Flavor changing neutral currents (FCNC) in $t\bar{t}$ decays at DZero

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On behalf of the DZero Collaboration
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Outline

• Motivation
• DZero detector
• Event selection
• FCNC signal modeling
• Limits on branching ratio $B(t \rightarrow Zq)$ and $\nu_{tqZ}$ coupling
• Summary
FCNC Motivation

- The standard model (SM) has been found to be in excellent agreement with experimental results
- SM Lagrangian does not contain flavor changing neutral currents terms
  - $t \rightarrow c, u$ quarks transitions only possible through radiative corrections

\[ q \rightarrow q' \]

- Expected branching ratio of $t \rightarrow Zc$ is $\sim 10^{-14}$, while $t \rightarrow Zu$ is $\sim 10^{-17}$
- Some theories beyond SM predict $B \sim 10^{-4}$
- Observation would certainly point to physics beyond the SM
FCNC Motivation

- Use a previous analysis of trilepton + imbalance in transverse momentum for WZ cross section: *Physics Letters B* 695, 67 (2011)
- Search for signal using new final state: X is any number of jets
  \[ p\bar{p} \rightarrow t\bar{t} \rightarrow ZqWb \rightarrow \ell\ell\ell\nu + X \]
- Extract or set limits on branching ratio of $t \rightarrow Zq$ ($q = u, c$)
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• Extract or set limits on branching ratio of \( t \rightarrow Zq \) (\( q = u, c \))
FCNC Motivation

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• Search for signal using new final state: X is any number of jets

\[
p\bar{p} \rightarrow t\bar{t} \rightarrow ZqWb \rightarrow \ell\ell\ell\nu + X
\]

• Extract or set limits on branching ratio of t→Zq (q = u, c)

• CDF results: B(t→Zq) < 3.7% (observed) with a < 5.0% (expected) at 95% C.L. using 1.9 fb\(^{-1}\)

  – Z→ℓℓ + ≥4 jets
  – Complementary search
FCNC Motivation

- Search for signal using new final state: X is any number of jets
  \[ p\bar{p} \rightarrow t\bar{t} \rightarrow ZqWb \rightarrow lll\nu + X \]
- Extract or set limits on branching ratio of \( t\rightarrow Zq \) (q = u, c)

- ATLAS results: B(t→Zq) < 17% (observed) with a < 12% (expected) at 95% C.L. using 35 pb\(^{-1}\) ATLAS-CONF-2011-061
  - Three leptons + MET + 2 jets
DZero Detector

- Consists of three sub-detectors:
  - Tracking: Reconstruct interaction vertices and measure momenta of charged particles, enclosed in a 1.9 T solenoid field
  - Calorimeter: EM and Hadronic calorimeters measure energies of hadrons, electrons and photons
  - Muon: consists of three layers of drift tubes and scintillation counters (one layer inside a 1.8 T toroidal magnet)
DZero Detector

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Event Selection

- Use 4.1 fb\(^{-1}\) of integrated luminosity collected in Tevatron Run II, with selection criteria optimized for \(s/\sqrt{s+b}\).
- Signal: FCNC \(t\bar{t}\), Main Backgrounds: \(WZ, ZZ, Z\gamma, Z/W\text{+Jets, SM } t\bar{t}\)
  - Determined using MC Simulations and Data

\[ \geq 3 \text{ isolated leptons, with high } p_T, \text{ separated in } \Delta R = \sqrt{(\Delta \eta^2 + \Delta \phi^2)} \]

Imbalance in transverse momentum (MET)

Three jet multiplicity bins; 0, 1, \(\geq 2\)

All from same vertex

Invariant dilepton mass within Z window
FCNC Signal Modeling

- Use CompHEP to generate the signal at the parton level (to correctly model the helicity structure) and PYTHIA for jet development and hadronization
  - Modified to include the following FCNC Lagrangian
    \[
    \mathcal{L}_{FCNC} = \frac{e}{2 \sin \theta_W \cos \theta_W} \bar{t} \gamma_\mu (v_Z - a_Z \gamma_5) c Z^\mu + h.c.
    \]

- Assume SM neutral current couplings (Z → q\bar{q} for up-type quarks):
  \[v_{tuZ} = 1/2 - \frac{4}{3} \sin^2 \theta_W = 0.192, \ a_{tuZ} = 1/2\]
FCNC Signal Modeling

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- Assume SM neutral current couplings ($Z \rightarrow q \bar{q}$ for up-type quarks): $v_{tuZ} = 1/2 - 4/3 \sin^2 \theta_W = 0.192$, $a_{tuZ} = 1/2$

From CompHEP: $p \bar{p} \rightarrow t \bar{t} \rightarrow Z q W^- b \rightarrow e^+ e^- q \mu^- \nu_\mu \bar{b}$

Define arbitrary angle, $\theta^*$, between momentum of $Z$ in the top rest frame and the positively charged lepton momentum from $Z \rightarrow ee$ in the $Z$ rest frame.

\[ FCNC \ t \rightarrow e^+ e^- q \]

\[ SM \ \bar{t} \rightarrow \mu^- \nu_\mu \bar{b} \]
Yields and Jet Distribution

- 35 candidate events
  - Expected background = 31.8 ± 0.3(stat) ± 3.9(syst) events
- Dominant Systematic Uncertainties: Lepton ID, Theoretical Cross Sections (including FCNC $t\bar{t}$ signal), Jet Energy Scale (JES), Jet Energy Resolution (JER)

All distributions are shown with $B(t\rightarrow Zq) = 5\%$
Scalar $H_T$ Distributions

- $H_T = \Sigma p_T(\text{leptons}) + \text{MET} + \Sigma p_T(\text{jets})$
- $H_T$ peak-value increases with jet multiplicity ($n_{\text{jet}}$)

**Diagram:**
- $DØ, 4.1 \text{ fb}^{-1}$
- $n_{\text{jet}} = 0$
- $n_{\text{jet}} = 1$
- $n_{\text{jet}} \geq 2$

**Legend:**
- $t\bar{t}$ FCNC, $B(t\rightarrow Zq)=5\%$
- Data
- WZ
- ZZ
- Other backgrounds
Limits on $B(t \to Zq)$

- Use $n_{\text{jet}}, H_T$, and reconstructed top quark mass ($m_{t\text{reco}}$) (from the two $Z$ leptons and jets) to separate signal from background
- Good separation is observed between signal and background using these three variables
Limits on $B(t\rightarrow Zq)$

- Use Poisson probabilities, with systematic uncertainty parameterized through Gaussian smearing, to extract the limits
- $B(t\rightarrow Zq) < 3.2\%$ (observed), $< 3.8\%$ (expected) at 95% C.L.
Limits on $v_{tqZ}$ Coupling

- Coupling limits:

  $v_{tqZ} < 0.19$ (observed), $< 0.21$ (expected) at 95% C.L.

\[ m_t = 175 \text{ GeV}, \sigma_{t\bar{t}} = 6.90 \text{ pb} \]
\[ a_{tuZ} = v_{tcZ} = a_{tcZ} = \kappa_{tc\gamma} = 0 \]

DØ, $L = 4.1 \text{ fb}^{-1}$
Candidate eee + 1 jet Event

- eee + 1 jet candidate event, with $m_t^{\text{reco}} = 351$ GeV
Summary

• No indication of new physics at this level of statistics
• Recently published in Physics Letters B 701, 313 (2011)
• $B(t \to Zq) < 3.2\%$ (observed), $< 3.8\%$ (expected) at 95% C.L.
• Coupling limits $v_{tqZ} < 0.19$ (observed), $< 0.21$ (expected) at 95% C.L.
  – World’s best limits on $v_{tqZ}$!

Long Live
Detailed Event Selection

• Look for a signal with 3 or more isolated leptons and an imbalance in transverse momentum (MET)
• Use 4.1 fb\(^{-1}\) of integrated luminosity collected from the Tevatron Run II, selection criteria optimized with \(s/\sqrt{s+b}\).
• Main Backgrounds: \(WZ, ZZ, Z\gamma, V+Jets, SM\) \(t\bar{t}\bar{b}\)
  – Determined using MC Simulations and Data
• General selection criteria for all leptons:
  – Invariant dilepton mass (74 GeV \(<\, M_{ee} \,< 104\) GeV, 65 GeV \(<\, M_{\mu\mu} \,< 115\) GeV, 60 GeV \(<\, M_{eeICR} \,< 120\) GeV)
  – Missing Transverse Energy \(>\) (20 - 30) GeV
  – Lepton \(p_T\) \(>\) (15 - 30) GeV
  – Lepton \(\Delta R\) \((=\sqrt{\Delta\phi^2 + \Delta\eta^2})\) \(>\) 0.5 - 0.6
  – \(\Delta Z_{DCA}\) (between any two lepton tracks) \(<\) 3 cm
  – Jet \(E_T\) \(>\) 20 GeV
FCNC Event Yields

<table>
<thead>
<tr>
<th>Source</th>
<th>$e^+e^-$</th>
<th>$e^+\mu$</th>
<th>$e^-\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WZ$</td>
<td>5.17 ± 0.06 ± 0.97</td>
<td>5.72 ± 0.07 ± 0.89</td>
<td>4.76 ± 0.06 ± 0.70</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>0.25 ± 0.03 ± 0.05</td>
<td>1.35 ± 0.06 ± 0.21</td>
<td>0.52 ± 0.04 ± 0.08</td>
</tr>
<tr>
<td>$V + jets$</td>
<td>0.42 ± 0.11 ± 0.08</td>
<td>0.14 ± 0.04 ± 0.06</td>
<td>0.48 ± 0.11 ± 0.01</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>0.18 ± 0.05 ± 0.07</td>
<td>&lt; 0.001</td>
<td>0.66 ± 0.07 ± 0.38</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>0.04 ± 0.01 ± 0.01</td>
<td>0.013 ± 0.004 ± 0.002</td>
<td>0.05 ± 0.01 ± 0.01</td>
</tr>
<tr>
<td>Total bkg.</td>
<td>6.05 ± 0.14 ± 0.98</td>
<td>7.22 ± 0.10 ± 0.92</td>
<td>6.43 ± 0.15 ± 0.71</td>
</tr>
<tr>
<td>Observed</td>
<td>7</td>
<td>10</td>
<td>9</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>$\mu^+\mu^-$</th>
<th>$e^+e^-_{IC}$</th>
<th>$e^+\mu^-_{IC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WZ$</td>
<td>6.09 ± 0.07 ± 1.00</td>
<td>1.46 ± 0.03 ± 0.24</td>
<td>1.78 ± 0.04 ± 0.25</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>1.31 ± 0.06 ± 0.22</td>
<td>0.08 ± 0.01 ± 0.02</td>
<td>0.46 ± 0.03 ± 0.07</td>
</tr>
<tr>
<td>$V + jets$</td>
<td>0.18 ± 0.05 ± 0.03</td>
<td>0.18 ± 0.07 ± 0.08</td>
<td>0.26 ± 0.18 ± 0.16</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>&lt; 0.001</td>
<td>0.10 ± 0.01 ± 0.03</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>0.04 ± 0.01 ± 0.01</td>
<td>0.010 ± 0.003 ± 0.002</td>
<td>0.022 ± 0.004 ± 0.003</td>
</tr>
<tr>
<td>Total bkg.</td>
<td>7.75 ± 0.13 ± 1.02</td>
<td>1.83 ± 0.08 ± 0.26</td>
<td>2.52 ± 0.19 ± 0.31</td>
</tr>
<tr>
<td>Observed</td>
<td>5</td>
<td>1</td>
<td>3</td>
</tr>
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McGivern, SUSY 2011
### FCNC Event Yields

<table>
<thead>
<tr>
<th>Source</th>
<th>$e e e$</th>
<th>$e e \mu$</th>
<th>$e \mu \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WZ$</td>
<td>$0.69 \pm 0.02 \pm 0.14$</td>
<td>$0.80 \pm 0.03 \pm 0.14$</td>
<td>$0.73 \pm 0.02 \pm 0.13$</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>$0.07 \pm 0.02 \pm 0.01$</td>
<td>$0.28 \pm 0.03 \pm 0.05$</td>
<td>$0.16 \pm 0.02 \pm 0.03$</td>
</tr>
<tr>
<td>$V + jets$</td>
<td>$0.21 \pm 0.08 \pm 0.04$</td>
<td>$0.06 \pm 0.03 \pm 0.02$</td>
<td>$0.21 \pm 0.06 \pm 0.01$</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>$0.04 \pm 0.03 \pm 0.02$</td>
<td>$&lt; 0.001$</td>
<td>$0.17 \pm 0.04 \pm 0.10$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$0.012 \pm 0.004 \pm 0.002$</td>
<td>$0.006 \pm 0.002 \pm 0.001$</td>
<td>$0.009 \pm 0.002 \pm 0.001$</td>
</tr>
<tr>
<td>Total bkg.</td>
<td>$1.02 \pm 0.09 \pm 0.15$</td>
<td>$1.15 \pm 0.05 \pm 0.15$</td>
<td>$1.09 \pm 0.05 \pm 0.17$</td>
</tr>
<tr>
<td>Observed</td>
<td>$1$</td>
<td>$2$</td>
<td>$1$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>$\mu \mu$</th>
<th>$ee_{ICRe}$</th>
<th>$ee_{ICRe}\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WZ$</td>
<td>$0.93 \pm 0.03 \pm 0.19$</td>
<td>$0.20 \pm 0.01 \pm 0.04$</td>
<td>$0.24 \pm 0.01 \pm 0.05$</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>$0.28 \pm 0.03 \pm 0.06$</td>
<td>$0.02 \pm 0.01 \pm 0.01$</td>
<td>$0.08 \pm 0.01 \pm 0.01$</td>
</tr>
<tr>
<td>$V + jets$</td>
<td>$0.07 \pm 0.03 \pm 0.03$</td>
<td>$0.04 \pm 0.03 \pm 0.04$</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>$&lt; 0.001$</td>
<td>$0.016 \pm 0.004 \pm 0.005$</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$0.013 \pm 0.004 \pm 0.002$</td>
<td>$0.008 \pm 0.003 \pm 0.001$</td>
<td>$0.008 \pm 0.002 \pm 0.001$</td>
</tr>
<tr>
<td>Total bkg.</td>
<td>$1.24 \pm 0.04 \pm 0.20$</td>
<td>$0.29 \pm 0.03 \pm 0.06$</td>
<td>$0.33 \pm 0.01 \pm 0.05$</td>
</tr>
<tr>
<td>Observed</td>
<td>$1$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
</tbody>
</table>

### ≥ 2 Jets Bin

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>$WZ$</td>
<td>$0.08 \pm 0.01 \pm 0.02$</td>
<td>$0.12 \pm 0.01 \pm 0.03$</td>
<td>$0.11 \pm 0.01 \pm 0.04$</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>$0.0108 \pm 0.005 \pm 0.003$</td>
<td>$0.04 \pm 0.01 \pm 0.02$</td>
<td>$0.03 \pm 0.01 \pm 0.02$</td>
</tr>
<tr>
<td>$V + jets$</td>
<td>$0.06 \pm 0.04 \pm 0.08$</td>
<td>$0.04 \pm 0.03 \pm 0.01$</td>
<td>$0.03 \pm 0.03 \pm 0.01$</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>$0.03 \pm 0.02 \pm 0.01$</td>
<td>$&lt; 0.001$</td>
<td>$0.05 \pm 0.02 \pm 0.03$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$0.011 \pm 0.004 \pm 0.002$</td>
<td>$0.006 \pm 0.003 \pm 0.001$</td>
<td>$0.03 \pm 0.01 \pm 0.01$</td>
</tr>
<tr>
<td>Total bkg.</td>
<td>$0.19 \pm 0.05 \pm 0.08$</td>
<td>$0.21 \pm 0.03 \pm 0.04$</td>
<td>$0.65 \pm 0.11 \pm 0.06$</td>
</tr>
<tr>
<td>Observed</td>
<td>$0$</td>
<td>$1$</td>
<td>$0$</td>
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<th>$ee_{ICRe}\mu$</th>
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<td>$0.03 \pm 0.01 \pm 0.01$</td>
<td>$0.03 \pm 0.01 \pm 0.01$</td>
</tr>
<tr>
<td>$ZZ$</td>
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<td>$0.004 \pm 0.003 \pm 0.004$</td>
<td>$0.008 \pm 0.004 \pm 0.002$</td>
</tr>
<tr>
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<td>$&lt; 0.001$</td>
<td>$0.07 \pm 0.04 \pm 0.04$</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>$&lt; 0.001$</td>
<td>$0.001 \pm 0.001 \pm 0.001$</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$0.018 \pm 0.004 \pm 0.003$</td>
<td>$0.002 \pm 0.002 &lt; 0.001$</td>
<td>$0.011 \pm 0.003 \pm 0.002$</td>
</tr>
<tr>
<td>Total bkg.</td>
<td>$0.50 \pm 0.09 \pm 0.05$</td>
<td>$0.11 \pm 0.04 \pm 0.04$</td>
<td>$0.05 \pm 0.01 \pm 0.01$</td>
</tr>
<tr>
<td>Observed</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
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