Observation of single top quark production at DØ

Reinhard Schwienhorst

CPPM Seminar, June 2009
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**

Higgs boson $\rightarrow$ W boson

**Fermions acquire mass through Higgs coupling**

Higgs boson $\rightarrow$ fermion
Top quark

Coupling strength
~1

Higgs boson

top quark
Top quark

Higgs boson

Coupling strength

~1

King of the Fermions

top quark
Higgs mass estimate

- Higgs boson
- Top quark
- W boson

Graph showing the relationship between the Higgs mass and the top quark mass, with the W boson mass as a parameter.
Key to electroweak symmetry breaking

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

s-channel

$q\rightarrow Wt$  $\bar{q}'\rightarrow \bar{b}t$

Tevatron:

$\sigma_{tot} = 3 \text{ pb}$

LHC:

$\sigma_{tot} = 326 \text{ pb}$
New physics

s-channel

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

New heavy boson

Flavor Changing Neutral Current

Modified Wtb coupling

Modified Wtb coupling

Associated production

\[ g \quad b \quad t \quad W \]
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:

$\begin{align*}
\text{s-channel} & \quad 1.12 \text{ pb (±5%)} \\
\text{t-channel} & \quad 2.34 \text{ pb (±6%)}
\end{align*}$

$(m_{top} = 170 \text{ GeV})$
Experimental setup:

Fermilab Tevatron in Run II

Proton-antiproton collider
CM energy 1.96 TeV

→ Energy frontier

Instantaneous luminosity > 350E30 cm⁻² s⁻¹

→ Luminosity frontier
Fermilab single top history

Publication history

Run I

- Search: PLB 517, 282 (2001)
- Search: PLB 622, 265 (2005)
- Search: PRD 75, 092007 (2007)
- W*: PRL 100, 211802 (2007)
- Evidence: PRD 78, 012005 (2008)
- W*: PRL 102, 092002 (2009)
- H*: (PRL) arXiv:0807.0859
- Observation: (PRL) arXiv:0903.0850

Run II

- Search: PRD 71, 012005 (2005)
- FCNC: (PRL) arXiv:0812.3400
- W*: (PRL) arXiv:0902.3276
- Observation: (PRL) arXiv:0903.0885

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><strong>December 2006</strong> DØ (0.9 fb$^{-1}$)</td>
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<td>PRL 98, 181802 (2007)</td>
</tr>
<tr>
<td>4.7 ± 1.3 pb</td>
<td>2.3 σ</td>
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<td>$V_{tb} &gt; 0.68$ at 95% CL</td>
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<tr>
<td><strong>September 2008</strong> CDF (2.2 fb$^{-1}$)</td>
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<td>PRL 101, 252001 (2008)</td>
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<td>2.2 ± 0.7 pb</td>
<td>4.9 σ</td>
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</table>

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Fermilab Tevatron
Run II Integrated Luminosity

Delivered 6.11 fb$^{-1}$
Recorded 5.37 fb$^{-1}$

2.3 fb$^{-1}$
Observation Analysis

0.9 fb$^{-1}$
Evidence Analysis

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Single top quark event signature

b-quark jet or light quark jet

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

Missing transverse energy
Single top quark event signature

s-channel

$W^\pm \rightarrow q'\bar{b}$

$t$-channel

$W^\pm \rightarrow q\bar{t}$

$\nu_l$
Background processes

- Total inelastic, QCD multijets: $10^{14}$
- Bottom quark pairs: $10^{10}$
- $W$ bosons: $10^8$
- $Z$ bosons: $10^6$
- Top quark pairs: $10^4$
- Single top quarks: $10^2$

Production cross-section (femtobarns)

(new physics)
Analysis outline

Trigger selection

S/B = 1/10^9

Single top event kinematics

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

b-quark tagging

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

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

$D\bar{O}$ 2.3 fb$^{-1}$

- Yield [Events/10 GeV]
- Yield [Events/20 GeV]
- Cos(LightQuark Jet, Lepton)$_{b\text{taggedtop}}$
- Jet2 $\eta$ Width
- $m_{\text{sig}}^{\text{top}}$ [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
- $M_t > 160$
  - P
  - More cuts

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

- **$H_t > 312$**
  - **Pass**
  - $M_t > 160$
    - **P**
      - **More cuts**
    - **More cuts**
  - **Fail**
    - $\eta > 1.2$
      - **P**
      - **More cuts**

- **Student thesis sample**
- **2nd student thesis sample**
Decision tree

- Cuts produce branches
- Terminal leaf: calculate purity = $N_S/(N_S+N_B)$ 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
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

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Matrix element analysis

Parton level matrix elements

Signal and background probability for each event is calculated from differential cross section

\[ P_{\text{Signal}}(\vec{x}) = \frac{1}{\sigma_S} d\sigma_S(\vec{x}) \quad \sigma_S = \int d\sigma_S(\vec{x}) \]

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

\[ L = \frac{P(\text{sig})}{P(\text{sig}) + P(\text{bkg})} \]
Matrix element distributions

Cross checks

Full data sample
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
Is there a signal?

**S/B Ratio**

[Graph showing the signal-to-background ratio with a peak at 2.0 for \( DØ \ 2.3 \text{ fb}^{-1} \)]

**Cumulative Events**

- Data
- Signal+Background
- Background

\( \sigma(tb + tqb) = 3.94 \text{ pb} \)

**Yield**

- \( DØ \ 2.3 \text{ fb}^{-1} \)
  - all channels
  - BNNcomb > 0.8

- \( DØ \ 2.3 \text{ fb}^{-1} \)
  - all channels
  - BNNcomb > 0.9

- \( DØ \ 2.3 \text{ fb}^{-1} \)
  - all channels
  - BNNcomb > 0.95

Graphs showing the yield for different cosines of light quark jet-lepton with btaggedtop.
Kinematics in the signal region

High Signal Region – $Q \times \eta$

High Signal Region – $m_{\text{top}}$

DØ 2.3 fb$^{-1}$

Ranked Combination Output > 0.92

DØ 2.3 fb$^{-1}$

Ranked Combination Output > 0.92

Yield [Events/0.8]

$Q(\text{lepton}) \times \eta(\text{light-quark jet})$

Yield [Events/30GeV]

Top Quark Mass [GeV]
# Systematic uncertainties

## Systematic Uncertainties

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

<table>
<thead>
<tr>
<th>$DØ$</th>
<th>2.3 fb$^{-1}$</th>
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</table>

### Larger terms

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>(2.1–7.0)%</th>
<th>(1-tag) (9.0–11.4)%</th>
<th>(1.1–13.1)%</th>
<th>(signal) (0.1–2.1)%</th>
<th>(bkgd)</th>
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<tbody>
<tr>
<td>$b$-ID tag-rate functions (includes shape variations)</td>
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<td>Jet energy scale (includes shape variations)</td>
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<td>Integrated luminosity</td>
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### Smaller terms

<table>
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<th>Source of Uncertainty</th>
<th>(0.5–16.0)%</th>
<th>(0.7–4.0)%</th>
<th>1.5%</th>
<th>13.7%</th>
<th>1.0%</th>
<th>1.0%</th>
<th>3.0%</th>
<th>5.8%</th>
<th>(1.8–3.9)%</th>
<th>(30–54)%</th>
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<th>shape only</th>
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<td>Alpgen $W+\text{jets}$ shape corrections</td>
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Shape systematics

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

• Bayesian statistical analysis
  \[ P(s|D) = P(D|s)\times P(s) \]
  – Posterior gives measured cross section and uncertainty

\[ \sigma_{\text{measured}} = 3.94 \pm 0.88 \text{ pb} \]
\[ \sigma_{\text{expected}} = 3.50^{+0.99}_{-0.77} \text{ pb} \]
Significance

- Significance (p-value) and linearity and many tests through extensive ensemble testing
  - Ensembles of pseudo-data at various signal cross sections

**BNN Combination**

- Slope = 1.017 ± 0.006
- Intercept = −0.009 ± 0.032

**DØ Combination**

- 67.8M pseudo-datasets (background-only)
- 17 above measured cross section
- p-value = 2.5 × 10^{-7}
- Observed significance = 5.03 σ
- $\sigma^{\text{meas}} = 3.94 \text{ pb}$
## DØ 2.3 fb⁻¹ Single Top Results

<table>
<thead>
<tr>
<th>Analysis Method</th>
<th>Single Top Cross Section</th>
<th>Significance</th>
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<tbody>
<tr>
<td></td>
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<td>Expected</td>
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<tr>
<td>Boosted Decision Trees</td>
<td>3.74 ±0.95^-0.79 pb</td>
<td>4.3 σ</td>
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<tr>
<td>Bayesian Neural Networks</td>
<td>4.70 ±1.18^-0.93 pb</td>
<td>4.1 σ</td>
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<tr>
<td>Matrix Elements</td>
<td>4.30 ±0.99^-1.20 pb</td>
<td>4.1 σ</td>
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<tr>
<td>Combination</td>
<td>3.94 ±0.88 pb</td>
<td>4.5 σ</td>
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</table>

### March 2009

- Decision Trees: 3.74 ±0.95^-0.79 pb
- Bayesian NNs: 4.70 ±1.18^-0.93 pb
- Matrix Elements: 4.30 ±0.99^-1.20 pb
- BLUE Combination: 4.16 ±0.84 pb
- BNN Combination: 3.94 ±0.88 pb

N. Kidonakis, PRD 74, 114012 (2006)  m_{top} = 170 GeV

ArXiv:0903.0850,
Submitted to PRL
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 $3.2 \text{ fb}^{-1}$
- Top mass $175 \text{GeV}$, 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>
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<td>DØ (2.3 fb$^{-1}$)</td>
<td>arXiv:0903.0850 (m$_{top}$ = 170 GeV)</td>
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<td><strong>Expected</strong></td>
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<td><strong>March 2009</strong></td>
<td>CDF (3.2 fb$^{-1}$)</td>
<td>arXiv:0903.0885 (m$_{top}$ = 175 GeV)</td>
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<td><strong>Expected</strong></td>
<td>2.3 ±0.5 pb</td>
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<td>&gt;5.9 σ</td>
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<tr>
<td><strong>Observed</strong></td>
<td>5.0 σ</td>
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</tbody>
</table>
Searches for new physics in single top

• Searches for new heavy boson W':

  \[ W' \]

  - CDF prelim result, 1.9 fb\(^{-1}\):
    M > 800 GeV and M > 825 GeV

• Similar: DØ Susy H\(^+\) search

• Flavor-changing neutral currents:

  \[ q \rightarrow q' \]
  \[ t \rightarrow b \]
  \[ u \text{ quark or } c \text{ quark} \]
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 ($f^R_2$)

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

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

| $f^R_1$ | 2
|-------|----------------------|
| $f^L_2$ | 2

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

- Observe three single top production modes separately
  - t-channel: easy 😊  s-channel and assoc. prod: harder 😞
- Observe new physics \((\text{if it can be seen})\)
- Measure \(V_{tb}\) to few %
- Study spin correlations
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


Diagram showing cross sections for different processes with various parameters.
Conclusions/Outlook

• Both Tevatron experiments have observed single top quark production at the 5 σ level

• Tevatron dataset continues to increase
  • Already over 5 fb⁻¹ recorded
  • Separate s-channel from t-channel
  • Continue to look for new physics

• LHC:
  • Precision measurements in single top
  • Look for new physics in single top
Additional Material
• Backgrounds are similar to Tevatron, yet different
  – W+jets less important
  – $t\bar{t}$ 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
Top quark electroweak charged current interaction

top quark decay
### Discriminating Variables

- 89 variables total, 20 to 50 in each channel

#### Best Variables to Separate Single Top from \( W + \text{Jets} \)

<table>
<thead>
<tr>
<th></th>
<th>( \hat{E}_T )</th>
<th>( p_T(\text{jet2}) )</th>
<th>( p_T^{\text{rel}}(\text{jet1}, \text{tag-\mu}) )</th>
<th>( E(\text{light1}) )</th>
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</thead>
<tbody>
<tr>
<td>Object kinematics</td>
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<tr>
<td>Event kinematics</td>
<td>( M(\text{jet1}, \text{jet2}) )</td>
<td>( M_T(W) )</td>
<td>( H_T(\text{lepton}, \hat{E}_T, \text{jet1}, \text{jet2}) )</td>
<td>( H_T(\text{jet1}, \text{jet2}) )</td>
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<tr>
<td>Jet reconstruction</td>
<td>( \text{Width}_\phi(\text{jet2}) )</td>
<td>( \text{Width}_\eta(\text{jet2}) )</td>
<td>( \Delta M_{\text{top}} )</td>
<td>( M_{\text{top}}(W, \text{tag1}, S2) )</td>
</tr>
<tr>
<td>Top quark reconstruction</td>
<td>( M_{\text{top}}(W, \text{tag1}) )</td>
<td>( \Delta M_{\text{top}} )</td>
<td>( M_{\text{top}}(W, \text{tag1}, S2) )</td>
<td></td>
</tr>
<tr>
<td>Angular correlations</td>
<td>( \cos(\text{light1}, \text{lepton})_{\text{btaggedtop}} )</td>
<td>( \Delta \phi(\text{lepton}, \hat{E}_T) )</td>
<td>( Q(\text{lepton}) \times \eta(\text{light1}) )</td>
<td></td>
</tr>
</tbody>
</table>

#### Best Variables to Separate Single Top from \( \text{Top Pairs} \)

<table>
<thead>
<tr>
<th></th>
<th>( p_T(\text{notbest2}) )</th>
<th>( p_T(\text{jet4}) )</th>
<th>( p_T(\text{light2}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object kinematics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Event kinematics</td>
<td>( M(\text{alljets} - \text{tag1}) )</td>
<td>( \text{Centrality}(\text{alljets}) )</td>
<td>( M(\text{alljets} - \text{best1}) )</td>
</tr>
<tr>
<td>Jet reconstruction</td>
<td>( \text{Width}_\eta(\text{jet4}) )</td>
<td>( \text{Width}_\phi(\text{jet4}) )</td>
<td>( \text{Width}_\phi(\text{jet2}) )</td>
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<tr>
<td>Top quark reconstruction</td>
<td>( \cos(\text{lepton}<em>{\text{btaggedtop}}, \text{btaggedtop}</em>{\text{CMframe}}) )</td>
<td>( Q(\text{lepton}) \times \eta(\text{light1}) )</td>
<td>( \Delta R(\text{jet1}, \text{jet2}) )</td>
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# Discriminating Variables

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<tr>
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<th>Jet Reconstruction</th>
<th>Angular Correlations</th>
<th>Top Quark Reconstruction</th>
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<tr>
<td>$p_T$ (lepton)</td>
<td>$\not{p}_T$</td>
<td>$E_T$</td>
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<td>$M(W,jet1)$ (leading jet top mass)</td>
</tr>
<tr>
<td>$p_T$ (jet1)</td>
<td></td>
<td>$H_T$</td>
<td>Width$_{\eta}$ (jet2)</td>
<td>$M(W,jet1,S2)$ (with second neutrino solution)</td>
</tr>
<tr>
<td>$p_T$ (jet2)</td>
<td></td>
<td>$H_T$</td>
<td>Width$_{\eta}$ (jet4)</td>
<td>$M(W,jet2)$</td>
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<tr>
<td>$p_T$ (jet3)</td>
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<td>$H_T$</td>
<td>Width$_{\eta}$ (tag1)</td>
<td>$M(W,jet2,S2)$</td>
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<tr>
<td>$p_T$ (jet4)</td>
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<td></td>
<td>$H_T$</td>
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</tr>
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Prospects for s and t separately

Points with systematics,
Lines without systematics

2005
2006
2009

Projection from 2005,
no systematics

Significance

Integrated Luminosity [fb^{-1}]

2005
2006
2009

t-channel
s-channel
Multivariate likelihood function

- Likelihood functions built from 7 variables (10 for 2-tags)
  - Kinematic variables
  - b-tag NN output
  - kinematic solver
    - Assign which jet comes from top decay
  - t-channel ME
    - No transfer functions, no integration
Multivariate likelihood function

- Likelihood functions built from 7 variables (10 for 2-tags)

Measured cross section:

\[ \sigma(s+t) = 1.8^{+0.9}_{-0.8} \text{ pb} \]

Expected/observed significance:

\[ 3.4\sigma / 2.0\sigma \]
Neural Networks

• 4 separate s+t networks
  – By jet and b-tag multiplicity
• Built from 10-14 variables each
  – Kinematic variables
  – angular correlations
  – B-tag NN output
Neural Network Result

Expected/observed significance:

$4.4\sigma / 3.2\sigma$

Measured cross section:

$\sigma( s+t) = 2.0^{+0.9}_{-0.8}\text{ pb}$
Matrix element

- Analyze 2-jet and 3-jet events
  - Include ttbar matrix element for both 2-jet and 3-jet events
  - Include b-tag NN as weight in likelihood ratio

Measured cross section:
\( \sigma(s+t) = 2.2^{+0.8}_{-0.7} \text{ pb} \)

Expected/observed significance:
\( 4.5\sigma / 3.4\sigma \)
CDF combination

- NEAT: NeuroEvolution of Augmenting Topologies
  - Optimization procedure chooses network structure and weights
  - And final binning
  - Train a few to also find optimum when including systematics

$\sigma_{\text{Single Top}} = 2.2^{+0.7}_{-0.7} \text{ pb}$

Expected/observed significance: $5.1\sigma / 3.7\sigma$
Other CDF analyses

• Boosted decision trees
  – Not in combination

• Separate s-channel search
  – $\sigma < 2.77 \text{ pb (95\% CL)}$

• $|V_{tb}|$ measurement using NEAT output

Measured cross section:

\[ \sigma(s+t) = 1.9^{+0.8}_{-0.7} \text{ pb} \]
• **Update to 0.9 fb$^{-1}$ analysis** (3.4 $\sigma$, *PRL* 98, 181802 (2007))
  – Improved Bayesian Neural Network analysis
  – Improved Matrix Element analysis
Recent improvements

• Improved W+jets modeling
  – Important background for top pairs and single top
  – Alpgen+Pythia with MLM matching
  – Normalize total count and HF fraction to data

• Fully reprocessed dataset
  – New calibrations, lower thresholds, ...

• Neural network
  b-quark tagging

![Graph showing b-tag efficiency for 0.5% mistag rate](image)
Multivariate methods

**Input:**
discriminating variables

**Method:**
multivariate analysis

**Output:**
signal likelihood

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

---

Cut-Based

Boosted decision trees

Neural networks

Bayesian neural networks

Decision trees

Likelihood

Matrix Elements

\[ \frac{d^2 \sigma_{pp \rightarrow \ell \ell}}{4 \pi} = \frac{2}{m_{b_2}^2} \times d \Phi_n \]
Single top event signature

- Basic event signature (e or $\mu$)
  - Single lepton trigger or lepton+jets trigger
  - One high-\ET leptons
    - $\ET > 20$ GeV or 15 GeV
  - Missing transverse energy
    - Missing $\ET > 25$ GeV or 15 GeV
  - 2-3 high-\ET jets (2-4 jets)
    - $\ET > 15$ GeV
  - At least one b-tag

Expect ~ 50 signal events per fb$^{-1}$

- After b-tagging
  - S:B ~ 1:20
Decision Trees

- Send each event down the tree
- Each node corresponds to a cut
  - Divide sample in two: Pass↔Fail
- A leaf corresponds to a node without branches
  - Defines purity = $N_S/(N_S+N_B)$ from MC sample
- Training: optimize Gini improvement
  - Gini = $2 \frac{N_S N_B}{(N_S + N_B)}$
- Output: purity for each event

- Boosting: average over many trees (~100)
  - Iterative tree building: train each new tree focusing more and more on misclassified events
Bayesian neural networks

• **NN with three layers**
  – 24 input nodes (variables)
  – 40 hidden nodes
  – Each node and each connection has a weight

• **Bayesian Idea:**
  – Rather than finding one value for each weight, use many values
  – Determine the posterior probability for each weight
  – Sample from the posterior

• In this case, 100 individual neural networks
  – Each network gets a weight based on training performance
Matrix Elements

• Calculate signal discriminant directly for each event

\[ D_s(\vec{x}) = P(S|\vec{x}) = \frac{P_{\text{Signal}}(\vec{x})}{P_{\text{Signal}}(\vec{x}) + P_{\text{Background}}(\vec{x})} \]

• Signal/Background probabilities are calculated from the differential cross section

\[ P_{\text{Signal}}(\vec{x}) = \frac{1}{\sigma_s} d\sigma_s(\vec{x}) \quad \sigma_s = \int d\sigma_s(\vec{x}) \]

• Calculate differential cross section for each event based on Feynman diagram and event kinematics

• Integrate over ME and measured momenta
Ensemble Tests

- Draw ~1,000,000 “pseudo-data” sets of events from the signal+background MC
  - Bootstrap with replacement
  - Several different signal XS values
- Repeat full statistical analysis and measure $\sigma$ for each

**SM Ensemble**

- **tbqtb**
  - Entries: 1000
  - Mean: 2.922
  - RMS: 1.513

**e+\mu-channel**

- Full systematics

**DT analysis**

- $\chi^2$/ndof = 4.89/4
- Slope = 1.07 ± 0.03
- Intercept = -0.12 ± 0.10
Sensitivity, p-value

- P-value: fraction of 0-signal ensembles measuring $\sigma$ above observed value
- Expected p-value: fraction of 0-signal ensembles measuring $\sigma$ above SM value
- Expected p-values:
  
  **Decision Trees**
  - p-value 1.9%

  **Matrix Elements**
  - p-value 3.7%

  **Bayesian NN**
  - p-value 9.7%
Test model on data

- **W+jets sample**
  
  = 2 jets, low event energy
  
  \[ (H_T (l,j) < 175 \text{ GeV}) \]

- **Top quark pairs**
  
  = 4 jets, high event energy
  
  \[ (H_T (l,j) > 300 \text{ GeV}) \]