Measurement of the Top Quark Mass at DZero In The Lepton + Jets Channel

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For The DØ Collaboration

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Outline

Introduction
Top quark at the Tevatron.

Top Quark Mass Measurement In The l+Jets Channel

Results from the 425 pb$^{-1}$ of data using b-tagging for:

- The Matrix Element Method.
- The Ideogram Method Result.
Top Quark

At the Tevatron, top quarks are primarily produced in pairs via the strong interaction. Since $|V_{tb}| \sim 1$, the top quark almost always decays to $Wb$ ($Ws$, $Wd$ CKM suppressed)

Event topology depends on the $W$ decay mode

Experimental signature in the lepton+jets channel:
- 1 high $p_T$ lepton
- 4 jets (2 b-jets)
- large $E_T^{mis}$
Top Quark Identification

Background Processes:

- Exactly 4 Calorimeter Jets
  \( p_T > 20 \text{ GeV} \)
  \( \mid \eta \mid < 2.5 \)
- Isolated Lepton
  \( p_T > 20 \text{ GeV} \)
  \( \mid \eta^e \mid < 1.1, \mid \eta^\mu \mid < 2.0 \)
- Missing Transverse Energy
  \( E_T^{\text{mis}} > 20 \text{ GeV} \)

W+jets production.
most significant

Multi-jet events:
from fake or miss-characterized lepton
and fake missing transverse energy
The Matrix Element Method

Set of observables: momenta of jets and lepton: $x$

Integrate over unknowns:
- kinematic variables of final state particles: $y$
  (4 quarks, a lepton, and a neutrino: 18 variables)
- longitudinal momenta of the incident partons ($q_1, q_2$)
  (2 variables) = 20 variables

Integral contains 15 (14) delta-functions for $e^-$ (mu)+jets:
- total energy-momentum conservation (4 variables)
- jet and lepton angles (considered to be perfectly measured)
  (10 variables)
- Electron momentum (considered perfectly measured)
  (1 variable)

Approximations:
- LO matrix element.
- $q \bar{q} \rightarrow t \bar{t}$ production process only (no gluon fusion ~15%)
The Matrix Element Method

We calculate a probability per event to be signal or background as a function of the top mass and the Jet Energy Scale (JES)

(Dominant systematic error in Run I).

If we had all the parton level information 'y' this probability would be just proportional to the differential cross section.

In reality is a bit more complicated:

\[ P_{t\bar{t}}(x; m_{top}, JES) = \frac{1}{\sigma(m_{top})} \int dq_1 dq_2 f(q) f(\bar{q}) d\sigma(y; m_{top}) Prob(x, y, JES) \]

Transfer Function: probability to measure \( x \), when parton-level \( y \) was produced.

Initial state

Differential cross section, based on LO Matrix Element ( \( q\bar{q} \rightarrow t\bar{t} \) ) only

Normalization: acceptance efficiency

Measurements: jets and leptons

Overall JES is a free parameter in the fit, constrained in situ by the mass of the W decaying hadronically.
The Matrix Element Method

b-tagging:
Weight each jet-parton assignment with b-tagging event probabilities.

\[ P_{N-tag}^{t\bar{t}}(x; m_{top}, JES) = \sum_j W_j^t P_{t\bar{t}}^j(x; m_{top}, JES) \]

24 possible weighted assignments between jets and partons

\[ P_{evt}^{N-tag}(x; m_{top}, JES) = f_{top} P_{N-tag}^{t\bar{t}}(x; m_{top}, JES) + (1 - f_{top}) P_{bkg}(x, JES) \]

\( f_{top} \): signal fraction is fitted simultaneously
Example of 2D Top Mass – JES Fit

200 simulated events ($m_t = 175$ GeV)
Calibration of the Method

Transform Leading-Order Matrix Element mass estimator to full simulation, including ISR/FSR and reconstruction effects.

Build 1000 pseudo-experiments using full DZero simulated events and calibrate out biases from the hypothesis made.

We measure the sample composition in data using a likelihood discriminant (based on topological variables) and we use these values to generate the ensembles composition.
Top Mass Calibration

offset = 1.932 +- 0.085 GeV
slope = 1.018+- 0.011

pull width = 1.11+- 0.01

1000 full-simulated pseudo-experiments
Top Mass Fit in 425pb$^{-1}$ lepton+jets Data

\[ m_{\text{top}} = 170.3 \pm 4.5 \,(\text{stat.} + \text{JES}) \pm 1.2 \,(\text{syst.}) \,\text{GeV} \]

Measured JES is consistent with the reference scale (JES=1)
The statistical errors include the JES error.
Major systematic error from b fragmentation and b/light jets response
Top Mass Fit Error in Data and MC

\[ m_{\text{top}} = 170.3 \pm ^{4.1}_{4.5} \, (\text{stat.} + \text{JES}) \pm ^{1.2}_{1.8} \, (\text{syst.}) \, \text{GeV} \]

The arrows show the upper and lower uncertainties in data respect to MC for the mass and for the JES.
Top Mass Using the Ideogram Method

**Basic Idea:** use event-by-event likelihood technique taking into account all possible jet combinations and the possibility that the event was signal or background (like Matrix Element method)

- Instead of ME method use constrained fit + topological discriminant. Also, in contrast to ME analysis, 4 or more jets are used.
The top mass likelihood is evaluated at the JES value with maximum likelihood (light blue line)
Ideogram Fit Error in MC and Data

\[ m_{top} = 173.3 \pm 4.4 \text{(stat. + JES)} \pm 2.1 \text{(syst.) GeV} \]

The arrows show the uncertainties in data respect to MC for the mass and for the JES.
Top Mass Measurement Current Status

**Impact on Standard Model**

**Higgs boson:**

\[ M_H = 85^{+39}_{-28}\, \text{GeV} \; ; \; \; M_H < 166\, \text{GeV} \, @ \, 95\, \text{CL} \]
Summary and Conclusions

The precise measurement of top quark mass allows to constrain the mass of the SM Higgs boson, and is one of the most important measurements at the Tevatron.

Top quark mass precision is improved after adding b-tagging information to both the Matrix Element and Ideogram techniques.

\[
m_{top} = 173.3 \pm 4.4 \text{ (stat. + JES) } \pm 2.1 \text{ (syst.) GeV} \quad \text{ID}
\]

\[
m_{top} = 170.3 \pm 4.5 \text{ (stat. + JES) } \pm 1.2 \text{ (syst.) GeV} \quad \text{ME}
\]

A new improved measurement of the top quark mass allows us to reach the 1.2% precision (Combined Dzero+CDF measurement).
Backup Slides
### ME Systematic Errors

\[ m_{\text{top}} = 170.3 \pm_{4.5}^{4.1} (\text{stat.} + JES) \pm_{1.8}^{1.2} (\text{syst.}) \, \text{GeV} \]

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Effect on top mass (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physics Modeling</strong></td>
<td></td>
</tr>
<tr>
<td>Signal modeling</td>
<td>+0.46</td>
</tr>
<tr>
<td>Background modeling</td>
<td>+0.40</td>
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<tr>
<td>PDF uncertainty</td>
<td>+0.16 - 0.39</td>
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<tr>
<td>b-fragmentation</td>
<td>+0.56</td>
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<tr>
<td>b/c semileptonic decays</td>
<td>+0.05</td>
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<tr>
<td><strong>Detector modeling</strong></td>
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<tr>
<td>JES pT dependence</td>
<td>+0.19</td>
</tr>
<tr>
<td>Relative b/light jet energy scale</td>
<td>+0.63 - 1.43</td>
</tr>
<tr>
<td>Trigger</td>
<td>+0.08 - 0.13</td>
</tr>
<tr>
<td>B-tagging</td>
<td>+0.24</td>
</tr>
<tr>
<td><strong>Method</strong></td>
<td></td>
</tr>
<tr>
<td>Signal fraction</td>
<td>+0.15</td>
</tr>
<tr>
<td>QCD background</td>
<td>+0.29</td>
</tr>
<tr>
<td>MC calibration</td>
<td>+0.48</td>
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</tbody>
</table>
**ID Systematic Errors**

**Physics Modeling**
- Signal modeling: $\pm 0.73$
- Background modeling: $\pm 0.20$
- PDF uncertainty: $\pm 0.023$
- $b$-fragmentation: $\pm 1.30$

**Detector modeling**
- Jet ID efficiency and resolution: $\pm 0.22$
- JES pT dependence: $\pm 0.45$
- Relative $b$/light jet energy scale: $\pm 1.15$
- Trigger: $0.61 - 0.28$
- B-tagging: $\pm 0.29$

**Method**
- Signal fraction: $\pm 0.12$
- QCD background: $\pm 0.28$
- MC calibration: $\pm 0.25$

\[ m_{\text{top}} = 173.3 \pm 4.43 \, \text{(stat.)} \pm 2.10 \, \text{(syst.)} \, \text{GeV} \]
Top Mass Fit in 0, 1, and 2-Tag Samples

0-Tag

1-Tag

2-Tag
Improving the Precision of the Method

Example: **Double-Tag events:**

4 dominant terms:

\[ W_j = \varepsilon_b^2 (1 - \varepsilon_l)^2 \]

\[ W_j = \varepsilon_b \varepsilon_c (1 - \varepsilon_b) (1 - \varepsilon_l) \]

\[ W_j = \varepsilon_l \varepsilon_b (1 - \varepsilon_l) (1 - \varepsilon_b) \rightarrow 0 \]

\( \varepsilon_b \sim 0.35, \quad \varepsilon_c \sim 0.1, \quad \varepsilon_l \sim 0.005 \)
Improving the Precision of the Method

Use b-tagging to improve the statistical precision of the Matrix Element Method.

b-tagging classifies events in 3 tag categories, with different S/B.

- **0-tag**: 73%, $f_{\text{top}} = 22%$
- **1-tag**: 20%, $f_{\text{top}} = 88%$
- **2-tag**: 7%, $f_{\text{top}} = 97%$

**W+jets flavor composition:**

![Pie charts showing W+jets flavor composition for 0-tag, 1-tag, and 2-tag categories.](image)
Improving the Precision of the Method

**b-tagging:**
Weight each jet-parton assignment with b-tagging event probabilities.

\[
P_{t\bar{t}}^{N-tag}(x;m_{top}, JES) = \sum_J W_J^{t\bar{t}} P_J^{t\bar{t}}(x;m_{top}, JES)
\]

\[
W_J^{t\bar{t}} = \frac{w_J^1 w_J^2 w_J^3 w_J^4}{\sum_K w_K^1 w_K^2 w_K^3 w_K^4}
\]

\[
w_J^i = \epsilon_{jet}(\alpha)(E_T, \eta) \quad \text{tagged jets}
\]

\[
w_J^i = (1 - \epsilon_{jet}(\alpha)(E_T, \eta)) \quad \text{untagged jets}
\]

**terms:**
\[\alpha = b, c, \text{light}\]

12 from \(W^2 \) from \(\bar{t}\)
Data Events
The slope is null for both top mass dependence on JES and JES dependence on mass.
JES Calibration

offset = -0.028 $\pm$ 0.001 GeV
slope = 0.945 $\pm$ 0.021

pull width = 1.09 $\pm$ 0.01

1000 full-simulated pseudo-experiments
Transfer Function

The transfer function $W(x,y; \text{JES})$ relate the individual top pair decay products at parton level $y$ to the measurements $x$ in the detector.

Assume perfect measurements for:
- Angles of all jets and lepton.
- Energy of the electron.

$$W(E_j, E_p, \text{JES}) = \frac{E_j}{\text{JES}}, \frac{E_p}{\text{JES}}$$
Top Mass Using the Ideogram Method
The sample composition is measured using a likelihood discriminant based on topological event variables (HT, Centrality, Aplanarity, Sphericity).

<table>
<thead>
<tr>
<th></th>
<th>e+jets</th>
<th>mu+jets</th>
<th>Fitted top quark fraction is not used for the top mass measurement.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of events</td>
<td>86</td>
<td>89</td>
<td></td>
</tr>
<tr>
<td>Signal fraction</td>
<td>47+/-12%</td>
<td>29+/-10%</td>
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</tbody>
</table>
The DZero Detector and the Tevatron

Tracking:
Silicon vertex detector (SMT)
Central Fiber Tracker (CFT)
2 T Superconducting Solenoid.  
|η| < 2.5

Preshowers

EM/HAD Calorimeter:
Central, |η|<1.1
Forward, |η|<4.2

Muon system:
1.8 T iron toroids.  
|η|<2.0

3-Level trigger system:
Level 1 (hardware): 2 kHz
Level 2 (hardware): 1 kHz
Level 3 (software): 50 Hz