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FERMILAB-Conf-97/166-E

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David W. Gerdes

For the CDF Collaboration

Department of Physics and Astronomy

The Johns Hopkins University

3400 North Charles Street, Baltimore, Maryland 21218

Fermi National Accelerator Laboratory

P.O. Box 500, Batavia, Illinois 60510

May 1997

To Appear in the Proceedings of the *XXXIInd Rencontres de Moriond, Electroweak Interactions and Unified Theories*, Les Arcs, Savoie, France, March 15-22, 1997

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TOP QUARK PRODUCTION AND DECAY AT THE TEVATRON¹

David W. Gerdes
(representing the CDF Collaboration)

*Department of Physics and Astronomy
The Johns Hopkins University
3400 North Charles Street, Baltimore, Maryland 21218*



Abstract: Recent measurements of the top quark production cross section and decay properties by the CDF and D0 experiments are described. The cross section has been measured in dilepton, lepton plus jets, and all-hadronic final states, and a measurement of $BR(t \rightarrow Wb)/BR(t \rightarrow Wq)$, where q is any quark, has been performed. The results, though statistics-limited, are consistent with each other and with theoretical predictions.

¹To appear in the proceedings of the XXXIInd Rencontres de Moriond, Electroweak Interactions and Unified Theories, Les Arcs, Savoie, France, March 15-22, 1997.

1 Overview of Top Quark Production

Since the observation of the top quark in 1995 by the CDF[1] and D0[2] collaborations, the Tevatron experiments have moved rapidly into a program of detailed studies of the top quark. In this paper I describe recent measurements of the top quark production cross section[3, 4] by CDF and D0 using a number of final state topologies. I also describe a recent CDF measurement of $BR(t \rightarrow Wb)/BR(t \rightarrow Wq)$, where q is any quark. Recent measurements of the top quark mass are described in Ref. [5].

At the Tevatron energy of $\sqrt{s} = 1.8$ TeV, most top quarks are produced in pairs via the annihilation processes $q\bar{q} \rightarrow t\bar{t}$ (90%) and $gg \rightarrow t\bar{t}$ (10%). Top quarks can also be produced singly by electroweak processes such as W -gluon fusion. While no signal has been isolated for the single-top process yet, it is included as a “background” when studying $t\bar{t}$ production. For the remainder of this paper we consider only the pair production of top quarks.

In the Standard Model each top quark decays nearly 100% of the time into Wb . Each W in turn can decay into a charged lepton plus neutrino, with a branching ratio of 1/9 to each lepton family, or into a $q\bar{q}'$ pair (“jets”), with a branching ratio of 2/3. Top quark candidate events are characterized by the decay modes of the two W 's. Most analyses done by the Tevatron experiments focus on final states containing at least one W decay to $e\nu$ or $\mu\nu$:

- **Dilepton** final states (5% of $t\bar{t}$ decays) contain two isolated, high- P_T leptons (e^+e^- , $\mu^+\mu^-$, or $e^\pm\mu^\mp$), significant missing transverse energy (\cancel{E}_T) from the undetected neutrinos, and two jets from b quarks.
- **Lepton + jets** final states (30% of $t\bar{t}$ decays) contain one isolated, high- P_T electron or muon, significant \cancel{E}_T , and typically three or more jets, two of which are from b 's.

While this paper will emphasize these two final state topologies, top decays to all-hadronic final states have been observed by CDF[6], and a handful of suggestive events have also been observed in the τ dilepton channel[7].

2 $t\bar{t}$ Production Cross Section

The top quark production cross section, $\sigma_{t\bar{t}}$, is of interest for several reasons. First, it is a test of QCD calculations[8, 9, 10]. Second, departures from the theoretical expectation could indicate new physics, such as production through a high-mass intermediate state or decays to final states other than Wb . By measuring $\sigma_{t\bar{t}}$ in as many channels as possible, we hope to gain a consistent picture of top as a Standard Model object or to identify the places where the theory may be in error. Finally, $\sigma_{t\bar{t}}$ is an important “engineering number” for estimating top yields in future experiments at the Tevatron and LHC[11]. The $t\bar{t}$ production cross section has been measured in the dilepton, lepton + jets, and all-hadronic final states using the full Run I datasets with integrated luminosities of approximately 110 pb^{-1} .

2.1 Dilepton Analysis

Dilepton events result from the process $t\bar{t} \rightarrow WbW\bar{b} \rightarrow \ell^+\nu b\ell^-\bar{\nu}\bar{b}$. The CDF dilepton analysis begins with a single inclusive lepton sample that also forms the starting point for the lepton plus jets analysis. Events in this sample contain an isolated e or μ with $P_T > 20$ GeV and pseudorapidity $|\eta| < 1$. A second, opposite-charge e or μ is then required with $P_T > 20$ GeV. The second lepton may satisfy looser quality cuts. Because top dilepton events contain two b jets, two jets are required with observed transverse energy² $E_T > 10$ GeV and $|\eta| < 2.0$. At least 25 GeV of \cancel{E}_T is required. If $\cancel{E}_T < 50$ GeV, the angle between the \cancel{E}_T vector and the nearest lepton or jet is required to be at least 15° . This cut reduces backgrounds from $Z \rightarrow \tau\tau$ and mismeasured jets. Finally, ee and $\mu\mu$ events with a dilepton invariant mass in the Z mass window between 75 and 105 GeV are removed, as are $ll\gamma$ events with a three-body invariant mass consistent with a radiative Z decay.

Nine candidates remain in the final CDF dilepton sample: one ee , one $\mu\mu$, and seven $e\mu$. Four of the nine events are b -tagged using the algorithms described below. The relative numbers of events are consistent with the expectations from $t\bar{t}$ Monte Carlo ($M_{top} = 175$ GeV), which predicts relative acceptances of 15%, 27%, and 58% in the ee , $\mu\mu$, and $e\mu$ channels respectively. The background is calculated to be 2.1 ± 0.4 events, and consists of lepton pairs from the Drell-Yan process, $Z \rightarrow \tau\tau$, W pair production, and fakes.

The D0 dilepton analysis also makes use of ee , $\mu\mu$, and $e\mu$ final states, with cuts similar to those described above. Electrons are searched for in the range $|\eta| < 2.5$, and muons in the range $|\eta| < 1.7$. The lepton P_T threshold is 15 GeV for the $\mu\mu$ and $e\mu$ analyses and 20 GeV for the ee analysis. At least two jets with corrected $E_T > 20$ GeV and $|\eta| < 2.5$ are required. In addition, since top events tend to have rather energetic jets, a cut is placed on the scalar summed transverse energy of the jets with $E_T > 15$ GeV plus the leading electron, if present. One ee , one $\mu\mu$, and three $e\mu$ events are observed, with a background of 1.4 ± 0.4 events.

2.2 Lepton Plus Jets Analysis

Lepton plus jets events arise from $t\bar{t} \rightarrow WbW\bar{b} \rightarrow \ell\nu b q\bar{q}'\bar{b}$. Four jets are therefore expected in the final state, two from b 's and two from the hadronic W decay. However, jets may be merged or lost due to detector effects, and additional jets may be produced from gluon radiation. The CDF and D0 analyses therefore begin by requiring an isolated lepton with $P_T > 20$ GeV, significant \cancel{E}_T , and at least three jets. There remains a significant QCD background from W plus multijet production, which can be reduced to acceptable levels through kinematic cuts or b -tagging.

The D0 analysis takes two complementary approaches. The “ ℓ +jets/ μ ” analysis seeks to tag a b jet by identifying a muon from $b \rightarrow \mu X$ in the vicinity of a jet. At least three

²Observed jet energies differ from the true parton energy because of both instrumental and physics effects. Instrumental effects include detector nonlinearity and cracks. In addition, fragmentation effects can cause energy to be deposited outside the jet clustering cone, and unrelated energy from multiple interactions or the underlying event can be deposited inside the clustering cone. CDF cuts on observed jet energies, while D0 applies a correction factor. The ratio between corrected and observed jet energies at CDF is rapidity- and E_T -dependent but averages approximately 1.4.

jets are required with corrected $E_T > 20$ and $|\eta| < 2$. The tagged muon is required to have $P_T > 4$ GeV and to be within $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \leq 0.5$ of a jet. Loose cuts are placed on the summed transverse energy of the jets, $H_T > 110$ GeV, and on the event's aplanarity, $\mathcal{A} > 0.040$. Eleven events are observed on a background of 2.4 ± 0.5 events. The dominant backgrounds are fake leptons, which are estimated from control samples in the data, and QCD W plus multijet production, which is modelled using the VECBOS[12] event generator interfaced to the HERWIG[13] parton shower model and passed through a full detector simulation. The background μ -tag rate, which includes both fake tags as well as real heavy flavor in the background, is estimated from multijet data.

The second D0 approach to the lepton plus jets channel makes use of kinematic information to distinguish $t\bar{t}$ events from the W plus multijet background. Top events generically have more energetic jets and are more spherical than the background, so the kinematic variables H_T and \mathcal{A} , defined above, are expected to have discriminating ability. A Monte Carlo optimization procedure is used to select the cuts on H_T and \mathcal{A} that minimize the expected cross section uncertainty. Events are required to have at least four jets with corrected $E_T > 15$ GeV and $|\eta| < 2$, to have $\cancel{E}_T > 25(20)$ GeV in the electron (muon) channel, and to satisfy $H_T > 180$ GeV, $\mathcal{A} > 0.065$. In addition, the scalar sum of the lepton transverse energy and the \cancel{E}_T is required to exceed 60 GeV, and the leptonically-decaying W is required to be loosely central, satisfying $|\eta_W| < 2$. Events that pass the ℓ +jets/ μ selection are excluded from this analysis. These kinematic cuts identify 19 events, with a background of 8.7 ± 1.7 events. Figure 1 shows the distribution in the H_T - \mathcal{A} plane of the data, $t\bar{t}$ signal Monte Carlo, and multijet and W +4-jet backgrounds.

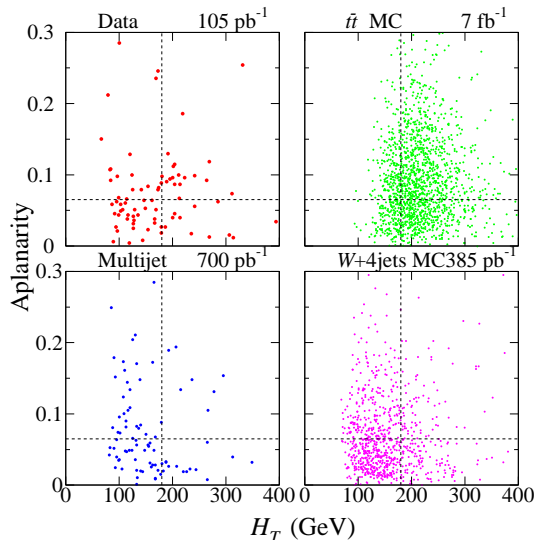


Figure 1: Distributions of \mathcal{A} vs. H_T in the D0 ℓ +jets analysis. Clockwise from upper left: ℓ +jets data; $t\bar{t}$ Monte Carlo ($M_{top} = 175$ GeV); W + 4-jet Monte Carlo; multijet background. Events above and to the right of the dashed lines pass the kinematic selection.

The CDF lepton + jets analysis begins with inclusive electron and muon samples, where the primary lepton is required to have $P_T > 20$ GeV, $|\eta| < 1$, and to be isolated. At least 20 GeV of \cancel{E}_T is required. At least three jets with observed $E_T > 15$ GeV and $|\eta| < 2$ are

then required. A total of 325 events pass these cuts, with a signal-to-background ratio of about 1:4. CDF uses two b -tagging techniques to reduce the W plus multijet background in this sample: soft lepton (SLT) tagging, and secondary vertex (SVX) tagging. The SLT tag requires an electron or muon with $P_T > 2$ GeV in the vicinity of one of the jets. This technique has an efficiency of $20 \pm 2\%$ for $t\bar{t}$ events that pass the initial selection, and has a typical fake rate per jet of 2%. The SVX technique uses precision tracking information from the silicon vertex detector[14] to reconstruct secondary vertices from b decays. The efficiency of this technique is $41 \pm 4\%$, with a typical fake rate per jet of 0.5%. Because of its high efficiency and low background, SVX-tagging is CDF's primary b -tagging technique.

After SVX-tagging, 34 events are identified on a background of 8.0 ± 1.4 . Eight of the events have two SVX-tagged jets. The background is dominated by real heavy flavor ($Wb\bar{b}$, $Wc\bar{c}$). Figure 2 shows the number of SVX-tagged jets as a function of jet multiplicity. The SLT technique identifies 40 events on a background, dominated by fakes, of 24 ± 3.5 .

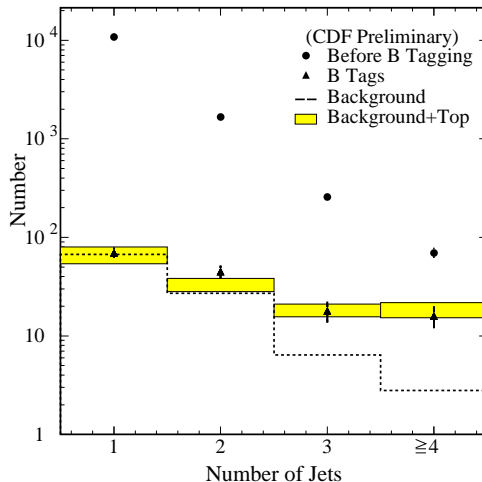


Figure 2: Number of SVX-tagged jets as a function of jet multiplicity. The $t\bar{t}$ signal region with $N_{jet} \geq 3$ shows a large excess of tags.

2.3 Other Channels

CDF has observed a $t\bar{t}$ signal and measured the cross section in the all-hadronic channel using a combination of kinematic cuts and SVX-tagging[6]. CDF has also reported[7] a modest excess of events in dilepton final states containing a τ candidate. D0 has increased their acceptance for $t\bar{t}$ production by including events with an isolated electron with $E_T > 20$ GeV and $|\eta| < 1.1$, at least 2 jets with corrected $E_T > 30$ GeV, large missing energy, $\cancel{E}_T > 50$ GeV, and high transverse mass, $M_T(l-\cancel{E}_T) > 115$ GeV. Events that pass the standard dilepton or lepton plus jets cuts are excluded. This selection provides sensitivity to τ decays and regains some dilepton and lepton plus jets events that fail the standard kinematic selection, for example because a lepton or jet was lost or mismeasured. Four events pass this “ $e\nu$ ” selection, with a background of 1.2 ± 0.4 events.

2.4 Cross Section Results

The $t\bar{t}$ acceptance is evaluated using the HERWIG event generator together with a detector simulation. Lepton identification and b -tagging efficiencies are corrected, where necessary, using values measured in the data. The acceptance is a slowly-rising function of M_{top} . To quote a cross section, CDF uses a top mass of 175 GeV, while D0 uses 173.3 GeV. Backgrounds are rescaled to account for the $t\bar{t}$ component of the data. The results from the various channels are shown in Table 1.

Table 1: Top quark production cross section results from the Tevatron experiments. Acceptances and cross sections are evaluated at $M_{top} = 175$ GeV for CDF and 173.3 GeV for D0.

Channel	Acceptance (%)	$\int \mathcal{L} dt$ (pb $^{-1}$)	Background	N_{obs}	$\sigma_{t\bar{t}}$ (pb)
Dilepton (CDF)	0.74 ± 0.08	109	2.1 ± 0.4	9	$8.5^{+4.4}_{-3.4}$
Dilepton (D0)	0.64 ± 0.11	125,105,108($ee, \mu\mu, e\mu$)	1.4 ± 0.4	5	
$e\nu$ (D0)	0.28 ± 0.08	108	1.2 ± 0.4	4	$6.3 \pm 3.3^*$
ℓ +jets/SVX (CDF)	3.5 ± 0.7	109	8.0 ± 1.4	34	$6.8^{+2.3}_{-1.8}$
ℓ +jets/SLT (CDF)	1.7 ± 0.3	109	24.3 ± 3.5	40	$8.0^{+4.4}_{-3.6}$
ℓ +jets/ μ (D0)	0.98 ± 0.15	107	2.4 ± 0.5	11	8.2 ± 3.5
ℓ +jets/kin (D0)	2.32 ± 0.45	110	8.7 ± 1.7	19	4.1 ± 2.0
All-hadronic (CDF)	4.7 ± 1.6	109	137 ± 11	192	$10.7^{+7.6}_{-4.4}$

*D0 Dilepton + $e\nu$ combined.

The results are consistent among the different channels, though in some cases the uncertainties are large. Combining the dilepton and ℓ +jets channels, D0 obtains

$$\sigma_{t\bar{t}}(M_{top} = 173.3) = 5.5 \pm 1.8 \text{ pb (D0)}.$$

Combining the dilepton and ℓ +jets channels, CDF obtains

$$\sigma_{t\bar{t}}(M_{top} = 175) = 7.5^{+1.9}_{-1.6} \text{ pb (CDF)}.$$

For comparison, a recent calculation by Catani *et al.*[9] gives $\sigma_{t\bar{t}}(175) = 4.75^{+0.73}_{-0.62}$ pb, while Berger and Contapaganos[8] obtain $\sigma_{t\bar{t}}(175) = 5.52^{+0.07}_{-0.42}$ pb.

3 Measurement of $BR(t \rightarrow Wb)/BR(t \rightarrow Wq)$

The ratio of branching ratios $B = BR(t \rightarrow Wb)/BR(t \rightarrow Wq)$, where q is any quark, is predicted to be nearly one in the Standard Model. CDF has measured B from the ratios double b -tagged, single b -tagged, and un-tagged dilepton and lepton plus jets events. Using the known efficiency for tagging a b jet, which is measured in b -enriched control samples, and a Monte Carlo model of the b jet acceptance in top events, B can be extracted from a likelihood fit.

The dilepton sample used for this analysis is the same one used in the cross section measurement described above. The ℓ +jets sample begins with the $W+\geq 3$ -jet sample (325

events) used in the cross-section measurement. The jets are required to have $E_T > 15$ GeV and $|\eta| < 2$. Then a fourth jet with observed $E_T > 8$ GeV and $|\eta| < 2.4$ is required, giving a sample of 163 events. The four-jet requirement facilitates jet-parton association when comparing data to $t\bar{t}$ Monte Carlo, and reduces the W plus multijet background. Events are classified into four non-overlapping subsamples: no tags, SLT tags but no SVX tags, single SVX tags, and double SVX tags. The number of background tags in the various subsamples is determined through an iterative rescaling as in the cross section measurement. The observed number of events, the backgrounds and the b -tagging efficiencies per jet are combined into a likelihood fit for B , resulting in

$$\begin{aligned} B &= 0.99 \pm 0.29 \text{ (stat. + syst.)} \\ &> 0.58(0.64) \text{ at } 95(90)\% \text{ C.L.} \end{aligned}$$

It is important to note that there is some model-dependence in this analysis. The Monte Carlo model used to calculate the $t\bar{t}$ acceptance assumes that all top decays are to Wq , i.e. that there are no top decays to non- W final states. For example, if the decay $t \rightarrow H^+b$ occurred with a sizable branching fraction, and if $M_{H^+} \approx M_W$, it would result in b -tagged events that are kinematically identical to ordinary ℓ +jets events. Such events would destroy the interpretation of the measured tag ratios as a measurement of B . However, a large branching ratio of top to non- W final states would also result in fewer than expected dilepton events and, therefore, a lower than expected cross section measurement in this channel. Work to combine all available information into limits on nonstandard decays is in progress.

This result can be converted into a lower limit on $|V_{tb}|$, albeit with additional assumptions. Assuming a three-generation unitary CKM matrix, this measurement gives $|V_{tb}| > 0.76$ at the 95% C.L. However, in this case $|V_{tb}|$ is much better determined from unitarity and independent measurements of the other CKM parameters—in fact it is the *best-known* CKM matrix element. In the case of four quark generations, there are additional CKM angles and phases, and it is not possible to fix $|V_{tb}|$ by a single measurement without making further assumptions. Even then, only weak constraints on $|V_{tb}|$ can be obtained.

4 Conclusions

The top quark production cross section has been measured in a number of final states both with and without b -tagging, and a measurement of the ratio of branching ratios $BR(t \rightarrow Wb)/BR(t \rightarrow Wq)$ has been performed. Taken as a whole, the data are starting to paint a consistent picture of the top quark as a Standard Model object. However, the measurements are statistics-limited, and exotic production mechanisms and large nonstandard branching ratios can not yet be ruled out[15].

The Tevatron experiments are currently undergoing major upgrades in preparation for running with the Main Injector in late 1999. In addition to the expected factor of 20 increase in integrated luminosity, and the 40% increase in the top production cross section that will come from raising the Tevatron energy from 1.8 to 2.0 TeV, the detector upgrades will result in significant improvements in b -tagging and lepton identification. All told, a factor of 50

increase in the size of the top sample appears feasible in the first few years of Main Injector running, with correspondingly bright prospects for precision top physics at the Tevatron.

5 Acknowledgements

I would like to thank the organizers for a very enjoyable “Rencontre.” Herb Greenlee and Rich Partridge provided me with details of the D0 analyses. This work is supported by NSF grant PHY-9604893 and by a DOE Outstanding Junior Investigator award.

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