Diboson production at CDF

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Diboson are unique probe of triple gauge couplings:

1. Sensitive to new physics: $ZZZ$, $ZZ\gamma$, $Z\gamma\gamma$ absent in SM
2. TeV with respect to LEP: explores higher energy range

- Significant backgrounds for several interesting processes
- Processes topologically similar to $WH$, $ZH$, SUSY.
CDF detector

- Proton-antiproton collision at $\sqrt{s} = 1.96$ TeV
- 36 bunches: crossing time = 396 ns
- Peak luminosity $3.61 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- Data taking efficiency $\sim 85\%$
- About 5.7 fb$^{-1}$ on tape
Improved Lepton Selection

- Lepton acceptance is a key in final states with 3 or more leptons!
- Try to use all tracks and electromagnetic objects found
- Use as much information as possible for each candidate

Electrons:
- Central calorimeter
- Forward calorimeter
- w/ or w/o Si-based track

Muons:
- Central muons with matched muon chamber hits
- (MIP): central and forward region

Tracks:
- Fill in regions not fiducial to calorimeters
- No distinction between e and μ.
1. Two leptons (e or µ) with $p_T(l_1) > 20$, $p_T(l_2) > 10$ GeV

2. Dilepton invariant mass $M_{ll} > 16$ GeV/c$^2$ to reduce heavy flavour backgrounds

3. Njet = 0, with $|\eta| < 2.5$ and $p_T > 15$ GeV to reduce tt and WW/WZ

4. Drell-Yan contamination reduced requiring that the $E_T$ transverse to each lepton is greater than 25 GeV (15 GeV for e µ)
Likelihood ratio formed from Matrix element probabilities

\[ \sigma^{\text{NLO}}(p\bar{p} \rightarrow WW) = 11.7 \pm 0.7\text{pb} \]

\[ \sigma(p\bar{p} \rightarrow WW) = 12.1^{+1.8}_{-1.6}\text{pb} \]
Two diagrams producing WW: s-channel, and t-channel.

s-channel is susceptible to anomalous triple gauge couplings: 
\[ \Delta K^z, \Delta K^\gamma, \Delta g_1^z, \Delta g_1^\gamma, \lambda^z, \lambda^\gamma \]

HISZ scheme ties these together to make 3 independent parameters

Analysis strategy:

1. Take generator level leading lepton \( p_T \) distribution from MCFM
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<table>
<thead>
<tr>
<th>$\Lambda$ (GeV)</th>
<th>$\lambda^z$</th>
<th>$\Delta g^z_1$</th>
<th>$\kappa^\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expected</strong></td>
<td>1.5</td>
<td>(-0.05, 0.06)</td>
<td>(-0.04, 0.14)</td>
</tr>
<tr>
<td><strong>Observed</strong></td>
<td>1.5</td>
<td>(-0.17, 0.17)</td>
<td>(-0.26, 0.35)</td>
</tr>
<tr>
<td><strong>Expected</strong></td>
<td>2.0</td>
<td>(-0.05, 0.06)</td>
<td>(-0.04, 0.13)</td>
</tr>
<tr>
<td><strong>Observed</strong></td>
<td>2.0</td>
<td>(-0.15, 0.15)</td>
<td>(-0.25, 0.32)</td>
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</table>
WZ cross section measurement

- Require 3 e or \( \mu \) leptons and missing transverse energy
- Sensitive to WWZ vertex coupling
- Unique access to WWZ separately from WW \( \gamma \)

\[ \sigma(p\bar{p} \rightarrow WZ) = 4.4 \pm 1.3\text{(stat.)} \pm 0.2\text{(sys.)} \pm 0.3\text{(lum.)}\text{ pb} \]

\[ \sigma(WZ)_{\text{NLO}} = 3.7\text{ pb} \]
- The $Z p_T$ distribution measured for the observed events is fitted for each of the parameters: $\lambda$, $\Delta g$, $\Delta \kappa$. This is done individually as well as two dimensional pairs. The $Z p_T$ distribution is used since it is sensitive to these couplings and it can be measured experimentally.

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4. 2D limits
ZZ production

- Very small cross section ($1.4 \pm 0.1 \text{ pb}$)
  - Campbell, Ellis, PRD 60 (1999) 113006
- Two decays mode considered
  1. $\ell \ell \ell \ell$: $\sim 0.5%$
     - Small BR
     - Clean Sample
  2. $\ell \ell \nu \nu$: $\sim 3%$
     - 6 times larger BR
     - Large Backgrounds (WW, WZ, Drell-Yan)

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**Observed Results**

<table>
<thead>
<tr>
<th>P-Value</th>
<th>Significance</th>
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<tbody>
<tr>
<td>0.12</td>
<td>1.2 $\sigma$</td>
</tr>
<tr>
<td>$1.1 \times 10^{-5}$</td>
<td>4.2 $\sigma$</td>
</tr>
<tr>
<td>$5.1 \times 10^{-6}$</td>
<td>4.4 $\sigma$</td>
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<tr>
<th>Measured Cross-Section</th>
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<tbody>
<tr>
<td>$1.4^{+0.7}_{-0.6} (\text{stat. } + \text{ syst.}) \text{ pb}$ (NLO prediction is 1.4 pb)</td>
</tr>
</tbody>
</table>
TGC: ZW and ZZ

- Trigger Lepton with $E_T > 20\text{GeV}$
- Second lepton with $E_T > 10\text{GeV}$
- $76 < M_{ll} < 106 \text{ GeV}$: suppress non Z production
- 2 jets (cone $\Delta R < 0.4$, $|\eta| < 2.5$)

Use 3 $p_T(Z \rightarrow ll)$ bins

<table>
<thead>
<tr>
<th>limits</th>
<th>values</th>
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<tbody>
<tr>
<td>$\sigma(WZ)$ $140 &lt; Z^0(p_T)$</td>
<td>234 fb</td>
</tr>
<tr>
<td>$\sigma(WZ)$ $210 &lt; Z^0(p_T)$</td>
<td>135 fb</td>
</tr>
<tr>
<td>$\sigma(ZZ)$ $140 &lt; Z^0(p_T)$</td>
<td>280 fb</td>
</tr>
<tr>
<td>$\sigma(ZZ)$ $210 &lt; Z^0(p_T)$</td>
<td>77 fb</td>
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First observation

- Selection:
  1. $E_T > 60$ GeV
  2. exactly two jets with $E_T > 25$ GeV and $\eta < 2.0$
  3. $E_T$ significance > 4
  4. $\Delta\phi(E_T, \text{jet}) > 0.4$

- Select $jj+\text{MET}$ events
  1. Benefited from L2 met/cal trigger upgrade (doi: 10.1109/NSSMIC.2006.354160)

- Acceptance to $\nu\nu$ and $l\nu$ events ($WW, WZ, ZZ$)

- QCD rejection: MetModel
  1. Reduced to only 16% out of selected events

- Remaining QCD: based on $\Delta\phi(\text{calMET} - \text{trkMET})$

- EWK $mJJ$ shape: checked with $\gamma+jj \rightarrow$ significantly reduces systematics
First observation

\[ \sigma(\text{WW} + \text{WZ} + \text{ZZ}) = 18.0 \pm 2.8(\text{stat}) \pm 2.4(\text{syst}) \pm 1.1(\text{lumi}) \text{pb} \]

SM: 16.8 \pm 0.5 \text{pb (MCFM + CTEQ6M)}

5.3 \sigma \text{ significance}

Leptonic $W$ candidate:

- one tight lepton (electron or muon) with $E_T > 20$ GeV, $\eta < 1.2$ and $E_T > 25$ GeV
- $M_T(W) > 30$ GeV/$c^2$ to get rid of large part of the QCD background

Hadronic $W$ candidate:

- At least 2 jets (reconstructed using JETCLU, $R = 0.4$) with:
  1. $E_T > 20$ GeV corrected for detector effects.
  2. $|\eta| < 2.4$
  3. $\Delta\eta < 2.5$
  4. Electron removal
Two different approaches used:

1. First approach uses the shape of $M_{jj}$ of the two leading jet to look for a clear resonance

- Use $p_T > 40$ GeV/c cut to smoothen $m_{jj}$ distribution
- Binned fit to extract signal: template EWK, QCD and signal.
- We estimate combining the two decays: $1070 \pm 232$ (stat.) $\pm 86$ (syst) $\sigma_{WW/WZ} \rightarrow l\nu jj$ events, for $4.61 \sigma$ where $4.9$ was expected.
- Finally, we measure:

$$\sigma_{WW/WZ} = 14.4 \pm 3.1\text{(stat.)} \pm 2.2\text{(syst.) pb}$$
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Second approach uses a multivariate technique to exploit all the information in the event: expect more sensitivity

Different selection since the shapes of the two discriminants are different:
- Exactly two tight jets with $E_T > 25$ GeV and $\eta < 2.0$
- Harder cut on $M_T(W) > 70$ GeV/$c^2$ and $E_T > 40$ GeV
- Use matrix element calculation to build discriminant (EPD) to separate signal and background
- Likelihood fit to extract signal.

Found a significance of $5.4 \sigma$ where $5.1$ was expected: First observation

$\sigma_{WW/WZ} = 17.7 \pm 3.1\text{(stat.)} \pm 2.4\text{(syst.)}\text{pb}$
Conclusion

- Measuring processes with cross sections similar to Higgs!
- New limits set on anomalous couplings
- First observation of diboson with leptons+jets:
  - Opens the way to diboson studies with jets

CDF Run II, $p\bar{p}$ at $\sqrt{s} = 1.96$ TeV

<table>
<thead>
<tr>
<th>Production Cross Section [pb]</th>
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<tbody>
<tr>
<td>$10^4$</td>
</tr>
<tr>
<td>$10^3$</td>
</tr>
<tr>
<td>$10^2$</td>
</tr>
<tr>
<td>$10^1$</td>
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<tr>
<td>$10$</td>
</tr>
<tr>
<td>$1$</td>
</tr>
<tr>
<td>$10^{-1}$</td>
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</tbody>
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- $W$, $Z$, $W\gamma$, $Z\gamma$, $WW$, $t\bar{t}$, $ZZ$}

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