Searches for New Physics in the Top Quark Samples at CDF

15th International Conference on Supersymmetry and the Unification of Fundamental Interactions
Parallel session: “ALTernatives”

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On behalf of the CDF Collaboration
**MOTIVATION**

Top is MASSIVE $M_{\text{TOP}} = 170.9 \pm 1.8$ GeV/c$^2$ (TEWG hep-ex/0703034)

Decays before hadronization

$\Gamma_t = 1.4 \text{GeV} \Rightarrow \eta/\Gamma_t \approx 5 \times 10^{-25} s < < \eta/\Lambda_{QCD} \approx 3 \times 10^{-24} s$

→ Spin information transferred to decay products

Special role in EWSB?

→ Top Yukawa coupling to Higgs is “natural” (~1)
→ $M_{\text{top}}$ together with $M_W$ constrains $M_{\text{Higgs}}$

New physics in the top quark samples?

Searches in the production:

$\sigma_{tt}, \sigma(gg\to tt)/\sigma(qq\to tt)

Z'\to tt

t'\to Wb

Searches in the decay:

Top charge.

FCNC $t\to Zq$

$W$ helicity
THE EXPERIMENTAL SETUP

- The CDF II detector:
  - Excellent tracking system:
    - Drift chamber: Central Outer Tracker.
    - Inner silicon detector: essential for b-tagging and vertexing.
  - EM and HAD calorimeters.
  - MUON systems.

- TEVATRON RUN II:
  - Proton-Antiproton Synchrotron
  - $\sqrt{s} = 1.96$ TeV
  - Aim for 6-8 fb$^{-1}$ by 2009.

- Searches for new physics in ~1 fb$^{-1}$ top quark samples

TOP PHYSICS require a good understanding of the entire detector

Delivered 3106.5
Recorded 2551.8
Eff = 82 %
TOP QUARK PRODUCTION & DECAY

Produce in pairs via strong interaction

At $\sqrt{s}=1.96 \pm 14$ TeV:
- $85 \pm 10\%$ $qq$
- $15 \pm 90\%$ $gg$

Decay via electroweak interaction $\sim 100\%$ BR($t \rightarrow W^+b$)

$tt \rightarrow W(\rightarrow lv)bW(\rightarrow lv)b$ (e+$\mu$: 5%)
- low background, low yield
  $\rightarrow$ DILEPTON SAMPLE

$tt \rightarrow W(\rightarrow lv)bW(\rightarrow qq)b$ (e+$\mu$:35%)
- background moderate, medium yield
  $\rightarrow$ LEPTON PLUS JETS SAMPLE

$tt \rightarrow W(\rightarrow qq)bW(\rightarrow qq)b$ all hadronic (45%)
- high background, high yield
### σ(pp-bar→tt-bar) MEASUREMENTS

<table>
<thead>
<tr>
<th>Method</th>
<th>σ$_{tt}$ (NLO-THEO)</th>
<th>σ$_{tt}$ (CDF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton+Track (L=1070 pb$^{-1}$)</td>
<td>6.7 ± 0.8 pb</td>
<td>7.3 ± 0.9 pb</td>
</tr>
<tr>
<td>Dilepton (L=1200 pb$^{-1}$)</td>
<td>6.2 ± 1.1 ± 0.7 ± 0.4 pb</td>
<td></td>
</tr>
<tr>
<td>Lepton+Jets: Kinematic ANN (L= 760 pb$^{-1}$)</td>
<td>8.3 ± 1.3 ± 0.7 ± 0.5 pb</td>
<td></td>
</tr>
<tr>
<td>Lepton+Jets: Vertex Tag (L=1120 pb$^{-1}$)</td>
<td>8.2 ± 0.5 ± 0.8 ± 0.5 pb</td>
<td></td>
</tr>
<tr>
<td>Lepton+Jets: Soft Muon Tag (L= 760 pb$^{-1}$)</td>
<td>7.8 ± 1.7 ± 1.0 ± 0.5 pb</td>
<td></td>
</tr>
<tr>
<td>MET+Jets: Vertex Tag (L= 311 pb$^{-1}$)</td>
<td>6.1 ± 1.2 ± 1.4 ± 0.4 pb</td>
<td></td>
</tr>
<tr>
<td>All-hadronic: Vertex Tag (L=1020 pb$^{-1}$)</td>
<td>8.3 ± 1.0 ± 2.0 ± 1.5 ± 0.5 pb</td>
<td></td>
</tr>
<tr>
<td>Combined (old SLT, all-had) (L= 760 pb$^{-1}$)</td>
<td>7.3 ± 0.5 ± 0.6 ± 0.4 pb</td>
<td></td>
</tr>
</tbody>
</table>

σ$_{tt}$ measured in ALL final states:
- Independent top quark samples with different non-SM sensitivities.

12% ACCURACY: THEORY & EXPERIMENT


σ$_{tt}$ (NLO-THEO) ≃ 6.7 ± 0.8 pb
(M$_{TOP}$=175GeV/c$^2$)
THE \( \sim 1 \text{ fb}^{-1} \) TOP QUARK SAMPLES

**DILEPTON SAMPLE**

- 2 high \( P_T \) leptons (e, \( \mu \)) \( P_T > 20 \text{ GeV/c} \)
- 2 high \( E_T \) jets.
- High Missing \( E_T \)

<table>
<thead>
<tr>
<th>Events</th>
<th>0 jet</th>
<th>1 jet</th>
<th>( \geq 2 ) jet</th>
<th>( HT &gt; 200 + OS )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>200</td>
<td>140</td>
<td>80</td>
<td>20</td>
</tr>
<tr>
<td>Bkgd</td>
<td>200</td>
<td>140</td>
<td>80</td>
<td>20</td>
</tr>
<tr>
<td>( \sigma = 6.7 \text{ pb} )</td>
<td>200</td>
<td>140</td>
<td>80</td>
<td>20</td>
</tr>
<tr>
<td>DY</td>
<td>200</td>
<td>140</td>
<td>80</td>
<td>20</td>
</tr>
<tr>
<td>Fake</td>
<td>200</td>
<td>140</td>
<td>80</td>
<td>20</td>
</tr>
</tbody>
</table>

**L+JETS SAMPLE**

- 1 high \( P_T \) lepton (e, \( \mu \)) \( P_T > 20 \text{ GeV/c} \)
- \( \geq 4 \) high \( E_T \) jets.
- High Missing \( E_T \)
- B-tagging with secondary vertex.

<table>
<thead>
<tr>
<th>Number of Tagged Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
</tr>
<tr>
<td>Data</td>
</tr>
</tbody>
</table>

| SIGNAL | | CONTROL |
|--------|-----------------|
| DATA   | 169             |
| L+JETS | 62              |

<table>
<thead>
<tr>
<th></th>
<th>Total Backgr.</th>
<th>( \sigma = 6.7 \text{ pb} )</th>
<th>Total SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATA</td>
<td>25.6±5.5</td>
<td>55.9±4.3</td>
<td>81.5±8.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Total Backgr.</th>
<th>( \sigma = 6.7 \text{ pb} )</th>
<th>Total SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATA</td>
<td>167 ± 5.9</td>
<td>153.5 ± 15.6</td>
<td>170 ± 17</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>( \geq 5 ) jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATA</td>
<td>4.7 ± 1.7</td>
</tr>
<tr>
<td>L+JETS</td>
<td>53.6 ± 5.5</td>
</tr>
</tbody>
</table>

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<thead>
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</table>
\( \sigma(gg \rightarrow tt) / \sigma(pp \rightarrow tt) : \langle N_{TRK} \rangle \text{ VS } \langle N_{gluon} \rangle \)

Sensitive to new top production & decay mechanisms simultaneously.


Top quark from gluino decays and top quark decays to stops

PRINCIPLE: \( gg \rightarrow tt \) tends to have more underlying event activity w.r.t \( qq \rightarrow tt \)

Calibrate \( \langle N_{TRK} \rangle \) (low \( P_T \) tracks) vs. \( \langle N_g \rangle \) correlation with \( W+\)jets and dijet data. Fit \( W+\)jets (b-tagged) data to \( \langle N_{TRK} \rangle \) templates: gluon-rich (DIJET 80-100 GeV) no-gluon (\( W+0 \) jets)

\[
\sigma(gg \rightarrow \tilde{t}\tilde{t}) / \sigma(p\bar{p} \rightarrow \tilde{t}\tilde{t}) = 0.07 \pm 0.14(\text{stat}) \pm 0.07(\text{syst})
\]
\( \sigma(gg \rightarrow tt)/\sigma(pp \rightarrow tt) \): neural network

- **PRINCIPLE**: \( gg \) (qq-bar) tt-bar events tend to be produced with unlike (like) spin.
- Use NN with 8 input variables:
  - 2 in the tt-bar reference frame: \( \beta \) and angle top quark-incoming parton.
  - Kinematic information from the production.
  - 6 angles between decay products in the “off-diagonal” bases
    - Spin correlation information from the decay.
- Fit data to templates built from the NN output shapes.

\[ \sigma(gg \rightarrow tt)/\sigma(pp \rightarrow tt) < 0.61 \text{ at } 95\% \text{ CL} \]
Search for resonant top pair production

- Sensitive to new resonant t-tbar production mechanisms:
  - Extended Gauge Theories
  - KK states of the gluon, Z
  - Topcolor
    - C. Hill, S. Park, PRD49, 4454, 1994

- Search for narrow width Z' (1.2% of the mass) with same coupling as Z0
  - no resonant interference with the s channel gluon production.

- Reconstruct Mtt-bar with kinematic fitter.
- Binned likelihood fit of data to 3 templates:
  - SM tt-bar, Z'→tt-bar, non tt-bar
  - Range of Z' masses (450-900 GeV/c^2)

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

95%CL: σ(Z'→tt-bar)< 0.7 pb^{-1}
for M_{Z'} > 700 GeV/c^2
Search for a Heavy Top $t' \rightarrow Wb$

- Hypothesis: $t'$ is pair-produced strongly, heavier than SM top quark, decay to $Wb$.
- 2HD models and N=2 SUSY models can accommodate a heavier 4th fermion generation with $m_{Z/2} < m_t < m_{Higgs}$ (hep-ph/0102144, hep-ph/0111028).

- Data fitted to templates ($t'$, top, background) with 2D binned likelihood ($H_T$ and $M_{RECO}$).

$m_t > 256 \text{ GeV} / c^2 \at 95\% CL$
Event Displays: high $H_T$ high $M_{REC}$ candidates

CDF Run 2 Preliminary

- $H_T$, GeV
- $M_{REC}$, GeV

- Green: $W^+\text{jets}$
- Blue: $t\bar{t}$, $m_t = 175$ GeV
- Black: Data, 760 pb$^{-1}$

- Run 194323
- Event 9830702

- Run 196441
- Event 5763952

- $p_T(\mu)$: 159 GeV
- $E_T$: 785 GeV
- $M_{REC}$: 474 GeV

- $E_T$: 177 GeV
- $E_T$: 82.3 GeV
- $E_T$: 29.8 GeV
- $E_T$: 192 GeV (b-tagged)

- $E_T$: 135 GeV
- $E_T$: 192 GeV (b-tagged)

- $E_T$: 312 GeV
- $p_T(e)$: 27.4 GeV
- $E_T$: 40.2 GeV
- $E_T$: 35.4 GeV
- $E_T$: 253 GeV
- $E_T$: 55.4 GeV

- $H_T$: 732 GeV
- $M_{REC}$: 425 GeV
- $E_T$: 263 GeV
Top quark charge: +2/3 or -4/3?

- Hypothesis: Top quark charge = -4e/3
  - New exotic quark part of a fourth generation. D. Chang et al. PRD 59, 09153(99)

- A challenging experimental method:
  - Jet Charge algorithm:
    \[ Q_{\text{jet}} = \frac{\sum q_i (p_i^{\text{track}} \cdot \hat{a}_{\text{jet}})^{0.5}}{\sum (p_i^{\text{track}} \cdot \hat{a}_{\text{jet}})^{0.5}} \]
  - Calibration with dijet data bb-bar enriched
  - “Purity”:= probability of correctly pairing Wb and getting the correct flavor of b-jet
  - Counting experiment:
    - 62 Standard Model-like (SM)
    - 48 Exotic Model-like (XM)
  - Likelihood versus f+: Fraction of pairs with charge 2e/3 in data.
  - Result:
    Consistent with charge 2e/3 hypothesis
    Exclude charge -4e/3 hypothesis at 81% confidence
Search for the FCNC decay $t\rightarrow Zq$

- SM: Top quark FCNC highly suppressed (GIM mechanism and CKM suppression)
- Beyond SM scenarios enhance top FCN decays providing observable BR’s

<table>
<thead>
<tr>
<th>Model</th>
<th>SM</th>
<th>Q=2/3 quark singlets</th>
<th>2HDM</th>
<th>MSSM</th>
<th>RPV-SUSY</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR($t\rightarrow qZ$)</td>
<td>$\sim 10^{-14}$</td>
<td>$\sim 10^{-4}$</td>
<td>$\sim 10^{-7}$</td>
<td>$\sim 10^{-6}$</td>
<td>$\sim 10^{-5}$</td>
</tr>
</tbody>
</table>

- Blind search in $tt \rightarrow Zq Wb$
  - $Z \rightarrow e^+e^-,\mu^+\mu^-$ (clean signature)
  - 4 jets (larger BR of hadronic $W \rightarrow qq'$)
  - Two separate signal regions: zero b-tags – one or more b-tag

- Backgrounds: from data-driven and MC methods
  - Dominant background: $Z$+Jets production
  - Smaller backgrounds: $tt$ and diboson ($WZ$, $ZZ$)
Search for the FCNC decay $t \rightarrow Zq$ (Cont.)

- Optimize event selection for best expected limit
  - Strongest discriminator: Mass $\chi^2$: reconstructed W, SM Top and NON-SM FCNC Top masses
    \[
    \chi^2 = \left( \frac{m_{W,\text{rec}} - m_{W,\text{PDG}}}{\sigma_{W,\text{rec}}} \right)^2 + \left( \frac{m_{t-Wb,\text{rec}} - m_{t,\text{PDG}}}{\sigma_{t-Wb}} \right)^2 + \left( \frac{m_{t-Zq,\text{rec}} - m_{t,\text{PDG}}}{\sigma_{t-Zq}} \right)^2
    \]

- Unblinding after optimization: observed numbers events consistent with background

<table>
<thead>
<tr>
<th>Selection</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Selection</td>
<td>141</td>
<td>130±28</td>
</tr>
<tr>
<td>Base Selection (Tagged)</td>
<td>17</td>
<td>20±6</td>
</tr>
<tr>
<td>Anti-Tagged Selection</td>
<td>12</td>
<td>7.7±1.8</td>
</tr>
<tr>
<td>Tagged Selection</td>
<td>4</td>
<td>3.2±1.1</td>
</tr>
</tbody>
</table>

$B(t \rightarrow Zq) < 10.6\%$ @ 95\% C.L

- New world’s best limit: improves previous limit by 25% (13.7\% from non-observation of $e^+e^- \rightarrow tq$ at LEP,L3)
W Helicity in Top Quark Decays

SM: Top quark decays via weak interaction to spin-1 $W^+$ boson and spin-1/2 $b$ quark → V-A coupling like all other fermions:

\[-\frac{ig}{2\sqrt{2}} \bar{t} \gamma^\mu (1 - \gamma^5) V_{tb} b W^\mu\]

$W_0$ longitudinal fraction $F_0 = 0.7$

$W_-$ left-handed fraction $F_- = 0.3$

$W_+$ right-handed fraction $F_+ = 0.0$


The presence of V+A could signal new physics: Left-right symmetric models? Mirror fermions?


W-helicity: \( \cos\theta^* \) method (I)

- Binned likelihood fitter:
- Fits data to signal and MC templates.
- Signal Templates: from theoretical curves plus detector efficiency and resolution corrected

\[ \frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta} = \frac{3}{4} (1-\cos^2\theta) F^0 + \frac{3}{8} (1-\cos\theta)^2 F^- + \frac{3}{8} (1+\cos\theta)^2 F^+ \]

- \( f_0 = 0.59 \pm 0.12_{\text{stat}} + 0.07_{\text{syst}} - 0.06_{\text{syst}} \)
- \( f_+ = -0.03 \pm 0.06_{\text{stat}} + 0.04_{\text{syst}} - 0.03_{\text{syst}} \) with \( f_+ = 0 \)
- \( f_+ < 0.10 @95\% \text{ CL} \)

tt-bar kinematics fully reconstructed.
- Extract \( \cos\theta \) by boosting lepton and top into W rest frame.

Unfolding of measured distribution:
Correct for efficiency and migration effects.
**W-helicity: cosθ* method (II)**

SECOND METHOD TO EXTRACT $F_0$ AND $F_+$

- Unbinned likelihood fitter.
- Fits data to signal and MC shapes:
  - 3rd order polynomial times exponent parameterizations from templates.
  - Simultaneous fit to extract: $F_0$ and $F_+$

$$f_0 = 0.74 \pm 0.25^{\text{stat}} \pm 0.06^{\text{syst}} \text{ and } f_+ = -0.06 \pm 0.10^{\text{stat}} \pm 0.03^{\text{syst}}$$

$$f_0 = 0.61 \pm 0.12^{\text{stat}} \pm 0.06^{\text{syst}} \text{ with } f_+ = 0$$

$$f_+ = -0.06 \pm 0.06^{\text{stat}} \pm 0.03^{\text{syst}} \text{ with } f_0 = 0.7 \text{ and } f_+ < 0.11 \text{ at 95\% CL}$$
CONCLUSIONS AND PROSPECTS

- The CDF top quark samples with $L = 1.1 - 1.2 \text{ fb}^{-1}$ have been reestablished:
  - Top pair production cross section has been measured and found in good agreement with QCD-NLO predictions.

- A lot of challenging and creative “ALTERNATIVE” searches have been performed on the CDF top quark samples in order to find NEW PHYSICS.
  - New production mechanisms: resonances, $t'$, etc
  - New decay mechanisms: FCNC $t \rightarrow Zq$
  - Search for deviations in SM values of measured top properties: charge, $W$ helicity.
  - For the time being are very statistical limited, but the methodology is in place.
  - 2fb$^{-1}$ analyses coming by the end of summer.

NO EVIDENCE OF NEW PHYSICS IN THE 1 fb$^{-1}$ CDF TOP QUARK SAMPLES

- All the ongoing CDF analysis techniques described can be applied to search for new physics in the TEVATRON PHASE OF THE LHC (early LHC data 0.1-1 fb$^{-1}$)
  - Background methods for total rates and shapes.
  - Determination of systematic uncertainties.
  - Statistical machinery to extract limits.
Charged Higgs from Top quark decays

Branching ratio for $t \to H^+ b$ significant (>10%) for small and large tan$\beta$

$H^+$ decays differently than $W^+$:
- $H^+ \to \tau^+ \nu_\tau$ enhanced if high tan$\beta$:
  - Excess of taus
- $H^+ \to t^* b \to W^+ b b$ for high $m(H^+)$ if low tan$\beta$:
  - Mimics SM signature but observe more b-tags
- $H^+ \to c s$: defect all channels.

Compare number of observed events in 4 ttbar final states:
- dilepton, $e\tau_h + \mu\tau_h$
- lepton+jets with single b-tag, and
- lepton+jets with double b-tags

(Phys. Rev. Lett 96,042003)

Limits on $\text{BR}(t \to H^+ b)$

\begin{align*}
M_{t^*} = 140 \text{ GeV} \\
\text{Branching ratio}
\end{align*}

\begin{align*}
M_{H^+} \text{ decays to} \\
\tau^+ \nu_\tau & \quad \cdot \quad \cdot \\
c s & \quad \cdot \quad \cdot \\
t^* b & \quad \cdot \quad \cdot \\
W^+ h^0 & \quad \cdot \quad \cdot \\
W^+ A^0 & \quad \cdot \quad \cdot \\
\text{BR}(t \to H^+ b)
\end{align*}

\begin{align*}
\text{CDF II Preliminary} \\
\text{Excluded 95\%CL} \\
m_{H^+} = 175 \text{ GeV/c}^2 \\
| L_{dt} | = 192 \text{ pb}^{-1}
\end{align*}

\begin{align*}
\text{Comparing number of observed events in 4 ttbar final states:} \\
dilepton, e\tau_h + \mu\tau_h \\
\text{lepton+jets with single b-tag, and} \\
\text{lepton+jets with double b-tags}
\end{align*}

(Phys. Rev. Lett 96,042003)


**W′-like resonances in the tb-bar decay channel.**

- Beyond SM models predict massive W-like bosons describing resonant \( t\bar{b} \) production:
  - Top Color PL B385,304 (1996)

- Single Top analysis methods applied to search for a narrow peak in \( M_{WJJ} \)

- Set limits on \( W' \) production and its coupling to fermion.

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**Graphical Representation:**

- 95% C.L. Limits (2+3 Jets) - CDF Run II Preliminary: 955 pb\(^{-1}\)

- Expected Limit
- ± 1 \( \sigma \) Expected Limit
- Observed Limit

- SM \( W: M(W') > M(\tau) \)
- SM \( W: M(W') < M(\tau) \)

---

- 3 Jets - CDF Run II Preliminary: 955 pb\(^{-1}\)

- Best Fit to Data of Only BG Constrained with Uncertainty

- Best Fit to Data of Unconstrained \( W' \) and BG Constrained within Uncertainty

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**Figure Caption:**

- July 26th, 2007  
  SUSY07 (Session “Alternatives”)  
  Susana Cabrera (IFIC)
A COMMON TOOL: THE “TOP MASS” KINEMATIC FITTER

- Reconstruction of kinematics:
  - Constrain jet-jet mass to W mass.
  - Constrain lepton-neutrino mass to W mass
  - Constrain b-lepton-neutrino and b-jet-jet to Top masses.
  - Top mass equal to anti-top mass
  - Lowest $\chi^2$ gives correct combination in 70% of the cases

$$\chi^2 = \sum_{i=A_4jets} \left( \frac{p_{T,i,fit} - p_{T,i,meas}}{\sigma_i} \right)^2 + \sum_{j=x,y} \left( \frac{p_{j,UE,fit} - p_{j,UE,meas}}{\sigma_{UE,j}} \right)^2 + \frac{(M_{lv} - M_W)^2}{\Gamma_W^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{blv} - m_t^{\text{reco}})^2}{\Gamma_t^2} + \frac{(M_{b^2lj} - m_t^{\text{reco}})^2}{\Gamma_t^2}$$