Single Top Quark Physics

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Outline

• Introduction
• Single top quark production
• Searches at the Fermilab Tevatron
• Outlook
  – Tevatron future
  – LHC prospects
• Conclusions
Introduction

What is Single Top?
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Higgs coupling

Electroweak charged-current coupling

 electroweak symmetry breaking

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Top quark electroweak charged current interaction

top quark decay
SM single top quark production

\[ q \rightarrow W^{-} t \chi^{-} \]

\[ q' \rightarrow W^{+} t \chi^{+} \]

\[ W^{-} b \]

\[ W^{+} t \]

\[ g \rightarrow tW \]

\[ t \rightarrow Wb \]

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

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

New heavy boson

s-channel

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

t-channel

\[ q \rightarrow Z, \gamma \rightarrow q \]
\[ c \rightarrow t \]

Associated production

\[ g \rightarrow t \rightarrow W \]
\[ b \]

Flavor Changing Neutral Current

Modified Wtb coupling
Single Top
Single Top at LEP and Hera: FCNC

- **LEP:**
  \[ e^+ e^- \rightarrow tc \]

- **Hera:**
  \[ ep \rightarrow et \]
Single Top Goals

**Tevatron**
- Observe single top production
- Measure production cross section
- Look for new physics
  - New particles, new couplings
- Observe top quark spin correlations
- Background to Higgs searches

**LHC**
- Observe single top production
- Measure production cross section precisely $V_{tb}$
- Look for new physics
  - New particles, new couplings
  - Modified Wtb coupling
- Study top quark properties
  - Spin, mass, charge, ...
- Background to many new physics searches
Current Tevatron Run II Results

Precious data!
Top quark pair production

\[
q \quad \text{gluon} \quad t \\
\bar{q} \quad \bar{t}
\]

\[\sigma \sim 7 \text{ pb}\]

Single top quark production

\[
q \quad W \text{ boson} \quad t \\
\bar{q}' \quad \bar{b}
\]

\[\sigma \sim 1 \text{ pb (s-channel)}\]
Single top quark event

High-momentum lepton

Missing (unbalanced) energy
**Event Sample Composition**

Leptons: \((e, \mu)\) \(E_T > 15\) GeV, \(\not{E}_T > 15\) GeV  
Jets: \(2 \leq n_{jets} \leq 4\), \(E_T\)\((jet)>15\) GeV, \(\geq 1\) b-tag

- **Background count** \(\sim 1\) event \(\times\) pb  
- **Signal count** \(\sim 0.05\) event \(\times\) pb  
- **Signal/Background** \(\sim 1/20\)
Discriminating Variables

Kinematic distributions

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

Data-background comparison

DØ Run II, 230pb⁻¹

- t-channel
- t̅t
- W+jets

Event Yield vs. $p_T(\text{jet}_1 \text{ untagged})$ [GeV]

Normalized to unit area

$\cos(\Theta_{i,q})$
Optimized Event Analysis

**Input:**
discriminating variables

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

**Method:**
multivariate analysis

**Output:**
signal probability

\[ P(\text{signal}) \]

Cut-Based  Likelihoods  Decision Trees  Neural Networks  Matrix Elements
Analysis Strategy

- Maximize signal acceptance
  - $E_T$ (leptons, jets) > 15 GeV
  - $2 \leq n_{jets} \leq 4$

Event Analysis

- full dataset
  - electron
    - 1 tag
    - 2 tags
  - muon
    - 1 tag
    - 2 tags

s-channel  t-channel

result

DØ Run II Preliminary, 370 pb⁻¹

Reconstructed top mass using the leading b-tagged jet (GeV)
Neural Network

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**Likelihood**

DØ Run II Preliminary, 370 pb⁻¹

95% CL cross section limits:

\[ \sigma_s < 5.0 \text{ pb} \]

\[ \sigma_t < 4.4 \text{ pb} \]

370 pb⁻¹

PLB 622, 265 (2005)
Analysis Strategy

- electron+muon combined
  - $E_T > 20$ GeV
  - $\equiv 2$ jets
- Kinematic fit
  - Identify top quark decay products
- NN b-tagging
Likelihood Analysis

95% CL cross section limits:

\[ \sigma_s < 5.1 \text{ pb} \]
\[ \sigma_t < 2.9 \text{ pb} \]
\[ \sigma_{s+t} < 4.3 \text{ pb} \]
Neural Network Analysis

- Separate networks for s-, t-channel, s+t
- 14 discriminating variables
  - Object kinematics
  - Event kinematics
  - Kinematic fitter output
  - NN b-tagger output
- Bayesian limit setting

95% CL cross section limits:

- $\sigma_s < 3.2$ pb
- $\sigma_t < 3.1$ pb
- $\sigma_{s+t} < 3.4$ pb
## Tevatron Summary

### NLO cross section

<table>
<thead>
<tr>
<th>Channel</th>
<th>DØ NN (230 pb$^{-1}$)</th>
<th>DØ Likelihood (370 pb$^{-1}$)</th>
<th>CDF Likelihood (700 pb$^{-1}$)</th>
<th>CDF NN (700 pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-channel</td>
<td>6.4</td>
<td>5.0</td>
<td>5.0</td>
<td>3.2</td>
</tr>
<tr>
<td>t-channel</td>
<td>5.0</td>
<td>4.4</td>
<td>2.9</td>
<td>3.1</td>
</tr>
<tr>
<td>s+t</td>
<td>5.1</td>
<td>4.3</td>
<td>2.9</td>
<td>3.4</td>
</tr>
</tbody>
</table>

### 95% CL upper cross section limits [pb]

- DØ NN: 6.4 pb, 5.0 pb, 5.1 pb
- DØ Likelihood: 5.0 pb, 4.4 pb, 4.3 pb
- CDF Likelihood: 5.0 pb, 2.9 pb, 3.4 pb
- CDF NN: 3.2 pb, 3.1 pb, 3.4 pb

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- 23
New Physics: extra heavy boson?

\[ \text{M}(W') > 650 \text{ GeV} \]

\[ \text{M}(W') = 600 \text{ GeV} \]

DØ Run II Preliminary, 230pb\(^{-1}\)

- Data
- Wprime (<10)
- tb + tqb
- t\(\bar{t}\)
- W+jets
- Multijet

\(\sqrt{s} [\text{GeV}]\)

Events

DØ Run II preliminary 230 pb\(^{-1}\)

- 95% C.L. limit
- W', SM-like coupl.

\(\text{M}(W') > 650 \text{ GeV}\)
Tevatron Single Top Future

- s+t combined
- Cut on NN output
- No systematics

Prospects

- Observe single top production in Run II
  - Discover new physics (if it's there)
- Measure $|V_{tb}|$ to $\sim 10\%$
Future Energy Frontier: LHC
Single Top future: LHC

s-channel: 10.7 pb  
\[ q \rightarrow W^+ t \]
\[ \bar{q}' \rightarrow W^- \bar{b} \]

\[ t \]

\[ u \rightarrow t d W^- \]

\[ g \rightarrow t b W^- \]

\[ \text{t-channel: 247 pb} \]

\[ \text{associated production: 68 pb} \]

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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
  - t\bar{t} more important
- t-channel observation early
  - Large cross section
- s-channel and Wt with 30 fb\(^{-1}\)
  - Separate by b-tag and jet multiplicity
Supersymmetry: Heavy $H^+$

$\begin{align*} 
q & \rightarrow H^+ \\
q' & \rightarrow b \\
t & \rightarrow q' \\
t & \rightarrow b
\end{align*}$

Light $H^+$:

$\begin{align*} 
t & \rightarrow H^+ \\
b & \rightarrow W^+
\end{align*}$

FCNC:

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

Top-Higgs Yukawa coupling measurement

$\begin{align*} 
g & \rightarrow g \\
t & \rightarrow t \\
\bar{t} & \rightarrow g
\end{align*}$
Conclusions

• The top quark is a key to understanding electroweak symmetry breaking

• We are close to observing electroweak top quark production at the Tevatron
  – Already ruling out many new physics scenarios
  – Advanced analysis methods to maximize sensitivity

• This is just the beginning
  – Tevatron dataset will increase \( \times 20 \) in next 4 years
  – LHC is just around the corner
Backup Slides
Tevatron Analysis Sensitivity

s-channel  t-channel  s+t

NLO cross section  0.88 pb  1.98 pb  2.86 pb

equipped 95% CL upper cross section limits [pb]

<table>
<thead>
<tr>
<th></th>
<th>DØ NN (230 pb⁻¹)</th>
<th>DØ Likelihood (370 pb⁻¹)</th>
<th>CDF Likelihood (700 pb⁻¹)</th>
<th>CDF NN (700 pb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.5</td>
<td>3.3</td>
<td>5.9</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>5.8</td>
<td>4.3</td>
<td></td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.7</td>
</tr>
</tbody>
</table>
Likelihood Analysis

- 12 discriminating variables
  - Object and event $E_T$
  - Angular correlations
  - Top quark reconstruction

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– Systematic uncertainties
  • Bkg normalization ~ 20%
  • b-tag modelling 6% - 17%
  • Particle ID ~ 5%
  • Trigger modeling ~ 5%

– Bayesian limit setting
  • Combining all channels

95% CL cross section limits:

\[ \sigma_s < 5.0 \text{ pb} \]
\[ \sigma_t < 4.4 \text{ pb} \]
Systematics and Event Selection Efficiencies

CDF takes uncertainties on shape systematics.

CDF II 695 pb$^{-1}$ Preliminary

<table>
<thead>
<tr>
<th>Source</th>
<th>$t$-channel</th>
<th>$s$-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>JES</td>
<td>1.8%</td>
<td>1.2%</td>
</tr>
<tr>
<td>ISR</td>
<td>1%</td>
<td>2%</td>
</tr>
<tr>
<td>FSR</td>
<td>5%</td>
<td>1%</td>
</tr>
<tr>
<td>PDF</td>
<td>2.5%</td>
<td>2.2%</td>
</tr>
<tr>
<td>MC</td>
<td>2%</td>
<td>1%</td>
</tr>
<tr>
<td>$\epsilon_{\text{evt}}$</td>
<td>10.3%</td>
<td>8%</td>
</tr>
</tbody>
</table>

Events detection efficiency$^{(*)}$

- **s-channel**: $1.87 \pm 0.15\%$
- **t-channel**: $1.21 \pm 0.17\%$

$^{(*)}$ Including $W \rightarrow \text{leptons} \text{ BR}$
To the network 2D output, maximum likelihood fit is applied and the best fits for t- /s- channel:

**t-channel:**

\[
\sigma_{t-ch} = 0.6^{+1.9}_{-0.6}(stat)^{+0.1}_{-0.1}(syst)\text{ pb}
\]

**s-channel:**

\[
\sigma_{s-ch} = 0.3^{+2.2}_{-0.3}(stat)^{+0.5}_{-0.3}(syst)\text{ pb}
\]

**Expected upper limits:**

- **t-channel:** \( \sigma < 4.2 \text{ pb} \)
- **s-channel:** \( \sigma < 3.7 \text{ pb} \)

\( \sigma < 3.1 \text{ pb} \) @ 95\% C.L. (OBSERVED)

\( \sigma < 3.2 \text{ pb} \) @ 95\% C.L.
Discriminating Variables

- **Object kinematics**
  - Jet $p_T$ for different jets
    - Tagged, untagged,...

- **Event kinematics**
  - $H$ (total energy)
  - $H_T$ (transverse energy)
  - $M$ (invariant mass)
  - $M_T$ (transverse mass)
  - Summing over various objects in the event

- **Angular variables**
  - Jet-jet separation
  - Jet pseudorapidity (t-channel)
  - Top quark spin
  - Sphericity, aplanarity

25 variables total
Neural Networks

Input Nodes: One for each variable $x_i$

- $M_T (\text{jet1, jet2})$
- $M (\text{all jets})$
- $p_T (\text{jet1, jet2})$
- $p_T (\text{not best2})$
- $p_T (\text{not best1})$
- $\cos(\Theta_{(j_k)} \times z_{\text{best1}})$
- $M (W, \text{best})$
- $M (W, \text{lag1})$
- $\Delta R (\text{jet1, jet2})$
- $\sqrt{s}$
- $p_T (\text{tag1})$

Hidden Nodes: Each is a sigmoid dependent on the input variables

$$n_k(\vec{x}, \vec{w}_k) = \frac{1}{1 + e^{-\sum_w w_{ik} x_i}}$$

Output Node: linear combination of hidden nodes

$$f(\vec{x}) = \sum w'_k n_k(\vec{x}, \vec{w}_k)$$

Sigmoid
Neural Network Output

---

**Neural Network Output**

**e+μ ≥ 1 tag**

---

**Neural Network Output**

**e+μ ≥ 1 tag**

---

**Neural Network Output**

**e+μ ≥ 1 tag**

---

**Neural Network Output**

**e+μ ≥ 1 tag**
Single Top Phenomenology Connection

• NLO calculations exist for the single top signal
  
  – Fully differential distributions, including top quark decay
  
  – s-channel } Harris, Laenen, Phaf, Sullivan, Weinzierl, PRD66, 054024 (2002); Sullivan, PRD 70 (2005); Cao, RS, Yuan, PRD74, 054023 (2005); Cao, RS, Benitez, Brock, hep-ph/0504230 (2005); Ellis, Campbell, Tramontano, PRD 70, 094012 (2004)


• Several parton-level studies have been done
  
  – Exploiting asymmetries to discover single top

  – Studying angular correlations at NLO (t-ch, s-ch, and Wjj)
    Sullivan, hep-ph/0510224

• W + 2 jets background at NLO
  Campbell, Ellis, Rainwater PRD68, 094021 (2003)
Conclusions

• We are on a quest to reveal the origin of electroweak symmetry breaking and particle mass
• Understanding the top quark is an important step
  – In particular its electroweak interaction
• The top quark is a central focus at the Tevatron
  – Run II is now producing many results
  – Single top quark search is close to SM sensitivity
• This is just the beginning
  – Analyzing ×4 dataset now
  – LHC is just around the corner

Dawn of Discoveries
b quarks as a tool: b-tagging

- Identification of b-quark jets
  2 possible methods:
  - Identify muon inside jet
    ~20% of all b-quark jets
  - Identify long-lived decay
    ~35% of all b-quark jets

Probability to tag a jet in a top event:
- b-quark jet: ~55%
- light-quark jet: ~0.5%
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Tevatron Single Top Future

- s+t combined
- NN search
- Cut on NN output (event counting)
- No systematics

Improvements
- b-tagging
  - More signal
- Jet energy resolution
  - Better top mass reconstruction

Prospects
- Observe single top production in Run II
  - Discover new physics (if it's there)
- Measure $|V_{tb}|$ to $\sim 10\%$

CDF II preliminary

<table>
<thead>
<tr>
<th>significance S / \sqrt{B}</th>
<th>integrated luminosity [ 1/fb ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>today 2007 2009</td>
<td></td>
</tr>
</tbody>
</table>

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We assume but don't actually know:

- Charge, Spin
- Electroweak interactions
  - Charged current (W boson)
    - Total width
    - CKM matrix
  - Neutral current (Z boson)

Really don't know:

- Coupling to Higgs?
- Modified weak coupling?
- SUSY? New physics?
Tevatron s-channel signature

\[ q \rightarrow W \rightarrow t \rightarrow b \nu \]

Cao, RS, Yuan PRD71, 054023 (2005)
Tevatron t-channel signature

Cao, RS, Benitez, Brock, Yuan, PRD72, 094027 (2005)
Single top cross section limit

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Published in PLB 622, 265 (2005)
Particle production at the LHC

production cross-section (femtobarns)

particles produced in first LHC year

\(10^2\) \(10^4\) \(10^6\) \(10^8\) \(10^{10}\) \(10^{12}\) \(10^{14}\)

TeV LHC

total inelastic

bottom quark pairs

\(W\) bosons

\(Z\) bosons

top quarks

SM Higgs bosons (\(\@150\) GeV)

SUSY (\(\@1\) TeV)
Tevatron luminosity projection

Note:
- Single experiment
- No systematics
- Expect further improvements

Separate s-channel from t-channel

Observation of single top

“Evidence for” single top

Date

Luminosity [fb⁻¹]

8.2 fb⁻¹

5.1 fb⁻¹

4.1 fb⁻¹

9/29/03  9/29/04  9/30/05  10/1/06  10/2/07  10/2/08  10/3/09

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Analysis Strategy

**full dataset**

- **electron**
  - $=1$ b-tag
  - $\geq 2$ b-tags

- **muon**
  - $=1$ b-tag
  - $\geq 2$ b-tags

**Event Analysis**

- **s-channel**
  - $Wbb$
  - $tt$

- **t-channel**
  - $Wbb$
  - $tt$

**2d histograms, Wbb vs tt filter**

- $tt$
  - **s-channel**
  - $Wbb$

- $tt$
  - **t-channel**
  - $Wbb$

**binned likelihood**

**result**
Neural Network Result

- Dominant systematics
  - Jet energy scale, b-ID: 10%
  - Background norm: 15-20%
  - Object ID: 5%
- Total systematic

\[ \sigma_t < 5.8 / 5.0 \text{ pb} \]
\[ \sigma_s < 4.5 / 6.4 \text{ pb} \]

Signal acceptance 15% 25%
Background sum 10% 26%

Expected/Observed limit:

- Published in PLB 622, 265 (2005)

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Event selection result

10,000 events with lepton, neutrino, ≥ 2 jets
expect ~250 top quarks

Backgrounds

Top quark pairs

In 360pb⁻¹, lepton+jets
Top Quark Events

=1 b-tag: 367 events

=2 b-tags: 76 events

Top quark pairs
Backgrounds
Dataset used in latest analysis
0.37 fb⁻¹

Publication with 0.24 fb⁻¹

19 April 2002 - 5 January 2006

Delivered
Recorded