Measurements of Top Quark Properties at the Tevatron

Oleg Brandt on behalf of the CDF and DØ collaborations

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What makes top so interesting?

- Compelling arguments that new physics will show up in the top sector:
  - Top is the **heaviest** quark discovered so far
  - Its Yukawa coupling is $0.996 \pm 0.006$
    - Special role in EWSB?
  - Since 16 years, our measurements have been *consistent with SM predictions* in the top sector *within uncertainties*
  - D0 and CDF collected **thousands** of $tt$ events, enabling precise studies of top properties
    - There are recent measurements displaying tension between Tevatron measurements and the SM predictions
A wealth of top properties

Measurements of Top Quark Properties at the Tevatron
A wealth of top properties

- Color flow
- W helicity
- Cross section
  - Differential cross section
  - Production mechanism
  - New physics contributions
- Anomalous couplings
- Rare decays
- Branching ratio
- CKM matrix element $|V_{tb}|$
- New physics contributions
- Mass, charge, width
- Spin correlation
- QCD charge asymmetry $A_{FB}$

+ electroweak single top production
A wealth of top properties

- Color flow
- W helicity
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A wealth of top properties

- Typically: we measure top properties in $tt$ events
  - $l^+j$ets channel: good compromise between kinematic reconstruction, high rate, and backgrounds
  - Dilepton channel: low backgrounds, but underconstrained kinematics and low rate

- Top production:
  - See talk by Silvia Amerio
- Top mass:
  - See talk by Zhenyu Ye
- Single Top production:
  - See talk by Viktor Bazterra
- New Physics hunt in the top sector:
  - DooKee Cho
\[ \Gamma_t = \frac{\Gamma(t \rightarrow Wb)}{\mathcal{B}(t \rightarrow Wb)} \]

[arXiv:1009.5686]
The decay width of the top quark, $\Gamma_t$, is measured in $t\bar{t}$ events.

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

The graph shows the number of events as a function of the number of tagged jets. The data is labeled as $D\O$ Data and includes categories for $t\bar{t}$, $W$+jets, and other processes.
Decay width of the top quark

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

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

Assume:
\[ \Gamma_{\text{decay}} = \Gamma_{\text{production}} \]

[arXiv:1009.5686]
Decay width of the top quark

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

measured in $tt$ events

Assume:

\[ \Gamma_{\text{decay}} = \Gamma_{\text{production}} \]

[arXiv:1009.5686]
Decay width of the top quark

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

measured in \( tt \) events

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

Assume:
\( \Gamma_{\text{decay}} = \Gamma_{\text{production}} \)

for \( m_t = 170 \text{ GeV} \)

World's most precise (indirect) determination of \( \Gamma_t \) to date

\[ \Gamma_t = 1.99^{+0.69}_{-0.55} \pm 0.27 \text{ GeV} \]

\[ \Gamma(t \rightarrow Wb)_{SM} = 1.26 \text{ GeV} \]

Direct determination of \( \Gamma_t \):
\[ 0.4 < \Gamma_t < 4.4 \text{ GeV} @68\% \text{ CL} \]

PRL 105, 232003 (2010)
Top-antitop spin correlations

- $\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25} \text{ s} \ll \text{hadronisation time}$
- Decay products carry info about spin of $tt$ system

$^3S_1$

- In this form possible only at the Tevatron:
  - High qq fraction (LHC: ~10%)
  - Production at threshold dominates

- Correlation strength (frame dependent):

$$C = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}$$

+ $^1S_0 \ (15\%)$
Top-antitop spin correlations

- $\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}$ s << hadronisation time
  - Decay products carry info about spin of $t\bar{t}$ system

  \[ ^3S_1 \]

  \[ \begin{array}{c}
  q \\
  \Rightarrow \\
  \Rightarrow \\
  \Rightarrow \\
  \Rightarrow \\
  t \\
  \Rightarrow \\
  \Rightarrow \\
  \Rightarrow \\
  \Rightarrow \\
  \bar{q} \\
  \end{array} \]

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- In this form possible only at the Tevatron:
  - High qq fraction (LHC: ~10%)
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  \[ C = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\downarrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\downarrow\uparrow} + N_{\uparrow\downarrow}} \]

- Analyse it using angular info:

  \[ \frac{1}{\sigma} \frac{d^2\sigma}{d \cos \theta_1 d \cos \theta_2} = \frac{1}{4} \left( 1 - C \cos \theta_1 \cos \theta_2 \right) \]
  (for dilepton channel case)
Top-antitop spin correlations

Dilepton channel

LH template fit to extract $C$

$$C = 0.10^{+0.45}_{-0.45} \text{ (stat+syst)}$$

[arXiv:1103.1871]

SM (NLO): $C = 0.777^{+0.027}_{-0.042}$

quantization axis along the beamline

I+jets channel

Binned LH template fit

$$C = 0.72 \pm 0.64_{\text{stat}} \pm 0.26_{\text{syst}}$$

[CDF Note 10211]
- Study the V-A nature of Wtb coupling
  - Deviations from SM would indicate new physics
    
    \[ f_- = 30.1\% \text{ (SM)} \]
    
    \[ f_+ = 0.04\% \text{ (SM)} \]
    
    \[ f_0 = 69.8\% \text{ (SM)} \]
• Study the V-A nature of Wtb coupling
  - Deviations from SM would indicate new physics

\[ f_- = 30.1\% \text{ (SM)} \]
\[ f_+ = 0.04\% \text{ (SM)} \]
\[ f_0 = 69.8\% \text{ (SM)} \]
Dilepton & \( l+jets \) channels

Define channel-dependent templates in \( \cos\theta^* \) (leptonic W) and \( |\cos\theta^*| \) (hadronic W) + LH fit

\[
\begin{align*}
f_0 &= 0.669 \pm 0.078 \text{ (stat.)} \pm 0.065 \text{ (syst.)} \\
f_+ &= 0.023 \pm 0.041 \text{ (stat.)} \pm 0.034 \text{ (syst.)}
\end{align*}
\]

Dilepton channel

Constrained fit of events to reconstruct \( \cos\theta^* \) + LH fit to templates in \( \cos\theta^* \)

\[
\begin{align*}
f_0 &= 0.78^{+0.19}_{-0.20} \text{ (stat.)} \pm 0.06 \text{ (syst.)} \\
f_+ &= -0.12^{+0.11}_{-0.10} \text{ (stat.)} \pm 0.04 \text{ (syst.)}
\end{align*}
\]

Model-independent results:

[arXiv:1011.6549]

[CDF Note 10333]
• Use colour-connections as selection tool
  - $H \rightarrow b\bar{b}$: colour singlet, $g \rightarrow b\bar{b}$: colour octet
  - tt events provide clean samples of W bosons (colour-singlet) and b-jets (colour-octet)
Use colour-connections as selection tool
- $H \rightarrow b\bar{b}$: colour singlet,
  $g \rightarrow b\bar{b}$: colour octet
- $tt$ events provide clean samples of
  $W$ bosons (colour-singlet) and $b$-jets (colour-octet)

Fraction of $W$ in singlet configuration

$$f_{\text{Singlet}} = 0.56 \pm 0.42$$

$$f_{\text{Singlet}} = 1 \ (\text{SM})$$

[arXiv:1101.0648]
Kinematic fit for best $W^+b$ and $W^-b\bar{b}$ combination
- Tag flavour of b-jets by a jet charge algorithm:

$$Q_{b-jet} = \frac{\sum q_i (\vec{p}_i \cdot \hat{a})^x}{\sum_i (\vec{p}_i \cdot \hat{a})^x}$$

$\hat{a}$ = jet axis
$\vec{p}_i$ = track momentum
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$\vec{p}_i$ = track momentum

Consistent with:
$Q_t = +2/3 @13\% \text{ CL}$
Exclude
$Q_t = -4/3 @95\% \text{ CL}$
Theoretical predictions (Tevatron-specific!):
- At LO, completely symmetric
- At higher orders, interference terms influence $t$ and $\bar{t}$ production asymmetrically, e.g.:
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  - New physics contributions to enhance asymmetry?
    * Massive axial vector gluons
    * Massive vector gluons
    * $Z'$, $W'$
    * technicolour
    * ...
    * ?
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- New physics contributions to enhance asymmetry?
  - Massive axial vector gluons
  - Massive vector gluons
  - \( Z' \), \( W' \)
  - technicolour
  - ...
  - ?
Colour Charge Asymmetry ($A_{FB}$)

- Form observable:

$$A_{fb} = \frac{N^{\Delta y>0} - N^{\Delta y<0}}{N^{\Delta y>0} + N^{\Delta y<0}}$$

- Use $b$-tagged events
- Use kinematic fitter for reco

$t\bar{t}$ rest frame
Colour Charge Asymmetry ($A_{FB}$)

- Form observable:
  \[
  A_{fb} = \frac{N_{\Delta y>0} - N_{\Delta y<0}}{N_{\Delta y>0} + N_{\Delta y<0}}
  \]

- Use b-tagged events
- Use kinematic fitter for reco

\[ \Delta y = y_t - y_{\bar{t}} \]

**tt rest frame**

**measurements of top quark properties at the tevatron**

**3/26/11**
Colour Charge Asymmetry ($A_{FB}$)

- Form observable:
  \[
  A_{fb} = \frac{N_{\Delta y > 0} - N_{\Delta y < 0}}{N_{\Delta y > 0} + N_{\Delta y < 0}}
  \]

- Use $b$-tagged events
- Use kinematic fitter for reco

Raw result (not unfolded) + description of acceptance & detector effects allowing comparison to any model

MC@NLO prediction: $1^{+2\%}_{-1\%}$

[D0 note 6062]
Colour Charge Asymmetry ($A_{FB}$)

- Similar analysis from CDF

Measurements of Top Quark Properties at the Tevatron

3/26/11
Similar analysis from CDF
- Subtract backgrounds
- Correct back to parton level

Measurements of Top Quark Properties at the Tevatron

Data: $0.158 \pm 0.074$
MC: $0.058 \pm 0.009$

~1.5$\sigma$
- Look at $A_{FB}$ as a function of $M_{tt}$

Pronounced dependence of $A_{FB}$ on $M_{tt}$!!!
New physics? SM prediction at $\alpha_s^4$? $\alpha_s^\infty$?
Soft QCD effects?
• Look at $A_{FB}$ as a function of $M_{tt}$

Pronounced dependence of $A_{FB}$ on $M_{tt}$!!!
New physics?
SM prediction at $\alpha_s^4$? $\alpha_s^\infty$?
Soft QCD effects?

Unfolding

<table>
<thead>
<tr>
<th>selection</th>
<th>$M_{t\bar{t}} &lt; 450$ GeV/$c^2$</th>
<th>$M_{t\bar{t}} \geq 450$ GeV/$c^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>data parton</td>
<td>$-0.116 \pm 0.146 \pm 0.047$</td>
<td>$0.475 \pm 0.101 \pm 0.049$</td>
</tr>
<tr>
<td>MCFM</td>
<td>$+0.040 \pm 0.006$</td>
<td>$0.088 \pm 0.013$</td>
</tr>
</tbody>
</table>
Similar findings in the dilepton channel:

\( A_{FB} (NLO) = 0.06 \pm 0.01 \)

\( A_{FB} \) (corrected) = 0.42 ± 0.15 (stat) ± 0.05 (syst)

\(~2.5\sigma\)
Some tension between SM prediction and Tevatron data

About twice the data is available for a closer look!

CDF and DØ will work hard to further advance the rich top physics program of the Tevatron!
We are looking ahead to more exciting measurements from the Tevatron!
Bonus slides
Measurements of Top Quark Properties at the Tevatron

$\sqrt{s} = 1.96 \text{ TeV}$

$\mathbf{L} \sim 9.5 \text{ fb}^{-1} \text{ p.e.}$
• Tevatron has shown a great performance in FY 2010!
• We keep enlarging our calibration samples
  - Better handles on experimental uncertainties:
    - e.g. Jet Energy Scale (JES), Jet Energy Resolution, etc.

Delivered: 10.5 fb$^{-1}$
Recorded: 9.5 fb$^{-1}$
Data taking eff.: >90%
CDF performed similar measurement in the dilepton channel:

Model-independent:

\[ f_0 = 0.78^{+0.19}_{-0.20}(\text{stat.}) \pm 0.06(\text{syst.}) \]

\[ f_+ = -0.12^{+0.11}_{-0.10}(\text{stat.}) \pm 0.04(\text{syst.}) \]

Constraining \( f_0 \):

\[ f_+ = -0.07^{+0.06}_{-0.05}(\text{stat.}) \pm 0.03(\text{syst.}) \]

Constraining \( f_+ \):

\[ f_0 = 0.62 \pm 0.11(\text{stat.}) \pm 0.06(\text{syst.}) \]
- Study the V-A nature of Wtb coupling
  - Deviations from SM would indicate new physics

\[ f_0 = \frac{\Gamma(t \rightarrow W_{\lambda=0} b)}{\Gamma(t \rightarrow Wb)} \quad SM: 69.6\% \]

\[ f_- = \frac{\Gamma(t \rightarrow W_{\lambda=-1} b)}{\Gamma(t \rightarrow Wb)} \quad SM: 30.3\% \]

\[ f_+ = \frac{\Gamma(t \rightarrow W_{\lambda=+1} b)}{\Gamma(t \rightarrow Wb)} \quad SM: 0.1\% \]
Perform a model-independent LH fit (5.4 fb$^{-1}$):

$$f_0 = 0.669 \pm 0.078 \, (\text{stat.}) \pm 0.065 \, (\text{syst.})$$

$$f_+ = 0.023 \pm 0.041 \, (\text{stat.}) \pm 0.034 \, (\text{syst.})$$

- Constraining $f_0$ to SM value:

$$f_+ = 0.010 \pm 0.022 \, (\text{stat.}) \pm 0.030 \, (\text{syst.})$$

$$f_0 = 0.708 \pm 0.044 \, (\text{stat.}) \pm 0.048 \, (\text{syst.})$$
- Both $l+j$-jets and dilepton channels are used
  - Define channel-dependent likelihood
  - Pick variables with best modeling of data by MC

- Perform LH fit on 5.4 fb$^{-1}$
  (model-independent):

$$f_0 = 0.669 \pm 0.078 \text{ (stat.)} \pm 0.065 \text{ (syst.)}$$

$$f_+ = 0.023 \pm 0.041 \text{ (stat.)} \pm 0.034 \text{ (syst.)}$$
CDF performed similar measurement in the dilepton channel:

Model-independent:

\[ f_0 = 0.78^{+0.19}_{-0.20} \text{(stat.)} \pm 0.06 \text{(syst.)} \]

\[ f_+ = -0.12^{+0.11}_{-0.10} \text{(stat.)} \pm 0.04 \text{(syst.)} \]
The decay width of the top quark could show contributions from new physics.

\[ \Gamma_t = \frac{\sigma(t\text{-channel}) \Gamma(t \rightarrow Wb)_{\text{SM}}}{\mathcal{B}(t \rightarrow Wb) \sigma(t\text{-channel})_{\text{SM}}} \]

\[ \Gamma(t \rightarrow Wb)_{\text{SM}} = 1.26 \text{ GeV} \]

\[ \sigma(t\text{-channel})_{\text{SM}} = 2.14 \pm 0.18 \text{ pb} \]

\[ \Gamma_t = 1.99^{+0.69}_{-0.55} \text{ GeV} \]

\[ \tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25} \text{ s} \]

\[ m_t = 170 \text{ GeV} \]

World’s most precise determination of \( \Gamma_t \) to date.
Measurements of Top Quark Properties at the Tevatron
- **tt pairs produced via strong interaction at the Tevatron:**

![Diagram of tt pairs production via strong interaction](image-url)

**Cross Section**

- $\sigma \approx 7 \text{ pb}$

**Legend**

- Jet
- $b\bar{b}$
- W/Z
- $t\bar{t}$
- Higgs
- New

**Reaction**

$p\bar{p} \rightarrow X$
- In the SM:
  - $|V_{tb}| = 0.9990 - 0.9992$
  @ 95% C.L. assuming 3 CKM generations
- Characterise $tt$ final states by top decays!

**Top Pair Branching Fractions**

- "alljets" 46%
- $\tau + \text{jets}$ 15%
- $\mu + \text{jets}$ 15%
- $e + \text{jets}$ 15%

**Branching Fractions**

- "Dileptons" 1%
- $\tau + \tau$ 2%
- $\tau + \mu$ 2%
- $\tau + e$ 2%
- $\mu + \mu$ 0%
- $\mu + e$ 0%
- $e + e$ 0%

**Event Samples**

- **Dilepton** (BR~5%, low bckg)
- **Lepton+jets** (BR~30%, moderate bckg)
- **All-hadronic** (BR~46%, huge bckg)
**Typical ttbar preselection**

<table>
<thead>
<tr>
<th>Dilepton</th>
<th>Lepton+jets</th>
<th>All-hadronic</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 high-p_T leptons</td>
<td>1 high-p_T lepton (&gt;20 GeV)</td>
<td>No leptons</td>
</tr>
<tr>
<td>Missing E_T</td>
<td>Missing E_T (&gt;40 GeV)</td>
<td>No missing E_T</td>
</tr>
<tr>
<td>2 jets</td>
<td>4 jets (&gt; 20GeV)</td>
<td>6 jets</td>
</tr>
<tr>
<td>≥ 0 b-tags</td>
<td>≥ 1 b-tag</td>
<td>≥ 1 b-tag</td>
</tr>
</tbody>
</table>

**S/B:**

![Dilepton](image1)

**Dilepton**
(BR~5%, low bckg)

![Lepton+jets](image2)

**Lepton+jets**
(BR~30%, moderate bckg)

![All-hadronic](image3)

**All-hadronic**
(BR~46%, huge bckg)
The DØ Detector

Calorimeter

Muon System

Tracking System

Solenoidal Magnetic Field

20 m
- In the SM:
  - $|V_{tb}| = 0.9990 - 0.9992$
    @ 95% C.L. assuming
    3 CKM generations
- Characterise $t\bar{t}$ final states by top decays
We are interested in **parton-level quantities** for our top measurements

- Map the energies of reco-level jets to particle jets (D0) / partons (CDF)
- This is referred to as a Energy Scale (JES) corr’n
- With the current size of samples:
  - $s(JES)/JES \sim 1.5\%$ (D0)
  - $s(JES)/JES \sim 3\%$ (CDF)

And many more:
- Lepton ID, $p_T$ scale