Single Top Quarks at DØ and Observation of the s-channel at the Tevatron

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University of Manchester

on behalf of the CDF and DØ Collaborations

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Content

Introduction
Inclusive production
\(t\)- and \(s\)-channel production
\(s\)-channel combination
Summary
Content

Introduction

Inclusive production

t- and s-channel production

s-channel combination

Summary
The Top Quark

- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: $m_{\text{top}} \sim \text{gold nucleus}$

large coupling to Higgs boson $\sim 1$: important role in electroweak symmetry breaking?

short lifetime: $\tau \sim 5 \cdot 10^{-25} \text{s} \ll \Lambda_{\text{QCD}}^{-1}$: decays before fragmenting → observe “naked” quark

Is the top quark the particle as predicted by the SM?
Single Top Quark Production

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

- **s-channel**
- **t-channel**
- **tW**

Important to measure all channels separately to search for new physics.
Content

Introduction
Inclusive production

D0

t- and s-channel production

s-channel combination

Summary
Single Top Quark Selection: l+jets

- cuts to minimise multijets production and exclude kinematic regions difficult to model

- 2 or 3 jets
- 1 lepton (e, μ)
- large missing $E_T$
- 1 or 2 b–jets

- expected (SM) signal yields after selection:
  - s–channel: $\approx 250$
  - t–channel: $\approx 400$
Single Top Quark Yields: pretag

- normalisation and heavy flavour composition from data
- shape from simulation

best s/b: ~1/200 before b-tagging

DØ 9.7 fb⁻¹

Leading jet $p_T$ [GeV]

Yield [Events/10 GeV]

Data
- $tb+tbq$
- $W+b$
- $W+c\bar{c}$
- $W+lp$
- $Z$+jets/Diboson
- $t\bar{t}$
- Multijets

simulation

data

simulation

simulation

normalised to NNLO

"isolated" $\mu^+$

(best s/b: ~1/200 before b–tagging)
Single Top Quark Yields: $b$-tagged

- $b$-tagged: $\sim 1/200$ before $b$-tagging
- $b$-tagged: $\sim 1/10$ after $b$-tagging

Simulation normalised to NNLO

DØ 9.7 fb$^{-1}$

- Data
- $tb+tqb$
- $W+b\bar{b}$
- $W+c\bar{c}$
- $W+lp$
- $Z+$jets/Diboson
- $t\bar{t}$
- Multijets

Yield [Events/10 GeV]

Leading jet $p_T$ [GeV]
Single Top s+t-channel Production

DØ 9.7 fb⁻¹

Yield [Events/10 GeV]

Missing $E_T$ [GeV]

Yield [Events/0.4]

Q(lepton) x $\eta$(light-quark jet)

9.7 fb⁻¹

PLB 726, 656 (2013)

Yield [Events/0.05]

2 b-tags
2-3 jets

Leading tagged jet b-ID output

Yield [Events/6 GeV]

DØ 9.7 fb⁻¹

Top Quark Mass [GeV]
Control Regions

W+jets enhanced

good agreement with background predictions

$\tilde{t}\tilde{t}$ enhanced

$D\bar{O}$ 9.7 fb$^{-1}$

$H_T < 175$ GeV

1 b-tag

2 jets

$D\bar{O}$ 9.7 fb$^{-1}$

$H_T > 300$ GeV

1-2 b-tags

3 jets

Yield [Events/10GeV]
Multivariate Analyses

Boosted Decision Tree

Boosted Neural Network

Matrix Element

background
signal
Multivariate Analyses

Boosted Decision Tree

Boosted Neural Network

Matrix Element

- use BNN to combine

Correlations

BDT 77% → 75%
BNN ME 73%
Single Top s- and t-channel Production

- trained separately
Single Top s- and t-channel Production

- trained separately
Single Top s- and t-channel Production

- trained separately
- use BNN output to form combined discriminant
s+t-channel Cross Section

- no assumption on $\sigma_t/\sigma_s$

\[
\sigma_{s+t} = 4.11^{+0.60}_{-0.55} \text{ pb} \\
\pm 14\%
\]

DØ 9.7 fb\(^{-1}\)

\[
\begin{align*}
\sigma_{\text{expected}} &= 3.34^{+0.53}_{-0.49} \text{ pb} \\
\sigma_{\text{observed}} &= 4.11^{+0.60}_{-0.55} \text{ pb}
\end{align*}
\]
**s+t-channel Cross Section**

- no assumptions on unitarity or number of quark generations
- assume: pure V–A vector coupling, SM top quark decay

\[\begin{align*}
|V_{tb}| &= 1.12^{+0.09}_{-0.08} \\
&\pm 7.6%
\end{align*}\]
Content

Introduction

Inclusive production

$t$- and $s$-channel production

$s$-channel combination

Summary
Single Top s- vs. t-channel

\[ \text{good agreement with Standard Model} \]

DØ 9.7 fb\(^{-1} \]

1 SD
2 SD
3 SD

Measurement
SM

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

\[ q' \rightarrow \bar{q}' \]
\[ W^+ \]
\[ t \]
\[ b \rightarrow \bar{b} \]
Single Top s- vs. t-channel

- important to study production channels separately

\[ q' \rightarrow q, \ W, \ t, \ b \rightarrow \bar{b} \]

FCNC

\[ u, c \rightarrow \bar{q}, \ \bar{q} \]

t-channel cross section [pb]

\[ 5 \]

\[ 4 \]

\[ 3 \]

\[ 2 \]

\[ 1 \]

\[ 0 \]

s-channel cross section [pb]


⇒ important to study production channels separately
important to study production channels separately
Single Top t-channel

\[ \sigma_t = 3.07^{+0.54}_{-0.49} \text{ pb} \pm 17\% \]

first observation, 5.4 fb\(^{-1}\): 2011

DØ 9.7 fb\(^{-1}\)

\[ \sigma_{\text{expected}} = 2.33^{+0.47}_{-0.44} \text{ pb} \]
\[ \sigma_{\text{observed}} = 3.07^{+0.54}_{-0.49} \text{ pb} \]

\[ \int \text{(integrate over s-channel)} \]

PLB 705, 313 (2011)

PLB 726, 656 (2013)
Single Top t-channel

\[ \int \text{(integrate over s-channel)} \]

\[ \rightarrow 7.7\sigma \text{ significance} \]

\[ q' \rightarrow q, W, t \]

first observation, 5.4 fb\(^{-1}\): 2011

PLB 705, 313 (2011)

DØ 9.7 fb\(^{-1}\)

bins

Expected 6.0 SD

Observed 7.7 SD

PLB 726, 656 (2013)
Single Top s-channel

$\sigma_s = 1.10^{+0.33}_{-0.31} \text{ pb}$

±29%

$\int (\text{integrate over t-channel})$

$\sigma_{\text{expected}} = 2.33^{+0.47}_{-0.44} \text{ pb}$

$\sigma_{\text{observed}} = 3.07^{+0.54}_{-0.49} \text{ pb}$
Single Top production at D0

$\sigma_s = 1.10^{+0.33}_{-0.31} \, \text{pb}$  
±29%

→ first evidence with 3.7σ significance

PLB 726, 656 (2013)
Content

Introduction
Inclusive production
\[ t- \text{ and } s-\text{channel production} \]
s-\text{channel combination}
Summary
The quest for a Tevatron combination

s-channel single top quark, Tevatron Run II, \( L_{\text{int}} \leq 9.7 \text{ fb}^{-1} \)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Cross section [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF ( l+\text{jets} )</td>
<td>( 1.41^{+0.44}_{-0.42} ) 3.8( \sigma )</td>
</tr>
<tr>
<td>CDF ( \not{p}_T+\text{jets} )</td>
<td>( 1.12^{+0.61}_{-0.57} ) 4.2( \sigma )</td>
</tr>
<tr>
<td>CDF combined</td>
<td>( 1.36^{+0.37}_{-0.32} ) 4.2( \sigma )</td>
</tr>
<tr>
<td>D0 ( l+\text{jets} )</td>
<td>( 1.10^{+0.33}_{-0.31} ) 3.7( \sigma )</td>
</tr>
</tbody>
</table>

Theory (NLO+NNLL)

\( 1.05 \pm 0.06 \text{ pb} \) [PRD 81, 054028, 2010]

\( m_{\text{top}} = 172.5 \text{ GeV} \)

(low top mass dependence)

→ good agreement with SM prediction
• combine individual discriminants including all correlations

- s-channel single top quark, Tevatron Run II, $L_{\text{int}} \leq 9.7 \text{ fb}^{-1}$
  - Data
  - SM signal
  - Expected background
  - Background uncertainty

- $7.5-9.7 \text{ fb}^{-1}$
Background Subtracted Discriminant

- posterior normalisations and uncertainties

![Graph showing s-channel single top quark, Tevatron Run II, $L_{\text{int}} \leq 9.7 \text{ fb}^{-1}$](chart)

- Data - observed background
- Observed signal
- Background uncertainty

Events/0.1 vs. Discriminant output $[\log_{10}(s/b)]$
## Uncertainties

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>CDF Norm</th>
<th>CDF Dist</th>
<th>D0 Norm</th>
<th>D0 Dist</th>
<th>Correlated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumi from detector</td>
<td>4.5%</td>
<td></td>
<td>4.5%</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>Lumi from cross section</td>
<td>4.0%</td>
<td></td>
<td>4.0%</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Signal modeling</td>
<td>2–10%</td>
<td>●</td>
<td>3–8%</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Background (simulation)</td>
<td>2–12%</td>
<td>●</td>
<td>2–11%</td>
<td>●</td>
<td>Yes</td>
</tr>
<tr>
<td>Background (data)</td>
<td>15–40%</td>
<td>●</td>
<td>19–50%</td>
<td>●</td>
<td>No</td>
</tr>
<tr>
<td>Detector modeling</td>
<td>2–10%</td>
<td>●</td>
<td>1–5%</td>
<td>●</td>
<td>No</td>
</tr>
<tr>
<td>b-jet-tagging</td>
<td>10–30%</td>
<td>●</td>
<td>15–40%</td>
<td>●</td>
<td>No</td>
</tr>
<tr>
<td>JES</td>
<td>0–20%</td>
<td>●</td>
<td>9–40%</td>
<td>●</td>
<td>No</td>
</tr>
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### Uncertainties

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<td></td>
<td>Norm</td>
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- **Total expected uncertainty:** 20%
- **Expected uncertainty without systematics:** 14%
s-channel Cross Section Extraction

s-channel single top quark, Tevatron Run II, \( L_{\text{int}} \leq 9.7 \text{ fb}^{-1} \)

- Posterior probability density distribution
- \( \sigma_s = 1.29^{+0.26}_{-0.24} \text{ pb} \)
- \( \sigma_s^{\text{SM}} = 1.05 \pm 0.06 \text{ pb} \)

\[ \sigma_s = 1.29^{+0.26}_{-0.24} \text{ pb} \pm 19\% \]
s-channel Cross Section Summary

s-channel single top quark, Tevatron Run II, $L_{\text{int}} \leq 9.7 \text{ fb}^{-1}$

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<tr>
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Theory (NLO+NNLL)
$1.05 \pm 0.06 \text{ pb}$ [PRD 81, 054028, 2010]

$m_{\text{top}} = 172.5 \text{ GeV} \quad \text{(low top mass dependence)}$

→ good agreement with SM prediction
• asymptotic approximation log-likelihood ratio

s-channel single top quark, Tevatron Run II, $L_{\text{int}} \leq 9.7$ fb$^{-1}$

Expected significance: 5.1 s.d.
Observed significance: 6.3 s.d.

**observed p-value: $1.8 \times 10^{-10}$**

→ observation of s-channel production: 6.3 s.d.
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$t$- and $s$-channel production

$s$-channel combination

Summary
Summary of Single Tops at Tevatron

Tevatron single top summary

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<td><strong>s-channel:</strong></td>
<td></td>
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<tr>
<td>CDF</td>
<td>1.36 $^{+0.37}_{-0.32}$</td>
</tr>
<tr>
<td>PRL 112, 231805 (2014)</td>
<td></td>
</tr>
<tr>
<td>D0</td>
<td>1.10 $^{+0.33}_{-0.31}$</td>
</tr>
<tr>
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<td></td>
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<tr>
<td>Tevatron combined</td>
<td>1.29 $^{+0.26}_{-0.24}$</td>
</tr>
<tr>
<td>PRL 112, 231803 (2014)</td>
<td></td>
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<tr>
<td><strong>t-channel:</strong></td>
<td></td>
</tr>
<tr>
<td>CDF</td>
<td>1.65 $^{+0.38}_{-0.36}$</td>
</tr>
<tr>
<td>CDF note 11033</td>
<td></td>
</tr>
<tr>
<td>D0</td>
<td>3.07 $^{+0.53}_{-0.49}$</td>
</tr>
<tr>
<td>PLB 726, 656 (2013)</td>
<td></td>
</tr>
<tr>
<td><strong>s+t:</strong></td>
<td></td>
</tr>
<tr>
<td>CDF</td>
<td>3.02 $^{+0.49}_{-0.48}$</td>
</tr>
<tr>
<td>CDF note 11033</td>
<td></td>
</tr>
<tr>
<td>D0</td>
<td>4.11 $^{+0.59}_{-0.55}$</td>
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<tr>
<td>PLB 726, 656 (2013)</td>
<td></td>
</tr>
</tbody>
</table>

7.5–9.7 fb$^{-1}$

29% • first evidence: 3.7σ

19% • first observation: 6.3σ

17%

14% • $|V_{tb}|$: 7.6% precision

(full Tevatron dataset)

- Tevatron combination for $\sigma_t$ and $\sigma_{s+t}$ to come

Theory (NLO+NNLL)
PRD81 054028 (2010), PRD83 091503 (2011)

$m_{top} = 172.5$ GeV
s-channel single top production is a legacy measurement at the Tevatron
Further Information

Tevatron physics for the informed public
http://www.fnal.gov/pub/today/frontier_science_result

Tevatron single top combinations
http://tevewwg.fnal.gov/singleTop/

CDF top physics results:
http://www-cdf.fnal.gov/physics/new/top/top.html

DØ top physics results:
http://www-d0.fnal.gov/Run2Physics/top/
The Tevatron $p\bar{p}$ Collider at Fermilab

- CDF
- $\sqrt{s} = 1.96$ TeV
- $\Delta t = 396$ ns

Run I 1987 (92)–95
Run II 2001–11: 100x larger dataset at increased energy
The CDF and DØ Detectors

Muon systems
EM and Had Calorimeters
Solenoid
Tracker
Silicon Vertex Detector
Single Top Quark Selection

\[ \sigma_s = 1.05 \pm 0.06 \text{ pb} \]
\[ \text{NLO+NNLL, } m_t = 172.5 \text{ GeV} \]
Kidonakis, PRD 81, 054028 (2010)

\[ \sigma_t = 2.12 \pm 0.16 \text{ pb} \]
\[ \text{NLO+NNLL, } m_t = 172.5 \text{ GeV} \]
Kidonakis, PRD 83, 091503 (2011)
Tevatron Integrated Luminosity

Run II Integrated Luminosity

19 April 2002 - 30 September 2011

Full data set analysed
Top Quark Pair Production

Tevatron (85%)

LHC (87%) (14 TeV)
Single Top Quark Observation

observation (s+t): 2009 (CDF, DØ)

⇒ multivariate analysis techniques
Single Top Quark Observation

observation (s+t): 2009 (CDF, DØ)

H→b¯b evidence: 2012 (CDF+DØ)

⇒ multivariate analysis techniques
Yield Comparison Tevatron–LHC

DØ

CMS
(arXiv:1209.4533v1)

s-channel  t-channel  W+jets  Z+jet, dibosons  tt+tW  Multijets
**W+jets Normalization**

- Find fractions of real and fake isolated $\ell$ in the data before b-tagging. Split samples in loose and tight isolation:

  \[ N_{\text{loose}} = N_{\text{loose \ fake}} + N_{\text{loose \ real}} \]
  \[ N_{\text{tight}} = \varepsilon_{\text{fake}} N_{\text{loose \ fake}} + \varepsilon_{\text{real}} N_{\text{loose \ real}} \]

  Obtain: $N_{\text{loose \ real}}$ and $N_{\text{loose \ fake}}$

- Obtain $\varepsilon_{\text{fake}}$ and $\varepsilon_{\text{real}}$ from MC and data samples

- Then apply b-tagging
  - Greatly reduce W+jets background ($W_{bb} \sim 5\%$ of $W_{jj}$)
  - Shift distributions, changes flavor composition
Single Top s- vs. t-channel

\[ W+\text{Jets, NN Discriminant} \]

CDF II Preliminary 7.5 fb\(^{-1}\)

- CDF Data
- 68.3% CL
- 95.5% CL
- 99.7% CL
- SM(NNLO)

⇒ good agreement with Standard Model
Measuring $|V_{tb}|$

Once we have a cross section measurement, we can make a direct measurement of $|V_{tb}|$, since $\sigma_{tb+tb} \propto |V_{tb}|^2$

$$
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix}
= 
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
$$

Most general $Wtb$ vertex [PLB 713, 165 (2012)]:

$$
L = \frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{tb} \left(f_1^L P_L + f_1^R P_R\right) t W^- \mu - \frac{g}{\sqrt{2}} \bar{b} \frac{i \sigma^{\mu \nu} q_v V_{tb}}{M_W} \left(f_2^L P_L + f_2^R P_R\right) t W^- \mu
$$

Assume:
- **SM top decay**: $V_{td}^2 + V_{ts}^2 \ll V_{tb}^2$
- Pure V-A interaction: $f_1^R = 0$
- CP conservation: $f_2^L = f_2^R = 0$

Do not assume:
- 3 generations
- Unitarity of CKM
- **New**: $\sigma_{tb}/\sigma_{tqb}$

We are effectively measuring the strength of the V-A coupling: $|V_{tb} f_1^L|$, which can be $>1$
Measuring $|V_{tb}|$

- Allow $|V_{tb} f_{1}^{14}|^2 > 1$
  - $|V_{tb} f_{1}^{14}| = 1.12^{+0.09}_{-0.08}$
- Assume $0 \leq |V_{tb}|^2 \leq 1$
  - $|V_{tb}| > 0.92$ @ 95% C.L.
- Additional systematic uncertainties
  - Theoretical uncertainty on single top cross sections
- Complementary to $R_{Wb/Wq}$ measurement in top decays [PRD 85, 091104 (2012)]
- Current limits @ 95% C.L.:
  - CDF (7.5 fb$^{-1}$): 0.78 < $|V_{tb}|$ ≤ 1
  - ATLAS (6 fb$^{-1}$ 8TeV): 0.80 < $|V_{tb}|$ ≤ 1
  - CMS (5 fb$^{-1}$ 8TeV): 0.81 < $|V_{tb}|$ ≤ 1
Consistency check: different methods

\[ \text{consistent with each other} \]
Production Channels at the LHC

status Moriond 2014

**ATLAS Preliminary**

**single top-quark production**

March 2014

\[ \sigma \text{ [pb]} \]

- **t-channel**
  - NLO+NNLL at \( m_t = 172.5 \text{ GeV} \)
  - MSTW2008 NNLO PDF
  - stat. uncertainty

- **Wt**

4.2\( \sigma \)

evidence

\[ \sigma = 1.04 \text{ fb}^{-1} \text{ PLB 717 (2012) 330} \]

\[ \sigma = 20.3 \text{ fb}^{-1} \text{ ATLAS-CONF-2014-007} \]

\[ \sigma = 2.05 \text{ fb}^{-1} \text{ PLB 716 (2012) 142} \]

\[ \sigma = 20.3 \text{ fb}^{-1} \text{ ATLAS-CONF-2013-100} \]

\[ \sigma \text{ s-channel 95\% C.L. limit 0.7 fb}^{-1} \text{ ATLAS-CONF-2011-118} \]

\( \sqrt{s} \) [TeV]

\( >t\)-channel and Wt agree with Standard Model
Production Channels at the LHC

status Moriond 2014

CMS Preliminary
Single top-quark production

6.1σ observation
0.7σ significance

⇒ not sensitive for s–channel production yet
## Summary of Single Top Cross Sections

<table>
<thead>
<tr>
<th>process</th>
<th>first observation</th>
<th>precision Tevatron*</th>
<th>precision LHC*</th>
</tr>
</thead>
<tbody>
<tr>
<td>s+t-channels</td>
<td><img src="image" alt="CMS, D0 logos" /></td>
<td>14% 9.7 fb⁻¹</td>
<td>–</td>
</tr>
<tr>
<td>t-channel</td>
<td><img src="image" alt="D0 logo" /></td>
<td>17% 9.7 fb⁻¹</td>
<td>9% 19.7 fb⁻¹</td>
</tr>
<tr>
<td>s-channel</td>
<td><img src="image" alt="Tevatron logo" /></td>
<td>19% ≤9.7 fb⁻¹ combination</td>
<td>&gt;100% 19.3 fb⁻¹</td>
</tr>
<tr>
<td>Wt production</td>
<td><img src="image" alt="CMS logo" /></td>
<td>–</td>
<td>23% 12.2 fb⁻¹</td>
</tr>
</tbody>
</table>

* = best single measurement, status Moriond 2014

→ all major single top quark production modes are observed
→ good agreement with the Standard Model
→ era of high precision measurements with single top quarks has already started...
Projection for s-channel (2011)

DØ Run II

- 2.3 fb⁻¹ observed
- 2.3 fb⁻¹ expected
- 5.4 fb⁻¹ observed
- 5.4 fb⁻¹ expected

a priori projection
√lumi projection
± 1σ

Luminosity [fb⁻¹]

s-channel significance [SD]