VBS and VBF results from ATLAS

Heather Russell, McGill University
On behalf of the ATLAS Collaboration
LHCP 2020 – 25 – 30 May 2020
Overview

vector boson fusion

$\mathcal{O}(\alpha_{\text{EW}}) = 3$

vector boson scattering

$\mathcal{O}(\alpha_{\text{EW}}) = 4$

NB: we cannot directly measure VBF or VBS – significant interference with other diagrams of the same order in $\alpha_{\text{EW}}$ means extracting the VBF/VBS component is not a gauge invariant operation

Measure electroweak production of $Vjj$ or $VVjj$

Details in C. Gutschow’s talk yesterday: https://indico.cern.ch/event/856696/contributions/3722393/
Overview – QCD background

Electroweak $Vjj$ production

$\sigma(\alpha_{EW}) = 3$

Strong $Vjj$ production

$\sigma(\alpha_{EW}) = 1$, $\sigma(\alpha_S) = 2$

Strong production has the same final state and usually has a higher cross-section: understanding and reducing this background is crucial to an effective electroweak $Vjj$ (or $VVjj!$) production measurement.
Electroweak Zjj production

Z boson decaying leptonically (2e/2μ)

Two jets
- Large rapidity separation
- Large invariant mass

No jets in the gap
**Electroweak Zjj production**

**ATLAS** Preliminary $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$, $Zjj \rightarrow lljj$

- **Strong Zjj** (SHERPA)
- **EW Zjj** (POWHEG+PY8)
- **Strong Zjj** (MG5+PY8)
- **EW Zjj** (HERWIG+VBFNLO')
- **Strong Zjj** (MG5.NLO+PY8')
- **EW Zjj** (SHERPA)
- **ZV, Other VV, top**

### Graph

Ratio MC prediction to data

- **Strong Zjj** is the largest background across the spectrum

- Monte Carlo modelling of both strong electroweak Zjj shows discrepancies between generators

- Modelling of strong Zjj is especially poor, particularly in the high-$m_{jj}$ signal-enriched region
Analysis is split into four regions with two uncorrelated variables:

- **Number of jets** between the leading and subleading jets
- **Centrality** of the reconstructed Z boson:

\[
\xi_Z = \left| \gamma_{\ell\ell} - 0.5(y_{j1} + y_{j2}) \right| / |\Delta y_{jj}|
\]

- **Three background-enhanced regions** and one signal region
Extracting the EW Zjj signal

Binned maximum likelihood fit is performed to reduce dependence on MC mismodelling, with $3 \times N_{\text{bins}} + 2$ free parameters:

1. bin-by-bin weights for strong Zjj, separate for low and high centrality but linked between $N_{\text{gap}}^{\text{jets}} \geq 1$ and $N_{\text{gap}}^{\text{jets}} = 0$

2. linear $f(x)$ applied to strong Zjj to correct for residual $N_{\text{gap}}^{\text{jets}}$ dependence

3. bin-by-bin electroweak Zjj signal strengths (same in all regions)
Perform fit again with alternative generators for strong $Z_{jj}$ component
Extract the electroweak $Zjj$ signal once for each of three strong $Zjj$ generators:

result is the midpoint of the envelope

Signal and control regions are unfolded for both electroweak and inclusive $Zjj$ yields:
Effective field theory interpretation

\[ \sigma_{EFT} = \sigma_{SM} + \sum c_j \frac{1}{\Lambda^3} \sigma_{SM,j} + \sum c_j \frac{1}{\Lambda^6} \sigma_{j} + \sum c_j c_k \frac{1}{\Lambda^6} \sigma_{jk} \]

Two CP-even and two CP-odd operators were tested

→ sensitivity to CP-odd operators through the parity-odd observable 

\[ \Delta \phi_{jj} = \phi_{\text{higher rapidity jet}} - \phi_{\text{lower rapidity jet}} \]

where \( jj \) = the two leading jets

<table>
<thead>
<tr>
<th>Wilson coefficient</th>
<th>Linear EFT</th>
<th>95% confidence limit [TeV(^{-2})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c_w/\Lambda^2 )</td>
<td>yes</td>
<td>(-0.30, 0.30)</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>(-0.31, 0.29), (-0.19, 0.41)</td>
</tr>
<tr>
<td>( \tilde{c}_w/\Lambda^2 )</td>
<td>yes</td>
<td>(-0.12, 0.12)</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>(-0.11, 0.14)</td>
</tr>
<tr>
<td>( c_{\text{HWB}}/\Lambda^2 )</td>
<td>yes</td>
<td>(-2.45, 2.45)</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>(-3.11, 2.10), (-6.31, 1.01)</td>
</tr>
<tr>
<td>( \tilde{c}_{\text{HWB}}/\Lambda^2 )</td>
<td>yes</td>
<td>(-1.06, 1.06)</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>(-0.23, 2.35)</td>
</tr>
</tbody>
</table>
Effective field theory interpretation

ATLAS Preliminary
Fit to $lljj$ EW $\Delta \phi(j_1, j_2)$ spectrum

$\tilde{c}_{\text{HWW}} \over \Lambda^2 = -0.10 \over \text{TeV}^2$

Ratio to SM

-2log $\frac{L_{\text{best}}}{L_{\text{best}}}$

$99 \% \text{ CL}$

$95 \% \text{ CL}$

$88 \% \text{ CL}$

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Electroweak
ZZjj production

Two Z bosons decaying leptonically ($4e/2e2\mu/4\mu$)

OR

One Z boson decaying leptonically ($2e/2\mu$) and the other invisibly ($2\nu$)

Two jets

- Different sides of the detector
- Large rapidity separation
- Large invariant mass

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arXiv:2004.10612
Electroweak ZZjj production

Analysis in two channels with slightly different selection:

**Signal region** defined by Z-mass and “electroweak” selection:

\[ y_{j1} y_{j2} < 0, \quad m_{jj} > 400 \text{ GeV (} llll)/300 \text{ GeV (} llln), \quad \Delta y(jj) > 2 \]

<table>
<thead>
<tr>
<th>Process</th>
<th>( lllljj )</th>
<th>( lllnnjj )</th>
</tr>
</thead>
<tbody>
<tr>
<td>EW ZZjj</td>
<td>20.6 ± 2.5</td>
<td>12.3 ± 0.7</td>
</tr>
<tr>
<td>QCD ZZjj</td>
<td>77 ± 25</td>
<td>17.2 ± 3.5</td>
</tr>
<tr>
<td>QCD ggZZjj</td>
<td>13.1 ± 4.4</td>
<td>3.5 ± 1.1</td>
</tr>
<tr>
<td>Non-resonant-( ll )</td>
<td>–</td>
<td>21.4 ± 4.8</td>
</tr>
<tr>
<td>( WZ )</td>
<td>–</td>
<td>22.8 ± 1.1</td>
</tr>
<tr>
<td>Others</td>
<td>3.2 ± 2.1</td>
<td>1.2 ± 0.9</td>
</tr>
<tr>
<td>Total</td>
<td>114 ± 26</td>
<td>78.4 ± 6.2</td>
</tr>
<tr>
<td>Data</td>
<td>127</td>
<td>82</td>
</tr>
</tbody>
</table>

Extract inclusive cross-section in the signal region, then use BDTs to separate the electroweak and QCD components

Fit BDT shape for maximum sensitivity

High non-ZZjj background
Observation of electroweak $ZZjj$ production!

$\sigma_{EW}^{zzjj} = 0.82 \pm 0.21$ fb

⇒ One of the smallest measured cross-sections by ATLAS!
Electroweak $Z\gamma jj$ production

One $Z$ boson decaying leptonically ($2e/2\mu$)

One photon not from final state radiation

Central $\ell\ell\gamma$ system

Two jets
- Large rapidity separation
- Large invariant mass

No $b$-jets

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Electroweak $Z\gamma jj$ production

Search in leptonic $Z\rightarrow \ell\ell$ events, partial Run 2 dataset (36/fb) sensitive to only $WWZ\gamma$ quartic coupling

Signal region defined by $|\Delta\eta_{jj}| > 1$ \&\& $\zeta(\ell\ell\gamma) = \left| \frac{y_{\ell\ell\gamma} - (y_{j_1} + y_{j_2})/2}{(y_{j_1} - y_{j_2})} \right| < 5$,
and zero $b$-jets
Control region with $\geq 1$ $b$-jet to constrain $t\bar{t}+\gamma$ background

BDT score distribution in SR and $N(b$-jet) distribution in CR used in maximum-likelihood fit to extract signal strength

Results:
Observed and expected significance: $4.1\,\sigma$
Fiducial cross-section:

\[
\sigma_{Z\gamma jj-\text{EW}}^{\text{fid.}} = 7.8 \pm 1.5\,(\text{stat.}) \pm 1.0\,(\text{syst.}) \pm 1.0\,(\text{mod.}) \text{ fb} \\
= 7.8 \pm 2.0 \text{ fb.}
\]
Additional results

Three additional electroweak diboson production results using 36/fb of Run 2 data: details in the backup

EWK $W^\pm W^\pm jj$
Obs.: 6.5 $\sigma$

EWK $WZjj$
Obs.: 5.3 $\sigma$

EWK $VVjj$
Obs.: 2.7 $\sigma$


Phys. Rev. D 100 (2019) 032007


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New differential cross-section measurement of electroweak $Zjj$ production, with strong limits on new physics through an effective field theory interpretation

Observation of electroweak $ZZjj$ production

⇒ Other recent ATLAS VBS results using 36/fb of the 13 TeV dataset: many results with the full Run 2 dataset are still to come!

post-session zoom chat: Meeting ID: 963 3146 1387 Password: 373372
Standard Model Production Cross Section Measurements

**ATLAS** Preliminary
Run 1,2 $\sqrt{s} = 5,7,8,13$ TeV

Recent results

**topic of this talk**

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**ATL-PHYS-PUB-2019-024**

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**Electroweak ZZjj production**

very large QCD background in the signal region

QCD modelling (shape) uncertainties are estimated by comparing Sherpa 2.2.2 and MadGraph5_aMC@NLO 2.6.1

EWK-QCD interference counted as an uncertainty on the EWK contribution (7% 4ℓ, 2% ℓℓνv)

QCD background is constrained in a dedicated QCD control region, defined by inverting [m_{jj} or Δy(jj)] requirements

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Electroweak $Wjj$ production

One leptonic ($e/\mu/\nu$) $W/Z$

One hadronic ($qq$) $W/Z$, boosted or resolved

Two additional jets
- Different sides of the detector
- Large invariant mass

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Phys. Rev. D 100 (2019) 032007
Electroweak $VVjj$ production

Search for electroweak $VV$ production in a semileptonic final state
Do not distinguish between $W \rightarrow qq'$ and $Z \rightarrow qq$; allow for both boosted (one large-radius jet) and resolved (two small-radius jets) topologies

Analysis performed in three channels, each with three signal regions:
SR: resolved $V \rightarrow jj$ (two jets), $64 < m_{jj} < 106$ GeV
High-purity SR: boosted $V \rightarrow jj$ jet passes 50% signal efficiency working point
Low-purity SR: boosted $V \rightarrow jj$ jet fail 50% WP but passes 80% WP

0-lepton: $vvqq + jj$
missing energy > 200 GeV

1-lepton: $\ell vqq + jj$
exactly 1 lepton > 27 GeV
missing energy > 80 GeV

2-lepton: $\ell \ell qq + jj$
2 leptons > 28, 20 GeV w/ $Z$ mass
Electroweak $VVjj$ production

6 separate BDTs are trained for 0/1/2 lepton and boosted and resolved regions

Binned profile likelihood fit in 21 channels shown on previous slide:
BDT output in signal regions
$m_{jj}^{\text{tag}}$ in $Z$, $W$, and $Vjj$ control regions
event yield in top control regions

Observed significance: $2.7 \sigma$
Expected significance: $2.5 \sigma$

Fiducial cross-section (combination):

$$\sigma_{\text{EWK} VVjj}^{\text{fiducial,obs.}} = \mu_{\text{EWK} VVjj}^{\text{obs.}} \cdot \sigma_{\text{EWK} VVjj}^{\text{fid, SM}} = 45.1 \pm 8.6 \text{ (stat.)} +15.9 -14.6 \text{ (syst.) fb}$$

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Phys. Rev. D 100 (2019) 032007
Electroweak $W^\pm W^\pm jj$ production

Two leptonic, same charge ($e/\mu$) $W$ bosons

Two additional jets
- Large rapidity separation
- Large invariant mass
**Electroweak \( W^\pm W^\pm jj \) production**

**electroweak-induced processes**

**example QCD process**

**ATLAS**
\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

**Events / 100 GeV**

- Data
- \( W^+W^-jj \) electroweak
- \( W^+W^-jj \) strong
- Non-prompt
- e/\( \gamma \) conversions
- WZ
- Other prompt
- Total uncertainty

**Process observed with the 2015-2016 36/fb dataset**

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Electroweak $WZjj$ production

One leptonic ($e/\mu$) $W$
One leptonic ($e/\mu$) $Z$

Two additional jets
- Large invariant mass
Electroweak $WZjj$ production

ATLAS
\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

WZjj SR

BDT used to discriminate between EW signal and QCD background:

Observed significance: 5.3\(\sigma\)
(expected: 3.2\(\sigma\))

\[
\begin{align*}
\text{eee} & : 0.71 \pm 0.18 \\
\mu\mu\mu & : 0.79 \pm 0.16 \\
\text{combined} & : 0.78 \pm 0.12 \\
\end{align*}
\]