Measurement of Single-Top Quark Production at the Tevatron

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on behalf of the CDF and D0 Collaborations

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Motivation: Production Rate is Proportional to $|V_{tb}|^2$

$$\sigma_t = (1.98 \pm 0.25) |V_{tb}|^2 \text{ pb}$$

$$\sigma_s = (0.88 \pm 0.11) |V_{tb}|^2 \text{ pb}$$

Compatible Results;

Associated production
(small, $\sim 0.3$ pb)
-- neglected here.
Appears in W+3-jet events.
Physics Motivations for Seeking Single Top

• Interesting signal -- $s$ and $t$-channel rates are differently sensitive to new interactions

• Single top quarks are $\sim 100\%$ polarized in the SM
  - Can test this with angular distributions of decay products

• A check of the $b$ PDF of the proton

• Exotic couplings -- see also L. Li’s talk

Technical Motivations for Seeking Single Top

- Single top is a background to \( WH \rightarrow l\nu bb \)
  Measurements are preferable to MC predictions

- Its backgrounds are backgrounds to \( WH \rightarrow l\nu bb \)
  (\( W+\)jets, ttbar, QCD, dibosons)

- We need to observe it on our way to observing a light Higgs boson
  - It has a larger cross section than \( WH \rightarrow l\nu bb \)
    (order of magnitude)
  - The kinematic signature is more distinct than \( WH \rightarrow l\nu bb \)
  - It’s a great testing ground for making a discovery using advanced signal/background separation techniques
General Strategy for Measuring Single Top Production

- Model signal with a Monte Carlo which reproduces NLO expectations
- Model Backgrounds with Pythia, ALPGEN, and data control samples
- Select events with basic features expected of single top events
  - A high-$P_T$ lepton (20 GeV or more (CDF), 15 GeV or more (D0))
  - Large Missing-$E_T$ (25 GeV or more (CDF), 15 GeV or more (D0))
  - Two or more jets (typically 20 GeV or more) -- Use high-$\eta$ jets!
  - One or more $b$-tags
  - Veto $Z \rightarrow$ leptons, cosmics, conversions
- Train multivariate discriminants to separate signals from backgrounds
  - Train separately for each number of jets and tags
- Fit Templates to data and extract cross sections and significances
- Check! Check! and Re-Check!
An Event that Looks Like Single Top

Run: 211883 Event: 1911511
CEM Charge: -1, Eta=-0.72
MET=41.85, MetPhi=-0.83
Jet1: Et=46.7, Eta=0.61, Tag=1
Jet2: Et=16.6, Eta=-2.91, Tag=0
QxEta = 2.91

Track Pt > 1 GeV
Tower Et > 3 GeV
Formidable Backgrounds!

- Tagged W+2-jet events
- Z+jets/Diboson
- Wbb
- tt
- Non-W
- W+Light-Flavor jets
- Wc
- Wcc
- Single Top Cross Section Measurements, Thomas Junk, ICHEP 2008
Backgrounds and signal in 2.7 fb\(^{-1}\) by number of jets

Predicted Rates in 0.9 fb$^{-1}$

- $W$+jets simulated with ALPGEN+Pythia, scaled to data.
  - $Wbb, Wcc$ scaled by $\alpha = 1.5 \pm 0.45$ after measurement in control samples
- Non-$W$ fraction estimated using loose lepton and low Missing-$E_T$ control samples -- data based models for kinematics
- top pairs modeled with MC

<table>
<thead>
<tr>
<th>Source</th>
<th>2 jets</th>
<th>3 jets</th>
<th>4 jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tb$</td>
<td>16 ± 3</td>
<td>8 ± 2</td>
<td>2 ± 1</td>
</tr>
<tr>
<td>$tqb$</td>
<td>20 ± 4</td>
<td>12 ± 3</td>
<td>4 ± 1</td>
</tr>
<tr>
<td>$\bar{t}t \rightarrow ll$</td>
<td>39 ± 9</td>
<td>32 ± 7</td>
<td>11 ± 3</td>
</tr>
<tr>
<td>$\bar{t}t \rightarrow l+\text{jets}$</td>
<td>20 ± 5</td>
<td>103 ± 25</td>
<td>143 ± 33</td>
</tr>
<tr>
<td>$W+b\bar{b}$</td>
<td>261 ± 55</td>
<td>120 ± 24</td>
<td>35 ± 7</td>
</tr>
<tr>
<td>$W+c\bar{c}$</td>
<td>151 ± 31</td>
<td>85 ± 17</td>
<td>23 ± 5</td>
</tr>
<tr>
<td>$W+jj$</td>
<td>119 ± 25</td>
<td>43 ± 9</td>
<td>12 ± 2</td>
</tr>
<tr>
<td>Multijets</td>
<td>95 ± 19</td>
<td>77 ± 15</td>
<td>29 ± 6</td>
</tr>
<tr>
<td>Total background</td>
<td>686 ± 41</td>
<td>460 ± 39</td>
<td>253 ± 38</td>
</tr>
<tr>
<td>Data</td>
<td>697</td>
<td>455</td>
<td>246</td>
</tr>
</tbody>
</table>
### SM Rate Estimates in 2.7 fb$^{-1}$

**CDF Run II Preliminary**  
Predicted 2-jet event yield with 2.7 fb$^{-1}$

<table>
<thead>
<tr>
<th>Source</th>
<th>s-channel</th>
<th>t-channel</th>
<th>Single top</th>
<th>$tt$</th>
<th>Diboson</th>
<th>$Z + jets$</th>
<th>$W + bottom$</th>
<th>$W + charm$</th>
<th>$W + light$</th>
<th>Non-$W$</th>
<th>Total background</th>
<th>Total prediction</th>
<th>Observed</th>
</tr>
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<tbody>
<tr>
<td>Observed</td>
<td>1874</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**CDF Run II Preliminary**  
Predicted 3-jet event yield with 2.7 fb$^{-1}$

<table>
<thead>
<tr>
<th>Source</th>
<th>s-channel</th>
<th>t-channel</th>
<th>Single top</th>
<th>$tt$</th>
<th>Diboson</th>
<th>$Z + jets$</th>
<th>$W + bottom$</th>
<th>$W + charm$</th>
<th>$W + light$</th>
<th>Non-$W$</th>
<th>Total background</th>
<th>Total prediction</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>902</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
B-Tag Neural Network

~Half of all tagged jets in the W+2jet sample are not b-jets!

- b-tag NN Operates on vertex-tagged jets to separate out charm and light-flavored jets
- 25 input variables including
  - # tracks with $d_0$ significance $> 3\sigma$
  - Individual track $d_0$ significance
  - vertex mass
  - lepton $p_T$ (if any)
  - $L_{xy}$ significance and raw $L_{xy}$
Other Important Discriminating Variables

Invariant mass of top decay products. Let’s bump-hunt!

\[ m_{jj} \] -- Distinguishes against W+jets
Checking Control Distributions

Transverse mass of W candidate

\( Q_\text{lepton} \eta \text{ light-jet} \) and \( H_T = \text{sum of all } E_T \text{ in event} \)
Multivariate Techniques 1: Boosted Decision Trees

Best-fit signal shown: 4.9 pb
Boosted Decision Tree Discriminants

CDF Run II Preliminary, L=2.7 fb$^{-1}$

KS: 95.3%
Chi2/DoF: 29.6/39: 84.8%

KS: 17.1%
Chi2/DoF: 19.2/20: 48.6%

KS: 27.9%
Chi2/DoF: 19.3/25: 76.4%

KS: 15.2%
Chi2/DoF: 22.5/14: 5.4%
Technique 2: Matrix Elements

Goal -- obtain relative probabilities of each event to come from each process. Same phase space, different matrix elements

Phase space factor:
Integrate over unknown or poorly measured quantities

Parton distribution functions

\[
P(p^\mu_l, p^\mu_{j1}, p^\mu_{j2}) = \frac{1}{O} \int d\rho_{j1} d\rho_{j2} dp_\nu \sum_{\text{comb}} \phi_4 \left| M(p^\mu_i) \right|^2 \frac{f(q_1)f(q_2)}{|q_1||q_2|} W_{\text{jet}}(E_{\text{jet}}, E_{\text{part}})
\]

Inputs:
lepton and jet 4-vectors - no other information needed!

Matrix element:
Different for each process.
Leading order, obtained from MadGraph

Transfer functions:
Account for detector effects in measurement of jet energy

Some processes have no matrix elements, like fakes -- Use a template fit like other analyses.
Matrix-Element Discriminants

Two from D0 -- s-channel and t-channel separately

CDF's is optimized together

Single Top Cross Section Measurements, Thomas Junk, ICHEP 2008
Technique 3: Neural Networks

- **D0**: Bayesian Neural Networks
  Radford Neal, “Bayesian Learning for Neural Networks”, Lecture Notes in Statistics No. 118, Springer-Verlag
- **CDF**: NeuroBayes Program
  [http://www.phi-t.de](http://www.phi-t.de)

- Differ in preprocessing and training.
- Avoids overtraining, even with many input variables
Neural Network Discriminant Distribution

Candidate Events vs NN Output

2/3 Jets

CDF II Preliminary 2.7 fb⁻¹

- Single top
- tt
- Wbb+Wc
- Wc
- Wqq
- Diboson
- Z+jets
- QCD
- Data

MC normalized to SM prediction
Technique 4: LEP-Style Projective Likelihood Discriminants

CDF Run II Preliminary, 2.7fb$^{-1}$

2-jet events

3-jet events
# Systematic Uncertainty Summary

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Rate</th>
<th>Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Energy Scale</td>
<td>0...16%</td>
<td>✓</td>
</tr>
<tr>
<td>Initial State Radiation</td>
<td>0...11%</td>
<td>✓</td>
</tr>
<tr>
<td>Final State Radiation</td>
<td>0...15%</td>
<td>✓</td>
</tr>
<tr>
<td>Parton Distribution Functions</td>
<td>2...3%</td>
<td>✓</td>
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<tr>
<td>Monte Carlo Generator</td>
<td>1...5%</td>
<td></td>
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<tr>
<td>Event Detection Efficiency</td>
<td>0...9%</td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>6%</td>
<td></td>
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<tr>
<td>Neural Net B-tagger</td>
<td></td>
<td>✓</td>
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<tr>
<td>Mistag Model</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>$Q^2$ scale in ALPGEN MC</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Input variable mismodeling</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Wbb+Wcc normalization</td>
<td>30%</td>
<td></td>
</tr>
<tr>
<td>Wc normalization</td>
<td>30%</td>
<td></td>
</tr>
<tr>
<td>Mistag normalization</td>
<td>17...29%</td>
<td></td>
</tr>
<tr>
<td>ttbar normalization &amp; $m_{\text{top}}$</td>
<td>23%</td>
<td>✓</td>
</tr>
<tr>
<td>Non-W Normalization</td>
<td>40%</td>
<td></td>
</tr>
<tr>
<td>Non-W Flavor Model</td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

Also:
- MC Stats in each bin independently
- ISR & FSR treated as correlated
Cross Section Measurements

• Both CDF and D0 use Bayesian posteriors integrated over uncertain nuisance parameters
• Flat prior taken in $\sigma_s + \sigma_t$

Example -- D0 BDT Fit
Excess seen in data over SM signal+background prediction.
Cross Section Combination and p-Value Calculation -- Evidence for Single Top!

Cross Section measurements combined with BLUE (Best Linear Unbiased Estimate)

Combined cross section measurement used as a test statistic. How many background-only pseudoexperiments would fake a signal this large?
A: $1.4 \times 10^{-4}$ of them. $\rightarrow 3.6 \sigma$ evidence.
Expected in SM: $2.3 \sigma$
CDF’s Cross Sections and P-values

\[
Q = \frac{P(\text{data} \mid s + b, \hat{\theta})}{P(\text{data} \mid b, \hat{\theta})}
\]

\(\theta=\text{nuisance parameters}\)

Neyman-Pearson Lemma: Q is the uniformly most powerful test; slightly more powerful than the cross section fit.

Best Sensitivity: NN analysis
3.7\(\sigma\) observed
5.0\(\sigma\) expected
CDF Combination: Super-Discriminant

- Evolutionary neural networks trained to give the best expected p-value, not an arbitrary error function
- Gained CDF 10% in significance for Moriond Combination
Summary of Measurements of $\sigma_s + \sigma_t$

<table>
<thead>
<tr>
<th>Method</th>
<th>Tevatron Single Top Summary</th>
<th>SM Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Likelihood Function</td>
<td>CDF</td>
<td>$2.0 \pm 0.9$</td>
</tr>
<tr>
<td>(2.7 fb$^{-1}$)</td>
<td></td>
<td>$0.8$</td>
</tr>
<tr>
<td>Matrix Element</td>
<td>CDF</td>
<td>$2.7 \pm 0.8$</td>
</tr>
<tr>
<td>(2.7 fb$^{-1}$)</td>
<td></td>
<td>$0.7$</td>
</tr>
<tr>
<td>Neural Network</td>
<td>CDF</td>
<td>$2.1 \pm 0.7$</td>
</tr>
<tr>
<td>(2.7 fb$^{-1}$)</td>
<td></td>
<td>$0.6$</td>
</tr>
<tr>
<td>Decision Tree</td>
<td>CDF</td>
<td>$2.4 \pm 0.8$</td>
</tr>
<tr>
<td>(2.7 fb$^{-1}$)</td>
<td></td>
<td>$0.7$</td>
</tr>
<tr>
<td>Decision Tree</td>
<td>D0</td>
<td>$4.9 \pm 1.4$</td>
</tr>
<tr>
<td>(0.9 fb$^{-1}$)</td>
<td></td>
<td>$1.4$</td>
</tr>
<tr>
<td>Matrix Element</td>
<td>D0</td>
<td>$4.8 \pm 1.6$</td>
</tr>
<tr>
<td>(0.9 fb$^{-1}$)</td>
<td></td>
<td>$1.4$</td>
</tr>
<tr>
<td>Bayesian NN</td>
<td>D0</td>
<td>$4.4 \pm 1.6$</td>
</tr>
<tr>
<td>(0.9 fb$^{-1}$)</td>
<td></td>
<td>$1.4$</td>
</tr>
</tbody>
</table>

Two-Dimensional Interpretation: Measuring $\sigma_s$ and $\sigma_t$ Separately

Template fit (marginalization) is done in 2D. Flat priors taken in the $(\sigma_s, \sigma_t)$ plane.

CDF: Dedicated NN’s/LF’s trained for the purpose of 2D fits.
Summary

• It’s an exciting time to be doing single top!

• D0: Evidence for single top production in 0.9 fb$^{-1}$ of data. $\sigma_s + \sigma_t = 4.7 \pm 1.3$ pb
  Significance = $3.6\sigma$
  Expected: $2.3\sigma$

• CDF: Evidence for single top production in 2.7 fb$^{-1}$ of data. $\sigma_s + \sigma_t = 2.0 -- 2.7$ pb Errors are $\pm 0.7$ pb per analysis.
  Expected sensitivity $5.0\sigma$ (Best single analysis)
  Observed significance: $3.7\sigma$

• Two-Dimensional contours measured
Backup Slides
Just Some of the Distributions Checked
P-Value Calculations

**LF: obs: 2.6σ**
- **exp: 3.8σ**

**ME: obs: 4.2σ**
- **exp: 4.8σ**

**NN: obs: 3.7σ**
- **exp: 5.0σ**

**BDT: obs: 3.6σ**
- **exp: 4.9σ**

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Single Top Cross Section Measurements, Thomas Junk, ICHEP 2008
Measurement of Single Top Production in 2.7 fb\(^{-1}\) of Tevatron Data

Update of 2.2 fb\(^{-1}\) measurement presented at Moriond 2008

- Similar Event Selection As D0.
  - Harder Missing \(E_T\) cut (25 GeV instead of 15 GeV)
  - Harder jet \(E_T\) cuts (all at 25 GeV; D0: 25, 20, 15 GeV)

- \(W+\text{Jets}\) rates scaled to data in untagged sample

- \(W+\text{HF}\) Fraction in Alpgen calibrated in \(W+1\)-jet sample
  HF \(k\)-factor (D0’s \(\alpha\)) = 1.4 ± 0.4 for \(Wbb\) and \(Wcc\)

- b-tagged \(W+\text{LF}\) calibrated with a tag-rate matrix times
  pretag \(W+\text{jets}\), minus HF, \(tt\text{bar}\) and non-\(W\)

- Non-\(W\) Fraction fit in each jet, tag category using
  Missing \(E_T\) distributions
2-jet bin input variables:

- $H_T$
- $\cos \theta_{\text{lepton, other jet}}$
- $Q \times \eta$
- $M_{jj}$
- $\log(M_{E_{t\text{-chan}}})$ from MADGRAPH (Stelzer and Willenbrock)
- ANN b-tag output
- $\chi^2(t\text{-channel})$ (replaces $m_{lvb}$)

Does not take advantage of correlations

Separate network trained for 3-jet events
Matrix Element Discriminant

For the same point in phase space, data composition given by ratios of matrix elements squared.

Event probability constructed by integrating matrix element squared times transfer function over unknown parton/neutrino momenta. Use $W_{bb}$, $W_{gg}$, $t\bar{t}$, $t$-channel signal, s-channel signal matrix elements, plus b-tag discriminant.

Some components (e.g. non-$W$) do not have matrix elements - template fits with MC and data-driven models.
Neural Network Discriminant

- Networks trained using NeuroBayes
- Four networks trained (2,3 jets)x(1,2 tags)
- CDF’s most sensitive analysis

Example templates in 2-jet, 1-tag category
Systematic Shape Uncertainties

A total of 370 shape uncertainties evaluated!

Most are quite small

Each template, each source of shape error, each channel (#tags, #jets, extra muons)
**Status of the CKM Matrix**

From the PDG review 2006 (Ceccucci, Ligeti, Sakai)

\[ V_{	ext{CKM}} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \]

\[ V_{	ext{CKM}} = \begin{pmatrix} 0.97383^{+0.00024}_{-0.00023} & 0.2272^{+0.0010}_{-0.0010} & (3.96^{+0.09}_{-0.09}) \times 10^{-3} \\ 0.2271^{+0.0010}_{-0.0010} & 0.97296^{+0.00024}_{-0.00024} & (42.21^{+0.10}_{-0.80}) \times 10^{-3} \\ (8.14^{+0.32}_{-0.64}) \times 10^{-3} & (41.61^{+0.12}_{-0.78}) \times 10^{-3} & 0.999100^{+0.000034}_{-0.000004} \end{pmatrix} \]

**Rigid SM prediction →**
**Measurement of \(|V_{tb}|\) is a solid test of assumptions**

- Magnitudes only
- 3x3 Unitarity enforced

Single Top Cross Section Measurements, Thomas Junk, ICHEP 2008 38
What Can Affect $|V_{tb}|$?

- 3x3 Unitarity is not true if the matrix is 4x4 (or more..)

$$V_{CKM} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} & V_{uX} \\
V_{cd} & V_{cs} & V_{cb} & V_{cX} \\
V_{td} & V_{ts} & V_{tb} & V_{tX} \\
V_{Yd} & V_{Ys} & V_{Yb} & V_{YX}
\end{pmatrix}$$

- Vector $t'$ quark is also a possibility

J. Alwall et. al., “Is $|V_{tb}| \sim 1$?”

Interesting constraints from precision EW measurements.
Why Measure Single Top Production?

- The top quark is very heavy! $m_t = 172.6 \pm 1.4$ GeV/c$^2$ -- Tevatron, March 2008

- Why are other quarks so light?

- Alternative Higgs model – t-tbar condensate?

- One of the main ingredients of the radiative corrections to $m_H$ is the top loop

- Is there more out there we cannot yet see?

The Top quark may be trying to tell us something!
It’s Not Looking Good For a Fourth Generation, However!

Higgs production via gluon-gluon fusion proceeds mostly via a top loop in a 3-gen model, and gets a boost from heavier quarks if they exist.

Propagators and vertex mass dependencies cancel in the triangle diagram.

\[ m_{H}^{EW-fit} = 87^{+36}_{-27} \text{ GeV} \]
Cross Section Measurements

- Bayesian Technique selected
- Flat prior in signal cross section $\sigma_{s+t}$
- Integrate out rate and shape uncertainties
- Check biases with pseudoexperiments with systematics fluctuated.
- $m_{\text{top}} = 175$ GeV assumed.

Linearity checked with systematically varied pseudoexperiments
Tevatron
ring radius=1 km

Protons on
antiprotons

$$\sqrt{s_{pp}} = 1.96 \text{ TeV}$$

Main Injector
commissioned in 2002

Recycler used
as another antiproton
accumulator

Start-of-store luminosities
exceeding $250 \times 10^{30}$ now are routine
High-Significance Events Near Cuts

- Isolation – removes QCD background, but signal likes to have the lepton close to a jet
- Jet energies and Missing Et have falling spectra, even for signal. Cuts are designed to keep within the validity region of the jet corrections
- $t$-channel signal throws one jet at very high $\eta$, challenging our ability to detect it. Geometrical detector acceptance and modeling of beam-splash and energy calibration set that cut.
- Lepton energy cut designed to get away from the 18-GeV trigger threshold
# CDF BDT Variable list, 2-jet bin

<table>
<thead>
<tr>
<th>Rank</th>
<th>Variable</th>
<th>2-jets, 1-tag Variable Importance</th>
<th>Variable</th>
<th>2-jets, 2-tag Variable Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>kaNN</td>
<td>4.597e-01</td>
<td>mJ1J2</td>
<td>7.453e-02</td>
</tr>
<tr>
<td>2</td>
<td>mJ1J2</td>
<td>1.799e-01</td>
<td>Mlnub</td>
<td>6.599e-02</td>
</tr>
<tr>
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<td>QEta</td>
<td>1.077e-01</td>
<td>wmt</td>
<td>6.453e-02</td>
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<tr>
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<td>Mlnub</td>
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<td>MetJ1Dphi</td>
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<tr>
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<td>J1Et</td>
<td>4.570e-02</td>
<td>Mlnuj1j2</td>
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<tr>
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<tr>
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CDF BDT Variable List, 3-jet bin

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Cross Section Measurements

- Bayesian posterior marginalized over uncertain nuisance parameters
- Flat prior taken in $\sigma_s + \sigma_t$

All Assuming $m_t = 175$ GeV

Single Top Cross Section Measurements, Thomas Junk, ICHEP 2008
Cross Section Measurements

- Bayesian technique selected
- Flat prior in $\sigma_s + \sigma_t$
- Systematic Uncertainties integrated over (marginalized)

Three measurements are highly correlated between 60% and 70%
High-Score Events: CDF BDT > 0.6