Top Quark Mass Measurement with a Matrix-Element Method in the Dilepton Channel

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On Behalf of the CDF Collaboration

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Tevatron and CDF detector

- **Tevatron**
  - Peak luminosity $>2.8 \times 10^{32}$ cm$^{-2}$s$^{-1}$
  - 2.5 fb$^{-1}$ delivered to experiments

- **CDF Detector - General purpose detector**
  - Precision tracking (Silicon + COT)
  - EM and Hadronic calorimeters
  - Muon detectors (extended for Run II)

- **>2.0 fb$^{-1}$ recorded at CDF**
  - Measurement shown uses 1 fb$^{-1}$ (up to March 2006)
Top quark decay: the dilepton channel

- Top quarks are primarily pair produced at Tevatron
  - Decay channel is defined by $W$ decay modes
- Both $W$s decay leptonically in $\sim 5\%$ of all decays
  - 2 leptons ($e$ or $\mu$), 2 jets (from $b$-quarks), large missing $E_T$ from $\nu$s

**Advantages**
- Clean: little background without need for $b$-tagging
- Least jets of any channel (less reliant on JES, less ambiguity in jets)

**Disadvantages**
- Low statistics
- 2 vs escape undetected—underconstrained system

**Backgrounds**
- Drell-Yan + jets (DY)
- Diboson + jets
- Mis-ID leptons ("fakes")
Measuring $M_{\text{top}}$ in the dilepton channel

**Important measurement**
- Contributes to overall knowledge of top mass
- Verify that we are measuring SM top
- If results across channels inconsistent, new physics might be in sample

**Difficult channel to work in**
- Low statistics
- Two neutrinos escape undetected
- Only one missing transverse energy measurement
  - Kinematically under-constrained
- Forced to make assumptions and integrate
- No hadronic $W$ to make in situ JES measurement

Tevatron Run I Top Mass

<table>
<thead>
<tr>
<th>Channel</th>
<th>Mass (GeV/c²)</th>
<th>Error (GeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF Dilepton</td>
<td>167.4 ± 10.3</td>
<td>± 4.8</td>
</tr>
<tr>
<td>D0 Dilepton</td>
<td>168.4 ± 12.3</td>
<td>± 3.6</td>
</tr>
<tr>
<td><strong>Run 1 World Average</strong></td>
<td><strong>178.0 ± 2.7</strong></td>
<td>± 3.3</td>
</tr>
</tbody>
</table>

(CDF+D0 Run I Average)
• Use differential cross-section to calculate probability of event coming from $M_{\text{top}}$

\[
\frac{1}{\sigma(M_t)} \frac{d\sigma(M_t)}{dx}
\]

• Formulate differential cross-section using LO matrix element and transfer functions

\[
\frac{d\sigma(M_t)}{dx} = \int d\Phi |\mathcal{M}_{tt}(p_i; M_t)|^2 \prod W(p_i, x) f_{PDF}(q_1) f_{PDF}(q_2)
\]

• Transfer functions link measured quantities $x$ to parton-level ones, $p_i$
  - Jet energy-parton energy
  - $t\bar{t} p_T$ - measured recoil

• Perform integrals over unknown quantities (8)

• Simplifying assumptions made for tractability
  - e.g. lepton momenta and jet angles perfectly measured

• Use similar differential cross-sections for background processes
  - Final probability becomes weighted sum of signal and background probabilities

\[
P(x|M_t) = P_s(x|M_t)p_s + P_{bg1}(x)p_{bg1} + P_{bg2}(x)p_{bg2} + \cdots
\]

Integrals still take 2-3 hours per event!
Dataset used

- 1 fb\(^{-1}\) of data collected up to March 2006 at CDF
- Basic selection: 2 high-\(p_T\) (>20 GeV/c) leptons, 2 high-\(E_T\) (>15 GeV) jets, large \(E_T\) (>25 GeV)
- Additional cuts to help reduce background
  - Elevate \(E_T\) requirement when \(m_\ell\) is close to \(Z\) mass
  - Require scalar sum of energies in event, \(H_T>200\) GeV

<table>
<thead>
<tr>
<th>Source</th>
<th>(N_{evs})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t\bar{t}) ((M_t=175\ \text{GeV}/c^2, \sigma=6.7\text{pb}))</td>
<td>50.2</td>
</tr>
<tr>
<td>(Z\rightarrow\ell\ell) ((\ell=\mu\mu, e\mu))</td>
<td>10.9</td>
</tr>
<tr>
<td>Fakes</td>
<td>8.7</td>
</tr>
<tr>
<td>(W/WZ)</td>
<td>5.1</td>
</tr>
<tr>
<td>(Z\rightarrow\tau\tau)</td>
<td>2.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>77.1</strong></td>
</tr>
<tr>
<td><strong>Observed</strong> ((1.0\ \text{fb}^{-1}))</td>
<td><strong>78</strong></td>
</tr>
</tbody>
</table>
Uncertainties

Statistical Uncertainty

• Expected for $M_{\text{top}} = 175 \text{ GeV/c}^2$, $\sigma = 5.0 \text{ GeV/c}^2$
• Expected for $M_{\text{top}} = 165 \text{ GeV/c}^2$, $\sigma = 4.2 \text{ GeV/c}^2$

Systematic Uncertainty

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta M_{\text{top}}$ (GeV/c$^2$)</th>
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<tbody>
<tr>
<td>Jet Energy Scale</td>
<td>3.5</td>
</tr>
<tr>
<td>Generator</td>
<td>0.9</td>
</tr>
<tr>
<td>Method</td>
<td>0.6</td>
</tr>
<tr>
<td>Sample Composition</td>
<td>0.7</td>
</tr>
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<td>Background Statistics</td>
<td>0.7</td>
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<td>Background Modeling</td>
<td>0.2</td>
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<tr>
<td>FSR</td>
<td>0.3</td>
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<td>PDFs</td>
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- Working on using $Z \rightarrow bb$ to improve
- Driven by small sample of (data-based) "fake" lepton events

- Improves with better methods and/or more data
- Improves with more CPU
\[ M_{\text{top}} = 164.5 \pm 3.9 \text{(stat.)} \pm 3.9 \text{(syst.)} \text{GeV/c}^2 \]

- Single most precise dilepton top mass measurement to-date
- With no improvements to method, projected stat. error with 4 fb\(^{-1}\) is 2.5 GeV/c\(^2\)
- Published in PRD 75, 031105(R)
- Previously (340 pb\(^{-1}\)) PRL 96, 152002, PRD 74 032009 (with more detail)
Cross-Checks

Lepton Flavor

CDF II Preliminary (1.0 fb⁻¹)

- **e-μ** (37 events) 164.6 ± 5.3
- **μ-μ** (26 events) 164.5 ± 7.0
- **e-e** (15 events) 162.0 ± 12.9
- **All** (78 events) 164.5 ± 3.9

- Measure mass separately for ee, eμ and μμ events
- Results consistent
Cross-Checks

Lepton Flavor

CDF II Preliminary (1.0 fb⁻¹) (stat. error only)

- e-µ (37 events) 164.6 ± 5.3
- µ-µ (26 events) 164.5 ± 7.0
- e-e (15 events) 162.0 ± 12.9
- All (78 events) 164.5 ± 3.9

Top mass (GeV/c²)

- Measure mass separately for ee, eµ and µµ events
- Results consistent

B-tagging

- Use secondary vertex tagging
  - Increases S:B to ~15:1
  - Retains ~60% of signal events
- See if measurement consistent with full sample
Cross-Checks

Lepton Flavor

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\[ M_{\text{top}} = 167.3 \pm 4.6 \text{(stat.)} \pm 3.8 \text{(syst.) GeV/c}^2 \]
Impact and outlook

- Measurement is included in world average
  - Carries ~5% weight
- Starts to get limited by systematic uncertainty
  - Cannot use in situ measurement of JES
    - Can use $Z \rightarrow b\bar{b}$ to measure $b$-jet specific JES
  - Studying genetically evolving neural net selection
  - Studying further optimization of integration

![Graph of Top Quark Mass](image)

**Best Tevatron Run II (preliminary, March 2007)**

- All-Jets: CDF ($943 \text{ pb}^{-1}$) $171.1 \pm 4.3$
- Dilepton: CDF ($1030 \text{ pb}^{-1}$) $164.5 \pm 5.6$
- Dilepton: D0 ($1000 \text{ pb}^{-1}$) $172.5 \pm 8.0$
- Lepton+Jets: CDF ($940 \text{ pb}^{-1}$) $170.9 \pm 2.5$
- Lepton+Jets: D0 ($900 \text{ pb}^{-1}$) $170.5 \pm 2.7$
- Tevatron ($Run \, I/Run \, II, \, March \, 2007$) $170.9 \pm 1.8$

$\chi^2/\text{dof} = 9.2/10$
Conclusion

- Application of Matrix Element technique to the dilepton channel
- Most precise single measurement of $M_{\text{top}}$ in the dilepton channel
  
  $M_{\text{top}} = 164.5 \pm 3.9 \text{(stat.)} \pm 3.9 \text{(syst.) GeV/c}^2$

- Included in current world average
- With no improvements to method, projected stat. error with 4 fb$^{-1}$ is $\sim 2$ GeV/c$^2$
  - Improvements to method in progress