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Search for anomalous Wtb couplings in ppbar collisions at sqrt(s) = 1.96 TeV (D0)

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We present new direct constraints on a general Wtb interaction using data corresponding to an integrated luminosity of 5.4 fb^{-1} collected by the D0 detector at the Tevatron $p\bar{p}$ collider. The standard model provides a purely left-handed vector coupling at the Wtb vertex, while the most general, lowest dimension Lagrangian allows right-handed vector and left- or right-handed tensor couplings as well. We obtain precise limits on these anomalous couplings by comparing the data to the expectations from different assumptions on the Wtb coupling using information from electroweak single top-quark production. We combine this with results studying the helicity of W bosons from top-quark decays in $t\bar{t}$ events.

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Seventeen years after the discovery of the top quark [1], all evidence supports the hypothesis that it is a standard-model (SM) fermion [2]. With a mass of about 173 GeV, it is sufficiently heavy to decay to a bottom quark and an on-shell W boson through the weak current. The SM Lagrangian completely specifies the Wtb coupling; it has a left-handed vector (V-A) structure, with a factor of $\gamma^\mu(1-\gamma^5)/2 \equiv \gamma^\mu P_L$ in the Lagrangian. The features of top-quark decay can then be calculated straightforwardly.

But perhaps this is not the case. What if top has anomalous Wtb couplings, beyond V-A? The most general lowest-dimension Lagrangian for the Wtb interaction can be written as

$$\mathscr{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu V_{tb}(f_V^L P_L + f_V^R P_R)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu V_{tb}}{M_W}(f_T^L P_L + f_T^R P_R)tW_\mu^- + h.c. \qquad (1)$$

where $P_R = (1+\gamma^5)/2$. This Lagrangian has both left- and right-handed vector (f_V^L, f_V^R) and left- and right-handed tensor (f_T^L, f_T^R) couplings at the Wtb vertex. In the SM, the coupling form factors $f_V^L = 1$ and $f_V^R = f_T^L = f_T^R = 0$. If the anomalous coupling factors were non-zero, we would see deviations from SM predictions in the measurements of the helicity fractions of W bosons from top decay, the rate of electroweak single-top production, and kinematic distributions in single-top events. Here we describe how we use those three measurements to constrain the size of the anomalous couplings.

In this meta-analysis, there is not enough statistical power to constrain all four couplings at once. Thus, they are probed in pairs; f_V^L and one anomalous coupling are considered simultaneously while assuming that the other two couplings are zero. From unitarity constraints we know that the tensor form factors must be less than 0.5. In principle, $b \to s\gamma$ measurements give more stringent constraints on the couplings than can be measured directly, but only if one assumes that there is no new physics beyond this in the bottom sector [3]. This analysis assumes that the coupling form factors are real (which implies CP conservation), that the top quark is spin-1/2 and almost always decays to Wb, and that single-top production is almost always through W exchange.

The data used for the analyses were collected with the D0 detector at the Fermilab Tevatron collider. The Tevatron generated $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV during Run II in 2001-11. D0 recorded a usable integrated luminosity of about 10 fb^{-1}, of which 5.4 fb^{-1} are used here. The D0 detector was composed of silicon and fiber trackers inside a 2 T solenoid magnet, a liquid-argon uranium calorimeter, and muon trackers and scintillators within toroid magnets.

The W helicity is studied in $t\bar{t}$ events. These include two final states: dileptons, with $t\bar{t} \to W^+W^-b\bar{b} \to \ell\nu\ell'\nu'b\bar{b}$, which is manifested as two leptons, missing transverse energy and at least two jets in the detector; and lepton plus jets, with $t\bar{t} \to W^+W^-b\bar{b} \to \ell\nu qq'b\bar{b}$, which is seen as one lepton, missing transverse energy and at least four jets. The dilepton sample has 319 events of which 69 ± 10 are estimated as background, while the lepton plus jets sample is 1431 events with 404 ± 32 background counts. The single-top events are selected with one lepton, missing transverse energy, and two or three jets, of which at least one is identified as arising from a b quark. The sample is constructed to be statistically independent of the $t\bar{t}$ samples.

The measurement of the W helicity fractions [4] is based around a reconstruction of the helicity angle in the top decay, which is defined as the angle between the direction opposite the top quark and the direction of the down-type fermion as measured in the W rest frame. Many tools are used in this reconstruction, including kinematic fits of the final-state objects with a constraint to the masses

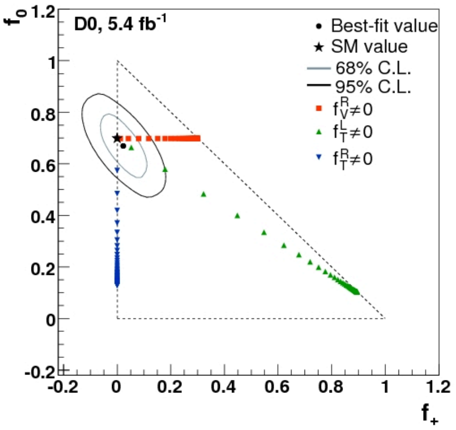

Figure 1: Likelihood contours at the 68% C.L. and the 95% C.L. as a function of W boson helicity fractions. Statistical uncertainties and systematic uncertainties that are uncorrelated with the single top quark measurement are included. The squares, triangles and upside-down triangles show f_V^R, f_T^L and f_T^R varying in fifty equal-size steps such that their ratio to f_V^L goes from zero to ten-to-one. The dashed triangle denotes the physically allowed region.

of the top and W particles that are assumed to be intermediate states, and a likelihood function used to identify the b jets. The resulting angular distributions have characteristic shapes for left, right and longitudinal W polarization. The helicity fractions are extracted through a binned maximum likelihood fit to the data using templates that represent the three helicity states and the background contribution.

The SM predicts that about 70% of the W bosons produced in top decay are longitudinally polarized, 30% are left-handed, and virtually none are right-handed. The measurement agrees very well with this prediction, as shown in Figure 1. The figure also shows how non-zero anomalous couplings would change the predicted helicity fractions f_0, f_- and f_+. For instance, an increase in f_V^R would cause f_+ to increase without changing f_0. By contrast, a non-zero f_T^R would decrease f_0 while increasing f_-. The helicity fractions only constrain the ratios of the coupling form factors. This is shown in Figure 2, which shows the likelihood density as a function of different pairs of form factors. As the helicity measurements agree with the SM predictions, the likelihood is largest at small values of the anomalous coupling factors.

In contrast to the strongly-produced $t\bar{t}$ pairs, single tops are produced through the electroweak mechanism and thus through the Wtb coupling, which means that the cross section is directly affected by any anomalous couplings. If the tensor couplings were as large as the SM coupling, the cross section would be about a factor of four larger. However, the cross section is relatively insensitive to the relative strength of the right- and left-handed vector couplings. Measurements of the single-top production rate [5] find that the production rate is consistent with SM predictions. Furthermore, SM single-top production can be distinguished from both the SM backgrounds and anomalous production and decay by kinematic variables. Some variables can also distinguish the different anomalous couplings from each other. Bayesian neural networks are used to combine the information provided by about twenty such variables, and thus to distinguish the SM and anoma-

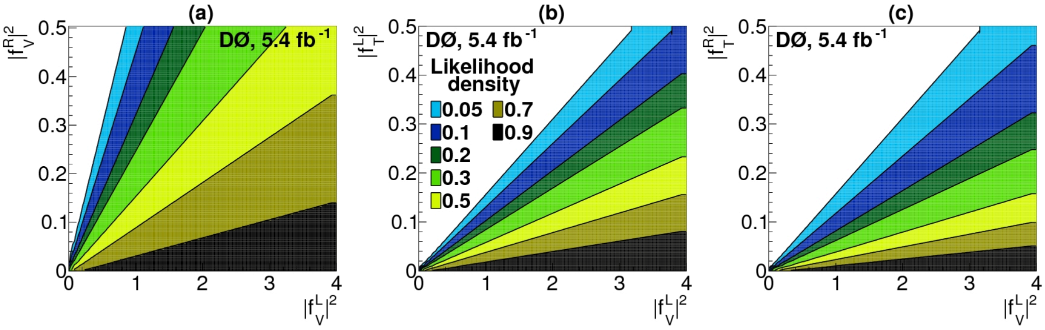

Figure 2: Likelihood density as a function of Wtb coupling form factors, for (a) right-vector vs. left-vector couplings, (b) left-tensor vs. left-vector couplings, and (c) right-tensor vs. left-vector couplings, using information from the W boson helicity measurement only. All systematic uncertainties are included. Each color corresponds to a contour of equal likelihood density.

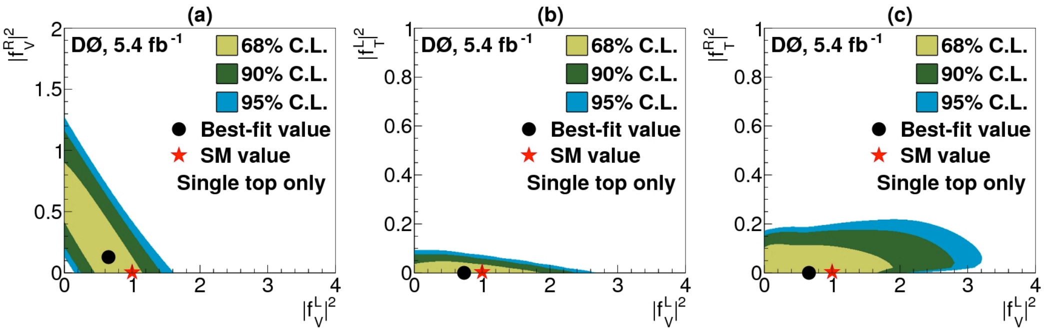

Figure 3: Form factor posterior density distribution for (a) right-vector vs. left-vector couplings, (b) left-tensor vs. left-vector couplings and (c) right-tensor vs. left-vector couplings, using information from the single top quark analysis only, for events with two or three jets. All systematic uncertainties are included.

lous signals. A Bayesian statistical approach is then used to compare the data to the predictions for anomalous couplings. The result is a set of two-dimensional probability distributions for the different anomalous-coupling scenarios, as shown in Figure 3. Again, the results are consistent with no anomalous couplings.

It is interesting to note that the probability bands of Figure 2 have a very different shape from those of Figure 3. This is because the W helicity measurement has greater sensitivity to the relative sizes of the left- and right-handed vector couplings than the single-top measurements, while single top is more sensitive to the size of the tensor couplings. The two measurements provide complementary information, and a combination of the two will provide the best constraints. The W helicity likelihood of Figure 2 is used as a prior for the single-top likelihood of Figure 3. The resulting likelihoods are shown in Figure 4. We then set limits on the anomalous couplings by integrating over the left-handed vector contribution to make one-dimensional probability densities. The resulting upper limits are given in Table 1.

The single-top measurement is statistics limited. The largest systematic uncertainties arise from uncertainties in the jet-energy scale, b-tagging efficiencies and background normalization.

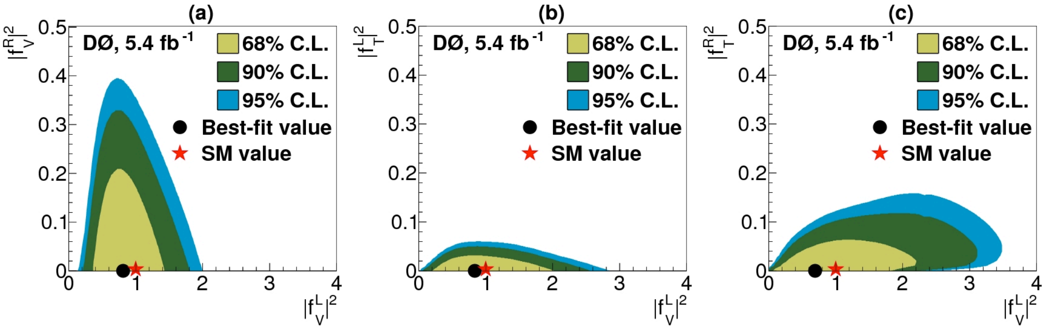

Figure 4: Posterior density distribution for the combination of W boson helicity and single top quark measurements for (a) right-vector vs. left-vector form factors, (b) left-tensor vs. left-vector form factors and (c) right-tensor vs. left-vector form factors. All systematic uncertainties are included.

Scenario	only W helicity	only single top	combination
$\lvert f_V^R\rvert^2$	0.62	0.89	0.30
$\lvert f_T^L\rvert^2$	0.14	0.07	0.05
$\lvert f_T^R\rvert^2$	0.18	0.18	0.12

Table 1: Observed upper limits on anomalous Wtb couplings at 95% C.L. from W boson helicity assuming $f_V^L = 1$, from the single top quark analysis, and from their combination, for which no assumption on f_V^L is made.

The anomalous-couplings measurement does depend on the overall signal normalization. The systematic and statistical uncertainties are about equal for the W helicity measurement. The largest systematic uncertainties arise from uncertainties in $t\bar{t}$ modeling, W+jets heavy flavor content, and limited template statistics. The helicity-fraction measurement is independent of the overall $t\bar{t}$ signal normalization. The correlations in systematic uncertainties between the two measurements are handled appropriately in the combination.

Studies of the W helicity in top decays and of single-top production rate and kinematics thus allow us to probe anomalous Wtb couplings. The two analyses are complementary, each sensitive to different anomalous couplings, making the combination quite powerful. The limits set on the couplings are the strongest to date [6]. This is probably the final D0 result on this topic, as the LHC experiments are rapidly gaining the advantage on statistics. At the age of seventeen, the top quark is old enough to drive a car, but all the evidence so far indicates that it only makes left turns.

References

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