Top Quark Mass in the Dilepton Channel at CDF

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On behalf of the CDF Collaboration

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Outline

• Experimental apparatus: Tevatron and CDF Detector
• The dilepton channel
  • Difficulties of measuring $M_{\text{top}}$ in this channel
• The Matrix Element method
  • Systematic Uncertainties
• Measurement in data
• World average and consistency with lepton+jets
• An additional measurement: b-tagged sample
Tevatron and CDF Detector

- Tevatron
  - In past year, e cooling implemented
  - Helps with anti-proton stacking
  - Peak luminosity \(>1.7 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}\)
  - 1.6 fb\(^{-1}\) delivered to experiments
- CDF Detector - General purpose detector
  - Precision tracking (Silicon + COT)
  - EM and Hadronic calorimeters
    - Endplug new for Run II
    - Muon detectors (extended for Run II)
  - 1.3 fb\(^{-1}\) recorded at CDF
  - Measurement shown uses 750 pb\(^{-1}\) (up to December 2005)
Top Decay: The Dilepton Channel

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

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
- Diboson + jets
- Mis-ID leptons (“fakes”)

![Diagram showing decay processes and backgrounds](image-url)
Measuring $M_{\text{top}}$ in the Dilepton Channel

Important measurement

- 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
The Matrix Element Method

- 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

$$\frac{d\sigma(M_t)}{dx} = \frac{1}{N} \int d\Phi_6 |M_{t\bar{t}}(p_i; M_t)|^2 \prod W(p_i, x) f_{PDF}(q_1) f_{PDF}(q_2)$$

- Transfer functions link measured quantities $x$ to parton-level ones, $p_i$
- Perform integrals over unknown quantities (6)
- Simplifying assumptions made for tractability
- Use similar differential cross-sections for background processes
  - Final probability becomes weighted sum of signal and background probabilities
    $$P(x|M_t) = P_s(x|M_t)p_s + P_{bg1}(x)p_{bg1} + P_{bg2}(x)p_{bg2} + \cdots$$
- First application of method to dilepton channel (340 pb$^{-1}$), published in PRL 96, 152002

Integrals still take 2-3 hours per event!
### Uncertainties

#### Statistical Uncertainty
- Expected for $M_{\text{top}}=175 \text{ GeV}/c^2$, $\sigma = 5.9 \text{ GeV}/c^2$
- Expected for $M_{\text{top}}=165 \text{ GeV}/c^2$, $\sigma = 5.1 \text{ GeV}/c^2$

#### Systematic Uncertainty

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta M_{\text{top}} \text{ (GeV}/c^2)$</th>
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<td>0.5</td>
</tr>
<tr>
<td>Method</td>
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</tr>
<tr>
<td>Sample Composition</td>
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<tr>
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Improves with better methods and/or more data

Improves with more CPU
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Working on using $Z \rightarrow bb$ to improve
**Uncertainties**

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Driven by small sample of (data-based) “fake” lepton events

- Improves with better methods and/or more data
- Improves with more CPU
Dataset Used

- 750 pb$^{-1}$ of data collected up to December 2005 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 $m_\ell\ell$ is close to $Z$ mass
  - Require scalar sum of energies in event, $H_T$>200 GeV

Source

<table>
<thead>
<tr>
<th>Event Type</th>
<th>$N_{evs}$</th>
</tr>
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<tbody>
<tr>
<td>$tt$ ($M_t=175$ GeV/$c^2$, $\sigma=6.7$ pb)</td>
<td>36.1</td>
</tr>
<tr>
<td>$Z\rightarrow e\mu$</td>
<td>7.8</td>
</tr>
<tr>
<td>Fakes</td>
<td>6.3</td>
</tr>
<tr>
<td>$WW/WZ$</td>
<td>3.6</td>
</tr>
<tr>
<td>$Z\rightarrow \tau\tau$</td>
<td>1.6</td>
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<tr>
<td>Total Expected</td>
<td>55.4</td>
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*Observed* (750 pb$^{-1}$) | 64
**Result**

\[ M_{\text{top}} = 164.5 \pm 4.5 \text{(stat.)} \pm 3.1 \text{(syst.) GeV/c}^2 \]

- Uses 64 events in 750 pb\(^{-1}\) of data
- **Most precise single measurement** of \( M_{\text{top}} \) in dilepton channel to-date
- Expected stat error of 5.1 GeV/c\(^2\) for \( M_t = 165 \) GeV/c\(^2\)
World Average and Consistency

- Dilepton measurement included in world average
  \[ M_{\text{top}} = 172.5 \pm 1.3 \text{(stat.)} \pm 1.9 \text{(syst.) GeV/c}^2 \]
- hep-ex/0603039
- 11% weight
- Will contribute more as systematics come to dominate
World Average and Consistency

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  \[ M_{\text{top}} = 172.5 \pm 1.3 \text{(stat.)} \pm 1.9 \text{(syst.) GeV/c}^2 \]
- hep-ex/0603039
- 11% weight
  - Will contribute more as systematics come to dominate
- How consistent is 164.5 with 173.4?
  - Need more data to tell if discrepant
  - Trend is intriguing
- Other ways to probe whether sample has unexpected content?
  - Measure mass in subsample with different purity
B-Tagged Measurement

- Require one or more b-tag in sample
- Removes nearly all background, leaves 60% of signal
- Comparable sensitivity to full sample

\[ M_{\text{top}} = 162.7 \pm 4.6 \text{(stat.)} \pm 3.0 \text{(syst.) GeV/c}^2 \]

- Result consistent with full sample
Conclusion and Outlook

- Application of Matrix Element technique to the dilepton channel
- Most precise single measurement of $M_{\text{top}}$ in the dilepton channel

\[ M_{\text{top}} = 164.5 \pm 4.5 \text{(stat.)} \pm 3.1 \text{(syst.) GeV/c}^2 \]

- Included in current world average (11% weight)
- With no improvements to method, projected stat. error with 4 fb$^{-1}$ is \( \sim 2 \text{ GeV/c}^2 \)
- Improvements to method in progress
Backup Slides
Measuring the Top Mass

1. Template-based

Reconstruct mass for each event

Form “templates” for signal (varying $M_{top}$) and background using simulated events

Perform maximum likelihood fit to extract measured $M_{top}$

Advantages: Takes all (simulated) detector effects into account, (relatively) computationally simple
Disadvantages: Only single number (recon. mass) per event in final Likelihood, all events have equal weight

2. Matrix Element-based

Form per-event probability using matrix element

Integrate over unmeasured quantities

Form ensemble probability and calibrate using simulated events

Advantages: More statistical power, probability curve rather than single mass per event, events weighted naturally
Disadvantages: Complex numerical integration (much CPU) → machinery does not account for all detector effects
Test of Method

- Response (left) is linear, sensitivity is degraded due to presence of unmodeled backgrounds
- Pulls (right), flat as function of top mass, $\sim 1.5$ ($\sim 1.4$ for signal only)
  - Using parton-level information (all assumptions held), pull width $\sim 1.0$
  - As assumptions violated (realistic events) pull widths increase
  - Apply scale factor flat in top mass

\[
\text{Fitted Pull Width} = \frac{M_{\text{meas}} - M_{\text{true}}}{\sigma_{M_{\text{top}}}}
\]
Test of Method

$M_0 = 178.0 \pm 0.2$

$s = 1.00 \pm 0.01$

Response unbiased after correction

Error estimation correct

$Fitted\ \text{Pull Width} = \frac{M_{meas} - M_{true}}{\sigma_{M_{top}}}$
Treating Backgrounds

- Final event probability is weighted sum of signal and background probabilities
  \[ P(x|M_t) = P_s(x|M_t)p_s + P_{bg1}(x)p_{bg1} + P_{bg2}(x)p_{bg2} + \cdots \]

- Weights are determined from expected fractional contribution of each source

- Form differential cross-sections as in signal for each modeled background process
  - Difficult to determined closed-form expression for backgrounds: use ME-based generators instead (e.g. ALPGEN)

- Example: DY+2 jets

- Modeled backgrounds
  - DY+jets
  - WW+jets
  - W+3 jets (for fakes)

- Product of per-event prob. densities give likelihood for sample
Data Events

- Only 31 candidate events from data collected in 2005
- Full data set has 64 events
- Curves are weighted signal+background probabilities
- Signal probability evaluated for $M_t = 130-220$ GeV/c$^2$