Single Top Quark Production at the Tevatron

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**Motivation:**

**Why study Single Top Quarks?**

- Measure the production rate and compare to SM predictions
  - Test of EW interaction
  - Probe for new physics
- Physics beyond the SM could look similar to single top processes
  - Various models look similar to s- or t-channel production
- Direct probe of $Wtb$ interaction
  - Direct measurement of CKM matrix element $|V_{tb}|$
- Single top similar to $WH \rightarrow$ testing ground for methods to extract a small signal
Single Top Cross Sections

- Single top quark production via electroweak interaction

<table>
<thead>
<tr>
<th>Collider</th>
<th>s-channel: $\sigma_{tb}$</th>
<th>t-channel: $\sigma_{tqb}$</th>
<th>Wt-channel: $\sigma_{tW}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron: p$p$ (1.96 TeV)</td>
<td>1.04 pb</td>
<td>2.26 pb</td>
<td>0.28 pb</td>
</tr>
<tr>
<td>LHC: pp (7 TeV)</td>
<td>4.6 pb</td>
<td>64.6 pb</td>
<td>15.7 pb</td>
</tr>
</tbody>
</table>

- Wt-channel: negligible at the Tevatron
- s-channel: challenging at the LHC
The Challenge

- (s+t) production cross section about $\frac{1}{2}$ of $t\bar{t}$
- Single top signature similar to W+jets background

Other important backgrounds:
- $t\bar{t}$
- Multijet

Simulated with Comphep (DØ) or POWHEG (CDF) + Pythia

Normalized to Data

Modeled using Alpgen+Pythia/Herwig

Normalized to Data

Modeled using MC

Normalized to SM cross section

Simulated with

Modeled using

Normalized to Data
Enrich data sample in single top-like events:

- Exactly one high $p_T$ isolated electron or muon
- Large $E_T$ for the neutrino
- 2, 3 (and 4) jets with high $p_T$

Angular and total energy cuts to reject multijet background

Important tool to reject background: b-jet identification
After Event Selection and before b-jet identification

- Before b-jet identification: *single top signal hardly visible!*
  - S/B of about 1:185

- W+jets normalized to data before b-jet identification

![Graph showing W boson transverse mass distribution](image-url)
Identification of b-Jets

- Important to increase $t\bar{t}$ purity
- $b$-hadron: travels some millimeters before it decays
- Neural Network (DØ)
  combines properties of displaced tracks and displaced vertices

![Graph showing b-jet efficiency and fake-rate against each other.](image)
After Event Selection and after b-jet Identification

- Require 1 or 2 identified b-jets
  - S:B about 1:20

- Background enriched samples (t\(\bar{t}\) and W+jets enriched) to check background modeling

- Using counting-only: Systematic uncertainty on background larger than signal

- Use **multivariate discriminant techniques** to separate signal from background
Further Signal Enhancement: Multivariate Discriminants

- Several techniques used for MVAs
  - Boosted Decision Trees (BDTs)
    - Application of sequential cuts
  - (Bayesian) Neural Networks
  - NEAT
    - Generic algorithms evolving a population of NNs
  - Matrix Elements
    - Use the full event kinematics
- Combination of different techniques
  - BLUE
  - For observation and now: use the outputs of the discriminants as input to a super-discriminant
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Used by CDF in new 7.5fb⁻¹ analysis
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Used by DØ in new 5.4fb⁻¹ analysis
Training and cross section extraction

- Train MVA on
  - s+t channel using SM ratio between s- and t-channel
  - t-channel with s-channel as background in training (not in fit)
  - s-channel with t-channel as background in training (not in fit)

- Bayesian method to extract cross section results
  - Integration over systematic uncertainties (modeled as Gaussian priors)

- Example: t-channel trained discriminant
Results: \((s+t)\)-Channel

- Trained discriminants on \(s+t\) channel

\[\sigma_{s+t} = 3.49^{+0.77}_{-0.71} \text{ pb} \]

- Main systematic uncertainties from
  - Luminosity
  - Jet-energy related uncertainties
  - Uncertainties on \(b\)-jet identification scale factors

\[\sigma_{s+t} = 3.04^{+0.57}_{-0.53} \text{ pb} \quad \text{for } m_t = 172.5\text{GeV}\]

PRD 84, 112001 (2011)
- s- and t-channel are differently sensitive to new physics
  - Measure both channels simultaneously
- Train on t-channel (DØ) or s-channel (CDF)

\[
\begin{align*}
\sigma_s &= 0.98 \pm 0.63 \text{ pb} \\
\sigma_t &= 2.90 \pm 0.59 \text{ pb}
\end{align*}
\]

In agreement with SM prediction

\[
\begin{align*}
\sigma_s &= 1.81^{+0.63}_{-0.58} \text{ pb} \\
\sigma_t &= 1.49^{+0.47}_{-0.42} \text{ pb}
\end{align*}
\]

PLB 705, 313 (2011)
t-Channel and s-channel

- In 2D: Integrate over s-channel → t-channel cross section
- Result: \( \sigma_t = 2.90 \pm 0.59 \text{ pb} \)
- First observation of t-channel with 5.5 standard deviations (SDs) significance
- s-channel trained MVA → not yet significant at DØ

![Graphs showing t-channel and s-channel](image)

PLB 705, 313 (2011)
Direct extraction of $V_{tb}$ from single top cross section

- No assumption about number of generations
- Assumption: $|V_{ts}|^2 + |V_{td}|^2 < |V_{tb}|^2$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$|V_{tb}| \propto \sigma(s+t)$
|V_{tb}| revisited

- Direct extraction of $V_{tb}$ from partial top width $|V_{tb}| \propto \Gamma(t \to b)$
  - No assumption about number of generations
  - NOT assuming $|V_{ts}|^2 + |V_{td}|^2 \ll |V_{tb}|^2$
  - NOT assuming SM ratio between s- and t-channel cross sections

$V_{CKM} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}$

PRD 85, 091104 (2012)
Summary

- Single Top at Tevatron: A real challenge!
  - Ideas and methods were developed and established
  - From cross section measurements to searches and properties studies
  - s-channel single top: A Tevatron Legacy

- More details on the results:

  DØ:  http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html
  CDF:  http://www-cdf.fnal.gov/physics/new/top/top.html
BACKUP
The Top Quark

- **Heaviest known elementary particle:**
  \[ m_t = 173.3 \pm 1.1 \text{GeV} \]
  
  arXiv:1007.3178

- **Standard Model:**
  - Single or pair production
  - Electric charge \(+\frac{2}{3}e\)
  - Short lifetime \(0.5 \times 10^{-24} \text{s}\)
    - **Bare quark** - no hadronization
  - \(~100\%\) decay into Wb
  - Large coupling to SM Higgs boson
### The Challenge

- Production cross section about $\frac{1}{2}$ of $t\bar{t}$
- Single top signature similar to $W+$jets background

#### Other important backgrounds:

- $t\bar{t}$
- and multijet
Further Signal Enhancement: Multivariate techniques

- 1. Select variables discriminating signal and background
- 2. Combination via a multivariate analysis (MVA) tool
- 3. Fit the distribution
Results:
Single Top Observation 2009

- Observation 14 years after top discovery
- Usage of multiple multivariate techniques by CDF and D0
  - BDT, Matrix Element, (B)NN, NEAT

5σ

5σ

arXiv:0908.2171
Partial width:

\[ \Gamma(t \rightarrow Wb) = \sigma(t - \text{channel}) \times \frac{\Gamma(t \rightarrow Wb)_{\text{SM}}}{\sigma(t - \text{channel})_{\text{SM}}} \]

Extract partial and total width from combination of R measurement and t-channel cross section

Correlations of systematics fully taken into account
Top Quark Width

- Definition of $R$:
  \[
  R = \frac{B(t \rightarrow Wb)}{B(t \rightarrow \{Wd + Ws + Wb\})}
  \]

- Using dilepton and lepton+jets $t\bar{t}$ events

- Measure: $B(t \rightarrow Wb) = 0.90 \pm 0.04$

- Extract partial and total top width

\[B(t \rightarrow \{Wd + Ws + Wb\}) = 1\]

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