In this document we present several recent (July 2008) results from studies of the top quark properties at the CDF and DØ experiments at the Tevatron. Measurements of several top quark properties, as well as tests of new physics in the top quark production and decay sectors are presented. In the latter case, no significant evidence for physics beyond the Standard Model is uncovered, and the tightest constraints to date are placed on most of the new physics scenarios investigated.

1. Introduction

According to the Standard Model (SM), in $p\bar{p}$ collisions at the Tevatron top quarks can be created in pairs via the strong force, or singly via the electroweak interaction. Due to its higher cross-section and smaller associated backgrounds, the strong production ($t\bar{t}$) represents the main channel used for performing detailed measurements of the properties of the top quark. In terms of its decay, a top quark is expected to disintegrate into a $W$ boson and a $b$-quark almost 100% of the time. Thus, the top candidate events can be classified based on the subsequent decays of the $W$ daughter into: a) “dilepton” events if both $W$ bosons decay leptonically, b) “lepton+jets” events if one $W$ decays leptonically and the other one hadronically, and c) “all hadronic” events if both $W$’s decay hadronically.

The last category of top candidates (all hadronic) are typically dominated by multijet background contributions, and will not be used in the results described here. In the following sections, we will present the results from top charge measurement, as well as measurements related to the production and the decay of top quarks.

2. Top Properties: Charge

While the top charge is expected to be $+\frac{2}{3}e$, there are models which include an exotic $-\frac{1}{3}e$ top quark that couples to a right-handed $b$ quark [1] and decays into a negative $W$ boson and a $b$ quark. Both the CDF and DØ experiments have performed measurements to test if the top charge is $\frac{2}{3}e$ or $-\frac{1}{3}e$. The challenge is therefore to reconstruct the charges of the $W$ bosons and the $b$ quarks in the event, and subsequently pair the $W$ and the $b$’s to reconstruct the top decay chain. In the CDF analysis, dilepton and lepton+jets top candidate events are selected by first requiring evidence for the leptonic decay of a $W$: an electron (muon) with large transverse energy $E_T(p_T) > 20$ GeV and large transverse missing energy from the undetected neutrino: $E_T > 20$ GeV. For the lepton+jets subsample, three jets with $E_T > 20$ GeV and a fourth jet with $E_T > 12$ GeV are required. To further reduce background contamination, at least two of these jets are required to be identified (tagged) as $b$-jets using displaced vertex information as measured by the CDF silicon vertex detector. In the case of the dilepton subsample, the presence of another high transverse momentum, opposite-sign lepton is demanded, along with the presence of at least two jets with $E_T > 15$ GeV. Of the two jets, one or both should have been tagged as $b$-jets by the silicon detector. A minimum threshold of 200 GeV on the total transverse energy in the event (scalar-sum including $E_T$) is also imposed.
The charge of the $b$-jets is determined by performing a $p_J$-weighted $^1$ sum of the charges of the tracks found within a cone of radius $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.4$ around the jet axis. A negative (positive) weighted sum indicates a $b$ ($\bar{b}$) quark. For real $b$-jets present in CDF data this method have been shown to determine the correct charge roughly 60% of the time.

Finally, the pairing of $W$ and $b$ in dilepton events is performed by computing the invariant mass of the lepton and $b$-jet ($M_{\ell b}$). This mass can be abnormally high for the wrong combinations; the CDF pairing exploits this fact, first by requiring one combination over a certain threshold and then choosing the opposite $\ell - b$ pairing. This procedure was estimated to have a 95% success rate, with an efficiency of 39%. In lepton+jets events, a kinematic fitter $\chi^2$ using reconstructed top and $W$ mass constraints is calculated and the lowest $\chi^2$ combination is retained. The correct pairing is found 86% of the time, with an efficiency of 53%.

The results of this analysis are presented in Figure 1. These results favour the SM hypothesis over the $\frac{-4}{3}e$ top charge hypothesis. The latter hypothesis is rejected at 87% confidence level (C.L.). We note that a top charge measurement has previously been performed by the DØ Collaboration $^2$ with similar conclusions.

![CDF Run II preliminary, L=1.5 fb$^1$](image)

Figure 1: CDF: The distribution of the product between the $W$ (lepton) charge and the jet charge. The histograms show the Standard Model expectation, while the points represent the CDF data.

3. Top Quark Production

3.1. Top Quark Production Mechanism: $q\bar{q}$ versus $gg$ initial state

At the Fermilab Tevatron, the top pairs are expected to originate predominantly from a $q\bar{q}$ initial state: $\sigma(gg \rightarrow t\bar{t}X)/\sigma(q\bar{q} \rightarrow t\bar{t}X) \approx 15% / 85%$, with somewhat large ($O(10\%)$) uncertainties.

Two CDF measurements $^3$ attempt to measure the production cross section ratio. The first measurement takes advantage of the large correlation between the average number of gluons and the average number of low $p_T$ charged particles present in a given sample. The $W+0$jet sample and the dijet (80-100GeV) sample are then used to extract the distributions of the low-$p_T$ track multiplicity in the “no-gluon” case, and the “gluon-rich” case, respectively (Figure 2). These two templates are used in a simple maximum likelihood fit to derive the fractions of the no-gluon

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$^1$ $p_J$ is the projection of track’s momentum along the jet axis.
and the gluon-rich events present in the CDF data. After background subtraction is performed, it is found that 
\[ \sigma(gg \rightarrow t\bar{t}X)/\sigma(q\bar{q} \rightarrow t\bar{t}X) = 0.07 \pm 0.14 \text{(stat)} \pm 0.07 \text{(syst)}. \]

The other CDF measurement of the production mechanism relies on an Artificial Neural Network (ANN) designed to separate events originating from q\bar{q} and gg initial state. The ANN uses eight variables, of which two (six) variables characterize the production (decay) of the top pair. A maximum likelihood fit yields \( \sigma(gg \rightarrow t\bar{t}X)/[\sigma(q\bar{q} \rightarrow t\bar{t}X) + \sigma(gg \rightarrow t\bar{t}X)] = -0.075 \), or \( \sigma(gg \rightarrow t\bar{t}X)/[\sigma(q\bar{q} \rightarrow t\bar{t}X) + \sigma(gg \rightarrow t\bar{t}X)] < 0.61 \) at 95% C.L. The two measurements are combined to obtain \( \sigma(gg \rightarrow t\bar{t}X)/[\sigma(q\bar{q} \rightarrow t\bar{t}X) + \sigma(gg \rightarrow t\bar{t}X)] = 0.07^{+0.15}_{-0.07} \) (stat+syst) (see Figure 2).

![Figure 2](image_url)

**Figure 2**: Left plot: CDF: The distributions of the low-\( p_T \) track multiplicity in the no-gluon and the gluon-rich cases. Right plot: CDF top production mechanism combination: Feldman-Cousins \( \sigma(gg \rightarrow t\bar{t}X)/[\sigma(q\bar{q} \rightarrow t\bar{t}X) + \sigma(gg \rightarrow t\bar{t}X)] \) plot showing the central value and the 68% and 95% C.L. intervals.

### 3.2. Forward-Backward Asymmetry in Top Production

The DØ Collaboration has recently published the first measurement of the forward-backward asymmetry in top production [4]. While a small asymmetry of the order of 5% is expected to arise from QCD calculations [5], several new physics phenomena could drastically increase this asymmetry [6]. The asymmetry \( A_{FB} \) is defined as the count ratio \( (N_F - N_B)/(N_F + N_B) \), where an event is counted as forward (backward) if the rapidity difference \( \Delta y = y_F - y_B \) is positive (negative). This measurement is performed in the reconstructed \( t\bar{t} \) rest frame. The results are shown in Table I. While the values of the asymmetry are somewhat higher than their expected values (a few percent, depending on jet channel) they also have sizable uncertainties, and are therefore in statistical agreement with these expectations.

| No. Events | \( \geq 4 \) jets | 4 jets | \( \geq 5 \) jets |
|------------|------------------|-------|-----------------|
| t\( t \) + X | 266{\pm}22 | 214\pm20 | 54{\pm}10 |
| W + jets | 70\pm21 | 61{\pm}19 | 7{\pm}5 |
| Multijets | 40{\pm}4 | 32{\pm}3.3 | 7.1{\pm}1.6 |
| \( A_{FB} \) | (12\pm8)% | (19\pm9)% | (-16\pm17)% |

A similar search has recently been performed by the CDF Collaboration [7]. The \( A_{FB} \) was measured in both the reconstructed rest frame of the t\( t \) system and in the laboratory frame, and corrected to the intrinsic parton-level
value to allow an easy comparison between the experimental $A_{FB}$ result and the theoretical predictions. The results $^{2}A_{FB}^{tt} = 0.24 \pm 0.13 \text{(stat)} \pm 0.04 \text{(syst)}$ and $A_{FB}^{W} = 0.17 \pm 0.07 \text{(stat)} \pm 0.04 \text{(syst)}$ are higher than, but consistent with the theoretical SM calculation.

### 3.3. Resonance Searches

#### 3.3.1. $t\bar{t}$ Resonance Searches

The DØ and CDF Collaborations have performed searches for narrow-width, high-mass particles $X$ decaying to top quark pairs. Such particles are predicted in many extensions of the SM, such as extended gauge theories [8], Kaluza-Klein excited states of gluons or $Z$ bosons [9], and topcolor [10] to name a few.

The DØ search uses the lepton+jets subsample. At least three high-$E_T$ jets are required to be present in every event; at least one of these jets should be identified as a $b$-jet using a neural networks tagging algorithm [11]. The four momenta of the jets, lepton, and neutrino $^3$ are used to reconstruct the invariant mass of the $t\bar{t}$ system.

The left plot of Figure 3 shows the distribution of the reconstructed top pair mass $M_{tt}$ in the lepton+$\geq 4$ jets channel for data (points) and SM expectation (colored histograms). A 650 GeV top-color-assisted signal [10] is shown by the white contribution stacked on top of the SM expectation (open histogram). The data are found to agree well with the SM expectation. 95 % C.L. limits are set on $\sigma X \cdot BR(X \rightarrow t\bar{t})$ for different $M_X$ values, as shown in the right plot of Figure 3. One can see that a leptophobic $Z'$ with a width $\Gamma_{Z'} = 1.2 \cdot M_{Z'}$ is excluded (95% C.L.) up to a mass of 760 GeV.

![Figure 3: Left plot: DØ: The reconstructed $M_{tt}$ spectrum in the $\geq 4$ jets channel, showing the data (points) and the SM contributions (color histograms). A 650 GeV top-color-assisted model is shown by the white (open) contributions. Right plot: DØ: 95% C.L. exclusion limits on $\sigma X \cdot BR(X \rightarrow t\bar{t})$.](image)

A similar search at CDF observes no significant evidence for new particles decaying to $t\bar{t}$. Using the lepton+$\geq 4$ jets sample, the CDF Collaboration has also measured the differential top pair production cross-section in bins of $M_{tt}$. The result is shown in Figure 4, where a good agreement between CDF data (points) and expected distribution (histogram) is apparent. To quantify this agreement, a “p-value”, defined as the fraction of SM simulated experiments which look as discrepant as the data or worse, is calculated; the result of 0.45 confirms no excess over SM prediction is observed.

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$^2$The expected relationship between the laboratory frame and the $t\bar{t}$ frame asymmetries is: $A_{FB}^{t\bar{t}} \sim 1.3 \cdot A_{FB}^{W}$.

$^3$The longitudinal, or $z$-component of the neutrino momentum is obtained from the $W$ mass constraint $M_{t\bar{t}} = M_W$. This condition yields a quadratic equation in $p_z^\nu$; if there are two real solutions, the smaller $|p_z|$ one is chosen. If there are no real solutions, then $p_z$ is set to zero.
3.3.2. Other Resonance Searches

Other resonance searches in the top sector at the Tevatron include $t'$ searches and scalar top searches. The CDF Collaboration has performed a search for a hypothetical new quark, $t'$, whose decay features the same final state particles as the SM top. The $t'$ particle could belong to a fourth quark generation in which the mass of the $b'$ partner is large enough to satisfy: $M_{b'} > M_{t'} - M_W$; in this case, $t'$ would decay predominantly into $Wq$ ($q = d, s, b$). The variables used to discriminate the $t'$ signal from the associated background (which includes SM $t\bar{t}$ production) are the $t'$ reconstructed mass $M_{\text{reco}}$ and the total transverse energy in the event $H_T$. A simultaneous analysis of these variables excludes the presence of a $t'$ signal up to a mass of 284 GeV (at 95% C.L.).

Searches for scalar top quarks (stop) have been performed by both the CDF and DØ Collaborations. Because of the large top mass, the mixing between the stop eigenstates can be substantial, and the lighter stop $\tilde{t}_1$ could be lighter than the top quark $[12]$. The DØ search focuses on this scenario in which $\tilde{t}_1\tilde{t}_1$ pairs are produced and subsequently decay as $\tilde{t}_1 \rightarrow \tilde{\chi}_1^+ b \rightarrow W^+ \tilde{\chi}_1^0 b$. The final state therefore resembles that of $t\bar{t}$ production, with some additional missing energy from the neutralinos. Multivariate likelihood discriminants are built for six models, defined by $M_{\tilde{t}_1}$ and $M_{\tilde{\chi}_1^\pm}$. In all cases, no significant evidence of a signal is found, and upper limits are set on the cross section of these models, ranging from 7-12 times the theoretical calculations (at 95% C.L.). The CDF analysis $[13]$ draws similar conclusions.

4. Top Quark Decay

4.1. $W$ helicity in Top Decay

The $V-A$ structure of the weak current $t \rightarrow Wb$ requires the following helicity fractions $F_0 = 0.7$, $F_- = 0.3$, and $F_+ = 0.0$ for the longitudinal, left-handed, and right-handed $W$ contributions, respectively. An $F_+$ value significantly different from zero would indicate the presence of physics beyond the SM. The DØ Collaboration has recently published $[14]$ results from the measurement of the fractions of $W$ helicity contributions using the $\cos \theta^*$
variable. Both the dilepton and the lepton+jets subsamples are used for this measurement. The $F_0$ and $F_+$ fractions are fitted simultaneously, while $F_-$ is constrained to $1 - F_0 - F_+$. The result of the fit is shown in Figure 5: $F_0 = 0.425 \pm 0.166 systematic\) and $F_+ = 0.119 \pm 0.090 systematic\) and $F_+ = 0.03 \pm 0.07 systematic\). The third method relies on the matrix element technique previously developed in Run I [15]. In this measurement the $F_+$ and $F_-$ fractions are fixed to zero and 1-$F_0$, respectively. The method yields $F_0 = 0.637 \pm 0.084 systematic\) and $F_+ = 0.069 systematic\).

The CDF Collaboration has employed a three-prong approach for performing this measurement. The first two methods rely on the cosine of the decay angle $\theta^*$ of the charged lepton in the $W$ rest frame measured with respect to the direction of motion of the $W$ boson in the top-quark rest-frame. Fitting for both $F_0$ and $F_+$ fractions simultaneously and combining the two analyses, CDF obtains $F_0 = 0.66 \pm 0.16 systematic\) and $F_+ = 0.03 \pm 0.07 systematic\). The third method relies on the matrix element technique previously developed in Run I [15]. In this measurement the $F_+$ and $F_-$ fractions are fixed to zero and 1-$F_0$, respectively. The method yields $F_0 = 0.637 \pm 0.084 systematic\) and $F_+ = 0.069 systematic\). The results from the three CDF methods are summarized in Figure 5.

To summarize, the DØ and CDF results are compatible with each other and with the SM expectations. More data will be needed for a conclusive determination of the three polarization fractions.

![Figure 5: Left plot: DØ: The simultaneous fit for the fractions of longitudinal and right-handed $W$ bosons from top decays. The ellipses are the 68% and 95% C.L. contours, the triangle borders the physically allowed region where $F_0$ and $F_+$ sum to one or less, and the star denotes the SM values. Right plot: CDF results from the three individual $W$ helicity analyses.](image)

### 4.2. Suppressed Top Decays: $t \rightarrow Zq$

In the SM, the flavor changing neutral current (FCNC) $t \rightarrow Zq$ is predicted to occur at a tiny $\mathcal{O}(10^{-14})$; however, several scenarios involving physics beyond the SM could enhance this branching ratio up to values of the order $\mathcal{O}(10^{-4})$. Thus, any sign of this rare decay at the Tevatron would be an indication of new physics.

A CDF search for $t \rightarrow Zq$ decays is based on a template fit to a $\chi^2$ variable using kinematic constraints present in the top FCNC events; one of these constraints is that the reconstructed mass of the $Zq$ system approach the top mass, within a small window. The subsample used for this study is the $Z \geq 4$ jets, where the $Z$ decayed to a pair of oppositely-charged electrons or muons. The analysis of the kinematic $\chi^2$ reveals no significant evidence for a

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* $\theta^*$ is the angle between the top quark and the lepton from $W$ decay, measured in the $W$ boson rest frame.
signal beyond the SM. A Feldman-Cousins approach yields the tightest constraint to date in this top decay channel: $BR(t \to Zq) < 3.7\%$ at 95\% C.L.

4.3. Exotic Top Decays: $t \to H^+ b$

Charged Higgs bosons are predicted in many extensions of the SM, such as supersymmetry or grand unified symmetries. If these bosons have massed below that of the top quark, the process $t \to H^+ b$ would lead to a decrease in the SM branching ratio $BR(t \to W^+ b)$ assumed to be very close to unity within the SM.

The DØ Collaboration has considered a purely leptophobic model in which $BR(H^+ \to c\bar{s})=100\%$, and the mass of the charged Higgs is close to the $W$ boson mass. Such a model would decrease the measured $t\bar{t}$ cross-section in the lepton+jets channel, while leaving the dilepton $t\bar{t}$ cross section unchanged. Using the ratio between the top pair cross section measured in the dilepton and the lepton+jets subsamples, one can then derive upper bounds on $BR(t \to H^+ b)$. At 95\% C.L. this upper limit is $BR(t \to H^+ b \to c\bar{s}b) < 0.35$.

The CDF Collaboration has also search for charged Higgs bosons from top decays. As opposed to the DØ approach, the CDF analysis seeks to exploit the difference between the dijet mass spectra from the regular $W$ decays $W \to c\bar{s}$ and the charged Higgs decays $H^+ \to c\bar{s}$. Invariant dijet mass templates are built for Higgs masses ranging between 90 and 150 GeV. No significant deviation from the SM is observed, and limits are set for the $BR(t \to H^+ b \to c\bar{s}b)$ as function of the charged Higgs mass. The 95\% C.L. limits on this branching ratio vary between 0.32 ($M_{H^+} = 90$ GeV) and 0.08 ($M_{H^+} = 130$ GeV).

5. Conclusions

We presented selected results from the studies of the properties of the top quarks at the Tevatron. Both the DØ and the CDF Collaborations have very mature and diversified top physics programs. The large amounts of data accumulated by the two experiments allow an unprecedented precision for most SM and beyond the SM measurements in the top sector. For updates of these results and numerous other top-quark-related measurements, we invite the reader to consult the DØ and CDF top group webpages [16].

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