Recent top physics results from the DØ experiment

Oleg Brandt on behalf of the DØ collaboration

II Physikalisches Institut, Georg-August-Universität Göttingen
What makes top so interesting?

• Compelling arguments that new physics can show up in the top sector:
  - Top is the heaviest quark discovered so far
  - Its Yukawa coupling is $0.996\pm0.006$
    - Special role in EWSB?
  - Since 17 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 data and the SM predictions ($A_{FB}$, $R_B$)
A wealth of top properties

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

+ electroweak single top production
Recent top physics results from DØ

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A wealth of top properties

- Typically: we measure top properties in $t\bar{t}$ events
  - Dilepton channel: low backgrounds, but underconstrained kinematics and low rate
  - $l^+\text{jets}$ channel: good compromise between kinematic reconstruction, high rate, and backgrounds
  - All-hadronic channel: highest branching ratio, very high backgrounds from QCD multijet production
    - + other orthogonal channels...

Single top: high backgrounds, moderate rate, direct access to some observables (e.g. $V_{tb}$)
More about the top birth place…

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

Tevatron

$L \sim 10.5 \text{ fb}^{-1}$
Initial state @ Tevatron (and LHC)

- **Initial state for top-antitop pair-production rather different between Tevatron and LHC:**

<table>
<thead>
<tr>
<th>Tevatron</th>
<th>LHC</th>
</tr>
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<tbody>
<tr>
<td><code>p̅p</code> initial state → CP eigenstate</td>
<td><code>pp</code> initial state</td>
</tr>
<tr>
<td>centre-of-mass energy: 1.96 TeV</td>
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<td>Initial state: <code>qq</code> (≈85%), <code>gg</code> (≈15%)</td>
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Dramatic differences for single top production:

<table>
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<tr>
<th>Collider</th>
<th>( s)-channel: ( \sigma_{tb} )</th>
<th>( t)-channel: ( \sigma_{tqb} )</th>
<th>( Wt)-channel: ( \sigma_{tW} )</th>
</tr>
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<tbody>
<tr>
<td>Tevatron: ( p\bar{p} ) (1.96 TeV)</td>
<td>1.04 pb</td>
<td>2.26 pb</td>
<td>0.28 pb</td>
</tr>
<tr>
<td>LHC: ( pp ) (7 TeV)</td>
<td>4.6 pb</td>
<td>64.6 pb</td>
<td>15.7 pb</td>
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Decay width of the top quark

\[ \Gamma_t = \frac{\Gamma(t \rightarrow Wb)}{\mathcal{B}(t \rightarrow Wb)} \]
Decay width of the top quark

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Assume:

\[ Wtb \] coupling identical in production & decay

Recent top physics results from DØ

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

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PLB 705, 313 (2011)  
DØ 5.4 fb⁻¹

---

6/6/12

Recent top physics results from DØ
Decay width of the top quark

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

measured in \(tt\) events

Assume:

\(Wtb\) coupling identical in production & decay

Recent top physics results from DØ

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

\[DØ, L=5.3 \text{ fb}^{-1}\]

\[\text{Data} \quad \text{tt} \ R=1 \quad \text{tt} \ R=0.5 \quad \text{tt} \ R=0 \quad \text{Background}\]

\[\text{PRD 84, 012008 (2011)}\]

\[\text{PLB 705, 313 (2011)}\]

\[DØ \ 5.4 \text{ fb}^{-1}\]

\[68\% \ C.L. \quad 90\% \ C.L. \quad 95\% \ C.L.\]

\[\text{Measurement} \quad \text{SM}^{[1]} \quad \text{Four generations}^{[2]} \quad \text{Top-flavor}^{[3]} \quad \text{FCNC}^{[4]}\]

Assume: 

$Wtb$ coupling identical in production & decay

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

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

Properly correlate $\sigma(t\text{-channel})$, $\beta(t \rightarrow Wb)$ \rightarrow measure $\Gamma_t$ from LH based on $t$-channel discriminant
Decay width of the top quark measured in $t\bar{t}$ events

Assume:

$Wtb$ coupling identical in production & decay

Recent top physics results from DØ

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

$\Gamma_t = 2.00^{+0.47}_{-0.43}$ GeV

$\tau_t = (3.29^{+0.90}_{-0.63}) \times 10^{-25}$ s

Properly correlate $\sigma(t$-channel), $\mathcal{B}(t \to Wb)$ \rightarrow measure $\Gamma_t$ from LH based on $t$-channel discriminant
To extract $|V_{tb}|$, use again $t$-channel discriminant

Form the LH as before but analyse

$$|V_{tb}|^2 \mathcal{B}(t \to Wb) \sigma(t\text{-channel})_{SM}, |V_{tb}| = 1$$

Form Bayesian posterior density:

PRD 85, 091104 (2012)
To extract $|V_{tb}|$, use again $t$-channel discriminant

Form the LH as before but analyse

$$|V_{tb}|^2 \mathcal{B}(t \rightarrow Wb) \sigma(t - \text{channel})_{SM}, |V_{tb}| = 1$$

Form Bayesian posterior density:

$$|V_{tb}| > 0.81 \text{ at 95\% C.L.}$$

No assumption that $t \rightarrow Wb$ exclusively or on relative $t$ to $s$ channel rates

PRD 85, 091104 (2012)
- Study the \( V-A \) nature of the \( Wtb \) coupling
- Deviations from SM would indicate new physics

\[
\begin{align*}
    f_- &= 30.1\% \text{ (NLO)} \\
    f_+ &= 0.04\% \text{ (NLO)} \\
    f_0 &= 69.8\% \text{ (NLO)}
\end{align*}
\]
Study the \textit{V-A} nature of the $Wtb$ coupling

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Dilepton & $l$+jets comb’d

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

Simultaneous 2-D fit results:

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

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

PRD 83, 032009 (2011)
Dilepton & I+jets comb’d

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

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\end{align*}
\]

\( \chi^2/N_{\text{DOF}} = 8.82/4, \text{ p-value} = 6\% \)

**Tevatron combination:**

- CDF + DØ combination
  - \( L = 2.7 - 5.4 \text{ fb}^{-1} \)
- 68\% and 95\% C.L. contours
- Combined result
- SM value
- CDF I+jets
- CDF dilepton
- DØ

**PRD 83, 032009 (2011)**

**PRD 85, 091104 (2012)**
Anomalous $Wtb$ couplings ($Wtb$ AC)

- Most general, lowest-dim, $CP$-conserving $Wtb$ vertex

$$\mathcal{L} = \frac{g}{\sqrt{2}} b\gamma^{\mu}V_{tb}(f_{V}^{L}P_{L} + f_{V}^{R}P_{R})tW_{\mu}^{--}$$

$$\quad - \frac{g}{\sqrt{2}} b\frac{i\sigma^{\mu\nu}q_{\nu}V_{tb}}{M_{W}}(f_{T}^{L}P_{L} + f_{T}^{R}P_{R})tW_{\mu}^{--} + h.c.$$
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\]

- **Extract $Wtb$ AC from single top production using:**
  - shapes of kinematic distributions
  - event rate (overall, $s$-channel vs $t$-channel)

- **Few assumptions:**
  - Single top quarks produced exclusively via a $W$ boson
  - $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$

[Underlined couplings are 0 in SM!]

Recent top physics results from DØ

arXiv:1110.4592 [hep-ex], PLB acc’d
Anomalous $Wtb$ couplings ($Wtb$ AC)

- Most general, lowest-dim, $CP$-conserving $Wtb$ vertex

$$\mathcal{L} = \frac{g}{\sqrt{2}} \overline{b} \gamma^\mu V_{tb} (f_V^L P_L + f_V^R P_R) tW_\mu^-$$

$$- \frac{g}{\sqrt{2}} \overline{b} \sigma^{\mu\nu} q_\nu V_{tb} \frac{1}{M_W} (f_T^L P_L + f_T^R P_R) tW_\mu^- + h.c.$$

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- Bayesian NN discriminant in $3 \ N_{jet} \times 2 \ N_{tag}$ bins:
  - Dedicated training for each signal model
    - Allow one of $\{f_V^R, f_T^L, f_T^R\}!=0$, and $f_V^L = 1$ for consistency!
Obtained limits:

Limits on Wtb AC from single top production

arXiv:1110.4592 [hep-ex], PLB acc’d
Wtb AC will alter:
- single top production
  (see previous slides)

arXiv:1204.2332 [hep-ex], PLB acc’d
Wtb AC will alter:
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- fractions of W bosons in the 3 helicity states

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Assume:
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arXiv:1204.2332 [hep-ex], PLB acc’d
**Wtb AC from single top + W helicity**

- **Wtb AC will alter:**
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**Recent top physics results from DØ**

*arXiv:1204.2332 [hep-ex], PLB acc’d*
Recent top physics results from DØ

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**Wtb AC from single top + W helicity**

### Combination of single top + W helicity

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

Significant improvement!
• Invariance under Lorentz transformation is a fundamental property of the SM
  - Thoroughly tested in the leptonic sector and for first generation, some tests for second generation, b-system
Invariance under Lorentz transformation is a fundamental property of the SM

- Thoroughly tested in the leptonic sector and for first generation, some tests for second generation, b-system
- Quantify Lorentz invariance violation (LIV) in the top sector using in the SM Extension formalism:

\[ |\mathcal{M}_{\text{SME}}|^2 = PF\bar{F} + (\delta P)F\bar{F} + P(\delta F)\bar{F} + PF(\delta \bar{F}) \]

\(P\) @ prod’n vertex \(F\) @ decay vertex \(\delta\) Dependence on SM extension coefficients

[D. Colladay and V.A. Kostelecky, Phys. Rev. D 58, 116002 (1998)]
[V.A. Kostelecky, Phys. Rev. D 69, 105009 (2004)]

- Parametrisate LIV \(f_{\text{SME}}(t)\) in terms of coefficients \(C_{\mu\nu}\):

\[ f_{\text{SME}}(t) = C_{\mu\nu} R^\mu_\alpha(t) R^\nu_\beta(t) A^{\alpha\beta} \]

arXiv:1203.6106 [hep-ex], PRL acc’d
Lorentz invariance violation

- **Invariance under Lorentz transformation is a fundamental property of the SM**
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- **Parametrisate LIV** \(f_{\text{SME}}(t)\) in terms of coefficients \(C_{\mu\nu}\):
  - \(f_{\text{SME}}(t) = C_{\mu\nu} R_\alpha^\mu(t) R_\beta^\nu(t) A^{\alpha\beta}\)
  - Non-zero \(C_{\mu\nu}\) will result in time dependent \(tt\) production due to the rotation of the Earth!

\textit{arXiv:1203.6106 [hep-ex], PRL acc’d}
Lorentz invariance violation

- The period is 1 or $\frac{1}{2}$ siderial day
  - 1 Solar day
    $\approx 0.997$ siderial day
  - Use time stamp to check periodicity!

$\sigma(t) \approx \sigma_{ave} \left[ 1 + f_{SME}(t) \right]$
The period is 1 or ½ siderial day
- 1 Solar day
  ≈ 0.997 siderial day
- Use time stamp to check periodicity!

\[ R_i \equiv \frac{1}{f_S} \left( \frac{N_i/N_{\text{tot}}}{\mathcal{L}_i/\mathcal{L}_{\text{int}}} - 1 \right) \]
Theoretical predictions (Tevatron-specific!):
- At LO, completely symmetric
- At higher orders, interference terms influence t and tbar production asymmetrically, e.g.:
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  - Massive axial vector gluons
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  - $Z'$, $W'$
  - Technicolour
  - ?
Colour Charge Asymmetry ($A_{FB}$)

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Recent top physics results from DØ
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

**Recent top physics results from DØ**

*PRD 84, 112005 (2011)*
Colour Charge Asymmetry ($A_{FB}$)

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

$tt$ rest frame

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  \]

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Recent top physics results from DØ:

- Raw result (not unfolded), after background subtraction:
  \[
  A_{FB} = 9.2 \pm 3.7\% 
  \]

- MC@NLO prediction:
  \[
  2.4 \pm 0.7 
  \]

PRD 84, 112005 (2011)

~2$\sigma$
Asymmetry would be enhanced:
- For high $m_{tt}$ for an $s$-channel resonance
- For high $|\Delta y|$ for a $t$-channel anomaly

<table>
<thead>
<tr>
<th>Subsample</th>
<th>Data</th>
<th>MC@NLO</th>
</tr>
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<tbody>
<tr>
<td>$m_{tt} &lt; 450$ GeV</td>
<td>$7.8 \pm 4.8$</td>
<td>$1.3 \pm 0.6$</td>
</tr>
<tr>
<td>$m_{tt} &gt; 450$ GeV</td>
<td>$11.5 \pm 6.0$</td>
<td>$4.3 \pm 1.3$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta y</td>
<td>&lt; 1.0$</td>
</tr>
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<td>$</td>
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<td>&gt; 1.0$</td>
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Less than $2\sigma$ throughout

PRD 84, 112005 (2011)
Any $A_{FB}$ at generator level will be reduced at reconstruction level due to
- Limited detector acceptance
- Limited resolution on $\Delta y$ ($\approx 0.7$)

PRD 84, 112005 (2011)
**Colour Charge Asymmetry ($A_{FB}$)**

- Any $A_{FB}$ at generator level will be reduced at reconstruction level due to:
  - Limited detector acceptance
  - Limited resolution on $\Delta y$ ($\approx 0.7$)

- Unfold $\Delta y$ to generator level
  - Bin migrations particularly relevant close to $\Delta y = 0$
    - Use sufficiently fine binned, regularised unfolding
    - Correct for possible biases with ensemble tests
    - (Cross-check with coarse-binned unfolding consistent)

---

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<th>$A_{FB}$ (%)</th>
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<td>9.2 ± 3.7</td>
<td>19.6 ± 6.5</td>
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<td>2.4 ± 0.7</td>
<td>5.0 ± 0.1</td>
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PRD 84, 112005 (2011)
Recent top physics results from DØ

There is a new measurement of $A_{FB}$ by CDF (CDF Note 10807, 8.7 fb$^{-1}$) → comparison plots are not available yet
Migrations around $\Delta y=0$ are tiny if lepton-based observables are used
- $\rightarrow$ define forward, backward events via $q_{\ell} y_{\ell} < 0$, $q_{\ell} y_{\ell} > 0$
**Migrations around $\Delta y$ are tiny if lepton-based observables are used**

- → define forward, backward events via $q_\ell y_\ell < 0$, $q_\ell y_\ell > 0$

**Table**

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<td>$14.2 \pm 3.8$</td>
<td>$15.2 \pm 4.0$</td>
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<tr>
<td>MC@NLO</td>
<td>$0.8 \pm 0.6$</td>
<td>$2.1 \pm 0.1$</td>
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</table>
We are looking ahead to more exciting measurements from the Tevatron!
Recent top physics results from DØ
Obtained limits:

Using events orthogonal to W helicity measurement ONLY

DØ, 5.4 fb$^{-1}$

- 68% C.L.
- 90% C.L.
- 95% C.L.

- Best-fit value
- SM value

Single top only

[arXiv:1110.4592]
Wtb AC from single top + W helicity

- Wtb AC will alter:
  - single top production
    (see previous slides)
  - fractions of W bosons
    in the 3 helicity states:

[arXiv:1204.2332]
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\[ \sigma(t) \approx \sigma_{\text{ave}} [1 + f_{\text{SME}}(t)] \]

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<td>$(c_Q)_{XX33}$</td>
<td>$-0.12 \pm 0.11 \pm 0.02$</td>
<td>$[-0.34, +0.11]$</td>
</tr>
<tr>
<td>$(c_Q)_{YY33}$</td>
<td>$0.12 \pm 0.11 \pm 0.02$</td>
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</tr>
<tr>
<td>$(c_Q)_{XY33}$</td>
<td>$-0.04 \pm 0.11 \pm 0.01$</td>
<td>$[-0.26, +0.18]$</td>
</tr>
<tr>
<td>$(c_Q)_{XZ33}$</td>
<td>$0.15 \pm 0.08 \pm 0.02$</td>
<td>$[-0.01, +0.31]$</td>
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<tr>
<td>$(c_Q)_{YZ33}$</td>
<td>$-0.03 \pm 0.08 \pm 0.01$</td>
<td>$[-0.19, +0.12]$</td>
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TABLE III: Limits on SME coefficients at the 95% C.L., assuming $(c_U)_{\mu\nu} \equiv 0.$

\[ \sigma(t) \approx \sigma_{\text{ave}} [1 + f_{\text{SME}}(t)] \]

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<td>$[-0.08, +0.27]$</td>
</tr>
<tr>
<td>$(c_U)_{YY33}$</td>
<td>$-0.10 \pm 0.09 \pm 0.02$</td>
<td>$[-0.27, +0.08]$</td>
</tr>
<tr>
<td>$(c_U)_{XY33}$</td>
<td>$0.04 \pm 0.09 \pm 0.01$</td>
<td>$[-0.14, +0.22]$</td>
</tr>
<tr>
<td>$(c_U)_{XZ33}$</td>
<td>$-0.14 \pm 0.07 \pm 0.02$</td>
<td>$[-0.28, +0.01]$</td>
</tr>
<tr>
<td>$(c_U)_{YZ33}$</td>
<td>$0.01 \pm 0.07 \pm &lt;0.01$</td>
<td>$[-0.13, +0.14]$</td>
</tr>
</tbody>
</table>

TABLE IV: Limits on SME coefficients at the 95% C.L., assuming $(c_Q)_{\mu\nu} \equiv 0.$

[arXiv:1203.6106]
Strong charge asymmetry (D0)

- Strong Colour charge asymmetry (D0, 5.4 fb\(^{-1}\))

\[ A = (9.2 \pm 3.6^{+0.8}_{-0.9})\% \iff A(MC@NLO) = (2.4 \pm 0.3^{+0.7}_{-0.5})\% \]
### Recent top physics results from DØ

<table>
<thead>
<tr>
<th></th>
<th>$l^+ \geq 4$ jets</th>
<th>$e^+ \geq 4$ jets</th>
<th>$\mu^+ \geq 4$ jets</th>
<th>$l+4$ jets</th>
<th>$l+\geq 5$ jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw $N_F$</td>
<td>849</td>
<td>455</td>
<td>394</td>
<td>717</td>
<td>132</td>
</tr>
<tr>
<td>Raw $N_B$</td>
<td>732</td>
<td>397</td>
<td>335</td>
<td>597</td>
<td>135</td>
</tr>
<tr>
<td>$N_{t\bar{t}}$</td>
<td>$1126 \pm 39$</td>
<td>$622 \pm 28$</td>
<td>$502 \pm 28$</td>
<td>$902 \pm 36$</td>
<td>$218 \pm 16$</td>
</tr>
<tr>
<td>$N_{W+jets}$</td>
<td>$376 \pm 39$</td>
<td>$173 \pm 28$</td>
<td>$219 \pm 27$</td>
<td>$346 \pm 36$</td>
<td>$35 \pm 16$</td>
</tr>
<tr>
<td>$N_{MJ}$</td>
<td>$79 \pm 5$</td>
<td>$56 \pm 3$</td>
<td>$8 \pm 2$</td>
<td>$66 \pm 4$</td>
<td>$13 \pm 2$</td>
</tr>
<tr>
<td>$A_{FB}$(%)</td>
<td>$9.2 \pm 3.7$</td>
<td>$8.9 \pm 5.0$</td>
<td>$9.1 \pm 5.8$</td>
<td>$12.2 \pm 4.3$</td>
<td>$-3.0 \pm 7.9$</td>
</tr>
<tr>
<td>MC@NLO $A_{FB}$(%)</td>
<td>$2.4 \pm 0.7$</td>
<td>$2.4 \pm 0.7$</td>
<td>$2.5 \pm 0.9$</td>
<td>$3.9 \pm 0.8$</td>
<td>$-2.9 \pm 1.1$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$l^+ \geq 4$ jets</th>
<th>$e^+ \geq 4$ jets</th>
<th>$\mu^+ \geq 4$ jets</th>
<th>$l+4$ jets</th>
<th>$l+\geq 5$ jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw $N_F^l$</td>
<td>867</td>
<td>485</td>
<td>382</td>
<td>730</td>
<td>137</td>
</tr>
<tr>
<td>Raw $N_B^l$</td>
<td>665</td>
<td>367</td>
<td>298</td>
<td>546</td>
<td>119</td>
</tr>
<tr>
<td>$N_{t\bar{t}}$</td>
<td>$1096 \pm 39$</td>
<td>$622 \pm 28$</td>
<td>$474 \pm 27$</td>
<td>$881 \pm 36$</td>
<td>$211 \pm 16$</td>
</tr>
<tr>
<td>$N_{W+jets}$</td>
<td>$356 \pm 39$</td>
<td>$173 \pm 28$</td>
<td>$198 \pm 27$</td>
<td>$323 \pm 36$</td>
<td>$31 \pm 16$</td>
</tr>
<tr>
<td>$N_{MJ}$</td>
<td>$79 \pm 5$</td>
<td>$56 \pm 3$</td>
<td>$8 \pm 2$</td>
<td>$66 \pm 4$</td>
<td>$14 \pm 2$</td>
</tr>
<tr>
<td>$A_{FB}^l$(%)</td>
<td>$14.2 \pm 3.8$</td>
<td>$16.5 \pm 4.9$</td>
<td>$9.8 \pm 5.9$</td>
<td>$15.9 \pm 4.3$</td>
<td>$7.0 \pm 8.0$</td>
</tr>
<tr>
<td>MC@NLO $A_{FB}^l$(%)</td>
<td>$0.8 \pm 0.6$</td>
<td>$0.7 \pm 0.6$</td>
<td>$1.0 \pm 0.8$</td>
<td>$2.1 \pm 0.6$</td>
<td>$-3.8 \pm 1.2$</td>
</tr>
</tbody>
</table>
Template method, 4.7 fb$^{-1}$ (DØ):
- $m_{\text{top}}$ free parameter $\rightarrow$ dilepton events are kinematically underconstrained
- Use the so-called neutrino-weighting algorithm:
  - Postulate eta-distributions of neutrinos from MC
  - Calculate weight distribution vs. $m_{\text{top}}$
  - Use 1$^\text{st}$ and 2$^\text{nd}$ moment of this distribution to form templates
- Apply in-situ JES calibration from $l+j$ets channel:
  - 1.013 $\pm$ 0.008(stat)
- Caveat:
  - $k_{\text{JES}}$ can be final state-dependent, so we derive a dedicated response correction
- Final result:

\[ m_t = 174.0 \pm 2.4(\text{stat}) \pm 1.4(\text{syst}) \text{ GeV} \]

Total uncertainty below 1 GeV for the first time!!!
### Tevatron combined values (GeV/c²)

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_t$</td>
<td>173.18</td>
</tr>
<tr>
<td>iJES</td>
<td>0.39</td>
</tr>
<tr>
<td>aJES</td>
<td>0.09</td>
</tr>
<tr>
<td>bJES</td>
<td>0.15</td>
</tr>
<tr>
<td>cJES</td>
<td>0.05</td>
</tr>
<tr>
<td>dJES</td>
<td>0.20</td>
</tr>
<tr>
<td>rJES</td>
<td>0.12</td>
</tr>
<tr>
<td>Lepton $p_T$</td>
<td>0.10</td>
</tr>
<tr>
<td>Signal</td>
<td>0.51</td>
</tr>
<tr>
<td>Detector Modeling</td>
<td>0.10</td>
</tr>
<tr>
<td>UN/MI</td>
<td>0.00</td>
</tr>
<tr>
<td>Background from MC</td>
<td>0.14</td>
</tr>
<tr>
<td>Background from Data</td>
<td>0.11</td>
</tr>
<tr>
<td>Method</td>
<td>0.09</td>
</tr>
<tr>
<td>MHI</td>
<td>0.08</td>
</tr>
<tr>
<td>Systematics</td>
<td>0.75</td>
</tr>
<tr>
<td>Statistics</td>
<td>0.56</td>
</tr>
<tr>
<td>Total</td>
<td>0.94</td>
</tr>
</tbody>
</table>

**In-situ JES calibration** $\sim \frac{1}{\sqrt{N}}$

**Size of calibration samples** $\sim \frac{1}{\sqrt{N}}$

**Various signal modeling uncert.** $\sim \sqrt{\text{brain effort}}$

Relative uncertainty: 0.54%

Expect this limit to be improved...
- CPT is essential for a locally Lorentz-invariant QFT
  - $m_{\text{particle}} \neq m_{\text{antiparticle}} \Rightarrow$ CPT violated!
- Top is the only quark where this test is possible:
- DØ measures directly and independently

\[ \Delta m = m_t - m_{\bar{t}} = 0.8 \pm 1.8 \, \text{(stat)} \pm 0.5 \, \text{(syst)} \, \text{GeV} \]
\[ \Delta m = \frac{m_t + m_{\bar{t}}}{2} \equiv 172.5 \, \text{GeV} \]
\[ \Delta m = -1.95 \pm 1.11 \, \text{(stat)} \pm 0.59 \, \text{(syst)} \, \text{GeV} \quad (8.7 \, \text{fb}^{-1}) \]
Top-antitop spin correlations

- Decay products carry information about spin of tt system

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

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

- Correlation strength (frame dependent):

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

- 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)
How can we adopt the superior matrix element* (ME) technique for the spin correlation measurement?

- Melnikov and Schulze (PLB 700, 17 (2011)):

\[
R(x) = \frac{P_{t\bar{t}}(x, H=1)}{P_{t\bar{t}}(x, H=0) + P_{t\bar{t}}(x, H=1)}
\]

- Construct templates in R

- Observable:
  - Fraction of events with spin corr.:
    \[
f = \frac{N_{t\bar{t}}(w./ spin \ correlation)}{N_{t\bar{t}}(all)}
\]
  - Translates into \( C \rightarrow f \ast C_{SM} \)
    - i.e. SM pred’n is \( f = 1 \)

* I will discuss the ME technique in detail in the context of \( m_{top} \) meas’t

Here: it gives probability \( P(x, H) \) that a given event came from the process described by the ME, given observed kinematics \( x \) and hypothesis \( H \)
Spin correlations w. matrix element

- Take ME from Mahlon & Parke (PLB 411, 173 (1997)):
  \[
  \sum \left| (M) \right|^2 = \frac{1 + H g_s^4}{2} F \overline{F} \left( 2 - \beta^2 s_t^2 \right) - H \frac{g_s^4}{9} F \overline{F} \Delta
  \]
  - H=1: correlated spins
  - H=0: uncorrelated spins

- Perform measurement:
  - Dilepton channel
  - mc@nlo generator
  - dataset as 2 slides ago

- Use binned LH fit with nuisance parameters

- We obtain:
  - \( f = 0.74 \pm 0.41 \) (stat+syst)
  - \( f > 0.14 \) @ 95% CL
  - \( f=0 \) excluded at 97.7% CL (99.6% exp.)
    - 30% more sensitivity!
      - But still statistically dominated (0.27)
Spin correlations w. matrix element

- Straight forward to extend the lepton+jets channel:
  - Same ME, mc@nlo as generator
  - Split in 4 and 4+ jet bins
  - Require two b-tags to reduce combinatorics (+ purity 90%)
  - Regard the other two highest $p_T$ jets as light jets
  - $\rightarrow$ four permutations

- Combine with dilepton result:
  - $f = 0.85 \pm 0.29$ (stat+syst)
  - $f < 0.34$ @ 95% CL
  - $f < 0.05$ @ 99.7% CL
  - $f = 0$ @ 3.1 SD !!!

  - First evidence for non-vanishing spin correlations!
Spin correlations Tevatron

\[ \bar{t}t \text{ spin correlations } C_{\text{beam}} \]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Data</th>
<th>Template</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF, 2.8fb(^{-1})</td>
<td>(dilepton template)</td>
<td>0.32(^{+0.55})(^{-0.78})</td>
<td></td>
</tr>
<tr>
<td>DØ, 5.4fb(^{-1})</td>
<td>(dilepton template)</td>
<td>0.50(\pm0.45)</td>
<td></td>
</tr>
<tr>
<td>DØ, 5.4fb(^{-1})</td>
<td>(dilepton ME)</td>
<td>0.57(\pm0.33)</td>
<td></td>
</tr>
<tr>
<td>CDF, 5.3fb(^{-1})</td>
<td>(l+jets template)</td>
<td>0.72(\pm0.69)</td>
<td></td>
</tr>
<tr>
<td>DØ, 5.3fb(^{-1})</td>
<td>(l+jets ME)</td>
<td>(0.89\pm0.33)</td>
<td>(\text{preliminary})</td>
</tr>
<tr>
<td>DØ combination, 5.4fb(^{-1})</td>
<td>(dilepton + l+jets ME)</td>
<td>(0.66\pm0.23)</td>
<td>(\text{preliminary})</td>
</tr>
</tbody>
</table>
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

\[
\begin{align*}
S_{\text{Singlet}} &= 0.56 \pm 0.42 \\
S_{\text{Singlet}} &= 1 \text{ (SM)}
\end{align*}
\]

[arXiv:1101.0648]
The CDF and DØ detectors

<table>
<thead>
<tr>
<th></th>
<th>CDF</th>
<th>DØ</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM calorimeter</td>
<td>14%/√E + 1%</td>
<td>22%/√E + 4%</td>
</tr>
<tr>
<td>Hadronic calorimeter</td>
<td>70%/√E + 5%</td>
<td>68%/√E + 5%</td>
</tr>
</tbody>
</table>

Silicon vertex detector
Tracking chamber
Solenoid
EM calorimeter
Hadron calorimeter
Muon system

CDF

DØ

Interaction point
24 Feb. 1995:
- Simultaneous PRL submission by CDF and DØ

CDF (67 pb\(^{-1}\)):
- \(\sigma = 6.8^{+3.6}_{-2.4}\) pb,
- observed 19 events, expected 6.9 bkg
  - bkg-only hypothesis rejected at 4.8\(\sigma\)
- \(m_{\text{top}} = 176\pm13\) GeV

D0 (50 pb\(^{-1}\)):
- \(\sigma = 6.4\pm2.2\) pb,
- observed 17 events, expected 3.8 bkg
  - \(\rightarrow\) bkg-only hypothesis rejected at 4.6\(\sigma\)
- \(m_{\text{top}} = 199\pm30\) GeV
24 Feb. 1995:
- Simultaneous PRL submission by CDF and DØ

CDF (67 pb\(^{-1}\)):
- \(\sigma = 6.8^{+3.6}_{-2.4}\) pb,
- observed 19 events, expected 6.9 bkg
  - bkg-only hypothesis rejected at 4.8\(\sigma\)
- \(m_{\text{top}} = 176\pm13\) GeV

DØ (50 pb\(^{-1}\)):
- \(\sigma = 6.4\pm2.2\) pb,
- observed 17 events, expected 3.8 bkg
  - \(\rightarrow\) bkg-only hypothesis rejected at 4.6\(\sigma\)
- \(m_{\text{top}} = 199\pm30\) GeV
- **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.

Measurements of Top Quark Properties at the Tevatron

Delivered: $10.5 \text{ fb}^{-1}$
Recorded: $9.5 \text{ fb}^{-1}$
Data taking eff.: $>90\%$
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%
- $\tau+$jets 15%
- $\mu+$jets 15%
- $e+$jets 15%

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

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

**All-hadronic**
(BR~46%, huge bckg)
## Typical ttbar preselection

<table>
<thead>
<tr>
<th></th>
<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>
<td></td>
</tr>
<tr>
<td>Missing E(_T)</td>
<td>Missing E(_T) (&gt;40 GeV)</td>
<td>No missing E(_T)</td>
<td></td>
</tr>
<tr>
<td>2 jets</td>
<td>4 jets (&gt; 20 GeV)</td>
<td>6 jets</td>
<td></td>
</tr>
<tr>
<td>≥ 0 b-tags</td>
<td>≥ 1 b-tag</td>
<td>≥ 1 b-tag</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Space/Background (S/B):</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dilepton</strong></td>
<td></td>
<td><strong>Lepton+jets</strong></td>
</tr>
<tr>
<td>(BR~5%, low bckg)</td>
<td></td>
<td>(BR~30%, moderate bckg)</td>
</tr>
<tr>
<td><strong>All-hadronic</strong></td>
<td></td>
<td>(BR~46%, huge bckg)</td>
</tr>
</tbody>
</table>

**Diagram:**

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