Multi-boson production at ATLAS

Al Goshaw
(Duke University)
for the ATLAS Collaboration

PHENO2016, Pittsburgh
May 10, 2016
A broad menu of EWK boson studies at the LHC

<table>
<thead>
<tr>
<th>Collisions</th>
<th>Measurement</th>
<th>Production</th>
<th>EWK Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>p + p at 7,8,13 TeV</td>
<td>V + 0 jets</td>
<td>EWK_{s-channel}</td>
<td>TGC</td>
</tr>
<tr>
<td></td>
<td>V + 2 forward jets</td>
<td>VBF</td>
<td>TGC</td>
</tr>
<tr>
<td></td>
<td>V V' + 0 jets</td>
<td>EWK_{s-channel}</td>
<td>TGC</td>
</tr>
<tr>
<td></td>
<td>V V' + 2 forward jets</td>
<td>VBS</td>
<td>QGC</td>
</tr>
<tr>
<td></td>
<td>V V' V'' + 0 jets</td>
<td>EWK_{s-channel}</td>
<td>QGC</td>
</tr>
</tbody>
</table>

Thanks to the LHC

From the excellent performance of ATLAS and CMS

Studies using increasingly Precise SM theory calculations

Test the SM and look for BSM physics

Thanks to the LHC from the excellent performance of ATLAS and CMS using increasingly precise SM theory calculations to test the SM and look for BSM physics.
Thanks to CERN and the LHC ...

pp collisions

Typical data set analyzed by ATLAS

7 TeV ~ 5 fb\(^{-1}\)
8 TeV ~ 20 fb\(^{-1}\)
13 TeV 2015 data sample of 3.2 fb\(^{-1}\)
13 TeV 2016 first collisions occurring now ...
Goal ~ 25 fb\(^{-1}\) by end of year *

* modulo DWF
Beautiful detector performance ...

\[ p + p \rightarrow Z(\mu^+ \mu^-) + Z(e^+ e^-) + \ldots \text{ at } 13 \text{ TeV} \]
### Recent ATLAS measurements for VV' and VVV

<table>
<thead>
<tr>
<th>Di-boson</th>
<th>Tri-boson</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \gamma$</td>
<td>$Z \gamma \gamma$</td>
</tr>
<tr>
<td>$W^\pm W^\mp$</td>
<td>$W^\pm \gamma \gamma$</td>
</tr>
<tr>
<td>$W^\pm W^\mp$</td>
<td>$W^\pm \gamma \gamma$</td>
</tr>
<tr>
<td>$W^\pm Z$</td>
<td>$W^\pm \gamma \gamma$</td>
</tr>
<tr>
<td>$Z Z$</td>
<td>$W^\pm Z$</td>
</tr>
<tr>
<td>$W^\pm Z$</td>
<td>$Z Z$</td>
</tr>
</tbody>
</table>

**Selected new results**

- Approved today!
- Make comparisons to the best available SM calculations
- Search for new physics via aTGC and aQGC
Anomalous Triple Gauge Coupling (aTGC)

aTGC vertex \( Z/\gamma \)

\( Z \)

\( i = 4: \) CP-violating, \( i = 5: \) CP-conserving

aTGC is modelled as effective Lagrangian depending on some parameters.

Example of \( ZZ\gamma \) and \( Z\gamma \): 4 anomalous coupling \( \lambda, \Delta k, \Delta g \): coefficient

SM

Generally aTGC is enhanced high \( p_T \) region.

Coupling Parameters Channel

<table>
<thead>
<tr>
<th></th>
<th>Parameters</th>
<th>Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW( \gamma )</td>
<td>( \lambda, \Delta k )</td>
<td>WW, W( \gamma )</td>
</tr>
<tr>
<td>WWZ</td>
<td>( \lambda, \Delta k )</td>
<td>WW, WZ</td>
</tr>
<tr>
<td>ZZ( \gamma )</td>
<td>( h^Z_3, h^Z_4 )</td>
<td>Z( \gamma )</td>
</tr>
<tr>
<td>Z( \gamma \gamma )</td>
<td>( h^\gamma_3, h^\gamma_4 )</td>
<td>Z( \gamma )</td>
</tr>
<tr>
<td>Z( \gamma Z )</td>
<td>( f^{\gamma}_4, f^{\gamma}_5 )</td>
<td>ZZ</td>
</tr>
<tr>
<td>ZZZ</td>
<td>( f^{Z}_4, f^{Z}_5 )</td>
<td>ZZ</td>
</tr>
</tbody>
</table>
Use $Z$ decays to $e^+ e^-$, $\mu^+ \mu^-$ and $\nu \bar{\nu}$ from 20.3 fb$^{-1}$ of data.

Cross sections measured for $Z(l^+ l^-) + \gamma$ ($E_T(\gamma) > 15$ GeV; $Z(l^+ l^-) > 40$ GeV) and for $Z(\nu \bar{\nu}) + \gamma$ ($E_T(\gamma) > 130$ GeV).

Major backgrounds ($Z/W+$jets, $\gamma+$jets) determined with data driven methods.

Compare measurements to SM theory calculations at NNLO (arxiv:1504.01330).

Search for BSM sources of $Z \gamma$ production from $aTGC$'s.
\[ p + p \rightarrow Z + \gamma + \ldots \text{ at } 8 \text{ TeV} \]

arxiv:1604.05232

\[
\text{ATLAS} \quad \sqrt{s} = 8 \text{ TeV}, \ 20.3 \text{ fb}^{-1}
\]

\[ N_{\text{jets}} \geq 0 \quad l^+l^-\gamma \text{ channel} \]

**ATLAS**

\[ d\sigma(p + p \rightarrow \gamma\gamma Z) / dE_T^\gamma \]

- Data
- Sherpa (CT10)
- MCFM (CT10)
- NNLO (MMHT2014)

**Compare unfolded differential spectra to SM Predictions (Sherpa+3 partons)**

**SM at NNLO ✓**
p + p → Z + γ + ... at 8 TeV

arxiv:1604.05232

Set aTGC limits on ZZγ and Zγγ using high Et photons

The best constraints to date on hiV (i=3,4 V=γ, Z).
Use $W$ decays to $e\nu$ and $\mu\nu$, $Z$ decays to $e^+e^-$ and $\mu^+\mu^-$ from 20.3 fb$^{-1}$ of data.

Event selected with at least one charged lepton with $E_T > 25$ GeV,

Backgrounds from $Z$+jets, $Z\gamma$, $WW$ and top estimated from data driven methods; other EWK backgrounds from MC simulations.

Total and differential cross sections measured for $66 < M(l^+l^-) < 116$ GeV

Precision of measurements require SM predictions beyond NLO.

NLO SM predictions (redline Powheg+Pythia) disagree with data.

\[ p + p \rightarrow W^+ + Z + \ldots \text{ at } 8 \text{ TeV} \]

SM at NLO not OK. \( \Rightarrow \) need for NNLO
The WZ channel has an approximate radiation zero similar to that of $W\gamma$ production and is therefore particularly sensitive to higher order QCD corrections (arXiv:1604.08576):

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>$\sigma_{\text{LO}}$ [pb]</th>
<th>$\sigma_{\text{NLO}}$ [pb]</th>
<th>$\sigma_{\text{NNLO}}$ [pb]</th>
<th>$\sigma_{\text{NLO}}/\sigma_{\text{LO}}$</th>
<th>$\sigma_{\text{NNLO}}/\sigma_{\text{NLO}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>13.654(1) $^{+1.3%}_{-2.1%}$</td>
<td>22.750(2) $^{+5.1%}_{-3.9%}$</td>
<td>24.690(16) $^{+1.8%}_{-1.9%}$</td>
<td>+66.6%</td>
<td>+ 8.5%</td>
</tr>
</tbody>
</table>

Compare the NNLO prediction to the ATLAS 8 TeV WZ measurement with $66 < M(l^+ l^-) < 116$ GeV:

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>$\sigma_{\text{LO}}$ [pb]</th>
<th>$\sigma_{\text{NLO}}$ [pb]</th>
<th>$\sigma_{\text{NNLO}}$ [pb]</th>
<th>$\sigma_{\text{ATLAS}}$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>13.261(9) $^{+1.3%}_{-2.1%}$</td>
<td>22.03(2) $^{+5.1%}_{-3.9%}$</td>
<td>23.92(3) $^{+1.7%}_{-1.8%}$</td>
<td>24.3 $^{+0.6}<em>{-0.6}$ (stat) $^{+0.6}</em>{-0.6}$ (syst) $^{+0.5}<em>{-0.5}$ (lumi) $^{+0.4}</em>{-0.4}$ (th)</td>
</tr>
</tbody>
</table>

SM at NNLO ✔
aTGC limits from $p + p \rightarrow W^\pm + Z + \ldots$ at 8 TeV

arxiv:1603.02151

Set aTGC limits on the WWZ coupling using the transverse mass of the WZ pair.

$$\mathcal{L} = ig_{WWV} \left[ g^V (W^{+\mu} W^{-\mu} - W^{+\mu} W^{\mu v}) V^\nu + k^V W^{+\mu} W^{-\nu} V^\mu + \frac{\lambda^V}{m_W^2} W^{+\mu} W^{-\nu} V^\rho V^\mu \right]$$

Combined WW and WZ measurements provide the best WWZ aTGC limits

ATLAS

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

$e^+ e^-$ (or $e^+ e^-$)

$e^+ e^-$ (or $e^+ e^-$)

Data 2012

W$^\pm$

Misid. leptons

$Z Z$

$Z \rightarrow \nu \bar{\nu}$

Others

Tot. unc.

$\Delta g_1^Z = 0.1$, $\Delta k^Z = 0.25$, $\lambda^Z = 0.1$

$\Delta g_1^Z = 0.3$, $\Delta k^Z = 0.19$, $\lambda^Z = 0$

$\Delta g_1^Z = 0.1$, $\Delta k^Z = 0.25$, $\lambda^Z = 0.1$

$\Delta g_1^Z = 0.3$, $\Delta k^Z = 0.19$, $\lambda^Z = 0$

-0.5 0 0.5 1.0 1.5 2.0 2.5

$\Delta g_1^Z$

$\Delta k^Z$

$\Delta \lambda^Z$

$\Delta \chi^2$

aTGC Limits at 95% CL

Al Goshaw Pheno 2016
Use $W$ decays to $e\nu$ and $\mu\nu$, $Z$ decays to $e^+e^-$ and $\mu^+\mu^-$ from 3.2 $fb^{-1}$ of data.

Event selected with at least one charged lepton with $Et > 25$ GeV,

Backgrounds from $Z$+jets, $Z$+$\gamma$, $WW$ and top estimated from data driven methods; other EWK backgrounds from MC simulations.

Total cross sections measured for $66 < M(l^+l^-) < 116$ GeV
Detector-level data (points with uncertainties). The solid red curve is the total background plus SM WZ signal with uncertainty indicated by the shaded violet band.

The SM WZ signal is calculated at NLO from Powheg+Pythia scaled by 1.17 to match the data.
\[ p + p \rightarrow W^\pm + Z + \ldots \text{ at } 13 \text{ TeV} \]

Approved today by ATLAS

\[ \sigma_{\text{fid.}}^{W^+Z} / \sigma_{\text{theory}}^{W^+Z} \]

**a)** Ratio of measured WZ fiducial cross sections compared to NLO SM prediction from Powheg+Pythia with CT10 pdf.

**b)** Ratio of \( W^+Z/W^-Z \) fiducial cross sections compared to NLO SM prediction from Powheg+Pythia with CT10 pdf.
p + p \rightarrow W^{\pm} + Z + ... \text{ at 13 TeV}

Just approved by ATLAS

Compare the ATLAS 13 TeV WZ measurement to the recent NNLO SM predictions (arXiv:1604.08576).

<table>
<thead>
<tr>
<th>√s [TeV]</th>
<th>σ_{LO} [pb]</th>
<th>σ_{NLO} [pb]</th>
<th>σ_{NNLO} [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>11.028(8)+0.5%−1.2%</td>
<td>17.93(1)+5.3%−4.1%</td>
<td>19.34(3)+1.6%−1.8%</td>
</tr>
<tr>
<td>8</td>
<td>13.261(9)+1.3%−2.1%</td>
<td>22.03(2)+5.1%−3.9%</td>
<td>23.92(3)+1.7%−1.8%</td>
</tr>
<tr>
<td>13</td>
<td>24.79(2)+4.2%−5.2%</td>
<td>44.67(3)+4.9%−3.9%</td>
<td>49.62(6)+2.2%−2.0%</td>
</tr>
</tbody>
</table>

SM at NNLO ✔

Al Goshaw  Pheno 2016
Tri-boson production at ATLAS and QGC's

\[ L_{S,0}, L_{S,1} \]
\[ L_{M,0}, L_{M,1}, L_{M,6}, L_{M,7} \]
\[ L_{M,2}, L_{M,3}, L_{M,4}, L_{M,5} \]
\[ L_{T,0}, L_{T,1}, L_{T,2} \]
\[ L_{T,5}, L_{T,6}, L_{T,7} \]
\[ L_{T,8}, L_{T,9} \]

<table>
<thead>
<tr>
<th></th>
<th>WWWW</th>
<th>WWZZ</th>
<th>ZZZZ</th>
<th>WWγZ</th>
<th>WWγγ</th>
<th>ZZZγ</th>
<th>ZZγγ</th>
<th>γγγγ</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ L_{S,0}, L_{S,1} ]</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>[ L_{M,0}, L_{M,1}, L_{M,6}, L_{M,7} ]</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>[ L_{M,2}, L_{M,3}, L_{M,4}, L_{M,5} ]</td>
<td>O</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>[ L_{T,0}, L_{T,1}, L_{T,2} ]</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>[ L_{T,5}, L_{T,6}, L_{T,7} ]</td>
<td>O</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>[ L_{T,8}, L_{T,9} ]</td>
<td>O</td>
<td>O</td>
<td>X</td>
<td>O</td>
<td>O</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
Select $W/Z$ leptonic decays from 20.3 fb$^{-1}$ of data.

- For $Z_{\gamma\gamma}$ photons with $E_T(\gamma) > 15$ GeV and $\Delta R(l-\gamma) > 0.4$
- For $W_{\gamma\gamma}$ photons with $E_T(\gamma) > 20$ GeV and $\Delta R(l-\gamma) > 0.7$

Compare measurements to SM theory calculations at NLO using MCFM.

Search for BSM sources of $Z_{\gamma\gamma}/W_{\gamma\gamma}$ production from $a$QGC's.
Observation of $Z\gamma\gamma$ signal with significance at the level 5 sigma.

Evidence for $W\gamma\gamma$ with significance at the level 3 sigma.

Within large data statistical uncertainties we find agreement with SM predictions at NLO using MCFM.
Use the $M(\gamma\gamma)$ spectrum to set aQGC limits:

- $M(\gamma\gamma) > 200\ [300]\ \text{GeV}$ for $Z(l^+\ l^-) + \gamma\gamma [Z(\nu\bar{\nu}) + \gamma\gamma]$:
  - $M(\gamma\gamma) > 300\ \text{GeV}$ for $W + \gamma\gamma$

Choose some parameters describing dimension 8 operators:

- $L_{M,2} = \frac{f_{M2}}{\Lambda^4} [B_B B^{\mu\nu}] \times [(D_\beta \phi)^\dagger D_\beta \phi]$
- $L_{M,3} = \frac{f_{M3}}{\Lambda^4} [B_B^\mu B_B^\nu] \times [(D_\beta \phi)^\dagger D_\phi^\mu \phi]$
- $L_{T,0} = \frac{f_{T0}}{\Lambda^4} \text{Tr} [\hat{W}_B \hat{W}^{\mu\nu}] \times \text{Tr} [\hat{W}_{aB} \hat{W}^{a\beta}]$
- $L_{T,5} = \frac{f_{T5}}{\Lambda^4} \text{Tr} [\hat{W}_B \hat{W}^{\mu\nu}] \times B_{aB} B^{a\beta}$
- $L_{T,9} = \frac{f_{T9}}{\Lambda^4} B_{aB} B^{a\mu} B_{B^\nu} B^{\nu\alpha}$

- $WW\gamma\gamma$ and $ZZ\gamma\gamma$ sensitive to $f_{M2}$ and $f_{M2}$
- $WW\gamma\gamma$, $ZZ\gamma\gamma$ and $Z\gamma\gamma\gamma$ sensitive to $f_{T0}$ and $f_{T5}$
- $ZZ\gamma\gamma$ and $Z\gamma\gamma\gamma$ sensitive to $f_{T0}$
(using convention of Eboli et al.)

\[ \begin{align*}
&W^+W^- \text{ CMS, } \sqrt{s}=8 \text{ TeV, } 19.4 \text{ fb}^{-1} \\
&W_\gamma\gamma \text{ ATLAS, } \sqrt{s}=8 \text{ TeV, } 20.3 \text{ fb}^{-1} \\
&Z\gamma\gamma \text{ ATLAS, } \sqrt{s}=8 \text{ TeV, } 20.3 \text{ fb}^{-1} \\
&WV_\gamma \text{ CMS, } \sqrt{s}=8 \text{ TeV, } 19.3 \text{ fb}^{-1}
\end{align*} \]

\[ \begin{array}{ccc}
\text{ATLAS} & 95\% \text{ C.L.} & \Lambda_\text{FF} = \infty \\
\text{f}_{t0}/\Lambda^4 & \text{f}_{t5}/\Lambda^4 & \text{f}_{t9}/\Lambda^4
\end{array} \]

Coupling strength [TeV^{-4}]

\[ \text{Channel Measurement [fb]} \quad \text{Prediction [fb]} \]

\[ \begin{array}{c}
\text{f}_{\ell\bar{\ell}} & \text{f}_{\ell\bar{\ell}} \\
\text{FF} & \text{FF} \\
\text{SM} & \text{SM}
\end{array} \]

\[ \text{The limits are presented in the formalism as implemented in V235} \]

\[ \text{p + p \rightarrow Z + \gamma + \gamma ... at 8 TeV} \]

\[ \text{arxiv:1604.05232} \]

<table>
<thead>
<tr>
<th>n</th>
<th>\Lambda_\text{FF} [TeV]</th>
<th>Limits 95% C.L.</th>
<th>Observed [TeV^{-4}]</th>
<th>Expected [TeV^{-4}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>\infty</td>
<td>\text{f}_{M2}/\Lambda^4</td>
<td>[-1.6, 1.6] \times 10^9</td>
<td>[-1.2, 1.2] \times 10^9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>\text{f}_{M3}/\Lambda^4</td>
<td>[-2.9, 2.7] \times 10^4</td>
<td>[-2.2, 2.2] \times 10^4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>\text{f}_{T0}/\Lambda^4</td>
<td>[-0.86, 1.03] \times 10^2</td>
<td>[-0.65, 0.82] \times 10^2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>\text{f}_{T5}/\Lambda^4</td>
<td>[-0.69, 0.68] \times 10^3</td>
<td>[-0.52, 0.52] \times 10^3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>\text{f}_{T9}/\Lambda^4</td>
<td>[-0.74, 0.74] \times 10^4</td>
<td>[-0.58, 0.59] \times 10^4</td>
</tr>
<tr>
<td>2</td>
<td>5.5</td>
<td>\text{f}_{M2}/\Lambda^4</td>
<td>[-1.8, 1.9] \times 10^4</td>
<td>[-1.4, 1.5] \times 10^4</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>\text{f}_{M3}/\Lambda^4</td>
<td>[-3.4, 3.3] \times 10^4</td>
<td>[-2.6, 2.6] \times 10^4</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>\text{f}_{T0}/\Lambda^4</td>
<td>[-2.3, 2.1] \times 10^3</td>
<td>[-1.9, 1.6] \times 10^3</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>\text{f}_{T5}/\Lambda^4</td>
<td>[-2.3, 2.2] \times 10^4</td>
<td>[-1.8, 1.8] \times 10^4</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>\text{f}_{T9}/\Lambda^4</td>
<td>[-0.89, 0.86] \times 10^6</td>
<td>[-0.71, 0.68] \times 10^6</td>
</tr>
</tbody>
</table>

\[ \text{W}^+\text{W}^- \quad \text{Z}^+\text{Z}^- \quad \text{Z}^+\text{Z}^- \quad \text{aQGC consistent with O} \]

\[ \text{SM} \checkmark \]

\[ \text{WW}_\gamma\gamma \quad Z\gamma\gamma \quad Z\gamma\gamma \quad \text{aQGC consistent with O} \]

\[ \text{SM} \checkmark \]

\[ \text{p + p \rightarrow W + \gamma + \gamma ... at 8 TeV} \]

\[ \text{arxiv:1503.03243} \]

<table>
<thead>
<tr>
<th>n</th>
<th>\Lambda_\text{FF} [TeV]</th>
<th>Observed [TeV^{-4}]</th>
<th>Expected [TeV^{-4}]</th>
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<tbody>
<tr>
<td>0</td>
<td>\infty</td>
<td>\text{f}_{T0}/\Lambda^4</td>
<td>[-0.9, 0.9] \times 10^2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>\text{f}_{M2}/\Lambda^4</td>
<td>[-0.8, 0.8] \times 10^4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>\text{f}_{M3}/\Lambda^4</td>
<td>[-1.5, 1.4] \times 10^4</td>
</tr>
<tr>
<td>1</td>
<td>\Lambda_\text{FF} = 600 \text{ GeV}</td>
<td>\text{f}_{T0}/\Lambda^4</td>
<td>[-7.6, 7.3] \times 10^2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>\text{f}_{M2}/\Lambda^4</td>
<td>[-4.4, 4.6] \times 10^4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>\text{f}_{M3}/\Lambda^4</td>
<td>[-8.9, 8.0] \times 10^4</td>
</tr>
<tr>
<td>2</td>
<td>\Lambda_\text{FF} = 500 \text{ GeV}</td>
<td>\text{f}_{T0}/\Lambda^4</td>
<td>[-2.7, 2.6] \times 10^3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>\text{f}_{M2}/\Lambda^4</td>
<td>[-1.3, 1.3] \times 10^5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>\text{f}_{M3}/\Lambda^4</td>
<td>[-2.9, 2.5] \times 10^5</td>
</tr>
</tbody>
</table>

\[ \text{p + p \rightarrow W + \gamma + \gamma ... at 8 TeV} \]

\[ \text{arxiv:1503.03243} \]

\[ \text{\Lambda_\text{FF} = 600} \text{ GeV} \]

\[ \text{for f}_{T0} \]

\[ \text{\Lambda_\text{FF} = 500} \text{ GeV} \]

\[ \text{for f}_{M2} \text{ and f}_{M3} \]

\[ \text{(using convention from VBFNLO)} \]
The ATLAS (and CMS) collaboration are making measurements of the production of two EWK bosons in pp collisions at 7, 8 and recently 13 TeV. Tri-boson production is just now being detected.

The theory community is keeping pace with the required SM theory predictions for di-boson production with QCD corrections at order $\alpha_s^2$.

Measurements and SM theory agree at these new levels of precision.

Testing the triple and quartic gauge couplings are putting stringent limits on the phase space of postulated anomalous-coupling parameters.

The advent of high statistics 13 TeV data will continue to increase the precision of multi-boson measurements, requiring new QCD+EWK calculations for testing the validity (or violation) of SM triple and quartic gauge-coupling.
Additional Information
Set aTGC limits on ZZ$\gamma$ and Z$\gamma\gamma$ using high Et photons

<table>
<thead>
<tr>
<th>Process</th>
<th>$pp \rightarrow \ell^+\ell^-\gamma$ and $pp \rightarrow \nu\bar{\nu}\gamma$</th>
<th>(\Lambda_{FF})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(%)</td>
<td>95% C.L.</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
<td>Expected</td>
</tr>
<tr>
<td>$h_1^\gamma$</td>
<td>([-9.5, 9.9] \times 10^{-4})</td>
<td>([-1.8, 1.8] \times 10^{-3})</td>
</tr>
<tr>
<td>$h_2^\gamma$</td>
<td>([-7.8, 8.6] \times 10^{-4})</td>
<td>([-1.5, 1.5] \times 10^{-3})</td>
</tr>
<tr>
<td>$h_3^\gamma$</td>
<td>([-3.2, 3.2] \times 10^{-6})</td>
<td>([-6.0, 5.9] \times 10^{-6})</td>
</tr>
<tr>
<td>$h_4^\gamma$</td>
<td>([-3.0, 2.9] \times 10^{-6})</td>
<td>([-5.5, 5.4] \times 10^{-6})</td>
</tr>
<tr>
<td>$\Lambda_{FF}$</td>
<td>4 TeV</td>
<td>4 TeV</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
<td>Expected</td>
</tr>
<tr>
<td>$h_1^\gamma$</td>
<td>([-1.6, 1.7] \times 10^{-3})</td>
<td>([-3.0, 3.1] \times 10^{-3})</td>
</tr>
<tr>
<td>$h_2^\gamma$</td>
<td>([-1.3, 1.4] \times 10^{-3})</td>
<td>([-2.5, 2.6] \times 10^{-3})</td>
</tr>
<tr>
<td>$h_3^\gamma$</td>
<td>([-1.2, 1.1] \times 10^{-5})</td>
<td>([-2.2, 2.1] \times 10^{-5})</td>
</tr>
<tr>
<td>$h_4^\gamma$</td>
<td>([-1.0, 1.0] \times 10^{-5})</td>
<td>([-1.9, 1.9] \times 10^{-5})</td>
</tr>
</tbody>
</table>

The best aTGC constraints to date on $h_i^V$ (i=3,4, V=$\gamma$,Z)

**ZZ$\gamma$ and Z$\gamma\gamma$ TGC consistent with 0 SM**
p + p \rightarrow W^+ + W^- + ... \text{ at 8 TeV}

arxiv:1603.01702

Set aTGC limits on ZWW and $\gamma$WW couplings using the leading lepton in the e/\mu final states.

\[ \mathcal{L} = i g_{WWV} \left[ g_1^V (W_{\mu\nu} W_{-\mu} - W_{+\mu} W_{\mu\nu}) V^\nu + k^V W_{\mu} W_{\nu} V^{\mu\nu} + \frac{\lambda^V}{m_W^2} W_{\mu} W_{\nu} V^{\rho\mu} \right] \]

Limits on

\[ \left( \frac{\Delta \theta_1^V}{1 + \frac{\delta}{\Lambda^2}} \right)^2, \left( \frac{\Delta k^V}{1 + \frac{\delta}{\Lambda^2}} \right)^2, \left( \frac{\lambda^V}{1 + \frac{\delta}{\Lambda^2}} \right)^2 \]

\( (V = Z, \gamma) \)

---

**Scenario**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expected</th>
<th>Observed</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda = \infty$</td>
<td>$\Lambda = 7$ TeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta \theta_1^Z$</td>
<td>$[-0.498, 0.524]$</td>
<td>$[-0.215, 0.267]$</td>
<td>$[-0.519, 0.563]$</td>
<td>$[-0.226, 0.279]$</td>
</tr>
<tr>
<td>$\Delta k^Z$</td>
<td>$[-0.053, 0.059]$</td>
<td>$[-0.027, 0.042]$</td>
<td>$[-0.057, 0.064]$</td>
<td>$[-0.028, 0.045]$</td>
</tr>
<tr>
<td>$\lambda^Z$</td>
<td>$[-0.039, 0.038]$</td>
<td>$[-0.024, 0.024]$</td>
<td>$[-0.043, 0.042]$</td>
<td>$[-0.026, 0.025]$</td>
</tr>
<tr>
<td>$\Delta \theta_1^\gamma$</td>
<td>$[-0.109, 0.124]$</td>
<td>$[-0.054, 0.092]$</td>
<td>$[-0.118, 0.136]$</td>
<td>$[-0.057, 0.099]$</td>
</tr>
<tr>
<td>$\lambda^\gamma$</td>
<td>$[-0.081, 0.082]$</td>
<td>$[-0.051, 0.052]$</td>
<td>$[-0.088, 0.089]$</td>
<td>$[-0.055, 0.055]$</td>
</tr>
</tbody>
</table>

---

Limits comparable to or better than previous ATLAS measurements.
Set aTGC limits on the ZWW coupling using the transverse mass of the WZ pair. Same paramaterization as for WW on page 13.
Use $W$ leptonic decays to $e \nu$, $\mu \nu$ from 20.3 fb$^{-1}$ of data.

Accept events if no jets with $E_T > 25$ GeV within $|\eta| < 4.5$.

Backgrounds from $W+$jets, Drell-Yan, top, multi-jets data-driven; Diboson ($WZ, ZZ W/\gamma$) from MC.

**SM theory calculations at NNLO**
$p + p \rightarrow W^\pm + W^\mp + \ldots$ at 8 TeV

arxiv:1603.01702

\[ \begin{align*}
\text{Final state} & \quad \text{Total Cross section } pp \rightarrow WW [\text{pb}] \\
\mu\mu & \quad 70.5^{+1.3}_{-1.3} \text{(stat)} \pm 5.5 \text{(syst)} \pm 2.1 \text{(lumi)} \\
\mu\mu & \quad 73.5^{+4.2}_{-4.1} \text{(stat)} \pm 7.5 \text{(syst)} \pm 2.3 \text{(lumi)} \\
\mu\mu & \quad 73.9^{+3.0}_{-3.0} \text{(stat)} \pm 7.1 \text{(syst)} \pm 2.2 \text{(lumi)} \\
\text{combined} & \quad 71.0^{+1.1}_{-1.1} \text{(stat)} \pm 5.7 \text{(syst)} \pm 2.1 \text{(lumi)}
\end{align*} \]

Unfolded differential spectra

Total WW Cross sections compared to SM

SM at NNLO ~ ✔
Use \( Z \) decays to \( e^+ e^- \) and \( \mu^+ \mu^- \) from 3.2 fb\(^{-1}\) of data.

Require leptons \( P_T > 20 \text{ GeV} \) and \( M(l^+l^-) \) 66-116 GeV.

A total of 63 events are observed with a total background of \( 0.62^{+1.08}_{-0.11} \) events.

SM predictions at NNLO

**p + p → Z + Z + ... at 13 TeV**

**arxiv:1512.05314**

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**SM at NNLO ✓**

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**ATLAS**

\(\sqrt{s} = 13\) TeV, 3.2 fb\(^{-1}\)

- Data
  - \(q\bar{q} \rightarrow ZZ \rightarrow 4l\)
  - \(gg \rightarrow ZZ \rightarrow 4l\)
- Prediction uncertainty
- Expected background: 0.6\(^{+1.06}\)\(^{-0.11}\)

---

\(\sigma_{\text{tot}}^{\text{ZZ}}\) prediction

\[
\sigma_{\text{tot}}^{\text{ZZ}} = 16.7^{+2.2}_{-2.0}\text{(stat.)}^{+0.9}_{-0.7}\text{(syst.)}^{+1.0}_{-0.7}\text{(lumi.)} \text{ pb} \quad 15.6^{+0.4}_{-0.4} \text{ pb}
\]

---

**Table 2:**

- **Theory:** PLB 750 (2015) 407
  - CT10 NNLO

---

**Measurements**

- **LHC Data 2015 (13 TeV)**
  - ATLAS ZZ → III \(m_\ell, 66-116 \text{ GeV}\) 3.2 fb\(^{-1}\)
  - CMS ZZ → III \(m_\ell, 66-116 \text{ GeV}\) 19.6 fb\(^{-1}\)

- **LHC Data 2012 (8 TeV)**
  - ATLAS ZZ \(\rightarrow \ell\bar{\nu} \ell\bar{\nu}\) \(m_\ell, 66-116 \text{ GeV}\) 4.5 fb\(^{-1}\)
  - CMS ZZ → III \(m_\ell, 60-120 \text{ GeV}\) 5.0 fb\(^{-1}\)

- **Tevatron Data (1=1.96 TeV)**
  - CDF ZZ → \(\ell\bar{\nu}\ell\bar{\nu}\) \(m_\ell, 66-116 \text{ GeV}\) 0.7 fb\(^{-1}\)
  - D0 ZZ → \(\ell\bar{\nu}\ell\bar{\nu}\) \(m_\ell, 60-120 \text{ GeV}\) 8.6 fb\(^{-1}\)