

# MEASUREMENTS OF TOP QUARK PROPERTIES AT THE TEVATRON

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The top quark is the most recently discovered of the standard model quarks, and studies of its properties are important tests of the standard model. Many measurements of top properties have been produced by the CDF and D0 collaborations, which study top quarks produced in  $p\bar{p}$  collisions at the Fermilab Tevatron with a center-of-mass energy  $\sqrt{s} = 1.96$  TeV. We describe recent results from top properties measurements at the Tevatron using datasets corresponding to integrated luminosities up to  $8.7 \text{ fb}^{-1}$ .

## 1 Introduction

Since its discovery in 1995 at the Tevatron,<sup>1</sup> the study of the production and properties of the top quark has been one of the most active areas of research in high energy particle physics. Its extremely large mass makes the top unique among quarks, in that it decays via the electroweak interaction before hadronization. Thus, properties such as spin can be measured through their effects on the kinematic distributions of the top decay products. This offers physicists a first chance to study a “bare” quark. With a Yukawa coupling near one, the top quark could play a special role in electroweak symmetry breaking, and its large mass could potentially lead to enhanced couplings to new physics. Precision measurements of top properties are important both as tests of the standard model and as potential avenues for the discovery of new physics.

The majority of top quarks analyzed at the Tevatron are produced as  $t\bar{t}$  pairs via the strong interaction, although they are also produced singly via the electroweak interaction, a mode that was not observed until 2009.<sup>2</sup> The standard model predicts that tops decay almost always via  $t \rightarrow Wb$ , so the decay modes of  $t\bar{t}$  pairs are described by the two  $W$  boson decays. Two decay modes are used in the analyses described in this document: the “dilepton” mode, where both  $W$ ’s decay to a lepton (electron or muon) and a neutrino, and the “lepton plus jets” mode, where one  $W$  decays leptonically and the other decays to a pair of quarks. A large portion of  $t\bar{t}$  pairs decay into the “all-hadronic” channel, where both  $W$ ’s decay to quark pairs, but this channel faces a very large background from QCD multi-jet production and is difficult to use in top properties measurements.

## 2 Asymmetry in $t\bar{t}$ Production

When top pairs are produced in  $p\bar{p}$  collisions, the standard model predicts a small asymmetry,  $\mathcal{O}(7\%)$  at next-to-leading order (NLO), in the number of top quarks that travel along the proton direction compared to the number that travel along the antiproton direction. Using

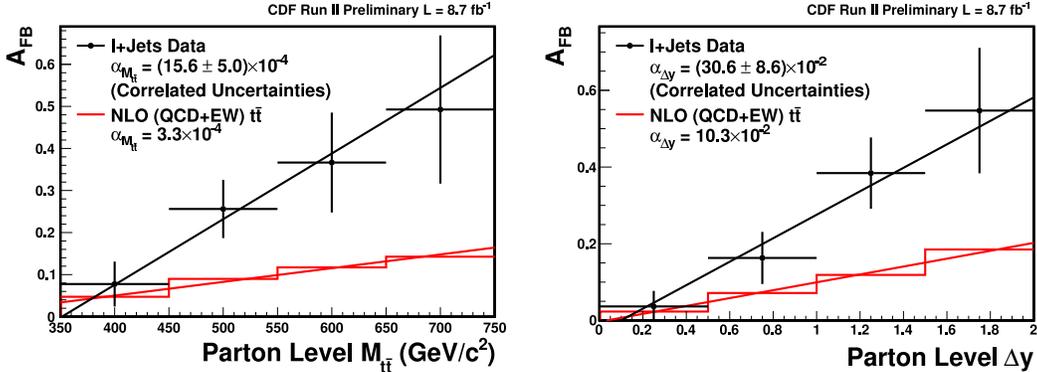


Figure 1: Parton-level  $A_{FB}$  as a function of  $M_{t\bar{t}}$  (left) and  $|\Delta y|$  (right) as measured at CDF.

approximately  $5 \text{ fb}^{-1}$ , analyses at CDF and D0 found asymmetries exceeding the prediction with moderate significance.<sup>3</sup> The CDF result in the lepton plus jets channel also observed an increase in the asymmetry as a function of the invariant mass of the  $t\bar{t}$  system ( $M_{t\bar{t}}$ ). The measurement of this asymmetry with the full Tevatron dataset is an important update and will be complementary to similar measurements at the Large Hadron Collider (LHC), where the effect must be measured in a different manner due to the symmetric  $pp$  initial state.

CDF has recently released a new measurement of the asymmetry using  $8.7 \text{ fb}^{-1}$ , corresponding to the full Tevatron dataset.<sup>4</sup> The asymmetry  $A_{FB}$ , defined in Equation 1, is measured using the frame-invariant variable  $\Delta y$ , the difference in rapidities between the top quark and the antitop quark. After removing the background contribution and correcting for acceptances and detector resolution effects, CDF measures a parton level asymmetry of  $(16.2 \pm 4.7)\%$ , compared to the prediction of  $6.6\%$  determined using the NLO event generator POWHEG<sup>5</sup> with a flat correction applied to account for electroweak contributions to the asymmetry.<sup>6</sup>

$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \quad (1)$$

The new CDF result also considers the mass and rapidity dependence of the asymmetry, measuring  $A_{FB}$  as a function of both  $M_{t\bar{t}}$  and  $|\Delta y|$ , as shown in Figure 1. In both cases, the asymmetry is found to be well-fit by a linear ansatz, and the best-fit slopes are measured and compared to the prediction. At the parton level, CDF finds the slope of  $A_{FB}$  vs.  $M_{t\bar{t}}$  to be  $(15.6 \pm 5.0) \times 10^{-4}$ , compared to a prediction of  $3.3 \times 10^{-4}$ . The slope of  $A_{FB}$  vs.  $|\Delta y|$  is measured to be  $(30.6 \pm 8.6) \times 10^{-2}$ , compared to a prediction of  $10.3 \times 10^{-2}$ . The significance of the deviation from the prediction is determined at the background-subtracted level, before the final corrections for acceptance and resolution effects are applied. Simulated experiments are performed based on the POWHEG prediction with electroweak corrections, and a p-value is determined by finding the fraction of such experiments in which the predicted slope is at least as large as that observed in the data. A p-value of  $6.46 \times 10^{-3}$  is found for the  $M_{t\bar{t}}$  dependence of the asymmetry, along with a p-value of  $8.92 \times 10^{-3}$  for the  $|\Delta y|$  dependence.

### 3 $t\bar{t}$ Spin Correlations

When top quark pairs are produced in hadronic collisions, the individual top quarks are unpolarized, but the  $t\bar{t}$  system has a definite spin state and thus the spins of the two quarks are correlated. The strength of this correlation, which is frame-dependent, is quantified as the fractional difference  $\kappa$  between the number of top pairs where the quark spins are aligned and the

number of pairs where the spins are oppositely aligned. Because tops decay before hadronization, spin information can be measured by considering the angular distributions of the top decay products.

Both CDF and D0 have performed measurements of the spin correlation, with the spin quantization axis being defined to be along the beam direction, where the standard model predicts  $\kappa = 0.78$ .<sup>7</sup> CDF uses template fitting methods to measure  $\kappa$  directly, finding  $\kappa = 0.72 \pm 0.69$  in the lepton plus jets decay channel<sup>8</sup> and  $\kappa = 0.042 \pm 0.563$  in the dilepton channel.<sup>9</sup> The CDF results are consistent with each other and with the standard model within large uncertainties.

D0 utilizes a new matrix element approach that enhances the sensitivity by approximately 30%. A matrix element method is used to define a discriminant based on the probability that a given event contains the standard model spin correlation. Combining measurements in the dilepton<sup>10</sup> and lepton plus jets<sup>11</sup> channels, D0 finds that the fraction of events which contain the standard model spin correlation is  $f = 0.85 \pm 0.29$ . This result provides the first  $3\sigma$  evidence for the existence of the spin correlation. The fraction of events containing the standard model correlation is then converted to a measurement of  $\kappa$ , giving  $\kappa = 0.66 \pm 0.23$ .

#### 4 $W$ Boson Helicity

In the standard model, top quarks decay nearly always to a  $W$  boson and a  $b$  quark, and the helicity states of the  $W$  are constrained according to the V-A nature of the  $W-t-b$  coupling. The standard model predicts that the fractions of longitudinal, left-handed, and right-handed  $W$  bosons, labeled  $f_0, f_-,$  and  $f_+$  respectively, in  $t\bar{t}$  events will be approximately 0.7, 0.3, and 0.0.

D0 and CDF have both performed measurements of these helicity fractions by considering angular distributions of the  $W$  decay products - particularly the lepton - in  $t\bar{t}$  candidate events. A combination of the  $W$  helicity results for the two experiments has recently been submitted for publication,<sup>12</sup> the first such published combination of  $W$  helicity measurements. With  $f_0 + f_- + f_+ = 1$ , the combined CDF and D0 measurements find  $f_0 = 0.722 \pm 0.081$  and  $f_+ = -0.033 \pm 0.046$ .

#### 5 Top Branching Ratio

The standard model prediction that top quarks almost always decay to  $Wb$  has also been tested in measurements by CDF and D0. Both collaborations have recently performed analyses to measure the ratio  $R = \mathcal{B}(t \rightarrow Wb)/\mathcal{B}(t \rightarrow Wq)$ , where  $\mathcal{B}(t \rightarrow WX)$  is the branching ratio for a top to decay to  $WX$ . The standard model predicts that  $R$  should be very close to 1. If the CKM matrix is assumed to be unitary, then a measurement of  $R$  can also be converted into a measurement of the CKM matrix element  $|V_{tb}|$ .

In  $t\bar{t}$  production and decay, the standard model expectation is that each event will contain two  $b$  quarks. Since jets originating from  $b$  quarks can be tagged by a displaced secondary vertex, and the efficiency for tagging such jets can be measured, the ratio  $R$  can be determined by dividing the sample of  $t\bar{t}$  candidate events into sub-samples with 0, 1, or 2  $b$ -tagged jets and comparing the relative sizes of each sub-sample to the predicted sizes determined from the tagging efficiency. Using a luminosity of  $5.4 \text{ fb}^{-1}$ , a recent D0 measurement in both the dilepton and lepton plus jets channels<sup>13</sup> finds  $R = 0.90 \pm 0.04$ , smaller than the standard model expectation at the level of approximately  $2\sigma$ , and measures  $|V_{tb}| = 0.95 \pm 0.02$ . With  $7.5 \text{ fb}^{-1}$ , a new CDF result in the lepton plus jets channel<sup>14</sup> measures  $R = 0.91 \pm 0.09$  and  $|V_{tb}| = 0.95 \pm 0.05$ , again somewhat below the prediction but with a significance that is smaller than the D0 result.

## 6 Top Width

The top quark width is expected to be approximately 1.5 GeV in the standard model, and both CDF and D0 have performed measurements to test this prediction. CDF has performed a direct measurement in the lepton plus jets decay channel with a luminosity of  $4.3 \text{ fb}^{-1}$ , using a likelihood fit to the reconstructed top quark mass distribution based on template samples with different input top widths.<sup>15</sup> This analysis results in a 95% C.L. limit of  $\Gamma_t < 7.6 \text{ GeV}$  and a 68% two-sided limit  $0.3 \text{ GeV} < \Gamma_t < 4.4 \text{ GeV}$ .

Using a luminosity of  $5.4 \text{ fb}^{-1}$ , D0 has performed a complementary measurement that indirectly measures the top width by combining results from other top properties measurements.<sup>16</sup> In particular, as shown in Equation 2, the total width of the top quark is determined from the ratio of the partial width for the process  $t \rightarrow Wb$ , as determined from the measured cross-section for single top production, to the branching ratio for  $t \rightarrow Wb$ , measured in the analysis described in Section 5. This method requires input from several measurements and from the theoretical predictions, but results in increased sensitivity compared to a direct measurement. D0 measures a width of  $\Gamma_t = 2.00_{-0.43}^{+0.47} \text{ GeV}$ , and converts this to a 95% C.L. limit on  $|V_{tb}|$ , finding  $0.81 < |V_{tb}| \leq 1$ .

$$\Gamma_t = \frac{\Gamma(t \rightarrow Wb)}{\mathcal{B}(t \rightarrow Wb)} \quad (2)$$

## 7 Conclusions

The full dataset collected at the Tevatron is now being used to measure top quark properties at CDF and D0. Many of these measurements, such as the  $A_{FB}$  measurement and the measurement of  $t\bar{t}$  spin correlations, are complementary to analyses that can be performed at the LHC, where the different center-of-mass energy and initial state will provide additional information about the couplings of the top quark. Many CDF and D0 analyses, such as the  $W$  helicity measurement in  $t\bar{t}$  decays described here, are now being combined to create Tevatron-wide results. Data-taking has ceased at the Tevatron, but there is still much left to be learned from analysis of the top quark samples collected at CDF and D0, and both collaborations continue to pursue precision results.

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