Measurements of the $t\bar{t}$ cross section at D0 and interpretations

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on behalf of the D0 collaboration
The Tevatron and the D0 detector

- Proton-antiproton collider
- $\sqrt{s} = 1.96 \text{ TeV}$
- collisions every 396 ns

06/06/2009
Peak inst. luminosity is now routinely above $300 \times 10^3 \text{ cm}^{-2}\text{s}^{-1}$
- Record (April 01 2009): $351 \times 10^3 \text{ cm}^{-2}\text{s}^{-1}$

May 29 2009: DO has recorded to tapes 6 $\text{ fb}^{-1}$ (out of 6.7 $\text{ fb}^{-1}$ delivered by the Tevatron)
top quark pairs production at the Tevatron

- p-pbar collider, $\sqrt{s}=1.96$ TeV
- via the strong interaction:

\[ \sigma_{pp \rightarrow tt} \] [pb]

Theoretical cross section (pb)

S. Moch and P. Uwer, PRD 78, 034003 (2008)

$m_{\text{top}}=173.1 \pm 0.6\text{(stat)} \pm 1.1\text{(syst)}$ GeV/$c^2$:

\[ \sigma_{\text{NNLO}}^{\text{NNLO}} = 7.32^{+0.47}_{-0.66} \text{pb} \]
SM top decay modes and search channels

- In SM: $|V_{tb}| \sim 1 \Rightarrow BR(t \rightarrow Wb) \sim 100%$
- The final states are driven by the W decay modes: $\{ e, \mu, \tau \sim 10.8\% \}$
  - hadrons $\sim 67.6\%$

**Top Pair Branching Fractions**

- **all jets**: 6 jets, 1 or 2 btag jets, Neural Network
- **lepton+jets**: 1 lepton, 3 jets, MET cut, 1 or 2 btag jets, kinematic likelihood
- **tau+jet**: 1 hadronic tau, 4 jets, MET cut, 2 btag jets
- **Dilepton**: 2 isolated leptons, 2 jets, MET, topological selection
- **tau+lepton**: 1 isolated lepton, 1 hadronic tau, 2 jets, MET, $\geq 1$ btag jet
$\sigma_{tt\bar{t}bar}$ in lepton + jets

- 1 isolated lepton ($e^\pm$ or $\mu^\pm$), with $p_T > 20$ GeV
- $\geq 3$ jets with $p_T > 20$ GeV, leading jet $p_T > 40$ GeV
- MET $> 20$ (for e+jets) or 25 GeV (for $\mu$ jets)
- $\Delta\phi(l^\pm,\text{MET})$ cut

- **b tagging analysis:**
  - the cross section is extracted by a maximum likelihood fit to the number of events in the 8 channels (e or $\mu$, 3 or 4 jets, 1 or 2 btag jets).
  \[ \sigma_{tt\bar{t}} = 8.05 \pm 0.54(\text{stat}) \pm 0.70(\text{syst}) \pm 0.49(\text{lumi}) \text{ pb} \]

- **kinematic likelihood discriminant analysis:**
  - a maximum likelihood fit to the likelihood discriminant distributions based on topological variables is performed in the 4 channels simultaneously (e or $\mu$, 3 or 4 jets)
  \[ \sigma_{tt\bar{t}} = 6.62 \pm 0.78(\text{stat}) \pm 0.36(\text{syst}) \pm 0.40(\text{lumi}) \text{ pb} \]

- **Combined results:**
  \[ \sigma_{tt\bar{t}} = 7.42 \pm 0.53(\text{stat}) \pm 0.46(\text{syst}) \pm 0.45(\text{lumi}) \text{ pb} \]
Dilepton and tau+lepton channels

**Dilepton:**
- ee, eµ, µµ

**tau+lepton:**
- eτ, µτ

- 2 opposite charged isolated leptons
- dilepton invariant mass
- MET cut, Δφ(µ,MET) cut
- Hₜ, sphericity, ...

- 1 isolated lepton
- 1 hadronic tau, opposite charge
- MET>15 GeV, Δφ(l,MET) cut
- ≥ 1 b-tagged jet

- hadronic taus are identified with neural networks, 1 for each tau type, based on isolation, shower shape and Cal-track correlations variables

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Type 1 τ

Type 2 τ

Type 3 τ

06/06/2009
### Dilepton and tau+lepton channels results

<table>
<thead>
<tr>
<th>Channel</th>
<th>ee</th>
<th>$e\mu$ (1 jet)</th>
<th>$e\mu$ ($\geq$ 2 jets)</th>
<th>$\mu\mu$</th>
<th>$e\tau$</th>
<th>$\mu\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity (pb$^{-1}$)</td>
<td>1074</td>
<td>1070</td>
<td>1070</td>
<td>1009</td>
<td>1038</td>
<td>996</td>
</tr>
<tr>
<td>$Z/\gamma^*$</td>
<td>$2.4^{+0.6}_{-0.5}$</td>
<td>$5.5^{+0.7}_{-0.8}$</td>
<td>$5.4^{+0.9}_{-1.0}$</td>
<td>$5.6^{+1.0}_{-1.2}$</td>
<td>$0.6^{+0.1}_{-0.1}$</td>
<td>$1.2^{+0.3}_{-0.2}$</td>
</tr>
<tr>
<td>$WW/WZ/ZZ$</td>
<td>$0.5^{+0.1}_{-0.1}$</td>
<td>$3.1^{+0.7}_{-0.7}$</td>
<td>$1.4^{+0.4}_{-0.4}$</td>
<td>$0.6^{+0.1}_{-0.1}$</td>
<td>$0.2^{+0.0}_{-0.0}$</td>
<td>$0.2^{+0.0}_{-0.0}$</td>
</tr>
<tr>
<td>Multijet/W+jets</td>
<td>$0.6^{+0.4}_{-0.4}$</td>
<td>$0.9^{+0.3}_{-0.2}$</td>
<td>$2.6^{+0.6}_{-0.5}$</td>
<td>$0.2^{+0.2}_{-0.2}$</td>
<td>$3.6^{+1.8}_{-1.8}$</td>
<td>$8.8^{+2.8}_{-2.8}$</td>
</tr>
<tr>
<td>Total background</td>
<td>$3.4^{+0.7}_{-0.6}$</td>
<td>$9.5^{+1.0}_{-1.1}$</td>
<td>$9.4^{+1.2}_{-1.2}$</td>
<td>$6.4^{+1.9}_{-1.1}$</td>
<td>$4.4^{+1.8}_{-1.8}$</td>
<td>$10.2^{+2.9}_{-2.9}$</td>
</tr>
<tr>
<td>Signal efficiency (%)</td>
<td>$1.3^{+0.1}_{-0.1}$</td>
<td>$1.0^{+0.0}_{-0.0}$</td>
<td>$3.9^{+0.0}_{-0.0}$</td>
<td>$1.1^{+0.0}_{-0.0}$</td>
<td>$0.23^{+0.1}_{-0.1}$</td>
<td>$0.28^{+0.1}_{-0.1}$</td>
</tr>
<tr>
<td>Expected signal</td>
<td>$11.2^{+0.8}_{-0.8}$</td>
<td>$8.6^{+1.1}_{-1.1}$</td>
<td>$35.2^{+2.6}_{-2.7}$</td>
<td>$8.8^{+0.8}_{-0.8}$</td>
<td>$10.3^{+1.1}_{-1.1}$</td>
<td>$12.2^{+1.1}_{-1.1}$</td>
</tr>
<tr>
<td>Total expected</td>
<td>$14.6^{+1.0}_{-1.0}$</td>
<td>$18.0^{+1.4}_{-1.6}$</td>
<td>$44.6^{+3.4}_{-3.6}$</td>
<td>$15.1^{+1.5}_{-1.6}$</td>
<td>$14.7^{+2.0}_{-2.0}$</td>
<td>$22.3^{+3.1}_{-3.1}$</td>
</tr>
<tr>
<td>Data</td>
<td>17</td>
<td>21</td>
<td>39</td>
<td>12</td>
<td>16</td>
<td>20</td>
</tr>
</tbody>
</table>

- **All dilepton channels (1.0 fb$^{-1}$):**
  - $m_t=170$ GeV: $\sigma_{t\bar{t}} = 7.1^{+1.0}_{-0.9} (\text{stat})^{+0.8}_{-0.6} (\text{syst})^{+0.6}_{-0.5} (\text{lumi})$ pb
  - $m_t=175$ GeV: $\sigma_{t\bar{t}} = 7.5^{+1.0}_{-1.0} (\text{stat})^{+0.7}_{-0.6} (\text{syst})^{+0.6}_{-0.5} (\text{lumi})$ pb

- **Tau+lepton (2.2 fb$^{-1}$, $m_t=175$ GeV):**
  \[ \sigma(t\bar{t}) = 7.32^{+1.34}_{-1.24} (\text{stat})^{+1.20}_{-1.06} (\text{syst}) \pm 0.45 (\text{lumi}) \text{ pb} \]
Simultaneous fit of all these channels (they are constructed to be orthogonal) via a joint likelihood where systematic uncertainties are included through “nuisance” parameters.

Summary of uncertainties on the combined cross section:

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta \sigma_{t\bar{t}}$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>+0.47 -0.46</td>
</tr>
<tr>
<td>Lepton identification</td>
<td>+0.15 -0.14</td>
</tr>
<tr>
<td>Tau identification</td>
<td>+0.02 -0.02</td>
</tr>
<tr>
<td>Jet identification</td>
<td>+0.11 -0.11</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>+0.19 -0.16</td>
</tr>
<tr>
<td>Tau energy scale</td>
<td>+0.02 -0.02</td>
</tr>
<tr>
<td>Trigger modeling</td>
<td>+0.11 -0.07</td>
</tr>
<tr>
<td>$b$ jet identification</td>
<td>+0.34 -0.32</td>
</tr>
<tr>
<td>Signal modeling</td>
<td>+0.17 -0.15</td>
</tr>
<tr>
<td>Background estimation</td>
<td>+0.14 -0.14</td>
</tr>
<tr>
<td>Multi-jet background</td>
<td>+0.12 -0.12</td>
</tr>
<tr>
<td>Luminosity</td>
<td>+0.56 -0.48</td>
</tr>
<tr>
<td>Other</td>
<td>+0.15 -0.14</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>+0.78 -0.69</td>
</tr>
</tbody>
</table>

$\sigma_{t\bar{t}} = 8.18 \text{ pb}$

$m_t = 170$ GeV

Submitted to PRD arXiv:0903.5525v1 [hep-ex]
Cross section measurement results overview

DØ Run II * = preliminary May 2009

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Cross Section [pb]</th>
<th>Error</th>
<th>( \Delta \sigma / \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l^+ \text{jets}, , \text{dilepton}, \tau^+ \text{lepton} ) (PRD)</td>
<td>7.84 \pm 0.45 \pm 0.46 \pm 0.54 \pm 0.56</td>
<td>( \pm 13% )</td>
<td></td>
</tr>
<tr>
<td>( l^+ \text{jets} ) (b-tagged &amp; topological, PRL)</td>
<td>7.42 \pm 0.53 \pm 0.46 \pm 0.45</td>
<td>( \pm 13% )</td>
<td></td>
</tr>
<tr>
<td>( l^+ \text{jets} ) (neural network b-tagged, PRL)</td>
<td>8.20 \pm 0.52 \pm 0.77 \pm 0.53 \pm 0.67</td>
<td>( \pm 13% )</td>
<td></td>
</tr>
<tr>
<td>\text{dilepton} (topological, PLB)</td>
<td>6.98 \pm 0.33 \pm 0.59 \pm 0.70 \pm 0.51</td>
<td>( \pm 20% )</td>
<td></td>
</tr>
<tr>
<td>( l^+ \text{track} ) (b-tagged) *</td>
<td>5.0 \pm 0.36 \pm 0.37 \pm 0.38</td>
<td>( \pm 30% )</td>
<td></td>
</tr>
<tr>
<td>( \text{tau+lepton} ) (b-tagged) *</td>
<td>7.32 \pm 1.34 \pm 1.20 \pm 0.45</td>
<td>( \pm 13% )</td>
<td></td>
</tr>
<tr>
<td>( \text{tau+jets} ) (b-tagged) *</td>
<td>5.1 \pm 4.3 \pm 0.7 \pm 0.3</td>
<td>( \pm 13% )</td>
<td></td>
</tr>
<tr>
<td>( \text{alljets} ) (b-tagged, PRD)</td>
<td>4.5 \pm 2.0 \pm 1.4 \pm 0.3</td>
<td>( \pm 13% )</td>
<td></td>
</tr>
</tbody>
</table>

\( m_{\text{top}} = 175 \text{ GeV} \)

CTEQ6.6M

M. Cacciari et al., JHEP 0809, 127 (2008)
S. Moch and P. Uwer, PRD 78, 034003 (2008)
Complementary measurement to the direct top mass measurement (not the same systematic uncertainties).

- Theory likelihood is defined according to PDF and scales uncertainties from:
  2. M. Cacciari et al., JHEP 09, 127 (2008);
  3. S. Moch and P. Uwer, Phys. Rev. D 78, 034003 (2008);

- Measurement likelihood is constructed with Gauss(σ,δσ)
- Theory and measurement likelihoods are multiplied to obtain a joint likelihood. We integrate over the cross section to get a likelihood function that depends only of the top quark pole mass and we compute 68% C.L.

### Theoretical prediction | $m_t$ (GeV)
---|---
NLO [1] | $165.5^{+6.1}_{-5.9}$
NLO+NLL [2] | $167.5^{+5.8}_{-5.6}$
approximate NNLO [3] | $169.1^{+5.9}_{-5.2}$
approximate NNLO [4] | $168.2^{+5.9}_{-5.4}$

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DØ, L = 1 fb⁻¹
Cross section ratio

- New decay modes can change measured $\sigma_{tt\bar{t}}$ depending on decay mode
- Ratio cancels many systematic uncertainties
- $\Rightarrow$ Sensitive to BSM physics
- Cross section ratio are computed by generating pseudo-datasets by varying the number of signal and background events around the expected number according to Poisson probabilities

$$R_{\sigma}^{\ell\ell/\ell j} = \frac{\sigma_{\ell\ell}^{\ell\ell}}{\sigma_{\ell\ell}^{\ell+\text{jets}}} = 0.86^{+0.19}_{-0.17}$$

$$R_{\sigma}^{\tau\ell/\ell\ell-jj} = \frac{\sigma_{\tau\ell}^{\tau\ell}}{\sigma_{\tau\ell}^{\ell+\text{jets}+\ell\ell}} = 0.97^{+0.32}_{-0.29}$$

consistent with the SM expectation of $R_{\sigma} = 1$
In SUSY, if $m(H^\pm)<m(\text{top})$
- tauonic model: $\text{BR}(H^\pm \rightarrow \tau^\pm \nu)=1$
- leptophobic model: $\text{BR}(H^\pm \rightarrow cs)=1$

We used the ratio measurements to set limits on the BR using the frequentist approach of Feldman and Cousins.
Charged Higgs: limits on BR(t$\rightarrow$H$^\pm$b)

- In SUSY, if m(H$^\pm$)<m(top)
  - tauonic model: BR(H$^\pm$$\rightarrow$$\tau^\pm$$\nu$)=1
  - leptophobic model: BR(H$^\pm$$\rightarrow$c$s$)=1

- We used the ratio measurements to set limits on the BR using the frequentist approach of Feldman and Cousins.

- Upper limits on the branching fractions BR(t$\rightarrow$H$^\pm$ b $\rightarrow$ $\tau^\pm$ $\nu$ b) < 15% and BR(t$\rightarrow$ H$^\pm$ b $\rightarrow$ c$s$ b)) < 50% for a 120 GeV charged-Higgs.
Exclusion limits have been computed from the 1 fb\(^{-1}\) cross section analyses. Results interpreted at LO assuming leptophobic/tauonic decay dominates in small/large tan\(\beta\) regions:
Conclusions

- Cross section measurement have been performed in many different channels to test SM predictions and search for new physics signals.
- Top mass has been extracted to the cross section measurements
- The ratio of cross sections are in agreement with SM predictions and limits on top to charged Higgs branching ratio has been set up.

NO EVIDENCE OF NEW PHYSICS IN THE 1.0/2.2 fb⁻¹ D0 TOP QUARK SAMPLES

- A lot more statistics is available. Stay tuned to updates and new measurements!