Measurement of the Top Quark Mass

Michael Begel
University of Rochester

for the DØ Collaboration

Frontiers in Contemporary Physics
Nashville, Tennessee
May 2005
Top Production

Top quarks are mainly produced in pairs via strong interactions at the Tevatron

- Heaviest known elementary particle
- Decays before it hadronizes
- $m_t > m_W$
- Constrains mass of the Standard Model Higgs

Top mass is a fundamentally interesting quantity
Classifying Top

\( t \rightarrow Wb \) is \( \approx 100\% \)

**\( t \rightarrow Wb \) is \( \approx 100\% \)**

**dilepton:**
- low BR, low BG

**lepton + jet:**
- BR & BG are manageable

Need to reconstruct electrons, muons, jets, \( b \)-jets, and missing transverse energy

at the Tevatron, the top is produced almost at rest and the decay products are much lighter; they have good angular separation in the lab frame and high transverse momentum
Jet Energy Scale

Top mass measurements require clean mapping between reconstructed objects and partons

- Reconstruct jets using iterative cone algorithm with midpoints ($R_{cone} = 0.5$)
- Calibrate jet energies to particle level
- Map jets to partons
- Correct jet energies to parton level
Jet Energy Scale

Top mass measurements require clean mapping between reconstructed objects and partons

- Response of calorimeter to jets is the dominant systematic uncertainty
- Jet energy scale derived from samples of
  - zero and minimum bias events
  - photon + jet events
  - $Z$ + jet events
  - dijet events
  - in data and simulation
Jet Energy Scale

Top mass measurements require clean mapping between reconstructed objects and partons

- Response of calorimeter to jets is the dominant systematic uncertainty

\[ E_{corr} = \frac{E_{meas} - O}{R \times S} \]

Response Correction
Showering Correction
hadronic response
particles in-&-out of cone
uninstrumented regions

Michael Begel
Dilepton Channel

Signature

- Two leptons
- Two neutrinos
- Two $b$ quarks
Dilepton Channel

**Signature**
- Two leptons
- Two neutrinos
- Two $b$ quarks

**Event Selection**
- Two high-$p_T$ leptons
- Missing $E_T$
- Two or more high-$p_T$ jets

**Backgrounds**
- Diboson ($WW, WZ, ZZ$)
- Drell-Yan
- $Z \rightarrow \tau\tau$
- $W +$ jets with fake lepton
### Dilepton Event Selection

**eμ Channel**
- electron $p_T > 15$ GeV, $|y| < 1.1$ or $1.5 < |y| < 2.5$
- muon $p_T > 15$ GeV, $|y| < 2$
- $\Delta R(e, \mu) > 0.25$
- $\not{E}_T > 25$ GeV
- $\Delta \phi(\mu, \not{E}_T) > 0.25$
- at least two jets with $p_T > 20$ GeV and $|y| < 2.5$
- $H_T > 140$ GeV

**ee Channel**
- two electrons $p_T > 15$ GeV, $|y| < 1.1$ or $1.5 < |y| < 2.5$
- exclude $80 < M_{ee} < 100$ GeV
- $\not{E}_T \geq 40$ GeV if $M_{ee} < 80$ GeV
- $\not{E}_T \geq 35$ GeV if $M_{ee} > 100$ GeV
- at least two jets with $p_T > 20$ GeV and $|y| < 2.5$
- sphericity $> 0.15$

### L ≈ 230 pb$^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>actual</th>
<th>$t\bar{t}$</th>
<th>$Z/\gamma^*$</th>
<th>$Z \rightarrow \tau\tau$</th>
<th>$WW/WZ$</th>
<th>fake e</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\mu$</td>
<td>8</td>
<td>5.2 ± 0.6</td>
<td>0.02 ± 0.02</td>
<td>0.4 ± 0.1</td>
<td>0.4 ± 0.2</td>
<td>0.20 ± 0.06</td>
</tr>
<tr>
<td>ee</td>
<td>5</td>
<td>1.9 ± 0.3</td>
<td>0.59 ± 0.09</td>
<td>0.13 ± 0.08</td>
<td>0.14 ± 0.09</td>
<td>0.07 ± 0.03</td>
</tr>
</tbody>
</table>
Matrix Weighting Method

- Underconstrained kinematics given two neutrinos
- Scan potential top masses
- Solve for top momentum
  - assume two leading jets correspond to the $b$ jets
  - $\Rightarrow$ 4 solutions per $tt$
  - include detector resolution effects
- Calculate weight as a function of $m_t$ for each event using Dalitz-Goldstein-Kondo method

$$w = f(x) f(x) \times p(E_\ell^* | m_t) p(E_\ell^* | m_t)$$

PDF probability that observed lepton energy comes from top quark with mass $m_t$
Matrix Weighting Method

- Choose value of $m_t$ with maximum likelihood
- Form binned likelihood with signal and background templates

$m_t = 175$ GeV signal template

$m_t = 120$ GeV signal template

$WW \rightarrow e\mu$ background template

$Z \rightarrow \tau\tau$ background template
Dilepton Mass Results

230 $pb^{-1}$ sample, 13 events selected, 2 events expected background

$m_t = 155^{+14}_{-13} (\text{stat}) \pm 7 (\text{sys})$ GeV

Average fit mass vs. input $m_t$

slope $\approx 1$
offset $\approx 0$
Dilepton Mass Results

8% CL with respect to 175 GeV

\( m_{\text{fit}} = 155 \text{ GeV} \)

input \( m_t = 175 \text{ GeV} \)

\( \delta m = 13.5 \text{ GeV} \)

Source Uncertainty

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistical</td>
<td>(+14/-13 \text{ GeV})</td>
</tr>
<tr>
<td>systematic</td>
<td>6.7 \text{ GeV}</td>
</tr>
<tr>
<td>jet energy scale</td>
<td>5.6 \text{ GeV}</td>
</tr>
<tr>
<td>event generation</td>
<td>3.0 \text{ GeV}</td>
</tr>
<tr>
<td>calibration</td>
<td>1.1 \text{ GeV}</td>
</tr>
<tr>
<td>background</td>
<td>1.0 \text{ GeV}</td>
</tr>
<tr>
<td>underlying event</td>
<td>1.0 \text{ GeV}</td>
</tr>
<tr>
<td>PDF</td>
<td>0.9 \text{ GeV}</td>
</tr>
<tr>
<td>total</td>
<td>15 \text{ GeV}</td>
</tr>
</tbody>
</table>
Lepton + Jets Channel

Signature

- One lepton
- One neutrino
- Two $b$ quarks
- Two light quarks
Lepton + Jets Channel

Signature
- One lepton
- One neutrino
- Two $b$ quarks
- Two light quarks

Event Selection
- One high-$p_T$ lepton
- Missing $E_T$
- Four or more high-$p_T$ jets

Backgrounds
- $W$ + jets
- Multi-jet with fake lepton
Lepton + Jets Channel

Signature
- One lepton
- One neutrino
- Two $b$ quarks
- Two light quarks

Event Selection
- One high-$p_T$ lepton
- Missing $E_T$
- Four or more high-$p_T$ jets
- $b$ tagging

Advantages of $b$ tagging
- Reduce backgrounds—increase S/B
- Reduce possible jet permutations
  - 0 tags: 12 ways to assign 4 jets to partons
  - 1 tag: 6
  - 2 tags: 2
Secondary Vertex Tagger

- Explicitly reconstruct 3D vertices using tracks in jets.

- Identify as a $b$ jet if the signed decay length significance $L/\sigma > 7$.

$\sigma(d_0) = 11 + 42 \text{ GeV}/p_T \mu m$

- 60% of $t\bar{t}$ events have at least one $b$-tagged jet
- 4% of $W + 4$ jet events have at least one $b$-tagged jet
Low-Bias Discriminant

Aplanarity

Choose variables with minimal dependence on $m_t$
Low-Bias Discriminant

Discriminant purity: 51%
b-tag purity: 76%
Lepton + Jet Event Selection

- isolated $e$ or $\mu$ with $p_T > 20$ GeV ($|y_e| < 1.1, |y_\mu| < 2$)
- $E_T > 20$ GeV
- low-bias discriminant $> 0.4$
- $\geq 4$ jets with $p_T > 20$ GeV and $|y| < 2.5$
- at least one jet permutation consistent with $t\bar{t}$ with $\chi^2 < 10$
- at least one $b$-tagged jet
- $\geq 4$ jets with $p_T > 15$ GeV and $|y| < 2.5$
- at least one jet permutation consistent with $t\bar{t}$

<table>
<thead>
<tr>
<th>Channel</th>
<th>topological analysis</th>
<th>$b$-tagged analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$e$+jets</td>
<td>$\mu$+jets</td>
</tr>
<tr>
<td>Actual</td>
<td>49</td>
<td>45</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>27.5 $\pm$ 2.2</td>
<td>20.4 $\pm$ 0.9</td>
</tr>
<tr>
<td>$W$ + jets</td>
<td>9.5 $\pm$ 0.45</td>
<td>22.0 $\pm$ 2.6</td>
</tr>
<tr>
<td>multijets</td>
<td>12 $\pm$ 0.55</td>
<td>2.6 $\pm$ 0.5</td>
</tr>
</tbody>
</table>

$\mathcal{L} \approx 230 \text{ pb}^{-1}$
Topological Analysis

- Scan over potential top masses
- Reconstruct top quark
  - 4 jets $\Rightarrow$ 12 unique solutions
  - 2 neutrino $p_z$ choices
  - $\Rightarrow$ 24 unique solutions
- Perform constrained kinematic fit
  - require both $W$’s have mass $\approx M_W$
  - require mass of the two $Wb$ pairs be equal
  - choose minimum $\nu |p_z|$
  - choose permutation with best $\chi^2$
- Form binned likelihood with signal and background ($W+4$ jet) templates
Topological Analysis

- Scan over potential top masses
- Reconstruct top quark
  - 4 jets $\Rightarrow$ 12 unique solutions
  - 2 neutrino $p_z$ choices
  - $\Rightarrow$ 24 unique solutions
- Perform constrained kinematic fit
  - require both $W$’s have mass $\approx M_W$
  - require mass of the two $Wb$ pairs be equal
  - choose minimum $\nu |p_z|$
  - choose permutation with best $\chi^2$
- Form binned likelihood with signal and background ($W + 4$ jet) templates
230 $pb^{-1}$ topological sample
44.2 ± 6.6 $t\bar{t}$ events

$m_t = 169.9 \pm 5.8 \text{ (stat)} \pm 7.8 \text{ (sys)} \text{ GeV}$
Lepton + Jets Mass Results

230 \( pb^{-1} \) \( b \)-tagged sample

49.2 ± 6.3 \( tt \) events

\( m_t = 170.6 \pm 4.2 \) \( (\text{stat}) \) \pm 6.0 \( (\text{sys}) \) GeV
### Lepton + Jets Mass Results

**Entries:** 193  
**Mean:** 7.103  
**RMS:** 1.787

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Jet Energy Scale</strong></td>
<td>+6.8 / −6.5</td>
</tr>
<tr>
<td><strong>Jet Resolution</strong></td>
<td>±0.9</td>
</tr>
<tr>
<td><strong>Gluon Radiation</strong></td>
<td>±2.6</td>
</tr>
<tr>
<td><strong>Signal Model</strong></td>
<td>+2.3</td>
</tr>
<tr>
<td><strong>Background Model</strong></td>
<td>+0.7</td>
</tr>
<tr>
<td><strong>b-tagging</strong></td>
<td>—</td>
</tr>
<tr>
<td><strong>Calibration</strong></td>
<td>±0.5</td>
</tr>
<tr>
<td><strong>Trigger Bias</strong></td>
<td>±0.5</td>
</tr>
<tr>
<td><strong>MC Statistics</strong></td>
<td>±0.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>+7.8 / −7.1</td>
</tr>
</tbody>
</table>

**Run II Preliminary**

---

**Source Uncertainty (GeV):**
- **topological:** +6.8 / −6.5  
- **b-tagged:** +4.7 / −5.3

**Jet Energy Scale:**
- **topological:** ±0.9  
- **b-tagged:** ±0.9

**Jet Resolution:**
- **topological:** ±2.6  
- **b-tagged:** ±2.4

**Gluon Radiation:**
- **topological:** +2.3  
- **b-tagged:** +2.3

**Signal Model:**
- **topological:** +0.7  
- **b-tagged:** ±0.8

**Background Model:**
- **topological:** ±0.7  
- **b-tagged:** ±0.7

**Calibration:**
- **topological:** ±0.5  
- **b-tagged:** ±0.5

**Trigger Bias:**
- **topological:** ±0.5  
- **b-tagged:** ±0.5

**MC Statistics:**
- **topological:** ±0.5  
- **b-tagged:** ±0.5

**Total:**
- **topological:** +7.8 / −7.1  
- **b-tagged:** ±6.0
Lepton + Jets: Ideogram

Method based on same kinematic fit with same low-bias discriminant $D_{LB}$, but improves statistical sensitivity by

- using all jet/ν solutions for fitted mass $m$, uncertainty $\sigma$, and $\chi^2$
- calculating event-by-event likelihood taking into account all jet/ν solutions and the probability that the event is background ($D_{LB}$)

**best permutations have most weight**

$$w_i = \exp(-\chi_i^2/2)$$

$$L(m_t, P_{sample}) = \sum_i w_i \left[ P_{evt} S(m_i, \sigma_i, m_t) + (1 - P_{evt}) BG(m_i) \right]$$

**background shape from Monte Carlo simulation**

$$S(m_i, \sigma_i, m_t) = \int dm' G(m', m_i, \sigma_i) BW(m', m_t, \Gamma_t)$$

signal likelihood based on Gaussian resolution and Breit-Wigner

gives relative weight to signal and background term according to estimated per event purity $P_{evt}(D_{LB}, P_{sample})$ so that the events that are most likely top count the most
Lepton + Jets: Ideogram

Lepton + jets selection without $b$-tagging

- $e$ or $\mu$ with $p_T > 20$ GeV
- $\geq 3$ jets with $p_T > 20$ GeV
- $\geq 4$ jets with $p_T > 15$ GeV
- lowest $\chi^2 < 10$, no cut on $D_{LB}$

$\mathcal{L} \approx 160 \text{ pb}^{-1}$

$m_t = 177.5 \pm 5.8 \text{ (stat)} \pm 7.1 \text{ (sys)}$ GeV

mean expected statistical uncertainty: 4.6 GeV
Summary

DØ has measured the top mass in two channels with 0.25 $fb^{-1}$ of Run II data.

We are currently improving the jet energy scale and our use of the jet energy scale within the top mass measurement.

Expect improved results soon.