Measurements of multi-boson production including vector-boson scattering at ATLAS

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On behalf of the ATLAS Collaboration

University of Science and Technology of China

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Introduction

- Multi-boson processes: a powerful probe to the electroweak gauge structure:
  - Better understand the Standard Model (SM)
    - Test directly the gauge boson self-interaction (SU(2))
    - Higgs mechanism for Electroweak Symmetry Breaking (EWSB)
      - e.g. vector boson scattering (VBS) processes for gauge unitarity
  - Search for Beyond the Standard Model (BSM) physics
    - Anomalous gauge boson coupling (aTGC, aQGC...)
    - Effective field theory (EFT), a more general way for new physics search
Introduction

• Analyses based on ATLAS run-II data collected during 2015~2016, 2017~2018

• Recent ATLAS results on multi-boson topic:
  • Observation of vector boson scattering (VBS):
    • $Z(l\bar{l})\gamma + 2j$ electroweak
    • $Z(\nu\bar{\nu})\gamma + 2j$ electroweak
    • $\gamma\gamma \rightarrow WW$
  • Observation of triboson:
    • $WWW$
  • Precision measurements and new physics interpretation:
    • Four lepton differential cross-section
    • Combined EFT fit with ATLAS boson differential measurements

[ATLAS-CONF-2021-038]
[arXiv:2109.00925]
[PLB 816 (2021) 136190]

[ATLAS-CONF-2021-039]

[JHEP 07 (2021) 005]

[ATL-PHYS-PUB-2021-022]
Electroweak production of Z(ll)γ2j

- Probe and measure Zγ version of VBS process
- Sensitive to the gauge boson self-interactions, both SM permitted and prohibited (aTGC, aQGC)

VBS-Zγ2j

EWK-Zγ2j

QCD-Zγ2j (main background)

- Topology characters:
  - More central boson pair with two forward hadronic jets in opposite hemisphere
  - Electroweak expected larger rapidity gap and invariant mass of jets

- Centrality discriminant: $\zeta(\ell\ell\gamma) = \left| \frac{y_{\ell\ell\gamma} - (y_{j_1} + y_{j_2})/2}{y_{j_1} - y_{j_2}} \right|$ to enhance the EWK processes

- Main background: QCD-Zγ2j, Z+jets, ttγ, WZjj, WWγ
Electroweak production of Z(\(\Pi\))\(\gamma\)\(2j\)

- VBS topology and centrality used to define signal region and condense EWK process events
- Statistic uncertainty in data of same magnitude as systematic uncertainties
- Systematic uncertainties dominated by signal & bkg modelling, and jet calibration
- MC template fit applied to data simultaneously in both signal region and control region, with normalization factors of QCD-Z\(\gamma\)\(2j\) floating, on \(m_{jj}\) distribution
Electroweak production of $Z(\ell\ell)\gamma2j$

- EWK production observation with significance: $10\sigma$ (exp. $11\sigma$)
- EWK cross-section:
  $$\sigma_{EW} = 4.49 \pm 0.40 \text{ (stat.)} \pm 0.42 \text{ (syst.) fb}$$
  $$\sigma_{EW}^{\text{pred}} = 4.73 \pm 0.01 \text{ (stat.)} \pm 0.15 \text{ (PDF)}^{+0.23}_{-0.22} \text{ (scale) fb}$$
- QCD+EWK cross-section:
  $$\sigma_{EW+QCD} = 20.6 \pm 0.6 \text{ (stat.)}^{+1.2}_{-1.0} \text{ (syst.) fb}$$
  $$\sigma_{EW+QCD}^{\text{pred}} = 20.4 \pm 0.1 \text{ (stat.)} \pm 0.2 \text{ (PDF)}^{+2.6}_{-2.0} \text{ (scale) fb}$$
Electroweak production of $Z(\nu\nu)\gamma_{2j}$

- Reported along with Higgs to invisible particles limit settings due to shared final state of 2 jets + 1 photon + missing ET
- Event selection and background suppression taking full advantage of VBS/VBF topology
  - C3 is the third jets (if there) centrality
  - Signal region requiring less central third jets, since EW processes tend to couple with reduced hadronic activity in the rapidity gap
- Fit simultaneously among signal region and control regions to constrain background process
- EWK production observation with significance: 5.2\sigma (exp. 5.1\sigma)
- EWK cross-section:
  \[
  \sigma_{Z(\rightarrow\nu\nu)\gamma_{EW}} = 1.31 \pm 0.20\text{(stat)} \pm 0.20\text{(syst)} \text{ fb}
  \]
  \[
  \text{exp.} \ 1.27 \pm 0.01\text{(stat)} \pm 0.17\text{(LO QCD MadGraph scale)} \pm 0.03\text{(pdf)} \text{ fb}
  \]

**Observables and Requirements**

<table>
<thead>
<tr>
<th>Observable</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{jet}}$ with $p_T &gt; 25 \text{ GeV}$</td>
<td>$\geq 2$</td>
</tr>
<tr>
<td>$</td>
<td>\eta(j_{1,2})</td>
</tr>
<tr>
<td>$p_T(j_1)$ [GeV]</td>
<td>$&gt; 60$</td>
</tr>
<tr>
<td>$p_T(j_2)$ [GeV]</td>
<td>$&gt; 50$</td>
</tr>
<tr>
<td>$\Delta R(j,\ell)$</td>
<td>$&gt; 0.4$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta n_{\text{jets}}</td>
</tr>
<tr>
<td>$C_3$</td>
<td>$&lt; 0.7$</td>
</tr>
<tr>
<td>$m_{\gamma}$ [TeV]</td>
<td>$&gt; 0.5$</td>
</tr>
<tr>
<td>truth-$E_{T\text{miss}}$ [GeV]</td>
<td>$&gt; 150$</td>
</tr>
<tr>
<td>$\Delta \phi(\text{truth}-E_{T\text{miss}}, j_i)$</td>
<td>$&gt; 1.0$</td>
</tr>
<tr>
<td>$p_T(\gamma)$ [GeV]</td>
<td>$&gt; 15, &lt; 110$</td>
</tr>
<tr>
<td>$</td>
<td>\eta(\gamma)</td>
</tr>
<tr>
<td>$E_{\text{cone20}}/E_{\gamma}$</td>
<td>$&lt; 0.07$</td>
</tr>
<tr>
<td>$\Delta R(\gamma, \text{jet-or-\ell})$</td>
<td>$&gt; 0.4$</td>
</tr>
<tr>
<td>$C_{\gamma}$</td>
<td>$&gt; 0.4$</td>
</tr>
</tbody>
</table>

**Centrality Defined**

Centrality defined in this analysis different from $Z(ll)\gamma_{2j}$:
- lower $C$ => less central
- higher $C$ => more central

**Signal Region**

$N_{\gamma}$ with $p_T > 4 \text{ GeV}$ and $|\eta| < 2.47$:

- 0

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2021/Nov/30

arXiv:2109.00925
Photon induced WW production

- LHC hadron collider used as a “photon collider”
- Only gauge boson self-interaction processes at LO!

- Process characters:
  - Purely EW interaction $\rightarrow$ low charged particle activity
  - Initial state proton stays intact or fragment but outside detector acceptance

- Selected isolated di-lepton vertex with no additional tracks
- Studied in events with low multiplicity of tracks

- Multiplicity of tracks badly modeled in background
  - A large number of data-driven methods used

- Background: QCD-induced WW, Drell-Yan, $\gamma\gammall$, non prompt leptons

choose further decay into different flavor leptons (e\(\mu\))
Photon induced WW production

PLB 816 (2021) 136190

- Numbers of tracks ($n_{trk}$) within 1mm of di-lepton vertex are used in classifying CRs and SR
  - Accurate modelling of $n_{trk}$ matters

- Data driven corrections on MC prediction:
  - Pileup: signal efficiency
    - effective beam-spot correction $\rightarrow$ density of pileup vertices
    - reweight based on number of tracks with $z_0$ sampling $\rightarrow$ track multiplicity
  - Underlying events: background prediction
    - use DY measurement to correct the mismodelling of number of tracks
  - Signal: additional rescattering after initial $\gamma\gamma\rightarrow$WW and dissociative components
    - $\gamma\gamma\rightarrow ll$ data at same-flavor lepton pair invariant mass larger than 160 GeV
Photon induced WW production

- **SR:**
  - $p_{T_{e\mu}} > 30$ GeV & $n_{trk} = 0$
  - expected purity ~57%
  - QCD WW ~33%

- **CR1:**
  - $p_{T_{e\mu}} < 30$ GeV & $1 \leq n_{trk} \leq 4$
  - DY dominates ~75%
  - DY normalization

- **CR2:**
  - $p_{T_{e\mu}} > 30$ GeV & $1 \leq n_{trk} \leq 4$
  - ~70% QCD WW
  - WW normalization

- **CR3:**
  - $p_{T_{e\mu}} < 30$ GeV & $n_{trk} = 0$
  - ~10% sig
  - constrain additional backgrounds similar with signal

- Simultaneously fit of SR and 3 CRs to reject background only hypothesis by **8.4σ (exp. 6.7σ)**
- Measured fiducial cross section $3.13 \pm 0.31$ (stat.) $\pm 0.28$ (syst.) fb
  - SM prediction is $2.34 \pm 0.27$ fb
Observation of WWW production

- First observation of triboson production in ATLAS

  \[
  q \rightarrow W \rightarrow q\bar{q} \quad \text{or} \quad Z/\gamma^* \rightarrow W \rightarrow q\bar{q} 
  \]

- WWW measured in 2 channels:
  - 2l channel: two same-sign leptons (e^±e^±, e^±μ^±, μ^±μ^±) + one jet pair
  - 3l channel: leptonic decay of all Ws with no same-flavor opposite-sign leptons

- Main background: WZ, γ conversion, charge-flip, non-prompt
Observation of WWW production

- BDT is used to classify signal and background in 2l and 3l channel separately
- Data-driven method to scale WZ, divide 0j, 1j, >1j control region

- Signal significance from the fit of the BDT score distribution
  - Simultaneous fit of BDT in 2l and 3l SRs and of mlll in 3 CRs

BDT variables

<table>
<thead>
<tr>
<th>2\ell</th>
<th>3\ell</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_{jj} - m_W)</td>
<td>(E_T^{\text{miss}}) significance (\times 10/E_T^{\text{miss}})</td>
</tr>
<tr>
<td>(p_T(\text{forward jet}))</td>
<td>(p_T(\ell_2))</td>
</tr>
<tr>
<td>(E_T^{\text{miss}}) significance</td>
<td>(N(\text{jets}))</td>
</tr>
<tr>
<td>(p_T(j_2))</td>
<td>same flavor (m_{ll})</td>
</tr>
<tr>
<td>minimum (m(\ell, j))</td>
<td>(m(\ell_2, \ell_3))</td>
</tr>
<tr>
<td>(m(\ell_2, j_1))</td>
<td>(\Delta\phi(\ell\ell, E_T^{\text{miss}}))</td>
</tr>
<tr>
<td>(N(\text{jets}))</td>
<td>minimum (\Delta R(\ell, \ell))</td>
</tr>
<tr>
<td>(p_T(\ell_2))</td>
<td>(p_T(\ell_3))</td>
</tr>
<tr>
<td>(m_{\ell\ell})</td>
<td>(m(\ell_2, E_T^{\text{miss}}))</td>
</tr>
<tr>
<td>(</td>
<td>\eta(\ell_1)</td>
</tr>
<tr>
<td>(N(\text{leptons in jets}))</td>
<td>(m(\ell_1, j_1))</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Signal Strength</th>
<th>Normalization Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mu(\text{WW}))</td>
<td>(WZ + 0 \text{ jets})</td>
</tr>
<tr>
<td>1.66 (\pm 0.28)</td>
<td>1.12 (\pm 0.11)</td>
</tr>
</tbody>
</table>
Observation of WWW production

- WWW process is observed with significance of $8.2\sigma$ (exp. $5.4\sigma$)

<table>
<thead>
<tr>
<th>Fit</th>
<th>Observed (expected) significances [$\sigma$]</th>
<th>$\mu$(WWW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^{\pm}e^{\pm}$</td>
<td>2.3 (1.4)</td>
<td>1.69 ± 0.79</td>
</tr>
<tr>
<td>$e^{\pm}\mu^{\pm}$</td>
<td>4.6 (3.1)</td>
<td>1.57 ± 0.40</td>
</tr>
<tr>
<td>$\mu^{\pm}\mu^{\pm}$</td>
<td>5.6 (2.8)</td>
<td>2.13 ± 0.47</td>
</tr>
<tr>
<td>$2\ell$</td>
<td>6.9 (4.1)</td>
<td>1.80 ± 0.33</td>
</tr>
<tr>
<td>$3\ell$</td>
<td>4.8 (3.7)</td>
<td>1.33 ± 0.39</td>
</tr>
<tr>
<td>Combined</td>
<td>8.2 (5.4)</td>
<td>1.66 ± 0.28</td>
</tr>
</tbody>
</table>

- WWW production cross-section:

$$\sigma(pp \rightarrow WWW) = 850 \pm 100 \text{ (stat.)} \pm 80 \text{ (syst.)} \text{ fb}$$

(SM prediction) $511 \pm 42$ fb
Four-lepton differential measurements

- Four-lepton final state (two same-flavor opposite-sign e or μ pairs)
  - Contains rich physics theoretically
  - Relatively clean experimentally
- Precise measurements and tests on SM
- Potential BSM interpretation

- Differential cross-sections or double differential cross-sections (in slice of a second variable) are measured as a function of different kinematic variables

high mass region for NP search
Four-lepton differential measurements

- **Fiducial phase space:**
  - Based on 4l final state, and try to be inclusive and model-independent

<table>
<thead>
<tr>
<th>Lepton selection</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon selection</td>
<td>Bare, $p_T &gt; 5$ GeV, $</td>
</tr>
<tr>
<td></td>
<td>Dressed, $p_T &gt; 7$ GeV, $</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Event selection</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Four-lepton signature</td>
<td>At least 4 leptons, with 2 Same-Flavour, Opposite-Sign pairs</td>
</tr>
<tr>
<td>Lepton kinematics</td>
<td>$p_T &gt; 20/10$ GeV for leading two leptons</td>
</tr>
<tr>
<td>Lepton separation</td>
<td>$\Delta R_{ij} &gt; 0.05$ for any leptons</td>
</tr>
<tr>
<td>$J/\psi$-Veto</td>
<td>$m_{ij} &gt; 5$ GeV for all SFOS pairs</td>
</tr>
<tr>
<td>Truth isolation</td>
<td>$p_{\text{cone30}}/p_T &lt; 0.16$</td>
</tr>
</tbody>
</table>

- **Background and uncertainties:**
  - Background from the non-prompt lepton
  - Statistical uncertainty dominant for most of the bins

- **Detector correction:**
  - Unfolding technique introduced to correct detector effects and get “particle-level data”

Data → per-lepton efficiency correction → fiducial correction → Bayesian iterative unfolding → efficiency correction → Unfolded data
Four-lepton differential measurements

- Differential cross-sections:
  - EFT interpretation:
    - Constrain on 22 Wilson coefficients of dim-6 operators, including Higgs couplings, gauge boson couplings, Zll vertex, 4-fermions interactions
    - Different variables are sensitive to different coefficients

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \left( \frac{C_i}{\Lambda^{(d-4)}} \right) \mathcal{O}_i$$

$$\sigma_{\text{pred}} = \sigma_{\text{SM}} \times \left( 1 + c_i \cdot \sigma_{\text{INT}} / \sigma_{\text{LO SM}} + c_i^2 \cdot \sigma_{\text{BSM}} / \sigma_{\text{LO SM}} \right)$$
Four-lepton differential measurements

- **B-L model interpretation**
  - Spontaneously U(1)B-L gauge symmetry breaking, giving birth to neutrino mass:**B-L model**
  - New particles introduced: Z’, exotic Higgs h_2 and RH neutrinos
    - Z’ interacts with SM through coupling g’ and h_2 mixes with SM Higgs with mixing angle α
  - Scenario considered:
    - Fixed parameters: Low Z’ mass (35 GeV) weakly coupled to SM (g’ = 10^{-3})
    - Differential cross-sections providing best expected sensitivity used to set limit on 2D mh_2 \sim \sinα parameter space
  - Improvements over previous results:
    - Sinα > 0.28 over most of the range
    - Constraints on mh_2 above 400 GeV
Combined EFT fit

- Combined EFT fit with some ATLAS published multi-boson measurements:
  - Inclusive four-lepton with 139 fb$^{-1}$ [JHEP 07 (2021) 005]

- EFT dimension-6 with 33 Warsaw basis operators
- Parametrization in Wilson coefficients $c_i^{(6)}$:

  \[
  \sigma \propto |M_{\text{SMEFT}}|^2 = |M_{\text{SM}}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2 \text{Re} \left( M_i^{(6)} M_{\text{SM}}^* \right) + \sum_i \left( \frac{c_i^{(6)}}{\Lambda^4} |M_i^{(6)}|^2 \right) + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2 \text{Re} \left( M_i^{(6)} M_j^{(6)*} \right) + O \left( \Lambda^{-4} \right)
  \]

- Joint fit of multiple coefficients with Principal Component Analysis
  - Construct a modified basis with linear combinations of the Warsaw basis operators
  - Two Wilson coefficients $c_w$ and $c_{Hq}^{(3)}$ and 13 combinations of other Warsaw coefficients
Combined EFT fit

- Correlation of systematics between measurements taken into account

<table>
<thead>
<tr>
<th>Correlated Uncertainty Source</th>
<th>WW</th>
<th>WZ</th>
<th>4ℓ</th>
<th>VBF Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity (correlated part)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Luminosity 2015/16</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Luminosity 2017/18</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Lepton efficiency (correlated part)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Pile-up modelling</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Pile-up jet suppression</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Jet energy scale (Pile-up modelling)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Jet energy scale y-inter-calibration</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

- Linear and linear+quadratic fits → the effect of truncation of EFT expansion illustrated

- Individual and combined fit → the correlation among coefficients illustrated

- Improvement of the combined fit

- No deviation from SM found

- Step forward towards ATLAS global EFT interpretations and beyond
• Multi-boson analysis @ ATLAS provided amount of results recently:
  • Observations:

<table>
<thead>
<tr>
<th>observation of vector boson scattering (VBS)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z(\ell\ell)\gamma + 2j$ electroweak</td>
<td>10σ</td>
</tr>
<tr>
<td>$Z(\nu\nu)\gamma + 2j$ electroweak</td>
<td>5.2σ</td>
</tr>
<tr>
<td>$\gamma\gamma \rightarrow WW$</td>
<td>8.4σ</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>observation of triboson</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$WWW$</td>
<td>8.2σ</td>
</tr>
</tbody>
</table>

• Precise measurements and new physics interpretation:

<table>
<thead>
<tr>
<th>Inclusive four lepton differential cross-sections</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>[JHEP 07 (2021) 005]</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Combined EFT fit with ATLAS boson differential measurements</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>[ATL-PHYS-PUB-2021-022]</td>
<td></td>
</tr>
</tbody>
</table>

• We’re looking forward to more exciting results in Run3!
Back-up: SM production cross-sections
Back-up: multi-boson cross-sections

Diboson Cross Section Measurements

VBF, VBS, and Triboson Cross Section Measurements

Reference: ATLAS Preliminary

Status: July 2021

Reference: ATLAS Preliminary

Status: July 2021
Back-up: Z(II)γ2j additional

- MC samples:
  - EW: MadGraph5_aMC@NLO at LO
  - QCD: MadGraph5_aMC@NLO merged with 0,1 extra jets at NLO
  - Sherpa 2.2.2 for cross check
  - Interf.: MadGraph5_aMC@NLO at LO (treat as uncertainty)

\[ m_{ll} + m_{lly} > 182 \text{ GeV cut to separate ISR/FSR photons} \]

**post-fit yields**

<table>
<thead>
<tr>
<th>Sample</th>
<th>SR</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{EW-Z\gamma jj} )</td>
<td>300 ± 36</td>
<td>55 ± 7</td>
</tr>
<tr>
<td>( N_{QCD-Z\gamma jj} )</td>
<td>987 ± 55</td>
<td>1352 ± 60</td>
</tr>
<tr>
<td>( N_{t\bar{t}-\gamma} )</td>
<td>72 ± 11</td>
<td>59 ± 9</td>
</tr>
<tr>
<td>( N_{WZ} )</td>
<td>17 ± 3</td>
<td>14 ± 3</td>
</tr>
<tr>
<td>( N_{Z+jets} )</td>
<td>85 ± 30</td>
<td>143 ± 43</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1461 ± 38</td>
<td>1624 ± 40</td>
</tr>
<tr>
<td><strong>( N_{obs} )</strong></td>
<td>1461</td>
<td>1624</td>
</tr>
</tbody>
</table>
Back-up: Photon induced WW production

- Pileup correction: additional pile up tracks around di-lepton vertex affects the signal selection efficiency
  - MC/Data reweighting to match average number of pp collision per bunch
  - Correction to account for differential beam-spot width during different runs in data
  - $t$Track density around random $z$ location in $Z\rightarrow ll$ events in data/MC

- Underlying event correction: modelling inaccurate could affect the accepted background events
  - Correct factor obtained using particle level $n_{\text{ch}}$ distribution measured in $Z\rightarrow ll$
  - Bayesian unfolding with 4 iterations to unfold the data, after subtracting $\gamma\gamma\rightarrow ll$ events and pile-up tracks
  - Reweight simulation using the measured data/MC ratio of particle-level $n_{\text{ch}}$ as function of final-state pT
Back-up: Photon induced WW production

**ATLAS**

$\sqrt{s} = 13$ TeV, $139$ fb$^{-1}$

$70$ GeV $< m_t < 105$ GeV

**Reweighting**
Back-up: Photon induced WW production

- Data driven correction from unfolded Drell-Yan:
  - HS and PU corrections applied on all of them
  - Remaining mismodelling taken as a systematics

- Signal data-driven:
  - MC: only elastic process considered
  - Bkg: mainly DY normalized at Z peak

[Charts and data plots related to ATLAS experiments showing distributions and corrections applied]
Back-up: Photon induced WW production

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Impact [% of the fitted cross section]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experimental</strong></td>
<td></td>
</tr>
<tr>
<td>Track reconstruction</td>
<td>1.1</td>
</tr>
<tr>
<td>Electron energy scale and resolution, and efficiency</td>
<td>0.4</td>
</tr>
<tr>
<td>Muon momentum scale and resolution, and efficiency</td>
<td>0.5</td>
</tr>
<tr>
<td>Misidentified leptons, systematic</td>
<td>1.5</td>
</tr>
<tr>
<td>Misidentified leptons, statistical</td>
<td>5.9</td>
</tr>
<tr>
<td>Other background, statistical</td>
<td>3.2</td>
</tr>
<tr>
<td><strong>Modelling</strong></td>
<td></td>
</tr>
<tr>
<td>Pile-up modelling</td>
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<td>Underlying-event modelling</td>
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<td>Signal modelling</td>
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<td>WW modelling</td>
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<td>Other background modelling</td>
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<tr>
<td><strong>Luminosity</strong></td>
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<tr>
<td><strong>Total</strong></td>
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</tbody>
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- Measured cross-section: \(3.13 \pm 0.31\) (stat.) \(\pm 0.28\) (syst.) fb
- HERWIG7 + data driven modeling correction: \(2.34 \pm 0.27\) fb
- MG5_aMC@NLO with two estimates of the survival probability: \(2.8 \pm 0.8\) fb or \(3.5 \pm 1.0\) fb
Back-up: Observation of WWW production

- 2l channel SR $M_{jj}$
- 2l channel SR $|\Delta\eta_{jj}|$
Back-up: Observation of WWW production

- 2l channel SR Mll

![Graph showing 2l channel SR Mll with data and background predictions.]

- 2l channel SR missing ET

![Graph showing 2l channel SR missing ET with data and background predictions.]
Back-up: Observation of WWW production

- 3l channel SR Mlll

- 3l channel SR missing ET significance
Back-up: four-lepton measurement

**Observables**
- Integrated cross-sections
- Differential cross-sections:
  - $m_{4l}$
  - $m_{4l}$ in slices of $p_T^{4l}$
  - $m_{4l}$ in slices of $|y_{4l}|$
  - $m_{4l}$ in slices of flavor categories: $4\mu, 2e2\mu, 4e$

- $m_{12}, m_{34}$
- $p_T^{12}, p_T^{34}$
- Rapidity difference between two lepton pairs $|\Delta y_{\text{pairs}}|$
- Azimuthal angle between the pairs $|\Delta \phi_{\text{pairs}}|$
- Azimuthal angle between leading/subleading leptons $|\Delta \phi_{\text{ll}}|$
- Polarization variables $\cos \theta^*_{12}, \cos \theta^*_{34}$ ($\theta^*$ angle between the negative lepton in the lepton pair rest frame, and the lepton pair in the lab frame)

---

Single Z ($60 < m_{4l} < 100$ GeV)

Higgs ($120 < m_{4l} < 130$ GeV)

On-shell ZZ ($180 < m_{4l} < 2000$ GeV)

Off-shell ZZ ($20 < m_{4l} < 60$ GeV OR $100 < m_{4l} < 120$ GeV OR $130 < m_{4l} < 180$ GeV)
Back-up: four-lepton measurement

- Uncertainties
- EFT linear-term-only fit
Back-up: four-lepton measurement

- BSM samples generated using Herwig7 at particle-level with LO precision
- B-L observable with greatest expected sensitivity used to set limit in a given 2D bin
Back-up: Combined EFT fit

- Impact of the seven most sensitive combinations
- Correlation across bins

**ATLAS** Preliminary \( \sqrt{s} = 13 \text{ TeV}, 36-39 \text{ fb}^{-1} \)

### Impact of the seven most sensitive combinations

- \( c_{w,0.29} \)
- \( c_{w,0.11} \)
- \( c_{w,0.17} \)
- \( c_{w,0.3} \)
- \( c_{w,0.8} \)
- \( c_{w,0.061} \)
- \( c_{w,0.12} \)

**Correlation across bins**

**ATLAS** Preliminary \( \sqrt{s} = 13 \text{ TeV}, 36-39 \text{ fb}^{-1} \)

- \( p_{T}^{\text{hj}} \text{ [GeV]} \)
- \( p_{T}^{\text{hj}} \text{ [GeV]} \)
- \( m_{T}^{WW}, m_{T}^{WW} \text{ [GeV]} \)
- \( m_{T}^{4l} \)
- \( m_{T}^{4l} \text{ [GeV]} \)
- \( \Delta_{T} \)

Correlation of Measurement Uncertainties

- 1
- 0.8
- 0.6
- 0.4
- 0.2
- 0
- -0.2
Back-up: Combined EFT fit

- Coefficients combination:

- 2D likelihood scan:
Back-up: Combined EFT fit

- Parameter correlations (linear model)

- Coefficient fitting limits:

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<tr>
<th>Parameter</th>
<th>Linear fit</th>
<th>Linear-plus-quadratic fit</th>
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