c)) of the reconstructed top quark $t(\text{lept})$ of the Parton Picture Template. The distributions contain events with three jets, one of them tagged as originating from a b hadron decay and one isolated muon.

Kinematic quantities of the jets assigned to the parton $b(\text{lept})$ are shown in figure 7.2.40. The transverse momentum distribution can be seen in figure 7.2.40(a). The maximum of the distribution for simulated signal events is at 60 GeV. Events from the production of W bosons, associated with jets, can be found at low transverse momentum values, together with the events from the multijet background. The distribution for top quark pair production is similar to the one for signal events. Figure 7.2.40(b) shows the pseudorapidity η of the jets assigned to the parton $b(\text{lept})$. It is symmetric around $\eta = 0$. The majority of the jets can be found in the central region of the detector, i.e. $|\eta| < 1$.

Figure 7.2.41(a) shows the transverse momentum distribution of the jets assigned to the parton $q(\text{scat})$ in the Parton Picture Template. The multijet background has a flat transverse momentum distribution. The transverse momentum spectrum for the background of top quark pair production is harder than for the signal events of electroweak top quark production. Both the total background distribution and the signal distribution peaks at 45 GeV. The pseudorapidity distribution of these jets is shown in figure 7.2.41(b). For $|\eta| < 1.5$ the distribution for signal events is flat, whereas the background distribution has a peak structure with maximum at $\eta = 0$. The distribution is symmetric around $\eta = 0$ for all contributing physics processes.

The transverse momentum distribution of jets assigned to the parton $b(\text{scat})$ of the Parton Picture Template is shown in figure 7.2.42(a). The distribution peaks at low values of transverse momentum (at 25 GeV) and has a steep falling edge. The cosine of the angle between the

Figure 7.2.40: The transverse momentum distribution of jets assigned to the parton b(left) is shown in figure 7.2.40(a), their pseudorapidity η in figure 7.2.40(b). Both histograms contain events with three jets, one of them tagged as a b-jet, and one isolated muon.

Figure 7.2.41: The transverse momentum distribution of jets assigned to the parton q(scatter) is shown in figure 7.2.41(a), their pseudorapidity distribution in figure 7.2.41(b) for events with three jets, one of them tagged as a b-jet, and one isolated muon.

W boson boosted to the rest frame of the top quark and the lepton boosted to the rest frame of the W boson is displayed in figure 7.2.42(b). The distribution is similar for signal and background events. The result of the likelihood method for the selected event configuration can be seen in figure 7.2.42(c). This variable can be useful to separate the background from top quark pair production. They are accumulated at low values of the likelihood result.

Events with three jets, two b-tagged jets, and one muon

Variables used in the multivariate analysis for events with three jets, two of them tagged as originating from a b hadron decay, missing transverse energy and one isolated muon are shown in figures 7.2.43 to 7.2.46. In this analysis bin, the statistical precision is limited, because of the requirement of two b-tagged jets. The important backgrounds are the production of W bosons, associated by two b-quarks, and both top quark pair processes, i.e. top quark pair production in the semileptonic channel and in the dilepton channel. Despite the limited statistics, there are variables that show a reasonable agreement between the expected background model and the

Figure 7.2.42: The transverse momentum of jets assigned to the parton b(scatter) is shown in figure 7.2.42(a). The cosine of the angle between the W boson, boosted to the rest frame of the top quark, and the muon, boosted into the rest frame of the W boson can be seen in figure 7.2.42(b). The result of the likelihood method for the selected event configuration is displayed in figure 7.2.42(c). All distributions contain events with three jets, one of them b-tagged, and one isolated muon.

observed data distributions and can thus be used in the Boosted Decision Tree analysis.

Figure 7.2.43(a) shows the mass of the reconstructed top quark $t(\text{lepton})$. The distributions for signal and background events peak at 175 GeV and have long tails towards high mass values. The transverse momentum of the reconstructed top quarks $t(\text{lepton})$ can be seen in figure 7.2.43(b). The background from top quark pair production on average has a higher transverse momentum, with a maximum at 60 GeV. The maximum of the signal distribution is at 45 GeV. The electroweak top quark signal has a flatter slope of the distribution towards higher transverse momenta. The pseudorapidity distribution of the top quarks $t(\text{lepton})$ is symmetric around $\eta = 0$ for all contributing physics processes and is displayed in figure 7.2.43(c).

Figure 7.2.43: Mass (figure 7.2.43(a)), transverse momentum (figure 7.2.43(b)) and pseudorapidity η (figure 7.2.43(c)) of the reconstructed top quarks $t(\text{lepton})$ for events with three jets, two of them tagged as a b-jet, and one isolated muon.

Properties of jets assigned to the parton b(lepton) of the Parton Picture Template are shown in figure 7.2.44. The transverse momentum distribution in figure 7.2.44(a) has long tails towards high transverse momenta. On average, the background from top quark pair production has the hardest transverse momentum spectrum, whereas the events from $Wb\bar{b}$ production can be found

at the lower end of the spectrum. The distribution for the signal events of electroweak top quark production peaks at 60 GeV, a value expected for a b-jet originating from the decay of a top quark. Figure 7.2.44(b) shows the transverse momentum distribution of the jets assigned to the parton b(left). It is symmetric around $\eta = 0$ for all contributing physics processes.

Figure 7.2.44: Transverse momentum (figure 7.2.44(a)) and pseudorapidity η (figure 7.2.44(b)) of jets assigned to the parton b(left) of the Parton Picture Template. The histograms contain events with three jets, two of them tagged as originating from the decay of a b hadron, and one isolated muon.

The transverse momentum distribution of jets assigned to the parton q(scatter) in the Parton Picture Template is shown in figure 7.2.45(a). The distribution is similar for signal and background events. Jets with a low transverse momentum are preferred in the role of parton q(scatter). The distribution peaks at a value of 30 GeV. The pseudorapidity distribution of these jets can be found in figure 7.2.45(b). For the signal events of electroweak top quark production, the distribution is flat for $|\eta| < 1.5$. The distribution of the background model has a peak structure with a maximum at $\eta = 0$. Both the distribution of background events and the distribution of signal events are symmetric around $\eta = 0$.

Figure 7.2.45: The transverse momentum distribution of jets assigned to the parton t(left) is shown in figure 7.2.45(a), their pseudorapidity η is shown in figure 7.2.45(b). Both distributions contain events with three jets, two of them tagged as a b-jet, and one isolated muon.

Figure 7.2.46(a) shows the transverse momentum distribution of jets assigned to the parton

b(scst). The background distribution is characterised by events from $Wb\bar{b}$ production at low values of transverse energy and by top quark pair production at high transverse momentum values. The distributions of the total background and of the signal sample of electroweak top quark production peak at 25 GeV, the background component of top quark pair production at 40 GeV. The cosine of the angle between the W boson, boosted to the rest frame of the top quark t(lept), and the muon, boosted into the rest frame of the W boson, can be seen in figure 7.2.46(b). The shapes for all contributing physics processes are similar. The result of the likelihood method for the selected event configuration can be seen in figure 7.2.46(c). This variable manages to accumulate the background of top quark pair production at low values. The slope of the falling edge in the first few bins is much steeper for the background model than for the simulated signal events.

Figure 7.2.46: Figure 7.2.46(a) shows the transverse momentum distribution of jets assigned to the parton b(scst). The cosine of the angle between the W boson W(lept), boosted into the top quark rest frame, and the muon, boosted into the W boson rest frame, is displayed in figure 7.2.46(b). The likelihood value for the selected event configuration can be seen in figure 7.2.46(c). All distributions show events with three jets, two of them tagged as originating from a b hadron decay, and one isolated muon.

Events with three jets, one b-tagged jet, and one electron

Figures 7.2.47 to 7.2.50 show the input variables to the statistical analysis from the reconstruction of the Parton Picture Template shown in figure 7.2.32 for events with three jets, one of them tagged as originating from a b hadron decay, and one isolated electron. The overall agreement between the observed data and the expected background model is good, allowing the variables to be used in the Boosted Decision Tree analysis.

Mass (see figure 7.2.47(a)), transverse momentum (see figure 7.2.47(b)), and pseudorapidity η (see figure 7.2.47(c)) of the reconstructed top quarks t(lept) are used in the Boosted Decision Tree analysis. The mass of the top quark is reconstructed around 175 GeV for the signal events of electroweak top quark production, indicating the good performance of the likelihood method used to select the best event configuration. The background events have a broader distribution. The events from $Wb\bar{b}$ production and the multijet events have very low values of reconstructed top quark masses. In the transverse momentum distribution a similar effect can

be seen. The multijet background and events from $Wb\bar{b}$ production are accumulated at lower values of transverse momenta. The distribution for the background of top quark pair production is similar to the distribution of single top quark signal events. The pseudorapidity distribution of the reconstructed top quarks $t(\text{left})$ is symmetric around $\eta = 0$ and rather flat for $|\eta| < 1$.

Figure 7.2.47: Three properties of the reconstructed top quarks $t(\text{left})$ are shown here. their mass in figure 7.2.47(a), their transverse momentum in figure 7.2.47(b), and their pseudorapidity η in figure 7.2.47(c). All distributions contain events with three jets, one of them tagged as a b-jet, and one isolated electron.

From jets assigned to the parton $b(\text{left})$ of the Parton Picture Template, the transverse momentum (see figure 7.2.48(a)) and the pseudorapidity η (see figure 7.2.48(b)) are used in the statistical analysis. The transverse momentum spectrum of the signal events from electroweak top quark production is harder than for the total background. Especially multijet events and events from the production of a W boson, accompanied by jets, can be found at the low end of the background distribution. The maximum of the distribution for signal events is at 60 GeV, a value expected for a jet originating from the decay of a top quark. The pseudorapidity distribution is symmetric around $\eta = 0$. The majority of jets can be found in the central region of the detector, i.e. at $|\eta| < 1$.

Figure 7.2.48: Transverse momentum (figure 7.2.48(a)) and pseudorapidity η (figure 7.2.48(b)) of jets assigned to the parton $b(\text{left})$ in events with three jets, one b-tagged jet, and one isolated electron.

Compared to the jets assigned to the b-partons of the Parton Picture Template, the reconstructed transverse momentum for jets assigned to the parton $q(\text{scat})$ is smaller on average. Their

transverse momentum distribution (shown in figure 7.2.49(a)) has its maximum at 40 GeV. For higher transverse momenta, the background distribution falls steeper than the distribution for the single top quark signal events. Especially multijet events and events from the production of a W boson with jets, dominate the low transverse momentum region of the background distribution, whereas the background from top quark pair production is the dominating background contribution for transverse momenta above 70 GeV. In pseudorapidity η , there is a step in the distribution at $|\eta| = 1.4$. This step is more distinct in the background distribution than in the distribution of the single top quark signal events. The background has a peak structure, with a maximum at $\eta = 0$, but the signal distribution remains rather flat for $|\eta| < 1.4$. For all contributing physics processes, the distribution is symmetric around $\eta = 0$.

Figure 7.2.49: The transverse momentum distribution of jets assigned to the parton $q(\text{scat})$ can be seen in figure 7.2.49(a). Their pseudorapidity distribution is displayed in figure 7.2.49(b). Both histograms contain events with three jets, one of them tagged as a b-jet, and one isolated electron.

The transverse mass of jets assigned to the parton $b(\text{scat})$ is shown in figure 7.2.50(a). The distribution is similar for signal and background events. Both distributions have their maximum at 30 GeV. The observed data events describe the distribution very well. The cosine of the angle between the W boson $W(\text{lept})$ and the electron is shown in figure 7.2.50(b). The W boson is boosted into the rest frame of the top quark, the electron is boosted into the rest frame of the W boson. The resulting distribution is similar for all contributing physics processes. The result of the likelihood method for the selected event configuration is displayed in figure 7.2.50(c). This variable has some separating power against the background from top quark pair production. This background contribution is accumulated at low likelihood values.

Events with three jets, two b-tagged jets, and one electron

For events with three jets, two of them tagged as originating from the decay of a b hadron, missing transverse energy and one isolated electron, the variables shown in figures 7.2.51 to 7.2.54 are used in the Boosted Decision Tree analysis. Their agreement between observed data and simulated background model is very good, considering the lack of statistics, due to the requirement of two b-tagged jets.

From the reconstructed top quark $t(\text{lept})$, three properties are used in the statistical analysis. The mass of these top quarks is shown in figure 7.2.51(a). The maximum of the distribution

Figure 7.2.50: The transverse momentum distribution of jets assigned to the parton $b(\text{scat})$ is shown in figure 7.2.50(a). The cosine of the angle between the reconstructed W boson $W(\text{lept})$, boosted into the top quarks' rest frame, and the electron, boosted into the rest frame of $W(\text{lept})$ can be seen in figure 7.2.50(b). The result of the likelihood method for the selected event configuration is shown in figure 7.2.50(c). All distributions contain events with three jets, one of them tagged as a b -jet, and one isolated electron.

is at 175 GeV for both signal and background events. The tail of the background distribution is dominated by events from top quark pair production. The production of W bosons with jets yields lower values of reconstructed mass. A similar statement can be made for the transverse momentum distribution (see figure 7.2.51(b)). Top quark pair production dominates the tail of the distribution, whereas the majority of events from the production of a W boson with jets are at low transverse momentum values. The maximum of the signal distribution is located at 50 GeV. In pseudorapidity η , the distribution is rather flat in the central region of $|\eta| < 1.0$ for signal and background events (see figure 7.2.51(c)). This is also the region where the majority of events can be found. The distribution is symmetric around $\eta = 0$ for all contributing physics processes.

Figure 7.2.51: Three properties of the reconstructed top quark $t(\text{lept})$ are used in the statistical analysis: its mass (figure 7.2.51(a)), its transverse momentum (figure 7.2.51(b)), and its pseudorapidity (figure 7.2.51(c)). The distributions show events from the analysis bin with three jets, two of them tagged as a b -jet, and one isolated electron.

The transverse momentum distribution of jets assigned to the parton $b(\text{lept})$ is shown in figure 7.2.52(a). The signal distribution peaks at 60 GeV, a value expected for a b -jet originating

from the decay of a top quark. The background of top quark pair production peaks in the same region and contributes the most to the tail of the transverse momentum spectrum of the background. Events from the production of W bosons with jets have a softer transverse momentum spectrum and are located in the lower region of the background distribution. The pseudorapidity distribution for these jets can be seen in figure 7.2.52(b). It is a symmetric distribution around $\eta = 0$ and the majority of jets assigned to the parton b(lept) were reconstructed in the central region of the detector, i.e. $|\eta| < 1.0$.

Figure 7.2.52: The transverse momentum distribution of jets assigned to the parton b(lept) can be seen in figure 7.2.52(a), their pseudorapidity distribution in figure 7.2.52(b). Both distributions contain events with three jets, two of them b-tagged, and one isolated electron.

The maximum of the transverse momentum distribution for jets assigned to the parton q(scatter) is at 25 GeV for both signal and background events (see figure 7.2.53(a)). In the background distribution, events from the production of W bosons with jets can be found predominantly in the region of low transverse momentum, together with the multijet events. For transverse momenta higher than 60 GeV, the background component of top quark pair production dominates the background distribution. The pseudorapidity distribution shown in figure 7.2.53(b) is symmetric around $\eta = 0$ for all contributing physics processes.

Figure 7.2.53: The transverse momentum distribution (figure 7.2.53(a)) and the pseudorapidity distribution (figure 7.2.53(b)) of jets assigned to the parton q(scatter) are shown for events with three jets, two of them b-tagged, and one isolated electron.

The transverse momentum distribution of jets assigned to the parton $b(\text{scat})$ is shown in figure 7.2.54(a). The signal and the background distributions peak at 30 GeV. The dominant background contribution in the region of low transverse momentum is the production of a W boson accompanied by jets. For transverse momenta higher than 50 GeV, events from top quark pair production dominate the background distribution. The cosine of the angle between the W boson $W(\text{lept})$ and the isolated electron is shown in figure 7.2.54(b). The W boson is boosted into the rest frame of the top quark $t(\text{lept})$, and the electron is boosted into the rest frame of the W boson. Figure 7.2.54(c) displays the result of the likelihood method for the selected event configuration. The background from top quark pair production is accumulated at very low values. The total background distribution starts to drop immediately, whereas the distribution of single top quark signal events remains flat at the beginning before it starts falling with a lower slope than the background distribution.

Figure 7.2.54: The transverse momentum of jets assigned to the parton $b(\text{scat})$ is shown in figure 7.2.54(a). Figure 7.2.54(b) shows the cosine of the angle between the W boson $W(\text{lept})$, boosted into the rest frame of the top quark $t(\text{lept})$, and the isolated electron, boosted into the rest frame of the W boson. The result of the likelihood method for the selected event configuration is shown in figure 7.2.54(c). All histograms contain events with three jets, two of them tagged as originating from the decay of a b hadron, and one isolated electron.

7.2.3 Decay of Top Quark Pairs in Semileptonic Events

From the leading order Feynman diagram of semileptonic top quark pair production (compare section 2.2.1) one would expect to have four jets in an event. Thus, finding these events as background contribution in events with three reconstructed jets means that one jet is missing for the complete reconstruction of the top quark decay chain. Reasons for the appearance for these events with three jets have been studied in [205] for the muon selection of this analysis. Briefly summarized, the dominant reasons are that the fragmentation products of two quarks overlap in the detector and are reconstructed as one jet instead of two jets, or that the jet points into a region outside the acceptance of the detector. In 66% of the events it is one of the two quarks from the hadronic W boson decay that could not be matched with a reconstructed jet. Another 15% of the time the b quark from the same decay branch could not be matched. In the remaining 19% of events it is the b quark from the other branch of the decay, where the W boson decays into a charged lepton and a neutrino, that could not be matched with a reconstructed jet. To take these reasons for jet losses into account, two different Parton Picture Templates are reconstructed in the PaxProcess for semileptonic top quark pair production.

The first Parton Picture Template shown in figure 7.2.55 reconstructs the so-called ‘hadronic branch’, i.e. the situation where the missing jet belonged to the b quark from the top quark decay branch where the W boson decays into a charged lepton and a neutrino. A top quark $t(\text{hadr})$ decays into a W boson named $W(\text{hadr})$ and a b quark labeled $b(\text{hadr})$. The W boson subsequently decays into two quarks, named $q(\text{hadr})$ and $Q(\text{hadr})$. The charged lepton and the neutrino are used to reconstruct a W boson $W(\text{lept})$, representing the W boson that would have given the second top quark combined with the lost b quark. Both the top quark $t(\text{hadr})$ and the W boson $W(\text{lept})$ are connected to a primary vertex and their vector sum results in another parton named CM, representing the center-of-mass system of the interaction.

The second Parton Picture Template is called ‘leptonic branch’ and represents the case where one of the three jets from the hadronic decay of the top quark, i.e. where the W boson decays into two quarks, is missing. A schematic drawing of the Parton Picture Template can be seen in figure 7.2.56. The two remaining jets from the hadronic decay of the top quark are labeled jet1 and jet2 and combined to a dijet four-vector. The top quark that can be reconstructed in this Parton Picture Template is the top quark $t(\text{lept})$. It decays into a W boson $W(\text{lept})$ and a b quark labeled $b(\text{lept})$. The W boson subsequently decays into a charged lepton and a neutrino. The dijet four-vector and the reconstructed top quark $t(\text{lept})$ are connected to a primary vertex. Their vector sum results in another parton named CM. It represents the center-of-mass system of the interaction.

7.2.3.1 Ambiguity Resolution

Although there are two different Parton Picture Templates, the same cut on the matching quality is applied. Events passing this cut are then used to identify variables to be used in the likelihood measures in order to resolve the twelvefold ambiguities in the assignment of reconstructed objects to partons in the Parton Picture Templates. The same cut can be used because the results of the matching procedure were used to identify which parton could not be matched with a reconstructed object. Only distributions of events are used that fulfill the matching quality criterion

Figure 7.2.55: This Parton Picture Template shows the reconstruction of the hadronic branch for the PaxProcess reconstructing semileptonic top quark pair decays in events with three jets, one charged lepton and missing transverse energy. A top quark $t(\text{hadr})$ decays into a b quark named $b(\text{hadr})$ and a W boson labeled $W(\text{hadr})$. The supplement ‘hadr’ indicates the hadronic decay of the W boson into two quarks ($q(\text{hadr})$ and $Q(\text{hadr})$) in the top quark decay chain. From the charged lepton and the missing transverse energy another W boson named $W(\text{lept})$ is reconstructed and also connected to the primary vertex. The vector sum of $W(\text{lept})$ and $t(\text{hadr})$ results in a parton named CM , that is incoming to the primary vertex and represents the center-of-mass system of the interaction.

68% matching quality cut for	
muons	electrons
0.24	0.28

Table 7.2.5: 68% matching quality cut in $\Sigma\Delta R$ for the muon and the electron channel in simulated semileptonic top quark pair events with three jets.

of $\Delta R < 0.24$ for the muon channel or $\Delta R < 0.28$ for the electron channel. These events then refer to the 68% events with the best matching between generated partons and reconstructed objects. The results for the matching quality cutoffs are also summarized in table 7.2.5 and visualized in figure 7.2.57(a) for the muon channel and in figure 7.2.57(b) for events in the electron channel.

For the reconstruction of the Parton Picture Template in the ‘hadronic branch’ of figure 7.2.55 two variables are used in the likelihood method. Only events are used where the comparison of the reconstructed objects with the generated partons shows that the b quark from the decay of the top quark with the leptonic decay of the W boson cannot be matched.

The first variable is the probability of the jet matched to parton $b(\text{hadr})$ to originate from a b hadron decay. The distribution of this variable for the muon channel can be found in figure 7.2.58(a), the distribution for the electron channel in figure 7.2.58(b). Both distributions show that more than 50% of the jets matched to this parton are tagged as a b -jet, in good agreement with the efficiency of the b -tagging algorithm. This variable should help to assign a

Figure 7.2.56: This Parton Picture Template shows the reconstruction of the leptonic branch of the PaxProcess reconstructing semileptonic top quark pair decays in events with three jets, one charged lepton and missing transverse energy. The top quark $t(\text{lept})$ decays into a b quark named $b(\text{lept})$ and a W boson labeled $W(\text{lept})$, where ‘lept’ indicates the decay of the W boson into a charged lepton and a neutrino in the top quark decay chain. The two remaining jets jet1 and jet2 are added up and the resulting dijet four-vector is then connected to the primary vertex. The vector sum of this dijet and the reconstructed top quark $t(\text{lept})$ results in the kinematic of the parton incoming to the primary vertex, named CM . This parton represents the center-of-mass system of the interaction.

Figure 7.2.57: 68% cutoff value for the matching quality $\Sigma\Delta R$ between generated partons and reconstructed objects for the muon 7.2.57(a) and the electron 7.2.57(b) channel of simulated semileptonic top quark pair events. Only quantities of events with good matching quality (grey area) are used as input to the likelihood method that is used to resolve the ambiguities in the jet-parton-assignment.

b -tagged jet to the parton $b(\text{had})$ in the later analysis.

The second variable in the likelihood method for the reconstruction of the hadronic branch is the mass of the W boson $W(\text{had})$. The distributions for matched events (see figure 7.2.59(a) for the muon channel and figure 7.2.59(b) for the electron channel) both peak at 80 GeV, as ex-

Figure 7.2.58: Input distributions for the likelihood method to resolve ambiguities in the semileptonic production of top-antitop-quark pairs in the Parton Picture Template reconstructing the ‘hadronic branch’ for events with three jets and one charged lepton. Figure 7.2.58(a) shows the probability of the jets matched to parton b(hadr) to be tagged as originating from a b hadron decay for the muon analysis, figure 7.2.58(b) shows the same quantity for the electron analysis.

pected. The tails of the distributions, especially towards higher values of reconstructed $W(\text{hadr})$ masses, come from events where the wrong jets are matched to the parton, despite the matching quality cut.

Figure 7.2.59: Input distributions for the likelihood method to resolve ambiguities in the semileptonic production of top quark-antitop-quark pairs in the Parton Picture Template reconstructing the ‘hadronic branch’ for events with three jets and one charged lepton. Figure 7.2.59(a) shows the reconstructed mass of the W boson $W(\text{hadr})$ for the muon analysis, figure 7.2.59(b) shows the same quantity for the electron analysis.

For the reconstruction of the Parton Picture Template for the ‘leptonic branch’ as shown in figure 7.2.56 four variables are used as input to the likelihood method that resolves the ambiguities in the assignment of reconstructed objects to the partons of the Parton Picture Template. The probability of the jet matched to the generated parton b(lept) to be tagged as originating from a b hadron decay is the first variable used in the likelihood method and can be seen in fig-

ure 7.2.60(a) for events with a muon in the final state and in figure 7.2.60(b) for events with an electron in the final state. In both cases the probability for the jet to be tagged by the b-tagging algorithm is more than 50%, reflecting the efficiency of the algorithm.

Figure 7.2.60: Input distributions for the likelihood method to resolve ambiguities in the semileptonic production of top quark-antitop-quark pairs in the Parton Picture Template reconstructing the ‘leptonic branch’ for events with three jets and one charged lepton. Figure 7.2.60(a) shows the probability of the jets matched to the generated parton b(lept) to be tagged as a b-jet for the muon channel analysis, figure 7.2.60(b) shows the same quantity for the electron channel analysis.

The cosine of the angle between the W boson boosted to the rest frame of the top quark and the lepton, boosted to the rest frame of the W boson, is a handle to choose the correct solution for the z component of the neutrino momentum. This distribution is shown in figure 7.2.61(a) for the muon channel and in figure 7.2.61(b) for the electron channel.

Figure 7.2.61: Input distributions for the likelihood method to resolve ambiguities in the semileptonic production of top quark-antitop-quark pairs in the Parton Picture Template reconstructing the ‘leptonic branch’ for events with three jets and one charged lepton. Cosine of the angle between the W boson, boosted to the top quark rest frame, and the charged lepton, boosted to the W boson’s rest frame is shown in figure 7.2.61(a) for muon events, and in figure 7.2.61(b) for electron events.

The invariant mass of the two jets that are not used to form the top quark $t(\text{lept})$ is also used as input to the likelihood method. The distributions for the muon channel events in figure 7.2.62(a) and for the electron channel events in figure 7.2.62(b) have two maxima. The first one at 80 GeV results from those events where the b quark of the top decay branch with the hadronic decay of the W boson into two quarks is missing. Then, the two jets not matched to $b(\text{lept})$ come from the hadronic decay of the W boson and their invariant mass peaks at 80 GeV. The other component of this distribution with the broader shape peaks at 130 GeV and results from events where one of the two quarks from the W boson decay is missing, i.e. it is the invariant mass of a jet matched to one of the two quarks from the W boson decay and a jet matched to the b quark from the hadronic decay branch.

Figure 7.2.62: Input distributions for the likelihood method to resolve ambiguities in the semileptonic production of top-antitop-quark pairs in the Parton Picture Template reconstructing the ‘leptonic branch’ for events with three jets and one charged lepton. The invariant mass of the two jets not matched to parton $b(\text{lept})$ is shown in figure 7.2.62(a) for the analysis in the muon channel and in figure 7.2.62(b) for the analysis in the electron channel.

Finally, a variable called ‘Ht measure’ is used. It is calculated as the scalar sum of the transverse energies of the lepton, the jet matched to parton $b(\text{lept})$ and the missing transverse energy:

$$\text{Ht measure} = E_t(\text{lepton}) + \text{MEt} + E_t(b(\text{lept})). \quad (7.2.3)$$

The resulting distribution for the muon channel is shown in figure 7.2.63(a), the one for the electron channel in figure 7.2.63(b).

The efficiency of the likelihood method is determined for each Parton Picture Template individually by comparing the configuration with the highest likelihood value with the configuration obtained from the matching of the reconstructed objects with the partons from the generator. The events used for the calculation of the efficiencies always contain the subsample that corresponds to the Parton Picture Template. Events where the generated parton $b(\text{lept})$ could not be matched with a reconstructed jet are taken into account for the efficiency of the reconstruction of the Parton Picture Template in the ‘hadronic branch’ (see figure 7.2.55). The efficiency of the likelihood method for the reconstruction of the ‘leptonic branch’, shown in figure 7.2.56, is calculated from events where either the parton $b(\text{hadr})$ or the one of the two quarks from the hadronic decay of the W boson could not be matched with a reconstructed jet. The efficiencies

Figure 7.2.63: Input distributions for the likelihood method to resolve ambiguities in the semileptonic production of top quark-antitop-quark pairs in the Parton Picture Template reconstructing the ‘leptonic branch’ for events with three jets and one charged lepton. The distributions show the Ht measure in the leptonic branch for events with a muon in the final state (see figure 7.2.63(a)) and for events with an electron in the final state (see figure 7.2.63(b)).

	muon channel	electron channel
$\epsilon_{68}[\%]$	64.4	58.2
$\epsilon_{100} [\%]$	58.2	51.5

Table 7.2.6: Efficiencies ϵ_{68} and ϵ_{100} of the likelihood method for the reconstruction of the ‘hadronic branch’ for the muon channel analysis and the electron channel analysis.

ϵ_{68} and ϵ_{100} , as described in definition 6.2.1, are summarized in table 7.2.6 for the ‘hadronic branch’ and in table 7.2.7 for the ‘leptonic branch’ for both the muon channel analysis and the electron channel analysis.

The probability to find the correct event configuration by chance is 33.3% for both Parton Picture Templates. The efficiencies are above 50% for all channels, reaching up to 64.4% for ϵ_{68} in the muon channel in the reconstruction of the ‘hadronic branch’.

7.2.3.2 Observables for Boosted Decision Trees

The event configuration with the highest likelihood value is selected in both reconstructed Parton Picture Templates. Variables from these configurations are then used as input to the Boosted

	muon channel	electron channel
$\epsilon_{68}[\%]$	62.7	60.6
$\epsilon_{100} [\%]$	59.7	57.6

Table 7.2.7: Efficiencies ϵ_{68} and ϵ_{100} of the likelihood method for the reconstruction of the ‘leptonic branch’ for the muon channel analysis and the electron channel analysis.

Decision Tree analyses in the different analysis bins. The comparison of these variables between observed data and the background model is presented in the following paragraphs.

Events with three jets, one b-tagged jet, and one muon

The variables used in the multivariate analysis from the reconstruction of the two Parton Picture Templates in this analysis bin with events containing three jets, one b-tagged jet, and one muon are shown in figure 7.2.64 to figure 7.2.66. Overall, the agreement of the observed data with the background model is very good and the variables presented here can be used in the statistical analysis.

From the reconstructed top quark $t(\text{hadr})$ of the ‘hadronic branch’, the mass (see figure 7.2.64(a)) and the transverse momentum (see figure 7.2.64(b)) are used as input to the Boosted Decision Trees. The mass distribution is very broad. The maximum of the distribution can be found at 175 GeV, the value used in the generator. In the background distribution, the components from top quark pair production show on average higher masses than the background from W boson production, associated by jets. The shape of the single top quark background is similar to the background of top quark pair production. In the transverse momentum distribution, the spectrum for the signal sample is harder than for the combined background sample. The signal distribution has its maximum at 60 GeV, whereas the background distribution peaks at 30 GeV. Events from the multijet background can be found at low values of transverse momentum. For the top quarks $t(\text{lept})$ reconstructed from the ‘leptonic branch’ Parton Picture Template, a similar statement can be made (see figure 7.2.64(c)).

Figure 7.2.64: Mass (figure 7.2.64(a)) and transverse momentum (figure 7.2.64(b)) for the reconstructed top quarks $t(\text{hadr})$ of the ‘hadronic branch’ Parton Picture Template. Figure 7.2.64(c) shows the transverse momentum of the reconstructed top quark $t(\text{lept})$ of the ‘leptonic branch’ Parton Picture Template. All histograms show events with three jets, one b-tagged jet, and one isolated muon.

The transverse momentum distribution of jets assigned to parton $b(\text{hadr})$ in the ‘hadronic branch’ is shown in figure 7.2.65(a). The maximum of the distribution is located at 25 GeV for both signal and background events. In the region between 30 GeV and 70 GeV the slope of the distribution for the background events is steeper than for the signal events. Figure 7.2.65(b) shows the transverse momentum of the reconstructed W boson $W(\text{lept})$ for the ‘hadronic branch’. The maximum of the distribution for background events can be found at 25 GeV,

whereas the signal distribution peaks at 50 GeV. The multijet background accumulates at low transverse momentum values.

Figure 7.2.65: Figure 7.2.65(a) shows the transverse momentum distribution of jets assigned to parton b(hadr) and figure 7.2.65(b) displays the transverse momentum distribution of the reconstructed W bosons W(lept). Both distributions are extracted from event configurations from the reconstruction of the ‘hadronic branch’ and contain events with three jets, one b-tagged jet, and one isolated muon.

Figure 7.2.66 contains events from the reconstruction of the Parton Picture Template in the ‘leptonic branch’. The transverse momentum distribution of jets assigned to parton b(lept) can be found in figure 7.2.66(a). The total background distribution has its maximum at 25 GeV, dominated by the production of W bosons associated by jets. The shapes for the signal events of electroweak top quark production and the background of top quark pair production are similar. They remain rather flat between 30 GeV and 70 GeV, before they start to drop. The mass of the dijet system is shown in figure 7.2.66(b). The distribution is similar for signal and background events, both with a maximum at 75 GeV. Figure 7.2.66(c) shows the result of the likelihood method used to identify the most likely event configuration in the ‘leptonic branch’ Parton Picture Template. The events from the production of top quark pairs in the semileptonic channel are shifted towards higher values of the likelihood value. This confirms the good performance of the likelihood method in resolving the ambiguities, since this PaxProcess was trained to identify decays of top quark pair production in the semileptonic channel. The distribution of single top quark signal events is almost flat over the widest range of the distribution.

Events with three jets, two b-tagged jets, and one muon

In events with three jets, two of them tagged as originating from the decay of a b hadron, missing transverse energy and one isolated muon, the background of multijet production is suppressed because of the requirement of two b-tagged jets. Because of this requirement, this analysis bin suffers from low statistics. However, it is still possible to obtain variables from the reconstruction of the two Parton Picture Templates that show a good agreement between observed data and simulated background model. These variables are shown in figures 7.2.67 to 7.2.70.

From the top quark t(hadr), reconstructed in the ‘hadronic branch’ Parton Picture Template, the mass (see figure 7.2.67(a)) and the transverse momentum (see figure 7.2.67(b)) are used in

Figure 7.2.66: The transverse momentum distribution of jets assigned to parton b(left) is shown in figure 7.2.66(a). Figure 7.2.66(b) displays the mass of the dijet system and in figure 7.2.66(c) the result of the likelihood method for the selected event configuration is shown. All variables are obtained from the reconstruction of the Parton Picture Template in the ‘leptonic branch’ for events with three jets, one b-tagged jet, and one isolated muon.

the Boosted Decision Tree analysis. The mass distribution is very broad for both signal and background events. The maximum of the distribution can be found at 175 GeV, the value used in the generator. Events from the production of a W boson, associated by jets, can be found predominantly at lower mass values. The high region of the mass distribution is dominated by events from top quark pair production. The slope of the falling edge of the distribution is much steeper for background than for signal events. Figure 7.2.67(b) shows the transverse momentum distribution of the reconstructed top quarks $t(\text{hadr})$. The maximum of the distribution is at 50 GeV. Again, events from top quark pair production dominate the region of high transverse momentum values of the background distribution, while events from the production of a W boson with jets contribute the most to the region of lower transverse momenta.

Figure 7.2.67: Mass (figure 7.2.67(a)) and transverse momentum (figure 7.2.67(b)) of the reconstructed top quarks $t(\text{hadr})$ from the Parton Picture Template reconstructing the ‘hadronic branch’. Both distributions show events with three jets, two of them tagged as b-jets, and one isolated muon.

The variables shown in figure 7.2.68 are also obtained by the reconstruction of the ‘hadronic branch’ Parton Picture Template. Figure 7.2.68(a) shows the mass of the reconstructed W boson $W(\text{hadr})$. The distribution peaks at 80 GeV and is similar for both signal and background

events, except, that the maximum of the signal distribution is broader. The transverse momentum distribution of the reconstructed W bosons $W(\text{lept})$ can be seen in figure 7.2.68(b). The distribution peaks at 45 GeV for the signal component, and at 60 GeV for the combined background distribution. The shapes of the distributions are similar for background and signal events. A shape difference can be seen in figure 7.2.68(c) in the transverse momentum distribution of jets assigned to parton $b(\text{hadr})$, especially when comparing the single top quark signal distribution with events from top quark pair production. The signal distribution is rather flat between 20 GeV and 60 GeV, whereas the distribution of the events from top quark pair production rises up to 60 GeV. Hence, the background distribution is dominated by events from top quark pair production in the region of high transverse momentum, while events from the production of a W boson accompanied by jets accumulate in the region of low transverse momentum.

Figure 7.2.68: Three variables obtained by the reconstruction of the ‘hadronic branch’ Parton Picture Template are shown: figure 7.2.68(a) displays the mass of the W boson $W(\text{hadr})$, figure 7.2.68(b) the transverse momentum of the reconstructed W boson $W(\text{lept})$, and figure 7.2.68(c) the transverse momentum of jets assigned to parton $b(\text{hadr})$. All distributions contain events with three jets, two b-tagged jets, and one isolated muon.

The transverse momentum of the reconstructed top quark $t(\text{lept})$ from the reconstruction of the ‘leptonic branch’ Parton Picture Template is shown in figure 7.2.69(a). Both signal and background distribution peak at 55 GeV. The region below the maximum is dominated by background of events from the production of W bosons accompanied by jets. Above 55 GeV the main background component are events from top quark pair production. The distribution for the signal events differs from the total background distribution the most in the region of transverse momenta. There, the slope of the background distribution is steeper. In the region around the maximum, the background distribution has a more distinct peak structure. In figure 7.2.69(b) the result of the likelihood method for the selected event configuration is presented. The Pax-Process is trained to identify top quark pair events in the semileptonic channel. The success of the training can be seen in the distribution, where on average, those events can be found at higher likelihood values.

The variables shown in figure 7.2.70 are also obtained from the reconstruction of the ‘leptonic branch’ Parton Picture Template. The transverse momentum distribution of jets assigned to parton $b(\text{lept})$ is displayed in figure 7.2.70(a). The single top quark signal distribution has its maximum at 55 GeV, with a tail towards higher transverse momenta. The background distribution peaks at 65 GeV, if one neglects the maximum at 25 GeV, that is due to the limited statistics

Figure 7.2.69: The transverse momentum of the reconstructed top quark t (left) from the reconstruction of the ‘leptonic branch’ Parton Picture Template is shown in figure 7.2.69(a). Figure 7.2.69(b) displays the result of the likelihood method for the selected event configuration in the ‘leptonic branch’. Both distributions contain events with three jets, two of them tagged as b -jets, and one isolated muon.

and high event weights of the multijet events. The region of high transverse momentum is dominated by the background of top quark pair production, whereas the low transverse momentum region is accumulated from the production of W bosons with jets. The mass of the dijet system in the ‘leptonic branch’ is shown in figure 7.2.70(b). The signal events peak at 80 GeV, and their distribution remains flat afterwards up to 120 GeV. In the background distribution, the component from top quark pair production in the semileptonic channel rises up to 120 GeV and dominates the high end of the distribution. In the region below 100 GeV, predominantly events from the production of W bosons with jets can be found.

Figure 7.2.70: Transverse momentum of jets assigned to parton b (left) in the ‘leptonic branch’ Parton Picture Template (figure 7.2.70(a)) and mass of the dijet system (figure 7.2.70(b)) for events with three jets, two of them b -tagged, and one isolated muon.

Events with three jets, one b -tagged jet, and one electron

For events with three jets, one of them tagged as originating from the decay of a b hadron, missing transverse energy, and one isolated electron, the comparison of observed data with the

background model for variables obtained from the reconstruction of the two Parton Picture Templates can be seen in figures 7.2.71 to 7.2.73. For those variables, the agreement is good. Thus, they can be used in the statistical analysis.

The mass of the reconstructed top quark $t(\text{hadr})$ from the reconstruction of the ‘hadronic branch’ is shown in figure 7.2.71(a). The distributions for signal events and the background from top quark pair production in the semileptonic channel have their maximum at 175 GeV. The distribution of the whole background peaks at 140 GeV. The lower mass range is dominated by multijet events and events from the production of a W boson accompanied by jets. The falling edge of the background distribution is steeper than for the signal events of electroweak top quark production. The transverse momentum distribution for the reconstructed top quarks can be seen in figure 7.2.71(b) for $t(\text{hadr})$ of the ‘hadronic branch’ and in figure 7.2.71(c) for the top quark $t(\text{lept})$ in the hadronic branch. In both cases, the signal distribution peaks at 60 GeV, at a higher value than the background distribution. Especially the multijet background has very low transverse momentum values of the top quarks. Towards higher values of transverse momentum, the contribution of top quark pair production in the semileptonic channel becomes more and more important.

Figure 7.2.71: The mass of the reconstructed top quark $t(\text{hadr})$ is shown in figure 7.2.71(a). The mass of its equivalent in the reconstruction of the ‘leptonic branch’, $t(\text{lept})$, is shown in figure 7.2.71(b). The transverse momentum of the latter can be seen in figure 7.2.71(c). All distributions contain events with three jets, one b-tagged jet, and one isolated electron.

The transverse momentum distribution of jets assigned to parton $b(\text{hadr})$ in the Parton Picture Template of figure 7.2.55 is shown in figure 7.2.72(a), and the transverse momentum of the reconstructed W boson $W(\text{lept})$ in figure 7.2.72(b). The first distribution peaks at 25 GeV for both signal events and background model. The background component of top quark pair production in the semileptonic channel is dominant at high transverse momenta, whereas multijet events and the production of W bosons with accompanied by jets can be found in the low transverse momentum region. The transverse momentum of the reconstructed W bosons $W(\text{lept})$ is on average higher for signal events than for background events. The slope of the rising edge is much steeper for the background model.

From the reconstruction of the Parton Picture Template in the ‘leptonic branch’, the three variables shown in figure 7.2.73 are used in the statistical analysis. Figure 7.2.73(a) shows the transverse momentum distribution of jets assigned to parton $b(\text{lept})$. The maxima of the

Figure 7.2.72: The transverse momentum distribution of jets assigned to parton b(hadr) is shown in figure 7.2.72(a). Figure 7.2.72(b) displays the transverse momentum distribution of the reconstructed W bosons W(lept). Both histograms contain events with three jets, one of them tagged as originating from the decay of a b hadron, and one isolated electron.

distributions are located at 25 GeV for the background model and at 45 GeV for the signal events of electroweak top quark production. Between 20 GeV and 60 GeV the signal distribution remains rather flat, whereas the background distribution rises up to its maximum and then starts to fall rapidly. The mass of the dijet system of the two quarks not connected to the top quark decay chain is shown in figure 7.2.73(b). The distribution is similar for signal and background events and has its maximum at 80 GeV. In figure 7.2.73(c) the result of the likelihood method can be seen for the selected event configuration. The events of the background component of top quark pair production in the semileptonic channel have on average higher values than the other physics processes. The majority of the multijet events can be found in the first bin of the distribution, already. The distribution for the signal events of single top quark production is rather flat over a wide range of values.

Figure 7.2.73: Figure 7.2.73(a) shows the transverse momentum distribution for jets assigned to parton b(lept) in the Parton Picture Template reconstructing the ‘leptonic branch’. The mass of the dijet system can be seen in figure 7.2.73(b). Figure 7.2.73(c) displays the result of the likelihood method for the selected event configuration in the ‘leptonic branch’. All distributions contain events with three jets, one of them tagged as a b-jet, and one isolated electron.

Events with three jets, two b-tagged jets, and one electron

Due to the requirement that two out of three jets should be identified as originating from the decay of a b hadron, the analysis bin with three jets, missing transverse energy and an isolated electron is poor in multijet events. The overall small statistics make this a challenging analysis bin. However, the variables shown in figures 7.2.74 to 7.2.77 show an acceptable agreement in the comparison of observed events with the expected background model and can thus be used as input to the statistical analysis.

Figure 7.2.74 shows two properties of the reconstructed top quarks $t(\text{had})$ from the reconstruction of the ‘hadronic branch’ of the Parton Picture Template. The mass distribution of these top quarks can be seen in figure 7.2.74(a). The distribution is very broad. The maximum for the signal events is located at 170 GeV, the background distribution peaks at 190 GeV. The tail of the background distribution for mass values higher than 200 GeV is dominated by top quark pair production in the semileptonic channel. In the region of low reconstructed top quark masses the background component of the production of W bosons with jets can predominantly be seen. The transverse momentum distribution of the reconstructed top quarks $t(\text{had})$ is similar for the background events and the simulated signal sample (see figure 7.2.74(b)).

Figure 7.2.74: Mass (figure 7.2.74(a)) and transverse momentum (figure 7.2.74(b)) of the reconstructed top quarks $t(\text{had})$ from the Parton Picture Template reconstructing the ‘hadronic branch’. Both histograms contain events with three jets, two of them tagged as b-jets, and one isolated electron.

The mass of the reconstructed W boson $W(\text{had})$ can be seen in figure 7.2.75(a). The maximum of the distribution is at 85 GeV. The peak of the single top quark signal distribution is broader than in the background distribution. Towards higher mass values, the background component of top quark pair production in the semileptonic channel dominates the background shape. For the reconstructed W boson $W(\text{lep})$, the transverse momentum distribution is shown in figure 7.2.75(b). The distribution is similar for signal and background events. However, shape differences can be found in the distribution shown in figure 7.2.75(c), the transverse momentum distribution of jets assigned to parton $b(\text{had})$. The maximum of the signal distribution is at 25 GeV, but the distribution remains rather flat up to a value of 60 GeV, before it starts to drop. The background distribution of top quark pair production in the semileptonic channel rises up to a value of 75 GeV and then starts to dominate the tail of the total background distri-

bution. Events from the production of W bosons with jets are accumulated at lower transverse momenta.

Figure 7.2.75: The mass of the reconstructed W boson $W(\text{hadr})$ is shown in figure 7.2.75(a). Figure 7.2.75(b) displays the transverse momentum distribution of the W boson $W(\text{lept})$, and in figure 7.2.75(c) the transverse momentum distribution of jets assigned to parton $b(\text{hadr})$ is shown. The histograms contain events with three jets, two of them are tagged as b-jets, and one isolated electron.

Figure 7.2.76(a) displays the transverse momentum distribution for the reconstructed top quarks $t(\text{lept})$ obtained from the Parton Picture Template of the ‘leptonic branch’. The spectrum is harder for the background events, dominated by the top quark pair production in the semileptonic channel for high transverse momenta. The signal distribution peaks at 55 GeV. The result of the likelihood method in the ‘leptonic branch’ is shown in figure 7.2.76(b). A clear trend of the events from top quark pair production in the semileptonic channel towards higher likelihood values is visible. The distribution for the single top quark signal events is flat over a wide range of the distribution.

Figure 7.2.76: The transverse momentum of the top quarks $t(\text{lept})$ from the reconstruction of the Parton Picture Template in the ‘leptonic branch’ is shown in figure 7.2.76(a). Figure 7.2.76(b) shows the result of the likelihood method for the selected event configuration. Both distributions contain events with three jets, two of them tagged as b-jets, and one isolated electron.

Figure 7.2.77(a) shows the transverse momentum distribution of jets assigned to parton $b(\text{lept})$ in the ‘leptonic branch’ Parton Picture Template. At 45 GeV the distribution of the

signal events reaches its maximum. The background peaks already at 35 GeV. In the region of low transverse momenta the production of W bosons with jets and the production of top quark pairs in the dilepton channel contribute the most to the background shape. Towards high transverse momenta, the top quark pair production in the semileptonic channel contributes the most. A good candidate variable for the separation of top quark pair production in the semileptonic channel from the electroweak top quark signal events is the variable shown in figure 7.2.77(b), the mass of the dijet system. The signal distribution has its maximum at 80 GeV, for top quark pair production the distribution rises up to a value of 110 GeV.

Figure 7.2.77: The transverse momentum distribution of jets assigned to parton b(left) is shown in figure 7.2.77(a). Figure 7.2.77(b) displays the invariant mass of the dijet system in the reconstruction of the ‘leptonic branch’. Both distributions contain events with three jets, two tagged as originating from the decay of a b hadron, and one isolated electron.

68% matching quality cut for	
muons	electrons
0.27	0.23

Table 7.2.8: 68% matching quality cut in $\Sigma\Delta R$ for the muon and the electron channel in simulated dilepton top quark pair events with three jets.

7.2.4 Decay of Top Quark Pairs in Dilepton Events

The Parton Picture Template for the reconstruction of dilepton top quark pair production in events with three jets, one charged lepton and missing transverse energy is shown in figure 7.2.78. Due to the event selection there is only one charged lepton in the reconstructed events, where one would expect two charged leptons from the leptonic decay of the two W bosons. Therefore, this Parton Picture Template can only reconstruct one top quark, called t(found). The reasons why there remain dilepton top quark pair events in the sample after the selection cuts were applied were investigated for the muon channel in [227]. One of the three jets is selected to play the role of the parton b(found). This parton and the W boson labeled W(found) are the decay particles of the top quark. The W boson then decays further into a charged lepton and a neutrino. The supplement ‘found’ indicates that this decay branch is reconstructed using the one lepton that was reconstructed in the events. The parton b(lost) represents the b-quark from the top quark decay branch where the charged lepton is not part of the reconstructed event. An additional third jet, labeled jet(add), is also connected to the primary vertex, together with the partons b(lost) and t(found). This jet has its origin in initial state or final state radiation, from multiple collisions, or the underlying event. The vector sum of the three partons connected to the primary vertex results in the kinematics of a parton called CM, representing the center-of-mass system of the interaction.

7.2.4.1 Ambiguity Resolution

There are twelve possible configurations in the assignment of reconstructed objects to partons for this Parton Picture Template. All configurations are evaluated in a likelihood method in the later analysis step. The input variables to this likelihood method come from generator studies. There, the reconstructed objects from the simulation are matched with the information of the generated partons. This matching procedure results in the best possible of all twelve configuration. To ensure that the resulting distributions for the dilepton top quark pair production are not affected by misreconstructed jets or jets from the underlying event, a quality cut on $\Sigma\Delta R$, the sum over the distances between the reconstructed objects and the generated parton they are matched to, is applied. Only quantities of the 68% best matched events are taken into account. Studying the muon and the electron channel independently, two different cutoff values are obtained. For the muon channel all matched events with $\Sigma\Delta R < 0.27$ are considered in the likelihood method, for the electron channel all matched events with $\Sigma\Delta R < 0.23$ are considered. The cutoff values in $\Sigma\Delta R$ are summarized in table 7.2.8 and visualized in figure 7.2.79(a) for the muon channel and in figure 7.2.79(b) for the electron channel.

The reconstruction of the decay chain with the best possible matching of reconstructed objects to generated partons has a pitfall for the dileptonic decay of top quark pairs in events with

Figure 7.2.78: Parton Picture Template reconstructing a dilepton top quark pair decay in events with three jets, one charged lepton and missing transverse energy. Because of the missing second charged lepton it is not possible to reconstruct the whole top quark pair decay. Therefore, the decay of one top quark named $t(\text{found})$ is reconstructed. The supplement denotes the branch in the top quark pair decay to which the charged lepton reconstructed in the event belongs. The top quark decays into a W boson $W(\text{found})$ and a b quark named $b(\text{found})$. The W boson then decays further into the charged lepton and a neutrino. A second jet is associated with a b quark $b(\text{lost})$, where ‘lost’ indicates that this b quark originates from the top decay where the charged lepton of the subsequent decay of the W boson was not reconstructed. A third jet named $\text{jet}(\text{add})$ represents an additional jet that was produced as initial or final state radiation. The top quark, the b quark $b(\text{lost})$, and the additional jet $\text{jet}(\text{add})$ are connected to a primary vertex. The vector sum of these three objects results in the kinematics for the incoming parton to the primary vertex, named CM , representing the center-of-mass system of the interaction.

Figure 7.2.79: 68% cutoff value for the matching quality $\Sigma\Delta R$ between generated partons and reconstructed objects in simulated muon 7.2.79(a) and electron 7.2.79(b) events of dilepton top quark pair production. Only quantities of events with good matching quality (grey area) are used as input to the likelihood method that is used to resolve the ambiguities in the jet-parton-assignment.

three jets, missing transverse energy and only one charged lepton. The reconstructed missing transverse momentum has its origin from two neutrinos. However, due to the missing charged lepton it is only possible to reconstruct one W boson using a mass constraint. Taking the whole missing transverse energy into account leads to wrong kinematics of the W boson. Therefore, the measured missing transverse energy is corrected before the W boson is reconstructed. The correction uses generator information of the W boson from the decay branch where the charged lepton was not detected. The values for the missing transverse energy ME_{x_f} and ME_{y_f} that are used in the quadratic equation to be solved in order to get the z component of the neutrino momentum are calculated in the following way:

$$ME_{x_f} = ME_{x_r} - P_x(W(\text{lost})), \quad (7.2.4)$$

$$ME_{y_f} = ME_{y_r} - P_y(W(\text{lost})). \quad (7.2.5)$$

Here, ME_{x_r} and ME_{y_r} denote the reconstructed x and y components of the missing transverse energy after detector simulation. $P_x(W(\text{lost}))$ and $P_y(W(\text{lost}))$ denote the x and y component of the generated W boson that cannot be reconstructed due to the missing second charged lepton. The kinematics of the generated W boson is used instead of the momentum components of the generated neutrino because in this way the contribution of the missing charged lepton to the reconstructed missing transverse energy is also taken into account.

The five variables used in the likelihood method to resolve the ambiguities are also described in [227] for the muon channel, but are repeated here for completeness and to be able to compare them with the additional analysis in the electron channel. The probability of the additional jet jet(add) to be tagged as originating from a b hadron is shown in figure 7.2.80(a) for the muon analysis and in figure 7.2.80(b) for the electron analysis. Almost all jets that are matched to parton jet(add) leave the b-tagging algorithm as untagged jets, as one would expect from their origin from initial or final state radiation.

The transverse momentum of the jets matched to parton jet(add) is also used as input to the likelihood method. The distribution in figure 7.2.81(a) displays the input for the muon channel analysis and figure 7.2.81(b) the one for the analysis in the electron channel. In both cases jets are matched that have a rather low transverse momentum, the maximum is at 30 GeV for both analysis channels.

The cosine of the angle between the W boson boosted to the rest frame of the top quark and the lepton, boosted to the rest frame of the W boson is a handle to choose the correct solution for the z component of the neutrino momentum. It takes into account both the reconstructed W boson and the reconstructed top quark. The distribution is shown in figure 7.2.82(a) for the muon channel and in figure 7.2.82(b) for the electron channel.

The distance ΔR between the jet matched to parton b(found) and the charged lepton is another variable that is used as input to the likelihood method. The distribution for the muon channel is shown in figure 7.2.83(a), the one for the electron channel in figure 7.2.83(b).

The pseudorapidity η of the reconstructed top quark t(found) is the fifth variable used to resolve ambiguities in the assignment of reconstructed objects and partons. Because the kinematic

Figure 7.2.80: Input distributions for the likelihood method to resolve ambiguities in the Par-ton Picture Template for dilepton top quark pair events with three jets and one charged lepton. Figure 7.2.80(a) shows the probability for the jets matched to parton jet(add) to be tagged as originating from a b hadron for the analysis in the muon channel. Figure 7.2.80(b) shows the same quantity for the events in the electron channel.

Figure 7.2.81: Input distributions for the likelihood method to resolve ambiguities in the Par-ton Picture Template for dilepton top quark pair events with three jets and one charged lepton. The transverse momentum for jets matched with parton jet(add) is shown in figure 7.2.81(a) for the analysis in the muon channel and in figure 7.2.81(b) for the analysis in the electron channel.

quantities of the reconstructed top quark are affected by both the reconstructed W boson (i.e. the choice of the z component of the neutrino momentum) and the jet assigned to b(found), the top quark's pseudorapidity is a good variable to be used in the likelihood method. Both for muon events (figure 7.2.84(a)) and electron events (figure 7.2.84(b)) the pseudorapidity distribution of the top quarks from the matching of reconstructed objects to generated partons is symmetric with a maximum at 0.

The efficiency of the likelihood method is determined by comparing the configuration with the highest likelihood value with the configuration obtained from the matching of the reconstructed objects with the partons from the generator. The efficiencies ϵ_{68} and ϵ_{100} , as described in definition 6.2.1, are summarized in table 7.2.9 for the muon channel analysis and the electron

Figure 7.2.82: Input distributions for the likelihood method to resolve ambiguities in the Parton Picture Template for dilepton top quark pair events with three jets and one charged lepton. These distributions show the cosine of the angle between the W boson in the top quark rest frame and the lepton boosted into the rest frame of the W boson for the muon channel (figure 7.2.82(a)) and the electron channel (figure 7.2.82(b)).

	muon channel	electron channel
$\epsilon_{68} [\%]$	44.8	37.3
$\epsilon_{100} [\%]$	40.8	33.9

Table 7.2.9: Efficiencies ϵ_{68} and ϵ_{100} of the likelihood method for the muon channel analysis and the electron channel analysis.

channel analysis. The probability to find the correct event configuration by chance is 16.7%. The efficiencies of the likelihood methods for the reconstruction of this Parton Picture Template are at least twice as high, reaching up to 44.8% for ϵ_{68} in the muon channel analysis.

7.2.4.2 Observables for Boosted Decision Trees

In the reconstruction of this Parton Picture Template, the same challenge has to be faced as in the Parton Picture Template for the PaxProcess with two jets in section 7.1.3: a way to reconstruct the neutrino kinematics is needed in order to reconstruct the top quark $t(\text{found})$. The attempt to solve this issue used here is discussed in [227] and will only be briefly summarized for completeness. At least two neutrinos contribute to the missing transverse energy for events from top quark pair production in the dilepton channel. In the selected events for this analysis, there is only one reconstructed charged lepton, i.e. the second one escaped detection. Thus, this undetected charged lepton also contributes to the missing transverse energy. In events where generator information was used to match the reconstructed objects to the generated partons, it is possible to approximate the neutrino kinematics using generator information of the W boson that was lost. The components p_i^ν of the neutrino momentum vector can be calculated according to equations 7.2.4 and 7.2.5. This method to calculate the neutrino kinematics has been used in the reconstruction of the event configuration that matched the reconstructed objects with the generated partons, i.e. the event configurations the input variables to the likelihood method

(a)

(b)

Figure 7.2.83: Input distributions for the likelihood method to resolve ambiguities in the Parton Picture Template for dilepton top quark pair events with three jets and one charged lepton. The distributions display the distance ΔR between the jet matched to parton b(found) and the charged lepton that was found in the event. In figure 7.2.83(a) this lepton is a muon, in figure 7.2.83(b) the same quantity is shown for the case where the charged lepton is an electron.

have been derived from.

The method used to approximate the x (y) component of p_x^ν (p_y^ν) of the neutrino momentum in the data analysis tries to minimize the fluctuations between the reconstructed neutrino momentum vector and the generated value. Therefore, values d_x and d_y are optimized according to

$$\Delta p_i^\nu = p_i - \frac{\text{ME}_i}{d_i}, \quad (7.2.6)$$

with $i = x, y$ and p_i being the neutrino momentum components from the generator for the neutrino that is used to reconstruct the parton W(found) in the Parton Picture Template. The values d_i are scanned in small steps from 1 to 8. For all events fulfilling the matching criterion of table 7.2.8, the values Δp_i^ν are calculated. The root mean square (RMS) of the resulting distribution for each value d_i is stored in a histogram. Figure 7.2.85(a) shows the distribution of these RMS values for different values of d_x for the p_x^ν component of the neutrino for the analysis in the muon channel. In figure 7.2.85(b) the same distribution is shown for the analysis in the electron channel.

Figure 7.2.84: Input distributions for the likelihood method to resolve ambiguities in the Parton Picture Template for dilepton top quark pair events with three jets and one charged lepton. The distribution of the pseudorapidity η of the reconstructed top quark t (left) is shown for events in the muon channel analysis in figure 7.2.84(a) and for events in the electron channel analysis in figure 7.2.84(b).

Figure 7.2.85: Root mean square of the histograms obtained by calculating $\Delta p_x^\nu = p_x - \frac{ME_x}{d_x}$ for events in the muon channel analysis (figure 7.2.85(a)) and the electron channel analysis (figure 7.2.85(b)) for different values of d_x .

For the variation of d_y in the calculation of Δp_y^ν , the distribution for the muon channel can be found in figure 7.2.86(a) and for the electron channel in figure 7.2.86(b).

In both analysis channels, the RMS distributions of the differences Δp_x^ν and Δp_y^ν have a minimum in the scanned range of d_x and d_y . At these points, the fluctuation between the approximated momentum vector and the true neutrino momentum (taken from generator information) are minimal.

The histograms of the mean values of the Δp_x^ν distributions are shown in figures 7.2.87(a) and 7.2.87(b) for the different values of d_x for the muon channel analysis and the electron channel analysis, respectively.

For Δp_y^ν the distributions of the mean value depending on different values of d_y are shown in figure 7.2.88(a) for the muon channel and in figure 7.2.88(b) for the analysis in the electron channel.

Figure 7.2.86: Root mean square of the histograms obtained by calculating $\Delta p_y^\nu = p_y - \frac{ME_y}{d_y}$ for events in the muon channel analysis (figure 7.2.86(a)) and the electron channel analysis (figure 7.2.86(b)) for different values of d_y .

Figure 7.2.87: Mean of the histograms obtained by calculating $\Delta p_x^\nu = p_x - \frac{ME_x}{d_x}$ for events in the muon channel analysis (figure 7.2.87(a)) and the electron channel analysis (figure 7.2.87(b)) for different values of d_x .

For the analysis in the muon channel, the mean of the Δp_y^ν distribution is much more shifted than for the analysis in the electron channel. This is most likely a feature of the so-called ‘muon hole’ of the DØ detector, a region where the efficiency to detect a muon is lower because one layer of muon chambers is replaced by a support structure of the detector. Muons pointing in this detector region will thus contribute to the y component of missing transverse energy reconstruction.

The optimal values for d_x and d_y are those values where the RMS distribution has its minimum. At these points, the fluctuations between the approximated p_i^ν momentum components and the true components are minimal. To also take the shift in the mean value of the Δp_i^ν distribution into account, this mean value is drawn versus the RMS value of the distribution for each value of d_x and d_y . The shift can then be identified as the value on the y -axis of the leftmost point in the distribution. The resulting distributions for the x components can be found in figure 7.2.89(a) for the muon channel and in figure 7.2.89(b) for the electron channel. The corresponding figures for the y component are shown in figure 7.2.90(a) for the analysis in the

Figure 7.2.88: Mean of the histograms obtained by calculating $\Delta p_y^\nu = p_y - \frac{ME_y}{d_y}$ for events in the muon channel analysis (figure 7.2.88(a)) and the electron channel analysis (figure 7.2.88(b)) for different values of d_y .

Muon channel		Electron channel	
d_x	d_y	d_x	d_y
2.90	2.90	2.75	2.95
Shift in x [GeV]	Shift y [GeV]	Shift in x [GeV]	Shift in y [GeV]
0.1	4.0	0.1	1.6

Table 7.2.10: This table summarizes the results of the optimization of the parameters d_x and d_y and the shifts of the mean value in the Δp_i^ν ($i = x, y$) distributions for the two analysis channels.

muon channel and in figure 7.2.90(b) for the analysis in the electron channel.

Figure 7.2.89: The mean values of the Δp_x^ν distributions for different values of d_x drawn versus the RMS of these distributions for the analysis in the muon channel (see figure 7.2.89(a)) and the analysis in the electron channel (see figure 7.2.89(b)).

The results for the values of d_i and for the shifts of the mean value for the two analysis channels are presented in table 7.2.10.

Using the values, p_x^ν and p_y^ν of the neutrino that is used together with the charged lepton

Figure 7.2.90: The mean values of the Δp_y^ν distributions for different values of d_y drawn versus the RMS of these distributions for the analysis in the muon channel (see figure 7.2.90(a)) and the analysis in the electron channel (see figure 7.2.90(b)).

in order to reconstruct the W boson $W(\text{found})$ during the reconstruction of the Parton Picture Template can be approximated as

$$p_x^\nu = \frac{ME_x}{2.90} - 0.1 \text{ GeV} \quad (7.2.7)$$

$$p_y^\nu = \frac{ME_y}{2.90} - 4.0 \text{ GeV} \quad (7.2.8)$$

in the analysis in the muon channel and as

$$p_x^\nu = \frac{ME_x}{2.75} - 0.1 \text{ GeV} \quad (7.2.9)$$

$$p_y^\nu = \frac{ME_y}{2.95} - 1.6 \text{ GeV} \quad (7.2.10)$$

for the analysis in the electron channel.

Using this approach for the approximation of the x and y momentum components of the neutrino, it is now possible to reconstruct the Parton Picture Template of figure 7.2.78. All four possible event configurations can be created and evaluated in the likelihood method. The configuration with the highest likelihood value is then used to obtain variables for the multivariate analysis. The comparisons between the observed data events and the background model for these variables are shown in the following paragraphs for the four different analysis bins.

Events with three jets, one b-tagged jet, and one muon

In the analysis bin with three jets, one of them tagged as originating from the decay of a b hadron, missing transverse energy and one isolated muon, four variables are taken into account for the analysis with Boosted Decision Trees. The comparison of simulated background events with the observed data is shown in figure 7.2.91 and figure 7.2.92. These variables are chosen because of their very good agreement in this comparison.

Figure 7.2.91(a) displays the mass of the reconstructed top quark $t(\text{found})$. The maximum of the background distribution is at 130 GeV, whereas the signal peaks at approximately 150 GeV. The difference between this reconstructed value and the value of 175 GeV, which was used in the generator, can be explained with the difficulties to reconstruct the correct neutrino momentum vector. The multijet background sits at low values of reconstructed top quark masses and peaks at 130 GeV. The transverse momentum distribution of these top quarks can be seen in figure 7.2.91(b). The distribution peaks at 55 GeV for both signal and background events. The falling edge of the distribution is steeper for the background events than for the signal events.

Figure 7.2.91: Mass (figure 7.2.91(a)) and transverse momentum (figure 7.2.91(b)) of the reconstructed top quarks $t(\text{found})$ for events with three jets, one of them tagged as a b-jet, and one isolated muon.

The transverse momentum distributions of jets assigned to partons $b(\text{found})$ and $\text{jet}(\text{add})$ are shown in figure 7.2.92(a) and figure 7.2.92(b), respectively. The spectrum for jets assigned to parton $b(\text{found})$ is harder for the events of electroweak top quark production than for the background events. The slope of the rising edge of the distribution is a lot steeper for the background distribution. The signal distribution reaches its maximum at 55 GeV. For the additional jet, the transverse momentum distributions are very similar for both signal and background events. The maximum of the distribution is reached in both cases at 25 GeV.

Events with three jets, two b-tagged jets, and one muon

Three variables from the reconstruction of this Parton Picture Template are used in the statistical analysis for the analysis bin with three jets, two of them tagged as originating from the decay of a b hadron, missing transverse energy and an isolated muon. The agreement between observed data and the background model is good, despite the limited statistics.

The mass of the reconstructed top quark $t(\text{found})$ is the first variable and shown in figure 7.2.93(a). The distribution for the signal events peaks at 160 GeV, together with the background events from top quark pair production. Events from the production of a W boson accompanied by jets are found at lower mass values, leading to a steeper rising edge of the distribution for the combined background. Figure 7.2.93(b) displays the transverse momentum distribution of jets assigned to parton $b(\text{found})$. The shapes for the signal and the background distributions

Figure 7.2.92: The transverse momentum distribution of jets assigned to parton b(found) can be seen in figure 7.2.92(a). Figure 7.2.92(b) shows the same quantity for the additional jet in the event. Both histograms contain events with three jets, one of them tagged as originating from the decay of a b hadron, and one isolated muon.

are very similar. In both cases the distribution peaks at 45 GeV. In figure 7.2.93(c) the transverse momentum distribution of the additional jet is presented. Again, the distributions are very similar for signal and background events, with a maximum at 25 GeV.

Figure 7.2.93: The mass of the reconstructed top quark $t(\text{found})$ is shown in figure 7.2.93(a). Figure 7.2.93(b) displays the transverse momentum of jets assigned to parton b(lept), the same quantity is shown for the additional jets in figure 7.2.93(c). These are the distributions from the reconstruction of this Parton Picture Template that are used in the statistical analysis for events with three jets, two b-tagged jets, and one isolated electron.

Events with three jets, one b-tagged jet, and one electron

In the analysis bin with three jets, one of them tagged as originating from the decay of a b hadron, missing transverse energy, and one isolated electron, four variables are used in the Boosted Decision Tree analysis. Their comparison between observed data and the background model is shown in figures 7.2.94 and 7.2.95. Their distributions agree well within the statistical precision.

The mass of the reconstructed top quark $t(\text{found})$ is shown in figure 7.2.94(a). Events from

the single top quark signal sample and from top quark pair production have distributions that peak at 150 GeV. The background from multijet events and from the production of W bosons accompanied by jets reconstruct much lower masses. Figure 7.2.94(b) shows the transverse momentum distribution of these top quarks $t(\text{found})$. Both signal and background distributions peak around 60 GeV. The multijet events are the dominant contributions to the background shape at low transverse momentum values.

Figure 7.2.94: The mass of the reconstructed top quark $t(\text{found})$ is shown in figure 7.2.94(a), its transverse momentum distribution in figure 7.2.94(b) for events with three jets, one b-tagged jet, and one isolated electron.

The transverse momentum distribution of the jets assigned to parton $b(\text{found})$ is shown in figure 7.2.95(a). The same property for the additional jet can be found in figure 7.2.95(b). The spectrum for the jets assigned to parton $b(\text{found})$ is harder for the signal sample of electroweak top quark production than for the background events. At low transverse momenta, events from the production of W bosons with jets and multijet events can be found. The maximum of the signal distribution is at 45 GeV.

Figure 7.2.95: Transverse mass distributions of jets assigned to parton $b(\text{found})$ (figure 7.2.95(a)) and jets assigned to the additional jet (figure 7.2.95(b)) for events with three jets, one of them tagged as a b-jet, and one isolated electron.

Events with three jets, two b-tagged jets, and one electron

For the analysis bin with three jets, two of them tagged as originating from the decay of a

b hadron, missing transverse energy, and an isolated electron, three variables are used as input to the Boosted Decision Tree analysis. They show a good agreement within the statistical precision of this analysis bin in the comparison of observed data and background model.

The first variable is the mass of the reconstructed top quark $t(\text{found})$ (see figure 7.2.96(a)). The signal distribution peaks at 160 GeV, the distribution for the background component of top quark pair production at 175 GeV, i.e. at the value used in the generator. However, the distribution is broad, with tails towards high values of reconstructed top quark masses. Figure 7.2.96(b) shows the transverse momentum distribution for jets assigned to parton b(found) of the Parton Picture Template. The events from top quark pair production in the semileptonic channel dominate the high transverse momentum region of the background distribution. The falling edge has a steeper slope for the total background, compared to the single top quark signal events. Both the signal and the background distribution have their maximum at 45 GeV. The transverse momentum distribution of the additional jet can be seen in figure 7.2.96(c). The hardest spectrum comes from events from top quark pair production in the semileptonic channel. In the region of low transverse momentum in the background distribution events from the production of W boson events with jets can be found. The maxima of the total background distribution and the signal distribution agree and are located at 25 GeV.

Figure 7.2.96: The mass of the reconstructed top quark $t(\text{found})$ is shown in figure 7.2.96(a). The transverse momentum distributions of jets assigned to parton b(found) and the additional jet can be seen in figure 7.2.96(b) and figure 7.2.96(c), respectively. All three distributions contain events with three jets, two of them tagged as b-jets, and one isolated electron.

7.2.5 Global Event Observables

This section deals with variables that are calculated from the properties of the reconstructed final state objects in an event passing the selection criteria, only. Hence, there are no ambiguities that need to be resolved as for the other PaxProcesses. However, a Parton Picture Template is used and reconstructed in order to have access to some of the observables. This Parton Picture Template is displayed in figure 7.2.97. There are three jets in an event. They are ordered by decreasing transverse momentum and labeled with jet1, jet2, and jet3 (with jet1 being the jet with the highest transverse momentum). The vector sum of these jets builds a new four-vector, the so-called *Hadronic Final State* (HFS). This HFS four-vector is then connected to the primary vertex of the event. The charged lepton and the reconstructed missing transverse energy of the event are used to reconstruct a W boson. This is done using a W boson mass constraint to get a z component for the neutrino momentum vector. The x and y component of this vector are taken from the reconstructed missing transverse energy components. From the two solutions for the z component of the neutrino momentum, the more central solution is used, i.e. the solution with the smaller absolute value of pseudorapidity η .

7.2.5.1 Observables for Boosted Decision Trees

In the following, the variables used in the statistical analysis with Boosted Decision Trees are presented for the four different analysis bins.

Events with three jets, one b-tagged jet, and one muon

The variables used in the multivariate analysis for events with three jets, one b-tagged jet, and one muon are shown in figure 7.2.98 to figure 7.2.115. Overall, the agreement of the observed data with the background model is good and these variables presented here can be used in the statistical analysis.

Figure 7.2.98(a) shows the mass of the HFS. Its transverse momentum can be seen in figure 7.2.98(b). For the mass, the background distribution starts steeper, dominated by events from the production of a W boson, accompanied by jets, and reaches its maximum earlier than the distribution from the single top quark signal events. The background distribution peaks at 150 GeV, the signal events at 175 GeV. Background events from top quark pair production can be found towards higher HFS masses. The transverse momentum spectrum is harder for the electroweak production of top quarks than for the background events. For the signal events, it peaks at 55 GeV, whereas the background distribution has its maximum at 35 GeV.

The angle between the HFS and the leading jet, jet1, is shown in figure 7.2.99(a). Both the HFS and jet1 were boosted into the center-of-mass reference frame. The signal distribution peaks at 0.7 rad, the background distribution already at 0.5 rad. The scalar sum of the transverse energy of the muon and the missing transverse energy can be seen in figure 7.2.99(b). The shapes of the signal and background distributions are very similar. The main difference is in the first few bins, where the multijet background accumulates.

Figure 7.2.97: Parton Picture Template for the PaxProcess that calculates event shape variables.

Although there are no ambiguities to be resolved, a Parton Picture Template is reconstructed in the event. The three jets are ordered by their transverse momentum and a new four-vector called Hadronic Final State (HFS) is built as the vector sum of these jets. This HFS four-vector and the four-vector for the reconstructed W boson are connected to the primary vertex. For the reconstruction of the W boson the z component of the neutrino momentum needs to be calculated. This is done by using the quadratic equation one gets from a W boson mass constraint and selecting the solution with the smaller pseudorapidity η . The W boson that is reconstructed from the neutrino and the charged lepton is then also connected to the primary vertex.

Figure 7.2.98: Mass (figure 7.2.98(a)) and transverse momentum (figure 7.2.98(b)) for the HFS for events with three jets, one of them tagged as a b-jet, and one isolated muon.

Figure 7.2.99: The angle between the HFS and jet1, both boosted into the center-of-mass reference frame, is shown in figure 7.2.99(a). The scalar sum of the transverse energy of the muon and the missing transverse energy is shown in figure 7.2.99(b). Both distributions contain events with three jets, one of them tagged as originating from the decay of a b hadron, and one isolated muon.

Figure 7.2.100(a) shows the transverse momentum distribution for the ‘best jet’ according to definition 6.2.3. The background distribution has two maxima. One at 25 GeV, the second one at 55 GeV, separated by a minimum at 35 GeV. Up to 35 GeV, the distribution for the signal events of electroweak top quark production is flat. Then it starts rising and reaches its maximum also at 55 GeV. In figure 7.2.100(b) the transverse momentum distribution of the weaker one of the two untagged jets is shown. A falling spectrum can be seen both for the combined background events and for the signal events. The background distribution is dominated by events from the production of W bosons accompanied by jets in the region of low transverse momentum. Towards higher transverse momenta, the background of top quark pair production in the semileptonic channel becomes important.

Figure 7.2.100: Transverse momentum distribution of the ‘best jet’ (figure 7.2.100(a)) and of the weakest, untagged jet (figure 7.2.100(b)) for events with three jets, one of them tagged as a b-jet, and an isolated muon.

The mass of the ‘b-tagged top quark’, as introduced in definition 6.2.6, peaks at 175 GeV for the signal events, i.e. at the value used in the generator. The distribution of the background events peaks at 120 GeV, dominated by events from the production of W bosons with jets. The

background from top quark pair production also peaks at 175 GeV. Figure 7.2.100(b) shows the ' $q \times \eta$ ' variable according to definition 6.2.7. While for the background events, this distribution is symmetric around 0, for the signal events the asymmetry is clearly visible and the maximum of the distribution is at +1.

Figure 7.2.101: Figure 7.2.101(a) displays the mass of the 'b-tagged top quark'. The ' $q \times \eta$ ' distribution is shown in figure 7.2.101(b). Both histograms contain events with three jets, one of them tagged as a b-jet, and one isolated muon.

The cosine of the angle between jet2 and the muon, both boosted into the rest frame of the 'b-tagged top quark', is shown in figure 7.2.102(a). The distribution is flat and similar for both signal and background events. In the same reference frame, the cosine of the angle between the leading jet of the two jets, not tagged as a b-jet, and the muon is calculated. The resulting distribution can be found in figure 7.2.102(b). For signal events, the distribution has a steep slope from low to high values, whereas the background distribution is only rising slowly.

Figure 7.2.102: Cosine of the angle between jet2 and the muon, measured in the rest frame of the 'b-tagged top quark' (figure 7.2.102(a)). Figure 7.2.102(b) shows the cosine of the angle between the leading untagged jet and the muon in the same reference frame. Both distributions show events with three jets, one of them tagged as a b-jet, and one isolated muon.

H , the scalar sum of energies of jets, is shown in figure 7.2.103 for three different jet configurations. For the first distribution in figure 7.2.103(a) all three jets of the event are taken into account. For the distribution in figure 7.2.103(b) all jets except for the 'best jet' (according to

definition 6.2.3) are taken into account, and in figure 7.2.103(c) the jet that was tagged as a b-jet is neglected. In all three cases, the signal distribution peaks at a higher value than the combined background distribution. However, considering only events from top quark pair production in the semileptonic channel, higher values of H are reconstructed.

Figure 7.2.103: Three variations of the calculation of H : using all jets (figure 7.2.103(a)), using all but the ‘best jet’ (figure 7.2.103(b)), and using all but the b-tagged jet (figure 7.2.103(c)). All distributions contain events with three jets, one of them tagged as a b-jet, and one isolated muon.

The scalar sum of the transverse momenta of the of the reconstructed objects is called Ht . Three different combinations of reconstructed objects are shown in the distributions in figure 7.2.104. Ht calculated from all three jets in the event can be seen in figure 7.2.104(a). The distribution in figure 7.2.104(b) also adds the transverse momentum of the muon and the missing transverse energy. In figure 7.2.104(c) the result of the calculation is shown using only two of the three jets, by neglecting the ‘best jet’. All three distributions show a similar characteristic. The maximum of the signal distribution is higher than for the combined background distribution. However, the individual background component of top quark pair production can be found at higher Ht values.

Figure 7.2.104: Three different versions in the calculation of Ht : taking only all three jets into account (figure 7.2.104(a)), using also information of the muon and missing transverse energy (figure 7.2.104(b)), and taking only two jets into account, neglecting the ‘best jet’ (figure 7.2.104(c)). All three distributions show events with three jets, one b-tagged jet, and one isolated muon.

The transverse momentum and the transverse mass of the W boson are shown in figure 7.2.105(a) and figure 7.2.105(b), respectively. The transverse momentum is on average

higher for the single top quark signal sample, than for the combined background sample. Especially the multijet background can be found at low transverse momentum values. Also for the transverse mass of the W boson, the multijet background can be found at the low end of the distribution. For values higher than 40 GeV, the shapes of the signal and background distributions are similar.

Figure 7.2.105: Transverse momentum (figure 7.2.105(a)) and transverse mass (figure 7.2.105(b)) of the W boson for events with three jets, one of them tagged as a b-jet, and one isolated muon.

The invariant mass of all jets, except for the ‘best jet’, is shown in figure 7.2.106(a). At the falling edge of the distribution, the slope of the background is steeper than for the signal events. The background events from top quark pair production in the semileptonic channel have the highest invariant mass on average. Figure 7.2.106(b) displays the invariant mass of jet1, jet2, and the W boson. Events of electroweak top quark production peak at 250 GeV, 25 GeV higher than the total background distribution. While at low invariant masses, the multijet background resides, at higher invariant masses the background from top quark pair production becomes more and more important.

Figure 7.2.106: Figure 7.2.106(a) shows the invariant mass of all jets except the ‘best jet’. In figure 7.2.106(b) the invariant mass of jet1, jet2, and the W boson can be seen. Both distributions contain events with three jets, one of them tagged as a b-jet, and one isolated muon.

The sum over the transverse momenta of all jets but the one that is tagged as a b-jet is shown in

figure 7.2.107(a). Both the distributions for the signal events and the background events peak at 45 GeV with the background distribution having the steeper falling edge. The transverse mass of jet1 and jet2 can be seen in figure 7.2.107(b). The maximum of the distribution of signal events is at 95 GeV. The background distribution rises faster and reaches its maximum already at 60 GeV. The region of low transverse masses is dominated by events from the production of a W boson accompanied by jets. The spectrum for the background of semileptonic top quark pair production is harder than the one of the signal sample.

Figure 7.2.107: The sum of the transverse momenta of all jets except the one jet that is tagged as a b-jet is shown in figure 7.2.107(a). The transverse mass of the jet1-jet2 combination is displayed in figure 7.2.107(b). Both distributions contain events with three jets, one of them tagged as originating from the decay of a b hadron, and one isolated muon.

The observable $\hat{S}$ is described in equation 7.1.8. Its distribution in this analysis bin can be found in figure 7.2.108(a). The falling edge of the distribution is steeper for the background events, because of the background from top quark pair production that can be found at higher $\hat{S}$ values. The sphericity of the event, calculated from all jets and the W boson has the same maximal value of 0.24 for signal and background events (see figure 7.2.108(a)). The falling edge of the distribution has a steeper slope for the background events.

The transverse momentum and the pseudorapidity distribution for jet1 are displayed in figure 7.2.109(a) and figure 7.2.109(b), respectively. The transverse momentum spectrum for the signal events of electroweak top quark production is on average harder than for the combined background events. It peaks at 70 GeV, 10 GeV higher than the background distribution. The pseudorapidity distribution is symmetric around $\eta = 0$ for all contributing physics processes.

In figure 7.2.110 the same properties as for jet1 are displayed for jet2. The transverse momentum distribution in figure 7.2.110(a) has a maximum at 40 GeV for both signal and background events. However, the peak of the background distribution is much broader. The background of semileptonic top quark pair production has the hardest transverse momentum spectrum of all contributing physics processes. The pseudorapidity distribution is symmetric around $\eta = 0$. The background events have a more distinct peak structure at $\eta = 0$ than the signal events.

For jet3, the transverse momentum distribution can be found in figure 7.2.111(a) and the pseudorapidity distribution in figure 7.2.111(b). Again, the transverse momentum spectrum is soft for events from the production of a W boson accompanied by jets. The hardest spectrum

Figure 7.2.108: The distribution of the $\hat{S}$ variable, is shown in figure 7.2.108(a). Figure 7.2.108(b) shows the sphericity of the event, calculated from the three jets and the W boson. Both distributions contain events with three jets, one b-tagged jet, and an isolated muon.

Figure 7.2.109: Transverse momentum (figure 7.2.109(a)) and pseudorapidity η (figure 7.2.109(b)) of the leading jet in the event. The histograms show events with three jets, one of them b-tagged, and one isolated muon.

comes from events from top quark pair production in the semileptonic channel. The shape of the distribution for the signal events and the total background are similar. In pseudorapidity, the distributions are symmetric around $\eta = 0$. However, the distributions do not show a peak structure, but a broad plateau in the region of $|\eta| < 1$.

The mass and the transverse momentum of the dijet system built by jet1 and jet2 are shown in figures 7.2.112(a) and 7.2.112(b). The rising edge of the mass distribution for the background events is steeper than for the signal events of electroweak top quark production. The origin of this feature are events from the production of W bosons accompanied by jets that accumulate at low mass values. The background of top quark pair production peaks at the same value as the signal events, at 120 GeV. The transverse momentum spectrum of this dijet system is harder for the signal events. The maximum of the distribution is located at 65 GeV.

The missing transverse energy is shown in figure 7.2.113(a). Multijet events can be found at the low region of the distribution. The maximum of the distribution is the same for the total background distribution and the signal events. The distribution of the SEt variable, according

Figure 7.2.110: Transverse momentum (figure 7.2.110(a)) and pseudorapidity η (figure 7.2.110(b)) for jet2 in events with three jets, one of them tagged as a b-jet, and one isolated muon.

Figure 7.2.111: Transverse momentum (figure 7.2.111(a)) and pseudorapidity η (figure 7.2.111(b)) for jet3 in events with three jets, one of them tagged as a b-jet, and one isolated muon.

Figure 7.2.112: Mass (figure 7.2.112(a)) and transverse momentum (figure 7.2.112(b)) of the dijet system of jet1 and jet2 for events with three jets, one of them tagged as a b-jet, and one isolated muon.

to definition 7.1.9, is shown in figure 7.2.113(b). It has a maximum at 180 GeV. The first few bins of the background distribution are filled with multijet events or events from the production of a W boson accompanied with jets, only. The background of top quark pair production has the highest SEt values on average. Its maximum is at 230 GeV.

Figure 7.2.113: Missing transverse energy (figure 7.2.113(a)) and SEt (figure 7.2.113(b)) for events with three jets, one b-tagged jet, and an isolated muon.

The scalar sum over the transverse energies of the final state objects in the event, Ht , is shown in figure 7.2.114(a), the sum over their scalar energies, H , in figure 7.2.114(b). The maximum of the signal distribution for Ht is 20 GeV higher than for the background events and peaks at 210 GeV. The background of semileptonic top quark pair production has on average the highest Ht values, with its distribution peaking at 270 GeV. The maximum of the signal distribution in H is at 340 GeV. The maximum of the background distribution is a broad region between 270 GeV and 360 GeV.

Figure 7.2.114: Ht and H of all reconstructed final state objects are shown in figure 7.2.114(a) and figure 7.2.114(b), respectively. Both distributions contain events with three jets, one of them tagged as a b-jet, and one isolated muon.

The aplanarity (see equation 7.1.14) and the sphericity of the event (see equation 7.1.15) are shown in figures 7.2.115(a) and 7.2.115(b). The shape of the aplanarity distribution is similar for both the signal events of electroweak top quark production and the background events. For sphericity, the distribution of the signal events of electroweak top quark production starts to drop earlier than the background distribution. The latter has then a steeper slope of the falling

edge. The spatial distance ΔR between jet1 and jet2 is shown in figure 7.2.115(c). Again, the distribution for signal and background events look similar. There are almost no events where the two jets are close to another. The maximum of the distribution can be found at a value of $\Delta R = 3$.

Figure 7.2.115: The event shape variables aplanarity and sphericity are shown in figure 7.2.115(a) and figure 7.2.115(b), respectively. The spatial distance ΔR between the two leading jets of the event can be seen in figure 7.2.115(c). All histograms contain events with three jets, one b-tagged jet, and one isolated muon.

Events with three jets, two b-tagged jets, and one muon

Variables used in the multivariate analysis for events with three jets, two of them tagged as originating from the decay of a b hadron, missing transverse energy and one isolated muon are shown in figures 7.2.116 to 7.2.132. In this analysis bin, the statistical precision is limited because of the requirement of two b-tagged jets. The important backgrounds are the production of W bosons, associated by two b-quarks, and both top quark pair processes, i.e. top quark pair production in the semileptonic channel and in the dilepton channel. Despite the limited statistics, there are variables that show a reasonable agreement between the expected background model and the observed data distributions and can thus be used in the Boosted Decision Tree analysis.

The mass of the HFS (see figure 7.2.116(a)) and its transverse momentum (see figure 7.2.116(b)) are used as input to the statistical analysis. The mass peaks at 170 GeV for both the signal events of electroweak top quark production and the background events. The region of low mass values is dominated by events from the production of W bosons accompanied by jets, in the region of high masses events from the production of top quark pairs become more important, leading to a steeper slope of the falling edge of the distribution for the combined background shape. The shape of the transverse momentum distribution is similar for signal and background events. It has its maximum at 55 GeV.

The angle between the HFS and jet1 in the center-of-mass reference frame is shown in figure 7.2.117(a). The signal events of single top quark production have on average a slightly larger angle than the background events. For the scalar sum of the missing transverse energy

Figure 7.2.116: Mass (figure 7.2.116(a)) and transverse momentum (figure 7.2.116(b)) of the HFS for events with three jets, two b-tagged jets, and one isolated muon.

and the transverse energy of the lepton the signal distribution peaks at a lower value than the distribution for the background events. The maximum of the background distribution is at 95 GeV, 10 GeV above the events of the signal sample.

Figure 7.2.117: The angle between the HFS and jet1 in the center-of-mass reference frame is shown in figure 7.2.117(a). The scalar sum of the missing transverse energy and the transverse energy of the muon is displayed in figure 7.2.117(b). Both distributions contain events with three jets, two of them tagged as originating from the decay of a b hadron, and one isolated muon.

The mass of the ‘b-tagged top quark’ (according to definition 6.2.6) is shown in figure 7.2.118(a). The background distribution has a slightly higher mean value, but both signal and background distributions have their maximum around 175 GeV. Figure 7.2.118(b) displays the transverse momentum of the ‘best jet’ (see definition 6.2.3). The maximum for the signal events is at 55 GeV. The high transverse momentum region in the background model is dominated by events from semileptonic top quark pair production, the region of low transverse momentum by $Wb\bar{b}$ production. The ‘ $q \times \eta$ ’ variable, as introduced in definition 6.2.7, hardly shows any asymmetry for the signal events. The background distribution is symmetric around 0.

The cosine of the angle between jet2 and the muon in the rest frame of the ‘b-tagged top quark’ is shown in figure 7.2.119(a). In the same reference frame, the cosine of the angle

Figure 7.2.118: The mass of the ‘b-tagged top quark’ is shown in figure 7.2.118(a). Figure 7.2.118(b) shows the transverse momentum spectrum of the ‘best jet’, and in figure 7.2.118(c) the ‘ q times η variable can be seen. All histograms contain events with three jets, two of them tagged as originating from the decay of a b hadron, and one isolated muon.

between the untagged jet and the muon is measured (see figure 7.2.119(b)). In both cases the background distribution is flat, whereas the distribution for the signal events is slightly rising towards higher values.

Figure 7.2.119: The angular correlation between jet2 and the muon (figure 7.2.119(a)) and the untagged jet and the muon (figure 7.2.119(b)) measured in the rest frame of the ‘b-tagged top quark’ for events with three jets, two b-tagged jets, and an isolated muon.

The scalar sum of the energies of the jets, H , in the event is calculated with three different jet contributions. Figure 7.2.120(a) shows the measurement if all three jets are taken into account. In figure 7.2.120(b), the ‘best jet’ is omitted in the calculation, and in figure 7.2.120(c) the ‘b-tagged jet’ (according to definition 6.2.4) is neglected. A similar statement can be made for all three distributions. The signal distributions of electroweak top quark production have their maximum at a lower value of H than the background model and a long tail towards higher values.

The sum over the transverse momenta in an event, Ht , is calculated for three different configurations of contributing reconstructed particles. Figure 7.2.121(a) shows the distribution that takes all jets of an event into account. In figure 7.2.121(b) also the missing transverse energy

Figure 7.2.120: Calculation of H taking into account all three jets (figure 7.2.120(a)), all jets except the ‘best jet’ (figure 7.2.120(b)) and all jets except the ‘b-tagged jet’ (figure 7.2.120(c)) for events with three jets, two of them tagged as originating from the decay of a b hadron, and one isolated muon.

and the isolated muon are considered. Only two jets are used in the calculation shown in figure 7.2.121(c), omitting the ‘best jet’. In all three distributions, the single top quark signal peaks at a lower value of Ht than the background model. There, the component of $Wb\bar{b}$ production can be found in the region of low Ht values. The region of high Ht values is dominated by the process of top quark pair production in the semileptonic channel.

Figure 7.2.121: Ht distribution for all jets (figure 7.2.121(a)), all jets, lepton and missing transverse energy (figure 7.2.121(b)) and all jets omitting the ‘best jet’ (figure 7.2.121(c)) for events with three jets, two of them tagged as a b-jet, and one isolated muon.

The invariant mass distribution of two jets, where the ‘best jet’ is neglected, is shown in figure 7.2.122(a). In figure 7.2.122(b) the invariant mass distribution for jet1, jet2 and the reconstructed W boson is displayed. Especially the contribution of the semileptonic top quark pair production leads to higher invariant mass values of the background model in both cases. In the second case, the difference between the maximum of the signal distribution (250 GeV) and the maximum of the distribution of top quark pair production is 50 GeV.

The sum over the transverse momenta of the jets of an event, neglecting the ‘b-tagged jet’, is shown in figure 7.2.123(a). On average, this variable has higher values for the background distribution, with events from the production of top quark pairs in the semileptonic decay channel contributing the most to the high region of the distribution. The transverse mass of jet1 and jet2 peaks at 95 GeV for the signal distribution. The background of $Wb\bar{b}$ production can be found

Figure 7.2.122: Invariant mass of two jets, neglecting the ‘best jet’ (figure 7.2.122(a)), and invariant mass of jet1, jet2 and the reconstructed W boson (figure 7.2.122(b)) for events with three jets, two of them tagged as a b-jet, and one isolated muon.

in the lower region of transverse mass, whereas the background of top quark pair production dominates the high transverse mass region, with its maximum at 140 GeV.

Figure 7.2.123: The sum over the transverse momenta of jets, neglecting the ‘b-tagged jet’, is shown in figure 7.2.123(a). Figure 7.2.123(b) displays the transverse mass of jet1 and jet2. Both distributions show events with three jets, two of them tagged as b-jets, and one isolated muon.

There is a big difference in the $\hat{S}$ distribution between the signal distribution and the background model in this analysis bin (see figure 7.2.124(a)). Neglecting the peak introduced by multijet events with a high event weight, the background distribution has its maximum at 360 GeV, about 60 GeV higher than the signal distribution. At low values of $\hat{S}$, the background from $Wb\bar{b}$ production shapes the background distribution predominantly. Above the maximum the production of top quark pair events in the semileptonic channel dominates the shape of the background distribution. Calculating sphericity using information of the three jets in the event and the reconstructed W boson results in the distribution shown in figure 7.2.124(b). While the signal distribution rises only up to a value of 0.25, the background distribution reaches its maximum at a value of 0.35 before it starts to drop.

The transverse momentum of the reconstructed W boson is shown in figure 7.2.125(a). The distribution is similar for signal and background events. The transverse mass of the W boson

Figure 7.2.124: The distribution of the $\hat{S}$ variable is shown in figure 7.2.124(a). The sphericity, calculated from all jets and the reconstructed W boson, is displayed in figure 7.2.124(b). Both distributions contain events with three jets, two of them b-tagged, and one isolated muon.

can be seen in figure 7.2.125(b). There, the distribution for the single top quark signal events has its maximum at 65 GeV. The background distribution peaks at 75 GeV.

Figure 7.2.125: The transverse momentum (figure 7.2.125(a)) and the transverse mass (figure 7.2.125(b)) of the reconstructed W boson are shown for events with three jets, two of them tagged as a b-jet, and one isolated muon.

Figure 7.2.126(a) displays the transverse momentum distribution of the leading jet of the event, jet1. Both signal and background distributions have their maxima at 65 GeV, but due to the hard spectrum of jets from top quark pair production, the background distribution does not fall as fast as the signal distribution. In pseudorapidity η , the distributions are symmetric around $\eta = 0$ for all contributing physics processes (see figure 7.2.126(b)).

The background distribution of the transverse momentum of jet2 (see figure 7.2.127(a)) starts to fall above 35 GeV. The signal distribution has its maximum at 45 GeV. The individual background component of top quark pair production in the semileptonic channel has its maximum at 60 GeV and dominates the background shape in the region of high transverse momenta. In pseudorapidity, the distribution is symmetric around $\eta = 0$ and, especially in the signal sample of electroweak top quark production, rather flat for $|\eta| < 0.7$.

Figure 7.2.126: Transverse momentum (figure 7.2.126(a)) and pseudorapidity η (figure 7.2.126(b)) of jet1 for events with three jets, two b-tagged jets, and one isolated muon.

Figure 7.2.127: Transverse momentum (figure 7.2.127(a)) and pseudorapidity η (figure 7.2.127(b)) of jet2 for events with three jets, two of them tagged as originating from a b hadron decay, and an isolated muon.

The same properties as for jet1 and jet2 are taken into account in the statistical analysis for jet3. The transverse momentum distribution can be found in figure 7.2.128(a). The single top signal distribution has its maximum in the very first bin, already. The total background distribution peaks at 25 GeV, the background from top quark pair production not before 38 GeV. The pseudorapidity distribution of jet3 is symmetric around $\eta = 0$ and flat for $|\eta| < 1.2$.

The mass of the dijet system built by the combination of jet1 and jet2 is shown in figure 7.2.129(a). The distribution peaks at 105 GeV for the single top quark events, with a long tail towards higher masses. The background distribution has its maximum already at 80 GeV, due to the multijet events with their high event weight. The background of top quark pair production in the semileptonic channel peaks at 140 GeV and dominates the background distribution from there on. The transverse momentum distribution of this system can be seen in figure 7.2.129(b). On average, the transverse momentum is higher for the background model.

The missing transverse energy distribution for the signal events peaks at 45 GeV (see figure 7.2.130(a)), approximately 10 GeV higher than the background distribution. The variable SEt , as introduced in equation 7.1.9, shows some power to separate the electroweak top quark

(a)

(b)

Figure 7.2.128: Transverse momentum (figure 7.2.128(a)) and pseudorapidity (figure 7.2.128(b)) for jet3 in an event with three jets, two b-tagged jets, and one isolated muon.

(a)

(b)

Figure 7.2.129: Mass (figure 7.2.129(a)) and transverse momentum (figure 7.2.129(b)) of the combination of jet1 and jet2 in events with a total of three jets, two of them tagged as b-jets, and one isolated muon.

signal from the top quark pair production in the semileptonic channel. The signal distribution peaks at 170 GeV, the combined background distribution at 190 GeV and the beforementioned component of top quark pair production at 230 GeV.

Ht , calculated as the sum over the transverse energies of the reconstructed objects in the event, is shown in figure 7.2.131(a). The signal distribution peaks at 230 GeV and starts to drop for higher Ht values. The background distribution is rather flat between 200 GeV and 340 GeV. The

Figure 7.2.130: Missing transverse energy (figure 7.2.130(a)) and the SEt variable (figure 7.2.130(b)) for events with three jets, two of them tagged as originating from the decay of a b hadron, and one isolated muon.

region of high Ht values is dominated by top quark pair production in the semileptonic channel. The sum over the scalar energies of the reconstructed objects is shown in figure 7.2.131(b). Both signal and background distributions have a plateau around their maxima. For the background model, this plateau is wider.

Figure 7.2.131: Sum over transverse energies of the reconstructed objects in the event (figure 7.2.131(a)) and the sum over their scalar energies (figure 7.2.131(b)) are presented for events with three jets, two of them tagged as a b -jet, and one isolated muon.

The event shape variables aplanarity (see equation 7.1.14) and sphericity (see equation 7.1.15) for this analysis bin are shown in figure 7.2.132(a) and figure 7.2.132(b), respectively. The shape of the aplanarity distributions are similar for the signal events of electroweak top quark production and the background model. The sphericity distribution of the signal events is flat between 0.1 and 0.3. In this region, the background distribution is still rising. The slope of the falling edge of the distribution is then similar for both signal and background events. The spatial difference ΔR between jet1 and jet2 is shown in figure 7.2.132(c). The distributions for signal and background events are similar. There are almost no events in which the two jets are very close. The distributions then rise up to a value of $\Delta R = 3$, before they start to fall for higher values.

Figure 7.2.132: The event shape variables aplanarity and sphericity are shown in figure 7.2.132(a) and figure 7.2.132(b). Figure 7.2.132(c) displays the spatial distance between the two leading jets. All distributions contain events with three jets, two of them tagged as b-jets, and one isolated muon.

Events with three jets, one b-tagged jet, and one electron

Variables used in the statistical analysis for events with three jets, two of them tagged as originating from the decay of a b hadron, missing transverse energy, and one isolated electron are shown in figures 7.2.133 to 7.2.149. In these figures the comparison of the observed data events with the expected background model is shown. Overall, the agreement is very good.

Figure 7.2.133(a) shows the mass of the HFS, figure 7.2.133(b) its transverse momentum distribution. The maximum of the signal distribution is at 170 GeV, 30 GeV higher than the maximum of the distribution of the total background. The region of low masses is dominated by multijet events and background from the production of a W boson accompanied by jets. Towards higher mass values, the background from top quark pair production in the semileptonic channel becomes more and more important. Also in the transverse momentum distribution, the maximum of the distribution for single top quark signal events is at a higher value (at 55 GeV) than for the background model. The background distribution is rising steeper at low transverse momentum values, influenced by the multijet events that can be found in this region.

Figure 7.2.133: Mass (figure 7.2.133(a)) and transverse momentum (figure 7.2.133(b)) of the HFS for events with three jets, one of them tagged as a b-jet, and one isolated electron.

The angle between the HFS and jet1, measured from the center-of-mass reference frame,

is shown in figure 7.2.134(a). The distributions for the signal and the background events are similar for this observable. The sum of the transverse energy of the electron and the missing transverse energy of the event is displayed in figure 7.2.134(b). This variable is a good candidate to separate the signal events from multijet events. The distribution of the latter peaks already at 40 GeV, whereas the maximum of the signal distribution can be found at 85 GeV, at the same value as the total background distribution.

Figure 7.2.134: Figure 7.2.134(a) shows the angle between the HFS and jet1 in the center-of-mass reference frame. The scalar sum of the transverse energy of the electron and the missing transverse energy of the event can be seen in figure 7.2.134(b). Both distributions contain events with three jets, one b-tagged jet, and one isolated electron.

The transverse momentum distribution of the ‘best jet’, according to definition 6.2.3, is shown in figure 7.2.135(a). The background distribution has its maximum at 35 GeV. The dominating background component for high transverse momentum values is the production of top quark pair events in the semileptonic channel. For the signal events of electroweak top quark production, the maximum is a plateau for transverse momentum values between 40 GeV and 60 GeV. The transverse momentum spectrum for the weaker of the two jets, that were not tagged as a b-jet, is displayed in figure 7.2.135(b). The distribution is a falling spectrum with a similar shape for both signal and background events.

The mass of the ‘b-tagged top quark’ (according to definition 6.2.6) peaks at 170 GeV for the signal events of single top quark production (see figure 7.2.136(a)). The individual background component of top quark pair production in the semileptonic channel peaks at the same value. However, the total background distribution has its maximum at 125 GeV, dominated in the low mass region by multijet events and events from the production of W bosons accompanied by jets. The ‘ $q \times \eta$ ’ variable, as introduced in definition 6.2.7, shows the expected asymmetry in the signal distribution, with a maximum at 1. The background distribution is symmetric around 0. The cosine of the angle between the leading jet that is not tagged as a b-jet and the electron is shown in the rest frame of the ‘b-tagged top quark’ in figure 7.2.136(c). Both the distributions of the signal events and of the background events have a positive slope. However, the slope of the signal distribution is steeper.

The sums over the scalar energies, H , of different jet configurations is shown in figure 7.2.137. First, all three jets of the event are taken into account (see figure 7.2.137(a)). The background

Figure 7.2.135: Transverse momentum of the ‘best jet’ (figure 7.2.135(a)) and transverse momentum of the weaker of the two jets not tagged as a b-jet (figure 7.2.135(b)). Both distributions contain events with three jets, one of them tagged as a b-jet, and one isolated electron.

Figure 7.2.136: The mass of the ‘b-tagged top quark’ is shown in figure 7.2.136(a). Figure 7.2.136(b) displays the ‘ $q \times \eta$ ’ variable and in figure 7.2.136(c) the cosine of the angle between the leading jet that is not tagged as a b-jet and the electron is presented (with both objects boosted into the rest frame of the ‘b-tagged top quark’). The three distributions show events with three jets, one b-tagged jet, and one isolated electron.

distribution rises fast because of events from the production of a W boson accompanied by jets and reaches its maximum at 190 GeV. The signal distribution peaks at 210 GeV and has the flatter slope for the falling edge of the distribution. If one neglects the ‘best jet’ (see figure 7.2.137(b)) or the ‘b-tagged jet’ (see figure 7.2.137(c)) from the calculation, the distribution of signal events of electroweak top quark production has its maximum at a higher value and the slope of the falling edge of the distribution is flatter. Towards higher values of H , the background events from top quark pair production in the semileptonic channel become the most significant background contribution.

Summing up the transverse momenta of the reconstructed objects instead of their scalar energies, different combinations of the variable Ht can be calculated. Figure 7.2.138(a) shows the result of the calculation when the transverse momenta of all three jets are used. Taking also the transverse momentum of the electron and the missing transverse energy into account, the distribution shown in figure 7.2.138(b) is obtained. In figure 7.2.138(c) only two jets are used

Figure 7.2.137: The sum over the scalar energies of jets, H , is shown for three different jet configurations: Figure 7.2.137(a) takes all three jets into account, in figure 7.2.137(b) the ‘best jet’ is omitted, and in figure 7.2.137(c) the b-tagged jet is omitted. All distributions contain events with three jets, one of them tagged as originating from the decay of a b hadron, and one isolated electron.

in the calculation, the ‘best jet’ was neglected. In all three cases, the distribution for the signal events has its maximum at a higher Ht value compared to the total background distribution. In the region of low Ht values, the multijet events and the background from the production of W bosons with jets are the dominant background sources. The high values of Ht come from the background of top quark pair production, especially from events in the semileptonic channel.

Figure 7.2.138: Calculation of Ht for three different configurations of contributing objects: for all three jets (figure 7.2.138(a)), for all jets, electron and missing transverse energy (figure 7.2.138(b)), and for only two jets, where the ‘best jet’ is omitted (figure 7.2.138(c)). All distributions show events with three jets, one of them tagged as originating from the decay of a b hadron, and one isolated electron.

The invariant mass of two of the three jets in an event is shown in figure 7.2.139(a). Here, the information of the ‘best jet’ is not taken into account. The distribution peaks at 55 GeV for both signal and background events. The invariant mass of jet1, jet2 and the reconstructed W boson is shown in figure 7.2.139(b). The maximum of the distribution is reached at 240 GeV for both signal and background events. In both cases the background component of multijet events is located at lower invariant mass values, the production of top quark pairs at higher invariant masses. The slope of the falling edge of the distribution is steeper for the background model in both invariant mass distributions.

The transverse momentum of the dijet system in which the b-tagged jet is excluded is

Figure 7.2.139: Invariant mass of two jets, not including the ‘best jet’ in the calculation (figure 7.2.139(a)). Figure 7.2.139(b) displays the invariant mass of jet1, jet2 and the reconstructed W boson. Both histograms contain events with three jets, one of them tagged as a b-jet, and one isolated electron.

shown in figure 7.2.140(a). The distribution is similar for signal and background events. Figure 7.2.140(b) shows $\hat{S}$ of the events (see equation 7.1.8). The maximum for both signal and background events is at 300 GeV. In the background model, events from the production of top quark pairs in the semileptonic decay channel have the highest $\hat{S}$.

Figure 7.2.140: Transverse momentum of the dijet system of the two jets not tagged as a b-jet (figure 7.2.140(a)) and variable $\hat{S}$ (figure 7.2.140(b)) for events with three jets, one of them tagged as a b-jet, and one isolated electron.

The sphericity of the events, calculated from the three jets and the reconstructed W boson, is shown in figure 7.2.141(a). The distributions for the signal events and the background events both have their maximum at 0.2. For values higher than 0.2, the signal distributions drops slightly faster. Figure 7.2.141(b) displays the transverse mass of the combination of jet1 and jet2. The maximum for the signal distribution of electroweak top quark production is at 75 GeV, 10 GeV higher than the background distribution.

The transverse momentum (see figure 7.2.142(a)) and the transverse mass (see figure 7.2.142(b)) of the reconstructed W boson are also used in the statistical analysis. On average, the transverse momentum of the reconstructed W boson is 10 GeV higher for the signal events of electroweak top quark production. The maximum of the signal distribution

Figure 7.2.141: The sphericity of the events, calculated from the three jets and the reconstructed W boson, is shown in figure 7.2.141(a). In figure 7.2.141(b) the transverse mass of the combination of jet1 and jet2 is displayed. Both distributions contain events with three jets, one jet tagged as originating from the decay of a b hadron, and one isolated electron.

is at 55 GeV. The transverse mass of the W boson is a good variable to separate the multijet background from the signal events. The multijet events can be found at the low end of the transverse mass distribution. For transverse masses higher than 50 GeV, the shapes of the signal and background distributions are similar.

Figure 7.2.142: Transverse momentum (figure 7.2.142(a)) and transverse mass (figure 7.2.142(b)) of the reconstructed W boson in events with three jets, one of them b-tagged, and one isolated electron.

On average the transverse momentum of the leading jet in the event is higher for the electroweak top quark sample than for the background model (see figure 7.2.143(a)). The distribution of the signal events peaks at 65 GeV, 15 GeV higher than the background distribution. In pseudorapidity, the distributions are symmetric around $\eta = 0$. The majority of jets is reconstructed in the central region of the detector, i.e. within $|\eta| < 1.0$.

For jet2, the transverse momentum spectrum is shown in figure 7.2.144(a). The background shows a falling spectrum, whereas the simulated signal events peak at 30 GeV. The region of low transverse momenta is dominated by multijet events and events from the production of W bosons with jets. In the high transverse momentum region predominantly events from top

Figure 7.2.143: Transverse momentum and pseudorapidity η of jet1 are shown in figure 7.2.143(a) and figure 7.2.143(b), respectively. The histograms contain events with three jets, one of them tagged as a b-jet, and one isolated electron.

quark pair production can be seen. In pseudorapidity, the distribution for jet2 is symmetric around $\eta = 0$ for all contributing physics processes.

Figure 7.2.144: Transverse momentum (figure 7.2.144(a)) and pseudorapidity η (figure 7.2.144(b)) of jet2 in events with three jets, one of them tagged as a b-jet, and one isolated electron.

The same properties as for jet1 and jet2 are used for jet3 in the Boosted Decision Tree analysis. Here, both signal and background distributions show a falling transverse momentum spectrum (see figure 7.2.145(a)). The pseudorapidity distribution shown in figure 7.2.145(b) is symmetric around $\eta = 0$. In the distribution of the signal events, there is a dip in the region of $|\eta| < 1.0$. The distribution has maxima at $|\eta| \approx 1.1$.

The invariant mass of the dijet system built from jet1 and jet2 can be seen in figure 7.2.146(a). The background distribution peaks at 80 GeV, 20 GeV below the maximum of the signal distribution of single top quark events. Up to an invariant mass of 220 GeV the slope of the falling edge of the background distribution is much steeper than for the signal distribution. In the tail of the distribution, the slopes are approximately equal. On average, the transverse momentum of this dijet system (see figure 7.2.146(b)) is higher for the signal events of electroweak top quark production. Especially events from the production of a W boson accompanied by jets

Figure 7.2.145: Transverse momentum distribution (figure 7.2.145(a)) and pseudorapidity distribution (figure 7.2.145(b)) for jet3 in events with three jets, one of them tagged as a b-jet, and one isolated electron.

and multijet events accumulate the low transverse momentum region, whereas above 100 GeV events from top quark pair production become the dominant background process.

Figure 7.2.146: Mass (figure 7.2.146(a)) and transverse momentum (figure 7.2.146(b)) of the dijet system of jet1 and jet2 for events with three jets, one of them b-tagged, and an isolated electron.

Figure 7.2.147(a) shows the missing transverse energy reconstructed in the events of this analysis bin. The falling edge of the distribution is similar for signal and background events, but the maximum of the distribution for events from electroweak top quark production is 10 GeV higher than for the background events. The signal distribution peaks at 45 GeV. At high missing transverse energies events from top quark pair production in the dilepton channel can be found, due to the higher number of neutrinos in the event. The variable SEt (see equation 7.1.9) is shown in figure 7.2.147(b). In this variable, the signal distribution peaks at 170 GeV, compared to the maximum at 130 GeV for the distribution of the background model. For the background model, the distribution is broader because of the component of top quark pair production that sets in at higher values and compensates the falling distribution of events from the production of W bosons with jets.

Adding also the transverse energy to SEt results in the distribution shown in figure 7.2.148(a). It peaks at 210 GeV for the signal events of electroweak top quark production,

Figure 7.2.147: Missing transverse energy (figure 7.2.147(a)) and SEt distribution (figure 7.2.147(b)) for events with three jets, one of them b-tagged, and one isolated electron.

approximately 20 GeV higher than the total background distribution. Above 300 GeV almost only events from the production of top quark pairs can be found in the background model. Summing up the scalar energies instead of the transverse energies yield the distribution displayed in figure 7.2.148(b).

Figure 7.2.148: The sum over the transverse energies in the event, including the missing transverse energy, is shown in figure 7.2.148(a). Figure 7.2.148(b) displays the distribution obtained by summing up the scalar energies instead. Both distributions contain events with three jets, one of them tagged as a b-jet, and one isolated electron.

The event shape variables aplanarity and sphericity were introduced in equations 7.1.14 and 7.1.15. Their distributions in this analysis bin can be seen in figures 7.2.149(a) and 7.2.149(b). For aplanarity, the distribution for the signal events is flat in the first two bins, whereas the distribution of the background model immediately begins to drop. In sphericity, the shapes are different between simulated signal events and the background model. The signal distribution peaks at 0.14. There, the background distribution is still rising, up to a value of 0.19. The spatial distance ΔR between the two leading jets in an event is shown in figure 7.2.149(c). Both the signal and the background distributions rise up to a value of $\Delta R = 3$, indicating that the probability to find two jets close to another in the η - φ -plane is small.

Figure 7.2.149: The event shape variables aplanarity and sphericity for events with three jets, one of them tagged as a b-jet, and one isolated muon, are shown in figure 7.2.149(a) and figure 7.2.149(b), respectively. The spatial distance ΔR for the two leading jets of the event is displayed in figure 7.2.149(c).

Events with three jets, two b-tagged jets, and one electron

The analysis bin with three jets, two of them tagged as originating from the decay of a b hadron, missing transverse energy and an isolated electron suffers from low statistics, due to the requirement of two b-tagged jets. The variables shown in figures 7.2.150 to 7.2.166 are selected to participate in the statistical analysis because of their reasonable agreement in the comparison of observed data events with the background model, given the statistical precision.

The mass of the HFS and its transverse momentum are shown in figure 7.2.150(a) and figure 7.2.150(b), respectively. On average, the background has higher HFS masses. The maximum of the background distribution is at 190 GeV. The signal events of electroweak top quark production reach their maximum at 170 GeV. The transverse momentum spectrum is similar for both signal and background events. The maximum of the distribution is at 50 GeV, and there are long tails towards higher transverse momenta.

Figure 7.2.150: Mass (figure 7.2.150(a)) and transverse momentum (figure 7.2.150(b)) of the HFS in events with three jets, two of them tagged as b-jets, and one isolated electron.

The angle between the HFS and the leading jet in the event in the center-of-mass reference frame is shown in figure 7.2.151(a). The distributions for signal and background events are

similar. The slope of the background distribution in the falling edge of the spectrum is slightly steeper. The scalar sum of the transverse energy of the electron and the missing transverse energy is displayed in figure 7.2.151(b). The multijet events are accumulated at very low values. At high values, the background events of top quark pair production can be found.

Figure 7.2.151: Angle between the HFS and jet1 in the center-of-mass reference frame (figure 7.2.151(a)) and the scalar sum of the transverse energy of the electron and the missing transverse energy (figure 7.2.151(b)) for events with three jets, two of them tagged as b-jets, and one isolated electron.

The transverse momentum distribution of the ‘best jet’ (according to definition 6.2.3) can be seen in figure 7.2.152(a). The distributions of this transverse momentum spectrum are similar for signal and background events. Both have their maximum at approximately 50 GeV. Figure 7.2.152(b) shows the mass of the ‘b-tagged top quark’ according to definition 6.2.6. The maximum of the signal distribution of events from electroweak top quark production is at 170 GeV, in the same bin as for the background model. Overall, the distribution of the background events is broader.

Figure 7.2.152: Transverse momentum of the ‘best jet’ (figure 7.2.152(a)) and the mass of the ‘b-tagged top quark’ (figure 7.2.152(b)) are shown for events with three jets, two b-tagged jets, and one isolated electron.

The asymmetry in the ‘q times η ’ variable (according to definition 6.2.7) is not as distinct for the signal events as for the analysis bin with only one b-tagged jet (see figure 7.2.153(a)). The distribution for the background events is symmetric around 0 for all contributing physics

processes. The cosine of the angle between the jet that was not tagged as originating from the decay of a b hadron and the electron, both boosted into the rest frame of the ‘b-tagged top quark’, is shown in figure 7.2.153(b). The slope of the distribution for signal events is steeper than the slope for the background events over a wide range of the distribution.

Figure 7.2.153: The ‘ q times η ’ variable is shown in figure 7.2.153(a). Figure 7.2.153(b) displays the cosine of the angle between the jet that was not tagged as a b-jet and the electron in the rest frame of the ‘b-tagged top quark’. Both distributions show events with three jets, two b-tagged jets, and one isolated electron.

The sum of the scalar energies of jets in an event, the variable H , is presented in figure 7.2.154 for three different combinations of jets. The distribution in figure 7.2.154(a) contains all three jets of the event. In figure 7.2.154(b) the ‘best jet’ was omitted and in figure 7.2.154(c) the ‘b-tagged jet’ was omitted in the calculation of H . All three distributions show similar features: the signal events of electroweak top quark production peak at a lower value of H compared to the total background distribution. The high values of H are dominated by the background component of top quark pair production in the semileptonic channel.

Figure 7.2.154: Three different jet configurations in the calculation of H are shown here: in figure 7.2.154(a) all three jets are taken into account, in figure 7.2.154(b) the ‘best jet’ is omitted in the calculation and the ‘b-tagged jet’ is omitted in figure 7.2.154(c). The three distributions contain events with three jets, two of them tagged as originating from the decay of a b hadron, and an isolated electron.

By summing up the transverse momenta of the reconstructed objects instead of their scalar energies, different combinations of the variable Ht can be calculated. Figure 7.2.155(a) displays

the result of the calculation when only the three jets are taken into account. Considering also the electron and the missing transverse energy leads to the distribution shown in figure 7.2.155(b). Taking only two jets into account by omitting the ‘best jet’, the distribution in figure 7.2.155(c) is obtained. All three ways to calculate Ht show similar features: the signal events of electroweak top quark production peak at lower values compared to the background model. The background distributions are dominated by events from $Wb\bar{b}$ production in the region of low Ht values. At high values, the production of top quark pairs in the semileptonic channel is the dominant background contribution.

Figure 7.2.155: Three different variations of the Ht variable: in figure 7.2.155(a) only the three jets are taken into account. The distribution in figure 7.2.155(b) also considers the lepton and the missing transverse energy of the event. Two jets are considered in figure 7.2.155(c). The ‘best jet’ is omitted in the calculation. The three distributions show events with three jets, two of them tagged as a b-jet, and one isolated muon.

The invariant mass of the dijet system built by neglecting the ‘best jet’ is shown in figure 7.2.156(a). The distribution peaks at 65 GeV for signal events of electroweak top quark production and the background distribution has its maximum at 85 GeV. Especially the background events from top quark pair production appear at high invariant mass values. The maximum of their individual shape is at 125 GeV. The invariant mass of jet1, jet2 and the reconstructed W boson can be seen in figure 7.2.156(b). Here, both the distribution for the signal events of electroweak top quark production and the distribution of the background model have their maximum at 250 GeV. On average, the invariant mass of the background model is higher than for the signal events. For the latter, the slope of the falling edge of the distribution is flatter.

The transverse momentum of the dijet system built by neglecting the ‘b-tagged jet’ is shown in figure 7.2.157(a). The shapes of the distributions for signal and background events are very similar. Both have their maximum at 45 GeV, followed by a long tail towards higher transverse momenta. The $\hat{S}$ distribution (according to equation 7.1.8) is displayed in figure 7.2.157(b). The signal distribution peaks at 300 GeV and has a tail towards higher values of $\hat{S}$. Almost all multijet events can be found below this value of 300 GeV. Multijet events and events from $Wb\bar{b}$ production have low $\hat{S}$ values, whereas the background from top quark pair production dominates the background distribution above 350 GeV.

The sphericity of the event, based on the calculation using the three jets and the reconstructed W boson, can be seen in figure 7.2.158(a). The signal distribution has its maximum at 0.3, whereas the background distribution rises up to a value of 0.4, before the distribution starts to

Figure 7.2.156: The invariant mass of two jets is shown in figure 7.2.156(a). The ‘best jet’ is omitted in the calculation. The invariant mass of jet1, jet2, and the reconstructed W boson is displayed in figure 7.2.156(b). The distributions contain events with three jets, two of them tagged as originating from the decay of a b hadron, and one isolated electron.

Figure 7.2.157: The transverse momentum distribution of the dijet system built by neglecting the ‘b-tagged jet’ is shown in figure 7.2.157(a). The observable $\hat{S}$ is shown in figure 7.2.157(b). The distributions contain events with three jets, two of them tagged as a b-jet, and one isolated electron.

drop again. Figure 7.2.158(b) shows the invariant mass distribution of the combination of jet1 and jet2. Again, the signal distribution reaches its maximum earlier, at a value of 85 GeV, compared to the maximum of the background distribution at 115 GeV. Events from $Wb\bar{b}$ production have the lowest invariant masses. The background from top quark pair production can be found predominantly at high invariant masses.

With the transverse momentum (figure 7.2.159(a)) and the transverse mass (figure 7.2.159(b)), two properties of the reconstructed W boson are used as input to the statistical analysis. On average, the transverse momentum is slightly higher for the signal events of electroweak top quark production compared with the background model. The shapes of the distributions of the transverse mass are similar, except for the excesses in the background model at low transverse masses, due to the multijet events.

For jet1, the transverse momentum spectrum is shown in figure 7.2.160(a) and the pseudora-

Figure 7.2.158: The sphericity of the events, calculated using the jets and the reconstructed W boson, is shown in figure 7.2.158(a). The transverse mass of the jet1-jet2 combination is shown in figure 7.2.158(b). Both distributions contain events with three jets, two of them tagged as a b-jet, and one isolated electron.

Figure 7.2.159: Transverse momentum and transverse mass of the reconstructed W boson are shown in figure 7.2.159(a) and figure 7.2.159(b), respectively. The distributions contain events with three jets, two of them tagged as originating from the decay of a b hadron, and one isolated electron.

pidity distribution is shown in figure 7.2.160(b). The transverse momentum distribution peaks at 65 GeV for signal events, and at 90 GeV for background events. The high values of transverse momentum are dominated by events from top quark pair production in the semileptonic channel. The pseudorapidity distribution is symmetric around $\eta = 0$ for all contributing physics processes. The signal distribution remains flat in the region of $|\eta| < 0.6$.

The transverse momentum distribution of jet2 is shown in figure 7.2.161(a). The events from $Wb\bar{b}$ production have a falling transverse momentum spectrum and accumulate at the low end of the distribution. The signal events of single top quark production peak at 40 GeV, the background component of top quark pair production has a maximum of its transverse momentum distribution at 60 GeV. The total background distribution has a broad flat area between 30 GeV and 65 GeV with no distinct maximum. The distribution of pseudorapidity of jet2 is symmetric around $\eta = 0$ for both signal and background events.

The transverse momentum distribution of jet3 is similar for signal and background events (see

Figure 7.2.160: Transverse momentum (figure 7.2.160(a)) and pseudorapidity η (figure 7.2.160(b)) for the leading jet in events with three jets, two of them tagged as a b-jet, and one isolated electron.

Figure 7.2.161: Transverse momentum and pseudorapidity η of jet2 are shown in figure 7.2.161(a) and figure 7.2.161(b), respectively for events with three jets, two of them tagged as b-jets, and one isolated electron.

figure 7.2.162(a)). It is a falling distribution. The majority of events from $Wb\bar{b}$ production can be found below 35 GeV. The pseudorapidity distribution of jet3 is symmetric around $\eta = 0$ and rather flat in the region of $|\eta| < 1.1$.

The invariant mass of the dijet system built by jet1 and jet2 is shown in figure 7.2.163(a). The signal distribution of events from electroweak top quark production has its maximum at 100 GeV. The background distribution, and also the individual shape of the background from top quark pair production, has its maximum at 135 GeV. The transverse momentum distribution of this dijet system is similar for signal events and the background model. The maximum of the distribution is at 55 GeV.

The missing transverse energy of events in this analysis bin is shown in figure 7.2.164(a). The distributions of signal and background events are similar, with a maximum at 45 GeV. The variable SEt , as defined in equation 7.1.9, can be useful in the separation of single top quark events from events from top pair production. The signal distribution peaks at 190 GeV, the background of top quark pair production in the semileptonic channel at 230 GeV.

Adding also the missing transverse energy to the SEt calculation, the distribution shown

Figure 7.2.162: Transverse momentum and pseudorapidity η of jet3 are shown in figure 7.2.162(a) and figure 7.2.162(b), respectively. The distributions contain events with three jets, two of them tagged as originating from the decay of a b hadron, and an isolated electron.

Figure 7.2.163: The invariant mass of the dijet system consisting of jet1 and jet2 is shown in figure 7.2.163(a). The transverse momentum distribution of this system is displayed in figure 7.2.163(b). The two histograms contain events with three jets, two of them b-tagged, and one isolated electron.

in figure 7.2.165(a) is obtained. Multijet events and events from $Wb\bar{b}$ production accumulate at the low edge of this distribution. Above 250 GeV, top quark pair production is the dominant background component, peaking at 290 GeV. The signal distribution of events from electroweak top quark production lies inbetween. The peak of this distribution is at 230 GeV. Using the same reconstructed objects, but using the scalar energy instead of the transverse energy, the distribution shown in figure 7.2.165(b) is obtained. The difference is less pronounced in this distribution. The distribution of the signal events peaks at 320 GeV, the background sample at 350 GeV. The slope of the falling edge of the background distribution is steeper than for the signal sample.

The event shape variables aplanarity and sphericity are introduced in equation 7.1.14 and equation 7.1.15. Their distributions in this analysis bin can be found in figure 7.2.166(a) and figure 7.2.166(b), respectively. For aplanarity, the distributions for signal and background events are similar. However, in sphericity, there is a difference. The signal distribution of electroweak top quark production peaks at 0.18, the background distribution at 0.23. The spatial difference

Figure 7.2.164: The missing transverse energy distribution is shown in figure 7.2.164(a). Figure 7.2.164(b) displays the SEt variable for events with three jets, two of them tagged as b-jets, and one isolated electron.

Figure 7.2.165: The sum of SEt and missing transverse energy is shown in figure 7.2.165(a). Using the scalar energy instead of the transverse energy in the calculation, the distribution in figure 7.2.165(b) is obtained. Both distributions show events with three jets, two of them tagged as b-jets, and one isolated electron.

ΔR between the two leading jets in the event is shown in figure 7.2.166(c). The distribution is similar for signal and background events. At low values of ΔR there are almost no events. The probability to find two jets in a distance ΔR rises linearly up to a value of $\Delta R = 3$, before it drops.

Figure 7.2.166: The event shape variables aplanarity and sphericity are shown in figures 7.2.166(a) and 7.2.166(b). Figure 7.2.166(c) shows the spatial distance ΔR between jet1 and jet2. The three distributions contain events with three jets, two of them b-tagged, and one isolated electron.

7.2.6 Summary of Observables for Events with Three Jets

A summary of the variables used in the statistical analysis for the four different analysis bins can be found in the following tables:

- For the muon analysis with one b-tagged jet the variables can be found in table 7.2.11 on page 318 and table 7.2.12 on page 319.
- For the muon analysis with two b-tagged jets the variables can be found in table 7.2.13 on page 320 and table 7.2.14 on page 321.
- For the electron analysis with one b-tagged jet the variables can be found in table 7.2.15 on page 322 and table 7.2.16 on page 323.
- For the electron analysis with two b-tagged jets the variables can be found in table 7.2.17 on page 324 and table 7.2.18 on page 325.

The discriminant output distributions for the Boosted Decision Tree configuration that is finally used in the analysis are presented on page 414 for the muon channel. Figure 9.1.1(c) shows the distribution for events with three reconstructed jets and one b-tag. The distribution for events with three jets and two b-tags is shown in figure 9.1.1(d). The discriminant output distributions for the two electron channel analysis bins with three reconstructed jets are shown in figures 9.1.2(c) (events with one b-tag) and 9.1.2(d) (events with two b-tags) on page 415.

Variable	Figure
Variables from the reconstruction of the single top s-channel PPT (see figure 7.2.1)	
Pseudorapidity η of b(lept)	7.2.8(a)
Transverse momentum of b(lept)	7.2.8(b)
Transverse momentum of b(prod)	7.2.9(a)
Pseudorapidity η of b(prod)	7.2.9(b)
Transverse momentum of q(scst)	7.2.10(a)
Pseudorapidity η of q(scst)	7.2.10(b)
Transverse momentum of the reconstructed top quark	7.2.11(a)
Transverse momentum of the reconstructed W boson	7.2.11(b)
Eta measure	7.2.12(a)
Ht measure	7.2.12(b)
Pseudorapidity η of W(virt)	7.2.13(a)
Likelihood measure	7.2.13(b)
Variables from the reconstruction of the single top t-channel PPT (see figure 7.2.32)	
Mass of the reconstructed top quark	7.2.39(a)
Transverse momentum of the reconstructed top quark	7.2.39(b)
Pseudorapidity η of the reconstructed top quark	7.2.39(c)
Transverse momentum of b(lept)	7.2.40(a)
Pseudorapidity η of b(lept)	7.2.40(b)
Transverse momentum of q(scst)	7.2.41(a)
Pseudorapidity η of q(scst)	7.2.41(b)
Transverse momentum of b(scst)	7.2.42(a)
Cosine of the angle between the W boson in the top quark rest frame and the lepton in the W boson rest frame	7.2.42(b)
Likelihood measure	7.2.42(c)
Variables from the reconstruction of the semileptonic top quark pair decay PPT see figures 7.2.55 and 7.2.56	
Mass of the reconstructed top quark (hadronic branch)	7.2.64(a)
Transverse momentum of the reconstructed top quark (hadronic branch)	7.2.64(b)
Transverse momentum of the reconstructed top quark (leptonic branch)	7.2.64(c)
Transverse momentum of b(hadr) (hadronic branch)	7.2.65(a)
Transverse momentum of W(lept) (hadronic branch)	7.2.65(b)
Transverse momentum of b(lept) (leptonic branch)	7.2.66(a)
Mass of the dijet system (leptonic branch)	7.2.66(b)
Likelihood measure (leptonic branch)	7.2.66(c)
Variables from the reconstruction of dilepton top quark pair decay PPT (see figure 7.2.78)	
Mass of the reconstructed top quark	7.2.91(a)
Transverse momentum of the reconstructed top quark	7.2.91(b)
Transverse momentum of b(found)	7.2.92(a)
Transverse momentum of jet(add)	7.2.92(b)

Table 7.2.11: Observables gained by the reconstruction of Parton Picture Templates and used as input for the Boosted Decision Tree analysis for events with three jets, one jet tagged as originating from a b hadron decay, and one muon.

Variable	Figure
Event shape variables and variables from the reconstruction of PPT (see figure 7.2.97)	
Mass of HFS	7.2.98(a)
Transverse momentum of the HFS	7.2.98(b)
Angle between HFS and jet1 in center-of-mass reference frame	7.2.99(a)
Scalar sum of lepton transverse momentum and missing transverse energy	7.2.99(b)
Transverse momentum of the best jet	7.2.100(a)
Transverse momentum of second leading untagged jet	7.2.100(b)
Mass of b-tagged top quark	7.2.101(a)
Lepton charge times pseudorapidity η of leading untagged jet	7.2.101(b)
Cosine of angle between jet2 and the charged lepton in the reference frame of the b-tagged top quark	7.2.102(a)
Cosine of the angle between the untagged jet and the lepton in the reference frame of the b-tagged top quark	7.2.102(b)
H of all jets	7.2.103(a)
H of all jets minus the best jet	7.2.103(b)
H of all jets minus the b-tagged jet	7.2.103(c)
Ht of all jets	7.2.104(a)
Ht of all jets, the charged lepton and missing transverse energy	7.2.104(b)
Ht of all jets minus the best jet	7.2.104(c)
Transverse momentum of the reconstructed W boson	7.2.105(a)
Transverse mass of the W boson	7.2.105(b)
Invariant mass of all jets minus the best jet	7.2.106(a)
Invariant mass of jet1, jet2 and the W boson	7.2.106(b)
Scalar sum of transverse momenta of all jets minus the b-tagged jet	7.2.107(a)
Transverse mass of jet1 and jet2	7.2.107(b)
$\hat{S}$	7.2.108(a)
Sphericity of all jets and the reconstructed W boson	7.2.108(b)
Transverse momentum of jet1	7.2.109(a)
Pseudorapidity η of jet1	7.2.109(b)
Transverse momentum of jet2	7.2.110(a)
Pseudorapidity η of jet2	7.2.110(b)
Transverse momentum of jet3	7.2.111(a)
Pseudorapidity η of jet3	7.2.111(b)
Mass of the dijet system of jet1 and jet2	7.2.112(a)
Transverse momentum of the dijet system of jet1 and jet2	7.2.112(b)
Missing transverse energy	7.2.113(a)
SEt of all reconstructed objects	7.2.113(b)
Ht of all reconstructed objects	7.2.114(a)
H of all reconstructed objects	7.2.114(b)
Aplanarity of the event	7.2.115(a)
Aplanarity of all reconstructed objects	7.2.115(b)
ΔR between jet1 and jet2	7.2.115(c)

Table 7.2.12: Event shape observables used as input for the Boosted Decision Tree analysis for events with three jets, one jet tagged as originating from a b hadron decay, and one muon.

Variable	Figure
Variables from the reconstruction of the single top s-channel PPT (see figure 7.2.1)	
Mass of the reconstructed top quark	7.2.14(a)
Transverse momentum of the reconstructed top quark	7.2.14(b)
Transverse momentum of b(lept)	7.2.15(a)
Pseudorapidity η of b(lept)	7.2.15(b)
Transverse momentum of b(prod)	7.2.16(a)
Pseudorapidity η of b(prod)	7.2.16(b)
Transverse momentum of q(scst)	7.2.17(a)
Pseudorapidity η of q(scst)	7.2.17(b)
Eta measure	7.2.18(a)
Ht measure	7.2.18(b)
Transverse momentum of the reconstructed W boson	7.2.19(a)
Pseudorapidity η of W(virt)	7.2.19(b)
Likelihood measure	7.2.19(c)
Variables from the reconstruction of the single top t-channel PPT (see figure 7.2.32)	
Mass of the reconstructed top quark	7.2.43(a)
Transverse momentum of the reconstructed top quark	7.2.43(b)
Pseudorapidity η of the reconstructed top quark	7.2.43(c)
Transverse momentum of b(lept)	7.2.44(a)
Pseudorapidity η of b(lept)	7.2.44(b)
Transverse momentum of q(scst)	7.2.45(a)
Pseudorapidity η of q(scst)	7.2.45(b)
Transverse momentum of b(scst)	7.2.46(a)
Cosine of the angle between the W boson in the top quark rest frame and the lepton in the W boson rest frame	7.2.46(b)
Likelihood measure	7.2.46(c)
Variables from the reconstruction of the semileptonic top quark pair decay PPT see figures 7.2.55 and 7.2.56	
Mass of the reconstructed top quark (hadronic branch)	7.2.67(a)
Transverse momentum of the reconstructed top quark (hadronic branch)	7.2.67(b)
Mass of W(hadr) (hadronic branch)	7.2.68(a)
Transverse momentum of W(lept) (hadronic branch)	7.2.68(b)
Transverse momentum of b(hadr) (hadronic branch)	7.2.68(c)
Transverse momentum of the reconstructed top quark (leptonic branch)	7.2.69(a)
Likelihood measure (leptonic branch)	7.2.69(b)
Transverse momentum of b(lept) (leptonic branch)	7.2.70(a)
Mass of the dijet system (leptonic branch)	7.2.70(b)
Variables from the reconstruction of dilepton top quark pair decay PPT (see figure 7.2.78)	
Mass of the reconstructed top quark	7.2.93(a)
Transverse momentum of b(found)	7.2.93(b)
Transverse momentum of jet(add)	7.2.93(c)

Table 7.2.13: Observables gained by the reconstruction of Parton Picture Templates and used as input for the Boosted Decision Tree analysis for events with three jets, two jets tagged as originating from a b hadron decay, and one muon.

Variable	Figure
Event shape variables and variables from the reconstruction of PPT (see figure 7.2.97)	
Mass of HFS	7.2.116(a)
Transverse momentum of the HFS	7.2.116(b)
Angle between HFS and jet1 in center-of-mass reference frame	7.2.117(a)
Scalar sum of lepton transverse momentum and missing transverse energy	7.2.117(b)
Mass of b-tagged top quark	7.2.118(a)
Transverse momentum of the best jet	7.2.118(b)
Lepton charge times pseudorapidity η of leading untagged jet	7.2.118(c)
Cosine of angle between jet2 and the charged lepton in the reference frame of the b-tagged top quark	7.2.119(a)
Cosine of the angle between the untagged jet and the lepton in the reference frame of the b-tagged top quark	7.2.119(b)
H of all jets	7.2.120(a)
H of all jets minus the best jet	7.2.120(b)
H of all jets minus the b-tagged jet	7.2.120(c)
Ht of all jets	7.2.121(a)
Ht of all jets, the charged lepton and missing transverse energy	7.2.121(b)
Ht of all jets minus the best jet	7.2.121(c)
Invariant mass of all jets minus the best jet	7.2.122(a)
Invariant mass of jet1, jet2 and the W boson	7.2.122(b)
Scalar sum of transverse momenta of all jets minus the b-tagged jet	7.2.123(a)
Transverse mass of jet1 and jet2	7.2.123(b)
$\hat{S}$	7.2.124(a)
Sphericity of all jets and the reconstructed W boson	7.2.124(b)
Transverse momentum of the reconstructed W boson	7.2.125(a)
Transverse mass of the W boson	7.2.125(b)
Transverse momentum of jet1	7.2.126(a)
Pseudorapidity η of jet1	7.2.126(b)
Transverse momentum of jet2	7.2.127(a)
Pseudorapidity η of jet2	7.2.127(b)
Transverse momentum of jet3	7.2.128(a)
Pseudorapidity η of jet3	7.2.128(b)
Mass of the dijet system of jet1 and jet2	7.2.129(a)
Transverse momentum of the dijet system of jet1 and jet2	7.2.129(b)
Missing transverse energy	7.2.130(a)
SEt of all reconstructed objects	7.2.130(b)
Ht of all reconstructed objects	7.2.131(a)
H of all reconstructed objects	7.2.131(b)
Aplanarity of the event	7.2.132(a)
Aplanarity of all reconstructed objects	7.2.132(b)
ΔR between jet1 and jet2	7.2.132(c)

Table 7.2.14: Event shape observables used as input for the Boosted Decision Tree analysis for events with three jets, two jets tagged as originating from a b hadron decay, and one muon.

Variable	Figure
Variables from the reconstruction of the single top s-channel PPT (see figure 7.2.1)	
Pseudorapidity η of b(lept)	7.2.20(a)
Transverse momentum of b(lept)	7.2.20(b)
Transverse momentum of b(prod)	7.2.21(a)
Pseudorapidity η of b(prod)	7.2.21(b)
Transverse momentum of q(scst)	7.2.22(a)
Pseudorapidity η of q(scst)	7.2.22(b)
Transverse momentum of the reconstructed top quark	7.2.23(a)
Transverse momentum of the reconstructed W boson	7.2.23(b)
Eta measure	7.2.24(a)
Ht measure	7.2.24(b)
Pseudorapidity η of W(virt)	7.2.25(a)
Likelihood measure	7.2.25(b)
Variables from the reconstruction of the single top t-channel PPT (see figure 7.2.32)	
Mass of the reconstructed top quark	7.2.47(a)
Transverse momentum of the reconstructed top quark	7.2.47(b)
Pseudorapidity η of the reconstructed top quark	7.2.47(c)
Transverse momentum of b(lept)	7.2.48(a)
Pseudorapidity η of b(lept)	7.2.48(b)
Transverse momentum of q(scst)	7.2.49(a)
Pseudorapidity η of q(scst)	7.2.49(b)
Transverse momentum of b(scst)	7.2.50(a)
Cosine of the angle between the W boson in the top quark rest frame and the lepton in the W boson rest frame	7.2.50(b)
Likelihood measure	7.2.50(c)
Variables from the reconstruction of the semileptonic top quark pair decay PPT see figures 7.2.55 and 7.2.56	
Mass of the reconstructed top quark (hadronic branch)	7.2.71(a)
Transverse momentum of the reconstructed top quark (hadronic branch)	7.2.71(b)
Transverse momentum of the reconstructed top quark (leptonic branch)	7.2.71(c)
Transverse momentum of b(hadr) (hadronic branch)	7.2.72(a)
Transverse momentum of W(lept) (hadronic branch)	7.2.72(b)
Transverse momentum of b(lept) (leptonic branch)	7.2.73(a)
Mass of the dijet system (leptonic branch)	7.2.73(b)
Likelihood measure (leptonic branch)	7.2.73(c)
Variables from the reconstruction of dilepton top quark pair decay PPT (see figure 7.2.78)	
Mass of the reconstructed top quark	7.2.94(a)
Transverse momentum of the reconstructed top quark	7.2.94(b)
Transverse momentum of b(found)	7.2.95(a)
Transverse momentum of jet(add)	7.2.95(b)

Table 7.2.15: Observables gained by the reconstruction of Parton Picture Templates and used as input for the Boosted Decision Tree analysis for events with three jets, one jet tagged as originating from a b hadron decay, and one electron.

Variable	Figure
Event shape variables and variables from the reconstruction of PPT (see figure 7.2.97)	
Mass of HFS	7.2.133(a)
Transverse momentum of the HFS	7.2.133(b)
Angle between HFS and jet1 in center-of-mass reference frame	7.2.134(a)
Scalar sum of lepton transverse momentum and missing transverse energy	7.2.134(b)
Transverse momentum of the best jet	7.2.135(a)
Transverse momentum of second leading untagged jet	7.2.135(b)
Mass of b-tagged top quark	7.2.136(a)
Lepton charge times pseudorapidity η of leading untagged jet	7.2.136(b)
Cosine of the angle between the untagged jet and the lepton in the reference frame of the b-tagged top quark	7.2.136(c)
H of all jets	7.2.137(a)
H of all jets minus the best jet	7.2.137(b)
H of all jets minus the b-tagged jet	7.2.137(c)
Ht of all jets	7.2.138(a)
Ht of all jets, the charged lepton and missing transverse energy	7.2.138(b)
Ht of all jets minus the best jet	7.2.138(c)
Invariant mass of all jets minus the best jet	7.2.139(a)
Invariant mass of jet1, jet2 and the W boson	7.2.139(b)
Scalar sum of transverse momenta of all jets minus the b-tagged jet	7.2.140(a)
$\hat{S}$	7.2.140(b)
Sphericity of all jets and the reconstructed W boson	7.2.141(a)
Transverse mass of jet1 and jet2	7.2.141(b)
Transverse momentum of the reconstructed W boson	7.2.142(a)
Transverse mass of the W boson	7.2.142(b)
Transverse momentum of jet1	7.2.143(a)
Pseudorapidity η of jet1	7.2.143(b)
Transverse momentum of jet2	7.2.144(a)
Pseudorapidity η of jet2	7.2.144(b)
Transverse momentum of jet3	7.2.145(a)
Pseudorapidity η of jet3	7.2.145(b)
Mass of the dijet system of jet1 and jet2	7.2.146(a)
Transverse momentum of the dijet system of jet1 and jet2	7.2.146(b)
Missing transverse energy	7.2.147(a)
SEt of all reconstructed objects	7.2.147(b)
Ht of all reconstructed objects	7.2.148(a)
H of all reconstructed objects	7.2.148(b)
Aplanarity of the event	7.2.149(a)
Aplanarity of all reconstructed objects	7.2.149(b)
ΔR between jet1 and jet2	7.2.149(c)

Table 7.2.16: Event shape observables used as input for the Boosted Decision Tree analysis for events with three jets, one jet tagged as originating from a b hadron decay, and one electron.

Variable	Figure
Variables from the reconstruction of the single top s-channel PPT (see figure 7.2.1)	
Mass of the reconstructed top quark	7.2.26(a)
Transverse momentum of the reconstructed top quark	7.2.26(b)
Transverse momentum of b(lept)	7.2.27(a)
Pseudorapidity η of b(lept)	7.2.27(b)
Transverse momentum of b(prod)	7.2.28(a)
Pseudorapidity η of b(prod)	7.2.28(b)
Transverse momentum of q(scst)	7.2.29(a)
Pseudorapidity η of q(scst)	7.2.29(b)
Eta measure	7.2.30(a)
Ht measure	7.2.30(b)
Transverse momentum of the reconstructed W boson	7.2.31(a)
Pseudorapidity η of W(virt)	7.2.31(b)
Likelihood measure	7.2.31(c)
Variables from the reconstruction of the single top t-channel PPT (see figure 7.2.32)	
Mass of the reconstructed top quark	7.2.51(a)
Transverse momentum of the reconstructed top quark	7.2.51(b)
Pseudorapidity η of the reconstructed top quark	7.2.51(c)
Transverse momentum of b(lept)	7.2.52(a)
Pseudorapidity η of b(lept)	7.2.52(b)
Transverse momentum of q(scst)	7.2.53(a)
Pseudorapidity η of q(scst)	7.2.53(b)
Transverse momentum of b(scst)	7.2.54(a)
Cosine of the angle between the W boson in the top quark rest frame and the lepton in the W boson rest frame	7.2.54(b)
Likelihood measure	7.2.54(c)
Variables from the reconstruction of the semileptonic top quark pair decay PPT see figures 7.2.55 and 7.2.56	
Mass of the reconstructed top quark (hadronic branch)	7.2.74(a)
Transverse momentum of the reconstructed top quark (hadronic branch)	7.2.74(b)
Mass of the reconstructed W boson (hadronic branch)	7.2.75(a)
Transverse momentum of W(lept) (hadronic branch)	7.2.75(b)
Transverse momentum of b(hadr) (hadronic branch)	7.2.75(c)
Transverse momentum of the reconstructed top quark (leptonic branch)	7.2.76(a)
Likelihood measure (leptonic branch)	7.2.76(b)
Transverse momentum of b(lept) (leptonic branch)	7.2.77(a)
Mass of the dijet system (leptonic branch)	7.2.77(b)
Variables from the reconstruction of dilepton top quark pair decay PPT (see figure 7.2.78)	
Mass of the reconstructed top quark	7.2.96(a)
Transverse momentum of b(found)	7.2.96(b)
Transverse momentum of jet(add)	7.2.96(c)

Table 7.2.17: Observables gained by the reconstruction of Parton Picture Templates and used as input for the Boosted Decision Tree analysis for events with three jets, two jets tagged as originating from a b hadron decay, and one electron.

Variable	Figure
Event shape variables and variables from the reconstruction of PPT (see figure 7.2.97)	
Mass of HFS	7.2.150(a)
Transverse momentum of the HFS	7.2.150(b)
Angle between HFS and jet1 in center-of-mass reference frame	7.2.151(a)
Scalar sum of lepton transverse momentum and missing transverse energy	7.2.151(b)
Transverse momentum of the best jet	7.2.152(a)
Mass of b-tagged top quark	7.2.152(b)
Lepton charge times pseudorapidity η of leading untagged jet	7.2.153(a)
Cosine of the angle between the untagged jet and the lepton in the reference frame of the b-tagged top quark	7.2.153(b)
H of all jets	7.2.154(a)
H of all jets minus the best jet	7.2.154(b)
H of all jets minus the b-tagged jet	7.2.154(c)
Ht of all jets	7.2.155(a)
Ht of all jets, the charged lepton and missing transverse energy	7.2.155(b)
Ht of all jets minus the best jet	7.2.155(c)
Invariant mass of all jets minus the best jet	7.2.156(a)
Invariant mass of jet1, jet2 and the W boson	7.2.156(b)
Scalar sum of transverse momenta of all jets minus the b-tagged jet	7.2.157(a)
$\hat{S}$	7.2.157(b)
Sphericity of all jets and the reconstructed W boson	7.2.158(a)
Transverse mass of jet1 and jet2	7.2.158(b)
Transverse momentum of the reconstructed W boson	7.2.159(a)
Transverse mass of the W boson	7.2.159(b)
Transverse momentum of jet1	7.2.160(a)
Pseudorapidity η of jet1	7.2.160(b)
Transverse momentum of jet2	7.2.161(a)
Pseudorapidity η of jet2	7.2.161(b)
Transverse momentum of jet3	7.2.162(a)
Pseudorapidity η of jet3	7.2.162(b)
Mass of the dijet system of jet1 and jet2	7.2.163(a)
Transverse momentum of the dijet system of jet1 and jet2	7.2.163(b)
Missing transverse energy	7.2.164(a)
SEt of all reconstructed objects	7.2.164(b)
Ht of all reconstructed objects	7.2.165(a)
H of all reconstructed objects	7.2.165(b)
Aplanarity of the event	7.2.166(a)
Aplanarity of all reconstructed objects	7.2.166(b)
ΔR between jet1 and jet2	7.2.166(c)

Table 7.2.18: Event shape observables used as input for the Boosted Decision Tree analysis for events with three jets, two jets tagged as originating from a b hadron decay, and one electron.

7.3 Processes for Events with Four Jets

The analysis bin with four reconstructed jets is the least sensitive one of the three jet bins considered in this analysis. For each of the signal processes a Parton Picture Template is reconstructed. The PaxProcess for s-channel production of single top quarks is presented in section 7.3.1, and the PaxProcess reconstructing the t-channel is introduced in section 7.3.2. The background process of top quark pair production in the semileptonic channel becomes the dominant background source in this jet multiplicity bin. Its PaxProcess in the MultiProcessFactory is explained in section 7.3.3. The contribution from the dilepton channel of top quark pair production is neglected because of the low number of expected events with four jets. Therefore, no Parton Picture Template is reconstructed for it. The production of W bosons associated by jets, and event shape variables are treated in section 7.3.4. A summary of the variables that result from these PaxProcesses which are used in the statistical analysis with Boosted Decision Trees can then be found in section 7.3.5.

7.3.1 s-Channel Production of Top Quarks

The Parton Picture Template for the reconstruction of s-channel electroweak top quark production is shown in figure 7.3.1. In addition to the top quark and the bottom quark at the primary

Figure 7.3.1: Parton Picture Template for the PaxProcess reconstructing the s-channel production of single top quarks. Because of the leptonic decay of the W boson into a lepton and a neutrino, all parton names in the top quark decay branch are supplemented with (lept). The b-quark that is produced at the W-t-b-vertex is named b(prod). The four-vectors of the two remaining light quarks are added up and form a new dijet four-vector that is also connected to the primary vertex.

vertex, a dijet four-vector is connected to the vertex. This four-vector is the vector sum of the two jets in the event that do not come from the hard interaction but from initial state or final state radiation. The properties of this dijet four-vector can also be used as additional observables in the multivariate analysis later.

68% matching quality cut for	
muons	electrons
0.51	0.49

Table 7.3.1: 68% matching quality cut in $\Sigma\Delta R$ for muon and electron s-channel single top events with four jets.

7.3.1.1 Ambiguity Resolution

The number of possible configurations in the assignment of reconstructed objects to the parton representation in the Parton Picture Template depends on the number of the solvability of the quadratic equation that calculates the z component of the neutrino momentum from the W boson mass constraint. With two real solutions, there are 24 possible configurations.

As described in section 6.2.1.2 all possible configurations are developed and evaluated in a likelihood method. The input histograms to this likelihood method come from studies where generator information is matched to reconstructed objects of the simulation. The 68% quality cutoff values in $\Sigma\Delta R$ for the muon and the electron samples can be found in table 7.3.1 and the corresponding plots can be found in figure 7.3.2.

Figure 7.3.2: 68% cutoff value for the matching quality $\Sigma\Delta R$ between generated partons and reconstructed objects for muon 7.3.2(a) and electron 7.3.2(b) events in the s-channel single top quark sample. Only quantities of events with good matching quality (grey area) are used as input to the likelihood method that is used to resolve the ambiguities in the jet-parton-assignment.

The cutoff values of 0.51 for muon events and 0.49 for electron events, respectively are very good, considering that five partons (four jets and one charged lepton) were matched.

Observables of the events passing the 68% cutoff criteria are used to fill the histograms used in the likelihood method for the ambiguity resolution. The weight of the simulated event is taken into account when filling the histograms. The observables used in the ambiguity resolution are chosen to give the highest efficiency when comparing the one configuration with the highest

likelihood measure to the configuration that has the best match between generator information and reconstructed objects (see 6.2.1.2). For the ambiguity resolution in this PaxProcess the six variables are used that will be presented in the following. Figure 7.3.3 shows the first variable. It is the b-tag probability of the jets assigned to the partons b(lept) (figure 7.3.3(a) for muons, figure 7.3.3(b) for electrons).

Figure 7.3.3: Input distributions for the likelihood method to resolve ambiguities in the s-channel PPT with four jets and one lepton. Figures 7.3.3(a) and 7.3.3(b) display the probability to be a b-tagged jet for the jets assigned to the parton b(lept) for the muon channel and the electron channel, respectively.

For the parton b(prod) the probability of the associated jet to be b-tagged is shown in figure 7.3.4(a) for the muon channel and figure 7.3.4(b) for the electron channel. It is interesting to note, that the reconstructed jets in simulated events that are matched to generator information that are assigned to the parton b(prod) have a higher probability to be b-tagged than the jets assigned to the parton b(lept) from the top quark decay.

Figure 7.3.4: Input distributions for the likelihood method to resolve ambiguities in the s-channel PPT with four jets and one lepton. Figures 7.3.4(a) and 7.3.4(b) display the probability to be a b-tagged jet for the jets assigned to the parton b(prod) for the muon channel and the electron channel, respectively.

Kinematic quantities of the dijet four-vector that is formed as the vector sum of the two jets that are not assigned to the electroweak top quark production process itself are also used in the

likelihood in this PaxProcess. Figures 7.3.5(a) and 7.3.5(b) show the dijet transverse momentum for simulated muon and electron events.

Figure 7.3.5: Input distributions for the likelihood method to resolve ambiguities in the s-channel PPT with four jets and one lepton. Figures 7.3.5(a) and 7.3.5(b) display transverse momentum of the reconstructed dijet four-vector for muon events and electron events, respectively.

The pseudorapidity η of the dijet four-vector can be seen in figure 7.3.6(a) for muon events and in figure 7.3.6(b) for electron events.

Figure 7.3.6: Input distributions for the likelihood method to resolve ambiguities in the s-channel PPT with four jets and one lepton. Figures 7.3.6(a) and 7.3.6(b) display the pseudorapidity η of the reconstructed dijet four-vector for muon events and electron events, respectively.

The transverse momentum of the jet associated with the parton b(left) in the Parton Picture Template is also used in the likelihood measure and can be seen in figure 7.3.7. The distribution for muon events is shown in figure 7.3.7(a), the one for electron events in figure 7.3.7(b).

The cosine between the W boson in the top quark rest frame and the charged lepton in the W boson rest frame is a handle to choose the correct solution for the z component of the neutrino momentum. This observable is shown in figure 7.3.8 for muon and electron events (figure 7.3.8(a) and figure 7.3.8(b), respectively).

Figure 7.3.7: Input distributions for the likelihood method to resolve ambiguities in the s-channel PPT with four jets and one lepton. The transverse momentum distributions of jets assigned to the parton b(lept) in the PPT for simulated muon and electron events are displayed in figures 7.3.7(a) and 7.3.7(b), respectively.

Figure 7.3.8: Cosine between the W boson in the top quark rest frame and the charged lepton in the W boson rest frame for muon events (figure 7.3.8(a)) and electron events (figure 7.3.8(b)).

The efficiency of the likelihood method is determined by comparing the configuration with the highest likelihood value with the configuration obtained from the matching of the reconstructed objects with the partons from the generator. The efficiencies ϵ_{68} and ϵ_{100} , as described in definition 6.2.1, are summarized in table 7.3.2 for the muon channel analysis and the electron channel analysis. The probability to find the correct event configuration by chance is 8.3%. All efficiencies are above this value. The efficiencies in the electron channel are lower than in the

	muon channel	electron channel
$\epsilon_{68}[\%]$	25.6	17.9
$\epsilon_{100}[\%]$	23.2	16.0

Table 7.3.2: Efficiencies ϵ_{68} and ϵ_{100} of the likelihood method for the muon channel analysis and the electron channel analysis.

muon channel, in which the selection of the variables used in the likelihood was optimized.

7.3.1.2 Observables for Boosted Decision Trees

The configuration with the highest likelihood measure is used to obtain observables for the multivariate analysis. In the following paragraphs the comparisons of data with simulated events for those variables entering the Boosted Decision Trees are shown for the different analysis bins.

Events with four jets, one b-tagged jet, and one muon

The variables used in the multivariate analysis for events with four jets, one b-tagged jet, and one muon are shown in figures 7.3.9 and 7.3.10. Within the statistical precision the variables are well described. Figure 7.3.9 shows the mass (7.3.9(a)) and the pseudorapidity η (7.3.9(b)) of the reconstructed dijet system and the likelihood measure of the ambiguity resolution (7.3.13(c)). One can see that background events are gathered towards the lower edge of the histogram.

Figure 7.3.9: Mass (7.3.9(a)) and pseudorapidity (7.3.9(b)) of the reconstructed dijet system. The likelihood measure from the ambiguity resolution is shown in 7.3.9(c) for events with one muon, four jets, and one b-tag.

Figure 7.3.10 shows transverse momenta of reconstructed jets that are assigned to the partons in the PPT. Figure 7.3.10(a) shows the transverse momentum of the jet assigned to the b-parton of the top decay b(left) and figure 7.3.10(b) shows the transverse momentum of the jet assigned to the parton b(prod). The signal peaks around 20 GeV in both distributions.

Events with four jets, two b-tagged jets, and one muon

The variables used in the multivariate analysis for events with four jets, two b-tagged jets, and one muon are shown in figures 7.3.11 and 7.3.12. Within the statistical precision the variables chosen as input for the statistical analysis are well described. Figure 7.3.11 shows the mass of the reconstructed top quark in 7.3.11(a). It is below the generated mass of 175 GeV. This shift comes from events where the wrong jet is assigned to the parton b(left). The mass of the reconstructed dijet system - a special four-vector in this PPT - is shown in 7.3.11(b). It peaks at around 120 GeV for the background events while the signal distribution is broader. The likelihood output of the ambiguity resolution is shown in figure 7.3.11(c). Background events are shifted towards lower likelihood values.

Figure 7.3.10: Transverse momentum of b(lept) (7.3.10(a)) and b(prod) (7.3.10(b)) for events with one muon, four jets, and one b-tag.

Figure 7.3.11: Mass of the reconstructed top quark t(lept) (7.3.11(a)), mass of the reconstructed dijet system (7.3.11(b)), and the likelihood measure from the ambiguity resolution (7.3.11(c)) for events with one muon, four jets, and two b-tags.

Figure 7.3.12 shows transverse momenta of reconstructed jets that are assigned to the partons in the PPT. Figure 7.3.12(a) shows the transverse momentum of the jet assigned to the b-parton of the top decay b(lept), and figure 7.3.12(b) shows the transverse momentum of the jet assigned to the parton b(prod). In both distributions the signal peaks at around 20 GeV. The background distribution for the jet assigned to b(prod) peaks at around 40 GeV and shows a good separation from the single top quark signal.

Events with four jets, one b-tagged jet, and one central electron

The variables used in the multivariate analysis for events with four jets, one b-tagged jet, and one central electron are shown in figures 7.3.13 and 7.3.14. Within the statistical precision the variables chosen as input for the statistical analysis are well described.

Figure 7.3.13 shows the mass (7.3.13(a)) and the pseudorapidity η (7.3.13(b)) of the reconstructed dijet system and the likelihood measure of the ambiguity resolution (7.3.13(c)). One can see that background events are gathered towards the lower edge of the histogram.

Figure 7.3.14 shows transverse momenta of reconstructed jets that are assigned to the partons in the PPT. Figure 7.3.14(a) shows the transverse momentum of the jet assigned to the b-parton

Figure 7.3.12: Transverse momenta of the jets assigned to the partons $b(\text{lept})$ (7.3.12(a)) and $b(\text{prod})$ (7.3.12(b)) for events with one muon, four jets, and two b-tags.

Figure 7.3.13: Mass (7.3.13(a)) and pseudorapidity (7.3.13(b)) of the reconstructed dijet system. The likelihood measure from the ambiguity resolution is shown in 7.3.13(c) for events with one electron, four jets, and one b-tag.

of the top decay $b(\text{lept})$, and figure 7.3.14(b) shows the transverse momentum of the jet assigned to the parton $b(\text{prod})$. The signal peaks around 20 GeV in both distributions.

Figure 7.3.14: Transverse momenta of the jets assigned to the partons $b(\text{lept})$ (7.3.14(a)) and $b(\text{prod})$ (7.3.14(b)) for events with one electron, four jets, and one b-tag.

Events with four jets, two b-tagged jets, and one central electron

The variables used in the multivariate analysis for events with four jets, one b-tagged jet, and one central electron are shown in figures 7.3.15 and 7.3.16. Within the statistical precision the variables chosen as input for the statistical analysis are well described. Figure 7.3.15 shows transverse momenta of reconstructed jets that are assigned to the partons in the PPT. Figure 7.3.15(a) shows the transverse momentum of the jet assigned to the b-parton of the top decay b(left) and figure 7.3.15(b) shows the transverse momentum of the jet assigned to the parton b(prod) in the PPT. As for the muon analysis, there is a good separation between the expected signal and the background in the distribution of the jet assigned to b(prod).

Figure 7.3.15: Transverse momenta of the jets assigned to the partons b(left) (7.3.15(a)) and b(prod) (7.3.15(b)) for events with one electron, four jets, and two b-tags.

The reconstructed mass of the dijet system in the PPT is shown in figure 7.3.16(a). The distribution for the expected signal is broader than the background distribution. The likelihood measure used to choose the most likely configuration is also used as input to the statistical analysis and shown in figure 7.3.16(b). The background events peak at low values, while the distribution for signal events does not show such a significant peak.

Figure 7.3.16: Mass of the dijet system (7.3.16(a)) and likelihood measure from the ambiguity resolution (7.3.16(b)) for events with one electron, four jets, and two b-tags.

7.3.2 t-Channel Production of Top Quarks

The Parton Picture Template for the reconstruction of t-channel electroweak top quark production is shown in figure 7.3.17.

Figure 7.3.17: Parton Picture Template for the PaxProcess reconstructing the t-channel production of single top quarks. Because of the leptonic decay of the W boson into a lepton and a neutrino, all parton names in the top decay branch are supplemented with (lept). The b-quark that is produced at the initial scatter process is named b(sc). The scattered light quark is named q(sc). The fourth jet, originating from initial state radiation or final state radiation, is named q(prod) and also connected to the primary vertex.

There are five four-vectors connected to the primary vertex. The four-vector named CM is the vector sum of the other four four-vectors and is entering the primary vertex to represent the kinematics of the initial interaction. The top quark that is produced during the scattering process is one of the outgoing four-vectors of the primary vertex and named t(lept). It decays into a b quark (named b(lept)) and a W boson (named W(lept)). The W boson then decays further into a lepton and a neutrino. The parton named q(sc) represents the scattered light quark from the scattering process that has emitted the virtual W boson (compare with the $2 \rightarrow 3$ process Feynman diagram in section 2.2.2). The parton with name b(sc) is the b-quark that comes from the initial scattering process. Usually it results in a very forward jet that very often escapes the reconstruction because of either missing detector instrumentation in the very forward direction or because of analysis cuts on the jet pseudorapidity. An additional jet that is reconstructed in the event and has its origin e.g. in initial state or final state radiation is labeled q(prod).

7.3.2.1 Ambiguity Resolution

The number of possible configurations in the assignment of reconstructed objects to the parton representation in the Parton Picture Template depends on the number of the solvability of the quadratic equation that calculates the z component of the neutrino momentum from the W boson mass constraint. Assuming two real solutions, there are 24 possible configurations.

68% matching quality cut for	
muons	electrons
1.96	2.08

Table 7.3.3: 68% matching quality cut in $\Sigma\Delta R$ for muon and electron t-channel single top events with four jets.

As described in section 6.2.1.2 all possible configurations are developed and evaluated in a likelihood method. The input histograms to this likelihood method come from studies where generator information is matched to reconstructed objects of the simulation. The 68% quality cutoff values in $\Sigma\Delta R$ for the muon and the electron samples can be found in table 7.3.3 and the corresponding plots can be found in figure 7.3.18.

Figure 7.3.18: 68% cutoff value for the matching quality $\Sigma\Delta R$ between generated partons and reconstructed objects for muon 7.3.18(a) and electron 7.3.18(b) events in the t-channel single top quark sample. Only quantities of events with good matching quality (grey area) are used as input to the likelihood method that is used to resolve the ambiguities in the jet-parton-assignment.

The cutoff values are very large for both the muon and the electron sample. However, taking into account a cone size of the cone jet algorithm of 0.5 these values say that on average each of the partons was still found on the edge of the associated jet cone. Hence, these cutoff values are considered as good to use them as matching quality cut to derive the input histograms for the likelihood method from events passing this cut. Distributions of seven different variables are used to find the most likely configuration. The probability for the jet associated with the parton b(left) to be b-tagged is used. The distributions for the muon and the electron channel are displayed in figure 7.3.19.

The same quantity is used for jets matched to the parton q(scatter) in the PPT. This parton plays the role of the light quark from the initial scattering process and is thus expected to be associated to a b-tagged jet less often. This is true as can be seen in figure 7.3.20 for the muon analysis (7.3.20(a)) and the electron analysis (7.3.20(b)).

In the process of the optimization of the likelihood method for this t-channel Parton Picture Template with four jets it turns out that the kinematic quantities of the light quark partons q(scatter) and q(prod) are important to increase the efficiency of the ambiguity resolution. In fig-

Figure 7.3.19: Probability of the jets assigned to the parton $b(\text{left})$ to be b-tagged. These distributions are used as inputs to the likelihood methods in the muon analysis (figure 7.3.19(a)) and the electron analysis (figure 7.3.19(b))

Figure 7.3.20: Probability of the jets matched to the parton $q(\text{scat})$ to be tagged as originating from a b hadron for simulated t-channel events with muons (figure 7.3.20(a)) and electrons (figure 7.3.20(b)).

Figure 7.3.21 the pseudorapidity distribution for reconstructed jets matched with the parton $q(\text{prod})$ is shown for muon events (figure 7.3.21(a)) and electron events (figure 7.3.21(b)).

Also the transverse momentum of the jets matched to the parton $q(\text{prod})$ is used as input to the likelihood method (see figure 7.3.22(a) for the distribution used in the muon analysis and figure 7.3.22(b) for the electron analysis). Their transverse momentum spectrum peaks at values close to the selection cuts for jets and falls steeply.

The transverse momentum spectrum for the jets matched to the parton $q(\text{scat})$ is harder, with typical transverse momenta of 50 GeV and up to 250 GeV. This can be explained by the origin of these jets. They are produced by a quark that has emitted a W boson. The recoil against a heavy gauge boson leads to higher transverse momenta (compared to the jets matched with parton $q(\text{prod})$).

The pseudorapidity distributions for jets matched to the b quark from the top decay is also used as input to the likelihood method. The distribution for the muon analysis is displayed in figure 7.3.24(a), the distribution for the electron analysis is shown in figure 7.3.24(b). Most of

Figure 7.3.21: Distribution of the pseudorapidities η for jets associated with the parton $q(\text{prod})$ in the Parton Picture Template. Figure 7.3.21(a) shows the distribution for events in the muon analysis, figure 7.3.21(b) shows the distribution for the electron analysis.

Figure 7.3.22: Transverse momentum of the jets matched with parton $q(\text{prod})$ for the muon analysis (figure 7.3.22(a)) and for the electron analysis (figure 7.3.22(b)).

these jets are reconstructed in the central region of the detector (i.e. $|\eta| < 1$). This is expected for this jet because of its origin from the decay of a heavy particle.

The efficiency of the likelihood method is determined by comparing the configuration with the highest likelihood value with the configuration obtained from the matching of the reconstructed objects with the partons from the generator. The efficiencies ϵ_{68} and ϵ_{100} , as described in definition 6.2.1, are summarized in table 7.3.4 for the muon channel analysis and the electron channel analysis. The probability to find the correct event configuration by chance is 8.3%.

	muon channel	electron channel
$\epsilon_{68}[\%]$	13.1	8.5
$\epsilon_{100}[\%]$	12.3	7.5

Table 7.3.4: Efficiencies ϵ_{68} and ϵ_{100} of the likelihood method for the muon channel analysis and the electron channel analysis.

Figure 7.3.23: Transverse momentum of jets matched with parton $q(\text{scat})$ for muon events (figure 7.3.23(a)) and electron events (figure 7.3.23(b)). These distributions are used as input to the ambiguity resolution for the t-channel Parton Picture Template in events with four jets.

Figure 7.3.24: Pseudorapidity η for jets matched to the b quark produced in the decay of the top quark for events where the W boson decays into a muon and a neutrino (figure 7.3.24(a)), and events where the W boson decays into an electron and a neutrino (figure 7.3.24(b)).

Except for ϵ_{100} of the electron channel, the efficiencies are above this value. The efficiencies in the electron channel are lower than in the muon channel, in which the selection of the variables used in the likelihood was optimized.

7.3.2.2 Observables for Boosted Decision Trees

The configuration with the highest likelihood measure is used to obtain observables for the multivariate analysis. In the following paragraphs the comparisons of data with simulated events for the variables entering the Boosted Decision Trees are shown for the different analysis bins.

Events with four jets, one b-tagged jet, and one muon

The variables used in the multivariate analysis for events with four jets, one b-tagged jet, and

one muon are shown in figures 7.3.25, 7.3.26, and 7.3.27. Within the statistical precision the variables chosen as input for the statistical analysis are well described. In figure 7.3.25(a) the mass of the reconstructed top quark is shown. The distribution peaks around the generated mass of 175 GeV for both the single top signal events and the semileptonic top quark pair events, while the W +jets events and the multijet events are more likely to be found at lower mass values. With ' $q \times \eta$ ' the observable typical for the single top t-channel process (as explained in section 7.1.2) is shown in figure 7.3.25(b). The single top signal distribution is slightly shifted towards positive values, while the background distribution is symmetric.

Figure 7.3.25: Mass of reconstructed top quark t(lept) (7.3.25(a)) and the product $q \times \eta$ of the lepton charge and the pseudorapidity of the jet assigned to the parton q(scst) (7.3.25(b)) for events with one muon, four jets, and one b-tag.

Figure 7.3.26 summarizes kinematic quantities used in the statistical analysis of jets assigned to partons that are directly connected to the primary vertex in the PPT. In figure 7.3.26(a) the transverse momentum of the jet assigned to the parton b(scst) is shown. The background shape between 20 GeV and 60 GeV is a result of the assignment of different parton roles to jets during the ambiguity resolution. The transverse momentum of the jet assigned to the parton q(scst) is shown in figure 7.3.26(b). The signal peaks at lower transverse momenta while the background peaks at around 40 GeV. The pseudorapidity of the jet assigned to the parton q(prod) is shown in figure 7.3.26(c).

The likelihood measure is shown in figure 7.3.27(a). For the single top signal the slope towards higher values is not as steep as for the background events. The background events show a more distinct peak structure for lower values of the likelihood measure. Figure 7.3.32(b) shows the pseudorapidity η of the jet assigned to the parton b(lept) from the decay of the top quark t(lept). Most of the jets chosen for this role are central ($|\eta| < 1$).

Events with four jets, two b-tagged jets, and one muon

The variables used in the multivariate analysis for events with four jets, two b-tagged jets, and one muon are shown in figures 7.3.28 and 7.3.29. Within the statistical precision the variables chosen as input for the statistical analysis are well described. In figure 7.3.26(a) the mass of the reconstructed top quark is shown. The background from top quark pair production shows a narrower peak than the single top signal events. The ' $q \times \eta$ ' observable is shown in figure 7.3.28(b) and shows a distinct central peak for the background, while the distribution for the single top

Figure 7.3.26: Transverse momentum of the jet assigned to the parton the $b(\text{scat})$ (7.3.26(a)), transverse momentum of the jet assigned to the parton $q(\text{scat})$ (7.3.26(b)), and pseudorapidity of the jet assigned to the parton $q(\text{prod})$ (7.3.26(c)) for events with one muon, four jets, and one b-tag.

Figure 7.3.27: Likelihood measure of the ambiguity resolution (7.3.27(a)) and pseudorapidity of the jet assigned to the parton $b(\text{left})$ (7.3.27(b)) for events with one muon, four jets, and one b-tag.

signal is flat. For the likelihood measure in figure 7.3.28(c) the slope for the background events is much steeper than for signal events.

Figure 7.3.28: Mass of the reconstructed top quark $t(\text{left})$ (7.3.28(a)), the product $q \times \eta$ of the lepton charge and the pseudorapidity of the jet assigned to the parton $q(\text{scat})$ (7.3.28(b)), and likelihood measure from the ambiguity resolution (7.3.28(c)) for events with one muon, four jets, and two b-tags.

Figure 7.3.29 summarizes kinematic quantities used in the statistical analysis of jets assigned to partons that are directly connected to the primary vertex in the PPT. In figure 7.3.29(a) the transverse momentum of the jet assigned to the parton b(scatter) is shown. The background distribution has its maximum at around 70 GeV. The expected single top signal has a softer transverse momentum spectrum. The transverse momentum of the jet assigned to the parton q(scatter) is shown in figure 7.3.26(b). The background peaks at around 50 GeV while the single top signal peaks at 20 GeV. The pseudorapidity of the jet assigned to the parton q(prod) is shown in figure 7.3.26(c). Both signal and background distributions are symmetric around $\eta = 0$. However, there are more data events than expected in the region between $0 < \eta < 1$. This excess in data is statistically still compatible with the background estimate.

Figure 7.3.29: Transverse momentum of the jet assigned to b(scatter) (7.3.29(a)), transverse momentum of the jet assigned to q(scatter) (7.3.29(b)), and pseudorapidity of the jet assigned to q(prod) (7.3.29(c)) for events with one muon, four jets, and two b-tags.

Events with four jets, one b-tagged jet, and one central electron

The variables used in the multivariate analysis for events with four jets, one b-tagged jet, and one central electron are shown in figures 7.3.30, 7.3.31, and 7.3.32. The selected variables are reasonably well described for the use in the statistical analysis with Boosted Decision Trees.

Figure 7.3.30 shows the mass of the reconstructed top quark and the ' $q \times \eta$ ' variable, the product of the pseudorapidity of the jet assigned to the parton q(scatter) and the charge of the charged lepton in the event. The reconstructed mass of the top quark (figure 7.3.30(a)) has its peak at around 175 GeV for the single top signal, with long tails towards higher top quark masses. The multijet background accumulates at lower mass values. The ' $q \times \eta$ ' distribution (figure 7.3.30(b)) is symmetrical for background events but shows a shift towards positive values for the single top quark signal samples.

The transverse momenta of the jets assigned to the partons b(scatter) (see figure 7.3.31(a)) and q(scatter) (see figure 7.3.31(b)) show a separation power to discriminate single top signal events from background events. In both cases the signal events peak at lower values. Figure 7.3.31(c) shows the pseudorapidity distribution of the jets associated with the parton named q(prod) in the Parton Picture Template. The distribution for the simulated events is very symmetric. However, the simulation seems to overestimate the observed data in the negative pseudorapidity region.

Figure 7.3.30: Mass of reconstructed top quark $t(\text{lept})$ (7.3.30(a)) and the product $q \times \eta$ of the lepton charge and the pseudorapidity of $q(\text{scst})$ (7.3.30(b)) for t -channel single top events with one electron, four jets, and one b -tag.

Figure 7.3.31: Transverse momentum of the jet assigned to the parton $b(\text{scst})$ (7.3.31(a)), transverse momentum of the jets assigned to the parton $q(\text{scst})$ (7.3.31(b)), and pseudorapidity of the jets assigned to the parton $q(\text{prod})$ (7.3.31(c)) for events with one electron, four jets, and one b -tag.

The likelihood measure for the selected configuration is shown in figure 7.3.32(a). The peak structure is more distinct for background events than for signal events. The background distribution also shows a steeper slope towards higher likelihood values. The jets selected to play the role of the parton $b(\text{lept})$ are very central ones. The majority of these jets is reconstructed in the central detector region, i.e. within $|\eta| < 1$ (see figure 7.3.32(b)).

Events with four jets, two b -tagged jets, and one central electron

The variables used in the multivariate analysis for events with four jets, two b -tagged jets, and one central electron are shown in figures 7.3.33 and 7.3.34. Five variables are selected from the reconstruction of this Parton Picture Template in this analysis bin for the statistical analysis. These variables show an acceptable agreement between the prediction based on simulated events and the observed data.

The mass of the reconstructed top quark is one of the five variables. It is displayed in figure 7.3.33(a). The simulated signal events show a peak with a maximum at around 175 GeV, the mass value used in the generator. The background distribution shows a similar peak. This

Figure 7.3.32: Likelihood measure of the ambiguity resolution (7.3.32(a)) and pseudorapidity η of the jets assigned to b(lept) in the Parton Picture Template (7.3.32(b)) for events with one electron, four jets, and one b-tag.

is no surprise since most background events are semileptonic decays of top quark pairs. These events also have a top quark with a W boson in the decay chain that decays into a charged lepton and a neutrino. Both signal and background distributions show a long tail towards high values of reconstructed top quark masses. The ' $q \times \eta$ ' distribution shown in figure 7.3.33(b) is the distribution with the worst description of the observed data, with two bins in the positive region being below the expectation. As for events with only one b-tagged jet, the signal distribution shows a slight shift towards positive values. The likelihood measure for the selected configuration can be seen in figure 7.3.33(c). While the distribution for signal events is almost flat, the background distribution peaks at low values of the likelihood measure and then continues in a steep descend.

Figure 7.3.33: Mass of the reconstructed top quark t(lept) (7.3.33(a)), $q \times \eta$ of the lepton charge and the pseudorapidity of q(scst) (7.3.33(b)), and likelihood measure from the ambiguity resolution (7.3.33(c)) for events with one electron, four jets, and two b-tags.

The transverse momentum of jets that were assigned the role of the parton b(scst) in the configuration with the highest likelihood measure is another variable that is used as input to the Boosted Decision Trees in this analysis bin. The comparison of simulated events with observed data for this observable is shown in figure 7.3.34(a). The transverse momentum spectrum for signal events is softer than for background events. The distribution of the pseudorapidity of jets

assigned to the parton $q(\text{prod})$ is symmetrical for signal and background events. A large number of jets is found in the forward regions of the detector, with pseudorapidities $\eta > 1$.

Figure 7.3.34: Transverse momentum of the jet assigned to $b(\text{scat})$ (7.3.34(a)) and pseudorapidity of the jet assigned to $q(\text{prod})$ (7.3.34(b)) for events with one electron, four jets, and two b-tags.

7.3.3 Decay of Top Quark Pairs in Semileptonic Events

Top quark pairs produced via strong interaction are the main background in the search for electroweak top quark production in events with four jets. Especially the so-called semileptonic decay, where one of the W bosons decays into a lepton and a neutrino, while the other W boson decays into two quarks, contributes to this jet multiplicity bin. The Parton Picture Template for the PaxProcess that reconstructs the semileptonic top pair decay is shown in figure 7.3.35.

Figure 7.3.35: Parton Picture Template for the PaxProcess reconstructing the semileptonic decay of top quark pairs. The two branches are classified after the decays of the W bosons in the top quark decay chain. The branch where the W boson decays into a lepton and a neutrino is supplemented with (lept) for leptonic branch. The hadronic branch where the W boson decays into two quarks is supplemented with (hadr).

7.3.3.1 Ambiguity Resolution

If there are two real solutions for the quadratic equation that calculates the z component of the neutrino momentum from a W boson mass constraint, there are 24 different possibilities to assign the reconstructed objects to the partons of the Parton Picture Template. In order to find the most likely of these 24 configurations, all configurations are developed and evaluated in a likelihood method (see section 6.2.1.2 for details). The input histograms to this likelihood method come from studies where generator information is matched to reconstructed objects of the simulation. Only distributions from reasonably well matched events are used. Therefore, a 68% quality cutoff in $\Sigma\Delta R$ is introduced. The cutoff values are derived separately for the muon and the electron analysis. The results are summarized in table 7.3.5 and visualized in figure 7.3.36.

Eight different variables are used in the likelihood method to resolve the ambiguities in the association of reconstructed jets objects to partons in the Parton Picture Template for this Pax-Process. The probabilities of the jet to be tagged as a jet originating from a b hadron is used for

68% matching quality cut for	
muons	electrons
0.91	1.17

Table 7.3.5: 68% matching quality cut in $\Sigma\Delta R$ for muon and electron semileptonic top quark pair events with four jets.

Figure 7.3.36: 68% cutoff value for the matching quality $\Sigma\Delta R$ between generated partons and reconstructed objects for muon events (7.3.36(a)) and electron events (7.3.36(b)) for semileptonic top quark pair production. Only quantities of events with good matching quality (grey area) are used as input to the likelihood method that is used to resolve the ambiguities in the jet-parton-assignment.

all four final state quarks of the Parton Picture Template. Figure 7.3.37 shows this probability for jets matched to the quark b(left), the b quark in the top decay branch, where the W boson decays into a charged lepton and a neutrino. For those cases where the charged lepton is a muon, the distribution can be seen in figure 7.3.37(a). For the cases where the W boson decays into an electron and a neutrino the result is shown in figure 7.3.37(b).

Figure 7.3.37: Probability of the jets matched to the parton b(left) to be tagged as a jet originating from a b hadron for muon events (figure 7.3.37(a)) and for electron events (figure 7.3.37(b)).

The probability for the jets matched to the b quark in the top decay branch where the W boson decays hadronically to be tagged as a jet originating from a b hadron is shown in figure 7.3.38. The distributions for analysis in the muon channel can be found in figure 7.3.38(a), the distributions for the electron channel in figure 7.3.38(b).

Figure 7.3.38: The probability of the jet associated with the parton $b(\text{hadr})$ to be tagged as originating from the decay of a b hadron is shown in figure 7.3.38(a) for the muon channel and in figure 7.3.38(b) for the electron channel.

As explained in section 6.2.1.2 the $b\text{-tag}$ of the jets in the files containing both information about the generated and the reconstructed event is assigned based on the tag rate functions and random numbers. Therefore it is possible to sort the two jets from the decay of the W boson after their probability to carry a $b\text{-tag}$. The distribution for the jet with the higher probability to be tagged as originating from a b hadron is shown in figure 7.3.39 the distribution for the jet with the lower probability is shown in figure 7.3.40.

Figure 7.3.39: Probability of the jet to be tagged as originating from a b hadron for the parton $Q(\text{hadr})$, the one of the two quarks from the W boson decay in the Parton Picture Template with the higher $b\text{-tag}$ probability. Distributions are shown for the muon channel (figure 7.3.39(a)) and the electron channel (figure 7.3.39(b)).

The cosine of the angle between the leptonically decaying W boson, boosted into the rest frame of the top quark, and the charged lepton, boosted into the rest frame of the W boson, is used as a handle to select the correct z component of the neutrino transverse momentum. The

Figure 7.3.40: Distribution of the probability of the jets to originate from a b hadron for the parton $q(\text{hadr})$ from the W boson decay. The name is associated to the jet with the lower probability to be b-tagged in simulated events. The histograms show the likelihood input for the muon channel (figure 7.3.40(a)) and the electron channel (figure 7.3.40(b)).

input distributions to the likelihood method for this variable can be seen in figure 7.3.41(a) for the muon channel and in figure 7.3.41(b) for the electron channel.

Figure 7.3.41: Cosine of the angle between the W boson $W(\text{lept})$ and the charged lepton, where the W boson is boosted into the rest frame of the top quark $t(\text{lept})$, and the charged lepton is boosted into the rest frame of the W boson $W(\text{lept})$. Figure 7.3.41(a) shows those events where the W boson decays into a muon, and figure 7.3.41(b) shows the electron channel.

In the production of top quark pairs via strong interaction it is possible to take advantage of the two top quarks in the event. In an ideal world there should not be any mass difference between the two reconstructed top quarks. This property can be used as a constraint in the ambiguity resolution. However, in the real world at hadron collider experiments there can be differences. Figure 7.3.42 shows the mass difference of the reconstructed top quarks after the matching of reconstructed objects with generated partons. The mass difference Δm_t is calculated as:

$$\Delta m_t = m(t_{\text{hadr}}) - m(t_{\text{lept}}). \quad (7.3.1)$$

The peak of the distributions is at negative values of Δm_t . The tails of the distributions towards high negative values of Δm_t come from the uncertainty of the jet energy scale. With three jets in the reconstruction of the top quark with a hadronic decay of the W boson, these uncertainties appear three times and lead to an underestimation of the reconstructed top quark mass. The top decay where the W boson decays leptonically has only one jet and thus suffers once from this jet energy scale uncertainty (although, of course, the three other jets need to be taken into account for the determination of the missing transverse energy that is used for the reconstruction of the neutrino from the W boson decay).

Figure 7.3.42: Difference in reconstructed top quark masses (see equation 7.3.1) for events where information about the reconstructed objects is matched with generator information. The tails at negative values of Δm_t are due to uncertainties on the calibration of the jet energy. Figure 7.3.42(a) shows the input distribution to the muon analysis, figure 7.3.42(b) the input to the electron analysis.

The variable shown in figure 7.3.8 is called *Ht measure*. It is calculated the following way:

$$\text{Htmeasure} = \frac{\sqrt{(P_t(t_{\text{hadr}}) + P_t(t_{\text{lept}}))^2 + (\text{mass}(t_{\text{hadr}}) + \text{mass}(t_{\text{lept}}))^2}}{\text{Ht}}, \quad (7.3.2)$$

where P_t denotes the transverse momentum of the reconstructed top quarks and mass their reconstructed masses. The variable Ht is the scalar sum over the transverse energies of the final state particles, i.e. the four jets, the charged lepton and the missing transverse energy,

$$\begin{aligned} \text{Ht} &= \sum_{\text{final state objects}} E_T \\ &= E_T(b(\text{lept})) + E_T(b(\text{hadr})) + E_T(Q(\text{hadr})) + E_T(q(\text{hadr})) \\ &\quad + E_T(\text{charged lepton}) + E_{T,\text{miss}}. \end{aligned} \quad (7.3.3)$$

At the Tevatron accelerator with its center-of-mass energy of 1.96 TeV top quark pairs are produced near the threshold, i.e. the fraction of the proton momentum carried by the (anti-)quark in the quark-antiquark-annihilation is just big enough to produce top quark pairs via strong interaction. This fact is reflected in this variable *Ht measure*.

The mass of the W boson cannot only be used as a mass constraint for the z component of the neutrino momentum. The reconstructed W boson mass from the two jets matched with the

Figure 7.3.43: H_t measure, as derived in equation 7.3.2, for muon events (figure 7.3.43(a)) and for electron events (figure 7.3.43(b)).

two light quarks from the generator information is used as an input variable for the ambiguity resolution. The resulting distributions shown in figure 7.3.44(a) for the muon channel and in figure 7.3.44(b) for the electron analysis have their peak shifted below 80 GeV. The reason for this shift is the same as the reason for the shift and the tails in the Δm_t distributions in figure 7.3.42: the uncertainty on the jet energy scale.

Figure 7.3.44: Reconstructed mass of the W boson from the two jets matched to the generator information of the partons $q(\text{hadr})$ and $Q(\text{hadr})$ in the Parton Picture Template. The input to the muon analysis is shown in figure 7.3.44(a), the input to the electron analysis in figure 7.3.44(b), respectively.

The efficiency of the likelihood method is determined by comparing the configuration with the highest likelihood value with the configuration obtained from the matching of the reconstructed objects with the partons from the generator. The efficiencies ϵ_{68} and ϵ_{100} , as described in definition 6.2.1, are summarized in table 7.3.6 for the muon channel analysis and the electron channel analysis. The probability to find the correct event configuration by chance is 8.3%. All efficiencies beat this value by at least a factor of 3, ϵ_{68} in the muon channel almost reaches 50% of correct assignments.

	muon channel	electron channel
$\epsilon_{68}[\%]$	48.7	35.5
$\epsilon_{100}[\%]$	40.5	29.4

Table 7.3.6: Efficiencies ϵ_{68} and ϵ_{100} of the likelihood method for the muon channel analysis and the electron channel analysis.

7.3.3.2 Observables for Boosted Decision Trees

The configuration with the highest likelihood measure is used to obtain observables for the multivariate analysis. In the following paragraphs the comparisons of data with simulated events for those variables entering the Boosted Decision Trees are shown for the different analysis bins.

Events with four jets, one b-tagged jet, and one muon

The variables used in the multivariate analysis for events with four jets, one b-tagged jet, and one muon are shown in figures 7.3.45, 7.3.46, and 7.3.47. For the selected variables the expected background distributions show a good agreement with the observed data.

In the analysis of the Parton Picture Template shown in figure 7.3.35, two top quarks are reconstructed. Observables from both top quarks are used as input to the Boosted Decision Trees. From the hadronic branch, where the W boson decays hadronically, the reconstructed top quark mass (figure 7.3.45(a)) and the transverse momentum of the reconstructed top quark (figure 7.3.45(b)) are used. For the simulated semileptonic top quark pair events the reconstructed mass of the top quark peaks at around the expected value of 175 GeV. The single top s- and t-channel events are forced into a top quark pair configuration. The reconstructed mass peak for these events is broader than for the semileptonic top quark pair events and it peaks at a lower value (around 150 GeV). Towards higher values of the transverse momentum of the reconstructed top quarks, the background distribution is falling steeper than the signal distribution.

Figure 7.3.45: Mass (7.3.45(a)) and transverse momentum (7.3.45(b)) of the reconstructed top quark $t(\text{hadr})$ for events with one muon, four jets and one b-tag.

From the reconstructed top quark where the W boson in the top quarks' decay chain decays leptonically the observables pseudorapidity (figure 7.3.46(a)) and transverse momentum

(figure 7.3.46(b)) are used as input to the statistical analysis. The distributions for the pseudorapidity are very symmetric for both the background and the signal events. The data distribution fluctuates a bit in the positive η region which is only a statistical effect. The interpretation of the transverse momentum distribution is similar to the one for the reconstruction of the top quark in the hadronic branch. The background has a steeper slope at higher values of transverse momentum. The single top signal events on average have a lower transverse momentum for the reconstructed $t(\text{lept})$ parton.

Figure 7.3.46: Pseudorapidity (7.3.46(a)) and transverse momentum (7.3.46(b)) of the reconstructed top quark $t(\text{lept})$.

The transverse momenta of the jets associated with the b -quarks in the top decays can be seen in figure 7.3.47(a) (for the branch with the hadronic decay of the W boson) and figure 7.3.47(b) (for the branch with the W boson decaying into leptons). Furthermore, figure 7.3.47(c) shows the result of the ambiguity resolution, i.e. the likelihood measure for the configuration that was selected. The transverse momentum spectrum of the jets playing the role of $b(\text{hadr})$ is falling steeper for the simulated background events than for the single top signal events. The same statement is true for the jets acting as parton $b(\text{lept})$. The likelihood measure has clearly shifted the semileptonic top quark pair events towards higher values than the single top signal events. As a consequence, this variable will contribute to the separation of signal events from the top quark pair events.

Events with four jets, two b -tagged jets, and one muon

The variables used in the multivariate analysis for events with four jets, two b -tagged jets, and one muon are shown in figures 7.3.48, 7.3.49, and 7.3.50. The requirement to have two jets identified to originate from b hadrons leaves top quark pair events as the dominant background in this analysis bin. There are only few W +jets events left and almost no more multijet events.

The variables selected for the Boosted Decision Tree analysis are the same ones than for the data sample with only one b -tagged jet. From the reconstruction of the branch of the Parton Picture Template with the hadronic decay of the W boson the variables from the reconstructed top quarks are their mass (see figure 7.3.48(a)) and their transverse momentum (see figure 7.3.48(b)). The mass of the reconstructed top quark shows a peak at 175 GeV for the semileptonic top quark pair production background. The peak for the single top quark signal

Figure 7.3.47: Transverse momentum of the jets assigned to b(hadr) (7.3.47(a)), transverse momentum of the jets assigned to b(lept) (7.3.47(b)), and likelihood measure of the ambiguity resolution (7.3.47(c)) for events with one muon, four jets and one b-tag.

events is at slightly lower values and much broader. The transverse momentum of the reconstructed top quark is lower for the single top events forced into a top quark pair production hypothesis.

Figure 7.3.48: Mass (7.3.48(a)) and transverse momentum (7.3.48(b)) of the reconstructed top quark t(hadr) for events with one muon, four jets and two b-tags.

Also for the reconstructed top quarks in the top quark decay branch where the W boson decays leptonically the transverse momentum for the single top signal events is on average lower than for the background events (see figure 7.3.49(a)). The distribution of the pseudorapidity η of these top quarks is symmetric around $\eta = 0$, but shows a more distinct peak structure for the background events than for the signal events (figure 7.3.49(b)).

The transverse momenta for jets assigned to the b quarks in the Parton Picture Template of this PaxProcess are on average lower for the simulated single top signal events than for the simulated background events. The signal distribution in figure 7.3.50(a) for jets assigned to the parton b(hadr) reaches its maximum already around 25 GeV, while the background distribution peaks at 50 GeV followed by a steeper decline. For jets assigned to the parton b(lept) the situation is similar (see figure 7.3.50(b)): the background peaks at 45 GeV, the signal at 25 GeV. Together with the results of the likelihood measure (shown in figure 7.3.50(c)), where most of the events from semileptonic top quark pair production have a higher value than the single

Figure 7.3.49: Pseudorapidity (7.3.49(a)) and transverse momentum (7.3.49(b)) of the reconstructed top quark t (left) for events with one muon, four jets and two b-tags.

top signal events, these variables are very well suited to separate the single top signal from semileptonic top quark pair events.

Figure 7.3.50: Transverse momentum of the jets associated with parton b (hadr) (7.3.50(a)), transverse momentum of jets associated with parton of b (lept) (7.3.50(b)), and likelihood measure of the ambiguity resolution (7.3.50(c)) for events with one muon, four jets and two b-tags.

Events with four jets, one b-tagged jet, and one central electron

The variables used in the multivariate analysis for events with four jets, one b-tagged jet, and one electron are shown in figures 7.3.51, 7.3.52, and 7.3.53. Overall, the agreement between the observed data and the background model is reasonably well.

In figure 7.3.51(a) the mass of the reconstructed top quark in the branch with the hadronic decay of the W boson is shown. For the semileptonic top quark pair events, there is a peak at 175 GeV, the input that was used in the generation of these events. The distribution for signal events of electroweak top quark production that are forced in a configuration of semileptonic top quark pair events has a maximum, too. It is reached at lower values, at around 130 GeV and shows a flatter descent towards higher mass values. The likelihood measure for the selected configuration after ambiguity resolution can be found in figure 7.3.51(b). The majority of signal events has low values. The multijet events also appear at low likelihood values.

Figure 7.3.51: Mass of the reconstructed top quark $t(\text{had})$ (7.3.51(a)) and likelihood measure of the ambiguity resolution (7.3.51(b)) for events with one electron, four jets and one b-tag.

From the reconstruction of the top quark in the branch where the W boson decays into leptons, the pseudorapidity η (figure 7.3.52(a)) and the transverse momentum (figure 7.3.52(b)) are chosen as input for the Boosted Decision Tree analysis. For the background events the pseudorapidity distribution shows a distinct peak structure, while the distribution of signal events reaches a plateau in the region of $|\eta| < 2$. The transverse momentum of the reconstructed top quarks $t(\text{lept})$ for single top signal events is on average lower than for the background events.

Figure 7.3.52: Pseudorapidity (7.3.52(a)) and transverse momentum (7.3.52(b)) of the reconstructed top quark $t(\text{lept})$.

The transverse momenta of the jets associated to the partons $b(\text{lept})$ and $b(\text{had})$ from the top quark decays are also used as input to the multivariate classifier in this analysis bin. The distributions can be seen in figure 7.3.53(a) and figure 7.3.53(b). In both cases the background distribution has a steeper slope towards higher transverse momenta.

Events with four jets, two b-tagged jets, and one central electron

The variables used in the multivariate analysis for events with four jets, two b-tagged jets, and one central electron are shown in figures 7.3.54, 7.3.55, and 7.3.56. Six variables from the reconstruction of the Parton Picture Template for this analysis bin are used to train the

Figure 7.3.53: Transverse momentum of jets assigned to the parton b(hadr) (7.3.53(a)), and transverse momentum of jets assigned to the parton b(lept) (7.3.53(b)) for events with one electron, four jets and one b-tag.

Boosted Decision Trees. These variables have an acceptable agreement between the background prediction and the observed data, taking into account the limited statistics in this analysis bin.

Figure 7.3.54 shows the mass of the reconstructed top quark t(hadr) (figure 7.3.54(a)) and its transverse momentum (figure 7.3.54(b)). The mass for the single top quark events peaks at lower values (about 130 GeV), while the background events (predominantly semileptonic top quark pair production) peak at the generated mass value of 175 GeV. The transverse momentum distribution of the reconstructed top quarks t(hadr) is on average slightly lower for the events of electroweak top quark production than for those from top quark pair production.

Figure 7.3.54: Mass (7.3.54(a)) and transverse momentum (7.3.54(b)) of the reconstructed top quark t(hadr) for events with one electron, four jets and two b-tags.

The likelihood measure of the configuration that was selected to be the most likely one in the reconstruction of the Parton Picture Template is shown in figure 7.3.55(a). While about half of the signal events can be found in the first bin of the histogram, the background events are shifted towards higher values. This is no surprise because the dominant background is semileptonic top quark pair production and the likelihood measure is optimized to identify this kind of events. The transverse momentum spectrum of the reconstructed top quark t(lept) is broader for background events than for the single top signal events, as can be seen in figure 7.3.55(b).

Figure 7.3.55: Likelihood measure of the ambiguity resolution (7.3.55(a)) and transverse momentum (7.3.55(b)) of the reconstructed top quark $t(\text{lept})$ for events with one electron, four jets and two b-tags.

As in the other analysis bins, the transverse momentum of the jets assigned to the b partons $b(\text{lept})$ and $b(\text{hadr})$ in the Parton Picture Template are also used for the statistical analysis. For the jets assigned to the parton $b(\text{hadr})$ the resulting distribution is shown in figure 7.3.56(a). Figure 7.3.56(b) shows the distribution for jets playing the role of parton $b(\text{lept})$ after the ambiguity resolution. In both distributions the spectra for the signal events is softer than for the background events.

Figure 7.3.56: Transverse momentum of jets assigned to the parton $b(\text{hadr})$ (7.3.56(a)), and transverse momentum of jets assigned with the parton $b(\text{lept})$ (7.3.56(b)) for events with one electron, four jets and two b-tags.

7.3.4 Global Event Observables

This section deals with variables that can be calculated or derived from the event without the resolution of ambiguities. However, a Parton Picture Template is used and reconstructed in order to have access to some of the observables. This Parton Picture Template is displayed in figure 7.3.57. The four jets in the event are ordered by their transverse momentum, with jet1 being the jet with the highest transverse momentum, and jet4 the jet with the lowest transverse momentum. The vector sum of these four jets builds a new four-vector, the so-called *Hadronic Final State* (HFS). This HFS four-vector is then connected to the primary vertex of the event. The charged lepton and the reconstructed missing transverse energy of the event are used to reconstruct a W boson. This is done using a W boson mass constraint to get a z component for the neutrino momentum vector. The x and y component of this vector are taken from the reconstruction algorithm for the missing transverse energy. From the two solutions for the z component of the neutrino momentum the decision is made to use the more central solution as the component in the neutrino four-vector, i.e. the solution with the smaller absolute value of pseudorapidity η .

7.3.4.1 Observables for Boosted Decision Trees

In the following, the variables used in the statistical analysis with Boosted Decision Trees are presented for the four different analysis bins.

Events with four jets, one b-tagged jet, and one muon

Variables of this PaxProcess used in the statistical analysis are shown in figures 7.3.58 to 7.3.71. These variables were chosen because of their good agreement in the comparison of simulated background with observed data and their potential to separate the events from the electroweak top quark signal from background events.

Figure 7.3.58 shows the angles between the HFS and the leading jet (figure 7.3.58(a)) and second leading jet (figure 7.3.58(b)). Those angles were calculated after boosting both the HFS and the jets into the center-of-mass frame. In both cases the background shows a more distinct peak structure. The angle between the HFS and jet2 is also slightly shifted towards higher values for the simulated signal events.

Figure 7.3.59 shows three different combinations of invariant masses. The invariant mass of all jets in the event minus the best jet (as defined definition 6.2.3 on page 118) is displayed in figure 7.3.59(b). If one subtracts the b-tagged jet (see definition 6.2.4) from all four jets, the resulting distribution can be seen in figure 7.3.59(b). Calculating the invariant mass of the two leading jets in transverse momentum and the W boson leads to the distribution shown in figure 7.3.59(c). For all three invariant masses the signal events have a broader distribution and peak at lower values.

The scalar sum of transverse momenta of jets is called H_t . As for the transverse masses in figure 7.3.59 there are different possible combinations to define several H_t variables. In

Figure 7.3.57: Parton Picture Template for the PaxProcess that calculates event shape variables.

Although there are no ambiguities to be resolved, a Parton Picture Templates is reconstructed in the event. The four jets are ordered by their transverse momentum and a new four-vector called Hadronic Final State (HFS) is built as the vector sum of these jets. This HFS four-vector and the four-vector for the reconstructed W boson are connected to the primary vertex. For the reconstruction of the W boson the z component of the neutrino momentum needs to be calculated. This is done by using the quadratic equation one gets from a W boson mass constraint and selecting the solution with the smaller pseudorapidity η . The W boson that is reconstructed from the neutrino and the charged lepton is then also connected to the primary vertex.

figure 7.3.60(a) the H_t variable is calculated using all jets but neglecting the best jet (see definition 6.2.3 on page 118). If one neglects the b-tagged jet (definition 6.2.4) instead of the best jet the calculation of H_t leads to the distribution shown in figure 7.3.60(b). The background peaks at around 150 GeV, while the signal peaks at lower values in both distributions.

The same configurations of jets that were used in the H_t variable are also used in the variable H . Instead of adding up the transverse momenta of jets, here their scalar energy is the quantity that is summed up. In figure 7.3.61(a) H for all jets except the best jet is presented, and in figure 7.3.61(b) the sum of scalar energies neglects the jet with the b-tag. In both distributions the background model has a more distinct peak structure than the signal events. Those show a very broad distribution.

The transverse momentum of the best jet is shown in figure 7.3.62(a). This variable shows a

(a)

(b)

Figure 7.3.58: Angle between the HFS and the jet with the highest transverse momentum (figure 7.3.58(a)) and angle between the HFS and the jet with the second highest transverse momentum (figure 7.3.58(b)). In both cases the four-vectors are boosted into the center-of-mass system of the event. These distributions are for events with four jets, one b-tagged jet and one muon.

(a)

(b)

(c)

Figure 7.3.59: Three different combinations of invariant masses. Figure 7.3.59(a) shows the invariant mass of all jets minus the best jet, figure 7.3.59(b) shows the invariant mass for all jets that are not b-tagged, and figure 7.3.59(c) shows the invariant mass of the two leading jets in transverse momentum and the W boson. All distributions show events with four jets, one b-tagged jet and one muon.

Figure 7.3.60: Scalar sum H_t of transverse momenta for different jet combinations. Figure 7.3.60(a) shows all jets minus the best jet, while figure 7.3.60(b) does not take the b-tagged jet into account. Both distributions show events with four jets, one b-tagged jet and one muon.

Figure 7.3.61: The distributions show the sum of the scalar energies of reconstructed jets in the event. In figure 7.3.61(a) all jets except the best jet are shown. Figure 7.3.61(b) shows the sum for all jets except for the b-tagged one. Both distributions show events with four jets, one b-tagged jet and one muon.

broad distribution for both signal and background events. Sorting the jets that are not identified as originating from a b hadron after their transverse momenta, the transverse momentum of the jet with the second highest transverse momentum can be seen in figure 7.3.62(b). The distribution reaches its maximum for the signal events at around 30 GeV. In that region the distribution for the semileptonic top quark pair events is still rising, until the number of events reaches a maximum at 50 GeV.

Figure 7.3.62: Transverse momentum of the best jet (figure 7.3.62(a)) and of the jet with the second highest transverse momentum of those jets that are not b-tagged (figure 7.3.62(b)). The distributions show events with four jets, one b-tagged jet and one muon.

The variables shown in figure 7.3.63 are chosen in order to exploit more angular correlations of the events. Figure 7.3.63(a) shows the cosine of the angle between the b-tagged jet and the lepton in the rest frame of the b-tagged top quark (as defined in section 6.2.1.2). The background distribution falls much steeper than the distribution for the simulated single top quark events. The difference in ΔR between the two jets with the highest transverse momenta is shown in figure 7.3.63(b). The minimal distance ΔR for all possible jet configurations is shown in figure 7.3.63(c). The observed data describe the background model not as well as in other distributions, but the agreement is still good, and thus this variable can be used in the statistical analysis.

Not only invariant masses, but also transverse masses can be used in the statistical analysis. The transverse masses of the combination of jet1 and jet2 is shown in figure 7.3.64(a) and the transverse mass of the W boson is displayed in figure 7.3.64(b). The latter one is a good variable to suppress the multijet background that accumulates at low values in this variable.

The centrality of the event is calculated as the ratio of the variables Ht and H for all jets:

$$\text{Centrality} = \frac{Ht}{H}. \quad (7.3.4)$$

The distribution of the centrality is shown in figure 7.3.65(a). The background distribution differs from the distribution for signal events and peaks at around 0.75. The simulated single top quark events have a broader distribution that has its maximum at around 0.55. Another way to calculate a ' $q \times \eta$ ' variable is to take the charge of the charged lepton from the W boson decay and the pseudorapidity η of the jet with the highest transverse momentum that is not tagged as originating from a b hadron decay. The result of this product $q \times \eta$ is shown in figure 7.3.65(b).

Figure 7.3.63: Figure 7.3.63(a) shows the cosine of the angle between the b-tagged jet and the charged lepton in the rest frame of the reconstructed b-tagged top quark. The distance ΔR between the two jets with the highest transverse momentum in the event can be seen in figure 7.3.63(b). ΔR_{min} , the minimal distance of all jet combinations, is shown in figure 7.3.63(c). The three distributions show events with four jets, one b-tagged jet and one muon.

Figure 7.3.64: Transverse mass of the jet1-jet2 system (figure 7.3.64(a)) and invariant mass of the W boson, calculated from the momentum components of the charged lepton and the missing transverse energy information (figure 7.3.64(b)). These distributions show events with four jets, one b-tagged jet and one muon.

The distribution for background events is more symmetric than for the signal events. Their distribution has a maximum at 0.5 and is shifted towards positive values. The variable $\hat{S}$ is another variable whose distribution shows a different shape for signal and background events. $\hat{S}$ is the mass of the resulting four-vector after summing up all jets and the reconstructed W boson in the event (see equation 7.1.8 on page 178). On average the background has higher values of $\hat{S}$. Similar to both signal and background distributions are the long tails to very high values of $\hat{S}$.

Figure 7.3.65: Centrality of all jets in the event (figure 7.3.65(a)), product $q \times \eta$ of the charged leptons charge and the leading jets pseudorapidity (figure 7.3.65(b)), and variable $\hat{S}$ (figure 7.3.65(c)) for events with four jets, one b-tagged jet and one muon.

The variable aplanarity is defined in equation 7.1.14 on page 181. The resulting distribution for this analysis bin can be found in figure 7.3.66(a). The slope for the background distribution is slightly steeper than the signal events. A second way to calculate centrality is to not only take the jets into account, but also use information about the charged lepton and missing transverse energy. The result of this calculation is shown in figure 7.3.66(b). The peak structure for the background distribution is more distinct than for the centrality calculation without the leptons. The broad distribution for the simulated signal events is similar to the jets-only calculation.

Figure 7.3.66: Aplanarity (figure 7.3.66(a)) and centrality (calculated with lepton information, figure 7.3.66(b)) for events with four jets, one b-tagged jet and one muon.

The combination of the two leading jets in transverse momentum can be combined to a dijet four-vector. Properties of this four-vector are another input to the statistical analysis. In particular its mass (figure 7.3.67(a)) and its transverse momentum (figure 7.3.67(b)) are used. The

mass of this dijet system is on average lower for simulated signal events than for background events, but the transverse momentum is slightly higher.

Figure 7.3.67: Mass (figure 7.3.67(a)) and transverse momentum (7.3.67(b)) of the vector sum of the two leading jets in transverse momentum for events with four jets, one b-tagged jet and one muon.

Like for the calculation of centrality in figure 7.3.66, there is also a second way to calculate the variables H and H_t by taking the lepton information from the decay of the W boson into account. The resulting distribution for H is displayed in figure 7.3.68(a). It is similar to the distribution based on the calculation on jets only, with a narrower peak structure for the background events than for the signal events. The distribution for the H_t variable in figure 7.3.68(b) shows a good separation between signal and background events. The signal distribution peaks at around 270 GeV, while the background distribution peaks approximately 40 GeV higher. Considering events from semileptonic top quark pair production alone, their distribution peaks at 350 GeV.

Figure 7.3.68: Variables H and H_t calculated using also lepton information. The distribution for H can be seen in figure 7.3.68(a), the distribution for H_t in figure 7.3.68(b). Events with four jets, one b-tagged jet and one muon are shown.

The four jets in the event are sorted according to their transverse momentum. The transverse momentum distributions for the leading two jets are shown in figure 7.3.69. The distributions for jet3 and jet4 can be found in figure 7.3.70. For all four transverse momentum spectra a similar statement can be made: the spectrum for the events of electroweak top quark production is softer than for the background events.

Figure 7.3.69: Transverse momentum distribution for the jet with the highest transverse momentum in the event (figure 7.3.69(a)) and for the jet with the second highest transverse momentum (figure 7.3.69(b)). These transverse momentum spectra are for the analysis bin with four jets, one b-tagged jet and one muon.

Figure 7.3.70: Transverse momentum distributions for jet3 (figure 7.3.70(a)) and jet4 (figure 7.3.70(b)) for events with four jets, one b-tagged jet and one muon.

The variable LepMet is calculated as the scalar sum of the transverse energy of the charged lepton and the missing transverse energy:

$$\text{LepMet} = E_{T,\text{lepton}} + E_{T,\text{miss}}. \quad (7.3.5)$$

The LepMet distribution is shown in figure 7.3.71(a). Figure 7.3.71(b) shows the comparison between background prediction and observed data for the variable SEt (see equation 7.1.9 on page 180). The LepMet variable manages to separate the signal from the multijet background that is shifted towards low values. SEt however has some discriminating power against the whole background composition. The signal distribution peaks at a value of 200 GeV, the background distribution peaks at a value of about 260 GeV.

Figure 7.3.71: The LepMet variable is shown in figure 7.3.71(a) and the SEt variable can be seen in figure 7.3.71(b) for events with four jets, one b-tagged jet, and one muon.

Events with four jets, two b-tagged jets, and one muon

The analysis bin with four jets, two of which are identified as originating from the decay of a b hadron, and one muon suffers from low statistics because of the b-tag requirement. However, there are variables that agree well in the comparison of the simulated background expectation and the observed data events and can thus be used as input variables in the Boosted Decision Tree analysis.

The angles between the HFS and both the leading and the second leading jet in the center-of-mass system are shown in figures 7.3.72(a) and 7.3.72(b), respectively. In both cases the distribution for signal events is slightly shifted towards higher angles compared to the shape of the background events.

Different combinations of invariant masses are shown in figure 7.3.73. First, the invariant mass of all jets minus the best jet (see definition 6.2.3 for details) is displayed in figure 7.3.73(a). Subtracting the b-tagged jet instead of the best jet, where b-tagged jet follows definition 6.2.4, results in the distribution found in figure 7.3.73(b). The third combination is the transverse mass of the two leading jets with the reconstructed W boson. This result can be seen in figure 7.3.73(c). For all three invariant masses the signal events have a broader distribution and peak at lower values than the background events.

Figure 7.3.72: Angle between the HFS and jet1 (figure 7.3.72(a)) and angle between the HFS and jet2 (figure 7.3.72(b)). In both cases the four-vectors are boosted into the center-of-mass system of the event. These distributions are for events with four jets, two b-tagged jets and a muon.

Figure 7.3.73: Three different combinations of invariant masses. Figure 7.3.73(a) shows the invariant mass of all jets minus the best jet, figure 7.3.73(b) shows the best jet minus the b-tagged jet (following definition 6.2.4), and figure 7.3.73(c) shows the invariant mass of jet1, jet2 and the reconstructed W boson. All three distributions are for events with four jets, two b-tagged jets and a muon.

The sum of the scalar energy of jets in the events H is shown in figures 7.3.74(a) and 7.3.74(b). In figure 7.3.74(a) the best jet was not taken into account in the summation, in the distribution in figure 7.3.74(b) the b-tagged jet (as defined in definition 6.2.4) was not taken into account. For both calculations of H the signal distribution has its maximum at lower values than the background distribution. Summing up the transverse momenta of the jets in the event omitting the best jet results, in the distribution shown in figure 7.3.74(c). The multijet background events are at low values of this H_t variable. The dominant background of semileptonic top quark pair events peaks at around 160 GeV and the distribution for single top quark events has its maximum at around 110 GeV.

Angular correlations for events in this analysis bin are shown in figure 7.3.75. The cosine of the angle between the b-tagged jet (following definition 6.2.4) and the lepton in the reference frame of the b-tagged top quark (see definition 6.2.6) is displayed in figure 7.3.75(a). There the slope of the falling distribution is steeper for background events. In figure 7.3.75(b) the difference in ΔR between the leading and second leading jet is shown, while in figure 7.3.75(c) the

Figure 7.3.74: Sum of scalar energies of jets H in the event, omitting the best jet in the summation (figure 7.3.74(a)) or the b-tagged jet (figure 7.3.74(b)). Figure 7.3.74(c) shows the sum of the transverse momenta of the jets instead, omitting the best jet. The distributions show events with four jets, two b-tagged jets and one muon.

minimal distance ΔR_{min} of all jet combinations in the event is shown. Both ΔR distributions are well described by the observed data.

Figure 7.3.75: The cosine of the angle between the b-tagged jet and the lepton in the reference frame of the b-tagged top quark is shown in figure 7.3.75(a). The distance ΔR between the two leading jets is shown in figure 7.3.75(b) and the minimal distance ΔR_{min} between all jet configurations in figure 7.3.75(c). The distributions show events with four jets, two b-tagged jets and one muon.

The transverse momentum distribution for the best jet is shown in figure 7.3.76(a). This is a very flat distribution for the signal events and has a more distinct peak structure for the background events. The transverse momentum distribution for the leading jet that is not tagged as originating from a b hadron peaks at the beginning of the distribution for signal events. The background distribution rises until 70 GeV and starts to fall from there.

Centrality (figure 7.3.77(a)), the ratio of H_t and H (see equation 7.3.4) of the jets, and the variable $\hat{S}$ (see equation 7.1.8), shown in figure 7.3.77(b), are also used in the statistical analysis. For the centrality of the event the background distribution has a long rising edge until it reaches its maximum at 0.8. The simulated single top quark events have a broad distribution with a maximum at 0.6. The maximum of the $\hat{S}$ distribution for signal events is at 350 GeV compared to the background that peaks at 420 GeV and has a narrower peak structure.

The ' $q \times \eta$ ' variable as defined in definition 6.2.7 is shown in figure 7.3.78(a). The transverse

Figure 7.3.76: Transverse momentum distribution for the best jet (figure 7.3.76(a)) and the leading jet that has no b-tag (figure 7.3.76(b)). Events with four jets, two of them with a b-tag, and one muon are shown.

Figure 7.3.77: Distributions of centrality (figure 7.3.77(a)) and $\hat{S}$ (figure 7.3.77(b)) for events with one muon, and four jets of which two are tagged as originating from a b hadron.

mass of the W boson calculated from the kinematics of the charged lepton and missing transverse energy can be seen in figure 7.3.78(b). Both distributions show good agreement between the observed data and the simulated background events.

The distributions for the aplanarity variable (see equation 7.1.14) and the centrality that is calculated taking also lepton information into account can be seen in figures 7.3.79(a) and 7.3.79(b), respectively. The shape of the aplanarity distribution is similar for both signal and background events. The centrality variable is a good separator for multijet events, but has also a different shape for signal events and the main background contributions coming from semileptonic top quark pair decays and associated production of a W boson with jets.

Mass and transverse momentum of the dijet system that results from the combination of the leading and the second leading jet are shown in figure 7.3.80. The mass distribution of the dijet system shown in figure 7.3.80(a) has a more distinct peak structure for background events than for signal events. Their distribution is broader and reaches its maximum at a slightly lower value. The same statement is true for the transverse momentum distribution (figure 7.3.80(b)) of the dijet system, although the shapes for signal and background are more similar.

Figure 7.3.78: Product ' $q \times \eta$ ' of the leading jet's pseudorapidity (figure 7.3.78(a)) and the transverse mass of the W boson, calculated from the kinematics of the charged lepton and the missing transverse energy in the event (figure 7.3.78(b)). Events with four jets, two of them b-tagged, and one muon are shown.

Figure 7.3.79: Distributions of the aplanarity of the events (figure 7.3.79(a)) and of the centrality of the events (figure 7.3.79(b)), the latter calculated using also information of the leptons in the event. These distributions show events with four jets, two b-tagged jets, and one muon.

The variables H and H_t are shown in figure 7.3.81 for the calculation using also the information about the leptons in the event as well as all jets. The distribution for H in figure 7.3.81(a) has a more pronounced peak structure for the background events than for the signal events. For H_t in figure 7.3.81(b) the maximum of the signal distribution is at around 280 GeV, while the background distribution reaches its maximum 40 GeV later.

Two kinematic variables of the second leading jet in transverse momentum are used in the Boosted Decision Tree analysis for this analysis bin, the transverse momentum and the pseudorapidity η . The transverse momentum spectrum for the background events is harder than for the single top signal events and has its maximum at 60 GeV (see figure 7.3.82(a)). In pseudorapidity η the distributions for both signal and background are very symmetric. There are more events in the observed data with positive pseudorapidities than with negative pseudorapidities, but this discrepancy is within the statistical uncertainty.

The transverse momentum of the leading jet is shown in figure 7.3.83(a) together with the

Figure 7.3.80: Mass (figure 7.3.80(a)) and transverse momentum (figure 7.3.80(b)) of the vector sum of the two leading jets in transverse momentum for events with four jets, two b-tagged jets, and one muon.

Figure 7.3.81: Distribution of the variables H in figure 7.3.81(a) and Ht in figure 7.3.81(b) for events with four jets, two b-tagged jets, and one muon.

LepMet variable (see figure 7.3.83(b) and equation 7.3.5) and the S_{ET} variable, shown in fig-

Figure 7.3.82: Transverse momentum of the second leading jet (figure 7.3.82(a)) and the pseudorapidity η of these jets (figure 7.3.82(b)) for events with four jets, two b-tagged jets, and one muon.

ure 7.3.83(c) and explained in equation 7.1.9. A common feature of all three variables is the steeper slope of the falling edge of the distributions. For S_{Et} and the transverse momentum of jet1, there is in addition a shift towards lower values for the single top signal events.

Figure 7.3.83: Transverse momentum of the leading jet (figure 7.3.83(a)), the LepMet variable (figure 7.3.83(b)), and the distribution for S_{Et} (figure 7.3.83(c)) for events with four jets, two b-tagged jets and one muon.

Events with four jets, one b-tagged jet, and one central electron

The input variables to the statistical analysis from this analysis bin won by the PaxProcess reconstructing the Parton Picture Template from figure 7.3.57 are shown in figures 7.3.84 to 7.3.97. These variables show a good agreement in the comparison of simulated background events with the observed data events.

After boosting both the Hadronic Final State (HFS) and the individual jets into the center-of-mass of the analyzed event, the angle between the direction of the HFS and jet1 (figure 7.3.84(a)) and the HFS and jet2 (figure 7.3.84(b)) calculated. For the distribution of the angle between the HFS and the leading jet the slope on the falling edge of the distribution is much steeper for the background events than for the signal events. The background distribution is shifted towards smaller angles compared to the expected signal events. The shapes of the distributions for the angle between the HFS and the second leading jet are much more similar for signal and background than for the angle between the HFS and the leading jet. Both distributions are broad.

Three different scenarios of invariant masses of jet combinations are shown in figure 7.3.85. Figure 7.3.85(a) shows the invariant mass distribution for all jets except for the best jet (as defined in definition 6.2.3). The signal distribution peaks at 110 GeV and has a long falling edge towards higher invariant masses. The background distribution has its maximum at 160 GeV and shows a narrower peak structure. A similar behaviour can be seen in figure 7.3.85(b), where the b-tagged jet was omitted instead of the best jet. The comparison of observed data to the simulated background events is better than in the first case. As a third invariant mass, the invariant mass of the two leading jets and the reconstructed W boson is calculated and plotted in figure 7.3.85(c). This distribution is broader than for the invariant masses using only jets. The difference between the maximum of the distribution for the single top quark events that peak at 250 GeV and the background events is approximately 50 GeV.

Figure 7.3.84: Angle between the HFS and the leading jet (figure 7.3.84(a)) and the second leading jet (figure 7.3.84(b)), with both HFS and the jets boosted to the center-of-mass reference frame. Distributions are for events with four jets, one b-tagged jet and one electron.

Figure 7.3.85: Different combinations of invariant masses. Figure 7.3.85(a) shows the invariant mass distributions for all jets but the best jets. Figure 7.3.85(b) omits the jet tagged as originating from a b hadron in the calculation, and in figure 7.3.85(c) the two leading jets and the reconstructed W boson are taken into account in the calculation of the invariant mass. All three distributions show events with four jets, one b-tagged jet and a central electron.

Instead of calculating the invariant masses of jets in an event, their scalar energies are summed up in order to get the observable H . Again, different combinations of jets can be built. The result for the summation for all jets except for the best jet can be found in figure 7.3.86(a). There is one bin in the histogram where the observed data do not describe the background estimation too well, around 200 GeV. However, for all other bins the description is reasonable. The background distribution has a higher maximum and a steeper falling edge than the signal distribution. Omitting the b-tagged jet in the calculation of H leads to the distribution shown in figure 7.3.86(b). At the rising edge of the distribution the observed data have a tendency to be lower than the expected background contribution in this region. But the discrepancy is small and within statistical errors. Therefore and because of the separation power of the variable, it is used as input for the Boosted Decision Tree analysis.

Exchanging the sum over the scalar energies with a sum over the transverse momenta of the jets, the same jet configurations can be built. Figure 7.3.87(a) shows this H_t variable for this

Figure 7.3.86: Sum of scalar energies H for all jets in the event except for the best jet (figure 7.3.86(a)) or except for the b-tagged jet (figure 7.3.86(b)) for events with one central electron, one b-tagged jet, and four jets overall.

analysis bin when omitting the best jet from the calculation, figure 7.3.87(b) shows the result of the calculation omitting the b-tagged jet. In both cases the single top signal events peak at lower H_t values than the simulated background events. Thus, both variables can be useful in the statistical analysis to separate the signal against the background.

Figure 7.3.87: Sum of transverse jet momenta for all jets except the best jet (figure 7.3.87(a)) and for all jets but the b-tagged jet (figure 7.3.87(b)) in events with one central electron, one b-tagged jet, and a total of four jets.

Angular correlations between jets are shown in figure 7.3.88. The cosine of the angle between the b-tagged jet and the charged lepton in the reference frame of the b-tagged top quark (as explained in definition 6.2.6) is shown in figure 7.3.88(a). The slope of the distribution is steeper for the background model than for the expected signal events from electroweak top quark production. The distance ΔR between the leading and the second leading jet can be found in figure 7.3.88(b). Except for one bin at $\Delta R = 3$, the agreement between the background model and the observed data events is good. The minimal distance of all possible jet pairings is shown in figure 7.3.88(c). There are some bins in the data distribution that fluctuate a lot around the background expectation, but the agreement is still acceptable.

The transverse momenta of the best jet and the jet with the second highest transverse momentum of those jets that are not tagged as originating from a b hadron are shown in figure 7.3.89(a)

Figure 7.3.88: Cosine of the angle between the charged lepton and the b-tagged jet in the reference frame of the b-tagged top quark (figure 7.3.88(a)). The distance ΔR between jet1 and jet2 is shown in figure 7.3.88(b) and the minimal distance ΔR_{min} of all possible jet combinations in figure 7.3.88(c) for events with four jets, one of them b-tagged, and one central muon.

and 7.3.89(b), respectively. The transverse momentum distribution for the best jet is very flat for the signal up to values of 60 GeV before it starts to fall. In the region up to 50 GeV the background distribution rises slowly. The description of the transverse momentum for the second leading untagged jet is off in the first bin of the histogram, but the rest of the distribution is reasonably well described by the observed data such that this observable is also used as input to the Boosted Decision Trees.

Figure 7.3.89: Transverse momentum of the best jet (figure 7.3.89(a)) and the jet with the second highest transverse momentum of those jets that are not tagged as coming from a b hadron decay (figure 7.3.89(b)) for events with a total of four jets, one of those b-tagged, and one central muon.

Centrality (as defined in equation 7.3.4) and the product ' $q \times \eta$ ' of the charge of the charged lepton and the pseudorapidity η of the leading untagged jet are shown in figure 7.3.90(a) and 7.3.90(b), respectively. The centrality of all jets in the event is shifted towards higher values for the background events, reaching its maximum at 0.75, while the signal distribution has its maximum already at 0.55. The ' $q \times \eta$ ' distribution shows the expected asymmetry towards positive values for the signal events of electroweak top quark production, while the background distribution is symmetric around 0. In figure 7.3.90(c) the $\hat{S}$ variable is shown (see equation 7.1.8). The distribution for the background reaches its maximum approximately 30 GeV later and has

a steeper falling edge than the expected distribution for the events from electroweak top quark production.

Figure 7.3.90: Centrality of all jets in the events is shown in figure 7.3.90(a), the ‘ $q \times \eta$ ’ variable in figure 7.3.90(b) and the $\hat{S}$ observable in figure 7.3.90(c) for events with one electron, and one of four jets being tagged as originating from a b hadron decay.

The transverse mass of the combination of jet1 and jet2 is well described in the comparison of simulated background events and observed data (see figure 7.3.91(a)). The description for the transverse mass of the W boson (see figure 7.3.91(b)), calculated from the kinematics of the charged lepton and the information about the missing transverse energy in the event, is not as good, but still acceptable. In this variable the multijet background accumulates at low values and thus this variable will be useful to separate this background component from the signal events in the statistical analysis.

Figure 7.3.91: Transverse mass calculated from the two leading jets in transverse momentum (figure 7.3.91(a)) and the transverse mass of the W boson (figure 7.3.91(b)) for events with one electron, four jets and one b-tagged jet.

The event shape variables (see equation 7.1.14) aplanarity and centrality, calculated using also information about the leptons in the event, can be found in figure 7.3.92(a) and figure 7.3.92(b). While the aplanarity distribution of the events has a similar shape for both signal and background samples, the shapes for centrality differ a lot. The signal distribution peaks at 0.6, where the background distribution is still on the rising edge, reaching its maximum at 0.85.

Observables of the dijet system built by the two leading jets in the event are also used in the statistical analysis. The mass of this dijet system shown in figure 7.3.93(a) has discriminating

Figure 7.3.92: Aplanarity (figure 7.3.92(a)) and centrality (figure 7.3.92(b)), calculated using both jet and lepton information in events with four jets, one central electron and one b-tagged jet.

power against the multijet background that is accumulated at lower values of this observable. The description of the transverse mass of the dijet system is poor for the lower region of the transverse mass spectrum, but acceptable in the higher regions. The shapes of signal and background events are similar.

Figure 7.3.93: Mass (figure 7.3.93(a)) and transverse momentum (figure 7.3.93(b)) of the dijet system built by the two leading jets in the event. The distributions show events with four jets, one of them tagged as a jet originating from a b quark initially, and one central electron.

The sum of scalar energies of all jets and the leptons in an event, H , is shown in figure 7.3.94(a). The summation over the transverse momenta of these reconstructed objects, H_t , is shown in figure 7.3.94(b). The maxima for the signal and the background distributions are separated by approximately 70 GeV. The multijet background can be found at low values of H_t .

Figure 7.3.94: The sum over the scalar energies in the event H is shown in figure 7.3.94(a), the sum over the transverse momenta of reconstructed objects in the event in figure 7.3.94(b). Both distributions show events with four jets, one b-tagged jet and one central electron.

The transverse momenta of the jets, ordered by their transverse momenta, are shown in figure 7.3.95 for the leading (figure 7.3.95(a)) and the second leading jet (figure 7.3.95(b)), and in figure 7.3.96 for jet3 (see figure 7.3.96(a)) and jet4 (see figure 7.3.96(a)).

Figure 7.3.95: Transverse momentum distribution for the jet with the highest transverse momentum in the event (figure 7.3.95(a)) and for the jet with the second highest transverse momentum in the event (figure 7.3.95(b)) for events with four jets, one b-tagged jet and one central electron.

The LepMet variable, i.e. the scalar sum of the transverse momentum of the charged lepton and the missing transverse energy, is displayed in figure 7.3.97(a). The multijet background peaks at very low values in this variable, the single top signal events at 90 GeV, and the total background at 100 GeV, with a steeper falling edge. Figure 7.3.97(b) shows the SEt variable as defined in equation 7.1.9. A big difference in this variable can be seen for signal and background

Figure 7.3.96: Transverse momentum of jet3 (figure 7.3.96(a)) and jet4 (figure 7.3.96(b)) for events with one b-tagged jet out of a total of four jets and one isolated electron.

events. The signal distribution peaks at 200 GeV, the background, dominated by semileptonic top quark pair decays, at 280 GeV.

Figure 7.3.97: Scalar sum of missing transverse energy and transverse momentum of the charged lepton (figure 7.3.97(a)) and the SEt variable (figure 7.3.97(b)) for events with one central electron, one jet tagged as coming from a b hadron decay, and four jets in total.

Events with four jets, two b-tagged jets, and one central electron

The limited statistics of the analysis bin with four jets, the requirement that two of these four jets should be tagged as originating from a b hadron decay and one isolated, central electron influences the comparison of observed data with simulated background events. The agreement between data and simulation is acceptable for the observables that are used as input to the statistical analysis and are shown in figure 7.3.98 to figure 7.3.104.

Boosted into the center-of-mass reference frame, the angle between the Hadronic Final State and the jet with the highest transverse momentum is calculated. The resulting distribution is shown in figure 7.3.98(a). The angle between the HFS and jet2 can be seen in figure 7.3.98(b). Both distributions show a fair agreement between data and background model.

(a)

(b)

Figure 7.3.98: Angle between the Hadronic Final State and the jet with the highest transverse momentum in the event (figure 7.3.98(a)) and the angle between the Hadronic Final State and the second leading jet in the event (figure 7.3.98(b)). Both the jet four-vectors and the four-vector of the Hadronic Final State are boosted into the center-of-mass reference frame. The distributions show events with four jets, two of them are tagged as originating from a b hadron, and one central electron.

For different configurations of reconstructed objects their invariant mass is calculated. For the distribution in figure 7.3.99(a) all jets except for the best jet as defined in definition 6.2.3 are used. The b -tagged jet (as defined in definition 6.2.4) is omitted for the distribution shown in figure 7.3.99(b). The invariant mass calculated in figure 7.3.99(c) takes only the two leading jets of the event into account, but also adds the reconstructed W boson. For all three invariant masses the same statement is true: the simulated single top signal event distributions peak at lower values than the background distributions.

The sum over the scalar energies of the jets in an event, H , is shown for two different jet configurations in figure 7.3.100(a) and figure 7.3.100(b). The first one describes the situation where the best jet is omitted, while in the second calculation of H the b -tagged jet was omitted. In both cases the background distribution has a more distinct peak structure, while the distribution for the simulated signal events is broader. Summing up the transverse momenta of the jets except for the best jet, leads to the distribution in figure 7.3.100(c). Here, the signal distribution reaches its maximum at lower values than the background model.

Further angular correlations are used as input to the statistical analysis. The cosine of the angle between the b -tagged jet and the charged lepton is calculated in the reference frame of the b -tagged top quark (see definition 6.2.6 for details and figure 7.3.101(a) for the resulting

Figure 7.3.99: Invariant mass of all jets but the best jet (figure 7.3.99(a)), of all jets but the b-tagged jet (figure 7.3.99(b)) and of the two leading jets and the reconstructed W boson (figure 7.3.99(c)) for events with a total of four jets, of which two are b-tagged, and one central electron.

Figure 7.3.100: The summation over the scalar energies of all jets except the best jet leads to the distribution shown in figure 7.3.100(a). Omitting the b-tagged jet instead results in the distribution displayed in figure 7.3.100(b). Adding up the transverse momenta instead, again without the best jet, results in the distribution in figure 7.3.100(c). All distributions contain events with four jets, two b-tagged jets, and one isolated electron.

distribution). The distance ΔR between the leading and the second leading jet in the event is shown in figure 7.3.101(b), the minimal distance ΔR_{min} of all possible jet pairings is shown in figure 7.3.101(c). All three distributions in figure 7.3.101 show a reasonable agreement in the comparison of observed data with simulated background events.

The transverse momentum distribution of the best jet can be seen in figure 7.3.102(a) and shows a broad distribution for the single top signal events and a rather poor agreement in the comparison of simulated events with observed data events. In the distribution for the leading of those jets that were not tagged as originating from a b hadron decay there is also one bin that fluctuates very low. However, all other bins agree very well with the expected distribution for the background events and the distribution for the signal peaks at the edge of the distribution, where the distribution for the background model is still rising. Therefore, this variable could be useful in the Boosted Decision Tree analysis.

The centrality of the event, calculated from all jets in the event, has a broad distribution for the simulated events of electroweak top quark production, whereas the background distribution

Figure 7.3.101: Cosine of the angle between the b-tagged jet and the charged lepton in the rest frame of the b-tagged top quark (figure 7.3.101(a)), distance ΔR between the two jets with the highest transverse momentum (figure 7.3.101(b)), and minimal distance ΔR_{min} of all possible jet pairings (figure 7.3.101(c)) for events with four jets, two of them b-tagged, and one central electron.

Figure 7.3.102: Transverse momentum distribution for the best jet in the event (figure 7.3.102(a)) and the leading untagged jet in the event (figure 7.3.102(b)) for events with one central electron, a total of four jets, two of which are b-tagged.

risers longer and peaks at 0.85 (see figure 7.3.103(a)). The ' $q \times \eta$ ' variable (as defined in definition 6.2.7) shows the expected asymmetric shape for the signal sample and a symmetric shape for the background model. The observed data have a tendency to be asymmetric in the opposite direction than the signal events, towards negative values in ' $q \times \eta$ '.

The variable $\hat{S}$ (see equation 7.1.8) and the reconstructed transverse mass of the W boson, calculated using kinematic information of the charged lepton and the missing transverse energy, are shown in figure 7.3.104. The $\hat{S}$ distribution in figure 7.3.104(a) reaches its maximum for the single top quark signal sample earlier than the distribution of the simulated background events. Except for the steeper slope of the falling edge of the transverse mass distribution of the W boson, the distributions for simulated signal and background events are alike.

Figure 7.3.103: Centrality, calculated from all jets in the event (figure 7.3.103(a)) and the ‘ $q \times \eta$ ’ variable (figure 7.3.103(b)) for events with one central electron, and four jets of which two are b-tagged.

Figure 7.3.104: Distribution of $\hat{S}$ (figure 7.3.104(a)) and the transverse mass of the W boson (figure 7.3.104(b)) for events with four jets, two b-tagged jets, and one isolated electron.

7.3.5 Summary of Observables for Events with Four Jets

A summary of the variables used in the statistical analysis for the four different analysis bins can be found in the following tables:

- For the muon analysis with one b-tagged jet the variables can be found in table 7.3.7 on page 387 and table 7.3.8 on page 388.
- For the muon analysis with two b-tagged jets the variables can be found in table 7.3.9 on page 389 and table 7.3.10 on page 390.
- For the electron analysis with one b-tagged jet the variables can be found in table 7.3.11 on page 391 and table 7.3.12 on page 392.
- For the electron analysis with two b-tagged jets the variables can be found in table 7.3.13 on page 393 and table 7.3.14 on page 394.

The discriminant output distributions for the Boosted Decision Tree configuration that is finally used in the analysis are presented on page 414 for the muon channel. Figure 9.1.1(e) shows the distribution for events with one b-tag. The distribution for events with two b-tags is shown in figure 9.1.1(f). The discriminant output distributions for the two electron channel analysis bins are shown in figures 9.1.2(e) (events with one b-tag) and 9.1.2(f) (events with two b-tags) on page 415.

Variable	Figure
Variables from the reconstruction of the single top s-channel PPT (see figure 7.3.1)	
Mass of the dijet system	7.3.9(a)
Pseudorapidity η of the dijet system	7.3.9(b)
Likelihood measure	7.3.9(c)
Transverse momentum of b(lept)	7.3.10(a)
Transverse momentum of b(prod)	7.3.10(b)
Variables from the reconstruction of the single top t-channel PPT (see figure 7.3.17)	
Mass of the reconstructed top quark	7.3.25(a)
Lepton charge times pseudorapidity η of q(scst)	7.3.25(b)
Transverse momentum of b(scst)	7.3.26(a)
Transverse momentum of q(scst)	7.3.26(b)
Pseudorapidity η of q(prod)	7.3.26(c)
Likelihood measure	7.3.27(a)
Pseudorapidity η of b(lept)	7.3.27(b)
Variables from the reconstruction of semileptonic top quark pair production PPT (see figure 7.3.35)	
Mass of reconstructed top quark t(hadr)	7.3.45(a)
Transverse momentum of reconstructed top quark t(hadr)	7.3.45(b)
Pseudorapidity η of reconstructed top quark t(lept)	7.3.46(a)
Transverse momentum of reconstructed top quark t(lept)	7.3.46(b)
Transverse momentum of b(hadr)	7.3.47(a)
Transverse momentum of b(lept)	7.3.47(b)
Likelihood measure	7.3.47(c)

Table 7.3.7: Observables gained by the reconstruction of Parton Picture Templates and used as input for the Boosted Decision Tree analysis for events with four jets, one jet tagged as originating from a b hadron decay, and one muon.

Variable	Figure
Event shape variables and variables from the reconstruction of the PPT in figure 7.3.57	
Angle between HFS and jet1 in center-of-mass reference frame	7.3.58(a)
Angle between HFS and jet2 in center-of-mass reference frame	7.3.58(b)
Invariant mass of all jets except the best jet	7.3.59(a)
Invariant mass of all jets except the b-tagged jet	7.3.59(b)
Invariant mass of jet1, jet2, and the W boson	7.3.59(c)
Ht of all jets except for the best jet	7.3.60(a)
Ht of all jets except for the b-tagged jet	7.3.60(b)
H of all jets except for the best jet	7.3.61(a)
H of all jets except for the b-tagged jet	7.3.61(b)
Transverse momentum of the best jet	7.3.62(a)
Transverse momentum of second leading untagged jet	7.3.62(b)
Cosine of angle between b-tagged jet and lepton in b-tagged top rest frame	7.3.63(a)
$\Delta R(\text{jet1}, \text{jet2})$	7.3.63(b)
ΔR_{min} of all jet pairings	7.3.63(c)
Transverse mass of jet1 and jet2	7.3.64(a)
Transverse mass of the W boson	7.3.64(b)
Centrality of all jets in the event	7.3.65(a)
$q \times \eta$ of lepton charge and leading untagged jet η	7.3.65(b)
$\hat{S}$	7.3.65(c)
Aplanarity of the event	7.3.66(a)
Centrality of the event	7.3.66(b)
Mass of the jet1-jet2 dijet combination	7.3.67(a)
Transverse momentum of the jet1-jet2 dijet combination	7.3.67(b)
H of all reconstructed objects	7.3.68(a)
Ht of all reconstructed objects	7.3.68(b)
Transverse momentum of jet1	7.3.69(a)
Transverse momentum of jet2	7.3.69(b)
Transverse momentum of jet3	7.3.70(a)
Transverse momentum of jet4	7.3.70(b)
Scalar sum of missing transverse energy and lepton transverse momentum	7.3.71(a)
SEt of all reconstructed objects	7.3.71(b)

Table 7.3.8: Event shape observables used as input for the Boosted Decision Tree analysis for events with four jets, one jet tagged as originating from a b hadron decay, and one muon.

Variable	Figure
Variables from the reconstruction of the single top s-channel PPT (see figure 7.3.1)	
tb4jtlmass	7.3.11(a)
Mass of the dijet system	7.3.11(b)
Likelihood measure	7.3.11(c)
Transverse momentum of b(lept)	7.3.12(a)
Transverse momentum of b(prod)	7.3.12(b)
Variables from the reconstruction of the single top t-channel PPT (see figure 7.3.17)	
Mass of the reconstructed top quark	7.3.28(a)
Lepton charge times pseudorapidity η of q(scst)	7.3.28(b)
Likelihood measure	7.3.28(c)
Transverse momentum of b(scst)	7.3.29(a)
Transverse momentum of q(scst)	7.3.29(b)
Pseudorapidity η of q(prod)	7.3.29(c)
Variables from the reconstruction of semileptonic top quark pair production PPT (see figure 7.3.35)	
Mass of reconstructed top quark t(hadr)	7.3.48(a)
Transverse momentum of reconstructed top quark t(hadr)	7.3.48(b)
Pseudorapidity η of reconstructed top quark t(lept)	7.3.49(a)
Transverse momentum of reconstructed top quark t(lept)	7.3.49(b)
Transverse momentum of b(hadr)	7.3.50(a)
Transverse momentum of b(lept)	7.3.50(b)
Likelihood measure	7.3.50(c)

Table 7.3.9: Observables gained by the reconstruction of Parton Picture Templates and used as input for the Boosted Decision Tree analysis for events with four jets, two jets tagged as originating from a b hadron decay, and one muon.

Variable	Figure
Event shape variables and variables from the reconstruction of PPT (see figure 7.3.57)	
Angle between HFS and jet1 in center-of-mass reference frame	7.3.72(a)
Angle between HFS and jet2 in center-of-mass reference frame	7.3.72(b)
Invariant mass of all jets except the best jet	7.3.73(a)
Invariant mass of all jets except the b-tagged jet	7.3.73(b)
Invariant mass of jet1, jet2, and the W boson	7.3.73(c)
H of all jets except for the best jet	7.3.74(a)
H of all jets except for the b-tagged jet	7.3.74(b)
Ht of all jets except for the best jet	7.3.74(c)
Cosine of angle between b-tagged jet and lepton in b-tagged top rest frame	7.3.75(a)
$\Delta R(\text{jet1}, \text{jet2})$	7.3.75(b)
ΔR_{min} of all jet pairings	7.3.75(c)
Transverse momentum of the best jet	7.3.76(a)
Transverse momentum of leading untagged jet	7.3.76(b)
Centrality of all jets in the event	7.3.77(a)
$\hat{S}$	7.3.77(b)
$q \times \eta$ of lepton charge and leading untagged jet η	7.3.78(a)
Transverse mass of the W boson	7.3.78(b)
Aplanarity of the event	7.3.79(a)
Centrality of the event	7.3.79(b)
Mass of the jet1-jet2 dijet combination	7.3.80(a)
Transverse momentum of the jet1-jet2 dijet combination	7.3.80(b)
H of all reconstructed objects	7.3.81(a)
Ht of all reconstructed objects	7.3.81(b)
Transverse momentum of jet2	7.3.82(a)
Pseudorapidity of the second leading jet	7.3.82(b)
Transverse momentum of jet1	7.3.83(a)
Scalar sum of missing transverse energy and lepton transverse momentum	7.3.83(b)
SEt of all reconstructed objects	7.3.83(c)

Table 7.3.10: Event shape observables used as input for the Boosted Decision Tree analysis for events with four jets, two jets tagged as originating from a b hadron decay, and one muon.

Variable	Figure
Variables from the reconstruction of the single top s-channel PPT (see figure 7.3.1)	
Mass of the dijet system	7.3.13(a)
Pseudorapidity η of the dijet system	7.3.13(b)
Likelihood measure	7.3.13(c)
Transverse momentum of b(lept)	7.3.14(a)
Transverse momentum of b(prod)	7.3.14(b)
Variables from the reconstruction of the single top t-channel PPT (see figure 7.3.17)	
Mass of the reconstructed top quark	7.3.30(a)
Lepton charge times pseudorapidity η of q(scst)	7.3.30(b)
Transverse momentum of b(scst)	7.3.31(a)
Transverse momentum of q(scst)	7.3.31(b)
Pseudorapidity η of q(prod)	7.3.31(c)
Likelihood measure	7.3.32(a)
Pseudorapidity η of b(lept)	7.3.32(b)
Variables from the reconstruction of semileptonic top quark pair production PPT (see figure 7.3.35)	
Mass of reconstructed top quark t(hadr)	7.3.51(a)
Likelihood measure	7.3.51(b)
Pseudorapidity η of reconstructed top quark t(lept)	7.3.52(a)
Transverse momentum of reconstructed top quark t(lept)	7.3.52(b)
Transverse momentum of b(hadr)	7.3.53(a)
Transverse momentum of b(lept)	7.3.53(b)

Table 7.3.11: Observables gained by the reconstruction of Parton Picture Templates and used as input for the Boosted Decision Tree analysis for events with four jets, one jet tagged as originating from a b hadron decay, and one electron.

Variable	Figure
Event shape variables and variables from the reconstruction of the PPT in figure 7.3.57	
Angle between HFS and jet1 in center-of-mass reference frame	7.3.84(a)
Angle between HFS and jet2 in center-of-mass reference frame	7.3.84(b)
Invariant mass of all jets except the best jet	7.3.85(a)
Invariant mass of all jets except the b-tagged jet	7.3.85(b)
Invariant mass of jet1, jet2, and the W boson	7.3.85(c)
H of all jets except for the best jet	7.3.86(a)
H of all jets except for the b-tagged jet	7.3.86(b)
Ht of all jets except for the best jet	7.3.87(a)
Ht of all jets except for the b-tagged jet	7.3.87(b)
Cosine of angle between b-tagged jet and lepton in b-tagged top rest frame	7.3.88(a)
$\Delta R(\text{jet1, jet2})$	7.3.88(b)
ΔR_{min} of all jet pairings	7.3.88(c)
Transverse momentum of the best jet	7.3.89(a)
Transverse momentum of second leading untagged jet	7.3.89(b)
Centrality of all jets in the event	7.3.90(a)
$q \times \eta$ of lepton charge and leading untagged jet η	7.3.90(b)
$\hat{S}$	7.3.90(c)
Transverse mass of jet1 and jet2	7.3.91(a)
Transverse mass of the W boson	7.3.91(b)
Aplanarity of the event	7.3.92(a)
Centrality of the event	7.3.92(b)
Mass of the jet1-jet2 dijet combination	7.3.93(a)
Transverse momentum of the jet1-jet2 dijet combination	7.3.93(b)
H of all reconstructed objects	7.3.94(a)
Ht of all reconstructed objects	7.3.94(b)
Transverse momentum of jet1	7.3.95(a)
Transverse momentum of jet2	7.3.95(b)
Transverse momentum of jet3	7.3.96(a)
Transverse momentum of jet4	7.3.96(b)
Scalar sum of missing transverse energy and lepton transverse momentum	7.3.97(a)
SEt of all reconstructed objects	7.3.97(b)

Table 7.3.12: Event shape observables used as input for the Boosted Decision Tree analysis for events with four jets, one jet tagged as originating from a b hadron decay, and one electron.

Variable	Figure
Variables from the reconstruction of the single top s-channel PPT (see figure 7.3.1)	
Transverse momentum of b(lept)	7.3.15(a)
Transverse momentum of b(prod)	7.3.15(b)
Mass of the dijet system	7.3.16(a)
Likelihood measure	7.3.16(b)
Variables from the reconstruction of the single top t-channel PPT (see figure 7.3.17)	
Mass of the reconstructed top quark	7.3.33(a)
Lepton charge times pseudorapidity η of q(scst)	7.3.33(b)
Likelihood measure	7.3.33(c)
Transverse momentum of b(scst)	7.3.34(a)
Pseudorapidity η of q(prod)	7.3.34(b)
Variables from the reconstruction of semileptonic top quark pair production PPT (see figure 7.3.35)	
Mass of reconstructed top quark t(hadr)	7.3.54(a)
Transverse momentum of reconstructed top quark t(hadr)	7.3.54(b)
Likelihood measure	7.3.55(a)
Transverse momentum of reconstructed top quark t(lept)	7.3.55(b)
Transverse momentum of b(hadr)	7.3.56(a)
Transverse momentum of b(lept)	7.3.56(b)

Table 7.3.13: Observables gained by the reconstruction of Parton Picture Templates and used as input for the Boosted Decision Tree analysis for events with four jets, two jets tagged as originating from a b hadron decay, and one electron.

Variable	Figure
Event shape variables and variables from the reconstruction of the PPT in figure 7.3.57	
Angle between HFS and jet1 in center-of-mass reference frame	7.3.98(a)
Angle between HFS and jet2 in center-of-mass reference frame	7.3.98(b)
Invariant mass of all jets except the best jet	7.3.99(a)
Invariant mass of all jets except the b-tagged jet	7.3.99(b)
Invariant mass of jet1, jet2, and the W boson	7.3.99(c)
H of all jets except for the best jet	7.3.100(a)
H of all jets except for the b-tagged jet	7.3.100(b)
Ht of all jets except for the best jet	7.3.100(c)
Cosine of angle between b-tagged jet and lepton in b-tagged top rest frame	7.3.101(a)
$\Delta R(\text{jet1, jet2})$	7.3.101(b)
ΔR_{min} of all jet pairings	7.3.101(c)
Transverse momentum of the best jet	7.3.102(a)
Transverse momentum of leading untagged jet	7.3.102(b)
Centrality of all jets in the event	7.3.103(a)
$q \times \eta$ of lepton charge and leading untagged jet η	7.3.103(b)
$\hat{S}$	7.3.104(a)
Transverse mass of the W boson	7.3.104(b)

Table 7.3.14: Event shape observables used as input for the Boosted Decision Tree analysis for events with four jets, two jets tagged as originating from a b hadron decay, and one electron.

8 Multivariate Analysis and Expected Sensitivity

In this chapter the optimization of the Boosted Decision Trees is discussed in section 8.1. The systematic uncertainties that are considered in the analysis are presented in section 8.2. Section 8.3 deals with the extraction of the cross section of electroweak top quark production from the output distributions of the Boosted Decision Trees using a Bayesian approach. The final decision which configuration of Boosted Decision Trees is used in the analysis is presented in section 8.4. The decision is based on the expected sensitivity, a quantity that is also discussed in this section.

8.1 Optimization of Boosted Decision Trees

The concept of Boosted Decision Trees as a multivariate classifier has already been introduced in section 6.3. In this section, the different procedure that was chosen to optimize the classifier is explained.

To avoid systematic uncertainties arising from the use of multivariate analysis techniques it is important to split the available samples of simulated events into three samples: the *training sample* is used together with the *test sample* in the iterative process of optimizing the classifier. The *yield sample* is not used in this process. Thus, it is unbiased and can be used for the measurement. The Monte Carlo samples are split by event numbers into three subsamples in each of the twelve independent analysis bins. Cross checks have been performed to make sure that the kinematic distributions in all three subsamples are comparable [172]. The total number of both data and simulated events for the different analysis channels is summarized in table 8.1.1.

The training of a single Boosted Decision Tree can take up to several hours. In the optimization procedure it is necessary to scan several possible configurations of the parameters described in section 6.3. In principle, it would be desirable to optimize each analysis channel independently. However, this is not practical considering the time it takes to train and evaluate a Boosted Decision Tree. Therefore a simplification is made: one configuration of the Boosted Decision Tree algorithm is used in all analysis bins. The optimization is performed in the analysis channel with two jets, one of them tagged as originating from a b hadron, and one isolated muon. This is one of the most sensitive analysis bins (see figure 5.3.1). Approximately 50 different configurations have been tested and the following parameters have been varied:

	Electron Channel			Muon Channel		
	2 jets	3 jets	4 jets	2 jets	3 jets	4 jets
Signal MC						
$t\bar{b}$	19,465	9,127	2,483	12,852	6,458	1,809
tqb	22,758	12,080	3,797	21,066	11,193	3,489
$t\bar{b}+tqb$	42,223	21,207	6,280	33,918	17,651	5,298
Background MC						
$t\bar{t}\rightarrow ll$	29,537	26,042	12,068	24,595	21,803	9,788
$t\bar{t}\rightarrow l+\text{jets}$	5,659	22,477	27,319	3,376	16,293	22,680
$Wb\bar{b}$	13,914	9,011	3,848	14,488	9,427	3,874
$Wc\bar{c}$	13,453	7,562	2,252	19,047	10,141	3,051
Wjj	61,497	34,162	8,290	66,201	36,673	9,169
Pretag data						
Multijets	6,993	4,043	1,317	658	462	151
Signal data	8,220	3,075	874	6,432	2,590	727
ZeroTag data						
Multijets	6,659	3,802	1,210	604	409	128
Data	7,833	2,831	752	6,122	2,378	599
OneTag data						
Multijets	322	226	93	51	49	21
Signal data	357	207	97	287	179	100
TwoTags data						
Multijets	12	15	14	3	4	1
Signal data	30	37	22	23	32	27

Table 8.1.1: Number of events for the electron and muon channels after selection.

- the number of boosting cycles,
- the minimal number of events in a final leaf,
- the boost parameter of the AdaBoost algorithm,
- the prune strength, and
- the number of steps used during the node cut optimization.

The signal sample that is used as input to the training consists of a combination of both simulated s- and t-channel single top quark events, assuming the Standard Model ratio of the two production processes. In the background sample the multijet events are omitted as input to the Boosted Decision Trees in the training step. There are only a few multijet events left in each subsample, but they have a rather high event weight. The high weights affect the node splitting decisions during the creation of a Boosted Decision Tree. To avoid that this small number of events introduces a bias in the building of the Boosted Decision Tree, it has been proven advantageous to neglect them. However, in the evaluation of a configuration, the multijet events contained in the test sample are taken into account.

The TMVA package provides quantities that can be used to rank the different Boosted Decision Tree configurations among each other. Three quantities have been used in this analysis:

- The *area* under the background rejection vs. signal efficiency curve should be maximal.
- The *separation* $\langle S^2 \rangle$ of the classifier output distribution

$$\langle S^2 \rangle = \frac{1}{2} \int_{-\infty}^{+\infty} \frac{(\hat{y}_S(y) - \hat{y}_B(y))^2}{\hat{y}_S(y) + \hat{y}_B(y)} dy \quad (8.1.1)$$

is 0 for identical signal and background distributions and 1 for distributions without overlap. For a given classifier y , $\hat{y}_S$ ($\hat{y}_B$) is the corresponding signal (background) probability density function.

- The *significance* G of the classifier output distribution should be maximized, with

$$G = \frac{|\langle \hat{y}_S \rangle - \langle \hat{y}_B \rangle|}{\sigma_S^2 + \sigma_B^2}. \quad (8.1.2)$$

Here, $\hat{y}_S$ and $\hat{y}_B$ are defined the same way as for the separation. σ_S and σ_B are the root-mean-squares of the distributions.

From the numerous configurations that have been evaluated, the four best performing configurations are chosen and trained for all twelve analysis channels. The decision which of the four configurations is used in the measurement is made based on the expected sensitivity for the whole analysis. This will be discussed in section 8.4. The performance of the four Boosted Decision Tree configurations in the analysis bin used for the optimization in terms of the area, separation, and significance are summarized in table 8.1.2. Figure 8.1.1 shows the background rejection vs. signal efficiency curve for the four configurations for events with three jets, one of which is tagged as a b-jet, and one central electron.

Boosted Decision Tree	Area [%]	Separation	Significance
1	77.2	0.227	0.716
2	77.1	0.224	0.712
3	77.0	0.222	0.722
4	76.9	0.222	0.722

Table 8.1.2: Resulting properties of the four Boosted Decision Tree configurations in the muon channel with two jets and one b-tag. Area is the area under the signal efficiency vs. background rejection curve, separation is calculated according to equation 8.1.1, and significance is determined according to equation 8.1.2.

Table 8.1.3 summarizes the configurations for the four Boosted Decision Trees. It shows that configurations that are very different (e.g. in terms of prune strength or number of boosting cycles) can lead to similar performances.

Figure 8.1.1: Example of a background rejection vs. signal efficiency curve for four different Boosted Decision Tree configurations. The goal is to maximize the area under the curve. In this example, the four configurations are trained on events with three jets, one of them tagged as a b-jet, and one isolated electron.

	BDT 1	BDT 2	BDT 3	BDT 4
Number of boosting cycles	100	100	400	400
Minimal number of events/leaf	20	20	20	20
Boost parameter β	0.2	0.15	0.2	0.15
Prune Strength	5.0	1.0	1.0	1.0
Prune method	Cost complexity			
Separation type	Gini index			

Table 8.1.3: Configuration parameters of the four Boosted Decision Tree configurations with the best performance in the analysis bin with two jets, one of them tagged as originating from the decay of a b hadron, and one isolated muon.

8.2 Systematic Uncertainties

This section describes the systematic uncertainties that are considered in this analysis. Two types of systematic uncertainties can be distinguished:

- *Shape changing* systematics affect the shapes of the Boosted Decision Tree output distributions for the signal and background samples. Two sources of systematic uncertainties are considered of this kind: the uncertainty on the jet energy scale (JES) and the uncertainty on the tag-rate functions (TRF).

- *Flat* systematics solely affect the background normalization and are uniform across all bins of the Boosted Decision Tree discriminant.

A summary of the relative systematic uncertainties due to each contribution is given in table 8.2.1. Detailed tables of uncertainties for each individual analysis bin are given in appendix B. The following systematic uncertainties are considered in the analysis:

- **Integrated luminosity**

The uncertainty on the integrated luminosity is 6.1 % and arises from the uncertainty on the measured inelastic $p\bar{p}$ cross section [228]. It affects the signal and the $t\bar{t}$ yields, since both contributions are normalized using the integrated luminosity.

- **Theoretical cross sections**

The NNLO theoretical cross section is used to normalize the $t\bar{t}$ background yield. For a top mass of 175 GeV this cross section has an uncertainty of 18 % [229]. The main contribution to this uncertainty is the uncertainty from the mass of the top quark. Other contributions are the choice of the scale and uncertainties from parton distribution functions.

- **Trigger efficiency**

The uncertainty on the trigger efficiency is calculated by shifting the trigger turn-on curves up and down by one standard deviation. This leads to a total uncertainty of 3 % in the electron channel and 6 % in the muon channel [174].

- **Primary vertex selection efficiency**

In the simulated event samples the longitudinal position of the primary interaction vertex is not well modeled. The deviation between the observed data and the simulated events is 3 %. This number is thus used as systematic uncertainty. It takes into account the beam profile along the longitudinal direction [230].

- **Jet reconstruction and identification**

This systematic takes into account differences in the number of jets distribution and differences in the pseudorapidity distribution for jets between data and simulated events. An uncertainty of 2 % is assigned to this effect [164].

- **Jet energy scale and jet energy resolution**

This is one of the shape changing systematics. The jet energy scale correction is raised and lowered by one standard deviation. Then, the whole analysis is repeated. Since in Monte Carlo events the jet energy resolution uncertainty is not taken into account in the jet energy scale uncertainty, the smearing of the jet energy is additionally varied by the size of the jet energy resolution in Monte Carlo events [196].

- **Jet fragmentation**

To determine the effect of this uncertainty, different fragmentation models implemented in HERWIG and PYTHIA are compared. This uncertainty also covers uncertainties due to initial and final state radiation.

- **Electron reconstruction and identification efficiency**

The scale factor for the electron reconstruction and the identification is parameterized as a function of the distance between the electron and the closest jet. It depends on the azimuth angle ϕ and the transverse momentum of the electron. The correction factor is varied by one standard deviation in the parameterized bins. The total uncertainty is 2 % [155].

- **Electron track match and likelihood efficiency**

This uncertainty is derived from the error on the electron track match and likelihood Monte Carlo correction factor. It is parameterized in pseudorapidity η and azimuth angle ϕ . The correction factor is varied by one standard deviation in the parameterized bins. The uncertainty is determined to be 5 % [153].

- **Muon reconstruction and identification efficiency**

The uncertainties on the Monte Carlo scale factor are estimated by the muon ID group using a tag-and-probe method. The uncertainty is determined by varying the correction factor by one standard deviation in the parameterized bins of pseudorapidity η and azimuth angle ϕ . A total uncertainty of 7 % is assigned [148].

- **Muon track matching and isolation**

This uncertainty derives from the error on the Monte Carlo correction factor on the muon track match and the isolation. The uncertainty is determined by varying the correction factor by one standard deviation in the parameterized bins of pseudorapidity η and azimuth angle ϕ . A total uncertainty of 2 % is assigned [148].

- **Matrix method normalization**

The normalization of the W +jets and multijet backgrounds is performed using the matrix method (see section 5.2.5). The error on the matrix method is dominated by the error on the efficiency that a lepton passes the electron likelihood or the muon isolation although it does not originate from the decay of a W boson. Furthermore, the limited statistics of the data sample used for the matrix method contributes to the total uncertainty. More details can be found in [198].

- **Ratio of $Wb\bar{b}+Wc\bar{c}$ to W +light parton events**

A 30 % uncertainty is assigned to this ratio [172]. This number is much larger than the fit to the events in the sample of events without b-tag because it also covers theoretical shape-dependent contributions that are not modeled in simulated events. The dominant of these theoretical errors is the shape change of the transverse momentum of the b-quark between NLO and LO $Wb\bar{b}$ events. The uncertainty on this ratio is folded into the overall matrix method normalization uncertainty.

- **Monte Carlo tag-rate functions**

This is the second of the shape-changing uncertainties. It originates from statistical errors due to limited Monte Carlo statistics in the determination of the tag-rate functions, parameterized in bins of pseudorapidity η and transverse momentum. Furthermore, it covers the error on the fraction of heavy flavor in the simulated QCD events that is used for the mistag rate determination [170].

Relative Systematic Uncertainties			
$t\bar{t}$ cross section	18%	Primary vertex	3%
Luminosity	6%	Electron reco ID	2%
Electron trigger	3%	Electron trackmatch & likelihood	5%
Muon trigger	6%	Muon reco ID	7%
Jet energy scale	wide range	Muon trackmatch & isolation	2%
Jet efficiency	2%	ϵ_{W+jets} (electron)	2%
Jet fragmentation	5 – 7%	ϵ_{W+jets} (muon)	2%
Heavy flavor ratio	30%	$\epsilon_{multijet}$ (electron)	3 – 40%
Tag-rate functions	2 – 16%	$\epsilon_{multijet}$ (muon)	2 – 15%

Table 8.2.1: A summary of the relative systematic uncertainties for each of the applied corrections and efficiencies. The uncertainty shown is the error on the correction or the efficiency before it has been applied to the simulated events or data samples.

8.3 Extraction of Single Top Production Cross Section

A Bayesian approach is used to extract the cross section of electroweak top quark production from output distributions of the Boosted Decision Trees. The cross section is measured by creating a Bayesian posterior density function. This posterior density function is often referred to as the *posterior*. It yields the probability density for all single top quark production cross sections. The posterior can be written as

$$P(\mathcal{A}|\mathcal{B}) = \frac{P(\mathcal{B}|\mathcal{A}) \times \pi(\mathcal{A})}{\pi(\mathcal{B})}. \quad (8.3.1)$$

The conditional probability $P(\mathcal{A}|\mathcal{B})$ is the posterior. It means, that a process $\mathcal{A}$ is true, given that another process $\mathcal{B}$ is also true. In this analysis, $\mathcal{A}$ is the total number of expected signal and background events, while $\mathcal{B}$ is the observed number of events. The posterior is equal to the conditional probability that process $\mathcal{B}$ is true, given that process $\mathcal{A}$ is also true, multiplied by the prior probability for $\pi(\mathcal{A})$ for process $\mathcal{A}$. This product is then divided by the prior probability $\pi(\mathcal{B})$ for process $\mathcal{B}$. The conditional probability $P(\mathcal{B}|\mathcal{A})$ can be interpreted as the probability to observe N events, where a number of n events is the expected number of signal and background events. The probability $P(\mathcal{B}|\mathcal{A})$ can be expressed as a Poisson probability density distribution function for the observed number of events, given the expectation. The Poisson probability density function can be written as

$$P(\mathcal{B}|\mathcal{A}) \equiv \mathcal{L}(N|n) = \frac{n^N \exp\{-n\}}{\Gamma(N+1)}. \quad (8.3.2)$$

The Gamma function $\Gamma(N+1)$ is used instead of $N!$ in order to deal with non-integer values when determining the expected cross section on Monte Carlo events only. The interpretation and application of this term as a likelihood $\mathcal{L}(N|n)$ will be explained later in this section.

Since the interesting quantity is the signal cross section and not the number of expected signal

and background events, n has to be re-written as

$$n = n_S + n_B = \alpha_S \times L \times \sigma_S + \sum_i n_{B,i}. \quad (8.3.3)$$

In this equation the term α_S is the signal acceptance, L is the integrated luminosity, σ_S is the signal cross section, and $\sum_i n_{B,i}$ is the sum over the yields of the different background components. Throughout the reminder of this section, the integrated luminosity L is absorbed by the acceptance term α_S ($\alpha_S \times L \rightarrow \alpha_S$). Due to this transformation also the likelihood and the prior need to be re-written:

$$\mathcal{L}(N|n) = \mathcal{L}(N|\sigma_S, \alpha_S, \vec{n}_B) \quad (8.3.4)$$

$$\pi(n) = \pi(\sigma_S, \alpha_S, \vec{n}_B). \quad (8.3.5)$$

The prior $\pi(n)$ factorizes and can be written as a term dependent on the cross section and a term dependent on the signal acceptance and the background yield:

$$\pi(n) \equiv \pi(\sigma_S, \alpha_S, \vec{n}_B) = \pi(\sigma_S) \times \pi(\alpha_S, \vec{n}_B). \quad (8.3.6)$$

The analysis is split into up to twelve different channels, depending on the number of jets in an event (two, three, or four jets), the number of b-tags in an event (one or two), and the lepton type (muon or electron). The information of these independent channels needs to be combined. Therefore, the original likelihood is replaced by a product of likelihoods, where each channel is represented by one likelihood:

$$\mathcal{L}(N|\sigma_S, \alpha_S, \vec{n}_B) \rightarrow \prod_i \mathcal{L}(N_i|\sigma_S, \alpha_{S,i}, \vec{n}_{B,i}). \quad (8.3.7)$$

The values for N , α_S , and $\vec{n}_B$ are obtained from one-dimensional histograms of the Boosted Decision Tree discriminant for each signal and background source. The range of the x -axis of the histograms is between 0 and 1. Values within this interval can be obtained in a final leaf of a Boosted Decision Tree. However, in the application purity values of 0 or 1 are seldom reached. Therefore, an asymmetric binning is used that tries to achieve that each bin of the histogram output contains some background events. This is done by searching the minimum value $x_{\min}$ and the maximum value $x_{\max}$ of the discriminant in the background samples. The interval $[x_{\min}, x_{\max}]$ is then divided into k equidistant bins with bin width Δb . Then, the first bin is extended to contain the interval $[0, x_{\min} + 1 \times \Delta b]$ and the last bin of the histogram is extended to contain the interval $[x_{\max} - 1 \times \Delta b, 1]$. Figure 8.3.1(a) illustrates the first case for Monte Carlo events of dilepton top quark pair production. The second case is illustrated in figure 8.3.1(b) for the resulting distribution of signal events. In both histograms of figure 8.3.1 20 bins are used in total.

The acceptance term α_S needed in the likelihood described in equation 8.3.7 can be obtained from the signal Monte Carlo:

$$\alpha_S = \frac{n_S}{\sigma_S}. \quad (8.3.8)$$

The expected number of background events $\vec{n}_B$ are contained in the histograms of the different background sources. The shape information of these quantities is included by further modifying

Figure 8.3.1: Illustration of the asymmetric binning used in the likelihood. Figure 8.3.1(a) shows the extension of the first bin to include the discriminant value of 0 for Monte Carlo events of dilepton top quark pair production. Figure 8.3.1(b) shows the resulting signal distribution, where the last bin is extended to include all discriminant values up to 1.

the likelihood for a given channel. The likelihood for each channel is written as the product of likelihoods in each bin of the histogram:

$$\mathcal{L}(N|\sigma_S, \alpha_S, \vec{n}_B) \rightarrow \prod_{k \text{ bins}} \mathcal{L}(N_k|\sigma_S, \alpha_{S,k}, \vec{n}_{B,k}). \quad (8.3.9)$$

The likelihood fit is performed on the combined Boosted Decision Tree output of the twelve analysis channels. Therefore, the individual discriminant distributions are combined one after the other into one histogram that contains the expected background distribution, one histogram that contains the expected signal distribution and one histogram containing the discriminant output of the observed data events. Examples are shown in figure 8.3.2 for the Monte Carlo only analysis. The x-axes of the histograms now show the number of bins used in the likelihood fit. In this example, the discriminant output distribution of each individual channel has 20 bins. Thus, the combined histogram has 240 bins. Figure 8.3.2(a) shows the combined background distribution of the twelve contributing analysis channels. In figure 8.3.2(b) the expected signal distribution is shown for the Standard Model cross section of 2.86 pb. For the expected measurement, the distribution of figure 8.3.2(c) shows the expected data distribution, i.e. the sum of the signal and the background distributions.

The acceptance and background yield dependence on the posterior are removed by integrating the likelihood and prior with respect to the signal acceptance and each background yield:

$$P(\sigma|N) = \frac{1}{P(N)} \int \int \mathcal{L}(N|\sigma_S, \alpha'_S, \vec{n}'_B) \times \pi(\sigma_S) \times \pi(\alpha'_S, \vec{n}'_B) d\alpha'_S d\vec{n}'_B. \quad (8.3.10)$$

The term $P(N)$ is the normalization of the posterior. It is needed to ensure that the posterior retains a probability density function that fulfills:

$$\int P(\sigma|N) d\sigma = 1. \quad (8.3.11)$$

To achieve a finite normalization, a cutoff value σ_{max} for the prior for the signal cross section $\pi(\sigma_S)$ is introduced. Because a flat prior represents a minimal bias towards the measured signal

Figure 8.3.2: Input histograms used in the likelihood fit that is performed to extract the cross section. The twelve individual channels are combined into one histogram. The x-axes show the number total number of bins, i.e. 12×20 bins in this example. The background distribution is shown in figure 8.3.2(a), the expected signal distribution is shown in figure 8.3.2(b), and the expected data distribution is shown in figure 8.3.2(c). Thus, the fit can be performed taking all channels into account properly.

cross section, the prior is chosen flat in the region $0 < \sigma < \sigma_{max}$ and 0 otherwise. The cutoff value σ_{max} is chosen large enough that contributions from the likelihood for all values of α_S or $\vec{n}_B$ are negligibly small beyond this value.

The definition of the prior is different if systematic uncertainties are considered or not. Without systematic uncertainties the signal acceptance and the expected background yields are perfectly known. Thus, the prior becomes a product of two delta functions:

$$\pi(\alpha'_S, \vec{n}'_B) = \delta(\alpha'_S - \alpha_S) \times \delta(\vec{n}'_B - \vec{n}_B). \quad (8.3.12)$$

The posterior $P(\sigma|N)$ thus becomes:

$$P(\sigma|N) = \frac{\mathcal{L}(N|\sigma_S, \alpha_S, \vec{n}_B) \times \pi(\sigma_S)}{\int \mathcal{L}(N|\sigma'_S, \alpha_S, \vec{n}_B) \times \pi(\sigma'_S) d\sigma'_S}. \quad (8.3.13)$$

With systematic uncertainties the prior is modified to reflect these uncertainties in α_S and $\vec{n}_B$. The $\pm 1\sigma$ uncertainty of each systematic uncertainty is propagated through the analysis

and results in uncertainties for the signal acceptance $\delta\alpha_S$ and the background yield $\delta\vec{n}_B$. They can be used to create a covariance matrix that takes into account the correlations between the different systematics. For example, the uncertainty on the integrated luminosity affects both the signal acceptance and the normalization of the background sources from top quark pair production. The covariance matrix $M_{i,j}$ for two signal or background sources i and j is defined as:

$$M_{i,j} = \text{cov}_{i,j} = p_i p_j \sum_{k=1}^m f_{i,k} f_{j,k}. \quad (8.3.14)$$

In this formula, p_i is the yield for the i^{th} signal or background source. The fractional uncertainty from the k^{th} systematic component for the i^{th} signal or background source is given by the term $f_{i,k}$. The prior $\pi(\alpha'_S, \vec{n}_B)$ is then calculated as a multivariate Gaussian:

$$\pi(\alpha'_S, \vec{n}'_B) = \frac{1}{\sqrt{(2\pi)^N \times |M_{i,j}|}} \times \exp \left\{ -\frac{1}{2} (\vec{x} - \mu)^T M_{i,j}^{-1} (\vec{x} - \mu) \right\}. \quad (8.3.15)$$

In the formula for the multivariate Gaussian the notation $\vec{x}$ represents a set of parameters $\{\alpha'_S, \vec{n}'_B\}$ and μ represents the nominal values $\{\alpha_S, \vec{n}_B\}$. The posterior is obtained using Monte Carlo importance sampling, i.e. a set of m values in the $\{\alpha_S, \vec{n}_B\}$ -space are generated according to the prior density defined in equation 8.3.15. The result of all the likelihood values is averaged:

$$\int \int \mathcal{L}(N|\sigma_S, \alpha_S, \vec{n}_B) \times \pi(\alpha_S, \vec{n}_B) d\alpha_S d\vec{n}_B = \frac{1}{m} \sum_{i=1}^m \mathcal{L}(N|\sigma_S, \alpha_S, \vec{n}_B). \quad (8.3.16)$$

The cross section of a process is determined from the posterior. It is defined as the value that maximizes the posterior. An example is shown in figure 8.3.3. The solid blue line indicates the position of the maximum of the posterior distribution. The dashed lines represent the $\pm 1\sigma$ uncertainty on the cross section measurement. This uncertainty is obtained by integrating the posterior above and below the maximum value until each side contains 33.15 % of the total area under the posterior. In the example, the measured cross section is 2.77 pb, the $+1\sigma$ error band covers 1.4 pb above the maximum of the posterior, and the -1σ error band covers -1.3 pb below the measured cross section.

If no excess of data above the expected background is found, it is possible to set an upper limit σ_{CL} on the production cross section of the process. For a given confidence limit CL , the upper cross section limit can be calculated by integrating the posterior until an area equal to the confidence limit is obtained:

$$\int_0^{\sigma_{CL}} P(\sigma|N) d\sigma = CL. \quad (8.3.17)$$

For the example measurement shown in figure 8.3.3, the upper limit on the cross section is 5.43 pb. The result of the limit calculation is shown in figure 8.3.4

From the posterior distribution two quantities can be obtained that can be used to optimize the sensitivity of an analysis:

1. Peak over width

The cross section at the maximum of the posterior divided by the width of the posterior distribution around the maximum is one quantity that can be considered in the optimization. In the example presented above, the value of this quantity is 2.2.

Figure 8.3.3: An example for the cross section measurement. The solid blue line indicates the position of the maximum of the posterior and the dashed blue lines show the $\pm 1\sigma$ error band on the measurement.

Figure 8.3.4: Example for an upper limit on the cross section. The posterior distribution is integrated until 95% of the area is covered.

2. Bayes Ratio

The Bayes ratio BR is calculated as the posterior probability at the maximum of the distribution (i.e. for a signal and background hypothesis) divided by the posterior probability for the background only hypothesis:

$$\text{BR} = \frac{P_{\max}}{P(\sigma = 0)}. \quad (8.3.18)$$

For larger Bayes ratios the sensitivity to measure a cross section different from zero increases. In the example presented above, the Bayes ratio calculates to 18.4.

The signal cross sections in this analysis is the combined s-channel plus t-channel cross section of electroweak top quark production. This means that the ratio of s/t-channel production $R_{s/t}$ is assumed to be consistent with the Standard Model:

$$R_{s/t} = \frac{\sigma_{s\text{-channel}}}{\sigma_{t\text{-channel}}} = \frac{0.88 \text{ pb}}{1.98 \text{ pb}} = 0.44. \quad (8.3.19)$$

The measurement of the individual s- and t-channel cross sections is an addition to this analysis foreseen once more integrated luminosity is available.

8.4 Expected Sensitivity on the Cross Section Measurement

The decision which of the four remaining Boosted Decision Tree configurations (see section 8.1) is used in the final analysis is based on the *expected sensitivity* of the analysis. While the optimization of the Boosted Decision Trees is performed on one analysis channel only (the one with one muon, two jets, and one of the jets is tagged as originating from the decay of a b hadron), for the expected sensitivity all twelve analysis channels are taken into account. The procedure how the cross section is extracted from the output distribution of the Boosted Decision Trees and for the combination of several analysis channels has been presented in section 8.3. For the expected measurement the distribution of observed data events is replaced by a distribution containing the background events and the expected contributions of the signal processes. The extraction of the cross section is then performed in the same way as with data, using the `top_statistics` toolkit [231]. The two quantities peak-over-width and Bayes ratio that are defined in the previous section are then used to evaluate the sensitivity of the analysis obtained by each Boosted Decision Tree configuration. The results are compared in two cases: the case where only statistical effects are considered, and the case where all systematic uncertainties are taken into account. For these two cases, the discriminant distributions have been histogrammed with different numbers of bins. The results in terms of cross section (xsec), peak-over-width (p/w), and Bayes ratio (BR) for the comparisons without systematic uncertainties are summarized in table 8.4.1. Table 8.4.2 shows the results for the case where the systematic uncertainties are taken into account. The differences in the configurations of the four Boosted Decision Trees and the labeling of them has been introduced in table 8.1.3.

Fields in the two tables that contain an ‘x’ in the column for the Bayes ratio arise from the fact that it is sometimes not possible to calculate the Bayes ratio for technical reasons. In general, without systematic uncertainties all Boosted Decision Tree configurations reproduce the Standard Model cross section of 2.86 pb with an uncertainty of ± 1 pb. Configuration 1 has the highest peak-over-width value for all binnings and the highest Bayes ratio in the case of 20 bins. For all four configurations, the sensitivity slightly rises with increasing number of bins. Taken the systematic uncertainties into account, the measured cross section is slightly lower then for all four configurations and for all binnings. However, the effect is negligible and all results are consistent with the Standard Model expectation. The maximal deviation can be seen for configuration 2 using 30 bins. There, a value of 2.74 pb is measured, well within the uncertainty of the measurement of +1.4 pb. The expected sensitivity is lower when the

	20 bins			30 bins			40 bins		
BDT	xsec [pb]	p/w	BR	xsec [pb]	p/w	BR	xsec [pb]	p/w	BR
1	$2.86^{+1.0}_{-1.0}$	2.93	147.5	$2.86^{+1.0}_{-1.0}$	2.93	x	$2.86^{+1.0}_{-1.0}$	2.98	x
2	$2.86^{+1.0}_{-1.0}$	2.86	106.4	$2.86^{+1.0}_{-1.0}$	2.90	136.1	$2.86^{+1.0}_{-1.0}$	2.93	x
3	$2.86^{+1.0}_{-1.0}$	2.86	107.2	$2.86^{+1.0}_{-1.0}$	2.89	117.8	$2.86^{+1.0}_{-1.0}$	2.91	x
4	$2.86^{+1.0}_{-1.0}$	2.87	110.1	$2.86^{+1.0}_{-1.0}$	2.90	127.8	$2.86^{+1.0}_{-1.0}$	2.92	x

Table 8.4.1: Comparison of the performance of the four remaining Boosted Decision Trees in terms of measured cross section (xsec), peak-over-width (p/w), and Bayes ratio (BR) for the case where only the statistical uncertainties are considered. Cases where the Bayes ratio could not be computed are filled with an ‘x’.

	20 bins			30 bins			40 bins		
BDT	xsec [pb]	p/w	BR	xsec [pb]	p/w	BR	xsec [pb]	p/w	BR
1	$2.78^{+1.4}_{-1.3}$	2.21	18.1	$2.80^{+1.4}_{-1.2}$	2.24	x	$2.79^{+1.4}_{-1.2}$	2.29	x
2	$2.75^{+1.4}_{-1.3}$	2.12	13.3	$2.74^{+1.4}_{-1.3}$	2.17	16.3	$2.75^{+1.4}_{-1.2}$	2.21	x
3	$2.79^{+1.4}_{-1.3}$	2.14	14.1	$2.79^{+1.4}_{-1.3}$	2.18	15.8	$2.78^{+1.4}_{-1.3}$	2.20	x
4	$2.79^{+1.4}_{-1.3}$	2.15	14.5	$2.78^{+1.4}_{-1.3}$	2.19	16.9	$2.78^{+1.4}_{-1.3}$	2.22	x

Table 8.4.2: Comparison of the performance of the four remaining Boosted Decision Trees in terms of measured cross section (xsec), peak-over-width (p/w), and Bayes ratio (BR) for the case where both statistical uncertainties and systematic uncertainties are considered. Cases where the Bayes ratio could not be computed are filled with an ‘x’.

systematic uncertainties are taken into account. However, the analysis is dominated by the low statistics. Also with systematic uncertainties configuration 1 shows the best performance. It has the smallest deviation from the Standard Model prediction and the highest values of peak-over-width and BR (where available). Based on these numbers, configuration 1 is chosen for the analysis with data.

The properties of the Boosted Decision Trees trained with configuration 1 for each analysis channel are summarized in table 8.4.3. The quantities area, separation, and significance have been introduced in section 8.1. The best performance is achieved in the analysis bin with one electron, two jets, and one b-tag, followed by the muon channel with the same jet configuration. This result can be explained by the high statistics in these channels and the good signal-to-background ratio. Both points help the algorithm to show a good performance and thus to improve the separation from signal from background events.

Lepton	Number of jets	Number of b-tags	Area [%]	Separation	Significance
muon	2	1	77.2	0.227	0.716
muon	2	2	73.3	0.186	0.704
muon	3	1	69.8	0.133	0.539
muon	3	2	66.8	0.167	0.549
muon	4	1	70.3	0.148	0.514
muon	4	2	75.5	0.209	0.505
electron	2	1	78.8	0.254	0.724
electron	2	2	76.5	0.241	0.677
electron	3	1	70.7	0.148	0.550
electron	3	2	71.0	0.177	0.527
electron	4	1	72.5	0.174	0.573
electron	4	2	77.2	0.256	0.564

Table 8.4.3: Properties of the Boosted Decision Trees built with configuration 1 for the twelve different analysis bins.

To check that the combination of all twelve analysis channels really yields the highest sensitivity, the measurement of the expected cross section is repeated for different combinations of lepton types, jet multiplicities, and numbers of b-tags. Table 8.4.4 summarizes the results for these configurations using histograms with 40 bins in terms of cross section (xsec), peak-over-width (p/w), and Bayes ratio (BR). All values are determined with all systematic uncertainties included.

Lepton(s)	Number of jets	Number of b-tags	Cross section [pb]	p/w	BR
muon+electron	2,3,4	1,2	$2.79^{+1.4}_{-1.2}$	2.29	x
muon	2,3,4	1,2	$2.84^{+2.1}_{-1.8}$	1.55	3.8
electron	2,3,4	1,2	$2.83^{+1.8}_{-1.6}$	1.81	x
muon+electron	2,3,4	1	$2.86^{+1.5}_{-1.3}$	2.17	x
muon+electron	2,3,4	2	$2.51^{+2.8}_{-2.3}$	1.10	x

Table 8.4.4: Summary of the expected sensitivity of the analysis for different combinations of lepton types, numbers of jets, and numbers of b-tags.

The table shows that the combination of all twelve analysis channels has the highest sensitivity. The electron channel alone is more sensitive than the muon channel alone. Events with one b-tag have a higher sensitivity than events with two b-tags. The latter can be understood by the limited amount of statistics for events with two b-tagged jets.

In table 8.4.2 it is shown that the expected sensitivity on the measured cross section increases with increasing number of bins in the histograms used for the likelihood fit. To investigate this issue further, more binnings have been tested. The dependence on the binning of the cross section and the peak-over-width parameter are shown in figure 8.4.1. All values are derived taken the systematic uncertainties into account.

(a)

(b)

Figure 8.4.1: Dependence on the binning of the histograms of the cross section (figure 8.4.1(a)) and the sensitivity on the cross section measurement in terms of peak-over-width (figure 8.4.1(b)). The solid black line in the upper plot represents the Standard Model signal cross section of 2.86 pb.

The cross section shows no trend with respect to the binning of the histograms. It is always measured a bit lower than the input cross section of 2.86 pb, but the Standard Model value is well covered by the uncertainty. The sensitivity of the cross section measurement rises steadily for increasing numbers of bins. However, the increase only has a flat slope.

Summary:

The configuration 1 of the four remaining Boosted Decision Tree configurations has the best expected sensitivity for the determination of the cross section of electroweak top quark production. This configuration uses:

- 100 boosting cycles,
- a minimal number of 20 events per final leaf,
- a boost parameter β of 0.2,
- a prune strength value of 5.0,
- used together with the ‘cost complexity’ pruning algorithm, and
- the ‘Gini index’ separation mode.

A Boosted Decision Tree with this configuration is trained for each of the twelve independent analysis channels. The simultaneous fitting of all twelve channels yields the most sensitive result. While the cross section measurement remains unbiased, the expected sensitivity on the cross section measurement depends slightly on the number of bins used for the histograms containing the discriminant output. The expected sensitivity of the cross section measurement rises slowly with increasing number of bins and ranges from 2.10 for 10 bins up to 2.74 for 500 bins.

9 Observed Results

In this chapter the measurements derived from a 1 fb^{-1} data set which has been recorded by the DØ detector are presented. In section 9.1 the result of the measurement of the electroweak top quark production cross section is presented. Based on the cross section measurement it is then possible to determine the CKM matrix element $|V_{tb}|$ directly. The result of this measurement is presented in section 9.2.

9.1 Cross Section Measurement

Figure 9.1.1 shows the good agreement between the background model and the observed data events in the six muon analysis channels for the Boosted Decision Tree with the configuration selected in section 8.4. The comparison for the six analysis channels with a final-state electron are shown in figure 9.1.2. The solid blue line shows the shape of the expected contribution of single top quark events. It indicates that the signal distribution is shifted towards higher discriminant values than the total background distribution, i.e. by applying the Boosted Decision Tree algorithm the separation of signal and background components is increased.

It is expected from the Monte Carlo study that a higher number of bins in the discriminant output histograms yields a better sensitivity on the signal cross section measurement. However, while for the Monte Carlo study the measured cross section remains constant for the different binnings, it rises for the observed cross section. Table 9.1.1 summarizes the results obtained for each choice of binning.

Figure 9.1.3(a) shows the measured cross section as a function of number of bins used in the histogram of each individual analysis channel for the statistics-only analysis. The binning dependency on the cross section measurement including also all systematic uncertainties is shown in figure 9.1.3(b). The shape of both distributions is similar. The cross section rises from 20 bins to 100 bins where it reaches a plateau. For more than 100 bins (up to 500 bins are considered in this analysis) the remaining fluctuations on the cross section values are well within the error bars.

Both the rise of the cross section and the plateau are an effect of the likelihood method that is used to extract the cross section from the Boosted Decision Tree output distributions. For a small number of bins, the cross section measurement is dominated by the differences between the expected number of background events and the observed number of data events due to the b-tag requirement. With increasing number of bins the fit becomes more and more sensitive to the shape differences of signal and background events in the Boosted Decision Tree discriminant distributions. As can be seen in the distributions of the Boosted Decision Tree discriminant outputs, most analysis bins contain data events with a high discriminant

Figure 9.1.1: Summary of the comparison of the background model with the observed data in the muon channel for the discriminant output of Boosted Decision Tree configuration 1. The left column shows the analysis bins with one b-tagged jet (the signal shapes are scaled up by a factor of 10), the right column shows the analysis bins with two b-tagged jets (the signal shapes are scaled up by a factor of 5). The first row displays events with two jets, the second row displays event with three jets, and the last row shows events with four jets.

value. These events are located in a region where the separation between the expected signal and background events is maximal. In these bins the likelihood fit prefers a large signal cross

Figure 9.1.2: Summary of the comparison of the background model with the observed data in the electron channel for the discriminant output of Boosted Decision Tree configuration 1. The left column shows the analysis bins with one b-tagged jet (the signal shapes are scaled up by a factor of 10), the right column shows the analysis bins with two b-tagged jets (the signal shapes are scaled up by a factor of 5). The first row displays events with two jets, the second row displays event with three jets, and the last row shows events with four jets.

section to fill up the difference between the observed data events and the expected background contribution. For the overall fit, this preference then results in the observed increase of the

Number of bins	statistics only		with systematics	
	Cross section [pb]	Peak-over-width	Cross section [pb]	Peak-over-width
10	$1.80^{+1.0}_{-0.9}$	2.00	$3.37^{+1.5}_{-1.3}$	2.62
20	$2.06^{+0.9}_{-0.9}$	2.27	$3.50^{+1.5}_{-1.2}$	2.84
30	$2.05^{+1.0}_{-0.9}$	2.21	$3.58^{+1.5}_{-1.3}$	2.83
40	$2.37^{+0.9}_{-0.9}$	2.59	$4.03^{+1.5}_{-1.3}$	3.09
50	$2.34^{+1.0}_{-0.9}$	2.54	$3.89^{+1.6}_{-1.3}$	3.09
60	$2.47^{+1.0}_{-0.9}$	2.7	$4.13^{+1.6}_{-1.3}$	3.26
70	$2.50^{+1.0}_{-0.9}$	2.78	$3.90^{+1.6}_{-1.2}$	3.20
80	$3.18^{+0.9}_{-0.9}$	3.57	$5.13^{+1.5}_{-1.4}$	3.65
90	$3.30^{+0.9}_{-0.9}$	3.67	$5.33^{+1.4}_{-1.5}$	3.65
100	$3.39^{+0.9}_{-0.9}$	3.81	$5.51^{+1.6}_{-1.3}$	4.20
125	$3.60^{+0.9}_{-0.9}$	3.96	$5.59^{+1.5}_{-1.2}$	4.54
150	$3.31^{+1.0}_{-0.9}$	3.71	$5.53^{+1.5}_{-1.2}$	4.42
175	$3.63^{+1.0}_{-0.9}$	4.01	$5.59^{+1.3}_{-1.3}$	4.46
200	$3.58^{+0.9}_{-0.9}$	3.93	$5.49^{+1.3}_{-1.2}$	4.52
250	$3.87^{+0.9}_{-0.9}$	4.26	$5.95^{+1.4}_{-1.3}$	4.72
300	$3.84^{+1.0}_{-0.9}$	4.20	$5.89^{+1.4}_{-1.7}$	3.56
350	$4.44^{+0.9}_{-0.9}$	4.92	$6.08^{+1.2}_{-1.1}$	5.61
400	$4.67^{+0.9}_{-0.9}$	5.24	$6.17^{+1.1}_{-1.0}$	6.09
450	$4.51^{+1.0}_{-0.9}$	5.09	$6.11^{+1.0}_{-1.0}$	6.28
500	$4.24^{+1.0}_{-0.9}$	4.78	$5.96^{+1.1}_{-1.0}$	5.77

Table 9.1.1: Results of the cross section extraction for different number of bins in the histogram of the Boosted Decision Tree output. The number of bins corresponds to a histogram in each of the twelve individual analysis channels. The results are shown for the statistics only analysis and the analysis that also considers the systematic uncertainties. In both cases, the significance of the cross section measurement in terms of peak-over-width of the posterior is also presented.

measured cross section. At some point the binning is fine enough that each data event falls into an own bin of the histogram. Thus, with a higher number of bins the distributions used in the likelihood fit become very similar and hardly change. The result is that the determined

(a)

(b)

Figure 9.1.3: Dependence of the observed cross section on the binning of the discriminant output distribution. The upper plot shows the statistics-only analysis. The lower plot also includes systematic uncertainties.

cross section is similar for each of the binnings once this saturation is reached. The statistics of simulated background events is high enough to allow a proper measurement also with a high number of bins. Approximately 80,000 simulated background events are available in the yield sample of each analysis bin. The number of simulated signal events in the yield sample ranges from 10,000 to 70,000, depending on the analysis channel. However, it is sensible to avoid extreme binnings that could lead to low statistics in the regions of very high and very low

discriminant output values.

The increase of the cross section once systematic uncertainties are added is also observed by other analyses on the same data sample using the same method to extract the cross section [232,233]. Based on pseudo-experiments the conclusion is made that a shift of this size is not unlikely.

The result of this analysis is determined using 100 bins in the histograms containing the Boosted Decision Tree output for each of the twelve independent analysis channels. The value of 100 bins is chosen because there the beforementioned plateau starts. The number of 100 bins has as well been used in another analysis on the same data set [232]. The observed cross section of electroweak top quark production with full systematics in the combination of all twelve independent analysis channels is thus:

$$\sigma(p\bar{p} \rightarrow tb + X, tqb + X) = 5.51_{-1.31}^{+1.62} \text{ pb.} \quad (9.1.1)$$

This result assumes a Standard Model cross section ratio of $\sigma_{\text{s-channel}}/\sigma_{\text{t-channel}} = 0.44$ and is extracted for a top quark mass of 175 GeV. Figure 9.1.4 shows the posterior probability density for this measurement. The upper plot (figure 9.1.4(a)) displays the posterior for the statistics-only analysis, while figure 9.1.4(b) shows the posterior for the measurement including also systematic uncertainties.

Looking at the plateau region the upward variation $\Delta\sigma_+$ and the downward variation $\Delta\sigma_-$ of the measured cross section owing to the number of bins can be extracted from table 9.1.1 and are determined to $\Delta\sigma_+ = +0.66 \text{ pb}$ (comparison with 200 bins) and $\Delta\sigma_- = -0.05 \text{ pb}$ (comparison with 400 bins). Both values are well within the uncertainty of the measured cross section using 100 bins for the discriminant output distribution.

Table 9.1.2 shows the result for various combinations of analysis channels with and without systematic uncertainties.

The individual results of the twelve analysis channels contributing to the final result are summarized in table 9.1.3 for the statistical measurement only, and for the measurement including also the systematic uncertainties. The two plots in figure 9.1.5 visualize these results.

The significance of the cross section measurement of $5.51_{-1.31}^{+1.62} \text{ pb}$ is 4.2 standard deviations. The measured cross section is above the next-to-leading order Standard Model expectation of 2.86 pb by 2 standard deviations. Three other searches for electroweak top quark production have been performed on the same data set and the individual results have been combined [10]. The result of this combination is $4.7 \pm 1.3 \text{ pb}$. Thus, within uncertainties, the cross section measured in this thesis agrees both with this combined measurement and with the individual measurements that have been used as input to the combination.

9.2 Measurement of the CKM Matrix Element $|V_{tb}|$

The cross section of electroweak top quark production is proportional to the square of the effective coupling between the top quark and the W boson, assuming that the exchange of a W boson

(a)

(b)

Figure 9.1.4: Measured posterior plots for all channels combined with statistical uncertainty only (figure 9.1.4(a)) and with statistical and systematic uncertainties (figure 9.1.4(b)).

is the only production mechanism for single top quarks. For this measurement, this assumption is made, i.e. production mechanisms of single top quarks that may arise through extension of the Standard Model (e.g. production via flavor changing neutral currents or the exchange of heavy scalar or vector bosons) are not considered here. However, no assumptions are made on the number of families in the Standard Model or on the unitarity of the CKM matrix. Both CDF [79] and DØ [80] have measured the ratio R , with

$$R = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}, \quad (9.2.1)$$

by comparing the rate of events with zero, one, and two b-tagged jets in top quark pair events. These measurements allow another assumption, namely that $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$. For

Analysis channel			Cross section [pb]	Cross section [pb]
Lepton(s)	# Jets	# B-tags	(w/o systematics)	(w/ systematics)
μ	2-4	1+2	$3.70^{+1.44}_{-1.31}$	$5.45^{+2.08}_{-1.80}$
e	2-4	1+2	$3.13^{+1.28}_{-1.20}$	$5.77^{+2.04}_{-1.85}$
$\mu + e$	2-4	1	$2.70^{+1.00}_{-0.92}$	$4.29^{+1.54}_{-1.26}$
$\mu + e$	2-4	2	$6.82^{+2.60}_{-2.38}$	$9.88^{+4.29}_{-3.27}$
$\mu + e$	2	1+2	$3.49^{+1.14}_{-1.07}$	$4.88^{+1.65}_{-1.45}$
$\mu + e$	3	1+2	$1.83^{+1.60}_{-1.50}$	$5.45^{+3.23}_{-2.81}$
$\mu + e$	4	1+2	$7.32^{+4.08}_{-3.57}$	$14.90^{+6.38}_{-6.05}$
$\mu + e$	2-4	1+2	$3.39^{+0.89}_{-0.95}$	$5.51^{+1.62}_{-1.31}$

Table 9.1.2: Measured s+t-channel cross section, without and with systematic uncertainties, for many combinations of the analysis channels. The final result of this analysis is shown in the lower right hand corner in bold type.

example, the result of the $D\bar{O}$ analysis is

$$|V_{td}|^2 + |V_{ts}|^2 = (-0.03^{+0.18}_{-0.16}) \cdot |V_{tb}|^2. \quad (9.2.2)$$

This result can also be interpreted such that the branching ratio $\text{BR}(t \rightarrow Wb) \simeq 100\%$ and that electroweak top quark production is dominated by the tbW interaction. This assumption has already been made in the measurement of the single top quark production cross section, where the Standard Model ratio for the cross sections of the individual channels $\sigma_s/\sigma_t=0.44$ has been used. Furthermore, it has been used in the generation of simulated events with top quarks, i.e. in the production of the single top quark and top quark pair Monte Carlo samples used in the analysis. The final assumption is that the tbW interaction conserves the CP symmetry and is of type V-A. The most general definition of the tbW vertex [234,235] is given by:

$$\Gamma_{tbW}^\mu = -\frac{g}{\sqrt{2}} V_{tb} \bar{u}(p_b) \left[\gamma^\mu (f_1^L P_L + f_1^R P_R) - \frac{i\sigma^{\mu\nu} k_\nu}{M_W} (f_2^L P_L + f_2^R P_R) \right] u(p_t). \quad (9.2.3)$$

In this definition k is the four-momentum of the W boson. The couplings f_1 and f_2 can principally violate the CP symmetry. However, in the Standard Model the tbW vertex is CP-conserving and the couplings are $f_1^L=1$ and $f_1^R=f_2^L=f_2^R=0$. Measuring a production cross section that differs from the Standard Model value can originate from $|V_{tb}|<1$, from anomalous couplings, or from a combination of both. Since in the generation of the Monte Carlo samples the Standard Model tbW vertex has been assumed, it can be used to search for anomalous couplings f_1^L . An anomalous coupling f_1^L would only affect the cross section of single top quark production. The cross section of $t\bar{t}$ production and the kinematic quantities remain unaffected. Therefore, two measurements are performed:

1. $|V_{tb} \times f_1^L|$:

This is a measurement of the strength of the V-A coupling. The result is allowed to be

Analysis channel			Cross section [pb]	Cross section [pb]
Lepton	# Jets	# B-tags	(w/o systematics)	(w/ systematics)
μ	2	1	$3.99^{+1.89}_{-1.66}$	$6.05^{+2.92}_{-2.40}$
μ	2	2	$5.83^{+4.67}_{-3.82}$	$8.79^{+6.80}_{-5.08}$
μ	3	1	$0.00^{+3.19}_{-0.00}$	$3.97^{+4.05}_{-3.30}$
μ	3	2	$6.24^{+6.27}_{-5.28}$	$4.25^{+7.89}_{-4.25}$
μ	4	1	$3.96^{+8.02}_{-3.96}$	$0.00^{+11.84}_{-0.00}$
μ	4	2	$13.56^{+13.21}_{-13.56}$	$14.20^{+ \text{dnc}}_{-14.20}$
e	2	1	$2.16^{+1.54}_{-1.38}$	$3.00^{+2.06}_{-1.80}$
e	2	2	$5.97^{+4.39}_{-3.75}$	$7.44^{+4.94}_{-6.17}$
e	3	1	$0.21^{+3.04}_{-0.21}$	$4.61^{+4.15}_{-3.70}$
e	3	2	$9.80^{+6.84}_{-5.73}$	$8.55^{+7.81}_{-6.07}$
e	4	1	$7.86^{+5.59}_{-4.54}$	$12.91^{+7.44}_{-5.98}$
e	4	2	$4.09^{+10.20}_{-4.09}$	$13.87^{+ \text{dnc}}_{-13.87}$

Table 9.1.3: Summary of the cross section measurements of the individual analysis channels contributing to the final result. The observed cross sections are stated for two cases: for the statistical analysis only, and for the analysis including also systematic uncertainties. For uncertainties stated as ‘dnc’ the numerical integration of the posterior does not converge.

larger than one.

2. $|V_{tb}|$:

With the additional assumption that $f_1^L = 1$ the result is limited to the range $0 \leq |V_{tb}| \leq 1$.

For the statistical analysis the `top_statistics` package [231] is used, i.e. the same methods that have been used to determine the cross section. The prior is chosen to be flat in $|V_{tb} \times f_1^L|^2$, that means it is also chosen flat in the cross section. To obtain the posterior for $|V_{tb}|$ (the second case mentioned above), the prior is restricted to the interval $[0,1]$.

Additional systematic uncertainties have to be considered in order to extract $|V_{tb}|$ from the measured cross section [61]. These uncertainties are summarized in table 9.2.1 for the s- and the t-channel process individually. To take correlations between the s- and the t-channel production process properly into account, the uncertainties are applied separately to the corresponding Monte Carlo samples.

The posterior distribution of the measurement of $|V_{tb} \times f_1^L|^2$ is shown in figure 9.2.1. The

Figure 9.1.5: Summary of the cross section measurements of the individual analysis channels contributing to the final measurement are shown together with the final result. The observed cross sections are stated for the measurement considering statistical uncertainties only (left plot), and for the measurement including systematic uncertainties in addition (right plot). For uncertainties stated as ‘dnc’ the numerical integration of the posterior does not converge.

	s-channel	t-channel
Top quark mass	8.5	13.0
Factorization scale	4.0	5.5
Parton distribution functions	4.5	10.0
Strong coupling constant α_s	1.4	0.01

Table 9.2.1: Additional systematic uncertainties in percent on the cross section factor required to extract $|V_{tb}|$.

most probable value for $|V_{tb} \times f_1^L|^2$ is given by the peak of the posterior and the uncertainty of the measurement is determined by integrating the posterior numerically until both the areas left and right of the maximum cover 32.15 % of the area under the posterior. Thus, the result for the measurement of $|V_{tb} \times f_1^L|^2$ is

$$|V_{tb} \times f_1^L|^2 = 2.01_{-0.58}^{+0.60}. \quad (9.2.4)$$

This can be translated into a result for $|V_{tb} \times f_1^L|$, the strength of the V-A coupling, of

$$|V_{tb} \times f_1^L| = 1.42_{-0.20}^{+0.21}. \quad (9.2.5)$$

Figure 9.2.1: Posterior probability density for $|V_{tb} \times f_1^L|^2$. The solid blue line shows the maximum of the posterior. The dashed blue lines display the error on the $|V_{tb} \times f_1^L|^2$ measurement.

The strength of the V-A coupling is thus about 2.0 standard deviations above the Standard Model expectation. However, such a deviation is expected considering that the measured cross section is also 2.0 standard deviations above the cross section predicted by the Standard Model. As in the cross section measurement the choice of the binning of the Boosted Decision Tree discriminant leads to variations in the result.

The posterior distribution for the case in which the prior is restricted to the range $[0,1]$ is shown in figure 9.2.2. With this restriction, the result for $|V_{tb}|^2$ is

Figure 9.2.2: Posterior probability density for $|V_{tb}|$. The prior is restricted to the interval $[0,1]$. The green line indicates the 95% confidence level lower limit on $|V_{tb}|^2$, the dashed blue line displays the lower error on $|V_{tb}|$.

$$|V_{tb}|^2 = 1.00^{+0.00}_{-0.16}. \quad (9.2.6)$$

This translates into a result for $|V_{tb}|$ of

$$|V_{tb}| = 1.00^{+0.00}_{-0.08}. \quad (9.2.7)$$

The posterior can also be used to set a 95% confidence level lower limit on $|V_{tb}|^2$:

$$|V_{tb}|^2 \geq 0.63 \text{ @ 95\% C.L.} \quad (9.2.8)$$

Translated into a 95% confidence level lower limit on $|V_{tb}|$, this results in

$$|V_{tb}| \geq 0.79 \text{ @ 95\% C.L.} \quad (9.2.9)$$

10 Conclusion

This analysis presents a measurement of the combined s+t-channel electroweak top quark production cross section at the Tevatron collider. An integrated luminosity of nearly 1 fb^{-1} of Run II data has been analyzed. After the selection of single top quark-like events, a Multi-Process Factory has been used to analyze each event under several physics process hypotheses. The novelty in this analysis is that an event is not only studied under the assumption of the signal process decay chain, but also under the assumption to originate from one of the major background physics processes. In three jet multiplicity bins a total of 13 decay chains are reconstructed and evaluated. The implementation and optimization of this technique is a first step towards analysis methods which are able to actively identify an event as a signal or background event. In this analysis the most likely decay chain of an event for each signal and background process under investigation is used to obtain decay chain dependent observables. The close connection of the observables to the partons of a physics process decay chain leads to an intuitive interpretation of the resulting distributions.

Observables gained in the Multi-Process Factory are used as input to a state-of-the-art multivariate analysis technique, Boosted Decision Trees. The configuration of these Boosted Decision Trees has been optimized with the goal to maximize the separation of the expected signal contribution from the overwhelming background. Using a Bayesian approach the discriminant distributions of the twelve independent analysis channels are fitted simultaneously. This analysis measures the combined s+t channel production cross section to be

$$\sigma(p\bar{p} \rightarrow tb + X, tqb + X) = 5.51^{+1.62}_{-1.31} \text{ pb}$$

for a top mass of 175 GeV and assuming a Standard Model s-channel to t-channel cross section ratio of $\sigma_s/\sigma_t = 0.44$. The significance of the cross section measurement is 4.2 standard deviations. The measured cross section value exceeds the Standard Model expectation by 2 standard deviations. The result of the analysis presented here is in good agreement with the result of $\sigma(p\bar{p} \rightarrow tb + X, tqb + X) = 4.8 \pm 1.3 \text{ pb}$, obtained from the combination of three other analyses performed on the same data set [10].

From the cross section measurement a measurement of the strength $|V_{tb} \times f_1^L|$ of the V-A coupling at the Wtb-vertex has been extracted. The result is

$$|V_{tb} \times f_1^L| = 1.42^{+0.21}_{-0.20}.$$

This value is above the Standard Model expectation by about 2 standard deviations. The measurement agrees within uncertainties with the measurement of $|V_{tb} \times f_1^L| = 1.31^{+0.25}_{-0.21}$ obtained by another analysis performed on the same data set [9].

Constraining the prior of this measurement to the interval $[0,1]$, i.e. setting the strength of the left-handed coupling $f_1^L = 1$, a result for the CKM matrix element $|V_{tb}|$ has been determined to

$$|V_{tb}| = 1.00^{+0.00}_{-0.08}.$$

From the posterior probability density of this measurement a lower limit for $|V_{tb}|$ has been set at 95% confidence level:

$$|V_{tb}| > 0.79 \text{ @ } 95\% \text{ C.L.}$$

Outlook

After the combined s+t channel single top quark production cross section has recently been observed by DØ [11] and CDF [12] in data sets containing at least twice as much integrated luminosity as has been included in the analysis presented in this thesis, the next goal will thus be the precise measurement of the individual cross sections of single top quark production via s-channel and t-channel. The ratio of these cross section is another test of the electroweak sector of the Standard Model.

The searches for the Higgs boson are going to benefit from a better precision of the measured single top quark production cross section in two ways. Firstly, because electroweak top quark production is one of the major background processes in the Higgs analyses. Thus, a well known single top quark cross section will reduce the uncertainty on the background model significantly. Secondly, the analysis methods successfully developed, optimized, and evaluated in the single top quark search have shown that it is possible to measure physics processes which occur in only one out of ten billion collisions at the Tevatron and which have a signature that is very similar to processes whose cross section are orders of magnitude larger. With the knowledge of these techniques and the detailed understanding of the detector apparatus, the DØ collaboration hopes to find evidence for the Higgs boson before the era of precision measurements at the Large Hadron Collider starts.

Recent developments in the software for physics analyses [218–220] will support experimental physicists in reaching this goal. For the method of the Multi-Process Factory applied in this analysis, this means that the configurability and the analysis design will improve further by means of automation and visualization. This will lead to an easier communication about the complex details of nowadays physics analyses among physicists and a to speed-up of the analysis turn-around.

With all these methods being developed and tested, the goal for the future will be to extract as much of the great physics potential the Large Hadron Collider provides as possible. While the search for single top quark production at the Tevatron will remain statistically limited, the high luminosity at the Large Hadron Collider will allow to extract clean data sets of single top quark candidate events and to study polarization effects of the top quark. Since many theories for physics beyond the Standard Model indicate that new physics effects might become visible in electroweak top quark production, the precise study of this process will be an exciting field to look into.

A Details on the Likelihood Measure

In section 6.2.1.1 a Likelihood measure is introduced in order to select one of n different configurations of the ambiguous reconstruction of a Parton Picture Template. The Likelihood measure $L(C)$ for each of the n different configurations C is calculated as

$$L(C) = \prod_{i=1}^k P(x_i|B), \quad (\text{A.0.1})$$

with k observables used in the calculation of the Likelihood measure. The term $P(x_i|B)$ in the Likelihood measure gives the probability to measure the value x of variable i under the assumption that the configuration C that is currently analyzed is the best configuration B . The best configuration B is obtained by matching the partons of the generated events with the reconstructed objects (see section 6.2.1.2).

The term $P(x_i|B)$ is a simplification. The interesting probability is $P(B|x_i)$, the probability that the configuration that is currently analyzed is the best configuration B , given the value of variable i that is measured. Following Bayes' theorem [236], $P(B|x_i)$ is calculated as

$$P(B|x_i) = \frac{P(x_i|B) \cdot P(B)}{P(x_i)}. \quad (\text{A.0.2})$$

It turns out that in this application, $P(B|x_i)$ is proportional to $P(x_i|B)$, because both $P(B)$ and $P(x_i)$ are constant. The probability $P(B)$ is known:

$$P(B) = \frac{1}{n}. \quad (\text{A.0.3})$$

It is the probability that one of the n possible configurations C is the correct configuration B . The probability $P(x_i)$ is the probability of all n configurations C to measure the value x for variable i . This is a constant value for all n configurations C of one event. Since the actual probability $P(B|x_i)$ is not necessary to determine the most likely configuration, it is taken advantage of

$$P(B|x_i) \propto P(x_i|B), \quad (\text{A.0.4})$$

which results in the Likelihood measure as stated in equation 6.2.1. The value of $P(x_i|B)$ for the value x of variable i is given by

$$P(x_i|B) = \int_{x_{\min}}^{x_{\max}} f(x_i|B) dx, \quad (\text{A.0.5})$$

where $x_{\min}$ ($x_{\max}$) are the lower (upper) bound of the bin containing the value x of variable i of the currently analyzed configuration in the histogram containing the probability density distribution of observable i for the best configuration B . $f(x_i|B)$ is the (binned) probability density function of observable i for the best configuration B .

B Systematic Uncertainties by Analysis Channel

Tables B.0.1–B.0.12 show the systematic uncertainties on the signal and background samples for the twelve different analysis bins.

From the tables it is possible to see correlations between the different analysis channels or between various samples for each uncertainty individually. A full correlation of the systematic uncertainty is assumed between all signal and background samples within a given row in each table. This also applies for rows with the same name in different tables. Exceptions to this assumption are the systematic uncertainties on the theoretical cross sections used to normalize the MC backgrounds (except for the two $t\bar{t}$ backgrounds), and the statistical uncertainty from the size of each Monte Carlo sample.

The $Wb\bar{b}$, $Wc\bar{c}$, and Wjj yield estimates in the analysis are not affected by any of the systematic uncertainties that affect the overall yield. Their normalization to data is done before b-tagging is applied. However, the systematic uncertainty introduced due to the application of b-tagging has an effect on the shapes of the kinematic distributions of these samples. The uncertainty of this shape-changing systematic is included bin-by-bin during the binned likelihood fit.

The uncertainty on the matrix method stated in the tables includes the uncertainty on the flavor composition in the W+jets sample in addition to the uncertainty on the matrix method itself. The flavor composition is by far the dominant source of uncertainty. Furthermore, the normalization of the different W+jets samples includes other Monte Carlo backgrounds. Their uncertainties thus also affect the $Wb\bar{b}$, $Wc\bar{c}$, and Wjj uncertainties. Since these other Monte Carlo backgrounds only contribute to about 3 % to the yield in the pretagged sample, their uncertainties are negligible compared with the other sources of uncertainty of the matrix method and are thus ignored.

The uncertainty on the total W+jets yield is lower than 30 % after b-tagging is applied. The first reason is, that not the entire sample consists of $Wb\bar{b}$ and $Wc\bar{c}$. Therefore, the uncertainty on the sum is smaller than 30%. The second reason is that an anti-correlation between the Wjj events and the $Wb\bar{b}+Wc\bar{c}$ events further reduces the uncertainty, because the normalization is done before b-tagging is applied, using the matrix method. After tagging, the total W+jets yield consists to about 75% of $Wb\bar{b}+Wc\bar{c}$ events. The uncertainty of the remaining 25% of

Wjj events due to the heavy flavor composition is anti-correlated with the uncertainty on $Wb\bar{b}+Wc\bar{c}$. This results in an anti-correlated uncertainty of 10% on the Wjj sample.

Tables B.0.1–B.0.12 show the total uncertainty on each background component separately. The statistical and the systematic parts are combined in quadrature in the final lines. The luminosity, cross section and branching fraction for the s-channel (tb) and t-channel (tqb) signal samples are not used for the signal acceptance during the cross section calculation. They are only used when yields are quoted. Therefore, they are presented in parentheses in the following tables.

	Single-Tagged Two-Jets Electron Channel Percentage Errors							
	tb	tqb	$t\bar{t}lj$	$t\bar{t}ll$	Wbb	Wcc	Wjj	Mis-ID e
<u>Components for Normalization</u>								
Luminosity	(6.1)	(6.1)	6.1	6.1	—	—	—	—
Cross section	(16.0)	(15.0)	18.0	18.0	—	—	—	—
Branching fraction	(1.0)	(1.0)	1.0	1.0	—	—	—	—
Matrix method	—	—	—	—	18.2	18.2	18.2	18.2
Primary vertex	2.4	2.4	2.4	2.4	—	—	—	—
Electron ID	5.5	5.5	5.5	5.5	—	—	—	—
Jet ID	1.5	1.5	1.5	1.5	—	—	—	—
Jet fragmentation	5.0	5.0	7.0	5.0	—	—	—	—
Trigger	3.0	3.0	3.0	3.0	—	—	—	—
<u>Components for Normalization and Shape</u>								
Jet energy scale	1.4	0.3	9.9	1.7	—	—	—	—
Flavor-dependent TRFs	2.1	5.9	4.6	2.4	4.4	6.3	7.4	—
<u>Statistics</u>	0.7	0.7	1.3	0.8	0.9	0.9	0.4	5.6
<u>Combined</u>								
Acceptance uncertainty	10.8	12.1	—	—	—	—	—	—
Yield uncertainty	19.3	19.3	24.1	21.1	18.8	19.3	19.7	19.1

Table B.0.1: Electron channel uncertainties, requiring exactly one tag and two jets.

	Single-Tagged Three-Jets Electron Channel Percentage Errors							
	tb	tqb	$t\bar{t}lj$	$t\bar{t}ll$	Wbb	Wcc	Wjj	Mis-ID e
<u>Components for Normalization</u>								
Luminosity	(6.1)	(6.1)	6.1	6.1	—	—	—	—
Cross section	(16.0)	(15.0)	18.0	18.0	—	—	—	—
Branching fraction	(1.0)	(1.0)	1.0	1.0	—	—	—	—
Matrix method	—	—	—	—	16.8	16.8	16.8	16.8
Primary vertex	2.4	2.4	2.4	2.4	—	—	—	—
Electron ID	5.5	5.5	5.5	5.5	—	—	—	—
Jet ID	1.5	1.5	1.5	1.5	—	—	—	—
Jet fragmentation	5.0	5.0	7.0	5.0	—	—	—	—
Trigger	3.0	3.0	3.0	3.0	—	—	—	—
<u>Components for Normalization and Shape</u>								
Jet energy scale	5.3	5.8	4.1	3.2	—	—	—	—
Flavor-dependent TRFs	2.1	4.5	2.9	2.1	4.4	6.2	7.6	—
<u>Statistics</u>	1.0	1.0	0.5	0.5	1.0	1.0	0.5	6.7
<u>Combined</u>								
Acceptance uncertainty	12.0	12.9	—	—	—	—	—	—
Yield uncertainty	20.0	19.8	22.0	21.2	17.4	18.0	18.5	18.1

Table B.0.2: Electron channel uncertainties, requiring exactly one tag and three jets.

	Single-Tagged Four-Jets Electron Channel Percentage Errors							
	tb	tqb	$t\bar{t}lj$	$t\bar{t}ll$	Wbb	Wcc	Wjj	Mis-ID e
<u>Components for Normalization</u>								
Luminosity	(6.1)	(6.1)	6.1	6.1	—	—	—	—
Cross section	(16.0)	(15.0)	18.0	18.0	—	—	—	—
Branching fraction	(1.0)	(1.0)	1.0	1.0	—	—	—	—
Matrix method	—	—	—	—	17.6	17.6	17.6	17.6
Primary vertex	2.4	2.4	2.4	2.4	—	—	—	—
Electron ID	5.5	5.5	5.5	5.5	—	—	—	—
Jet ID	1.5	1.5	1.5	1.5	—	—	—	—
Jet fragmentation	5.0	5.0	7.0	5.0	—	—	—	—
Trigger	3.0	3.0	3.0	3.0	—	—	—	—
<u>Components for Normalization and Shape</u>								
Jet energy scale	11.8	10.4	1.4	7.6	—	—	—	—
Flavor-dependent TRFs	2.1	3.6	1.9	2.1	4.5	6.2	7.7	—
<u>Statistics</u>	2.0	2.0	0.7	1.0	2.0	1.0	0.8	10.2
<u>Combined</u>								
Acceptance uncertainty	16.1	15.3	—	—	—	—	—	—
Yield uncertainty	22.7	21.5	21.6	22.3	18.3	18.7	19.3	20.3

Table B.0.3: Electron channel uncertainties, requiring exactly one tag and four jets.

	Single-Tagged Two-Jets Muon Channel Percentage Errors							
	tb	tqb	$t\bar{t}lj$	$t\bar{t}ll$	Wbb	Wcc	Wjj	Mis-ID e
<u>Components for Normalization</u>								
Luminosity	(6.1)	(6.1)	6.1	6.1	—	—	—	—
Cross section	(16.0)	(15.0)	18.0	18.0	—	—	—	—
Branching fraction	(1.0)	(1.0)	1.0	1.0	—	—	—	—
Matrix method	—	—	—	—	20.7	20.7	20.7	20.7
Primary vertex	3.0	3.0	3.0	3.0	—	—	—	—
Muon ID	7.4	7.4	7.4	7.4	—	—	—	—
Jet ID	1.5	1.5	1.5	1.5	—	—	—	—
Jet fragmentation	5.0	5.0	7.0	5.0	—	—	—	—
Trigger	6.0	6.0	6.0	6.0	—	—	—	—
<u>Components for Normalization and Shape</u>								
Jet energy scale	5.3	6.1	20.1	6.8	—	—	—	—
Flavor-dependent TRFs	1.8	5.9	4.5	2.0	4.4	6.3	7.5	—
<u>Statistics</u>	9.0	0.7	1.0	1.0	0.8	0.8	0.4	14.0
<u>Combined</u>								
Acceptance uncertainty	16.7	15.4	—	—	—	—	—	—
Yield uncertainty	23.1	21.5	30.7	23.2	21.2	21.7	22.0	25.0

Table B.0.4: Muon channel uncertainties, requiring exactly one tag and two jets.

	Single-Tagged Three-Jets Muon Channel Percentage Errors							
	tb	tqb	$t\bar{t}lj$	$t\bar{t}ll$	Wbb	Wcc	Wjj	Mis-ID e
<u>Components for Normalization</u>								
Luminosity	(6.1)	(6.1)	6.1	6.1	—	—	—	—
Cross section	(16.0)	(15.0)	18.0	18.0	—	—	—	—
Branching fraction	(1.0)	(1.0)	1.0	1.0	—	—	—	—
Matrix method	—	—	—	—	20.8	20.8	20.8	20.8
Primary vertex	3.0	3.0	3.0	3.0	—	—	—	—
Muon ID	7.4	7.4	7.4	7.4	—	—	—	—
Jet ID	1.5	1.5	1.5	1.5	—	—	—	—
Jet fragmentation	5.0	5.0	7.0	5.0	—	—	—	—
Trigger	6.0	6.0	6.0	6.0	—	—	—	—
<u>Components for Normalization and Shape</u>								
Jet energy scale	9.3	9.0	10.8	7.6	—	—	—	—
Flavor-dependent TRFs	1.8	4.4	2.6	1.9	4.3	6.2	7.6	—
<u>Statistics</u>	2.0	2.0	0.8	0.7	1.0	1.0	0.7	14.3
<u>Combined</u>								
Acceptance uncertainty	16.1	16.5	—	—	—	—	—	—
Yield uncertainty	22.7	22.3	25.2	23.5	21.2	21.7	22.1	25.2

Table B.0.5: Muon channel uncertainties, requiring exactly one tag and three jets.

	Single-Tagged Four-Jets Muon Channel Percentage Errors							
	tb	tqb	$t\bar{t}lj$	$t\bar{t}ll$	Wbb	Wcc	Wjj	Mis-ID e
<u>Components for Normalization</u>								
Luminosity	(6.1)	(6.1)	6.1	6.1	—	—	—	—
Cross section	(16.0)	(15.0)	18.0	18.0	—	—	—	—
Branching fraction	(1.0)	(1.0)	1.0	1.0	—	—	—	—
Matrix method	—	—	—	—	20.6	20.6	20.6	20.6
Primary vertex	3.0	3.0	3.0	3.0	—	—	—	—
Muon ID	7.4	7.4	7.4	7.4	—	—	—	—
Jet ID	1.5	1.5	1.5	1.5	—	—	—	—
Jet fragmentation	5.0	5.0	7.0	5.0	—	—	—	—
Trigger	6.0	6.0	6.0	6.0	—	—	—	—
<u>Components for Normalization and Shape</u>								
Jet energy scale	14.6	14.6	7.1	10.9	—	—	—	—
Flavor-dependent TRFs	1.9	3.4	1.6	1.8	4.3	6.1	7.7	—
<u>Statistics</u>	2.0	2.0	0.7	1.0	2.0	2.0	1.0	21.8
<u>Combined</u>								
Acceptance uncertainty	19.6	19.9	—	—	—	—	—	—
Yield uncertainty	25.3	24.9	23.8	24.7	21.1	21.6	22.0	30.0

Table B.0.6: Muon channel uncertainties, requiring exactly one tag and four jets.

	Double-Tagged Two-Jets Electron Channel Percentage Errors							
	tb	tqb	$t\bar{t}lj$	$t\bar{t}ll$	Wbb	Wcc	Wjj	Mis-ID e
<u>Components for Normalization</u>								
Luminosity	(6.1)	(6.1)	6.1	6.1	—	—	—	—
Cross section	(16.0)	(15.0)	18.0	18.0	—	—	—	—
Branching fraction	(1.0)	(1.0)	1.0	1.0	—	—	—	—
Matrix method	—	—	—	—	26.5	26.5	26.5	26.5
Primary vertex	2.4	2.4	2.4	2.4	—	—	—	—
Electron ID	5.5	5.5	5.5	5.5	—	—	—	—
Jet ID	1.5	1.5	1.5	1.5	—	—	—	—
Jet fragmentation	5.0	5.0	7.0	5.0	—	—	—	—
Trigger	3.0	3.0	3.0	3.0	—	—	—	—
<u>Components for Normalization and Shape</u>								
Jet energy scale	0.8	4.1	8.0	1.8	—	—	—	—
Flavor-dependent TRFs	12.9	12.9	13.5	13.0	12.2	13.6	16.1	—
<u>Statistics</u>	0.7	0.7	1.3	0.8	0.9	0.9	0.4	28.9
<u>Combined</u>								
Acceptance uncertainty	16.7	17.2	—	—	—	—	—	—
Yield uncertainty	23.1	22.8	26.6	24.6	29.1	29.8	31.0	39.2

Table B.0.7: Electron channel uncertainties, requiring exactly two tags and two jets.

	Double-Tagged Three-Jets Electron Channel Percentage Errors							
	tb	tqb	$t\bar{t}lj$	$t\bar{t}ll$	Wbb	Wcc	Wjj	Mis-ID e
<u>Components for Normalization</u>								
Luminosity	(6.1)	(6.1)	6.1	6.1	—	—	—	—
Cross section	(16.0)	(15.0)	18.0	18.0	—	—	—	—
Branching fraction	(1.0)	(1.0)	1.0	1.0	—	—	—	—
Matrix method	—	—	—	—	22.1	22.1	22.1	22.1
Primary vertex	2.4	2.4	2.4	2.4	—	—	—	—
Electron ID	5.5	5.5	5.5	5.5	—	—	—	—
Jet ID	1.5	1.5	1.5	1.5	—	—	—	—
Jet fragmentation	5.0	5.0	7.0	5.0	—	—	—	—
Trigger	3.0	3.0	3.0	3.0	—	—	—	—
<u>Components for Normalization and Shape</u>								
Jet energy scale	4.8	4.0	3.5	2.9	—	—	—	—
Flavor-dependent TRFs	12.7	12.4	12.6	12.8	12.0	13.3	16.4	—
<u>Statistics</u>	1.0	1.0	0.7	0.7	1.0	1.0	0.5	25.8
<u>Combined</u>								
Acceptance uncertainty	17.2	16.8	—	—	—	—	—	—
Yield uncertainty	23.5	22.5	25.1	24.6	25.2	25.8	27.5	34.0

Table B.0.8: Electron channel uncertainties, requiring exactly two tags and three jets.

	Double-Tagged Four-Jets Electron Channel Percentage Errors							
	tb	tqb	$t\bar{t}lj$	$t\bar{t}ll$	Wbb	Wcc	Wjj	Mis-ID e
<u>Components for Normalization</u>								
Luminosity	(6.1)	(6.1)	6.1	6.1	—	—	—	—
Cross section	(16.0)	(15.0)	18.0	18.0	—	—	—	—
Branching fraction	(1.0)	(1.0)	1.0	1.0	—	—	—	—
Matrix method	—	—	—	—	19.5	19.5	19.5	19.5
Primary vertex	2.4	2.4	2.4	2.4	—	—	—	—
Electron ID	5.5	5.5	5.5	5.5	—	—	—	—
Jet ID	1.5	1.5	1.5	1.5	—	—	—	—
Jet fragmentation	5.0	5.0	7.0	5.0	—	—	—	—
Trigger	3.0	3.0	3.0	3.0	—	—	—	—
<u>Components for Normalization and Shape</u>								
Jet energy scale	10.9	8.3	1.6	7.6	—	—	—	—
Flavor-dependent TRFs	12.5	12.2	12.0	12.6	12.0	13.2	16.6	—
<u>Statistics</u>	2.0	2.0	0.7	1.0	2.0	1.0	0.8	26.7
<u>Combined</u>								
Acceptance uncertainty	19.8	18.2	—	—	—	—	—	—
Yield uncertainty	25.4	23.6	24.6	25.5	23.0	23.6	25.6	33.1

Table B.0.9: Electron channel uncertainties, requiring exactly two tags and four jets.

	Double-Tagged Two-Jets Muon Channel Percentage Errors							
	tb	tqb	$t\bar{t}lj$	$t\bar{t}ll$	Wbb	Wcc	Wjj	Mis-ID e
<u>Components for Normalization</u>								
Luminosity	(6.1)	(6.1)	6.1	6.1	—	—	—	—
Cross section	(16.0)	(15.0)	18.0	18.0	—	—	—	—
Branching fraction	(1.0)	(1.0)	1.0	1.0	—	—	—	—
Matrix method	—	—	—	—	27.6	27.6	27.6	27.6
Primary vertex	3.0	3.0	3.0	3.0	—	—	—	—
Muon ID	7.4	7.4	7.4	7.4	—	—	—	—
Jet ID	1.5	1.5	1.5	1.5	—	—	—	—
Jet fragmentation	5.0	5.0	7.0	5.0	—	—	—	—
Trigger	6.0	6.0	6.0	6.0	—	—	—	—
<u>Components for Normalization and Shape</u>								
Jet energy scale	5.2	9.1	19.7	6.9	—	—	—	—
Flavor-dependent TRFs	12.9	12.8	13.4	12.9	12.2	13.5	16.1	—
<u>Statistics</u>	1.3	0.9	0.7	0.7	1.0	1.0	0.5	57.7
<u>Combined</u>								
Acceptance uncertainty	19.0	20.3	—	—	—	—	—	—
Yield uncertainty	24.8	25.2	32.9	26.5	30.2	30.7	31.9	64.0

Table B.0.10: Muon channel uncertainties, requiring exactly two tags and two jets.

	Double-Tagged Three-Jets Muon Channel Percentage Errors							
	tb	tqb	$t\bar{t}lj$	$t\bar{t}ll$	Wbb	Wcc	Wjj	Mis-ID e
<u>Components for Normalization</u>								
Luminosity	(6.1)	(6.1)	6.1	6.1	—	—	—	—
Cross section	(16.0)	(15.0)	18.0	18.0	—	—	—	—
Branching fraction	(1.0)	(1.0)	1.0	1.0	—	—	—	—
Matrix method	—	—	—	—	25.0	25.0	25.0	25.0
Primary vertex	3.0	3.0	3.0	3.0	—	—	—	—
Muon ID	7.4	7.4	7.4	7.4	—	—	—	—
Jet ID	1.5	1.5	1.5	1.5	—	—	—	—
Jet fragmentation	5.0	5.0	7.0	5.0	—	—	—	—
Trigger	6.0	6.0	6.0	6.0	—	—	—	—
<u>Components for Normalization and Shape</u>								
Jet energy scale	10.2	7.6	10.1	7.8	—	—	—	—
Flavor-dependent TRFs	12.6	12.3	12.4	12.7	12.0	13.1	16.4	—
<u>Statistics</u>	2.0	2.0	0.8	0.6	1.0	1.0	0.6	50.0
<u>Combined</u>								
Acceptance uncertainty	20.8	19.4	—	—	—	—	—	—
Yield uncertainty	26.3	24.5	27.7	26.7	27.7	28.2	29.9	55.9

Table B.0.11: Muon channel uncertainties, requiring exactly two tags and three jets.

	Double-Tagged Four-Jets Muon Channel Percentage Errors							
	tb	tqb	$t\bar{t}lj$	$t\bar{t}ll$	Wbb	Wcc	Wjj	Mis-ID e
<u>Components for Normalization</u>								
Luminosity	(6.1)	(6.1)	6.1	6.1	—	—	—	—
Cross section	(16.0)	(15.0)	18.0	18.0	—	—	—	—
Branching fraction	(1.0)	(1.0)	1.0	1.0	—	—	—	—
Matrix method	—	—	—	—	26.5	26.5	26.5	26.5
Primary vertex	3.0	3.0	3.0	3.0	—	—	—	—
Muon ID	7.4	7.4	7.4	7.4	—	—	—	—
Jet ID	1.5	1.5	1.5	1.5	—	—	—	—
Jet fragmentation	5.0	5.0	7.0	5.0	—	—	—	—
Trigger	6.0	6.0	6.0	6.0	—	—	—	—
<u>Components for Normalization and Shape</u>								
Jet energy scale	1.6	15.0	7.0	11.5	—	—	—	—
Flavor-dependent TRFs	12.4	12.1	11.8	12.4	11.7	13.3	16.5	—
<u>Statistics</u>	2.0	2.0	0.7	1.0	2.0	2.0	1.0	100.0
<u>Combined</u>								
Acceptance uncertainty	18.0	23.2	—	—	—	—	—	—
Yield uncertainty	24.1	27.6	26.5	27.9	29.0	29.7	31.2	103.4

Table B.0.12: Muon channel uncertainties, requiring exactly two tags and four jets.

C Calculation of the z-Component of the Neutrino Momentum

In most Parton Picture Templates used in the Multi-Process Factory, the leptonic decay of a W boson into a charged lepton l and a neutrino ν needs to be reconstructed:

$$W^- \rightarrow l^- + \bar{\nu}_l \quad \text{or} \quad W^+ \rightarrow l^+ + \nu_l$$

. The kinematics of the charged lepton is known. It was reconstructed using information from the tracking detectors and the calorimeter or muon detectors. The neutrino interacts only via the weak force and thus escapes detection. Only a significant amount of missing transverse energy in an event can be a sign for the presence of a neutrino in the decay. Thus, the missing transverse energy is assigned to the neutrino. However, the z -component p_z of the neutrino momentum is still unknown. Two possible solutions can be found using the known mass of the W boson as a constraint. The mass of the W boson was set to 80.4 GeV [206]. The calculation is based on the conservation of momenta,

$$p_W = p_\nu + p_l. \quad (\text{C.0.1})$$

Using the W boson mass constraint yields

$$m_W = 80.4 \text{ GeV} = \sqrt{(p_\nu + p_l)^2} \quad (\text{C.0.2})$$

and

$$m_W^2 = 2 \cdot p_\nu p_l \Leftrightarrow \frac{m_W^2}{2} = E_\nu E_l - \vec{p}_\nu \vec{p}_l, \quad (\text{C.0.3})$$

using $p_\nu^2 = m_\nu^2 = 0$ and $p_l^2 = m_l^2 \approx 0$. For all processes, p_x^ν and p_y^ν are taken from the reconstruction of the missing transverse energy, i.e.

$$p_i^\nu = \cancel{E}_i, \quad (\text{C.0.4})$$

with $i = x, y$.

Now, $\vec{p}_\nu \vec{p}_l$ from the right hand side of equation C.0.3 is evaluated using the theorem

$$\cos(\phi_1 - \phi_2) = \cos \phi_1 \cos \phi_2 + \sin \phi_1 \sin \phi_2. \quad (\text{C.0.5})$$

This yields:

$$\begin{aligned} \vec{p}_\nu \vec{p}_l &= \begin{pmatrix} p_{x,\nu} \\ p_{y,\nu} \\ p_{z,\nu} \end{pmatrix} \cdot \begin{pmatrix} p_{x,l} \\ p_{y,l} \\ p_{z,l} \end{pmatrix} \\ &= \begin{pmatrix} p_{T,\nu} \cdot \cos \phi_\nu \\ p_{T,\nu} \cdot \sin \phi_\nu \\ p_{z,\nu} \end{pmatrix} \cdot \begin{pmatrix} p_{T,l} \cdot \cos \phi_l \\ p_{T,l} \cdot \sin \phi_l \\ p_{z,l} \end{pmatrix} \\ &= p_{T,\nu} p_{T,l} \cdot (\cos \phi_\nu \cos \phi_l + \sin \phi_\nu \sin \phi_l) + p_{z,\nu} p_{z,l}, \end{aligned} \quad (\text{C.0.6})$$

where the notation $p_{T,\nu}$ ($p_{T,l}$) refers to the transverse momentum of the neutrino (charged lepton).

Applying equation C.0.3 again leads to

$$E_\nu E_l = \frac{m_W^2}{2} + \cos(\phi_\nu - \phi_l) p_{T,\nu} p_{T,l} + p_{z,\nu} p_{z,l} = E_l \sqrt{p_{T,\nu}^2 + p_{T,l}^2}. \quad (\text{C.0.7})$$

A new variable X is introduced, with

$$X = \frac{m_W^2}{2} + \cos(\phi_\nu - \phi_l) p_{T,\nu} p_{T,l}. \quad (\text{C.0.8})$$

Substituting X and squaring equation C.0.7 leads to

$$\begin{aligned} E_l^2 \cdot (p_{T,\nu}^2 + p_{T,l}^2) &= X^2 + 2X p_{z,\nu} p_{z,l} + (p_{z,\nu} p_{z,l})^2 \\ \Rightarrow p_{z,\nu}^2 (E_l^2 - p_{z,l}^2) - 2X p_{z,\nu} p_{z,l} + (E_l^2 p_{T,\nu}^2 - X^2) &= 0. \end{aligned} \quad (\text{C.0.9})$$

This is a quadratic equation in the variable $p_{z,\nu}$. The solutions $p_{z,\nu}^{1,2}$ of this equation are thus given by:

$$p_{z,\nu}^{1,2} = \underbrace{\frac{X p_{z,l}}{(E_l^2 - p_{z,l}^2)}}_R \pm \underbrace{\sqrt{\frac{(X p_{z,l})^2 - E_l^2 p_{T,\nu}^2 - X^2}{(E_l^2 - p_{z,l}^2)}}}_D. \quad (\text{C.0.10})$$

The number of solutions and thus the number of ambiguities introduced by the reconstruction of the W boson depends on the value of the difference in the numerator of D . If

$$(X p_{z,l})^2 - E_l^2 p_{T,\nu}^2 - X^2 > 0$$

there are two solutions $p_{z,\nu}^{1,2}$. This means that two neutrinos are reconstructed, and subsequently two configurations with different W bosons are evaluated. In the case

$$(X p_{z,l})^2 - E_l^2 p_{T,\nu}^2 - X^2 = 0$$

the square root does not contribute to the $p_{z,\nu}$ solution. The value of R is then the only solution, and there is no ambiguity to be resolved for the reconstruction of the W boson.

For those cases where the results are imaginary, i.e.

$$(X p_{z,l})^2 - E_l^2 p_{T,\nu}^2 - X^2 < 0,$$

the imaginary contribution is neglected and only the real part of the result, R , is taken into account. Hence, only one W boson is reconstructed.

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Lebenslauf

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Erklärung

Hiermit erkläre ich, dass ich die vorliegende Dissertation selbständig erarbeitet und ausschließlich die aufgeführten Referenzen verwendet habe. Alle Quellen und Zitate sind als solche kenntlich gemacht, und die Literaturangaben sind nach meinem besten Wissen und Gewissen korrekt und vollständig wiedergegeben.