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

$$\sigma_t = 1.98 \pm 0.25 \text{ pb}$$
$$\sigma_s = 0.88 \pm 0.11 \text{ pb}$$

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 4\(^{\text{th}}\) generation?
   - Test of \(b\) quark structure function: DGLAP evolution

2. Same final state signature as Higgs: WH, H \(\rightarrow\) 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:

$W + \text{jets}$, $b\bar{b}$, $t\bar{t}$, $Z + \text{jets}$, diboson

After event selection: $S/B = 1/16$

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

| Total predicted background | $549 \pm 95$
| Predicted single-top | $37.8 \pm 5.8$
| Total prediction | $587 \pm 95$
| Observation | $644$

Using CDF II data with $L_{int} = 955 \text{ pb}^{-1}$
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$^{-1}$)

**Entries 644**

CDF II Preliminary 955 pb$^{-1}$

- CDF II data
- Fit Sum (with stat. error)
- $W +$ beauty
- $W +$ charm
- $W +$ light

Replace Yes-No by continuous variable

**Events per 0.125 units**

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:

$$P(p_{\ell}^{\mu}, p_{j_1}^{\mu}, p_{j_2}^{\mu}) = \frac{1}{\sigma} \int dE_1 \, dE_2 \, dp_{\nu} \sum_{\text{comb}} |M(p_{\ell}^{\mu})| \left( \frac{f(q_1)f(q_2)}{|q_1| \cdot |q_2|} \right) \phi_4 W_j(E_j, E_p)$$

- 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.
- $\phi_4$ parton distribution functions (CTEQ5)

Input: lepton and 2 jets 4-vectors!

Integration over part of the phase space $\Phi_4$

Computation of $P$ for signal and background processes:

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

Combination of all matrix element probabilities to one discriminant:

\[
\text{EPD} = \frac{b \cdot (\alpha P_{tch} + \beta P_{sch})}{b \cdot (\alpha P_{tch} + \beta P_{sch} + \gamma P_{Wbb}) + (1 - b)(\delta P_{Wcc} + \epsilon P_{Wcj})}
\]

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

\[\alpha, \beta, \gamma, \delta, \epsilon = \text{normalisation coefficients}\]

\[\text{a priori sensitivity: } 2.5 \sigma\]
Observation: 2.3 $\sigma$ excess of single-top events

$\sigma_{Single \ Top} = 2.7^{+1.5}_{-1.3} \, pb$
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

Separate Search

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

a priori sensitivity: 2.6 \( \sigma \)

\[ \sigma (t\text{-chan.}) = 0.2 \pm 1.1 \text{ pb (SM: 1.98 pb)} \]

\[ \sigma (s\text{-chan.}) = 0.7 \pm 1.5 \text{ pb (SM: 0.88 pb)} \]
2.3 Likelihood Discriminants

Use t- and s-channel likelihood discriminants in a 2D fit

<table>
<thead>
<tr>
<th>p-value</th>
<th>95% C.L. limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>observed</td>
<td>58.3%</td>
</tr>
<tr>
<td>expected</td>
<td>2.3% (2.0σ)</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><strong>Expected p-value</strong></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><strong>Observed p-value</strong></td>
<td>54.6%</td>
<td>21.9%</td>
<td>1.0% ≅ 2.3 σ</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%

*correlation ρ=70%

*correlation 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.
Observe no evidence for resonant $W'$ production.

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

Mass limits: Based on the theoretical cross section prediction

Improved mass limits:
$M(W') > 760$ GeV if $M(W'_{\text{R}}) > M(\nu_{\text{R}})$
$M(W') > 790$ GeV if $M(W'_{\text{R}}) < M(\nu_{\text{R}})$

latest DØ limits:
$M(W'_{\text{L}}) > 610$ GeV
$M(W'_{\text{R}}) > 630$ GeV (670 GeV)

Previous limit of CDF Run I:
$M(W'_{\text{R}}) > 566$ GeV
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} ) pb</td>
<td>( \sigma (s+t) &lt; 2.6 ) pb</td>
<td>( \sigma (s+t) &lt; 2.7 ) pb</td>
</tr>
<tr>
<td>( \sigma (t) &lt; 2.6 ) pb</td>
<td>( \sigma (s) &lt; 3.7 ) 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 \( W' \rightarrow tb \):

  \[
  \begin{align*}
  M(W') &> 760 \text{ GeV} \text{ if } M(W'_{R}) > M(\nu_{R}) \\
  M(W') &> 790 \text{ GeV} \text{ if } M(W'_{R}) < M(\nu_{R})
  \end{align*}
  \]
Backup
### Result of Background Estimation

CDF II Preliminary 955 pb$^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>$W + 2$ jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Wb\bar{b}$, $Wc\bar{c}$, $Wc$</td>
<td>303.0 ± 89.6</td>
</tr>
<tr>
<td>Mistags</td>
<td>136.1 ± 19.7</td>
</tr>
<tr>
<td>QCD multijet</td>
<td>26.2 ± 15.9</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>58.4 ± 13.5</td>
</tr>
<tr>
<td>Diboson, $Z +$ jets</td>
<td>25.6 ± 6.3</td>
</tr>
<tr>
<td>Total Background</td>
<td>549.3 ± 95.2</td>
</tr>
<tr>
<td>$t$-channel</td>
<td>22.4 ± 3.6</td>
</tr>
<tr>
<td>$s$-channel</td>
<td>15.4 ± 2.2</td>
</tr>
<tr>
<td>Total Prediction</td>
<td>587.1 ± 96.6</td>
</tr>
<tr>
<td>Observation</td>
<td>644</td>
</tr>
</tbody>
</table>
Background estimation and modeling is the most critical part of the analysis. Takes about 80% of the effort. But, publicly it is not talked about much.

<table>
<thead>
<tr>
<th>Monte Carlo based background estimate</th>
<th>Data based background estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>• top-antitop production</td>
<td>• top-antitop production</td>
</tr>
<tr>
<td>• diboson (WW, WZ, ZZ)</td>
<td>• diboson (WW, WZ, ZZ)</td>
</tr>
<tr>
<td>• Z+HF</td>
<td>• Z+HF</td>
</tr>
<tr>
<td>rates are predicted using theoretical cross section and MC acceptances</td>
<td>rates are predicted using theoretical cross section and MC acceptances</td>
</tr>
<tr>
<td>( N^{\text{pred}} = \sigma^{\text{theo}} \varepsilon_{\text{evt}} \int \mathcal{L} , dt )</td>
<td>( N^{\text{pred}} = \sigma^{\text{theo}} \varepsilon_{\text{evt}} \int \mathcal{L} , dt )</td>
</tr>
<tr>
<td>( \varepsilon_{\text{evt}} = \varepsilon^{\text{MC}} \varepsilon^{\text{BR}} \varepsilon^{\text{corr}} \varepsilon^{\text{trigger}} )</td>
<td>( \varepsilon_{\text{evt}} = \varepsilon^{\text{MC}} \varepsilon^{\text{BR}} \varepsilon^{\text{corr}} \varepsilon^{\text{trigger}} )</td>
</tr>
<tr>
<td>6.6% of the background is MC based</td>
<td>( W + \text{heavy flavor} )</td>
</tr>
<tr>
<td></td>
<td>fraction: 51.6%</td>
</tr>
<tr>
<td></td>
<td>heavy flavor fractions Alpgen MC plus corrections from inclusive jet samples</td>
</tr>
<tr>
<td></td>
<td>( W + \text{mistagged light quark jets} )</td>
</tr>
<tr>
<td></td>
<td>fraction: 23.2%</td>
</tr>
<tr>
<td></td>
<td>mistag matrix</td>
</tr>
<tr>
<td></td>
<td>( \text{QCD multijet (non-W)} )</td>
</tr>
<tr>
<td></td>
<td>fraction: 4.5%</td>
</tr>
<tr>
<td></td>
<td>fits to the missing ( E_T ) distribution</td>
</tr>
</tbody>
</table>
tagging rates are determined in inclusive jet samples (high statistics control samples)

look at signed 2D decay length

negative tag rates give an estimate on positive mistags due to resolution effects

tag rates are parametrized as a function of 6 variables: jet $\eta$, jet $E_T$, $\Sigma E_T$, $N_{\text{track}}$ of $N_{\text{vertex}}$, $Z_0$ of the primary vertex

corrections to positive tag rates:
1.) enhancement of mistags in heavy flavor events
2.) account for long lived particles: $K_S$, $K_L$, $\Lambda$

Scaled Fit

- Data
- Bottom
- Charm
- Light

Signed Tag Mass
non-W Estimation

traditional method:
fit of side-band regions of the MET ⊗ isolation plane

Problem: estimates are too low
MET and $M_T(W)$ distributions are seriously mismodeled

→ Tighter cuts: MET > 25 GeV
→ Estimates of the pretag and tagged non-W rates using fits to the MET distribution
→ Still large uncertainties: ±43%
# Systematic Rate Uncertainties

**CDF II Preliminary 955 pb\(^{-1}\)**

<table>
<thead>
<tr>
<th>Source</th>
<th>(t)-channel</th>
<th>(s)-channel</th>
<th>single-top</th>
<th>(tt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JES</td>
<td>± 2.1 %</td>
<td>± 1.4 %</td>
<td>± 1.8 %</td>
<td>± 8.6 %</td>
</tr>
<tr>
<td>ISR</td>
<td>± 2.6 %</td>
<td>± 1.6 %</td>
<td>± 2.2 %</td>
<td>± 10.1 %</td>
</tr>
<tr>
<td>FSR</td>
<td>± 3.4 %</td>
<td>± 1.4 %</td>
<td>± 2.6 %</td>
<td>± 11.4 %</td>
</tr>
<tr>
<td>PDF</td>
<td>± 2.5 %</td>
<td>± 2.2 %</td>
<td>± 2.4 %</td>
<td>± 2.4 %</td>
</tr>
<tr>
<td>MC</td>
<td>± 2.0 %</td>
<td>± 1.0 %</td>
<td>± 1.6 %</td>
<td>± 3.0 %</td>
</tr>
<tr>
<td>(\epsilon_{\text{evt}})</td>
<td>± 8.1 %</td>
<td>± 6.3 %</td>
<td>± 7.4 %</td>
<td>± 7.1 %</td>
</tr>
<tr>
<td>Luminosity</td>
<td>± 6.0 %</td>
<td>± 6.0 %</td>
<td>± 6.0 %</td>
<td>± 6.0 %</td>
</tr>
<tr>
<td>Cross section</td>
<td>± 13.0 %</td>
<td>± 13.0 %</td>
<td>± 13.0 %</td>
<td>± 19.7 %</td>
</tr>
<tr>
<td>(M_{\text{top}}) (not applied)</td>
<td>± 2.9 %</td>
<td>± 2.7 %</td>
<td>± 2.8 %</td>
<td></td>
</tr>
</tbody>
</table>
Calculation of neutrino $p_z$ from $W$ mass constraint:

$$M_W^2 = (p_{\mu_l} + p_{\mu_{\nu}})^2$$

→ quadratic equation for $p_z$

→ 2 solutions

Solution with smaller $|p_z|$ is correct 70% of the time.

Due to resolution effects in 30% of events have complex solutions.

small black pts: all data
big black pts: EPD > 0.8
big red pts: EPD > 0.95
W' → tb: Zoom of Limit Region

![Graph showing 95% C.L. Limits for W' mass vs. cross-section.]