"Measurements of the $t\bar{t}$ Production Cross-Section at the Tevatron Run II CDF Experiment Using B-Tagging"

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DPF 2004, UC Riverside
The CDF Detector Upgrade

- Most of the detector has been upgraded.
- Main upgrade:
  - new Silicon Vertex Detector (larger coverage)
  - 7 double-sided layers.
  - 1 single-sided layer on beam pipe (not used here).
  - 90 cm long.
  - (instead of 4 layers of 50 cm in Run I)
Topology and Selection of “Lepton+Jets” $t\bar{t}$ Events

• Decay chain:
  – Both top quarks decay to $W+b$.
  – $W \rightarrow q\bar{q}$.
  – $W \rightarrow l\nu_l$ ($l=e$ or $\mu$).

• Branching ratio $\approx 30\%$:
  large B.R., and reasonable background

• Signature and selection:
  – 1 High $p_T$ lepton: $> 20$ GeV
    Isolated: $I^{0.4} < 10\%$
  – High Missing $E_T$: $> 20$ GeV
  – 4 jets:
    require $\geq 3$ jets of $E_T > 15$ GeV
  – 2 B-jets, can be tagged by reconstructing secondary vertices, or identifying soft muons:
    require $\geq 1$ tagged jet
Overview of the Analyses

• I will show results from 4 similar analyses.
• All analyses share the same lepton ID, jet and missing $E_T$ selection.
• Differ in b-tagger and signal extraction technique.
• 2 B-Taggers:

**Secondary Vertex Tagger:**

1) Evaluation of background and event counting.
2) Using the double-tag sub-sample.
3) Kinematic fit to extract the signal fraction.

**Soft Muon Tagger:**

4) Evaluation of background and event counting.
Secondary Vertex B-Tagging Algorithm

• Take advantage of the long life-time of B hadrons:
  \[ c\tau \approx 450 \, \mu m \]

• Secondary Vertex algorithm.

• Select good quality tracks with large impact parameter.

• Try to reconstruct a vertex.

• Tag vertices with large (transverse) decay length significance:
  \[ \frac{L_{xy}}{\sigma L_{xy}} > 3 \]

Decay Length of B-Jets in t \bar{t} MC

CDF II Preliminary
HT = 358 GeV

Jet1 79.6 GeV
Jet2 50.4 GeV
Jet3 31.7 GeV
Jet4 25 GeV
Jet5 20 GeV
MET 66.7 GeV
Electron 72.6 GeV

CDF II Reference VTX from beamline
Secondary VTX
I.P. = 2.3 mm
L_{xy} = 3 mm
L_{xy} = 2.3 mm
Secondary Vertex B-Tagging Efficiency

- Use sample of semi-leptonic decay b-jets as a control sample to normalize the MC to data:
  \[ \frac{\epsilon_{\text{data}}}{\epsilon_{\text{MC}}} = 81 \pm 7 \% \]

- Error dominated by statistics, and understanding of control sample Heavy Flavor content.

- Check in multi-jet events the \( E_T \) dependence of the b-tagging efficiency, as well as the mistag rate of the algorithm.

- Efficiency for tagging at least one jet in a \( t\bar{t} \) event (l+\( \geq 3 \) jets, incl. data-MC scaling):
  \[ \epsilon_{\geq 1\,\text{tag}}^{t\bar{t}} = 53 \pm 4\% \]
Measurement with Secondary Vertex B-Tagging (I)

Method:

• Simple counting analysis:

\[ \sigma_{tt} = \frac{N_{tt}}{L} = \frac{N_{obs} - N_{bkd}}{A_{tt}\epsilon_{tt}} \]

  - \(N_{obs}\): Number of observed events
  - \(N_{bkd}\): Number of expected background events
  - \(A_{tt}\) \(\epsilon_{tt}\): Acceptance x b-tag efficiency = fraction of produced \(tt\) events that are actually detected
  - \(L\): Integrated Luminosity

• In order to increase sensitivity, reject background by using the total (transverse) energy in the event:

  \(H_T = \text{Scalar Sum of Jets } E_T, \text{ Lepton } p_T, \text{ Missing } E_T\)

• Requiring \(H_T > 200 \text{ GeV}\) rejects \(>1/3\) of background, keeping 96% of \(tt\) signal.
Key issue of this analysis: Understanding the $W+$jets sample composition

- We use both data and MC to evaluate the backgrounds.

- $Wb\bar{b}, Wc\bar{c}, Wc$: Monte Carlo provides Heavy Flavor fraction of $W+$jets, normalization from data
- $Wq\bar{q}$ (mistag): Mistag rates measured in multi-jet control sample
- QCD (multi-jets): $W$ faked either by fake lepton, or semileptonic $B$ decay
  Use non-isolated lepton sample
- Single Top, $WW, WZ, ZZ$: from MC
Measurement with Secondary Vertex B-Tagging:

- 48 tagged events with 3 or more jets and $H_T > 200$GeV (57 without $H_T$ cut).

$$\sigma_{t\bar{t}} = 5.6^{+1.2}_{-1.0} (\text{stat.})^{+1.0}_{-0.7} (\text{syst.}) \text{ pb}$$

<table>
<thead>
<tr>
<th>Syst.</th>
<th>Err on $\sigma_{t\bar{t}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance</td>
<td>10%</td>
</tr>
<tr>
<td>B-tagging</td>
<td>8.6%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>6%</td>
</tr>
<tr>
<td>Bgd</td>
<td>4.4%</td>
</tr>
</tbody>
</table>

CDF II preliminary

- require $H_T > 200$ for $\geq 3$ jets
Measurement of $\sigma_{tt}$ with double-tag events

- Look at the sub-sample of events with 2 tagged jets.
- Very pure signal: $S/B=9$
- Interesting check of the B content of $W+\text{jets}$ sample.
- 8 candidates $\rightarrow$ dominated by statistics.

CDF II preliminary

\[ \sigma_{tt} = 5.4 \pm 2.2 \pm 1.1 \text{ pb} \]

- 2-jet events: $\leq 2\sigma$ excess
- But not seen in the single-tag sample
Measurement with Secondary Vertex B-Tagging, Using a Kinematic Fit

- Uses the same secondary vertex tagger, and same sample (but no $H_T$ cut).
- Fit the $E_T$ distribution of the leading jet to extract the fraction of $t\bar{t}$ events.
- This variable is both sensitive and well-understood.
- Avoids evaluating the background contributions. Background shape from 0-tag data → does not rely on Monte Carlo (complementary method)

Background template:

![Background template](image1)

Signal template (Herwig):

![Signal template](image2)
Measurement with Secondary Vertex B-Tagging, Using a Kinematic Fit

- Result based on 162 $pb^{-1}$.
- 57 candidates.
- The fit gives a $t\bar{t}$ fraction of:
  $0.67^{+0.13}_{-0.16}$
  consistent with previous analysis.
- Cross-section:
  $\sigma_{t\bar{t}} = 6.0^{+1.5}_{-1.8}\text{(stat.)} \pm 0.8\text{(syst.)} \text{ pb}$
- Cross-check: measurements with other kinematic variables, such as second leading jet, or sum of two leading jets $E_T$ give consistent results.
Soft Muon B-Tagging Algorithm

- Identify muons coming from B hadron semi-leptonic decays.
- Match tracks in drift chamber with segments in muon chambers.
- Likelihood fit based on muon system information only.
- Efficiency measured from $J/\psi$, $Z^0$ samples.
  Main uncertainty due to higher track occupancy in $t\bar{t}$ events than in control sample.
- Fake rate determined from $\gamma$+jets control sample, parametrized in $\eta$, $\phi$, and $p_T$:
  Average fake rate = 0.7%
- Actual efficiency is lowered by the semi-leptonic decay branching ratio:
  Efficiency to tag at least one jet in a $t\bar{t}$ event:
  $\epsilon = (14 \pm 0.3^{+0}_{-1.1})\%$ for 3-jet events
  $\epsilon = (16 \pm 0.3^{+0}_{-1.3})\%$ for $\geq$4-jet events
Measurement with Soft Muon Tagger

- Test of the Heavy Flavor properties of the $t\bar{t}$ sample.
- Same counting method as shown before with Sec. Vec algorithm.
- Lower efficiency $\rightarrow$ poorer statistics, but larger data sample (no silicon detector required)
- Backgrounds are evaluated with same methods: dominated by mistags and QCD
- 20 candidates in 194 $\text{pb}^{-1}$ of data.

$$\sigma_{t\bar{t}} = \frac{N_{\text{obs}} - N_{\text{bkd}}}{\epsilon_{t\bar{t}}L} = 4.2^{+2.9}_{-1.9}\text{(stat.)} \pm 1.4\text{(syst.)} \text{ pb}$$

CDF II Preliminary

- Wbb, Wcc, Fake
- non-W
- Drell-Yan
- Wc
- WW, WZ, ZZ, Z$\rightarrow \tau\tau$
- Single top
- Total Bckg $\pm 1\sigma$
- Data (194 $\pm 11 \text{ pb}^{-1}$)

Require $H_T > 200 \text{ GeV for } \geq 3 \text{ jets}$

Number of tagged events

Number of jets in $W$+jets

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DPF 2004, UC Riverside
Conclusion

- $\sigma_{t\bar{t}}$ has been measured with significantly larger statistics than in Run I, at a new center-of-mass energy ($\sqrt{s} = 1.96$ TeV):

- So far, results are consistent with a Standard Model $t\bar{t}$ signal with $m_t \approx 175$ GeV ($\sigma_{t\bar{t}}^{SM} = 6.7^{+0.7}_{-0.9}$ pb):

  \[ m_t = 175 \]

- Publication in preparation.

- Looking forward to more data...

![Top Production Cross Sections with B-Tagging at CDF II](image)
## Background Summary Sec. Vertex (backup)

<table>
<thead>
<tr>
<th>Background</th>
<th>$W + 1$ jet</th>
<th>$W + 2$ jets</th>
<th>$W + 3$ jets</th>
<th>$W + \geq 4$ jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events before tagging</td>
<td>15314</td>
<td>2448</td>
<td>179</td>
<td>91</td>
</tr>
<tr>
<td>mistags</td>
<td>$40.6 \pm 4.9$</td>
<td>$16.8 \pm 2.2$</td>
<td>$3.2 \pm 0.5$</td>
<td>$2.3 \pm 0.4$</td>
</tr>
<tr>
<td>$Wb\bar{b}$</td>
<td>$21.2 \pm 7.6$</td>
<td>$14.1 \pm 4.7$</td>
<td>$1.7 \pm 0.6$</td>
<td>$1.2 \pm 0.5$</td>
</tr>
<tr>
<td>$Wc\bar{c}$</td>
<td>$10.7 \pm 4.7$</td>
<td>$6.1 \pm 2.4$</td>
<td>$0.6 \pm 0.3$</td>
<td>$0.4 \pm 0.2$</td>
</tr>
<tr>
<td>$Wb\bar{b}, Wc\bar{c}$, mistags (Method 2)</td>
<td>$72.5 \pm 13.2$</td>
<td>$37.0 \pm 7.5$</td>
<td>$5.6 \pm 1.0$</td>
<td>$3.8 \pm 0.8$</td>
</tr>
<tr>
<td>$Wc$</td>
<td>$37.7 \pm 12.3$</td>
<td>$9.2 \pm 3.4$</td>
<td>$0.8 \pm 0.3$</td>
<td>$0.3 \pm 0.1$</td>
</tr>
<tr>
<td>$WW/WZWZZ, Z \rightarrow \tau\tau$</td>
<td>$2.3 \pm 0.5$</td>
<td>$2.6 \pm 0.5$</td>
<td>$0.3 \pm 0.1$</td>
<td>$0.08 \pm 0.06$</td>
</tr>
<tr>
<td>non-$W$</td>
<td>$26.7 \pm 2.8$</td>
<td>$12.5 \pm 1.9$</td>
<td>$2.5 \pm 0.5$</td>
<td>$11.9 \pm 0.4$</td>
</tr>
<tr>
<td>single top</td>
<td>$2.7 \pm 0.4$</td>
<td>$4.7 \pm 0.7$</td>
<td>$0.8 \pm 0.1$</td>
<td>$0.2 \pm 0.03$</td>
</tr>
<tr>
<td>Total</td>
<td>$141.8 \pm 18.9$</td>
<td>$66.0 \pm 8.9$</td>
<td>$10.0 \pm 1.2$</td>
<td>$6.3 \pm 0.9$</td>
</tr>
<tr>
<td>Corrected Total</td>
<td>$141.8 \pm 18.9$</td>
<td>$66.0 \pm 8.9$</td>
<td>$13.8 \pm 2.0$</td>
<td></td>
</tr>
<tr>
<td>Observed positive tags</td>
<td>160</td>
<td>73</td>
<td>21</td>
<td>27</td>
</tr>
</tbody>
</table>
# Results

<table>
<thead>
<tr>
<th>Background</th>
<th>W + 1 jet</th>
<th>W + 2 jets</th>
<th>W + 3 jets</th>
<th>W +≥ 4 jets</th>
<th>W+≥ 3 jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events before tagging</td>
<td>18314</td>
<td>2889</td>
<td>226</td>
<td>111</td>
<td>337</td>
</tr>
<tr>
<td>Fake, Wb̅b, Wc̅c</td>
<td>115.9 ± 11.6</td>
<td>41.2 ± 4.1</td>
<td>6.4 ± 0.6</td>
<td>4.3 ± 0.4</td>
<td>10.7 ± 1.1</td>
</tr>
<tr>
<td>Wc</td>
<td>10.4 ± 2.9</td>
<td>4.1 ± 1.3</td>
<td>0.4 ± 0.1</td>
<td>0.12 ± 0.05</td>
<td>0.55 ± 0.18</td>
</tr>
<tr>
<td>WW, WZ, ZZ, Z → τ⁺τ⁻</td>
<td>1.13 ± 0.17</td>
<td>1.36 ± 0.07</td>
<td>0.18 ± 0.03</td>
<td>0.04 ± 0.01</td>
<td>0.20 ± 0.02</td>
</tr>
<tr>
<td>Non-W</td>
<td>21.1 ± 9.9</td>
<td>8.1 ± 3.9</td>
<td>1.5 ± 0.8</td>
<td>0.7 ± 0.5</td>
<td>2.4 ± 1.2</td>
</tr>
<tr>
<td>Drell-Yan</td>
<td>3.1 ± 0.6</td>
<td>0.64 ± 0.27</td>
<td>0.18 ± 0.14</td>
<td>0.0 ± 0.0</td>
<td>0.18 ± 0.14</td>
</tr>
<tr>
<td>Single-Top</td>
<td>0.51 ± 0.04</td>
<td>0.95 ± 0.06</td>
<td>0.15 ± 0.01</td>
<td>0.036 ± 0.003</td>
<td>0.19 ± 0.01</td>
</tr>
<tr>
<td>Total Background</td>
<td>152.2 ± 15.5</td>
<td>56.3 ± 5.9</td>
<td>8.9 ± 1.0</td>
<td>5.2 ± 0.7</td>
<td>14.2 ± 1.6</td>
</tr>
<tr>
<td>Corrected Background</td>
<td></td>
<td></td>
<td>11.59 ± 1.5</td>
<td>11.59 ± 1.5</td>
<td>13.7 ± 2.7</td>
</tr>
<tr>
<td>t̅t̅ expectation</td>
<td>0.36 ± 0.09</td>
<td>3.0 ± 0.5</td>
<td>5.6 ± 0.9</td>
<td>8.1 ± 1.8</td>
<td>13.7 ± 2.7</td>
</tr>
<tr>
<td>Total Background plus t̅t̅</td>
<td>152.5 ± 15.5</td>
<td>59.3 ± 5.9</td>
<td>25.3 ± 3.1</td>
<td>25.3 ± 3.1</td>
<td></td>
</tr>
<tr>
<td>Tagged Events</td>
<td>139</td>
<td>48</td>
<td>13</td>
<td>7</td>
<td>20</td>
</tr>
</tbody>
</table>

\[ \sigma_{\tilde{t}\tilde{t}} = 4.2^{+2.9}_{-1.9} \text{ (stat.)} \pm 1.4 \text{ (sys.) pb} \]