Top Quark Properties at the Tevatron

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on behalf of the CDF and DØ collaborations

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Top Quark at the Tevatron

- **Fermilab Tevatron:**
  - World’s highest particle energy collisions
  - ~4 miles circumference protons-antiprotons

  - $\sqrt{s} = 1.8$ TeV
  - Discover top quark in 1994!
  - Integrated luminosity 120 pb$^{-1}$

- **Run II (2001-present)**
  - $\sqrt{s} = 1.96$ TeV
  - Integrated luminosity by April, 05:
    - In tape ~600pb$^{-1}$
    - Analyzed up to ~350 pb$^{-1}$

- 2 multi-purpose detectors
  - $D\emptyset$ and CDF

World’s only top factory!
Run II Detectors

- Inner Silicon Tracking
- Tracking Chambers
- Solenoid
- EM and Hadronic Calorimeters
- Muon Detectors
Top Quark Physics

- Top is very massive \( \Rightarrow \) It probes physics at much higher energy scale than the other fermions.
  
  \[ M_{\text{top}} \text{ (Run I world average)} = 178 \pm 4.3 \text{ GeV} \]

- Top decays before hadronizing \( \Rightarrow \) momentum and spin information is passed to its decay products. No hadron spectroscopy.
  
  \[ \tau_{\text{top}} \approx 10^{-24} \text{ sec} \]

- Top mass constrains the Higgs mass \( \Rightarrow \) \( M_{\text{top}} \), enters as a parameter in the calculation of radiative corrections to other Standard Model observables it is also related, along with the mass of the W boson, to the that of the Higgs boson.

12 orders of magnitude for the fundamental SM fermions!!!!
In proton-antiproton collisions at TeVatron energies, top quarks are primarily produced in pairs via the strong interactions.

\[ \sigma(\bar{p}p \rightarrow t\bar{t} @ M_{top} = 178 GeV) \approx 6.1 \text{ pb} \]

\(~85\%\) and \(~15\%\) from quark and gluon interactions, respectively.

\(~\text{one top event every 10 BILLION inelastic collisions}\)
Top Quark Decay

- $M_{\text{top}} > M_W$ decays to real Ws
  - $\text{Br}(t \rightarrow Wb) \sim 100\%$

- Final state is given by $W^+$ and $W^-$ decays
  - $\text{Br}(W \rightarrow \text{leptons}) = 1/3$
  - $\text{Br}(W \rightarrow \text{quarks}) = 2/3$

- Excellent branching ratio
- Large Signal/Background
- Larger branching ratio
- Reasonable Signal/Background
- Less statistics
- Excellent S/B
- Under constrained kinematics
- Over-constrained kinematics

Br($W \rightarrow \text{leptons}$) = 1/3
Br($W \rightarrow \text{quarks}$) = 2/3
The Top Properties Tour

- Top Width
- Top Mass
- Top Spin
- Top Charge

W helicity
CP Violation
Anomalous Couplings

Production X-Section
Production Kinematics
Resonance Production
Top Spin Polarization

|V_{tb}|
Rare/non SM decays
Branching Fractions
In this Talk

- W helicity
- Top Mass
- Top Spin Polarization
- Resonance Production
Event Topology

- Energetic, central, and spherical
- Missing transverse energy ($E_T$) from neutrino in lepton+jets and dilepton modes
- High transverse energy, $E_T$, jets
- Two b-jets
- Possible additional jets from gluon radiation (ISR, FSR)
- Events are busy:
  - need to reconstruct parton level to measure top properties
  - different ways to assign jets to partons

- General characteristics of the background:
  - No neutrinos, less $E_T$
  - No b-jets
  - Leptons could be fakes (less isolated)
  - Less central
Tagging b-jets

- Use different properties of the B hadrons to identify (tag) them
- Reduce backgrounds from light-quark/gluon jets
- Reduce combinatorics effects

B hadrons are long-lived

Vertex of displaced tracks

60%  
0.5%  

Top Event Tagging Efficiency

False Tag Rate (QCD jets)
Jet Energy Scale (JES)

- Determine the true parton energy from measured jet energy in a cone

Complex detector properties

Algorithms with complex behavior such as cone, cone-midpoint, KT

Complex underlying physics

Need to correct for detector, algorithm and physics effects to obtain the true energy of the jets: Jet Energy Scale (JES)
How well do we know the energy of the jets (or quarks)?

Events with lots of jets => dominant uncertainty for some top analyses, i.e, top mass in lepton+jets channel.

Also expect significant improvements from D∅ very soon.

-3% jet $P_T$ uncertainty in top events

~factor of 2 decrease!
Top Quark Mass Measurements
Publishing Top Quark Masses for 15 years

In 2010 this point should have negligible uncertainties

lower limits prior to discovery in $e^+e^-$ and $pp$ collisions and from the $W$ boson width

from EW fits
direct measurement by CDF
direct measurement by D0
world average from direct measurements

new D0 analysis
Top Quark Mass

The mass of the top quark is given by

\[ m_{\text{top}} = 178.0 \pm 15.7 \text{ GeV/c}^2 \]

This result is not included in the Tevatron average. The Tevatron Run-I result is 178.0 \pm 4.3 GeV/c^2.

**Observations:**
- **CDF di-l:** 167.4 \pm 11.4 GeV/c^2, weight 6%
- **DØ di-l:** 168.4 \pm 12.8 GeV/c^2, weight 7%
- **CDF l+j:** 176.1 \pm 7.3 GeV/c^2, weight 22%
- **DØ l+j:** 180.1 \pm 5.3 GeV/c^2, weight 58%
- **CDF all-j:** 186.0 \pm 11.5 GeV/c^2, weight 7%

\[ \chi^2 / \text{dof} = 2.6 / 4 \]

**Legend:**
- High \( Q^2 \) except \( m_t \), 68% CL
Run II began in March 2001:
- take data, commissioning detectors,
- calibrate detectors,
- tune Monte Carlo and detector simulation,
- prepare analysis

By the end of 2004 after 3 years of Run II running the top mass measurement did not reach to Run I precision (~5.1 GeV)

Better precision comes from l+jets (golden channel), but are we looking at the same top among channels?

By the end of Run I, the JES uncertainty was as large as the statistical uncertainty ~3.5 GeV

Different methods: try to optimize the statistical and systematic performance

Results by the end of 2004

<table>
<thead>
<tr>
<th>Channel</th>
<th>CDF Run 2 Preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dilepton: $\phi$ of $\nu$</td>
<td>170.0 ± 16.6 ± 7.4</td>
</tr>
<tr>
<td>(L = 193pb$^{-1}$)</td>
<td></td>
</tr>
<tr>
<td>Dilepton: $p_T$ $t\bar{t}$</td>
<td>176.5 ± 17.2 ± 6.9</td>
</tr>
<tr>
<td>(L = 193pb$^{-1}$)</td>
<td></td>
</tr>
<tr>
<td>Dilepton: $\nu$ weighting</td>
<td>168.1 ± 11.0 ± 9.8</td>
</tr>
<tr>
<td>(L = 200pb$^{-1}$)</td>
<td></td>
</tr>
<tr>
<td>Lepton+Jets: Multivariate</td>
<td>179.6 ± 6.4 ± 6.8</td>
</tr>
<tr>
<td>(L = 162pb$^{-1}$)</td>
<td></td>
</tr>
<tr>
<td>Lepton+Jets: Template</td>
<td>177.2 ± 4.9 ± 6.6</td>
</tr>
<tr>
<td>(L = 162pb$^{-1}$)</td>
<td></td>
</tr>
<tr>
<td>Lepton+Jets: DLM</td>
<td>177.8 ± 4.5 ± 6.2</td>
</tr>
<tr>
<td>(L = 162pb$^{-1}$)</td>
<td></td>
</tr>
<tr>
<td>Run 1 CDF Lepton+Jets (only)</td>
<td>176.1 ± 5.1 ± 5.3</td>
</tr>
<tr>
<td>Run 1 D0 Lepton+Jets (only)</td>
<td>180.1 ± 3.6 ± 3.9</td>
</tr>
<tr>
<td>Run 1 World Average (only)</td>
<td>178.0 ± 2.7 ± 3.3</td>
</tr>
</tbody>
</table>

Top mass (GeV/c$^2$)
Template Technique

- Determine mass of the top quark using a quantity strongly dependent on the top quark mass \( M_{\text{top}} \) (usually Reconstructed \( M_{\text{top}} \)).

- **Determine the Reconstructed \( M_{\text{top}} \) per event**: Minimize a \( \chi^2 \) expression for the resolutions and kinematic relationships in the ttbar system. Choose jet to parton assignment and \( P_{\nu z} \) based on best fit quality. Build signal and background templates.

- **Obtain the measurement from the data**: Compare Reconstructed \( M_{\text{top}} \) from data with same from randomly generated and simulated signal at various input top mass (\( M_{\text{top}} \)) and backgrounds using an unbinned likelihood fit.

\[
L = L_{\text{shape}} \times L_{\text{background}}
\]
Template Analysis at CDF

- Improve statistical power of the method dividing the sample in 4 subsamples that have different background contamination and different sensitivity to the top mass

- Extend 1-D template (only on reconstructed $M_{top}$) to maximize sensitivity to JES:
  - $M_{top}$ and JES are simultaneously determined in likelihood fit using shape comparisons of reconstructed $M_{top}$ and reconstructed $M_{jj}$ distributions, taking correlations between them

- Use a priori CDF information on JES (page 8): JES Gaussian constraint (mean=0, width=1 $\sigma$)
  
  \[-\ln L_{JES} = \frac{(JES - JES_{STD})^2}{2\sigma^2_{JES}} = \frac{(JES - 0)^2}{2 \cdot 1^2}\]

<table>
<thead>
<tr>
<th>Sample</th>
<th># b-tags</th>
<th>Jet $E_T$ cut [GeV]</th>
</tr>
</thead>
</table>
| 2-tag  | 2        | 3 jets w/ $E_T > 15$
           |           | 4th jet w/ $E_T > 8$
| 1-tag(L)| 1        | 3 jets $E_T > 15$
           |           | 4th jet $8 < E_T < 15$
| 1-tag(T)| 1        | 4 jets $E_T > 15$
| 0-tag  | 0        | 4 jets $E_T > 21$  

4/21/05
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Template Results from CDF

\[ M_{\text{top}} = 173.5^{+3.7}_{-3.6} \text{(stat + JES)} \text{ GeV/c}^2 \] NEW
Template Results from CDF

Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>( \delta M_{\text{top}} ) (GeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-jets modeling</td>
<td>0.6</td>
</tr>
<tr>
<td>Method</td>
<td>0.5</td>
</tr>
<tr>
<td>ISR</td>
<td>0.4</td>
</tr>
<tr>
<td>FSR</td>
<td>0.6</td>
</tr>
<tr>
<td>Background shape</td>
<td>1.1</td>
</tr>
<tr>
<td>PDF</td>
<td>0.3</td>
</tr>
<tr>
<td>Other MC modeling</td>
<td>0.4</td>
</tr>
<tr>
<td>Total</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Most of these can be reduced with more data

\[
M_{\text{top}} = 173.5^{+3.7}_{-3.6} \text{ (stat + JES)} \pm 1.7 \text{ (syst) GeV/c}^2
\]

\[
= 173.5^{+4.1}_{-4.0} \text{ GeV/c}^2
\]

Measurement is more precise than the current world average!

CDF Run II Preliminary (318 pb\(^{-1}\))
Template Results from DØ

- Topological
  - No b-tagging requirement
  - Construct a discriminant using topological variables ($D_{LB}$) to improve S/B

$M_{\text{top}} = 173.5 \pm 5.8\text{(stat)}^{+7.8}_{-7.1}\text{(syst)} \text{ GeV/c}^2$

- At least one b-tagged jet:
  - no requirement on discriminant $D_{LB}$
  - First top mass at DØ top mass measurement with b-tagging

$M_{\text{top}} = 170.6 \pm 4.2\text{(stat)} \pm 6.0\text{(syst)} \text{ GeV/c}^2$

Reconstructed $M_{\text{top}}$ (GeV)
Matrix Element Technique

- Determine mass of the top quark evaluating a probability using all the variables in the event, integrate over all unknowns

\[ P(x; M_{top}) = \frac{1}{\sigma} \int \frac{d^n\sigma(y; M_{top})}{d\sigma(y)} dq_1 dq_2 f(q_1) f(q_2) W(x, y) \]

- Sum over all permutations of jets and neutrino solutions

- Background process probabilities are or not be explicitly included in the likelihood

- Top mass: maximize \( \prod_i P_i(x; M_{top}) \)
  - Each event has its own probability
  - Correct permutation is always considered (along with the other eleven)
  - All features of individual events are included, thereby well measured events contribute more information than poorly measured events

\( W(y, x) \) is the probability that a parton level set of variables \( y \) will be measured as a set of variables \( x \)

\( d^n\sigma \) is the differential cross section; LO Matrix element

\( f(q) \) is the probability distribution that a parton will have a momentum \( q \)
Matrix Element at DØ

- Last result from Run I: June, 2004
  - Reduced the statistical uncertainty from 5.6 to 3.6 (expected error from 7.4 to 4.4) => 2.4 times more data
  - Total uncertainty from 7.3 (lepton+jets CDF) to 5.3 (D0)

- Run II results from DØ and CDF coming soon!

Nature Vol 429, Page 640
Other Matrix Element based $M_{\text{top}}$

- **DLM**: only a signal probability, requires b-tagging

- New results with decrease JES and more data coming soon!

\[ M_{\text{top}} = 177.8 \pm 4.5 \text{ (stat)} \pm 5.0 \text{ (syst)} \text{ GeV/c}^2 \]

- **Ideogram**: Uses same kinematic fit as DØ template method, and includes $D_{\text{LB}}$ discriminant in likelihood fit

\[ M_{\text{top}} = 177.5 \pm 5.8 \text{ (stat)} \pm 7.1 \text{ (syst)} \text{ GeV/c}^2 \]
How the analyses solve the problem of under-constrained kinematics?

- Integrate over 2 variables
- Weight neutrino solutions
- Follow template procedure

\[ \delta M_{\text{top}} \sim 9 \text{ GeV}! \]

\[ M_{\text{top}} = 168.1 \pm 11.0 \text{ (stat)} \pm 8.6\text{(syst)} \text{ GeV/c}^2 \]

\[ S/B \sim 3/1 \]

MPV expectation with 320pb\(^{-1}\) \[ M_{\text{top}} = 155 \pm 14.0 \text{ (stat)} \pm 7.0\text{(syst)} \text{ GeV/c}^2 \]
Summary of Top Mass Results

<table>
<thead>
<tr>
<th>Source</th>
<th>Mass (GeV/c^2)</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>World Average</td>
<td>178.0</td>
<td>±2.7 ± 3.3</td>
</tr>
<tr>
<td>(Run 1 only)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D0 Dilepton</td>
<td>155.0</td>
<td>±14.0 ± 7.0</td>
</tr>
<tr>
<td>(L = 230 pb^{-1})</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>(L = 230 pb^{-1})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CDF Lepton+Jets</td>
<td>173.5</td>
<td>±3.7 ± 1.7</td>
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<tr>
<td>(L = 318 pb^{-1})</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
W helicity
Are there new interactions at this high energy scale?

Measuring the helicity of the $W$ boson examines the nature of the $tbW$ vertex, and provides a stringent test of Standard Model

$W_0$ Longitudinal fraction $F_0$

$W_-$ Left-Handed fraction $F_-$

$W_+$ Right-Handed fraction $F_+$

V-A coupling

V-A SUPPRESSED
In the Standard Model (with $m_b=0$):

$$w(\cos \varphi_{\ell \bar{b}}) = F_- \cdot \frac{3}{8} (1 - \cos \varphi_{\ell \bar{b}})^2 + F_0 \cdot \frac{3}{8} (1 - \cos^2 \varphi_{\ell \bar{b}}) + F_+ \cdot \frac{3}{8} (1 + \cos \varphi_{\ell \bar{b}})^2$$

The $P_T$ of the lepton has information about the helicity of the W boson:

- **longitudinal**: leptons are emitted perpendicular to the W (harder lepton $P_T$)
- **left-handed**: leptons are emitted opposite to W boson (softer lepton $P_T$)

In the Standard Model (SM):

- $F_- = 0.3$
- $F_0 = 0.7$
- $F_+ = 0$
**Longitudinal Fraction, F_0**

- Likelihood analysis of P_T spectrum
- Combined lepton+jet and dilepton samples: 70 events

- Likelihood analysis of cos θ*
- Combined lepton+jet and dilepton samples: 31 events

\[
F_0 = 0.27 \pm 0.35 \text{ (stat + syst)}
\]

\[
F_0 < 0.88 \text{ @ 95\%CL}
\]

- Assuming F_+ = 0
- Dominated by statistical uncertainties

- Run I best result (DØ) 125 pb\(^{-1}\): 0.56 \(\pm\) 0.31 using ME Technique
Likelihood on $\cos\theta^*$

Topological selection: **80 events**

$b$-tagged selection: **31 events**

Assuming $F_0=0.70$

Dominated by statistical uncertainties

*Run I best result (CDF) 109pb$^{-1}$: $F_+<0.18$ @95% CL using $\cos\theta^*$
ttbar  Spin  Correlations
ttbar Spin Correlations

- Agreement between $\sigma_{\text{ttbar}}$ experimental and theoretical expectations => assume top has spin 1/2.

- Since $\Gamma_t \sim 1.4$ GeV
  - spin transferred to final state (decay products correlated to top quark spin).
  - use polarization properties of the top quark as additional observables for testing the SM and to search for New Physics.

- Can be observed in single-top since it is produced 100% correlated.

- Some net polarization of top quark in pair production: $N(t_\uparrow) = N(t_\downarrow)$ but in the proper spin quantization axes a large asymmetry between like- and unlike-spin configurations can be observed

$\Leftarrow k = 0.88$ SM, correlation coefficient between top- antitop spin polarizations.

- $\text{DØ Run I: } k > -0.25 @ 68\% \text{ CL.}$
- $\text{CDF Run II preliminary sensitivity study } 340\text{pb}^{-1} \sigma = 1.6, 2\text{fb}^{-1} \sigma = 0.62.$
Search for ttbar Resonances
ppbar→X→ttbar

- Test ttbar production from new sources such as narrow resonances

\[ p\bar{p} \rightarrow X^0 \rightarrow t\bar{t} \]

- Many models of New Physics predict new particles coupled to the 3rd generation, in particular the top quark.

- Better analyses techniques, from templates to ME based searches.

- Use the differential cross section to reconstruct the \( M_{ttbar} \) at parton level.

- Follow template procedure for establishing limits.

---

**SM ttbar (Pythia)**

Red: parton level \( M_{ttbar} \)

Blue: reconstructed \( M_{ttbar} \)

**Run I search of Z' with G=1.2\%M:**

CDF(D0): \( M_{Z'} > 480(560) \) GeV @ 95% CL
Conclusions

- Top quark physics program at the Tevatron Run II is extremely rich: from QCD tests to search for New Physics.
- Challenging final states:
  - requires to fully use detector capabilities
- Method of extraction of observables are getting far more sophisticated:
  - making maximal use of the statistics
  - smarter ways to account for systematic uncertainties
- We are moving from discovery to precision measurements of top quark properties.

\[ M_{\text{top}} = 173.5^{+4.1}_{-4.0} \text{ GeV/c}^2 \]
Top Quark at APS

- Top Mass in all-jets channel CDF, Georghe Lungu, Top Quark Session I, yesterday: using ME
- Top Mass in dilepton channel CDF, Tuula Maki, Top Quark Session I, yesterday: using Pz ttbar
- Top Mass in dilepton channel CDF: Simon Sabik, Top Quark Session I, yesterday: using neutrino weighting
- Top Mass in lepton+jets channel CDF: Jean-Francois Arguin, Top Quark Session I, yesterday: using 2-D template
- Top Mass in lepton+jets CDF/LHC: James Lamb, Top Quark Session I, yesterday: using decay length
- Top Mass in lepton+jets D0: Philipp Schienferdecker, Top Quark Session II, today: using D0 matrix element in Run II
- Top Mass in lepton+jets D0: Robert Harrington, Top Quark Session II, today: using D0 matrix element in Run II + b-tagging
- Top Mass in dilepton D0: Petr Homola, Top Quark Session II, today: neutrino weighting
- Top Mass in lepton+jets D0: Martijn Mulders, Top Quark Session II, today: matrix element Ideogram
- Top Mass in dilepton D0: Jeff Temple, Top Quark Session II, today: neutrino weighting
- X->ttbar at CDF: Top Quark Session III, Brandon Parks, Valentin Necula, NN and ME technique
- W-helicity: Top Quark Session III, Bryan Gmyrek, cos(theta*)
**$M_{top}$ Measurement in lepton+jets Channel**

- Larger branching ratio
- Reasonable Signal/Background
- Over-constrained kinematics

**Signature**
- Two b quarks
- Two light quarks
- High $p_T$ lepton
- Neutrino (undetected)
  - $P_x$ and $P_y$ from $E_T$ conservation
  - $P_z$ constrained by kinematics

Leading 4 jets combinatorics
- 12 possible jet-parton assignments
  - 6 with 1 b-tag
  - 2 with 2 b-tags

ISR + FSR: Extra jets from initial/final state gluons

**Typical event selection:**
- One high $p_T$ lepton (20 GeV)
- 4 or more jets (>15 GeV)
- $E_T$ (>20 GeV)
- b-tagging (optional)

Two different techniques: Template and Matrix Element based
\( M_{\text{top}} \) Measurement in Dilepton Channel

- Less statistics
- Excellent S/B
- Underconstrained kinematics: need to assume knowledge of some quantity
- Less combinatorics: 2 jets
- Smaller jet systematics

**Signature:**
- Two b quarks
- Two high \( P_T \) leptons
- Two neutrinos

**Typical event selection:**
- One high \( P_T \) lepton (>15 GeV)
- Oppositely charged high \( P_T \) lepton or isolated track (>15 GeV)
- Two or more high \( P_T \) jets (>20 GeV)
- \( E_T > 25 \text{ GeV} \)

**Backgrounds:**
- Diboson, Drell-Yan, Z\( \rightarrow \)tautau, W+jets (fake lepton)