Single top quark physics at the Tevatron and the LHC

Reinhard Schwienhorst

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Outline

• Introduction
• Tevatron
  - SM
  - New physics
• LHC
  - SM
  - New physics
• Conclusions
Higgs field

Electroweak symmetry breaking

Higgs boson

W boson
Higgs field

Higgs boson

Electroweak symmetry breaking

W boson
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Coupling strength $\sim 1$

Electroweak symmetry breaking
Coupling strength ~ 1

Higgs boson

Electroweak symmetry breaking

W boson

top quark
The diagram illustrates the relationship between the masses of the W boson, Higgs boson, and top quark. The LEP2 and Tevatron (preliminary) data are shown in blue, while the LEP1 and SLD data are in red. The 68% confidence level (CL) bands are indicated by the shaded green regions. The masses are plotted on the axes, with the top quark at the center, connected to the Higgs boson and W boson by chains, symbolizing their interactions or connections in the theoretical framework of particle physics.
Key to electroweak symmetry breaking

- Top quark
- Higgs boson
- W boson
Top quark decay

top quark

bottom quark

W boson

space

time
t-channel single top quark production

light quark line

W boson

heavy quark line
Wt associated production

- gluon
- bottom quark
- W boson
- top quark
s-channel single top production

light quark

light quark’

top quark

bottom quark

space

time

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SM single top quark production

**Tevatron:** $\sigma_{tot} = 3 \text{ pb}$

**LHC:** (7 TeV) $\sigma_{tot} = 76 \text{ pb}$

**LHC:** (14 TeV) $\sigma_{tot} = 326 \text{ pb}$

SM tasks:
- Weak interaction of bare quarks
- Measure total cross section $\rightarrow$ CKM matrix element $|V_{tb}|$
- Top polarization, PDFs
New physics in single top

New interactions: FCNC

New coupling: modified $Wtb$ coupling or anomalous CKM matrix

New particles: heavy boson or charged Higgs or $T'$ or $B'$

New physics tasks:
- measure individual cross sections → different modes sensitive to different new physics
- look for specific new physics scenarios
  - $W'$, fourth generation quarks, charged Higgs
  - gluon FCNC
  - anomalous $Wtb$ couplings
Experimental setup:
Fermilab Tevatron in Run II

Proton-antiproton collider
CM energy 1.96 TeV
→ Energy frontier - until a year ago
Instantaneous luminosity >4E32 cm\(^{-2}\)s\(^{-1}\)
→ Proton-antiproton luminosity frontier
Fermilab single top history

Publication history

- **Search:** PRD 63, 031101 (2000)
- **Search:** PLB 517, 282 (2001)
- **Search:** PLB 622, 265 (2005)
- **W:** PLB 641, 423 (2006)
- **Search:** PRD 75, 092007 (2007)
- **Evidence:** PRL 98, 181802 (2007)
- **FCNC:** PRL 99, 191802 (2007)
- **W:** PRL 100, 211802 (2007)
- **Evidence:** PRD 78, 012005 (2008)
- **Wtb:** PRL 101, 221801 (2008)
- **Wtb:** PRL 102, 092002 (2009)
- **H:** (PRL) arXiv:0807.0859
- **Observation:** (PRL) arXiv:0903.0850

- tau search PLB 690, 5 (2010)
- t-chan meas. PLB 682, 363 (2010)
- FCNC PLB 693, 81 (2010)
- top width PRL 106, 22001 (2011)
- W’ PLB 699, 145 (2011)
- t-chan obs. (PLB) arXiv:1105.2788
- s+t meas (PRD) arXiv:1108.3091
- Wtb coupl. (PLB) arXiv

- **Search:** PRD 65, 091102 (2002)
- **Search:** PRL 70, 081802 (2003)
- **Search:** PRD 69, 052003 (2004)
- **Evidence:** PRL 101, 252001 (2008)
- **Evidence:** (PRL) arXiv:0812.3400
- **W:** (PRL) arXiv:0902.3276
- **Observation:** (PRL) arXiv:0903.0885

- MET+jets PRD 81, 072003 (2010)
- Observation PRD 82, 112005 (2010)
Single top quark event signature

b-quark jet or light quark jet

High-momentum lepton (e or μ)

Missing transverse energy
Single top quark event signature

s-channel

Proton

Antiproton

t-channel

q
g

W

b

ν

l

q'

q'

b

ν

l

High-momentum lepton (e or μ)

Missing transverse energy
Background processes

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

cross-check sample

W+Jets Cross-Check Sample

DØ 2.3 fb⁻¹

1 b-tag
2 jets

Hₜ < 175 GeV

Data

tb + tqb
Wbb
Wcc
Wjj + Wcj
Non-W
Multijets

all channels

0 2 4

0 50 100 150

Q(Lepton) x η(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
Tevatron analysis outline

Trigger selection

S/B = 1/10^9

Single top event kinematics

S/B = 1/250, 50,000 events/fb

b-quark tagging

S/B = 1/20, 2000 events/fb

Statistical analysis

Combination

Multivariate techniques

BDT

NN

ME
Multivariate methods

**Input:** discriminating variables

- Event energy
- Quark jet angle
- Reconstructed top mass
- ..... 

**Method:** multivariate analysis

- Bayesian neural networks
- Boosted decision trees
- Decision trees
- Neural networks
- Likelihood
- Matrix Elements

**Output:** signal likelihood

\[
d^n \sigma_{t \to W^* b} \frac{d^2 \Phi_n}{4 \pi q_1 q_2 q_3 q_4} \times \frac{1}{m_1 m_2} 
\]
Several multivariate filters combined in one final discriminant
- BNN (DØ)
- NEAT (CDF)
Results and combination

- Each experiment observes 5 $\sigma$ significance
- DØ and CDF measurements are consistent to 1.6 $\sigma$
- Combination of MVA distributions
  - Bayesian statistical analysis
  - Taking all uncertainty correlations into account
CKM matrix element $V_{tb}$

- Cross section $\propto |V_{tb}|^2$
  - 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 unitarity
t-channel production

- New analysis with 5.4 fb$^{-1}$
- Dedicated t-channel filter
- No assumption about s-channel
- 5.5 $\sigma$ significance
Top quark properties

- Top quark width from t-channel cross section
  - use $R = \frac{B(t \to Wb)}{B(t \to Wx)}$ to obtain full width
  
  $\Gamma_t = 2.05^{+0.57}_{-0.52}$ GeV
  $\tau_t = (3.2^{+1.1}_{-0.7}) \times 10^{-25}$ s

- Top quark polarization from spin correlation

- Analysis using likelihood function
- Test for right-handed coupling in top production
Tevatron new physics searches
Gluon-FCNC in single top

D0: 2→2 process
★ Same final state as t-channel
★ Multivariate analysis using BNN

CDF: 2→1 process
★ Multivariate analysis using NN

95% CL limits:

<table>
<thead>
<tr>
<th>Process</th>
<th>( \kappa_{gtu}/\Lambda )</th>
<th>( \kappa_{gtc}/\Lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section</td>
<td>0.20 pb</td>
<td>0.27 pb</td>
</tr>
<tr>
<td>( B(t \rightarrow qg) )</td>
<td>( 2.0 \times 10^{-4} )</td>
<td>( 3.9 \times 10^{-3} )</td>
</tr>
</tbody>
</table>
Single top anomalous coupling

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

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

- $W$ helicity measurement and single top anomalous couplings searches are both sensitive: combine (PRL 102, 092002 (2009))

- Updated measurement with 5.4 fb$^{-1}$

\[ |f^R_1|^2 < 0.93 \]
\[ |f^L_2|^2 < 0.13 \]
\[ |f^R_2|^2 < 0.06 \]
Search for \( W' \) boson

- Explore simultaneously left-handed and right-handed couplings
- 95% CL limits:
  \[ M_{W'} > 863 \text{ GeV} \text{ (SM-like)} \]
  \[ M_{W'} > 885 \text{ GeV} \text{ (R, } M_{W'} < m_{nR}) \]
  \[ M_{W'} > 890 \text{ GeV} \text{ (R, } M_{W'} > m_{nR}) \]
  \[ M_{W'} > 916 \text{ GeV} \text{ (L+R)} \]
Large Hadron Collider
Large Hadron Collider
Measurement of t-channel production

- 36 pb\(^{-1}\) of 2010 data

Event selection:
- 1 electron or muon 
  \(E_T(p_T) > 30/20\) GeV
- \(M_T(W) > 50/40\) GeV
- \(= 2\) jets \((p_T > 30\) GeV\), \(\geq 1\) b-tag
- fewer channels than Tevatron, tighter cuts

Background modeling:
- normalize \(W+\)jets and QCD to data
- top background to theory

Analysis procedure:
- BDT with 37 variables
- 2-d fit to light jet \(\eta\) and spin correlation
t-channel result

- Combination using BLUE

combined: observed cross section: 
\[ \sigma_t = 83.6 \pm 29.8 \text{ pb} \]

Observed significance: 3.5 \( \sigma \)

Observed \( |V_{tb}| > 0.68 \) at 95% CL

arXiv:1106.3052 [hep-ex]
Measurement of t-channel production

- 700 pb\(^{-1}\) of 2011 ATLAS data

\[ H_T = \sum E_T (\text{lepton}, E_T^{\text{Miss}}, \text{jets}) \ [\text{GeV}] \]

\[ m_{\text{top}} (lb) \ [\text{GeV/c}^2] \]

Total Delivered: 5.21 fb\(^{-1}\)
Total Recorded: 4.88 fb\(^{-1}\)

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Cut-based t-channel analysis

- $|\eta_{\text{non-b jet}}| > 2.0, |\eta_{\text{b-jet}}| < 2.0$
- $140 \text{ GeV} < \text{top quark mass} < 190 \text{ GeV}$
- $|\Delta \eta(\text{lepton, b-tagged jet})| < 1.5$
- $H_T > 180 \text{ GeV}$
- separate by lepton flavor, top charge and $n_{\text{jets}}$

Observed cross section:

$\sigma_t = 90^{+32}_{-22} \text{ pb}$

Observed significance:

$7.6 \sigma$
Neural network result

- 22 input variables
- fit shape to signal and W+jets background
- Systematic uncertainties:
  - jet energy scale, b-tagging

NN: Observed cross section:
$$\sigma_t = 105^{+37}_{-31} \text{ pb}$$
t-channel summary

![Graph showing σ (pb) vs. √s (TeV)]

- CMS Preliminary, 35.9 pb⁻¹
- D0
- CDF
- NLO 5f
- ATLAS 700 pb⁻¹

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CMS Wt measurement

- Never before seen!
- Cut-based analysis using 2.1fb\(^{-1}\) of 2011 data
  - Important variable: \(p_T\) system
- Cross section from simultaneous fit to Wt and top pairs
- Observed significance 2.7\(\sigma\)
ATLAS Wt associated production

- Search in lepton+jets and di-leptons

Dilepton backgrounds:

Top quark pairs
- Model using MC@NLO
- Normalize to data

Drell-Yan
- Model using Alpgen
- Normalize to data

Smaller backgrounds from $Z\rightarrow\tau\tau$, dibosons, $W$+jets, multijets

Set limit of 39 pb ($2.5 \times \sigma_{Wt}^{SM}$)
s-channel analysis

- Search in 700 pb$^{-1}$
- cut-based selection
- s-channel limit at 95% CL: 26.5 pb
LHC new physics searches
ATLAS FCNC search

- first single top new physics search
- single-top production
ATLAS FCNC search

- first single top new physics search
- single-top production

First of many new physics searches!
Many more new physics searches

● Anomalous couplings

\[ \mathcal{L} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{tb} (f_1^L P_L + f_1^R P_R) t W^-_\mu \]

\[ -\frac{g}{\sqrt{2}} \bar{b} \frac{i \sigma^{\mu\nu} q_\nu}{M_W} (f_2^L P_L + f_2^R P_R) t W^-_\mu + h.c. \]

- In single top and in combination with ttbar

● Resonance searches
  - New heavy boson W’
    ▶ With anomalous couplings?
    ▶ With different CKM matrix - ttbar asymmetry?
    ▶ Charged Higgs decaying to tb
  - Fourth generation quarks
    ▶ B’ or T’ decaying to single top

● New particles produced together with single top
  - Charged Higgs

● If discoveries are made elsewhere first?
  - Measure coupling to top
Many more new physics searches

• Anomalous couplings - magnitude

\[
\mathcal{L} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{tb} (f_1^L P_L + f_1^R P_R) t W^-_\mu \\
- \frac{g}{\sqrt{2}} \bar{b} \sigma^{\mu\nu} q_\nu \frac{1}{M_W} (f_2^L P_L + f_2^R P_R) t W^-_\mu + h.c.
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- Anomalous couplings - magnitude, complex phase

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  - Fourth generation quarks
    ▶ $B'$ or $T'$ decaying to single top
Many more new physics searches

• Anomalous couplings - magnitude, complex phase, CKM

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  - Measure coupling to top
China in ATLAS single top

- Shandong University
  - Cunfeng Feng with Jin Wang, Peng Ge

- Also at other institutions
  - Xiaohu Sun and Jin Wang also at Grenoble
    - t-channel and FCNC
  - Huaqiao Zhang at MSU
  - Peng Ge also at MSU
    - Wt and B’ search
Summary/Outlook

• Single top production observed at Tevatron and LHC
  - Tevatron s-channel+t-channel observation in 2009
  - Tevatron t-channel isolation in 2011
  - LHC t-channel observation in 2011
  - LHC first limit on Wt and s-channel
  - Next: Wt and s-channel observation
  - Single top as background to Higgs and other searches

• Single top as a tool to look for new physics
  - Tevatron: W’, FCNC, H+, anomalous couplings
  - LHC: FCNC
  - Next: many more LHC new physics searches

Larger LHC datasets will bring separate observation of all single top processes and many new physics searches