Top Physics at CDF

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XVIII Rencontres de Physique de La Vallee d’Aoste
La Thuile
3/5/2004
Motivations for Studying Top

• Only known fermion with a mass at the natural electroweak scale
  Window into the problem of EWSB?

• New physics may appear in production (e.g. topcolor) or in decay (e.g. charged Higgs).
Run I Top Studies

- Observed in 1995 in first ~70 pb\(^{-1}\) of Run I data.
- Final Run I top analyses based on ~110 pb\(^{-1}\).
  - Production cross sections in many channels
  - Mass: 174.3 ± 5.1 GeV (CDF/DØ combined)
  - Event kinematics
  - W helicity, limits on single top production..

- overall consistency with the Standard Model.
- but only ~100 top candidates
  → analyses statistics-limited.
Improvements for Run II

- **Accelerator:**
  
  \[ \sqrt{s} = 1.96 \text{ TeV} \text{ (was 1.8 TeV in RunI)} \]
  
  ->30-40% increase in top cross section

- **CDF Detector:**
  
  - New DAQ
  - New Silicon system
    -> improved b-tagging
  - Extended muon systems
  - Calorimeter endplug for forward coverage
  - New central drift chamber
Tevatron Peak Luminosity

Record Luminosity: $6.3 \times 10^{31}$ (3x better than Run I)
First store w/antiprotons from recycler
Current to tape: 350pb$^{-1}$, for this talk: up to 200pb$^{-1}$
Tevatron Luminosity

Predicted for 2004: 380 pb\(^{-1}\) delivered (design)

<table>
<thead>
<tr>
<th>FY</th>
<th>Design Projection</th>
<th>Base Projection</th>
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<tbody>
<tr>
<td></td>
<td>per year</td>
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<td>FY03</td>
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<td>FY04</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>
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</table>
Pair-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
t-tbar Final States

- **Dilepton**
  - BR = 11%
  - 2 high-$p_T$ leptons + 2 b-jets + missing-$E_T$

- **Lepton + jets**
  - BR = 44%
  - single lepton + 4 jets (2 b-jets) + missing-$E_T$

- **All-hadronic**
  - BR = 45%
  - six jets, no missing-$E_T$

- **Tools:**
  - Lepton ID (tracking, detector coverage)
  - Calorimetry (calibration)
  - B identification (tagging)
  - Simulation

Highest signal:noise
- High pt decay products
- Central/spherical topology

More challenging backgrounds (QCD multijet)
Programme:

- Top cross-section
  - dilepton channel
  - Lepton+jets channel
- Single top physics
- Top Mass
- W helicity in top decay

New results
Measuring the $t\bar{t}b\bar{b}$ Cross Section

- 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 Section: lepton+track

- Signature: 1 lepton+1 isolated track, missing $E_t$, $\geq 2$ central jets
- Acceptance: $\sim 2x$ better than Run I
- $\sim 20\%$ from $\tau$
- Background:

Drell-Yan

\[ q \quad \gamma^*/Z \quad \bar{q} \]

WW, ZZ, WZ

\[ q \quad w^+ \quad \bar{q} \quad w^- \]

W+jets ("fakes")

\[ g \quad u \quad W \]

Relative weight depends on number of jets
Dilepton Cross Section: lepton+track

<table>
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<td>error</td>
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<td>DY</td>
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<td>16.59</td>
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<td>Total Pbg</td>
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<td>23.48</td>
<td>3.44</td>
<td>5.57</td>
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<tr>
<td>Fakes</td>
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<td>1.57</td>
<td>4.16</td>
<td>0.49</td>
<td>1.48</td>
<td>0.19</td>
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<tr>
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<td>5.90</td>
<td>27.64</td>
<td>3.47</td>
<td>7.06</td>
<td>1.02</td>
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<td>64.97</td>
<td>5.90</td>
<td>31.02</td>
<td>3.47</td>
<td>18.59</td>
<td>1.05</td>
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<td>observed</td>
<td>73</td>
<td></td>
<td>26</td>
<td></td>
<td>19</td>
<td></td>
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</tbody>
</table>

Measured cross section for different jet $E_T$ and track $p_T$ thresholds

New result

$$\sigma_{tt} = 6.9^{+2.7}_{-2.4} \text{(stat)} \pm 1.2 \text{(syst)} \pm 0.4 \text{(lumi)} \text{pb}$$
**Dilepton cross section: ee, e\(\mu\), \(\mu\mu\)**

Different background composition, higher S:N, lower acceptance

⇒ Events with 1 “tight” and 1 “loose” e or \(\mu\)

\[
\sigma_{tt} = 8.7^{+3.9}_{-2.6} (\text{stat}) \pm 1.4 (\text{syst}) \pm 0.5 (\text{lumi}) \text{ pb}
\]

lepton composition: 1 ee, 3 \(\mu\mu\), 9 e\(\mu\)

⇒ 2 “tight” leptons (e, \(\mu\))

\[
\sigma_{tt} = 8.1^{+4.4}_{-3.4} (\text{stat}) \pm 1.6 (\text{syst}) \pm 0.5 (\text{lumi}) \text{ pb}
\]

lepton composition: 1 ee, 2 \(\mu\mu\), 4 e\(\mu\)
Jet Multiplicity in Dilepton Events

Lepton + track:

- ee, e\(\mu\), \(\mu\mu\):

**Event count per jet bin**

CDF II Preliminary 200 pb\(^{-1}\)

- WW + WZ + ZZ
- + Drell-Yan
- + fakes
- + \(t\bar{t}\) (\(\sigma_{SM} = 8.7\) pb)

**ttbar signal bin**
Dilepton Kinematics

Run I: had seen hints of discrepancy in kinematic distribution:

- **Missing $E_T$**
  - $N_{\text{jet}} \geq 2$

- **$H_T$: Scalar summed $E_T$ of jets, leptons, and missing $E_T$**
  - $N_{\text{jet}} \geq 2$

With higher statistics in Run II, see good agreement with SM
Dilepton event display

- 2 electrons ($E_{T1}=73$ GeV, $P_{T2}=63$ GeV)
- Missing $E_T = 59$ GeV
- 2 central jets + 1 forward jet

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New results

Cross Section - lepton+jets using kinematic fits

Isolate signal from large W+jets background using kinematic shapes: $H_t$, (scalar sum of energy in the event)

W+≥3 jets: observe 519 events

Top fraction from fit: 0.13±0.04

$$\sigma_{tt} = 4.7 \pm 1.6 (stat) \pm 1.8 (syst) \text{pb}$$

Largest systematic: jet energy scale
Tagging high-$p_T$ jets: Silicon vertex tag (SVX-tag)

- Signature of a B decay is a displaced vertex:
  - Long lifetime of B hadrons ($c\tau \sim 450 \, \mu m$) + boost
  - B hadrons travel $L_{xy} \sim 3$ mm before decay with large charged track multiplicity

Top event efficiency: 55%
False tag rate (QCD jets): 0.5%
Cross Section - lepton+jets using kinematic fits + SVX-tag

In addition to shape information: require at least one b-tag

\[ \sigma_{tt} = 6.9^{+1.6}_{-1.9} (\text{stat} + \text{fit}) \pm 0.9 (\text{syst}) \text{pb} \]

W+3 or more jets: observe 35 events

Top fraction from fit: \(0.88^{+1.0}_{-1.6}\)

Using 108 pb\(^{-1}\)
Cross Section - lepton+jets using SVX-tag

2d displacement of tagged jets:

Number of jets per event:

W+>=3 jets: 35 positive tags

Expected background (mistags, QCD,..): 15.1+2

Using 107 pb⁻¹

$$\sigma_{tt} = 4.5^{+1.4}_{-1.3} \text{(stat)} \pm 0.8 \text{(syst)} \text{pb}$$
**Cross Section - lepton+jets using “Soft Lepton Tag”**

Tag semi-leptonic decays of B

⇒ leptons have a softer $p_T$ spectrum than W/Z leptons
⇒ They are less isolated
⇒ Identify low-$p_T$ muon

Top Event (>2 jets)
Tag Efficiency: 15%
False Tag Rate (QCD jets): 3.6%

- $b \rightarrow \ell v c$ (BR $\sim$ 20%)
- $b \rightarrow c \rightarrow \ell v s$ (BR $\sim$ 20%)

Using 125 pb$^{-1}$

$\sigma_{tt} = 4.1^{+4.0}_{-2.8} (stat) \pm 1.9 (syst) pb$
Summary of Cross Section Results

$$\sqrt{s}$$ Dependence:

$\Rightarrow$ Main data driven systematics (jet energy scale, ISR, $\varepsilon_{btag}$) scale with $1/\sqrt{N}$

RunII($2fb^{-1}$) $\delta\sigma_{tt}/\sigma_{tt} < 10\%$
Single Top Physics

- Probe top EW coupling
direct determination of $V_{tb}$
- Sensitivity to new physics:
t-channel: anomalous couplings, FCNC
  s-channel: new charged gauge bosons
- Strategy:
  Isolate $W^+$ exactly 2 jets and tag one jet
  Likelihood Fit to $Q^*\eta$ (t-channel)
  Likelihood Fit to $H_t$ (combined)

Q: charge of lepton, $\eta$: pseudorap of forward jet

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Single Top Physics

Templates from MC (combined):

<table>
<thead>
<tr>
<th>Process</th>
<th>N events Combined Search</th>
<th>t-channel search</th>
</tr>
</thead>
<tbody>
<tr>
<td>t-channel</td>
<td>2.39 ± 0.56</td>
<td>2.34 ± 0.54</td>
</tr>
<tr>
<td>s-channel</td>
<td>1.19 ± 0.25</td>
<td>1.16 ± 0.24</td>
</tr>
<tr>
<td>ttbar</td>
<td>3.47 ± 1.04</td>
<td>3.39 ± 1.02</td>
</tr>
<tr>
<td>non-top</td>
<td>20.7 ± 4.1</td>
<td>17.4 ± 3.3</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td><strong>27.8 ± 4.3</strong></td>
<td><strong>24.3 ± 3.5</strong></td>
</tr>
</tbody>
</table>
New results

Search for Single Top

Fit to the data (combined search):

- **t-channel search:**
  \( \sigma_t(\text{combined}) < 13.7 \text{pb} @95\% \text{ C.L.} \)

- **Uncertainty:**
  - \( \delta\sigma(tbX) = 26\% \)
  - \( \delta\Gamma(t \to Wb) = 28\% \)
  - \( \delta|V_{tb}| = 14\% \)

Using 162 pb\(^{-1}\) of data:

- \( \sigma_t(\text{t-channel}) < 8.5 \text{pb} @95\% \text{ C.L.} \)
- \( \sigma_t(\text{combined}) < 13.7 \text{pb} @95\% \text{ C.L.} \)

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$M_{\text{top}}$ is a precision electroweak parameter that helps constrain the mass of the Higgs.
Top Mass: Lepton + 4 jets with SVX-tag

22 vertex-tagged events from lepton+4 jet sample

CDF Run II Preliminary (~108 pb⁻¹)

\[ M_{\text{top}} = 177.5 \pm 12.7 / -9.4 \text{ (stat.)} \pm 7.1 \text{ (syst.)} \text{ GeV/c}^2 \]

-6 parton/jet matching assignments possible
-test for consistency with top using kinematic constraints
-pick lowest \( \chi^2 \)
-fit resulting mass distribution to background + signal templates at different values of \( M_{\text{top}} \)

Likelihood fit result: \( m_{\text{top}} = 177.5 \pm 12.7 \text{ (stat.)} \pm 7.1 \text{ (syst.)} \text{ GeV/c}^2 \)

Dominant syst: jet energy scale, expecting significant impr. soon
Top Mass: Dilepton Channel

- Underconstrained system
- Use $P_{tt\bar{t}z}$ to weight the mass fit distribution
- Likelihood fit to top mass templates

$175.0^{+17.4}_{-16.9}$ (stat) ± 7.9 (syst) GeV/c²

Improved tools are underway:

- Results expected soon
W Helicity Measurement

• Top decays before it can hadronize, because width $\Gamma_t = 1.4$ 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 reflected in kinematics: $W$ lepton pt, ...
Helicity affects lepton $P_T$ in lab frame

**Templates from MC:**

- Long + l.h. + bg
- Long
- Left-handed
- Background
- Data 108÷126 pb$^{-1}$

**CDFI Result (106 pb$^{-1}$):**

$F_0 = 0.91 \pm 0.37 \pm 0.13$

$F_+ < 0.28$ @ 95% C.L.

**CDFII result soon**

**SM V-A predicts $W$ helicity:**

- $F_0 = 70\%$ longitudinal
- $F_- = 30\%$ left-handed

[V+A: 70\% long., 30\% r.-h.]
Conclusion and Outlook

Now using 2x the RunI data set

• Improving measurements of cross section, mass
• W helicity, single top... are making progress.
• We expect ~50x more data compared to Run I!
• What’s ahead: top → H⁺
  
  Study of τ channels
  measure $V_{tb}$
  $t\bar{t}bar$ resonant production
  rare decays
Backup Slides
CDF Run II Preliminary

Unsmeared $p(\beta)$

Smeared $p(\beta)$

$\sigma_{\text{Single Top}} < 13.7 \text{ pb at 95\% C.L.}$

$\beta_{95} = 4.2$ (statistical only)

$\beta_{95} = 4.8$ (incl. systematics)

Probability Density $p(\beta)$

Relative number of events $\beta$ from fit

162pb$^{-1}$
Matrix Element Method

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

\( d^n \sigma \) is the differential cross section

\( W(y, x) \) 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 \( q \)

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

- Leading-Order \( t\bar{t}bar \rightarrow \text{lepton+jets} \) 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
    \[ P_{measured}(x; \alpha) = Acc(x) P(x; \alpha) \]
  - Form a Likelihood as a function of: Top Mass, \( F_0 \) (longitudinal fraction of W bosons)
- Only \( W+\)jets, 80%
- VECBOS subroutines for \( W+\)jets
- Same detector resolutions as for signal
- All permutations, all values of \( P(\nu) \)
- Integration done over the jet energies

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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 $F$ parameters can be approximated as:

$$F_- = \frac{2 \omega}{1 + 2 \omega} \approx 0.3$$

$$F_0 = \frac{1}{1 + 2 \omega} \approx 0.7$$

$$F_+ = 0$$

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

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