Tevatron W/Z/γ Results Part II

Attack of the DiBosons

15th Topical Conference on Hadron Collider Physics

Michael Kirby for the CDF and D0 Collaborations
Why study DiBoson production?

• Heavy Boson + photon, Two Heavy Bosons
• Natural extension of well understood and measured W and Z production
• Precise predictions available from many NLO calculations
• Small cross sections provide challenge
• Sensitive to non-Standard Model physics, internal structure of W and Z
• Places limits on Anomalous Trilinear Couplings
• Good confirmation of SU(2)\textsubscript{L} x U(1)\textsubscript{Y} structure of Electroweak sector
DiBoson Production at the Tevatron
The Tevatron at Fermilab

- Tevatron proton anti-proton collider at Fermilab
  - $E_{\text{Beam}} = 980$ GeV
  - 36x36 bunches with 396ns spacing

\[ \sqrt{s} = 1.96 \text{TeV} \text{ RunII} \]

- Increased instantaneous Luminosity
  - Typical: $4 - 5 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$
  - Record: $\sim 7.83 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$
  - Tevatron has delivered in total $\sim 500 \text{ pb}^{-1}$
  - Long term, by the end of FY09
    - Base goal: 4.4 fb$^{-1}$ Design: 8.5 fb$^{-1}$
The D0 Run II Detector

- Forward Mini-drift chambers
- Central Scintillator
- Forward Scintillator
- Shielding
- New Solenoid, Tracking System
- Si, SciFi, Preshowers

+ New Electronics, Trig, DAQ

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The CDF Run II Detector

$|\eta| = 1$.

$|\eta| = 2$.

$$\frac{\delta P_T}{P_T^2} \approx 0.15\% \ (GeV / c)^{-1}$$
**Wγ Production**

- Includes the Triple Gauge Coupling
  - Anomalous terms ($\Delta \kappa, \lambda$)
  - SM ($\Delta \kappa=0, \lambda=0$)

- Interference between ISR and TGC produces Radiation Amplitude Zero
- only in SU(2)xU(1) group
- After Detector Simulation

![Diagram of Wγ Production](image)

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Anomalous Couplings

In the $E_{T\gamma}=0$ limit, couplings equated with classical magnetic dipole and electric quadrupole

$$\mu_W = \frac{e}{2M_W} (2 + \Delta\kappa + \lambda)$$

$$Q^e_W = -\frac{e}{M_W^2} (1 + \Delta\kappa - \lambda)$$
Wγ Event Selection

- μ Selection
  - Central Track assoc. μ hits
  - $P_T > 20$ GeV
  - CDF - $|\eta_\mu| < 1.0$
  - D0 - $|\eta_\mu| < 2.0$

- Electron Selection
  - EM Cluster > 25 GeV
  - Matched Track
  - Shower Shape Discrimination
  - CDF - $|\eta_e| < 1.1, 1.2 < |\eta_e| < 2.6$
  - D0 - $|\eta_e| < 1.1, 1.6 < |\eta_e| < 2.5$

- Missing Transverse Energy
  - > 20 GeV for μ candidates
  - > 25 GeV for e candidates
Wγ Event Selection Cont

• γ Selection
  – Central Calorimeter
  – Shower profile discrimination
  – Calor. and Track Isolation
  – ET > 7 GeV (CDF)
  – ET > 8 GeV (D0)

• γ-lepton separation
  – ΔR(l,γ)>0.7

• Background dominantly from W + jets
  – leading π⁰ fakes photon in jets

• Additional Bckgs - Zγ, Wγ →τνγ, misreconstruction
## Wγ Results

<table>
<thead>
<tr>
<th></th>
<th>Lum=202/pb</th>
<th>Lum=162/pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_\gamma^-</td>
<td>&gt; 7 GeV</td>
<td>&gt; 8 GeV</td>
</tr>
<tr>
<td>N(W+γ) Signal</td>
<td>221.6 ± 11.7</td>
<td>84.9 ± 17.0</td>
</tr>
<tr>
<td>Tot Bkg</td>
<td>94.7 ± 23.6</td>
<td>124.1 ± 12.5</td>
</tr>
<tr>
<td>Total SM</td>
<td>316.3 ± 26.3</td>
<td>209 ± 21.4</td>
</tr>
<tr>
<td>Data</td>
<td>323</td>
<td>223</td>
</tr>
</tbody>
</table>

Measured $\sigma(W_γ) \times \text{BR}(W \rightarrow l\nu) =$  
19.9 ±2.7 (stat+sys) ±1.1 (lumi) pb

NLO Theory = 19.3 ±1.3 pb

Measured $\sigma(W_γ) \times \text{BR}(W \rightarrow l\nu) =$  
19.3 ±6.7 (stat +sys) ±1.2 (lumi) pb

NLO Theory = 16.4 ±0.4 pb
$E_T^\gamma$ Results

CDF Run 2 Preliminary 202/pb

D0 Run 2 Preliminary 162/pb

CDF Data
$W_\gamma \rightarrow l\nu_\gamma$
$W + jet$
$Z_\gamma$
$\tau_\nu_\gamma$
$\Delta R(l, \gamma)$ Results

CDF Run 2 Preliminary 202/pb

- data 323 events
- $W_{\gamma \rightarrow l\gamma}$ MC + BG
- QCD + $Z_{\gamma}$ + $\tau\gamma$
- $Z_{\gamma}$ + $\tau\gamma$
- $\tau\gamma$

D0 Run 2 Preliminary 162/pb

- Data
- Monte Carlo + Background
- Background

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\( W_\gamma: \ell-\mathcal{E}_T \) Transverse Mass

D0 Run 2 Preliminary 162/\text{pb}

- Data
- Monte Carlo + Background
- Background

Events/10 GeV

MT (GeV)
Cluster Transverse Mass

CDF Run 2 Preliminary 202/pb

Greater sensitivity to Anomalous Couplings and RAZ in high CTM region
Zγ Production

- No ZZγ Triple Gauge Coupling in Standard Model at tree level
  - no Radiation Amplitude Zero
  - Anomalous terms (h^γ_{i0}, h^Z_{i0})
  - SM (h^γ_{i0}=0, h^Z_{i0}=0)
- Excellent cross check for Wγ production
- Anomalous terms can be related to the dipole and quadrupole moments
Zγ Event Selection

• µ Selection
  – Central Track
  – $P_T > 20$ GeV
  – opposite charge
  – CDF - $|\eta_\mu| < 1.0$

• Electron Selection
  – EM Cluster $> 25$ GeV
  – CDF - $|\eta_e| < 2.6$

• Invariant Mass $> 40$ GeV

• Photon selection
  – $E_{T\gamma} > 7$ GeV
  – $\Delta R(l, \gamma) > 0.7$

• Background from $Z + \text{jets}$
# Zγ Results

<table>
<thead>
<tr>
<th></th>
<th>Lum=202/pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(Z+g) Signal</td>
<td>65.8 ± 3.8</td>
</tr>
<tr>
<td>Tot Bkg</td>
<td>4.7 ± 1.4</td>
</tr>
<tr>
<td>Total SM</td>
<td>70.5 ± 4.0</td>
</tr>
<tr>
<td>Data</td>
<td>70</td>
</tr>
</tbody>
</table>

### Backgrounds

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Z+jet</td>
<td>4.5 ± 1.3</td>
</tr>
<tr>
<td>FakeZ+γ</td>
<td>0.2 ± 0.15</td>
</tr>
</tbody>
</table>

Measured \(\sigma(Z\gamma)\times BR(Z\rightarrow ll) = 4.5 \pm 0.5 \text{ (stat + sys)} \pm 0.3 \text{ (lumi)} \text{ pb}\)

NLO Theory = 4.5 ± 0.3 pb (\(E_\gamma > 7\text{ GeV, } \Delta R(l, \gamma) > 0.7\))

Note: \(\sigma(W\gamma)/\sigma(Z\gamma) \approx 3\) while \(\sigma(W)/\sigma(Z) \approx 10\)
Z$\gamma$ Results

CDF Run 2 Preliminary 202/pb

N_{events}/7\text{GeV}

$E_T^\gamma$ (GeV)

CDF Run II Data

Z$\gamma \rightarrow \mu \mu$

$Z + \text{jet}$

CDF Run 2 Preliminary 202/pb

N_{events}/0.3

$\Delta R(\text{near } l, \gamma)$

CDF Run II Data

Z$\gamma \rightarrow \mu \mu$

$Z + \text{jet}$

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Z\gamma Results
WW, WZ, and ZZ Production

• Complementary probe of Triple Gauge Coupling
  – higher Boson and Lepton $P_T$ indicates Anom. Coup.
• Small cross sections make for challenging measurement
• Study using leptonic decays of the W and Z
• Important foundation for Higgs searches
CDF: \(\sigma(p\bar{p} \rightarrow WW \rightarrow l^+\nu l^-\bar{\nu})\)

Two complementary approaches

Dileptons: \(l^+, l^-\): identified e, \(\mu\)

(Identified e, \(\mu\)) + Iso track

Missing \(E_T\) Significance (\(\sqrt{\text{GeV}}\))

\[ E_{T,\text{sig}} = \frac{\sum E_T}{\sqrt{\sum E_T}} \]

- Reject \(76 < M_{ll} < 106\) & \(E_{T,\text{sig}} < 3.0\)
- \(E_T > 25\)
- No High Et jets
- Opposite sign & Isolation

High S/B

Increased acceptance

- \(\not{E_T} < \text{5.5 in all } M_{ll}\)
- \(E_T > 25\)
- \(\text{Njets} \leq 1\)
- Opposite sign & Isolation

- \(\not{E_T} \neq \text{DY, } Z\tau\tau\)
- \(\not{E_T} \neq \text{WZ/ZZ, } Z\tau\tau\)
- \(\not{E_T} \neq \text{top dilepton, Fakes, Fakes}\)
CDF: WW cross section

<table>
<thead>
<tr>
<th></th>
<th>l+track</th>
<th>e,\mu</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW</td>
<td>16.3±0.4</td>
<td>11.3 ±1.3</td>
</tr>
<tr>
<td>Bkg</td>
<td>15.1±0.9</td>
<td>4.77±0.70</td>
</tr>
<tr>
<td>WW+Bkg</td>
<td>31.5±1.0</td>
<td>16.1±1.6</td>
</tr>
<tr>
<td>Data</td>
<td>39</td>
<td>17</td>
</tr>
</tbody>
</table>

NLO (Campbell & Ellis, 1999) $\sigma^{WW}=12.5±0.8$ pb

$\sigma(p\bar{p} \rightarrow WW) = 14.3^{+5.6}_{-4.9}(stat) ± 1.6(syst) ± 0.9(lum)$ pb

$\sigma(p\bar{p} \rightarrow WW) = 19.4 ± 5.1(stat) ± 3.5(syst) ± 1.2(lum)$ pb
CDF: WW Beyond SM

Anomalous TGC WWZ/WWγ

$gg \rightarrow H \rightarrow WW$ $140 < M_H < 180$ GeV/c²

Jet:
>15 GeV
Cone 0.4
WW→\textit{e}\textit{e}\nu\nu or ZZ→\textit{e}\textit{e}\nu\nu?
**ZW, ZZ study in Run II**

**Event selections**

- **Four lepton events**
  - Signal: ZZ
  - Background: Z/W+jets, multijet
  
  $$M(l_1^+l_1^-), \ M(l_2^+l_2^-) \in (76, 106) \text{ GeV}$$

<table>
<thead>
<tr>
<th>variable</th>
<th>cut values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of leptons</td>
<td>4</td>
</tr>
</tbody>
</table>

- **Three lepton events**
  - Signal: ZZ, ZW
  - Background: Z/W+jets, multijet
  
  $$M(l_1^+l_1^-) \in (76, 106) \text{ GeV}$$

<table>
<thead>
<tr>
<th>variable</th>
<th>cut values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of leptons</td>
<td>3</td>
</tr>
<tr>
<td>$E_T$</td>
<td>&gt; 20 GeV</td>
</tr>
</tbody>
</table>

- **Two lepton events**
  - Signal: ZZ, ZW
  - Background: WW, Drell Yan, Top, W+jets
  
  $$M(l_1l_2) \in (76, 106) \text{ GeV}$$

<table>
<thead>
<tr>
<th>variable</th>
<th>cut values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of leptons</td>
<td>2</td>
</tr>
<tr>
<td>$N_{jet}$</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>$E_T$ significance</td>
<td>&gt; 3</td>
</tr>
<tr>
<td>$\Delta \phi(E_T, l/jet)$</td>
<td>&gt; 20°</td>
</tr>
</tbody>
</table>
# ZW, ZZ study in Run II

CDF Run II Winter 2004 Preliminary, $\mathcal{L}=194$ pb$^{-1}$

<table>
<thead>
<tr>
<th>Process</th>
<th>$l_1l_2l_3l_4$</th>
<th>$l_1l_2l_3E^T_T$</th>
<th>$l_1l_2E^T_T$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>0.07 ± 0.01</td>
<td>0.13 ± 0.01</td>
<td>0.87 ± 0.14</td>
<td>1.07 ± 0.15</td>
</tr>
<tr>
<td>ZW</td>
<td>-</td>
<td>0.81 ± 0.07</td>
<td>0.86 ± 0.14</td>
<td>1.67 ± 0.19</td>
</tr>
<tr>
<td>ZZ+ZW</td>
<td>0.07 ± 0.01</td>
<td>0.94 ± 0.08</td>
<td>1.73 ± 0.27</td>
<td>2.74 ± 0.33</td>
</tr>
<tr>
<td>WW</td>
<td>-</td>
<td>-</td>
<td>1.26 ± 0.20</td>
<td>1.26 ± 0.20</td>
</tr>
<tr>
<td>Fake</td>
<td>0.01 ± 0.02</td>
<td>0.07 ± 0.06</td>
<td>0.56 ± 0.30</td>
<td>0.64 ± 0.34</td>
</tr>
<tr>
<td>Drell-Yan</td>
<td>-</td>
<td>-</td>
<td>0.31 ± 0.13</td>
<td>0.31 ± 0.13</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>-</td>
<td>-</td>
<td>0.08 ± 0.02</td>
<td>0.08 ± 0.02</td>
</tr>
<tr>
<td>Total Background</td>
<td>0.01 ± 0.02</td>
<td>0.07 ± 0.06</td>
<td>2.21 ± 0.38</td>
<td>2.29 ± 0.42</td>
</tr>
<tr>
<td>Expected S. + B.</td>
<td>0.08 ± 0.02</td>
<td>1.01 ± 0.10</td>
<td>3.94 ± 0.57</td>
<td>5.03 ± 0.64</td>
</tr>
<tr>
<td>Data</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

- Cross section upper limit consistent with SM prediction of $5.2 \pm 0.4$ pb

\[ \sigma (p\bar{p} \rightarrow ZZ/ZW + X) < 13.9 \text{ pb} \]  

← 95% Conf Limit
The Next Steps

- Tevatron has excellent DiBoson production studies ongoing.
- Will measure limits on Anomalous Triple Gauge Couplings
  - $W\gamma$, $Z\gamma$, $WW$, $ZW$, and $ZZ$
- Establish baseline for other DiBoson production
- Already have $WW$ searches for Higgs production and improving upon understanding of HW production (see Michael Gold’s talk on Thursday)
- Non-dilepton analyses are underway