Diboson Production at the Tevatron

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FNAL

For the CDF and DØ Collaborations

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Diboson Production

• SU(2)_L x U(1)_Y electroweak sector
  – Non-Abelian theory with self-interacting gauge bosons

  \[
  \begin{array}{ccc}
  W & W & Z \\
  \gamma & & W \\
  \end{array}
  \]

  – We can study trilinear boson couplings by analyzing events with two (or more) bosons in the final state

• Most of new physics models predict multiple weak bosons in the final state

• Diboson events are a background for other important physics (H→WW, tt→dileptons etc.)
Boson Reconstruction in CDF and DØ

- **W** reconstruction
  - High-$p_T$ lepton candidates, missing $E_T$
- **Z** reconstruction
  - A pair of two high-$p_T$ lepton candidates
- **γ** reconstruction
  - Electro-magnetic object reconstructed with a transverse energy of at least 7(CDF) or 8(DØ) GeV; object must be isolated and pass shower shape quality requirements
  - Photon candidate is reconstructed in the central region of the calorimeter ($|\eta| < 1.1$)
Photon Reconstruction

• Photon identification is quite challenging
  – Big background from jets with high energy $\pi^0$
    • Use as much information on track isolation and energy deposition as possible
  – No clean photon samples available (sample of $H\rightarrow\gamma\gamma$ events would be very useful!)
    • Have to use both data and Monte Carlo simulation to measure photon efficiency
    • Photon identification systematic error is one of the dominant in $W\gamma$ and $Z\gamma$ analyses
**$W_\gamma$ Production**

- Require $g$ to be isolated from leptons by at least

$$\Delta R(\gamma, \ell) = \sqrt{\Delta \eta^2 + \Delta \phi^2} > 0.7$$

- reduce FSR processes

- Sensitive to $WW_\gamma$ trilinear coupling

- Anomalous coupling would
  - Change the shape of $\gamma E_T$ distribution (more high-$E_T$ photons)
  - Enhance the cross-section

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Photon $E_T$ Spectrum

Sensitive region to anomalous couplings
### Wγ Cross-section Results

<table>
<thead>
<tr>
<th></th>
<th>Electron(Muon)</th>
<th>Electron(Muon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity, pb⁻¹</td>
<td>202(192)</td>
<td>162(82)</td>
</tr>
<tr>
<td>E_Tγ</td>
<td>&gt; 7 GeV</td>
<td>&gt; 8 GeV</td>
</tr>
<tr>
<td>Total background</td>
<td>94.7 ± 23.6</td>
<td>124.1 ± 12.5</td>
</tr>
<tr>
<td>Candidates</td>
<td>323</td>
<td>223</td>
</tr>
<tr>
<td>σ, pb</td>
<td>19.7 ± 2.8^{stat+syst ± 1.1}_{lumi}</td>
<td>19.3 ± 6.7^{stat+syst ± 1.2}_{lumi}</td>
</tr>
<tr>
<td>NLO Theory, pb</td>
<td>19.3 ± 1.4</td>
<td>16.4 ± 0.4</td>
</tr>
</tbody>
</table>

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U. Baur et al.

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Any indication of non-zero trilinear couplings indicates new physics.
Photon \( E_T \) Spectrum

CDF Preliminary

- CDF Run II Data
- \( Z\gamma \rightarrow \gamma \gamma \)
- \( Z + \text{jet} \)

D0 RunII Preliminary

- \( \mu\mu \) Data
- QCD
- QCD + \( \mu\mu \) MC

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## $Z\gamma$ Cross-section Results

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<tr>
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<th>Electron (Muon)</th>
<th>Electron (Muon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity, pb$^{-1}$</td>
<td>202 (192)</td>
<td>177 (144)</td>
</tr>
<tr>
<td>$E_T\gamma$</td>
<td>$&gt; 7$ GeV</td>
<td>$&gt; 8$ GeV</td>
</tr>
<tr>
<td>Background</td>
<td>4.5 ± 0.8</td>
<td>14.8 ± 1.5</td>
</tr>
<tr>
<td>Candidates</td>
<td>70</td>
<td>101</td>
</tr>
<tr>
<td>$\sigma$, pb</td>
<td>$5.3 \pm 0.7_{\text{stat+syst}} \pm 0.3_{\text{lumi}}$</td>
<td>$3.9 \pm 0.5_{\text{stat+syst}} \pm 0.3_{\text{lumi}}$</td>
</tr>
<tr>
<td>NLO Theory, pb</td>
<td>5.4 ± 0.4</td>
<td>4.3 ± 0.4</td>
</tr>
</tbody>
</table>

*U. Baur et al.*
WW Production

- Sensitive to $ZWW$ and $\gamma WW$ couplings
- Select events with two high-$p_T$ leptons, large missing $E_T$
  - $(ee)$ and $(\mu\mu)$ channels have large background from $Z$ decays;
  $(e\mu)$ is much cleaner, major background from $W\gamma$ process.
- CDF: “lepton+track” – require only one reconstructed high -$p_T$ lepton and a charged track
  - increases efficiency,
  - includes $W\rightarrow\tau\nu$ decays
## WW Production

<table>
<thead>
<tr>
<th></th>
<th>ee</th>
<th>$\mu\mu$</th>
<th>$e\mu$</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CDF</strong> Expected signal</td>
<td>$2.90 \pm 0.34$</td>
<td>$2.75 \pm 0.32$</td>
<td>$5.69 \pm 0.66$</td>
<td>$11.3 \pm 1.3$</td>
</tr>
<tr>
<td><strong>CDF</strong> Background</td>
<td>$1.97 \pm 0.40$</td>
<td>$1.14 \pm 0.28$</td>
<td>$1.66 \pm 0.31$</td>
<td>$4.77 \pm 0.7$</td>
</tr>
<tr>
<td><strong>CDF</strong> Candidates</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>17</td>
</tr>
</tbody>
</table>

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<tr>
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<th>$e\mu$</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>D0</strong> Expected signal</td>
<td>$3.26 \pm 0.05$</td>
<td>$2.01 \pm 0.05$</td>
<td>$10.8 \pm 0.1$</td>
<td>$16.1 \pm 0.1$</td>
</tr>
<tr>
<td><strong>D0</strong> Background</td>
<td>$2.30 \pm 0.26$</td>
<td>$1.94 \pm 0.43$</td>
<td>$3.81 \pm 0.30$</td>
<td>$8.05 \pm 0.7$</td>
</tr>
<tr>
<td><strong>D0</strong> Candidates</td>
<td>6</td>
<td>4</td>
<td>15</td>
<td>25</td>
</tr>
</tbody>
</table>
**WW Cross-section Results**

- **Dilepton final state**
  - CDF: \( \sigma(pp \rightarrow WW) = 14.3^{+5.6}_{-4.9} \text{(stat)} \pm 1.6 \text{(syst)} \pm 0.9 \text{(lumi)} \)
  - DØ: \( \sigma(pp \rightarrow WW) = 13.8^{+4.3}_{-3.8} \text{(stat)} \pm 1.0 \text{(syst)} \pm 0.9 \text{(lumi)} \)

- **Lepton+track**
  - CDF: \( \sigma(pp \rightarrow WW) = 19.4 \pm 5.1 \text{(stat)} \pm 3.5 \text{(syst)} \pm 1.2 \text{(lumi)} \)

- Cross-sections are consistent with SM prediction
- Work on extracting \( ZWW \) and \( \gamma WW \) trilinear couplings is in progress.

**NLO Theory: 13.5 pb (CTEQ5L)**

J.M. Campbell and R.K. Ellis
• Select events with three high-$p_T$ lepton (electron or muon) candidates and missing $E_T$

• We expect $1.02 \pm 0.07$ signal events with estimated background of $0.39 \pm 0.02$ events

• Observe one event with three muon candidates
  – Set an upper-limit on $WZ$ cross-section of $15.1 \text{ pb}$ at 95% C.L.
  – NLO Theory predicts $3.7 \pm 0.1 \text{ pb}$

J.M. Campbell and R.K. Ellis
WZ and ZZ Production

- Statistics is not sufficient, try to set limit on combined WZ and ZZ production

- Require a Z candidate decaying in either electrons or in muons in the event and
  - large missing transverse energy (Z→νν) or
  - a third lepton (e or μ) and missing E_T or
  - two leptons

- Expect 2.72 ± 0.33 signal events with estimated background of 2.29 ± 0.42 events

- Observe 4 candidate events in data (all in Z+missing E_T)
- Set an upper limit on WZ+ZZ production of 13.9 pb
  - NLO Theory prediction is 5.2 ± 0.4 pb.

J.M. Campbell and R.K. Ellis
Conclusions

- We report measurements of $W\gamma$, $Z\gamma$, and $WW$ cross-sections.
  - First observation of $WW$ production
- Results are consistent with the Standard Model predictions
- Limits are set on $WZ$ and $ZZ$ processes
- Measurements are being interpreted in the framework of anomalous coupling
- Expect final results and publications soon…