Measurements of Top Quark Properties at the Tevatron

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On behalf of the CDF and D0 Collaborations
Why Study the Top Quark?

- Unique among quarks in many ways
  - Very heavy - special role in electroweak symmetry breaking or enhanced couplings to new physics?
  - Very short lifetime - spin information and other properties passed directly to decay products

- CDF and D0 have collected thousands of top events
  - Precision studies of top properties are possible
  - Many analyses are unique to the Tevatron and/or complementary to LHC measurements

- Covered today:
  - W helicity in top decay
  - Branching ratio
  - Top width
  - Spin correlations
  - Top forward-backward asymmetry
Measuring Top Properties

- **Top almost always decays to $Wb$**
  - Decay modes characterized by $W$ decays

- **Two main modes for top properties analyses:**
  - **Lepton+Jets**: one $W$ decays to quarks, one to $e(\mu) + \nu$
    - Moderate backgrounds, reasonable branching ratio; fully constrained kinematically
    - Usually require a $b$-tag to reduce backgrounds
  - **Dilepton**: both $W$'s decay to $e(\mu) + \nu$
    - Very low backgrounds, but small branching ratio; under-constrained kinematically
**W Boson Helicity in Top Decays**

\[ \omega(\cos \theta^*) \propto 2(1 - \cos^2 \theta^*) f_0 + (1 - \cos \theta^*)^2 f_- + (1 + \cos \theta^*)^2 f_+ \]

- Study V-A nature of \( Wtb \) coupling
- Extract \( f_0, f_+ \) from distribution of \( \theta^* \) (angle between lepton and top direction in \( W \) rest frame)

**For pre-tagged events**

CDF Run II Preliminary (5.1 fb\(^{-1}\))

- CDF: 
  \[ f_0 = 0.71 \pm 0.19 \]
  \[ f_+ = -0.07 \pm 0.10 \]
  (CDF Conf. Note 10543)

- D0: 
  \[ f_0 = 0.669 \pm 0.102 \]
  \[ f_+ = 0.023 \pm 0.053 \]
  (PRD 83, 032009 (2011))

**First Published CDF and D0 Combination** \((arXiv:1202.5272[hep-ex]):\)

- \( f_0 = 0.722 \pm 0.081 \)
- \( f_+ = -0.033 \pm 0.046 \)
Top ($t \to b$) Branching Ratio

- **SM**: $t \to Wb$ in $\sim 100\%$ of decays
- **Expect 2 $b$’s in each top-antitop event**
  - How often does this happen?
  - Tagging efficiency determines expected size of samples with 0, 1, or 2 tagged jets
  - Determine $R$ from measured size of each subsample
- **Derive $|V_{tb}|$ from result (assume CKM unitary)**

$$R = \frac{B(t \to Wb)}{B(t \to Wq)}$$

**DØ**: $R = 0.90 \pm 0.04$

$$|V_{tb}| = 0.95 \pm 0.02$$

PRL 107, 121802 (2011)

**CDF**: $R = 0.91 \pm 0.09$

$$|V_{tb}| = 0.95 \pm 0.05$$

CDF Conf. Note In Preparation
Top Width at CDF

- **SM Prediction:** $\Gamma_t \sim 1.5$ GeV
- **CDF:** template method
  - $4.3 \text{ fb}^{-1}$
- Direct measurement of top decay width
  - Likelihood fit to the reconstructed top mass distribution based on templates with various input widths
  - $0.3 \text{ GeV} < \Gamma_t < 4.4 \text{ GeV}$ at 68% C.L.
  - $\Gamma_t < 7.6 \text{ GeV}$ at 95% C.L.

PRL 105, 232003 (2010)
Top Width at D0

- **D0**: derived measurement based on other top properties results
  - Complementary to CDF measurement
  - Requires theory input, but gains in sensitivity
  - Also provides a limit on $|V_{tb}|$

\[
\Gamma_t = \frac{\Gamma(t \rightarrow Wb)}{B(t \rightarrow Wb)}
\]

From top pair production

\[
\Gamma(t \rightarrow Wb) = \sigma(t - \text{channel}) \frac{\Gamma_{SM}(t \rightarrow Wb)}{\sigma_{SM}(t - \text{channel})}
\]

\[
\Gamma_t = 2.00^{+0.47}_{-0.43} \text{ GeV} \quad 0.81 < |V_{tb}| \leq 1 \text{ at 95% C.L.}
\]

Top-Antitop Spin Correlations

- Top pairs are produced with a definite spin state depending on production mechanism
  - Quark-Antiquark Annihilation (~85%): Spin 1
  - Gluon Fusion (~15%): Spin 0

- Top decays before hadronization (only known quark to do so!)
  - Spin information passed to decay products – the correlated spins can be measured from decay product angular distributions

- Correlation strength (frame dependent!) is defined as:

\[
\kappa = \frac{N_{\uparrow \uparrow} + N_{\downarrow \downarrow} - N_{\uparrow \downarrow} - N_{\downarrow \uparrow}}{N_{\uparrow \uparrow} + N_{\downarrow \downarrow} + N_{\uparrow \downarrow} + N_{\downarrow \uparrow}}
\]

\[
\kappa^{SM}_{beam} = 0.78^{+0.03}_{-0.04}
\]

Measuring the Spin Correlation

- Results shown here assume spin quantized along beam axis

- **CDF:**
  - Template fits based on decay product angular distributions
    \[ \kappa_{\text{CDF}}^{Lep+Jet} = 0.72 \pm 0.69 \]  
    \[ \kappa_{\text{CDF}}^{\text{Dilepton}} = 0.042 \pm 0.563 \]
    CDF Conf. Note 10211
    CDF Conf. Note 10719

- **D0:** 3 \( \sigma \) Evidence For Spin Correlations!
  - New matrix element approach
    - Significantly increased sensitivity
  - Likelihood fit based on probabilities that events are signal events and do (or do not) contain SM spin correlation
    \[ \kappa_{\text{D0}}^{\text{Combo(Dil,Lep+Jet)}} = 0.66 \pm 0.23 \]
  
- 9
  
  PRL 108, 032004 (2012)
  
D. Mietlicki  Moriond 2012
The Forward-Backward Asymmetry

- Do tops have a preference to travel along the proton or antiproton direction?
- Measure asymmetry in $\Delta y$
- **Leading order**: standard model predicts no asymmetry
- **Next-to-leading order**: small positive asymmetry
  - NLO predictions shown today based on MC generator **Powheg** with electroweak corrections added

$$\Delta y = y_t - y_{\bar{t}}$$

$$A_{FB}^{NLO} = 6.6\%$$

**Powheg**: JHEP 0709, 126 (2007)

The Asymmetry in \(~5\) fb\(^{-1}\)

- Inclusive asymmetries exceed standard model predictions by \(~1.5-2\) \(\sigma\)
- Somewhat ambiguous mass and rapidity dependence
  - Only two bins in \(M_{tt}/\Delta y\)

### Measurement

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Parton Level</th>
<th>(A_{FB%})</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF Lep+Jets(^1)</td>
<td></td>
<td>15.8 ± 7.4</td>
</tr>
<tr>
<td>CDF Dilepton(^2)</td>
<td></td>
<td>42 ± 16</td>
</tr>
<tr>
<td>CDF Combined(^3)</td>
<td></td>
<td>20.1 ± 6.7</td>
</tr>
<tr>
<td>D0 Lep+Jets(^4)</td>
<td></td>
<td>19.6 ± 6.5</td>
</tr>
</tbody>
</table>

### Background Subtracted \(A_{FB\%}\) (%)

|                     | \(|\Delta y| < 1.0\) | \(|\Delta y| \geq 1.0\) |
|---------------------|---------------------|----------------------|
| D0 Lep+Jet          | 6.1 ± 4.1           | 21.3 ± 9.7           |
| CDF Lep+Jet         | 2.9 ± 4.0           | 29.1 ± 9.6           |

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\(^1\)CDF L+J: PRD 83, 112003 (2011); \(^2\)CDF Dil: CDF Conf. Note 10436; 
\(^3\)CDF Combo: CDF Conf. Note 10584; \(^4\)D0 L+J: PRD 84, 112055 (2011)
The Asymmetry at CDF in the Full Dataset

- Updates from CDF’s 5.3 fb\(^{-1}\) lepton+jets analysis:
  - Add new data stream and increase luminosity to 8.7 fb\(^{-1}\)
    - 2498 events (double sample size)
  - Use NLO generator Powheg for signal modeling
  - Parton level shape corrections use regularized unfolding algorithm
    - Proper multi-binned measurement of rapidity and mass dependence

- Parton Level \(A_{FB}\): 16.2 ± 4.7 %
  (NLO: 6.6%)

CDF Conf. Note 10807
Background-Subtracted $M_{tt}$ and $\Delta y$ Dependence

- Predicted background contribution has been removed
  - Measure asymmetry in only top events
- No correction to parton level yet
  - No assumptions about the underlying physics
- Data well-described by linear ansatz — determine best-fit slope
  - $\chi^2$/d.o.f $\leq 1$ for both $\Delta y$ and $M_{tt}$ dependence
- Determine p-value by comparing observed slope to NLO prediction
  - How often will NLO slope fluctuate to be at least as large as in the data?

<table>
<thead>
<tr>
<th>Slope Parameter $\alpha$</th>
<th>$A_{FB}$ vs. $M_{tt}$</th>
<th>$A_{FB}$ vs. $\Delta y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>$(11.1 \pm 2.9) \times 10^{-4}$</td>
<td>$(20.0 \pm 5.9) \times 10^{-2}$</td>
</tr>
<tr>
<td>SM</td>
<td>$3.0 \times 10^{-4}$</td>
<td>$6.7 \times 10^{-2}$</td>
</tr>
<tr>
<td>p-value</td>
<td>$0.00646$</td>
<td>$0.00892$</td>
</tr>
</tbody>
</table>

CDF Run II Preliminary $L = 8.7 \text{ fb}^{-1}$

$A_{FB}$ vs. $M_{tt}$ GeV/c$^2$

$A_{FB}$ vs. $\Delta y_t$

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Parton Level $M_{tt}$ and $\Delta y$ Dependence

- Correct for acceptance and detector resolution
  - Regularized unfolding algorithm addresses resolution effects
  - Multiplicative acceptance correction factor applied to each bin
  - Both corrections use the NLO generator Powheg as the top model
- Parton level results can be compared directly to theory
- Determine best-fit slope for observed data and compare to NLO prediction

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<th>$A_{FB}$ vs. $\Delta y$</th>
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</thead>
<tbody>
<tr>
<td>Data</td>
<td>$(15.6 \pm 5.0) \times 10^{-4}$</td>
<td>$(30.6 \pm 8.6) \times 10^{-2}$</td>
</tr>
<tr>
<td>SM</td>
<td>$3.3 \times 10^{-4}$</td>
<td>$10.3 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

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Conclusions

- The full Tevatron dataset is now being studied in top properties measurements.
- Many areas of study (spin correlations, $A_{FB}$) are complementary to LHC measurements.
- CDF and D0 combinations are available (W helicity) or in progress for many properties measurements.
- Please see the websites of CDF’s and D0’s Top Groups and the Tevatron Electroweak Working Group for more information and results not presented today:
  - http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/
  - http://tevewwg.fnal.gov
- Data-taking is done, but there’s a lot left to be learned from the Tevatron’s top quark sample!
Backup Slides
Comparison of Two-Bin Parton Level $A_{FB}$ to Previous Results

- Previous version of CDF analysis only provided parton-level results for two bins of $M_{tt}$ and $\Delta y$
- Table compares the new result in the same two bins to the previous results (all numbers are percentages)

<table>
<thead>
<tr>
<th>Selection</th>
<th>NLO (QCD+EW)</th>
<th>CDF, 5.3 fb$^{-1}$</th>
<th>D0, 5.4 fb$^{-1}$</th>
<th>CDF, 8.7 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>6.6</td>
<td>15.8 ± 7.4</td>
<td>19.6 ± 6.5</td>
<td>16.2 ± 4.7</td>
</tr>
<tr>
<td>$M_{tt} &lt; 450$ GeV/c$^2$</td>
<td>4.7</td>
<td>$-11.6 ± 15.3$</td>
<td></td>
<td>7.8 ± 4.8 (Bkg. Subtracted)</td>
</tr>
<tr>
<td>$M_{tt} \geq 450$ GeV/c$^2$</td>
<td>10.0</td>
<td>47.5 ± 11.2</td>
<td></td>
<td>11.5 ± 6.0 (Bkg. Subtracted)</td>
</tr>
<tr>
<td>$</td>
<td>\Delta y</td>
<td>&lt; 1.0$</td>
<td>4.3</td>
<td>2.6 ± 11.8</td>
</tr>
<tr>
<td>$</td>
<td>\Delta y</td>
<td>\geq 1.0$</td>
<td>13.9</td>
<td>61.1 ± 25.6</td>
</tr>
</tbody>
</table>
Source of the Asymmetry?

- Is it a problem with the current understanding of the SM?
  - Mis-modeled top pair $P_T$ spectrum?
  - Higher order corrections?
- Is it new physics?
  - Many new models have been proposed
    - Axigluon, Z-prime, W-prime, ...
  - Other top properties measurements can help differentiate between the possibilities
    - Differential cross-section in $M_{tt}$
    - Top spin or polarization
Reconstruction Level $A_{FB}$

- **Event selection:**
  - One high $P_T$ central lepton
  - At least four jets
    - At least one $b$-tag
  - Large missing $E_T$
  - Total transverse energy $H_T$ above 220 GeV

- **Background model:**
  - Diboson, single top, $Z$+jets from MC
  - $W$+jets shape from MC
  - QCD shape from data
  - $W$+jets and QCD normalization from fit to missing $E_T$ spectrum

- **Events reconstructed via $\chi^2$-based kinematic fit to top-antitop hypothesis**

- **Event count:**
  - 2498 total candidates
  - 505 predicted background

$$A_{FB}^{reco.} = 6.6 \pm 2.0\%$$

$$A_{FB}^{bkg\_sub.} = 8.5 \pm 2.5\%$$
The Asymmetry Over the Data-Taking Period

- Look at the background-subtracted asymmetry as a function of the number of events in the sample
  - Verify it was not cause by some time-dependent detector effect
  - “0 events” = start of Run II
- $A_{FB}$ remains constant (within uncertainties) over the entire sample

CDF Run II Preliminary $L = 8.7 \text{ fb}^{-1}$
Leptonic Asymmetry

- Motion of lepton in semi-leptonic top decay correlated with parent top
  - A real top pair asymmetry will manifest itself here as well
- Measure asymmetry in $q^* \eta_{lep}$ [lepton +jets] or $(\eta^+_{lep} - \eta^-_{lep})$ [dilepton]
- Smaller expected asymmetry than in $\Delta y$ ($\sim 1-2\%$ after event selection without backgrounds)

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Background Subtracted Leptonic $A_{FB}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D0 Lep+Jet</td>
<td>$14.2 \pm 3.8$</td>
</tr>
<tr>
<td>CDF Lep+Jet</td>
<td>$6.6 \pm 2.5$</td>
</tr>
<tr>
<td>CDF Dilepton</td>
<td>$21 \pm 7$</td>
</tr>
</tbody>
</table>

CDF Run II Preliminary $L = 8.7$ fb$^{-1}$