The State of the Top Quark: Recent Results from CDF

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KITP seminar

- Status of Accelerator and CDF
- Top at the Tevatron
- Top cross-section measurements
- Search for Single Top production
- Top quark mass
- Improvements

An Experimentalist’s Motivation

I work with quarks

Ooooo... I'm getting all goosebumpy.

When Trish discovers Ned works exclusively with top quarks, she will be putty in his hands.
FY04 Integrated Luminosity

FY04 Goals:
Base: 230 pb\(^{-1}\)
Stretch: 310 pb\(^{-1}\)

Accelerator Long Term Goal

- Oct.-Nov. 2003 - shutdown to work on recycler, magnet alignment and vacuum
  - Instantaneous luminosity improved
  - Integrated luminosity > 8pb\(^{-1}\)/week
- Last week ran using pbars from recycler
- End of 2004 expect ~500 pb-1 of data
- Sept-Dec 04 shutdown to work on electron cooling
- End of 2009 expect integrated luminosity of
  - 4.4 fb-1 (no electron cooling)
  - If electron cooling in the Recycler expect 8.5 fb-1
    - will give 40% increase in integrated luminosity per week
    - Commissioned by June 2005
**CDF Detector Upgrades**

- 7-8 silicon layers
- $1.6 < r < 28 \text{ cm}$, $|z| < 45 \text{ cm}$
- $|\eta| \leq 2.0$, $\cos\theta = 0.964$
- $\sigma(\text{hit}) \sim 14 \, \mu\text{m}$

Some resolutions:

- $p_T \sim (0.7 \pm 0.1 \, p_T)\%$
- $J/\psi$ mass $\sim 15 \text{ MeV}$
- EM $E \sim 16%/\sqrt{E}$
- Had $E \sim 100%/\sqrt{E}$
- $d_0 \sim 6 + 22/p_T \, \mu\text{m}$
- Primary vtx $\sim 10 \, \mu\text{m}$
- Secondary vtx $r_\phi \sim 14 \, \mu\text{m}$
- $r-z \sim 50 \, \mu\text{m}$

- 96 layer drift chamber $|\eta| \leq 1.0$
- $44 < r < 132 \text{ cm}$, 30k channels
- $\sigma(\text{hit}) \sim 150 \, \text{mm}$
- $dE/dx$ for $p$, $K$, $\pi$ id

- Tile/fiber endcap calorimeter $1.1 < |\eta| < 3.5$
- $\mu$ coverage to $|\eta| \leq 1.5$
- 80% in phi

**Top Quark Production**

Top pairs via strong interaction:

- $90\% q\bar{q}$ $10\% gg$ at Tevatron $\sqrt{s} = 1.8 \text{ TeV}$
- $85\% q\bar{q}$ $15\% gg$ at Tevatron $\sqrt{s} = 1.96 \text{ TeV}$
- $10\% q\bar{q}$ $90\% gg$ at LHC $\sqrt{s} = 14 \text{ TeV}$

Parton density function of proton

$x_1 x_2 = \frac{s}{s} \geq 4m_t^2/m^2$

so $x_1 \approx x_2 \approx \frac{2m_t}{\sqrt{s}}$

Tevatron $\sqrt{s} = 1.96 \text{ TeV}$ $x \approx 0.18$

LHC $\sqrt{s} = 14 \text{ TeV}$ $x \approx 0.02$
Top Properties

- Top mass
- Production Cross Section
- Production Kinematics
- Top Spin Polarization
- Resonance Production

Branching Ratios
- Rare Decays
- Non-SM decay (t_H^*b)

Also, $V_{tb}$ from single top production

Top Quark Decay

Top quark decays to Wb almost 100% in Standard Model

- $\Gamma(t \rightarrow Wb) \sim 1.5$ GeV means $\tau_t \sim 4\times10^{-25}$ s
  - Too short for hadronization
  - No top spectroscopy!
  - Spin observable in decay products

3 characteristic event signatures from WW decay

**Dilepton:** BR small but pure

2 high $p_T$ leptons, high MET, $\geq 2$ jets

**Lepton+Jets:** BR larger but less pure

1 high $p_T$ lepton, high MET, $\geq 4$ jets (1 b-tag)

**All-hadronic:** BR largest but huge QCD bkg

$\geq 6$ jets (2 b-tags)  (No all-hadronic results yet)
Top Pair Production Cross-Section

\[ \sigma(t\bar{t}) = \frac{N_{\text{obs}} - N_{\text{bkg}}}{A\int L} \]

4 pieces:

- Estimate acceptance from top Monte Carlo
- Estimate number of background events
- Measure integrated luminosity to ± 6%
- Observe number of candidates in data

2 channels:

- Dilepton – 2 measurements
- Lepton+Jets – 4 measurements (so far)

Cross-section: Dilepton Channel

Two similar analyses:

- Two identified leptons
  - Run I style analysis
- One identified lepton + one isolated track $|\eta|<1.0$
  - Increase acceptance in future
    - Add forward leptons and tracks $|\eta|<2.0$
- Both analyses require:
  - Electron/muon with $E_T/P_T > 20$ GeV
  - High MET > 20 GeV or 25 GeV
  - $\geq 2$ high $E_T$ jets (JETCLU cone 0.4)
Cross Sections in Dilepton Events

Lepton + Track Analysis:
- Observe 19 candidates in 200 pb\(^{-1}\) of data
- Background estimate 7.0 ± 1.0 events

\[ \sigma_{tt} = 6.9^{+2.7}_{-2.4} \text{ (stat)} \pm 1.2 \text{ (sys)} \pm 0.4 \text{ (lum)} \text{ pb} \]

Two Identified Leptons:
- Observe 10 candidates in 126 pb\(^{-1}\) of data
- Background estimate 2.9 ± 0.9 events

\[ \sigma_{tt} = 7.6 \pm 3.4 \text{ (stat)} \pm 1.5 \text{ (sys)} \text{ pb} \]

Cross-section: Lepton+Jets Channel

Four different analyses:
- Three use b-tagging
  - Displaced Vertex Tagging (SVX)
    - Run I style analysis
    - Fit to kinematic variables (New for Run II)
  - Soft Lepton Tagging (SLT)
    - New result - uses muons only
- One uses no b-tagging
  - Fit to discriminating kinematic variables (New for Run II)
- All have common event selection
  - 1 identified high \(E_T>20\) GeV electron or muon
  - High MET > 20 GeV
  - \(\geq 3\) high \(E_T>15\) GeV jets (JETCLU cone 0.4)
**Silicon B-tagging in Run 2**

Charged Particles

Primary Vertex

Impact Parameter

Secondary Vertex

b-quark lifetime
\[ c\tau \sim 450\,\mu m \]

\[ \rightarrow b \text{ hadrons travel} \]

\[ L_{xy} \sim 3\,\text{mm before decay} \]

**SECVTX: Secondary Vertex Tagger**

Jet is tagged if \( L_{xy}/\sigma_{xy} > 3 \) (typical \( \sigma_{xy} \sim 150\,\mu m \))

- Efficiency to tag a ttbar event:
  \[ \epsilon \text{ (event tag)} \sim 55\% \]

**Run I Style - SVX b-tag**

- Observe 35 candidates in 108 ± 6 pb\(^{-1}\) of data
- Background estimate 15.1 ± 2.0 events

\[ \sigma_{tt} = 4.5 \pm 1.4 \text{ (stat)} \pm 0.8 \text{ (sys)} \text{ pb} \]

**CDF II preliminary**

- Background
- Background errors
- Background + t\bar{t} (theory 6.7 pb)
- Bkgnd + t\bar{t} errors
- Data (107.9 pb\(^{-1}\))

<table>
<thead>
<tr>
<th>Systematic Source</th>
<th>Uncertainty (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td>0.46</td>
</tr>
<tr>
<td>Acceptance</td>
<td>0.26</td>
</tr>
<tr>
<td>b-tag efficiency</td>
<td>0.36</td>
</tr>
<tr>
<td>Luminosity</td>
<td>0.27</td>
</tr>
</tbody>
</table>
Use fits to kinematics instead?

Jet $E_T$ Shape plus SVX b-tag

- Same 35 events as previous analysis in 108 pb$^{-1}$

$$\sigma_{tt} = 6.9 \pm 1.6^{+1.8}_{-1.8} \text{ (stat)} \pm 0.9 \text{ (sys)} \text{ pb}$$
**Kinematic Fit without a b-tag**

- 2x data
- Cross-check of b-tag result
- But higher background
  - W+jets, Z+jets, WW, WZ from MC
  - Non-EWK from data non-isolated leptons
- Choose $H_T$ as discriminating variable based on expected statistical sensitivity

**$H_T$ Fit to Signal Region**

**W+≥3 Jets**
Top Fraction: $12.5 \pm 4.2\%$

**W+≥4 Jets**
Top Fraction: $51.2 \pm 12.9\%$
### Systematic Effects W+≥3 Jets

<table>
<thead>
<tr>
<th>Effect</th>
<th>Shape</th>
<th>Acceptance</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Scale</td>
<td>28%</td>
<td>5.1%</td>
<td>30%</td>
</tr>
<tr>
<td>Generator</td>
<td>0.60%</td>
<td>---</td>
<td>0.6%</td>
</tr>
<tr>
<td>Q² Choice</td>
<td>14%</td>
<td>---</td>
<td>14%</td>
</tr>
<tr>
<td>PDF</td>
<td>3.3%</td>
<td>5.3%</td>
<td>8.6%</td>
</tr>
<tr>
<td>ISR (Pythia)</td>
<td>0.56%</td>
<td>0.78%</td>
<td>1.3%</td>
</tr>
<tr>
<td>Luminosity</td>
<td></td>
<td></td>
<td>5.9%</td>
</tr>
<tr>
<td>Background model</td>
<td>16%</td>
<td>1.7%</td>
<td>16%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>38.3%</strong></td>
</tr>
</tbody>
</table>

### Top Pair Production cross-section

#### Summary of results (pb)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Analysis</th>
<th>Int. Lum</th>
<th>σ_{tt}</th>
<th>Stat</th>
<th>Syst</th>
<th>Lum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dilepton</td>
<td>Lepton+Track</td>
<td>200 pb^{-1}</td>
<td>6.9</td>
<td>2.6</td>
<td>1.2</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Two Lepton</td>
<td>126 pb^{-1}</td>
<td>7.6</td>
<td>3.4</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Lepton+Jets</td>
<td>SVX b-tag</td>
<td>108 pb^{-1}</td>
<td>4.5</td>
<td>1.4</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lead Jet E_{T} + SVX</td>
<td>108 pb^{-1}</td>
<td>6.9</td>
<td>1.7</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SLT muons</td>
<td>126 pb^{-1}</td>
<td>4.1</td>
<td>3.5</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H_{T} kin fit (W≥3 jets)</td>
<td>195 pb^{-1}</td>
<td>4.7</td>
<td>1.6</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H_{T} kin fit (W≥4 jets)</td>
<td>195 pb^{-1}</td>
<td>8.0</td>
<td>2.0</td>
<td>3.0</td>
<td></td>
</tr>
</tbody>
</table>

#### Theoretical cross sections

Tevatron $\sqrt{s} = 1.96 \text{ TeV}$  

<table>
<thead>
<tr>
<th>m_{t} (GeV)</th>
<th>Min (pb)</th>
<th>Ref (pb)</th>
<th>Max (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>170</td>
<td>6.79</td>
<td>7.83</td>
<td>8.69</td>
</tr>
<tr>
<td>175</td>
<td>5.82</td>
<td>6.70</td>
<td>7.41</td>
</tr>
<tr>
<td>180</td>
<td>5.00</td>
<td>5.75</td>
<td>6.34</td>
</tr>
</tbody>
</table>
**Search for Single Top**

- CDF and D0 have performed searches for s and t channels separately in Run 1.
- CDF has also searched for combined process: \( \sigma(t) < 14 \text{ pb at 95\% C.L.} \)

**Electroweak Wtb Vertex**

<table>
<thead>
<tr>
<th>t-channel (Wg-Fusion)</th>
<th>s-channel ((W^+))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u(\bar{d}) )</td>
<td>( d(\bar{u}) )</td>
</tr>
</tbody>
</table>

\[ H_T \text{ for Events in W+1,2,3 Jet Bins (CDF Run 1 Data)} \]

- Expect about 100-150 events in 2 fb\(^{-1}\)
- If SM is correct, observation in Run 2a
- Measure \(|V_{tb}|\) with 10-15\% precision

**What makes single top so difficult?**

- Challenge: discriminate signal from background in W+2jet region
  - Top pair production is now a background!
  - Multivariate methods will be important

**Event distributions**

- Non-top
- \( tt \)
- Signal

All normalized to unit area for shape comparison
Single Top Search in Run I

All Run I searches saw excess of events in data
Recent artificial Neural Net search 22% more sensitive
  - a priori limit $\sigma < 9.6$ pb @ 95% CL
  - Observed limit $\sigma < 24.4$ pb @ 95% CL

7 input variables are
$E_T$ of lepton and jets, MET, $H_T$, dijet $P_T$, $Q_1$
3 outputs to classify ttbar, QCD, Signal

Single Top Combined Search in Run II

• No excesses yet in Run II...
• Observed limit $\sigma < 17.5$ pb @ 95% CL
• Observed limit $\sigma < 13.7$ pb @ 95% CL using 162 pb-1
Single Top t-channel Search

- Distinguish t- from s-channel using $Q \times \eta$
  - Disadvantage t-channel only 2/3 of single top
- **Observed limit** $\sigma < 15.4 \text{ pb} \ @ \ 95\% \ CL$
- **Observed limit** $\sigma < 8.5 \text{ pb} \ @ \ 95\% \ CL$ with 162 pb$^{-1}$

EWSB Constraints

Precision measurements of top and W masses constrain the mass of the Standard Model Higgs:

- $M_W : CDF \oplus D\emptyset$
  - $\sigma_M \sim 30 \text{ MeV} \ (2 \text{ fb}^{-1})$
- $M_t : CDF$ or $D\emptyset$
  - $\sigma_M < 3 \text{ GeV} \ (2 \text{ fb}^{-1})$

Precision top mass measurement crucial!
5 GeV shift in $m_t$ implies 37% shift in $m_H$
Top Mass in Lepton + Jets

Use constrained fit technique with 2 dof
\[ M_L = M_W, \quad M_{jj} = M_W, \quad M_{t1} = M_{t2}, \quad p_T \text{ balance} \]

4 jets = 12 possible jet-parton combinations
\( \times 2 \) solutions for neutrino \( p_z \)

!!!Use b-tagging to reduce permutations!!!

Choose combination with lowest \( \chi^2 \)

---

Run II Top Mass: Lepton + Jets

1 high \( p_T \) lepton, high MET, \( \geq 3 \) jets, 1 b-tag

4\textsuperscript{th} jet \( E_T > 8 \text{ GeV} \) (usually 15 GeV)

22 events, expect \( 6.5 \pm 2.0 \) from bkg

Same technique as Run I
- All events carry same weight
- Fit to shapes from MC

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic (GeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jets</td>
<td>6.2</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>2.6</td>
</tr>
<tr>
<td>PDF</td>
<td>2.0</td>
</tr>
<tr>
<td>Other MC modeling</td>
<td>1.0</td>
</tr>
<tr>
<td>Generators</td>
<td>0.6</td>
</tr>
<tr>
<td>Bkgd shape</td>
<td>0.5</td>
</tr>
<tr>
<td>b-tag</td>
<td>0.1</td>
</tr>
<tr>
<td>Total</td>
<td>7.1 GeV</td>
</tr>
</tbody>
</table>

CDF Run II preliminary 108 pb\(^{-1}\)

\[ m_{\text{top}} = 177.5 \pm 12.7 \text{ (stat)} \pm 7.1 \text{ (sys)} \text{ GeV}/c^2 \]
Top Mass – Expected Statistical Errors

CDF Run II (108 pb$^{-1}$)
Preliminary
Expected 8.8 GeV
Observed +12.7, -9.4 GeV

D0 Run I (125 pb$^{-1}$)
Preliminary
Expected 5.4 GeV
Observed 3.6 GeV

The Standard Model Higgs

Cross Section for Tevatron Production

- gg → H rate large but too much bb dijet background
- bb background ~6μb
- Main modes: WH, ZH

- Best search channels:
  \( M_H < 135 \text{ GeV} \)
  lvbb, vvb, llbb

  \( M_H \geq 135 \text{ GeV} \)
  llvv, lljj
Main Higgs Channels

\[ l\nu bb \]
- lepton trigger \((e, \mu)\)
- \(E_T(l) > 20 \text{ GeV}\)
- missing \(E_T > 20 \text{ GeV}\)
- 2 jets \((E_T > 15, 10 \text{ GeV})\)
- \(b\) tag (tight/loose)
- \(\cos\Delta\phi\) (jet-MET) ...
- reconstruct bb mass

\[ \nu\nu bb \]
- missing \(E_T\) trigger
- 2 jets \((E_T > 20, 15 \text{ GeV})\)
- \(b\) tag (tight/loose)
- \(p_T(bb), \ldots\)
- reconstruct bb mass

SM Higgs Reach

CDF+D0 combined integrated luminosity thresholds assuming 10% mass resolution, NN selection, nominal systematics
Higgs Discovery Potential

- SM Higgs
  - With 2 fb-1 and no signal exclude Mass > 120 GeV
  - Need 5 fb-1 for 3σ discovery

- MSSM Higgs
  - Better exclusion reach with 5fb-1 than SM

Top as a Background

Examples:
- WH with $H\rightarrow bb$
  - Need excellent understanding of top kinematics to set limits
  - Remember $m_H<120\text{GeV}$ is the most difficult mass range at LHC
- $H\rightarrow ZZ^*\rightarrow 4l$
- $H\rightarrow WW$
- SUSY searches
Improvements

• Improve SVX b-tagging by adding
  – Forward tracking with ISL
  – 3D tracking
  – Innermost layer of silicon (L00)
• New detector simulation and reconstruction code
  – Better jet corrections
  – Greatly improved detector simulation
  – Above improvements for b-tagging
• Need time to understand detector
• Adding new analysis techniques
  – So far focused repeating Run I analysis

Conclusions

• We see top!
  – Several cross section measurements + mass
• Have twice as much data as Run I
  – Expect new results with larger data sample for winter 04
• New analysis techniques starting
• Expect publications this summer with 200pb-1
• Stilled limited by systematic uncertainties
  – Need time to understand detector
  – Summer 2004 new top mass result with better precision than Run I