Observation of single top quark production at DØ

Reinhard Schwienhorst
Outline

• Introduction
• Single top quark production
• Observation of single top quark production at DØ
• New physics searches
• Other experiments (CDF, LHC)
• Conclusions
Electroweak symmetry breaking

Gauge boson coupling to Higgs field

Fermions acquire mass through Higgs coupling
Top quark

Higgs boson

Coupling strength

~1
Top quark

Coupling strength ~1

Higgs boson

King of the Fermions
Higgs mass estimate

- Higgs boson
- W boson
- top quark

![Diagram showing the relationship between Higgs mass, top quark mass, and W boson mass. The diagram includes data from LEP2 and Tevatron (preliminary) and LEP1 and SLD, with a 68% confidence level.](image-url)
Key to electroweak symmetry breaking

- top quark
- Higgs boson
- W boson
SM single top quark production

Tevatron:

\[ \sigma_{\text{tot}} = 3 \text{ pb} \]

LHC:

\[ \sigma_{\text{tot}} = 326 \text{ pb} \]
New physics

s-channel

New heavy boson

q
\bar{q}'
W'
t
\bar{b}

q
\bar{q}'
W'
t
\bar{b}

Flavor Changing Neutral Current

\begin{align*}
q & \rightarrow q \\
Z, \gamma, g & \rightarrow t
\end{align*}

Associated production

Modified Wtb coupling

\begin{align*}
g & \\
b & \rightarrow t
\end{align*}
Tevatron single top goals

- Discover single top quark production!
- Measure production cross sections → CKM quark mixing matrix element $V_{tb}$
- Look for physics beyond the standard model
  - Coupled to the heavy top quark
- Study top quark spin correlations
- Understand as background to many other searches
- Explore analysis techniques that will also be used elsewhere

Production cross sections:

(N)NLO calculation: $s$-channel $1.12 \text{ pb (±5\%)}$ $t$-channel $2.34 \text{ pb (±6\%)}$

($m_{\text{top}} = 170 \text{ GeV}$)
Experimental setup:
Fermilab Tevatron in Run II

Proton-antiproton collider
CM energy 1.96 TeV
→ Energy frontier
Instantaneous luminosity $>400 \times 10^3 \text{cm}^{-2} \text{s}^{-1}$
  → >4 interactions per crossing, 1.7M crossing per second
→ Luminosity frontier
Fermilab single top history

Publication history

- Search: PLB 517, 282 (2001)
- Search: PLB 622, 265 (2005)
- W': PLB 641, 423 (2006)
- Search: PRD 75, 092007 (2007)
- W': PRL 100, 211802 (2007)
- Evidence: PRD 78, 012005 (2008)
- H': (PRL) arXiv:0807.0859
- Observation: (PRL) arXiv:0903.0850

Run I

- W': PRL 90, 081802 (2003)
- Search: PRD 71, 012005 (2005)
- FCNC: (PRL) arXiv:0812.3400
- W': (PRL) arXiv:0902.3276
- Observation: (PRL) arXiv:0903.0885

Run II

Measurement history

<table>
<thead>
<tr>
<th>Single Top Cross Section</th>
<th>Signal Significance</th>
<th>CKM Matrix Element $V_{tb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
<td>Observed</td>
</tr>
<tr>
<td>December 2006</td>
<td>DØ (0.9 fb⁻¹)</td>
<td>4.7 ± 1.3 pb</td>
</tr>
<tr>
<td>September 2008</td>
<td>CDF (2.2 fb⁻¹)</td>
<td>2.2 ± 0.7 pb</td>
</tr>
</tbody>
</table>

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Single top quark event signature

- High-momentum lepton (e or $\mu$)
- Missing transverse energy
- Proton ➔ $W$ ➔ $b$ ➔ $t$ ➔ $\nu_l$ ➔ $q'$
- Antiproton ➔ $W$ ➔ $b$ ➔ $t$ ➔ $\nu_l$ ➔ $q$
- b-quark jet or light quark jet
- b-quark jet
Single top quark event signature

s-channel

High-momentum lepton (e or $\mu$)

Missing transverse energy

t-channel
Background processes

- Total inelastic, QCD multijets
- Bottom quark pairs
- $W$ bosons
- $Z$ bosons
- Top quark pairs
- Single top quarks (new physics)
Analysis outline

Trigger selection

Single top event kinematics

b-quark tagging

S/B = 1/10^9

S/B = 1/250, 115,000 events

S/B = 1/20, 4500 events in 24 channels

Statistical analysis

Combination

Multivariate techniques

BDT

BNN

ME

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Analysis samples

- Divide into 24 analysis channels
  - By b-tag multiplicity (1, 2), jet multiplicity (2, 3, 4), data taking period (before/after upgrade), lepton (e, \(\mu\))

- Cross-check samples
  - Enriched in W+jet events
  - Enriched in top pair events

- Check data/background agreement for all variables and multivariate filters in all samples
Important discriminating variables

- $tb + tqb$
- $W$+jets
- Other
- $t\bar{t}$
- Multijets

**DØ 2.3 fb$^{-1}$**
- all channels

**Yield [Events/10 GeV]**

- Missing $E_T$ [GeV]
- $H_T(jets, l, \nu)$ [GeV]
- $\cos$(LightQuark Jet, Lepton)$_{btaggedtop}$
- Jet2 $\eta$ Width
- $m^{sig}_{top}$ [GeV]
- $Q$(lepton) x $\eta$(light-quark jet)
Discriminating variables

- Object kinematics
- Event kinematics
- Angular correlations
- Jet reconstruction
- Top reconstruction

- Started from ~ 600 variables
- Considered ~200 for multivariate filters
- Chose 97 depending on method and channel
How to build a decision tree: cut-based analysis

- $H_t > 312$
  - Pass
- $M_t > 160$
  - More cuts

Student thesis sample
How to build a decision tree: orthogonal data samples

- $H_t > 312$
  - Pass
    - $M_t > 160$
      - $P$
      - More cuts
      - Student thesis sample
  - Fail
    - $\eta > 1.2$
      - $P$
      - More cuts
      - 2nd student thesis sample
**Decision tree**

- Cuts produce branches
- Terminal leaf: calculate purity $= \frac{N_S}{N_S+N_B}$ from MC signals and backgrounds
- Each data event is assigned the purity value of the leaf it falls into
- Typical trees: hundreds of leaves
Boosted decision tree

- Cuts produce branches
- Terminal leaf: calculate purity = \( \frac{N_S}{N_S + N_B} \)
  from MC signals and backgrounds
- Each data event is assigned the purity value of the leaf it falls into
- Typical trees: hundreds of leaves
- **Boosting:**
  Average over many trees, each built by iteratively increasing weight of mis-classified events
- Typically 20-100 boosting cycles
Boosted decision tree distributions

Cross checks

Full data sample

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Bayesian neural networks

- NN with three layers, 24 input nodes, 40 hidden nodes
- Bayesian Idea:
  - Determine the posterior probability for each weight at each node
  - Sample from this posterior
  - Here: Average over 100 networks
Bayesian neural network distributions

Cross checks

Pretagged Cross-Check Sample

DØ 2.3 fb⁻¹

Event Yield

Bayesian Neural Networks Output

all channels

Wbb
Wcc
Wjj + Wcj
Z+jets
Dibosons
$t\bar{t}$
Multijets

$H_T < 175$ GeV
1 b-tag
2 jets

$t\bar{t}$-Pairs Cross-Check Sample

DØ 2.3 fb⁻¹

Event Yield

Bayesian Neural Networks Output

$H_T > 300$ GeV
1,2 b-tags
4 jets
t$\bar{t} \rightarrow l +$jets
Multijets

W+jets Cross-Check Sample

DØ 2.3 fb⁻¹

Event Yield

Bayesian Neural Networks Output

$tb + t\bar{b}$
Wbb
Wcc
Wjj + Wcj
Z+jets
Non-W
Multijets

Full data sample

DØ 2.3 fb⁻¹

Event Yield

Bayesian Neural Networks Output

Data
$tb + t\bar{b}$
Wbb
Wcc
Wjj + Wcj
Z+jets
t$\bar{t} \rightarrow l +$jets
Multijets

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Matrix element analysis

Parton level matrix elements

Signal discriminant

$P_{signal}(\vec{x}) = \frac{1}{\sigma_S} d\sigma_S(\vec{x}) \quad \sigma_S = \int d\sigma_S(\vec{x})$

- Integration over final state momenta
  - And over reconstructed momenta, transfer function

- Include ME for s-channel, t-channel, top pairs, diboson, W+jets (including gluons)
- Determine weights in two HT regions
Matrix element distributions

Cross checks

Full data sample

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Combination: Another BNN

– Gain because each method provides unique separation

– Simple BNN, only 3 inputs: BDT, BNN, ME
Combination distribution

- Combine 24 channels,
  50 bins per channel,
  sort bins by s/b

Final Discriminant

DØ 2.3 fb⁻¹

Signal Region

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Is there a signal?

**S/B Ratio**

DØ 2.3 fb⁻¹

**Cumulative Events**

DØ 2.3 fb⁻¹

σ(tb + tqb) = 3.94 pb

**Sum bins right-to-left**

**Yield**

DØ 2.3 fb⁻¹

all channels
BNNcomb > 0.8

DØ 2.3 fb⁻¹

all channels
BNNcomb > 0.9

DØ 2.3 fb⁻¹

all channels
BNNcomb > 0.95
Kinematics in the signal region

High Signal Region – $Q \times \eta$

- **DØ 2.3 fb$^{-1}$**
- Ranked Combination Output > 0.92

High Signal Region – $m_{top}$

- **DØ 2.3 fb$^{-1}$**
- Ranked Combination Output > 0.92

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# Systematic uncertainties

## Systematic Uncertainties

**Ranked from Largest to Smallest Effect on Single Top Cross Section**

\[
\text{DØ } 2.3 \text{ fb}^{-1}
\]

### Larger terms

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>(b)-ID tag-rate functions</td>
<td>(2.1–7.0)%</td>
</tr>
<tr>
<td>(includes shape variations)</td>
<td>(9.0–11.4)%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>(1.1–13.1)%</td>
</tr>
<tr>
<td>(includes shape variations)</td>
<td>(0.1–2.1)%</td>
</tr>
<tr>
<td>(W+)jets heavy-flavor correction</td>
<td>13.7%</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>6.1%</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>4.0%</td>
</tr>
<tr>
<td>Initial- and final-state radiation</td>
<td>(0.6–12.6)%</td>
</tr>
<tr>
<td>(b)-jet fragmentation</td>
<td>2.0%</td>
</tr>
<tr>
<td>(t\bar{t}) pairs theory cross section</td>
<td>12.7%</td>
</tr>
<tr>
<td>Lepton identification</td>
<td>2.5%</td>
</tr>
<tr>
<td>(Wbb/Wcc) correction ratio</td>
<td>5%</td>
</tr>
<tr>
<td>Primary vertex selection</td>
<td>1.4%</td>
</tr>
</tbody>
</table>

### Smaller terms

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monte Carlo statistics</td>
<td>(0.5–16.0)%</td>
</tr>
<tr>
<td>Jet fragmentation</td>
<td>(0.7–4.0)%</td>
</tr>
<tr>
<td>Branching fractions</td>
<td>1.5%</td>
</tr>
<tr>
<td>(Z+)jets heavy-flavor correction</td>
<td>13.7%</td>
</tr>
<tr>
<td>Jet reconstruction and identification</td>
<td>1.0%</td>
</tr>
<tr>
<td>Instantaneous luminosity correction</td>
<td>1.0%</td>
</tr>
<tr>
<td>Parton distribution functions (signal)</td>
<td>3.0%</td>
</tr>
<tr>
<td>(Z+)jets theory cross sections</td>
<td>5.8%</td>
</tr>
<tr>
<td>(W+)jets and multijets normalization to data</td>
<td>(1.8–3.9)%</td>
</tr>
<tr>
<td>(W+)jets (multijets)</td>
<td>(30–54)%</td>
</tr>
<tr>
<td>Diboson theory cross sections</td>
<td>5.8%</td>
</tr>
<tr>
<td>Alpgen (W+)jets shape corrections</td>
<td>shape only</td>
</tr>
<tr>
<td>Trigger</td>
<td>5%</td>
</tr>
</tbody>
</table>
Shape systematics

– Mainly jet energy scale and b-tag modeling
Statistical analysis

• Bayesian statistical analysis

\[ P(s|D) = P(D|s)*P(s) \]

– Posterior gives measured cross section and uncertainty

\[ D\bar{O} \ 2.3 \ \text{fb}^{-1} \]

\[ \sigma_{\text{measured}} = 3.94 \pm 0.88 \ \text{pb} \]

\[ \sigma_{\text{expected}} = 3.50^{+0.99}_{-0.77} \ \text{pb} \]
Significance

• Significance (p-value) and linearity and many tests through extensive ensemble testing
  – Ensembles of pseudo-data at various signal cross sections
## DØ 2.3 fb⁻¹ Single Top Results

<table>
<thead>
<tr>
<th>Analysis Method</th>
<th>Single Top Cross Section</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
<td>Measured</td>
</tr>
<tr>
<td>Boosted Decision Trees</td>
<td>3.74 ±0.95 pb</td>
<td>4.6 σ</td>
</tr>
<tr>
<td>Bayesian Neural Networks</td>
<td>4.70 ±1.18 pb</td>
<td>5.4 σ</td>
</tr>
<tr>
<td>Matrix Elements</td>
<td>4.30 ±0.99 pb</td>
<td>4.9 σ</td>
</tr>
<tr>
<td>Combination</td>
<td>3.94 ±0.88 pb</td>
<td>5.0 σ</td>
</tr>
</tbody>
</table>

### March 2009

**N. Kidonakis, PRD 74, 114012 (2006)**

\[ m_{\text{top}} = 170 \text{ GeV} \]
CKM matrix element $|V_{tb}|$

- Measurement: $|V_{tb} \times f_L^1|$
  - Assume top decays to $b$ ($V_{tb} \gg V_{ts}, V_{td}$)
- No constraint on # of generations
- Then assume $f_L^1 = 1$
  - lower limit on $V_{tb}$
  - At the 95% C.L.: $|V_{tb}| > 0.78$
**Analyses based on 3.2 fb⁻¹**

- Top mass 175GeV,
- NLO cross sections
- Increased acceptance

**Added MET+Jets channel**

- 5 multivariate methods,
- even more search channels
## Tevatron summary

<table>
<thead>
<tr>
<th>Single Top Cross Section</th>
<th>Signal Significance</th>
<th>CKM Matrix Element $V_{tb}$</th>
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<tbody>
<tr>
<td><strong>March 2009</strong></td>
<td>DØ (2.3 fb$^{-1}$)</td>
<td>arXiv:0903.0850 (m$_{top}$ = 170 GeV)</td>
</tr>
<tr>
<td>3.94 ± 0.88 pb</td>
<td>4.5 σ</td>
<td>$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$</td>
</tr>
<tr>
<td><strong>March 2009</strong></td>
<td>CDF (3.2 fb$^{-1}$)</td>
<td>arXiv:0903.0885 (m$_{top}$ = 175 GeV)</td>
</tr>
<tr>
<td>2.3 $^{+0.6}_{-0.5}$ pb</td>
<td>&gt;5.9 σ</td>
<td>$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$</td>
</tr>
</tbody>
</table>
Searches for new physics in single top

• Searches for new heavy boson $W'$:

  \[ W' \]

  \[ q \] \[ t \]
  \[ \bar{q}' \] \[ \bar{b} \]

  – CDF prelim result, 1.9fb$^{-1}$:
    $M > 800 \text{ GeV}$ and $M > 825 \text{ GeV}$

• Similar: DØ Susy $H^+$ search

• Flavor-changing neutral currents:

  \[ g \]
  \[ q \] \[ q \]
  \[ u \text{ quark or} \]
  \[ c \text{ quark} \]

PRL 100, 211803 (2008)
Single top polarization – anomalous coupling

- Left-vector ($f^L_1$, =1 in SM), right-vector ($f^R_1$), left-tensor ($f^L_2$), right-tensor ($f^R_2$)

\[ \mathcal{L} = - \frac{g}{\sqrt{2}} b \gamma^\mu V_{tb} (f^L_1 P_L + f^R_1 P_R) t W^- \mu 
- \frac{g}{\sqrt{2}} b \frac{i \sigma^{\mu\nu} q_\nu}{M_W} (f^L_2 P_L + f^R_2 P_R) t W^- \mu + h.c. \]

- Single top is sensitive to magnitude (PRL 101, 221801 (2008))
- $t\bar{t}$ to ratios of couplings (W helicity, PRL 100, 062004 (2008))
- Best sensitivity through combination (PRL 102, 092002 (2009))

\[ |f^R_1|^2 < 0.72 \]
\[ |f^L_2|^2 < 0.30 \]
\[ |f^R_2|^2 < 0.19 \]
Single top at the LHC

- **s-channel**: 10.7 pb
- **t-channel**: 247 pb
- **Associated production**: 68 pb

- Observe three single top production modes separately
  - t-channel: easy
  - s-channel and assoc. prod: harder
- Observe new physics *(if it can be seen)*
- Measure $V_{tb}$ to few %
- Study spin correlations
• Backgrounds are similar to Tevatron, yet different
  – W+jets less important
  – \(\bar{t}t\) is dominant background
• t-channel observation early
  – Large cross section
  – Could be seen with simple cuts
• s-channel and Wt with \(\sim 30\) fb
  – Separate by b-tag and jet multiplicity
  – Earlier observation requires multivariate techniques
LHC: new physics in single top

- Dedicated searches for specific signatures
  - New heavy boson W'
  - FCNC interactions via gluon, photon, Z
  - Anomalous couplings

- Measure SM cross sections in detail
  - And compare their ratios

\[ \text{T. Tait, C.-P. Yuan, Phys. Rev. D63 (2001) 0140018} \]
Conclusions/Outlook

• The Tevatron experiments are getting to know the top quark very well

• Both experiments have observed single top quark production

• Tevatron dataset will increase to over 5 fb\(^{-1}\)
  • Separate s-channel from t-channel
  • Look for new physics

• LHC:
  • Precision measurements in single top
  • Look for new physics connected to heavy top quark