Top quark mass measurement at Tevatron

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On behalf of the CDF and D0 collaboration
Top quark

- Top quark is the heaviest known elementary particle
- Top quark mass is not predicted by SM
- Can constrain SM Higgs boson mass
  - Important contribution in radiative correction of $W$
  - Important test of SM
Top quark decay

- Pair production is predominated
- ~100% decay to W boson plus b quark
- Decay topologies rely on the decay of W boson
  - two jet (70%) or lepton and neutrino (30%)
  - Important to look all channel
    - New physics would make different phenomena for different channel

Challenge for mass measurement
- Up to six jet - Jet energy scale, jets to parton assignment
- Up to two neutrino – Missing energy – Event reconstruction
- Large QCD backgrounds
b-tagging

- B hadron can be identified by long displacement
- b tagging reduce # of jet-to-parton assign.
  - Ex) lepton+jets channel
  - 24 (0-btags), 6(1-btags), 2(2-btags)
- b tagging improve signal to background ratio significantly – 40% effi., 0.5% fake

<table>
<thead>
<tr>
<th>Sample</th>
<th>Di-lepton (e,μ)</th>
<th>Lepton+jets (e,μ)</th>
<th>All Hadronic NN selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-b-tags S/B</td>
<td>1:1</td>
<td>1:4</td>
<td>1:20</td>
</tr>
<tr>
<td>1-b-tags S/B</td>
<td>4:1</td>
<td>4:1</td>
<td>1:5</td>
</tr>
<tr>
<td>2-b-tags S/B</td>
<td>20:1</td>
<td>20:1</td>
<td>1:1</td>
</tr>
<tr>
<td>Events in 1 fb⁻¹ (≥ 1 b-tag)</td>
<td>25</td>
<td>180</td>
<td>150 (2 b-tags)</td>
</tr>
</tbody>
</table>
Jet energy scale

**In situ JES calibration**

**Measured JES uncertainty**

- Lepton+jets : 1.0 GeV/c$^2$
- Dilepton : 2.9 GeV/c$^2$

(CDF 4.8 fb$^{-1}$, template method)

**Moriond QCD 2010, Hyunsu Lee, The University of Chicago**
Measurement technique (Matrix element technique)

- Try to extract as much information as possible from every event using theoretical prediction for \(t\bar{t}\) production and decay.
- Integrate over unknown parton energies given a measured jet energy.
- For each event, we calculate probability to be \(t\bar{t}\) with certain mass \(M_{\text{top}}\) (also JES).
- Background probability is also calculated using background matrix element.
- Perform the likelihood fit using event probability.

\[
P(\bar{x}; M_{\text{top}}, JES) \propto \int ME \times TF \times PDF
\]
3.6 fb\(^{-1}\), 817 data events

- NN based b-tagging to increase efficiency
- Transfer function was estimated for four different eta region for b-jet, light jet, and lepton
- We modeled background only using W+jets ME
- 24 different permutations were summed by taking into account b-tagging information
- \textit{In situ} JES calibration

\[ 173.7 \pm 0.8 \text{ (stat)} \pm 1.6 \text{ (JES+syst)} \text{ GeV/c}^2 \]
\[ =173.7 \pm 1.8 \text{ GeV/c}^2 \]
CDF lepton+jets, ME

- 4.8 fb\(^{-1}\) data – 1070 events
  - We increase muon acceptance by adding MET+jets trigger (30% more events)
  - Additional NN based selection

- Transfer function was parameterized by eta and jet mass for b-jet and light jet
- \textit{In situ} JES calibration

- This is the most precise top quark measurement to date

$$172.8 \pm 0.7\text{(stat)} \pm 0.6\text{(JES)} \pm 0.8\text{(syst)} \text{ GeV/c}^2$$

$$=172.8 \pm 1.3 \text{ GeV/c}^2$$
CDF lepton+jets, ME

CDF Run II Preliminary, 4.8 fb$^{-1}$

<table>
<thead>
<tr>
<th>Systematic source</th>
<th>Systematic uncertainty (GeV/$c^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>0.11</td>
</tr>
<tr>
<td>MC generator</td>
<td>0.25</td>
</tr>
<tr>
<td>ISR and FSR</td>
<td>0.15</td>
</tr>
<tr>
<td>Residual JES</td>
<td>0.49</td>
</tr>
<tr>
<td>$b$-JES</td>
<td>0.26</td>
</tr>
<tr>
<td>Lepton $P_T$</td>
<td>0.14</td>
</tr>
<tr>
<td>Multiple hadron interactions</td>
<td>0.10</td>
</tr>
<tr>
<td>PDFs</td>
<td>0.14</td>
</tr>
<tr>
<td>Background modeling</td>
<td>0.33</td>
</tr>
<tr>
<td>Gluon fraction</td>
<td>0.03</td>
</tr>
<tr>
<td>Color reconnection</td>
<td>0.37</td>
</tr>
<tr>
<td>Total</td>
<td>0.84</td>
</tr>
</tbody>
</table>

172.8 ± 0.7(stat) ± 0.6(JES) ± 0.8(syst) GeV/$c^2$

=172.8 ± 1.3 GeV/$c^2$
Measurement technique (template method)

- Identify variables $\vec{x}$ sensitive to $M_{\text{top}}$ (or JES)
- Using MC, generate signal distribution of $\vec{x}$ as a function of $M_{\text{top}}$ (or JES)
- Parametrize templates in terms of probability density function then assign the probability for certain mass and JES

\[ P(\vec{x}; M_{\text{top}}, \Delta JES) \]

Event reconstruction in the lepton+jets

\[
\chi^2 = \frac{1}{2} \sum_{i=\ell,4j} \left( \frac{p_{i,\text{fit}}^{\ell,4j} - p_{i,\text{meas}}^{\ell,4j}}{\sigma_i^2} \right)^2 + \frac{1}{2} \sum_{j=x,y} \left( \frac{U_{j,\text{fit}}^{x,y} - U_{j,\text{meas}}^{x,y}}{\sigma_j^2} \right)^2 + \frac{1}{2} \left( \frac{M_{jj} - M_W}{\Gamma_W^0} \right)^2 + \frac{1}{2} \left( \frac{M_{\ell\nu} - M_W}{\Gamma_W^0} \right)^2 + \frac{1}{2} \left( \frac{M_{bJ} - m_t^{\text{reco}}}{\Gamma_t^0} \right)^2 + \frac{1}{2} \left( \frac{M_{b\ell\nu} - m_t^{\text{reco}}}{\Gamma_t^0} \right)^2
\]

- Construct likelihood based on probabilities
CDF lepton+jets and dilepton, Template

- 4.8 fb\(^{-1}\) data – 977 Lepton+jets(LJ)
  - 344 Dilepton(DIL)
  - Chi2(<9) cut was applied for LJ
- Simultaneously use LJ+DIL
- Fully three dimensional PDF using three observables in LJ
  - 3\(^{rd}\) observables is reconstructed mass using kinematic fit with different combinatoric of jet to parton assignment (2\(^{nd}\) best fit)
- LJ only measurement
  - 172.0 ± 1.5 GeV/c\(^2\)
  - Complement technique, consistent result

171.9 ± 0.8 (stat) ± 0.8(JES) ± 0.9(syst) GeV/c\(^2\)

=171.9 ± 1.5 GeV/c\(^2\)
CDF dilepton channel, template

- Two observables taking into account correlation
  - Reconstructed mass and $m_{T2}$

- Interesting observable $m_{T2}$
  - Transverse mass with two missing particles
  - Introduced for mass measurement of New physics particles which have two missing particles
  - We firstly use $m_{T2}$ in real data

$170.6 \pm 2.2 \text{ (stat)} \pm 3.1 \text{ (syst)} \text{ GeV/c}^2 = 170.6 \pm 3.8 \text{ GeV/c}^2$
Top mass from cross section

- Top quark cross section measurement constraints top quark mass with taking into account theoretical calculation

PRD 80 (2009) 071102

NLO : $165.5^{+6.1}_{-5.9}$ (PRD 78 (2008) 013004)

NLO+NLL : $167.5^{+5.8}_{-5.6}$ (JHEP 09 (2008) 127)

NLLO(approx.) : $169.1^{+5.9}_{-5.2}$ (PRD (2008) 074005)

NLLO (approx.) : $168.2^{+5.9}_{-5.4}$ (PLB 360 (1995) 47)

Complement technique, consistent result
## Combined Top Quark Mass Measurements

**CDF**
- **CDF LJ (ME):** \(172.8 \pm 1.3 \text{ GeV/c}^2\)
- **CDF LJ (TM):** \(172.1 \pm 1.5 \text{ GeV/c}^2\)
- **CDF DIL (TM):** \(170.6 \pm 3.8 \text{ GeV/c}^2\)

**D0**
- **D0 LJ (ME):** \(172.0 \pm 1.5 \text{ GeV/c}^2\)
- **D0 LJ (TM):** \(171.5 \pm 1.5 \text{ GeV/c}^2\)

**Combined Results:**
- **Top Quark Mass:** \(m_{\text{top}} = 173.1 \pm 1.3 \text{ GeV/c}^2\)

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**Note:**
- Preliminary results from Moriond QCD 2010.
- The combination of measurements from CDF and D0 shows consistency with the expected top quark mass.

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**Graph:**
- Mass distribution of top quark candidates from various runs and analyses, highlighting the combined results with error bars.

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**Technical Details:**
- **CDF:**
  - Run I and II events.
  - Mass bins from 150 to 200 GeV/c^2.
  - Preliminary results with systematic uncertainties.

- **D0:**
  - Run I and II events.
  - Similar mass distribution and error analysis.

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**Additional Information:**
- **CDF DIL (TM):**
  - Additional constraints from dilepton mode.
  - Combined with CDF LJ (ME) and D0 LJ (ME) measurements.

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*Acknowledgments:*
- Authors: Hyunsu Lee, The University of Chicago.

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Moriond QCD 2010, Hyunsu Lee, The University of Chicago
D0 top-antitop mass difference

- 1 fb\(^{-1}\) modified matrix element
  \[ P(\tilde{x}; M_t, M_{\tilde{t}}) \text{ instead of } P(\tilde{x}; M_{\text{top}}, JES) \]

- Test of CPT violation in the top sector
  - First time in the quark and high mass

\[ \Delta M = 3.8 \pm 3.7 \text{ GeV/c}^2 \]

Good agreement with SM
Limited by statistics
Will be updated with more data
Conclusion

• 0.75% precision in world average (a year ago)
  \[ m_{\text{top}} = 173.1 \pm 1.3 \text{ GeV/c}^2 \]

• 0.75% precision by single measurement (now)
  \[ m_{\text{top}} = 172.8 \pm 1.3 \text{ GeV/c}^2 \]

• We may have new measurement from LHC (next year)
  ❖ However Tevatron will have the most precise measurement for a while
Backup
Global EWK fit and Higgs constraints


\[ m_H = 87^{+35}_{-26} \text{ GeV/c}^2 \quad m_H < 157 \text{ GeV/c}^2 \text{ (95\% CL)} \]

\[ m_H < 187 \text{ GeV/c}^2 \text{ (95\% CL)} \]

With direct limit from LEPII

Moriond QCD 2010, Hyunsu Lee, The University of Chicago
CDF all hadronic channel

- 2.9 fb\(^{-1}\) date, template method
- Two dimensional template
  - Reconstructed top mass and dijet mass from W boson decay
- NN discrimination to reduce dominant QCD backgrounds
  - Jet shape to discriminate gluon jet from quark jet
  - 1btag S:B=1:4 (3452 candidates)
  - 2btag S:B=1:1 (441 candidates)

174.8 ± 1.7 (stat) ± 1.9 (JES+syst) GeV/c\(^2\)
= 174.8 ± 2.7 GeV/c\(^2\)
CDF dilepton channel, ME

- 2.0 fb\(^{-1}\) data, Matrix element method
- Event selection was optimized for top quark mass measurement using NN
- More sensitive analysis than template method

\[ m_t = 171.2 \pm 2.7 \text{ (stat)} \pm 2.9 \text{ (syst)} \text{ GeV/c}^2 \]

\[ = 171.2 \pm 4.0 \text{ GeV/c}^2 \]
D0 dilepton channel

- We have two b-jets, two lepton, and two neutrino
  - Underconstraint system

- Event reconstruction to build template is challenging
  - Neutrino weighting
    - Integrate over expected neutrino eta distribution to obtain a probability for certain top mass

- Matrix element calculation
  - Integrate over unknown neutrino momentum

- We use Z to tau tau +jets for background modeling

- Matrix weighting
  - 1.0 fb\(^{-1}\), template method
    - 174.7 ± 4.4(stat) ± 2.0(syst) GeV/c\(^2\)
  - 3.6 fb\(^{-1}\), ME, Only use e\(\mu\) events
    - 174.8 ± 3.3(stat) ± 2.6(syst) GeV/c\(^2\)

\[174.7 ± 2.9 \text{ (stat)} ± 2.4 \text{ (syst) GeV/c}^2\]
\[= 174.7 ± 3.8 \text{ GeV/c}^2\]
$m_{T2}$

- Introduced to measure the mass of new physics particle
  - Most of new physics predict long-live stable particle – dark matter candidate
  - We expect missing particle at the final state
  - If we consider pair production of new physics particle, it will have two missing particle

- Top dilepton channel have exactly same final state

$$m_{T2} = \min[\max(m_{T1}, m_{T2})]$$

$q_T + p_T = \text{missing } p_T$

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*Alan Barr, Christopher Lester and Phil Stephens
• Leptonical decay of top
  - t→blv
  - We measure b and lepton but don’t know neutrino
    - 4 unknown
  - Known parameter
    - W mass, neutrino mass (2 unknown)
  - If we assume the top quark mass and neutrino eta direction, we can measure neutrino x,y momentum
  - Same thing happen for the other leg

• Getting weight using measured missing transverse energy

\[ w_i = \exp\left(-\frac{(E_x - P_x^{\nu} - P_x^{\ell})^2}{2\sigma_x^2}\right) \cdot \exp\left(-\frac{(E_y - P_y^{\nu} - P_y^{\ell})^2}{2\sigma_y^2}\right) \]
\[ w_i = w_i(m_{\text{top}}, \eta_1^{\nu}, \eta_2^{\nu}) \]
- Some over neutrino rapidities
  \[ W(m_t) = \int d\eta_1 \int d\eta_2 P(\eta_1) P(\eta_2) \sum_j \sum_i w(m_t)_{i,j} \]

- We have maximum weight \( m_t \) as reconstructed mass (\( m_t^{NWA} \))

- We scan \( m_t \) with 3GeV size and then decrease the step size upto 0.15GeV near the peak

- We have gaussian fit in the near of peak to get \( m_t \) continuously