Multiboson Production at ATLAS

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Electroweak Precision and New Physics

- Precision test of higher order predictions
  - higher order corrections more important at higher center of mass energies
  - recently available NNLO QCD and NLO EWK theoretical calculations.
- Study of triple and quartic gauge boson couplings (TGC and QGC)
  - Gauge boson couplings fixed within the standard model (SM).
  - Strong test of the SM couplings
  - Indirect search for new physics via anomalous gauge boson couplings
- Search for multiboson final states never observed before.
Standard Model Production Cross Section Measurements

ATLAS Preliminary

\( \sqrt{s} = 5,7,8,13 \text{ TeV} \)

- **Theory**
  - LHC pp \( \sqrt{s} = 5 \text{ TeV} \)
    - Data \( 0.03 - 0.3 \text{ fb}^{-1} \)
  - LHC pp \( \sqrt{s} = 7 \text{ TeV} \)
    - Data \( 4.5 - 4.9 \text{ fb}^{-1} \)
  - LHC pp \( \sqrt{s} = 8 \text{ TeV} \)
    - Data \( 20.2 - 20.3 \text{ fb}^{-1} \)
  - LHC pp \( \sqrt{s} = 13 \text{ TeV} \)
    - Data \( 3.2 - 139 \text{ fb}^{-1} \)

- **EW Z\(Z\)jj**
- **WWW**
Observation of WWW production

- Unexplored at the LHC, provides direct Test of gauge boson self-coupling
- Final States Considered
  - $WWW \rightarrow l^\pm v l^\pm v q q$ and $WWW \rightarrow l^\pm v l^\pm v l^\mp v$ with $l = e$ or $\mu$
- Main Backgrounds: $WZ$, non-prompt leptons (mainly $t\bar{t}$)
  - Data-driven estimates for non-prompt leptons and charge mis-identified leptons backgrounds
- Two BDTs used to improve signal to background separation in $2l$ and $3l$ signal regions
- Binned maximum-likelihood fit performed on BDT distributions in signal regions and $m_{lll}$ distribution in $WZ$ Control regions
Observation of WWW production

WWW production observed with significance 8.0σ (expected 5.4σ)! 

- **Measurement**
  - ATLAS
  - $\sqrt{s} = \text{13 TeV, 139 fb}^{-1}$
  - Total
  - Stat.

- **Significance Calculation**
  - $\ell^{\pm}\ell^{\pm}\nu jj$
  - $\ell^{\pm}\ell^{\pm}\nu \ell^{\pm}\nu$
  - Combined

- **Results**
  - $\mu = 1.75 \pm (0.30 \pm 0.22)$
  - $\mu = 1.32 \pm (0.37 \pm 0.35)$
  - $\mu = 1.61 \pm (0.25 \pm 0.19)$

- **Statistical and Systematic Uncertainties**
  - Uncertainty on the signal strength is mainly statistical
  - Largest systematic uncertainties
    - uncertainty on data-driven background estimates (6%)
    - WZ theory uncertainties

- **Significance Table**
<table>
<thead>
<tr>
<th>Fit</th>
<th>$\mu$(WWW)</th>
<th>Significance observed (expected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^{\pm}e^{\pm}$</td>
<td>1.54 ± 0.76</td>
<td>2.2 (1.4) σ</td>
</tr>
<tr>
<td>$e^{\pm}\mu^{\pm}$</td>
<td>1.44 ± 0.39</td>
<td>4.1 (3.0) σ</td>
</tr>
<tr>
<td>$\mu^{\pm}\mu^{\pm}$</td>
<td>2.23 ± 0.46</td>
<td>5.6 (2.7) σ</td>
</tr>
<tr>
<td>2$\ell$</td>
<td>1.75 ± 0.30</td>
<td>6.6 (4.0) σ</td>
</tr>
<tr>
<td>3$\ell$</td>
<td>1.32 ± 0.37</td>
<td>4.8 (3.8) σ</td>
</tr>
<tr>
<td>Combined</td>
<td>1.61 ± 0.25</td>
<td>8.0 (5.4) σ</td>
</tr>
</tbody>
</table>
VBS $Z(\to \nu\nu)\gamma jj$ production

- **VBF Topology**
  - $m_{jj} > 250$ GeV
  - $|\Delta \eta_{jj}| > 3.0$, $|\Delta \phi_{jj}| < 2.5$
- **Large MET > 150 GeV**
- **one central photon**
  - $15 < p_T < 110$ GeV
  - Centrally located wrt the jets ($C_\gamma > 0.4$)

\[ C_\gamma = \exp \left[ \frac{4}{(\eta_1 - \eta_2)^2} \left( \eta_\gamma - \frac{\eta_1 + \eta_2}{2} \right)^2 \right], \]
**VBS Z(→vv)γjj production**

- **Main Backgrounds**
  - Wγ, non prompt photons, Zγ strong production
- **Cut based selection with MET triggers**
- **Search performed in mjj bins**

- **Observed Significance**
  - 5.2σ (5.1σ expected)
- **Fiducial cross-section**
  - 1.31 ± 0.29 fb (theory: 1.27 ± 0.17 fb)
- **Largest systematic uncertainties**
  - jet energy scale, Vγ theory and normalization

**Signal Strength**

\[ 1.03 \pm 0.16(\text{stat}) \pm 0.19(\text{syst}) \pm 0.02(\text{lumi}) \]
Observation of EW $Z(\ell\ell)\gamma\gamma$

- Measured in the $ee\gamma\gamma$ and $\mu\mu\gamma\gamma$ channels
- Main backgrounds:
  - Strong $Z\gamma\gamma$, fake $\gamma$, $tt\gamma$
- Key observable:
  - $Z\gamma$ centrality $\zeta_{ll\gamma}$; SR: $\zeta_{ll\gamma} < 0.4$
  - $m_{jj} > 150$ GeV
- Fit performed to $m_{jj}$ spectrum
Observation of EW $Z(\ell\ell)\gamma jj$

- Observation with large (10$\sigma$) *significance* as expected
  \[ \mu_{EW} = 0.95^{+0.14}_{-0.13} \]
  \[ = 0.95 \pm 0.08 \text{ (stat)} \pm 0.11 \text{ (syst)} \]
- $Z\gamma$ modelling uncertainty have an impact similar to the experimental uncertainties.

- Fiducial cross section is measured:
  - $\sigma_{\text{fid}} = 4.49 \pm 0.58 \text{ fb}$, ($\sigma_{\text{pred}} = 4.73 \pm 0.27 \text{ fb}$)

<table>
<thead>
<tr>
<th></th>
<th>Data stat.</th>
<th>MC stat.</th>
<th>Background</th>
<th>Reco</th>
<th>EW mod.</th>
<th>QCD mod.</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \sigma_{EW}/\sigma_{EW}$ [%]</td>
<td>$\pm 9$</td>
<td>$\pm 1$</td>
<td>$\pm 1$</td>
<td>$\pm 5$</td>
<td>$^{+6}_{-5}$</td>
<td>$^{+5}_{-4}$</td>
<td>$\pm 13$</td>
</tr>
</tbody>
</table>

- The **strong+EW $Z\gamma jj$ cross section** is measured
  - 20.6+1.4 fb (predicted: 20.4+2.6 fb)
From Cross-section Measurements to New Physics

Effective Field Theory

• EFT describes several possible new physics scenarios at energy scale $\Lambda$

\[ L_{\text{SMEFT}} = L_{\text{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots \]

• Measurements sensitive to the effects of new physics → constrain the coefficients of SMEFT expression (Wilson coefficients)

• Use Run2 differential cross section measurements from various final states to test SMEFT ($\Lambda=1$ TeV)
  • $WW$ (ev$\mu$ν, 36 fb$^{-1}$) : $p_T^{\text{lead,lep}}$
  • $WZ$ (36 fb$^{-1}$) : $m_T^{WZ}$
  • $4l$ (139 fb$^{-1}$) : $m_{ZZ}$ in three different regions of $m_{4l}$
  • $Z+2j$ (139 fb$^{-1}$) : $\Delta\phi j j$

• Constraining dim-6 operators ignoring odd-dimensional operators (lepton and baryon number violations) and non-leading terms
Combined EFT interpretation WW, WZ, 4l and Z+2j

- 33 CP-even operators are considered
- Profile likelihood ratio test scan for two Wilson coefficients (fixing other coefficients to 0)
Combined EFT interpretation WW, WZ, 4l and Z+2j

- Modified basis constructed with linear combinations of the warsaw basis vectors
- Constraints obtained on further 13 linear combinations of Wilson coefficients
  - Group together Wilson coefficients with similar physics impact
- Investigate both linear $O(\Lambda^{-2})$ as well as quadratic $O(\Lambda^{-4})$ contributions

\[ c'_{VIII}^{[i]} \] – affect vector boson coupling to fermions
\[ c'_{2q2l}^{[i]}, c'_{4q}^{[i]} \] – four fermion coefficients

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**ATLAS Preliminary** \( \sqrt{s} = 13 \text{ TeV}, 36-139 \text{ fb}^{-1} \)

\[ \Lambda = 1 \text{ TeV} \]

- Lin, individual
- Lin, profified
- Lin+quad, indiv
- Lin+quad, prof

\[ c'_{VIII}^{[i]} \]

\[ c'_{2q2l}^{[i]}, c'_{4q}^{[i]} \]
Summary

- Small cross-sections for multiboson production processes → small signal swamped by large, challenging backgrounds
- Precision analyses only recently possible.
- Most measurements are still statistics limited.
- Differential measurements made with more data → very useful for EFT interpretations

- Looking Forward to Run3 datasets for interesting new results!