Single Top Quark Production at CDF

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On behalf of the CDF Collaborations

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The Tevatron and CDF

Run II: $\sqrt{s} = 1.96$ TeV
Tevatron stopped providing collisions on September 30, 2011

Tevatron was the birthplace of the top quark, observed in 1995 (Tevatron Run I) by CDF and D0

Luminosity (pb$^{-1}$)

- Delivered: $\sim 12$ fb$^{-1}$
- CDF recorded $\sim 10$ fb$^{-1}$
Top Quark Production at Tevatron

- **QCD pair production**
- **First observed at Tevatron in 1995**
  
  \[ \sigma_{SM} = 7.35^{+0.28}_{-0.33} \text{ pb} \]
  
  (for \( m_{Top} = 173 \text{ GeV} \))
  
  \([\text{PRL 110, 252004 (2003)}]\)

- Dominant process at Tevatron (~85%)
- Dominant process at LHC (~15%)
Top Quark Production at Tevatron

- **QCD pair production**
  - First observed at Tevatron in 1995
  - $\sigma_{SM} = 7.35^{+0.28}_{-0.33}$ pb
    - (for $m_{Top} = 172.5$ GeV)

- **EWK single-top production**
  - First observed at Tevatron in 2009
    - $s$-channel: $\sigma_{SM} = 1.06 \pm 0.06$ pb
    - $t$-channel: $\sigma_{SM} = 2.1 \pm 0.1$ pb
      - (for $m_{Top} = 172.5$ GeV)
      - PRL 103 092001 (2009), PRL 103 092002 (2009)
      - PRD 83, 091503 (2011)
      - PRD 81, 054028 (2010)
      - PRD 82, 054018 (2010)
      - arxiv:1210.7813.

- **Single top associated production** $Wt$: $\sigma \sim 0.25$ pb, too small at the Tevatron

Dominant processes:
- at Tevatron: ~85% $s$-channel, ~15% $t$-channel
- at LHC: ~29% $s$-channel, ~64% $t$-channel
Single top production: Tevatron versus LHC

- Tevatron and LHC are both sensitive to t-channel
- Tevatron is not sensitive to Wt production but has an advantage in s-channel

\[ \text{Tevatron: } \sigma_{\text{tot}} = 3 \text{ pb} \]
\[ \text{LHC: } \sigma_{\text{tot}} = 114 \text{ pb @ 8 TeV} \]

<table>
<thead>
<tr>
<th>Cross section(pb)</th>
<th>t\bar{t}</th>
<th>s-channel</th>
<th>t-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron(1.96 TeV)</td>
<td>7.08 \times 33</td>
<td>1.05 \times 5.3</td>
<td>2.08 \times 42</td>
</tr>
<tr>
<td>LHC(8 TeV)</td>
<td>234</td>
<td>5.55</td>
<td>87.2</td>
</tr>
</tbody>
</table>

(N. Kidonakis, arXiv:1210.7813)
Why measure Single Top Production?

- $\sigma_{\text{single top}} \propto |V_{tb}|^2$
- Give access to the W-t-b vertex
  - $\Rightarrow$ probe V-A structure
  - $\Rightarrow$ access to top quark spin
- Allows direct measurement of Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{tb}|$:

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix}
= 
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

Direct measurements:
- Ratio from $B_s$ oscillations
- Not precisely measured
- Inferred using unitarity

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  \( \Rightarrow \) access to top quark spin
- Allows direct measurement of Cabibbo-Kobayashi-Maskawa (CKM) matrix element \( |V_{tb}| \):
  \( \Rightarrow \) Is this Matrix 3x3?
  \( \Rightarrow \) Is there a 4\(^{th}\) generation?
  \( \Rightarrow \) Does unitarity hold?

\[ |V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1 \]

- Precision electroweak measurements rule out "simple" fourth generation extensions, but see for example:
Sensitivity to New Physics

- New physics may affect the rate of t and s channel differently

- Flavor changing neutral currents (t-Z-c, t-γ-c, t-g-c)

- heavy W' boson
- charged Higgs H^+
- Kaluza Klein excited W'^{kk}

T. Tait, CP Yuan PRD63, 014018 (2001)
The Challenge

- Single Top observation came 14 years after top discovery....
  ⇒ Single Top production is a rare process at the Tevatron: $S/B \sim 1: 10^9$ before any selection
  ⇒ not an easy measurement
- First step:
  ⇒ Trigger on high $P_T$ leptons/MET
  ⇒ Improves $S:B$ by $\sim 10^6$
- Second step:
  ⇒ Topological event selection
  ⇒ Efficient $b$-jet selection
  ⇒ Careful background estimates → average $S/B \sim 1/20$
Third step: no single variable provides sufficient signal-background separation:
⇒ take advantage of small signal-background separation in many variables
⇒ Perform multivariate analysis (MV)
⇒ Multiple variables combined into a single more powerful discriminant to separate S from B
⇒ analyses shown here use artificial NN techniques
Event Selection

- In the SM top quark decays most of the times to Wb
- (1) \( W + 2 \) or \( 3 \) energetic jets selection
  - One high \( p_T \) isolated lepton (e or \( \mu \)) from the decay of the W
  - Large missing transverse energy, MET, from the neutrino
  - At least one jet identified as “b” jet

- (2) MET + jets Selection
  - MET > 35 GeV
  - Veto leptons
  - 2 or 3 energetic jets
  - At least one jet identified as “b” jet

- Orthogonal Event Selections: (2) adds 33% acceptance to (1)
Background Modeling

- **W + jets**
  ⇒ Normalization and flavor composition from data
  ⇒ Shape from simulation
- **Diboson, Z+jets** from simulation
- **top pair production**
  ⇒ normalization to NNLO
  ⇒ Shape from Alpgen
- **QCD multijet production**
  ⇒ Normalization from data
  ⇒ Shape from data

<table>
<thead>
<tr>
<th>Process</th>
<th>2 jets 1 b-tag</th>
<th>3 jets 1 b-tag</th>
<th>2 jets 2 b-tags</th>
<th>3 jets 2 b-tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/Z+jets</td>
<td>4378 ± 547</td>
<td>1295 ± 164</td>
<td>213 ± 56</td>
<td>84 ± 20</td>
</tr>
<tr>
<td>tt</td>
<td>474 ± 49</td>
<td>1067 ± 109</td>
<td>98 ± 14</td>
<td>284 ± 42</td>
</tr>
<tr>
<td>Diboson</td>
<td>203 ± 22</td>
<td>62.7 ± 7</td>
<td>10 ± 1</td>
<td>4 ± 1</td>
</tr>
<tr>
<td>Non-W</td>
<td>316 ± 126</td>
<td>141 ± 57</td>
<td>7 ± 4</td>
<td>3 ± 3</td>
</tr>
<tr>
<td>t-channel</td>
<td>193 ± 25</td>
<td>84 ± 11</td>
<td>6 ± 1</td>
<td>15 ± 2</td>
</tr>
<tr>
<td>s-channel</td>
<td>128 ± 11</td>
<td>43 ± 4</td>
<td>32 ± 4</td>
<td>12 ± 2</td>
</tr>
<tr>
<td>Wt-channel</td>
<td>16 ± 4</td>
<td>26 ± 7</td>
<td>1 ± 0</td>
<td>2 ± 1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>5707 ± 877</td>
<td>2719 ± 293</td>
<td>367 ± 66</td>
<td>403 ± 53</td>
</tr>
<tr>
<td><strong>Observed</strong></td>
<td>5533</td>
<td>2432</td>
<td>335</td>
<td>355</td>
</tr>
</tbody>
</table>
**lvbb s+t Analysis**

- Lepton+jets with $7.5 \text{ fb}^{-1}$
- # of jets/b-tags to define samples (4)
- Train NN with 11-14 variables
- Use s-channel as signal in only 2jet-2tag channel, t-channel for the rest
- Use admixture of systematics shifted samples $\rightarrow$ 3% improvement
- Validate data-background agreement in 0-tag sample
**Measure cross section using maximum likelihood fit to the binned NN output distributions**

**Assume uniform prior probability density for the c.s.**

**Integrate the posterior probability density over the parameters associated with all sources of systematic uncertainties**

\[ \sigma_{s+t+Wt} = 3.04^{+0.57}_{-0.53} \text{ pb} \]

**CDF II Preliminary 7.5 fb^{-1}**

**CDF Pub. Note 10793**

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**t-channel vs s-channel**

- We assume a uniform prior-probability density distribution in the two-dimensional plane \((\sigma_s, \sigma_{(t+W_t)})\).
- Determine the cross sections that maximize the posterior-probability density distribution.
- The t-channel and Wt processes are combined as they share the same final-state topology.

\[
\sigma_s = 1.81^{+0.63}_{-0.58} \text{ pb} \\
\sigma_{(t+W_t)} = 1.66^{+0.53}_{-0.47} \text{ pb}
\]

CDF 7.5 fb\(^{-1}\):

- \(\sigma_s^{SM} = 1.06 \pm 0.06 \text{ pb}\)
- \(\sigma_{t+Wt}^{SM} = 2.34 \pm 0.30 \text{ pb}\)

CDF Pub. Note 10793

Theor:
- PRD 83, 091503 (2011)
- PRD 81, 054028 (2010)
- PRD 82, 054018 (2010)
**METbb s+t analysis**

- Full CDF Run II dataset (9.5 fb\(^{-1}\))
- Recover non-reconstructed electrons and muons and \(W \rightarrow \tau \nu\) (hadronic decay)
- Completely orthogonal dataset to \(\ell + \text{jets}\) selection
- # of jets/b-tags to define samples (6)
- Several NN used against QCD, \(V + \text{jets}\) and \(t\bar{t}\)bar, for s- and t-channels
- \(\text{NN}_{\text{sig}}^{s+t}\) final discriminant is used to separate both s- and t-channel signal from remaining background
- Assume SM \(\sigma_s/\sigma_t\)

\[\sigma_{s+t} = 3.53^{+1.25}_{-1.16} \text{ pb}\]

CDF Pub. Note 11033

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CKM matrix element $|V_{tb}|$

- $\sigma(s+t+Wt) \propto |V_{tb}|^2$ → calculate posterior pdf in terms of $|V_{tb}|^2$

- To transform $\sigma(s+t)$ measurement into $|V_{tb}|$, assume:
  - $\Rightarrow$ SM top quark decay: $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$
  - $\Rightarrow$ V-A and CP conserving $Wtb$ vertex
  - $\Rightarrow$ No assumption on number of families or CKM unitarity

- Complementary with $tt$ decay measurements of the ratio $R$

$$|V_{tb,meas}|^2 = \frac{\sigma_{meas}}{\sigma_{SM}} \cdot |V_{tb,SM}|^2$$

$|V_{tb}| = 0.95 \pm 0.09$ (stat+syst) $\pm 0.05$ (theo)

$|V_{tb}| > 0.78$ (95% C.L.)

CDF Pub. Note 10793

11% precision
The results of the two analyses ($l+$jets and MET+jets) are combined by taking the product of their likelihoods and simultaneously varying correlated uncertainties.

$$\sigma_{s+t} = 3.02^{+0.49}_{-0.48} \text{ pb} \pm 16\% \text{ precision}$$

$t$-channel, considering the $s$-channel as background constrained to theoretical prediction:

$$\sigma_t = 1.65^{+0.38}_{-0.36} \text{ pb} \pm 23\% \text{ prec.}$$

$$|V_{tb}| > 0.84 \text{ @ 95\% C.L.}$$
s-channel optimized analyses

- New lepton+jets and MET+jets s-channel optimized analyses based on Higgs search techniques and selection
- Use CDF full Run II data set, extra lepton trigger adds 10% more leptons
- Innovative multivariate tagger, non-overlapping tagging categories
- Both use NN trained for s-channel in all categories

\[ \sigma_s = 1.41^{+0.44}_{-0.42} \text{ (stat+syst) pb} \]

\[ \sigma_s = 1.12^{+0.61}_{-0.57} \text{ (stat+syst) pb} \]

PRL 112, 231804 (2014)  
PRL 112, 231805 (2014)
$s$-channel results

$l+\text{jets}$

CDF Run II Preliminary (9.4 fb$^{-1}$)

$\sigma_s = 1.41^{+0.44-0.42}_{-0.42} \text{ (stat+syst) pb}$

PRL 112, 231804 (2014)
CDF $s$-channel combination

$\sigma_s = 1.36^{+0.37}_{-0.32}\, (\text{stat+syst})\, \text{pb}$

$\pm 27\%$ precision

Single Top $s$-channel Combination  CDF Run II Preliminary, $L = 9.5\, \text{fb}^{-1}$

- **Observed Value**
- **Background Only**
- **Signal + Background**

Observed p-value: $0.000016\, (4.2\sigma)$
Expected p-value: $0.000320\, (3.4\sigma)$

$4.2\, \text{s.d. significance}$

PRL 112, 231805 (2014)
Conclusion

- Single top quark was observed by CDF and D0 in 2009
- Since then, single top measurements have been refined
- Single top quark s-channel production evidence in 2014
- See next talk by C. Schwanenberger for Tevatron combined s-channel observation

- Now CDF single top quark program is almost complete
  \(\Rightarrow\) All measurements in agreement with the SM prediction
  \(\Rightarrow\) Single top quark is one of Tevatron legacies!

- Tevatron combined s+t production cross section is underway
- 2.5 years after the end of RunII CDF continues providing valuable top physics results
Single top & Higgs search

- Single top quark production was a background for searches for a low mass Higgs boson at the Tevatron
  ⇒ $s$-channel single top shares same final state $l\nu bb$ with Higgs production associated with a $W$-boson (WH-production)
- Single top observation was a Benchmark to WH Higgs search $\sigma_{WH} \sim 1/10 \sigma_{Singletop}$

**Analysis strategy**

- **Goal:** combine multiple variables into a single, more powerful discriminant to separate signal from background.

- Several methods have been used:
  - Likelihood functions,
  - Matrix Element,
  - Neural network (NN),
  - Boosted decision tree.

- Check discriminant performance using data control samples.

- Perform the statistical analysis:
  - Build Bayesian posterior probability density to measure cross section.
  - Shape normalization and systematics treated as nuisance parameters.
  - Correlations between uncertainties properly accounted for.