Top Quark Mass Measurement in the lepton+jets channel using Template Method and Dynamical Likelihood Method at CDF

Kohei Yorita
Waseda University, Japan
For the CDF collaboration
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APS/DPF @ Riverside CA
Introduction

- From RunI results: New World Average (2004)
  \[ M_t = 178.0 \pm 4.3 \text{ GeV (} \pm 2.7 \pm 3.3 \text{)} \]  
  *hep-ex/0404010*

- Top quark is heavy (~ 180 GeV)
  Yukawa coupling \( \sim 1 \).
  *The mass is near the Electro-Weak Symmetry Breaking Scale.*

- Correlated with Higgs mass, together with W boson mass.

\[ y_t = \frac{\sqrt{2} m_t}{v} \approx 1 \]

\[ \delta M_W \propto (M_{\text{top}}^2, \ln(M_H)) \]

- Standard Model Higgs Mass:
  Most probable: \( 114 \pm 69 \text{ GeV} \)
  Upper limit (95% CL): \( 260 \text{ GeV} \)

- In this talk,
  1. Dynamical Likelihood Method (DLM)
     lepton+jets \( \geq 1 \)b tag
  2. Template Method
     lepton+jets 0tag, \( \geq 1 \)tag, \( \rightarrow \) combined

RunII Goal: \( \pm 2 \sim 3 \text{ GeV!} \)
Event Selection

- "lepton+jets" decay mode
  Final State: lepton(e, μ, ν), 4jets(2bjets)

- SVX b jet tagging
  Identify by finding a vertex of displaced tracks
  Excellent silicon detector!

<table>
<thead>
<tr>
<th>Cuts</th>
<th>DLM</th>
<th>Template(btag)</th>
<th>Template(0tag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton/MET</td>
<td>One central electron or muon(Et(Pt)&gt;20GeV), Met&gt;20GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>nJets</td>
<td>&gt;=4jets(Et&gt;15)</td>
<td>&gt;=3.5jets(Et&gt;15,&gt;8)</td>
<td>&gt;=4jets(Et&gt;21)</td>
</tr>
<tr>
<td>b tag</td>
<td>&gt;= 1 btag</td>
<td>&gt;= 1 btag</td>
<td>NO</td>
</tr>
<tr>
<td>kinematical fit</td>
<td>No</td>
<td>YES ($\chi^2 &lt; 9$)</td>
<td>YES ($\chi^2 &lt; 9$)</td>
</tr>
<tr>
<td>Observed</td>
<td>22 ev (L=162pb$^{-1}$)</td>
<td>28 ev (L=162pb$^{-1}$)</td>
<td>39 ev (L=194pb$^{-1}$)</td>
</tr>
<tr>
<td>S/B</td>
<td>~ 4.2</td>
<td>~3.0</td>
<td>~ 0.7</td>
</tr>
</tbody>
</table>

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Dynamical Likelihood Method


For i-th event, likelihood is defined as,

\[ L^i(M_{\text{top}}) = \sum_{I_t} \sum_{I_s} \int \frac{2\pi^4}{\text{Flux}} F(z_a, z_b, p_T) \left| M \right|^2 \delta(s_w - (\ell + \nu)^2) w(I_t, x | y; M_{\text{top}}) dx ds_w \]

- \( F \): Parton distribution function for \((z_a, z_b)\) and Pt of \(t\bar{t}\) system
- \( M \): Matrix element of \(t\bar{t}\) process, \( \left| M \right|^2 = \left| M_{\text{prod}} \right|^2 \prod(s_x) \left| M_{\text{dec}} \right|^2 \)
- \( w \): Transfer function, \( x \); partons ↔ \( y \); observables

Two Summations and one integration:

- \( I_t \): Jets to partons combination (6: 1-tag, 2: 2-tag)
- \( I_s \): Two \( \nu_z \) solutions

In practice, integration of \( x, s_w \) made by Monte Carlo Method.

- Extract top mass by maximum likelihood method,

\[ \Lambda(M_{\text{top}}) = -2 \ln \left( \prod_{\text{event}} L^i(M_{\text{top}}) \right) \rightarrow \bar{M}_{\text{top}} = M_{\text{top}} \text{ min. } \Lambda(M_{\text{top}}) \]
In the method, first, all events are assumed to be signal. Need to correct background effect.

Backgrounds pull likelihood peak down. (Have Lower Mass)

Pseudo experiments (22ev) by varying background fraction to look at effects on signal tt events.

Use this map to extract the top mass.

<table>
<thead>
<tr>
<th>source</th>
<th>W+4j</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mistag</td>
<td>1.2 ± 0.37</td>
</tr>
<tr>
<td>Wbb</td>
<td>0.7 ± 0.29</td>
</tr>
<tr>
<td>Wcc</td>
<td>0.3 ± 0.12</td>
</tr>
<tr>
<td>Wc</td>
<td>0.2 ± 0.12</td>
</tr>
<tr>
<td>Single top</td>
<td>0.17 ± 0.03</td>
</tr>
<tr>
<td>WW</td>
<td>0.08 ± 0.05</td>
</tr>
<tr>
<td>nonW</td>
<td>1.6 ± 0.38</td>
</tr>
<tr>
<td>Bkg tot.</td>
<td>4.2 ± 0.71</td>
</tr>
<tr>
<td>N obs.</td>
<td>22</td>
</tr>
<tr>
<td>tt (6.7pb)</td>
<td>20.9</td>
</tr>
</tbody>
</table>

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No bias was found. The statistical uncertainties are also scaled by the slope of mapping function properly.
Results: DLM

Observed events: Total 22 events; electrons 12, Muons 10

22 events joint likelihood

CDF Run II Preliminary (162 pb⁻¹)

After Background Consideration (4.2 events)

\[ 176.5 \pm 3.4 \ (\text{stat. only}) \text{ GeV/c}^2 \]

\[ 177.8 \pm 4.5 \ (\text{stat. only}) \text{ GeV/c}^2 \]

Correct background-pulling

4.2 events expected.
### Statistical & Systematic Uncertainty

#### Expected statistical Error

**Black arrows:**
- **Data:** $+4.5, -5.0$ GeV
- **Monte Carlo:**
  - **Mean:** $+5.4, -5.0$ GeV
  - **MPV:** $+4.5, -4.1$ GeV

#### Systematic uncertainty

<table>
<thead>
<tr>
<th>Sources</th>
<th>delta $M_{top}$ (GeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Energy Scale</td>
<td>5.3</td>
</tr>
<tr>
<td>Transfer function</td>
<td>2.0</td>
</tr>
<tr>
<td>PDF</td>
<td>2.0</td>
</tr>
<tr>
<td>Generator</td>
<td>0.6</td>
</tr>
<tr>
<td>MC Modeling</td>
<td>0.6</td>
</tr>
<tr>
<td>ISR</td>
<td>0.5</td>
</tr>
<tr>
<td>FSR</td>
<td>0.5</td>
</tr>
<tr>
<td>Bkg fraction (±5%)</td>
<td>0.5</td>
</tr>
<tr>
<td>Bkg Modeling</td>
<td>0.5</td>
</tr>
<tr>
<td>Spin correlation</td>
<td>0.4</td>
</tr>
<tr>
<td>NLO effect</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6.2 GeV</strong></td>
</tr>
</tbody>
</table>

(NLO: re-weighted qq and gg fractions)

**DLM:** $M_{top} = 177.8 \pm 4.5 \pm 6.2$ (stat.) (syst.) GeV/c²

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(1) For each event, invariant mass of top is reconstructed by minimizing $\chi^2$ defined as,

$$\chi^2 = \sum_{i=\text{jets}} \left( \frac{(p_{i,\text{fit}} - p_{i,\text{meas}})^2}{\sigma_i^2} \right) + \sum_{j=\text{other}} \left( \frac{(p_j - p_{j,\text{meas}})^2}{\sigma_j^2} \right) + \frac{(M_j - M_{j,\text{fit}})^2}{\Gamma_j^2} + \frac{(M_W - M_{W,\text{fit}})^2}{\Gamma_W^2} + \frac{(M_{l,l} - M_{l,l,\text{fit}})^2}{\Gamma_l^2} + \frac{(M_{t,t} - M_{t,t,\text{fit}})^2}{\Gamma_t^2},$$

- Jets resolution term
- Unclustered Energy term
- W mass and Top mass term

(2) Additional selection cut on resulting $\chi^2$

(3) Build templates of $M_t$ with smallest $\chi^2$ from MC for
   - Signal with different top mass
   - Each background source


(5) Fit to the data using unbinned likelihood.
Template (btag) : $M_{\text{top}} = 174.9 \pm 7.1 \text{ (stat.)} \pm 6.5 \text{ (syst.)} \text{GeV/c}^2$

Stat. error from the fit is scaled up by 1.065 to provide 68% coverage of the true mass value.

**Jet Energy Scale : 6.3 GeV**

<table>
<thead>
<tr>
<th>Category</th>
<th>Background (events)</th>
<th>$M_{\text{top}} \text{(GeV/c}^2\text{)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W + \geq 3.5$ jets</td>
<td>$7.0 \pm 0.8$</td>
<td>$174.9^{+6.7}_{-7.2}$</td>
</tr>
<tr>
<td>no constraint</td>
<td>$16.7^{+3.3}_{-7.3}$</td>
<td>$177.7^{+6.4}_{-8.4}$</td>
</tr>
</tbody>
</table>
Template Method with 0tag

CDF II Preliminary (193.5 pb⁻¹)

Constrained Fit

Unconstrained Fit

<table>
<thead>
<tr>
<th>Input (signal)</th>
<th>Output</th>
<th>(M_{\text{top}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.5 ± 3.2</td>
<td>16 ± 3</td>
<td>179.1 ± 10.5</td>
</tr>
<tr>
<td>No constraint</td>
<td>26 ± 13</td>
<td>177.5 ± 9.1</td>
</tr>
</tbody>
</table>

Template (0tag) : \(M_{\text{top}} = 179.1 \pm 10.5 \text{ (stat.)} \pm 8.4 \text{ (syst.) GeV/c}^2\)

Jet Energy Scale : 8.3 GeV

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Divided into 4 sub-samples:
- 2 tag (4 combinations)
- 1 tag (12 combinations)
  - 3.5 jets, 4 jets different S/B
- 0 tag, (24 combinations)

Mass templates built for each sub-samples.
Likelihood procedure uses information of all sub-samples simultaneously to determine best top mass.

\[ L = L_{2\text{tag}} \times L_{1\text{tag},4j} \times L_{1\text{tag},3.5j} \times L_{0\text{tag}} \]

Uncertainty is scaled up by 1.058 for 68% error coverage.
Results: Template Method

Combined likelihood curve

\[ L = L_{2 \text{tag}} \times L_{1 \text{tag}, 4j} \times L_{1 \text{tag}, 3.5j} \times L_{0 \text{tag}} \]

Likelihood vs top mass

Template: \( M_{\text{top}} = 176.7 \pm 6.0 \) (stat.) \( \pm 7.1 \) (syst.) GeV/c^2

<table>
<thead>
<tr>
<th>Source of Systematics</th>
<th>( \Delta M_{\text{top}} ) (GeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Energy Scale</td>
<td>6.8</td>
</tr>
<tr>
<td>ISR</td>
<td>1.2</td>
</tr>
<tr>
<td>FSR</td>
<td>1.2</td>
</tr>
<tr>
<td>PDFs</td>
<td>0.4</td>
</tr>
<tr>
<td>Generators</td>
<td>0.3</td>
</tr>
<tr>
<td>Background Shape</td>
<td>1.0</td>
</tr>
<tr>
<td>Other MC modeling</td>
<td>0.8</td>
</tr>
<tr>
<td>( b ) tagging</td>
<td>0.1</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.3</td>
</tr>
<tr>
<td>Total</td>
<td>7.1</td>
</tr>
</tbody>
</table>

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Summary

DLM : (Current CDF official)
\[ M_{\text{top}} = 177.8 \pm 4.5 \text{ (stat.)} \pm 6.2 \text{ (syst.) GeV/c}^2 \]

Combined Template : (less assumption, RunI check)
\[ M_{\text{top}} = 176.7 \pm 6.0 \text{ (stat.)} \pm 7.1 \text{ (syst.) GeV/c}^2 \]

(1) Now our measurements are dominated by systematics.
   - Reduce Jet Energy Scale Uncert. by a better understanding of cal. simulation.

(2) Add more data (expect : >40xRunI in RunII) (now : 1.5xRunI)

(3) Measurement of hadronic W mass
   - constrain light jet energy scale

(4) Will try to combine diff. methods, diff. channels to get one value!

Again, RunII goal is an error of 2~3 GeV
Back up slides
Some Plots (Data vs MC)

- The data are well understood by MC!
- Agreement is quite good!

(H_t : Et scalar sum of lepton, jets, Met)
DLM : Comparisons

- **Event-by-event Maximum Likelihood Mass with wide range of [125-225] GeV.**

Note: First(last) bin includes under(over) flow.

**Event likelihood**

For i-th event,

$$L_{ev}^{i} = \int L^{i}(M) dM$$

A event has one likelihood value.

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Back-Up