Top Quark Properties at the Tevatron

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on behalf of the CDF and D0 Collaborations
Tevatron program explores all top properties as well as possible sources of new physics:

**top quark production**
- top pair production
- Single top production

**top quark properties**
- Mass, spin, width, charge

**top quark decay**
- W boson helicity in top decays
- Probe the W-t-b vertex

**Exotic sources of top quarks**
- Non SM top
- Forward-backward asymmetries
Top mass
Top spin
Top width
Top charge
Top quark mass is a fundamental parameter of the Standard Model.

Since $M_{\text{top}}$ is very large, quantum loops involving top quarks are important when calculating precision observables.

Measuring the $W$ boson mass and top quark mass precisely allows for prediction of the mass of the Higgs boson (...if it exists!) and constrain new physics.
Measure jets not partons
Jet-parton assignment
QCD radiation
Undetected neutrino energy

Jet energy scale uncertainty:
Need corrections to obtain parton energy
Jet Energy Scale
$\sigma_{\text{JES}}/\text{JES} \approx 3\%$ to $6\%$
dominant contribution to $\delta M_{\text{top}}(\text{syst})$

Can be reduced via
in situ calibration of the JES using the $W$ mass

Constrain the invariant mass of the non $b$-tagged jets to be 80.4 GeV/$c^2$

Uncertainty on JES scales directly with statistics!
High Precision Mass Measurement at CDF

CDF Dilepton and Lepton+Jets combination

Template Method:
Consider a set of observables $x$ sensitive to $M_{\text{top}}$.
Evaluate and plot the set for each event → “Templates”
Maximize a likelihood where observed distributions are compared to expectations for different $M_{\text{top}}$ and signal fractions $f_{\text{ttbar}}$

$$\mathcal{L}_{\text{sample}} \propto \prod_{\text{events}} \prod_{\bar{x}} \mathcal{L}_{\text{shape}}(x_i | f_{\text{ttbar}}, M_{\text{top}})$$

Main uncertainties:
Jet-energy-scale, MC modeling

CDF (4.8 fb$^{-1}$) Joint Template Analysis

$M_{\text{top}} = 171.9 \pm 1.1(\text{stat+JES}) \pm 0.9(\text{syst})$ GeV/c$^2$
**ME Method:**
Define the probability $P_{\text{evt}}$ that the observed kinematics arise from possible signal or bkg kinematics at parton level, then maximize $L = \prod P_{\text{evt}}(M_{\text{top}}, \text{JES}, f_{\text{top}}(M_{\text{top}}, \text{JES}))$.

$$P_{\text{evt}}(\tilde{x}) = f_{\text{top}} \cdot P_{\text{sig}}(\tilde{x}, m_t, \text{JES}) + (1 - f_{\text{top}}) P_{\text{bkg}}(\tilde{x}, \text{JES})$$

$$P_{\text{sig}}(\tilde{x}) = \frac{1}{\sigma(m_t, \text{JES})} \int f(q_1) dq_1 f(q_2) dq_2 \times |M(\tilde{y})|^2 \phi(\tilde{y}) dy \times W(\tilde{x}, \tilde{y}; \text{JES})$$

D0 (3.6 fb\(^{-1}\)) Lepton + Jets Matrix Element Technique

$M_{\text{top}} = 173.7 \pm 0.8(\text{stat}) \pm 0.8(\text{JES}) \pm 1.4(\text{syst})$ GeV/c\(^2\)
Tevatron Combination

**Mass of the Top Quark (*Preliminary*)**

- CDF-I di-l: $167.4 \pm 10.3 \pm 4.9$
- D0-I di-l: $168.4 \pm 12.3 \pm 3.6$
- CDF-II di-l: $171.2 \pm 2.7 \pm 2.9$
- D0-II di-l: $174.7 \pm 2.9 \pm 2.4$
- CDF-I l+j: $176.1 \pm 5.1 \pm 5.3$
- D0-I l+j: $180.1 \pm 3.9 \pm 3.6$
- CDF-II l+j: $172.1 \pm 0.9 \pm 1.3$
- D0-II l+j: $173.7 \pm 0.8 \pm 1.6$
- CDF-I all-j: $186.0 \pm 10.0 \pm 5.7$
- CDF-II all-j: $174.8 \pm 1.7 \pm 1.9$
- CDF-II trk: $175.3 \pm 6.2 \pm 3.0$
- Tevatron March'09: $173.1 \pm 0.6 \pm 1.1$

**Tevatron (March 2009):**

\[ M_{\text{top}} = 173.1 \pm 0.6 \text{ (stat)} \pm 1.1 \text{ (syst)} \text{ GeV/c}^2 \]

Best results of each experiment in each channel from Run I and Run II combined

Results from different channels and methods are consistent

Take into account the statistical and systematic uncertainties and their correlations


Precision now limited mainly by systematic uncertainties

Joint effort on improving knowledge of systematics
Magnitude of systematic uncertainties are comparable, dominated by sources which should continue to scale with the statistics of the sample.

Top quark mass precision for single measurement already well beyond RunII goals

### Dilepton and Lepton+Jets

<table>
<thead>
<tr>
<th>Systematics Source</th>
<th>$\Delta M_{\text{top}}$ [GeV]</th>
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<td>JES</td>
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<tr>
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<tr>
<td>Color Reconnection</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>0.9</strong></td>
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</table>
1 week ago, a new CDF measurement of the top quark mass has been approved. This is the most precise measurement ever done, even more precise than the world average.

The technique used is similar to the Matrix Element Method. Uses a Neural Network discriminant to distinguish signal and background.

CDF (4.8 fb^{-1}) Lepton+Jets, Multivariate:
\[ M_{\text{top}} = 172.8 \pm 0.7 \text{ (stat)} \pm 0.6 \text{ (JES)} \pm 0.8 \text{ (syst)} \text{ GeV/c}^2 = 172.8 \pm 1.3 \text{ (total) GeV/c}^2 \]
Direct measurement of top antitop mass difference

Mass difference would imply \textit{CPT-violation}
Measured in lepton + jets events (ME technique)

First time measured for a “bare quark”
Consistent with SM expectations

PRL 103, 132001 (2009)

D0 (1 fb$^{-1}$):
$\Delta M_{\text{top}} = 3.8 \pm 3.7$ GeV/c$^2$

Statistics limited
Top Antitop Spin correlations

Top spins are correlated only if *top lifetime is short enough*
Spin-spin correlation is observable in the top quark decay products

\[
\kappa = \frac{N(\uparrow \uparrow) + N(\downarrow \downarrow) - N(\uparrow \downarrow) - N(\downarrow \uparrow)}{N(\uparrow \uparrow) + N(\downarrow \downarrow) + N(\uparrow \downarrow) + N(\downarrow \uparrow)}
\]

CDF Run II preliminary \( L = 4.3 \text{ fb}^{-1} \)

Helicity Axis
\( K(\text{SM}) = 0.40 \)

CDF (4.3 fb\(^{-1}\)) Lepton+Jets:
\( K = 0.60 \pm 0.50 \) (stat) \( \pm 0.16 \) (syst)

D0 (4.2 fb\(^{-1}\)) Dilepton:
\( K = -0.17 + 0.65 - 0.53 \) (stat + syst)
Short lifetime of top quark decay results in large width $\Gamma_{SM} \sim 1.5$ GeV

Deviation from SM could indicate presence of $t \rightarrow bH^+ \text{ etc.}$

Different width would change top mass line shape $\rightarrow$ use templates

Method comes from top mass analysis, uses in situ calibration of JES

Dominating source of systematic uncertainty becomes jet resolution

CDF (4.3 fb⁻¹):
$\Gamma_{top} < 7.5$ GeV at 95% C.L.
Test hypothesis whether top quark is an exotic particle with $Q_{\text{top}} = 4/3$
Select Lepton + Jets with *two* $b$-tags

Opposite sign (SM)
Same sign (XM)

Exotic Model
D. Chang et al., PRD 59 (1999) 091503

CDF (2.7 fb$^{-1}$):
Excludes $Q_{\text{top}} = 4/3$ at 95% C.L.

D0 (0.37 fb$^{-1}$):
Excludes $Q_{\text{top}} = 4/3$ at 92% C.L.
PRL 98, 041801 (2007)
W helicity
Wtb vertex
W boson helicity in Top Quark Decay

- Examines the nature of the tWb vertex, probing the structure of weak interactions near the Electro-Weak Symmetry Breaking scale
- Stringent test of V-A interaction in SM
- Standard Model predicts purely left handed tWb coupling
- Model-independent measurement based on reconstruction of cosθ* distribution
- Distribution of cosθ* depends on the W helicity fractions

$W_0$ longitudinal fraction $f_0 = 0.7$

$W_-$ left-handed fraction $f_- = 0.3$

$W_+$ right-handed fraction $f_+ = 0.0$

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$W_-$ left-handed fraction $f_- = 0.3$

$W_+$ right-handed fraction $f_+ = 0.0$

$\cos\theta^*$ angle between the momenta of the down-type fermion and the top quark in the W boson rest frame for each top.
Measure $f_0$ and $f_+$ simultaneously, model independent

**D0 LeptonJets + Dilepton (2.7 fb$^{-1}$):**

- $f_0 = 0.49 \pm 0.11$ (stat) $\pm 0.09$ (syst)
- $f_+ = 0.11 \pm 0.06$ (stat) $\pm 0.05$ (syst)

**CDF LeptonJets (2.7 fb$^{-1}$), Matrix Element:**

- $f_0 = 0.88 \pm 0.11$ (stat) $\pm 0.06$ (syst)
- $f_+ = -0.15 \pm 0.07$ (stat) $\pm 0.06$ (syst)

Consistent with the Standard Model
Constrain form factors for anomalous tWb coupling
Combine information from single top production and W helicity measurement from ttbar decay

\[ L_{tWb} = \frac{g}{\sqrt{2}} W_\mu^\tau b \gamma^\mu \left( f_1^L P_L + f_1^R P_R \right) t - \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^\tau b \sigma^{\mu\nu} \left( f_2^L P_L + f_2^R P_R \right) t \]

In Standard Model: \( f_1^L = 1, \quad f_2^L = f_1^R = f_2^R = 0 \)

\[ |f_1^R|^2 < 0.72 \]

for \( |f_1^L|^2 = 1 \)

\[ |f_2^L|^2 < 0.19 @ 95\% \text{ CL} \]

\[ |f_2^R|^2 < 0.20 \]

Consistent with Standard Model
FB Asymmetry
New physics could give rise to asymmetry ($Z'$, axigluons,..)

Standard Model predicts
NLO QCD: $A_{fb} = 0.05 \pm 0.015$

CDF (3.2 fb$^{-1}$):
$A_{fb} = 0.19 \pm 0.07$ (stat) $\pm 0.02$ (syst)

D0 (1.0 fb$^{-1}$):
$A_{fb} \text{ det} = 0.12 \pm 0.08$ (stat) $\pm 0.01$ (syst)

PRL 100, 142002 (2008)
Exotic Decay
If a charged higgs of around ~100 GeV/c\(^2\) exists, then the branching ratio of top to charged higgs may be LARGE (as high as 10 to 40%).

- This search assumes \(m_A < 2m_b\), a region in parameter space not yet experimentally excluded.

- Taus should leave low pT isolated tracks in top events.
Search for Charged Higgs in Top Decay

If kinematically allowed, $t \rightarrow H^+ b$ happens in SUSY Charged Higgs decay: $H^+ \rightarrow c \bar{s}$ or $H^+ \rightarrow \tau \nu$

- Branching ratios depend on $\tan \beta$

**Observable:**

Altered rates in final states:
$L+\text{jets}$ to Dilepton to $\tau + X$

**Extract limits**

arXiv:0908.1811
Conclusions

- Top quark physics is a rich field in HEP and a broad top physics program is in progress at the Tevatron

- Top quark mass measurements
  - Most measurements are systematically limited
  - Mass measured to <1% precision for single analysis

- So far, top quark data is consistent with the SM

- Tevatron expects to double data sets if running through 2011
  - We expect improvements in our understanding of top physics!

- With the LHC, an huge top quark factory is beginning operations and top physics will continue to play a significant role:
  - Understanding of systematic uncertainties would become crucial
  - Top is a standard candle, tool for calibrating JES, b-tagging
The Big Bang Theory!

Top Quark is on prime time!

...don't miss Tevatron's next Top result:
http://www-cdf.fnal.gov/physics/new/top/top.html
http://www-d0.fnal.gov/Run2Physics/WWW/results/top.htm