Recent Results on Top and Electroweak Physics from CDF

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For the CDF Experiment
XXXVIIIth Rencontres de Moriond
ELECTROWEAK INTERACTIONS AND UNIFIED THEORIES
March 21, 2003

• Performance of the Tevatron/CDF
• Electroweak Physics
  - W/Z production cross sections and Ratios
  - Forward-Backward Asymmetry
  - WW production
• Top Physics
  - Top production cross sections
  - Top mass
• Summary
Fermilab Tevatron

Operated with proton bunches on antiproton bunches at CM energy of 1.96 TeV

Chicago

Booster

CDF

DØ

Tevatron

Main Injector (new)

p source
Run 2 CDF Detector

Upgraded Components

- Tracking
  - Silicon
    - 707K channels
    - Full Coverage of luminous region
    - Radial coverage from 1.35-28 cm
  - Central Outer Tracker
    - 30k sense wires, 44-132 cm
    - 96 dE/dx samples/track

- Time of Flight
- Expanded Muon Coverage

- Endplug Calorimeter

- Trigger (pipelined)
  - Drift Chamber Tracks @ L1
  - Silicon Tracks @ L2

- Fully Digital DAQ (132 ns)
Run 2a goals:

16 pb\(^{-1}\)/wk
250 pb\(^{-1}\) by summer’03
2 fb\(^{-1}\) for Run 2a

~ 130 pb\(^{-1}\) on tape
~ 5-7 pb\(^{-1}\)/wk @ > 90% efficiency

Current Tevatron status

Run 2a goal is 5-8 \(10^{31}\)

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Overview of EWK

First priority is to reestablish baseline measurements:
- $W \rightarrow \ell \nu$, $Z \rightarrow \ell \ell$ Cross Sections
- Ratio of $W/Z$ Cross Sections
- Forward/Backward Asymmetry

Goal is to improve our understanding of the Standard Model EWK parameters.

$W$ Charge Asymmetry
- Constraints on PDFs

$W$ Mass Measurement
- Dominated by Systematics

Diboson Production
- $WW$, $WZ$, $W\gamma$
- Triboson Couplings
  • Anomalous couplings may indicate New Physics
Event selection
One isolated high \(p_T\) central e
\(E_T > 25\) GeV

Number of Candidates: 38628 in 72 pb\(^{-1}\)
Background (~6.4%):
QCD: 1344 ± 82 ± 672
\(Z \to ee\): 344 ± 17
\(W \to \tau\nu\): 768 ± 22

\[ \sigma \ast B(W \to ev) = 2.64 \pm 0.01_{\text{stat}} \pm 0.09_{\text{syst}} \pm 0.15_{\text{lum}} \text{ nb} \]

NNLO @ \(\sqrt{s}=1.96\) TeV: 2.69 ± 0.10 nb
\[ \sigma_{W^*B} (W \rightarrow \mu \nu) \]

**Event selection**

- One isolated high \( p_T \) central \( \mu \)
- \( p_T > 20 \text{ GeV} \)
- Veto \( Z \) and Cosmics

**Number of Candidates:**

- 21599 in 72 pb\(^{-1}\)

**Background (11%)**:

- QCD: \( 222 \pm 58 \)
- cosmics: \( 276 \pm 195 \)
- \( Z \rightarrow \mu \mu \): \( 1147 \pm 44 \)
- \( W \rightarrow \tau \nu \): \( 691 \pm 31 \)

\[ \sigma_{W^*B} (W \rightarrow \mu \nu) = 2.64 \pm 0.02_{\text{stat}} \pm 0.12_{\text{syst}} \pm 0.16_{\text{lum}} \text{ nb} \]
\[ \sigma_W^* B(W \to \tau \nu) \]

**Event selection**

- One isolated (cal+track)
- high \( E_T \) central \( \tau \)
- \( E_T > 25 \) GeV
- e removal

**Candidates:** 2345 in 72 \( \text{pb}^{-1} \)

**Backgrounds (~ 26 %):**

- QCD: \( 363 \pm 52 \)
- \( W \to e\nu \): \( 103 \pm 11 \)
- \( W \to \mu\nu \): \( 91 \pm 27 \)
- Cosmics: \( 35 \pm 13 \)
- \( Z \to \tau\tau \): \( 20 \pm 2 \)

\[ \sigma_W^* B(W \to \tau \nu) = 2.62 \pm 0.07_{\text{stat}} \pm 0.21_{\text{syst}} \pm 0.16_{\text{lum}} \text{ nb} \]
$\sigma Z^*B(Z\rightarrow ee)$

Luminosity: $72 \text{ pb}^{-1}$

Observed Events: 1830 Events

Background ($\sim 0.5\%$): $8.7 \pm 4.7_{\text{stat}} \pm 2.4_{\text{syst}}$

NNLO Prediction: $252 \pm 9 \text{ pb}$

$\sigma Z^*B(Z\rightarrow ee) = 267.0 \pm 6.3_{\text{stat}} \pm 15.2_{\text{syst}} \pm 16_{\text{lum}}\text{pb}$
\[ \sigma_{Z} B(Z \rightarrow \mu \mu) \]

Luminosity: 72 pb\(^{-1}\)

Observed Events: 1632 Events

Background (\sim 0.8\%): 14 \pm 14

NNLO Prediction: 252 \pm 9 pb

CDF Run II Preliminary, 72pb \(^{-1}\)

\[ \sigma_{Z} B(Z \rightarrow \mu \mu) = 246 \pm 6_{\text{stat}} \pm 12_{\text{syst}} \pm 15_{\text{lum}} \text{ pb} \]
Summary of W and Z Cross Sections

\[ \sigma_W = 2.640 \pm 0.012_{\text{stat}} \pm 0.093_{\text{syst}} \pm 0.158_{\text{lum}} \text{ pb} \]

\[ \sigma_Z = 251.5 \pm 4.3_{\text{stat}} \pm 10.6_{\text{syst}} \pm 15.1_{\text{lum}} \text{ pb} \]
**SM Consistency Checks**

\[ R = \frac{\sigma(pp \to W) \Gamma(W \to e\nu) \Gamma(Z)}{\sigma(pp \to Z) \Gamma(W) \Gamma(Z \to e\nu)} \]

- **\( R_e \)**: 9.88 ± 0.24\text{stat} ± 0.47\text{sys}
- **\( R_\mu \)**: 10.69 ± 0.27\text{stat} ± 0.33\text{sys}
- **\( R_{\text{combined}} \)**: 10.54 ± 0.18\text{stat} ± 0.33\text{sys}
- **\( \Gamma(W)e \text{ [GeV]} \)**: 2.29 ± 0.06\text{stat} ± 0.10\text{sys}
- **\( \Gamma(W)\mu \text{ [GeV]} \)**: 2.11 ± 0.05\text{stat} ± 0.07\text{sys} ± 0.02\text{ext}
- **\( \Gamma(W)_{\text{comb.}} \text{ [GeV]} \)**: 2.146 ± 0.078

- \( R = 10.67 \pm 0.15 \) NNLO(1.96 TeV) [Nucl. Phys. B359,343 (1991)] [Phys. Rev. Lett. 88,201801 (2002)]
- \( \frac{\text{BR}(W \to \tau\nu)}{\text{BR}(W \to e\nu)} = 0.99 \pm 0.04\text{stat} ± 0.07\text{sys} \)
- \( \frac{g_\tau}{g_e} = 0.99\pm0.02_{\text{stat}}\pm0.04_{\text{sys}} \)
**Forward Backward Asymmetry**

\( A_{FB} \)

\[
\frac{d\sigma(q\bar{q} \rightarrow Z / \gamma \rightarrow e^+e^-)}{d \cos \theta} = A(1 + \cos^2 \theta) + B \cos \theta
\]

\[
A_{FB} = \frac{N_F - N_B}{N_F + N_B} = \frac{\sigma(\cos \theta > 0) - \sigma(\cos \theta < 0)}{\sigma(\cos \theta > 0) + \sigma(\cos \theta < 0)} = \frac{3B}{8A}
\]

- \( A_{FB} \) is a direct probe of the relative strengths of the vector and axial-vector couplings.
- \( A_{FB} \) modified by neutral gauge bosons beyond the SM.
- Extract \( \sin^2\theta_{\text{eff}} \) from \( A_{FB} \).

\( A, B \) depend on I, \( Q_q, (M_\gamma)^2 \)
WW pair production

<table>
<thead>
<tr>
<th>SM expectation:</th>
<th>2.74 ± 0.59</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background:</td>
<td>1.52 ± 0.64</td>
</tr>
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</table>

Extrapolation of Run I results

Theory: 1.8 TeV → ∼9.5 pb with 10% uncertainty

Theory: 1.96 TeV → 13.25 ± 0.25 pb (hep-ph/9905386)

Run I CDF experiment → 10.2 ± 6.3-5.1 (stat) ± 1.6(sys) pb

Run II Extrapolation: 10.2 * (13.25/9.5) = 14.2 pb
The Discovery of the top quark in 1995 was no big surprise. What was surprising is that its mass is almost 40 times that of the b quark, and tantalizingly close to the scale of EWSB.

The Fermilab Tevatron has been the only place, and will be until the LHC turns on in ~2008, to study the top quark.

Everything we know about top is based on about 100 events from the Tevatron Run 1 by the D0 and CDF collaborations.

With 30 times more top events, as expected in Run 2a, we hope to try and answer such questions as:

- Why is top so heavy?
- Is it or the third generation special?
- Is top involved with EWSB?
- Is it connected to new physics?
Production and Decay of the Top Quark

At the Tevatron, top quarks are primarily produced in pairs.

\[ \tau_{\text{top}} \approx 4 \times 10^{-25} \text{ s} \]
\[ \Lambda^{-1} \approx 10^{-23} \text{ s} \]
Top decays as free quark!
BR\((t \rightarrow Wb) \) @ 100%

3 classes of signal
Dilepton: 2 high-\( P_T \) leptons, 2 bjets, large Missing \( E_T \): BR 5%
Lepton + jets: 1 high-\( P_T \) lepton, 4 jets (2 b's), large \( E_T \): BR 30%
All-hadronic: 6 jets: BR 44%

Branching ratios for \( t\bar{t} \) decay modes

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## Top production numbers

<table>
<thead>
<tr>
<th></th>
<th>Run 1</th>
<th>Run 2a</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM Energy (TeV)</td>
<td>1.8</td>
<td>1.96</td>
</tr>
<tr>
<td>L(cm$^{-2}$ s$^{-1}$)</td>
<td>$2 \times 10^{31}$</td>
<td>$2 \times 10^{32}$</td>
</tr>
<tr>
<td>L(fb$^{-1}$)</td>
<td>0.11</td>
<td>2.0</td>
</tr>
<tr>
<td>$\sigma$(tt) (pb)</td>
<td>5.0</td>
<td>7.0</td>
</tr>
<tr>
<td>$\sigma$(single top) (pb)</td>
<td>2.5</td>
<td>3.4</td>
</tr>
<tr>
<td>N(tt) produced</td>
<td>500</td>
<td>14000</td>
</tr>
<tr>
<td>N(singel t) produced</td>
<td>250</td>
<td>7000</td>
</tr>
<tr>
<td>N(tt$\rightarrow$dilepton)</td>
<td>4</td>
<td>150</td>
</tr>
<tr>
<td>N(tt$\rightarrow$l+3j) (1 tag)</td>
<td>25</td>
<td>1400</td>
</tr>
<tr>
<td>N(tt$\rightarrow$l+4j) (2 tags)</td>
<td>5</td>
<td>600</td>
</tr>
</tbody>
</table>
Top Properties

Production Cross Section
Resonance production?
Production kinematics

SM

New Physics?

W helicity
Top spin polarization
Top Mass

Production kinematics

Decay modes
Branching ratios
CKM matrix element |V_{tb}|

Rare decays
$t \rightarrow Z c / \gamma c$, $t \rightarrow W Z b$, ...

Non-SM decays
$t \rightarrow H^{±}$, $t \rightarrow \tilde{t}$, ...

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Top cross section

Measurement of the cross section is primarily a “counting experiment”

\[ \sigma(t\bar{t}) = \frac{N_{\text{obs}} - N_{\text{bkg}}}{A \cdot \int L} \]

\[ \sigma_{t\bar{t}}(\sqrt{s} = 1.96 \text{ TeV}) \approx 1.30 \times \sigma_{t\bar{t}}(\sqrt{s} = 1.8 \text{ TeV}) \]

Run 1 cross section results ~100 pb⁻¹

- DØ combined (m_t = 172 GeV/c²): 5.9±1.7 pb
- CDF combined (m_t = 175 GeV/c²): 6.5±1.7 pb
- CDF L+jets (topological): 4.1±2.1 pb
- DØ L+jets (topological): 5.1±1.5 pb
- CDF L+jets (SVX b-tag): 9.2±4.3 pb
- CDF L+jets (Soft Lepton Tag): 8.3±3.6 pb
- DØ L+jets (Soft Lepton Tag): 7.6±3.5 pb
- CDF Hadronic: 7.1±3.2 pb
- DØ Hadronic: 8.4±4.5 pb
- CDF Dilepton: 5.9±1.7 pb

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**σ_{tt}** dilepton cross section

- **Event selection**
  - 2 High $P_T$ ($P_T > 20$ GeV) oppositely charged leptons (e,µ).
  - Both isolated: $I_{CAL} < 0.1$
  - Veto Z’s, cosmics, and conversions
  - Neutrinos: large missing $E_T > 25$ GeV
  - at least 2 jets with $E_T > 10$ GeV
  - Total transverse energy of the event > 200 GeV
- $\text{BR} \sim 5\%$, detection eff $\sim 11\%$, expect $S/B \sim 9$, $S \sim 2.5$
- 5 candidate events in $72 \text{ pb}^{-1}$
- Backgrounds from Drell Yan, $Z^0 \rightarrow \tau\tau$, WW : $0.30 \pm 0.12$

$$\sigma_{tt} = 13.2 \pm 5.9_{\text{stat}} \pm 1.5_{\text{syst}} \text{ pb}$$

NLO for $M_{\text{top}} = 175$ GeV: $6.70^{+0.71}_{-0.88}$ pb
**σ_{tt} : lepton + jets**

- **Event selection**
  - 1 High momentum, central, and isolated lepton
    - \(P_T > 20\) GeV/c, e or \(\mu\).
  - Veto Z’s, cosmics, and conversions
  - Neutrinos: large missing \(E_T > 20\) GeV
  - 3 or more jets with \(E_T > 15\) GeV
  - at least 1 jet with secondary vertex tag (SVX)

- 15 observed events in 57.5 pb\(^{-1}\)

- Backgrounds from \(Wbb, Wcc, \text{mistags}, Wc, \text{non-W}: 3.8 \pm 0.5\)

**CDF II preliminary**

\[ \sigma_{tt} = 5.3 \pm 1.9_{\text{stat}} \pm 0.8_{\text{syst}} \text{ pb} \]

NLO for \(M_{\text{top}} = 175\) GeV: \(6.70^{+0.71}_{-0.88}\) pb
Top mass: lepton + jets

Select lepton + 4 jet events, similar to the $\sigma(tt)$ measurement, except no requirement on silicon.

METHOD

Use 2C constrained fitting technique with constraints $M_{l\nu} = M_W$, $M_{jj} = M_W$, $M_{t1} = M_{t2}$

24 combinations:

12 correspond to the jet parton match

every combination has 2 solutions for neutrino $P_Z$

Choose combination with lowest $\chi^2$. 

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Reconstructed top masses from data are compared to parameterized templates of top and background Monte Carlo.

CDF II Preliminary (72 $\text{pb}^{-1}$)

Herwig 175 $\text{GeV}/c^2$

$\chi^2/\text{ndf}=1.12$

signal

Vecbos

$\chi^2/\text{ndf}=0.96$

background
Use a continuous likelihood method to extract top mass and statistical uncertainty.

\[ M_{\text{top}} \] is the minimum of the log-likelihood distribution.

\[ \sigma_{\text{top}} \] corresponds to a change of 0.5 units in the log-likelihood.

CDF II Preliminary (72 pb\(^{-1}\))

\[ M_{\text{TOP}} = 171.2 \pm 13.4 \pm 9.9 \text{ GeV/c}^2 \]

CDF Run 1 combined 176.1 ± 6.5 GeV/c²
Summary

• Run 2a is well underway and we are in the process of reestablishing some basic physics measurements and getting a better understanding of the CDF detector
  - W/Z Cross Sections and Ratios
  - tt Cross Section
  - Top mass

• Some of the more complicated analyses will follow
  - W Mass

• With larger samples (later this year) we will be able to extend our Run I searches for extensions to the standard model
  - Diboson couplings
  - Top Properties

• By summer we hope to have ~200 pb\(^{-1}\).
• Goal for Run 2a is still 2000 pb\(^{-1}\)