Search for New Physics Contamination in the Top Quark Samples and Measurements of the Wtb Coupling at DØ

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For the D0 Collaboration

SUSY 09, the 17th International Conference on Supersymmetry and the Unification of Fundamental Interactions,
Northeastern University, Boston
Outline

- Introduction
  - why look at top?
- Search for scalar top quarks
- Search for associated ttH production
- Anomalous Wtb couplings
  - Top quark pair production
  - Single top quark production
Why Look at The Top Quark?

• Was discovered at Fermilab in 1995

• The heaviest known fundamental particle
  – \( m_t = 173.1 \pm 1.3 \text{ GeV} \) (~0.75% precision)
  – \( \tau = 5 \times 10^{-25} \text{ s} \ll \Lambda_{QCD}^{-1} \) Decays before hadronization

• Mass close to scale of electroweak symmetry breaking
  – Only quark for which coupling to Higgs is significant
  – May shed light on EWSB mechanism

• Top quark plays special role in many of the new physics models

• Even more than a decade after its discovery, our sample consists of ~ 1000 top quark events
  – Many of the measurements of top quark properties are still statistics limited
Our Tools

- ~ 20 countries
- ~ 80 institutions
- ~ 700 enthusiastic physicists per experiment

The Tevatron Accelerator

The DØ Detector

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Top Quark at the Tevatron

Production

Top quark pair production

\[ \sigma_{tt} \approx 7 \text{ pb} \]

Single Top quark production

- **t-channel**
  \[ \sigma \approx 2 \text{ pb} \]

- **s-channel**
  \[ \sigma \approx 1 \text{ pb} \]

Decay

Within Standard Model $t \rightarrow Wb \approx 100\%$

Top Pair Branching Fractions

- "alljets" 46%
- \( \tau + \text{jets} \) 15%
- \( \mu + \text{jets} \) 15%
- "dileptons" 2%
- "lepton+jets" 2%
- MET 1%
- (BR=46%, huge bckg)
- (BR=5%, low bckg)
- (BR=30%, moderate bckg)
• Dominant Backgrounds
  – Dominant backgrounds arise from W+jets and multijet production (ℓ+jets channel) and Z+jets WW+jets (dilepton channel)
  – When searching for new physics in top sector, SM top quark production itself becomes the dominant background

• Signal and Background Modeling
  – The SM top pair samples are generated with ALPGEN for the matrix elements and parton showers followed by PYTHIA for the hadronization
  – Single top quarks production is modeled using SINGLETOP based on COMPHEP
  – Other backgrounds are also modeled using ALPGEN or PYTHIA except multijet background which is determined from data
General Selection

- For lepton + jets channel require one isolated electron or muon, 3 or more jets and missing energy.

- Since top quark decay final states include jets originating from b quarks and most of the background doesn’t, we make use of b-tagging algorithm to further reduce our background contributions.

- Events are divided into sub-samples depending on lepton, jets and b-tags.

- These channels are kept separate and are combined at the end to get the final result.
  - All channels are constructed to be orthogonal.

Selection in l+jets channel:

- For electrons:
  - $p_T > 20 \text{ GeV}, |\eta| < 1.1$
- For muons:
  - $p_T > 20 \text{ GeV}, |\eta| < 2.0$
- Missing $E_T$:
  - $e: > 20 \text{ GeV}; \mu: > 25 \text{ GeV}$
- Jets:
  - $\geq 3 \text{ jets}$
  - $p_T > 20 \text{ GeV}, |\eta| < 2.5$
  - $p_{T,1} > 40 \text{ GeV}$
Search for Scalar Top Quark

The expected next-to-leading-order (NLO) cross section at a center of mass energy of 1.96 TeV for a mass equal to 175 GeV is:

- ~1 pb for scalar top quark
- ~7 pb for SM top quark

For this analysis we assume stop mass smaller than the top quark and $B(\tilde{\ell}_1 \rightarrow \tilde{\chi}_1^0 b) = 1$

The $\tilde{t}\tilde{t}$ event signatures can be very similar to $tt$ possible hidden admixture!
Search for Scalar Top Quark

- Exploit kinematic differences to distinguish stop from SM background
- Build a likelihood discriminant to distinguish signal from the background

Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Values</th>
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<tbody>
<tr>
<td>W+jets Backgnd Modeling</td>
<td>24-74%</td>
</tr>
<tr>
<td>Theoretical x-section</td>
<td>13-20%</td>
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<tr>
<td>Jet energy scale</td>
<td>6-30%</td>
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<tr>
<td>b-tagging</td>
<td>.1-27%</td>
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Results

- The observed cross section limits are a factor of 2−13 larger than the theory prediction and agree with the expected limits within uncertainties.
t\bar{t}H Production at DØ

- Could be enhanced in BSM scenarios such as 2HDMs (MSSM)
- Any new physics (e.g. G' --> t t' H) could show up independent from SM associated Higgs production

- Spectacular signature
- This is the first time we are looking at 5 or more jets with 3 or more b-jets separately events

- Contributes to overall sensitivity (at low masses)
- Interesting at LHC

\[ \mathcal{L} = 2.1 \text{ fb}^{-1} \]
we use differences in final state, number of jets, number b-jets and kinematical difference to separate signal from background:

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\[ t\bar{t}H \rightarrow t\bar{t}b\bar{b} \]

Sheer Beauty

\[ \mathcal{L} = 2.1 \text{ fb}^{-1} \]

\[ \mu+\text{jet event with 3 } b\text{-tags and 5 jets.} \]

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Results

- Set 95% CL upper limit on the $t\bar{t}H$ cross section times branching ratio

- Limits strongly depend on the mass of the Higgs boson

- An alternative method: simultaneous fitting of the top quark pair production and the $t\bar{t}H$ cross section
  - No reliance of the event kinematics only on the difference in jet and b-tag multiplicity between signal and background.
  - A sub-dataset of 1 fb$^{-1}$ is used for this study
Using $t\bar{t}H$ Search to Look for $t'$

- Associated Higgs production in top pair events can be used to explore a model that includes both a $G'$ boson and a $t'$ quark.

Measurement of $|V_{tb}|$

- Under the assumption of unitarity and three generations of quarks: $|V_{tb}| = 0.9991(00)$

$$R = \frac{B(t \rightarrow Wb)}{B(t \rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$$

- Can measure the branching ratio by counting the rate of $b$-tags in $t\bar{t}b$ar events

$R = 0.97^{+0.09}_{-0.08} (\text{stat + syst})$

$|V_{tb}| > 0.89$ @ 95% C.L.

[ hep-ex/08011326 (2008) ]
Anomalous Wtb Coupling

• If top quark plays a special role in EWSB its couplings to W bosons may differ from predictions
• Modifications to top quark interactions, in particular with weak gauge bosons, could yield the first signs of new physics

Most general CP-conserving Wtb vertex up to mass dimensions 5

\[ L_{tWb} = \frac{g}{\sqrt{2}} W_\mu^- b \gamma^\mu \left( f_1^L P_L + f_1^R P_R \right) t - \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^- b \sigma^{\mu\nu} \left( f_2^L P_L + f_2^R P_R \right) t + h.c. \]

where, in the SM \( f_1^L \approx 1, f_2^L = f_1^R = f_2^R = 0 \)

• Probing tWb vertex:

Both measurements can be combined to fully specify the tbW vertex (Phys. Lett. B 631, 126 (2005))
Model-independent measurement of the $W$ boson helicity from $t \rightarrow Wb$ decays in top pair production

- A different Lorentz structure of the $t \rightarrow Wb$ interaction would alter the fractions of $W$ bosons produced in each polarization state from the SM.

- Model-independent measurement based on reconstruction of $\cos \theta^*$ distribution. Distribution of $\cos \theta^*$ depends on the $W$ boson helicity fractions.

- Generate samples corresponding to each of the three $W$ boson helicity states by reweighting the generated $\cos \theta^*$ distributions.

- Simultaneous measurement of $f_0$ and $f_+$ (the negative helicity fraction $f_-$ is then fixed by the requirement that $f_- + f_0 + f_+ = 1$).
Measuring W Boson Helicity

- Use a maximum likelihood fit, for the data to be consistent with the sum of signal and background in the $\cos\theta^*$ distribution

- The fit parameters are the W helicity fractions $f_0$ and $f_+$

- Get the W helicity fractions from the best fit
Results

- A model-independent measurement of the helicity of W bosons in top pair production

\[
\begin{align*}
    f_0 &= 0.490 \pm 0.106 \text{ (stat.)} \pm 0.085 \text{ (syst.)} \\
    f_+ &= 0.110 \pm 0.059 \text{ (stat.)} \pm 0.052 \text{ (syst.)}
\end{align*}
\]

- if \( f_0 \) constrained to the standard model value

\[
    f_+ = 0.019 \pm 0.031 \text{ (stat.)} \pm 0.047 \text{ (syst.)}
\]

This is the most precise such measurement

Main source uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>( f_+ )</th>
<th>( f_0 )</th>
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</thead>
<tbody>
<tr>
<td>ttbar Modeling</td>
<td>0.028</td>
<td>0.055</td>
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<tr>
<td>Back. Modeling</td>
<td>0.026</td>
<td>0.039</td>
</tr>
<tr>
<td>Jet Energy Scale</td>
<td>0.019</td>
<td>0.029</td>
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</table>
Anomalous couplings in Single top Production

- Most general CP-conserving $Wtb$ vertex up to mass dimension 5 involves four couplings
  - Left and Right handed Vector(1) couplings
  - Left and Right handed Tensor(2) couplings

$$L_{Wb} = \frac{g}{\sqrt{2}} W^- b \gamma^\mu \left( f_1^L P_L + f_1^R P_R \right) t - \frac{g}{\sqrt{2} M_W} \partial_\nu W^- b \sigma^{\mu\nu} \left( f_2^L P_L + f_2^R P_R \right) t$$

where, in the SM \( f_1^L \approx 1, f_2^L = f_1^R = f_2^R = 0 \)
Limit Setting

- Bayesian approach for limit setting
- Simultaneous limit setting for two signals by calculating 2 dimensional posterior probability density

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<tr>
<th>Scenario</th>
<th>Cross Section</th>
<th>Coupling</th>
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<tbody>
<tr>
<td>$(L_1, L_2)$</td>
<td>$4.4^{+2.3}_{-2.5} \text{ pb}$</td>
<td>$</td>
</tr>
<tr>
<td>$(L_1, R_1)$</td>
<td>$5.2^{+2.6}_{-3.5} \text{ pb}$</td>
<td>$</td>
</tr>
<tr>
<td>$(L_1, R_2)$</td>
<td>$4.5^{+2.2}_{-2.2} \text{ pb}$</td>
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First experimental limits on tensor couplings!
(PRL 101, 221801 (2008))
Combining W Helicity and Anom. Wtb Couplings

• General Analysis of Single Top Production and W Helicity in Top Decay
  (PLB 631, 126 (2005))

• Combine W helicity measurement in top pair decays
  with

• Anomalous couplings measurement in single top (PRL 101, 221801 (2008))

\[ f_{0,\text{meas}} - f_0 \left( f_1^L, f_2^L, f_1^R, f_2^R \right) \]
\[ f_{+,\text{meas}} - f_+ \left( f_1^L, f_2^L, f_1^R, f_2^R \right) \]
\[ \Delta \sigma_{s,\text{meas}} - \Delta \sigma_s \left( f_1^L, f_2^L, f_1^R, f_2^R \right) \]
\[ \Delta \sigma_{t,\text{meas}} - \Delta \sigma_t \left( f_1^L, f_2^L, f_1^R, f_2^R \right) \]
Observed posterior from the data for single top

Observed posterior from the data for single top and W helicity combined

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Conclusion and Outlook

• I have shown only a small subset of a large and diverse top program to search new physics at D0
• Analyses are becoming increasingly exciting:
  – Ever increasing statistics – more phase space
  – Multiple interpretations – can exclude many models at the same time
• A lot more data to come!!!

We may not have to wait for the LHC in order to be surprised
Conclusion and Outlook

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