Top Quark Mass Measurements at CDF Run II

Kohei Yorita
University of Chicago
For the CDF Collaboration

SLAC
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Brand New Results from CDF!

Run I World Average (hep-ex/0404010)

\[ M_{\text{top}} \text{(world)} = 178.0 \pm 4.3 \text{ GeV/c}^2 \]

Current CDF Official Value !
(Template Method)

\[ M_{\text{top}} \text{(CDF)} = 173.5 \pm 4.1 \text{ GeV/c}^2 \]

Better than Run I world average

In the Lepton+Jets channel with 318 pb\(^{-1}\) data, (single meas.)

\[ M_{\text{top}} \text{(x-check)} = 173.8 \pm 4.3 \text{ GeV/c}^2 \text{ (Very New !)} \]

As a cross check, the same dataset and lepton+jets, but using Matrix Element Method (DLM)
1. The Tevatron & CDF
3. Top Quark Physics
4. Why Top Mass?
5. Top Quark Production and Decay

7. Key Points of the Measurements
8. Top Quark Mass Measurements (L+jets)
   - Template Technique: (1D and 2D)
   - Dynamical Likelihood Method (DLM)

7. Summary

Q: How many particles in me?
The TeVatron

The World’s only Top Factory!

- The Tevatron is a proton-antiproton collider with 980 GeV/beam

\[ \sqrt{s} = 1.96 \text{TeV in RunII} \ (1.8 \text{TeV RunI}) \]

Record > 1.2 \times 10^{32} !

Delivered luminosity: > 1 fb^{-1} !!!
(Run I: 110 pb^{-1})
Collider Detector at Fermilab (CDF)

◆ Run II Upgrades

> Tracking System
  - New silicon tracker
    —> b jet tagging !!!
  - New central drift chamber

> New time of flight detector

> New Forward Calorimeter
  - Jet (|η|<2.0) for top physics

  \[ \frac{\sigma_E}{E} \approx 14\% / \sqrt{E} \]

  \[ \frac{\sigma_E}{E} \approx 80\% / \sqrt{E} \]

> Extended muon coverage

> New Electronics, DAQ, Trigger

\[ \eta = -\log(\tan(\theta/2)) \]
Some CDF Pictures

Assembly hall at CDF

Move In to Collision hall! (Installation...)

Muon Chamber

COT

Si detector
CDF : Data taking efficiency is stably ~80-90%!

Now CDF has a total integrated luminosity of 800 pb$^{-1}$ on tape!!!
Top Quark Production and Decay

- **Tree level Diagram**
  - Production Cross Section
    - $\sigma(m_t=175\,GeV) \approx 6.7\,pb$
    - $\sigma(m_t=178\,GeV) \approx 6.1\,pb$
    - $\sigma(m_t=180\,GeV) \approx 5.7\,pb$
    - ~30% increase from Run I
    - $q\bar{q}$, $gg$ fractions reversed at LHC

- **Final states** (depend on W decay)
  - Dilepton ($e, \mu$)  BR=5%
  - Lepton ($e, \mu$) + jets  BR=30%
  - All jets  BR=44%
  - $\tau + X$  BR=21%

- * Higher statistics than dilepton
- * Lower background than All jets

Golden Channel

Identify “leptonic W” by selecting
(5) Isolated lepton (Et>20 GeV)
(6) Missing Et > 20 GeV
Muons +MET +4jets (2 bjets) candidate

Run 178855
Event 5504617

Number of Jets = 4
Missing Et = 45 GeV
Muon Pt = 37 GeV

Tagged Jet 1: Et = 111 GeV, Phi = 79, L2d = 7 mm
Tagged Jet 2: Et = 38 GeV, Phi = 355, L2d = 1 mm

Counting Method (lepton+jets)

CDF Run II Preliminary (318 pb⁻¹)

M_{top} = 178 GeV/c²

June 7th, 2005  Kohei Yorita, U of Chicago, SLAC Seminar
Top Quark Physics

- Interesting physics in the top sector
  - Production Mechanism
  - Direct contact with $V_{tb}$
  - Decay into $W+b$ before hadronization ($\tau = 4 \times 10^{-25}$ s)
- Unique opportunity to probe bare quark properties.
  (top spin(/correlation)? charge?)

- Top quark mass at EWSB scale
  what does this tell us?
  - Is top the gateway to new physics?

- Decay modes
- Branching ratios
- Production X section
- Resonance production
- Production kinematics
- W helicity (V-A?)
- Top Quark Mass
- Top Spin polarization
- SM
- New Physics?
- CKM matrix
- Rare decays
- FCNC e.t.c.
- Non-SM decays
Why is Top Mass Interesting?

1. Fundamental Standard Model parameter.
2. Special Relation to Higgs mass, together with W boson mass.

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

3. Top quark is heavy (~175 GeV = \( M_{b\text{-quark}} \times 35 \)) Yukawa coupling \( \sim 1 \).

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

* Near the EWSB scale.
* If we can measure strength of this coupling (i.e., \( ttH \)), a test of the Higgs sector in the SM can be possible.

4. By using the top mass as a constraint, \( tt\bar{t} \) full event reconstruction can be possible. This is very powerful for a test of SM (spin correlation, W helicity e.t.c.), or search for non-SM physics! (\( tt \) resonance e.t.c.)

RunII Goal: \( \delta M \sim 2 \text{ GeV} \) at CDF!
Top Mass Run I Review

- **Old World Average (1999)**
  \[ M_t = 174.3 \pm 5.1 \text{ GeV} (\pm 3.2 \pm 4.0) \]
  (Fermilab-TM-2084)

- **New World Average (2004)**
  \[ M_t = 178.0 \pm 4.3 \text{ GeV} (\pm 2.7 \pm 3.3) \]

- **New DØ l+j measurement,**
  (Nature 429, 638-642 (2004))

- **Standard Model Higgs Mass:**
  - Most probable: \( 96 \text{ GeV} \rightarrow 126 \pm 73 \text{ GeV} \)
  - Upper limit (95% CL): \( 219 \text{ GeV} \rightarrow 280 \text{ GeV} \)
Key Points of The Analysis

- **Backgrounds and Combinations** (jet-parton assignments)
  - **b jet tagging** is very important.
  - **How?** : SECVTX b-tagging *(excellent silicon detector!)*

B hadrons are long-lived.
Identify by Vertex of displaced tracks from primary.

- **Background Reduction**
  - Background processes are mostly non-heavy flavor (W+jets, QCD)

- **Reduce Combinatorics** (Ambiguity to form top and anti-top)
  - 2 b tag : 2 jet-parton permutations
  - 1 b tag : 6 jet-parton permutations
  - 0 b tag : 12 ways to assign 4 jets to 4 partons

Tight Tagger
- 40% / jet
- 60% / tt event

Mistag :
- ~ 0.5% / jet
Key : Jet Energy Scale
~ Precision on the determination of jet energies is necessary for $M_t$ measurements ~

All Jets are formed by dR=0.4 cone-clustering algorithm.

(1) “Relative to Central”
Calibrate forward calorimeter to central calorimeter.
- uniform response in eta correction

(2) “Absolute Scale” (to Hadron)
Correction for non-linearity and energy loss in un-instrumental region.

(3) “Out of Cone” (to Parton)
Correction for leakages outside the cone.

(4) Other : Very Small Corrections
- Multiple Interaction (minbias, func. of $N_{\text{vertex}}$)
- Underlying Event (minbias, nVtx = 0)

$$P_{\text{Parton}} = P_{\text{Calorimeter}}^{\text{jet}} \times \left( C_{\text{Rel}} - C_{\text{MI}} \right) \times C_{\text{Abs}} - C_{\text{UE}} + C_{\text{OOC}}$$
Jet Energy Uncertainty

Jet Energy Systematic
Run II 2005 : O(~3%)
Run II 2004 : O(~6%)
Now, better than Run I!

- Better understanding of Calorimeter tuning.

> In the top quark mass measurements, there are lots of constraints available to improve precision. e.g.) W Mass Constraint

Total fractional uncertainty on jet Pt

Central $\eta$ region

Run II 2005: 

Run II 2004: 

Run I: 

Corrected jet $P_T$ (GeV)

Fractional systematic uncertainty

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Top Quark Mass Measurements

~ Lepton+jets ~

1D Template Method
2D Template Method
Dynamical Likelihood Method
(Matrix Element)
1D Template Method

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

$$\chi^2 = \sum_{i=L,H} \frac{1}{\sigma_i^2} (p_{iT,i,fit} - p_{iT,i,meas})^2 + \sum_{j=x,y} \frac{1}{\sigma_j^2} (p_j^{UE,fit} - p_j^{UE,meas})^2 + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{b\ell} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_t)^2}{\Gamma_t^2} + \frac{(M_{b\ell\nu} - M_t)^2}{\Gamma_t^2}$$

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

(2) Additional selection cut on resulting $\chi^2(<9)$

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


(5) Fit to the data using unbinned likelihood.
1D Template : Subdivision

- Use 4 categories of events with different background content and reconstructed mass shape.

<table>
<thead>
<tr>
<th></th>
<th>2-tag</th>
<th>1-tag(T)</th>
<th>1-tag(L)</th>
<th>0-tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>j1-j3</td>
<td>$E_T &gt; 15$</td>
<td>$E_T &gt; 15$</td>
<td>$E_T &gt; 15$</td>
<td>$E_T &gt; 21$</td>
</tr>
<tr>
<td>j4</td>
<td>$E_T &gt; 8$</td>
<td>$E_T &gt; 15$</td>
<td>$15 &gt; E_T &gt; 8$</td>
<td>$E_T &gt; 21$</td>
</tr>
<tr>
<td>S:B</td>
<td>18:1</td>
<td>4:1</td>
<td>1:1</td>
<td>1:1</td>
</tr>
</tbody>
</table>

- Subdivision improves statistical uncertainty.
- Subdivision does not improve systematic uncertainty.

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

Expected Fraction of Sensitivity

<table>
<thead>
<tr>
<th></th>
<th>2-tag</th>
<th>1-tag(T)</th>
<th>1-tag(L)</th>
<th>0-tag</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35%</td>
<td>45%</td>
<td>9%</td>
<td>11%</td>
</tr>
</tbody>
</table>

Template RMS (GeV)

27  32  31  37
1D Template : Data Fit

**2-tag Reconstructed Top Mass (GeV/c^2)**

CDF Run II Preliminary

- Data (16 evts)
- Signal + Bkgd
- Bkgd only

**1-tag(T) Reconstructed Top Mass (GeV/c^2)**

CDF Run II Preliminary

- Data (57 evts)
- Signal + Bkgd
- Bkgd only

**Curves: expected signal and background from global best fit**

25 ev

- Log-likelihood vs top mass: Combined sample

40 ev

**M_{top}^{(1D)} = 173.2 \pm 2.9 \text{ (stat.)} \pm 3.4 \text{ (syst.) GeV/c}^2**
CDF Run II Preliminary (318 pb$^{-1}$)

<table>
<thead>
<tr>
<th>Systematic Source</th>
<th>Uncertainty (GeV/c$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Energy Scale</td>
<td>3.1</td>
</tr>
<tr>
<td>B-jet energy</td>
<td>0.6</td>
</tr>
<tr>
<td>Initial State Radiation</td>
<td>0.4</td>
</tr>
<tr>
<td>Final State Radiation</td>
<td>0.4</td>
</tr>
<tr>
<td>Parton distribution functions</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>MC statistics</td>
<td>0.4</td>
</tr>
<tr>
<td>B-tagging</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3.4</strong></td>
</tr>
</tbody>
</table>

Our measurement is systematic dominant!

- Statistical: <3.0 GeV
- Jet Energy Scale: 3.1 GeV
- Syst. Total: 3.4 GeV

This was ~ 6.2 GeV before (2004)

Big Improvement since an year ago!
CDF’s improved Jet Energy Scale uncertainty almost half since an year ago.

1D Template: ~ 4.4 GeV total uncertainty

Further Improvements of Jet Energy Scale (JES) Uncertainty

2D Template Technique

M_{top} + JES Simultaneous Fit using top mass and W mass templates

P1(m_{reco}^{top}; m_{top}, JES) and P2(m_{reco}^{jj}; m_{top}, JES)

Datasets and event selection are exactly the same as 1D template.

World’s Best Measurement!
Strong Motivation again.. : 
- Current world average uncertainty (±4.3 GeV/c^2):
  - 2.6 GeV/c^2 from JES
  - 2.7 GeV/c^2 from stat.

Jets are very hard to calibrate because there is no nice resonance..

Obviously, in the future, even now, this will give a limitation of precision!

Solution: Use W → jj Mass!
1. Identify jets coming from W
2. Reconstruct their invariant mass m_{jj}
3. m_{jj} strongly dependent on JES
4. M_W uncertainty is completely negligible (< 34 MeV)
5. m_{jj} mostly independent of M_{top}

JES from W → jj is mostly statistical

Scale with Luminosity !!!!!
How to make $M_{jj}$ template?

◆ Which jets form W?
- All Non-btagged jets pairs are taken into account equally.
- $1/3/6 \, m_{jj}$ per event with $2/1/0$ b-tag

◆ Measuring JES
- Make $M_{jj}$ templates by varying JES
- $1 \, \sigma$ defined by CDF jet group
- Fit data with $W_{jj}$ to measure JES!
JES vs Mtop vs Mjj Correlations

PDFs (Mjj | Mtop, JES=0): 2tag

$M_{jj}$ independent of $M_{top}$

$M_{top}$ strongly depends on JES

✓ So $M_{top}$ and JES are simultaneously determined in likelihood fit using shape comparisons of $M_t$ and $M_{jj}$ template to take into account these correlations.

$$-\ln L_{JES} = \frac{(JES - JES_{STD})^2}{2 \sigma_{JES}^2} = \frac{(JES - 0)^2}{2 \cdot 1^2}$$

$L_{total} = L_{2\,tag} \times L_{1\,tagT} \times L_{1\,tagL} \times L_{0\,tag} \times L_{JES}$

A Gaussian constraint on JES from the standard calibration is included in likelihood as a priori (0±1)
How about b jets?

- $M_{\text{top}}$ measurement is sensitive to energy scale of b jets.  
  (W mass is constrained.)  
- But studies show most uncertainty is shared by light quark and b jets.

→ Most b-jets energy scale can be set using $W \rightarrow jj$  
- Only 0.6 GeV/c² additional uncertainty on $M_{\text{top}}$ due to b-jet-specific systematics.

<table>
<thead>
<tr>
<th>b Jet Systematic Source</th>
<th>Uncertainty (GeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HQ Fragmentation</td>
<td>0.4</td>
</tr>
<tr>
<td>(Peterson $\varepsilon_b = 25-60 \times 10^{-4}$)</td>
<td></td>
</tr>
<tr>
<td>Semileptonic decay</td>
<td>0.4</td>
</tr>
<tr>
<td>B-jets colour flow</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.6</strong></td>
</tr>
</tbody>
</table>
Top Mass Result with 318 pb$^{-1}$

$$M_{\text{top}}^{(2D)} = 173.5^{+2.7}_{-2.6} \text{ (stat)} \pm 2.5 \text{(JES)} \pm 1.7 \text{(syst.) } \text{GeV/c}^2$$

c.f. 1D JES : 3.1 GeV

CDF Run II Preliminary

Black curve from global best fit.
JES Results with 318 pb$^{-1}$

- Agreement data-MC JES is quite good.
- Combined $W \rightarrow jj$ and prior JES yield 20% improvement

\[ JES = -0.10^{+0.78}_{-0.80} \sigma \]

Reconstructed dijet (W) mass:

Black curve from global best fit.
Statistical uncertainty

Expected $\sigma(M_{top})$ (Stat. + JES)

CDF Run II Preliminary (318 pb$^{-1}$)
Num. obs. ev., $M_{top} = 172.5$ GeV/c$^2$

Median uncert. = 4.2 GeV/c$^2$
Data: 9.2% of expts w. smaller uncert.

Likelihood vs $(M_{top}, JES)$

CDF Run II Preliminary (318 pb$^{-1}$)

✓ We are a bit on the lucky side, but reasonable. (~9.2%)
Higgs Mass (SM global fit) using only 2D Template Results

\[ M_{\text{top}} \text{ (CDF)} = 173.5 \pm 4.1 \pm 4.0 \text{ GeV/c}^2 \]

Only based on this measurement, SM global fit returned,

\[ M_{\text{Higgs}} = 94^{+54}_{-35} \text{ GeV/c}^2 \]

(upper limit (95%CL) 208 GeV/c^2)

C.f) Run I world average constraint:

\[ M_{\text{Higgs}} = 126^{+73}_{-48} \text{ GeV/c}^2 \]

Very preliminary Projection and Fit result.
Traditional calibrations of JES based on dijet and/or gamma-jet balance are expected to be limited in the future.

Using $W \rightarrow jj$ : JES uncertainty scales with statistics. So we can reach JES uncert. below 1 GeV/c$^2$ in Run II.

Reaching a total top mass uncertainty of 2 GeV/c$^2$ can be possible in Run II.
Brief summary so far……

> Results from 1D and 2D template are presented.

> Another category:
   - 1D template (Secvtx + Jet Probability Algorithm for b tagging)
     \[
     M_{\text{top}} = 173.0 \pm \frac{2.9}{2.8} \text{(stat.)} \pm 3.3 \text{ (syst.) GeV/c}^2
     = 173.0 + 4.4 - 4.3 \text{ GeV}
     \]

◆ All lepton+jets results are obtained from template technique.
  and consistent each other. (173.5(2D), 173.2(1D), 173.0(1D+JP))

◆ What else?
  Matrix Element Technique should be a good cross check and
  even can aim to have the best result.
  Dynamical Likelihood Method (DLM)!
The Method:
- Basic idea is to use matrix elements convoluted likelihood.

Event Selection:
(Not the same as template !!!)
- Exactly 4 tight jets: $E_t > 15$ GeV, $|\eta| < 2.0$
- Do not use 4 more jets and loose 4$^{th}$ jet ($E_t > 8$)
- At least one SVX b-tagged jet
- Do not use 0 b tag events. (to increase S/B.)
Likelihood Definition in DLM

For i-th event, likelihood is defined as,

\[ L^i(M_{top}) = \sum_{I_t} \sum_{I_s} \int \frac{2\pi^4}{\text{Flux}} F(z_a, z_b) f(Pt) |M|^2 w(x, y) dx \]

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

All possible combinatorial terms are taken into account.
- 12/4 sum for 1/2 b tag in total.
- \( I_t \): Jet-parton, \( I_s \): neutrino Pz \((S_w = (l+\nu)^2)\)

Analysis procedure

1. At first, all events are considered as signal \( \bar{t}t\) bar.
2. “Signal Likelihood” is calculated for each event.
3. Take joint likelihood of all events.
4. Bias correction by using “mapping function”.
   Mapping function: function of bkg fraction.

\[ \Lambda(M_{top}) = -2\ln \left( \prod_{\text{event}} L^i(M_{top}) \right) \]
DLM : Demonstration!

-2*log(likelihood) after 10 event!

Example

$-2\log(\text{likelihood})$ after 10 events is shown. The likelihood distribution for $M_{\text{top}}$ is illustrated, with $M_{\text{top}}$ values from 166 to 184. The peaks at $M_{\text{top}} = 172$ and $M_{\text{top}} = 176$ are indicated with $\sigma^-$ and $\sigma^+$ respectively. The likelihood is minimized at these points, showing the preferred values for $M_{\text{top}}$. A vertical line at $M_{\text{top}} = 174$ represents the central value, with a deviation of $\pm 1.0$.
Using SM-Matrix Element is too much assumption?

(1) CDF has probed the properties of top quark but
  - NO significant discrepancy has been observed.
    (Discovery mode ⇒ Detailed study)

(2) In the Standard Model, no fundamental/direct prediction of Mt.

(3) Too much rely on SM?
  - All Monte Carlo Events are generated based on SM.

(4) Only considering Leading-Order ME. How about NLO?
  - At first order, selecting events with exactly 4 jets minimizes it.
    Need careful study (related to ISR/FSR, PDF uncertainty)

(5) **BIG ADVANTAGE**: Using maximal event information.
    The most effective term is “propagator” (not too much assumption here!!)

< Apparently, it is worth pursuing !!!>
How likelihood dist. looks like?

Signal example: - log(likelihood)

Blue: all added up
Red: right comb.
Black: wrong comb.
Peak around 175 GeV

Bkg example: - log(likelihood)

Blue: all added up
Black: each comb.
Range [155-195] GeV
Likelihood tends to be higher in lower mass region.

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Each Background Effect
~ 2 GeV shift at 21 %.

Mapping Function
Slope changes stably.

* From 1000 pseudo expt. for each point

<table>
<thead>
<tr>
<th>Source</th>
<th>W+4jets (318pb-1)</th>
<th>Mistag</th>
<th>5.97 ± 0.80</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Wbb</td>
<td>1.87 ± 0.83</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wcc</td>
<td>0.99 ± 0.46</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wc</td>
<td>0.60 ± 0.25</td>
</tr>
<tr>
<td>Single top</td>
<td></td>
<td>0.41 ± 0.09</td>
<td></td>
</tr>
<tr>
<td>Diboson</td>
<td></td>
<td>0.39 ± 0.08</td>
<td></td>
</tr>
<tr>
<td>QCD</td>
<td></td>
<td>2.85 ± 1.33</td>
<td></td>
</tr>
<tr>
<td>Bkg Total</td>
<td></td>
<td>13.07 ± 2.19</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td></td>
<td>63 (e:39, mu:24)</td>
<td></td>
</tr>
</tbody>
</table>

Bkg : 21%
Linearly / Pull check

- No bias for central value.
- 5% correction for the statistical uncertainty.
  - Assumption is only held for tt events. (4p-4j matched.)
  - Not held if ISR/FSR gluon enters leading 4jets.
  - Not held for dilepton or backgrounds.....
DLM Results (318 pb$^{-1}$)

63 events joint likelihood

CDF Run II Preliminary (318 pb$^{-1}$)

After Background Consideration (13.1 events)

$173.8 \pm 2.7_{-2.5}^{+2.7}$ (stat only) GeV/c$^2$

Correction at background fraction of 21%.

$M_{top} \approx 173.8$ GeV/c$^2$

$M_{top} \ (DLM) = 173.8 \pm 2.7_{-2.5}^{+2.7} \ (\text{stat.}) \pm 3.3 \ (\text{syst.}) \ \text{GeV/c}^2$
**Data/MC comparison of Statistical uncertainty**

- CDF Run II Preliminary (318 pb\(^{-1}\))
- MC Signal: \(M_{\text{top}} = 175\ GeV/c^2\)
- 10% prob. MC < Data

**Systematic uncertainty**

<table>
<thead>
<tr>
<th>Sources</th>
<th>(\Delta M_{\text{top}} (\text{GeV/c}^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Energy</td>
<td>3.0</td>
</tr>
<tr>
<td>Transfer Function</td>
<td>0.2</td>
</tr>
<tr>
<td>ISR</td>
<td>0.4</td>
</tr>
<tr>
<td>FSR</td>
<td>0.5</td>
</tr>
<tr>
<td>PDF</td>
<td>0.5</td>
</tr>
<tr>
<td>Generator</td>
<td>0.3</td>
</tr>
<tr>
<td>bkg fraction (6.7%)</td>
<td>0.6</td>
</tr>
<tr>
<td>bkg Modeling</td>
<td>0.6</td>
</tr>
<tr>
<td>b tagging</td>
<td>0.2</td>
</tr>
<tr>
<td>b jet energy</td>
<td>0.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3.3</strong></td>
</tr>
</tbody>
</table>
Data/MC Comparisons

◆ Event-by-event Maximum Likelihood Mass
Note: Last bin includes overflow.

$$L_{ev}^i = \int_{155}^{195} L^i(M) dM$$

Event likelihood
For i-th event,
Improvement for JES uncertainty?
~ Hadronic W(jj) Mass ~

Remove W Mass constraint from likelihood. Instead, top Mass is constrained. Then pick up 2 jets W mass At maximum likelihood point.

(7) We have a confidence to use W Mass as a constraint!

(2) In principle, DLM can use this to reduce jet energy uncertainty like 2D Template!!!

- Future improvement here!!!
Summary

> Tevatron is performing very well. Delivered luminosity more than 1 fb\(^{-1}\). CDF recorded >800 pb\(^{-1}\) data

> 2D template (\(M_t+\text{JES}\)) provided the best measurements in the world.
  -- Lots of work to reduce systematics,
  - especially JES!!!

> New techniques are developed. DLM and template results are consistent.
> Other technique/channel (dilepton/all jets)
  are coming very soon!

> Plan to publish these two results by the end of this summer.(PRDs)

> Combination on going..

Will reach goal of measuring \(m_t\) to ~ 2 GeV in Run II! Getting Close!!!

CDF Run 2 Preliminary (June 2 2005)

- Run 1 World Average (Run 1 only)
  \[ 178.0 \pm 2.7 \pm 3.3 \]

- Run 1 D0 Lepton+Jets (Run 1 only)
  \[ 180.1 \pm 3.6 \pm 3.9 \]

- Run 1 CDF Lepton+Jets (Run 1 only)
  \[ 176.1 \pm 5.1 \pm 5.3 \]

- Lepton+Jets: \(M_{\text{top}, \text{reco}} + W \rightarrow jj\) (L = 318 pb\(^{-1}\))
  \[ 173.5 \pm 2.7 \pm 3.0 \]

- Lepton+Jets: DLM (L = 318 pb\(^{-1}\))
  \[ 173.8 \pm 2.7 \pm 3.3 \]

- Dilepton: \(\nu\) weighting (L = 200 pb\(^{-1}\))
  \[ 168.1 \pm 11.0 \pm 8.6 \]

- Dilepton: \(\phi\) of \(\nu\) (L = 193 pb\(^{-1}\))
  \[ 170.0 \pm 16.6 \pm 7.4 \]

- Dilepton: \(P_z(t\bar{t})\) (L = 193 pb\(^{-1}\))
  \[ 176.5 \pm 17.2 \pm 6.9 \]
Backup
The Central Calorimeters ($\eta = 0.2-0.6$) are better calibrated/understood. Correction factor is a function of $Pt$ and $\eta$, extracted from dijet balance. (check $\gamma$ -jet balance) 

Uncertainty : ~ 1% level (depends on $\eta$ region and $Pt$) - estimated by varying the selection requirements and fitting procedure.
JES : Absolute Scale Correction (to hadron level)

Correction for non-linearly and un-instrumental region, based on MC by using single particles (pion, protons, neutrons). We tuned MC much better and map to hadron level from cal. level.

Uncertainty : 2 ~ 3% level (strong dependency on Pt)
- Single particle E/P, fragmentation.
- Smaller error : MC/data in tower boundaries, cal. calibration with time.
JES : Out of Cone Correction (to parton level)

Correction for energy leakage outside the cone. (0.4 for top physics)
0.4 is small compared to typical QCD events since tt events are crowded but Lose >10% energy for jets with Et<20 GeV.

Uncertainty : 2 ~ 8% level (strongly depends on Pt)
- Difference between data and MC is taken into account.
(We can compare energy sum outside the cone of jets.)
Results on Blind Sample

5 blinds samples generated by CDF Top Mass group

0.3 GeV is stat. only.

All is w/l 1 standard deviation.

* Some are Pythia, Others are Herwig. (P - H Syst. = - 0.3 GeV)

We observed “NO BIAS”.
DLM measurements of nonSM model (tt resonance X(700))

Sample: X(700) to tt (M=175 GeV), top decay follows SM

Reconstructed mass from 30 events P.E. is $176.8 \pm 0.4$ GeV. If X(700) is 100% in the sample, we see 2 GeV bias.
Additional Checks on DLM

16 events overlap between this round and before (162 pb\(^{-1}\))

**-4.1 GeV**

Entries: 16
Mean: -2.188
RMS: 18.83
Underflow: 0
Overflow: 0
Integral: 16
### Transfer function \( w(x, y) \)

<table>
<thead>
<tr>
<th>definition</th>
<th>Sample</th>
<th>Other</th>
</tr>
</thead>
</table>
| \[
\frac{E_T(\text{Parton}) - E_T(\text{Jet})}{E_T(\text{Parton})}
\] | All Mass 130-230, 5 GeV step averaged | 1/Nx weight |

**Comment**
- Slicing “Et” of jets into 10 bins and eta into 3 bins
- To minimize top mass dependence of TF. 130-230 is wide enough for search range.
- Avoid double counting

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Parton Energy is inferred by random generation along the T.F.
## Details on Systematic Uncertainty

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<tr>
<th>Systematic</th>
<th>TMT 2-D</th>
<th>TMT 1-D</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta M_{\text{top}}$ (GeV)</td>
<td>$\Delta \text{JES} (\sigma)$</td>
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<tr>
<td>JES</td>
<td>(2.5 )</td>
<td>-</td>
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<td>$b$-jet modeling</td>
<td>0.6</td>
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<td>ISR</td>
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<td>MC statistics</td>
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<td>Method</td>
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<tr>
<td><strong>TOTAL</strong></td>
<td>1.7</td>
<td>0.36</td>
</tr>
</tbody>
</table>
Details on Systematics: ISR/FSR

- In Run I, switch ISR on/off using PYTHIA, $dM_{\text{top}} = 1.3\text{GeV}$

- In Run II: systematic approach
  ISR/FSR effects are governed by DGALP evolution eq.:

\[
\langle P_t \rangle \text{ of the DY(II) as a function of } Q^2
\]

CDF Run II preliminary (193pb$^{-1}$)

\[
\langle P_t \rangle \text{ versus } \log(M^2)
\]

Pt(tt) at generator

ISR syst: 0.4 GeV
Details on Systematics: b jet

Application of $W \rightarrow jj$ to $M_{top}$ Measurement

Application of $W \rightarrow jj$ to b-jets
→ must consider additional uncertainties from b-jets:

Studied in CDF Note 7238, 7252

- Heavy quark fragmentation: 0.4 GeV/c$^2$
- Semileptonic decays: 0.4 GeV/c$^2$
- Color flow: 0.3 GeV/c$^2$
- Total: 0.6 GeV/c$^2$