

Longitudinal polarisation of electroweak gauge bosons in $WZjj$ -EW production with ATLAS

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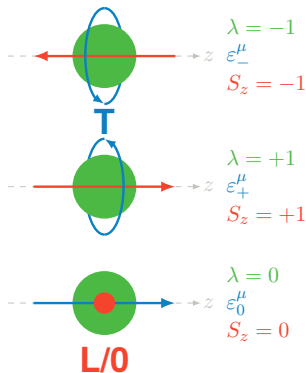


1 Motivation

2 Analysis strategy

3 Results

Longitudinal bosons: probes of the Higgs mechanism



Polarisation: the spin state of the boson with respect to a chosen spin-quantisation axis

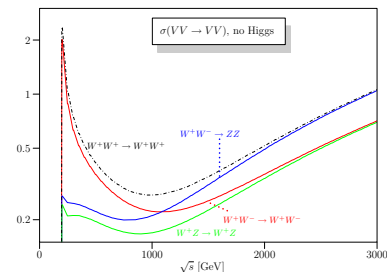
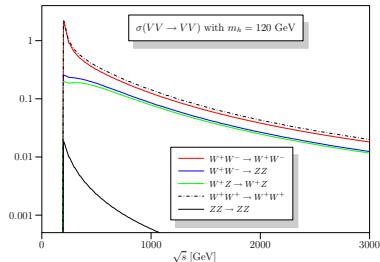
Helicity basis: the axis is the direction of motion,

$$h = \frac{\vec{S} \cdot \vec{p}}{|\vec{p}|}, \text{ with states } \lambda = -1, 0, +1$$

$$SU(2)_L \times U(1)_Y \xrightarrow{\text{BEH}} U(1)_{\text{EM}}$$

- Three broken generators $\rightarrow$ three Goldstone bosons, **absorbed** by $W^\pm$ and Z
 - A massive vector gains a third degree of freedom: the **longitudinal** polarisation
- For $p^\mu = (E, 0, 0, p_z)$:
- $$\epsilon_\pm^\mu = \frac{1}{\sqrt{2}} (0, \mp 1, -i, 0) \quad \epsilon_0^\mu = \frac{1}{m_V} (p_z, 0, 0, E)$$
- $\epsilon_0^\mu \propto \frac{E}{m_V}$: at high energy V_0 acts as the Goldstone boson, and the $V_0 V_0 \rightarrow V_0 V_0$ amplitudes **grow with energy**

- Only the **Higgs exchange** cancels the growth and **restores unitarity**



Deviation from SM prediction in σ_{VBS} hints at **physics beyond the Standard Model**

Longitudinal VBS cross-sections [1]

The master formula

$$\frac{1}{\sigma_{WZ \rightarrow \ell' \pm \nu_{\ell} \ell \ell}} \frac{d^2 \sigma_{WZ \rightarrow \ell' \pm \nu_{\ell} \ell \ell}}{d\Omega_W^* d\Omega_Z^*} = \left(\frac{3}{4\pi}\right)^2 \text{Tr} \left[\underbrace{\rho^{WZ}}_{\text{production}} \underbrace{(\Gamma^W \otimes \Gamma^Z)^\top}_{\text{decay}} \right]$$

- ρ^{WZ} : 9×9 matrix [10], how the pair is **produced** $\rightarrow$ holds the fractions
- Γ^W, Γ^Z : the **decay density matrices**, fixed by the $V \rightarrow \ell\ell$ couplings, the **decay angles of the leptons arise from them**

$\Rightarrow$ each fraction has its own shape in $\cos \theta_W^*$ and $\cos \theta_Z^*$: they are **sensitive to the polarisation**

longitudinal $\propto \sin^2 \theta^*$

transverse $\propto 1 + \cos^2 \theta^*$

The fractions of polarisation

	Z_0	Z_T	
W_0	f_{00}	f_{0T}	f_{0X}
W_T	f_{T0}	f_{TT}	
	f_{X0}		

- Each boson longitudinal (0) or transverse (T): four joint states, $\sum = 1$
- $f_{0X} = f_{00} + f_{0T}$: a longitudinal W, regardless of the Z
- $f_{X0} = f_{00} + f_{T0}$: a longitudinal Z, regardless of the W
- f_{00} : both longitudinal

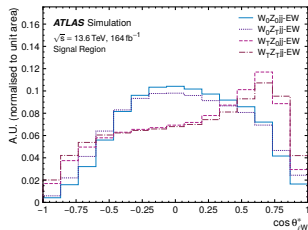
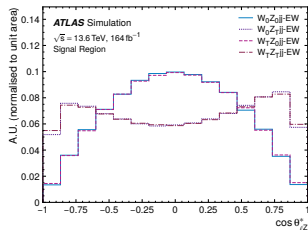
$\Rightarrow f_{0X}, f_{X0},$ and f_{00} : the **three fractions measured here**

The reference frame

The reference frame

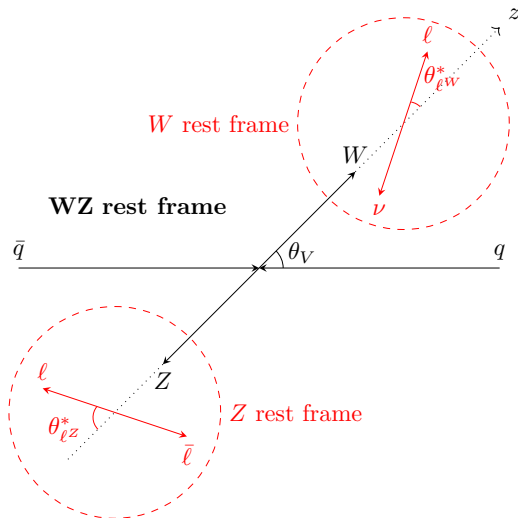
Polarisation is **not Lorentz invariant**[†]: the axis is the boson direction in the WZ centre-of-mass, the **modified-helicity** frame

- 1 WZ centre-of-mass: the **production angle** θ_V sets the axis
- 2 into each boson rest frame, where the decay angles are read:
 θ_W^* and θ_Z^*



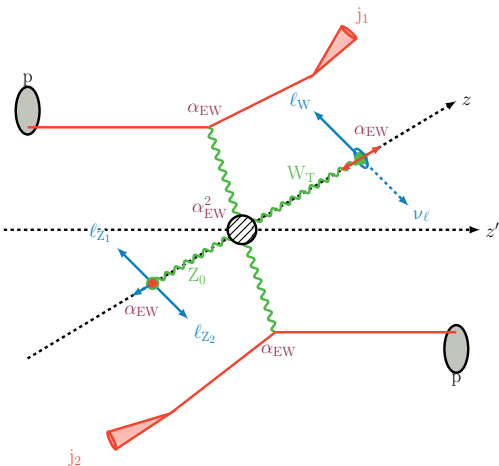
In each boson rest frame, θ_W^* and θ_Z^* carry the polarisation of the parent

[†] Lorentz invariant: unchanged by a change of frame



- 1 Motivation
- 2 Analysis strategy
- 3 Results

WZjj-EW: signal, selection, and this measurement



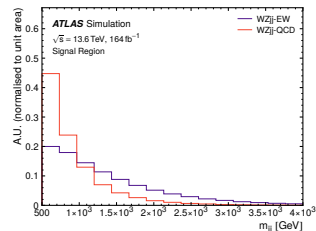
$$pp \rightarrow W^{\pm} Z jj \rightarrow \ell^{\pm} \nu_{\ell} \ell^{\pm} \ell^{\mp} jj$$

- Each incoming quark **radiates** a boson, the two **rescatter** into the WZ pair, at order α_{EW}^6
- Three charged leptons and E_T^{miss} : the Z fully reconstructed, the W up to its neutrino
- The quarks are **barely deflected**: two forward **tagging jets** in opposite hemispheres, large $\Delta\eta_{jj}$ and m_{jj}
- In WZjj-QCD colour flows between the quark lines: more central jets, smaller m_{jj}

Selection and signal region

- Exactly **three leptons**, the SFOC pair closest to m_Z makes the Z
- Two tagging jets, $m_{jj} > 500$ GeV, no b-jet
- Fiducial region of the previous WZ and WZjj measurements [13, 6]

► Fiducial



This talk [11, 12]

First measurement of polarisation in WZjj-EW, 140 fb^{-1} at 13 TeV and 164 fb^{-1} at 13.6 TeV

Backgrounds and control regions

Two families of background

- **Irreducible:** three real leptons in the final state $\rightarrow$ no selection removes them: $WZjj$ -QCD first, $ZZjj$ -QCD and $ZZjj$ -EW with a lepton lost, tZj , $t\bar{t} + V$, VVV , $WZjj$ -INT, and $WZjj$ -EW in τ
- **Reducible:** one lepton faked by a jet, a hadron decay or a photon conversion $\rightarrow$ badly modelled by simulation and **estimated from data**

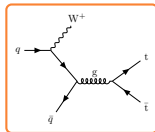
Control regions

- Orthogonal regions enriched in a given background and depleted in signal, to constrain its normalisation from data

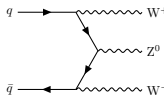
Region	Definition	For
b-CR	$N_b > 0$	tZj , $t\bar{t} + V$
ZZ-CR	≥ 4 baseline leptons	$ZZjj$ -QCD

- Their normalisations are **free in the fit**

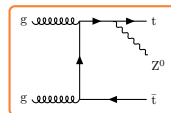
Irreducible



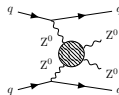
$t\bar{t}W$



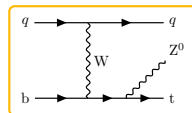
VVV



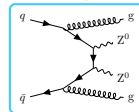
$t\bar{t}Z$



$ZZjj$ -EW

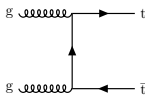


tZj

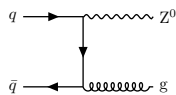


$ZZjj$ -QCD

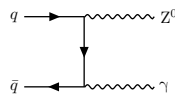
Reducible



$t\bar{t}$, hadron decay



$Z + \text{jets, jet}$

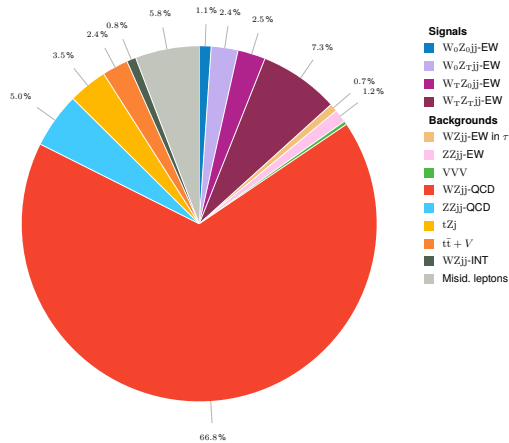


$Z\gamma$, conversion

The multivariate strategy

- **Three separate measurements**, of very different difficulty:
 - W_0Z_{0jj} -EW: $\sim 1\%$ of the yield, the hardest
 - W_0Z_{Xjj} -EW: $\sim 3.6\%$, limited by the neutrino
 - W_XZ_{0jj} -EW: $\sim 3.6\%$, the most promising, $Z \rightarrow \ell\ell$ fully reconstructed
- Two questions to answer per event, so **two networks**:
 - *is it signal?*
 $\rightarrow \approx 250$ WZ_{jj} -EW against ≈ 1610 background events
 - *is it the targeted polarisation?*
 $\rightarrow \approx 20$ W_0Z_{0jj} -EW, ≈ 65 W_0Z_{Xjj} -EW, ≈ 67 W_XZ_{0jj} -EW events
- Their outputs are combined into a **2D discriminant plane**, binned and fitted as a template

Signal region yield composition



Pre-fit yields in the signal region, Run 2 + Run 3 [11, 12] [Yields](#)

Two deep neural networks

S. vs B.

- Four outputs: WZjj-EW, WZjj-QCD, ZZjj-QCD, others
- Led by the **VBS topology**: m_{jj} , N_{jets} , $\Delta\eta_{jj}$

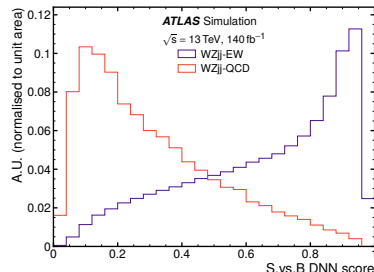
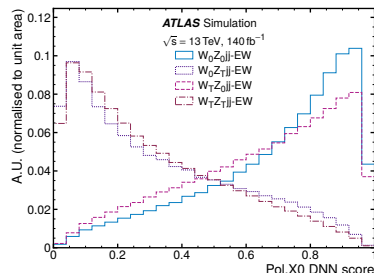
Polarisation

- Pol. 00, Pol. 0X, Pol. X0, trained on the polarised states, led by $\cos\theta^*$ of their boson

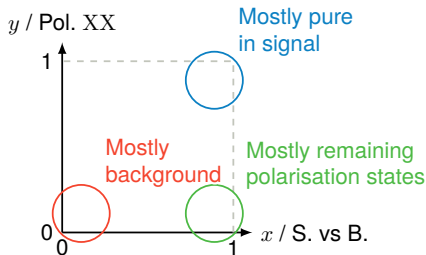
A robust training

- Top 25 inputs of three rankings, **pruned** at no cost
- **5-fold**: no event scored by a network that saw it
- Hyperparameters by **Bayesian optimisation**
- **Modelling cross-check**: generators agree to a few %

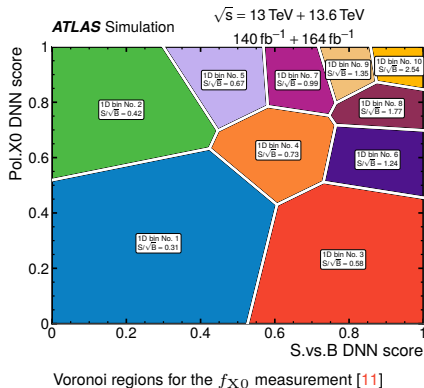
⇒ judged not on the ROC but on the **expected significance of a template fit**



The discriminant plane: k -means and Voronoi binning



- x : the S. vs B. output, the probability of being WZjj-EW
- y : the polarisation output, the probability of being the targeted state
- **Top right**: signal, in the targeted polarisation
- **Bottom right**: signal, in the other states
- **Left**: background
- The binning has to **enhance the top-right corner**



- **k -means** on the signal events, weighted by $\frac{S}{\sqrt{B}}$, pulls the centres to the most significant regions $\rightarrow$ the centres seed a **Voronoi tessellation** of the plane $\rightarrow$ the cells, sorted by $\frac{S}{S+B}$, are **unrolled** into a 1D template of $k = 10$ bins

$\Rightarrow$ follows the **non-linear** shape of the signal, a few % more expected significance than the best grid [12]

The fit

Binned profile-likelihood fit, Run 2 and Run 3 together

- **SR**: the unrolled Voronoi template
- **CRs**: $ZZ (m_{jj})$ $\rightarrow$ ZZ-CR and b-jets (a BDT) $\rightarrow$ b-CR fix $\mu_{ZZjj-QCD}$, $\mu_{t\bar{t}+V}$, μ_{tZj} per run

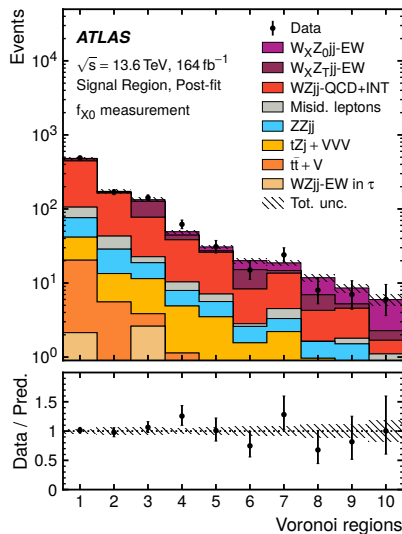
Parameters of interest (POI)

Targeted $\propto \mu_{WZjj-EW} \times f_{XX}^{fid.}$ Other states $\propto \mu_{WZjj-EW} \times (1 - f_{XX}^{fid.})$

- $\mu_{WZjj-EW}$: the WZjj-EW signal strength
- $f_{XX}^{fid.} \in [0, 1]$: the targeted fraction, measured **directly**, common to both runs

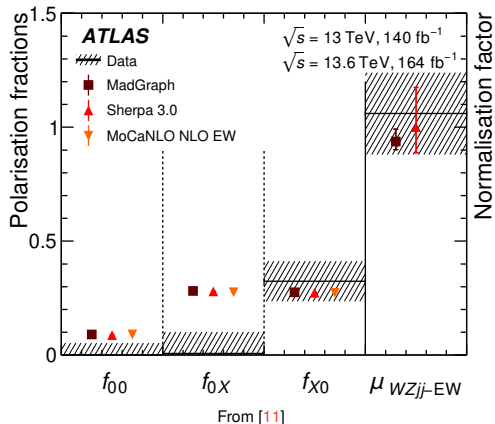
Theory input

- No polarised VBS generator at NLO: NLO EW from MoCanLO [14], -14.5% for W_0Z_0 against -19.6% for W_TZ_T , ignored it would **bias the fractions**



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Polarisation fractions and cross-sections



First evidence for a longitudinal Z in VBS

$$f_{X0} = 0.324^{+0.092}_{-0.085} \quad \text{at} \quad 4.0\sigma$$

in agreement with the predictions within one standard deviation

Cross-sections

Fiducial, per lepton flavour:

- $\sigma_{WZjj-EW}^{13 \text{ TeV}} = 0.347 \pm 0.079 \text{ fb}$

The first WZjj-EW cross-section at 13.6 TeV

$$\sigma_{WZjj-EW \rightarrow \ell' \nu_{\ell} \ell \ell jj}^{\text{fid., 13.6 TeV}} = 0.374 \pm 0.094 \text{ fb}$$

against $0.373^{+0.065}_{-0.041}$ predicted

- f_{00} and f_{0X} fluctuate *down* to the physical boundary while f_{X0} fluctuates *up*
- All three measurements are **statistically dominated**, and stable between the Run 2, Run 3, and combined fits [11, 12]

Upper limits

- Best-fit f_{00} and f_{0X} sit at the boundary $f = 0$, so one-sided limits are quoted

Fraction	Expected	Observed
f_{00}	0.21	< 0.12
f_{0X}	0.46	< 0.19

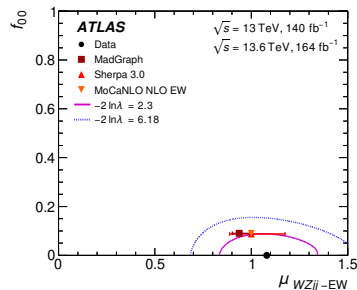
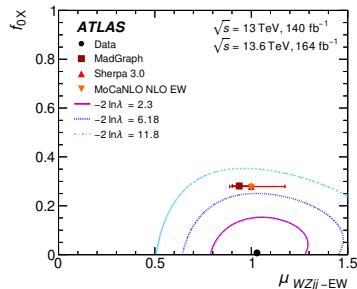
95 % CL upper limits, Run 2 + Run 3

- Both observed limits are tighter than expected, the direct consequence of the downward fluctuation
- Under the SM, observing $f_{0X} \leq 0.007$ has a probability of 0.6 %, a 2.5σ fluctuation

$f_{0X} \searrow 0 \Rightarrow W_T Z_{0jj}\text{-EW} \nearrow$ and $W_T Z_{Tjj}\text{-EW} \nearrow$
compatible with

$f_{X0} \nearrow$ since $W_X Z_{0jj}\text{-EW} = W_T Z_{0jj}\text{-EW} + W_0 Z_{0jj}\text{-EW}$

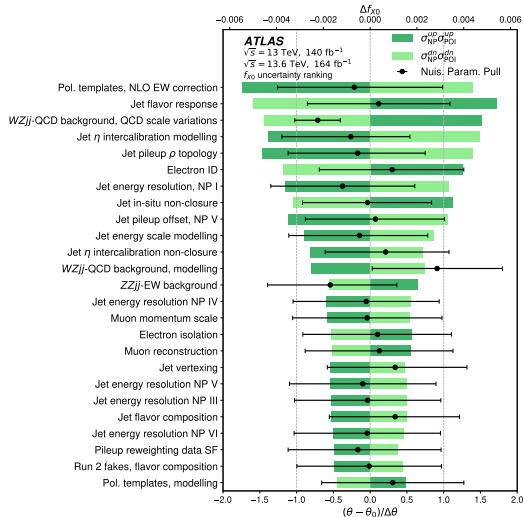
The two are compatible: a f_{0X} at zero means more $W_T Z_{0jj}\text{-EW}$ events, and those make most of $W_X Z_{0jj}\text{-EW}$



Uncertainties

Relative uncertainty [%]	f_{X0}	$\mu_{WZjj-EW}$
WZjj-EW theory modelling	1.7	4.9
WZjj-QCD theory modelling	1.6	5.0
Jets	3.6	6.6
Pile-up	0.5	1.9
MC statistics	2.4	1.1
Others	≤ 1.3	≤ 1.6
All systematics	5.2	10.2
Luminosity	0.4	1.2
Statistics	26.6	13.8
Total	27.1	17.2

- f_{X0} is **statistically limited**: 26.6 % statistical against 5.2 % systematic
- Leading systematics: jets, MC statistics, WZjj-EW and WZjj-QCD modelling



Impact of the nuisance parameters on f_{X0} [11]

First evidence for longitudinally polarised Z bosons in WZjj-EW

$$f_{X0} = 0.324^{+0.092}_{-0.085}$$

4.0σ (2.9σ expected)

First limits on the other longitudinal states

$$f_{00} < 0.12 \quad f_{0X} < 0.19 \text{ at } 95\% \text{ CL}$$

First WZjj-EW cross-section at 13.6 TeV

$$0.374 \pm 0.094 \text{ fb per lepton flavour, as in the SM}$$

The analysis

- Run 2 + Run 3, 304 fb^{-1} : **deep neural networks** and a **Voronoi binning** of their scores
- Compared with NLO EW predictions from MoCANLO, NLO EW effects on the templates included as an uncertainty
- Paper submitted to JHEP: [arXiv:2607.20246](https://arxiv.org/abs/2607.20246) [11], details in [12]
- Presented at **ICHEP 2026** and in a **CERN seminar**, featured in the **CERN Courier**

What comes next

- **Statistically limited:** more Run 3 data and the HL-LHC will turn the limits on W_0 and $W_0 Z_0$ into measurements

A new experimental probe of electroweak symmetry breaking through VBS

Questions

References

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- [9] [ATLAS Collaboration](#), *Evidence for Longitudinally Polarized W Bosons in the Electroweak Production of Same-Sign W Boson Pairs in Association with Two Jets in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector*, [Phys. Rev. Lett. 135 \(2025\) 111802](#), [arXiv: 2503.11317 \[hep-ex\]](#) (Cited on page [4](#)).
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- [11] [ATLAS Collaboration](#), *Evidence for longitudinally polarised Z bosons in electroweak $W^\pm Z$ production in association with two jets from pp collisions at $\sqrt{s} = 13$ TeV and 13.6 TeV with the ATLAS detector*, 2026, [arXiv: 2607.20246 \[hep-ex\]](#),
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Backup

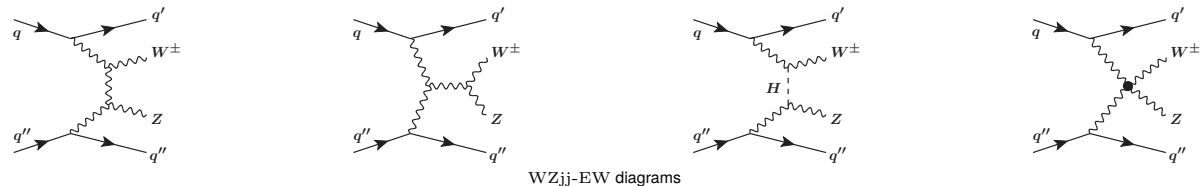
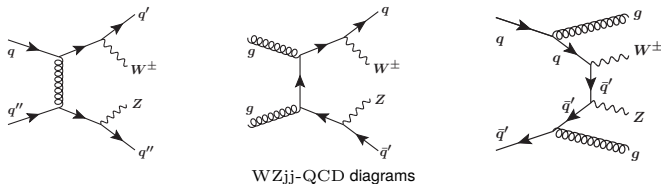
A Analysis details

B Fit and control regions

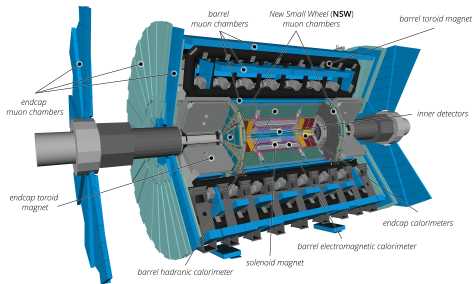
C Results

Evidence for longitudinally polarised Z bosons in electroweak $W^\pm Z$ production in association with two jets from pp collisions at $\sqrt{s} = 13$ TeV and 13.6 TeV with the ATLAS detector

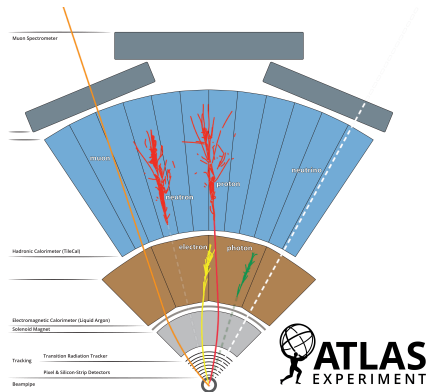
CERN-EP-2026-213, arXiv:2607.20246, submitted to JHEP [11], PhD thesis [12]



The ATLAS detector and the reconstruction



- From the beam outwards: **inner detector** ($|\eta| < 2.5$, 2 T), **calorimeters** ($|\eta| < 4.9$), **muon spectrometer** ($|\eta| < 2.7$)



- Electrons: track and electromagnetic cluster, muons: inner-detector and spectrometer tracks combined
- Jets: anti- k_t $R = 0.4$ on particle-flow objects, E_T^{miss} from all calibrated objects

Leptons	$ \eta < 2.5$, dressed ($\Delta R < 0.1$), resonant-shape assignment
Z leptons	$p_T > 15 \text{ GeV}$, $ m_{\ell\ell} - m_Z < 10 \text{ GeV}$, $\Delta R(\ell_1^Z, \ell_2^Z) > 0.2$
W lepton	$p_T > 20 \text{ GeV}$, $m_T^W > 30 \text{ GeV}$, $\Delta R(\ell^Z, \ell^W) > 0.3$
Jets	anti- k_t $R = 0.4$, $p_T > 40 \text{ GeV}$, $ \eta < 4.5$, $\Delta R(j, \ell) > 0.3$
Tagging jets	two leading jets with $\eta_{j1} \cdot \eta_{j2} < 0$, $m_{jj} > 500 \text{ GeV}$
Excluded	b-quark in the initial or final state (tZj)

Detector level: the same, plus the b-jet veto, a fourth-lepton veto, tight identification and isolation for the W lepton, and a trigger-matched lepton with $p_T > 27 \text{ GeV}$ (25 GeV in 2015)

Polarised cross-sections at NLO EW (MoCANLO)

Mode	σ^{LO} [fb]	δ^{EW} [%]	$\sigma^{\text{NLO EW}}$ [fb]	f [%]	
				LO	NLO EW
Full	0.272 08	−18.5	0.2216	103.4	103.4
Unpolarised	0.267 77	−18.5	0.2183	101.8	101.8
$W_0 Z_0$	0.023 045	−14.5	0.0197	8.8	9.2
$W_0 Z_T$	0.049 365	−17.9	0.0405	18.8	18.9
$W_T Z_0$	0.049 023	−17.9	0.0402	18.6	18.8
$W_T Z_T$	0.141 725	−19.6	0.1140	53.9	53.1
Interference	0.004 62	−15.0	0.0039	1.8	1.8
$\Sigma_{\text{pol.}}$	0.263 158	−18.5	0.2144	100.0	100.0
$W_0 Z_X$	0.072 410	−16.8	0.0602	27.5	28.1
$W_X Z_0$	0.072 068	−16.8	0.0599	27.4	28.0

- Polarisation defined in the WZ **centre-of-mass frame**
- Interferences between states ($\sim 2\%$) and off-shell effects ($\sim 1.5\%$) included in the fractions [14]
- Polarised states in the **double-pole approximation**: only the doubly resonant diagrams, the boson momenta projected on-shell in the numerator, the Breit–Wigner lineshape kept. Off-shell effects: the full off-shell result against the unpolarised DPA, Full/Unpolarised = 1.016

W^+Z at $\sqrt{s} = 13.6$ TeV. Interference: the unpolarised DPA minus the polarised sum [14, 12]

Pre-fit event yields

	SR				ZZ-CR				b-CR			
	Run 2		Run 3		Run 2		Run 3		Run 2		Run 3	
Data	646		953		210		235		666		766	
Total prediction	800	± 190	1060	± 270	204	± 11	240	± 24	687	± 56	751	± 75
$W_X Z_{0jj}$ -EW	29.2	± 0.7	37.6	± 2.0								
$W_X Z_{Tjj}$ -EW	78.0	± 2.2	102.1	± 5.9								
WZjj-EW					0.6	± 0.1	0.8	± 0.2	5.1	± 1.3	3.4	± 0.9
WZjj-QCD	530	± 190	710	± 260	6.3	± 2.1	8.7	± 3.0	93	± 36	75	± 27
Misidentified leptons	46	± 11	62	± 19	1.7	± 0.4	2.2	± 0.5	155	± 38	195	± 61
ZZjj-QCD	41.6	± 2.9	51.8	± 9.4	158.4	± 8.6	181	± 20	10.1	± 0.6	9.0	± 0.9
tZj	28.5	± 1.0	37.3	± 3.5	0.4	$\pm <0.1$	0.8	± 0.1	134.1	± 5.0	154.4	± 9.4
$t\bar{t} + V$	20.9	± 0.7	22.9	± 2.3	10.0	± 0.3	11.9	± 1.0	289	± 11	312	± 19
ZZjj-EW	6.7	± 1.7	15.4	± 3.9	22.8	± 5.7	30.4	± 7.7	0.3	± 0.1	0.3	± 0.1
WZjj-INT	6.5	± 1.3	9.2	± 1.9	0.1	$\pm <0.1$	0.1	$\pm <0.1$	0.6	± 0.1	0.4	± 0.1
WZjj-EW in τ	5.9	± 0.6	7.5	± 0.8								
VVV	2.4	± 0.6	3.7	± 0.9	4.1	± 1.0	4.8	± 1.2	0.4	± 0.1	0.4	± 0.1

Before the fit, total systematic uncertainties [11]

Post-fit event yields (f_{X0} fit)

	SR		ZZ-CR		b-CR	
	Run 2	Run 3	Run 2	Run 3	Run 2	Run 3
Data	646	953	210	235	666	766
Total prediction	668 $\pm$ 23	934 $\pm$ 28	210 $\pm$ 14	238 $\pm$ 15	663 $\pm$ 26	771 $\pm$ 28
$W_X Z_{0jj}$ -EW	36 $\pm$ 11	48 $\pm$ 14				
$W_X Z_{Tjj}$ -EW	76 $\pm$ 18	103 $\pm$ 24				
$WZjj$ -EW			0.6 $\pm$ 0.1	0.8 $\pm$ 0.2	5.0 $\pm$ 1.3	3.4 $\pm$ 0.9
$WZjj$ -QCD	393 $\pm$ 30	573 $\pm$ 37	5.0 $\pm$ 0.4	6.8 $\pm$ 0.6	62.2 $\pm$ 10.0	59.1 $\pm$ 5.0
Misidentified leptons	45 $\pm$ 10	54 $\pm$ 15	1.7 $\pm$ 0.4	2.2 $\pm$ 0.5	152 $\pm$ 36	168 $\pm$ 48
$ZZjj$ -QCD	44.0 $\pm$ 4.0	52.4 $\pm$ 5.4	170 $\pm$ 15	183 $\pm$ 16	9.9 $\pm$ 0.6	9.3 $\pm$ 0.5
tZj	33.3 $\pm$ 6.4	44.1 $\pm$ 8.9	0.5 $\pm$ 0.1	1.0 $\pm$ 0.2	157 $\pm$ 30	182 $\pm$ 35
$t\bar{t} + V$	19.8 $\pm$ 2.4	25.7 $\pm$ 3.6	9.5 $\pm$ 1.2	13.3 $\pm$ 1.8	275 $\pm$ 32	349 $\pm$ 42
$ZZjj$ -EW	5.6 $\pm$ 1.3	13.5 $\pm$ 3.2	19.1 $\pm$ 4.6	26.7 $\pm$ 6.3	0.2 $\pm$ 0.1	0.2 $\pm$ 0.1
$WZjj$ -INT	6.5 $\pm$ 1.3	9.4 $\pm$ 1.9	0.1 $\pm$ <0.1	0.1 $\pm$ <0.1	0.6 $\pm$ 0.1	0.4 $\pm$ 0.1
$WZjj$ -EW in τ	5.9 $\pm$ 0.6	7.6 $\pm$ 0.8				
VVV	2.4 $\pm$ 0.6	3.7 $\pm$ 0.9	4.1 $\pm$ 1.0	4.9 $\pm$ 1.2	0.4 $\pm$ 0.1	0.4 $\pm$ 0.1

$\mu_{t\bar{t}+V} = 0.96 \pm 0.12$ (1.09 ± 0.14), $\mu_{tZj} = 1.18 \pm 0.22$ (1.15 ± 0.22), $\mu_{ZZ} = 1.09 \pm 0.11$ (0.97 ± 0.11) for Run 2 (Run 3)

Input variables of the networks

Variable	S. vs B.	Pol. 00	Pol. 0X	Pol. X0
N_{jets}	✓	×	×	×
E_{j1}^j	✓	×	×	×
p_T^{j1}	✓	×	×	✓
p_T^{j2}	×	×	×	✓
η^{j1}	×	✓	✓	✓
η^{j2}	✓	✓	✓	×
ϕ^{j2}	×	×	✓	×
m_{jj}	✓	×	×	×
$\Delta\eta_{jj}$	✓	✓	✓	✓
$\Delta\phi_{jj}$	✓	✓	✓	×
$\Delta R(j_1, Z)$	×	✓	✓	✓
$\langle p_T^{jj} \rangle$	×	×	×	✓
$A_{jj}^{p_T}$	✓	✓	✓	×
$R_{\text{hard}}^{p_T}$	✓	×	×	×
p_T^W	✓	✓	✓	✓
p_T^Z	×	✓	✓	✓
p_T^{WZ}	✓	✓	✓	✓

Variable	S. vs B.	Pol. 00	Pol. 0X	Pol. X0
r_{21}	×	✓	×	×
m_T^{WZ}	×	✓	✓	✓
E_T^{miss}	×	×	✓	✓
ℓ_{Z1}^T	×	✓	×	✓
ℓ_{Z2}^T	×	×	×	✓
$p_T^{\ell W}$	×	×	✓	✓
$p_T^{\ell Z1}$	✓	✓	✓	✓
$\eta^{\ell Z2}$	×	✓	×	✓
$\eta^{\ell W}$	✓	✓	✓	✓
$\cos\theta_W^*$	×	✓	✓	×
$\cos\theta_Z^*$	×	✓	×	✓
$ \cos\theta_V $	✓	✓	✓	×
$\Delta\phi(\ell_{Z1}, \ell_{Z2})$	✓	✓	×	×
$\Delta\phi(\ell_W, \nu_\ell)$	✓	×	✓	×
ζ_ℓ	✓	×	×	×
A_y^{WZ}	✓	✓	✓	✓
$z_{3\ell}$	×	×	×	✓

⇒ 18 variables for S. vs B., 20, 19, and 20 for the polarisation networks, out of 44, chosen by a ranking and pruning on the fit significance [11, 12]

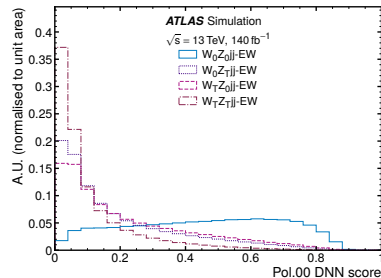
Input features: ranking and pruning

- Start from the full list of variables
- Ranked with **three independent methods**
- **Top 25** across the three, then **prune** until the ROC and the AUC start to degrade
- S. vs B.: the methods agree on m_{jj} , N_{jets} , $\Delta\eta_{jj}$, then ζ_ℓ , **the defining observables of the VBS topology**
- Polarisation networks: each follows **the boson it targets**, $\cos\theta^*$ first, then that boson's decay kinematics
- Input modelling checked in a validation region $150 < m_{jj} < 500 \text{ GeV}$

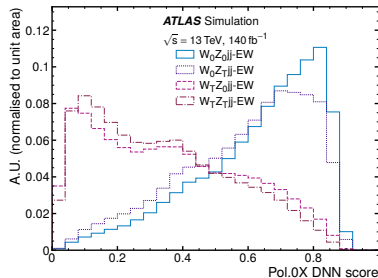
⇒ pruning costs no performance and reduces the risk of overfitting

Details in [12], selected inputs in [11] [▶ Input variables](#)

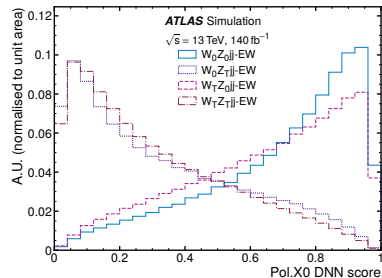
Polarisation DNN outputs



Pol. 00, AUC 0.84



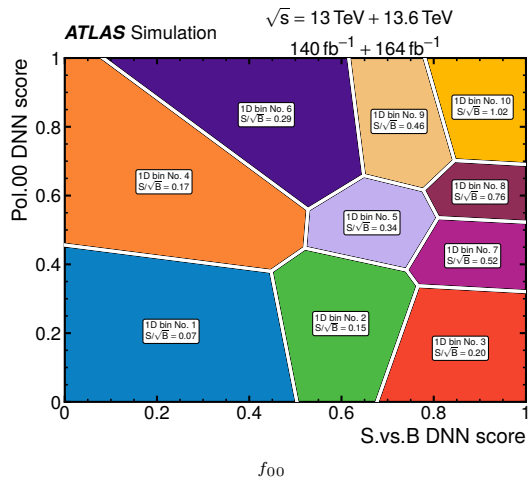
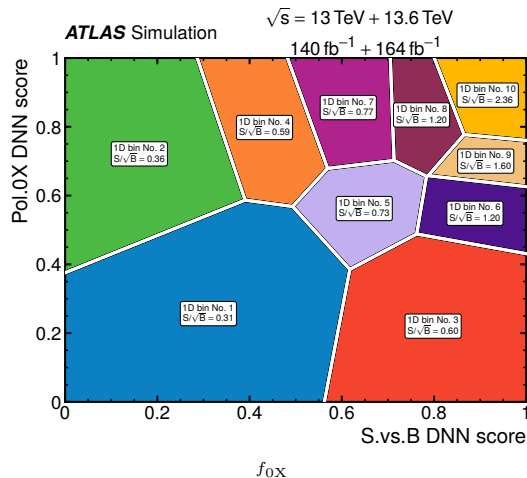
Pol. 0X, AUC 0.80



Pol. X0, AUC 0.84

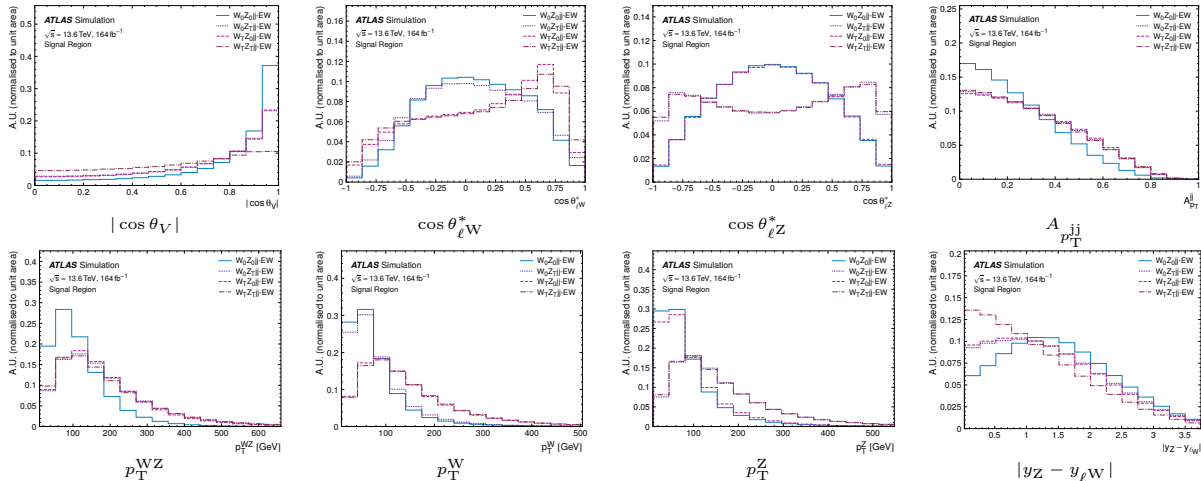
Score distributions of the polarised $WZ_{jj}\text{-EW}$ states, SHERPA 3.0, Run 2, normalised to the same integral [11]

Voronoi regions of the other two measurements



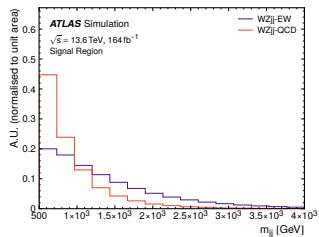
With the $S/\sqrt{B}$ of each region [11]

Variables sensitive to polarisation

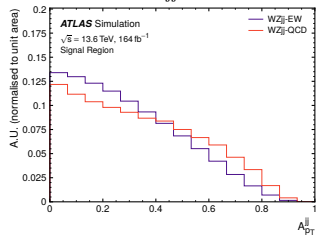


Run 3 shapes of the polarised states. The W needs the neutrino p_z , estimated by a neural network [4]: the Z is better reconstructed, hence f_{χ_0} is the most sensitive fraction

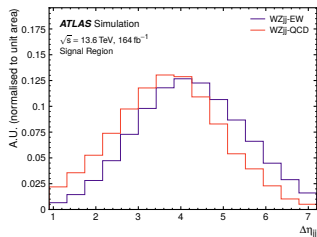
Variables separating EW from QCD



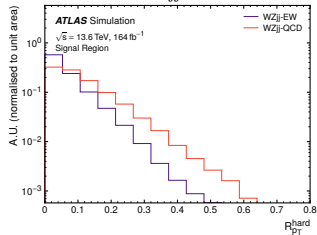
m_{jj}



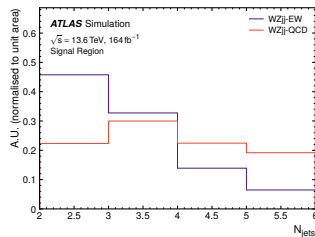
A_{PT}^{jj}



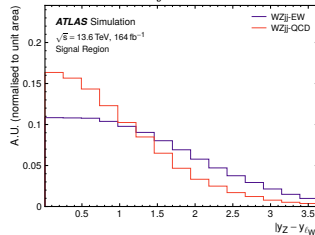
$\Delta\eta_{jj}$



R_{PT}^{hard}



N_{jets}



$|y_Z - y_{lW}|$

Run 3 shapes. Input modelling checked in a validation region $150 < m_{jj} < 500 \text{ GeV}$, the most important variables measured in the signal region at 13 TeV [6]

A Analysis details

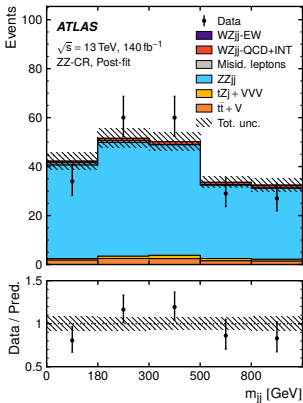
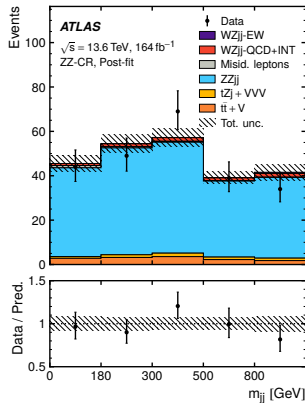
B Fit and control regions

C Results

Purpose

ZZ production with one lepton lost is the second irreducible background. Requiring **four or more baseline leptons** isolates it

- Fitted variable: m_{jj} , which separates the softer ZZ_{jj}-QCD from the harder signal
- **Common to the three measurements**, one normalisation factor per run, **uncorrelated** between the runs



$\Rightarrow \mu_{\text{ZZjj-QCD}} = 1.09^{+0.11}_{-0.10}$ (Run 2) and $0.97^{+0.11}_{-0.10}$ (Run 3), both compatible with unity

Run 2 alone previously gave 1.08 ± 0.11 [6]

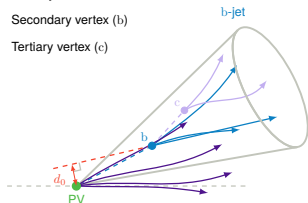
Control region: b-jets

Purpose

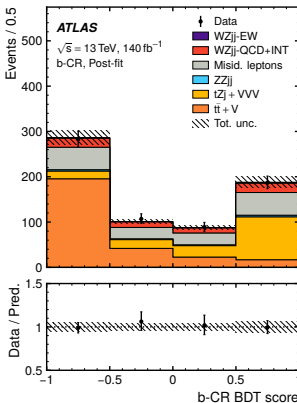
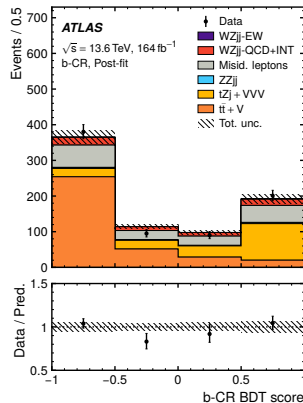
b-quark processes are vetoed in the SR, so requiring **one b-tagged jet** turns that veto into a control region for tZj and $t\bar{t} + V$

- Fitted variable: a dedicated **BDT**, tZj at +1 and $t\bar{t} + V$ at -1
- Two normalisation factors at once, per run and **uncorrelated**

- Primary vertex
- Secondary vertex (b)
- Tertiary vertex (c)



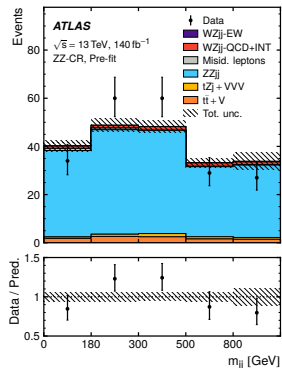
From [12]



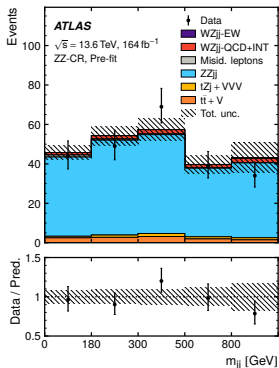
$\Rightarrow \mu_{t\bar{t}+V} = 0.96 \pm 0.12$ (Run 2) and 1.09 ± 0.14 (Run 3), $\mu_{tZj} = 1.18 \pm 0.22$ (Run 2) and 1.15 ± 0.22 (Run 3)

Run 2 alone previously gave 0.90 ± 0.13 and 1.23 ± 0.22 [6]

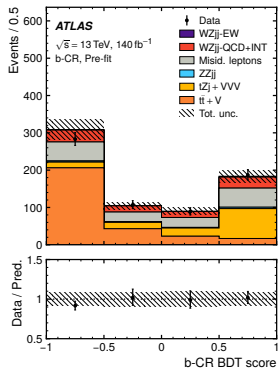
Control regions before the fit



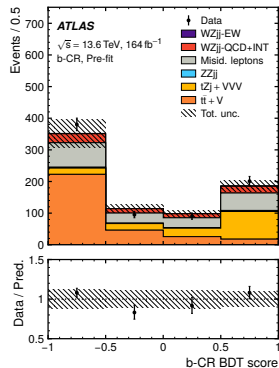
ZZ-CR, Run 2



ZZ-CR, Run 3



b-CR, Run 2



b-CR, Run 3

A Analysis details

B Fit and control regions

C Results

Polarisation fractions: the numbers

	Data $\pm$ total ($\pm$ statistical, $\pm$ systematic, $\pm$ luminosity)	MADGRAPH	SHERPA 3.0	MoCANLO NLO EW
f_{00}	$0.000^{+0.053}_{-0.000}$ ($^{+0.053}_{-0.000}$, < 0.001 , < 0.0001)	0.0902 ± 0.0005	0.087 ± 0.001	0.0902 ± 0.0005
f_{0X}	$0.007^{+0.094}_{-0.007}$ ($^{+0.093}_{-0.000}$, $^{+0.009}_{-0.007}$, $^{+0.0001}_{-0.0005}$)	0.2808 ± 0.0002	0.2793 ± 0.0009	0.2758 ± 0.0008
f_{X0}	$0.324^{+0.092}_{-0.085}$ ($^{+0.091}_{-0.084}$, $^{+0.017}_{-0.018}$, $^{+0.0015}_{-0.0014}$)	0.2758 ± 0.0003	0.274 ± 0.001	0.2745 ± 0.0008
$\mu_{WZjj-EW}$	1.06 ± 0.18 (± 0.15 , ± 0.11 , ± 0.01)	$0.94^{+0.05}_{-0.04}$	$1.00^{+0.2}_{-0.1}$	

Evidence for longitudinal Z bosons

f_{X0} : 4.0σ observed (2.9σ expected)
agrees with NLO EW

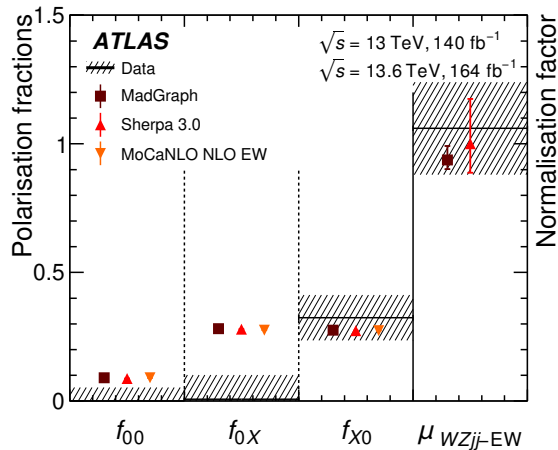
Upper limits at 95 % CL

$f_{0X} < 0.19$ (expected 0.46)
 $f_{00} < 0.12$ (expected 0.21)

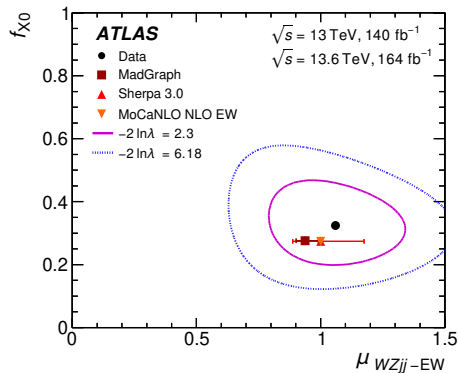
No W_0 seen

f_{0X} expected at 2.6σ
 $P(f_{0X} < 0.007 | \text{SM}) = 0.60 \%$,
corresponding to 2.5σ

Fraction against signal strength: the f_{X0} fit



Fractions and $\mu_{WZjj-EW}$ (from the f_{X0} fit) against MADGRAPH, SHERPA 3.0 and MoCANLO NLO EW



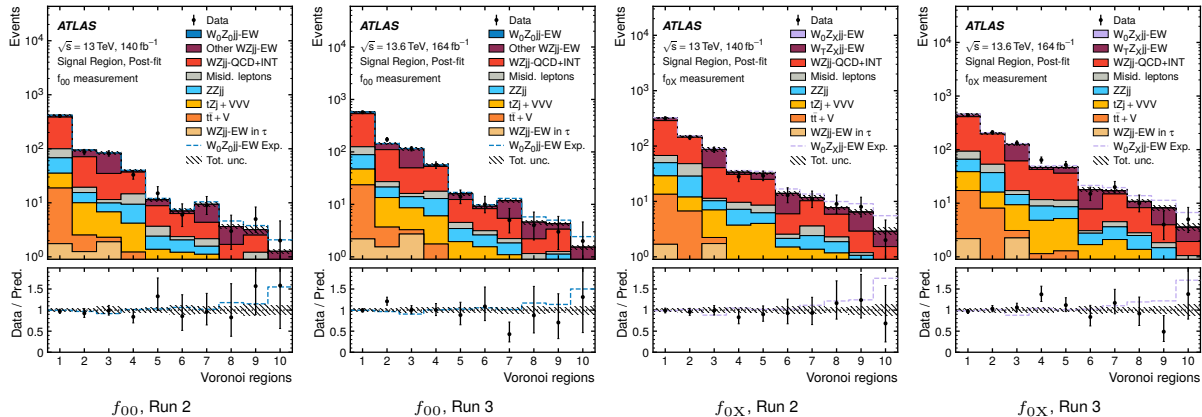
- New physics enhancing or suppressing a state would shift **both** f and $\mu_{WZjj-EW}$
- f_{X0} and $\mu_{WZjj-EW}$ consistent with the SM

	Measured [fb]	Predicted [fb]	
		SHERPA 3.0	MADGRAPH
$\sqrt{s} = 13 \text{ TeV (Run 2)}$	0.347 ± 0.079	0.335	0.314
$\sqrt{s} = 13.6 \text{ TeV (Run 3)}$	0.374 ± 0.094	$0.373^{+0.065}_{-0.041}$	0.345

- Fiducial, per lepton flavour, each run fitted alone, from the f_{X0} fit. Values from the f_{0X} and f_{00} fits agree within 10 %
- Predictions: sum of the four polarised states, MC statistical uncertainty below 0.1 % [12], SHERPA at 13.6 TeV with its PDF and scale uncertainties [11]
- Run 3 alone: 0.374 ± 0.077 (statistical) ± 0.053 (systematic) ± 0.009 (luminosity) fb, the **first WZjj-EW cross-section at 13.6 TeV**
- Signal strength relative to SHERPA 3.0: measured $\mu_{\text{WZjj-EW}} = 1.06 \pm 0.18$, predicted $0.94^{+0.05}_{-0.04}$ by MADGRAPH and $1.00^{+0.2}_{-0.1}$ by SHERPA 3.0
- 13 TeV measured before in [6]

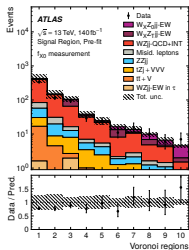
⇒ in agreement with the SM predictions [11, 12]

Post-fit distributions: the f_{00} and f_{0X} fits

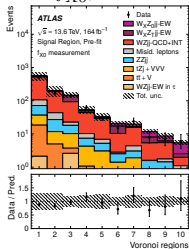


Dashed line: post-fit SM with the polarised WZ_{jj} -EW contributions at their pre-fit values

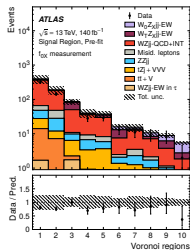
Signal region before the fit



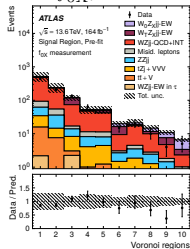
f_{X0} , Run 2



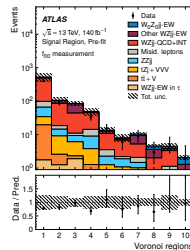
f_{X0} , Run 3



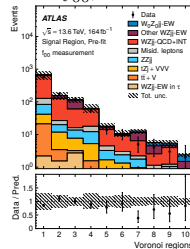
f_{0X} , Run 2



f_{0X} , Run 3

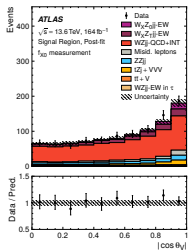
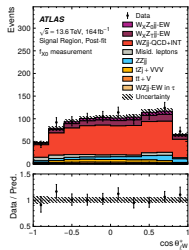
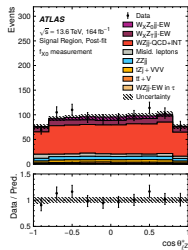
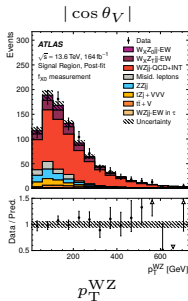
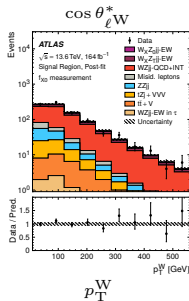
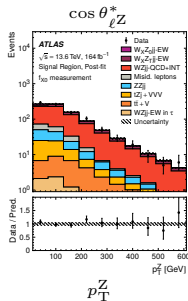


f_{00} , Run 2

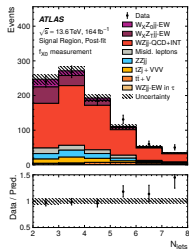


f_{00} , Run 3

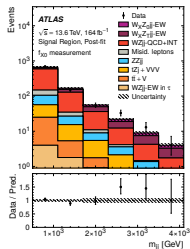
Run 3 input variables after the f_{X0} fit (1/2)



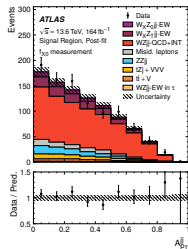
Run 3 input variables after the f_{X0} fit (2/2)



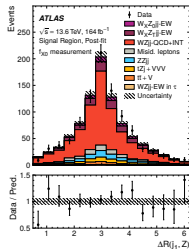
N_{jets}



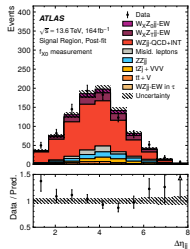
m_{jj}



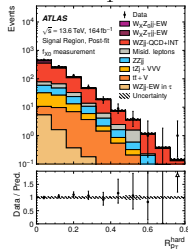
$A_{p_T}^{jj}$



$\Delta R(j_1, Z)$



$\Delta \eta_{jj}$



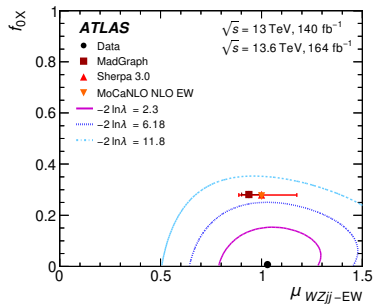
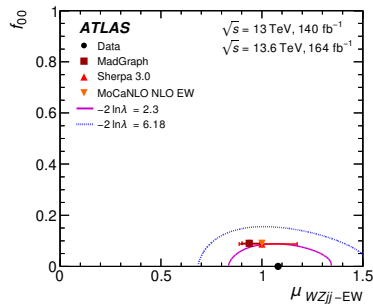
$R_{p_T}^{\text{hard}}$

	Combined	Individual fits	
		Run 2	Run 3
f_{00}	$0.000^{+0.053}_{-0.000}$	$0.056^{+0.102}_{-0.056}$	$0.000^{+0.041}_{-0.000}$
f_{0X}	$0.007^{+0.094}_{-0.007}$	$0.000^{+0.114}_{-0.000}$	$0.024^{+0.126}_{-0.024}$
f_{X0}	$0.324^{+0.092}_{-0.085}$	$0.411^{+0.148}_{-0.130}$	$0.270^{+0.137}_{-0.123}$
$\mu_{WZjj-EW}$	1.055 ± 0.181	1.037 ± 0.236	1.004 ± 0.252
$\sigma_{WZjj-EW}^{13 \text{ TeV}}$ [fb]	0.353 ± 0.061	0.347 ± 0.079	0.374 ± 0.094
$\sigma_{WZjj-EW}^{13.6 \text{ TeV}}$ [fb]	0.393 ± 0.068		

Upper limits and correlations

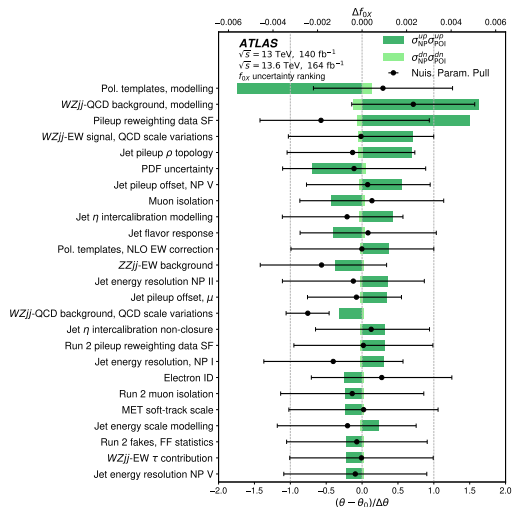
	f_{00}	f_{0X}
Expected	0.21	0.46
$\pm 1\sigma$	[0.15, 0.29]	[0.35, 0.58]
$\pm 2\sigma$	[0.08, 0.36]	[0.24, 0.70]
$\pm 3\sigma$	[0.02, 0.44]	[0.13, 0.81]
Observed	0.12	0.19

95 % CL upper limits

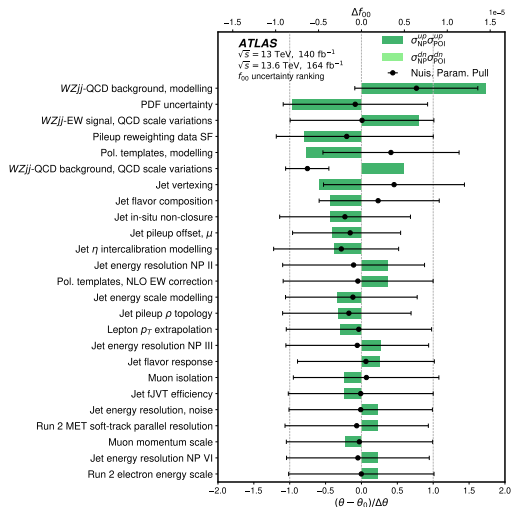


Contours at $-2 \ln \lambda = 2.3$ (full) and 6.18 (dashed), and 11.8 (dotted-dashed) for f_{0X} . MoCaNLO is computed for W^+Z only, its $\mu_{WZjj-EW}$ is set to 1

Impact of the nuisance parameters on f_{0X} and f_{00}



f_{0X}



f_{00}

f_{X0} in the talk [Uncertainties](#) [11]

Navigation shortcuts

① Motivation

② Analysis strategy

③ Results

A Analysis details

B Fit and control regions

C Results