SEARCH FOR SCALAR BOTTOM QUARKS FROM GLUINO DECAYS IN
PROTON-ANTIPROTON COLLISIONS AT A CENTER-OF-MASS ENERGY
OF 1.96 TEV

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Carsten Rott

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ABSTRACT

Rott, Carsten. Ph.D., Purdue University, December, 2004. Search for Scalar Bottom Quarks from Gluino Decays in Proton-Antiproton Collisions at a Center-of-Mass Energy of 1.96 TeV. Major Professor: Daniela Bortoletto.

We have performed a search for the scalar bottom quark ($\tilde{b}_1$) from gluino ($\tilde{g}$) decays in an R-parity conserving SUSY scenario with $m_{\tilde{g}} > m_{\tilde{b}_1}$, by investigating a final state of large missing transverse energy, with three or more jets, and some of them from the hadronization of b-quarks. A data sample of 156 pb^{-1} collected by the Collider Detector at Fermilab at a center-of-mass energy of $\sqrt{s} = 1.96 \text{ TeV}$ was used. For the final selection, jets containing secondary displaced vertices were required. This analysis has been performed 'blind', in that the inspection of the signal region was only made after the Standard Model prediction was finalized. Comparing data with SUSY predictions, we can exclude masses of the gluino and sbottom of up to 280 and 240 GeV/c^2 respectively.

1. Introduction

1.1 The Standard Model

Elementary particle physics has the goal of identifying the fundamental building blocks of our world. It is the search for particles, that are truly elementary, thus having no substructure. This quest is deeply connected to understanding the forces that act between these fundamental particles. The ultimate goal is to find a theory of everything, with the grand unification of all particles and forces, in which the complexity of the universe reduces to a single law.

1.2 Introduction to Particles and Forces

There are four known fundamental forces which govern the interaction of matter in our universe: Gravity, electromagnetism, weak, and strong interaction. These forces are mediated by so called carrier particles. All force carriers have integer spin, obey Bose-Einstein statistics [1], and are called gauge bosons. The electromagnetic force is mediated via the exchange of massless photons γ . The weak force is transmitted by exchange of three massive intermediate vector bosons, the $W^\pm$ and Z . The strong force is mediated via eight massless gluons. While all other forces are mediated by spin 1 gauge bosons gravity is mediated by the graviton which is spin 2. An additional gauge boson of spin 0, the Higgs boson H^0 , which is discussed in section 1.6 is needed in the Standard Model. All forces, or interactions, between these fundamental particles are described by three local gauge symmetries.

Besides gauge bosons one observes a second type of fundamental particles. These particles have half-integer spin and are called fermions. They follow Fermi-Dirac statistics [1] and are constrained by the Pauli exclusion principle.

1.3 Particles of the Standard Model

There are two fundamentally different types of fermions, quarks and leptons. They both interact electroweakly, but only the quarks feel the strong force.

Mesons are combinations of two quarks ($q\bar{q}$), and baryons combinations of three quarks (qqq). Recently, there has been also discussion about the discovery of a combination of five quark objects, which form stable states the Pentaquarks [2], which are ($qqqq\bar{q}$) states. Since quarks are fermions they satisfy the Pauli exclusion principle, which states that two fermions cannot occupy the same state. Hence, quarks carry an intrinsic property called 'color', which is the charge of the strong interaction. Quarks combine to hadrons in such a way that they are color-neutral (or color-less particles). There are six massive quarks up(u), down(d), strange(s), charm(c), bottom(b), and top(t). Out of the six quarks three of them (u,c,t) have a charge of $Q = 2/3$ and are also known as up-type quarks. The other three quarks are down-type and carry an electric charge of $Q = -1/3$ (d,s,b). The three up and down-type quarks can be paired to form three "sets" of quarks which have increasing mass. Each "set" of quarks is called a generation, or family. Quarks are regarded as elementary particles, they do not possess any known substructure.

Leptons are also elementary, they are regarded as point like particles. Searches for excited leptons have all gave negative results [3]. Similarly, leptons can be grouped into three generations like quarks. The up/down quarks are first generation quarks, while the electron/electron neutrino leptons are first generation leptons. All leptons are characterized by the lepton number L . With exception of neutrino oscillation, the lepton number seems to be conserved within each generation ($L_{e,\mu,\tau}$). Hence, for example the muon decay takes place in the form ($\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$). Quarks and leptons are summarized in Table 1.1.

Table 1.1

Particles of the Standard Model. Masses are taken from the Particle Data Group (PDG) [4], and from *Physics of Neutrinos* [5]. Note: The value for the top mass [6] represents the current best estimate for the top quark “pole” mass. For the analysis summarized in this thesis a top mass of $m_t = 175 \text{ GeV}/c^2$ was used.

	Generation		
	1	2	3
Quarks	up (u)	charm (c)	top (t)
	$m_u = 1.5 - 4.5 \text{ MeV}/c^2$	$m_c = 1.290_{-0.045}^{+0.040} \text{ GeV}/c^2$	$m_t = 178.0 \pm 4.3 \text{ GeV}/c^2$
	$Q = +\frac{2}{3}$	$Q = +\frac{2}{3}$	$Q = +\frac{2}{3}$
	down (d)	strange (s)	bottom (b)
Leptons	$m_d = 5 - 8.5 \text{ MeV}/c^2$	$m_s = 80 - 155 \text{ MeV}/c^2$	$m_b = 4.206 \pm 0.031 \text{ GeV}/c^2$
	$Q = -\frac{1}{3}$	$Q = -\frac{1}{3}$	$Q = -\frac{1}{3}$
	Electron (e^-)	Muon (μ^-)	Tau (τ^-)
	$m_e = 0.511 \text{ MeV}/c^2$	$m_\mu = 106 \text{ MeV}/c^2$	$m_\tau = 1.78 \text{ GeV}/c^2$
Neutrinos	$Q = -1$	$Q = -1$	$Q = -1$
	Electron neutrino (ν_e)	Muon neutrino (ν_μ)	Tau neutrino (ν_τ)
	$m_{\nu_e} < 3 \text{ eV}/c^2$	$m_{\nu_\mu} < 0.19 \text{ MeV}/c^2$	$m_{\nu_\tau} < 18.2 \text{ MeV}/c^2$
	$Q = 0$	$Q = 0$	$Q = 0$

1.4 The Standard Model

The Standard Model (SM) is an attempt to describe the properties and interactions of elementary particles. It unifies the electromagnetic, weak, and strong interactions in a quantum field theory based on the symmetry group $SU(3)_C \times \underbrace{SU(2)_L \times U(1)_Y}_G$, where C denotes color, L handedness (or chirality) and Y hypercharge.

There is one coupling constant associated with each group:

- Strong coupling constant α_S for the strong interactions
- Charge e for electromagnetic interactions
- Fermi constant G_F

Electromagnetism and weak force can be unified in one model, the Glashow-Salam-Weinberg (GSW) model of the electroweak interactions, where G is the electroweak symmetry group. Hence, the Standard Model combines Quantum Chromodynamics (QCD) and the GSW model of the electroweak interactions, into one theory. In the following subsections we focus on the three symmetry groups separately. We start with Quantum Electrodynamics (QED) described in section 1.5.1, as it represents the simplest example of a gauge theory. We then go over the electroweak unification in section 1.5.2, before coming to Quantum Chromodynamics in section 1.5.3.

1.5 Theoretical Description

1.5.1 Quantum Electrodynamics

Quantum electrodynamics (QED) emerged as the prototype of modern Quantum field theories (QFT). It was developed in the late 1940s and early 1950s chiefly by Feynman, Schwinger and Tomonaga, describing electromagnetic interactions of electrons and photons. It is a quantized and relativistically invariant theory. The strength of the interaction between the photon and charged fermions is described by the coupling constant α . The value of α depends on the momentum transfer q^2 in an interaction, which makes it a running coupling constant. At $q^2 = 0$, the coupling constant is the fine structure constant, $\alpha = \frac{e^2}{4\pi\hbar c} = \frac{1}{137}$. At the scale of the Z-Boson, α becomes $\alpha(m_Z = 91 \text{ GeV}) \simeq \frac{1}{128}$. There are two important properties of QED, gauge invariance and renormalizability.

Quantum Electrodynamics is a gauge theory, which means, it is invariant under a change of phase or gauge. Global U(1) gauge symmetry gives rise to the conservation

of electromagnetic charge Q . Imposing local gauge invariance ($\psi \rightarrow e^{i\theta(x)}\psi$) on the theory, necessitates the introduction of a gauge field, which describes the interactions among charged particles and corresponds to the photon γ . Photons do not carry charge, due to the Abelian¹ nature of the unitary $U(1)$ symmetry group, and therefore do not interact with each other at tree-level. They only self couple through higher-order fermionic loops, which makes it a long range interaction.

1.5.2 Electroweak Theory

Electroweak theory unifies the electromagnetic interaction, described by quantum electrodynamics, with the weak interactions. It was originally proposed by Weinberg [7] and Salam [8] in 1967. The idea of this unification is to combine both interactions into one single theoretical framework, in which they would appear as two manifestations of the same fundamental electroweak interaction. There is a huge difference in strength of the weak and electromagnetic force, which can be understood by the different nature of the mediators. The gauge bosons of the weak interaction are extremely massive, while the electromagnetic force is mediated by the massless photon. The mediators of the weak force are heavy because of the “Higgs mechanism”, which is described in section 1.6. Electroweak unification was developed before the observation of the W and Z-Boson. It aimed to explain processes such as the β -decay in the framework of field theory.

The electromagnetic and weak forces can be combined in the $SU(2) \times U(1)$ group. $SU(2)$ is a group of dimension 3 and has therefore three generators $\mathbf{T}^\alpha (\alpha = 1, 2, 3)$. In the 2×2 matrix representation they are given by the $1/2$ times the three Pauli spin matrices:

$$\mathbf{T}^1 = \frac{1}{2} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \mathbf{T}^2 = \frac{1}{2} \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \mathbf{T}^3 = \frac{1}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \quad (1.1)$$

---

¹A group for which the elements commute (i.e., $AB = BA$ for all elements A and B) is called an Abelian group

which obey the following commutation relation:

$$[\mathbf{T}^a, \mathbf{T}^b] = i\epsilon_{abc}\mathbf{T}^c. \quad (1.2)$$

The unification of the two interactions is accomplished in two steps. First, global gauge invariance under the SU(2) gauge transformation leads to the conservation of the weak-isospin charge, $\mathbf{T}$. Requiring the Lagrangian to be invariant under local SU(2) transformations introduces a weak-isospin triplet of gauge fields, $W^i (i = 1, 2, 3)$. The SU(2) group is non-Abelian which leads to the self-interactions of these gauge fields.

The second step requires invariance under the U(1) transformation, which leads to the conservation of weak-hypercharge Y . Demanding local gauge invariance leads to the introduction of a weak-hypercharge singlet vector gauge field, B_μ . The gauge fields can be rewritten as follows:

$$W_\mu^\pm(x) = \frac{1}{\sqrt{2}}(W_\mu^1(x) \pm iW_\mu^2(x)) \quad (1.3)$$

$$\begin{pmatrix} B_\mu(x) \\ W_\mu^3(x) \end{pmatrix} = \begin{pmatrix} \cos \theta_W & -\sin \theta_W \\ \sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} A_\mu(x) \\ Z_\mu(x) \end{pmatrix} \quad (1.4)$$

where $A_\mu(x)$ represents the photon field. This is the gauge form of the electromagnetic interaction in QED and is identified with the photon γ . Under a gauge rotation the field transforms as:

$$A_\mu \rightarrow A'_\mu(x) - \frac{1}{g}\partial_\mu\theta(x) \quad (1.5)$$

where g is the coupling constant.

The weak-hypercharge, Y , the third component of weak-isospin, T_3 , and the electric charge, Q , are linearly related by the Gell-Mann Nishijima formula

$$Q = \frac{Y}{2} + T_3.$$

Hence, global and local conservation of weak-isospin and hypercharge naturally implies charge conservation, as required by QED. Since the U(1) symmetry is not violated, the photon still does not interact with itself, as in QED. Since U(1) is

Abelian, none of the gauge bosons carry weak-hypercharge. In contrast $SU(2)$ is non-Abelian, this means the weak vector boson fields $W^\pm$ and Z do carry weak-isospin and, therefore, electric charge. The $W_\mu^\pm$ and Z_μ fields are identified as the $W^\pm$ and Z^0 bosons. This $SU(2)_L \times U(1)$ theory with massless gauge bosons does not reflect the breaking of the symmetry between electromagnetism and the weak force and that the W and Z weak gauge bosons have mass. In 1983 CERN's SPS provided unambiguous signals of W particles [9] during a series of experiments conducted by Carlo Rubbia on the machine designed by Simon van der Meer. UA1 and UA2 found the Z a few months later [10]. The observation of these vector bosons provided an important test of the Standard Model and Rubbia and van der Meer were awarded the 1984 Nobel Prize in physics.

The weak mixing angle θ_W (Weinberg angle) ($e = g \sin \theta_W = g' \cos \theta_W$) determines the mixing between the third component of weak-isospin and weak-hypercharge (or equivalently, the mixing of the weak and electromagnetic interactions). Since the $W^\pm$ and Z^0 bosons carry weak-isospin, they interact directly. Measurements of these gauge couplings and the Weinberg angle θ_W are an essential test of the Standard Model.

For example $\sin^2 \theta_W$ is determined from the W and Z mass, other Z pole observables, and neutral current processes. The value of $\sin^2 \theta_W$ depends on the renormalization prescription. The measured value, from many different processes at the m_Z pole, is $\sin^2 \theta_W = 0.23120 \pm 0.00015$ [4].

The electroweak force is usually described as $SU(2)_L \times U(1)_Y$. The subscript L indicates that only the lefthanded components of the fermion fields interact via weak-isospin (and conversely, the righthanded antifermion fields). The weak-hypercharge interaction does not distinguish between the fermion chirality (handedness). Consequently, the fermions appear as lefthanded doublets and righthanded singlets (scalars) for the electroweak interaction. Table 1.2 summarizes the fermion and boson states in the electroweak theory together with their quantum numbers: Y , $\mathbf{T}$, and T_3 .

Table 1.2
Fermion and boson states in the electroweak theory with their quantum numbers.

Particle Type	Fields	$\mathbf{T}$	T_3	$\mathbf{Y}$
Leptons	$l_L = \begin{pmatrix} \nu_L^e \\ e_L \end{pmatrix}$	$\frac{1}{2}$	$\frac{1}{2}$	-1
	e_R	0	0	-2
Quarks	$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{3}$
	u_R	0	0	$\frac{4}{3}$
	d_R	0	0	$-\frac{2}{3}$

In the Standard Model both quarks and leptons are assigned to be left-handed doublets and right-handed singlets. The quark mass eigenstates are not the same as the weak eigenstates, the matrix relating these bases is a 3×3 unitary transformation matrix V_{ij} operating on the down-type quarks, known as the Cabibbo-Kobayashi-Maskawa (CKM) matrix V_{CKM} [11]. It determines the superposition of the strong flavor eigenstates to form the weak-isospin eigenstates. Leptons, in contrast to quarks, were long believed not to change flavor (i.e. generation) in the weak interaction, but the observation of neutrino oscillations proved the opposite.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad (1.6)$$

Only the down-type quarks (d, s, b) are mixed in the theory; the up-type quark weak and strong eigenstates are assumed to be identical by a choice of phase.

The complex matrix elements V_{ij} are not observables. Because the V_{CKM} is unitary it can be described in terms of four observables parameters. Wolfenstein [12]

suggested a rather convenient approximate parameterization of the CKM matrix given by:

- $|V_{us}| = \lambda$
- $|V_{cb}| = A \cdot \lambda^2$
- $|V_{ub}| \cdot \cos \gamma = A \cdot \lambda^3 \cdot \rho$
- $|V_{ub}| \cdot \sin \gamma = A \cdot \lambda^3 \cdot \eta$

In the Wolfenstein convention the V_{CKM} matrix reduces to:

$$V_{CKM} \simeq \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4) \quad (1.7)$$

Taking the first and the third column of V_{CKM} , together with the unitarity ($VV^\dagger = 1$) implies:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad (1.8)$$

The three terms in the sum trace out a triangle on a complex plane. It is called the unitary triangle because it is the consequence of the unitary property of V_{CKM} . The angles of the triangle are given by:

$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right), \gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \quad (1.9)$$

The unitary triangle is shown in Figure 1.1

The particle-antiparticle interchange symmetry C and the space inversion P (parity) hold for strong and electromagnetic interactions. Since weak-isospin couples only to left-handed particles, it violates C and P symmetries maximally. Right-handed fermions (and left-handed antifermions) have zero weak-isospin. Due to the vector - axial vector (V-A) structure of the weak interaction, CP is almost conserved. CP violation has been observed in the decay of K^0 and $\bar{K}^0$ mesons and for B^0 decays. All CP violation seen so far in the kaon system can be explained as phases in the

Figure 1.1. Unitary triangle

mass matrix. Precise Measurements of CP asymmetries in the B system (where the asymmetries are predicted to be large) will allow the unitarity triangle to be overconstrained, determining if CP violation comes only from the V_{CKM} matrix.

1.5.3 Quantum Chromodynamics

Quantum Chromodynamics (QCD) was developed in 1973 [13] to describe the behavior of quarks as being held together by the strong force carried by gluons. QCD is described by the SU(3) symmetry group, leading to eight conserved quantities. There are three primary color charges (each representing one degree of freedom) which come in color-anticolor pairs. The gauge bosons of the theory are called gluons and results from imposing local gauge invariance. Gluons are neutral massless vector bosons that form an SU(3) color octet, meaning that they carry one color and one

anti-color charge, and are subject to the color force themselves. These eight massless gluons g_i , are the mediators of the strong interaction. Color symmetry is an exact symmetry, meaning that the interaction is independent of the color of the quarks (a green quark scattering off a red quark is the same as a red quark scattering off a blue quark). The available color configurations for quarks and gluons are given below:

- quarks: R, B, G
- antiquarks: $\bar{R}, \bar{B}, \bar{G}$
- gluons g_i with $i \in \{\bar{R}B, \bar{R}G, \bar{B}R, \bar{G}R, \bar{B}G, \bar{G}B, \frac{1}{\sqrt{2}}(\bar{R}R - \bar{B}B), \frac{1}{\sqrt{6}}(\bar{R}R + \bar{B}B - 2\bar{G}G)\}$,

With G, R, B being the colors green, red, and blue respectively. $\bar{G}$ corresponds to anti-green, etc. Gluons interact with each other directly and with the same coupling constant, but different color factors. Since QCD is a non-Abelian theory, the force carriers interact with each other, resulting in the very different behavior of the strong interaction compared to the electromagnetic interaction. Due to the gluon-gluon interaction, the strong force increases with distance. As two quarks move apart from each other, gluons exchanged between the two quarks interact with each other as well as with the quarks. The increasing force either binds the quarks together, or the color string breaks when the energy density of the color field between the quarks is great enough to create a quark-antiquark pair, resulting in two separate hadrons. This results in quark confinement. Quarks appear only in bound states forming colorless SU(3) singlets, and not as free particles, with exception of the top quark, which decays before it hadronizes. The confinement radius is approximately 1 fm. The lowest energy color singlet configurations of quarks are mesons consisting of quark-antiquark pairs ($q\bar{q}$), or baryons (quark triplet (qqq)). The lowest mass mesons are the pions (e.g. $\pi^+ = u\bar{d}$). The lowest mass baryon is the proton ($p = uud$), which is the only stable free hadron in the Standard Model. It's lifetime is experimentally measured to be on the time scale of $> 10^{31}$ years [4]. All other free hadrons eventually decay through a cascade of particles into the lightest leptons (the electron and neutrinos), photons and protons.

We assume a high energy $p\bar{p}$ collision. In such a collision free quarks, or gluons can be produced, also referred to as partons (the constituents of hadrons). Such a parton produced in a high-momentum transfer interaction will hadronize into a jet of colorless hadrons traveling roughly collinearly with each other and with the original direction of the outgoing parton. Thus, information about the outgoing partons from the high- q^2 interaction is largely preserved in the corresponding jet. Quarks in the proton, that are not actively involved in the collision are called spectators. They also condense into colorless objects. The amplitude of a strong interaction process at a given momentum scale, q^2 , can be parameterized in terms of the running coupling constant $\alpha_s(q)$. A conventional definition of α_s is given by [4]:

$$\alpha_s(q) = \frac{4\pi}{(11 - \frac{2}{3}n_f) \ln(q^2/\Lambda^2)} \left[1 - 2 \frac{(51 - \frac{19}{3}n_f) \ln(\ln(q^2/\Lambda^2))}{(11 - \frac{2}{3}n_f)^2 \ln(q^2/\Lambda^2)} \right] + \text{higher order terms} \quad (1.10)$$

where n_f is the number of quarks with mass less than the energy scale q . The dimensional parameter, Λ , is the QCD scale parameter and the only adjustable parameter in QCD, apart from the quark masses. The scale parameter is determined by comparing QCD predictions to experimental data and is also dependent on the momentum scale of the interaction. For most processes, the measured value of Λ_{QCD} is consistent with $\sim 200 \text{ MeV}/c$. Eqn. (1.10) shows a $1/\ln(q^2/\Lambda^2)$ behavior. Hence, for large q^2 (at small distances) the coupling becomes vanishingly small. This phenomenon is called asymptotic freedom. At high energy, where $\alpha_s \rightarrow 0$, quarks behave as if they were free particles. This allows for high- q^2 processes to be described very well by perturbative calculations in expansions of the coupling constant α_s . At the scale of the mass of the heaviest vector boson (Z^0), $\alpha_s(m_Z) \simeq 0.12$. However, for low- q^2 interactions ($\leq 300 \text{ MeV}^2/c^2$), the coupling approaches unity. Perturbative calculations tend to break down in this region and we therefore rely mostly on phenomenological models.

In a typical proton-antiproton collision, only one parton from each hadron is involved in the hard scattering process. Asymptotic freedom makes it possible to calculate this collision process to first-order as the interaction between a single parton

in each of the colliding hadrons. The remaining spectator partons only interact with the struck partons during hadronization. The hadronization process occurs at a much lower energy scale, and is therefore non-perturbative, but it occurs well after the high- q^2 interaction. The particles from the remnant hadronization form what is usually referred to as the underlying event. In a proton-antiproton collision besides the hard 2-to-2 parton scattering processes, the resulting event originates from the two outgoing partons (plus final state radiation(FSR)) and particles that come from the breakup of the hadrons in the collision (the beam-beam remnants). The “underlying event” consists of the beam-beam remnants plus initial-state radiation (ISR). The structure of the underlying event is similar to that of the soft inelastic $p\bar{p}$ collisions, usually called minimum bias events.

1.6 Higgs Mechanism

Despite the phenomenal success and the predictive powers of the Standard Model, we do not have yet, experimental evidence for some portion of it. One aspect of the Standard Model formalism is the unification of the electromagnetic and weak interactions through the exploitation of a local gauge symmetry. Nevertheless, this part of the theory requires the $W^\pm$ and Z^0 to be massless, which contradicts observation.

The spontaneous breaking of the EWK gauge symmetry is realized through the Higgs mechanism [14]. It is through this mechanism, that the fundamental massive fermions and bosons acquire their mass, which is implemented through the introduction of a scalar doublet self-interacting field.

We introduce the Higgs field ϕ as

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad (1.11)$$

One member of the doublet, ϕ^0 , acquires a nonzero vacuum expectation value (vev) to break $SU(2)_L \times U(1)_Y$ down to $U(1)_{em}$. The coupling to the gauge field is given by:

$$(D_\mu \phi)^\dagger (D^\mu \phi) \quad (1.12)$$

The gauge fields interact with the matter fields ψ_R, ψ_L through the covariant derivative

$$D_\mu = \partial_\mu + ig\mathbf{W}_\mu\mathbf{T} + ig'B_\mu Y \quad (1.13)$$

which is dictated by the gauge principle. In Eqn. (1.13) g is the coupling constant for the weak interaction that arises from the construction of the gauge theory. $\mathbf{W}$ is given in the vector notation $\mathbf{W} = (W^1, W^2, W^3)$. $\mathbf{T}$ are the three operators of SU(2) $\mathbf{T}_i = \frac{\sigma_i}{2}$. For $Y = \frac{1}{2}$ one finds:

$$D_\mu = \partial_\mu + ig\frac{\sigma}{2}\mathbf{W}_\mu + i\frac{g'}{2}B_\mu \quad (1.14)$$

Assuming a self-interaction of the scalar field (Higgs potential) described by:

$$V(\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 \quad (1.15)$$

with $\mu^2 > 0$. The potential is minimal at $\phi^\dagger\phi = \frac{\mu^2}{2\lambda}$ (for $\frac{\partial V}{\partial\phi} = 0$). The vacuum expectation value of the Higgs is given by

$$\langle \phi \rangle = e^{i\frac{\zeta(x)\sigma}{2v}} \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \quad (1.16)$$

where $v = \sqrt{\frac{\mu^2}{\lambda}}$. One can now redefine the Higgs field ϕ in Eqn. (1.11). Using three real functions $\zeta(x)$, which are the massless Nambu-Goldstone bosons associated with broken SU(2) and one massive scalar field H ($\frac{\partial^2 V}{\partial H^2} = 2\mu^2 = m^2$)

$$\phi = e^{i\frac{\zeta(x)\sigma}{2v}} \begin{pmatrix} 0 \\ \frac{v+H(x)}{\sqrt{2}} \end{pmatrix} \quad (1.17)$$

under gauge transformation by choosing $\Lambda = \frac{\zeta(x)}{2v}$ one can eliminate the field $\zeta(x)$ in such a way that one obtains:

$$\phi \rightarrow U[\Lambda(x)]\phi = \begin{pmatrix} 0 \\ \frac{v+H(x)}{\sqrt{2}} \end{pmatrix} \quad (1.18)$$

Hence, after this gauge transformation² one obtains:

$$\phi^+ = 0 \quad (1.19)$$

$$\phi^0 = \frac{v+H(x)}{\sqrt{2}} \quad (1.20)$$

---

²this is called the unitary gauge

Now inserting ϕ into Eqn. (1.13) one obtains:

$$\begin{aligned}
(D_\mu \phi)^\dagger (D^\mu \phi) &= \left| (\partial_\mu + i g \frac{\sigma}{2} \mathbf{W}_\mu + i \frac{g'}{2} B_\mu) \left(\frac{v + H(x)}{\sqrt{2}} \right) \right|^2 \\
&= \frac{1}{2} (\partial_\mu H(x))^2 \\
&\quad + \frac{1}{8} \left[g^2 (W_\mu^1 W^{1\mu} + W_\mu^2 W^{2\mu}) + (-g W_\mu^3 + g' B_\mu) (-g W^{3\mu} + g' B^\mu) \right] v^2 \\
&\quad + \dots
\end{aligned} \tag{1.21}$$

After rewriting W^1, W^2 as $W^\pm = \frac{W^1 \mp i W^2}{\sqrt{2}}$, and expressing W^3 and B through Z and A (using Eqn. (1.4)) one obtains:

$$(D_\mu \phi)^\dagger (D^\mu \phi) = \frac{1}{2} (\partial_\mu H(x))^2 + \left(\frac{g^2}{4} W_\mu^+ W^{-\mu} + \frac{g^2 + g'^2}{8} Z_\mu Z^\mu \right) v^2 + \dots \tag{1.22}$$

This shows that the W_μ and Z^μ fields acquire masses of

$$\begin{aligned}
m_H^2 &= 2\lambda v^2 \\
m_W^{\pm 2} &= \frac{g^2 v^2}{4} \\
m_Z^2 &= \frac{g^2 + g'^2}{4} v^2 \\
m_\gamma^2 &= 0
\end{aligned} \tag{1.23}$$

through the Weinberg angle correlation $\tan \theta_W = \frac{g'}{g}$ one gets $m_Z^2 = \frac{m_W^2}{\cos^2 \theta_W}$.

By introducing the Higgs field, we were able to generate masses for the gauge bosons. It is through Yukawa-type interactions of the Higgs doublet with the fundamental fermion fields, that the nonzero vacuum expectation value causes nonzero mass terms in the final Lagrangian for the Standard Model for fundamental fermions. The mass of the electron is given by $m_e = \frac{g_e v}{\sqrt{2}}$, where g_e is the electron Yukawa coupling, a measure of the strength of the interaction between the Higgs and the electron. From the measured $W^\pm$ mass, one finds $v = (G_F \sqrt{2})^{-1/2} \simeq 246 \text{ GeV}$. Similar mass relations exist for all the fundamental fermions and the Z boson. The photon remains massless, consistent with experiment. One consequence of the Higgs mechanism is the introduction of a new neutral, scalar particle, the Higgs boson H^0 . This massive boson arises from the nonzero vev acquired by a member of the scalar doublet introduced to break electroweak symmetry. The mass of the Higgs itself is

not predicted from the theory since it depends on the unknown Higgs self-coupling λ : $m_{H^0} = \sqrt{2\lambda v^2}$. The triumph of the Higgs mechanism is the prediction of the mass ratio of the W and Z weak bosons.

1.7 Unanswered Questions

The Standard Model has been highly successful, it makes many predications most of which have been tested to very high precision, among others the branching ratios of the Z decays (into various quarks and leptons) measured at LEP and the Tevatron [4]. The Standard Model does not predict the values of the coupling constants nor the masses of the quarks and leptons.

We list other unanswered questions and shortcomings of the Standard Model:

- Why are there 3 generations/dimensions/colors ?
- What is the relation between the strong and electroweak forces ?
- Why are the electric charge of the proton and the electron exactly opposite ?
What is the relation between quarks and leptons ?
- How can gravity be accommodated in the theory ?
- What is the origin of CP violation ?
- How do we understand neutrino oscillations and massive neutrinos ?

2. Beyond the Standard Model

2.1 Problems of the Standard Model

Despite the experimental success of the Standard Model as a theory describing the strong and electroweak interactions of elementary particles, this model is not theoretically satisfactory for various reasons. There are several sources of theoretical discontent. The so called hierarchy problem is due to the large difference between the scale of the electroweak and gravitational interactions [15, 16]. The latter is the Planck scale $m_P = (8\pi G_{\text{Newton}})^{-1/2} = 2.4 \times 10^{18} \text{ GeV}/c^2$ where quantum gravitational effects become important. Compared to the electroweak scale which is approximately equal to the mass of the W and Z Boson, the Planck mass is 16 orders of magnitude larger. A scalar field ϕ can have a bare mass term $m^2\phi$. The mass term is not stable against quantum corrections. The renormalization of m^2 is quadratically divergent in the Standard Model, so that if the Standard Model is somehow cut off at a mass scale M , the one-loop renormalization is of order αM^2 and it would be unnatural for $m^2 \ll \alpha M^2$. In a model with spontaneous electroweak symmetry breaking, the problem affects not only the Higgs mass, but also its expectation value. Hence, it affects the masses of other particles that get their masses from gauge symmetry breaking such as the W , Z , quarks, and charged leptons. It is unnatural to have $m_W \simeq 80 \text{ GeV}/c^2$ or $m_Z \simeq 90 \text{ GeV}/c^2$, and the Higgs below $200 \text{ GeV}/c^2$, unless the Standard Model is somehow cut off and embedded in a richer structure that tames the ultraviolet divergence in the Higgs boson mass at an energy no bigger than about $1 \text{ TeV}/c^2$.

The Standard Model is also inconsistent with the definitive evidence of neutrino oscillations from the Super-Kamiokande (SuperK) experiment [17] and the Sudbury Neutrino Observatory [18], indicating massive neutrinos.

In addition the large number of free parameters associated with the Standard Model such as three gauge couplings strength (α_s , g , g'), nine Yukawa couplings, that give matter fields masses, four parameters associated with the CKM matrix, and at least another two parameters associated with the Higgs-sector (m_H , and v the vacuum expectation value of the Higgs potential) might also indicates that it is not the ultimate theory.

2.2 Physics Beyond the Standard Model and Higgs

The one part of the Standard Model about which there is no clear experimental information available is the mechanism of electroweak symmetry breaking. The simplest possibility is the Higgs mechanism. Despite some very small discrepancies, the Standard Model is in very good agreement with experimental data and until the direct observation, these precision electroweak measurements are the only key to the Higgs mass. The measurements suggests that the Higgs mass is less than $190 \text{ GeV}/c^2$ as summarized by the Particle Data Group [4] (see Figure 2.1), and LEP Electroweak Working Group [19, 20] (see Figure 2.2).

The Standard Model predicts that there is only one Higgs boson. Other models aim also at explaining the electroweak symmetry breaking and some predict new physics in addition:

- *Higgsless* models based on dynamical symmetry breaking [21].
- *Large extra dimensions* and models with branes, plus possible strong dynamics [22–25].
- *Little Higgs* [26, 27] models explain the lightness of the Higgs because it is a pseudo-Goldstone Boson.
- *Supersymmetry* [28–30]

Figure 2.1. One-standard-deviation in the mass of the W Boson m_W as function of the top quark mass m_t is shown for direct and indirect data, and the 90% CL region allowed by all data. The black lines indicate the predictions for different SM Higgs masses, with the width of the band reflecting the uncertainty in $\alpha_s(m_Z)$.

New models are heavily constrained by the precision measurements that have contributed to the success of the Standard Model. The following section will focus on the explaining the virtues and drawbacks of one of those approaches: Supersymmetry.

2.3 Supersymmetry

Supersymmetry (SUSY) is an extension of the Standard Model that would provide one possible solution of the hierarchy problem. It assigns to each Standard Model particle a supersymmetric partner by introducing a supersymmetry transfor-

Figure 2.2. χ^2 of the SM global fit as a function of the Higgs mass for three different estimates of the hadronic contribution to the effective value of $\alpha_{em}(m_Z)$. The shaded band covers other theoretical uncertainties.

mation that turns a bosonic state into a fermionic state, and vice versa. The operator Q which generates this transformations must be an anticommuting spinor, with

$$\begin{aligned} Q|\text{Boson} \rangle &= |\text{Fermion} \rangle \\ Q|\text{Fermion} \rangle &= |\text{Boson} \rangle \end{aligned} \quad (2.1)$$

Since spinors are intrinsically complex objects, $Q^\dagger$ (the hermitian conjugate of Q) is also a symmetry generator. Supersymmetry is the maximum possible extension of the Lorentz group. $Q, Q^\dagger$, are fermionic generators, they satisfy the following relations:

$$\{Q, Q^\dagger\} = P^\mu \quad (2.2)$$

$$\{Q^\dagger, Q^\dagger\} = \{Q, Q\} = 0 \quad (2.3)$$

$$[Q, P^\mu] = [Q^\dagger, P^\mu] = 0 \quad (2.4)$$

where P^μ is the momentum operator of spacetime translations. Each chiral fermion $f_{L,R}$ has a scalar partner $\tilde{f}_{L,R}$. For each massless gauge boson A_μ , with the helicity states ± 1 , there is a massless spin 1/2 gaugino partner, with the helicity states $\pm \frac{1}{2}$. In the Minimal Supersymmetric extension of the Standard Model (MSSM) there must be two complex Higgs doublets and associated Higgsinos, to avoid triangle gauge anomalies [31]. The condition for cancellation of gauge anomalies is given by:

$$Tr[Y^3] = Tr[T_3^2 Y] = 0 \quad (2.5)$$

which is always vanishes in the Standard Model. Since the fermionic partner of a Higgs chiral supermultiplet must be a weak isodoublet with weak hypercharge $|Y| = 1/2$, it would break the anomaly cancellation. If a second Higgs supermultiplet is introduced with $Y = \pm 1/2$, then the total contribution to the anomaly traces from the two fermionic members of the Higgs chiral multiplets vanishes. Table 2.1 shows the chiral supermultiplets in the MSSM, and Table 2.2 the vector supermultiplets.

After symmetry breaking, superpartners within each of these groups may mix, if they share the same quantum numbers. The gluino is the spin 1/2 partner of the gluon. Since the gluon is the only colored gauge boson the gluino does not mix with any of the other gauginos. The gluino field must have 16 degrees of freedom (DF) like the gluon (8 color DF and 2 spin DF for massless gluons).

The gluino is a massive Majorana fermion (there is no distinct antigluon), thus having 8 color times 2 spin degrees of freedom, meeting the required 16 degrees of freedom. The winos and bino mix with the Higgsinos to give four neutralinos $\tilde{\chi}_i^0$ and two charginos $\tilde{\chi}_i^\pm$.

The Minimal SUSY model essentially doubles the spectrum of the Standard Model. SUSY also complicates some successes of the Standard Model. One triumph of the Standard Model is how it naturally conserves baryon and lepton number, because there are no renormalizable (perturbative) couplings of Standard Model fields

Table 2.1
Chiral supermultiplets in the MSSM.

Name	Spin 0	Spin $\frac{1}{2}$	$SU(3)_C \times SU(2)_L \times U(1)_Y$
Squarks, quarks ($\times 3$ generations)	$\tilde{Q} = (\tilde{u}_L, \tilde{u}_R)$	$Q = (u_L, u_R)$	$(3, 2, \frac{1}{6})$
	$\tilde{u}_R^*$	$u_R^\dagger$	$(\bar{3}, 2, -\frac{2}{3})$
	$\tilde{d}_R^*$	$d_R^\dagger$	$(\bar{3}, 2, \frac{1}{3})$
Sleptons, leptons ($\times 3$ generations)	$\tilde{L} = (\tilde{\nu}, \tilde{e}_L)$	$L = (\nu, e_L)$	$(1, 2, -\frac{1}{2})$
	$\tilde{e}_R$	e_R	$(1, 1, 1)$
Higgs, Higgsinos	$H_u = (H_u^+, H_u^0)$	$\tilde{H}_u = (\tilde{H}_u^+, \tilde{H}_u^0)$	$(1, 2, \frac{1}{2})$
	$H_d = (H_d^0, H_d^-)$	$\tilde{H}_d = (\tilde{H}_d^0, \tilde{H}_d^-)$	$(1, 2, -\frac{1}{2})$

Table 2.2
Vector supermultiplets in the MSSM.

Name	Spin $\frac{1}{2}$	Spin 1	$SU(3)_C \times SU(2)_L \times U(1)_Y$
Gluino, gluon	$\tilde{g}$	g	$(8, 1, 0)$
Wino's, W's	$\tilde{W}^\pm, \tilde{W}^0$	$W^\pm, W^0$	$(1, 3, 0)$
Bino, B	$\tilde{B}$	B	$(1, 1, 1)$

that violate those symmetries. This is lost with supersymmetry, where renormalizable interactions causing proton decay are possible. The most commonly adopted solution to this problem is to assume a new symmetry called R parity and a corresponding quantum number denoted by R . R is defined as:

$$R = (-1)^{3(B-L)+2S} \quad (2.6)$$

R parity is a discrete, multiplicative symmetry defined by the spin S , baryon number B , and lepton number L of the particle. Hence, for Standard Model particles

$R = 1$, and for SUSY particles $R = -1$. If R parity is conserved, SUSY particles must be produced in pairs and the lightest supersymmetric particle (LSP) is stable [30]. Under rather general assumptions R parity is automatically conserved in many GUT models [32]. Cosmological considerations concerning the presence of matter in the universe after the Big-Bang [33, 34] indicated that the lightest supersymmetric particle (LSP) should be neutral and not strongly interacting. Neutralinos could be a good candidate for the non-baryonic cold matter [35] in the universe.

2.3.1 Virtues of Supersymmetry

It is well established that SUSY has the following virtues:

- SUSY can make a small Higgs mass natural.
- The measured value of $\sin^2\theta_W$ favors SUSY GUTs.
- It is consistent with electroweak tests.
- It favors a heavy top mass.

SUSY is a unique new symmetry that relates bosons to fermions. Relating bosons to fermions also makes it possible to explain the smallness of the Higgs mass, since it can make small fermion masses natural. SUSY is consistent with Grand Unification, and therefore part of its successes. Measurements of $\sin^2\theta_W$, as well as bounds on the proton lifetime, are in agreement with the supersymmetric version of Grand Unification. Grand Unification is the key to understanding quark and lepton quantum numbers. The unification scale m_{GUT} inferred from low energy data is relatively close to the Planck scale, but high enough to be consistent with the proton lifetime. The neutrino mass scale suggested by GUTs is $m_\nu \simeq \frac{m_W^2}{m_{GUT}} \simeq 10^{-2}$ eV , which is consistent with observations. The main motivations for SUSY based on GUTs, are that the measured value of $\sin^2\theta_W$ agrees with Grand Unification only if supersymmetry is included. Without including SUSY, the unification scale and proton lifetime are

predicted to be too small. So the successes of SUSY GUTs encourage the search for supersymmetry, and discovery of supersymmetry would enhance the attractiveness of GUTs. This makes SUSY part of a larger attractive picture in GUTs.

The Superpartners get masses from electroweak breaking and SUSY breaking so it would be natural for them to be slightly above the Z mass, which gets its mass only from electroweak breaking. Assuming the minimal supersymmetric spectrum, one derives at tree level $m_{Higgs} < m_Z \simeq 91 \text{ GeV}/c^2$. Experimentally a Higgs of mass below $114.4 \text{ GeV}/c^2$ is excluded [36]. After a large radiative correction due to the heavy top quark, the theoretical bound on the Higgs mass is found to be $m_{Higgs} < 130 \text{ GeV}/c^2$.

2.4 The Case for a Light Sbottom

The supersymmetric partners (spin-0 boson superpartners) $\tilde{f}_{L,R}$ of the weak eigenstates of the left and right handed quarks and charged leptons, mix to form mass eigenstates $\tilde{f}_1$ and $\tilde{f}_2$. They have different isospins $I = 0, \frac{1}{2}$, but may mix as the electroweak gauge symmetry is broken. For each flavor the mixing can be described by a 2×2 mixing matrix in the basis of $\tilde{f}_{L,R}$, it takes the following general form:

$$M_{\tilde{f}}^2 \equiv \begin{pmatrix} m_{\tilde{f}_{LL}}^2 & m_{\tilde{f}_{LR}}^2 \\ m_{\tilde{f}_{RL}}^2 & m_{\tilde{f}_{RR}}^2 \end{pmatrix} \quad (2.7)$$

The diagonal terms are given by:

$$m_{\tilde{f}_{LL}}^2 = M_2^2 + m_f^2 + m_{\tilde{f}_L}^{D^2} \quad (2.8)$$

$$m_{\tilde{f}_{RR}}^2 = M_1^2 + m_f^2 + m_{\tilde{f}_R}^{D^2} \quad (2.9)$$

where M_2 are the SUSY-breaking parameters (soft supersymmetry-breaking mass) for superpartners of $SU(2)_L$ doublets, and M_1 are parameters for singlets, m_f is the

mass of the corresponding fermion and $m_{\tilde{f}_{L,R}}^{D^2}$ is a contribution due to the quartic D terms in the effective potential:

$$m_{\tilde{f}_L}^{D^2} = m_Z^2 \cos 2\beta (I_3 + \sin^2 \theta_W Q_f) \quad (2.10)$$

$$m_{\tilde{f}_R}^{D^2} = m_Z^2 \cos 2\beta (\sin^2 \theta_W Q_f) \quad (2.11)$$

The off-diagonal mixing term takes the general form

$$m_{\tilde{f}_{L,R}}^2 = m_f (A_f + \mu \kappa) \quad (2.12)$$

where μ is the Higgs mass parameter, A_f the trilinear coupling to the Higgs sector. For down type quarks $\kappa = \tan \beta$ ($f = d, s, b$ and $f = e, \mu, \tau$), while for up type quarks ($f = u, c, t$) $\kappa = \cot \beta$. Since the off-diagonal elements of the mass matrix are proportional to the mass of the corresponding Standard Model partner, $m_f(A_f - \mu \kappa)$, the mixing is likely to be relevant for the fermions of the third family. The mixing in the stop sector is expected to be large because of the large top mass but it may also be important for the $\tilde{b}_{L,R}$ and $\tilde{\tau}_{L,R}$ if $\tan \beta$ is large.

Let us now explain in detail the mixing in the sbottom sector. The mass matrix for the sbottom system [37] in the $(\tilde{q}_L, \tilde{q}_R)$ basis is given by:

$$M_b^2 = \begin{pmatrix} M_2^2 + m_b^2 + m_Z^2 \cos 2\beta (\frac{1}{2} + \frac{1}{3} \sin^2 \theta_W) & m_b(A_b - \mu \tan \beta) \\ m_b(A_b - \mu \tan \beta) & M_1^2 + m_b^2 + \frac{1}{3} m_Z^2 \cos 2\beta \sin^2 \theta_W \end{pmatrix} \quad (2.13)$$

The mass eigenvalues are then given by:

$$m_{\tilde{b}_{1,2}}^2 = \frac{1}{2} (m_{\tilde{b}_L}^2 + m_{\tilde{b}_R}^2) \mp \frac{1}{2} \sqrt{(m_{\tilde{b}_L}^2 - m_{\tilde{b}_R}^2)^2 + 4m_b^2(A_b - \mu \tan \beta)^2} \quad (2.14)$$

with

$$m_{\tilde{b}_L}^2 = M_2^2 + m_b^2 - m_Z^2 \cos 2\beta (\frac{1}{2} - \frac{1}{3} \sin^2 \theta_W) \quad (2.15)$$

and

$$m_{\tilde{b}_R}^2 = M_1^2 + m_b^2 - \frac{1}{3} m_Z^2 \cos 2\beta \sin^2 \theta_W \quad (2.16)$$

The mass eigenstates can be written in term of the mixing angle $\theta_{\tilde{b}}$

$$\begin{pmatrix} \tilde{b}_1 \\ \tilde{b}_2 \end{pmatrix} = \begin{pmatrix} \cos \theta_{\tilde{b}} & \sin \theta_{\tilde{b}} \\ -\sin \theta_{\tilde{b}} & \cos \theta_{\tilde{b}} \end{pmatrix} \quad (2.17)$$

where the $\cos \theta_{\tilde{b}}$ is given by:

$$\cos \theta_{\tilde{b}} = \text{sign}(m_b(A_b - \mu \tan \beta)) \sqrt{\frac{m_b^2(A_b - \mu \tan \beta)^2}{(m_{\tilde{b}_L}^2 - m_{\tilde{b}_1}^2)^2 + m_b^2(A_b - \mu \tan \beta)^2}} \quad (2.18)$$

and

$$\sin \theta_{\tilde{b}} = \sqrt{\frac{(m_{\tilde{b}_L}^2 - m_{\tilde{b}_1}^2)}{(m_{\tilde{b}_L}^2 - m_{\tilde{b}_1}^2)^2 + m_b^2(A_b - \mu \tan \beta)^2}} \quad (2.19)$$

2.5 Sbottom/Stop/Gluino Production at Hadron Colliders

At hadron colliders stop or sbottom production would proceed via the strong interaction, while at lepton colliders electroweakly. The coupling of the stop and sbottom to the Z depends on the mixing angle $\theta_{\tilde{t}}$, and $\theta_{\tilde{b}}$ respectively. Hence, at lepton colliders the production cross section is not only a function of the squark mass, but also of the corresponding mixing angle θ . This coupling and therefore the production cross section is maximal for $\theta_{\tilde{b}} = 0^\circ$.

The production of gluinos and squarks at Hadron colliders is described in greater detail elsewhere [38], we focus here on the production mechanism of gluinos at the Tevatron. The production mechanisms for gluino pair production are given in Figure 2.3 and for sbottom pair production in Figure 2.4. At the Tevatron center-of-mass energy gluinos are produced through gluon-gluon-fusion and quark-antiquark annihilation. We used PROSPINO [39] to calculate the gluino pair production cross section at the Tevatron at LO (using CTEQ5L [40]) and NLO (using CTEQ5M [40]). Table 2.3 lists the gluino pair production cross section as a function of the gluino mass. The gluino pair production cross section (see Figure 2.5) at the Tevatron center-of-mass energy is large, and approximately one order of magnitude higher

than the direct sbottom production. The sbottom pair production mechanism is shown in Figure 2.6.

Figure 2.3. Main LO gluino pair production mechanisms at the Tevatron center of mass energies. Note that the t-channel diagram on the right results in a dependence of the production cross section on the squark mass.

Figure 2.4. Direct sbottom pair production at the Tevatron center of mass energies. The same Feynman diagram also apply to the stop quark production

The most relevant parameter that affects the value of the gluino cross section is the squark-mass (see Table 2.4). The dependence comes in through the gluino production via t-channel exchange of a virtual squark (see right diagram in Figure 2.3). The production cross section dominantly depends on the first generation squarks, since the virtual squark couples to the corresponding Standard Model quarks (antiquarks) in the proton (antiproton), which are dominated by their large light quark content. The squark masses of the first two generations and the stop was as-

Figure 2.5. NLO gluino pair production cross section at $\sqrt{s} = 1.96$ TeV computed with PROSPINO for different renormalization scales.

Figure 2.6. NLO direct sbottom pair production cross section at $\sqrt{s} = 1.96$ TeV computed with PROSPINO for different renormalization scales.

sumed to be degenerate and equal to the squark mass $m_{\tilde{q}} = 500$ GeV/ c^2 . For larger squark masses the gluino pair production would be higher as seen in Table 2.4.

Table 2.3: Gluino production cross section as a function of the gluino mass computed with PROSPINO at LO (using CTEQ5L) and NLO (using CTEQ5M).

$m_{\tilde{q}}$ GeV/ c^2	$m_{\tilde{g}}$ GeV/ c^2	Scale	σ_{LO} pb	σ_{NLO} pb
500	155.	1.0	$27.16 \pm .0016$	$49.32 \pm .0021$
500	160.	1.0	$22.12 \pm .0015$	$39.99 \pm .0021$
500	165.	1.0	$18.06 \pm .0016$	$32.50 \pm .0021$
500	170.	1.0	$14.87 \pm .0016$	$26.61 \pm .0019$
500	175.	1.0	$12.27 \pm .0015$	$21.85 \pm .0020$
Continued on next page				

Table 2.3 – continued from previous page

$m_{\tilde{q}}$ GeV/ c^2	$m_{\tilde{g}}$ GeV/ c^2	Scale	σ_{LO} pb	σ_{NLO} pb
500	180.	1.0	$10.12 \pm .0016$	$18.01 \pm .0023$
500	185.	1.0	$8.399 \pm .0016$	$14.83 \pm .0020$
500	190.	1.0	$6.988 \pm .0016$	$12.30 \pm .0020$
500	195.	1.0	$5.804 \pm .0015$	$10.15 \pm .0023$
500	200.	1.0	$4.853 \pm .0015$	$8.491 \pm .0020$
500	205.	1.0	$4.045 \pm .0016$	$7.052 \pm .0020$
500	210.	1.0	$3.384 \pm .0015$	$5.859 \pm .0020$
500	215.	1.0	$2.830 \pm .0015$	$4.917 \pm .0020$
500	220.	1.0	$2.374 \pm .0015$	$4.101 \pm .0019$
500	225.	1.0	$1.996 \pm .0015$	$3.447 \pm .0020$
500	230.	1.0	$1.672 \pm .0015$	$2.885 \pm .0019$
500	235.	1.0	$1.412 \pm .0015$	$2.416 \pm .0020$
500	240.	1.0	$1.190 \pm .0016$	$2.040 \pm .0020$
500	245.	1.0	$1.001 \pm .0015$	$1.706 \pm .0019$
500	250.	1.0	$0.8439 \pm .0015$	$1.441 \pm .0022$
500	255.	1.0	$0.7105 \pm .0015$	$1.209 \pm .0020$
500	260.	1.0	$0.6004 \pm .0015$	$1.018 \pm .0019$
500	265.	1.0	$0.5055 \pm .0016$	$0.8594 \pm .0021$
500	270.	1.0	$0.4257 \pm .0016$	$0.7232 \pm .0020$
500	275.	1.0	$0.3599 \pm .0015$	$0.6099 \pm .0019$
500	285.	1.0	$0.3030 \pm .0016$	$0.4335 \pm .0019$
500	290.	1.0	$0.2552 \pm .0016$	$0.3658 \pm .0019$
500	295.	1.0	$0.2162 \pm .0015$	$0.3084 \pm .0019$
500	300.	1.0	$0.1825 \pm .0015$	$0.2596 \pm .0019$
500	305.	1.0	$0.1534 \pm .0016$	$0.2189 \pm .0019$
Continued on next page				

Table 2.3 – continued from previous page

$m_{\tilde{q}}$ GeV/ c^2	$m_{\tilde{g}}$ GeV/ c^2	Scale	σ_{LO} pb	σ_{NLO} pb
500	310.	1.0	$0.1296 \pm .0015$	$0.1842 \pm .0019$
500	315.	1.0	$0.1093 \pm .0015$	$0.1553 \pm .0019$
500	320.	1.0	$0.0921 \pm .0015$	$0.1307 \pm .0019$
500	325.	1.0	$0.0777 \pm .0016$	$0.1100 \pm .0019$
500	330.	1.0	$0.0654 \pm .0016$	$0.0924 \pm .0020$
500	335.	1.0	$0.0550 \pm .0015$	$0.0776 \pm .0020$
500	340.	1.0	$0.0463 \pm .0015$	$0.0656 \pm .0018$
500	345.	1.0	$0.0390 \pm .0016$	$0.0547 \pm .0019$
500	350.	1.0	$0.0327 \pm .0016$	$0.0460 \pm .0018$

2.6 SUSY Signatures

SUSY signatures are determined by the nature of the lightest supersymmetric particle (LSP) and whether R parity is conserved or not. Conservation of R parity implies that all SUSY particles are pair produced and that all decay chains end up in the LSP, which is stable and leaves the detector. If the LSP is charge- and color-neutral, then the typical SUSY signature is missing transverse energy. The lightest neutralino is a typical candidate, that is predicted in gauge-mediated or super gravity models to be the LSP. The neutrino is a typical candidate for cold dark matter [35].

2.6.1 Gluino Decays

The decay of the gluino can only proceed through an on-shell or a virtual squark. Two body-decays $\tilde{g} \rightarrow q\tilde{q}$ will dominate, if they are allowed, because the relevant gluino-quark-squark coupling is of QCD strength. Figure 2.7 shows the coupling of

Table 2.4

Gluino pair production cross section as a function of squark mass and scale computed with PROSPINO at LO (using CTEQ5L) and NLO (using CTEQ5M).

$m_{\tilde{q}}$ GeV/ c^2	$m_{\tilde{g}}$ GeV/ c^2	Scale	σ_{LO} pb	σ_{NLO} pb
500	300	0.5	0.222	0.325
1000	300	0.5	0.606	0.735
2000	300	0.5	0.846	0.964
500	300	1.0	0.153	0.260
1000	300	1.0	0.423	0.608
2000	300	1.0	0.589	0.806
500	300	2.0	0.110	0.205
1000	300	2.0	0.305	0.494
2000	300	2.0	0.426	0.662

the gluino to squarks and quarks. Since the top and bottom squarks could be lighter than all of the other squarks, it is quite possible that $\tilde{g} \rightarrow t\tilde{t}_1$ and/or $\tilde{g} \rightarrow b\tilde{b}_1$ are the only available two-body decay mode(s) for the gluino, in which case they will dominate over all others. If the gluino is lighter than all the squarks, then it will decay only through off-shell squarks [41, 42], so $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_i^0$ and $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_i^\pm$. In this scenario we expect many different final states, which can lead to many competing gluino decay chains. These cascade decays can have final-state branching fractions that are individually small and therefore could be quite sensitive to the parameters of the model.

Figure 2.7. Gluino-quark-squark coupling.

2.6.2 Squark Decays

If the decay $\tilde{q} \rightarrow q\tilde{g}$ is kinematically allowed, it will always dominate, because the quark-squark-gluino vertex (see Figure 2.7) is of QCD strength. Otherwise, the squarks can decay into a quark plus neutralino or chargino: $\tilde{q} \rightarrow q\tilde{\chi}_i^0$ or $\tilde{q} \rightarrow q\tilde{\chi}_j^\pm$. The direct decay to the LSP $\tilde{q} \rightarrow q\tilde{\chi}_1^0$ is always kinematically favored, and for right-handed squarks it can dominate because $\tilde{\chi}_1^0$ is mostly bino.

2.6.3 Sbottom Quarks from Gluino Decay

At hadron colliders, strongly interacting particles have the largest production cross section, and therefore scalar quarks and gluinos will be by far the most copiously produced particles. Calculations show that even if the gluino is more than $100 \text{ GeV}/c^2$ heavier than the lightest sbottom the cross section of $\tilde{g}\tilde{g}$ and $\tilde{b}_1\tilde{b}_1$ is similar at the Tevatron. The gluino pair production is an order of magnitude higher than the direct sbottom production cross section for the same particle masses.

Gluinos can only decay through on-shell or virtual squarks [29]. Since we assume that the gluino is heavier than the sbottom, the gluino decay to bottom-sbottom dominates over any other channel. The only exception is the decay $\tilde{g} \rightarrow t\tilde{t}_1$. Due to the large top mass and the stop exclusion limit (about $96 \text{ GeV}/c^2$ for stop [4] with

$\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} > 10 \text{ GeV}/c^2$, for most of the parameter space covered in this search, the decay of gluino into stop-top is kinematically not allowed. In this analysis we assume $\text{BR}(\tilde{g} \rightarrow b\tilde{b}_1 = 100\%)$. The lighter sbottom $\tilde{b}_1$ will sequentially decay through one of the relevant decays:

- $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$
- $\tilde{b}_1 \rightarrow b\tilde{\chi}_2^0$
- $\tilde{b}_1 \rightarrow b\tilde{\chi}_3^0$
- $\tilde{b}_1 \rightarrow b\tilde{\chi}_4^0$
- $\tilde{b}_1 \rightarrow t\tilde{\chi}_1^\pm$

Calculations of the decay rate of the sbottom have been performed [37]. The branching ratios as a function of the higgsino mass parameter μ for $m_{\tilde{q}} = 330 \text{ GeV}/c^2$, $A_{\tilde{t}} = A_{\tilde{b}} = 300 \text{ GeV}/c^2$, and $\tan\beta = 20$ is given in Figure 2.8. It can be seen that the favored decay channel is $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$, for most values of μ .

Some of the decays might be kinematically forbidden (for example, the decay $\tilde{b}_1 \rightarrow t\tilde{\chi}_1^\pm$ is kinematically forbidden in our region of parameter space, due to the large top mass and the limits on the chargino (currently at about $94 \text{ GeV}/c^2$, for details refer to [4])), and therefore the branching ratio $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ might even be larger. For this analysis we assume $\text{BR}(\tilde{g} \rightarrow b\tilde{b}_1 = 100\%)$. Figure 2.9 shows a schematic view of the process searched for in this analysis.

In summary the production of gluino pairs is followed by the decay into sbottom-bottom, and the sequential decay of the sbottom into bottom-neutralino, which leads to a signature of four b-jets and missing transverse energy from the neutralinos escaping detection.

Figure 2.8. Branching ratios [37] for sbottom decays as a function of the higgsino mass parameter μ .

2.6.4 Other BSM Searches with the same Final State

In this subsection we describe other Beyond the Standard Model (BSM) searches that also lead to a signature of $\cancel{E}_T + \text{b-jets}$.

$\tilde{\chi}_2^0$ Cascade Decay

In this scenario [43, 44] one assumes the production of squarks and gluinos which then decay into neutralinos $\tilde{\chi}_2^0$, which sequentially decay via $\tilde{\chi}_2^0 \rightarrow h^0 \tilde{\chi}_1^0$. The neutralino escapes detection and leaves $\cancel{E}_T$ in the detector and the Higgs decays into two b's ($h^0 \rightarrow b\bar{b}$). The kinematics of this signature allows for the reconstruction of the Higgs mass through the b-jets invariant mass.

Figure 2.9. Gluino pair production decaying into sbottom-bottom , followed by the decay $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$.

Standard Model Higgs

Z associated Higgs production with $ZH \rightarrow \nu\bar{\nu}b\bar{b}$, which results in a final state of two b-jets and missing energy. The b-jets can be used to reconstruct the b-mass.

Scalar Bottom Pair Production

Sbottom is pair produced at the hadron collider and then decays via $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$, resulting in a final state of two b-jets and missing energy.

2.6.5 Existing SUSY Mass Limits

Both at Lepton and Hadron colliders, as well as e^+p colliders, searches for SUSY particles have been performed. We focus here on R parity conserving SUSY scenarios, which imply that SUSY particles are pair produced and the lightest supersymmetric particle (LSP) is stable. A review of recent third generation scalar quark searches is given in [45].

Figure 2.10. Contour exclusion limits in the $m_{\tilde{b}_1}$ - $m_{\tilde{\chi}_1^0}$ plane by searches performed at CDF and LEP.

Figure 2.11. Contour exclusion limits in the $m_{\tilde{g}}$ - $m_{\tilde{q}}$ plane by searches for jets and missing energy performed at the Tevatron and LEP.

Figure 2.10 and 2.11 shows the current exclusion limits for gluinos and scalar bottom quarks obtained through searches performed at the LEP and Tevatron collider experiments. The gluino with a mass below $195 \text{ GeV}/c^2$ is ruled out with 95% C.L. independent of the squark mass [4, 46]. The sbottom can be excluded for masses below $94 \text{ GeV}/c^2$ at 95% C.L. under the assumptions $\text{BR}(\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0) = 100\%$, the

sbottom and neutralino are not mass degenerate ($\Delta m = m_{\tilde{b}} - m_{\tilde{\chi}_1^0} > 20 \text{ GeV}/c^2$) and for maximal mixing, where the mixing angle $\theta_{\tilde{b}}$ is chosen such that the cross section is minimal [4, 47]. In addition the search for direct sbottom quark production at CDF [48] provided a 95% C.L. exclusion limit for the sbottom depending on the neutralino mass. Sbottoms are excluded up to about $145 \text{ GeV}/c^2$ for a neutralino mass of $60 \text{ GeV}/c^2$.

Accelerator searches for a stable $\tilde{\chi}_1^0$ can exclude neutralino masses below $46 \text{ GeV}/c^2$ at 95% C.L. (see Figure 2.12) [4, 47, 49].

Figure 2.12. 95% C.L. exclusion limit in the $m_{\text{LSP}}\text{-}\tan\beta$ plane from the combined LEP results.

3. Experiment

In this chapter we describe the Fermi National Accelerator Laboratory (FNAL) [50] accelerator facility and the Collider Detector at Fermilab (CDF) Run II experiment which provided the data used in this analysis.

3.1 The Tevatron

The Tevatron is a proton antiproton superconducting collider at the Fermi National Accelerator Laboratory (FNAL) in Batavia, Illinois. It currently operates with 36 proton on 36 antiproton bunches at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV and a bunch spacing of 396 ns. The bunches are arranged in 3 bunch trains of 12 bunches each, followed by an abort gap [51]. The Tevatron operates at an RF frequency of 53 MHz, with a total of 1113 buckets (19 ns in length). In the active period there is every 21 buckets one filled with a bunch, so that an active period consists of 21 buckets $\cdot 11 + 1$ bucket = 232 buckets which is equivalent to 4.4 μ s. The abort gap corresponds to 139 buckets equivalent to 2.6 μ s.

Until the completion of the Large Hadron Collider (LHC) [52] at CERN, the Tevatron provides the world's highest energy collisions. In contrast to the Tevatron being a $p\bar{p}$ storage ring, the LHC is a pp machine. At the LHC center-of-mass energy the dominant physics production process will be gluon-gluon fusion.

In collider operations the Tevatron takes 150 GeV protons and antiprotons provided by the main injector and accelerates them to 980 GeV. Figures 3.1 and 3.2 provide a schematic view of the Fermilab accelerator complex.

The acceleration cycle starts with the production of protons from ionized hydrogen atoms H^- , which are accelerated to 750 KeV by a Cockroft-Walton electrostatic accelerator. Pre-accelerated hydrogen ions are then injected into the Linac where

Figure 3.1. Schematic overview of acceleration process at Fermilab.

they gain an energy of 400 MeV by passing through the 150 m long chain of radio-frequency (RF) accelerator cavities. To obtain protons, the H^- ions pass through a carbon foil which strips their electrons off. Inside the Booster the protons are merged into bunches and accelerated to an energy of 8 GeV prior to entering the Main Injector, which is a synchrotron with a circumference of 3 km. In the Main Injector the proton bunches are accelerated further to an energy of 150 GeV and coalesced¹ together to high density prior to injection into the Tevatron, a superconducting collider of 1 km radius. In the Tevatron a total of 36 proton and antiproton bunches are accelerated to an energy of 980 GeV. The production of the antiproton beam is significantly more complicated. The cycle starts with extracting the 120 GeV proton beam from the Main Injector onto a stainless steel target. This

¹coalescing is the process of merging proton bunches into a bucket

Figure 3.2. Overview of the Fermilab accelerator complex.

process produces a variety of different particles, among which are antiprotons. The antiproton production efficiency is about $2 \cdot 10^{-5}$ /proton. The created antiprotons are then separated from other particles by focusing through a lithium lens prior to injecting them into the Debuncher, which decreases the momentum spread of the particles. After that, the continuous antiproton beam is directed into the Accumulator where the antiprotons are stored at an energy of 8 GeV and stacked to 10^{12} particles per bunch, which takes up to 12 hours. The antiproton bunches are then injected into the Main Injector and accelerated to 150 GeV. Finally, 36 bunches of antiprotons are inserted into the Tevatron where they are accelerated to an energy of 980 GeV. Proton and antiproton bunches circulate around the Tevatron in opposite directions. Their orbits cross at the B0 and D0 collision points, where interactions

are observed by the CDF and DØ detectors respectively. The low beta quads control the squeeze and the separators control the collisions at the interaction points.

Figure 3.3 shows the integrated delivered luminosity by the Tevatron as a function of the day of the year, since the start of Run II in March 2001. It is compared to the total acquired luminosity by CDF shown in Figure 3.4. CDF's data taking efficiency has continuously improved since the start up of Run II and currently averages well above 80%. The analysis described in this document used the dataset collected in the time period of February 2002 to September 2003.

Figure 3.3. Total delivered luminosity by the Tevatron as a function of the day of the year, given per year of operation. A continuous improvement of the performance of the Tevatron can be seen.

Figure 3.4. Total acquired luminosity by CDF since the beginning of Run II on March 5, 2001.

3.2 The Collider Detector at Fermilab

The Collider Detector at Fermilab (CDF II) [53] shown in Figure 3.5 is a multipurpose experiment with azimuthal and forward-backward symmetry, designed to study high energy $p\bar{p}$ collisions. It combines precision charged particle tracking with fast projective calorimetry together with fine grained muon detection. The tracking system is contained inside a superconducting solenoid of 4.8 m length and 1.5 m

radius. It generates a 1.4 T magnetic field parallel to the beam axis. The muon and calorimetry systems are located outside of the solenoid. The solenoid is made of an Al-stabilized NbTi superconductor and operated at liquid helium temperature which is able to carry currents of up to 5 kA. The magnetic field is uniform with an accuracy of 0.1% throughout the entire tracking volume.

Figure 3.5. Isometric view of the CDF Run II detector.

CDF uses a coordinate system with the positive z -axis lies along the direction of the incident proton beam, ϕ is the azimuthal angle, θ is the polar angle (measured from the detector center), and p_T is the component of momentum in the transverse plane. The rapidity, y , of a particle is given by $y = \frac{1}{2} \ln \left[\frac{E+p_z}{E-p_z} \right]$. Rapidity differences are useful in physics analysis, since they are invariant to a Lorentz boost. The pseudo-rapidity, η , is defined as $\eta = -\ln(\tan(\frac{\theta}{2}))$. The pseudo-rapidity η equals the rapidity y in the massless approximation (limit $E \gg mc^2$). Figure 3.6 shows

the η -coverage of the individual components of the CDF tracking system. If η is measured from the detector center, then it is called the detector η_d .

Figure 3.6. Longitudinal view of the CDF Run II tracking system. The pseudo-rapidity η is defined as $\eta = -\ln(\tan(\frac{\theta}{2}))$, where θ is the polar angle measured from the proton direction.

3.2.1 Tracking System

The tracking system is subdivided into an inner and outer tracker. The inner tracker relies on a silicon strip detector and the central outer tracker (COT) relies on a gaseous drift chamber each of which represents a stand-alone tracking system.

Figure 3.7. The schematic view shows 1/6 section of the COT end plate. The average radius of each Super Layer(SL) and its orientation which alternates between stereo(S) and axial(A) is given, and in addition the number of cells. The dimensions are given in units of cm. The enlargements shows the field slot and sense slot geometry of a super layer in detail.

The CDF Run II Silicon Vertex Detector

The CDF II silicon detector consists of three subdetectors, each using different silicon sensor designs and layouts:

- SVX II (Run II Silicon Vertex Detector) is the core of the silicon tracking system. It consists of 360 double-sided ladders² in a layout of six 15 cm axial sections of twelve 30° ϕ -slices in five radial layers. The innermost SVX II layer is located at 2.5 cm and the outermost at 10.6 cm from the beam. Three of the layers are 90° layers and two are small angle stereo layers, with a 1.2° angle. In the 90° stereo layers, the sensors have strips running lengthwise on the p-n

²Four silicon sensors are connected by wirebonds and supported on a light weight support structure. This assembly is referred to as a ladder.

junction side to measure the $r - \phi$ position. On the n-side strips are running laterally to measure the $r - z$ position. In the small angle stereo layers on the n-side the strips are running at an angle of 1.2° with respect to those on the p-n junction side.

- ISL (Intermediate Silicon Layers) [54, 55] serves as a link between the inner silicon tracking region and the outer wire tracker. The 1.9 m long ISL consists of two layers of double-sided small angle stereo (1.2°) ladders at radii of 20 cm and 28 cm.
- L00 [56] (Layer 00) is a single-sided layer of 48 ladders mounted at 1.5 cm from the beamline directly on the beampipe.

A more detailed summary of the specifications of the silicon tracker is given in Table 3.1 and an introduction to Silicon detectors is given in appendix A and B. The three subdetectors share a common readout system. The system called the SVX3D chip [57] is based on a custom designed ASIC with 128 channels. The chip can be logically divided into an analog and a digital section. The analog section has, for each of the 128 channels, a FE low noise integrator followed by a 46 cell analog pipeline with 4 buffer cells, used to store the information while waiting for a Level 1 accept. The digital section has 8 bit ADC Wilkinson comparators, a Dynamical Pedestal Subtraction (DPS) feature for common noise suppression, and after DPS has sparsification logic to increase the readout speed. The chip operates in dead-timeless mode, which means that it is able simultaneous to acquire and integrate data while digitizing. Figure 3.8 shows the silicon coverage and Figure 3.9 gives an r-z view of the silicon detector.

3.2.2 Central Outer Tracker

The Central Outer Tracker (COT) is a cylindrical open-cell drift chamber, that is located between the TOF and inner silicon tracker in the radial range from 40 cm

Figure 3.8. Silicon detector coverage in the r - z perspective, showing all subcomponents. The z coordinate is highly compressed.

to 138 cm. In z it extends from -155 cm to $+155$ cm. Hence, providing full coverage for $|\eta| < 1$ and it has a maximum acceptance of $|\eta| < 2$, shown in Figure 3.10. The wire chamber was designed to ensure that the drift time is smaller than the 132 ns bunch spacing³ originally envisioned for Run IIb. The maximum drift time has to be small to resolve the bunch crossings, and not to suffer from event pileup. It can be kept below 100 ns by using an Argon/Ethane/ CF_4 (50:35:15) gas mixture, that has a fast drift velocity of about $100 \mu\text{m}/\text{ns}$. Since the Tevatron is running in 36 bunch operation, which corresponds to 396 ns between bunch crossings, a (50:50) Argon-Ethane mixture + 1.7% isopropyl alcohol is currently used [58]. This gas mixture yields a maximum drift time of 177 ns, which is sufficient for 36 bunch operation. The small content of isopropyl alcohol is intended to reduce aging and build up on

³Originally planned crossing rate for Run IIb [60] was 7.6 MHz

Figure 3.9. $r - \phi$ view of the CDF II silicon system including the SVX II cooling bulkheads and ISL support structure.

the wires [59]. The COT is segmented into 8 super-layers (SL), with each super-layer containing 12 sense wires which alternate with 13 potential wires, which provide the field shaping within the cell.

The super-layers are alternating stereo and axial, where in axial layers, potential and sense wires are parallel, while in stereo layers the wires are tilted with an angle of $\pm 2.0^\circ$ [61]. Hence, axial layers and stereo layers provide a measurement of the charged track position in $r - \phi$, and z respectively. Both sense and potential wires are $40 \mu\text{m}$ in diameter and of gold plated tungsten. The cathode planes (field sheet) are $6.35 \mu\text{m}$ thick Mylar with a $450 \text{ \AA}$ Gold layer on both sides. The field sheets are shared between the two neighboring Super cells. To compensate for the Lorentz angle of the drifting electrons in the magnetic field the super cell is tilted by 35° with respect to the radial direction.

Table 3.1

Summary of the specs for L00, SVX II, and ISL. α is the angle between the strips on the p-n junction side with respect to those on the n-side. Layers with 1.2° are small angle stereo layer and 90° are axial layers.

Layer	Radii (cm)	$\phi(\mu m)$	$\frac{\phi'}{z}(\mu m)$	α
00	1.35 / 1.62	50	-	-
1	2.5 / 3.0	60	141	90°
2	4.1 / 4.6	62	125.5	90°
3	6.5 / 7.0	60	60	1.2°
4	8.2 / 8.7	60	141	90°
5	10.1 / 10.6	65	65	1.2°
6F	19.7 / 20.2	112	112	1.2°
6C	22.6 / 23.1	112	112	1.2°
7F	28.6 / 29.0	112	112	1.2°

3.2.3 Calorimeter

CDFs calorimeters have the purpose of measuring the energy of charged and neutral particles produced in the interaction. Therefore, they also provide a measure of the energy of particles leaving the detector without interacting, by measuring the transverse energy imbalance in the detector. The calorimeters extends to $|\eta| < 3.6$.

CDF uses scintillator sampling calorimeters, divided into inner electromagnetic and outer hadronic sections. The entire calorimeter is segmented into projective towers. Each tower consists of alternating layers of passive material and scintillator tiles. The signal is read via wavelength shifters (WLS) embedded in the scintillators. The light from WLS is transmitted to photo-multiplier tubes (PMT).

The central calorimeter is a scintillator sampling system with tower segmentation. It is largely unchanged from Run I and each wedge consists of a lead-scintillator EM

Figure 3.10. This schematic r-z view shows the pseudorapidity coverage of the inner and outer tracker (SVX II, ISL, and COT).

section backed by a steel scintillator hadron section. The central calorimeter system consists of two subdetectors, the Central Electromagnetic Calorimeter and Hadronic Calorimeter, CEM and CHA, respectively. It has a segmentation of 15° ϕ -wedges and 0.11 in units of pseudorapidity. The CHA is radially outside the CEM and covers the pseudorapidity range $|\eta| < 0.9$. The Endwall Hadronic Calorimeter (WHA) extends the coverage to $0.9 < |\eta| < 1.3$. The electromagnetic and hadronic plug calorimeters PEM and PHA cover the region $1.1 < |\eta| < 3.6$. A transverse segmentation of 7.5° in ϕ was chosen both for the EM and hadron towers. The finer azimuthal segmentation, was chosen to optimize identification of electrons in semileptonic b-decays. The PEM is a 23 layer lead / scintillator sampling calorimeter. Each layer is composed of 4 mm scintillator and 4.5 mm lead which translates into $21X_0$ (radiation length⁴) at normal

⁴The radiation length X_0 describes the characteristic amount of matter transversed, for high-energy electrons to lose all but $1/e$ of its energy by bremsstrahlung, which is equivalent to $\frac{7}{9}$ of the length of the mean free path for pair e^+e^- production of high-energy photons. The average energy loss due to

incidence. The $\eta - \phi$ segmentation is such as to maintain the pointing geometry of the towers back toward the detector center. The energy resolution of the detector is $\frac{16\%}{\sqrt{E_T}} \otimes 1\%$ (1% constant term). Table 3.2 summarizes the calorimeter subsystems and their characteristics.

Table 3.2

The energy resolution for the EM calorimeter is given for a single incident electron and that for the hadronic calorimeter for a single incident pion. λ_0 refers to the interaction length and X_0 to the radiation length.

Calorimeter	Coverage	Thickness	Energy resolution
CEM	$ \eta < 1.1$	$18 X_0$	$\frac{13.5\%}{\sqrt{E_T}} \otimes 2\%$
CHA	$ \eta < 0.9$	$4.5 \lambda_0$	$\frac{75\%}{\sqrt{E_T}} \otimes 3\%$
WHA	$0.7 < \eta < 1.2$	$4.5 \lambda_0$	$\frac{75\%}{\sqrt{E_T}} \otimes 3\%$
PEM	$1.1 < \eta < 3.6$	$21 X_0, 1 \lambda_0$	$\frac{16\%}{\sqrt{E_T}} \otimes 1\%$
PHA	$1.2 < \eta < 3.6$	$7 \lambda_0$	$\frac{80\%}{\sqrt{E_T}} \otimes 5\%$

The first layer of the PEM is made out of 10 mm thick scintillator tiles which are read out by Multi-Anode Photo-multiplier tubes (MAPMT) through SMQIE (A charge integrator and encoder chip) electronics. This preshower detector is called the Plug Preradiator (PPR). In addition there is also a plug shower maximum detector (PES), at the depth of the maximum of a typical electromagnetic shower, located about 6 radiation lengths (X_0) into the plug. It consists of 6400 scintillator strips covering an η range from 1.1 - 3.5 and divided into 16 octants, 8 on each side, where each octant has 2 layers.

The Shower Maximum detectors are used to determine the shower position and transverse development at shower maximum. The Central Shower Maximum (CES)

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bremsstrahlung for an electron of energy E is related to the radiation length by $\left(\frac{dE}{dx}\right)_{brems} = -\frac{E}{X_0}$ and the probability for an electron pair to be created by a high-energy photon is $\frac{7}{9}X_0$.

is a wire chamber using (95:5) Argon/CO₂. Charge is deposited on orthogonal strips and wires.

The Preradiator detectors are used to separate photons from pions and to improve electron ID. The Central Preradiator (CPR) is a wire chamber using (95:5) Argon/CO₂ mixture. Charge is deposited on the wires.

The Central Crack detectors (CCR) are used to cover ϕ cracks in the calorimeter acceptance. These detectors are strip chambers using a 95% / 5% Argon/CO₂ mixture with charge deposited on the strips.

The readout in CES, CPR, and CCR is through preamplifiers and SMQIE electronics.

3.2.4 Muon Detector

Muons are capable of transversing large amounts of material, before losing a significant amount of energy. In contrast to muons, the majority of particles produced in $p\bar{p}$ collisions are absorbed by the calorimeter material. Hence, the muon system is the outermost layer of our detector. To purify the muon sample, additional layers of steel absorber are placed immediately after the calorimeter and the magnet return yoke.

The CDF muon systems can be divided into four subsystems, that provide combined coverage in the rapidity interval $|\eta| < 1.5$. The central muon detector is divided into three subsystems:

- CMU (Central Muon Detector)
- CMP (Central Muon Upgrade)
- CMX (Central Muon Extension)

The CMU consists of 144 modules, each contains 16 rectangular cells. The cells are stacked in four layers in the radial direction with a small azimuthal offset in order to facilitate the reconstruction of the muon trajectory. Each wire pair is instrumented

with a TDC to readout the timing information, which is then used to measure the ϕ location. The location in z is obtained via charge division, where the collected charge is measured by ADC's attached to the ends of each wire. Figure 3.11 shows the CMU cell structure.

Figure 3.11. Transverse view of the CMU showing the four layers in radial direction.

The CMP detector is a second set of muon detectors behind the CMU in the central region, covering the rapidity region $|\eta| \leq 0.6$, it is behind an additional 60 cm of steel. It forms a square box around the CMU. Hence, the exact pseudo-rapidity coverage varies with azimuth as shown in Figure 3.12. The central upgrade chambers (CMP) are rectangular single-wire drift tubes that are configured in four layers of alternating staggered half-cells. The chambers operate in proportional mode with a maximum drift time of approximately $1.4 \mu\text{s}$. Preamplifiers are mounted at the end of the stacks and signals are read out by a single TDC per wire. A layer of rectangular scintillation counters, called the CSP, is mounted to the outer surface of the CMP.

The Central Muon Extension (CMX) is an addition to the central muon detectors, with which it slightly overlaps. It consists of conical sections of drift tubes covering the pseudo-rapidity region from 0.65 to 1.0. The CMX is divided in 15° azimuthal

sectors. Each section consists of four layers of twelve drift tubes, that have a half-cell offset with respect to each other. The outer surfaces of CMX are covered by the Central Scintillator Extension (CSX) a layer of trapezoidal scintillator tiles.

The muon system, consists of multiple layers of single wire chambers that are topped by scintillation counters. Since the typical drift time in the wire chambers exceeds the bunch crossing time, the scintillators will be critical for associating muon tracks.

The intermediate (IMU) muon chambers consists of a barrel-shaped array of muon chambers (BMU) and scintillators (BSU), mounted parallel to the beamline. These Barrel Scintillators consist of rectangular plastic scintillators, each covering 2.5° in azimuthal angle and the equivalent of 1.25 in η .

Figure 3.12 shows a map of the muon coverage of the four muon detectors.

Figure 3.12. Map of the muon coverage as a function of azimuthal angle ϕ and pseudorapidity η .

A recent overview of the performance of the CDF Run II muon system can be found at [62, 63].

3.2.5 Time-of-Flight Detector

The ionization energy loss, measured through dE/dx in the Central Outer Tracker, can be used for particle identification. The dE/dx measurement provides about one standard deviation separation between charged kaons and charged pions for momenta greater than 2 GeV/ c .

In order to enhance particle identification capability, the Time-of-Flight detector (TOF) [64] was added as one of the major CDF Run II upgrades. The TOF detector consists of 216 about 3 m long scintillator bars, located between the COT and the cryostat of the superconducting solenoid at a mean radius of 140 cm and covers a pseudo-rapidity range of $|\eta| < 1$. In combination with the momentum measurement p from the tracking system, the TOF detector provides particle identification by determining the particles mass: $m = \frac{p}{c} \sqrt{\frac{c^2 t^2}{L^2} - 1}$, where L is the path length also obtained from the tracking system. The time t of arrival of a particle at the scintillator is measured with respect to the collision time, t_0 . The TOF system achieves a resolution of 100 ps, which allows for at least two standard deviation separation between $K^\pm$ and $\pi^\pm$ for momenta $p < 1.6$ GeV/ c , complementing the dE/dx measurement from COT.

The Time-of-Fight detector was not used in this analysis since we are primary dealing with high E_T jets and not concerned with the identification of low p_T particles. Figure 3.13 shows an example of the performance of the particle ID using TOF.

3.2.6 Luminosity Measurements

The luminosity at hadron colliders can be determined from the rate of inelastic $p\bar{p}$ interactions. At CDF it is measured using low pressure gaseous Cherenkov counters

Figure 3.13. The reconstructed mass vs. momentum using the TOF for tracks with positive and negative momentum. Clusters of data points show a clear separation for low p_T , pions, kaons and protons.

placed at small angles relative to the beam direction. The plug calorimeter covers the region down to a polar angle of 3° relative to the beam axis. The Cherenkov Luminosity Counters (CLC) [65, 66] occupy the conical hole between the plug and the beampipe in the center. The CLC luminosity monitoring detector is composed of a well segmented array of counters shown schematically in Figure 3.14.

The CLC uses the fact that a particle that transverses a medium with a velocity v , that is larger than the velocity of light in that medium c_m creates a cone of Cherenkov radiation around the particle's direction. Since the CLC points toward the nominal interaction point, it is more sensitive to particles coming directly from the detector center. The CLC was designed to provide an accurate measurement of

Figure 3.14. Schematic view of the luminosity monitor inside a quadrant of CDF located at $|\theta| < 3^\circ$.

the instantaneous and the total integrated luminosity for the CDF II experiment. The counters are oriented with their small end pointing to the interaction point and consist of gas filled truncated cones, that are 2 m long, 2 cm in diameter, and made out of aluminized Mylar. The Cherenkov light produced by charged particles radiating in the gas inside the cone is collected at the large end of the cone by a fast photo-multiplier tube (PMT).

In the absence of a crossing angle the luminosity $\mathcal{L}$ can be obtained using the following beam characteristics [67]:

$$\mathcal{L}_{inst} = N_b f_{BC} \frac{N_p \cdot N_{\bar{p}}}{4\pi\sigma^2} \quad (3.1)$$

where $N_p, N_{\bar{p}}$ are the numbers of protons, and antiprotons per bunch, respectively. N_b refers to the number of bunches in the ring, f_{BC} is the bunch crossing frequency

which is on average 1.7 MHz for 36×36 bunch operations, and σ is the beam width, assuming a Gaussian distribution for the beam. The CLC measures the average number of interactions per bunch crossing μ and the luminosity is then extracted using:

$$\mu \cdot f_{BC} = \sigma_i \cdot \mathcal{L} \quad (3.2)$$

Where σ_i is the inelastic proton-antiproton scattering interaction cross section⁵. The number of interactions n per bunch crossing follows Poisson statistics and is given by:

$$\mathcal{P}(n) = \frac{\mu^n e^{-\mu}}{n!} \quad (3.3)$$

The probability of empty bunch crossings $n = 0$ can for example be used as an estimator for μ .

$$\mathcal{P}(0) = e^{-\mu} \quad (3.4)$$

The total systematic uncertainty on the luminosity is about 6%, which originates from uncertainties in the acceptance (4.4%) and from the inelastic cross section (4%).

3.2.7 Trigger and Data Acquisition

The average interaction rate at the Tevatron is 1.7 MHz for 36×36 bunches. The actual interaction rate is higher, since the minimum bunch spacing is 396 ns, between the bunches in a bunch train, which leads to a crossing rate of 2.53 MHz. The interaction rate is orders of magnitude higher than the rates that the data acquisition system can handle. Furthermore, the majority of collisions are not of interest. This leads to implementation of a system that preselects events online and decides if the corresponding detector data of an event is written to tape or discarded. This is the task of the trigger system which evaluates if a given event should be read out, reconstructed and stored. The CDF trigger system consists of three trigger levels, at which decisions based on increasingly more complex event information are made. Level 1 (L1) and Level 2 (L2) are hardware based systems while the Level 3

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⁵The proton-antiproton inelastic cross section is about 60.7 mb

(L3) filters resemble the offline reconstruction code. L1 and L2 only hold a subset of event data, on which they make a decision either to pass it on for subsequent processing or to reject it.

Figure 3.15 shows the global CDF II trigger system and the accept rates for the different trigger levels. In total, the bunch crossing frequency of 2.53 MHz is reduced to below 75 Hz Level 3 output. The Level 2 output rate is limited to about 300 Hz and Level 3 to about 50 Hz with an average event size of about 250 kB [68].

Figure 3.15. Block diagram showing the global Level 1 and Level 2 trigger system.

Figure 3.16 shows the CDF Run II hardware trigger system.

The vast majority of events is already discarded at L1, if they do not show any interesting signature. It incorporates tracking, using an eXtremely Fast Tracker

RUN II TRIGGER SYSTEM

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Figure 3.16. Block diagram showing the CDF Run II trigger system.

(XFT) [69], calorimeter, and muon information. The resulting track list is sent to the extrapolation box (XTRP) for matching with the other Level 1 primitives. The XFT uses the track information obtained from the four axial COT layers ($r - \phi$ only). The decision time at L1 can take up to $5.5 \mu\text{s}$.

The Level 2 trigger consists of several asynchronous subsystems which provide input data to programmable Level 2 processors. Events passing Level 1 are written into one out of four Level 2 buffers. If all four Level 2 buffers are filled the experiment starts to incur deadtime. The Level 2 decision is based on:

- Level 2 cluster finder (L2CAL): The Level 2 cluster finding algorithm combines contiguous regions of calorimeter towers with non-trivial energy. Clusters are seeded by a tower above a “seed” threshold of a few GeV. All towers above a “shoulder” threshold (lower) that form a contiguous region are added.
- Shower Maximum Data: The shower maximum detector provides a much better spacial resolution than a calorimeter wedge. Tracks from the central tracker are matched to the shower maximum and therefore provides a significant reduction in combinatorial background for electrons and photons.
- Silicon Vertex Tracker [70, 71] (SVT): The SVX II information is combined with the Level 1 tracking information from the central tracking chamber. It computes the track ϕ , p_T and impact parameter d_0 . Hereby the efficiency and resolution is comparable to that of the offline track reconstruction. The SVT enables triggering on displaced tracks, that have a large impact parameter d_0 . Tracks reconstructed from the decay products of long lived particles (like b , c , K_s , Λ , ...) are in general not consistent with originating from the primary vertex and therefore possess a large impact parameter. The possibility to trigger on displaced tracks leads to a significant enhancement in the heavy flavor fraction of the trigger data sample obtained in this way.

If an event is accepted at Level 2 the entire detector is read out and processed in the Level 3 trigger which consists of a Linux PC farm. It is divided into 16 subfarms, each consisting of 12-16 processor nodes. The subfarms perform the event reconstruction and make a final Level 3 trigger decision. This leads to a further reduction in the output rate by about a factor four. Events that satisfy the Level 3 trigger requirements are then transferred to the mass storage.

4. Trigger Path and Event Preselection

4.1 Gluino Pair Production

The sbottom pair production cross section and gluino pair production cross section at the Tevatron center of mass energy of $\sqrt{s} = 1.96$ TeV has been computed with the PROSPINO program [39] at leading (LO) and next-to-leading order (NLO). The gluino pair production cross section is a function of the gluino mass and is in the range of 10 pb to 1 pb for gluino masses of 190 GeV/ c^2 to 260 GeV/ c^2 at the Tevatron center of mass energy. Hence, gluino production is approximately one order of magnitude higher than direct sbottom production, for similar masses of the two particles. The gluino and sbottom production cross sections are shown in Figure 2.5 and Figure 2.6, respectively. We assume a branching ratio of 100% for $\tilde{g} \rightarrow \tilde{b}_1 \bar{b}$ and $\tilde{b}_1 \rightarrow b \tilde{\chi}_1^0$ decay. The large gluino pair production cross section together with a distinctive final state makes the search for sbottom quarks in the gluino pair production channel extremely powerful. However the direct sbottom pair production is less model dependent, since it does not make an assumption on the gluino mass.

As a cross check, the gluino pair production cross sections obtained with PROSPINO at LO were compared with those obtained from ISAJET also at LO. The results given in Table 4.1 are in good agreement.

Figure 4.1 shows the gluino pair production cross section computed for different choices of parton distribution function (PDF) [72], which gives the probability of finding a parton f , with fraction x of the hadron momentum. The production cross section can vary as much as 12% for different PDFs, depending on the gluino mass.

Table 4.1

Comparison of leading order gluino pair production cross section using CTEQ5L, obtained with ISAJET and PROSPINO, respectively.

$m(\tilde{g})$	ISAJET $\sigma_{\text{LO}}[\text{pb}]$	PROSPINO $\sigma_{\text{LO}}[\text{pb}]$
200 GeV/c^2	7.10	7.795 ± 0015
250 GeV/c^2	1.61	$1.750 \pm .0015$
300 GeV/c^2	0.39	$0.4232 \pm .0016$

Figure 4.1. Gluino pair production NLO cross section at $\sqrt{s} = 1.96 \text{ TeV}$ as a function of the gluino mass, computed with the PROSPINO program [39] for the CTEQ4M, CTEQ5M, and MRST98 PDFs.

Figure 4.2. Relative difference on the gluino pair production cross section as a function of the gluino mass for the CTEQ4M, CTEQ5M, and MRST98 PDFs.

4.2 Event Kinematics

A gluino pair decaying into bottom-sbottom, with sbottom sequentially decaying into a bottom quark and a neutralino ($p\bar{p} \rightarrow \tilde{g}\tilde{g} \rightarrow \bar{b}\tilde{b}_1 b\bar{\tilde{b}} \rightarrow \bar{b}b\tilde{\chi}_1^0 b\bar{b}\tilde{\chi}_1^0$) results in a

final state with 4 b -quark jets and two neutralinos. The two neutralinos $\tilde{\chi}_1^0$ escape detection and will each yield missing energy. This can be detected as an imbalance of the transverse component of the energy deposited in the calorimeter.

$$\cancel{E}_T = \sum_i (E_i \sin \theta_i) \vec{n}_i \quad (4.1)$$

The long lifetime of the B -hadrons translates into a macroscopic decay length ($L = c\tau \cdot \gamma\beta$, with $c\tau \sim 450 \mu\text{m}$). This decay length is large enough so that some of the hadrons in the b -jets may have a displaced vertex from the interaction point and the tracks from the decay products can be used to reconstruct a secondary vertex of the B -hadron decay. It requires the precision tracking, which is made possible by the CDF Silicon Vertex Detector.

We are interested in final states with 4 b -jets and large missing transverse energy. The event kinematics is determined by the mass differences between the gluino and sbottom $\Delta M = m_{\tilde{g}} - m_{\tilde{b}}$, and the mass difference between the sbottom and the neutralino $\Delta m = m_{\tilde{b}} - m_{\tilde{\chi}_1^0}$. Figure 4.3 shows the offline E_T distribution for the third leading jet from a gluino Monte Carlo sample. The uncorrected offline $\cancel{E}_T$, for different values of the mass difference between the gluino and sbottom, for a neutralino mass of $m_{\tilde{\chi}_1^0} = 80 \text{ GeV}/c^2$ and a gluino mass $m_{\tilde{g}} = 260 \text{ GeV}/c^2$ is shown in Figure 4.4. For low ΔM the b -quark from the $\tilde{g}$ corresponds to the jet with the lowest transverse energy E_T due to the reduced available phase space. However, the neutralinos ($\tilde{\chi}_1^0$) from the sbottom decay have high transverse momentum, which yields higher $\cancel{E}_T$. For high ΔM , the b quarks from the gluino decays are the jets with the highest E_T . In this case the neutralinos from the sbottom decays are produced with a considerable boost, and therefore they tend to be back to back, which yields a lower $\cancel{E}_T$.

Figure 4.5 and 4.6 compare the p_T distributions for the three leading jets in signal events for large and small mass difference ΔM , respectively and $m_{\tilde{\chi}_1^0} = 60 \text{ GeV}/c^2$. It can be seen that in a mass scenario with small ΔM (nearly mass degenerate gluino and sbottom), the third b -jet is expected to have E_T below about 20 GeV.

Figure 4.3. E_T of the third leading jet reconstructed with cone 0.4 and $|\eta| < 2.2$ for a mass difference between the gluino and sbottom of 20, 60, and 140 GeV/c^2 .

Figure 4.4. Offline uncorrected $\cancel{E}_T$ as function of the mass difference $\Delta M = m_{\tilde{g}} - m_{\tilde{b}_1}$ with $m_{\tilde{g}} = 260 \text{ GeV}/c^2$, $m_{\tilde{\chi}_1^0} = 80 \text{ GeV}/c^2$.

4.3 Data Selection

Sbottom quarks from gluino decays yield a very rich signature of four b-jets and large $\cancel{E}_T$. Most distinguishing is the large missing transverse energy, therefore it is natural to chose a $\cancel{E}_T$ based trigger. There are three $\cancel{E}_T$ based analysis triggers implemented:at CDF

- MET45 (requires $\cancel{E}_T > 45 \text{ GeV}$)
- MET35 (requires $\cancel{E}_T > 35 \text{ GeV}$ and two 10 GeV jets)
- MET_BJET (requires $\cancel{E}_T > 20 \text{ GeV}$ and two displaced tracks)

These triggers are described in greater detail in the appendix C.

The signal acceptance for the $\cancel{E}_T$ based triggers have been estimated using trigger simulation. The signal acceptance after applying the trigger requirements can be seen in Figure 4.7, for $m_{\tilde{\chi}_1^0} = 40 \text{ GeV}/c^2$, $m_{\tilde{g}} = 260 \text{ GeV}/c^2$, for varying sbottom masses.

Figure 4.5. E_T spectrum for b-jets at generator level for a large mass difference between the the gluino and sbottom ($\Delta M = 60 \text{ GeV}/c^2$).

Figure 4.6. E_T spectrum for b-jets at generator level for a small mass difference between the the gluino and sbottom ($\Delta M = 10 \text{ GeV}/c^2$).

It can be seen that the MET35 trigger path (see Section 4.3.1) yields efficiencies above 80% for the mass scenarios of interest. The signal acceptance is slightly higher for the MET35 trigger compared to the MET45 trigger. Hence, the MET35 trigger sample was chosen for this analysis¹.

4.3.1 Missing Transverse Energy and Jets Data Sample

The datasets used in this analysis were collected using the MET35 trigger path, that is part of the E stream (Exotic), and written to the **emet** dataset, after processing on the reconstruction farm. Data collected in the period from February 2002

¹The MET_BJET trigger is a highly complicated trigger, that was not considered for use in this analysis. This analysis was performed at the beginning of Run II and was the first one to use the MET35 trigger sample. It was a logical decision to try to understand the MET35 trigger first before moving to the MET_BJET trigger, that is currently considered for example for the Standard Model Higgs Search. The signal acceptance using the MET35 trigger is large and was not seen as a major source of inefficiency in the analysis.

Figure 4.7. Signal acceptance computed with CDF’s trigger simulation, as a function of the mass difference between the sbottom and the gluino, for three different triggers (MET35, MET45, and Multijet [73]). The neutralino mass $m_{\tilde{\chi}_1^0} = 40 \text{ GeV}/c^2$ and gluino mass $m_{\tilde{g}} = 260 \text{ GeV}/c^2$ were fixed.

through January 2003, were reprocessed using a production software version 4.8.4a and are part of the **emet08** dataset. The data from January 2003 through September 2003 belong to the **emet09** dataset, which used production software 4.9.1. The data were then reprocessed for this analysis with offline software 4.11.2 to take the newest offline corrections to the data into account.

4.3.2 Analysis Software

As analysis framework, we used the stntuple [74], which is a comprehensive multi-branch ROOT [75] ntuple, where data is organized in blocks (each block corresponds

to a branch). We use stntuple version dev_240b², which is based on the offline software version 4.11.2.

4.3.3 Trigger Path

The data were collected with the missing transverse energy and two jets trigger, MET35. At Level-1 it requires $\cancel{E}_T$ above 25 GeV, where the $\cancel{E}_T$ is calculated over all the trigger towers with more than 1 GeV of total transverse energy. At Level-2 two calorimeter trigger jet clusters (seed tower threshold of 3 GeV, shoulder tower threshold of 1 GeV) with $E_T \geq 10$ GeV are required. At Level-3 the $\cancel{E}_T$ is recalculated using the full calorimeter information (towers with $E_T > 0.1$ GeV) and computed with respect to the detector center $z = 0$. The Level-3 threshold for the $\cancel{E}_T$ is 35 GeV.

4.3.4 Run Selection

In order to perform our analysis we have to rely on good calorimetry, electron/muon and silicon information. For this purpose we required that the detector components relevant for this analysis were marked “good” by the online and offline operators during the corresponding data taking period (Run). To ensure good data quality, CDF has an official good run list. We used the latest good run list available at the time of the analysis, that was applied here.

The MET35 trigger requirement changed in July 2002 to its current version. The previous version MET35 had a different L2 requirement of one L2 cluster of 15 GeV instead of two clusters of 10 GeV. The collected dataset from the previous trigger version with integrated silicon is very small. Hence, we exclude runs taken with the obsolete version of the trigger.

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²dev_240b was created as a modification of the default stntuple version dev_240 to include high p_T B-tagging.

4.3.5 Luminosity

After these run selection requirements, the remaining integrated luminosity is

$$\mathcal{L}_{\text{total}} = 155.9 \text{ pb}^{-1} \quad (4.2)$$

($\mathcal{L}_{\text{emet08}} = 39.3 \text{ pb}^{-1}$, $\mathcal{L}_{\text{emet09}} = 116.6 \text{ pb}^{-1}$). The luminosity was scaled up by a factor of 1.019 [76] compared to the measured luminosity at CDF ³. For the emet08 and emet09 dataset 25% and 85% of the data pass the good run requirements, respectively. This difference mostly comes from the good silicon requirement, and reflects the improved performance of the detector and accelerator after the start up period.

4.3.6 Data Clean Up

Detector inefficiencies and non-collision backgrounds can produce energy deposition in the calorimeter that fake an energy imbalance. Some of the processes leading to such effects are:

- Beam halo muons [77] bremsstrahlung in the calorimeter in or out of coincidence with real $p\bar{p}$ collisions. In the former case they will increase the $\cancel{E}_T$ trigger rate, while in the later it will appear as an overlapped $\cancel{E}_T$.
- Cosmic ray showers, which are likely to pass through sections of the calorimeter, and can cause an energy imbalance in the detector.
- $p\bar{p}$ collisions produced far from the nominal collision point, are more likely to have some of the energy undetected.
- Hot channels in the calorimeter which give a fake large energy to towers.

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³To allow the comparison of CDF and DØ cross section measurements in Run II, the collaborations agreed to use a common $p\bar{p}$ inelastic cross section for normalization, for this purpose an average of the CDF and E811 measurements was chosen. Following this procedure the CDF luminosity needs to be scaled by a factor of 1.019.

To discard such events, a secondary dataset was created with a higher purity by applying cuts similar to those of Run I [46] and other Run-II analyses [78,79]. The “clean-up” selection is organized in three consecutive passes:

- Pass 1

- At least one central jet ($|\eta_d| < 0.9$) with $E_T > 10$ GeV (where η_d is the detector η).
- Event Electromagnetic Fraction (EEMF):

$$EEMF = \frac{\sum_{j=1}^{N_{jet}} E_T^j \cdot EMF_j}{\sum_{j=1}^{N_{jet}} E_T^j} > 1 \quad (4.3)$$

where EMF_j is the fraction of the jet energy deposited in the electromagnetic calorimeter. Only jets with $E_T > 10$ GeV are considered.

- At least one COT track with $p_T > 0.5$ GeV/c and one axial super layer with six or more hits on it.

- Pass 2

- Event Charge Fraction (ECHF):

$$ECHF = \frac{\sum_{j=1}^{N_{jet}} CHF_j}{N_{jet}} > 0.1 \quad (4.4)$$

where CHF_j is the jet charge fraction which is defined as the ratio of the sum of the p_T of the tracks matched to matching to the jet energy E_T .

- At least one good primary vertex in the event (for the vertex definition see Section 4.4).

- Pass 3

- Exclude a geometrical region of the calorimeter, where jets would be mis-measured, called the ‘chimney’, which is a hole in the calorimeter that hosts cryogenic and instrumental connections to the inner detector. The jets that fall into the chimney region ($\phi = (60^\circ, 100^\circ)$ and $\eta = (0.5, 1.0)$)

are almost certainly mis-measured. Hence, we exclude any event that has a jet with $E_T > 10$ GeV that falls into the chimney region.

- We require that the event primary vertex falls within $|z| < 60$ cm of the nominal interaction point at the detector center.
- Topological cuts are applied to eliminate muon beam halo⁴ events [79].

Table 4.2 summarizes the sample reduction after each of these cuts.

Table 4.2
Event reduction in the MET35 data sample.

Data sample	emet08 (MET35)	emet09(MET35)
Events after good run requirements	214604	849291
$\cancel{E}_{T\text{offline}} > 35$ GeV	191277	788928
fails one central jet ($\cancel{E}_T > 10$ GeV, $ \eta < 0.9$)	43148	207651
fails one central good track	11611	23217
fails $EEMF > 0.1$	12059	29671
fails $ECHF > 0.1$	65388	273071
fails fails Primary Vertex	19786	52826
fails $ z < 60$ cm	78187	303919
fails chimney cut	7838	30713
fails beamhalo filter	5	34
Remaining events after clean up	83046 (38.7%)	335258 (39.5%)

Figure 4.8 shows the $\cancel{E}_T$ spectrum before and after applying these cuts on the MET35 dataset, which was taken from January 2003 through September 2003. It

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⁴Proton and antiproton losses leads to particles traveling parallel to the beamline, that can produce showers in the calorimeter.

can be seen that the long $\cancel{E}_T$ tails of large missing transverse energy are reduced significantly by the clean up cuts.

Figure 4.8. Offline $\cancel{E}_T$ distribution for the MET35 dataset before (open histogram) and after (shaded histogram) applying the $\cancel{E}_T$ cleaning cuts.

For the data preselection the following cuts were applied:

- Offline $\cancel{E}_T > 35$ GeV where the $\cancel{E}_T$ was calculated with respect to the detector center.
- Total calorimeter transverse energy calculated with respect to the detector center less than 2 TeV.

4.4 Event Primary Vertex

A primary vertex z finding algorithm [80] was applied to find the z position of the event primary vertex of the proton antiproton interaction. This algorithm is based on taking an error weighted average of the track z_0 , passing minimal quality requirements. The z -vertex position is then given by:

$$z_{\text{vertex}} = \frac{\sum_i z_i^0 / \delta_i^2}{\sum_i 1 / \delta_i^2} \quad (4.5)$$

where z_i^0 is the z_0 of the i^{th} track and δ_i the associated error. As a minimum quality requirement on the z -vertex we require that it contains at least two good COT tracks. In events with multiple z -vertices, we select the one that has the largest transverse energy associated to it, by taking the scalar sum of the E_T of the tracks attached to the vertex. The primary vertex z position was then used to correct the calorimeter energies.

For b-tagging precise knowledge of the collision point is needed. Hence, we use a primary vertex finding algorithm that is seeded by the primary vertex z position. The position of the primary vertex is determined by fitting the tracks within a 1 cm window around the seed vertex. The vertex fit is performed using CTVMFT [81], which is a commonly used FORTRAN based vertex fitting package, to obtain an event-by-event primary vertex, that was then used for secondary vertex tagging.

4.5 Trigger Efficiency

The trigger as described earlier acts as a fast decision maker based on information available to the online data acquisition system, to determine if an event should be kept or discarded. The online data reconstruction represents a simplified version, of the offline reconstruction and is therefore not as precise as the full offline reconstruction code. The selection efficiency of events depends on the online trigger. This trigger efficiency can be measured as a function of the related offline quantities. The collected data intrinsically includes the trigger efficiency, since it had to pass the

online trigger condition, in order to be part of our offline dataset. When comparing data with the simulation, this efficiency needs to be taken into account for. There exist two options:

- Simulate the online trigger and decide based on this information if a Monte Carlo event would pass the trigger or not.
- Parameterize the trigger efficiency using related offline quantities and use this parameterization to weight the Monte Carlo events according to the probability that they would pass the online trigger.

The second method has two advantages:

- This method does not have to rely on the trigger simulation and can instead use the parameterization of the trigger efficiency obtained from the data itself.
- The Monte Carlo sample can be used more effectively, since we do not reject Monte Carlo events, but instead we can assign a weight to them.

We chose the second method to be used for this analysis.

To estimate the trigger acceptance to be applied to the Monte Carlo processes, the trigger efficiency of the MET35 trigger was measured using unbiased datasets. We used the JET-20 and high p_T muon trigger sample to measure the Level-1 and Level-2 trigger efficiency. The JET-20 data sample requires at least one calorimeter cluster with $E_T \geq 15$ GeV at Level-2, which could bias the measured efficiency due to the particular characteristics of the energy flow in jet events. Hence, we also used the high p_T muon data, which is independent of the calorimeter.

The MET35 trigger is a combined trigger, in the sense that it requires $\cancel{E}_T$ at Level-1 and at least two Level-2 calorimeter clusters with $E_T > 10$ GeV. The trigger efficiency turn-on of Level-1 is computed as a function of the offline $\cancel{E}_T$.

For each value of the offline $\cancel{E}_T$, the L1 $\cancel{E}_T$ trigger efficiency is defined as:

$$\epsilon(\cancel{E}_T) = \frac{\text{\#Events passing L1\_MET35 requirement in unbiased Trigger}}{\text{\#Events passing unbiased Trigger}} \quad (4.6)$$

where the L1 requirement of the MET35 trigger requires $\cancel{E}_T$ to be above 25 GeV .

For those events passing the Level-1 trigger condition, the Level-2 trigger efficiency is computed. The MET35 trigger requires at Level 2 at least two calorimeter jet clusters with $E_T > 10$ GeV anywhere in the calorimeter. Therefore, we computed the Level 2 trigger efficiency as function of the offline E_T of the second reconstructed leading jet. The jet energy is computed with respect to the detector center and the jet is reconstructed within a radius of 0.4.

The L2 trigger efficiency is defined as:

$$\epsilon(E_T(2.\text{jet})) = \frac{\text{\#Events passing L2 + L1MET35 requirement in unbiased Trigger}}{\text{\#Events passing L1MET35 in unbiased Trigger}} \quad (4.7)$$

The trigger turn-on for Level 1, as well as for Level 2 was fitted with the fit function Eqn. (4.8):

$$\epsilon(x) = \frac{\epsilon_0}{1 + \exp -\frac{x-A_0}{\Delta}} \quad (4.8)$$

where ϵ_0 , is the asymptotic efficiency, A_0 the point at which the turn on reaches half efficiency, and Δ , describes the width of the turn-on. The efficiency is a function of x , which is $\cancel{E}_T$ and E_T of the second leading jet, for the Level-1 and Level-2 triggers, respectively.

The Level-1 trigger efficiency turn-on curves as a function of the offline $\cancel{E}_T$ could be sensitive to the calorimeter calibrations applied in different periods of time, as well as to the differences between the central and plug calorimeters. Figure 4.9 shows the $\cancel{E}_T$ trigger turn-on curves for data acquired in different time periods (that correspond to data taking periods between Tevatron shutdowns), and for events where the leading jet is reconstructed in the central calorimeter ($|\eta| < 1$), and when the leading jet is reconstructed in the plug calorimeter.

Figure 4.10 shows the trigger turn-on measured with the JET-20 and high p_T muon data samples and the obtained fitted function using the parameterization. The fit parameters for the two samples are summarized in Table 4.3.

Figure 4.11 shows the fitted function for the L1 and L2 trigger turn-on , computed using the high p_T muon sample. Muons are minimum ionizing particles (MIP), and

Figure 4.9. $\cancel{E}_T$ trigger turn-on efficiency for the MET35 trigger measured in the JET-20 sample, when the leading jet is in the central calorimeter (open crosses), in the plug calorimeter (solid squares) or anywhere (solid circles). Top left: for the period from September 2002 to January 2003. Top right: for the period from January 2003 to March 2003. Bottom: for the period from June 2003 to September 2003.

release their energy in narrow regions of the calorimeter. Hence, the turn-on curve is sharper than for the JET-20 sample shown in Figure 4.12.

The difference in the trigger turn-on efficiencies between both parameterizations as well as those between the different time periods and whether the leading jet falls

Figure 4.10. L2 Trigger turn-on efficiency curve for the MET35 trigger measured in the JET-20 sample (left), and measured in the high p_T muon sample (right). Central and Plug refers to the leading jet in that event being in the central or plug calorimeter.

Figure 4.11. Trigger efficiency turn-on curve for the MET35 trigger measured with the high p_T muon sample Left: L1 turn-on as function of the offline $\cancel{E}_T$. Right: L2 turn-on as function of the E_T of the second leading jet.

Figure 4.12. Trigger efficiency turn-on curve for the MET35 trigger measured with the JET-20 sample. Left: L1 turn-on as function of the offline $\cancel{E}_T$. Right: L2 turn-on as function of the E_T of the second leading jet.

into the central or plug calorimeter were taken into account as part of the systematic uncertainties (see Section 7.4). The fit parameters for Eqn. (4.8) obtained using the different samples, time periods, and geometrical requirements on the leading jet are summarized in Table 4.4.

Table 4.3
Parameterization of the Level-2 trigger turn-on as a function of the second leading jet trigger efficiency.

Sample	ϵ_0	A_0	Δ
JET-20	0.995 ± 0.005	10.8 ± 0.5	1.3 ± 0.1
Muon	0.994 ± 0.001	10.9 ± 0.02	1.1 ± 0.01

The weight assigned to Monte Carlo events depending on the offline reconstruction quantities is given by:

$$w = \epsilon_{\text{L1}}(\cancel{E}_T) \times \epsilon_{\text{L2}}(E_T(2.\text{jet})) \times \epsilon_{\text{L3}}(\cancel{E}_T) \quad (4.9)$$

since the $\cancel{E}_T$ reconstruction algorithm at L3 is identical to the offline missing transverse energy reconstruction, the efficiency for passing L3 $\cancel{E}_T$ requirement was set to 0 for $\cancel{E}_T \leq 35$ GeV and 1 for $\cancel{E}_T > 35$ GeV .

Table 4.4
 Parameterization of the L1 MET35 trigger efficiency with the JET-20 and high p_T muon data samples, for the different time periods and depending on the leading jet being in the central or plug calorimeter.

February 2002 - September 2002			
Sample	ϵ_0	A_0	Δ
JET-20 Anywhere	1.00 ± 0.06	30.2 ± 0.8	5.0 ± 0.6
JET-20 Central	1.00 ± 0.05	26.5 ± 0.5	3.8 ± 0.6
JET-20 Plug	0.99 ± 0.08	32.7 ± 1.1	4.3 ± 0.6
Muon Anywhere	1.00 ± 0.03	29.4 ± 0.4	3.6 ± 0.4
Muon Central	1.00 ± 0.04	28.1 ± 0.5	3.7 ± 0.6
Muon Plug	0.97 ± 0.05	30.1 ± 0.6	3.1 ± 0.4
September 2002 - March 2003			
Sample	ϵ_0	A_0	Δ
JET-20 Anywhere	0.98 ± 0.02	26.8 ± 0.2	2.9 ± 0.3
JET-20 Central	0.96 ± 0.03	25.7 ± 0.2	2.6 ± 0.4
JET-20 Plug	0.98 ± 0.03	27.6 ± 0.3	2.8 ± 0.3
Muon Anywhere	1.00 ± 0.03	29.4 ± 0.4	3.6 ± 0.4
Muon Central	1.00 ± 0.04	28.1 ± 0.5	3.7 ± 0.6
Muon Plug	0.97 ± 0.05	30.1 ± 0.6	3.1 ± 0.4
March 2003 - June 2003			
Sample	ϵ_0	A_0	Δ
JET-20 Anywhere	0.98 ± 0.03	27.0 ± 0.3	3.1 ± 0.4
JET-20 Central	0.96 ± 0.3	25.6 ± 0.3	2.4 ± 0.5
JET-20 Plug	1.00 ± 0.4	28.4 ± 0.5	3.2 ± 0.5
Muon Anywhere	1.00 ± 0.03	29.4 ± 0.4	3.6 ± 0.4
Muon Central	1.00 ± 0.04	28.1 ± 0.5	3.7 ± 0.6
Muon Plug	0.97 ± 0.05	30.1 ± 0.6	3.1 ± 0.4

5. Reconstruction

The jets, tracks, and leptons in data and Monte-Carlo simulation used in this analysis are reconstructed with the latest CDF reconstruction algorithms which provide detector geometry corrections and calibrations in order to obtain optimal performance for physics. This section describes tracking, B-Tagging, and jet reconstruction. It also introduces jet energy corrections and related corrections for the missing transverse energy, in order to improve their agreement between data and simulation. The algorithms and procedure to reconstruct high-level objects from raw detector data are discussed. Since this analysis heavily relies on $\cancel{E}_T$ and B-Tagging we focus on these topics.

5.1 Tracking

Particles trajectories can be reconstructed using information collected by tracking detectors. In this analysis we distinguish two different types of tracks, COT standalone tracks, which only use the tracking information from the central outer tracker and tracks seeded by the COT information but also have silicon hits. These tracks are called OI (Outside-In) tracks. In an homogeneous magnetic field charged particles travel on a helix that can be described by five parameters [82] given below:

$\cot \theta$	cotangent of the polar angle at minimum approach.
C	half curvature (same sign as the charge of the particle).
z_0	z position at point of minimum approach to origin of the helix.
d_0	signed impact parameter: distance between helix and origin at minimum approach.
ϕ_0	direction of track at point of minimum approach.

5.2 Jet Reconstruction

Calorimeter jets are reconstructed from the energy depositions in the calorimeter cells using a jet clustering algorithm [83], based on the original UA1 JETCLU [84, 85] algorithm, which is an iterative fixed cone algorithm using a cone size of radius $R = \sqrt{(\Delta\phi)^2 + (\Delta r)^2}$. We use jets with $R = 0.4$ that pass the following quality criteria:

- The fraction of the jet energy deposited in the electro-magnetic part of the calorimeter, with respect to its total energy is required to be between 0.1 and 0.9.
- Uncorrected clustered energy $E_T^{raw} > 10$ GeV
- The corrected energy of the jet $E_T^{corr} > 15$ GeV
- The jets are required to have $|\eta| < 2.0$

5.3 Jet Corrections

Standard methods have been developed at CDF to correct the measured jet energies to determine the energies which can be compared to theory. The jet energy corrections correct for seven different effects that can distort the measured jet energy. They correct for the response of the calorimeter to different particles, non-linear response of the calorimeter to the particle energies, uninstrumented regions of the detector, spectator interactions, and energy radiated outside the cone selected for jet clustering. Depending on the physics analyses, a subset of these corrections are applied. The corrections used by this analysis are listed below:

- Online/Offline calibrations, which provides the correct calorimeter energy scale.
- Relative corrections are applied to raw jet energies to make jet energy response uniform along η in different calorimeter towers.

- Raw scale corrections, which include absolute corrections for the calorimeter, and scale corrections between data and simulation.

Jet energy corrections could scale the jet energy down by about 10% or up by a maximum of about 40% as seen in Figure 5.1. We expect no jet to have corrected energy above 15 GeV if its uncorrected clustered energy is below 10 GeV.

Figure 5.1. The jet energy correction scale factor as a function of the detector η_d . The distribution was obtained from the MET35 sample.

5.4 Missing Energy Corrections

Particles escaping detection will cause an energy imbalance in the detector. Due to the beam pipe and limited calorimeter coverage in the high η region the detector does not possess hermetic coverage. In addition even though the energy of the colliding proton and antiproton is well known, the energies of the partons involved in the hard scattering process are not. For these two reasons we compute the transverse component of the missing energy, since we expected it to vanish, unless particles escape detection.

The missing transverse energy is calculated through the vector sum of all calorimeter deposits up to $|\eta| \leq 3.6$. The raw missing transverse energy is defined as the negative vector sum of the transverse energy in the calorimeter, given by:

$$\cancel{E}_x = - \sum_{i=1}^{N_{towers}} E_x^i, \quad (5.1)$$

$$\cancel{E}_y = - \sum_{i=1}^{N_{towers}} E_y^i \quad (5.2)$$

where the sum is taken over all towers of the detector (CEM, CHA, PHA, PEM, WHA) above a default threshold of 0.1 GeV. The magnitude of the missing transverse energy is then given by

$$\cancel{E}_T = \sqrt{(\cancel{E}_x)^2 + (\cancel{E}_y)^2} \quad (5.3)$$

The azimuthal angle $\phi_{\cancel{E}_T}$ is given by:

$$\phi_{\cancel{E}_T} = \tan^{-1} \left(\frac{\cancel{E}_y}{\cancel{E}_x} \right) \quad (5.4)$$

For the same reasons that we need to correct the jet energy scale, the measured missing transverse energy must also be corrected. Hence, the $\cancel{E}_T$, must be recomputed using corrected jets. The components of the missing transverse energy corrected for the jet energies are given by:

$$\cancel{E}_x^{corr-jet} = \cancel{E}_x^{RAW} + \sum_i^{N_{cluster}} (E_x^{i,corr} - E_x^{i,RAW}) \quad (5.5)$$

$$\cancel{E}_y^{corr-jet} = \cancel{E}_y^{RAW} + \sum_i^{N_{cluster}} (E_y^{i,corr} - E_y^{i,RAW}) \quad (5.6)$$

In addition muons transversing the calorimeter will also introduce missing energy, since only a small fraction of their energy is deposited in the calorimeter. If those muons are detected in the muon chambers we can correct the missing energy by using the muon momentum measured in the tracking chamber. :

$$\cancel{E}_x^{corr} = \cancel{E}_x^{corr-jet} - \sum_i^{N_{muons}} p_x^i \quad (5.7)$$

$$\cancel{E}_Y^{corr} = \cancel{E}_Y^{corr-jet} - \sum_i^{N_{muons}} p_y^i \quad (5.8)$$

We then use the corrected $\cancel{E}_T$ and also recompute the azimuthal angle $\phi_{\cancel{E}_T}$.

5.5 B-Tagging

There are different approaches to identifying jets that originate from the hadronization of b-quarks. Three high p_T B-Tagging algorithms have been used at CDF:

- The Soft Lepton Tagger [86] identifies low p_T (soft) leptons (e , or μ) coming from semileptonic b-decays.
- The Jet Probability Tagging algorithm [87] calculates the probability that the tracks associated with a jet originate from the event primary vertex.¹ It provides a continuous output between 0 and 1, reflecting the probability that a jet is a b-jet.
- The Secondary Vertex Tagging algorithm “SecVtx” [80] reconstructs a secondary displaced vertex in the jet.

SecVtx [80] is the most common high p_T B-Tagging algorithm used at CDF and the only one available at the time of this analysis. In addition it provides a better efficiency and lower fake rate compared to SLT.

SecVtx finds long lifetime B-Hadrons which have decay lengths large enough to be detected by CDF’s silicon vertex detector. This algorithm reconstructs the secondary vertex using tracks with large impact parameter d_0 , associated with a jet and a common primary vertex, that needs to be precisely known (see Section 4.4). The average lifetime of a B-hadron is given by $c\tau \simeq 450 \mu\text{m}$. The actual decay length $\Delta l = c\tau \cdot \beta\gamma$ is on the order of several mm, due to the Lorentz boost. SecVtx uses a two pass approach to finding secondary vertices. In the first pass, applying loose

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¹Even though the output is continuous, for practical reasons (tagging efficiency, tag rate matrix, ...), most analysis are also limited to fixed output values (1%, and 5%) for B-Tagging.

track selection criteria, it attempts to reconstruct a secondary vertex with at least three tracks. Failing this, it makes tighter track selection requirements and attempts to reconstruct a two track vertex in a second pass.

SecVtx is a jet based tagging algorithm, where only displaced tracks within the jet cone are considered. For the first pass we require at least three tracks that have $p_T > 0.5 \text{ GeV}/c$ and impact parameter significance $|d_0|/\sigma_{d_0} > 2.5$. For the second pass we require at least two tracks with $p_T > 1.0 \text{ GeV}/c$ and $|d_0|/\sigma_{d_0} > 3.0$. A set of cuts involving the p_T of the tracks, the number of silicon hits attached to the track, the quality of those hits, and requirements on the track fit are used to reject tracks of poor quality. A secondary vertex fit is then attempted using the tracks selected. If the vertex fit is successful, the two-dimensional decay length L_{xy} is computed. L_{xy} is positive if the secondary vertex is in direction of the jet and has a negative value if it is opposite to the jet. Figure 5.2 shows the definition of L_{xy} . The two-dimensional decay length, L_{xy} is the principal discriminant to identify B-jets, and it is required that $L_{xy}/\sigma_{L_{xy}} > 3$ for a positive tag. Vertices with $L_{xy}/\sigma_{L_{xy}} < -3$ are negative tags and useful in calculating the positive fake tag rate (see Section 6.2.2).

The b-tagging efficiency was measured for data and Monte Carlo and found to be higher for Monte Carlo. Hence, we apply a scale factor SF to scale the Monte Carlo to match the data ($\epsilon = \text{SF} \cdot \epsilon_{\text{MC}}$). The scale factor was measured to be $\text{SF} = 0.82 \pm 0.06$ [80].

5.6 Lepton Identification and Rejection

One distinctive characteristic of the gluino-sbottom signal is that we do not expect any isolated leptons in the events. In contrast some of the major Standard Model backgrounds are likely to produce high- p_T isolated leptons. Moreover top, Diboson (ZZ , WW , WZ), or W +jets can have large $\cancel{E}_T$ as a result of the neutrino from the decay of the W escaping detection, but this decay of the W -boson ($W \rightarrow l\nu_l$) also yields a high- p_T isolated lepton. Leptons in the signal, are due to the semileptonic

Figure 5.2. Schematic view of the secondary vertex tagging algorithm.

decays of the B-hadrons ($BR = 10.1 \pm 2.3\%$), which are non-isolated since they are close to the products of the b quark hadronization, the p_T of leptons from b-decay is also softer. Hence, we reject background by vetoing events with high p_T isolated leptons. To ensure good lepton rejection we use loose lepton identification cuts, to have high lepton identification efficiency.

5.6.1 Electron Identification and Rejection

Central electrons are identified using the following measured quantities:

- The transverse energy of the electron cluster E_T in the electromagnetic calorimeter.
- The ratio between the cluster energy and the track momentum (E/P).
- The ratio of the energy in the hadronic cluster to the electromagnetic cluster ($E_{\text{HAD}}/E_{\text{EM}}$).

- The lateral shower profile of the electromagnetic shower L_{shr} , which is a measure of the lateral sharing of energy among adjacent cluster towers.
- The distance between the extrapolated track and the CES measurement of the shower position $|\Delta X|$ and $|\Delta Z|$, in the $r - \phi$ view and z view, respectively.
- The quantity χ^2_{strip} , which is the χ^2 comparison of the CES shower profile with that of test-beam electrons.
- Tracking isolation ISO^{trk} , defined as ratio of the sum of p_T of all tracks in a cone of radius $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \leq 0.4$ and the p_T of the electron.

In addition for plug electrons the following quantity was used:

- $\chi^2(3 \times 3)$ is the χ^2 value of the 3×3 plug electromagnetic cluster fit that matches the electron object.

Isolated Electron Selection

Table 5.1 shows the requirements for the identification of a loose isolated electron, both central and plug.

Figure 5.3 and 5.4 show the distribution of the different identification variables for signal and the most relevant backgrounds for central electrons.

5.6.2 Muon Identification and Rejection

The measured quantities that were used for muon identification are listed below:

- The transverse momentum p_T of the track associated with the muon.
- The electromagnetic energy E_{EM} and hadronic energy E_{HAD} deposited in the calorimeter associated with the muon.
- Z_0 the reconstructed z position at the point of minimum approach to the origin of the helix associated with the muon track.

Table 5.1
Summary of loose electron identification cuts for central and plug electrons.

Central Electrons	
E_T	$\geq 10 \text{ GeV}$
E/P	< 4
HAD/EM	< 0.125
L_{shr}	< 0.2
$ \Delta X $	$< 3 \text{ cm}$
$ \Delta Z $	$< 5 \text{ cm}$
χ^2_{strip}	< 10
ISO^{trk}	< 0.2
Plug Electrons	
E_T	$\geq 10 \text{ GeV}$
HAD/EM	< 0.125
$\chi^2(3 \times 3)$	< 10

- The distance ΔX between the extrapolated track and the matched track segment in the corresponding muon chambers.

The requirements for muon identification are listed in Table 5.2. As for the case of the electrons, the p_T cut is optimized to be loose enough to guarantee good rejection while keeping high signal efficiency.

5.6.3 Track Isolation and Tau Rejection

For the rejection of hadronic τ decays as well as high- p_T isolated leptons that do not satisfy the fiducial cuts, we veto on the presence of high p_T isolated tracks. We loop over all the tracks in the event with $p_T \geq 10 \text{ GeV}/c$. For each track we compute the isolation defined as the $\sum p_T$ of all tracks in a cone of 0.4 radius around

Figure 5.3. Distribution of the electron identification variables as sequential cuts are applied as listed in Table 5.1. The areas of all histograms have been normalized to unity.

the seed track, divided by the p_T of the seed track. Figure 5.5 shows the track multiplicity distribution for signal and $t\bar{t}$, $Z \rightarrow \nu\nu$, $W \rightarrow e\nu$, $W \rightarrow \mu\nu$, and $W \rightarrow \tau\nu$ events, as well as the isolation distribution for those tracks. As we can see, a cut on the isolation of 0.1 provides good signal to background discrimination. Figure 5.6 shows the number of high p_T isolated track objects for signal and for the major backgrounds. By vetoing high p_T isolated tracks we can achieve high signal efficiency, while rejecting a large fraction of the background events.

Figure 5.4. Distribution of the electron identification variables as cuts progress. The areas of all histograms have been normalized to unity.

5.6.4 Further Optimization of the Lepton Veto

To evaluate the lepton veto, a few benchmark values of various gluino/sbottom/LSP mass scenarios were chosen, and the signal over square root of background was calculated. The lepton ID cuts were softened and tightened, with only a minor impact on the $S/\sqrt{B}$ as shown in Table 5.3).

Table 5.2
Summary of muon identification cuts.

CMU, CMP, CMU-CMP, CMX	
p_T	$\geq 10 \text{ GeV}/c$
EM	$< 2 \text{ GeV}$
HAD	$< 6 \text{ GeV}$
$HAD + EM$	$> 0.1 \text{ GeV}$
$ Z_0 $	$< 60 \text{ cm}$
CMU or CMU-CMP $ \Delta X $	$< 3 \text{ cm}$
CMP $ \Delta X $	$< 6 \text{ cm}$
CMX $ \Delta X $	$< 6 \text{ cm}$
CMIO	
p_T	$\geq 10 \text{ GeV}/c$
EM	$< 2 \text{ GeV}$
HAD	$< 6 \text{ GeV}$
$HAD + EM$	$> 0.1 \text{ GeV}$
$ Z_0 $	$< 60 \text{ cm}$

For the signal, we expect most of the jets to have originated from the hadronization of B mesons, and therefore to be characterized by a high track multiplicity inside the jet. Figure 5.7 shows the track multiplicity² for the leading and second leading jet in the event, together with the statistical significance of signal over W/Z plus jets backgrounds. Good rejection of remaining background events with high signal efficiency can be achieved requiring a track multiplicity for the leading jet of at least two tracks, and requiring at least one track for the second leading jet.

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²The tracks were the default tracks as provided by the standard CDF jet collection ($p_T > 0.5 \text{ GeV}/c$).

Figure 5.5. Top: number of tracks with $p_T > 10 \text{ GeV}/c$. Bottom: minimum track isolation.

Tables 5.4, 5.5 show the efficiency of the lepton veto cuts in removing Standard Model background.

5.6.5 Lepton Identification Validation

In order to validate the lepton ID cuts, Monte Carlo predictions were compared with data. The Monte Carlo of the $W/Z + 1, 2, 3$ parton processes were modeled with ALPGEN and processed with the CDF detector simulation. As a check, events were

Figure 5.6. Number of tracks per event with $p_T > 10 \text{ GeV}/c$ and isolation < 0.1 .

selected, that survive the $\cancel{E}_T$ clean up cuts (Section 4.3), have offline $\cancel{E}_T > 35 \text{ GeV}$ and failed the lepton veto, *i.e.* they have at least one isolated lepton present in the event. For these events, the transverse mass of the $\cancel{E}_T$ and the lepton, and the di-muon mass were computed for the W boson and Z boson samples, respectively. The same procedure was followed for the Monte Carlo and events were processed through the trigger simulation described in Section 4.5. Data events were classified into three groups, depending on the number of extra jets with $E_T > 10 \text{ GeV}$ found in the event: 0, 1 or 2. We compare the di-muon invariant mass spectrum of each of these groups with the ALPGEN samples of $W/Z + 0$, $W/Z + 1$, and $W/Z + 2$ partons, respectively. Figure 5.8 shows the transverse mass spectra for the different multiplicities of extra jets, where the Monte Carlo was normalized to the number of data events inside of a mass window around the W peak. Figure 5.9 shows the invariant mass spectra for the different multiplicities of extra jets, where the Monte Carlo was normalized to the number of data events inside of a mass window around the Z mass peak. The distributions show good agreement, except at low invariant masses in the di-muon data sample, due to J/ψ decays.

Table 5.3

Statistical significance of signal events over background for different lepton veto cuts for $\mathcal{L} = 200\text{pb}^{-1}$. Default cuts refer to those given in table 5.1 plus at least three jets with $E_T > 10$ GeV and $\cancel{E}_T^{corr} > 35$ GeV.

Benchmark point	I	II	III	IV
$m_{\tilde{g}}[\frac{\text{GeV}}{c^2}]$	200	200	200	220
$m_{\tilde{b}}[\frac{\text{GeV}}{c^2}]$	160	100	180	100
$m_{\tilde{\chi}_1^0}[\frac{\text{GeV}}{c^2}]$	60	60	100	60
Isolated lepton veto	$\frac{S}{\sqrt{B}}$			
default	14.99	13.42	11.40	6.91
default ($\frac{E}{P} < 2$)	14.92	13.36	11.34	6.87
default ($\frac{Had}{Em} < 0.1$)	14.97	13.40	11.38	6.90
default ($\frac{Had}{Em} < 0.0055 + 0.00045 * E \frac{E}{P} < 2$)	12.81	11.49	9.72	5.89
default (no χ_{wire}^2 cut)	12.49	13.35	11.40	6.83
default (no χ_{wire}^2 cut, $N_{trk,jet1} \geq 1$)	15.19	13.62	11.62	7.00
default (no χ_{wire}^2 cut, $N_{trk,jet1} \geq 2$)	15.50	13.91	11.83	7.13
default (no χ_{wire}^2 cut, $N_{trk,jet1} \geq 2 + N_{trk,jet2} \geq 1$)	15.68	13.92	11.96	7.44

Figure 5.7. Top: Number of tracks (default tracks from the CDF jet collection) in the leading jet (left) and statistical significance of signal over W/Z plus jets background as a function of the number of tracks in the leading jet (right). Bottom: Number of tracks (default tracks from the CDF jet collection) in the second leading jet (left), and statistical significance of signal over W/Z plus jets background as a function of the number of tracks in the second leading jet (right).

Table 5.4

The fraction of events is given that survive the clean up and basic selection cuts. Where the basic cuts require at least 3 jets with $E_T^{raw} > 10$ GeV, $|\eta| < 2.0$ and $\cancel{E}_T > 35$ GeV. Signal stands for the corresponding signal sample in a $(m_{\tilde{g}}, m_{\tilde{b}_1}, m_{\tilde{\chi}_1^0})$ mass scenario.

Process	MC Events	MetClean (eff)	Basic Cuts (eff)
tt	296,000	0.87	0.40
$W \rightarrow e\nu + 2$ partons	189,131	0.61	0.09
$W \rightarrow \mu\nu + 2$ partons	257,500	0.40	0.02
$W \rightarrow \tau\nu + 2$ partons	295,097	0.53	0.05
$Z \rightarrow ee + 2$ partons	247,500	0.74	0.03
$Z \rightarrow \mu\mu + 2$ partons	290,827	0.41	0.03
$Z \rightarrow \tau\tau + 2$ partons	245,784	0.63	0.05
$Z \rightarrow \nu\nu + 2$ partons	299,967	0.40	0.03
$Z \rightarrow b\bar{b} + 2$ partons	137,588	0.72	0.01
WW	25,878	0.75	0.10
WZ	20,000	0.74	0.08
ZZ	285,000	0.76	0.07
Signal (200,100,60)	12,889	0.88	0.60
Signal (200,160,60)	12,000	0.88	0.65
Signal (200,180,100)	10,000	0.88	0.49
Signal (220,100,60)	12,000	0.88	0.64

Table 5.5

Number of Monte Carlo events that survive the different vetoes. Electron, Muon, and high p_T isolated Track refers to the number of events that survive each of these vetoes independently. Total lepton veto refers to the number of events that survive all the vetoes combined. Signal stands for the corresponding signal sample in a $(m_{\tilde{g}}, m_{\tilde{b}_1}, m_{\tilde{\chi}_1^0})$ mass scenario.

Process	Basic Cuts	Electron	Muon	Iso. Track	Lepton Veto	Acceptance
tt	119,417	87,903	88,291	51,619	34.4%	13.9%
$W \rightarrow e\nu + 2 \text{ partons}$	17,519	3,711	17,453	5,994	10.6%	1.0%
$W \rightarrow \mu\nu + 2 \text{ partons}$	6,288	6,156	2,806	2,143	29.4%	0.7%
$W \rightarrow \tau\nu + 2 \text{ partons}$	14,211	12,324	13,743	9,797	61.6%	3.0%
$Z \rightarrow ee + 2 \text{ partons}$	6,227	937	5,900	265	0.8%	0.02%
$Z \rightarrow \mu\mu + 2 \text{ partons}$	7,858	7,721	1,576	875	8.9%	0.24%
$Z \rightarrow \tau\tau + 2 \text{ partons}$	11,091	8,629	9,096	4,539	33.3%	1.5%
$Z \rightarrow \nu\nu + 2 \text{ partons}$	7,547	7,406	7,521	7,165	92.9%	2.3%
$Z \rightarrow b\bar{b} + 2 \text{ partons}$	764	749	721	684	82.7%	0.46%
WW	2,640	1,491	2,335	1,189	30.3%	3.1%
WZ	1,638	1,076	1,453	883	42.3%	3.5%
ZZ	20,004	17,466	17,618	13,882	66.0%	4.6%
Signal (200,100,60)	7,676	7,565	7,347	7,028	86.7%	51.6%
Signal (200,160,60)	7,858	7,740	7,521	7,297	88.0%	57.6%
Signal (200,180,100)	4,922	4,852	4,740	4,633	89.6%	44.1%
Signal (220,100,60)	7,698	7,594	7,395	6,897	85.4%	54.8%

Figure 5.8. Reconstructed transverse mass ($\cancel{E}_T$ + central electron object) for data and ALPGEN $W \rightarrow e\nu + 0$ jets (top left), + 1 jet (top right) and + 2 jets (bottom). All events are required to satisfy the $\cancel{E}_T$ clean up cuts and have at least one lepton central object, defined as in Section 5.6. Jets are required to have at least $E_T > 10$ GeV. Monte Carlo is normalized to the number of data events around the W mass peak.

Figure 5.9. Reconstructed di-muon invariant mass for data and ALP-GEN $Z \rightarrow \mu\mu + 0$ jets (top left), $+ 1$ jet (top right) and $+ 2$ jets (bottom). All events are required to satisfy the $\cancel{E}_T$ clean up cuts and have at least one lepton central object, defined as in Section 5.6. Jets are required to have at least $E_T > 10$ GeV. Monte Carlo is normalized to the number of data events around the Z mass peak.

6. Signal and Background Simulation

6.1 Signal

Signal events were generated using the ISAJET event generator version 7.51 with parton distribution functions CTEQ5L [40]. The ISAJET parameters are described in appendix D. Monte Carlo data were generated along a mass grid in the gluino sbottom plane. The gluino masses were varied between $180 \text{ GeV}/c^2$ and $290 \text{ GeV}/c^2$ in steps of $10 \text{ GeV}/c^2$. Sbottom masses were varied beginning from $140 \text{ GeV}/c^2$ in steps of $10 \text{ GeV}/c^2$ towards the gluino mass. In addition to consider the nearly mass degenerate case, Monte Carlo events were generated with a mass difference between the gluino and sbottom of $6 \text{ GeV}/c^2$. The neutralino mass was fixed at $60 \text{ GeV}/c^2$, and any squark mass but the sbottom was set to $500 \text{ GeV}/c^2$. The gluino was forced to decay into sbottom-bottom followed by $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$. For each mass grid point 20K events were generated.

6.2 Standard Model Background

Many Standard Model processes have a signature resembling gluino pair production, decaying into sbottom bottom, with the sequential decay of the sbottom into bottom neutralino. These processes were all considered and taken into account when estimating the expected Standard Model background. The background was estimated using a combination of data itself and Monte Carlo simulation. Several different event generators were utilized, depending on the performance and implementation of physics processes. The Standard Model background contributions can be grouped into three main categories:

- QCD-multijet production

- W/Z+jets and Di-boson
- Top

which are each described in the following sections.

6.2.1 QCD-multijet Background

The QCD-multijet production can be divided into two parts, QCD heavy flavor ($b\bar{b}/c\bar{c}$ production) and light flavor production.

The heavy flavor production results in a final state of two or more jets, with two of them originating from the hadronization of the heavy flavor quarks. The production cross section is large with respect to the expected gluino pair production cross sections. If a jet is mis-measured, or one or more of the heavy flavor quarks decays semileptonically, then these events can have a substantial $\cancel{E}_T$. In both cases, of jet energy mismeasurement and semileptonic decay, the missing energy is highly correlated with the corresponding jet. For a semileptonic decay, the neutrino, points in the direction of the heavy-flavor jet, which results in an event where the missing energy is likely to be aligned with the jet. Similarly if one of the jets is mis-measured, the missing energy will point in the direction of or opposite to the jet.

The light flavor QCD-multijet background, can fake the signal, if the $\cancel{E}_T$ is caused by the jet mis-measurement and in addition if one or more of the light flavor jets are misidentified as a heavy flavor jet, which we refer to as a fake b-tag. This contribution was estimated directly from data as described in more detail in Section 6.2.2.

6.2.2 Fake B-Tag Rate

The total number of b-tags in an event is the sum of heavy flavor tags and fake tags. The probability for a fake b-tag can be estimated through a parameterization determined using a generic jet sample [88]. The probability that a jet is mis-tagged

is computed as a function of the E_T of the jet, $N_{\text{trk}}^{\text{good}}$, the number of good tracks associated with the jet, $\sum E_T^{\text{jets}}$ the sum of the transverse jet energies, and the η, ϕ of the jet [80].

The negative tag rate r_-^i is defined for each bin i in the space of $(E_T, N_{\text{trk}}^{\text{good}}, \sum E_T^{\text{jets}}, \eta, \phi)$, by:

$$r_-^i = \frac{\# \text{ tagged jets with } L_{xy} < 0 \text{ in bin } i}{\# \text{ taggable jets in bin } i} \quad (6.1)$$

where a jet is defined as taggable if it has two good tracks [80]. L_{xy} is the decay length. A positive decay length means that the scalar product of the vector from the primary vertex to the displaced vertex and the jet vector is positive. A negative decay length indicates that this product is negative, which means that the displaced vertex was reconstructed using the tracks associated to the jet, opposite from the jet. A negative decay length is clearly unphysical. Hence, a secondary vertex that is reconstructed opposite to the jet direction must be a fake vertex. Under the assumption that the probability of reconstructing a fake vertex on the positive or negative side of the jet is the same, one can estimate the positive fake tag rate, through the parameterization of the negative side tags. Due to material effects and long lived particles ($K_s, \Lambda, \dots$), the fake b-tag rate is about 20% higher for positive secondary vertices. Hence, we apply a scale factor $\alpha = 1.2 \pm 0.1$ to the negative mistag rate to accurately predict the positive fake b-tag contribution [104].

6.2.3 Heavy Flavor QCD-multijet Background

For the heavy flavor QCD-multijet background we generated multiple b-filtered¹ QCD-multijet Monte Carlo samples using the PYTHIA event generator [90]. A specific tune of the PYTHIA event generator developed for the CDF detector with parameters tuned to reproduce the underlying event measured by the CDF collaboration well [91, 92] was used. In order to obtain a sample that has all the contributions from flavor excitation, gluon splitting and direct production, we generated all $2 \rightarrow 2$

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¹Events were required to have at least one b-quark at the generator level.

process and applied a generator level b-filter to select events with b quarks (see appendix E for a closer description of heavy flavor production). QCD-multijet samples were generated using different $\hat{p}_T$, which is defined as the transverse momentum of the final partons in the hard interaction with respect to the initial ones, in a reference frame where the initial partons have no transverse momentum. Table 6.1 summarizes the different samples used, their corresponding cross section, the number of events after b-filtering, and the equivalent luminosity.

Table 6.1
 PYTHIA QCD-multijet Monte Carlo samples with at least one b-quark at generator level The given cross section in this table is the LO PYTHIA cross section as obtained from the event generator for the b-filtered QCD-multijet sample.

$\hat{p}_T$ range	σ [pb]	MC Events	Luminosity $\mathcal{L}$
$180 \text{ GeV}/c < \hat{p}_T$	$1.93 \cdot 10^1$	767024	39.7 fb^{-1}
$120 \text{ GeV}/c < \hat{p}_T < 180 \text{ GeV}/c$	$2.26 \cdot 10^2$	467135	2.1 fb^{-1}
$60 \text{ GeV}/c < \hat{p}_T$	$1.06 \cdot 10^4$	1573445	148 pb^{-1}
$40 \text{ GeV}/c < \hat{p}_T < 60 \text{ GeV}/c$	$6.27 \cdot 10^4$	2345267	37 pb^{-1}
$20 \text{ GeV}/c < \hat{p}_T < 40 \text{ GeV}/c$	$1.26 \cdot 10^6$	838750	0.7 pb^{-1}

The generator level b-filter had an efficiency of about 5.5% at low $\hat{p}_T$ and about 6.3% at high $\hat{p}_T$. No momentum cut on the b parton was applied. Figure 6.1 shows the differential cross sections obtained from a b-filtered QCD-multijet Monte Carlo sample with $\hat{p}_T > 60 \text{ GeV}/c$ and shows the different contributions of the gluon splitting, flavor excitation and direct production to the total cross section.

The combination of the different samples depending on the $\hat{p}_T$ is described in more detail in appendix F.

Figure 6.1. Differential cross sections obtained of the b-filtered QCD-multijet Monte Carlo sample which was generated with $\hat{p}_T > 60 \text{ GeV}/c$.

6.2.4 QCD-multijet Background Normalization

The QCD-multijet background due to heavy flavor production was estimated using the PYTHIA event generator. The PYTHIA production cross section at LO not necessarily describes the data well. We generated b-filtered QCD-multijet events. In addition to b-jets, we also expect some contribution from c-jets. QCD-multijet events with large $\cancel{E}_T$, have to be very energetic, which translates into a large value for $\hat{p}_T$. At large $\hat{p}_T$, the ratio between $c\bar{c}$ and $b\bar{b}$ production is constant as shown in Figure 6.2.

Figure 6.2. Ratio of charm to beauty as a function of $\cancel{E}_T$ in the event. For large $\cancel{E}_T$, the ratio is constant.

To estimate the total heavy flavor contribution in data correctly, we normalize the b-filtered QCD-multijet sample to data, using a region that is dominated by QCD-multijet production. It is defined by $35 \text{ GeV} < \cancel{E}_T < 50 \text{ GeV}$ and no high p_T

isolated leptons. The normalization is done, after basic clean up and preselection cuts have been applied to data and Monte Carlo. At this stage the sample is completely dominated by QCD-multijet background. No $\Delta\phi$ cuts between the $\cancel{E}_T$ and jets have been applied, which are aimed at rejecting the QCD-multijet background. We define the scale factor α as:

$$\alpha = \frac{N_{\text{obs}} - N_{\text{other background}}}{N_{\text{QCD MC}}} = \frac{(3490 \pm 59) - (772 \pm 332)}{3136 \pm 276} = 0.867 \pm 0.132 \quad (6.2)$$

where N_{obs} , is the number of observed B-Tags, $N_{\text{other background}}$ includes all the contribution from backgrounds other than Heavy Flavor QCD-multijet. Those backgrounds include top, W/Z+jets, Di-boson, and fake b-tags. $N_{\text{QCD MC}}$ is the contribution from heavy flavor QCD-multijet Monte Carlo. Figure 6.3 shows the $\Delta\phi(\cancel{E}_T, \text{jets})$ distribution for tagged jets before and after applying the scale factor. Figure 6.4 shows some of the relevant distributions after scaling the heavy flavor QCD-multijet Monte Carlo. All distributions are found to be in good agreement including the E_T of the third jet shown in Figure 6.5.

6.2.5 Top

Events due to $t\bar{t}$ production are similar to the signal, since they yield events with high jet multiplicities, two b -jets, and can have large $\cancel{E}_T$ from the W boson decay. An inclusive $t\bar{t}$ sample was generated using the PYTHIA event generator. As cross section for top production we use $6.7^{+0.7}_{-0.9}$ pb based on theoretical predictions [93].

6.2.6 Di-boson, W/Z + jets

W and Z plus multijet production and Di-boson contribute also to the total background. The size of the Monte Carlo sample, the corresponding NLO cross section

Figure 6.3. Comparing the predicted and observed events in the QCD-multijet dominated control region, before and after scaling the heavy flavor QCD-multijet Monte Carlo. The contribution from fake tags is shown on top of the predicted QCD-multijet, Top and Electroweak background. The dotted line describes the error bands on the total number of predicted events. The black crosses are the number of observed events in data.

(which is described in more detail in Section 6.3) and the luminosity equivalent to the sample size are given in Table 6.2.

The samples were generated using ALPGEN [94] version 1.1, using the CTEQ5L [40] parton distribution function (PDF). The HERWIG [95] 6.4 Monte Carlo was

Table 6.2
Background samples sizes, cross sections and corresponding luminosity.

Background channel	Number of Events	σ_{NLO} [pb]	Luminosity $\mathcal{L}$
$W \rightarrow e\nu_e + 2$ partons	189K	319.8	$591.4 pb^{-1}$
$W \rightarrow \mu\nu_\mu + 2$ partons	258K	319.8	$805.2 pb^{-1}$
$W \rightarrow \tau\nu_\tau + 2$ partons	295K	319.8	$922.8 pb^{-1}$
$Z \rightarrow e^+e^- + 2$ partons	246K	30.7	$8.00 fb^{-1}$
$Z \rightarrow \mu^+\mu^- + 2$ partons	291K	30.7	$9.47 fb^{-1}$
$Z \rightarrow \tau^+\tau^- + 2$ partons	246K	30.7	$8.00 fb^{-1}$
$Z \rightarrow \nu\nu + 2$ partons	300K	184.2	$1.63 fb^{-1}$
$Z \rightarrow b\bar{b} + 2$ partons	138K	144.3	$953.5 pb^{-1}$
WW	26K	11.1	$2.33 fb^{-1}$
ZZ	29K	1.26	$22.6 fb^{-1}$
WZ	20K	3.24	$6.17 fb^{-1}$
$t\bar{t}$	356K	6.7	$53.1 fb^{-1}$

used to shower the partons. The ALPGEN event generator describes in detail the multiparton hard processes in hadronic collisions. The exact matrix element calculation is performed to first order in α_s , for a large set of parton level processes, including $W + n$ partons and $Z + n$ partons, with $n \leq 4$. The following parameters were used at generator level:

- Renormalization scale Q^2 was set to the sum of the squares of the transverse momentum of the vector boson and the sum of the squares of the transverse momenta of the outgoing partons.
- Two or more final state partons were required.
- The final state gluon or quark is required to have $p_T > 8 \text{ GeV}/c$ and $|\eta| < 3$.

- The separation between the partons is required to be larger than 0.2 in $\eta - \phi$ -space.
- Charged leptons from W/Z-boson decay where required to have $p_T > 1 \text{ GeV}/c$ and $|\eta| < 6$.

6.3 NLO Cross Section Calculations

To compute the cross sections at NLO of the EWK processes (W/Z+jets/Di-boson), we use MCFM [96] (A Monte Carlo for FeMtobarn processes at Hadron Colliders). The cross sections obtained from this program had been reported to be in good agreement with data. We use the cross sections computed at NLO for W/Z+2 partons and Di-boson shown in Table 6.3. Contributions from processes with lower jet multiplicities had been found to be negligible due to the very low selection efficiency. The process $Z \rightarrow \nu\nu + 2$ partons is not implemented at NLO in MCFM and its cross section is taken to be six times that of $\sigma(Z \rightarrow ll + 2 \text{ partons})$. For the $Z \rightarrow b\bar{b} + 2$ partons process which is also not implemented at NLO in MCFM we took the LO ALPGEN cross section of $114.1 \pm 0.1 \text{ pb}$ and we scale it by a k -factor obtained from the ratio of the NLO MCFM cross section to the LO ALPGEN cross section for the $Z \rightarrow ll + 2$ partons ($k = 1.29$) and $W \rightarrow l\nu + 2$ partons ($k = 1.24$) process. We take the average of the two k -factor and scale the cross section by a factor $k = 1.265$. Hence, we predict a cross section of $144.3 \pm 2.9 \text{ pb}$ for the $Z \rightarrow b\bar{b} + 2$ partons process. Figure 6.6 shows the NLO cross section obtained by MCFM for the process $Z \rightarrow ll + 2$ partons as a function of $Q_{norm} = \sqrt{m_Z^2 + \langle p_T(Z) \rangle^2}$. It is used to set both the renormalization and factorization scale. The central value at $Q = Q_{norm}$ seems to fluctuate high. Hence, we computed three values for the cross section at the central value Q for $Q/Q_{norm} = 1.01, 1.00, 0.99$ and used the average, which was found to be $30.7 \pm 1.1 \text{ pb}$.

Table 6.3
MCFM NLO cross sections for $W/Z + 2$ partons processes used in this analysis.

Process	σ_{NLO} [pb]
$W \rightarrow l\nu_l + 2$ partons	319.8 ± 4.9
$Z \rightarrow ll + 2$ partons	30.7 ± 1.1
$Z \rightarrow \nu\nu + 2$ partons	184.2 ± 2.5
WW	11.11 ± 0.04
WZ	3.235 ± 0.010
ZZ	1.260 ± 0.004

The obtained cross sections have a systematic uncertainty of 12%, that we have computed varying the renormalization and factorization scale, from 0.5 to 2 as shown in Table 6.4.

Table 6.4
 $W/Z + 2$ partons MCFM NLO cross sections as a function of the normalization scale. As a systematic uncertainty on the MCFM NLO cross section we take the largest difference found here.

Process	MCFM σ_{NLO} [pb]	Difference
$Q_{\text{norm}} \quad W \rightarrow l\nu_l + 2$ partons	319.8 ± 4.9	
$0.5Q_{\text{norm}} \quad W \rightarrow l\nu_l + 2$ partons	341.4 ± 15.2	7.8%
$2Q_{\text{norm}} \quad W \rightarrow l\nu_l + 2$ partons	295.0 ± 8.2	6.8%
$Q_{\text{norm}} \quad Z \rightarrow ll + 2$ partons	30.1 ± 1.1	
$0.5Q_{\text{norm}} \quad Z \rightarrow ll + 2$ partons	33.6 ± 1.2	11.6%
$2Q_{\text{norm}} \quad Z \rightarrow ll + 2$ partons	27.4 ± 0.8	9.0%

As a cross check, we compare the LO cross sections obtained with MCFM and the cross sections obtained directly from ALPGEN (Table 6.5). As expected, they are in reasonable agreement.

Table 6.5
ALPGEN LO and MCFM LO cross section comparisons.

Process	ALPGEN σ_{LO} [pb]	MCFM σ_{LO} [pb]
$W \rightarrow l\nu_l$	2038 ± 0.6	2070.4 ± 1.7
$W \rightarrow l\nu_l + 1 \text{ partons}$	688.0 ± 0.8	705.0 ± 1.4
$W \rightarrow l\nu_l + 2 \text{ partons}$	258.7 ± 1.2	263.0 ± 2.3
$Z \rightarrow ll$	180.6 ± 0.2	179.1 ± 0.1
$Z \rightarrow ll + 1 \text{ partons}$	64.0 ± 0.1	64.8 ± 0.1
$Z \rightarrow ll + 2 \text{ partons}$	23.3 ± 0.1	24.3 ± 0.2

6.4 Monte Carlo Event Reconstruction

Events have been passed through the full detector simulation using runMC and were then reprocessed with latest software version available for the CDF standard ntuple. RunMC is a software package based on the CDF software framework, that combines event generation, detector simulation and production in one single program.

Figure 6.4. Comparison of Monte Carlo prediction with data after the QCD scale factor has been applied. The contribution from fake tags is shown on top of the predicted QCD-multijet, Top and Electroweak background. The dotted line describes the error bands on the total number of predicted events. Black crosses are observed events in data.

Figure 6.5. E_T spectrum of the 3^{rd} leading jet in the QCD dominated region, used for normalizing the QCD Monte Carlo sample.

Figure 6.6. $Z \rightarrow ll + 2 \text{ partons}$ and di-Boson production cross section as a function of Q/Q_{norm} .

7. Control Regions, Event Selection, and Systematic Uncertainties

7.1 Event Selection Optimization

We need to ensure that the dataset we consider in this analysis is well defined and not contaminated by bad data before comparing the data sample to Monte Carlo and optimizing the selection cuts. Therefore, we select only data from Runs in which all detector components relevant for this analysis were marked good (see Section 4.3.4). Events are required to pass the $\cancel{E}_T$ clean up cuts (see Section 4.3), in order to ensure that they do not originate from beam, or detector related effects. Further events are preselected based on the intrinsic trigger requirements. We require the offline $\cancel{E}_T^{\text{raw}}$ to be above 35 GeV. This requirement is identical to that applied at Level 3, but due to different online and offline calibration constants, an event passing the Level 3 trigger condition could still end up having missing transverse energy below 35 GeV. It is unphysical for an event to have more than 2.0 TeV of energy associated with it, therefore we reject those events.

Hence, we apply the following cuts on the MET35 dataset:

- Good Run requirements (see Section 4.3.4).
- $\cancel{E}_T$ clean up cuts (see Section 4.3).
- $\cancel{E}_T^{\text{raw}} > 35 \text{ GeV}$ computed with respect to the detector center ($z = 0 \text{ cm}$).
- $\sum E_T^{\text{raw}} < 2.0 \text{ TeV}$.

only after these cuts we can be sure that the data is not contaminated and we apply a second set of cuts. These cuts are aimed at preselecting a subset of the data,

that can then be compared with the Monte Carlo. The selection is based on the fundamental signal event characteristics.

- $N_{\text{jets}} \geq 3$ with $E_T^{\text{corr}} \geq 15$ GeV ($E_T^{\text{raw}} \geq 10$ GeV, $|\eta| < 2.0$)
- $\cancel{E}_T^{\text{corr}} \geq 35$ GeV

We require the events to be inclusive single tagged¹. In QCD-multijet events the $\cancel{E}_T$ tends to be aligned with the jets, since the $\cancel{E}_T$ is most likely to be caused by jet mismeasurements or by semileptonic b-decays. In both cases the $\cancel{E}_T$ points in direction of the jet, in contrast to the signal in which the dominant source of $\cancel{E}_T$ in the events comes from the two neutralinos escaping detection. In the signal there does not exist a strong correlation between the $\cancel{E}_T$ and the jets. To reduce the QCD-multijet background contribution, we require that the $\cancel{E}_T$ is not aligned with the jets. To optimize the selection requirements we compute the signal over square root of background, as a function of the minimum $\Delta\phi(\cancel{E}_T, \text{jets})$, where the minimum $\Delta\phi$ is evaluated separately using the first two, first three, first four leading jets, and the minimum $\Delta\phi$ between the $\cancel{E}_T$ and any of the jets in the event. For the optimization we define a basic signal region with no high p_T isolated leptons and $\cancel{E}_T > 50$ GeV. Figure 7.1 shows the different background contributions and signal for three representative mass scenario points. The $\frac{S}{\sqrt{B}}$ ratio is then calculated using all signal and background events accepted as a function of the selection criteria. All events shown have three or more corrected jets, because of the preselection requirement. Cutting on the minimum $\Delta\phi(\cancel{E}_T, \text{jets})$ using the first three jets, the first four jets or all the jets in the event yield very similar $\frac{S}{\sqrt{B}}$. However, the signal acceptance is higher by cutting only on the first three jets, since more phase space is left. Computing the $\frac{S}{\sqrt{B+S}}$ yields the same results.

To cover a broad range of different gluino/sbottom mass scenarios with one selection criteria, we try to obtain a high $\frac{S}{\sqrt{B}}$ for all different mass scenario points and

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¹This is needed to correctly estimate the total QCD background, since we use the heavy flavor QCD Monte Carlo sample and the mis-tag rate matrix to estimate the contribution from light flavor.

Figure 7.1. The $\frac{S}{\sqrt{B}}$ is shown for three benchmark scenario points:
 1. ($m_{\tilde{g}} = 260 \text{ GeV}/c^2$, $m_{\tilde{b}_1} = 160 \text{ GeV}/c^2$, $m_{\tilde{\chi}_1^0} = 60 \text{ GeV}/c^2$),
 2. ($m_{\tilde{g}} = 240 \text{ GeV}/c^2$, $m_{\tilde{b}_1} = 180 \text{ GeV}/c^2$, $m_{\tilde{\chi}_1^0} = 60 \text{ GeV}/c^2$),
 3. ($m_{\tilde{g}} = 240 \text{ GeV}/c^2$, $m_{\tilde{b}_1} = 220 \text{ GeV}/c^2$, $m_{\tilde{\chi}_1^0} = 60 \text{ GeV}/c^2$). The solid histogram describes the Standard Model background which is the combination of QCD-multijet, $W/Z + \text{jets}$ and Top. (Note: The background is completely dominated by QCD-multijet at this stage). The minimum azimuthal angle $\Delta\phi(\cancel{E}_T, \text{jet})$, between the $\cancel{E}_T$ and each of the three highest p_T jets in the event. The left vertical axis describes the number of events, for the background (as solid histogram) and signal events (solid line), which are small and only slightly above the horizontal axis. The dotted lines, give the $\frac{S}{\sqrt{B}}$ shown on the right vertical axis as a function of $\Delta\phi(\cancel{E}_T, \text{jet})$.

not restrict ourself to a specific scenario. In order to keep a large signal acceptance with a high $\frac{S}{\sqrt{B}}$ we decide to cut on the minimum $\Delta\phi(\cancel{E}_T, \text{jet})$ for the first three

jets. After applying this cut we investigate if any other selection criteria can yield a significant improvement. Additional $\Delta\phi$ cuts between jets and $\cancel{E}_T$ yield no further improvement. It can be seen that by increasing the $\cancel{E}_T$ the total $\frac{S}{\sqrt{B}}$ can be substantially increased as seen in Figure 7.2.

Figure 7.2. The $\frac{S}{\sqrt{B}}$ (right vertical axis) is plotted as a function of the $\cancel{E}_T$ selection cut, for three different benchmark mass scenario points (dotted lines). It can be seen that by increasing the $\cancel{E}_T$ the total $\frac{S}{\sqrt{B}}$ can be substantially increased.

7.2 Control Regions

After the basic selection cuts have been applied one can divide the data into four regions, depending on the $\cancel{E}_T$ and if high p_T isolated leptons are present or not in the event. We expect the signal to have large $\cancel{E}_T$ and no high p_T isolated leptons. We can define three control regions and the signal region.

- Region C0 : Events with isolated high p_T leptons, $35 \text{ GeV} < \cancel{E}_T < 50 \text{ GeV}$.
- Region C1 : Events with no isolated high p_T leptons, $35 \text{ GeV} < \cancel{E}_T < 50 \text{ GeV}$.
- Region C2 : Events with isolated high p_T leptons, $\cancel{E}_T > 50 \text{ GeV}$.
- Region C99 : Events with no isolated high p_T leptons, $\cancel{E}_T > 50 \text{ GeV}$.
- Signal Region : Events with no isolated high p_T leptons, $\cancel{E}_T > 80 \text{ GeV}$.

Figure 7.3 shows a schematic plot defining signal and control regions. C99 is the signal like region which is signal enriched, that was then studied to define the final selection cuts to achieve optimal signal sensitivity.

Figure 7.3. Schematic plot showing the definition of signal and control regions.

The control regions play an important part in the analysis. Each of the control regions is dominated by a different background. Control region C0 has similar background contributions from Top, QCD-Multijet, W/Z+jets, and Di-boson. Control region C1 is dominated by the contribution from QCD-Multijet. Control region C2 provides a cross check of the Top background. By predicting the observed events in data correctly in each of the control regions we gain confidence that the background estimation is reliable. We compute the total number of expected background events in the three control regions. We observe good agreement between the number of observed and expected inclusive single b-tagged events as shown in Table 7.1.

In addition to predicting the total number of Standard Model background events correctly, we study the relevant distributions in each of the control regions, which provides a more thorough cross check. Figure 7.4, Figure 7.5, and Figure 7.6 show the $\Delta\phi$ in the different control regions between the b-tagged jets and the $\cancel{E}_T$. It can be seen that Standard Model background describes the data distributions well.

Figure 7.7, Figure 7.8, and Figure 7.9 show the jet E_T distributions, $\sum E_T$, and good track multiplicity in the tagged jets for the different control regions. It can be seen that Standard Model background describes the data distributions well.

Figure 7.10 shows the $\cancel{E}_T$ spectrum, for exclusive single b-tagged events with high p_T isolated leptons present and Figure 7.11 for inclusive double b-tagged events. Both spectra show good agreement between Standard Model background predictions and observations.

Table 7.1

Total number of expected events in the control regions. Fake B-Tag is the contribution from the light flavor jets , that are misidentified as heavy flavor jets. The total number of predicted events is in agreement with the number of observed events in data. We quote the statistical uncertainties here.

Control Region	C0	C1	C2
$\cancel{E}_T$	35 – 50 GeV	35 – 50 GeV	> 50 GeV
Isolated high p_T lepton	required	vetoed	required
$W \rightarrow e\nu + 2$ partons	1.38 ± 0.56	0.38 ± 0.30	2.76 ± 0.77
$W \rightarrow \mu\nu + 2$ partons	1.23 ± 0.44	0.60 ± 0.31	2.95 ± 0.68
$W \rightarrow \tau\nu + 2$ partons	0.26 ± 0.19	5.14 ± 0.87	1.63 ± 0.47
$Z \rightarrow ee + 2$ partons	$0.00^{+0.02}_{-0}$	$0.00^{+0.02}_{-0}$	0.02 ± 0.02
$Z \rightarrow \mu\mu + 2$ partons	0.12 ± 0.04	0.05 ± 0.03	0.13 ± 0.04
$Z \rightarrow \tau\tau + 2$ partons	0.31 ± 0.07	0.15 ± 0.05	0.27 ± 0.07
$Z \rightarrow \nu\nu + 2$ partons	0.08 ± 0.08	1.04 ± 0.29	0.62 ± 0.22
$Z \rightarrow b\bar{b} + 2$ partons	$0.00^{+0.13}_{-0}$	2.15 ± 0.55	0.13 ± 0.13
ZZ	0.17 ± 0.03	1.11 ± 0.08	0.41 ± 0.05
WZ	0.12 ± 0.05	0.16 ± 0.06	0.22 ± 0.07
WW	0.26 ± 0.12	0.21 ± 0.11	0.48 ± 0.16
Total W/Z+jets/Di-boson	3.9 ± 0.8	11.0 ± 1.2	9.6 ± 1.2
$t\bar{t}$	11.7 ± 0.2	8.2 ± 0.1	35.2 ± 0.3
QCD-multijet MC	13.4 ± 2.9	105.3 ± 12.3	2.9 ± 1.1
Fake B-Tag	5.8 ± 3.0	24.3 ± 12.1	8.0 ± 4.4
Total Predicted	34.8 ± 4.2	148.8 ± 17.3	55.7 ± 4.7
Observed	36	121	63

Figure 7.4. $\Delta\phi$ distributions in control region C0. Top left plot shows $\Delta\phi(\cancel{E}_T, \text{anyjet})$, where any jet is any b-tagged jet that passes our jet requirements. Top right plot shows $\Delta\phi(\cancel{E}_T, 1^{st} \text{ jet})$, where 1st jet is the leading jet in the event, if it is b-tagged. Bottom left plot shows $\Delta\phi(\cancel{E}_T, 2^{nd} \text{ jet})$, where 2nd jet the second leading jet in the event, if it is b-tagged. Bottom right plot shows $\Delta\phi(\cancel{E}_T, 3^{rd} \text{ jet})$, where 3rd jet the third leading jet in the event, if it is b-tagged. For each plot the angle of the $\cancel{E}_T$ with respect to the b-tag is shown, where the b-tag is in the highest, 2nd highest, or 3rd highest jet.

Figure 7.5. $\Delta\phi$ distributions in control region C1. Top left plot shows $\Delta\phi(\cancel{E}_T, \text{anyjet})$, where any jet is any b-tagged jet that passes our jet requirements. Top right plot shows $\Delta\phi(\cancel{E}_T, 1^{\text{st}} \text{ jet})$, where 1st jet is the leading jet in the event, if it is b-tagged. Bottom left plot shows $\Delta\phi(\cancel{E}_T, 2^{\text{nd}} \text{ jet})$, where 2nd jet the second leading jet in the event, if it is b-tagged. Bottom right plot shows $\Delta\phi(\cancel{E}_T, 3^{\text{rd}} \text{ jet})$, where 3rd jet the third leading jet in the event, if it is b-tagged. For each plot the angle of the $\cancel{E}_T$ with respect to the b-tag is shown, where the b-tag is in the highest, 2nd highest, or 3rd highest jet.

Figure 7.6. $\Delta\phi$ distributions in control region C2. Top left plot shows $\Delta\phi(\cancel{E}_T, \text{anyjet})$, where any jet is any b-tagged jet that passes our jet requirements. Top right plot shows $\Delta\phi(\cancel{E}_T, 1^{st} \text{ jet})$, where 1st jet is the leading jet in the event, if it is b-tagged. Bottom left plot shows $\Delta\phi(\cancel{E}_T, 2^{nd} \text{ jet})$, where 2nd jet the second leading jet in the event, if it is b-tagged. Bottom right plot shows $\Delta\phi(\cancel{E}_T, 3^{rd} \text{ jet})$, where 3rd jet the third leading jet in the event, if it is b-tagged. For each plot the angle of the $\cancel{E}_T$ with respect to the b-tag is shown, where the b-tag is in the highest, 2nd highest, or 3rd highest jet.

Figure 7.7. Distributions in control region C0. E_T of the b-tagged jets (top left) and E_T of the 1st (top right), 2nd (middle left), 3rd (middle right) jet if it is b-tagged. Sum of the jet energy of the events (bottom left), and the good track multiplicity for b-tagged jets (bottom right).

Figure 7.8. Distributions in control region C1. E_T of the b-tagged jets (top left) and E_T of the 1st (top right), 2nd (middle left), 3rd (middle right) jet if it is b-tagged. Sum of the jet energy of the events (bottom left), and the good track multiplicity for b-tagged jets (bottom right).

Figure 7.9. Distributions in control region C2. E_T of the b-tagged jets (top left) and E_T of the 1^{st} (top right), 2^{nd} (middle left), 3^{rd} (middle right) jet if it is b-tagged. Sum of the jet energy of the events (bottom left), and the good track multiplicity for b-tagged jets (bottom right).

Figure 7.10. $\cancel{E}_T$ spectrum, for events with a b-tag jet and one or more high p_T isolated leptons.

Figure 7.11. $\cancel{E}_T$ spectrum, for inclusive double b-tagged events with one or more high p_T isolated leptons.

7.3 Cuts Summary

In the following list we enumerate the applied selection cuts:

1. Good run selection
2. $\cancel{E}_T$ Clean up (see Section 4.3) (includes $Z_{vertex} \leq 60$ cm and Beam Halo Filter).
3. Offline $\cancel{E}_T > 35$ GeV with respect to $z = 0$ cm, $\sum E_T < 2.0$ TeV.
4. BasicData: $N_{jets} \geq 3$ with $E_T^{corr} \geq 15$ GeV ($E_T^{raw} \geq 10$ GeV, $|\eta| < 2.0$),
 $\cancel{E}_T^{corr} \geq 35$ GeV.
5. Isolated high p_T lepton veto.
6. $\Delta\phi$ cuts (see Section 7.1).
  - $\Delta\phi(\cancel{E}_T, 1, 2, 3. \text{ jet}) > 40^\circ$.
7. $\cancel{E}_T^{corr} > 80$ GeV.
8. Divide signal region:
  - Exclusive single SecVtx Tag
  - Inclusive double SecVtx Tag

We perform the exclusive single SecVtx Tag and inclusive double SecVtx Tags in parallel to have a better constraint on the background and signal.

Table 7.2
Signal acceptance (for $m_{\tilde{g}} = 240 \text{ GeV}/c^2, m_{\tilde{b}_1} = 180 \text{ GeV}/c^2, m_{\tilde{\chi}_1^0} = 60 \text{ GeV}/c^2$) as selection cuts are applied.

	Signal MC
Trigger	83.1%
Cleanup	73.6%
BasicData	64.9%
Lepton veto	53.7%
$\Delta\phi$ cuts	38.8%
$\cancel{E}_T > 80 \text{ GeV}$	21.6%
Inclusive single b-tag	16.7%
Exclusive single b-tag	7.7%
Inclusive double b-tag	9.0%

7.4 Systematic Uncertainties

The systematic uncertainties on the backgrounds to the signal of the gluino-sbottom analysis have been studied in detail.

7.4.1 Background Uncertainties

For the prediction of the number of estimated background events, the following uncertainties are considered:

- Luminosity: the systematic uncertainty in the luminosity is taken to be 6% (see section 3.2.6).
- We used standard error propagation, to propagate the uncertainty due to the PDF selected in our simulation. A detailed discussion of the method used to estimate the PDF uncertainties is given in the following sources [97–102]. PDF uncertainty on the cross section for all background processes is found to be 2%.
- The uncertainty due to the $\Delta\phi$ cuts between the jets and $\cancel{E}_T$ is partially contained in the jet corrections uncertainty, that lead to changes in the $\cancel{E}_T$ angle, while keeping the ϕ of the jets constant. Nevertheless to explore separately the effect due to the $\Delta\phi$ cuts, we apply the jet correction and correct the $\cancel{E}_T$, but leave the $\cancel{E}_T \phi$ unchanged. We compute the difference in acceptance and find the change to be smaller than 0.5% both for signal and background. As an upper estimate we assign a systematic of 0.5% due to the $\Delta\phi$ cuts.
- The uncertainty due to the calorimeter energy scale has been determined, by varying the jet energy corrections separately by one standard deviation and recomputing the acceptances. The different corrections are independent and the total uncertainty is obtained by adding the uncertainties due to the individual correction in quadrature. The systematics on the energy scale have been determined separately for all different backgrounds For the top background an

uncertainty of 16% for single b-tag and 14.5% for inclusive double b-tagged events has been determined. For W/Z+jets/Di-boson backgrounds an uncertainty of 25% for both exclusive single b-tag and inclusive double b-tagged events, is used. We take 25% as an upper limit on the of the energy scale uncertainty for all W/Z+jets/Di-boson backgrounds. QCD-multijet Monte Carlo shows a similar dependence on the energy scale and we find an uncertainty of 25% for single b-tagged and inclusive double b-tagged events.

- QCD Monte Carlo scale factor uncertainty: The QCD Monte Carlo scale factor was found to be 0.867 ± 0.132 (see Section 6.2.4). We scale the QCD-multijet Monte Carlo down by 13% which results in a systematic uncertainty on the QCD-multijet Monte Carlo of 15%.
- The systematic uncertainty on the b-tagging efficiency is taken to be the error on the b-tagging efficiency scale factor between data and Monte Carlo, which was found to be 7% [80, 89]. For the double b-tag this uncertainty is consequently doubled to 14%.
- We assign a 8% systematic uncertainty on the SecVtx tagging rate matrix [103] as determined by comparing the tag rate matrix prediction and the observed tag rate, with respect to the data sample, trigger bias, statistics, and mismeasurements in the $\sum E_T$. We double the systematic uncertainty when predicting double b-tagged events.
- We assign an 11% systematic uncertainty [104] to the scale factor used to predict the positive fake b-tags with the negative side of the SecVtx tagging rate matrix. This scale factor is due to hadronic interactions of particles in the beampipe, or the silicon, which can produce conversions giving a displaced vertex and contamination from long-lived light hadrons.
- The W/Z+partons cross section are computed with MCFM simulation. A 11.5% systematic error is found by varying the normalization scale by increas-

ing or dividing the renormalization and factorization scale by a factor of two. (see Section 6.3)

- We assign a trigger efficiency uncertainty for background and signal simulation. It is found by comparing the acceptance using different trigger turn on functions, depending on the time period and evaluated using the high p_T muon sample or the jet sample. For top, W/Z+jets/Di-boson Monte Carlo and QCD-multijet background the trigger efficiency uncertainty is found to be 2.5% or smaller.
- We assign a lepton veto systematic of 2.0%. We have to consider two separate effects. First, it is possible that an event containing a real lepton is not rejected, due to the limited lepton identification (ID) efficiency. The difference in the lepton ID efficiency in data and Monte Carlo is our systematic. The loose electrons ID efficiency in data is 94.0% [105] for standard selection cuts and an 96.1% for Monte Carlo. Hence, this translate into a systematic uncertainty of 2%. We need also to consider the effect of misidentified leptons or fake leptons. We compute the lepton fake rate on data and Monte Carlo using a sample lacking in leptons such as the inclusive jet sample. A difference of 2.0% is found, which we use as systematic uncertainty. Hence, we assign a total uncertainty on the lepton veto of 2.0%.

Systematic uncertainties are summarized in Table 7.3. We distinguish between uncertainties that are correlated between signal and background and those that are uncorrelated.

7.4.2 Signal Acceptance Uncertainties

The signal acceptance uncertainty has been computed for a representative range of mass scenario points. If no dependence was found and the behavior was similar for different mass scenarios the systematic uncertainty was taken to be the upper

Table 7.3
Summary of the correlated and uncorrelated systematic error on background.

Uncertainty	W/Z+jets/Di-boson		TOP		QCD-multijet	
B-Tags	= 1	≥ 2	= 1	≥ 2	= 1	≥ 2
Luminosity	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%
Tagging efficiency	7.0%	14.0%	7.0%	14.0%	7.0%	14.0%
Energy scale	25.0%	25.0%	16.0%	14.5%	25.0%	25.0%
Trigger efficiency	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
Total correlated	28.0%	29.5%	18.5%	21.0%	27.0%	29.5%
PDF uncertainty	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
QCD scale factor	-	-	-	-	15.0%	15.0%
Cross section	11.5%	11.5%	13.5%	13.5%	-	-
Lepton veto	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
$\Delta\phi$ cuts	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
Total uncorrelated	11.5%	11.5%	13.5%	13.5%	15.0%	15.0%
Total	30.5%	31.5%	23.0%	25.0%	31.0%	33.0%

estimate of it and used for the mass scenarios. If a strong dependence on the mass of the sparticles was found, the uncertainty was determined as a function of the masses. The relative systematic uncertainties on the acceptance of our signal are listed in Table 7.4.

The uncertainty on the signal acceptance due to the parton content of the proton is found using a standard reweighting method [97]. The uncertainty due to the initial (ISR) and final state radiation (FSR) modeling in ISAJET is found by turning ISR and FSR separately off. This uncertainty has a strong dependence on the mass difference between the gluino and sbottom, as can be seen in Table 7.5. A dependence on the absolute mass of the gluino is not seen as shown in Table 7.6. The systematic

Table 7.4
Signal acceptance uncertainty for non-degenerate gluino and sbottom mass.

Signal acceptance uncertainties	Exclusive single b-tag	Inclusive double b-tag
Luminosity	6.0%	6.0%
Trigger Efficiency	2.5%	2.5%
Tagging Efficiency	7.0%	14.0%
Energy Scale	10.0%	10.0%
Total correlated	14.0%	18.5%
PDF	2.0%	2.0%
ISR/FSR	7.5%	5.0%
MC Statistics	3.0%	3.0%
Vertex Cut	0.5%	0.5%
$\Delta\phi$ Cuts	0.5%	0.5%
Lepton veto	2.0%	2.0%
Total uncorrelated	8.5%	6.5%
Total	16.5%	19.5%

uncertainty due to the trigger efficiency is found using different parameterizations obtained for the muon and the JET-20 sample, as described in Section 4.5.

As Monte Carlo statistics we assign a systematic error that is calculated using the uncertainty in the signal acceptance due to Monte Carlo statistics.

7.5 Final Optimization and Expected Limit

In order to optimize the $\cancel{E}_T$ cut for the signal region we compute the expected limit for five different $\cancel{E}_T$ cuts ($\cancel{E}_T > 50, 60, 70, 80, 90$ GeV). As an example of the

Table 7.5

The uncertainty in the signal acceptance due to ISR/FSR shows a strong dependence on the mass difference between the gluino and sbottom.

Mass scenario			Exclusive	Inclusive
$m_{\tilde{g}}$	$m_{\tilde{b}_1}$	$m_{\tilde{\chi}_1^0}$	single b-tag	double b-tag
GeV / c^2	GeV / c^2	GeV / c^2		
240	200	60	5.5%	5.0%
240	210	60	7.5%	3.5%
240	220	60	14.0%	5.5%
240	230	60	14.0%	9.5%
240	234	60	26.5%	9.0%

Table 7.6

The uncertainty in the signal acceptance due to ISR/FSR shows little dependence on the gluino mass, if we keep the mass difference, between gluino and sbottom constant.

Mass scenario			Exclusive	Inclusive
$m_{\tilde{g}}$	$m_{\tilde{b}_1}$	$m_{\tilde{\chi}_1^0}$	single b-tag	double b-tag
GeV / c^2	GeV / c^2	GeV / c^2		
220	214	60	28.0%	9.0%
230	224	60	26.0%	10.0%
240	234	60	26.5%	9.0%

total background contribution, for $\cancel{E}_T > 50$ GeV we obtain the following number of expected events for the signal region, given in Table 7.7.

Figure 7.12 shows the $\cancel{E}_T$ distribution for exclusive single b-tag and inclusive double tagged events. We find that the requirement of $\cancel{E}_T > 80$ GeV to optimize

Table 7.7
Number of expected events in signal region with $\cancel{E}_T > 50$ GeV .

Process	Exclusive single b-tag	Inclusive double b-tag
W/Z+jets/Di-boson	$17.0 \pm 1.4 \pm 5.0$	$1.2 \pm 0.3 \pm 0.4$
TOP	$15.1 \pm 0.8 \pm 2.9$	$4.7 \pm 0.4 \pm 1.0$
QCD-multijet MC	$27.0 \pm 5.7 \pm 12.0$	$4.7 \pm 2.7 \pm 1.8$
Fake B-tag	$16.8 \pm 7.8 \pm 2.3$	$0.2 \pm 0.2 \pm 0.1$
Total Predicted	75.9 ± 16.7	10.9 ± 3.5

Figure 7.12. $\cancel{E}_T$ distribution for exclusive single b-tag and inclusive double b-tagged events. Total expected background and three selected signal scenarios are shown.

the physics reach. Table 7.8 summarizes the total number of expected background events for the different $\cancel{E}_T$ cuts and the number of signal events that can be excluded at 95% C.L. assuming the observed number of events to be equal to the total predicted background. Figure 7.13 shows the corresponding expected exclusion limit for exclusive single b-tagged events.

Table 7.8

Expected number of background events for different $\cancel{E}_T$ cuts. The two errors given on the background is the correlated and uncorrelated error. The number of signal events, that can be excluded at 95% C.L. are also given. The number of expected signal events are given for the following mass scenario $m_{\tilde{g}} = 240 \text{ GeV}/c^2$, $m_{\tilde{b}_1} = 200 \text{ GeV}/c^2$, $m_{\tilde{\chi}_1^0} = 60 \text{ GeV}/c^2$. The number given in the brackets is the signal acceptance.

$\cancel{E}_T$ GeV	Expected background	Assumed observed	N^{Limit} at 95% C.L.	Expected signal
> 50	$75.9 \pm 12.0(\text{corr}) \pm 11.6(\text{uncorr})$	76	50.4	40.4 (0.127)
> 60	$40.1 \pm 4.4(\text{corr}) \pm 6.7(\text{uncorr})$	40	26.3	36.1 (0.113)
> 70	$26.1 \pm 2.7(\text{corr}) \pm 4.2(\text{uncorr})$	26	18.6	32.4 (0.103)
> 80	$16.6 \pm 1.8(\text{corr}) \pm 2.4(\text{uncorr})$	17	14.2	26.4 (0.083)
> 90	$11.4 \pm 1.4(\text{corr}) \pm 1.6(\text{uncorr})$	12	11.9	21.9 (0.069)

Figure 7.13. Expected exclusion limit from exclusive single b-tagged events for five different definitions of the signal region depending on the $\cancel{E}_T$ cuts.

For the double b-tag we are dominated by small statistics on the QCD-multijet Monte Carlo (Figure 7.12). In order not to be biased by small statistics and Monte Carlo weights we use $\cancel{E}_T > 80 \text{ GeV}$ which showed the largest $S/\sqrt{B}$, as shown earlier in Figure 7.2. Table contains the total number of expected inclusive double b-tagged events using a $\cancel{E}_T$ cut of 80 GeV.

8. Results

8.1 Results

The analysis was performed blind, which means that we only looked in the signal region after the selection cuts had been finalized and the predicted number of events agreed with the observed events in the control region.

In the signal region (using $\cancel{E}_T > 80$ GeV) we expect 16.4 ± 3.7^1 exclusive single b-tagged and 2.6 ± 0.7 inclusive double b-tagged events, as given in Table 8.1.

Table 8.1

Number of expected events in signal region with $\cancel{E}_T > 80$ GeV. The uncertainty given is statistical and systematic. Total QCD-multijet is the combination of heavy flavor QCD-multijet Monte Carlo and the contribution from light flavor fake b-tags.

Process	Exclusive single b-tag	Inclusive double b-tag
W/Z+jets/Di-boson	$5.66 \pm 0.76(\text{stat}) \pm 1.72(\text{sys})$	$0.61 \pm 0.21(\text{stat}) \pm 0.19(\text{sys})$
Top	$6.18 \pm 0.12(\text{stat}) \pm 1.42(\text{sys})$	$1.84 \pm 0.06(\text{stat}) \pm 0.46(\text{sys})$
QCD-multijet MC	$0.85 \pm 0.19(\text{stat}) \pm 0.26(\text{sys})$	$0.14 \pm 0.06(\text{stat}) \pm 0.05(\text{sys})$
Fake B-tag	$3.72 \pm 1.62(\text{stat}) \pm 0.50(\text{sys})$	$0.04 \pm 0.04(\text{stat}) \pm 0.01(\text{sys})$
Total QCD-multijet	$4.57 \pm 1.64(\text{stat}) \pm 0.57(\text{sys})$	$0.18 \pm 0.08(\text{stat}) \pm 0.05(\text{sys})$
Total Predicted	$16.41 \pm 1.81(\text{stat}) \pm 3.15(\text{sys})$	$2.63 \pm 0.23(\text{stat}) \pm 0.66(\text{sys})$
Observed	21	4

We observe 21 exclusive single b-tagged events by requiring $\cancel{E}_T > 80$ GeV as shown in Figure 8.1. The $\cancel{E}_T$ spectrum for inclusive double b-tagged events is shown in Figure 8.2. Four events are observed with 2.6 ± 0.7 expected from Standard

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¹with the error being the result of the statistical and systematic error added in quadrature.

Model background. The distributions are found to be in good agreement with the predictions from Standard Model.

Figure 8.1. $\cancel{E}_T$ spectrum, for exclusive single b-tagged events with no high p_T isolated leptons.

Figure 8.2. $\cancel{E}_T$ spectrum, for inclusive double b-tagged events with no high p_T isolated leptons.

The gluino pair production cross section decaying into sbottom bottom is given by:

$$\sigma \cdot \text{BR}(\tilde{g} \rightarrow \tilde{b}_1 b) = \frac{N}{\epsilon \cdot \mathcal{L}} \quad (8.1)$$

where N is the number of events in the signal region, ϵ is the selection efficiency as a function of the gluino and sbottom mass, and $\mathcal{L}$ is the integrated luminosity. Assuming a branching ratio $\text{BR}(\tilde{g} \rightarrow \tilde{b}_1 b) = 100\%$ we can derive a cross section upper limit based on the acceptance and relative acceptance error. The upper limit cross section is given by $\sigma^{\text{lim}} = \frac{N^{\text{lim}}}{\epsilon \cdot \mathcal{L}}$.

We use a Bayesian likelihood method [106] to determine the upper limit on the possible number of signal events N^{lim} . For the determination of the upper limit on the possible number signal events we take the correlation of the uncertainties between the background and signal acceptance properly into account. Table 8.2 shows the

predicted number of Standard Model background events for the signal region with the associated correlated and uncorrelated uncertainties.

Table 8.2

Number of expected events in signal region with $\cancel{E}_T > 80$ GeV. The error given is the correlated and uncorrelated error. In Table 8.3 a breakdown of the different W/Z + jets/Di-boson contributions is given.

Process	Exclusive single b-tagged
W/Z + jets/Di-boson	$5.66 \pm 1.58(\text{corr}) \pm 1.02(\text{uncorr})$
Top	$6.18 \pm 1.14(\text{corr}) \pm 0.85(\text{uncorr})$
QCD-multijet MC	$0.85 \pm 0.23(\text{corr}) \pm 0.23(\text{uncorr})$
Fake B-tags	$3.72 \pm 0.0(\text{corr}) \pm 1.70(\text{uncorr})$
Total Predicted	$16.41 \pm 2.95(\text{corr}) \pm 2.17(\text{uncorr})$
Observed	21
Process	Inclusive double b-tagged
W/Z + jets/Di-boson	$0.61 \pm 0.18(\text{corr}) \pm 0.22(\text{uncorr})$
Top	$1.84 \pm 0.39(\text{corr}) \pm 0.26(\text{uncorr})$
QCD-multijet MC	$0.14 \pm 0.04(\text{corr}) \pm 0.07(\text{uncorr})$
Fake B-tags	$0.04 \pm 0.0(\text{corr}) \pm 0.04(\text{uncorr})$
Total Predicted	$2.63 \pm 0.61(\text{corr}) \pm 0.35(\text{uncorr})$
Observed	4

The breakdown of the W/Z + jets/Di-boson background in the signal region is given in Table 8.3.

For the exclusive single b-tagged analysis we expect 16.4 ± 3.7 and observe 21 events. Using the Bayesian likelihood method we can exclude 20.6 signal events at 95% C.L. For inclusive double b-tagged events we observe four events with 2.6 ± 0.7 expected from standard model background, which leads to 8.7 signal events that can

Table 8.3
Composition of the total W/Z+jets/Di-boson background in the signal region.

Process	Exclusive single b-tagged	Inclusive double b-tagged
$W \rightarrow e\nu + 2 \text{ partons}$	0.64 ± 0.37	0.00 ± 0.00
$W \rightarrow \mu\nu + 2 \text{ partons}$	0.47 ± 0.27	0.00 ± 0.00
$W \rightarrow \tau\nu + 2 \text{ partons}$	1.63 ± 0.47	0.33 ± 0.19
$Z \rightarrow ee + 2 \text{ partons}$	0.00 ± 0.00	0.00 ± 0.00
$Z \rightarrow \mu\mu + 2 \text{ partons}$	0.01 ± 0.01	0.00 ± 0.00
$Z \rightarrow \tau\tau + 2 \text{ partons}$	0.08 ± 0.04	0.00 ± 0.00
$Z \rightarrow \nu\nu + 2 \text{ partons}$	1.70 ± 0.36	0.06 ± 0.06
$Z \rightarrow b\bar{b} + 2 \text{ partons}$	0.00 ± 0.00	0.00 ± 0.00
ZZ	0.94 ± 0.07	0.18 ± 0.03
WZ	0.08 ± 0.04	0.03 ± 0.02
WW	0.11 ± 0.08	0.00 ± 0.00
Total	$5.7 \pm 1.5(\text{corr}) \pm 1.0(\text{uncorr})$	$0.6 \pm 0.2(\text{corr}) \pm 0.2(\text{uncorr})$

be excluded at 95% C.L. Table 8.4 and 8.5 gives a list of the observed events in the signal region. Figure 8.8, 8.9, and 8.10 show the event displays of some selected events.

Figure 8.6 shows the obtained exclusion limits in the $m_{\tilde{g}}, m_{\tilde{b}_1}$ plane, for the exclusive single and inclusive double SecVtx b -tagging requirement. Figure 8.7 shows the obtained upper limit cross section at 95% C.L. as a function of the sbottom mass and for a fixed gluino mass. Figure 8.5 shows the upper limit cross section at 95% C.L. as a function of the gluino mass for a fixed mass difference between the gluino and sbottom of 60 GeV/ c^2 .

Table 8.4

Exclusive single b-tagged events observed in the signal region. The $\cancel{E}_T$ and jet energies are given after applying the jet corrections.

Exclusive single b-tagged Events								
Dataset	Run	Event	$\cancel{E}_T$	N_{jet}	E_T leading jets [GeV]			
			GeV		1 st	2 nd	3 rd	4 th
emet08	148856	599097	87.0	4	81.3	68.4	48.9	42.2
emet08	149493	504754	97.1	3	73.0	69.9	17.0	
emet08	151477	2490416	89.6	3	46.5	37.3	22.6	
emet08	151844	2975586	103.1	4	66.7	52.4	38.9	18.3
emet08	154021	1825302	105.6	3	224.8	22.8	21.4	
emet08	155145	444716	91.9	3	49.1	45.4	19.6	
emet08	155920	213260	104.7	4	79.3	58.1	57.1	52.0
emet09	160437	1460402	82.8	3	68.5	26.8	25.6	
emet09	160533	3042363	114.8	6	52.8	52.3	33.4	24.1
emet09	160988	2107297	240.5	5	94.7	82.4	47.8	41.2
emet09	162396	5229	80.6	3	65.4	28.4	18.9	
emet09	163385	294225	80.0	4	94.0	78.2	72.7	15.7
emet09	152599	521298	96.5	3	41.5	40.9	37.3	
emet09	152615	701534	82.6	5	100.5	52.7	44.6	44.5
emet09	153618	247107	86.5	4	114.3	30.9	23.8	17.8
emet09	164989	2270126	196.6	3	155.3	54.5	36.1	
emet09	165314	1337	108.8	4	109.3	54.2	44.9	16.4
emet09	166653	126914	100.9	3	97.5	41.8	33.4	
emet09	166662	8048692	91.3	5	71.1	43.3	28.3	27.5
emet09	166927	4101727	85.7	6	190.7	103.2	60.2	19.2
emet09	167186	540049	178.5	4	219.5	116.5	67.3	23.5

Table 8.5

Inclusive double b-tagged events in the signal region. The $\cancel{E}_T$ and jet energies are given after applying the jet corrections.

Inclusive double b-tagged Events								
Dataset	Run	Event	$\cancel{E}_T$	N_{jet}	E_T leading jets [GeV]			
			GeV		1 st	2 nd	3 rd	4 th
emet08	148154	809998	127.0	3	81.0	35.9	29.6	
emet09	162178	2053478	99.6	6	82.4	44.7	31.8	29.9
emet09	163113	3710957	86.4	3	85.3	51.6	30.0	
emet09	165873	4313671	129.8	4	95.4	61.1	41.2	33.9

Figure 8.3. $\Delta\phi$ distributions in the signal region. The distributions are in agreement with the predictions from the Standard Model.

Figure 8.4. Comparing distributions for data and predictions in the signal region. E_T of the b-tagged jets (top left) and E_T of the 1^{st} (top right), 2^{nd} (middle left), 3^{rd} (middle right) jet if it is b-tagged. Sum of the jet energy of the events (bottom left), and the good track multiplicity for b-tagged jets (bottom right).

Figure 8.5. 95% C.L. upper cross section limit as a function of the gluino mass and a fixed mass difference between the gluino and sbottom of $60 \text{ GeV}/c^2$.

Figure 8.6. 95% C.L. exclusion contours in the $m_{\tilde{g}}$ and $m_{\tilde{b}_1}$ plane.

Figure 8.7. 95% C.L. upper cross section limit as a function of the sbottom mass and a fixed gluino mass $m_{\tilde{g}} = 240 \text{ GeV}/c^2$. It can be seen that for the nearly mass degenerate gluino sbottom scenario the limit obtained from exclusive single b-tagged events is better. As we approach very small mass differences the systematic error gets dominated by ISR/FSR, which prevents us from setting a better limit.

8.2 Signal Candidate Events

Figure 8.8. Run 160988 Event 2107297

Figure 8.9. Run 160437 Event 1460402

Figure 8.10. Run 163113 Event 540049

Table 8.6
Expected limits for exclusive single b-tagged analysis.

Luminosity	Assumed observed	Expected events	Uncorrelated uncertainty	Correlated uncertainty	N^{lim}
156 pb ⁻¹	21	16.41	±2.17	±2.95	20.6
156 pb ⁻¹	17	16.41	±2.17	±2.95	16.1
0.5 fb ⁻¹ (x3.2)	53	52.60	±6.96	±9.46	38.8
2.0 fb ⁻¹ (x12.8)	211	210.4	±27.8	±37.8	137.7

8.3 Future Prospects and Expected Limits

We calculate the expected upper limit on signal events at 95% C.L. by scaling the number of expected events according to the luminosity and recalculating the limits. Table 8.6 gives the number of signal events that can in this way be excluded at 95% C.L. for exclusive single b-tagged analysis. Table 8.7 gives the the upper limit cross section for various mass scenario points for different luminosities. Similarly for the inclusive double b-tagged analysis the limits are recalculated, in Table 8.8 and Table 8.9. The upper cross section limit at 95% C.L. for exclusive single and inclusive double b-tagged events are shown in Figure 8.11. We expect to be sensitive to gluino masses well above 300 GeV/ c^2 , with a data sample of 2 fb⁻¹.

In the appendix I the signal acceptances for different mass scenario points is summarized.

Table 8.7
Upper limit cross section at 95% C.L. for exclusive single b-tagged events.

		Observed	Expected limit		
		$\mathcal{L} = 156 \text{ pb}^{-1}$	$\mathcal{L} = 156 \text{ pb}^{-1}$	$\mathcal{L} = 0.5 \text{ fb}^{-1}$	$\mathcal{L} = 2.0 \text{ fb}^{-1}$
$m_{\tilde{g}}$	$m_{\tilde{b}_1}$	$N^{\text{lim}} = 20.6$	$N^{\text{lim}} = 16.1$	$N^{\text{lim}} = 38.8$	$N^{\text{lim}} = 137.7$
GeV/ c^2	GeV/ c^2	$\sigma^{\text{lim}} [\text{pb}]$	$\sigma^{\text{lim}} [\text{pb}]$	$\sigma^{\text{lim}} [\text{pb}]$	$\sigma^{\text{lim}} [\text{pb}]$
200	140	3.080	2.400	1.809	1.605
210	150	2.576	2.013	1.513	1.342
220	160	2.061	1.611	1.211	1.074
230	170	1.921	1.501	1.128	1.001
240	180	1.723	1.346	1.012	0.898
250	190	1.529	1.195	0.898	0.797
260	200	1.435	1.121	0.843	0.748
270	210	1.222	0.955	0.718	0.637
280	220	1.306	1.020	0.767	0.680
290	230	1.285	1.004	0.755	0.670

Table 8.8
Upper limit cross section at 95% C.L. for inclusive double b-tagged events.

		Observed	Expected limit		
		$\mathcal{L} = 156 \text{ pb}^{-1}$	$\mathcal{L} = 156 \text{ pb}^{-1}$	$\mathcal{L} = 0.5 \text{ fb}^{-1}$	$\mathcal{L} = 2.0 \text{ fb}^{-1}$
$m_{\tilde{g}}$	$m_{\tilde{b}_1}$	$N^{\text{lim}} = 8.65$	$N^{\text{lim}} = 7.23$	$N^{\text{lim}} = 13.0$	$N^{\text{lim}} = 35.5$
GeV/ c^2	GeV/ c^2	σ^{lim} [pb]	σ^{lim} [pb]	σ^{lim} [pb]	σ^{lim} [pb]
200	140	1.219	1.019	0.571	0.390
210	150	0.975	0.815	0.457	0.312
220	160	0.812	0.679	0.381	0.260
230	170	0.687	0.574	0.322	0.220
240	180	0.616	0.515	0.289	0.197
250	190	0.595	0.498	0.279	0.190
260	200	0.502	0.419	0.235	0.160
270	210	0.478	0.400	0.224	0.153
280	220	0.467	0.391	0.219	0.150
290	230	0.419	0.350	0.196	0.134

Table 8.9
Expected limits for inclusive double b-tagged analysis.

Luminosity	Observed	Expected	Uncorrelated	Correlated	N^{lim}
		events	error	error	
156 pb $^{-1}$	4	2.63	± 0.35	± 0.61	8.65
156 pb $^{-1}$	3	2.63	± 0.35	± 0.61	7.23
0.5 fb $^{-1}$ ($\times 3.2$)	9	8.43	± 1.12	± 1.96	13.0
2.0 fb $^{-1}$ ($\times 12.8$)	34	33.7	± 4.5	± 7.8	35.5

Figure 8.11. Expected 95% C.L. upper limit cross section as a function of the gluino mass and a fixed mass difference between the gluino and sbottom of 60 GeV/c² for exclusive single b-tag analysis (left) and inclusive double b-tag analysis (right).

9. Conclusion

We searched for scalar bottom quarks from gluino decays in 156 pb^{-1} of CDF Run II data collected between July 2002 and September 2003. We investigated a final state with large missing transverse energy and three or more jets. We performed two analyses, to accommodate different event kinematics, depending on the mass differences between the gluino and scalar bottom. We either required one of the jets in the event to be b-tagged, or two or more of the jets to be so identified as b-jets. Three control regions were defined, each of them dominated by a different set of Standard Model backgrounds. The analysis was performed blind, in the sense that the signal region was investigated only after all selection cuts had been finalized and agreement between Standard Model predictions and observed events in the control regions had been achieved in all relevant distributions. We observe 21 exclusive single b-tagged events which is in agreement with Standard Model background expectations of 16.4 ± 3.7 events. We predict 2.6 ± 0.7 inclusive double b-tagged events from Standard Model background and observe 4 events. Hence, no evidence for scalar bottom quarks from gluino decays was observed and we are able to set a 95% C.L. exclusion limit as a function of the mass of the gluino and scalar bottom [107].

The requirements imposed in this analysis were aimed at keeping the search as broad as possible. The obtained exclusion limit is given as a function of the sparticle masses. This allows for a reinterpretation of the limits in a specific SUSY model, which would predict certain sparticle masses and branching ratios. The limits can then be scaled accordingly.

The analysis methods developed and applied in this search are relevant for many other searches for physics beyond the Standard Model, among them searches for the Standard Model Higgs Boson, and for third generation scalar quarks. Even though, we chose one benchmark model, it provides a general test of the Standard Model,

in a region of parameter space in which new physics might be seen. Signatures with missing transverse energy indicate one or more particles escaping detection. For example, postulated exotic particles like the neutralino, which would be an excellent candidate for cold dark matter, would just leave the detector without a trace, except through a measurable energy imbalance.

The Tevatron will continue to define the high energy accelerator physics frontier for the next few years, until the era of the Large Hadron Collider will begin, but it cannot provide the final answer about supersymmetry. The Large Hadron Collider is needed to increase the energy scale and to address physics at the TeV scale. Nevertheless it is important to perform searches for physics beyond the Standard Model at the Tevatron. If supersymmetry would occur in a region of parameter space accessible to the Tevatron, then searches like the one described here present a discovery potential for the Tevatron. The Tevatron is also an excellent training ground for the LHC. The experience gained and the analysis methods tested at the Tevatron will help with a fast and successful start up of the LHC.

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APPENDIX

A. Silicon

Silicon (Si) is one of the most widely used semiconductors, because of its unique properties. It has a diamond like structure, an atomic weight of 28.09 u, an atomic number of $Z = 14$ and a density of $2.33 \frac{g}{cm^3}$. Silicon has a band gap of 1.1 eV, low enough to ensure production of free charge carriers from a minimum-ionizing particle (MIP), but high enough to avoid very large dark current generation at room temperature.

Silicon has excellent mechanical properties (high modulus of elasticity) and it is a low Z element, which helps limiting multiple scattering. The mean square of the scattering angle increases linearly with the thickness t , and is quadratic in Z ($\langle \theta^2 \rangle \sim Z^2 t$). Silicon has the big advantage over other detector materials that it has many commercial applications in integrated circuits (IC). An IC combines several circuit elements on a single chip of semiconductor material, as opposed to a “non-integrated” circuit, in which the transistors, diodes, resistors, etc., are fabricated separately and then assembled. Silicon is easy to handle and wafers can be mass-produced with very high purity levels and assembled in complex geometries with no degradation of their electrical characteristics. A more detailed description of silicon detectors can be found in [108].

B. Silicon Detectors

Initially silicon vertex detectors were used in fixed target experiments. They were unreliable and required large electronic modules to read them out. Hence, the use of silicon vertex detectors in collider experiments became possible only after the technology became more robust and the electronics to read them out became small enough so that they could be mounted near the sensors without taking too much space and introducing too much material in the inner detector, which is a source for multiple scattering. The electronics also had to be made radiation hard, so that it could withstand the environment next to the beam. The lifetime of the silicon vertex detector is required to be of the same order as the expected running time of the detector experiment, or it needs to be replaced. The sensors became thinner, to minimize the multiple scattering of the particles passing through it. Today a large variety of silicon vertex detectors are in use in fixed target, collider experiments, and on satellites ¹. See Table B.1 for a comparison of the sizes of various experiments using silicon vertex detectors.

Semiconductor detectors, or solid-state detectors are used in high energy physics as high-resolution charged particle track detectors. They make use of the fact that charged particles passing through a semiconductor create electron-hole pairs. The principle is similar to gas ionization devices like wire chambers or Geiger counters, where a passing charged particle leaves a track of ions and electrons. The advantage of a semiconductor detector is that the average energy needed to create an electron-hole pair is small. For silicon $\langle E_{h-e} \rangle = 3.62 \text{ eV}$, which is roughly a factor of 10 less than that required for gas ionization.

To protect the active region of the detector (bulk) from environmental contamination and to terminate the silicon lattice at the surface in a way that reduces the

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¹AMS is scheduled to fly on the International Space Station in October 2005 [109].

Table B.1

The comparison of some of the major experiments using silicon trackers shows the continuous growth in size and complexity of the systems.

Size of Silicon Detector Components			
Experiment	Year	Number of Channels	Silicon Area [m ²]
CMS	2007	100×10^5	223
ATLAS	2007	61.5×10^5	60
AMS 2	2005	1.96×10^5	6.5
CDF (SVX II)	2001	7.39×10^5	10.7
DØ 2	2001	7.93×10^5	4.7
Babar	1999	1.40×10^5	0.95
L3	1993	0.86×10^5	0.23
CDF (SVX')	1992	0.40×10^5	0.70

density of surface states, a thin silicon dioxide layer is often grown on the surface of the silicon wafer (oxide passivation).

C. Missing E_T Trigger

Listing of the four missing transverse energy triggers:

MET35_&_TWO_JETS trigger:

- L1: $\cancel{E}_T > 25$ GeV
- L2: 2 clusters (10 GeV , $|\eta| = (0, 3.6)$)
- L3: $\cancel{E}_T > 35$ GeV

MET_BJET trigger:

- L1: $\cancel{E}_T > 15$ GeV + 2 XFT tracks
- L2: 2 SVT tracks ($p_T > 2$ GeV , $1\text{mm} > d_0 > 100\mu\text{m}$)
- L3: $\cancel{E}_T > 20$ GeV

MET45 trigger:

- L1: $\cancel{E}_T > 25$ GeV
- L2: AUTO
- L3: $\cancel{E}_T > 45$ GeV

L1 MET25 calibration trigger:

- L1: $\cancel{E}_T > 25$ GeV (prescale 100)
- L2: AUTO
- L3: AUTO

D. ISAJET Parameter File

ISAJET parameter file used to generate signal Monte Carlo events. The file below is for a mass scenario of gluino mass $m_{\tilde{g}} = 200 \text{ GeV}/c^2$, sbottom mass $m_{\tilde{b}_1} = 180 \text{ GeV}/c^2$, and neutralino mass $m_{\tilde{\chi}_1^0} = 60 \text{ GeV}/c^2$. A detailed description of the parameters can be found in the ISAJET manual [110].

```

PBAR + P --> SUSY
1960.,1,1000,0/
SUPERSYM
BEAMS
'P','AP'/
TMASS
175.,-1.,-1./
PDFLIB
'NPTYPE',1.D0,'NGROUP',4.D0,'NSET',46.D0,'TMAS',175.D0/
SQUARK
500.00,500.00,500.00,500.00,180.00,500.00/
SLEPTON
500.00,500.00,500.00,500.00,500.00,500.00/
GAUGINO
200.00,60.00,500.00,500.00/
JETTYPE1
'GLSS'/
JETTYPE2
'GLSS'/
SEED                               /Random no. seed

```

0.432533568246E+14 /

PT

.1,930.0,.1,930.0/

NTRIES

100000/

END

STOP

E. Heavy Flavor Production Mechanisms

E.1 Direct Production

Heavy flavor can be created in a QCD hard 2-to-2 process through quark-antiquark annihilation $q\bar{q} \rightarrow b\bar{b}$ or gluon-gluon fusion $gg \rightarrow b\bar{b}$, shown in Figure E.1.

Figure E.1. Lowest-order Feynman diagrams of $b\bar{b}$ direct production.

E.2 Flavor-excitation

In a QCD hard 2-to-2 reaction a b-quark is scattered out of the initial-state into the final-state by a gluon or a light quark via the subprocess $gb \rightarrow gb$, or $qb \rightarrow qb$, shown in Figure E.2.

Figure E.2. Feynman diagrams of flavor-excitation process.

E.3 Gluon Splitting

Gluon splitting is a higher order $2 \rightarrow 3$ parton process producing $b\bar{b}$ through a gluon that is radiated off and splits into a heavy flavor pair, shown in Figure E.3.

Figure E.3. Examples of Feynman diagrams contributing to the gluon splitting process.

F. Combining QCD-multijet Samples

QCD-Multijet Monte Carlo samples were generated using different $\hat{p}_T$ ranges. The production cross-section was then taken from the event generator. Samples were generated in such a way that they did not have overlapping $\hat{p}_T$ ranges, and where it was unavoidable cuts were placed to select events only of a specified $\hat{p}_T$ range. In this way one can simply add the contributions from the different QCD-Multijet samples taking the corresponding cross-section for the $\hat{p}_T$ range in order to obtain the total contribution. Through normalization to data one obtains a scale factor that was applied to the cross-sections.

Figure F.1. Combination of three QCD-multijet samples generated at different $\hat{p}_T$ ($20 - 40 \text{ GeV}/c$, $40 - 60 \text{ GeV}/c$, $> 60 \text{ GeV}/c$). The three plots show the number of events passing as a function of the $\hat{p}_T$ after applying clean up and basic selection cuts and $\cancel{E}_T > 35 \text{ GeV}$ (left), $\cancel{E}_T > 50 \text{ GeV}$ (middle), and $\cancel{E}_T > 80 \text{ GeV}$ (right).

Figure F.1 shows the combination of QCD background samples generated with different $\hat{p}_T$. It can be seen that, by requiring $\cancel{E}_T > 80 \text{ GeV}$, as done for the signal region, only events with $\hat{p}_T > 60 \text{ GeV}/c$ contribute.

G. Groups

Table G.1
Common groups

Group		Matrices in group
$U(n)$	$n \times n$	unitary
$SU(n)$	$n \times n$	unitary and $\det A = 1$
$O(n)$	$n \times n$	orthogonal
$SO(n)$	$n \times n$	orthogonal and $\det A = 1$

A unitary matrix U is one whose inverse is equal to its transpose conjugate ($U^{-1} = \tilde{U}^*$). If the determinant of the matrix is equal to unity it is called special S . Real unitary $n \times n$ matrices, form a group $O(n)$, which stands for orthogonal matrix. For an orthogonal matrix the following is true $O^{-1} = \tilde{O}$

H. Gauge Bosons of the Standard Model

Table H.1
Gauge Bosons of the Standard Model.

Gauge Bosons of the Standard Model (1-spin)
g
γ
Z
$W^\pm$

Table H.2
Particles of the Standard Model.

Particles of the Standard Model ($\frac{1}{2}$ -spin) / Fermions					
Quarks			Leptons		
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	u_R	d_R	$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_R$		e_R
$\begin{pmatrix} c \\ s \end{pmatrix}_L$	c_R	s_R	$\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_R$		μ_R
$\begin{pmatrix} t \\ b \end{pmatrix}_L$	t_R	b_R	$\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_R$		τ_R

I. Signal Acceptance Tables

Table I.1: Signal acceptance and number of expected events for neutralino mass of $60 \text{ GeV}/c^2$.

[illegible]

Table I.1 – continued from previous page

Mass Scenario			σ_{NLO}	Acceptance		Expected Events	
$m_{\tilde{g}}$	$m_{\tilde{b}_1}$	$m_{\tilde{\chi}_1^0}$		single	double	single	double
GeV/ c^2	GeV/ c^2	GeV/ c^2	pb	b-tag	b-tag	b-tag	b-tag
220	170	60	4.10	0.0657	0.0707	41.9	45.1
220	180	60	4.10	0.0736	0.0657	47.0	41.9
220	190	60	4.10	0.0706	0.0639	45.1	40.8
220	200	60	4.10	0.068	0.0398	43.4	25.4
220	210	60	4.10	0.063	0.0241	40.2	15.4
220	214	60	4.10	0.0628	0.0227	40.1	14.5
230	140	60	2.88	0.054	0.067	24.2	30.0
230	150	60	2.88	0.0616	0.0733	27.6	32.9
230	160	60	2.88	0.0668	0.0778	29.9	34.9
230	170	60	2.88	0.0688	0.0808	30.8	36.2
230	180	60	2.88	0.0683	0.0823	30.6	36.9
230	190	60	2.88	0.075	0.075	33.6	33.6
230	200	60	2.88	0.0822	0.0686	36.9	30.8
230	210	60	2.88	0.0752	0.0477	33.7	21.4
230	220	60	2.88	0.0701	0.0267	31.4	11.9
230	224	60	2.88	0.0678	0.0241	30.4	10.8
240	140	60	2.04	0.054	0.067	17.1	21.3
240	150	60	2.04	0.0646	0.0775	20.5	24.6
240	170	60	2.04	0.0769	0.0933	24.4	29.6
240	180	60	2.04	0.0767	0.0901	24.3	28.6
240	190	60	2.04	0.081	0.0941	25.7	29.9
240	200	60	2.04	0.083	0.0885	26.3	28.1
240	210	60	2.04	0.084	0.0734	26.7	23.3
240	220	60	2.04	0.0774	0.0492	24.6	15.6

Continued on next page

Table I.1 – continued from previous page

Mass Scenario			σ_{NLO}	Acceptance		Expected Events	
$m_{\tilde{g}}$ GeV/ c^2	$m_{\tilde{b}_1}$ GeV/ c^2	$m_{\tilde{\chi}_1^0}$ GeV/ c^2		single b-tag	double b-tag	single b-tag	double b-tag
240	230	60	2.04	0.0718	0.024	22.8	7.63
240	234	60	2.04	0.0749	0.0238	23.8	7.56
250	140	60	1.44	0.0647	0.0754	14.5	16.9
250	150	60	1.44	0.0717	0.0836	16.0	18.7
250	160	60	1.44	0.0717	0.0866	16.0	19.4
250	170	60	1.44	0.0799	0.0916	17.9	20.5
250	180	60	1.44	0.079	0.0989	17.7	22.2
250	190	60	1.44	0.0864	0.0932	19.3	20.9
250	200	60	1.44	0.0901	0.0972	20.2	21.8
250	210	60	1.44	0.0964	0.1006	21.6	22.5
250	220	60	1.44	0.0919	0.0775	20.6	17.3
250	230	60	1.44	0.0852	0.0463	19.1	10.3
250	240	60	1.44	0.0778	0.0275	17.4	6.17
250	244	60	1.44	0.0757	0.0255	16.9	5.72
260	140	60	1.02	0.0647	0.0754	10.2	11.9
260	150	60	1.02	0.0757	0.0869	12.0	13.8
260	160	60	1.02	0.0747	0.0954	11.8	15.1
260	170	60	1.02	0.0819	0.1014	13.0	16.1
260	180	60	1.02	0.0837	0.1026	13.3	16.3
260	190	60	1.02	0.0894	0.1032	14.2	16.4
260	200	60	1.02	0.0921	0.1106	14.6	17.5
260	210	60	1.02	0.0932	0.1082	14.8	17.2
260	220	60	1.02	0.1015	0.0974	16.1	15.4
260	230	60	1.02	0.0979	0.0804	15.5	12.7

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Table I.1 – continued from previous page

Mass Scenario			σ_{NLO}	Acceptance		Expected Events	
$m_{\tilde{g}}$ GeV/ c^2	$m_{\tilde{b}_1}$ GeV/ c^2	$m_{\tilde{\chi}_1^0}$ GeV/ c^2		single b-tag	double b-tag	single b-tag	double b-tag
260	240	60	1.02	0.0913	0.0527	14.5	8.38
260	254	60	1.02	0.0793	0.0275	12.6	4.37
270	140	60	0.72	0.0705	0.083	7.91	9.31
270	150	60	0.72	0.0808	0.0863	9.06	9.68
270	160	60	0.72	0.0781	0.097	8.76	10.8
270	170	60	0.72	0.0838	0.1009	9.40	11.3
270	180	60	0.72	0.0875	0.1084	9.82	12.1
270	190	60	0.72	0.0958	0.112	10.7	12.5
270	200	60	0.72	0.094	0.12	10.5	13.4
270	210	60	0.72	0.1081	0.116	12.1	13.0
270	220	60	0.72	0.0966	0.1109	10.8	12.4
270	230	60	0.72	0.1091	0.0966	12.2	10.8
270	240	60	0.72	0.0991	0.0826	11.1	9.27
270	250	60	0.72	0.0915	0.0537	10.2	6.02
270	260	60	0.72	0.0822	0.0285	9.22	3.19
280	140	60	0.51	0.0732	0.0849	5.82	6.75
280	150	60	0.51	0.0832	0.094	6.61	7.47
280	160	60	0.51	0.0807	0.1015	6.41	8.07
280	170	60	0.51	0.0877	0.1016	6.97	8.07
280	180	60	0.51	0.0864	0.1134	6.86	9.01
280	190	60	0.51	0.0964	0.1189	7.66	9.45
280	200	60	0.51	0.0959	0.1211	7.62	9.62
280	210	60	0.51	0.0991	0.1137	7.87	9.04
280	220	60	0.51	0.1012	0.1187	8.04	9.43

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Table I.1 – continued from previous page

Mass Scenario			σ_{NLO}	Acceptance		Expected Events	
$m_{\tilde{g}}$	$m_{\tilde{b}_1}$	$m_{\tilde{\chi}_1^0}$		single	double	single	double
GeV/ c^2	GeV/ c^2	GeV/ c^2	pb	b-tag	b-tag	b-tag	b-tag
280	230	60	0.51	0.106	0.1118	8.42	8.88
280	240	60	0.51	0.1108	0.1061	8.80	8.43
280	250	60	0.51	0.104	0.0852	8.26	6.77
280	260	60	0.51	0.0983	0.0534	7.81	4.24
280	270	60	0.51	0.0884	0.0311	7.02	2.47
290	140	60	0.37	0.0761	0.0858	4.38	4.94
290	150	60	0.37	0.0793	0.0957	4.57	5.52
290	160	60	0.37	0.081	0.1003	4.67	5.78
290	170	60	0.37	0.083	0.1051	4.78	6.06
290	180	60	0.37	0.0877	0.1209	5.05	6.97
290	190	60	0.37	0.092	0.1163	5.30	6.70
290	200	60	0.37	0.0991	0.127	5.71	7.32
290	210	60	0.37	0.1074	0.1199	6.19	6.91
290	220	60	0.37	0.1116	0.1246	6.43	7.18
290	230	60	0.37	0.1028	0.1325	5.92	7.64
290	240	60	0.37	0.1079	0.1206	6.22	6.95
290	250	60	0.37	0.1115	0.1053	6.43	6.07
290	260	60	0.37	0.1093	0.0843	6.30	4.86
290	270	60	0.37	0.1019	0.0524	5.87	3.02
290	280	60	0.37	0.0862	0.0297	4.97	1.71

Table I.2
Signal acceptance and number of expected events for neutralino mass
of 100 GeV/ c^2 .

Mass Scenario			σ_{NLO}	Acceptance		Expected Events	
$m_{\tilde{g}}$	$m_{\tilde{b}_1}$	$m_{\tilde{\chi}_1^0}$		single	double	single	double
GeV/ c^2	GeV/ c^2	GeV/ c^2	pb	b-tag	b-tag	b-tag	b-tag
260	110	100	1.02	0.0664	0.0307	10.56	4.88
260	130	100	1.02	0.0563	0.0514	8.95	8.17
260	150	100	1.02	0.0578	0.0606	9.19	9.64
260	170	100	1.02	0.0608	0.0636	9.67	10.11
260	190	100	1.02	0.0636	0.0845	10.11	13.44
260	210	100	1.02	0.074	0.094	11.77	14.95
260	230	100	1.02	0.0767	0.0727	12.20	11.56
260	250	100	1.02	0.0666	0.0311	10.59	4.95

VITA

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Carsten Rott was born in Hannover, Germany on May 16, 1974. He completed his high school education at the Gymnasium Burgdorf in Spring 1994. He then performed community service as alternative to German military service at the “Haus und Familien Pflege der Diakonie in Burgdorf”. He attended Universität Hannover from Fall 1995 to Summer 1998 in the German Physics Diploma program. He subsequently accepted a one year exchange fellowship at Purdue University to pursue the Masters Degree, which he received in Summer 1999. He decided to stay at Purdue University and to enter into the Ph.D program. He joined the CDF collaboration at Fermilab, as a student of Daniela Bortoletto, where he conducted his thesis research until receiving his Ph.D in Physics in December 2004.