Single top production at the Tevatron

- Electroweak production of top quarks
- Signal and selection
- Recent DØ and CDF results
  - CDF $s+t$ measurement (7.5 fb$^{-1}$)
  - DØ $s$-channel evidence (9.7 fb$^{-1}$) \textcolor{red}{NEW}
  - CDF $s+t$ measurement in MET+jets (9.1 fb$^{-1}$)
- Searches for anomalous Wtb couplings DØ (5.4 fb$^{-1}$)
- Summary
Electroweak top quark production

Main production mechanism is $t\bar{t}$ via the strong interaction:

\[ \sigma(tt) \sim 7.1 \text{ pb} @ \text{TeV} \quad \sigma(tt) \sim 234 \text{ pb} @ \text{LHC8} \]

Top quarks can be produced alone via the weak interaction:

\[ \sigma(t) \sim 3.2 \text{ pb} @ \text{TeV} \quad \sigma(t) \sim 115 \text{ pb} @ \text{LHC8} \]

- 3 production processes: different topologies and properties
- Offers direct access to $|V_{tb}|$, test V-A nature of SM, probes b PDF
- Window to new physics: new particles, anomalous couplings
- LHC w.r.t TeV: s-channel x5, t-channel x40, tW x100, $t\bar{t}$ x30

<table>
<thead>
<tr>
<th>TeV</th>
<th>LHC8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.04 \pm 0.06$ pb</td>
<td>$5.6 \pm 0.2$ pb</td>
</tr>
<tr>
<td>$2.1 \pm 0.1$ pb</td>
<td>$87 \pm 3$ pb</td>
</tr>
<tr>
<td>$0.22 \pm 0.08$ pb</td>
<td>$22 \pm 2$ pb</td>
</tr>
</tbody>
</table>

Kidonakis, MSTW2008, NNLO approximation, for $m_t = 173$ GeV

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Experimental status

<table>
<thead>
<tr>
<th></th>
<th>σ (NNLO) [pb]</th>
<th>tb</th>
<th>tqb</th>
<th>tW</th>
</tr>
</thead>
<tbody>
<tr>
<td>TeV prediction</td>
<td></td>
<td>1.04</td>
<td>2.26</td>
<td>0.28</td>
</tr>
<tr>
<td>CDF (7.5 fb⁻¹)</td>
<td></td>
<td>1.8 ± 0.6</td>
<td>1.49 ± 0.45</td>
<td>-</td>
</tr>
<tr>
<td>DØ (9.7 fb⁻¹)</td>
<td></td>
<td>1.10 ± 0.33</td>
<td>3.07 ± 0.53</td>
<td>-</td>
</tr>
<tr>
<td>LHC prediction (7 TeV)</td>
<td></td>
<td>4.6</td>
<td>64.6</td>
<td>15.7</td>
</tr>
<tr>
<td>ATLAS (0.7-2.1 fb⁻¹)</td>
<td></td>
<td>&lt;20.5 (95%CL)</td>
<td>83 ± 20</td>
<td>17 ± 6</td>
</tr>
<tr>
<td>CMS (1.2-4.9 fb⁻¹)</td>
<td></td>
<td>-</td>
<td>67 ± 6</td>
<td>16 ± 5</td>
</tr>
</tbody>
</table>

Challenging measurement

- Extract small signal out of a large background with large uncertainties
- Lower cross section: \( \sigma_t \sim \frac{1}{2} \sigma_{tt} \)
- \( l + \text{MET} + 2 \text{ jets} \) (harder environment)
- Test bed for Higgs searches
- Want to measure separate channels

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Signal selection

- Selection designed to be as open as possible: describe backgrounds well
  - Only one isolated $\ell$; 2, 3 (4) jets; 1,2 b-tags; MET

- S/B $\sim 1/200$ before b-tagging

- Best S/B $\sim 1/10$ after b-tagging

- Dominated by $W$+jets backgrounds
  - 2 jet: $Wb\bar{b}$ 27%, $Wc\bar{c}$+cj 23%, $W$+lf 24% of total yield
  - 3 jet: $Wb\bar{b}$ 16%, $Wc\bar{c}$+cj 12%, $W$+lf 14% of total yield

CDF 7.5 fb$^{-1}$

<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>
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</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>Total</td>
<td>5707 ± 877</td>
<td>2719 ± 293</td>
<td>367 ± 66</td>
<td>403 ± 53</td>
</tr>
<tr>
<td>Observed</td>
<td>5533</td>
<td>2432</td>
<td>335</td>
<td>355</td>
</tr>
</tbody>
</table>

CDF 3.2 fb$^{-1}$
Background modeling

- Diboson, Z+jets, $t\bar{t}$ normalized to SM (NLO) cross section
- Multijets from data with non-isolated lepton (DØ) or “sideband” $\ell$ (CDF)
- W+jets from Alpgen ($Wjj$, $Wb\bar{b}$, $Wc\bar{c}$, $Wcj$)
  - Correct angular distributions jet $\eta$ and $\Delta R(j_1,j_2)$ before b-tagging
- W+jets and multijets (QCD) are normalized to data before b-tagging
  - CDF fits templates of W+jets and non-W in MET distribution
    - W+light and W+hf from tag rates in control data
  - DØ uses Matrix Method for overall scale, and MCFM for W+hf
    - Crosscheck W+hf fraction in 0-tag sample and b-ID output fits

![Graphs and plots]

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Single top at the Tevatron

CDF 3.2 fb$^{-1}$
CDF NN analysis 7.5 fb$^{-1}$

- Added new lepton category
  - ISOTRK → 15% gain in acceptance
- Train NN with 11-14 variables
  - Use s-channel only in 2 jet 2 tag, t-channel for the rest
  - Use admixture of systematics shifted samples → 3% improvement
- Validate data-background agreement in 0-tag sample
DØ multivariate analysis 9.7 fb⁻¹

- Optimized selection for s-channel sensitivity
- DØ has used three different techniques: BDT, BNN, ME
  - BDT uses 30 well-modeled variables, BNN uses 4-vectors
  - Improved ME, better t\(\bar{t}\) model, and b-tag weights for discriminants
DØ combined discriminants

- Obtain separate cross section measurements on same data
- Each method selects different event kinematics
- Around 75% correlation $\rightarrow$ Combination improves significance

![Graphs showing s-channel and t-channel discriminants for DØ 9.7 fb$^{-1}$ data.](image)

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Single top at the Tevatron
s+t cross section results

CDF 7.5 fb\(^{-1}\) (\(m_t=172.5\) GeV) Note 10793

\[ \sigma(s+t) = 3.0^{+0.6}_{-0.5} \text{ pb} \quad (\pm 19\%) \]

DØ 9.7 fb\(^{-1}\) (\(m_t=172.5\) GeV) arXiv: 1307.0731

\[ \sigma(s+t) = 4.1\pm 0.6 \text{ pb} \quad (\pm 14\%) \]

Previous Tevatron combination (3.2+2.3 fb\(^{-1}\)):

\[ \sigma(s+t) = 2.76^{+0.58}_{-0.47} \text{ pb} \quad (\pm 21\%, \ m_t=170\) GeV) \]

Main systematics:
- B-tagging
- W+jets normalization
- Jet energy scale / resolution

Does not assume SM \(\sigma_{tb}/\sigma_{tqb}\) ratio

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Constraining $V_{tb}$

- Single top allows to study $V_{tb}$ at production
- $\sigma(s,t) \propto |V_{tb}|^2 \rightarrow$ calculate posterior pdf in terms of $|V_{tb}|^2$
- To transform $\sigma(s+t)$ measurement into $V_{tb}$, assume:
  - SM top quark decay: $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$
  - Pure V-A and CP conserving $W_{tb}$ vertex
- No assumption on number of families or CKM unitarity (DØ doesn't assume SM $\sigma_s/\sigma_t$ ratio either)
- Complementary with $t\bar{t}$ decay measurements of $R$ and $W$ helicity

CDF $7.5 \text{ fb}^{-1}$:
$|V_{tb}| = 0.92^{+0.10}_{-0.08} \pm 0.05(\text{theo})$

DØ $9.7 \text{ fb}^{-1}$:
$|V_{tb}\,^L_V| = 1.12^{+0.09}_{-0.08}$
SM-independent 2D measurements

- Relax s:t SM ratio in posterior
  - DØ 9.7 fb⁻¹:
    \[ \sigma_s = 1.10 \pm 0.33 \text{ pb} \ (\pm 29\%) \]
    \[ \sigma_t = 3.07 \pm 0.53 \text{ pb} \ (\pm 17\%) \]
  - CDF 7.5 fb⁻¹:
    \[ \sigma_s = 1.81 \pm 0.63 \text{ pb} \ (\pm 33\%) \]
    \[ \sigma_t = 1.49 \pm 0.47 \text{ pb} \ (\pm 30\%) \]

- New physics can alter ratio

- Specialized searches in single top by DØ and CDF:
  - Anomalous couplings
  - FCNC
  - \( W' \)
  - \( H^\pm \)
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Single top at the Tevatron

DØ first evidence for s-channel

\[ \sigma_{\text{expected}} = 2.33^{+0.47}_{-0.44} \text{ pb} \]
\[ \sigma_{\text{observed}} = 3.07^{+0.53}_{-0.49} \text{ pb} \]

\[ \sigma_{\text{expected}} = 1.08^{+0.31}_{-0.30} \text{ pb} \]
\[ \sigma_{\text{observed}} = 1.10^{+0.33}_{-0.31} \text{ pb} \]
CDF 9.1 fb\(^{-1}\) MET+jets analysis

- MET+jets selection only
- Recover partially reconstructed electrons and muons
- Include W→τν (hadronically-decaying taus as jets)
- Completely orthogonal dataset to ℓ+jets selection
- Train several MVA against QCD and t\(\bar{t}\), then combine with NN

\[ \sigma_{s+t} = 3.0^{+1.5}_{-1.4} \text{ pb} \quad (\pm 50\%) \]
W helicity and anomalous Wtb couplings

\[ \mathcal{L} = \frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{tb} (f_V^L P_L + f_V^R P_R) \tau W^-_\mu - \frac{g}{\sqrt{2}} \bar{b} i\sigma^{\mu\nu} q_\nu V_{tb} (f_T^L P_L + f_T^R P_R) \tau W^-_\mu \]

- In SM: \( f_V^L = 1 \) and \( f_V^R = f_T^L = f_T^R = 0 \)

- Change rate and kinematics of single top production
  - Assume Wtb production and \( |V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2 \)
  - Train BNN discriminant against each separate signal

- Change \( f_- (30\%) \), \( f_0 (70\%) \), \( f_+ (0\%) \) rates in W helicity from \( t\bar{t} \) decays

- Use \( \cos\theta^* \) as discriminant (angle between \( \ell \) and \( t \) in W rest frame)
Summary of s+t measurements

Single Top Quark Cross Section

- DØ $e/\mu$+jets 5.4 fb$^{-1}$: $3.43^{+0.73}_{-0.74}$ pb
- CDF $e/\mu$+jets 7.5 fb$^{-1}$: $3.04^{+0.57}_{-0.53}$ pb
- CDF MET+jets 9.1 fb$^{-1}$: $3.04^{+1.46}_{-1.39}$ pb
- DØ $e/\mu$+jets 9.7 fb$^{-1}$: $4.11^{+0.59}_{-0.55}$ pb

$m_t = 172.5$ GeV

N. Kidonakis
PRD 74 114012 (2006)
Single top at the Tevatron

\begin{figure}
\centering
\includegraphics[width=\textwidth]{single_top_plot.png}
\caption{Cross-section \( \sigma \) in pb as a function of \( \sqrt{s} \) in TeV.}
\end{figure}
Conclusions

- Very rich single top physics program
  - Top width: $\Gamma_t = 2.0^{+0.5}_{-0.4} \text{ GeV}$
  - Polarization: consistent with -1
  - $W'$: $W'_L > 863 \text{ GeV} @ 95\% \text{ C.L.}$
  - FCNC: $B(t \rightarrow gu) < 2.0 \times 10^{-4}$
  - $H^+$: Type I 2HDM ($m_H, \tan\beta$) exclusion
  - Anomalous couplings

- Important to measure $s$ and $t$ separately
- DØ shows evidence for s-channel (3.7 SD)
- $\sigma(s+t)$ measured with 14% precision
- $\sigma(t)$ measured with 17% precision
- $|V_{tb}|$ measured to $\sim 8\%$ precision (DØ+CDF)
- Single top observation is a legacy measurement from the Tevatron
  - Planning CDF+DØ combination with full dataset in the fall
 Extras
Event characteristics

*tb Category: $D_{tb} > 0.8$*

*tb & tqb Depleted Region*
Event characteristics

$tqb$ Category: $D_{tqb} > 0.8$

$tb$ & $tqb$ Depleted Region

**Top Quark Mass [GeV]**

![Histogram](image1.png)

**Q(lepton) X $\eta$(light-quark jet)**

![Histogram](image2.png)
### Source of Uncertainty

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Rate</th>
<th>Shape</th>
<th>Processes affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy scale</td>
<td>0–8%</td>
<td>X</td>
<td>all</td>
</tr>
<tr>
<td>Initial and final state radiation</td>
<td>0–6%</td>
<td>X</td>
<td>single top, $t\bar{t}$</td>
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<tr>
<td>Parton distribution functions</td>
<td>0–1%</td>
<td>X</td>
<td>single top, $t\bar{t}$</td>
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<tr>
<td>Acceptance and efficiency scale</td>
<td>1–7%</td>
<td></td>
<td>single top, $t\bar{t}$, diboson, $Z/\gamma^*+jets$</td>
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<tr>
<td>Luminosity</td>
<td>6%</td>
<td>X</td>
<td>all</td>
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<tr>
<td>Jet flavor separator</td>
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<td>all</td>
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<tr>
<td>Mistag model</td>
<td>X</td>
<td></td>
<td>$W+\text{light}$</td>
</tr>
<tr>
<td>Non-W model</td>
<td>X</td>
<td></td>
<td>Non-$W$</td>
</tr>
<tr>
<td>Factorization and renormalization</td>
<td>X</td>
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<td>$Wb\bar{b}$</td>
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<tr>
<td>Jet $\eta$ and $\Delta R$ distribution</td>
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<td>$W+\text{light}$</td>
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<td>Non-$W$ normalization</td>
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<td>$Wb\bar{b}$ and $Wc\bar{c}$ norm</td>
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<td>$Wb\bar{b}$, $Wc\bar{c}$</td>
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<td>$Wc$ normalization</td>
<td>30%</td>
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<td>$Wc$</td>
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<td>$t\bar{t}$</td>
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<td>Monte Carlo generator</td>
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<td>single top, $t\bar{t}$</td>
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<td>Single top normalization</td>
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<td>Top mass</td>
<td>2–12%</td>
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<td>single top, $t\bar{t}$</td>
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</tbody>
</table>

* X indicates the sources of uncertainty from shape variation
* Sources listed below double line are used only in $|V_{tb}|$ measurement

### Top mass [GeV]

<table>
<thead>
<tr>
<th>Top mass [GeV]</th>
<th>t-channel</th>
<th>s-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>170</td>
<td>2.80</td>
<td>1.31</td>
</tr>
<tr>
<td></td>
<td>+0.57</td>
<td>+0.77</td>
</tr>
<tr>
<td></td>
<td>-0.61</td>
<td>-0.74</td>
</tr>
<tr>
<td>172.5</td>
<td>2.90</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>+0.59</td>
<td>+0.62</td>
</tr>
<tr>
<td></td>
<td>-0.59</td>
<td>-0.63</td>
</tr>
<tr>
<td>175</td>
<td>2.53</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>+0.58</td>
<td>+0.51</td>
</tr>
<tr>
<td></td>
<td>-0.57</td>
<td>-0.50</td>
</tr>
</tbody>
</table>
\[ P_{\text{total}}^n(t\bar{t}) = R^2 A(bb) P_t^n(bb) + 2R(1-R)A(bq) P_t^n(bq) + (1-R)^2 A(q\bar{q}) P_t^n(q\bar{q}), \]

**R measurement**

**W helicity**

\[ |f_V^L| = 1 + |C^{(3,3+3)}_{\phi q}| \frac{v^2}{V_{tb} \Lambda^2}, \]
\[ |f_V^R| = \frac{1}{2} |C^{33}_{\phi q}| \frac{v^2}{V_{tb} \Lambda^2}, \]
\[ |f_T^L| = \sqrt{2} |C^{33}_{uW}| \frac{v^2}{V_{tb} \Lambda^2}, \]
\[ |f_T^R| = \sqrt{2} |C^{33}_{dW}| \frac{v^2}{V_{tb} \Lambda^2}, \]

**Negative Helicity**
\[ f = 0.30 \]
\[ \begin{align*}
    t &\rightarrow \uparrow \\
    b &\rightarrow \downarrow
\end{align*} \]

**Longitudinal Helicity**
\[ f = 0.70 \]
\[ \begin{align*}
    t &\rightarrow \uparrow \\
    b &\rightarrow \uparrow
\end{align*} \]

**Positive Helicity**
\[ f = 0 \]
\[ \begin{align*}
    t &\rightarrow \uparrow \\
    b &\rightarrow \downarrow
\end{align*} \]
Top quark width

- Direct measurements limited by $m_t$ resolution

$$\Gamma_t = \frac{\Gamma(t \to Wb)}{B(t \to Wb)} = \frac{\sigma(t - \text{channel}) \frac{\Gamma(t \to Wb)_{SM}}{\sigma(t - \text{channel})_{SM}}}{B(t \to Wb)}$$

$$\sigma(t) B(t \to Wb) = 2.90 \pm 0.59 \text{ pb}$$

PLB 705, 313 (2011)

$$R = \frac{B(t \to Wb)}{B(t \to Wq)} = 0.90 \pm 0.04$$

PRL 107, 121802 (2011)

SM NLO: $\Gamma_t = 1.3$ GeV

For $m_t = 172.5$ GeV:

$$\Gamma_t = 2.0 \pm 0.5 \pm 0.4 \text{ GeV}$$

$$\tau_t = (3.3 \pm 0.9 \pm 0.6) \times 10^{-25} \text{ s}$$

Assumes:
- production by W-b fusion
- top decays into any $Wq$
- $B(t \to Wq) = 1$

Most precise determination