

Observation and measurements of vector-boson scattering with ATLAS

The European Physical Society Conference on High Energy Physics



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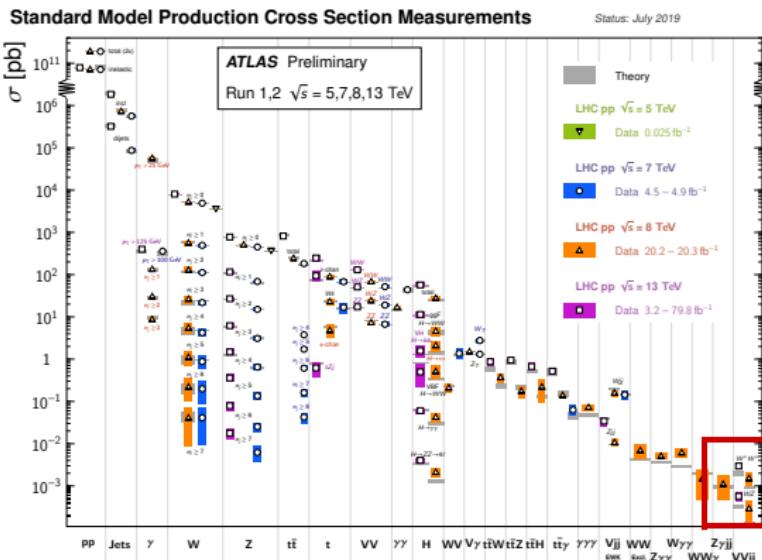
Philip Sommer,
on behalf of the ATLAS Collaboration

University of Sheffield

13.07.2019

Introduction

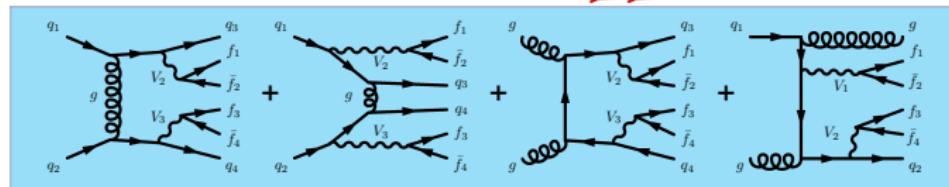
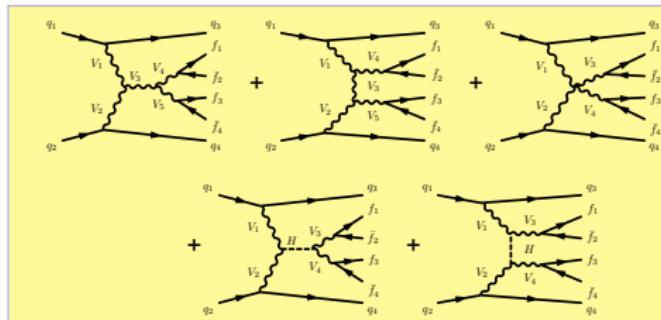
- ▶ Vector boson scattering is amongst the rarest processes currently accessible at the LHC
- ▶ ATLAS has performed studies of vector boson scattering in:
 - ▶ $W^\pm W^\pm jj$ final states ([arXiv:1906.03203](#))
 - ▶ $W^\pm Z jj$ final states ([Phys. Lett. B 793 \(2019\) 469](#))
 - ▶ semi-leptonic $VVjj$ final states ([arXiv:1905.07714](#))
 - ▶ ($Z\gamma jj$ at 8 TeV, not shown today)
 - ▶ First measurement of $ZZjj$ final states in ATLAS ([ATLAS-CONF-2019-033](#)) **NEW!**



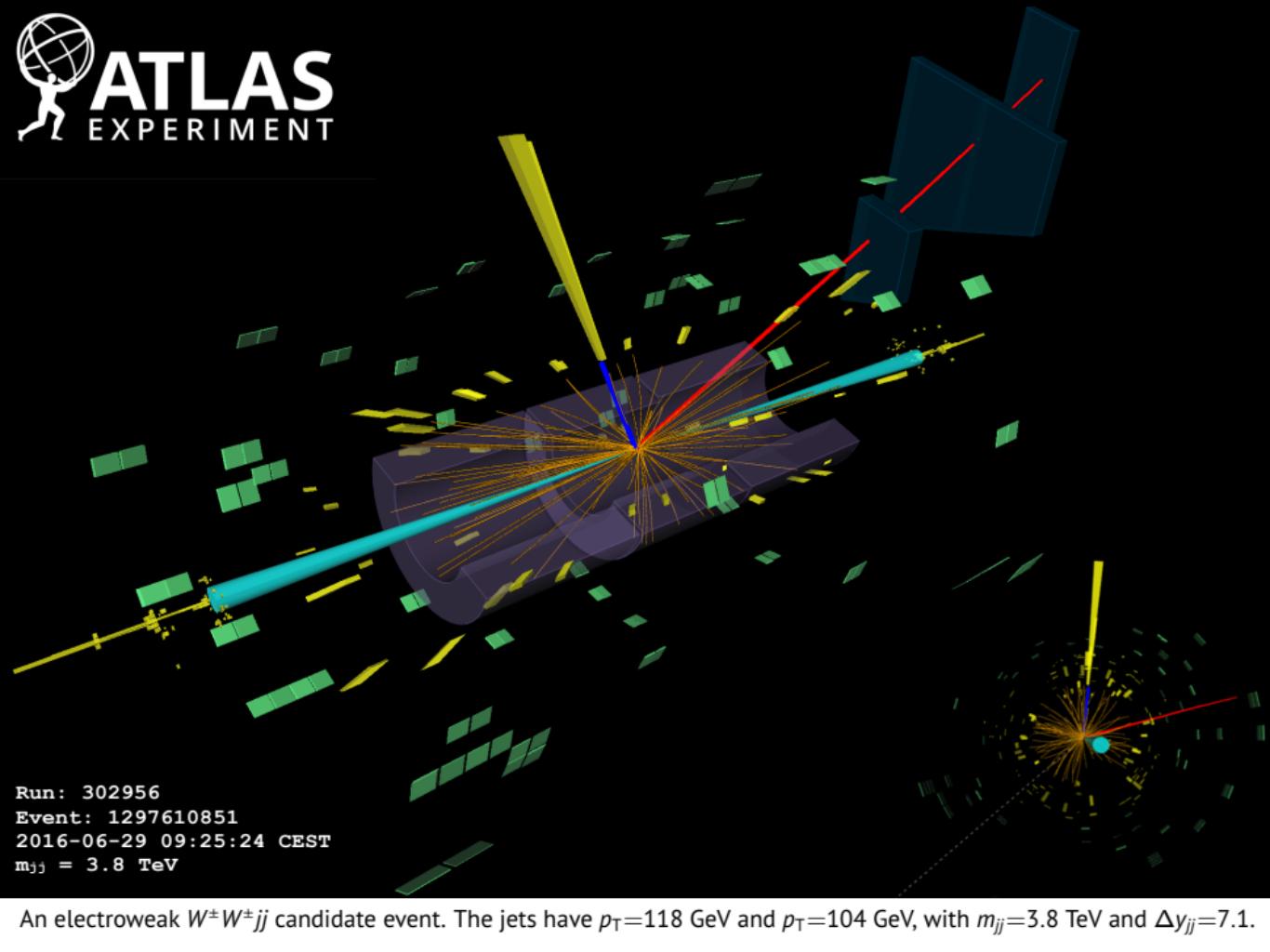
- ▶ Most studies still based on 36.1 fb^{-1} of pp data recorded at $\sqrt{s} = 13$ TeV in the years 2015 and 2016
- ▶ First results with full run-2 dataset of 139 fb^{-1} available

Vector Boson Scattering

- ▶ Electroweak symmetry breaking required for a renormalisable electroweak theory
- ▶ VBS diagrams involve *s*- and/or *t*-channel exchange of Higgs boson
- ▶ At the LHC the $VVjj$ final state can be produced by:
 - ▶ purely electroweak interactions at Born level
 - ▶ processes involving both strong and electroweak interactions



- ▶ Interference between electroweak and strong production assigned as uncertainty on our measured signal cross sections (evaluated at LO with Madgraph)
- ▶ Not included in the theoretical prediction



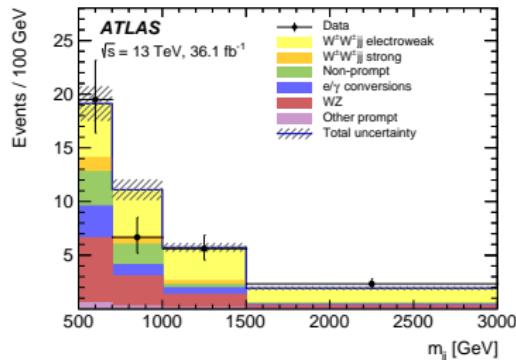
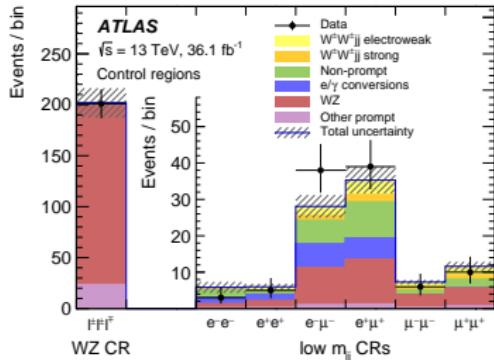
Run: 302956

Event: 1297610851

2016-06-29 09:25:24 CEST

$m_{jj} = 3.8 \text{ TeV}$

An electroweak $W^\pm W^\pm jj$ candidate event. The jets have $p_T=118 \text{ GeV}$ and $p_T=104 \text{ GeV}$, with $m_{jj}=3.8 \text{ TeV}$ and $\Delta y_{jj}=7.1$.



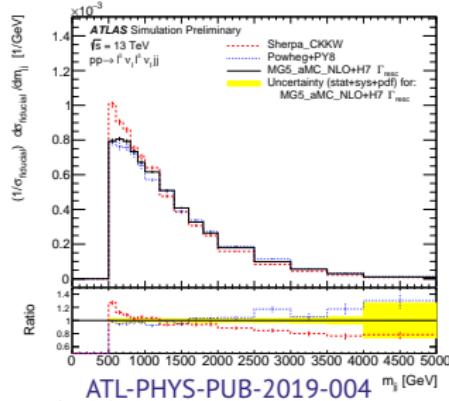
- The analysis explores different background compositions in a likelihood fit to five bins in m_{jj} (by fitting e^+e^+ , e^-e^- , $e^+\mu^+$, $e^-\mu^-$, $\mu^+\mu^+$, $\mu^-\mu^-$ separately)

- Separate bin to constrain $WZjj$ yield

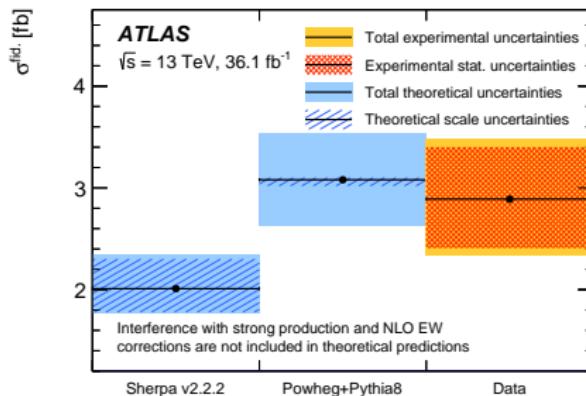
$$0.86^{+0.07}_{-0.07} \text{ (stat.)}^{+0.18}_{-0.08} \text{ (exp. syst.)}^{+0.31}_{-0.23} \text{ (mod. syst.)}$$

- Background-only hypothesis rejected with 6.5σ

(where 4.4σ and 6.5σ expected from Sherpa and PowhegBox+Pythia8, respectively)



$W^\pm W^\pm jj$ – Results



- ▶ The fiducial cross section is measured to:

$$\sigma^{\text{fid.}} = 2.89^{+0.51}_{-0.48} \text{ (stat.)}^{+0.24}_{-0.22} \text{ (exp. syst.)}^{+0.14}_{-0.16} \text{ (mod. syst.)}^{+0.08}_{-0.06} \text{ (lumi.) fb}$$

compared to $2.01^{+0.33}_{-0.23}$ fb (Sherpa2.2.2) and $3.08^{+0.48}_{-0.46}$ fb (PowhegBox+Pythia8)

- ▶ The multi-leg configuration of Sherpa mitigates effects of the non-optimal colour-flow setting on differential distributions
- ▶ Using a PowhegBox+Pythia8 signal template yields consistent results within the modelling uncertainty

- ▶ Signal extracted by fitting a BDT discriminant built from 15 variables

- ▶ jet kinematics

$$(m_{jj}, p_T^{j1}, p_T^{j2}, \Delta\eta_{jj}, \Delta\phi_{jj}, y^{j1}, n_{\text{jets}})$$

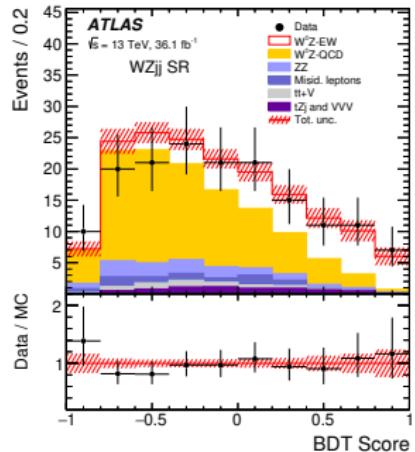
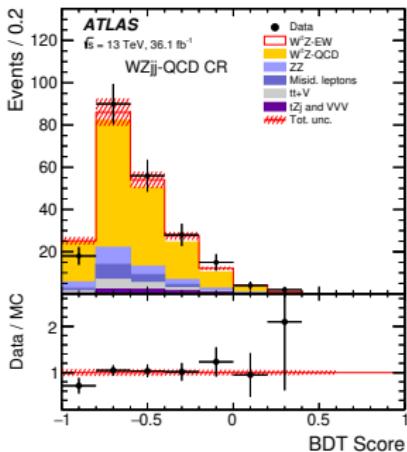
- ▶ diboson kinematics

$$(p_T^W, p_T^Z, \eta^W, |y_Z - y_{\ell, W}|, m_T^W)$$

- ▶ combined jet-diboson

$$(\Delta R(j_1, Z), R_{p_T}^{\text{hard}}, \zeta_{\text{lep}})$$

- ▶ Background constrained in three control regions



- ▶ Overestimation of strong $WZjj$ production in Sherpa2.2.2, $\mu_{WZ\text{-QCD}} = 0.56 \pm 0.16$
- ▶ Difference in electroweak $WZjj$ between Sherpa2.2.2 and MG5_aMC@NLO
- ▶ Background only hypothesis rejected with 5.3σ (expected 3.2σ)

	SR	WZjj-QCD CR	b-CR	ZZ-CR
Data	161	213	141	52
Total predicted	200 ± 41	290 ± 61	160 ± 14	45.2 ± 7.5
$WZjj\text{-EW}$ (signal)	24.9 ± 1.4	8.45 ± 0.37	1.36 ± 0.10	0.21 ± 0.12
$WZjj\text{-QCD}$	144 ± 41	231 ± 60	24.4 ± 1.7	1.43 ± 0.22
Misid. leptons	9.8 ± 3.9	17.7 ± 7.1	30 ± 12	0.47 ± 0.21
$ZZjj\text{-QCD}$	8.1 ± 2.2	15.0 ± 3.9	1.96 ± 0.49	35 ± 11
tZj	6.5 ± 1.2	6.6 ± 1.1	36.2 ± 5.7	0.18 ± 0.04
$t\bar{t} + V$	4.21 ± 0.76	9.11 ± 1.40	65.4 ± 10.3	2.8 ± 0.61
$ZZjj\text{-EW}$	1.80 ± 0.45	0.53 ± 0.14	0.12 ± 0.09	4.1 ± 1.4
VVV	0.59 ± 0.15	0.93 ± 0.23	0.13 ± 0.03	1.05 ± 0.30

Event yields, pre-fit

WZjj – Results

- The fiducial cross section is measured to be:

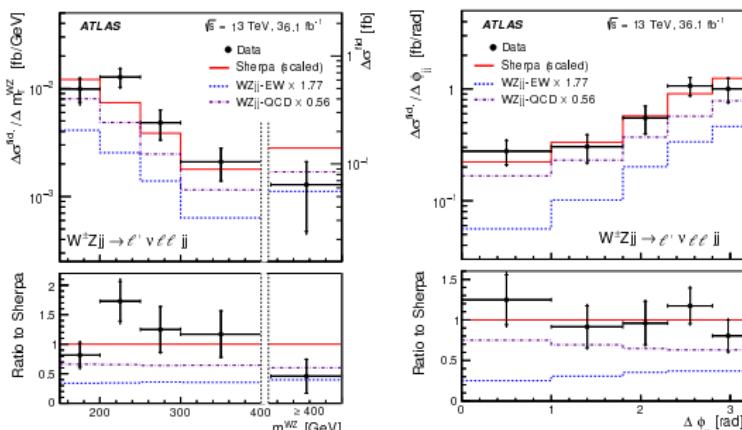
$$\sigma_{WZjj-EW}^{fid.} = 0.57^{+0.14}_{-0.13} \text{ (stat.)}^{+0.05}_{-0.04} \text{ (exp. syst.)}^{0.05}_{-0.04} \text{ (mod. syst.)}^{+0.01}_{-0.01} \text{ (lumi.) fb}$$

compared to $0.321^{+0.028}_{-0.024}$ fb from Sherpa2.2.2

- Additional results in a combined strong + electroweak fiducial region:

$$\sigma_{WZjj-QCD+EW}^{fid.} = 1.68 \pm 0.25 \text{ fb}$$

- Including differential distributions



EFT motivated

QCD motivated

- Variables motivated by EFT interpretations ($m_T(WZ)$, $\sum p_T^\ell$, $\Delta\phi(W, Z)$)
- Variables motivated by QCD studies (n_{jets} , m_{jj} , $\Delta\phi_{jj}$, Δy_{jj})

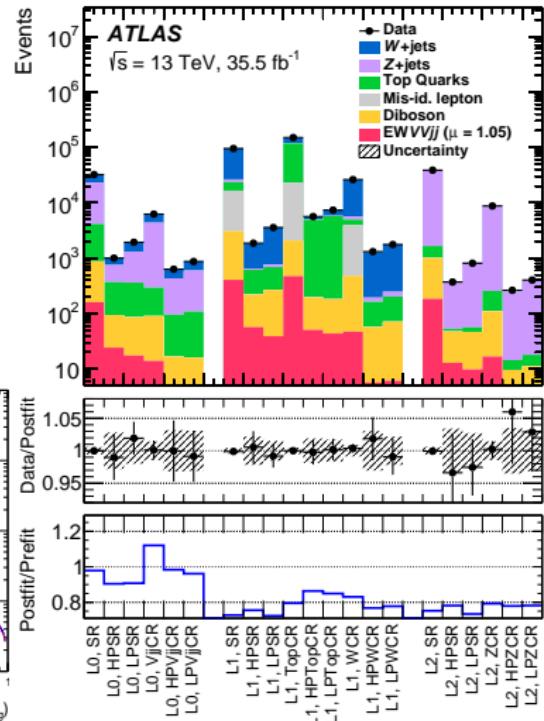
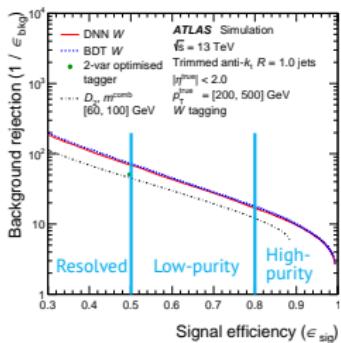
- ▶ Search for electroweak $V V jj$ production, where one V decays leptonically and one hadronically

- ▶ 0 lepton: $Z \rightarrow \nu\nu$ or $W \rightarrow \ell\nu$ with V_{had}
- ▶ 1 lepton: $W \rightarrow \ell\nu$ with V_{had}
- ▶ 2 lepton: $Z \rightarrow \ell\ell$ with V_{had}
- ▶ Further categorisation into:
 - ▶ Large- R jet category (anti- k_t 1.0)
 - with a low- and a high-purity region
 - ▶ Two small- R jet category (anti- k_t 0.4)

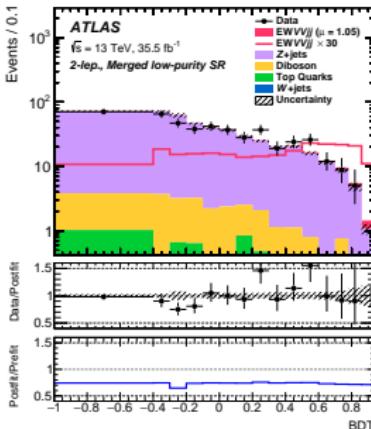
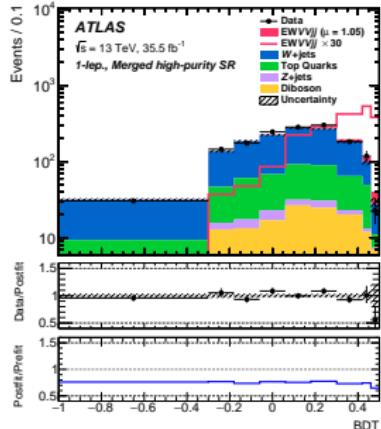
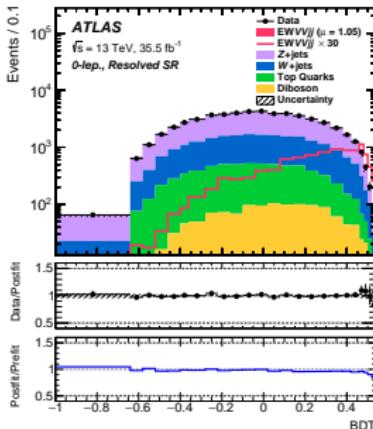
⇒ Nine signal regions

- ▶ Main backgrounds are $V+jets$ production, i.e. the reco. V_{had} consists of QCD jets!

→ Control regions for W, Z and $t\bar{t}$



V V jj – Results



- The background-only hypothesis is rejected with 2.7σ (where 2.5σ are expected from MG5_aMC@NLO)
- The fiducial cross section is measured to be:

$$\sigma^{\text{fid.}} = 45.1 \pm 8.6 \text{ (stat.)}^{+15.9}_{-14.6} \text{ (syst.) fb}$$

in the combined fiducial phase space, compared to 43.0 ± 2.4 predicted by MG5_aMC@NLO

- Fiducial cross sections are also reported for each signal category separately

- ▶ Measurement of ZZjj production in a phase space enriched in electroweak events
 - ▶ $m_{jj} > 300 \text{ GeV}$ (4ℓ) and $m_{jj} > 400 \text{ GeV}$ ($2\ell 2\nu$)
 - ▶ $y^{j1} \cdot y^{j2} < 0$, $\Delta y_{jj} > 2$
- ▶ Separate analyses in $4\ell jj$ and $2\ell 2\nu jj$ final states
- ▶ First SM publication with full run-2 dataset

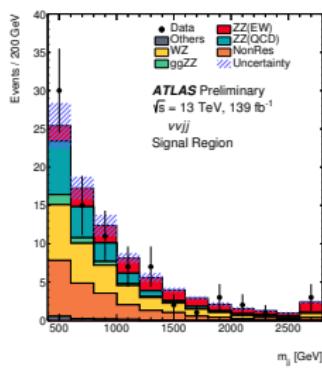
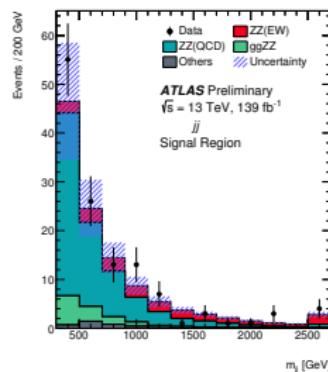
Process	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
EW ZZjj	20.6 ± 2.5	12.3 ± 0.7
QCD ZZjj	77.4 ± 25.0	17.2 ± 3.5
QCD ggZZjj	13.1 ± 4.4	3.5 ± 1.1
Non-resonant- $\ell\ell$	-	21.4 ± 4.8
WZ	-	22.8 ± 1.1
Others	3.2 ± 2.1	1.2 ± 0.9
Total	114.3 ± 25.6	78.4 ± 6.2
Data	127	82

- ▶ Measured cross sections:

$$\sigma_{4\ell jj}^{\text{fid.}} = 1.27 \pm 0.12(\text{stat.}) \pm 0.08(\text{syst.}) \text{ fb}$$

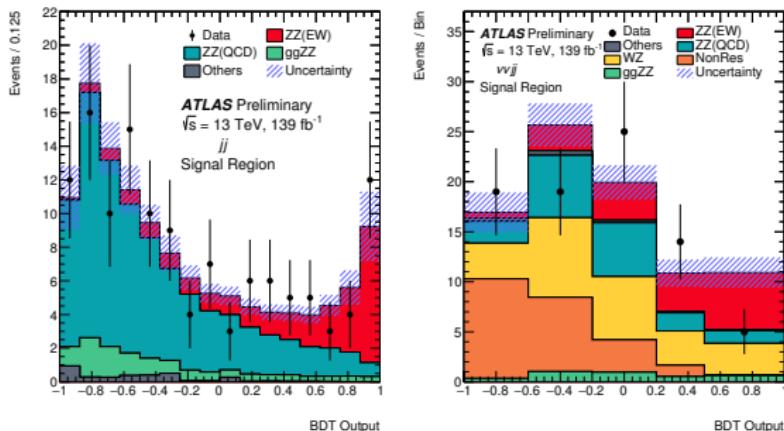
$$\sigma_{2\ell 2\nu jj}^{\text{fid.}} = 1.22 \pm 0.30(\text{stat.}) \pm 0.18(\text{syst.}) \text{ fb}$$

- ▶ in agreement with the predictions from MG5_aMC@NLO of $1.14 \pm 0.20 \text{ fb}$ and $1.07 \pm 0.12 \text{ fb}$, respectively



Observation of Electroweak $ZZjj$ Production

- The electroweak signal is extracted using a BDT with 12 (4ℓ) or 13 ($2\ell 2\nu$) variables
- A fit of the BDT discriminant is performed simultaneously in $4\ell jj$ and $2\ell 2\nu jj$ (with a 4ℓ QCD CR defined by events failing Δy_{jj} or m_{jj})



- Electroweak $ZZjj$ production is observed **for the first time** with the background-only hypothesis rejected with 5.5σ (expected 4.3σ from MG5_aMC@NLO)
- The fiducial cross section is measured to be:

$$\sigma_{ZZjj-EW}^{\text{fid.}} = 0.82 \pm 0.21 \text{ fb}$$

in agreement with the MG5_aMC@NLO prediction of $0.61 \pm 0.03 \text{ fb}$

Conclusions

- ▶ Electroweak $W^\pm W^\pm jj$ and $WZjj$ production observed by ATLAS in 36.1 fb^{-1} of data
 - ▶ fiducial cross section of electroweak $W^\pm W^\pm jj$ measured
 - ▶ fiducial cross section of electroweak $W^\pm Zjj$ measured
 - ▶ differential cross section of $W^\pm Zjj$ measured in a phase space enriched in VBS events
- ▶ These are amongst the most elusive processes measured at the LHC so far
- ▶ Search of semi-leptonic $VVjj$ production with a significance of 2.7σ (expected 2.5σ)
- ▶ The full run-2 dataset offers the possibility for detailed studies of VBS final states
- ▶ First observation of electroweak $ZZjj$ production in the full run-2 dataset of 139 fb^{-1}

Backup