Measurement of the $t\bar{t}$ Production Cross Section and Spin Correlation in the Dileptonic Decay Channel

Jens Konrath for the DØ Collaboration

Outline

- Top production & decay
- Event selection
- Instrumental & SM Backgrounds
- Cross section measurements
- Kinematic reconstruction of dilepton events
- Spin correlation
At the Tevatron, top quarks are produced mainly in pairs via the strong interaction: 85% $q\bar{q}$, 15% $gg$ at LO and $\sqrt{s} = 1.96$ TeV.

- Decay channels defined by W decays
- Branching ratios ($\tau$ only included as $\tau \rightarrow e, \mu$)
  - All-hadronic: 44%
  - Lepton+Jets: 34%
  - Dilepton: 1% $ee$ and $\mu\mu$, 2% $e\mu$

- Dilepton final state: 2 leptons, 2 jets and $E_T$
- Small BR, but small standard model backgrounds

Top Pair Decay Channels
Top Production Cross-section

- Important test of QCD at high $p_T$
  - Test QCD NLO prediction
  - Higher x-section if resonant top production or non-SM production
- Measurements of different decay channels
  - Exotic top decays modify contributions to different channels
- Measurements with different methods
  - Kinematic analyses vs. B-tagging analyses show discrepancies if $t\rightarrow Wb$ is different from SM
- Sample verification for properties measurements
Event Selection

\[ \geq 2 \text{ jets, } p_T > 20 \text{ GeV} \]
\[ E_T > 35 \text{ GeV} \]
\[ \geq 2 \text{ jets, } p_T > 20 \text{ GeV} \]

isolated leptons passing quality cuts, \( p_T > 15 \text{ GeV} \)

isolated lepton passing quality cuts, \( p_T > 15 \text{ GeV} \)
Background Processes

- **ee channel:**
  - $Z \rightarrow ee + \geq 2$jets + $\mathbb{E}_T$, (WW, WZ, ZZ)$\rightarrow$ee + $\geq 2$jets + $\mathbb{E}_T$
  - Veto events with $M_{ee} \leq 15$ GeV and $80$ GeV < $M_{ee}$ < $100$ GeV
  - Cut on $\mathbb{E}_T$ depending on $M_{ee}$

- **e$\mu$ channel:**
  - $Z \rightarrow \tau\tau + \geq 2$jets $\rightarrow$e$\mu$ + $\geq 2$jets + $\mathbb{E}_T$, (WW,WZ)$\rightarrow$e$\mu$ + $\geq 2$jets + $\mathbb{E}_T$
  - Cut on $H_T = p_T$(leading lepton) + $p_T$(2 leading jets)

- **$\mu$\$\mu$ channel:**
  - $Z \rightarrow \mu\mu + \geq 2$jets + $\mathbb{E}_T$, (WW, WZ, ZZ)$\rightarrow$\mu$\mu$ + $\geq 2$jets + $\mathbb{E}_T$
  - $\chi^2$ test of $Z \rightarrow \mu\mu$ hypothesis
  - Contour cut in the $\mathbb{E}_T$ vs. $\Delta\phi$(leading $\mu$, $\mathbb{E}_T$) plane
Instrumental Backgrounds

- **Fake electron background (ee, e\(\mu\))**: Jet misidentified as an electron, or a non-isolated electron (b-decay)
  Estimation of background: Fit to electron likelihood

- **Fake muon background (e\(\mu\), \(\mu\mu\))**: Non-isolated muon misidentified as being isolated
  Background estimated from data

- **Fake \(E_T\) background (ee)**: 
  \(Z/\gamma^* + \text{jets events do not produce real } E_T \text{ (no } \nu\); fake \(E_T\) can appear due to instrumental effects
  Estimated from \(\gamma + \text{jets sample} (E_T \text{ fake rate}) \text{ and } Z/\gamma^* \rightarrow \text{ee selection in low } E_T \text{ region (reversed } E_T \text{ cut)}

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Event Yields

- Signal expectation for $\sigma_{tt} = 7$ pb
- Signal efficiency for $m_{\text{Top}} = 175$ GeV

<table>
<thead>
<tr>
<th>Category</th>
<th>ee</th>
<th>$\mu\mu$</th>
<th>$e\mu$ ($\geq 2$ jets)</th>
<th>$e\mu$ (1 jet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>integrated luminosity (pb$^{-1}$)</td>
<td>1036</td>
<td>1046</td>
<td>1046</td>
<td>1046</td>
</tr>
<tr>
<td>$Z/\gamma^*$</td>
<td>$2.4^{+0.4}_{-0.4}$</td>
<td>$2.7^{+0.4}_{-0.4}$</td>
<td>$3.6^{+0.7}_{-0.8}$</td>
<td>$5.5^{+0.8}_{-0.8}$</td>
</tr>
<tr>
<td>$WW/WZ$ and other MC</td>
<td>$0.4^{+0.2}_{-0.2}$</td>
<td>$0.5^{+0.1}_{-0.1}$</td>
<td>$1.4^{+0.6}_{-0.6}$</td>
<td>$3.4^{+1.4}_{-1.4}$</td>
</tr>
<tr>
<td>Instrumental background</td>
<td>$0.2^{+0.2}_{-0.1}$</td>
<td>$0.4^{+0.2}_{-0.2}$</td>
<td>$1.8^{+0.6}_{-0.6}$</td>
<td>$1.2^{+0.4}_{-0.4}$</td>
</tr>
<tr>
<td><strong>Total background</strong></td>
<td>$3.0^{+0.5}_{-0.5}$</td>
<td>$3.6^{+0.5}_{-0.5}$</td>
<td>$6.7^{+1.2}_{-1.2}$</td>
<td>$10.2^{+1.8}_{-1.7}$</td>
</tr>
<tr>
<td>Signal efficiency (%)</td>
<td>$8.3^{+1.2}_{-1.2}$</td>
<td>$5.1^{+0.4}_{-0.4}$</td>
<td>$12.4^{+0.9}_{-1.0}$</td>
<td>$3.1^{+0.3}_{-0.3}$</td>
</tr>
<tr>
<td>Expected signal</td>
<td>$9.5^{+1.4}_{-1.4}$</td>
<td>$5.8^{+0.5}_{-0.5}$</td>
<td>$28.6^{+2.1}_{-2.4}$</td>
<td>$7.1^{+0.6}_{-0.7}$</td>
</tr>
<tr>
<td>Total Sig. + Bkg.</td>
<td>$12.5^{+1.5}_{-1.5}$</td>
<td>$9.4^{+0.7}_{-0.7}$</td>
<td>$35.3^{+2.8}_{-3.2}$</td>
<td>$17.2^{+2.0}_{-2.1}$</td>
</tr>
<tr>
<td>Selected events</td>
<td>16</td>
<td>9</td>
<td>32</td>
<td>16</td>
</tr>
</tbody>
</table>

$$
\sigma(p \bar{p} \rightarrow t \bar{t}) = \frac{N_{\text{observed}} - N_{\text{background}}}{A_{\text{tot}} \int L dt}
$$
Cross Section Results

\[ ee : \quad \sigma_{\bar{t}t} = 9.6^{+3.2}_{-2.7} (\text{stat})^{+1.9}_{-1.6} (\text{syst}) \pm 0.6 (\text{lumi}) \text{ pb} \]

\[ e\mu : \quad \sigma_{\bar{t}t} = 6.1^{+1.4}_{-1.2} (\text{stat})^{+0.8}_{-0.7} (\text{syst}) \pm 0.4 (\text{lumi}) \text{ pb} \]

\[ \mu\mu : \quad \sigma_{\bar{t}t} = 6.5^{+4.0}_{-3.2} (\text{stat})^{+1.1}_{-0.9} (\text{syst}) \pm 0.4 (\text{lumi}) \text{ pb} \]

\[ \text{dilepton} : \quad \sigma_{\bar{t}t} = 6.8^{+1.2}_{-1.1} (\text{stat})^{+0.9}_{-0.8} (\text{syst}) \pm 0.4 (\text{lumi}) \text{ pb} \]
After Final Selection Cuts
Systematic Uncertainties

- Jet energy scale, MC normalization and lepton identification give largest contribution

<table>
<thead>
<tr>
<th>Systematic Uncertainty Source (pb)</th>
<th>$\ell\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy calibration</td>
<td>$+0.3-0.3$</td>
</tr>
<tr>
<td>Jet identification</td>
<td>$+0.1-0.1$</td>
</tr>
<tr>
<td>Primary vertex identification</td>
<td>$+0.3-0.2$</td>
</tr>
<tr>
<td>Muon identification</td>
<td>$+0.2-0.2$</td>
</tr>
<tr>
<td>Electron identification</td>
<td>$+0.6-0.5$</td>
</tr>
<tr>
<td>Trigger</td>
<td>$+0.2-0.2$</td>
</tr>
<tr>
<td>Fake background</td>
<td>$+0.2-0.2$</td>
</tr>
<tr>
<td><strong>MC normalization</strong></td>
<td>$+0.3-0.3$</td>
</tr>
<tr>
<td>Other</td>
<td>$+0.2-0.2$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$+0.9-0.8$</td>
</tr>
</tbody>
</table>
Spin Correlation

- Top has a very short lifetime: $\tau \approx 10^{-25}$ s $\Rightarrow$ decay before hadronisation
- Top spin is not diluted by hadronisation but passed on to decay products

- Allows to test top production and decay:

$$\frac{1}{\sigma} \frac{d^2 \sigma}{d (\cos \theta_i) d (\cos \theta_\perp)} = \frac{1 + \kappa \cos \theta_i \cos \theta_\perp}{4}$$

- $\kappa$ is 0.806 at NLO for the Tevatron using the beamline as quantisation axis

Asymmetry

$$\kappa = \frac{1}{4 \sigma} \left( \int_0^1 \frac{d \sigma}{d (\cos \theta_i \cos \theta_\perp)} d (\cos \theta_i \cos \theta_\perp) - \int_{-1}^0 \frac{d \sigma}{d (\cos \theta_i \cos \theta_\perp)} d (\cos \theta_i \cos \theta_\perp) \right)$$
Kinematic Reconstruction of Dilepton Events

- Neutrino four-vectors are unknown ⇒ underconstrained system of equations
- Zero, two or four solutions per event
- Twofold ambiguity: $b$ (anti-)quark $\Leftrightarrow$ jet assignment
Estimating the Sensitivity

\[ Sensitivity = 4 \frac{\text{Asymmetry}(\kappa = 1) - \text{Asymmetry}(\kappa = 0)}{\sigma_{\text{Asymmetry}}(\kappa = 0)} \]

\( \kappa = 1 \)  
A = 0.05  
\( \kappa = 0 \)  
A = -0.04  
RMS = 0.37

Sensitivity = 0.26

Expected 1\( \sigma \) stat. Error: 1/Sensitivity / \( \sqrt{N} \)

50 dilepton Events: \( \delta \kappa = 0.55 \)
Summary & Outlook

- Dilepton cross sections have been measured with the full Run Ila dataset
  \[ \sigma_{t\bar{t}} = 6.8^{+1.2}_{-1.1} \text{ (stat)} ^{+0.9}_{-0.8} \text{ (syst)} \pm 0.4 \text{ (lumi)} \text{ pb} \]

- The dilepton event selections are ready for top properties analyses
- Finalize cross section analyses for publication
- Improve kinematic reconstruction & measure spin correlation
Backup Slides
Dimuon Selection

- Contour cut: $E_T$ vs. $\Delta \phi$ (leading $E_T$)
  - 2 neutrinos $\Rightarrow$ a first cut is set: $E_T > 35$ GeV
  - To prevent from misreconstructed muon momenta: $\Delta \phi$ (leading $E_T$) $< 175^\circ$
  - To further reduce background, $E_T$ cut is increased for $\Delta \phi$ (leading $E_T$) close to $0^\circ$ or $180^\circ$
Z Rejection

- Z\(\rightarrow\)ll is the main background in the dileptonic decay channels
- Cut on \(M_{ee}\) to reject \(Z\rightarrow\) ee
- \(\chi^2\) test of \(Z\rightarrow\mu\mu\) hypothesis performs better than dimuon invariant mass cut
Object Selection

- **Leptons:**
  - Loose electrons: Track matched calorimeter cluster with shower shape & isolation cuts, $p_T > 15$ GeV, $|\eta|<1.1$ or $1.4<|\eta|<3.6$.
  - Tight electrons: additional likelihood cut
  - Muons: Cosmic veto, central track match, isolation cuts, $p_T > 15$ GeV, $|\eta|<2.0$

- **Primary Vertex:** $|z_{PV}|<60$ cm, $n_{Tracks} \geq 3$, $\Delta z(PV, \text{lepton}) < 1$ cm

- **Jets:** Apply JES, standard jet ID, no overlap with EM clusters

- **$E_T$:** Propagate JES corrections and muon $p_T$ to $E_T$
Dielectron Selection

- Luminosity: 1.07 fb$^{-1}$
- Analysis cuts:
  - 2 tight electrons
  - $\geq$ 2 jets
  - $E_T$ depends on $M_{ee}$: $E_T > 40$ GeV for $15 \text{ GeV} < M_{ee} < 80 \text{ GeV}$ and $E_T > 35$ GeV for $M_{ee} > 100 \text{ GeV}$
  - Sphericity $> 0.15$
- Trigger: ORing of all dielectron triggers; Signal efficiency $\approx 94\%$
Electron-Muon Selection

- Luminosity: $1.04 \text{ fb}^{-1}$
- Analysis cuts:
  - Exactly one loose electron
  - $\geq 1$ medium muon
  - No common track between the electron and any loose track matched muons
  - $\geq 2$ jets
  - $\Delta R(\text{selected } e, \text{ jet}) > 0.5$ and $\Delta R(\text{selected } \mu, \text{ jet}) > 0.5$
  - $H_T = p_T(\text{leading lepton}) + p_T(2 \text{ leading jets}) > 115$
- Trigger: Oring of e triggers + matching online/offline objects; Signal Efficiency $\approx 86\%$
Dimuon Selection

- Luminosity: 1.05 fb$^{-1}$
- Analysis cuts:
  - Veto any top_loose electron
  - $\geq 2$ tight isolated muons
  - $\geq 2$ jets
  - $M_{\mu\mu} > 30$ GeV
  - Contour cut in the $E_T - \Delta \phi$ (leading $E_T$) plane
  - $Z$ fitter $\chi^2 > 8$
- Trigger: Oring of all single muon triggers & matching reco / trigger objects (tracks, muons); Signal efficiency $\approx 88\%$
After All Cuts: Jet & Myon $p_T$

$p_T$ of leading jet

$p_T$ of second jet

$p_T$ of leading muon

$p_T$ of second muon
After All Cuts: $E_T$, Invariant Mass, $Z$ fit $\chi^2$, $\Delta\phi$(leading $\mu$, $E_T$)