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# Top Quark Production and Decay Measurements from CDF

K. Tollefson
For the CDF Collaboration

*University of Rochester*
*Rochester, New York 14627*

*Fermi National Accelerator Laboratory*
*P.O. Box 500, Batavia, Illinois 60510*

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K. Tollefson

*University of Rochester, Department of Physics and Astronomy, Rochester, NY 14627, USA*
*E-mail: kirsten@fnal.gov*

The CDF collaboration is completing a number of studies on the top quark, based on samples collected during Run I of the Tevatron Collider. The production and decay properties of the top quark are being examined in most of the $t\bar{t}$ decay channels, and many of these results have recently been published. The study of the top quark has moved beyond measurements of its mass and production cross section, to detailed studies of $W$ polarization in top decays, single top production, branching fractions, the $W-t-b$ coupling, and searches for rare decays.

## 1 Introduction

The existence of the top quark was firmly established in early 1995 when the two collider experiments at the Tevatron, CDF and DØ, observed a significant number of events in excess of the background [1]. The characteristics of these events were consistent with $t\bar{t}$ production and decay [2]. Initial measurements of the top quark mass indicated a mass [3] of approximately 175 GeV/c$^2$, nearly 40 times more massive than the $b$ quark. It is essential to fully explore this remarkable quark for both its standard model properties and for hints of physics beyond the standard model. Since its discovery, the 1992-1996 Tevatron collider run has concluded and analysis of the current dataset is nearly complete. This paper reviews the status of our understanding of top quark production and decay.

During Run I the Tevatron operated at a center-of-mass energy of 1.8 TeV with a peak luminosity near $2 \times 10^{31}$ $cm^{-2}sec^{-1}$. The CDF results described below are based on 110 pb$^{-1}$ of integrated luminosity. A detailed description of the CDF detector can be found elsewhere[4].

## 2 Identification of Top Quark Samples

At the Tevatron, the dominant form of top quark production is $t\bar{t}$ pair production via $q\bar{q}$ annihilation. A NLO calculation indicates an expected production cross section [5] for $t\bar{t}$ in the range of 4.7-5.5 $pb$ for $M_{top} = 175$ $GeV/c^2$. This production process is rather rare, having a cross section which is nine orders of magnitude less than the total inelastic cross section. It is also possible to produce events which contain only one top quark (single top production) although the expected cross section [6], as well as the acceptance for such decays, is smaller than that for $t\bar{t}$ events. For a top quark mass of 175 GeV/c$^2$, the top quark width is expected to be about 1.8 GeV/c$^2$, so the top quark decays before hadronizing. In the standard model, a $t$ or $\bar{t}$ quark decays almost 100% of the time to a real $W$ boson and a $b$ quark. Figure 1 shows the Feynman diagram for top quark production and standard model top quark decay. The subsequent decays of the $W$ bosons lead to many possible final states. CDF classifies top events into three categories according to the decay channels of the two $W$ bosons; the lepton plus jets channel, the dilepton channel, and the all-hadronic channel.

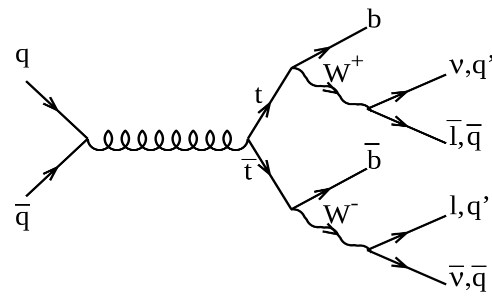


Figure 1: The tree-level Feynman diagram for top quark production by $q\bar{q}$ annihilation and standard model top quark decay.

### *2.1 The Lepton Plus Jets Channel*

In this channel, one $W$ decays leptonically ($W \rightarrow \ell\nu$) while the other decays hadronically ($W \rightarrow q\bar{q}'$). Events are characterized by one high $P_T$ lepton, missing energy from the neutrino, and normally four jets, each created by the hadronization of a final state quark ($q$, $\bar{q}'$, $b$, $\bar{b}$). The lepton ($e$ or $\mu$) plus jets channel represents about 30% of the $t\bar{t}$ decays but suffers from a large background of $W$ plus multijet production. CDF requires the presence of three or more jets, an isolated electron or muon and missing transverse energy [7]. Even after these selection criteria the signal-to-background ratio is 1 to 6. The amount of background is further reduced by identifying the bottom quark(s) from the $t$ or $\bar{t}$ decay using one of two methods. The first method attempts to identify the semileptonic decay of the $b$ quark, $b \rightarrow \ell X$ or $b \rightarrow c \rightarrow \ell X$, with $\ell$ being a muon or electron. This method is referred to as soft lepton tagging or SLT. The second $b$-tagging method uses the precision tracking of the silicon vertex (SVX) detector and the long-lifetime

Table 1: Event summaries for various $t\bar{t}$ decay channels. The data samples are based on 110 $\mathrm{pb}^{-1}$ of integrated luminosity. The combined cross section result does not include the $\tau$ dilepton measurement.

| Channel | Mode | Data | Background | $\sigma(t\bar{t})$ $(pb)$ |
|---|---|---|---|---|
| Lepton plus jets | SVX $b$-tag | 34 | $9.2 \pm 1.5$ | $6.2^{+2.1}_{-1.7}$ |
| | SLT $b$-tag | 40 | $22.6 \pm 2.8$ | $9.2^{+4.3}_{-3.6}$ |
| Dilepton | $ee, \mu\mu$, or $e\mu$ | 9 | $2.4 \pm 0.5$ | $8.2^{+4.4}_{-3.4}$ |
| | $e\tau$ or $\mu\tau$ | 4 | $2.0 \pm 0.4$ | $15.6^{+16.3}_{-10.3}$ |
| All Hadronic | 1 SVX $b$-tag | 187 | $142 \pm 12$ | $9.6^{+4.4}_{-3.6}$ |
| | 2 SVX $b$-tag | 157 | $120 \pm 18$ | $11.5^{+7.7}_{-7.0}$ |
| Combined | | | | $7.6^{+1.8}_{-1.5}$ |

of $B$ hadrons to locate decay vertices that are displaced from the primary interaction point. This method is called silicon vertex tagging or SVX.

### *2.2 The Dilepton Channel*

In this channel, both $W$'s decay leptonically. Events are characterized by two high $P_T$ leptons of opposite charge, substantial missing energy from two neutrinos, and two jets. CDF searches mainly for dilepton events with electrons or muons ($ee$, $\mu\mu$ or $e\mu$) [8]. This channel has a better signal-to-background ratio than the lepton plus jets channel but it suffers from low statistics since it only represents about 5% of all $t\bar{t}$ decays.

CDF has also looked for dilepton events containing $\tau$ leptons [9]. The sample is restricted to events with one $W$ boson decaying to an electron or muon, and the other decaying to a $\tau$ lepton. In principle this should double the number of dilepton events since 5% of all $t\bar{t}$ decays are $e\tau$ or $\mu\tau$. However the $\tau$ selection is less efficient than the $e$ or $\mu$ selection, resulting in a total $\tau$ dilepton acceptance which is about 5 times smaller than that for the $ee$, $\mu\mu$ or $e\mu$ events.

### *2.3 The All Hadronic Channel*

In this channel, both $W$'s decay hadronically and the final state appears as 6 jets [10]. The all-hadronic channel accounts for 44% of all $t\bar{t}$ decays and has the advantage of no missing energy since there are no neutrinos in the final state. However, this channel is dominated by background from QCD multijet production. To reduce the background CDF requires 5 or more jets with either one SVX $b$-tagged jet and kinematic requirements, or two SVX $b$-tagged jets and looser kinematic requirements.

## 3 The $t\bar{t}$ Production Cross Section

The number of observed events and expected backgrounds in each of the channels described previously is summarized in Table 1. Given these numbers, the acceptance in each channel, and the luminosity, it is a simple calculation to determine the $t\bar{t}$ production cross section. Table 1 also lists the cross section measurements in each channel. Currently, the accuracies of the cross section measurements are limited statistically. These measurements can be compared to the NLO theoretical predictions from QCD of $\sim 5\,pb$ [5]. A measured cross section that is significantly higher than the QCD prediction could indicate new production mechanisms beyond the standard model. In addition, a comparison of the cross section extracted from different decay channels provides a test of the decays open to the top quark. The measurements from the lepton plus jets, dilepton, and all-hadronic channels, were combined, properly accounting for correlated errors, resulting in a CDF combined cross section [7] of [a]:

$$\sigma(t\bar{t}) = 7.6 \,^{+1.8}_{-1.5}\ pb \qquad (1)$$

## 4 Properties of the Top Quark

Once the $t\bar{t}$ events have been found, it is important to use these events to explore the properties of the top quark. There are many different measurements that can be made in the top quark sector of the standard model [11]. In addition to the measurement of the $t\bar{t}$ production cross section described above, and the measurement of the top quark mass described elsewhere in these proceedings, there are a variety of other measurements being made and several of these are presented below.

[a] The $\tau$ dilepton cross section measurement is not included in the combined result.

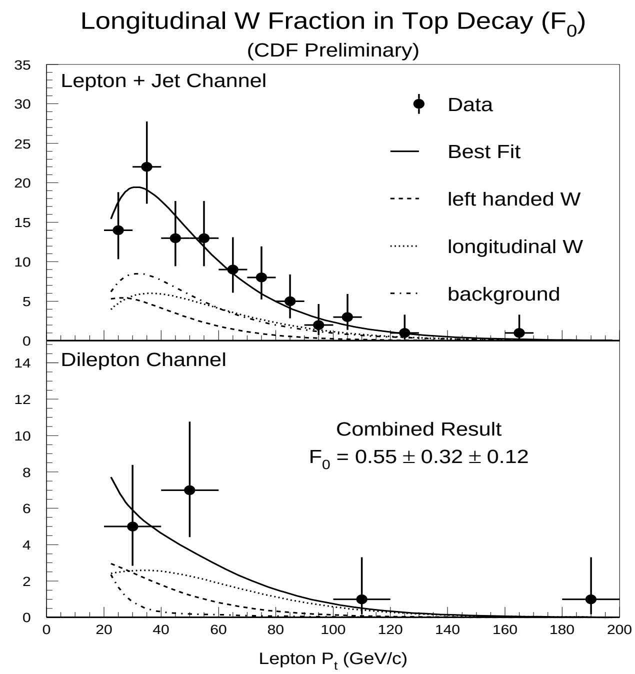


Figure 2: Fit of the CDF lepton $P_T$ spectra in the dilepton and lepton plus jets samples to a mixture of $t\bar{t}$ events with longitudinal and left-handed $W$ decays and background.

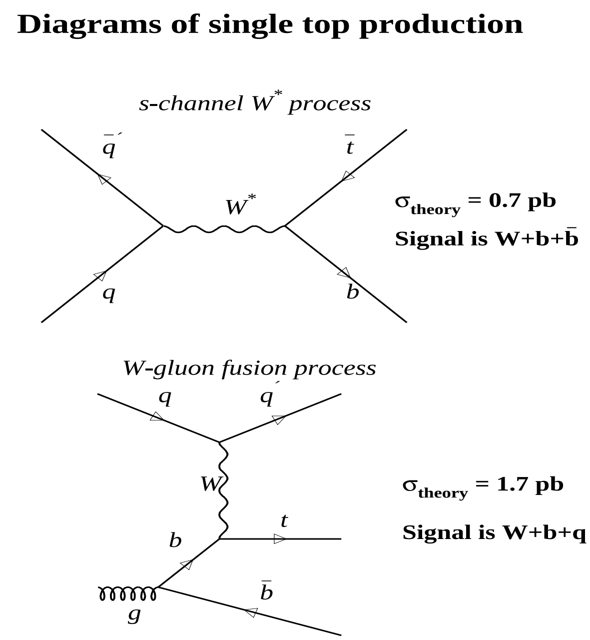


Figure 3: Feynman diagrams[2] for single top production.

### 4.1 Measurement of the Polarization of W's in Top Quark Decay

The standard model predicts that the polarization of $W$ bosons in top quark decay be either left-handed or longitudinal. For a top quark mass of 175 GeV/c, the expected fraction of longitudinal $W$'s in top quark decay is:

$$F_0 \;=\; \frac{M_{top}^2}{2M_W^2 + M_{top}^2} \;=\; 70\ \%. \qquad (2)$$

CDF measures this fraction by using the shape of the lepton $P_T$ spectra in the lepton plus jets and dilepton data samples. This technique takes advantage of the fact that a charged lepton from a left-handed $W$ tends to move opposite the $W$ direction, while that from a longitudinal $W$ tends to be perpendicular to the $W$ direction. In the lab frame, this results in a $P_T$ spectrum for leptons from longitudinal $W$'s which is significantly harder than those from left-handed $W$'s.

In the dilepton sample, the $e^+e^-$ and $\mu^+\mu^-$ events are removed, due to an inability to reliably model the background $P_T$ spectrum for these events. The lepton plus jets sample is broken up into three distinct samples depending on their $b$-tagging status, in a manner similar to that used in the CDF mass analysis [13].

The lepton $P_T$ distribution observed in the data is shown in Figure 2, along with a fit to a mixture of $t\bar{t}$ events with longitudinal $W$ decays, $t\bar{t}$ events with left-handed $W$ decays, and background. The result from a simultaneous fit to the dilepton and lepton plus jets channels is:

$$F_0 \;=\; 0.55 \;\pm\; 0.32(stat) \;\pm\; 0.12(syst). \qquad (3)$$

This result has been corrected for the kinematic acceptance difference between top quarks which decay to longitudinal $W$'s versus those that decay to left-handed $W$'s. The largest systematic effect comes from the uncertainty in the shape of the background in the lepton plus jets sample.

### 4.2 Single Top Production

Single top quarks can be produced by two processes: the s-channel $W^*$ process or the $W-$gluon fusion process. Figure 3 shows the Feynman diagrams for these processes and their theoretical cross sections [6]. A single top event is characterized by a $W$ and two jets. In the $W^*$ process the two jets are from $b$ decays whereas for $W-$gluon one jet is from a $b$ quark and the other from a light quark. Currently CDF only has preliminary results from the $W-$gluon fusion process. Events are required to have an electron or muon from the leptonically decaying $W$ and exactly two jets, one of which must be identified as a $b$ candidate by either an SVX or SLT tag.

The $W$-gluon events are distinguished from background by looking at a combination of kinematic properties. The pseudo-rapidity[b] distribution, $\eta$, of the light

[b] Pseudo-rapidity, $\eta$, is defined as the $-log(tan(\theta/2))$ where $\theta$ is

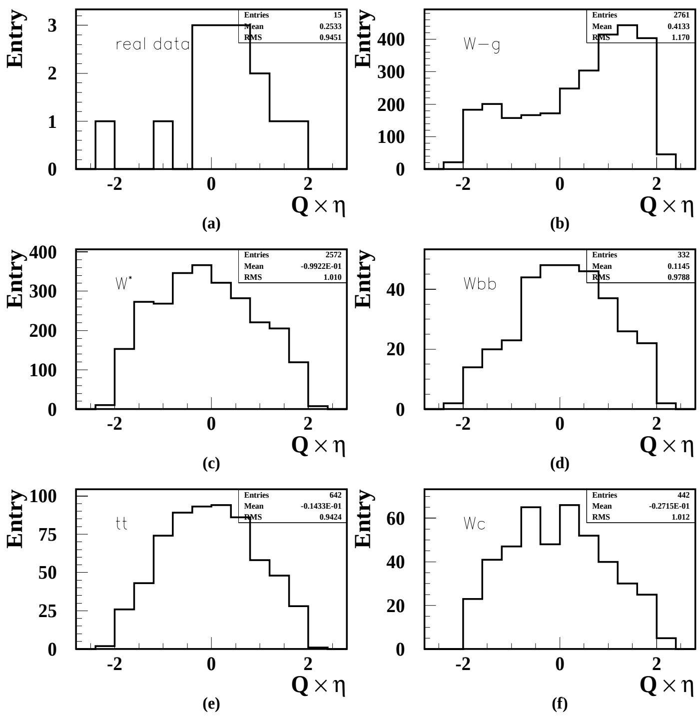


Figure 4: The lepton charge, $Q$, times pseudo-rapidity, $\eta$, distributions for a) $W$+2 jet data, b) $W$-gluon fusion single top, c) $W^*$ single top, d) $Wb\bar{b}$ Monte Carlo, e) $t\bar{t}$ Monte Carlo, and f) $Wc$ Monte Carlo events.

quark (non-tagged) jets tends to be positive for top quarks and negative for anti-top quarks. By taking the product of the lepton charge, $Q$, and $\eta$ a distribution which is more asymmetric for $W-$gluon events than background events is formed. Figure 4 shows the $Q$ times $\eta$ distributions for $W$-gluon events and several backgrounds. A binned maximum likelihood is used to fit this distribution to extract an upper limit on single top production cross section in the $W-$gluon fusion channel of:

$$\sigma(W - \text{gluon}) \quad < \quad 15.4\, pb \quad (95\%\ \text{C.L.}) \tag{4}$$

### 4.3 $BF(t \to Wb)/BF(t \to Wq)$

In the standard model, the top quark is expected to decay to a $W$ boson and a $b$ quark with a branching fraction near 1. Since each $t\bar{t}$ event should have two $b$ quarks, a prediction for the number of events with 0, 1, or 2 $b$-tags can be made if the $b$-tagging efficiency is known. By comparing the prediction to the observed tagging multiplicities in both the dilepton and the lepton plus jets decay channels, CDF has extracted the preliminary result:

$$R_b \;=\; \frac{BF(t \to Wb)}{BF(t \to Wq)} \;=\; 0.99 \;\pm\; 0.29 \tag{5}$$

### 4.4 Rare Decays

Although the decay $t \to Wb$ dominates, the standard model predicts the top quark can decay into other final states such as $t \to \gamma q$, $t \to Zq$, $t \to WWc$ and $t \to WZb$, which for $M_{top} \sim 175$ GeV/c$^2$ is near threshold. However, the branching fraction to these final states is expected to be extremely small, BF $\sim 10^{-10}$. These decays occur through higher order diagrams involving loops and triboson vertices. CDF has made a search for the decay mode $t \to \gamma q$ by looking for two classes of events. The first type has a final state of a $W$ boson ($W \to \ell\nu$), a photon, and jet activity. The second type has a final state with a high energy photon and four or more jets with one jet tagged as a $b$ quark. In addition, a search has been made for the leptonic decay of a $Z$ boson in place of the photon. Using these data samples, CDF establishes a limit on the branching fractions [12]

$$BF(t \to \gamma q) \quad < \quad 3.3\% \quad (95\%\ \text{C.L.}) \tag{6}$$

$$BF(t \to \gamma Z) \quad < \quad 33\% \quad (95\%\ \text{C.L.}). \tag{7}$$

The primary difference between the limits of these two channels is the small branching fraction from demanding $Z \to \ell\ell$. Although these limits are far from the expected standard model prediction, they are the first direct limits of these branching ratios. Even with the large statistics available in Run II, the limit of these rare decay modes will only approach $\approx 10^{-3}$, still far from the standard model expectations.

### 4.5 $Br(t \to l\nu b)$

If top decays via the process $t \to Xb$ instead of $t \to Wb$, where the decay modes of $X$ are very different from those of a $W$ boson, we would expect to obtain a value for the branching ratio $Br(t \to l\nu b)$ which is different that the standard model expectation of 1/9. The method used by CDF is to take the ratios of the $t\bar{t}$ production cross section measurements times standard model branching fraction using the lepton plus jets, dilepton, and all-hadronic samples. Each ratio can be written as a function of the branching ratio $Br(t \to l\nu b)$, and a likelihood technique is used to extract a measurement of this branching fraction from each ratio. The three results obtained are shown in Table 2. The weighted average of the two best results (the all-hadronic to lepton plus jets and the dilepton to all-hadronic ratios) give the CDF published[7] result of:

$$Br(t \to l\nu b) \;=\; 0.094 \;\pm\; 0.024 \tag{8}$$

the polar angle measured relative to the positive $z$ axis (taken as the direction of the outgoing proton beam) assuming a $z$-vertex position of zero.

Table 2: The measured value for $Br(t \to l\nu b)$ using the three ratios of measured cross section times standard model branching fractions.

| Ratio | $Br(t \to l\nu b)$ |
|---|---|
| Dilepton/Lepton plus jets | $0.127 \pm 0.044$ |
| All Hadronic/Lepton plus jets | $0.083 \pm 0.031$ |
| Dilepton/All Hadronic | $0.104 \pm 0.022$ |

The correlated uncertainty due to the common channel is accounted for, as well as the effect of the contamination of decays across different channels.

## 5 Summary

The first explorations of the top quark have been made at the Tevatron. With the discovery of the top quark complete, the attention of physicists has turned towards measuring the properties of the top quark. The measurements include the production cross section, the measurement of the $W$ polarization in top decays and branching ratios, limits on single top production and rare decays and the measurement of the top quark mass. In all respects the top quark appears to be what the standard model predicts. Perhaps the only surprise is the accuracy to which the experiments have been able to measure the top quark mass [13]. Currently, most measurements are statistically limited and for that reason the collaboration is looking forward to Run II with great anticipation.


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