Search for Single-Top Production at CDF

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1. Single Top-Quark Production

top quark production via the weak interaction

Experimental Signature: charged lepton + missing $E_T$ + 2 energetic jets

Theoretical cross section predictions at $\sqrt{s} = 1.96$ TeV

$\sigma_t = 1.98 \pm 0.25$ pb

$\sigma_s = 0.88 \pm 0.11$ pb


Why look for Single-Top?

1. Test of the SM prediction. Does it exist?
   - Cross section $\propto |V_{tb}|^2$
   - Test unitarity of the CKM matrix, e.g.
   - Hints for existence of a 4th generation?
   - Test of $b$ quark structure function: DGLAP evolution

2. Same final state signature as Higgs: WH, H → bbbar.
   Understanding single-top backgrounds is a prerequisite for Higgs searches at the Tevatron.

3. Test non-SM phenomena
   - Search $W'$ or $H^+$ (s-channel signature)
   - Search for FCNC, e.g. $ug \rightarrow t$
   - ...
Single-Top Sample at CDF

backgrounds are the challenge

main backgrounds:
\[ W + \text{jets}, b\bar{b}, t\bar{t}, Z + \text{jets}, \text{diboson} \]

after event selection: \( S/B = 1/16 \)

- 1 isolated high-\( p_T \) lepton (e, \( \mu \)) \( p_T > 20 \text{ GeV}, |\eta_e| < 2.0 \text{ and } |\eta_\mu| < 1.0 \)
- MET > 25 GeV
- Jets: \( N_{\text{jets}} = 2, E_T > 15 \text{ GeV}, |\eta| < 2.8 \geq 1 \text{ b tag (secondary vertex tag)} \)

<table>
<thead>
<tr>
<th>total predicted background</th>
<th>549 ± 95</th>
</tr>
</thead>
<tbody>
<tr>
<td>predicted single-top</td>
<td>37.8 ± 5.8</td>
</tr>
<tr>
<td>total prediction</td>
<td>587 ± 95</td>
</tr>
<tr>
<td>observation</td>
<td>644</td>
</tr>
</tbody>
</table>

using CDF II data with \( L_{\text{int}} = 955 \text{ pb}^{-1} \)
Improved $b$ Jet Identification

About 50% of the background in the $W + 2$ jets sample do NOT contain $b$ quarks even though a secondary vertex was required!

jet and track variables, e.g. vertex mass, decay length, track multiplicity, …

⊕ neural network
⇒ powerful discriminant

New possibility: In situ measurement of the flavor composition in the $W + 2$ jets sample

Fit to NN output for $W + 2$ jets events with one secondary vertex (955 pb$^{-1}$)

Replace Yes-No by continuous variable

mistags / charm .................... beauty
2. Search Strategies

Follow two search strategies:

1. „Combined Search“
   t-channel and s-channel single-top regarded as one single-top signal. Cross section ratio is fixed to SM value. Important for „discovery“ and test $|V_{tb}| << 1$

2. „Separate Search“
   t-channel and s-channel are regarded as separate processes
   2D fit in $\sigma(s)$ vs. $\sigma(t)$ plane
   important to be sensitive to new physics processes

Three multivariate methods:

1. Matrix elements (combined search)
2. Neural networks (combined and separate search)
3. Likelihood discriminants (combined and separate search)
2.1 Matrix Element Analysis

Idea: Compute an event probability $P$ for signal and background hypotheses:

$$P(p_{\ell}^{\mu}, p_{j_1}^{\mu}, p_{j_2}^{\mu}) = \frac{1}{\sigma} \int dE_{j_1} dE_{j_2} dp_{V}^{z} \sum_{\text{comb}} |M(p_{\ell}^{\mu})|^2 \frac{f(q_1) f(q_2)}{|q_1| \cdot |q_2|} \phi_4 W_j(E_j, E_p)$$

Leading Order matrix element (MadEvent)

$W_j(E_j, E_p)$ is the probability of measuring a jet energy $E_j$ if $E_p$ was produced.

Input: lepton and 2 jets 4-vectors!

Integration over part of the phase space $\Phi_4$

Parton distribution functions (CTEQ5)

Computation of $P$ for signal and background processes:

- Single-top: $s$-channel and $t$-channel
- $W_{cj}$
- $W_{bb}$ and $W_{cc}$

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Matrix Element Discriminant

Combination of all matrix element probabilities to one discriminant:

\[ \text{EPD} = \frac{b \cdot (\alpha P_{tch} + \beta P_{sch})}{b \cdot (\alpha P_{tch} + \beta P_{sch} + \gamma P_{W_{bb}}) + (1 - b)(\delta P_{W_{cc}} + \epsilon P_{W_{cj}})} \]

\[ b = \frac{1 + \text{neural network } b \text{ tagger output}}{2} \]

\( \alpha, \beta, \gamma, \delta, \epsilon \) = normalisation coefficients

a priori sensitivity: 2.5 \( \sigma \)
Matrix Elements: Result

Observation: 2.3 $\sigma$ excess of single-top events

CDF Run II Preliminary, $L=955 pb^{-1}$

$\sigma_{Single \ Top} = 2.7^{+1.5}_{-1.3} \ pb$
2.2 Neural Network Analysis

Idea:
combine many variables into one
more powerful discriminant

18 variables are used, among them $Q \cdot \eta$, reconstructed top quark mass, top quark polarisation angle, Jet $E_T$ and $\eta$, NN $b$ tagger output, $W$ boson $\eta$, ...
Neural Networks: Fit Result

**Combined Search**

\[ \sigma_{(t\text{-chan.})} = 0.2^{+1.1}_{-0.2} \text{ pb (SM: 1.98 pb)} \]

\[ \sigma_{(s\text{-chan.})} = 0.7^{+1.5}_{-0.7} \text{ pb (SM: 0.88 pb)} \]

Deficit

\[ \sigma_{\text{Fit}} = 0.0^{+1.2}_{-0.0} \text{ (stat. + syst.) pb} \]

**Separate Search**

A priori sensitivity: 2.6 \( \sigma \)
2.3 Likelihood Discriminants

**Overall scaled by 1.1**
CDF Run II Preliminary, L=955 pb⁻¹

Events/0.1

<table>
<thead>
<tr>
<th></th>
<th>p-value</th>
<th>95% C.L. limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>observed</td>
<td>58.3%</td>
<td>2.7 pb</td>
</tr>
<tr>
<td>expected</td>
<td>2.3% (2.0σ)</td>
<td>2.9 pb</td>
</tr>
</tbody>
</table>

*p-value* = probability that observation is due to background fluctuation alone

Expected limits: assume no single-top present in ensemble tests

Best fit:
\[
\sigma_{t\text{chan}} = 0.2^{+0.9}_{-0.2} \text{ pb}
\]
\[
\sigma_{s\text{chan}} = 0.1^{+0.7}_{-0.1} \text{ pb}
\]

Observe deficit in the signal region!
Overview and Compatibility

<table>
<thead>
<tr>
<th>Method</th>
<th>Neural Networks</th>
<th>Matrix Elements</th>
<th>Likelihood Function</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1D</td>
<td>2D</td>
<td>1D</td>
</tr>
<tr>
<td>Expected p-value</td>
<td>0.5% ≥ 2.6 σ</td>
<td>0.4% ≥ 2.6 σ</td>
<td>0.6% ≥ 2.5 σ</td>
</tr>
<tr>
<td>Observed p-value</td>
<td>54.6% 21.9%</td>
<td>1.0% ≥ 2.3 σ</td>
<td>58.5%</td>
</tr>
</tbody>
</table>

At present, CDF results (955 pb⁻¹) differ: two analyses see no evidence, one has a signal at almost the SM rate.

**Consistency of 4 analyses based on common ensemble tests assuming the SM ratio of t-channel to s-channel: ~ 1%.**

correlation

ρ=59%

ρ=70%

ρ=65%
Why do the results differ?

Analyses were essentially ready in July 2006. Differing results caused a multitude of cross checks. Background estimate was completely redone. Background modeling was refined. Results remained essentially unchanged.

Analyses are correlated (60 – 70%), but there are conceptual differences which allow to retrace why NN/LD classify the highest purity ME events as background like.

1. **Neutrino reconstruction**
   - NN/LD use measured MET, ME does not, but integrates over all $p_z$ values.
   - NN chooses the smaller $p_z$ solution, LD uses best $\chi^2$ of kinematic fit.

2. **Choice of b jet for top quark reconstruction**
   - LD chooses based on kinematic fit. In 1-tag events NN takes the tagged jet, in 2-tag events NN chooses according to $q \cdot \eta$.
   - ME calculates weighted sum over both possibilities.

3. **NN uses soft jet information** (8 GeV < $E_T$ < 15 GeV), ME and LD do not.

4. **ME uses transfer functions**, NN/LD use standard jet corrections.
3. Search for $W' \rightarrow t\bar{b}$ Events

- $W'$ occurs in some extensions of the SM with higher symmetry.
- Complementary to searches in $W' \rightarrow e\nu / \mu\nu$ (e.g. $W'$ of leptophobic nature).
- Select $W + 2$ or $3$ jets events.
- Background estimate same as SM search.
- Use $M(l\nu jj)$ as discriminant
- Neglect interference with SM $W$ boson.

![Graph showing the mass distribution of W' signal and background events]

**new**
Mass Limits on $W'$

Observe no evidence for resonant $W'$ production.

Experimental result: Upper limits on $\sigma \cdot \text{BR}(W'\to tb)$ range from 2.5 pb to 0.4 pb.


Improved mass limits:
- $M(W') > 760 \text{ GeV}$ if $M(W'_R) > M(\nu_R)$
- $M(W') > 790 \text{ GeV}$ if $M(W'_R) < M(\nu_R)$

latest DØ limits:
- $M(W'_L) > 610 \text{ GeV}$
- $M(W'_R) > 630 \text{ GeV}$ (670 GeV)

Previous limit of CDF Run I:
- $M(W'_R) > 566 \text{ GeV}$
  (Phys. Rev. Lett. 90, 081802 (2003))
Summary and Outlook

- Exciting times for single-top analysts!
  sensitivity of individual analyses: \( \approx 2.5 \sigma \) (955 pb\(^{-1}\))
  Future will tell whether CDF and DØ will meet at the SM value or whether we will see a surprise either way.

- 3 CDF analyses give different results:
  
<table>
<thead>
<tr>
<th>matrix elements</th>
<th>neural networks</th>
<th>likelihood ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3 ( \sigma ) excess</td>
<td>no evidence</td>
<td>no evidence</td>
</tr>
<tr>
<td>( \sigma (s+t) = 2.7^{+1.5}_{-1.3} \text{ pb} )</td>
<td>( \sigma (s+t) &lt; 2.6 \text{ pb} )</td>
<td>( \sigma (s+t) &gt; 2.6 \text{ pb} )</td>
</tr>
<tr>
<td>( \sigma (t) &lt; 2.6 \text{ pb} )</td>
<td>( \sigma (s) &lt; 3.7 \text{ pb} )</td>
<td></td>
</tr>
</tbody>
</table>

- Single-top analyses paved the way for Higgs searches, especially WH at the Tevatron.
  Taste of LHC physics: good lesson to learn about extracting small signals \( \Rightarrow \) techniques for LHC

- Next public step will be the analysis of 2 fb\(^{-1}\) (sensitivity: 3.6 \( \sigma \) for single analysis).

- New, improved mass limits on \( W' \rightarrow tb \):
  \[
  \begin{align*}
  M(W^{'}) & > 760 \text{ GeV if } M(W'_R) > M(\nu_R) \\
  M(W^{'}) & > 790 \text{ GeV if } M(W'_R) < M(\nu_R)
  \end{align*}
  \]