MEASUREMENTS OF TOP QUARK PROPERTIES AT THE TEVATRON

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Since the discovery of the top quark nearly twenty years ago, the CDF and DZero collaborations have been working to see if measurements of top quark properties agree with predictions from the Standard Model. We present multiple analyses of $p\bar{p}$ collisions with $\sqrt{s} = 1.96$ TeV at the Tevatron, using integrated luminosities up to 9.4 fb^{-1} for various $t\bar{t}$ decay signatures. Included in our discussion are measurements of W helicity, t quark decay branching fractions, t quark width and $t\bar{t}$ forward-backward production asymmetries.

1 Introduction

The top quark (t) was discovered in 1995 by the CDF and DZero experiments using $p\bar{p}$ collisions from the Tevatron. At the time of discovery, each experiment had tens of t quark candidate events. Now each experiment has data samples consisting of thousands of t quark candidates. The top quark is the heaviest known fermion and the only constituent of matter heavier than the Higgs Boson. Because of the extremely large mass of the top quark, mass measurements test the internal consistency of electroweak symmetry breaking in the Standard Model (SM) via the relationship between the H, W and t masses. Measurements of top quark properties are necessary to test the SM and to perhaps provide discrepancies that give insight into physics beyond the Standard Model.

In this paper, we focus on top quark pair production ($p\bar{p} \to t\bar{t}$), the main production mechanism for top quarks at the Tevatron. In the Standard Model, the top decays via the weak force to ($t \to Wq$), where q is a b quark nearly 100% of the time. The W boson can decay leptonically ($W \to l\nu$) or hadronically ($W \to q\bar{q}'$). The decay of the W boson decides which objects we identify the $t\bar{t}$ decay with. In this paper, we discuss measurements made in the dilepton channel ($t \to WbW\bar{b} \to ll\nu\nu b\bar{b}$) and the lepton+jets channel ($t \to WbW\bar{b} \to l\nu q\bar{q}'b\bar{b}$). In both of these channels, unless otherwise specified, l is either an electron or a muon. In the following sections we describe a group of analyses that measure properties of the production and the decay of the top quark.

2 W helicity

The W boson from top quark decay can have three possibility helicity states: right-handed (+), left-handed (-) and longitudinal (0). The Standard Model predicts that $\sim 70\%$ of W bosons have longitudinal helicity (f_0), while $\sim 30\%$ are left-handed (f_-) and $\sim 0\%$ are right-handed (f_+). Any deviations from these fractions in a sample of top quark events could point to physics beyond the SM, either in $t\bar{t}$ production or at the $t \to Wb$ decay vertex.

The CDF collaboration recently published a measurement using the matrix element method with 8.7 fb^{-1} in the lepton+jets channel [1]. For each event, probabilities are found using the leading order matrix elements for the event to be a signal event produced with a given helicity and for the event from background production. Each jet-parton assignment is used to construct this probability. All of the probabilities are combined together to form a likelihood, and this likelihood is maximized to get measured values for f_0, f_+ and the fraction of signal events in the data sample. By utilizing the matrix element method, this analysis uses more information from $t\bar{t}$ decay than previous CDF lepton+jets analyses and achieves better statistical power. The results are $f_0 = 0.726 \pm 0.066$ (stat) ± 0.067(syst) and $f_+ = -0.045 \pm 0.043$(stat) ± 0.058(syst), which are consistent with the Standard Model.

The CDF and DZero Collaborations published a combined result for the W helicity [2]. The result combines three measurements: a CDF matrix element analysis using 2.7 fb^{-1} of data in lepton+jets channel; a CDF template-based analysis using 5.1 fb^{-1} of data in the dilepton channel; and a DZero template-based analysis using 5.4 fb^{-1} of data in both the lepton+jets and dilepton channels. The template-based analyses use distributions in the reconstructed helicity angle, $\cos\theta^*$, to extract f_0 and f_+. The three measurements are combined using the measured values and the covariance matrices for the uncertainties. the results are $f_0 = 0.722 \pm 0.062$(stat) ± 0.052(syst) and $f_+ = -0.033 \pm 0.034$(stat) ± 0.031(syst), in good agreement with the standard model predictions.

3 Branching ratio of the t quark

The branching ratio of top quark decays is $R = \frac{t \to Wb}{t \to Wq}$. The branching ratio can also be described in terms of CKM matrix elements: $R = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$. In the Standard Model, R is extremely close to 1 (0.998). Any large deviation from 1 would indicate that new physics is involved in the decay of the top quark.

The latest measurement of R from the CDF collaboration uses 8.7 fb^{-1} of data in the lepton+jets channel [3]. To differentiate between $t\bar{t}$ decays with different branching ratios, events are broken up by the number of jets and the number of b tags into six different categories: 3 jets, one b-tag; 3 jets, ≥ 2 b-tags; 4 jets, one b-tag; 4 jets, ≥ 2 b-tags; ≥ 5 jets, one b-tag and ≥ 5 jets, ≥ 2 b-tags. The analysis excludes events with 0 b-tags, which are dominated by background processes. Each category is put into a bin in a histogram. Templates are made for $t\bar{t}$ signal distributions with different R values and for the background distributions. A maximum likelihood fit is used to simultaneously measure the $t\bar{t}$ cross section ($\sigma_{t\bar{t}}$) and the branch fraction. As the background normalization has some dependence on $\sigma_{t\bar{t}}$, the fit is run iteratively until the measured value for $\sigma_{t\bar{t}}$ converges.

The results of the maximum likelihood fit are $\sigma_{t\bar{t}} = (7.5 \pm 1.0)$ pb and $R = 0.94 \pm 0.09$, with a statistical uncertainty for R of 0.04 and total systematic uncertainty for R of 0.08. As one might expect, the systematic uncertainties are dominated by uncertainties on the b-tagging, where migrations between bins would have a large effect on the measured value of R, and uncertainties on the background normalization. The measurement is good agreement with the SM, and places a lower limit on the branching ratio of $R > 0.785$ at 95% confidence level. Assuming that the CKM matrix is unitary and that there are only three generations of quarks, we measure $|V_{tb}| = 0.97 \pm 0.05$ and place a lower limit of $|V_{tb}| > 0.89$ at 95% confidence level. These results are consistent with previous measurements from the Tevatron.

4 Width of the t quark

The CDF collaboration has released result of a direct measurement of the width of the top quark, using 8.7 fb^{-1} of data in the lepton+jets channel [4]. The observed decay products are kinematically reconstructed with the constraints $m_W = 80.4$ GeV and $m_{t,1} = m_{t,2}$. The analysis essentially uses the shape of the reconstructed top mass distribution to extract the width. Probability density functions (p.d.f.) found using Kernel Density Estimation, $P(m_t^{\text{reco}}, m_{jj}|\Gamma_t, \Delta_{\text{JES}})$, are made for the reconstructed top mass, m_t^{reco} and the invariant mass of the two jets assigned to the W boson, m_{jj}, given different top widths (Γ_t) and the change in the nominal JES (Δ_{JES}). For signal, multiple p.d.f.s with different Γ_t and Δ_{JES} are made, while for background p.d.f.s with different Δ_{JES} are made. A likelihood, constructed from these probabilities for all events, is maximized to find the measured values of Γ_t and Δ_{JES}.

Pseudo experiments are used with the Feldman-Cousins scheme to calibrate the analysis and calculate the uncertainties. Before calibration, the width from data is $\Gamma_t = 1.63$ GeV. After calibration, the final result is

$$\Gamma_t = 2.21^{+1.46}_{-0.92}\text{ (stat)}^{+1.12}_{-0.62}\text{ (syst) GeV},$$

in good agreement with the standard model prediction of 1.25 GeV. As might be expected, the largest systematic uncertainties are from jet resolution and different simulated effects, such as color reconnection and the fraction of $t\bar{t}$ events arising from gg versus $q\bar{q}$. Using the Heisenberg Uncertainty Principle, the lifetime of the top quark is measured to be $\tau_t = 2.98^{+3.00}_{-1.35} \times 10^{-25}$s.

5 Forward-backward $t\bar{t}$ production asymmetry

At the Tevatron, the color charge asymmetry in production for $q\bar{q} \to t\bar{t}$ is manifested as a forward-backward asymmetry, A_{FB}, in $p\bar{p} \to t\bar{t}$. One of the more simple quantities to reconstruct and measure is the asymmetry based on the lepton from $t\bar{t}$ decay, A^l_{FB}, which is defined as:

$$A^l_{\text{FB}} = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}, \tag{1}$$

where q_l is the charge of the lepton and y_l is the rapidity of the lepton. Both the CDF and DZero Collaborations have recently released results for the lepton-based asymmetry, DZero in the dilepton channel using 5.4 fb^{-1} of data [5] and CDF in the l+jets channel using 9.4 fb^{-1} of data [7]. Both collaborations present asymmetries made from distributions of data after subtracting the predicted shapes and normalizations from background processes. As the angular resolution for leptons is extremely good, there is no need to unfold distributions from background-subtracted data for effects from reconstruction. Lepton-based distributions are corrected for effects from acceptance, which differ for the dilepton and lepton+jets channels. The CDF Collaboration applies an additional correction to extrapolate the asymmetry beyond the angular range of the CDF detector to the inclusive range for leptons from $t\bar{t}$ decay.

The results from the DZero dilepton analysis are summarized in Table 2 of the publication [5]. For the sake of brevity, they will not be shown here. All of the results are in good agreement with the predicted asymmetries from MC@NLO, with additional QCD+EW corrections. The results for A^l_{FB} are combined with the results from the DZero A^l_{FB} measurement in the lepton+jets channel [6], for value of $A^l_{\text{FB}} = (11.8 \pm 3.2)\%$, which is about 2σ higher than the predicted value of $(4.7 \pm 1.1)\%$.

In the lepton+jets channel, the CDF Collaboration measures lepton-based asymmetries that are somewhat higher than the predictions. For asymmetries made from background-subtracted data, CDF measures $A^l_{\text{FB}} = (7.0 \pm 1.9\text{ (stat)} \pm 1.1\text{ (syst)})\%$, which can be compared to the prediction from POWHEG of 2.3%. After applying an acceptance correction and extrapolating the asymmetry, CDF finds $A^l_{\text{FB}} = (9.4 \pm 2.4\text{ (stat)}^{+2.2}_{-1.7}\text{ (syst)})\%$, which is about 2σ higher than the prediction of 3.8% [8].

6 An alternative to the asymmetry

The CDF collaboration has released a new analysis that aims to measure the entire angular distribution in t production via $\cos(\theta_t)$ via Legendre moments, rather than summarize the distribution into one number, A_{FB} [9]. Previous $t\bar{t}$ asymmetry measurements from CDF and DZero have measured the asymmetry in multiple regions of $|\Delta y|$, which give a slightly more detailed picture about the entire distribution. The analysis uses 9.4 fb^{-1} of data in the lepton+jets channel, with almost the same selection as the CDF A_{FB} measurement [10]. The only change is a relaxed requirement on the E_T of one of the four jets, from 20 GeV to 12 GeV. This change reduces effects from acceptance and allows more events into the analysis. A χ^2-based kinematic fit is used to reconstruct the $t\bar{t}$ four-vectors and extract $\cos(\theta_t)$ for each event.

The following equation decomposes a given function into the Legendre moments: $a_l = \frac{2l+1}{2}\int_{-1}^{1} dx f(x) P_l(x)$, where $P_l(x)$ is the lth Legendre polynomial ($P_0 = 1$, $P_1 = x$, $P_2 = \frac{1}{2}(3x^2 - 1), \cdots$). For this analysis, the function is the sum of Dirac delta functions at the reconstructed values of $\cos(\theta_t)$, $f(\cos\theta) = \sum_i \delta(\cos\theta - \cos\theta_i)$. The combination of the equations results in $a_l = \frac{2l+1}{2}\sum_i P_l(\cos\theta_i)$. The a_i are unfolded for effects from acceptance and reconstruction by inverting the matrix in $a^{\text{detector}}_l = \frac{2l+1}{2}\sum_m K_{lm} a^{\text{parton}}_m$, where a^{detector}_l is lth reconstructed moment, a^{parton}_m is mth parton-level moment and K_{lm} is the migration matrix between these moments, found from simulated $t\bar{t}$ events.

Because this analysis measures the entire distribution in $\cos\theta_t$, it has more differentiating power between different new physics models than a standalone $A_{\rm FB}$ analysis. The results of this technique applied to CDF data are shown in Table 1. The moment with the largest deviation from the predicted moments [8] is a_1, which differs by 2σ. All other measured moments are in good agreement with the predictions.

Table 1: Measured Legendre moments of $\cos\theta_t$ from CDF data, with statistical and systematic uncertainties.

Legendre degree (l)	a_l for data (stat+syst)	a_l predicted from NLO (QCD+EW)
1	$0.40 \pm 0.09 \pm 0.08$	$0.15^{+0.066}_{-0.033}$
2	$0.44 \pm 0.14 \pm 0.21$	$0.28^{+0.053}_{-0.030}$
3	$0.11 \pm 0.20 \pm 0.08$	$0.030^{+0.014}_{-0.007}$
4	$0.22 \pm 0.25 \pm 0.11$	$0.035^{+0.016}_{-0.008}$

Conclusions

New results for measurements of top quark properties at the Tevatron have been presented, with many analyses using the entire Tevatron data sample. These analyses make precision measurements of various aspects of top quark production and decay, via the W helicity, branching fraction, width and asymmetry. None of the results provide a smoking gun for physics beyond the Standard Model, but some deviations from the predictions remain. These results use novel, advanced analysis techniques, and exemplify the dedication and passion of experimenters at both the CDF and DZero Collaborations.

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References

1. T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. D **87**, 031104 (2013) [arXiv:1211.4523 [hep-ex]].
2. T. Aaltonen *et al.* [CDF and D0 Collaborations], Phys. Rev. D **85**, 071106 (2012) [arXiv:1202.5272 [hep-ex]].
3. The CDF Collaboration, CDF note 10887, http://www-cdf.fnal.gov/physics/new/top/confNotes/cdf10887_BRratio8.7fb.pdf (2012).
4. The CDF Collaboration, CDF note 10936, http://www-cdf.fnal.gov/physics/new/top/2012/TMT_width_p38/publicnote.pdf (2012).
5. V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **87**, 011103(R) (2013) [arXiv:1207.0364 [hep-ex]].
6. V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **84**, 112005 (2011).
7. The CDF Collaboration, CDF note 10975, http://www-cdf.fnal.gov/physics/new/top/2013/AfbLep_public_page/cdf10975_afblep.pdf (2013).
8. W. Bernreuther and Z. -G. Si, Phys. Rev. D **86**, 034026 (2012) [arXiv:1205.6580 [hep-ph]].
9. The CDF Collaboration, CDF note 10974, http://www-cdf.fnal.gov/physics/new/top/2013/TopAngularXS/cdf10974_PubTopCosTheta.pdf (2013).
10. T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. D **87**, 092002 (2013) [arXiv:1211.1003 [hep-ex]].