Search for Single Top Quark Production at DØ in Run II

Reinhard Schwienhorst

Columbia University Nuclear/Particle & Astroparticle Seminar, 4/27/2005
Outline

• Introduction
  – Top quark
  – Electroweak top quark production
• The DØ experiment at the Tevatron
• Search for single top at DØ
  – Event selection
  – Discriminating variables
  – Final analysis method
    • Cut-based analysis
    • Neural network analysis
    • Decision Tree analysis
• Conclusions/Outlook
Top Quark

- Discovered in 1995 by CDF and DØ at the Tevatron
- Heaviest of all fermions
  - 40 times heavier than b quark
- Only quark that decays before it hadronizes
  - Clean laboratory to study quark properties
- Couples strongly to SM Higgs boson
  - Electroweak symmetry breaking

**LEPTONS**

<table>
<thead>
<tr>
<th>Charge</th>
<th>Electron neutrino Mass: 0?</th>
<th>Muon neutrino 0?</th>
<th>Tau neutrino 0?</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Electron 0.511</td>
<td>Muon 105.7</td>
<td>Tau 1,777</td>
</tr>
</tbody>
</table>

**QUARKS**

<table>
<thead>
<tr>
<th>Charge</th>
<th>Up Mass: 5</th>
<th>Charm 1,500</th>
<th>Strange 160</th>
<th>Bottom 4,250</th>
</tr>
</thead>
<tbody>
<tr>
<td>+2/3</td>
<td>2</td>
<td>-1/3</td>
<td>-1/3</td>
<td>Top ~180,000</td>
</tr>
</tbody>
</table>
Fundamental Interactions

- **Strong force**
  - Top quark production in hadron colliders

\[ q g t \]

- **Electroweak neutral current**
  - Top quark production in lepton colliders

\[ e^+ \gamma/Z e^- t \]

*Top quark pair creation*
Top Quark Interactions

• Electroweak charged current
  • So far, we only really know that it does decay

Top quark decay
  – Electroweak charged current also responsible for nuclear Beta decay
Top Quark Electroweak Interaction

top quark decay

Wtb vertex has many angles
Electroweak Production of Top at the Tevatron

\[ W \]
Electroweak Production of Top at the Tevatron

$s$-channel

$q, \bar{q}' \to W, t, \bar{b}$

$O(\alpha_s)$ corrections:
Electroweak Production of Top at the Tevatron

\[ q \rightarrow W \rightarrow t + \bar{b} \]

s-channel

[Inset graph: Fraction vs. jet $p_T$ threshold [GeV]]

Cao, RS, Yuan hep-ph/0409040
Electroweak Production of Top at the Tevatron

t-channel

\( t \rightarrow u \rightarrow d \rightarrow b \rightarrow t \)
Electroweak Production of Top at the Tevatron

$$t\text{-channel}$$

\[ \begin{array}{c}
\text{u} \\
\text{b} \\
\text{t}
\end{array} \]

\[ \begin{array}{c}
\text{d} \\
\text{t}
\end{array} \]

$$O(\alpha_s)$$ corrections:
Electroweak Production of Top at the Tevatron

Cao, RS, Benitez, Brock, Yuan hep-ph/0504230
Tevatron Single Top Goals

- Observe single top quark production
- Measure production cross sections $\rightarrow V_{tb}$
  - Separately for s-channel and t-channel

Weak interaction eigenstates are not mass eigenstates
Top quark must decay to a $W$ plus a $d$, $s$, or $b$ quark

$$V_{td}^2 + V_{ts}^2 + V_{tb}^2 = 1 \quad \rightarrow \quad V_{tb} > 0.999$$

New physics that couples to the top quark:

$$V_{td}^2 + V_{ts}^2 + V_{tb}^2 + V_{tx}^2 = 1$$

Only weak constraints on $V_{tb}$
Tevatron Single Top Goals

- Observe single top quark production
- Measure production cross sections
  - CKM matrix element $V_{tb}$
- Look for physics beyond the Standard Model
  - Different sensitivity for s-channel and t-channel

Example: Top-Flavor

$W'$

bottom quark

top quark

Reinhard Schwienhorst, Michigan State University
Tevatron Single Top Goals

• Observe single top quark production
• Measure production cross sections
  • CKM matrix element $V_{tb}$
• Look for physics beyond the Standard Model
• Study top quark spin correlations – probe V-A
  • Physics with ~100% polarized top quarks
Tevatron Single Top Goals

• Observe single top quark production
• Measure production cross sections
  • CKM matrix element $V_{tb}$
• Look for physics beyond the Standard Model
• Study top quark spin correlations – probe V-A
• Irreducible background to associated Higgs production

Gateway to the Higgs
Single Top Status

- Production cross section:
  - NLO calculation: $0.88 \text{pb (±8%)}$  $1.98 \text{pb (±11%)}$
  - Run I 95% CL limits, DØ:  $< 17 \text{pb}$  $< 22 \text{pb}$
    - CDF:  $< 18 \text{pb}$  $< 13 \text{pb}$  $< 14 \text{pb}$
  - Run II CDF 95% CL limits:  $< 14 \text{pb}$  $< 10 \text{pb}$  $< 18 \text{pb}$

- Other Standard Model production mode ($Wt$) negligible
Discovery of Single Top?

- Excess of lepton+MET+2jet events at UA1 in 1984
  - Consistent with production of single top quark and bottom quark
  - SPS: $\sqrt{s}=540\text{GeV}$
- $M_{\text{top}} \approx 40\text{GeV}$
Discovery of Single Top?

- Excess of lepton+MET+2jet events at UA1 in 1984
  - Consistent with production of single top quark and bottom quark
    - $M_{\text{top}} \approx 40\text{GeV}$
  - Not confirmed after more data and better background estimation
    - $W+$jets production!

Reinhard Schwienhorst, Michigan State University
Single Top at LEP and Hera: FCNC

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

- **Hera:**
  \[ ep \rightarrow et \]
Experimental Detection of Single Top Events
Experimental Setup:
Fermilab Tevatron in Run II

Proton-Antiproton Collider
CM Energy 1.96TeV
→ Energy Frontier
Experimenters

- 19 countries
- 80 institutions
- 670 physicists
Apparatus: Run II DØ Detector

- Muon System
- Silicon Detector
- Calorimeter
- Tracker
- Fiber Tracker
Collecting Data: Triggering

Multi-level, pipelined, buffered Trigger Strategy

- Level 1: one interaction every 396ns
  - Fast trigger pick-offs from all detectors
  - Trigger on hit patterns in individual detector elements
- Level 2: Combine Level 1 regions and objects
  - Custom dataflow hardware/firmware
  - Event reconstruction on Pentium CPUs
- Level 3: Full detector readout
  - Complete event reconstruction on Linux processor farm
Dataset used in this analysis
0.23 fb$^{-1}$
Analysis Outline

Goal: Maximize Sensitivity

1. Event Selection
   - Select $W$-like events
   - Maximize acceptance
   - Model backgrounds

2. Separate signal from backgrounds
   - Find discriminating variables
   - Cut/combine in multivariate analysis

3. Determine cross section
   - Event counting
   - Binned likelihood
Event Selection

- **Trigger:**
  - Electron + ≥1 jets, muon + ≥1 jets

- **Lepton:**
  - 1 electron: $p_T > 15\text{GeV}$, $|\eta^{\text{det}}| < 1.1$
  - 1 muon: $p_T > 15\text{GeV}$, $|\eta^{\text{det}}| < 2.0$

- **Neutrino:** $E_T > 15\text{GeV}$

- **Jets:**
  - $p_T > 15\text{GeV}$, $|\eta^{\text{det}}| < 3.4$, $p_T (\text{jet 1}) > 25\text{GeV}$
  - $2 \leq n_{\text{jets}} \leq 4$

- Reject mis-reconstructed events
Event Selection: b-tagging

Algorithm: Secondary Vertex Tag

- Final state:
  - 2 high-$p_T$ b-jets
  - Require $\geq 1$ b-tagged jet

- Final state:
  - 1 high-$p_T$ b-jet
  - 1 high-$p_T$ light quark jet
  - Require $\geq 1$ b-tagged jet
  - Require $\geq 1$ untagged jet

mistag rate: $\sim 0.2\%$
Background Modeling

- Based on data as much as possible
- W/Z+jets production
  - Estimated from MC/data
    - Distributions from MC
    - Normalization from pre-tagged sample
    - Flavor fractions from NLO
- Multijet events (misidentified lepton)
  - Estimated from data
- Top pair production
  - Estimated from MC
- Diboson (WZ, WW)
  - Estimated from MC
Event Yield

<table>
<thead>
<tr>
<th></th>
<th>s-channel</th>
<th>t-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut acceptance</td>
<td>23%</td>
<td>22%</td>
</tr>
<tr>
<td>b-tag efficiency</td>
<td>54%</td>
<td>38%</td>
</tr>
<tr>
<td>Signal yield</td>
<td>5.5</td>
<td>8.5</td>
</tr>
<tr>
<td>BKgnd yield</td>
<td>287</td>
<td>276</td>
</tr>
<tr>
<td>Signal/bkbgnd</td>
<td>1:52</td>
<td>1:32</td>
</tr>
</tbody>
</table>

Pre-tagged
7100 events
=1 b-tag
252 events
≥2 b-tags
31 events
Systematic Uncertainties

Monte Carlo Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory cross sections</td>
<td>15%</td>
</tr>
<tr>
<td>SVT modeling, single (double) tag</td>
<td>10% (20%)</td>
</tr>
<tr>
<td>Jet Energy Scale</td>
<td>10%</td>
</tr>
<tr>
<td>Trigger Modeling</td>
<td>6%</td>
</tr>
<tr>
<td>Jet Fragmentation</td>
<td>6%</td>
</tr>
<tr>
<td>Jet ID</td>
<td>5%</td>
</tr>
<tr>
<td>$\ell$ ID</td>
<td>5%</td>
</tr>
</tbody>
</table>

- Some uncertainties also affect shape
  - JES, b-tag and trigger modeling
- Total Uncertainty
  - $=1$ tag $\geq 2$ tags
  - Signal acceptance 15% 25%
  - Background sum 10% 26%

*Result is statistics limited*
A Treasure Chest of Discriminating Variables
Object $p_T$

- $p_T$ of jets:
  - Both s-channel and t-channel:
    - Jet 1 \text{tagged}
  - Only t-channel:
    - Jet 1 \text{untagged}
    - Jet 2 \text{untagged}
  - Only s-channel:
    - Jet 1 \text{non-best}
    - Jet 2 \text{non-best}
Event Energy

- Total energy $H = \sum_i E^i$
- Transverse energy $H_T = \sum_i E^i_T$
  - Both s-channel and t-channel:
    - $H$(all jets – Jet$1_{tagged}$)
  - Only t-channel:
    - $H_T$(all jets)
    - $H_T$(all jets – Jet$1_{tagged}$)
  - Only s-channel:
    - $H$(all jets – Jet$best$)
    - $H_T$(all jets – Jet$best$)
Reconstructed Objects

- Both s-channel and t-channel:
  - \( M(\text{all jets}) \)
  - \( p_T(\text{all jets} – \text{Jet}_1\text{tagged}) \)
  - \( M(\text{top}_{\text{tagged}}) \)
  - \( \sqrt{s} \)
- Only t-channel:
  - \( M(\text{all jets} – \text{Jet}_1\text{tagged}) \)
- Only s-channel:
  - \( M_T(\text{Jet}_1, \text{Jet}_2) \)
  - \( p_T(\text{Jet}_1, \text{Jet}_2) \)
  - \( M(\text{all jets} – \text{Jet}_1\text{best}) \)
  - \( M(\text{top}_{\text{best}}) \)
Angular Correlations

- Both s-channel and t-channel:
  - $\Delta R(\text{Jet}1, \text{Jet}2)$

- Only t-channel:
  - $\eta(\text{Jet}1_{\text{untagged}}) \times Q(\text{lepton})$
  - $\cos(\text{lepton}, \text{Jet}1_{\text{untagged}})_{\text{top} \text{tagged}}$
    - Spin correlation in optimal basis
  - $\cos(\text{all jets}, \text{Jet}1_{\text{tagged}})_{\text{all jets}}$

- Only s-channel:
  - $\cos(\text{lepton}, Q(\text{lepton}) \times z)_{\text{top} \text{best}}$
    - Spin correlation in optimal basis
  - $\cos(\text{all jets}, \text{Jet}1_{\text{non-best}})_{\text{all jets}}$
Separating Signal from Backgrounds

• Three analysis methods
  
  Cut-Based  Neural Networks  Decision Trees

• Each using the same structure:
  
  – Optimize separately for s-channel and t-channel
    • Optimize separately for electron and muon channel (same variables)
  
  – Focus on dominant backgrounds: W+jets, tt
    • W+jets – train on \(tb-Wbb\) and \(tqb-Wbb\)
    • \(tt\) – train on \(tb-\quad tt \rightarrow l + jets\) and \(tqb-\quad tt \rightarrow l + jets\)
  
  – Based on same set of discriminating variables
  
  → 8 separate sets of cuts/networks/trees
1. Cut-Based Analysis

**s-channel**
- Full dataset
  - Electron: \(=1\) b-tag, \(\geq2\) b-tags
  - Muon: \(=1\) b-tag, \(\geq2\) b-tags

**t-channel**
- Full dataset
  - Electron: \(=1\) b-tag, \(\geq2\) b-tags
  - Muon: \(=1\) b-tag, \(\geq2\) b-tags

\[\geq1\] untagged jet

Apply cuts

Count events

Result
1. Cut-Based Analysis

- Cuts on sensitive variables to isolate single top
  - Optimize s-channel and t-channel searches separately
  - Loose cuts on energy-related variables:
    
    \[ p_T(jet_{1\text{tagged}}) \]
    \[ H(\text{alljets} - jet_{1\text{tagged}}) \]
    \[ H(\text{alljets} - jet_{1\text{best}}) \]
    \[ H_T(\text{alljets}) \]
    \[ M(\text{top}_{\text{tagged}}) \]
    \[ M(\text{alljets}) \]
    \[ M(\text{alljets} - jet_{1\text{tagged}}) \]
    \[ \sqrt{s} \]

<table>
<thead>
<tr>
<th>Event Yields</th>
<th>s-channel</th>
<th>t-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-channel signal</td>
<td>4.5</td>
<td>3.2</td>
</tr>
<tr>
<td>t-channel signal</td>
<td>5.5</td>
<td>7</td>
</tr>
<tr>
<td>W+jets</td>
<td>103</td>
<td>73</td>
</tr>
<tr>
<td>top pairs</td>
<td>28</td>
<td>56</td>
</tr>
<tr>
<td>multijet</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Background sum</td>
<td>153±25</td>
<td>149±25</td>
</tr>
<tr>
<td>Observed</td>
<td>152</td>
<td>148</td>
</tr>
<tr>
<td>Signal/Bkgnd</td>
<td>1:34</td>
<td>1:21</td>
</tr>
</tbody>
</table>
**Result**

- No evidence for single top signal
  - Set 95% CL upper cross section limit
    - Using Bayesian approach
    - Combine all analysis channels (e, μ, =1 tag, ≥2 tags)
    - Take systematics and correlations into account

Expected limit: set \(N_{\text{obs}}\) to background yield

- Expected/Observed limit:
  - \(\sigma_s < 9.8 / 10.6 \text{ pb}\)
  - \(\sigma_t < 12.4 / 11.3 \text{ pb}\)
2. Neural Network Analysis

s-channel

- full dataset
- electron
  - =1 b-tag
  - ≥2 b-tags
- muon
  - =1 b-tag
  - ≥2 b-tags
- construct networks
- 2d histograms, Wbb vs tt filter
- binned likelihood
- result

- full dataset
- electron
  - =1 b-tag
  - ≥2 b-tags
- muon
  - =1 b-tag
  - ≥2 b-tags
- ≥1 untagged jet
- construct networks
- 2d histograms, Wbb vs tt filter
- binned likelihood
- result

t-channel
Neural Networks

Input Nodes: One for each variable $x_i$

Output Node: linear combination of hidden nodes

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

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

- Focus on the largest backgrounds: $Wbb$ and $tt\rightarrow l+jets$
- Same variables for electron and muon channel
- Same filter for $=1$ tag and $\geq 2$ tags
Neural Network Output

- Data
- s-channel (×10)
- tt
- W+jets
- multijet

\[ e^+\mu \geq 1 \text{ tag} \]

**tb-Wbb NN output**

- Data
- s-channel (×10)
- tt
- W+jets
- multijet

\[ e^+\mu \geq 1 \text{ tag} \]

**tb-\bar{t}t NN output**

- Data
- s-channel (×10)
- tt
- W+jets
- multijet

\[ e^+\mu \geq 1 \text{ tag} \]

**tqb-Wbb NN output**

- Data
- s-channel (×10)
- tt
- W+jets
- multijet

\[ e^+\mu \geq 1 \text{ tag} \]

**tqb-\bar{t}t NN output**

- Data
- s-channel (×10)
- tt
- W+jets
- multijet

\[ e^+\mu \geq 1 \text{ tag} \]
Result

- No evidence for single top signal
  - Set 95% CL upper cross section limit
  - Using Bayesian approach and binned likelihood
  - Including bin-by-bin systematics and correlations

**Build binned likelihood from 2-d histograms**
**Result**

**Expected/Observed limit:**

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

- Most sensitive analysis method
- Improvement compared to cut-based analysis due to:
  - Multivariate analysis
  - Binned likelihood fit

---

excellent!
3. Decision Tree Analysis

**s-channel**

- Full dataset
- Electron
  - =1 b-tag
  - ≥2 b-tags
- Muon
  - =1 b-tag
  - ≥2 b-tags

Construct decision trees

2d histograms, Wbb vs tt DT

Form likelihood

Result

---

**t-channel**

- Full dataset
- Electron
  - =1 b-tag
  - ≥2 b-tags
  - ≥1 untagged jet
- Muon
  - =1 b-tag
  - ≥2 b-tags

Construct decision trees

2d histograms, Wbb vs tt DT

Form likelihood

Result
3. Decision Tree Analysis

- For each event, gives probability for an event to be signal
- Widely used in social sciences, recently also in HEP
  - GLAST, Miniboone object ID (see Byron Roe W&C)

- Send each event down the tree
- Each node corresponds to a cut
  - Pass cut (P): right
  - Fail cut (F): left
- A leaf corresponds to a node without branches
  - Defines purity = $N_S/(N_S+N_B)$
- Training: optimize Gini improvement
  - $\text{Gini} = 2 \frac{N_S N_B}{(N_S+N_B)}$
- Output: purity for each event
Result

- No evidence for single top signal
  - Set 95% CL upper cross section limits
  - Same Bayesian likelihood approach as NN analysis

Expected/Observed limit:

\[ \sigma_s < 4.5 / 8.3 \text{ pb} \]

\[ \sigma_t < 6.4 / 8.1 \text{ pb} \]

- Sensitivity comparable to Neural Network analysis
# Summary

<table>
<thead>
<tr>
<th></th>
<th>s-channel</th>
<th>t-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLO cross section</td>
<td>0.88 pb</td>
<td>1.98 pb</td>
</tr>
<tr>
<td>95% CL upper cross section limits [pb]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DØ Run I</td>
<td>17</td>
<td>22</td>
</tr>
<tr>
<td>CDF Run II (160pb⁻¹)</td>
<td>13.6</td>
<td>10.1</td>
</tr>
<tr>
<td><strong>This analysis (230pb⁻¹)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cut-based</td>
<td>10.6</td>
<td>11.3</td>
</tr>
<tr>
<td>DTs &amp; binned likelihood</td>
<td>8.3</td>
<td>8.1</td>
</tr>
<tr>
<td>NNs &amp; binned likelihood</td>
<td>6.4</td>
<td>5</td>
</tr>
</tbody>
</table>
Sensitivity to non-SM Single Top

DØ Run II Preliminary, 230 pb^{-1}

- Standard Model
- Top-flavor (m_x=1 TeV)
- Ztc FCNC (g_{Ztc} = g_Z)
- 4th family (V_{ts} = 0.5)
- Top-pion (m_t=250 GeV)
  - PRD63, 014018 (2001)

Using only muon channel data

Using only electron channel data
Tevatron Single Top Prospects

- Observe single top production in Run II
  - Observe new physics (if it's there)
- Measure $V_{tb}$ to $\sim 10\%$
Future Wtb Studies: LHC

- Observe three single top production modes
- Measure $V_{tb}$ to few %
Conclusions

• DØ Run II single top analysis with 230pb$^{-1}$ completed
  – Detector, trigger, software etc working and understood
  – 95% CL cross section limits of $\sigma_s < 6.4$ pb, $\sigma_t < 5.0$ pb
  – Factor 2 improvement over previous limits
  – Reaching sensitivity to new physics
• Single Top is an exciting opportunity for Run II
  – New and old (SM) physics
• This is just the beginning
  – Expect $\times 3$ dataset by end of year
  – Improve all aspects of the analysis

Dawn of Run II Discoveries
Backup Slides
Ensemble Tests

- Limits from pseudo-experiments
  - Vary count in each bin according to Poisson distribution

![Graph showing expected and observed limits](image)

- Expected limit: 10 pb
- Observed limit: 7 pb
Follow NN approach closely: Same configuration, samples, variables

Decision Tree Output

\[
\text{e+\(\mu\) } \geq 1 \text{ tag}
\]
# Cut-Based Analysis Details

<table>
<thead>
<tr>
<th>Channel</th>
<th> </th>
<th>s-channel Variables</th>
<th>Cuts</th>
<th>Variables</th>
<th>Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electron</strong></td>
<td>=1 Tag</td>
<td>$p_T(\text{jet}_{1\text{tagged}})$</td>
<td>$&gt; 27$ GeV</td>
<td>$H_T(\text{alljets})$</td>
<td>$&gt; 71$ GeV</td>
</tr>
<tr>
<td> </td>
<td> </td>
<td>$M(\text{alljets} - \text{jet}_{1\text{tagged}})$</td>
<td>$&lt; 70$ GeV</td>
<td>$M(\text{alljets})$</td>
<td>$&gt; 57$ GeV</td>
</tr>
<tr>
<td> </td>
<td> </td>
<td>$\sqrt{s}$</td>
<td>$&gt; 196$ GeV</td>
<td>$\sqrt{s}$</td>
<td>$&gt; 203$ GeV</td>
</tr>
<tr>
<td> </td>
<td> </td>
<td>$</td>
<td>175 - M(\text{top}_{tagged})</td>
<td>$</td>
<td>$&lt; 57$ GeV</td>
</tr>
<tr>
<td> </td>
<td>$\geq 2$ Tags</td>
<td>$p_T(\text{jet}_{1\text{tagged}})$</td>
<td>$&gt; 42$ GeV</td>
<td>$p_T(\text{jet}_{1\text{tagged}})$</td>
<td>$&gt; 34$ GeV</td>
</tr>
<tr>
<td> </td>
<td> </td>
<td>$M(\text{alljets} - \text{jet}_{1\text{tagged}})$</td>
<td>$&lt; 98$ GeV</td>
<td>$M(\text{alljets} - \text{jet}_{1\text{tagged}})$</td>
<td>$&lt; 75$ GeV</td>
</tr>
<tr>
<td> </td>
<td> </td>
<td>$H(\text{alljets} - \text{jet}_{1\text{tagged}})$</td>
<td>$&lt; 304$ GeV</td>
<td>$H(\text{alljets} - \text{jet}_{1\text{tagged}})$</td>
<td>$&lt; 504$ GeV</td>
</tr>
<tr>
<td> </td>
<td> </td>
<td>$H(\text{alljets} - \text{jet}_{\text{best}})$</td>
<td>$&lt; 304$ GeV</td>
<td>$H(\text{alljets} - \text{jet}_{\text{best}})$</td>
<td>$&lt; 504$ GeV</td>
</tr>
<tr>
<td><strong>Muon</strong></td>
<td>=1 Tag</td>
<td>$p_T(\text{jet}_{1\text{tagged}})$</td>
<td>$&gt; 33$ GeV</td>
<td>$</td>
<td>175 - M(\text{top}_{tagged})</td>
</tr>
<tr>
<td> </td>
<td> </td>
<td>$M(\text{alljets} - \text{jet}_{1\text{tagged}})$</td>
<td>$&lt; 74$ GeV</td>
<td>$\sqrt{s}$</td>
<td>$&gt; 210$ GeV</td>
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<tr>
<td> </td>
<td> </td>
<td>$H(\text{alljets} - \text{jet}_{1\text{tagged}})$</td>
<td>$&lt; 504$ GeV</td>
<td>$M(\text{alljets})$</td>
<td>$&gt; 70$ GeV</td>
</tr>
<tr>
<td> </td>
<td> </td>
<td>$H(\text{alljets} - \text{jet}_{\text{best}})$</td>
<td>$&lt; 504$ GeV</td>
<td>$H_T(\text{alljets})$</td>
<td>$&gt; 58$ GeV</td>
</tr>
<tr>
<td> </td>
<td>$\geq 2$ Tags</td>
<td>$p_T(\text{jet}_{1\text{tagged}})$</td>
<td>$&gt; 33$ GeV</td>
<td>$</td>
<td>175 - M(\text{top}_{tagged})</td>
</tr>
<tr>
<td> </td>
<td> </td>
<td>$M(\text{alljets} - \text{jet}_{1\text{tagged}})$</td>
<td>$&lt; 74$ GeV</td>
<td> </td>
<td> </td>
</tr>
<tr>
<td> </td>
<td> </td>
<td>$H(\text{alljets} - \text{jet}_{1\text{tagged}})$</td>
<td>$&lt; 504$ GeV</td>
<td> </td>
<td> </td>
</tr>
<tr>
<td> </td>
<td> </td>
<td>$H(\text{alljets} - \text{jet}_{\text{best}})$</td>
<td>$&lt; 504$ GeV</td>
<td> </td>
<td> </td>
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</tbody>
</table>
### Variables:

<table>
<thead>
<tr>
<th>Individual object kinematics</th>
<th>Signal-Background Pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_T(\text{jet}<em>{1</em>{\text{tagged}}}) )</td>
<td>( W_{bb} )</td>
</tr>
<tr>
<td>( p_T(\text{jet}<em>{1</em>{\text{untagged}}}) )</td>
<td></td>
</tr>
<tr>
<td>( p_T(\text{jet}<em>{2</em>{\text{untagged}}}) )</td>
<td></td>
</tr>
<tr>
<td>( p_T(\text{jet}<em>{1</em>{\text{nonbest}}}) )</td>
<td></td>
</tr>
<tr>
<td>( p_T(\text{jet}<em>{2</em>{\text{nonbest}}}) )</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Global event kinematics</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_T(\text{jet}<em>{1,\text{jet}</em>{2}}) )</td>
</tr>
<tr>
<td>( p_T(\text{jet}<em>{1,\text{jet}</em>{2}}) )</td>
</tr>
<tr>
<td>( M(\text{alljets}) )</td>
</tr>
<tr>
<td>( H_T(\text{alljets}) )</td>
</tr>
<tr>
<td>( M(\text{alljets} - \text{jet}<em>{1</em>{\text{tagged}}}) )</td>
</tr>
<tr>
<td>( H(\text{alljets} - \text{jet}<em>{1</em>{\text{tagged}}}) )</td>
</tr>
<tr>
<td>( H_T(\text{alljets} - \text{jet}<em>{1</em>{\text{tagged}}}) )</td>
</tr>
<tr>
<td>( p_T(\text{alljets} - \text{jet}<em>{1</em>{\text{tagged}}}) )</td>
</tr>
<tr>
<td>( M(\text{alljets} - \text{jet}_{\text{best}}) )</td>
</tr>
<tr>
<td>( H(\text{alljets} - \text{jet}_{\text{best}}) )</td>
</tr>
<tr>
<td>( H_T(\text{alljets} - \text{jet}_{\text{best}}) )</td>
</tr>
<tr>
<td>( M(\text{top}<em>{\text{tagged}}) = M(W,\text{jet}</em>{1_{\text{tagged}}}) )</td>
</tr>
<tr>
<td>( M(\text{top}<em>{\text{best}}) = M(W,\text{jet}</em>{\text{best}}) )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Angular variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta R(\text{jet}<em>{1,\text{jet}</em>{2}}) )</td>
</tr>
<tr>
<td>( Q(\text{lepton}) \times \eta(\text{jet}<em>{1</em>{\text{untagged}}}) )</td>
</tr>
<tr>
<td>( \cos(\text{lepton}, Q(\text{lepton}) \times z)<em>{\text{top}</em>{\text{best}}} )</td>
</tr>
<tr>
<td>( \cos(\text{lepton}, \text{jet}<em>{1</em>{\text{untagged}}} \text{top}_{\text{tagged}}) )</td>
</tr>
<tr>
<td>( \cos(\text{alljets}, \text{jet}<em>{1</em>{\text{tagged}}} \text{alljets}) )</td>
</tr>
<tr>
<td>( \cos(\text{alljets}, \text{jet}_{\text{nonbest}} \text{alljets}) )</td>
</tr>
</tbody>
</table>
Maximize Sensitivity: Final State Reconstruction

jet → lepton → t quark → W → b quark, lepton, neutrino, \( \bar{b} \) quark
Final State Reconstruction

- Reconstruct $W$ from lepton and $E_T$
- Reconstruct top quark from $W$ and leading b-tagged jet
- Reconstruct light quark as leading untagged jet
Final State Reconstruction

- Reconstruct $W$ from lepton and $\not{E_T}$
- Reconstruct top quark from $W$ and one of the jets using Best Jet Algorithm:
  - Pick jet for which $M(W,\text{jet})$ is closest to true top mass (175GeV)
- Reconstruct $\bar{b}$-quark as leading non-best jet
Tevatron delivered luminosity is exceeding “baseline” and “design” projections
Mis-reconstructed Events?

- Cosmic rays (muons)
- Mis-reconstructed vertex
  - Affects missing transverse energy
- Mis-reconstructed jets
  - fake electron
  - fake isolated muon

→ Primary vertex constraints
  - Primary vertex with ≥3 tracks
  - Lepton is required to originate from primary vertex

→ Triangle Cuts
Event Yield

\[ Y = L \times \sigma \times Br \times Acc(cuts) \times Eff(b-tag) \]

Acc(cuts)  Eff(b-tag)
s-channel:  23%  54%
t-channel:  22%  38%

Event Yields

<table>
<thead>
<tr>
<th></th>
<th>s-channel</th>
<th>t-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-channel signal</td>
<td>5.5</td>
<td>4.7</td>
</tr>
<tr>
<td>t-channel signal</td>
<td>8.6</td>
<td>8.5</td>
</tr>
<tr>
<td>W+jets</td>
<td>169</td>
<td>164</td>
</tr>
<tr>
<td>top pairs</td>
<td>78</td>
<td>76</td>
</tr>
<tr>
<td>multijet</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>Background sum</td>
<td>287±44</td>
<td>276±41</td>
</tr>
<tr>
<td>Observed</td>
<td>283</td>
<td>271</td>
</tr>
</tbody>
</table>
Signal Modeling

- CompHEP-based generator
  - Includes O($\alpha_s$) diagrams → reproduces NLO distributions
  - Including top quark spin correlations
- Normalize to NLO cross sections
- t-channel: match 2→3 and 2→2 processes
Single Top – Expectation

- Predictions for Run II were to be sensitive to single top production with $\sim 500 \text{pb}^{-1}$ – *Where is it?*
  - Observation with $2 \text{fb}^{-1}$
  - Starting to be interesting much sooner
- We have recorded $>400 \text{pb}$ at DØ already
  - Observation soon?

Stelzer, Sullivan, Willenbrock, PRD58 (98)
Single Top – Expectation vs Reality

- Predictions for Run II were to be sensitive to single top production with \( \sim 500 \text{pb}^{-1} \) – Where is it?

  - Detector performance not (yet) as good as expected
    - \( b \)-tagging \( \sim 45\% \) per jet
    - Trigger, ID <100\%
    - Jet resolution not (yet) as good as expected
  - \( W+jets \) background larger than expected
    - NLO calculations: LO\( \times 1.5 \)
  - Top mass, gluon PDF, ...

Many effects, all in the wrong direction!
Level 2 Trigger

- Design: reduce 6kHz L1 accept rate to 1kHz
- Both custom hardware/firmware and commodity-based components
  - Dataflow from L1 and detector systems in custom systems
  - Algorithms in software running on commodity-based system
- Build Physics objects
  - Jets and EM objects are built from L1 calorimeter towers
  - Central tracks are built from L1 track trigger tracks
    - Now also Secondary Vertex Tagging
    - Muons are reconstructed from raw muon chamber hits
- Combine objects from different detector systems
  - Track matching to muons, electrons, or jets
- Allow for 128 different combinations
  - 1-1 matching of bits between L1 and L2
Trigger Level 1/Level 2 Dataflow

Detector -> L1 Trigger -> L2 Pre-Processors -> L2 Global

L1 Muon -> L2 Muon
L1 Calorimeter -> L2 Calorimeter
L1 Tracking -> L2 Tracking
Silicon Track Trigger

Trigger Framework, coordinates L1 trigger and L2 trigger and detector readout
Trigger Hardware: Custom-built vs Commodity

- **Trigger Level 1/Level 2 relies heavily on custom-built hardware/firmware**
  - Cards designed/built mostly by Engineers – feedback from Physicists
  - Systems commissioned mostly by Physicists – help from Engineers
  - Firmware written by Engineers/Physicists
    - Most Firmware tasks too complex to be written by Physicists alone

- **Trigger Level 2/Level 3 relies heavily on commodity systems**
  - Off-the-shelf products (computers, interfaces/cables)
  - Interfaced to custom-built cards
  - Software written by Physicists
Top Quark Spin

- Top Quark decays before it hadronizes
  - Full spin information is preserved in the decay products
  - Electroweak charged current interaction is left-handed

- Top polarization in the top rest frame:

  Lepton moves along top spin direction
  Angle between light quark and lepton:

  ![Diagram with arrows indicating top quark, b-quark, lepton, and W boson with annotated helicities and directions]
Quark Charged Current Interactions

- Observed and studied in particle decays
  
- Direct production of real $W$ boson

- Virtual corrections to electroweak processes
Tevatron Top Physics

- Top Pair Production at a Proton-Antiproton collider
  - Production cross section
  - Top mass
    - Implications for Standard Model Higgs
  - Look for new Physics
    - In top production and decay
  - Many more
Relative Contributions to NLO rate including Top Production and Decay

**s-channel**
- NLO rate: 0.86pb
- Born level: 65%
- Initial state: 22%
- Final state: 11.5%
- Decay: 1.2%

**t-channel**
- NLO rate: 1.9pb
- Born level: 105%
- Light quark: 13%
- Heavy quark: -11%
- Decay: -7%

Cao, RS, Yuan hep-ph/0409040

- **O(as) corrections large for the s-channel**
  - Only small rate correction for the t-channel
- **Decay correction is 2nd order effect, top mass and top width**

Reinhard Schwienhorst, Michigan State University
Kinematic effect of $O(\alpha_s)$ Corrections

- After simple parton level selection cuts:
  - 1 lepton, $p_T>15\text{GeV}$, $|\eta|<2$, missing $E_T>15\text{GeV}$
  - $\geq2$ jets, $p_T>15\text{GeV}$, $|\eta|<3$

- Example: s-channel jet multiplicity

![Diagram showing jet multiplicity fraction and cross section](image)
Single Top t-channel at NLO

- After simple cuts
  - Large number of 3-jet events
  - Depends strongly on jet $p_T$ and $\eta$ cuts

\[ \sigma \text{ [fb]} \]

Jet multiplicity

fraction [%]

- $|\eta_{\text{jet}}| < 3$
- $|\eta_{\text{jet}}| < 2$
- $|\eta_{\text{jet}}| < 1$

Jet multiplicity fraction

Jet multiplicity

fraction [%]

- $N_{\text{jets}} = 2$
- $N_{\text{jets}} = 3$

Jet multiplicity fraction

Jet multiplicity

fraction [%]

- $N_{\text{jets}} = 2$
- $N_{\text{jets}} = 3$

Jet multiplicity fraction

Jet multiplicity

fraction [%]
Tevatron Single Top Quark Production

s-channel

\[ q \to W \to t \to b \]

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

\[ \nu \to l \]

\[ \sigma \text{ [fb/GeV]} \]

\[ E_T \text{ [GeV]} \]

\[ \eta \]

Plots showing the distribution of b quark jets, b jets, leptons, and \( E_T \) in Tevatron single top quark production.
Tevatron Single Top Quark Production

t-channel

\[
\begin{align*}
q & \rightarrow W^{-} t b \\
q' & \rightarrow W^{+} t b \\
W & \rightarrow l \nu
\end{align*}
\]