Single Top Quark Production at the Tevatron

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On behalf of the CDF and DØ Collaborations

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Top quarks are most commonly produced in pairs through the strong interaction.

\[ \sigma(t\bar{t}) = 7.46^{+0.48}_{-0.67} \text{ pb} \]

@ \( m_t = 172.5 \text{ GeV/c}^2 \)


EW processes can produce single top quarks in association with b quarks.

- **s-channel**: \( \sigma = 1.12 \pm 0.05 \text{ pb} \)
- **t-channel**: \( \sigma = 2.34 \pm 0.13 \text{ pb} \)

@ \( m_t = 170 \text{ GeV/c}^2 \)

Kidonakis PRD 74, 114012 (2006)

SM measurements

- CKM: \( |V_{tb}| \)
- Top width and polarization...
  - Width: Grohsjean, TRK02, 7/23 11:25

New Physics

- Anomalous couplings, FCNC
  - Anomalous couplings: Sharyy, TRK02, 7/23 9:20

- Resonance searches (W', H+)
  - W': Scodellaro, TRK10, 7/24 15:20
Single $t$ production predicted 10 years before $t$ discovered in pair production, but no evidence until 12 years after!

Half the cross section of $\tilde{t}\tilde{t}$, but much more difficult background situation.

- S:B after event selection 1:20 for Single $t$
- 5:1 for $\tilde{t}\tilde{t}$

Backgrounds:
- QCD, $W+$jets, $Z+$jets, Diboson, $\tilde{t}\tilde{t}$
The Data

2002-2005
- Lower instantaneous luminosities (typical peak ~1E32)
- ~1.5 fb\(^{-1}\) integrated luminosity delivered

2006-2010
- Higher instantaneous luminosities (typical peak ~3E32)
- Upgraded detectors
- ~7.5 fb\(^{-1}\) delivered

All results described in this talk have been published within the past year, and are based on 2.3-4.8 fb\(^{-1}\) of ‘good’ data.

Results presented today use up to this much...
... and at least this much.
Evidence, DØ & CDF
- DØ: \( \sigma = 4.9 \pm 1.4 \text{ pb} \)
  - 3.6 \( \sigma \), 0.9 fb\(^{-1}\)
  - PRL 98, 181802 (2007)
- CDF: \( \sigma = 2.2^{+0.7}_{-0.6} \text{ pb} \)
  - 3.7 \( \sigma \), 2.2 fb\(^{-1}\)
  - PRL 101, 252001 (2007)

FCNC Production, DØ & CDF
- Search for \( u(c) + g \to t \) processes
- CDF: \( \sigma < 1.8 \text{ pb} \) PRL 102, 151801 (2008)
  - \( \kappa_{tu}/\Lambda < 0.018 \text{ TeV}^{-1} \), \( \kappa_{tc}/\Lambda < 0.069 \text{ TeV}^{-1} \)

Anomalous Wtb Couplings, DØ

Resonance searches, DØ & CDF
Signal is modeled using SINGLETOP (DØ) and MADEVENT (CDF).

Most backgrounds modeled using ALPGEN, with PYTHIA parton hadronization. W+Heavy Flavor jets are underestimated, so are scaled up by a factor of ~1.4, which is obtained from data/MC comparisons.

QCD background is obtained from data, using orthogonal samples (non-isolated leptons for DØ, extrapolation from low missing transverse energy for CDF).

W+jets and QCD are normalized to data, all others to SM NNLO cross sections before b-tagging.
Event Selection

Lepton + jets selection
- 2 or 3 (or 4 for DØ) jets
- 1 or 2 jets $b$-tagged
- High $p_T$ isolated $e$ or $\mu$
- Large missing transverse energy, $E_T$

Still big background problem
- S:B $\sim$1:20, Signal acceptance $\sim$3%
- Need multivariate analysis (MVA) techniques to discriminate

Event Yields

<table>
<thead>
<tr>
<th>Event</th>
<th>DØ 2.3 fb$^{-1}$</th>
<th>CDF 3.2 fb$^{-1}$</th>
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<tr>
<td>$tb + t\bar{q}b$ signal</td>
<td>223 ± 30</td>
<td>191 ± 28</td>
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<td>$W^+$jets</td>
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<td>2,204 ± 542</td>
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DØ Single Top 2.3 fb$^{-1}$ Signals and Backgrounds

- 2 jets
- 3 jets
- 4 jets

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**Multivariate Methods**

- Combine the modest discriminating power of many separate variables into one very effective discriminant.
- Data is separated into several individual analysis channels based on $N_{\text{jet}}, N_{b\text{-tag}}$, and lepton type (DØ only). MVAs are performed on each channel separately, then combined.

### Likelihood Functions (CDF only)
- Combine 7-10 variables into a single likelihood function

$$L = \frac{\prod_{i=1}^{n_{\text{var}}} p_i^{\text{sig}}(x_i)}{\prod_{i=1}^{n_{\text{var}}} p_i^{\text{sig}}(x_i) + \prod_{i=1}^{n_{\text{var}}} p_i^{\text{bkg}}(x_i)}$$

### Matrix Elements
- Using full event kinematics from reconstructed 4-momenta, calculate probability for S and B hypotheses
- Include all parton level matrix elements

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**Boosted Decision Trees**
- Sequence of binary split cuts for S/B separation
- Pass or fail, events continue to be analyzed, terminating in leaf nodes classified as S or B based on signal purity
- Boosting: performance and stability improved by averaging over many trees
- Many variables (DØ: 64, CDF: 20), adding more does not degrade performance

**Neural Networks**
- Combine variables using node-to-node weights and thresholds
- Fewer variables (DØ: 18-28, CDF: 11-18), adding too many degrades performance
- DØ: Bayesian NN – average over many NN, avoid overtraining
- CDF: NeuroBayes – incl. jet flavor separation

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**Event Yield**

**DØ 2.3 fb⁻¹**

- Boosted Decision Trees Output
- Bayesian Neural Networks Output
**Other Methods (CDF)**

Separate s-channel search
- s-channel sensitive to W', H^+
- Likelihood function analysis optimized for s-channel only in lepton+jets
- Double b-tagged events only

- $\sigma_s < 3.49$ pb at 95% CL

CDF Conf. Note 9712

**$E_T$ + Jets**
- Performed on a sample orthogonal to lepton+jets, with un-reconstructed leptons
- Recover hadronic taus from W decay
- Neural net based
- Combined with 3.2 fb^{-1} lepton+jets analyses

- PRD 81, 072003 (2010)

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Combining the separate MVAs into one, more powerful discriminant

- Individual analyses are ~60-90% correlated

**DØ: Bayesian Neural Network**
- Similar to individual BNN analysis, but with the three MVA results as inputs
- Cross-checked with BLUE (Best Linear Unbiased Estimator)

**CDF: NeuroEvolution of Augmenting Topologies (NEAT)**
- Competition of NNs that includes binning, systematics, etc. using 5 lepton+jets inputs
- Choose the NN that optimizes expected p-value
- Then do simultaneous fit with $E_T^{jet}$+jets

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Observation!

<table>
<thead>
<tr>
<th>Lumi (fb⁻¹)</th>
<th>Cross Section (pb)</th>
<th>Expected Significance</th>
<th>Observed Significance</th>
<th>Publication</th>
</tr>
</thead>
<tbody>
<tr>
<td>DØ</td>
<td>2.3</td>
<td>3.94 ± 0.88</td>
<td>4.5σ</td>
<td>PRL 103, 092001 (2009)</td>
</tr>
<tr>
<td>CDF</td>
<td>3.2</td>
<td>2.3³±⁰.⁶⁻⁰.⁵</td>
<td>5.9σ</td>
<td>PRL 103, 092002 (2009)</td>
</tr>
</tbody>
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$|V_{tb}|^2 \propto \sigma(s+t)_{\text{meas}} / \sigma(s+t)_{\text{SM}}$

Need to make some assumptions:

- $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$
- Pure V-A, CP conserving interaction: $f_1^R = f_2^L = f_2^R = 0$
- Does not assume 3 generations or CKM unitarity

| $|V_{tb}|$ | Measurement | Lower Limit $(0 \leq |V_{tb}|^2 \leq 1)$ |
|---------|-------------|---------------------------------|
| DØ      | 1.07±0.12   | 0.78                            |
| CDF     | 0.91±0.13   | 0.71                            |
Bayesian analysis using discriminants from all 9 DØ and CDF MVA outputs.

Compatible with SM
- Compatible with each other at 1.6σ

arXiv: 0908.2171
SM single $t$ production is almost pure V-A, i.e. 100% left-handed polarization
Non-SM production can introduce V+A, right-handed couplings
2D Likelihood analysis with separate LLLL (SM) and RRLL discriminants

CDF Conf. Note 9920

V-A Production
$\sigma_{LLLL} = 1.72$ pb

V+A Production
$\sigma_{RRLL} = 0$ pb

Polarization
$$\frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -1^{+1.5}_{-0}$$
First $t$-channel Evidence: DØ

- Sensitive to FCNC, anomalous couplings
- Train the MVAs to select $t$-channel events only
- Measure $s$- and $t$-channel cross sections simultaneously
  - $s/t$ is not constrained to SM value

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<th>$\sigma$(pb)</th>
<th>Exp. Sig.</th>
<th>Obs. Sig.</th>
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<tr>
<td>$t$-channel</td>
<td>3.1±0.9</td>
<td>3.7$\sigma$</td>
<td>4.8$\sigma$</td>
</tr>
<tr>
<td>$s$-channel</td>
<td>1.0±0.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PLB 690, 5 (2010)
Reconstruct hadronically decaying taus

- 1 and 3 prong, with and without $\pi^0$s
- Use Boosted Decision Trees for tau ID
- Use Boosted Decision Trees for signal discrimination

- 44-70 variables

Published 6/7/10!
Gluon mediated flavor-changing neutral currents can produce single $t$
- Negligible in SM, large in BSM (SUSY, composite,…)
- Topology similar to EW $t$-channel production
  - Same selection except require one and only one $b$-tag

BNN analysis
arXiv: 1006.3575
Submitted to PLB 6/18/10!

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{tg}$ (pb)</th>
<th>$\kappa_{tg}/\Lambda$ (TeV$^{-1}$)</th>
<th>$B(t\rightarrow qg)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tgu$</td>
<td>0.2</td>
<td>0.013</td>
<td>$2.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>$tgc$</td>
<td>0.27</td>
<td>0.057</td>
<td>$3.9 \times 10^{-3}$</td>
</tr>
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$$L_{FCNC} = \frac{\kappa_{tg}}{\Lambda} f_{g\sigma}^\mu\nu \frac{\lambda^a}{2} tG_{\mu\nu}^a,$$

DØ 2.3 fb$^{-1}$

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The study of single top quark physics at the Tevatron has been extremely rich and productive.

In the past year, we’ve published:
- Observation of single top production
- Evidence for t-channel production
- Top quark polarization
- New limits on FCNC
- New W' search (Scodellaro, 7/24 15:20)
- Top width measurement (Grohsjean, 7/23 11:25)

Established single $t$ analysis methods now being used to search for Higgs, …

New analyses with more than twice the data very soon, 10 fb$^{-1}$ by next year, possibly running 3 more years!

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