How Charming is the Truth?
The Search for Top Flavor Changing Neutral Currents
$t \rightarrow Z c$
at CDF Run II

Charles Plager, UCLA
On behalf of the CDF Collaboration
CERN Seminar
July 2nd, 2008
Outline

The Tevatron and the CDF Experiment

The Search for Top FCNC Decay

Strategy
Tevatron Run II: 2001–2009 (2010?)

- Proton-antiproton collider: $\sqrt{s} = 1.96$ TeV.
- 36×36 bunches, collisions every 396 ns.
- Record instantaneous peak luminosity: $315 \cdot 10^{30}$ cm$^{-2}$ s$^{-1}$!
- Luminosity goal: 5.5 – 6.5 fb$^{-1}$ of integrated luminosity by 2009, running in 2010 currently under discussion.
- Two multi-purpose detectors: CDF and DØ.
Tevatron Performance

- Tevatron continues to perform very well:
  - More than 4.3 fb\(^{-1}\) delivered.
  - More than 3.5 fb\(^{-1}\) recorded by CDF.

The Tevatron just delivered 56 pb\(^{-1}\) in *single week*!

---

Luminosity (1/pb)

- Delivered
- Acquired

Run I Total

\(\sim 100\) pb\(^{-1}\)
The CDF II Detector

Central Muon Detector

Hadronic Wall Calorimeter

Central Calorimeter (Em/Had)

Plug Calorimeter (Em/Had)

Forward Muon Detector

Solenoid Magnet

Antiprotons

Luminosity Monitor

Silicon Vertex Detectors

Central Outer Tracker

[CDF]

$\eta = -\ln \tan(\theta/2)$
Outline

The Tevatron and the CDF Experiment

Top Quark Physics

The Search for Top FCNC Decay

Summary
Top Quark History

- CDF and DØ Run I announced the top quark discovery March, 1995.

- This discovery did not “just happen”:
  - Other experiments had been looking for the previous 20 years with no (real) top quark discovery.
    - PETRA (DESY): $e^+e^-$
    - SppS (CERN): $p\bar{p}$
    - LEP I (CERN): $e^+e^-$
  - Run I was in its fourth year (after three years of Run 0 and many years of designing, building, and commissioning the detectors).
For those not intimately familiar with Tevatron high $p_T$ Physics:

**Top:** 1 in 10 Billion

Reducing and understanding backgrounds is the key.
Top Quark Review

- **Top:** the Golden quark (~ 175 GeV/c²)
  - Only fermion with mass near EW scale.
  - 40 times heavier than the bottom quark.

- Very wide (1.5 GeV/c²)
  - The top quarks decay before they can hadronize.
    - We can study the decay of the bare quark.
- Usually observed in pairs.
- **Fundamental question:**
  - Is it the truth, the Standard Model (SM) truth, and nothing but the truth?
    - Did we really find the top quark?
    - Is it the SM top quark?
    - Is it only the SM top quark?
- The top quark is an ideal place to look for Beyond the Standard Model Physics!

\[ \bar{t}t \text{ Pair Lepton + Jets Decay} \]
New Era of Top Precision Physics!

- CDF and DØ now have more than thirty (30 !!!) times as much integrated luminosity as we did when they discovered the top quark in Run I!

- With the data we have recorded, we are now able to have large, very pure top samples.

- Of the almost 50 results that CDF sent to the winter conferences, more than half were in top physics!
What Can We Study About Top Quarks?

Branching ratios
Rare decays
Non-SM decays
Decay kinematics
W helicity
$|V_{tb}|$

Top physics is very rich.

Top charge
Top spin
Top lifetime
Top mass

Production cross section
Resonance production
Production kinematics
Spin polarization
Top Pair Decay Modes

- According to the SM, top quarks almost always decay to Wb.

- When classifying the decay modes, we use the W decay modes:
  - Leptonic
    - Light leptons (e or \(\mu\))
    - Tauonic (\(\tau\))
  - Hadrons

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Branching Fraction</th>
<th>Relative Background</th>
<th>Final State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dilepton - no (\tau)s</td>
<td>(\sim 5%)</td>
<td>Low</td>
<td>(\ell \ell \nu\nu bb)</td>
</tr>
<tr>
<td>Lepton + Jets - no (\tau)s</td>
<td>(\sim 30%)</td>
<td>Medium</td>
<td>(\ell \nu bb jj)</td>
</tr>
<tr>
<td>All Hadronic</td>
<td>(\sim 45%)</td>
<td>High</td>
<td>bb jjjjjj</td>
</tr>
<tr>
<td>Tauonic</td>
<td>(\sim 20%)</td>
<td>High</td>
<td></td>
</tr>
</tbody>
</table>
Important Tool: Lepton ID

- For many analyses, we need a very pure set of high $p_T$ electrons and muons.
  - Electrons (as we reconstruct them):
    - Have charged particle track.
    - Leave almost all of their energy in the electromagnetic calorimeter.
    - Ask for no other nearby tracks.
      - We do not want leptons from (heavy flavor) jets.
  - Muons:
    - Have charged particle track.
    - ~ Minimum ionizing (leave little energy in either the electromagnetic or hadronic calorimeter)
    - Find a “stub” of a track in dedicated muon detector systems on outside of CDF.
    - Ask for no other nearby tracks.
Important Tool: Jet Reconstruction

- We think of *partons*, but we reconstruct *jets*.

- We need to convert "raw" jets to "corrected" jets - Jet Energy Scale (JES) correction.
  - Takes into account detector effects, neutral particles in jets, particles outside of the jet cone, underlying events, multiple interactions, …

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Important Tool: B Jet Tagging

• Since we (often) expect $t \rightarrow W b$, b jet tagging is a very important tool.
  – Most backgrounds do not have bottom quark jets.

  
  
  

• We rely on the long $b$ quark lifetime.
  – $B$ hadrons can travel several millimeters before decaying.
  – Use displaced vertices or many displaced tracks (impact parameter).

CDF Event: Close-up View of Layer 00 Silicon Detector

Run 178855
Event 5504617

Number of Jets = 4
Missing $E_T = 45$ GeV
Muon $p_T = 37$ GeV

2.4 cm
b-tag

Tagged Jet 1: $E_T = 111$ GeV, $\Phi = 79$, $L2d = 7$ mm
Tagged Jet 2: $E_T = 38$ GeV, $\Phi = 355$, $L2d = 1$ mm

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Top Physics *Finally* Makes Prime Time

*The Big Bang Theory!* Mondays on CBS.

Top FCNC

Top Branching Fractions
Top FCNC Outline

The Search for Top FCNC Decay

Introduction

Search For Invisible Top Decays

Direct FCNC Search

Acceptances

Backgrounds

Unblinding

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Flavor Changing Neutral Currents

- Flavor changing neutral current (FCNC) interactions:
  - Transition from a quark of flavor A and charge Q to quark of flavor B with the same charge Q.
  - Examples: $b \rightarrow s\gamma$, $t \rightarrow Hc$, ...

- 1960s: only three light quarks (u,d,s) known, mystery in kaon system:

- Solution: “GIM Mechanism” (Glashow, Iliopoulos, Maiani, 1970)
  - Fourth quark needed for cancellation in box diagram: prediction of charm quark.
  - Cancellation would be exact if all quarks had the same mass: estimate of charm quark mass.
Top Flavor Changing Neutral Currents

- SM Higgs mechanism: weak neutral currents (NC) do not change the flavor of quarks/leptons (“flavor-diagonal”)
  ⇒ no FCNC at “tree level.”

- FCNC possible e.g. via penguin diagrams.

- Suppression of this mode:
  - GIM mechanism
  - Cabibbo suppression

- Expected SM branching fraction (Br) for $t \rightarrow Zc$ as small as $10^{-14}$.

- Any signal at the Tevatron or LHC: New Physics.
Top FCNC & New Physics

- FCNC are **enhanced** in many models of physics beyond the SM.
- Enhancement mechanisms:
  - FCNC interactions at tree level.
  - Weaker GIM cancellation by new particles in loop corrections.
- Examples:
  - **New quark singlets**: \( Z \) couplings not flavor-diagonal \( \rightarrow \) tree level FCNC.
  - **Two Higgs doublet models**: modified Higgs mechanism.
- Flavor changing Higgs couplings allowed at tree level.
- Virtual Higgs in loop corrections.
  - **Supersymmetry**: gluino/neutralino and squark in loop corrections.

<table>
<thead>
<tr>
<th>Model</th>
<th>( \text{BR}(t \rightarrow Zq) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Model</td>
<td>( \mathcal{O}(10^{-14}) )</td>
</tr>
<tr>
<td>( q = 2/3 ) Quark Singlet</td>
<td>( \mathcal{O}(10^{-4}) )</td>
</tr>
<tr>
<td>Two Higgs Doublets</td>
<td>( \mathcal{O}(10^{-7}) )</td>
</tr>
<tr>
<td>MSSM</td>
<td>( \mathcal{O}(10^{-6}) )</td>
</tr>
<tr>
<td>( R )-Parity violating SUSY</td>
<td>( \mathcal{O}(10^{-5}) )</td>
</tr>
</tbody>
</table>

Previous Limits

- Run I Search:
  - 110 pb\(^{-1}\) of data
  - tt → Zc Wb → Z+≥4j
  - Limit: Br (t → Zc) < 33% at 95% C.L.

- Limit from LEP II
  - search for single top production:
    \[ e^+ e^- → t \bar{c} \]
  - 634 pb\(^{-1}\)
  - Limit: Br (t → Zc) < 13.7% at 95% C.L.
  ⇒ Best limit so far with Z bosons.
Search for Invisible Top Decays

• It is the *relative* reconstruction efficiency \( \otimes \) acceptance that determines the relative yield.
  
  - \( R_{wx/ww} \) is the relative acceptance when one top decays to the \( Wb \) while the other decays to the new decay, \( XY \).
  
  - \( R_{xx/ww} \) is the relative acceptance when both top quarks decays to the new decay, \( XY \).

\[
\text{Yield} \propto P(t \bar{t} \rightarrow Wb Wb) + P(t \bar{t} \rightarrow Wb XY) \cdot R_{wx/ww} \\
+ P(t \bar{t} \rightarrow XY XY) \cdot R_{xx/ww}
\]

• Compare expected yield to observed number of candidate events.
  
  - Create Feldman-Cousins acceptance bands using number of observed events.
  
  - \( t \rightarrow Zc, t \rightarrow gc, t \rightarrow \gamma c, t \rightarrow \text{Invisible} \).
Search for Invisible Top Decays, cont.

- From Cacciari et al. (hep-ph: 0804.2800) assuming CTEQ PDFs.
- Expected Limits:

<table>
<thead>
<tr>
<th>Decay</th>
<th>$\mathcal{B}_{wx/ww}$ (%)</th>
<th>175 GeV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t \to Zc$</td>
<td>32</td>
<td>$28^{+14}_{-12}$</td>
</tr>
<tr>
<td>$t \to gc$</td>
<td>27</td>
<td>$26^{+14}_{-11}$</td>
</tr>
<tr>
<td>$t \to \gamma c$</td>
<td>13</td>
<td>$24^{+12}_{-10}$</td>
</tr>
<tr>
<td>$t \to \text{invisible}$</td>
<td>0</td>
<td>$20^{+10}_{-8}$</td>
</tr>
</tbody>
</table>

- Observed Limits:

<table>
<thead>
<tr>
<th>Decay</th>
<th>$\mathcal{B}_{wx/ww}$ (%)</th>
<th>Upper Limit (%) (175 GeV)</th>
<th>Upper Limit (%) (172.5 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(t \to Zc)$</td>
<td>32</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>$\mathcal{B}(t \to gc)$</td>
<td>27</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>$\mathcal{B}(t \to \gamma c)$</td>
<td>18</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>$\mathcal{B}(t \to \text{invisible})$</td>
<td>0</td>
<td>9</td>
<td>10</td>
</tr>
</tbody>
</table>

![Integral of L x dt = 1.9 fb⁻¹](image)

Better Than L3’s Published Limit!

World’s First Measurement!
Top FCNC Direct Search: Roadmap

- Basic question: how often do top quarks decay into $Z_c$?
  - Measure (or set limit) on branching fraction, $\text{Br}(t \rightarrow Z_c)$.
  - Normalize to lepton + jets top pair decays.

- Selection of decay channels for $tt \rightarrow Z_c Wb$:
  - $Z \rightarrow$ charged leptons: very clean signature, lepton trigger.
  - $W \rightarrow$ hadrons: large branching fractions, no neutrinos.
    $\Rightarrow$ Event can be fully reconstructed
  - Final signature: $Z + \geq 4$ jets.

---

$Z$ Decay Modes:
- $70\%$ of $Z \rightarrow \nu\nu$
- $3\%$ of $Z \rightarrow e\bar{e}/\mu\mu$
- $20\%$ of $Z \rightarrow \tau\bar{\tau}$
- $7\%$ of $Z \rightarrow$ hadrons

$W$ Decay Modes:
- $21\%$ of $W \rightarrow l\nu$
- $11\%$ of $W \rightarrow \tau\nu$
- $68\%$ of $W \rightarrow$ hadrons
Search for FCNC: Ingredients

\[ \chi^2_{\text{mass reconstruction}} = \left( \frac{m_W \text{ recon} - m_W}{\sigma_W} \right)^2 + \left( \frac{m_{tWB} \text{ recon} - m_t}{\sigma_{tWB}} \right)^2 + \left( \frac{m_{tZc} \text{ recon} - m_t}{\sigma_{tZc}} \right)^2 \]
Top Mass Reconstruction

- For our signal, we have three hadronic masses to reconstruct:
  - $W$ mass
  - $t \rightarrow Wb$ mass
  - $t \rightarrow Zc$ mass

- To improve resolution, we correct the $W$ and $Z$ daughters so that the masses are correct.
  - Rescale the daughters within their resolutions.
  - Smaller mass resolution $\Rightarrow$ Better signal separation.

Signal MC with partons correctly matched to reconstructed objects.

$t \rightarrow Wb$ mass resolution:
$20 \text{ GeV} \Rightarrow 16 \text{ GeV}$!
• We do not know which partons are reconstructed as which jets.  
  ⇒ Loop over all 12 permutations and take lowest $\chi^2$ value.
Round 1: Blind Analysis

• Event signature: $Z \rightarrow l^+ l^- + 4$ jets.

• Motivation for blind analysis: Avoid biases by looking into the data too early.

• Blinding & unblinding strategy:
  – Initial blinded region: $Z + \geq 4$ jets.
  – Later: add control region in $Z + \geq 4$ jets from high side tail of mass $\chi^2$.
  – Optimization of analysis on data control regions and Monte Carlo (MC) simulation only.
  – Very last step: “opening the box”, i.e., look into signal region in data.
  – Counting experiment:
    ⇒ Compared expected background to observed events.
The Search for Top FCNC Decay

Introduction

Search For Invisible Top Decays

Direct FCNC Searches

Acceptances

Backgrounds

Unblinding

Fitting For Everything
Lepton + Track Z Candidates

- Use isolated track (instead of tight lepton) for second lepton.
  - Doubles acceptance.
  - Almost all backgrounds have real leptons.

- Base Event Selection:
  - Tight lepton + track lepton Z candidate.
  - At least four jets (|\eta| < 2.4, corrected E_T > 15 GeV).
To B-Tag or not to B-Tag?

- **Advantage** of requiring b-tag:
  - Better discrimination against main background (Z + jets).

- **Disadvantage**:
  - Reduction of data sample size.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Before tagging</th>
<th>At least 1 b-tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td>130 (100%)</td>
<td>20 (15%)</td>
</tr>
<tr>
<td>Relative Signal Acceptance</td>
<td>100%</td>
<td>50%</td>
</tr>
</tbody>
</table>

- **Solution**: Use both!
  - Split sample in *tagged* (at least one tagged jet) and *anti-tagged* (no tagged jets).
  - Optimize cuts individually for tagged and anti-tagged samples.
  - Combine samples in limit calculation.
Acceptance Calculation: Catch 22?

\[ N_{\text{signal}} = \left[ (P(t\bar{t} \rightarrow WbZc) \cdot A_{WZ}) + (P(t\bar{t} \rightarrow ZcZc) \cdot A_{ZZ}) \right] \cdot \sigma_{t\bar{t}} \cdot \int \mathcal{L} \, dt \]
Solution: Running Acceptance

\[
N_{\text{signal}} = \left[ (\mathcal{P}(t\bar{t} \rightarrow WbZc) \cdot A_{WZ}) + (\mathcal{P}(t\bar{t} \rightarrow ZcZc) \cdot A_{ZZ}) \right] \cdot \sigma_{t\bar{t}}(B_Z) \cdot \int L \, dt
\]

... 1/2 page of algebra ...

\[
= B_Z \cdot (N_{LJ} - B_{LJ}) \cdot \frac{A_{WZ}}{A_{LJ_{WW}}} \cdot \frac{(2 \cdot (1 - B_Z) + K_{ZZ/WW} \cdot B_Z)}{(1 - B_Z)^2 + 2 \cdot B_Z(1 - B_Z) \cdot R_{wz/ww} + B_Z^2 \cdot R_{zz/ww}}
\]

- Acceptance and \( \sigma_{t\bar{t}} \) depend on \( B_Z \).
- Our limit code recalculates acceptance as a function of branching fraction.
- Normalization to double-tagged top pair cross section measurement:
  - Smallest overlap \( R_{wz/ww} \) between acceptances.

\[
\begin{align*}
B_Z &\equiv Br(t \rightarrow Zc) = 1 - Br(t \rightarrow Wb) \\
A_{WZ} &\equiv \text{FCNC acceptance} \\
A_{ZZ} &\equiv \text{Double FCNC acceptance} \\
A_{LJ_{WW}} &\equiv \text{L+J acceptance for SM } t\bar{t} \\
A_{LJ_{WZ}} &\equiv \text{L+J acceptance for FCNC} \\
A_{LJ_{zz}} &\equiv \text{L+J acceptance for FCNC} \\
K_{ZZ/WW} &\equiv A_{ZZ}/A_{WZ} \\
R_{wz/ww} &\equiv A_{LJ_{WZ}}/A_{LJ_{WW}} \\
R_{zz/ww} &\equiv A_{LJ_{zz}}/A_{LJ_{WW}}
\end{align*}
\]
Expected Backgrounds

- How do you search for a signal that is likely not there? **Understand the background!**

- Standard model processes that can mimic $Z + \geq 4$ jets signature:
  - **$Z+$Jets**: $Z$ boson production in association with jets
    $\rightarrow$ dominant background for top FCNC search, most difficult to estimate
  - **Standard model top pair** production
    $\rightarrow$ small background
  - **Dibosons**: $WZ$ and $ZZ$ diboson production $\rightarrow$ small background
  - **$W+$Jets, $WW$**: negligible

- Top FCNC background estimate: mixture of data driven techniques and MC predictions
Z+Jets Production

• MC tool for Z+Jets: ALPGEN
  – Modern MC generator for multiparticle final states
  – “MLM matching” prescription to remove overlap between jets from matrix element and partons showers

• Comparing ALPGEN with data:
  – Leading order generator: no absolute prediction for cross section.
  – After normalization to total Z yield, still underestimates of number of events with large jet multiplicities.

• Our strategy: only shapes of kinematic distributions from MC, normalization from control samples in data.
  – Normalize to the high side tail of mass $\chi^2$ in data.
• Fit from high side of $\chi^2$ tail:
  $130 \pm 28$ total background events.

• Background tagging rate:
  - 5 of 31 events are tagged.
  - Combine with data-based method in lower jet bins.
  $\Rightarrow 15\% \pm 4\%$ background event tag rate.

<table>
<thead>
<tr>
<th>Selection</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Selection</td>
<td>$130\pm28$</td>
</tr>
<tr>
<td>Base Selection (Tagged)</td>
<td>$20\pm6$</td>
</tr>
</tbody>
</table>
Optimized Signal Region Selection

- Optimized for best average expected limit.

<table>
<thead>
<tr>
<th>Kinematic Variable</th>
<th>Optimized Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z$ Mass</td>
<td>∈ [76,106] GeV/(c^2)</td>
</tr>
<tr>
<td>Leading Jet $E_T$</td>
<td>≥ 40 GeV</td>
</tr>
<tr>
<td>Second Jet $E_T$</td>
<td>≥ 30 GeV</td>
</tr>
<tr>
<td>Third Jet $E_T$</td>
<td>≥ 20 GeV</td>
</tr>
<tr>
<td>Fourth Jet $E_T$</td>
<td>≥ 15 GeV</td>
</tr>
<tr>
<td>Transverse Mass</td>
<td>≥ 200 GeV</td>
</tr>
<tr>
<td>$\sqrt{\chi^2}$</td>
<td>&lt; 1.6 (b-tagged)</td>
</tr>
<tr>
<td></td>
<td>&lt; 1.35 (anti-tagged)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Selection</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anti-Tagged Selection</td>
<td>7.7±1.8</td>
</tr>
<tr>
<td>Tagged Selection</td>
<td>3.2±1.1</td>
</tr>
</tbody>
</table>

- Systematic uncertainties are taken into account, but do not affect limit very strongly.

**Expected Limit:**

6.8% ± 2.9%
First Look

• Before we unblind the signal regions, we want to check our base predictions:

<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>
</tbody>
</table>

• So far, so good… Let’s open the box!
Open the Signal Box

- Opening the box with 1.1 fb\(^{-1}\)
  - Event yield consistent with background only.
  - Fluctuated about 1\(\sigma\) high: slightly “unlucky.”
  - Or is it the first hint of a signal?!

<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(\pm 28)</td>
</tr>
<tr>
<td>Base Selection (Tagged)</td>
<td>17</td>
<td>20(\pm 6)</td>
</tr>
<tr>
<td>Anti-Tagged Selection</td>
<td>12</td>
<td>7.7(\pm 1.8)</td>
</tr>
<tr>
<td>Tagged Selection</td>
<td>4</td>
<td>3.2(\pm 1.1)</td>
</tr>
</tbody>
</table>

- Result:
  \[ \mathcal{B}(t \rightarrow Zq) < 10.4\% \text{ @ 95\%C.L.} \]
  - Expected limit: 6.8\% \pm 2.9\%.
Mass $\chi^2$ (95% C.L. Upper Limit)

CDF II Preliminary
$fL \ dt = 1.12 \ fb^{-1}$

- Data
- FCNC Signal (10.4%)
- Total Background
- Total Syst. Uncertainties
- $\chi^2$ Cut

Entries

0 2 4 6 8
0 5 10 15 20

Tagged Selection

Anti-Tagged Selection

$\sqrt{\chi^2}$

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Top FCNC Outline

The Search for Top FCNC Decay

Search For Invisible Top Decays

Direct FCNC Searches

Backgrounds

Unblinding

Fitting For Everything
Round 2: Is That The Best We Can Do?

- More $\int L dt$:
  - Add 70% more data (1.9 fb$^{-1}$).

- Fit $\chi^2$ Shape:
  - Previous version: counting experiment.
  - Template fit to $\sqrt{\chi^2}$ shape: exploit full shape information, less sensitive to background normalization.

- Build on previous experience:
  - Same event selection
  - Same acceptance algebra
  - Same method of calculating (most) systematic uncertainties
Differences From Counting Experiment

- **Advantages:**
  - Absolute estimation of $Z + \text{jets}$ background is difficult. This drove the counting experiment.
  - Since we are fitting:
    - No absolute $Z + \text{jets}$ background estimation needed.
    - No estimate of $Z + \text{jets}$ tagging fraction needed.
      ⇒ Let these both float in the fit.
      - Smaller backgrounds are fixed to SM expectations.

- **Disadvantages:**
  - Counting experiment does not have shape systematic uncertainties.
    - **Counting experiment:** Only worry about ratios of acceptances.
    - **Fit $\chi^2$:** We need to understand and account for this.
Shape Uncertainties

• What do we mean by “shape uncertainties”?

• We considered many choices for shape uncertainties.

• The two dominant effects were much larger than all others.
  – Factorization/Renormalization ($Q^2$) scale for $Z + \text{jets MC}$.
  – Jet energy scale uncertainties.
Shape Uncertainties: $Q^2$

- ALPGEN: two $Q^2$ “knobs” to turn.
  
  - Factorization/renormalization scale:
    \[ Q = q\text{fac} \times \sqrt{M_Z^2 + \sum p_T^2(p)} \]
  
  - Vertex $Q^2$ (for evaluation of $\alpha_s$):
    \[ Q = k\text{tfac} \times p_T \]
  
  - We turn both at the same time.

  - Not enough to explain data.
Shape Uncertainties: JES

- We need to convert “raw” jets to “corrected” jets
  ⇒ Jet Energy Scale correction (JES)
  - Takes into account detector effects, neutral particles in jets, particles outside of the jet cone, underlying events, multiple interactions, …

Charles Plager

CERN Seminar, July 2nd, 2008
• Now that we have JES shifts, how do we incorporate this in our machinery?  
  ⇒ Implemented compound horizontal template morphing.

• Horizontal morphing is simply interpolating between two normalized cumulative 
  distribution functions (i.e., the normalized integral of the histogram).
  
  – The **green** C.D.F. curve is the 75% interpolation between the **blue** and **red** C.D.F. 
  curves.
Does Morphing Work?

- Test with Gaussians
  - Easy to verify it is working as expected.
- Works on much more complicated shapes.
  - Squares
  - Half-circles
  - mass $\chi^2$ shapes
Signal and Control Regions

- “How do we control shape uncertainties without hiding a small signal?”

- Solution: add control region with little signal acceptance:
  - Constrain shape uncertainties without “morphing away” signal.
  - Definition: At least one optimized $E_T$ or $m_T$ cut failed (do not look at any b-tagging information).

<table>
<thead>
<tr>
<th>Kinematic Variable</th>
<th>Optimized Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse Mass</td>
<td>$\geq 200$ GeV</td>
</tr>
<tr>
<td>Leading Jet</td>
<td>$\geq 40$ GeV</td>
</tr>
<tr>
<td>Second Jet</td>
<td>$\geq 30$ GeV</td>
</tr>
<tr>
<td>Third Jet</td>
<td>$\geq 20$ GeV</td>
</tr>
<tr>
<td>Fourth Jet</td>
<td>$\geq 15$ GeV</td>
</tr>
</tbody>
</table>

![Pie charts showing signal and background distributions.](cern-seminar-chart.png)
Constraining Z + Jets Background

- We have validated that the MC works fairly well in a jet bin, but we do not trust it across jet bins.
  \[ \Rightarrow \text{No absolute Z + jet constraints.} \]
- Use MC to predict the ratio of Z + jets acceptance in the two signal regions to the control region.

\[ R_{\text{sig}} \equiv \text{Ratio of Z + jets in the signal regions to the control region.} \]
\[ \Rightarrow 20\% \text{ constraint} \]
\[ \Rightarrow \text{No constraint!} \]
Fitting $\chi^2$ Roundup

• No absolute $Z + \text{jet}$ background estimate needed.
• For the template fit, we need to deal with shape uncertainties.
  – Find dominant sources $\Rightarrow$ JES
  – Morphing of JES templates in fitter.
• Do not want to “morph away” a real signal $\Rightarrow$ Control region.
  – Use control region also for $Z + \text{jet}$ constraints.
• Investigated effect of shape not being from JES $\Rightarrow$ Small effect.

**Best Fit to Pseudo-Experiment**

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Feldman-Cousins in Five Minutes

- How are we going to interpret our results?
- Feldman-Cousins answers the question: 
  “What range of true values are likely to lead to this measured value?”
- Why use Feldman-Cousins?
  – Guarantees coverage.
  – Data tell us whether we should report a measurement or a limit.
  – Our method incorporates systematic uncertainties easily.
Top FCNC Feldman-Cousins Bands

FCNC Feldman-Cousins Band (95% C.L.)

True $B(t \rightarrow Zq)$

Measured $B(t \rightarrow Zq)$

CDF II Preliminary

$\mathcal{L} dt = 1.9$ fb$^{-1}$
Pseudo-Experiments (PEs)

**Pseudo-experiment:** Generate all necessary numbers/templates to emulate data from an experiment.

1. Generate random numbers to simulate all systematic uncertainties.
   - Pay attention to correlations.
   - Vary **all** systematic uncertainties.
   - Verify all numbers are physical.
   - Morph all templates appropriately.
2. Generate numbers of background and signal events.
3. For each type of event, use templates to generate mass $\chi^2$.
4. Fit as if data.
5. Repeat!

PEs for True $B(t \rightarrow Zq) = 0.0150$
FC Band Construction In A Nutshell

- Use Likelihood Ratio Ordering Principle:

\[ \text{Likelihood Ratio} (\mu_{\text{meas}}) = \frac{P(\mu_{\text{meas}}|\mu_{\text{true}})}{P(\mu_{\text{meas}}|\mu_{\text{best}})} \]

PEs generated with all statistical and systematic uncertainties.

Likelihood Ratio for \( B(t \rightarrow Zq) = 0.0150 \) (95% C.L.)

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Expected Limit

FCNC Feldman-Cousins Band (95% C.L.)

PEs for True B(t → Zq)=0.0000

Entries

hmeasBF_bf0000
Entries: 250000
Mean: -0.002052
RMS: 0.02305

FCNC Expected Limit

Expected Limit:
Mean: (5.0 ± 2.2)%
Median: (4.7 ± 2.1)%

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The Fit to the Data

![Graph showing best fit to mass $\chi^2$](image)

### Fit Parameter ($\int L\,dt = 1.9\,fb^{-1}$) | Value
---|---
Branching Fraction, $B(t \rightarrow Zq)$ (%) | $-1.49 \pm 1.52$
$Z$+Jets Events in Control Region, $Z_{\text{control}}$ | $129.0 \pm 11.1$
Ratio Signal/Control Region, $R_{\text{sig}}$ | $0.52 \pm 0.07$
Tagging Fraction, $f_{\text{tag}}$ (%) | $20.0 \pm 5.9$
Jet Energy Scale Shift, $\sigma_{\text{JES}}$ | $-0.74 \pm 0.43$
FCNC Feldman-Cousins Band (95% C.L.)

Best Fit:
\[ B(t \rightarrow Zq) = -0.0149 \]

95% C.L. Limit:
\[ B(t \rightarrow Zq) < 3.7\% \]

CDF II Preliminary
\[ \int L \, dt = 1.9 \text{ fb}^{-1} \]
Summary

- CDF and the Tevatron are running very well.
  - Thanks Tevatron!

- We just finished Run II’s first search for Top FCNC $t \rightarrow Z c$.
  - Using 1.9 $fb^{-1}$, we have the world’s best limit: $Br\ (t \rightarrow Z c) < 3.7\%$ at 95% C.L.

- Using data-based background techniques will be very important for the LHC.
Money Plot

Best Fit to Mass $\chi^2$

- **Tagged**
  - (13 Events)
  - Data (1.9 fb$^{-1}$)
  - FCNC $t\bar{t}$ (3.7%)
  - Fit Uncertainty
  - $Z +$ Jets (HF & LF)
  - Standard Model $t\bar{t}$
  - Diboson (WZ, ZZ)

- **Anti-Tagged**
  - (53 Events)
  - CDF II Preliminary
  - $\int L \, dt = 1.9$ fb$^{-1}$

- **Control**
  - (136 Events)

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New Era of Precision Top Physics!

2010 PDG Top Entry

\( I(J^P) = 0(\frac{1}{2}^+) \)

Charge = \( \frac{2}{3} \) e \quad Top = +1

Mass \( m = 172.6 \pm 1.4 \) GeV \[^{[b]}\] (direct observation of top events)
Mass \( m = 172.3^{+10.2}_{-7.6} \) GeV \quad (Standard Model electroweak fit)

\[ t \] DECAY MODES

<table>
<thead>
<tr>
<th>Mode</th>
<th>Fraction ( \Gamma_i/\Gamma )</th>
<th>Confidence level ( \Delta \Gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W q (q = b, s, d) )</td>
<td>( W b )</td>
<td>( \ell \nu ) anything [ c,d ] ( 9.4 \pm 2.4 ) %</td>
</tr>
<tr>
<td>( \tau \nu ) ( b )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \gamma q (q = u,c) )</td>
<td></td>
<td>( \gamma q ) ( q = u,c ) [ e ] ( &lt; 5.9 \times 10^{-3} ) \quad 95%</td>
</tr>
</tbody>
</table>

\[ \Delta \Gamma = 1 \text{ weak neutral current (T1) modes} \]

<table>
<thead>
<tr>
<th>Mode</th>
<th>( \Gamma_i/\Gamma_1 )</th>
<th>Confidence level ( \Delta \Gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z q (q = u,c) )</td>
<td>( T_1 ) (</td>
<td>f</td>
</tr>
</tbody>
</table>

\( \gamma q (q = u,c) \)
\( \gamma q (q = u,c) \)

5\sigma Evidence for single top production

(Your analysis here?)
Thank You!
Best Fit to Mass $\chi^2$

**Tagged**
(13 Events)
- Data (1.9 fb$^{-1}$)
- FCNC $t\bar{t}$ (3.7%)
- Fit Uncertainty
- $Z +$ Jets (HF & LF)
- Standard Model $t\bar{t}$
- Diboson (WZ, ZZ)

**Anti-Tagged**
(53 Events)
CDF II Preliminary
$\int L \, dt = 1.9$ fb$^{-1}$

**Control**
(136 Events)

$\sqrt{\chi^2}$