Measurements of inclusive neutral diboson production with ATLAS

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On behalf of ATLAS collaboration
Outline

- Introduction to ATLAS
- Physics motivation
- Measurement of unfolded invariant mass of 4-leptons at 13 TeV
- Measurement of Z\gamma with Z\rightarrow vv at 13 TeV
- Summary
CERN and LHC
The analysis presented in this talk use the 36.1 fb⁻¹.
Physics motivation

- Search for the neutral TGC coupling which is forbidden in SM
- Sensitive to gluon induced process; potential BSM hint in the quark-loop
- Important channel for constraint on Higgs property.
Interesting topics:

- Behavior of full m(4l) spectrum.
- Measurement of gg\rightarrow 4l signal strength: K-factor w.r.t current LO/NLO simulation.
- Branching ratio of Z\rightarrow 4l
- Measurement of off-shell Higgs production: indirect constraint on Higgs width
- BSM searches in the higher energy region: anomalous neutral TGC (aTGC), BSM Higgs coupling ...

arXiv:1902.05892
Modelling of each process

- **Quark induced 4l (q→4l) process**
  - Nominal: modelled by “*Sherpa-2.2.2 + NNPDF3.0-NNLO*”, and reweighted with virtual NLO EW effects as function of m(4l).
  - Cross checked with: “*Powheg-Box v2 (NLO) + CT10 PDF*” interfaced with Pythia 8, correction to higher-order precision (NNLO QCD and NLO EW)

- **Gluon induced 4l (g→4l) process**
  - Off-Higgs region three components: gg→H*→4l, continuum gg→4l, interference term.
  - Nominal: modelled by “*Sherpa-2.2.2 + NNPDF3.0-NNLO*”, and reweighted to the NLO QCD precision as function of m(4l); An additional 1.2 factor is further applied to account for potential NNLO/NLO effects.
  - Cross checked with: “*MCFM (LO) + CT10 PDF*” interfaced with Pythia 8, correction to NNLO QCD precision
Analysis strategy

Reco-level SR selections

**Object selection**

<table>
<thead>
<tr>
<th>Electron</th>
<th>Muon</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Loose</em> working point</td>
<td><em>Loose</em> working point</td>
</tr>
<tr>
<td>( E_T &gt; 7 \text{ GeV and }</td>
<td>\eta</td>
</tr>
<tr>
<td>(</td>
<td>z_0 \cdot \sin\theta</td>
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<tr>
<td>(</td>
<td>z_0 \cdot \sin\theta</td>
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</tbody>
</table>

**Event level selections**

Quadruplet Selection:
- SFOS lepton pairs with smallest and second-smallest \(|m(ll)-mZ|\) as primary and secondary lepton pair;
- \( p_T > 20/15/10 \text{ GeV for leading three leptons; Mass window for 2l pairs.} \)

- J/\( \psi \) veto; Lepton isolation; Lepton transverse impact parameter; 4-lepton vertex fit

- Quite pure 4-lepton signal events
  - On-shell Higgs signal S/B ~ 1:2
  - < 5% contamination (non-ZZ) in the \( m_{4l} > 180 \text{ GeV} \) region

- Major backgrounds:
  - Fake background \( \rightarrow \) Zjets, ttbar
  - 4 prompt leptons \( \rightarrow \) VVV, ttV

- Fiducial phase space definition is close to the reco-level SR selections at particle level.
Unfolded inclusive m(4l)

Reco-level distribution in SR

Differential cross section in Fid region
Interpretation: \( gg \rightarrow 4l \) signal strength, \( Br(Z \rightarrow 4l) \)

All the interpretations are done at the particle level

- **gg\( \rightarrow 4l \) signal strength ( \( \mu_{gg \rightarrow 4l} \))**
  - A likelihood scan in the range \( m4l \sim [180, 1200] \) GeV.

<table>
<thead>
<tr>
<th>Generator</th>
<th>Observed ( \mu_{gg \rightarrow 4l} )</th>
<th>Predicted ( \mu_{gg \rightarrow 4l} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sherpa 2.2.2 with K-factor</td>
<td>1.3 ± 0.5</td>
<td>1.0 ± 0.4</td>
</tr>
<tr>
<td>MCFM, LO QCD</td>
<td>2.7 ± 0.9</td>
<td>2.2 ± 0.9</td>
</tr>
</tbody>
</table>

- **Measurement of \( Br(Z \rightarrow 4l) \)**
  - Lowest \( m(4l) \) bin [75, 100] GeV
  - All the uncertainties are treated uncorrelated.

\[
\mathcal{B}_{Z \rightarrow 4\ell} = \frac{N_{\text{fid}} \times (1 - f_{\text{non-res}})}{\sigma_Z \times A_{\text{fid}} \times L}
\]

<table>
<thead>
<tr>
<th>Measurement</th>
<th>( B_{Z \rightarrow 4\ell}/10^{-5} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS, ( \sqrt{s} = 7 ) TeV and ( 8 ) TeV</td>
<td>4.31±0.34(stat)+0.17(syst)</td>
</tr>
<tr>
<td>CMS, ( \sqrt{s} = 13 ) TeV</td>
<td>4.83(^{+0.22}_{-0.22})(stat)+0.08(theo)+0.12(lumi)</td>
</tr>
<tr>
<td>ATLAS, ( \sqrt{s} = 13 ) TeV</td>
<td>4.70 ± 0.32(stat) ± 0.21(syst) ± 0.14(lumi)</td>
</tr>
</tbody>
</table>
Interpretation: off-shell Higgs signal strength

- The double-differential distribution for “m4l-D_{ME}” is used to constrain the off-shell Higgs production process at high mass (m4l>180 GeV)
- Assuming that the contribution of the box diagram is as predicted by the SM.

- Interference is quite significant between off-shell signal and continuum ggZZ production
  \[ SBI = S + I + B \]
  S: signal (gg\(\rightarrow\)H*\(\rightarrow\)ZZ); B: background (gg\(\rightarrow\)ZZ);
  I: interference term

- Interference is varied with signal strength. The signal related distribution built (signal strength, \(\mu_{off}\)):
  \[ \mu_{off} \cdot S + \sqrt{\mu_{off}} \cdot I + B \]

<table>
<thead>
<tr>
<th>Observed (\mu_{off})</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 6.5 @ 95% C.L.</td>
<td>&lt; 5.4 @ 95% C.L.</td>
</tr>
</tbody>
</table>

Consistent with recent reco-level results **PLB 786 (2018) 223**
Interpretation: modified Higgs couplings

- Constrain possible BSM modifications of the couplings of H to top quarks ($c_t$) and gluons ($c_g$, 0 in the SM).
- Measurements at higher mass (> 180 GeV) can decouple $c_t$ and $c_g$, as the partonic centre-of-mass energy of the process becomes larger than the top-quark mass.

- The yield from $gg \rightarrow 4l$ is parameterised as a function of $c_t$ and $c_g$ [J. Exp. Theor. Phys. 120 (2015) 354].

\[
\frac{d\sigma(c_t, c_g)}{dm_{4l}} = F_0 + F_1 \left( c_t + c_g \frac{F_{\Delta}(\infty)}{Re F_{\Delta}(m_t)} \right)^2 + F_3 \left( c_t + c_g \frac{F_{\Delta}(\infty)}{Re F_{\Delta}(m_t)} \right)^2 + F_2 c_t^2 + F_4 c_t
\]

SM: $c_t = 1, c_g = 0$

- First interpretation with ATLAS data $\rightarrow$ improved the sensitivity compared to previous LHC result (CMS)
Z_\gamma production with Z\to vv at 13TeV

- Advantage of Z_\gamma with Z\to vv:
  - Higher branching ratio than Z_\gamma with Z\to ll (e or \mu); more sensitive in higher energetic region.
  - Less contamination than Z_\gamma with Z\to qq.

- Measurement in this analysis:
  - Integrated and differential cross section in a dedicated fiducial phase space.
  - Inclusive (no Njets requirement) and exclusive (Njets=0) results.

- Searches: anomalous neutral TGC coupling.
Signal region definition

**Signal topology:** one high-pT and isolated γ, and a large $E_T^{\text{miss}}$

<table>
<thead>
<tr>
<th>Photons</th>
<th>Leptons</th>
<th>Jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T &gt; 150$ GeV</td>
<td>$p_T &gt; 7$ GeV</td>
<td>$p_T &gt; 50$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 2.37$, excluding $1.37 &lt;</td>
</tr>
</tbody>
</table>

**Event selection**

- Lepton number = 0 : suppress events with leptons, e.g. $W\gamma$ with $W\rightarrow lv$
- $E_T^{\text{miss}} > 150$ GeV and $E_T^{\text{miss}}$ -signif >10.5 : suppress the events with fake $E_T^{\text{miss}}$
- $\Delta\phi(E_T^{\text{miss}},\gamma)$ : suppress $pp\rightarrow W(\ell v)+X$

$$E_T^{\text{miss}}\text{ signif} : \quad E_T^{\text{miss}}/\sqrt{\Sigma p_T^{\text{jet}} + E_T^{\gamma}}$$
Signal and backgrounds

- **Modelling of signal**
  - Sherpa 2.2.2 + NNPDF3.0-NNLO
  - Alternative for systematic uncertainty: Sherpa 2.1.1, MG5_aMC@NLO

- **Backgrounds components**
  - \( W\gamma \) with \( W \rightarrow l\nu \): 60% arises from \( \tau \) hadronic decay in \( W \rightarrow \tau\nu \); misdetection of \( e/\mu \)
  - \( \gamma + \text{jet} \): large \( E_T^{\text{miss}} \) due to mismeasurement of jet resolution.
  - \( e/\text{jet} \rightarrow \gamma \): misidentified photon.

- **Background estimation**
  - \( W\gamma \) and \( \gamma + \text{jet} \): 2 CRs with reversing SR definition (1 lepton, or small \( E_T^{\text{miss}} \)-sig value);
  - \( e \rightarrow \gamma \): fake factor of \( e \rightarrow \gamma \)
  - \( \text{jet} \rightarrow \gamma \): 2D sideband, defined with photon isolation and identification.

<table>
<thead>
<tr>
<th>( N_{\text{jets}} )</th>
<th>( N_{\text{jets}} = 0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{W\gamma} )</td>
<td>650 ± 40 ± 60</td>
</tr>
<tr>
<td>( N_{\gamma + \text{jet}} )</td>
<td>409 ± 18 ± 108</td>
</tr>
<tr>
<td>( N_{e \rightarrow \gamma} )</td>
<td>320 ± 15 ± 45</td>
</tr>
<tr>
<td>( N_{\text{jet} \rightarrow \gamma} )</td>
<td>170 ± 30 ± 50</td>
</tr>
<tr>
<td>( N_{Z(\ell\ell)\gamma} )</td>
<td>40 ± 3 ± 3</td>
</tr>
</tbody>
</table>

| \( N_{\text{bkg total}} \) | 1580 ± 50 ± 140 | 1000 ± 40 ± 90 |
| \( N_{\text{sig (exp)}} \) | 2328 ± 4 ± 135  | 1710 ± 4 ± 91  |
| \( N_{\text{sig+bkg total}} \) | 3910 ± 50 ± 190 | 2710 ± 40 ± 130 |
| \( N_{\text{data (obs)}} \) | 3812             | 2599           |
Result of integrated cross section

Fiducial region is defined at particle level which is close to reco-level SR definition.

\[ \sigma_{\text{ext-fid}} = \frac{N - B}{A_{Z\gamma} \cdot C_{Z\gamma} \cdot \int L \, dt} \]

The likelihood function is defined as

\[ \mathcal{L}(\sigma, \theta) = \text{Poisson}(N \mid S(\sigma, \theta) + B(\theta)) \cdot \text{Gaussian}(\theta_0 \mid \theta) \]

Good agreement between measurements and NNLO predictions!

<table>
<thead>
<tr>
<th>Measurement</th>
<th>( N_{\text{jets}} \geq 0 )</th>
<th>( N_{\text{jets}} = 0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{\text{ext-fid.}} , [\text{fb}] )</td>
<td>( 83.7^{+3.6}<em>{-3.5} , \text{(stat.)}^{+6.9}</em>{-6.2} , \text{(syst.)}^{+1.7}_{-2.0} , \text{(lumi.)} )</td>
<td>( 52.4^{+2.4}<em>{-2.3} , \text{(stat.)}^{+4.0}</em>{-3.8} , \text{(syst.)}^{+1.2}_{-1.1} , \text{(lumi.)} )</td>
</tr>
<tr>
<td>( \sigma_{\text{ext-fid.}} , [\text{fb}] )</td>
<td>( 78.1 \pm 0.2 , \text{(stat.)} \pm 4.7 , \text{(syst.)} )</td>
<td>( 55.9 \pm 0.1 , \text{(stat.)} \pm 3.9 , \text{(syst.)} )</td>
</tr>
</tbody>
</table>
Differential cross sections

- Good agreement is also observed in the differential measurements w.r.t Sherpa and NNLO MCFM.
- Besides variable $E_T^\gamma$, differential cross section results of $p_T(vv)$ and $N_{jets}$ are provided in publication.
- The last bin in $E_T^\gamma$ (>600 GeV) is also used for aTGC searches.
Constraint on aTGC parameter

- The framework of the effective vertex function approach: four CP-violating ($h^V_1, h^V_2$) and four CP-conserving ($h^V_3, h^V_4$)
- These parameters would influence the event yield of $Z\gamma$, especially behaving quite significant in higher energetic region.

$$N_{Z\gamma}^{aTGC}(h^V_3, h^V_4) = \sigma_{Z\gamma}^{aTGC}(h^V_3, h^V_4) \cdot C_{Z\gamma} \cdot A_{Z\gamma} \cdot C^*(\text{parton}\rightarrow\text{particle}) \cdot \int L \, dt.$$ 

- Higher $E_T^{\gamma}$ bin (>600 GeV) is used for the aTGC searches.
- 3-7 times improved limits w.r.t. ATLAS 8TeV measurement
Summary

- 4l (mainly ZZ production) and Zγ productions are reported with latest results (using 36.1 fb⁻¹) : gg→4l signal strength, Br(Z→4l), BSM Higgs coupling, and aTGCs (ZZγ, Zγγ) searches.
- Looking forward more results with full Run-2 dataset!

Thanks!