Top: latest results from Tevatron – cross-section and mass

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For the CDF and D0 collaborations
FPCP 2003, Paris, June
Outline

- Tevatron Status
- The upgrades of the CDF and D0 detectors
- Top Production and Decay
- Top Physics Program for Run II
- First Cross-Section Measurements at 1.96 TeV, in the Dilepton and Lepton+jets channels
- Top Mass Measurements in CDF (Run II) and D0 (Run I)
- Top Physics Prospects
Tevatron Upgrades/Status

- **Run II upgrades**
  - $E_{CM}$ increase from 1.8 → 1.96 TeV → larger cross sections
  - Higher luminosity
    - Run I peak: $2.4 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$
    - Run II goal: $3 - 4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
    - Run II peak: $4.7 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$

- Analysis-quality data accumulated by Jan '03
  - CDF: 72.0 pb$^{-1}$
    - (57.5 pb$^{-1}$ with silicon)
  - D0: 30 - 50 pb$^{-1}$

- Immediate goal for accelerator:
  - Deliver 225 pb$^{-1}$ in FY 2003

- Run IIa goal: 2 fb$^{-1}$
**CDF and D0 Detectors Upgrades**

### Tracking:
- Expanded silicon coverage
- New drift chamber (COT)
- Extended lepton-ID: $|\eta|>1.0 \rightarrow 2.0$
  - End Plug calorimeter
  - Expanded muon coverage

### New Inner tracking
- silicon tracker, fiber tracker
- 2T superconducting solenoid

### Upgraded $\mu$ system for better $\mu$ -ID

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Top Production and Decay

In proton-antiproton collisions, at 1.96 TeV, top quarks are primarily produced in pairs.

- single top production:
  - smaller rate ($\sigma = 1.5 \text{ pb}$)
  - large backgrounds
  - not observed yet

$\sigma_{tt}$ increased by 30% with the CM energy increase from 1.8 $\rightarrow$ 1.96 TeV.

$\text{Br}(t \rightarrow W^+b) \sim 100\%$ in SM.

Based on the W decay modes $\rightarrow$ 3 experimental signatures:

1. **Dilepton** Very small backgrounds, but very small rate
2. **Lepton+Jets** Manageable backgrounds and good rate
3. **All Jets** Large QCD Background
Run I: discovery mode
( Fermilab 1995) → crude look at top’s properties
Run II: precision mode
→ we hope to answer fundamental questions:

Why is the top so heavy?
Is the third generation special?
Is top involved in EWSB?
Is the top the liaison to new physics?
Production Cross-Sections

\( \sigma_{t\bar{t}} \) measurement:
- benchmark measurements
- test of perturbative QCD
- probe for physics beyond SM
  - non-SM production, \( X \rightarrow tt \)
  - non-SM decay, \( t \rightarrow Xb \)
  - SUSY models with a \( tt \)-like signal
- Higgs production (WH,ZH) is a background and the opposite

Run I: \( \delta\sigma_{t\bar{t}} / \sigma_{t\bar{t}} \sim 26\% \)
Run IIa (2 fb\(^{-1}\)): \( \delta\sigma_{t\bar{t}} / \sigma_{t\bar{t}} \sim 7\% \)

Theoretical cross-section:
At NLO @ \( \sqrt{s}=1.96\) TeV for \( M_{\text{top}} = 175\) GeV:

\[
\sigma_{t\bar{t}} = 6.7^{+0.71}_{-0.88} \text{ pb}
\]

To estimate signal contribution we use 7 pb

\[
\sigma_{t\bar{t}} = \frac{N_{\text{obs}} - N_{\text{bck}}}{A \cdot L}
\]
σ_{t\bar{t}} in the Dilepton Decay Mode

Event Selection

- 2 high-\( E_T \), isolated leptons (e, \( \mu \))
  - \( \tau \) to be included for the future
- large missing energy \( E'_T \)
  - D0: Raised \( E'_T \) cut in Z window
- CDF: Veto Z-mass window events for ee, \( \mu \mu \)
- at least 2 jets with large \( E_T \)
- large transverse energy flow
  \[ H_T = \Sigma (E_{T_{\text{leptons}}}, E_{T_{\text{jets}}}) \]

Backgrounds

- WW/WZ, Z/\( \gamma^* \) → \( \tau\tau \) determined from Monte Carlo (MC)
- Z/\( \gamma^* \)→ee, \( \mu \mu \) from data+MC
- W+jets, QCD Heavy Flavor from data
## Dilepton Channel (ee, e\(\mu\), \(\mu\mu\)) \(\sigma_{\text{tt}}\)

<table>
<thead>
<tr>
<th>Source</th>
<th>ee (events)</th>
<th>(\mu\mu) (events)</th>
<th>e(\mu) (events)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L (pb(^{-1}))</td>
<td>48.0</td>
<td>42.6</td>
<td>33.0</td>
</tr>
<tr>
<td>Background</td>
<td>1.00 ± 0.49</td>
<td>0.60 ± 0.01</td>
<td>0.07 ± 0.01</td>
</tr>
<tr>
<td>Signal</td>
<td>0.25 ± 0.02</td>
<td>0.30 ± 0.04</td>
<td>0.50 ± 0.01</td>
</tr>
<tr>
<td>Run II data</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Run II Preliminary:

\[
\sigma_{\text{tt}} = 29.9^{+21.0}_{-15.7} \left(\text{stat}\right)^{+14.1}_{-6.1} \left(\text{sys}\right)^{+3.0}_{-3.0} \left(\text{lum}\right) \text{pb}
\]
$e\mu + 2\text{ jets Top Candidate}$

**Transverse View**

$E_T(e^+) = 20.3 \text{ GeV}$  
$p_T(\mu^-) = 58.1 \text{ GeV/c}$  
$E_T^{\text{jet}}(1) = 141.0 \text{ GeV}$  
$E_T^{\text{jet}}(2) = 55.2 \text{ GeV}$  
$E_T = 91 \text{ GeV}$  
$H_T(e) = 216 \text{ GeV}$

**Longitudinal View**
Dilepton Channel  $\sigma_{t\bar{t}}$

<table>
<thead>
<tr>
<th>Source</th>
<th>ee (events)</th>
<th>$\mu\mu$ (events)</th>
<th>$e\mu$ (events)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td>0.10 ± 0.06</td>
<td>0.09 ± 0.05</td>
<td>0.10 ± 0.04</td>
</tr>
<tr>
<td>Signal</td>
<td>0.47 ± 0.05</td>
<td>0.59 ± 0.07</td>
<td>1.44 ± 0.16</td>
</tr>
</tbody>
</table>

Run II data

$\sigma_{t\bar{t}} = 13.2 \pm 5.9$(stat) $\pm 1.5$(syst) $\pm 0.8$(lum) pb

Run II Preliminary: 72 pb$^{-1}$

Data sample luminosity: 72 pb$^{-1}$

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Kinematics of Dilepton Candidates

Run 1
L = 109 pb\(^{-1}\)
1.8 TeV
9 events

Run 2 Preliminary
L = 72 pb\(^{-1}\)
1.96 TeV
5 events

Events with very large missing \( E_T \) in Run 1

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A high \( P_T \) isolated, charged lepton (e, \( \mu \)), large missing \( E_T^\text{miss} \) (\( \nu \) undetected)

Large jet multiplicity (\( \geq 3 \))

Cosmic ray, electron conversion removal, dilepton veto, Z boson veto.

Further selections to reduce the background

- **topological:**
  - \( \geq 4 \) jets (DØ)
  - \( b \) jets with Soft Lepton Tag (SLT)
    - \( \geq 3 \) jets, \( \geq 1 \) SLT tag (DØ)
  - \( b \) jets with displaced vertex (SECVTX)
    - \( \geq 3 \) jets, \( \geq 1 \) b tag (CDF)
Lepton+Jets Topological $\sigma_{tt}$

Event Pre-Selection

- Preselect a sample enriched in $W$ events
  - an EM object or $\mu$ with large $P_T$ and large missing energy
  - Veto soft $\mu$'s in sample, veto dilepton events

Backgrounds

- QCD multi-jets evaluated from data vs. $N_{jets}$
  - $e$+jets: due to fake jets ($\pi^0$ and $\gamma$)
  - $\mu$+jets: due to heavy flavor decays
- $W$ multi-jets background in the 4 jet bin estimated using data by Berends scaling law before topological cuts

$$\alpha = 0.145 \pm 0.02$$

$\alpha \equiv \frac{\sigma(W + (n + 1)_{jets})}{\sigma(W + n_{jets})}$
### Results for Topological Analysis

**QCD background estimation**

<table>
<thead>
<tr>
<th>Source</th>
<th>e+jets</th>
<th>µ+jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>L (pb⁻¹)</td>
<td>49.5</td>
<td>40.0</td>
</tr>
<tr>
<td>Background</td>
<td>2.7 ± 0.6</td>
<td>2.7 ± 1.1</td>
</tr>
<tr>
<td>Signal</td>
<td>1.8</td>
<td>2.4</td>
</tr>
<tr>
<td>Run II data</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

### Topological Selection

- ≥ 4 jets (|η| < 2.5(µ) or |η| < 2.0(e),  p_T >15 GeV)
- Aplanarity >0.065
- H_T(E_T^jets) >180 GeV (e)
- H_T(E_T^jets+p_T^W)>220GeV (µ)
Lepton+jets $\sigma_{tt}$ with an SLT tag

Event Selection

- preselection as for topological $\sigma_{tt}$
- $\geq 3$ jets
- softer topological cuts:
  - $H_T(\Sigma E_T^{jets}) > 110$ GeV
  - Aplanarity $> 0.04$
- soft $\mu$ inside a jet
  ($b\rightarrow \mu$, $b\rightarrow c\rightarrow \mu$)

Backgrounds

- QCD and $W+jets$ determined from data

<table>
<thead>
<tr>
<th>Source</th>
<th>$e+jets$</th>
<th>$\mu+jets$</th>
</tr>
</thead>
<tbody>
<tr>
<td>L (pb$^{-1}$)</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>Background</td>
<td>$0.2 \pm 0.1$</td>
<td>$0.7 \pm 0.4$</td>
</tr>
<tr>
<td>Expected Signal</td>
<td>0.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Run II data</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

Lepton+jets channels (SLT + Topological) combined $\sigma$

Run II Preliminary:

$$\sigma_{tt} = 5.8^{+4.3}_{-3.4} \text{ (stat)} +^{4.1}_{-2.6} \text{ (sys)} +^{0.6}_{-0.6} \text{ (lum)} \ \text{pb}$$

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**Lepton+jets $\sigma_{tt}$ with a SECVTX-tag**

**Event Selection**

- Preselect a sample enriched in W events as already mentioned.
- $\geq 3$ jets with $E_T > 15$ GeV
- $\geq 1$ jet with secondary vertex tag (SECVTX)

A jet is tagged as b jet if it has at least 2 good tracks and the displacement $L_{xy}$ satisfies $L_{xy}/\sigma_{xy} > 3$ (typical $\sigma_{xy} \sim 150$ $\mu$m, while $L_{xy} \sim 3$ mm)

**Probability of tagging a $tt$ event:**

$$\varepsilon(\text{event tag}) = 45 \pm 1 \pm 5\%$$
Backgrounds Estimation

**Backgrounds**

- **Mistags:** from # tagged jets with \(L_{xy}<0\) in inclusive jet data
- **W+heavy flavor:** from \(W+\)jets data, b tag rate and flavor composition
- **Non W:** from data
- **WW, WZ, Z→ττ, single top:** from Monte Carlo simulation

1 and 2 jet bins are used as a control sample, the top events are in \(\geq 3\) jet bins
- 15 Candidates in ~ 57.5 pb⁻¹
Lepton+jets $\sigma_{tt}$ - SECVTX-tagging

<table>
<thead>
<tr>
<th>Source</th>
<th>W+1jet</th>
<th>W+2 jets</th>
<th>W+3jets</th>
<th>W+4jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bkgr+Signal</td>
<td>34.0 ± 5.0</td>
<td>18.7 ± 2.4</td>
<td>7.4 ± 1.4</td>
<td>7.6 ± 2.0</td>
</tr>
<tr>
<td>Run II data</td>
<td>31</td>
<td>26</td>
<td><strong>7</strong></td>
<td><strong>8</strong></td>
</tr>
</tbody>
</table>

$\sigma_{tt} = 5.3 \pm 1.9\text{ (stat)} \pm 0.8\text{ (sys)} \pm 0.3\text{ (lum)} \text{ pb}$

Run II Preliminary:

Data sample luminosity: 57.5 pb$^{-1}$

CDF II preliminary

CDF Preliminary

*Theory results from M. Carri`ere et al.

$M_{tt} = 175 \text{ GeV}$, $M_{tt}/2 < \mu < M_{tt}$

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A “golden” lepton+jets candidate

- tt $l$+jet candidate: Nov 02 2002
- run: 153693 event: 799494
- $\mu$ + 4 jets, with 2 SECVTX b-tags
Top Cross-Sections Summary

D0 Preliminary

CDF Run II Preliminary

D0: All channels combined
Run II Preliminary:

$$\sigma_{t\bar{t}} = 8.5^{+4.5}_{-3.6} \text{ (stat)}^{+6.3}_{-3.5} \text{ (sys)}^{+0.8}_{-0.8} \text{ (lum)} \text{ pb}$$

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Top Mass: Lepton+jets

**Event Selection**

- Select $\geq 4$ jet events, similar to $\sigma_{tt}$ analysis, except no requirement for a jet to be $b$-tagged.

**Reconstruction Method**

- Each event→up to 24 solutions consistent with a top decay:
  - 12 different jet-partons assignments
  - Every combination has two solutions for the $\nu$ longitudinal momentum
- Impose $M_t = M_t$, $M(j,j) = M(l,\nu) = M_W$
  - PDG: $M_W$, $\Gamma_W$, $\Gamma_t$
- 2-C fit applied, chose the event top mass corresponding to the lowest $\chi^2$ (iff $\chi^2 < 10$)
- Parameterized templates of top masses (150, 200) GeV and bkgd
- Continuous likelihood to extract top mass and statistical uncertainty
33 candidates after event selection
- 8 events with a b tagged

\[ M_{\text{top}} = 171.2^{+14.4}_{-12.5} \text{ (stat)} \pm 9.9 \text{ (sys)} \text{GeV/c}^2 \]

### Systematic uncertainty summary

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (GeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Energy Measurement</td>
<td>9.3</td>
</tr>
<tr>
<td>Initial and Final State Radiation</td>
<td>2.4</td>
</tr>
<tr>
<td>Background Shape</td>
<td>0.3</td>
</tr>
<tr>
<td>Parton Distribution Functions</td>
<td>1.8</td>
</tr>
<tr>
<td>Monte-Carlo Generators</td>
<td>1.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>9.9</strong></td>
</tr>
</tbody>
</table>

Work to improve understanding of detector

CDF II Preliminary (72 pb^{-1})
\[ M_{\text{TOP}} = 171.2 \pm 13.4 \pm 9.9 \text{ GeV/c}^2 \]
Identifying a b-jet has a great impact:
- Smaller combinatorics → improves the mass resolution by ~10% 
- Reduction in background → S/B = 3, increase by 300% 
- Allow to loosen the 4th jet selection cuts (40% more events)

In 57.5 pb⁻¹ there are 11 candidates with at least one jet tagged as a b-jet

\( M_{\text{top}} \) with b-tagging is coming…

CDF Run II Preliminary

\[ \int L dt \approx 56 \text{ pb}^{-1} \]

B-tagged Events
- Data
- Wb⁻b⁻ bkgd
- 175 GeV t\(\bar{t}\) MC + bkgd

Reconstructed Top Quark Mass, B-tagged Events

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Run I Mass: lepton+4 jets events

Similar with Kondo’s method, uses full set of event observables

- Define a signal event probability
  \[ P_{tt}(x_i, M_{top}) \]

- Define a background probability
  \[ P_{bkg}(x_i) \]

- Build an event probability
  \[ P(x_i; \alpha) = c_1 P_{tt}(x_i, M_{top}) + c_2 P_{bkg}(x_i) \]
  where \( \alpha = (M_t, c_1, c_2) \)

- Build a likelihood \( L(\alpha) \), minimize \(-\ln L(\alpha)\) to get \( c_1, c_2 \) and \( M_t \)

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

LO ME used, 4 jets required exclusively, additional cut on background probability (to improve the sample purity)
Run I: Preliminary result

D0 Run I Statistics [PRD 58(1998), 052001]

- Events $91 \rightarrow 71$ with exactly 4 jets $\rightarrow 22$ after probability cut

- $\log(\text{likelihood})$ vs $M_t$

- $\text{likelihood vs } M_t$

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

Run I D0 lepton+jets:

$173.3 \pm 5.6 \text{(stat)} \pm 5.5 \text{ (syst) GeV/c}^2$

Stat : 5.6 GeV from PRD 2001 improvement on the statistical uncertainty ($\sim 2.4 \times \text{stats}$)
Summary & Conclusions

- Top physics is extremely rich and has a great potential
  - Many top analyses are in progress
    - we re-established the benchmark top quark measurements
    - we are getting close to Run I precision
  - Improvements are underway
    - Better detector understanding
    - Increase the tagging efficiencies of b jets
    - Include forward leptons
- We are enthusiastic about the top physics prospects at the Tevatron until first LHC results
- Expect results from larger samples soon
  - Many measurements will supersede those of Run I
- Test the Standard Model to even greater precision
## Top Physics Prospects for 2 fb^{-1}

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Est. Uncertainty</th>
<th>Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_t$</td>
<td>2-3 GeV/c^2</td>
<td>Indirect $M_H$</td>
</tr>
<tr>
<td>$\delta \sigma_{tt}$</td>
<td>7%</td>
<td>QCD Couplings</td>
</tr>
<tr>
<td>$\delta[\sigma_{ll}/\sigma_{l+j}]$</td>
<td>12%</td>
<td>Non-SM Decays</td>
</tr>
<tr>
<td>$\delta[B(t\rightarrow Wb)/B(t\rightarrow WX)]$</td>
<td>2.8%</td>
<td>“”</td>
</tr>
<tr>
<td>$\delta[B(t\rightarrow Wb)/B(t\rightarrow Xb)]$</td>
<td>9%</td>
<td>“”</td>
</tr>
<tr>
<td>$\delta[B(t\rightarrow W_{long})]$</td>
<td>5.5%</td>
<td>Non-SM Coup.</td>
</tr>
<tr>
<td>$\delta[B(t\rightarrow W_{V+A})]$</td>
<td>2.7%</td>
<td>W helicity</td>
</tr>
<tr>
<td>$\delta[\sigma^*B(Z'\rightarrow t t)]$</td>
<td>~90 fb</td>
<td>Exotics</td>
</tr>
<tr>
<td>$\delta \sigma_{tbX+btX}$</td>
<td>24%</td>
<td>Observe single top</td>
</tr>
<tr>
<td>$\delta \Gamma(t\rightarrow Wb)$</td>
<td>26%</td>
<td></td>
</tr>
<tr>
<td>$\delta V_{tb}$</td>
<td>13%</td>
<td>CKM Matrix</td>
</tr>
</tbody>
</table>
End of talk : Backup Slides
Reconstructed top masses from data are compared to parameterized templates of top and background Monte Carlo for masses (150, 200) GeV.

Use a continuous likelihood method to extract top mass and statistical uncertainty.

The bump in the background shape around 130 GeV is due to the kinematic selection of the events.
Constraint $M_{\text{Higgs}}$ with a $M_{\text{top}}$ and $M_{\text{W}}$.
Direct Higgs Search

CDF and DØ have a joint effort underway to re-evaluate some key channels in this Higgs reach plot. Results by ~ June.
**Single Top**

- **t-channel (Wg-Fusion)**
  - $u(\bar{d}) \rightarrow W^+ b$
  - $d(\bar{u}) \rightarrow W^+ t$
  - $g \rightarrow W^+ b$

2.44 ± 0.12 pb

Steltzer, et al. '98

- **s-channel ($W^*$)**
  - $u \rightarrow W^+ t$

0.88 ± 0.12 pb

Smith/Willenbrock '96

- **associated production**
  - $b \rightarrow W^+ t$

s<0.1 pb

Tait '99

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