Measurement of Di-Boson Production at LHC

Eyal Brodet
Tel-Aviv University
On behalf of the ATLAS and CMS Collaborations
Leading Di-Boson Production

Di-Boson: WW, WZ, ZZ
Where $V = \text{Vector Boson}$

Triple gauge diagram: forbidden for ZZ in SM
Di-Boson Total Cross Sections

- $WW = 111.6\text{pb}$ measurable at low luminosity
- $WZ = 47.8\text{pb}$
- $ZZ = 14.8\text{pb}$ measurable at high luminosity

Results: cern-open-2008-020
Note: all studies except where mentioned otherwise use leptonic decays of $W$ and $Z$ at pp at CM energy of 14TeV
Motivation and Di-Boson Studies at LHC

- Test SM at the highest LHC energy
- Background for Higgs search
- Measure cross sections
- Measure triple gauge couplings
- Measure polarization of bosons
Cross Sections Measurements

- Possible to measure at early stage (e.g. for WW and WZ)
- Need relatively low luminosity
- Precision will improve with time
- Need to know well luminosity and structure functions
WW Cross Section Measurement with CMS

Main Cuts:

- 2 opposite sign leptons with $P_t > 20\text{GeV}$
- Missing Energy $>45\text{GeV}$
- Di-lepton mass NOT on Z mass
- Jet Veto: $E_t > 20\text{GeV}$

For $L = 100\text{pb}^{-1}$ with 10 TeV

Result from: CMS PAS EWK-09-002

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Main cuts:

- 4 Leptons with $P_t > 5\text{GeV}$
- Rapidity $< 2.7$
- Pair leptons to be on Z mass
- Almost no background

For $L = 10 \text{ fb}^{-1}$
Signal and Background for Di-Boson with ATLAS for 1fb⁻¹

Result from: CERN-OPEN-2008-020

<table>
<thead>
<tr>
<th>Diboson mode</th>
<th>Signal</th>
<th>Background</th>
<th>Signal eff.</th>
<th>$\sigma_{\text{stat}}$</th>
<th>$p$-value</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+W^- \rightarrow e^+\nu\mu^+\nu$</td>
<td>347 ± 3</td>
<td>64 ± 5</td>
<td>12.6% (BDT)</td>
<td>5.4%</td>
<td>$3.6 \times 10^{-166}$</td>
<td>27.4</td>
</tr>
<tr>
<td>$W^+W^- \rightarrow \mu^+\nu\mu^-\nu$</td>
<td>70 ± 1</td>
<td>17 ± 2</td>
<td>5.2% (BDT)</td>
<td>12.0%</td>
<td>$8.8 \times 10^{-30}$</td>
<td>11.3</td>
</tr>
<tr>
<td>$W^+W^- \rightarrow e^+\nu e^-\nu$</td>
<td>52 ± 1</td>
<td>11 ± 2</td>
<td>4.9% (BDT)</td>
<td>13.9%</td>
<td>$1.9 \times 10^{-24}$</td>
<td>10.1</td>
</tr>
<tr>
<td>$W^+W^- \rightarrow \ell^+\nu\ell^-\nu$</td>
<td>103 ± 3</td>
<td>17 ± 2</td>
<td>2.0% (cuts)</td>
<td>9.9%</td>
<td>$1.4 \times 10^{-54}$</td>
<td>15.5</td>
</tr>
<tr>
<td>$W^\pm Z \rightarrow \ell^\pm\nu\ell^+\ell^-$</td>
<td>128 ± 2</td>
<td>16 ± 3</td>
<td>15.2% (BDT)</td>
<td>8.8%</td>
<td>$3.0 \times 10^{-76}$</td>
<td>18.4</td>
</tr>
<tr>
<td></td>
<td>53 ± 2</td>
<td>8 ± 1</td>
<td>6.3% (cuts)</td>
<td>13.7%</td>
<td>$3.1 \times 10^{-30}$</td>
<td>11.4</td>
</tr>
<tr>
<td>ZZ $\rightarrow 4\ell$</td>
<td>17 ± 0.5</td>
<td>2 ± 0.2</td>
<td>7.7% (cuts)</td>
<td>24.6%</td>
<td>$6.0 \times 10^{-12}$</td>
<td>6.8</td>
</tr>
<tr>
<td>ZZ $\rightarrow \ell^+\ell^-\nu\bar{\nu}$</td>
<td>10 ± 0.2</td>
<td>5 ± 2</td>
<td>2.6% (cuts)</td>
<td>31.3%</td>
<td>$7.7 \times 10^{-4}$</td>
<td>3.2</td>
</tr>
</tbody>
</table>
WZ Cross Sections Measurement with CMS

- Split into $W^+Z$ and $W^-Z$ (total 47.8 pb)
- Focus at fully leptonic decay mode

- Main feature: 3 isolated leptons

- For 300 pb$^{-1}$ get about 35 signal events With 40% background
WZ Cross Section Measurement with CMS

Main Cuts:

- 3 leptons Pt > 20
- Transverse W mass > 50 GeV
- 2 leptons on Z mass: 50-120 GeV

Figure 3: Z^0 candidate invariant mass for all four channels combined, normalized to integrated luminosity of 300 pb^{-1}.
Significance as a function of luminosity in the WZ case

Result from:
CMS PAS
EWK-08-003
Triple Gauge Couplings

- The most general $WW\gamma$, $WWZ$ effective Lagrangian has 14 couplings
- Using only C and P conserving terms and assume QED gauge invariance we are left with 5 couplings:

$$g_1^Z = 1, \quad k_{\gamma,Z} = 1$$

$$\lambda_{\gamma,Z} = 0$$

TGC values according to SM:
Triple Gauge Couplings

- Look at WW process
- Transverse mass distribution
Comparison Between TGC Limits of LHC, Tevatron and LEP2: 95\%CL

<table>
<thead>
<tr>
<th>ATLAS for 30 fb^{-1}</th>
<th>D0 for 0.16 fb^{-1}</th>
<th>LEP2:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta g_1^Z = [-0.14, 0.25]$</td>
<td>$\Delta k_\gamma = [-0.056, 0.51]$</td>
<td>$\Delta g_1^Z = [-0.051, 0.034]$</td>
</tr>
<tr>
<td>$\Delta k_\gamma = [-0.056, 0.51]$</td>
<td>$\Delta k_\gamma = [-0.88, 0.96]$</td>
<td>$\Delta k_\gamma = [-0.105, 0.069]$</td>
</tr>
<tr>
<td>$\lambda_\gamma = [-0.052, 0.100]$</td>
<td>$\lambda_\gamma = [-0.2, 0.2]$</td>
<td>$\lambda_\gamma = [-0.059, 0.026]$</td>
</tr>
</tbody>
</table>

With constraints:

$\Delta k_Z = \Delta g_1^Z - \Delta k_\gamma \tan^2 \theta_W$

$\lambda_Z = \lambda_\gamma$
Neutral Triple Gauge Couplings

In ZZ Case:

Forbidden in SM at Tree level
ATLAS Study Results
Likelihoods and 95% C.L

Results from: ATL-PHYS-PUB-2007-015

\[-0.0051 < f_4^Z < 0.0051\]
\[-0.0075 < f_4^\gamma < 0.0075\]
\[-0.0053 < f_5^Z < 0.0055\]
\[-0.0078 < f_5^\gamma < 0.0078\]
Comparison to LEP2

- ZZ: Great improvement from LEP2
- The improvement in ZZ is due to strong energy dependence of anomalous TGC contribution to ZZ production
- E.g. $F^Z_4$ limit 0.005 at LHC, c.f. 0.3 at LEP2
ZZ and WZ Polarization

- Z,W polarization: longitudinal and transverse
- At LHC unique opportunity to observe and study longitudinal Z,W
- Do this by studying the angular distribution of the Z,W decay products,
  \[ \cos \theta^*_l \]
Angular variables

\[ V = Z, W^+, W^- \]

II Production Axis

\[ \overline{q} \quad q \]

\[ Z \quad l \quad l^* \]

\[ \theta_I \quad \theta_I^* \]

\[ \theta_W \]
Looking at $\cos \theta_1$ for e.g. WZ:

- Angular distribution in the W rest frame:

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos \theta_1} = \rho_{--} \frac{3}{8}(1 + \cos \theta_1^*)^2 + \rho_{++} \frac{3}{8}(1 - \cos \theta_1^*)^2 + \rho_{00} \frac{3}{4} \sin^2 \theta_1^*$$

- Angular distribution in the Z rest frame:

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos \theta_1} = \rho_{--} \frac{3}{8}(1 + \cos \theta_1^{*2} + 2A\cos \theta_1^*) + \rho_{++} \frac{3}{8}(1 + \cos \theta_1^{*2} - 2A\cos \theta_1^*) + \rho_{00} \frac{3}{4} \sin^2 \theta_1^*$$

where $\rho_{--}, \rho_{++}, \rho_{00}$ are the diagonal elements of the spin density matrix (SDM)

- $\rho_{00}$ corresponds to longitudinal polarization

- Extract $\rho_{--}, \rho_{++}, \rho_{00}$ from the data
Reconstruction $\cos\theta_i$

- In ZZ: trivial
- Problem in WZ: $\sqrt{s}$ is unknown, missing $P_L$ (neutrino)
- Therefore can not know the boost to reconstruct $\cos\theta_i$
- Solution: require lepton mom. and missing $P_t$ to be on W mass
Reconstruction $\cos \theta_1$

- Gives quadratic equation with 2 solutions for the $P_L$ (neutrino)
- For each $P_L$ (neutrino) solution find the events contribution to the cross section
- Average 2 solutions for $P_L$ (neutrino) according to the cross section weight
- Find estimated $\sqrt{s}$ and find $\cos \theta_1^*$
Difference Between True and Reconstructed $\sqrt{\hat{s}}$

Result from: ATL-PHYS-PUB-2009-078

![Histogram showing the difference between true and reconstructed $\sqrt{\hat{s}}$ with mean -2.276 GeV and RMS 33.43 GeV.](image)
\[ \rho_{00} \text{ As a Function of } \sqrt{s} \text{ For WZ} \]

Result from:
ATL-PHYS-PUB-2009-078

For \( L = 100 \text{fb}^{-1} \)
$\rho_{00}$ As a Function of $\sqrt{s}$ For ZZ

Result from:
ATL-PHYS-PUB-2008-002

For $L = 100\text{fb}^{-1}$
Summary

- Di-Boson cross section can be measured with low luminosity
- TGC expected limits for WWZ, WWγ, ZZZ and ZZγ were presented
- Expected limits on NTGC improved in LHC from LEP2
- With high luminosity, polarization measurements in ZZ and WZ events are feasible
Backup slides
## TGC limits

Table 21: One-dimensional 95% C.L. interval of the WWZ and WWγ anomalous coupling sensitivities from the WW final state analysis for 0.1, 1, 10 and 30 fb\(^{-1}\) integrated luminosities, with \(\Lambda = 2\) TeV.

<table>
<thead>
<tr>
<th>Int. Lumi (fb(^{-1}))</th>
<th>(\Delta \kappa_Z)</th>
<th>(\lambda_Z)</th>
<th>(\Delta g_i^Z)</th>
<th>(\Delta \kappa_\gamma)</th>
<th>(\lambda_\gamma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>[-0.242, 0.356]</td>
<td>[-0.206, 0.225]</td>
<td>[-0.741, 1.177]</td>
<td>[-0.476, 0.512]</td>
<td>[-0.564, 0.775]</td>
</tr>
<tr>
<td>1.0</td>
<td>[-0.117, 0.187]</td>
<td>[-0.108, 0.111]</td>
<td>[-0.355, 0.616]</td>
<td>[-0.240, 0.251]</td>
<td>[-0.259, 0.421]</td>
</tr>
<tr>
<td>10.0</td>
<td>[-0.035, 0.072]</td>
<td>[-0.040, 0.038]</td>
<td>[-0.149, 0.309]</td>
<td>[-0.088, 0.089]</td>
<td>[-0.074, 0.165]</td>
</tr>
<tr>
<td>30.0</td>
<td>[-0.026, 0.048]</td>
<td>[-0.028, 0.027]</td>
<td>[-0.149, 0.251]</td>
<td>[-0.056, 0.054]</td>
<td>[-0.052, 0.100]</td>
</tr>
</tbody>
</table>

Table 3: Anomalous gauge coupling limits (95% C.L.) for WWγ and WWZ from the Tevatron experiments, with \(\Lambda = 2\) TeV.

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Source</th>
<th>L (fb(^{-1}))</th>
<th>(\lambda_Z)</th>
<th>(\Delta \kappa_Z)</th>
<th>(\Delta \kappa_\gamma)</th>
<th>(\lambda_\gamma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WWγ from W(^{\pm})γ</td>
<td>D0 [27]</td>
<td>0.16</td>
<td></td>
<td></td>
<td>[-0.88, 0.96]</td>
<td>[-0.2, 0.2]</td>
</tr>
<tr>
<td>WWZ from W(^{\pm})Z</td>
<td>D0 [24]</td>
<td>1.0</td>
<td>[-0.17, 0.21]</td>
<td>[-0.12, 0.29]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WWZ from W(^{\pm})Z</td>
<td>CDF</td>
<td>1.9</td>
<td>[-0.13, 0.14]</td>
<td>[-0.82, 1.27]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WWZ = WWγ from W(^{+})W(^{-})</td>
<td>D0 [30]</td>
<td>0.25</td>
<td>[-0.31, 0.33]</td>
<td>[-0.36, 0.33]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WWZ = WWγ from W(^{+})W(^{-}), W(^{\pm})Z</td>
<td>CDF [31]</td>
<td>0.35</td>
<td>[-0.18, 0.17]</td>
<td>[-0.46, 0.39]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>