Top Physics at the Tevatron

David Gerdes
University of Michigan

representing the CDF and DØ Collaborations

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Motivations for Studying Top

- Only known fermion with a mass at the natural electroweak scale
  - Special role in precision electroweak physics
  - Window into the problem of EWSB?
- New physics may appear in production (e.g. topcolor) or in decay (e.g. charged Higgs).
- Can only be studied at Tevatron prior to LHC.
A Brief History of Top

- Observed in 1995 in first $\sim 70$ pb$^{-1}$ of Run I data.
- Final Run I top analyses based on $\sim 110$ pb$^{-1}$.
  - Production cross sections in many channels
  - Mass: $174.3 \pm 5.1$ GeV (CDF/DØ combined)
  - Event kinematics
  - W helicity measurement
  - Limits on single top production, rare/non-SM decays
- Overall consistency with the Standard Model.
- But only $\sim 100$ analyzable top events
  $\rightarrow$ analyses statistics-limited.
Improvements for Run II

- **Accelerator**
  - Energy upgrade: $1.8 \rightarrow 1.96 \text{ TeV}$
    - 30-40% increase in top cross section
  - Luminosity upgrades: factor of ~2-3 so far

- **Detectors**
  - **CDF**: new Si vertex detector, outer tracker, endplug calorimeter, extended muon coverage
  - **DØ**: magnetic tracking system (scint. fibers + silicon), preshower system, muon upgrades
  - **Both**: Upgraded DAQ/trigger systems to deal with change from 3.5\(\mu\)s to 396 ns bunch crossing interval.
Tevatron Peak Luminosity

Typical recent stores: $3-4 \times 10^{31}$

Run IIa goal: $8 \times 10^{31}$
Integrated Luminosity

Results from first \( \sim 100 \text{ pb}^{-1} \) presented today.

Goal for 2004: additional 310-380 \( \text{pb}^{-1} \) delivered.

delivered ~325 \( \text{pb}^{-1} \)
on tape ~270 \( \text{pb}^{-1} \)

Taking data with \( \sim 90\% \) efficiency.
Production and Decay Basics

Pair Production:

85%

15%

NB: qq, gg fractions reversed at LHC

Event topology determined by the decay modes of the W's

$\sigma_{\text{theory}} \approx 7 \text{ pb}$

$\text{BR}(t \rightarrow Wb) \approx 100\%$

b-jet: identify via secondary vertex or soft lepton tag
\textbf{t-tbar Final States}

- Dilepton (ee, \(\mu\mu, e\mu\))
  - BR = 5\%
  - 2 high-\(P_T\) leptons + 2 b-jets + missing-\(E_T\)

- Lepton (e or \(\mu\)) + jets
  - BR = 30\%
  - single lepton + 4 jets (2 from b’s) + missing-\(E_T\)

- All-hadronic
  - BR = 44\%
  - six jets, no missing-\(E_T\)

- \(\tau\text{had} + X\)
  - BR = 23\%

Most favorable channels for top physics:
- e-e (1/81)
- mu-mu (1/81)
- tau-tau (1/81)
- e-mu (2/81)
- e-tau (2/81)
- mu-tau (2/81)
- e+jets (12/81)
- mu+jets (12/81)
- tau+jets (12/81)
- jets (36/81)

More challenging backgrounds, but measurements still possible.
Measuring the $t\bar{t}$bar Cross Section

- Basic engineering number, starting point for all top physics.
- Requires detailed understanding of backgrounds and selection efficiencies.
- Test of QCD
  - Latest calculations: NNLO + NNNLL
  - Departures from prediction could indicate nonstandard production mechanisms, i.e. production through decays of SUSY states.
Dilepton Cross Sections: DØ

Results from first 90 - 110 pb\(^{-1}\)

- \textit{ee channel}
  - Observe 2 events, bkgd. 0.6 ± 0.5
- \textit{\(\mu\mu\) channel}
  - Observe 0 events, bkgd. 0.7 ± 0.4
- \textit{e\(\mu\) channel}
  - Observe 3 events, bkgd. 0.4 ± 0.4)

\[
\sigma_{tt} = 8.7^{+6.4}_{-4.7} \text{(stat)}^{+2.7}_{-2.0} \text{(syst)} \pm 0.9 \text{(lum) pb}
\]
Two complementary analyses (126 pb$^{-1}$)

- **Tight**: Two good-quality leptons + MET + 2 jets
  - 10 candidates (2 ee, 3 µµ, 5 eµ), bkgd. $2.9 \pm 0.9$
  - 6 events b-tagged (one double-tag); expect 4 top
  - $\sigma_{tt} = 7.6 \pm 3.4 \text{ (stat)} \pm 1.5 \text{ (sys)} \text{ pb}$

- **Loose**: Lepton + isolated track + MET + 2 jets
  - 13 candidates, bkgd. $5.1 \pm 0.9$
  - 5 events b-tagged (one double-tag); expect 4 top
  - $\sigma_{tt} = 7.3 \pm 3.4 \text{ (stat)} \pm 1.7 \text{ (sys)} \text{ pb}$
Jet Multiplicity in Dilepton Events

CDF Run II Preliminary

Event count per jet bin

entries/jet bin

0 10 20 30 40 50 60

n_{jet}

WW+WZ+ZZ
+ Drell-Yan
+ fakes
+ tt

126 pb^{-1}

ttbar signal bin
Double $b$-tagged Lep+Trk event at CDF

CDF II Preliminary Secondary Vertex

Jet2 63.2 GeV $L_{xy} = 13 \text{ mm}$
Jet1 69.7 GeV $L_{xy} = 16 \text{ mm}$

$E_T$ $\gamma$ 87 GeV

I.P.

$t_l$ 25.9 GeV

$\mu$ TCL 34.7 GeV

$E_T = 38.66 \text{ GeV}$
Dilepton Kinematics

CDF Run II Preliminary $\int L \, dt = 126 \text{ pb}^{-1}$

Scalar summed $E_T$ of jets, leptons, and missing $E_T$

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Dilepton Kinematics, contd.

Lepton $P_T$ softer than expected. Statistical fluctuation or a hint of something new?
Lepton + Jets Cross Section: DØ

Using topological cuts

Backgrounds from QCD estimated from data as fcn. of MET, Njets.

Backgrounds from W+jets estimated using Berends scaling hypothesis, \( \sigma(W+n+1 \text{ jets})/\sigma(W+n \text{ jets}) = \text{constant} \).

After aplanarity, \( H_T, Njet \geq 4 \) cuts:

Observe 26 events, bkgd. 18.5 ± 2.5.

Using soft muon b-tag

Orthogonal selection to topological analysis.

QCD and W+jets backgrounds estimated as in topological analysis.

Fake tag rate estimated using jet data.

Observe 15 events, bkgd. 3.3 ± 1.3.
Lepton + Jets Kinematics

DØ Run II Preliminary

$\sigma_{tt} = 8.0^{+2.4}_{-2.1} (\text{stat})^{+1.7}_{-1.5} (\text{syst}) \pm 0.8(\text{lum}) \text{pb}$

b-tagged events populate the top signal region

$e+jets \quad 92 \text{pb}^{-1}$

$\mu+jets \quad 94 \text{pb}^{-1}$

Sum-$E_T$ of jets (GeV)

Aplanarity
Lepton + jets with Secondary Vertex B-Tag at DØ

Tag by reconstructing sec. vtx.:

Tag by counting displaced tracks:

\[ \sigma_{tt}^{-} = 10.8^{+4.9}_{-4.0} \, (stat)^{+2.1}_{-2.0} \, (syst) \pm 1.1(lum) \, pb \]

\[ \sigma_{tt}^{-} = 7.4^{+4.4}_{-3.6} \, (stat)^{+2.1}_{-1.8} \, (syst) \pm 0.7(lum) \, pb \]

45 pb\(^{-1}\)

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µ+jets double tagged event at DØ
Jet Multiplicity in b-tagged events: CDF

CDF II preliminary

- mistags
- Wbb
- Wcc
- non-W
- Wc
- WW, WZ, Z → ττ
- Single top
- Total bkgd ± 1σ
- Data (107.9 pb$^{-1}$)

Number of tagged events vs Number of jets in W+jets:

- Top signal region
Jet Multiplicity (with top contribution)

\[ \sigma_{\ell+\text{jets}} = 4.5 \pm 1.4\text{(stat)} \pm 0.8\text{(syst)} \text{ pb} \]
L+jets: Tagged Jet $E_T$
Summary of Cross Section Results
Cross Section $\sqrt{s}$-Dependence

CDF and DØ Run II Preliminary

$\sigma (pb)$ vs $\sqrt{s} (GeV)$

Kidonakis NNLO-NNNLL+ (hep-ph/0303186)
Cacciari et al. (hep-ph/0303085)

CDF Run II (Dilepton), DØ Run II
CDF Run I, CDF Run II (l+jets), DØ Run I
$M_{\text{top}}$ is a precision electroweak parameter that helps constrain the mass of the Higgs.
Top Mass in Run II (CDF)

• Lepton + 4 jets with sec. vertex b-tag
  - Many kinematic constraints: 4C fit
  - 12 parton/jet matching assignments possible; pick combination with lowest $\chi^2$.
  - Fit resulting to mass distribution to background + signal templates.

• Dilepton channel
  - Underconstrained system
  - Use $P_{tt\bar{t},z}$ to weight the mass fit distribution
  - Likelihood fit to top mass templates.
Run II Top Mass: lepton + jets

CDF Run II Preliminary ($\sim 108$ pb$^{-1}$)

$M_{\text{top}} = 177.5 \pm 12.7 / -9.4$ (stat.) $\pm 7.1$ (syst)

Events/(15 GeV/c$^2$)

Data (22 evts)
Signal + Bkgd
Bkgd only

Reconstructed Top Mass, Tagged Events (GeV/c$^2$)
Run II Top Mass: Dilepton Channel

6 events

124 pb$^{-1}$

$175.0^{+17.4}_{-16.9}$ (stat) $\pm 7.9$ (syst) GeV/c$^2$
New Run I Mass Measurement (DØ)

- The template method has some disadvantages:
  - One combination chosen for fit
  - Single template describes the distribution
  - All events treated with equal weight
- New analysis makes better use of available information
  - All measured quantities used in fit (except unclustered energy)
  - Each event has its own probability distribution
  - Well-measured events contribute more
Matrix Element Method

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

\[ P(x; \alpha) = c_1 P_{\text{ttbar}}(x; \alpha) + c_2 P_{\text{background}}(x) \]

- Leading-Order ttbar->lepton+jets matrix element, PDFs
- 12 jet permutations, all values of \( P(\nu) \)
- Phase space of 6-object final state
- Detector resolutions
  - Convolute probability to include all conditions for accepting or rejecting an event
    \[ P_{\text{measured}}(x; \alpha) = Acc(x) P(x; \alpha) \]
  - Form a Likelihood as a function of: Top Mass, \( F_0 \) (longitudinal fraction of W bosons)

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

\( f(q) \) is the probability distribution than a parton will have a momentum \( q \)
Error Comparable to Previous Run I Measurements Combined

$M_{\text{top}} = 180.1 \pm 3.6 \text{ (stat)} \pm 4.0 \text{ (syst)} \text{ GeV}/c^2$

Previous DØ result using template method had stat. uncertainty of 5.6 GeV. New method is equivalent to 2.4 times more data!
W Helicity Measurement

• Top decays before it can hadronize, because width $\Gamma_t = 1.4 \text{ GeV} > \Lambda_{\text{QCD}}$.
  - Decay products preserve information about the underlying Lagrangian.
  - Unique opportunity to study the weak interactions of a bare quark, with a mass at the natural electroweak scale!

• SM Prediction:
  - W helicity in top decays is fixed by $M_{\text{top}}, M_W$, and V-A structure of the $tWb$ vertex.
**W Helicity Measurement, contd.**

The angular dependence of the semileptonic decay in the W rest frame is given by

\[ w(\cos \varphi_{l^-b}) = F_- \cdot \frac{3}{8} (1 - \cos \varphi_{l^-b})^2 + F_0 \cdot \frac{3}{8} (1 - \cos^2 \varphi_{l^-b}) + F_+ \cdot \frac{3}{8} (1 + \cos \varphi_{l^-b})^2 \]

The angular dependence is shown in the diagrams for different decay modes:
- **left**: 
  \[ w(\cos \varphi) \]
- **long.**: 
  \[ w(\cos \varphi) \]
- **right**: 
  \[ w(\cos \varphi) \]

SM predictions (for \( m_b = 0 \)):

\[ F_- = \frac{2\omega}{1 + 2\omega} \approx 0.3 \]
\[ F_0 = \frac{1}{1 + 2\omega} \approx 0.7 \]
\[ F_+ = 0 \]

where \( \omega = \frac{M_W^2}{M_{\text{top}}^2} \)

**parameter to measure**
W Helicity Results

New DØ Run I measurement:

- Natural extention of the ME method developed for top mass measurement.
- Extend the ME to include generalized dependence on $F_0$.
  \[ F_0 = 0.56 \pm 0.31 \text{(stat)} \pm 0.04 \text{(syst)} \]
- Application to Run II data is in progress.
Helicity affects lepton $P_T$ in lab frame

See general agreement with SM, but limited statistics. Analysis in progress.

David Gerdes
University of Michigan
Model independent search for a narrow resonance $X \rightarrow tt$
exclude a narrow, leptophobic $X$ boson with $m_X < 560 \text{ GeV/c}^2$ (CDF)
and $m_X < 585 \text{ GeV/c}^2$ (D0)
### Tevatron Luminosity Projections

<table>
<thead>
<tr>
<th></th>
<th>Design Projection</th>
<th>Base Projection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>per year</td>
<td>Accumulated</td>
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<tr>
<td>FY03</td>
<td>0.22</td>
<td>0.30</td>
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<tr>
<td>FY04</td>
<td>0.38</td>
<td>0.68</td>
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<td>FY05</td>
<td>0.67</td>
<td>1.36</td>
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<tr>
<td>FY06</td>
<td>0.89</td>
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<td>FY07</td>
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<td>3.78</td>
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<td>FY08</td>
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<td>6.15</td>
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<tr>
<td>FY09</td>
<td>2.42</td>
<td>8.57</td>
</tr>
</tbody>
</table>

With recycler and electron cooling
Conclusions and Outlook

• The top quark is back!
• First Run II measurements of cross section, mass are available and will improve rapidly.
• Other analyses (W helicity, single top...) are making excellent progress.
• It is the start of a program of precision top physics—and hopefully top surprises—at the Tevatron.
• We still expect at least 50x more data compared to Run I!
The Road Ahead

• Search for $\text{top} \rightarrow H^+$
• Study of $\tau$ channels - pure $3^{\text{rd}}$ generation decay mode.
• Single top production, measure $V_{tb}$
• $ttbar$ resonant production, strong EWSB
• Searches for rare decays
• Is top *the connection* to new physics?
## Top Mass Uncertainties, lepton + jets

### CDF Run II Preliminary

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (GeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>+12.7 -9.4</td>
</tr>
<tr>
<td>Jet scale</td>
<td>6.2</td>
</tr>
<tr>
<td>FSR</td>
<td>2.2</td>
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<tr>
<td>PDFs</td>
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<tr>
<td>ISR</td>
<td>1.3</td>
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<tr>
<td>Other MC modeling</td>
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<tr>
<td>Generator</td>
<td>0.6</td>
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<tr>
<td>Backgrounds</td>
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<tr>
<td>b-tagging</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total systematic</strong></td>
<td><strong>7.1</strong></td>
</tr>
</tbody>
</table>

Dominated by calorimeter energy scale in simulation; will improve soon.