DØ Note 5838-CONF

Measurement of anomalous top quark couplings at D0

The DØ Collaboration
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We present measurements of the Wtb coupling form factors using information from single top quark production and from the helicity of W bosons from top quark decays in $t\bar{t}$ events, and also set upper limits on form factors for anomalous Wtb couplings, based on a sample of 0.9 fb^{-1} of single top candidate events and up to 2.7 fb^{-1} of $t\bar{t}$ candidates collected by the D0 detector at the Tevatron $p\bar{p}$ collider.

Preliminary Results for Winter 2009 Conferences

The large data samples from Run II of the Tevatron allow the top quark to be studied in unprecedented detail. Since the top quark is by far the most massive known fermion, with a coupling to the Higgs field of order unity, such studies may shed light on the mechanism of electroweak symmetry breaking.

Within the standard model (SM), the dominant coupling of the top quark is to the bottom quark and W boson (Wtb) and has the form $V-A$. Departures from the SM can arise from new physics [1], and in this analysis we therefore consider a more general form for the Wtb coupling

The effective Lagrangian describing the Wtb interaction, including operators up to dimension five, is [2]:

$$\begin{aligned}\mathcal{L} &= -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}(f_1^L P_L + f_1^R P_R)tW_{\mu}^{-} \\ &- \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}V_{tb}}{M_W}(f_2^L P_L + f_2^R P_R)tW_{\mu}^{-} + h.c.,\end{aligned} \tag{1}$$

where M_W is the mass of the W boson, q_{ν} is its four-momentum, V_{tb} is the Cabibbo-Kobayashi-Maskawa matrix element, and $P_L = (1-\gamma_5)/2$ ($P_R = (1+\gamma_5)/2$) is the left-handed (right-handed) projection operator. We assume that CP is conserved at the Wtb vertex, meaning that the all the form factors $f_i^{L,R}$ are taken to be real. We also assume that the top quark has spin $\frac{1}{2}$.

Deviations from the SM values of the form factors ($f_1^L = 1$, $f_2^L = f_1^R = f_2^R = 0$) would alter the $b \to s\gamma$ branching fraction, and measurements of this quantity have been used to limit the right-handed vector and tensor couplings [3]. While these constraints are more restrictive than those we present, they rely on assumptions of the absence of other non-SM contributions to b quark decay, while the direct measurement presented here avoids such assumptions.

We measure the values of the couplings using up to 2.7 fb^{-1} of data collected by the D0 experiment [4] at the Fermilab Tevatron $p\bar{p}$ collider between 2002 and 2008 ("Run II"). Variations in the coupling form factors would mainly manifest themselves in two distinct ways that are observable at D0: (i) by changing the rate and kinematic distributions of electroweak single top quark production, and (ii) by altering the fractions of W bosons from top quark decay produced in each of the three possible helicity states. We combine information from our measurement of W boson helicity fractions in $t\bar{t}$ events [5] with information from single top quark production, using the general framework given in Ref. [6]. This analysis is an update of the result presented in Ref. [7] with a larger sample of $t\bar{t}$ events used in the W boson helicity measurement.

We follow the approach adopted in Ref. [7] and investigate one pair of coupling form factors at a time out of the full set of left/right (L/R) and vector/tensor (1/2) form factors (f_1^L, f_1^R, f_2^L, and f_2^R). For each pair of couplings under investigation we assume that the other two couplings have the SM values. We consider three cases, pairing the left-handed vector coupling form factor f_1^L with each of the other three form factors. We refer to these as (L_1, R_1), (L_1, L_2), and (L_1, R_2). For each pair of form factors, a likelihood distribution is extracted from the W helicity measurement in the angular distribution of top quark decays. All $t\bar{t}$ pair events with decays to at least one lepton (electron or muon) are included in the W helicity measurement. This likelihood is combined in a Bayesian statistical analysis with the result of the search for anomalous couplings in the single top quark final state, yielding a two-dimensional posterior probability density as a function of both form factors. We extract limits on $|f_1^R|^2$, $|f_2^L|^2$, and $|f_2^R|^2$ by projecting the two-dimensional posterior onto the corresponding form factor axis.

The W boson helicity measurement, described in Ref. [5], uses events in both the ℓ+jets ($t\bar{t} \to W^+W^-b\bar{b} \to \ell\nu q\bar{q}'b\bar{b}$) and dilepton ($t\bar{t} \to W^+W^-b\bar{b} \to \ell\nu\ell'\nu'b\bar{b}$) final states, and is extracted form the distribution of θ^*, the angle between the down-type fermion and top quark momenta in the W boson rest frame. To evaluate θ^* in any event, we assign a momentum to the neutrino(s) either through a constrained kinematic fit (for the ℓ+jets channel) or an algebraic solution (for the dilepton channel).

We use the ALPGEN leading-order Monte Carlo (MC) event generator [8], interfaced to PYTHIA [9], to model $t\bar{t}$ events as well as W+jets and Z+jets background events. We generate both SM $V-A$ and $V+A$ Wtb couplings, and reweight events to model any given W boson helicity state. We use the CTEQ6L1 parton distribution functions [10] and set the top quark mass to 172.5 GeV. The response of the D0 detector to the MC events is simulated using GEANT [11]. We model the background from multijet production, where a jet is misidentified as an isolated electron or muon, using events from data containing lepton candidates that pass all of the lepton identification requirements except one, but otherwise resemble the signal events. We use MC to model other smaller backgrounds.

We select events with a multivariate likelihood discriminant that uses both kinematic and b-lifetime information to distinguish $t\bar{t}$ events from background, and obtain a sample of 786 ℓ+jets (175 dilepton) events with an expected background contribution of 225 ± 10 (51 ± 8) events from 2.2 (2.7) fb^{-1} of data.

A binned maximum likelihood fit compares the $\cos\theta^*$ distribution of the selected events to expectations from each W boson helicity state and the background. We vary both the longitudinal and right-handed helicity fractions f_0 and f_+ in the fit and find the relative likelihood of any set of helicity fractions being consistent with the data. The result is presented in Fig. 1, which also demonstrates how non-SM values for the coupling form factors alter the W helicity fractions. Further details can be found in Ref. [5]. In Fig. 1, the red bins are those explored when f_1^R is non-zero, the green when f_2^L is non-zero, and the blue when f_2^R is non-zero. The constraints on anomalous couplings arising from the W helicity measurement can be visualized by comparing the red, green, and blue lines to contours of constant $\Delta \ln L$ obtained from the measurement (the outermost contour corresponds to $\Delta \ln L = 4.5$, or 3 standard deviation). The red line does not reach $\Delta \ln L$ values smaller than those at the point for the SM, meaning that the data does not prefer non-zero values for f_1^R. The green and blue lines, however, traverse several contours of smaller $\Delta \ln L$ than the SM point, meaning that the data does prefer a non-zero value for f_2^L and f_2^R. The best-fit for the W helicity fractions suggest a model in which more than one of the anomalous couplings is non-zero, a scenario not explored in the present analysis.

To measure the Wtb form factors, we express the relative likelihoods in terms of the squares of the form factors for anomalous Wtb couplings using the relationships given in Ref. [6]. The resulting likelihoods are presented in the upper row of Fig. 4. The contours of equal likelihood are straight lines, reflecting the fact that the W helicity measurement only constrains ratios of the coupling form factors.

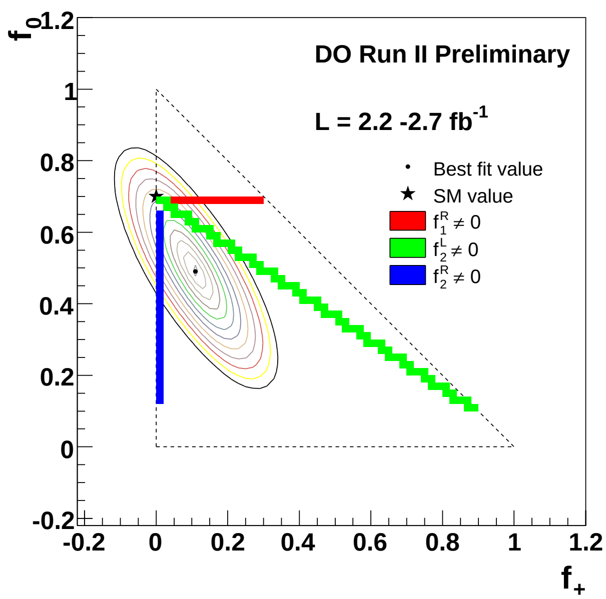

FIG. 1: Graphical representation of the change in W boson helicity fractions away from the SM values (shown by the star) if the anomalous couplings are present.

Both the ratios and the magnitudes of the form factors can be constrained in the single top analysis. The dominant modes for single top quark production at the Tevatron are the s-channel production and decay of a virtual W boson and the t-channel exchange of a W boson. Evidence for production of single top quarks has been reported by the D0 and CDF collaborations [12, 13]. The total cross section for SM single top quark production at a top quark mass of 172.5 GeV is predicted to be 3.15 ± 0.3 pb [14]. However, both the cross section and the angular correlations of the final state objects are modified in the presence of anomalous couplings. D0's first constraints on anomalous Wtb couplings were set using only information from single top quark candidate events [15], under the assumption that single top quarks are produced exclusively through W boson exchange and that the Wtb vertex dominates top quark production and decay. We use the same assumptions in the present analysis.

We study single top quark production in events with one lepton (electron with $p_T > 15$ GeV or muon with $p_T > 18$ GeV) and $\not\!\!E_T > 15$ GeV. From 0.9 fb^{-1} of data we select a sample that is statistically independent of the events used to analyze the W helicity by requiring two or three jets with $p_T > 15$ GeV with the leading jet having $p_T > 25$ GeV. Vetoing events with more than three jets is the only change in the single top portion of the analysis from the result presented in [15]. We also require that at least one of the jets be identified as originating from a b hadron (using a b-tagging algorithm). Details of the selection criteria and background modeling are given in Ref. [12].

We model the single top quark signal using the COMPHEP-SINGLETOP MC event generator [16] where anomalous Wtb couplings are considered in both the production and decay of the top quark. The background modeling for the single top analysis is based on the same samples of W+jets and multijet backgrounds as used in the W helicity $t\bar{t}$ analysis. The $t\bar{t}$ contribution to background in the single top quark sample is small and is modeled by simulated SM

$t\bar{t}$ events, and is normalized to the theoretical cross section [17].

Selection efficiencies for single top quark signals with different Wtb couplings are $\approx$ (1–2)% for events with one b tag and $< 1\%$ for events with two b tags. We select 1152 events, which we expect to contain 56 ± 12 SM single top quark events. We use boosted decision trees [18, 19] to separate single top quark candidates from the large background.

Systematic uncertainties on modeling signal and background are described in detail in Refs. [5] and [12]. We take all systematic uncertainties and their correlations into account. Systematic uncertainties on the measured W boson helicity arise from finite MC statistics and uncertainties on the top quark mass, jet energy calibration, and MC models of signal and background. Variations in these components affect the measurement through altering the estimate of background in the final sample (i.e., if the selection efficiency changes) and by modifying the distribution of $\cos\theta^\star$. Systematic uncertainties in the single top analysis arise from the normalization of W+jets, the estimate of the W+jets flavor composition, and the top quark pair background modeling.

Most of the systematic uncertainties are taken as completely correlated between the two analyses. Systematic uncertainties that affect only the W helicity analysis are MC statistics and MC background model. Systematic uncertainties arising from the uncertainty in luminosity affect only the single top analysis.

We use a Bayesian statistical analysis [20] to combine the result on W helicity result with that on single top anomalous couplings. The likelihood from the W helicity analysis is used as a prior to the analysis of single top anomalous couplings and shown in Fig. 2.

For the pairs of coupling form factors given in Table I, we compare the boosted decision tree output for data with the sum of backgrounds and the two single top signal channels. In the scenario where f_1^L and f_2^L are non-zero, the two amplitudes interfere, which we take into account by using a superposition of three signal samples: one with only left-handed vector couplings, one with only left-handed tensor couplings, and one with both coupling form factors set to one (which includes the interference term). We then compute a likelihood as a product over all separate analysis channels. We assume Poisson distributions for the observed counts, and use multivariate Gaussian distributions to model the uncertainties on the combined signal acceptance and background yields, including correlations. The uncertainties are evaluated through MC integration. We generate an ensemble of 5000 samples, each with a different shift in systematic uncertainties, and compute the Bayesian posterior for each sample. The final posterior is then the ensemble average of all individual posteriors.

The two-dimensional posterior probability density is computed as a function of $|f_1^L|^2$ and $|f_X|^2$, where f_X is f_1^R, f_2^L, or f_2^R. These probability distributions are shown in Fig. 4. In all three scenarios we observe essentially no anomalous contributions, and favor the left-handed hypothesis over the alternative hypothesis. The central value of $|f_1^L|^2$ is > 1.0 in all cases, which reflects the fact that we observe more single top candidate events than would be expected form the SM cross section. We compute 95% C.L. upper limits on the anomalous form factors by integrating out the left-handed vector contribution to obtain one-dimensional posterior probability densities. The measured values are given in Table I.

In comparison, posterior probability densities from the single top anomalous coupling analysis alone (without the W helicity prior) are shown in Fig. 3. The limits at 95% C.L. without the W helicity constraints are $|f_1^R|^2 < 1.83$, $|f_2^L|^2 < 0.52$, and $|f_2^R|^2 < 0.24$. Since the single top anomalous coupling measurement alone is not able to distinguish left-handed vector from right-handed vector couplings, the W helicity analysis improves the $|f_1^R|^2$ limit significantly. Conversely, it does not add much information to the right-tensor coupling limit where most of the sensitivity is provided by the single top anomalous coupling analysis.

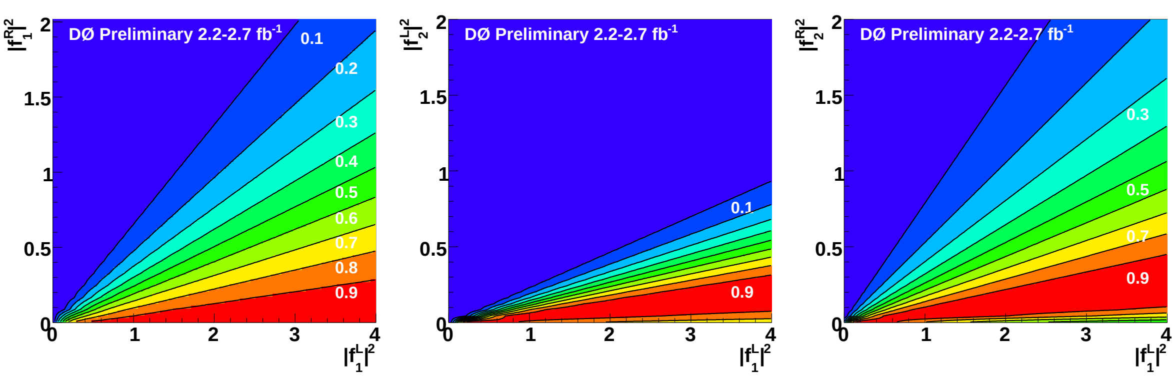

FIG. 2: Priors from the measured W boson helicity fractions for right- vs left-handed vector coupling (left), left-handed tensor vs left-handed vector coupling (center), and right-handed tensor vs left-handed vector coupling (right). The priors are shown as equally spaced contours in probability between 0.0 and 1.0.

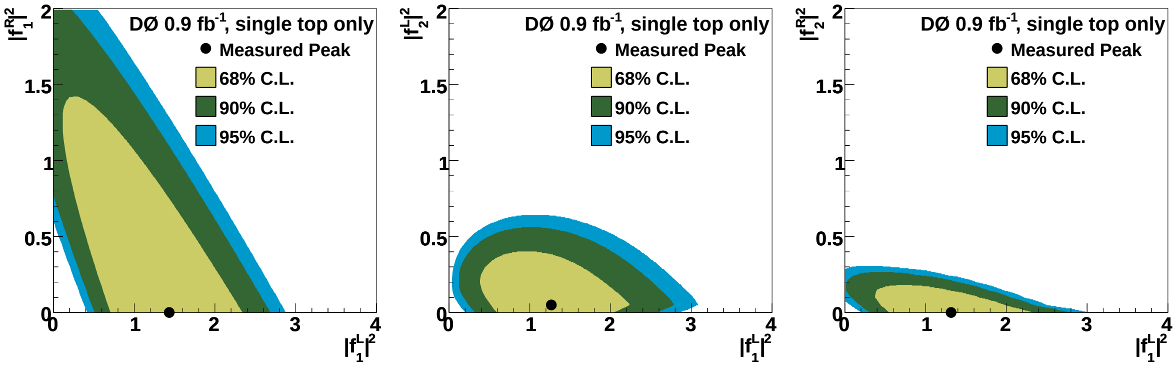

FIG. 3: Posterior densities from the single top anomalous coupling analysis only, for right- vs left-handed vector coupling (left), left-handed tensor vs left-handed vector coupling (center), and right-handed tensor vs left-handed vector coupling (right). The posterior density is shown in terms of contours of equal probability density.

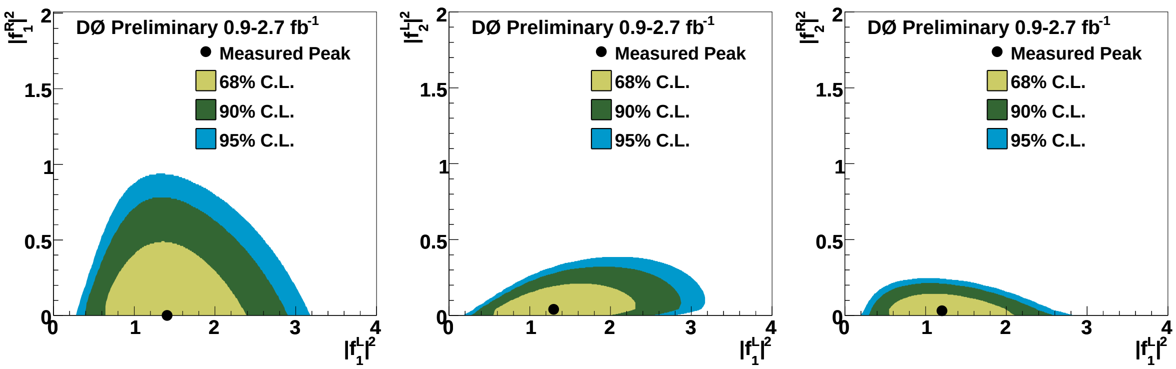

FIG. 4: Final posterior densities for right- vs left-handed vector coupling (left), left-handed tensor vs left-handed vector coupling (center), and right-handed tensor vs left-handed vector coupling (right). The posterior density is shown in terms of contours of equal probability density.

In summary, we have measured the Wtb coupling form factors by combining information from the W boson helicity in top quark decays in $t\bar{t}$ events and single top quark production, thus using all applicable top quark measurements by D0. We find consistency with the SM, and set 95% C.L. limits on anomalous Wtb couplings. Our limits represent significant improvements over previous results [7, 15].

[1] T. Tait and C.-P. Yuan, Phys. Rev. D **63**, 14018 (2001).
[2] G.L. Kane, G.A. Ladinsky, and C.-P. Yuan, Phys. Rev. D **45**, 124 (1992).
[3] F. Larios, M.A. Perez, and C.-P. Yuan, Phys. Lett. B **457**, 334 (1999); G. Burdman, M.C. Gonzales-Garcia, and S.F. Novaes, Phys. Rev. D **61**, 114016 (2000), and references therein.
[4] V.M. Abazov *et al.* (D0 Collaboration), Nucl. Instrum. Methods A **565**, 463 (2006).
[5] V.M. Abazov *et al.* (D0 Collaboration), D0 Note 5722-CONF (2008). `http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/TOP/T69/T69.pdf`
[6] C.R. Chen, F. Larios, and C. P. Yuan, Phys. Lett. B **631**, 126 (2005).
[7] V.M. Abazov *et al.* (D0 Collaboration), to be published in Phys. Rev. Lett. arXiv.org:0901.0151 [hep-ex] (2009).
[8] M.L. Mangano *et al.*, JHEP **07**, 001 (2003). We used ALPGEN version 2.05.
[9] T. Sjöstrand *et al.*, arXiv:0308153 (2003). We used PYTHIA version 6.323.
[10] J. Pumplin *et al.*, JHEP **07**, 012 (2002); D. Stump *et al.*, JHEP **10**, 046 (2003).
[11] R. Brun and F. Carminati, CERN Program Library Long Writeup W5013, 1993 (unpublished).
[12] V.M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **98**, 181802 (2007); V.M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D **78**, 12005 (2008).
[13] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Letters **101**, 252001 (2008).
[14] Z. Sullivan, Phys. Rev. D **70**, 114012 (2004).
[15] V.M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Letters **101**, 221801 (2008).

TABLE I: Measured values of the form factors for anomalous Wtb couplings, with uncertainties and upper limits at 95% C.L. for three scenarios.

Scenario	Coupling	Coupling limit if $f_1^L = 1$
(f_1^L, f_1^R)	$\vert f_1^L\vert^2 = 1.36^{+0.56}_{-0.46}$	
	$\vert f_1^R\vert^2 < 0.72$	$\vert f_1^R\vert^2 < 0.72$
(f_1^L, f_2^L)	$\vert f_1^L\vert^2 = 1.44^{+0.65}_{-0.51}$	
	$\vert f_2^L\vert^2 < 0.30$	$\vert f_2^L\vert^2 < 0.19$
(f_1^L, f_2^R)	$\vert f_1^L\vert^2 = 1.16^{+0.51}_{-0.44}$	
	$\vert f_2^R\vert^2 < 0.19$	$\vert f_2^R\vert^2 < 0.20$

[16] E. Boos *et al.*, Phys. Atom. Nucl. **69**, 1317 (2006); E. Boos *et al.* (CompHEP Collaboration), Nucl. Instrum. Methods Phys. Res. A **534**, 250 (2004).

[17] N. Kidonakis and R. Vogt, Phys. Rev. D **68**, 114014 (2003).

[18] L. Breiman *et al.*, *Classification and Regression Trees* (Wadsworth, Stamford, 1984).

[19] Y. Freund and R.E. Schapire, in *Machine Learning: Proceedings of the Thirteenth International Conference*, edited by L. Saitta (Morgan Kaufmann, San Fransisco, 1996) p. 148.

[20] I. Bertram *et al.*, FERMILAB-TM-2104 (2000).