Search for Anomalous Wtb Couplings at D0

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Top-quark decay

- Top is a standard-model fermion
- It is sufficiently heavy (~173 GeV) to decay to a bottom quark and an on-shell W boson through the weak current
- The SM Lagrangian specifies that the Wtb coupling has a left-handed vector (V-A) structure, with

\[ \gamma^\mu (1 - \gamma^5) / 2 \equiv \gamma^\mu P_L \]

in the Lagrangian
Unless that isn’t true...

Maybe top has anomalous Wtb couplings, beyond V-A?

Consider the general Lagrangian for the Wtb interaction:

\[
\mathcal{L} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{tb} (f_L^V P_L + f_R^V P_R) t W^-_{\mu} \\
- \frac{g}{\sqrt{2}} \bar{b} i \sigma^{\mu\nu} q_\nu V_{tb} \frac{f_L^T P_L + f_R^T P_R}{M_W} t W^-_{\mu} + h.c.
\]

Introduces RH vector and LH, RH tensor couplings

In the SM, coupling form factors \(f_L^V = 1\) and \(f_R^V = f_L^T = f_R^T = 0\)

If there were anomalous couplings, we would see deviations from SM predictions in measurements of

helicity fractions of W bosons in top decay,

rate of electroweak single-top production, and

kinematic distributions in single-top events
Knowledge, assumptions

- Not enough data to constrain all four couplings at once:
  - Probe $f_L^V$ and one anomalous coupling simultaneously, while assuming other two couplings are zero

Existing information:

- Unitarity constraints require tensor form factors to be less than 0.5
- $b \rightarrow s\gamma$ measurements give more stringent constraints on the couplings than can be measured directly, but only if one assumes no new physics beyond this in the bottom sector:

Assumptions in the analysis:

- Coupling form factors are real, implying CP conservation
- Top quark is spin-1/2
- Top decays almost always to $Wb$
- Single top production is almost always through $W$ exchange

References:
Basics

- Tevatron: $\sqrt{s} = 1.96\,\text{TeV}$, $p\bar{p}$ collisions, Run II 2001-11; ~12 fb$^{-1}$ delivered, these analyses use 5.4 fb$^{-1}$.

- D0: silicon and fiber trackers inside 2 T solenoid, liquid argon-uranium calorimeter, muon trackers/scintillator with toroid

- $W$ helicity is studied in $t\bar{t}$ events:
  - dilepton: $t\bar{t}\rightarrow W^+W^-b\bar{b}\rightarrow l\nu l'\nu'b\bar{b}$ = two leptons, missing transverse energy, at least two jets
    - 319 events selected, 69 ± 10 background
  - lepton+jets: $t\bar{t}\rightarrow W^+W^-b\bar{b}\rightarrow l\nu qq'b\bar{b}$ = one lepton, missing transverse energy, at least four jets
    - 1431 events selected, 404 ± 32 background

- Single top events are selected with one lepton, missing transverse energy, two or three jets, at least one identified as $b$
  - Orthogonal to $W$ helicity sample
Reconstruct helicity angle

- Angle between direction opposite the top quark and direction of down-type fermion, measured in W rest frame
- Many tools used in reconstruction: kinematic fits with constraint to top and W masses, b-jet likelihood....
- Characteristic distributions for left, right, longitudinal W polarization
- Extract helicity fractions with binned maximum likelihood fit to data using templates for signal, background

FIG. 8: Distribution of $\cos\theta^*$ in $t\bar{t}$ MC samples that were reweighted to derive the distributions for purely left-handed, longitudinal, or right-handed W bosons. The distribution for leptonically- and hadronically-decaying W bosons in $\ell^+\text{jets}$ events are shown in (a) and (b), respectively, and the distribution for dilepton events is shown in (c). For hadronically decaying W bosons the $\cos\theta^*$ distribution for left- and right-handed W bosons are identical. All of the distributions are normalized to unity.

SYSTEMATIC UNCERTAINTIES

Systematic uncertainties are evaluated using simulated event ensembles in which both changes in the background yield and changes in the shape of the $\cos\theta^*$ templates in signal and background are considered. The simulated samples from which the events are drawn can be either the nominal samples or samples in which the systematic effect under study has been shifted away from the nominal value. In general, the systematic uncertainties assigned to $f_0$ and $f_+^A$ are determined by taking an average of the absolute values of the differences in the average fit output values between the nominal and shifted $V^{-A}$ and $V^{+A}$ samples.

The jet energy scale, jet energy resolution, and jet identification efficiency each have relatively small uncertainties that are difficult to observe above fluctuations in the MC samples. To make the effects more visible, we vary the jet energy scale, jet energy resolution, and jet identification efficiency by ±10% and ±5%, respectively.
W helicity measurement

- Reconstruct helicity angle
  - Angle between direction opposite the top quark and direction of down-type fermion, measured in W rest frame
  - Many tools used in reconstruction: kinematic fits with constraint to top and W masses, b-jet likelihood...
  - Characteristic distributions for left, right, longitudinal W polarization
- Extract helicity fractions with binned maximum likelihood fit to data using templates for signal, background
W helicity results

- SM predicts $f_0 = 70\%$, $f_- = 30\%$, $f_+ \approx 0$
- Result agrees very well with SM
- Non-SM couplings would change the helicity fractions
- This can be used to constrain the ratios of the coupling form factors
Single-top production rate

- Single top quarks are produced through Wtb coupling → anomalous couplings affect production rate
- Small signal on big W+jets background, but substantially altered by (some) anomalous couplings

<table>
<thead>
<tr>
<th>Source</th>
<th>2 jets</th>
<th>3 jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tb$ ($f_{LT} = 1$)</td>
<td>730 ± 38</td>
<td>316 ± 25</td>
</tr>
<tr>
<td>$tqb$ ($f_{LT} = 1$)</td>
<td>117 ± 6.2</td>
<td>86 ± 8.6</td>
</tr>
<tr>
<td>$tb$ ($f_{LV} = f_{LT} = 1$)</td>
<td>607 ± 31</td>
<td>284 ± 21</td>
</tr>
<tr>
<td>$tqb$ ($f_{LV} = f_{LT} = 1$)</td>
<td>268 ± 15</td>
<td>167 ± 16</td>
</tr>
<tr>
<td>$tb$ ($f_{RV} = 1$)</td>
<td>105 ± 6.0</td>
<td>43 ± 3.8</td>
</tr>
<tr>
<td>$tqb$ ($f_{RV} = 1$)</td>
<td>122 ± 7.2</td>
<td>61 ± 5.3</td>
</tr>
<tr>
<td>$tb$ ($f_{RT} = 1$)</td>
<td>756 ± 42</td>
<td>344 ± 27</td>
</tr>
<tr>
<td>$tqb$ ($f_{RT} = 1$)</td>
<td>103 ± 5.8</td>
<td>67 ± 6.3</td>
</tr>
<tr>
<td>$tb$ (SM, $f_{LV} = 1$)</td>
<td>104 ± 16</td>
<td>44 ± 7.8</td>
</tr>
<tr>
<td>$tqb$ (SM, $f_{LV} = 1$)</td>
<td>140 ± 13</td>
<td>72 ± 9.4</td>
</tr>
<tr>
<td>$tt$</td>
<td>433 ± 87</td>
<td>830 ± 133</td>
</tr>
<tr>
<td>$W$+jets</td>
<td>3,560 ± 354</td>
<td>1,099 ± 169</td>
</tr>
<tr>
<td>$Z$+jets and dibosons</td>
<td>400 ± 55</td>
<td>142 ± 41</td>
</tr>
<tr>
<td>Multijets</td>
<td>277 ± 34</td>
<td>130 ± 17</td>
</tr>
<tr>
<td>Total SM prediction</td>
<td>4,914 ± 558</td>
<td>2,317 ± 377</td>
</tr>
<tr>
<td>Data</td>
<td>4,881</td>
<td>2,307</td>
</tr>
</tbody>
</table>
Single-top kinematics

- SM single top can be distinguished from both SM backgrounds and anomalous production/decay by kinematic variables
- And different anomalous couplings distinct from each other
- Warning: anomalous signals in plots above are x10 SM single top!
- Use Bayesian neural network to distinguish anomalous, SM signals
- 18-22 kinematic variables in each BNN
- Trained with non-SM process as signal, all others as background
Use Bayesian statistical approach to compare data to predictions for anomalous couplings

- Background normalization is absolute, not fit
- Result is 2D probability density distributions for different scenarios
- Data consistent with SM
  - Note shape of probability bands compared to those obtained from W helicity!

**Single-top results**

- **FIG. 2:** Comparison of the SM backgrounds and data for selected events.
- **FIG. 3:** (color online) Form factor posterior density distribution.
- **FIG. 4:** Posterior density distribution for the combination for events with two or three jets. All systematic uncertainties are included.

**TABLE II:** One-dimensional upper limits at 95% C.L. for searchCouncil (Sweden); and CAS and CNSF (China).

- **(a)** Yield [Events/0.04]
- **(b)** Yield [Events/0.04]
- **(c)** Yield [Events/0.04]
- **(d)** Yield [Events/0.04]
- **(e)** Yield [Events/0.04]
Use the W helicity likelihood as a prior for the single-top analysis

Set limits on anomalous couplings by integrating over the left-handed vector contribution to make 1D probability densities
Systematic uncertainties

- Single-top measurement is statistics limited
- Largest systematic uncertainties from jet energy scale, b-tagging efficiencies, background normalization
- Measurement depends on overall signal normalization
- Systematic and statistical uncertainties are about equal for the W helicity measurement
- Largest systematic uncertainties from \( t\bar{t} \) modeling, W+jets heavy flavor content, template statistics
- Measurement independent of \( t\bar{t} \) normalization
- Correlations in systematic uncertainties between the two analyses are handled appropriately
Studies of W helicity in top decays and of single-top production rate and kinematics allow us to probe anomalous Wtb couplings.

The two analyses are complementary, making the combination powerful.

Best limits on anomalous couplings to date:

- PLB 713, 165 (2012)
- This is probably the final D0 result on this topic -- LHC is gaining advantage on statistics.

Top quark at age 17: old enough to drive, but only makes left turns!
Extra Slides
Alternative parameterization through effective operators due to Aguilar-Saavedra, NPB 812, 181 (2009), also Zhang, Greiner, Willenbrock, arXiv: 1201.6670 and PRD 83 034006 (2011)

Λ is scale of new physics, ν is EWK symmetry breaking scale, C’s are constants for dimension-6 effective operators for 3rd-generation quarks

Assuming Λ=1 TeV, find:

\[ |C_{\phi q}^{(3,3+3)}| < 14.7, \quad |C_{\phi \phi}^{33}| < 18.0, \quad |C_{dW}^{33}| < 2.5, \quad |C_{uW}^{33}| < 4.1 \]

(ATLAS appears to have stronger limits due different statistical treatment)