Single Top Quark Production at the Tevatron

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on behalf of the DØ and CDF collaborations
Experimental setup

FNAL, Batavia, IL, USA
proton-antiproton collider
center of mass energy: 1.96 GeV
two multipurpose detectors
Top quark production @ Tevatron

- top pair production via strong interaction:

\[ \sigma_{\bar{t}t} = 6.77 \pm 0.42 \text{ pb} \]

[N. Kidonakis, R. Vogt, Phys. Rev. D 68 114014 (2003)]

- single top production via electroweak interaction:

\[ \sigma_{s-channel} = 0.88 \pm 0.14 \text{ pb} \]

[Z. Sullivan, Phys. Rev. D 70 114012 (2004)]

\[ \sigma_{t-channel} = 1.98 \pm 0.30 \text{ pb} \]

Every 3\textsuperscript{rd} top quark event is a single top event!

All cross sections for \( m(\text{top}) = 175 \text{ GeV} \)
Physics with single top quark events

- Measurement of the production cross sections:
  - $\sigma_{s+t}$ combined
  - $\sigma_s, \sigma_t$ individually
- Direct measurement of CKM matrix element $|V_{tb}|$
- Study top quark spin polarization
- Understand single top as background process
- Establish analysis techniques for small signals
- Search for new physics:
  - Heavy gauge bosons
  - Anomalous $Wtb$ couplings
  - Charged Higgs production
  - ...

Single top is an exciting field!
Event selection

- One isolated high-\(E_T\) lepton (electron or muon)
- Missing transverse energy (from the neutrino)
- 2-4 jets
- at least one b-tagged jet (to reduce multijet background)
Challenge of single top

- We expect ~50 signal events per fb$^{-1}$
- Still, signal is lower than background uncertainty
  - Counting experiment not possible
  - Use multivariate analysis techniques

Event selection

\[ \text{discriminating variables} \rightarrow \text{Multivariate analysis} \rightarrow \text{Cross section} \]
Based on 0.9 fb\(^{-1}\) of Tevatron RunII data

Using (up to) 24 analysis channels

Three different multivariate analysis techniques:

- Boosted decision trees
- Bayesian neural networks
- Matrix element method

[Phys. Rev. Lett. 98, 181802 (2007)]
s+t cross section measurements

Single top quark production describes high discriminant distributions!
Consistent results with three different multivariate classifiers
Combining the three analyses

- Use the BLUE method (*Best Linear Unbiased Estimator*) to combine the results
- Determine correlations and weights from ensembles

|       | BDT | BNN | ME |
|-------|-----|-----|----|
| BDT   | 1   | 0.66| 0.64 |
| BNN   | 0.66| 1   | 0.59 |
| ME    | 0.64| 0.59| 1   |

- **Expected** $\sigma_{s+t} : 3.0 \pm 1.3 \text{ pb}$
- **Measured** $\sigma_{s+t} : 4.7 \pm 1.3 \text{ pb}$

- **Expected sensitivity**: $2.3 \sigma$
- **Observed significance**: $3.6 \sigma$

Evidence for single top quark production!

[arXiv.org:0803.0739, accepted by PRD]
• Calculate contours for different levels of confidence in the t-channel vs. s-channel plane

• Analysis based on Boosted Decision Tree analysis (optimised for s+t channel)

Measurement is in good agreement with the SM prediction
Measurement of $|V_{tb} x f^L_1|$  

- Based on result of Boosted Decision Tree analysis  
- Assumptions:  
  - $|V_{tb}|^2 \gg |V_{td}|^2 + |V_{ts}|^2$  
  - Left-handed form factor $f^L_1 = 1$  
  - No constraint on number of generations
Results of the CDF Collaboration

- Based on 2.2 fb⁻¹ of Tevatron RunII data
- Four different multivariate analysis techniques:
  - Boosted decision trees
  - Neural networks
  - Matrix element method
  - Multivariate likelihood function
s+t cross section measurements (I)

Boosted Decision Trees

Neural Networks

Exp. sensitivity: $4.6\sigma$
Obs. significance: $2.8\sigma$

$\sigma_{\text{Single Top}} = 1.9^{+0.8}_{-0.7} \text{ pb}$

Exp. sensitivity: $4.4\sigma$
Obs. significance: $3.2\sigma$
s+t cross section measurements (II)

**Matrix Elements**

**Likelihood Function**

CDF Run II Preliminary, L=2.2 fb⁻¹

- **exp. sensitivity:** 4.5σ
- **obs. significance:** 3.4σ

**σ_{Single Top} = 2.2^{+0.8}_{-0.7} pb**

**CDF Run II Preliminary, 2.2 fb⁻¹**

- s-channel
- t-channel
- WCC/WC
- Wbb
- W+LF
- z+jets
- Diboson
- non-W

**σ_{s+t} = 1.8^{+0.9}_{-0.8} pb**

**exp. sensitivity:** 3.4σ
**obs. significance:** 2.0σ
Combining three analyses

- Use another Neural Network to combine Neural Network, Likelihood Function and Matrix Element analyses
- Cross check with BLUE method gives similar result

| LF | ME | NN |
|----|----|----|
| LF | 1  | 0.60 | 0.74 |
| ME | 1  | 0.61 |     |
| NN | 1  |     | 1    |

A 5σ observation of single top is around the corner!

exp. sensitivity: 5.1σ
obs. significance: 3.7σ
Measurement of $|V_{tb}|$

- Extract $|V_{tb}|$ from combined analysis
- Assuming a flat prior on $|V_{tb}|^2$

Measurement of $|V_{tb}|$

- $|V_{tb}| = 0.89 \pm 0.14$ (exp.) $\pm 0.07$ (theory)
s- and t-channel search

- Use Neural Networks from the combined analysis
- Adding an additional s-channel Neural Network for 2 jets and 1 b-tag
- Perform a 2 parameter likelihood fit to data

Example for ttbar
Neural Network template

\[
\sigma_{t\text{-channel}} = 0.8^{+0.7}_{-0.6} \text{ (stat. + syst.) pb}
\]
\[
\sigma_{s\text{-channel}} = 1.6^{+0.9}_{-0.8} \text{ (stat. + syst.) pb}
\]
\textbf{SM single top summary}

- Both CDF and DØ perform several analyses searching for the production of single top quarks

- Individual analyses and the combinations are in good agreement with the SM predictions

\[
\begin{array}{|c|c|c|}
\hline
& \text{CDF and DØ tb+tqb Cross Section} & \\
\hline
\text{CDF Decision Trees} & 1.9 \pm 0.8 \pm 0.7 \text{ pb} & \\
2.2 \text{ fb}^{-1} & \\
\hline
\text{CDF Matrix Elements} & 2.2 \pm 0.8 \pm 0.7 \text{ pb} & \\
2.2 \text{ fb}^{-1} & \\
\hline
\text{CDF Neural Networks} & 2.0 \pm 0.9 \pm 0.8 \text{ pb} & \\
2.2 \text{ fb}^{-1} & \\
\hline
\text{CDF Likelihood Funcs.} & 1.8 \pm 0.9 \pm 0.8 \text{ pb} & \\
2.2 \text{ fb}^{-1} & \\
\hline
\text{CDF Combination preliminary} & 2.2 \pm 0.7 \pm 0.7 \text{ pb} & \\
& \\
\hline
\text{DØ Decision Trees} & 4.9 \pm 1.4 \pm 1.4 \text{ pb} & \\
0.9 \text{ fb}^{-1} & \\
\hline
\text{DØ Matrix Elements} & 4.8 \pm 1.6 \pm 1.4 \text{ pb} & \\
0.9 \text{ fb}^{-1} & \\
\hline
\text{DØ Bayesian NNs} & 4.4 \pm 1.6 \pm 1.4 \text{ pb} & \\
0.9 \text{ fb}^{-1} & \\
\hline
\text{DØ Combination PRD} & 4.7 \pm 1.3 \pm 1.3 \text{ pb} & \\
& \\
\hline
N. Kidonakis, PRD 74, 114012 (2006) & \\
Z. Sullivan, PRD 70, 114012 (2004) & \\
\hline
\end{array}
\]
Searches for New Physics

$W'$

FCNC
DØ [PRL 99:191802 (2007)]

charged Higgs
Search for W'

- Analysis performed in 0.9 fb$^{-1}$
- Search for $W'_R$ and $W'_L$ separately
- Selection similar to single top analyses
- Binned likelihood analysis using $\sqrt{S}$

**Diagrams:**

- **Left Diagram:**
  - Graph: Events/20 GeV vs. $\sqrt{s}$ [GeV]
  - Symbols: data, $W'$ 700 GeV, $W'$ 800 GeV, single top, $t\bar{t}$, W+jets, multijets

- **Right Diagram:**
  - Graph: Events/20 GeV vs. $\sqrt{s}$ [GeV]
  - Symbols: data, $W'$ 700 GeV, $W'$ 800 GeV, single top, $t\bar{t}$, W+jets, multijets
Search for $W'$

- Fit region with $\sqrt{S} > 400 \text{ GeV}$
- Set 95% C.L for $W'_L$ and $W'_R$ masses and couplings:
  - $M(W'_L) > 731 \text{ GeV}$
  - $M(W'_R; l, q) > 739 \text{ GeV}$
  - $M(W'_R; q, q) > 768 \text{ GeV}$

Phys. Rev. Lett. 100, 211803 (2008)
Search for $W'$

- Analysis of $1.9 \text{ fb}^{-1}$ of RunII data using single top selection
- Assume SM-like couplings to fermions for mass analysis
- Use $b$-tagged events with 2 or 3 jets
- Fit invariant mass of reconstructed $W$ and the two leading jets

![Graphs showing $M_{WJJ}$ distributions for 2 jets 1 tag and 3 jets 1 tag with data and various contributions.]

KS: 16.3%
Chi2/DoF: 13.4/20: 84.1%

KS: 93.7%
Chi2/DoF: 15.7/17: 52.7%
Search for $W'$

- Set 95% C.L. on $W'$ mass and couplings
- Result:
  - $M(W') > 800 \text{ GeV}$ ($M(W') > M(\nu_R)$)
  - $M(W') > 825 \text{ GeV}$ ($M(W') < M(\nu_R)$)

Limits on heavy gauge boson production in single top final state!
Search for charged Higgs

- Two-Higgs Doublet Model (2HDM) extension to the SM predicts five Higgs bosons, two carry electric charge ($H^+$, $H^-$)
- Three types of 2HDMs in order to avoid FCNCs:
  - Type I: One doublet gives mass to all quarks and leptons
  - Type II: One doublet gives mass to up-type quarks and neutrinos, other doublet gives mass to down-type quarks and charged leptons
  - Type III: Two doublets contribute to quark and lepton masses. Top-charm mixing parameter $\xi$ [H.-H. He and C.-P. Yuan, PRL 83 (1999) 28]
- Cross sections up to:
  - Type I: $\sim$10pb (Type I)
  - Type II: $\sim$0.5pb (Type II) with $\tan \beta = 100$
  - Type III: $\sim$0.1 pb (Type III) with $\xi=5$
Search for charged Higgs

- Analyse events with 2 jets, one or two b-tags, and an electron or a muon (4 channels)
- Binned likelihood fit on reconstructed invariant mass of jets and reconstructed W

95% CL Upper Limit on 2HDM Types-I & -III $H^+$ Production

95% CL Upper Limit on 2HDM Type-II $H^+$ Production

Limits on 2HDM cross sections!
Summary & Outlook

- Both DØ and CDF see $3\sigma$ evidence for single top quark production
- First direct measurements of $|V_{tb}|$
- Transfer of analysis techniques to signal processes beyond Standard Model in progress

- Excellent Tevatron performance combined with high efficiency data taking promises interesting measurements in the single top final state in the (near) future!
Backup
Systematic uncertainties

### DØ

| Source of Uncertainty                  | Size  |
|---------------------------------------|-------|
| Top pairs normalization               | 18%   |
| W+jets & multijets normalization      | 18–28%|
| Integrated luminosity                 | 6%    |
| Trigger modeling                      | 3–6%  |
| Lepton ID corrections                 | 2–7%  |
| Jet modeling                          | 2–7%  |
| Other small components                | Few % |
| Jet energy scale                      | 1–20% |
| Tag rate functions                    | 2–16% |

+ systematics affecting shape

### CDF

| Syst. Uncertainty                     | Rate   | Shape |
|---------------------------------------|--------|-------|
| Jet Energy Scale                      | 0...16%|       |
| Initial state radiation               | 0...11%|       |
| Final state radiation                 | 0...15%|       |
| Parton Distribution Function          | 2...3%  |       |
| MC Generator                          | 1...5%  |       |
| Event Detection Efficiency            | 0...9%  |       |
| Luminosity                            | 6%     |       |
| NN Flavor-Separator                   |        |       |
| Mistag model                          |        |       |
| Q2 scale in ALPGEN MC                 |        |       |
| Input variable mismodeling            |        |       |
| Wbb+Wcc normalization                 | 30%    |       |
| Wc normalization                      | 30%    |       |
| Mistag normalization                  | 17...29%|       |
| Top-pair normalization & mtop         | 23%    |       |

HQ&L2008, Melbourne, Australia | Matthias Kirsch | RWTH Aachen University | June 5th 2008
Cross checks

• Check background modelling in
  ➢ W+jets dominated region ($H_T < 175$ GeV)
  ➢ Region dominated by top pair production ($H_T > 300$ GeV)
Do we see single tops?

- Look at high BDT output
- Looking at reconstructed top quark mass and $q$(lepton) * $\eta$(untagged jet) distribution (Tevatron specific t-channel variable)

Distributions in good agreement with SM single top hypothesis
Boosted Decision Trees

- Machine learning technique, widely used in social sciences
- Extension to a cut-based analysis
- Cut at each node on variable giving the best separation
- Use adaptive boosting to dilute the discrete output of a single decision tree
- Reweight misclassified events
- Calculate purity $p$ in each final leaf (discriminant)
Matrix method

- Uses the 4-vectors of reconstructed leptons and jets
- Use matrix elements of main signal and background Feynman diagrams to compute an event probability density for signal and background hypotheses

\[
P_i(\vec{x}) = \frac{1}{\sigma} \int \ldots \int \sum_{\text{comb}} d^n \sigma_i(\vec{y}) dq_1 dq_2 f(q_1) f(q_2) W(\vec{x} ; \vec{y})
\]

\[D_S(\vec{x}) = \frac{P_S(\vec{x})}{P_S(\vec{x}) + P_{bkgd}(\vec{x})}\]

- Calculate discriminant D (S = s- or t-channel):