Multiboson production and polarisation measurements with the ATLAS detector

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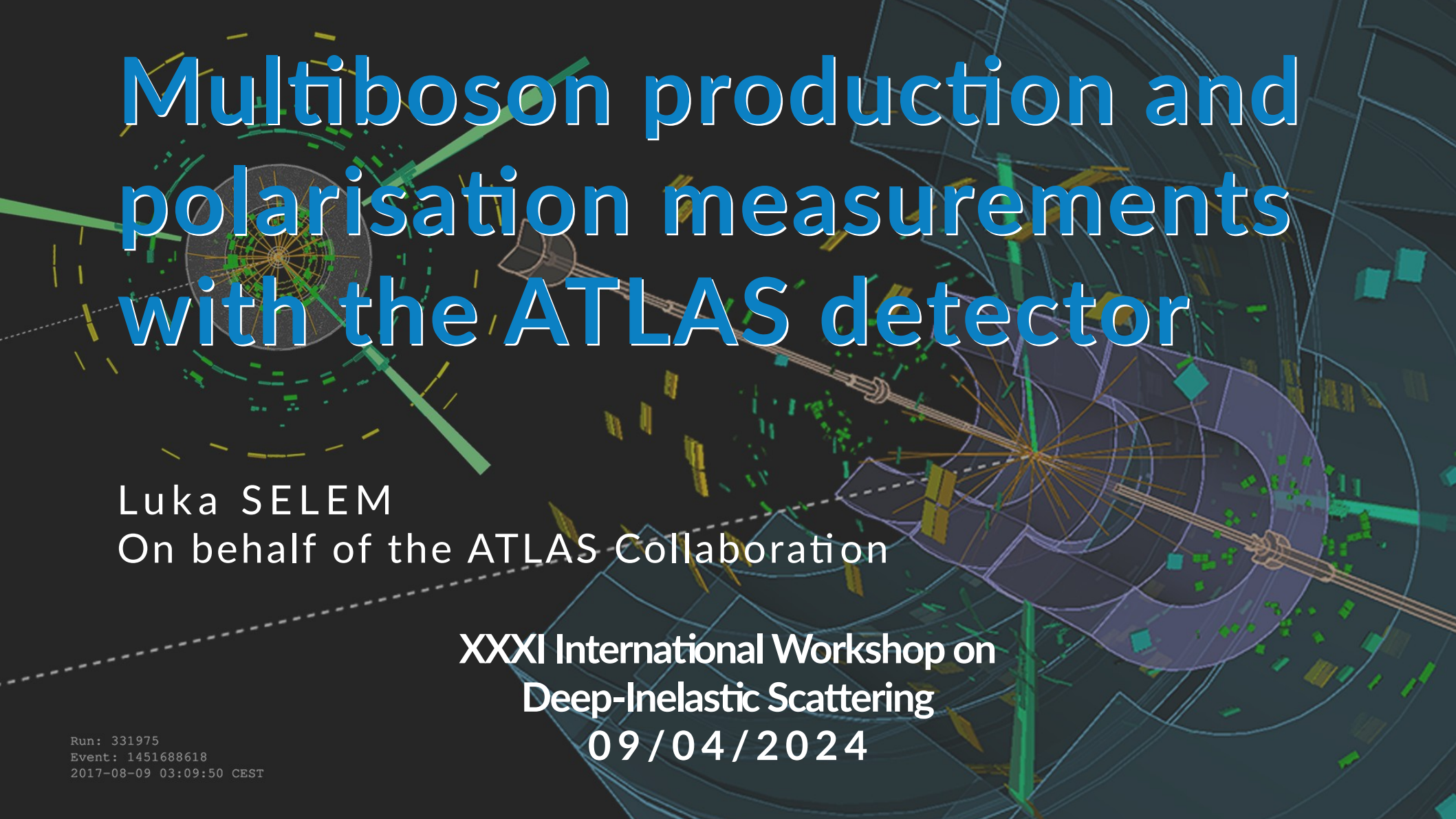
On behalf of the ATLAS Collaboration

XXXI International Workshop on
Deep-Inelastic Scattering
09/04/2024

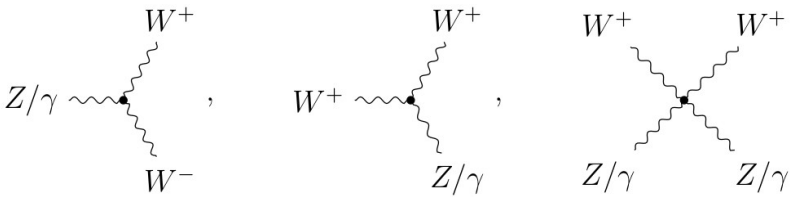


Motivation for multiboson measurements

Triple and quadruple gauge couplings

– Probe the **non-abelian structure** of the electroweak sector

➔ search for **deviations**



Longitudinal polarisation

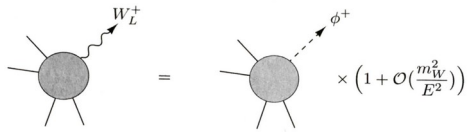
– First step toward **longitudinal VBS**

– Sensitive to **new physics** ?

➔Goldstone equivalence theorem

Goldstone equivalence theorem

"At high energy, longitudinal vector bosons are analogous to goldstone bosons"



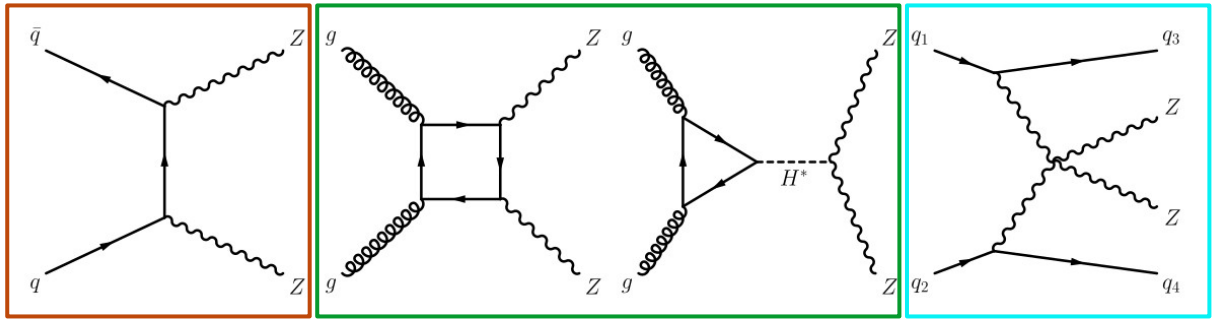
Diboson results

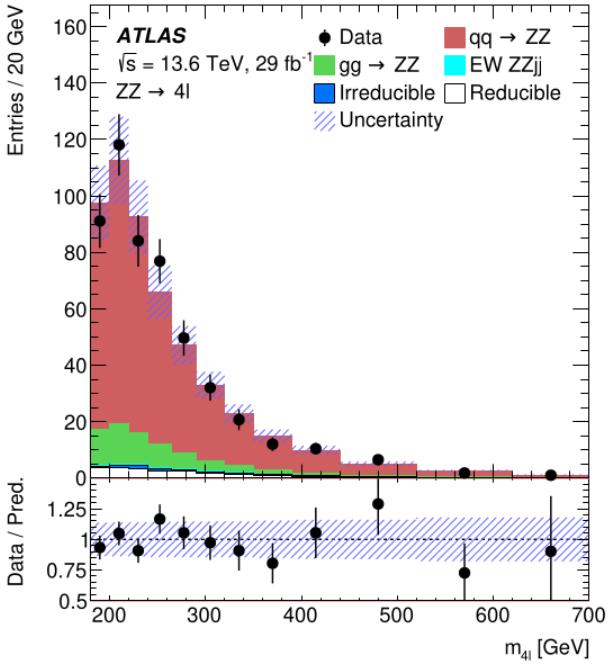
ZZ→ 4l at 13.6 TeV arXiv:2311.09715

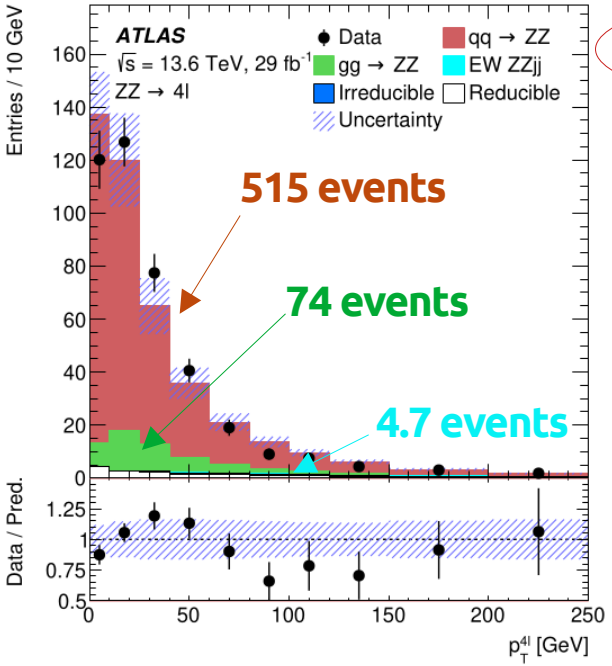
ZZ polarisation arXiv:2310.04350

WZ polarisation at high pT arXiv:2402.16365

ZZ → 4 lepton with Run 3 data arXiv:2311.09715







ZZ→ 4l decay channel

➔First **Run 3** measurement

Four-lepton signature	≥ 2 SFOC pairs
Lepton kinematics	$p_T > 27/10$ GeV
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.05$
Low-mass $\ell^+\ell^-$ veto	$m_{ij} > 5$ GeV
Z mass window	$66 < m_{\ell\ell,1}, m_{\ell\ell,2} < 116$ GeV
ZZ on-shell	$m_{4l} > 180$ GeV

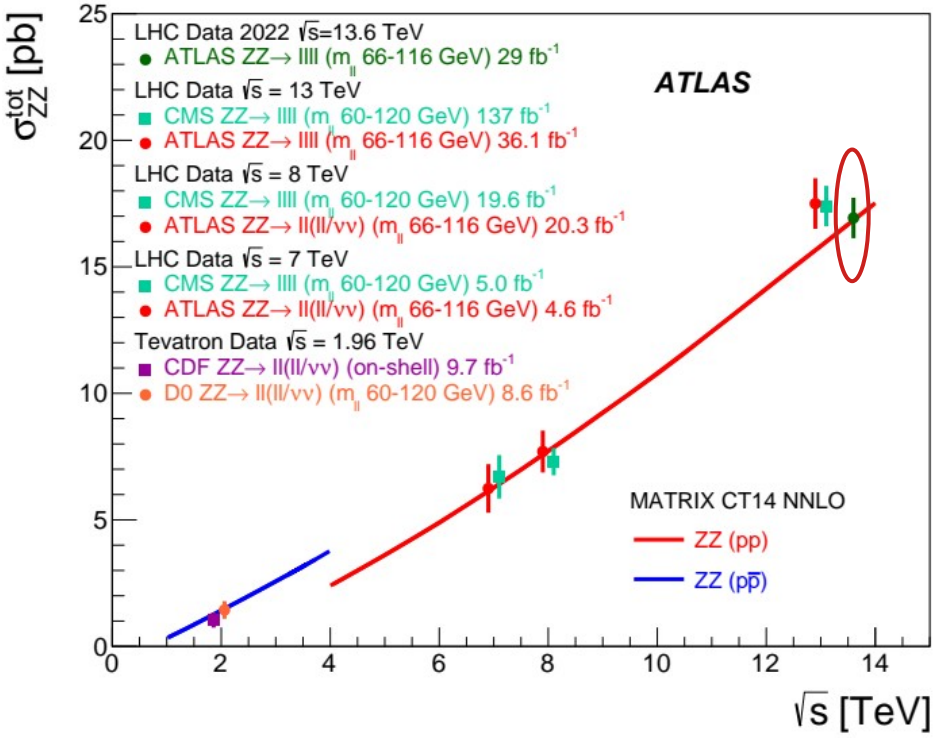
Backgrounds :

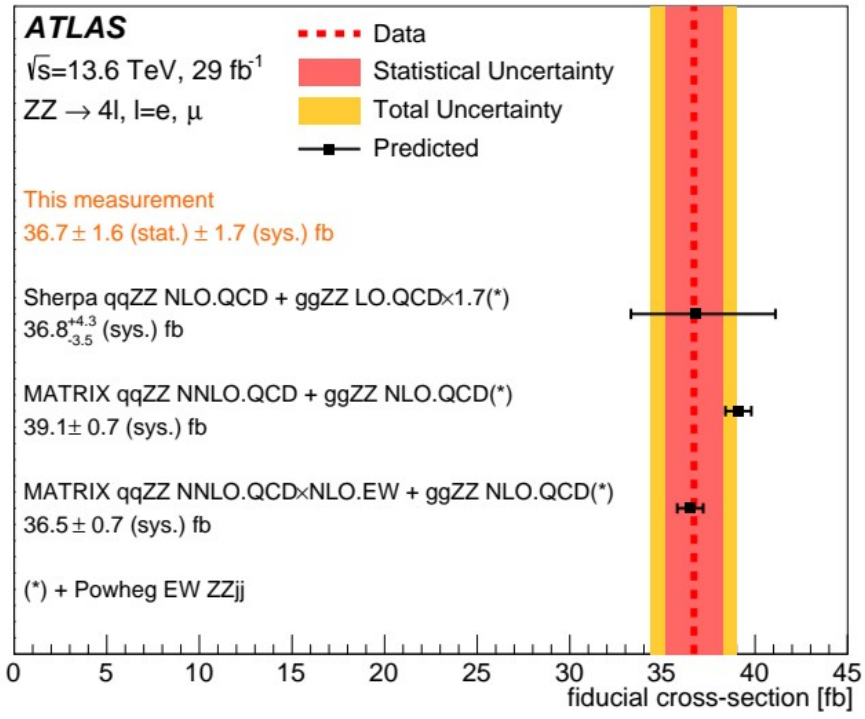
- **Irreducible** : triboson and ttZ
  - ➔ ~8 events
- **Reducible** : Z+jets, WZ, tt
  - ➔ Data driven Fake Factor method
  - ➔ ~25 events

ZZ inclusive cross section at 13.6 TeV

First measurement at **13.6 TeV** for this process

- Year 2022 : **29 fb-1**
- **6.5 %** precision, statistically dominated

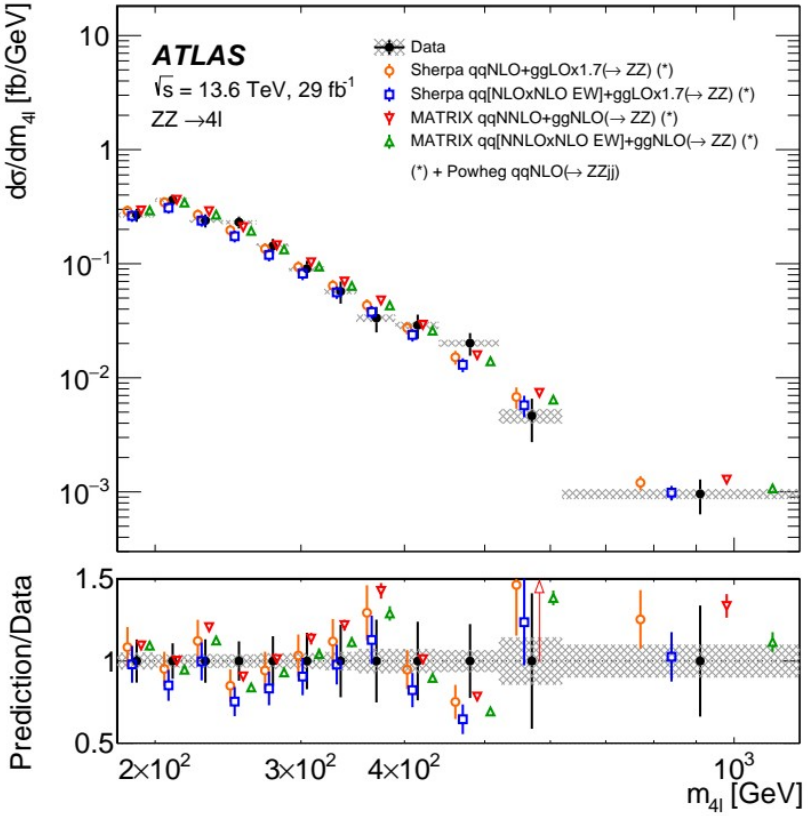


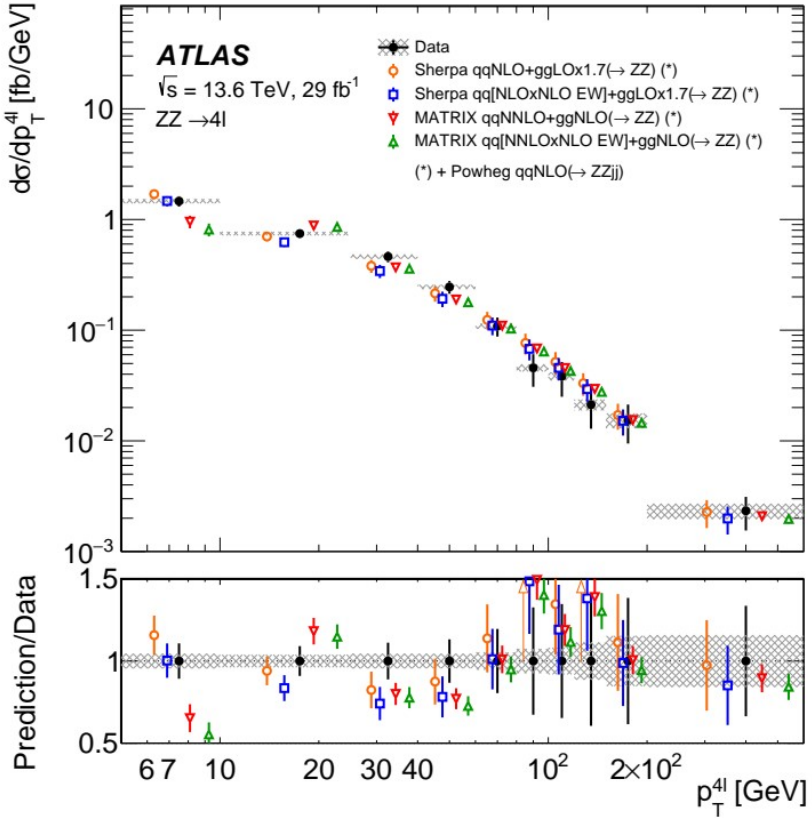


ZZ differential cross sections at 13.6 TeV

Iterative bayesian unfolding for m_{4l} and p_T^{4l}

➔ Good agreement in most of the bins





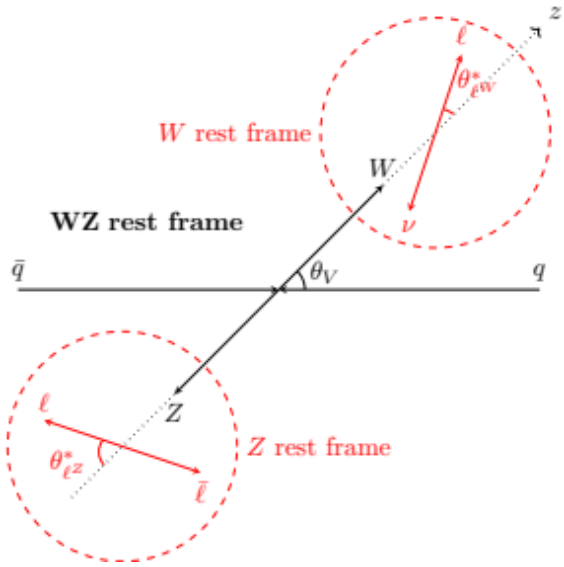
Ingredients for polarisation measurements

First joint-polarisation measurement : inclusive WZ arXiv:2211.09435 (2022)

- Experimental compromise between **signature** and **event yield**
- Set the general methodology: fit on data with polarisation templates

Frame dependence of polarisation:

➔ Natural choice is diboson rest frame



Discriminating variable:

- Extract most polarisations as possible : Model independence !
- Low statistics !

Polarised templates

- Representative of higher order corrections ?
- Modelling uncertainty
- Interference term ?

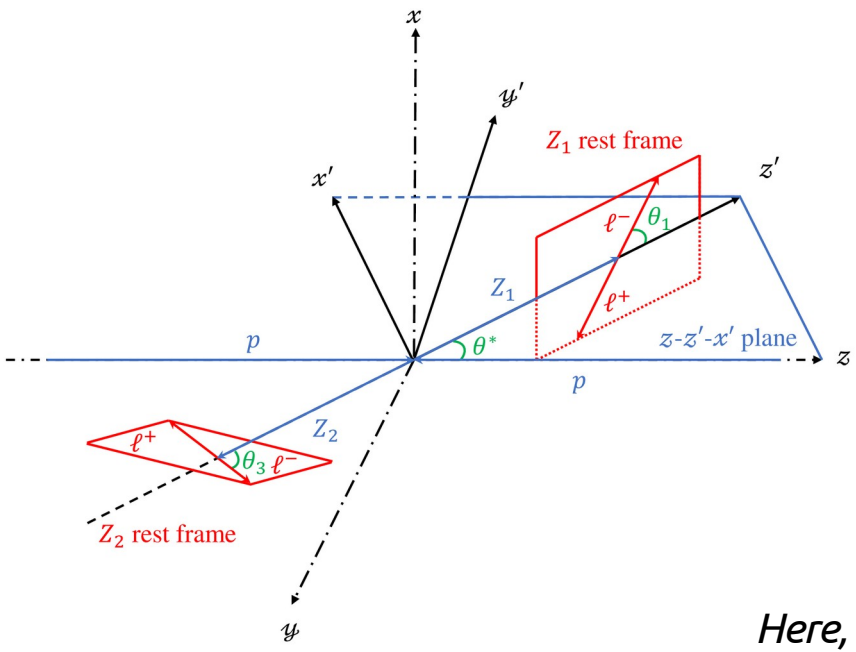
ZZ Run 2 polarisation arXiv:2310.04350

Same ZZ→ 4l event selection *(+ tighter Z mass window $|m_{ll} - m_Z| \leq 10$ GeV)*

➔ **Fully reconstructed, lower event yield**

In **ZZ rest frame**

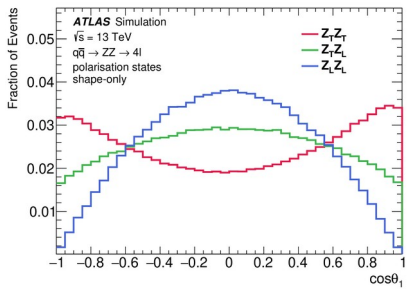
➔ Joint-polarisation pseudo-cross sections for Z_LZ_L, Z_LZ_T, Z_TZ_T

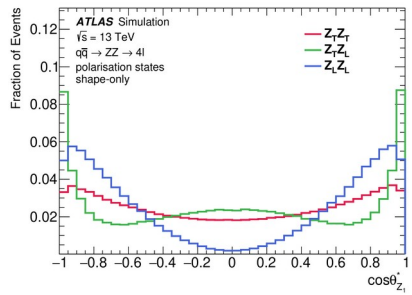


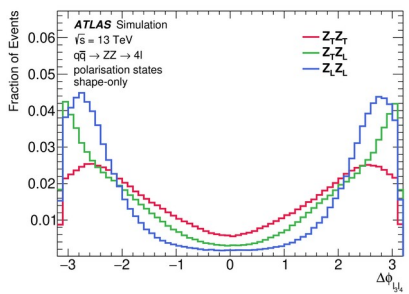
BDT variables

- $\cos\theta_1$
- $\cos\theta_3$
- $\cos\theta^*_{Z1}$
- $\Delta\varphi_{l1l2}$
- $\Delta\varphi_{l3l4}$

Discriminating variable:
BDT trained for LL against LT & TT







Here, "L" means "longitudinal"

Polarisation templates

Polarised Templates:

- MadGraph LO +0,1j **polarised** for qq→ ZZ and ZZ VBS
- Sherpa NLO **inclusive** for gg → ZZ

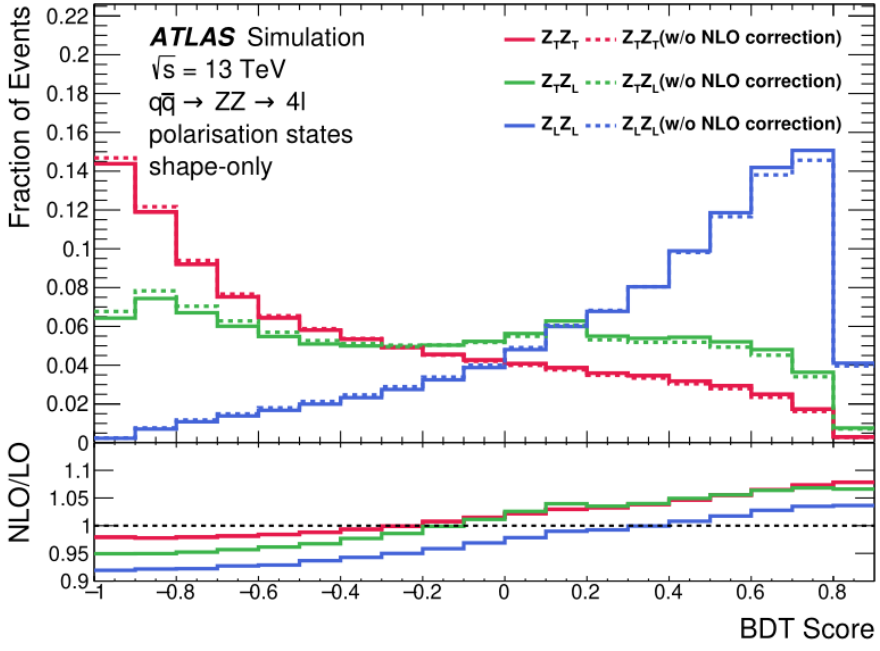
Reweighting *(except for ZZ VBS)*

- 1D fixed order **polarised** reweighting **NLO QCD+EW** along **$\cos\theta_1$**
- **Interference term** reweighting inclusive qq → ZZ by `(Inclusive − Σ polarised)`
- 2D **inclusive** reweighting along **$\cos\theta^*_{Z1}$** and **$\Delta\varphi_{l1l2}$**

Modelling uncertainty

- 1D reweighting with **ΔY(Z1, Z2)**
- Remaining **inclusive non-closure** `Inclusive − (Σ polarised + Interference)`

Normalised : *LO vs NLO shape differences*

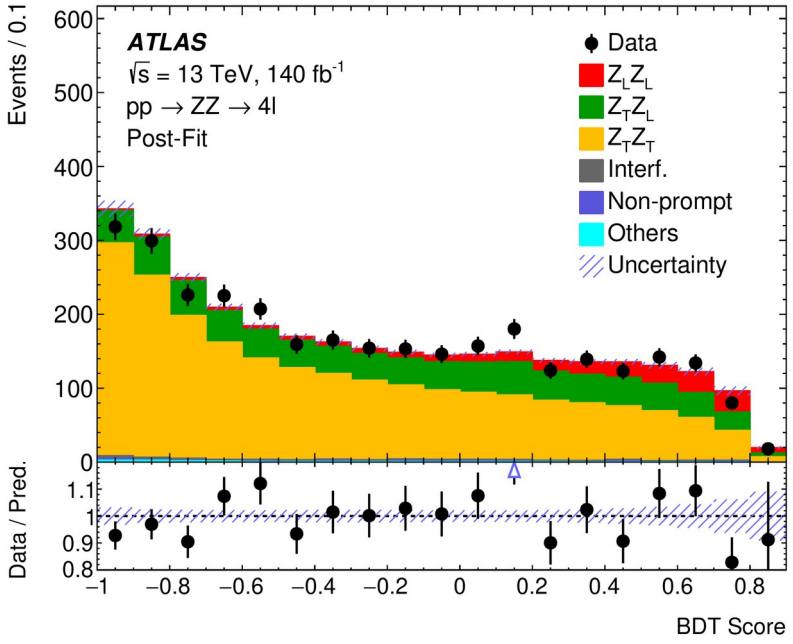


Evidence for joint-polarisation states

μ_{LL} = 1.15 ± 0.27(stat.) ± 0.11(syst.)

➔ Evidence for LL joint-polarisation at **4.3σ** against background only, **consistent with SM**

➔Main uncertainties from **statistical power**, **interferences** and **modelling**



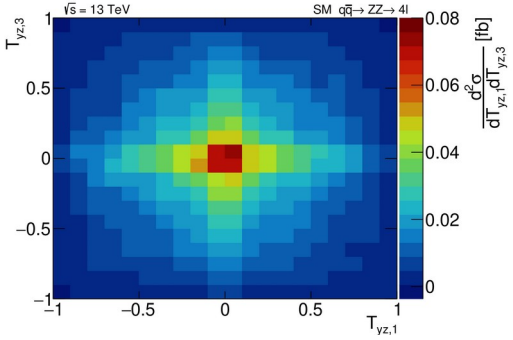
Contribution	Relative uncertainty [%]
Total	24
Data statistical uncertainty	23
Total systematic uncertainty	8.8
MC statistical uncertainty	1.7
Theoretical systematic uncertainties	
$q\bar{q} \to ZZ$ interference modelling	6.9
NLO reweighting observable choice for $q\bar{q} \to ZZ$	3.7
PDF, α_s and parton shower for $q\bar{q} \to ZZ$	2.2
NLO reweighting non-closure	1.0
QCD scale for $q\bar{q} \to ZZ$	0.2
NLO EW corrections for $q\bar{q} \to ZZ$	0.2
$gg \to ZZ$ modelling	1.4
Experimental systematic uncertainties	
Luminosity	0.8
Muons	0.6
Electrons	0.4
Non-prompt background	0.3
Pile-up reweighting	0.3
Triboson and $t\bar{t}Z$ normalisations	0.1

ZZ CP properties

Maximize sensitivity to CP-odd aNTGC

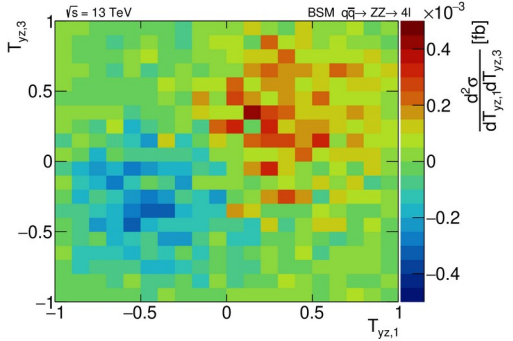
➔ **Optimal Observable** from $T_{yz} = \sin\varphi \cos\theta$ plane

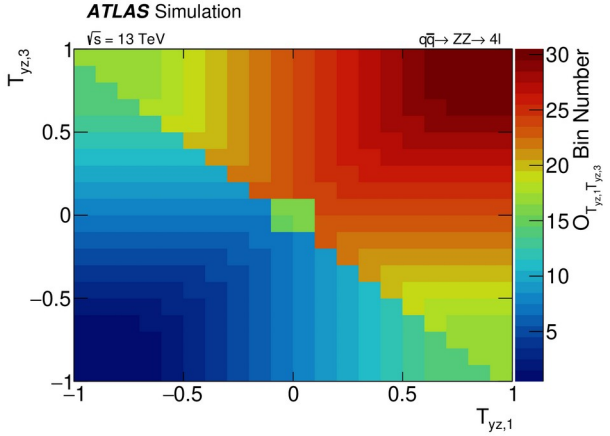
SM



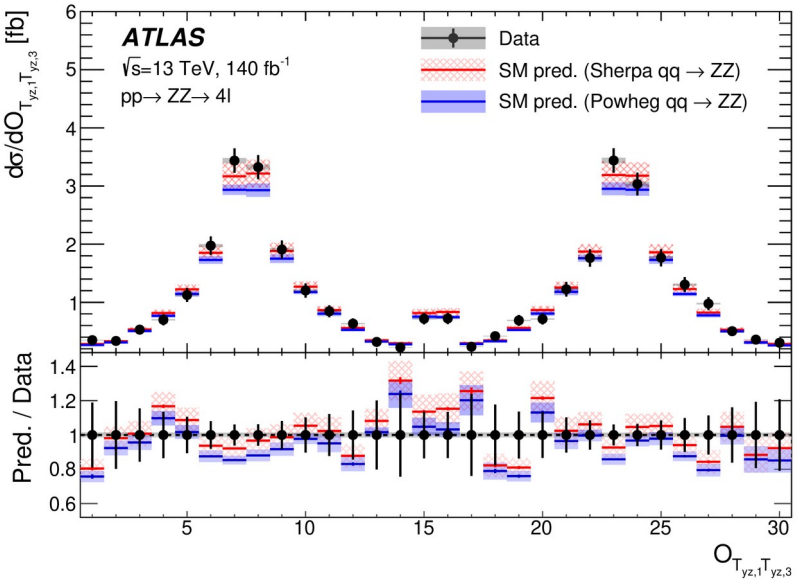
vs

aNTGC





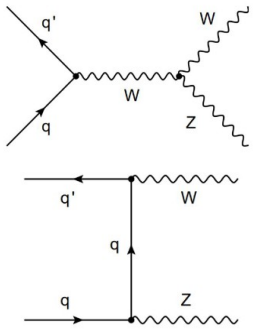
Unfolded result



Constraints on CP-odd aNTGC parameters

aNTGC parameter	Interference only		Full	
	Expected	Observed	Expected	Observed
f_Z^4	$[-0.16, 0.16]$	$[-0.12, 0.20]$	$[-0.013, 0.012]$	$[-0.012, 0.012]$
f_γ^4	$[-0.30, 0.30]$	$[-0.34, 0.28]$	$[-0.015, 0.015]$	$[-0.015, 0.015]$

WZ features in specific phase spaces arXiv:2402.16365



Signal regions			
	Radiation Amplitude Zero	00-enhanced region 1	00-enriched region 2
Pass inclusive WZ event selection	✓	✓	✓
Transverse momentum of the Z boson (p_T^Z)	-	[100, 200] GeV	> 200 GeV
Transverse momentum of the WZ system (p_T^{WZ})	< 20, 40, 70 GeV	< 70 GeV	

Here, "0" means "longitudinal"

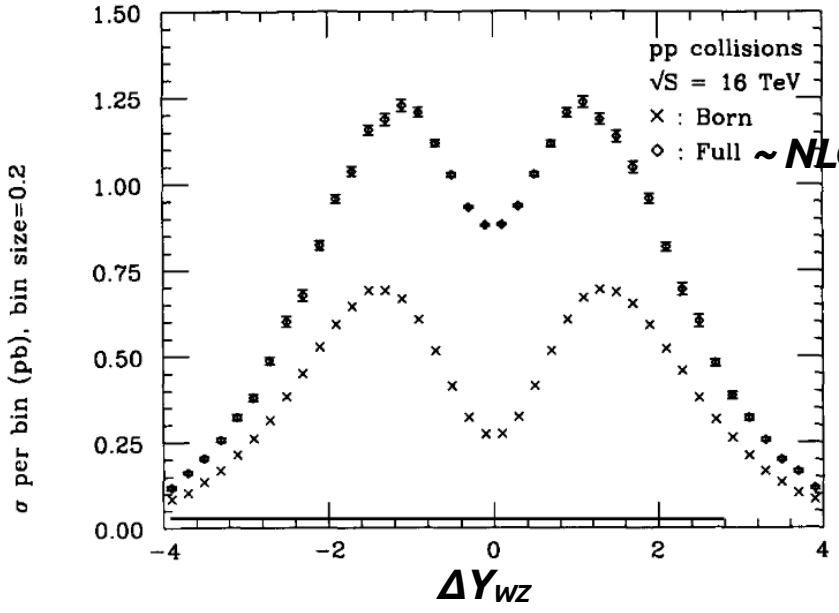
Extract polarisation in **00-enriched region**

- Probe polarisation fraction energy dependence

➔ Cut on $\mathbf{p_T^Z}$: f_{00} should increase

Radiation amplitude zero effect

- Consequence of gauge structure
- Already seen in Wγ events
- Effect diluted by NLO corrections : **cut on P_T^{WZ}**



~ NLO QCD

[S. Frixione et al.]

WZ polarisation energy dependence

Discriminating variable

- BDT **00** against **0T+T0** and **TT**

➔ **3 templates** ≠ inclusive measurement

Polarised Templates:

- MadGraph LO +0,1j **polarised**

Reweighting

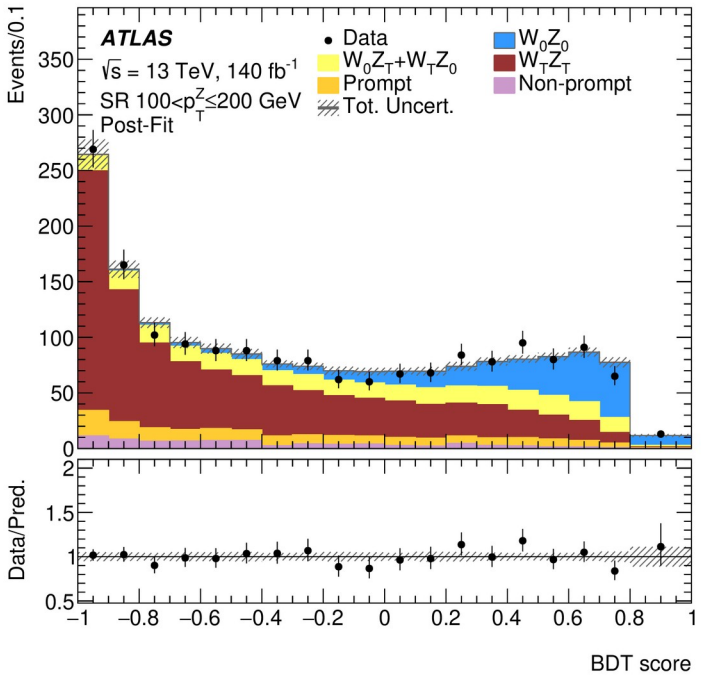
- Inclusive **NLO QCD** rescaling
- **Data scale factor** in the **inclusive region**
- **Interferences are negligible**

Modelling uncertainty

- Compared to polarised NLO QCD+EW predictions
- NLO QCD+EW vs NLO QCD x EW

Training variable	Definition
$\Delta Y(\ell_W Z)$	Rapidity difference between the W lepton and Z boson
p_T^{WZ}	Transverse momentum of the WZ system
$p_T(\ell_W)$	Transverse momentum of the W lepton
$p_T(\ell_2^Z)$	Transverse momentum of the subleading Z lepton
E_T^{miss}	Missing transverse momentum
$\cos\theta_{\ell_Z}$	Cosine of the angle of the Z lepton in the WZ rest frame w.r.t the z-axis
$\cos\theta_{\ell_W}$	Cosine of the angle of the W lepton in the WZ rest frame w.r.t. the z-axis

BDT variables



WZ polarisation energy dependence

	Measurement		Prediction		
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV		$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
f_{00}	$0.19 \pm^{0.03}_{0.03}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	$0.13 \pm^{0.09}_{0.08}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	f_{00}	0.152 ± 0.006	0.234 ± 0.007
f_{0T+T0}	$0.18 \pm^{0.07}_{0.08}$ (stat) $\pm^{0.05}_{0.06}$ (syst)	$0.23 \pm^{0.17}_{0.18}$ (stat) $\pm^{0.06}_{0.10}$ (syst)	f_{0T}	0.120 ± 0.002	0.062 ± 0.002
f_{TT}	$0.63 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.04}_{0.04}$ (syst)	$0.64 \pm^{0.12}_{0.12}$ (stat) $\pm^{0.06}_{0.06}$ (syst)	f_{T0}	0.109 ± 0.001	0.058 ± 0.001
f_{00} obs (exp) sig.	5.2 (4.3) σ	1.6 (2.5) σ	f_{TT}	0.619 ± 0.007	0.646 ± 0.008

Enriched in 00 joint-polarisation :

- **0.19** and **0.13** to be compared to **0.067** in inclusive phase space
- **Consistent with SM**

Uncertainties: 21.7% and **66.9%** (f_{00})

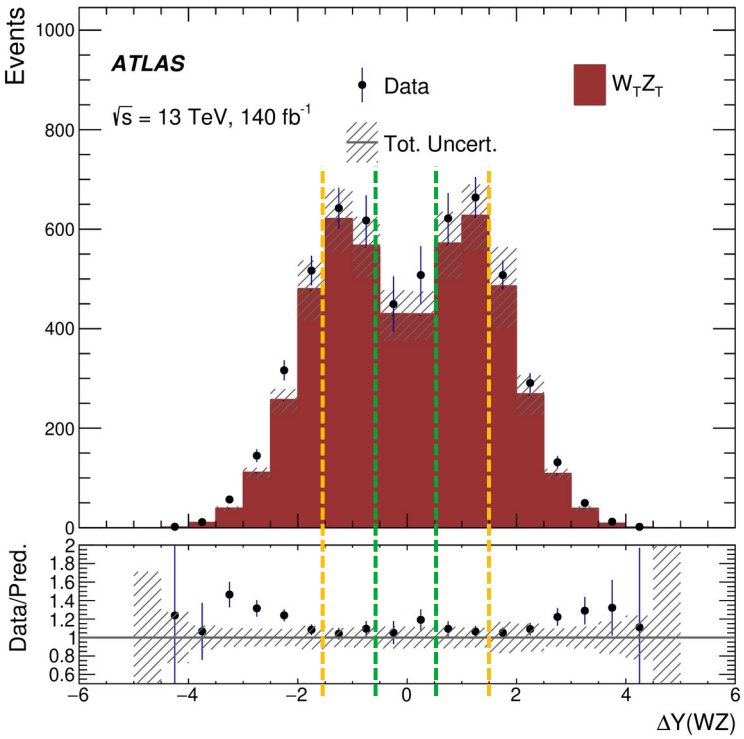
- Statistically dominated
- Sub leading uncertainties from QCD higher order effects

Source	Impact on f_{00} [%]	
Experimental	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
Luminosity	0.1	0.2
Electron calibration	1.0	0.9
Muon calibration	1.1	1.3
Jet energy scale and resolution	5.9	9.0
E_T^{miss} scale and resolution	1.0	0.6
Flavor-tagging inefficiency	0.1	0.2
Pileup modelling	1.6	1.1
Non-prompt background estimation	5.8	0.8
Modelling		
Background, other	1.4	1.6
Model statistical	2.5	5.6
NLO QCD effects	6.8	8.2
NLO EW effects	1.1	3.3
Effect of additive vs multiplicative QCD+EW combination	1.3	3.8
Interference impact	1.4	0.7
PDF, Scales, and shower settings	3.5	9.2
Experimental and modelling	12.1	17.7
Data statistical	18.0	64.5
Total	21.7	66.9

Radiation Amplitude Zero effect

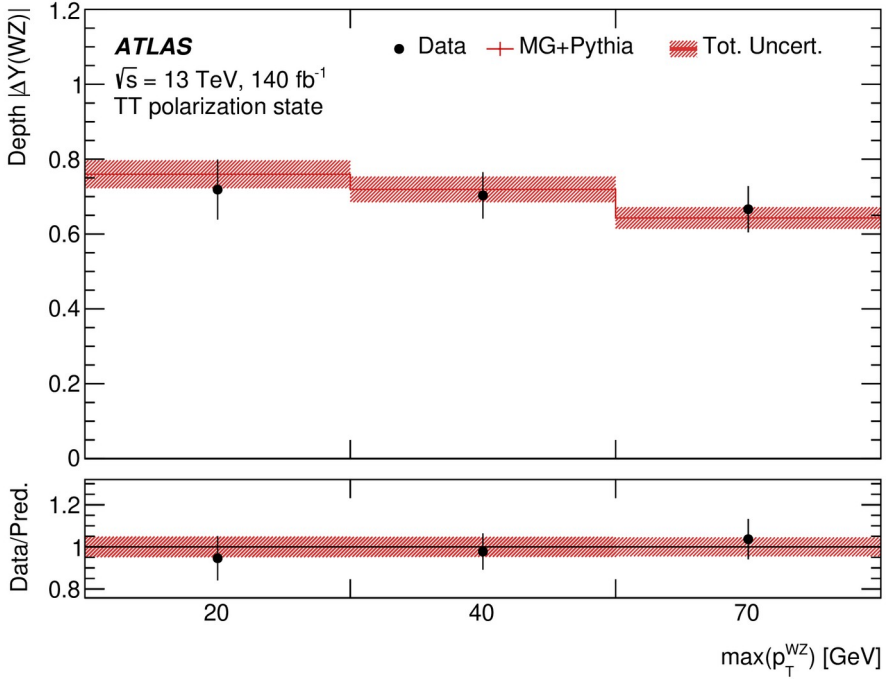
Subtracting background and 0T, T0 and 00 contributions,

For $p_T^{WZ} < 20$ GeV



*Depth of the **unfolded** ΔY_{WZ} dip*

$D = 1 - 2 \times N_{central}/N_{sides}$



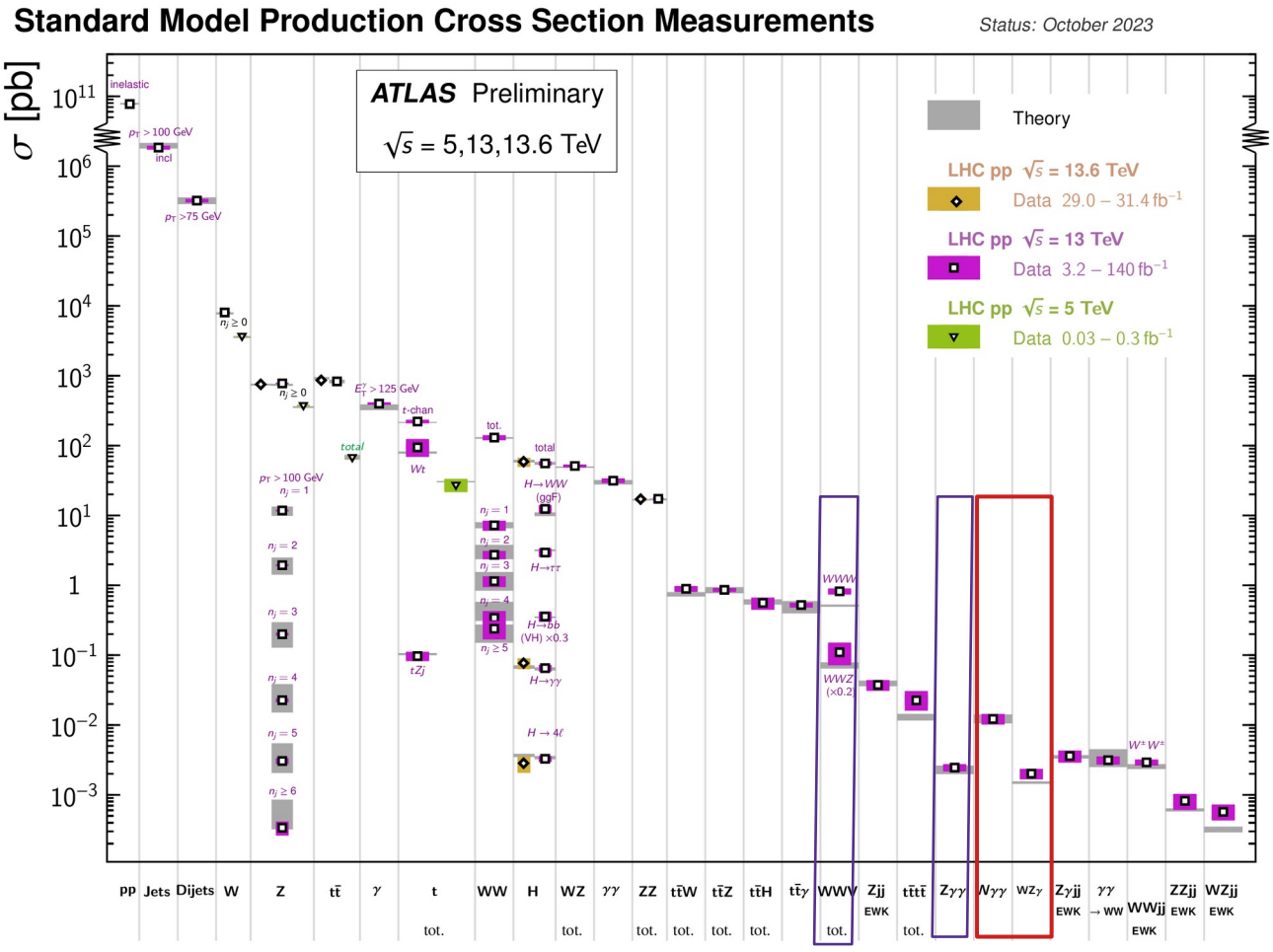
Good agreement with SM

Triboson results

WZy arXiv:2305.16994

Wyy arXiv:2308.03041

Previous triboson measurements



Since Run 1 :

- **Zγγ** (ATLAS and CMS)
- γγγ (ATLAS, Run 1 only)

Run 2:

- VVV (CMS)
- WWγ (CMS)
- **WWW** (ATLAS)

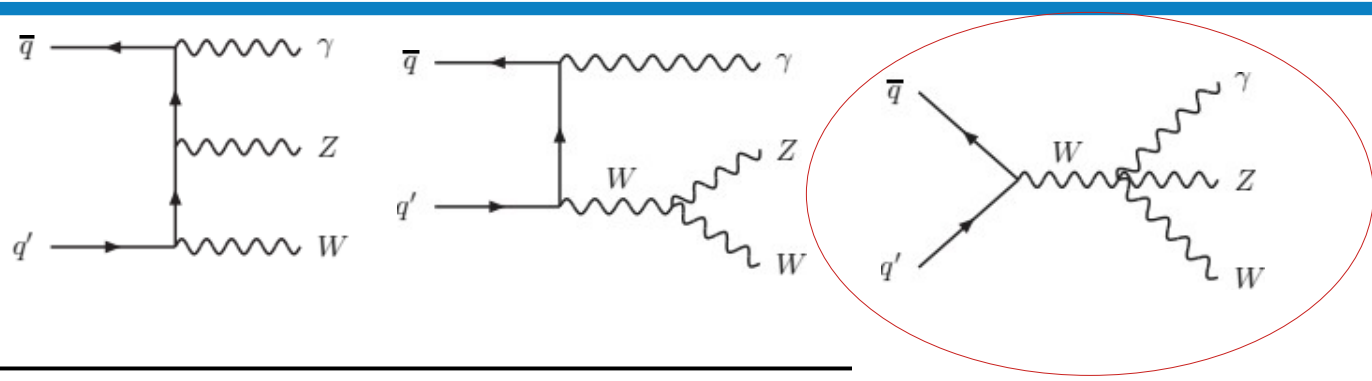
Here:

- **WZγ** : arXiv:2305.16994
- **Wγγ** : arXiv:2308.03041

The WZγ process [arXiv:2305.16994]

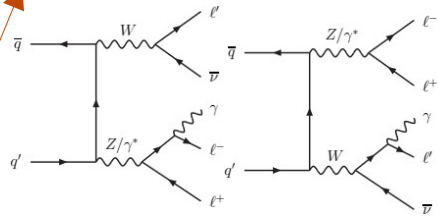
Targeting the WWZγ quartic gauge coupling

➔ Signature:
2 SFOC leptons
+ 1 lepton + MET
+ 1 photon



	SR definition	
*Reject ZZγ → **ZZγ CR***	Lepton veto	no additional leptons with $p_{\mathrm{T}}^{\ell_4} > 10\ GeV$
Identify one Z boson	Z-leptons assignment	smallest $\lvert m_{\ell\ell} - m_Z \rvert$
	ΔR	$\Delta R(\ell,\gamma) > 0.4, \quad \Delta R(\mu, e) > 0.2$
*Reject ZZ → **ZZ CR***	$ZZ(e \to \gamma)$ rejection	$\lvert m(e_W,\gamma) - m_Z \rvert > 10\ GeV$
Identify one W boson	Missing p_{T}	$E_{\mathrm{T}}^{\mathrm{miss}} > 20\ GeV$
	Z candidate mass	$m_{\ell\ell} > 81\,GeV$

Reject FSR



Non-prompt background : Zγ , WZ, ZZ, ttγ

➔ Data driven “Fake Factor” method

Irreducible background : ZZ, ZZγ

➔ Control regions

WZγ observation

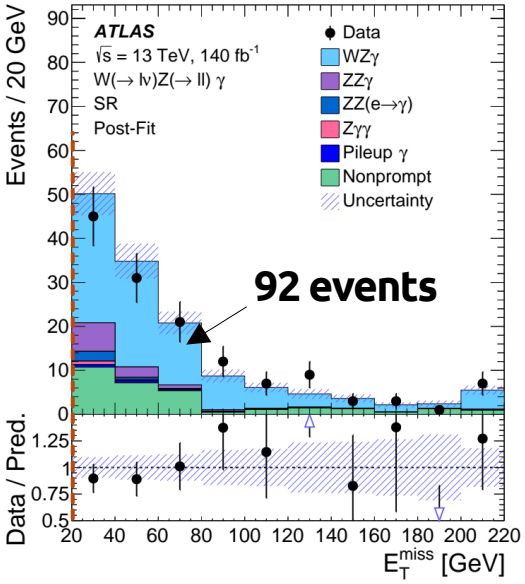
Three bin fit: SR, ZZ CR, ZZγ CR

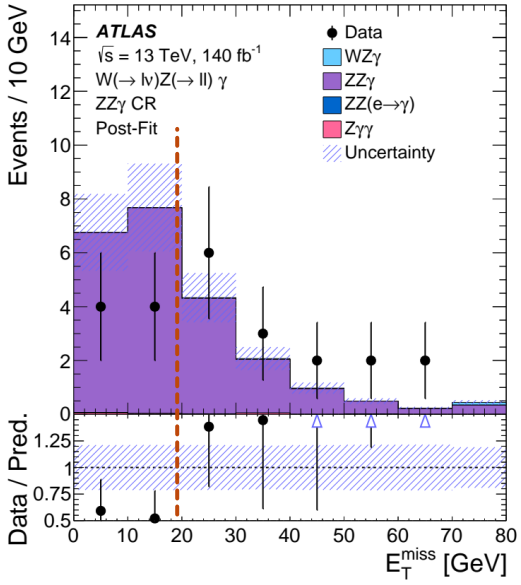
- WZγ observed with **6.3σ**
- Consistent with SM at **1.5σ**
- Statistically dominated **(15%)**

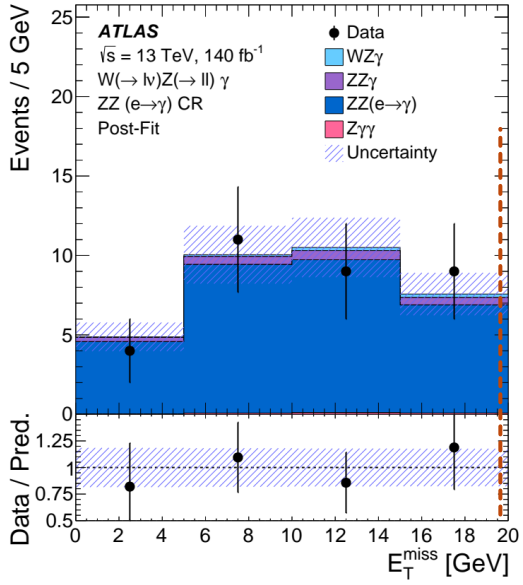
$\mu_{WZ\gamma} = 1.34 \pm 0.20\,(stat.) \pm 0.10\,(syst.) \pm 0.07\,(theory)$

$\mu_{ZZ\gamma} = 1.19 \pm 0.25$ $\mu_{ZZ} = 0.98 \pm 0.19$

$\sigma_{WZ\gamma}^{Fid} = 2.01 \pm 0.30\,(stat.) \pm 0.16\,(syst.)$

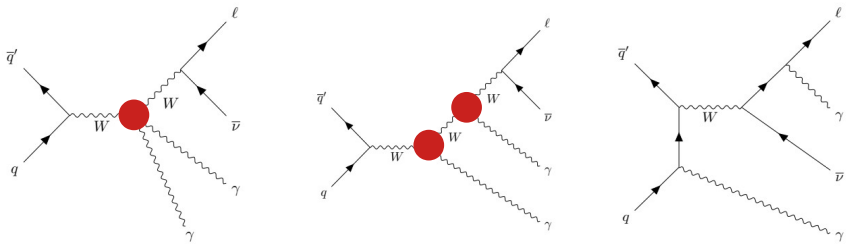




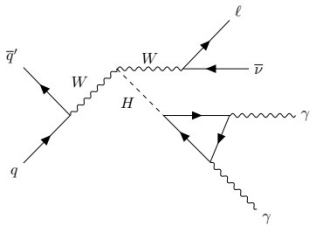


The Wγγ process [arXiv:2308.03041](https://arxiv.org/abs/2308.03041)

WWγγ and WWγ gauge coupling
+
Background for
W → WH



Treated as background

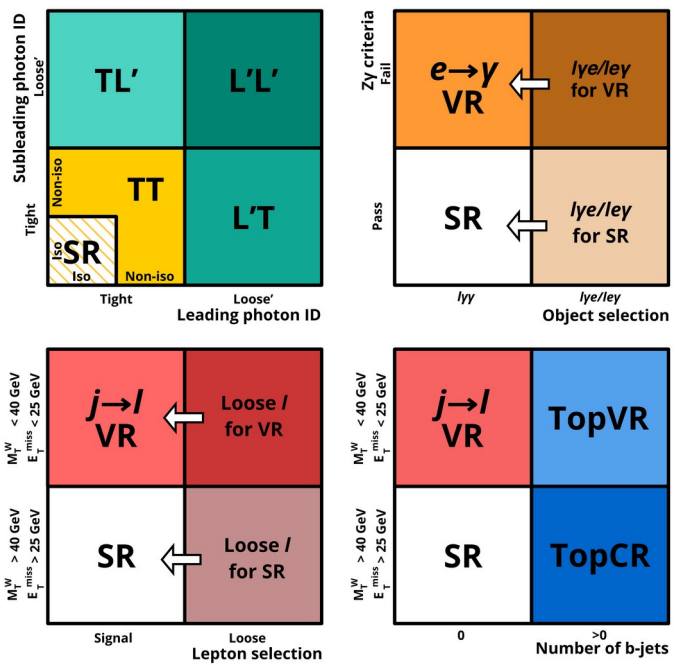


Event selection :

- **2** isolated **γ**, **1** isolated **e** or **μ**, **MET** > 25 GeV, m_T^W > 40 GeV
- **Multi boson veto** : 2nd lepton veto
- **Zγ veto** : $m_{l\gamma}$, $m_{l\gamma\gamma} \notin [82 ; 100]$ GeV ; $p_T^{l\gamma\gamma} > 30$ GeV

Background : Main challenge

- Non-prompt **γ** or **e** : **j→ γ** , **e → γ** , **j → l**
- **Top CR**



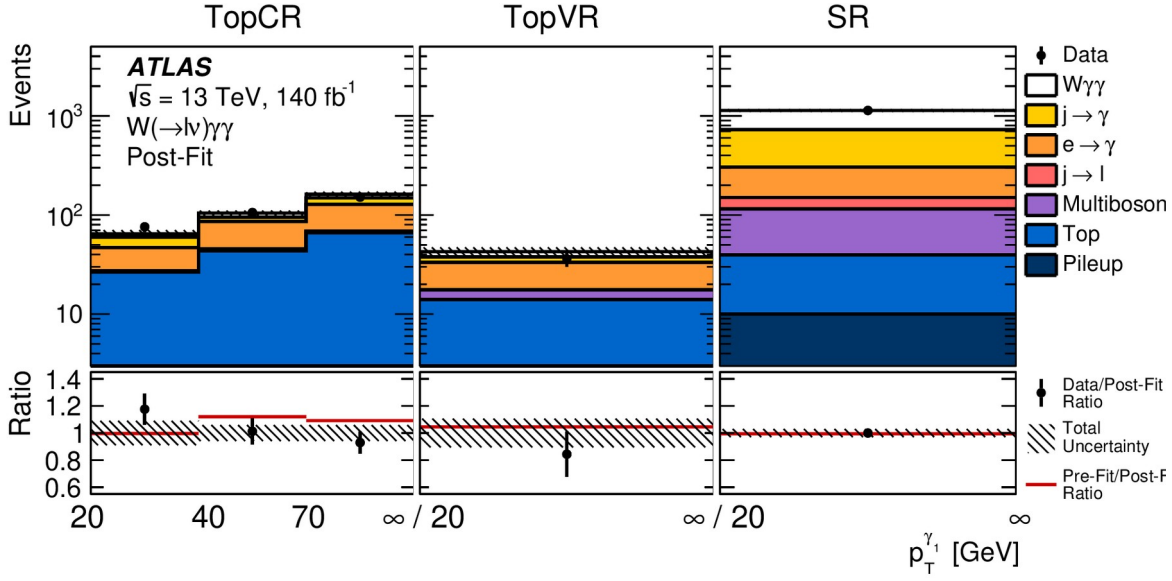
Wγγ template fit

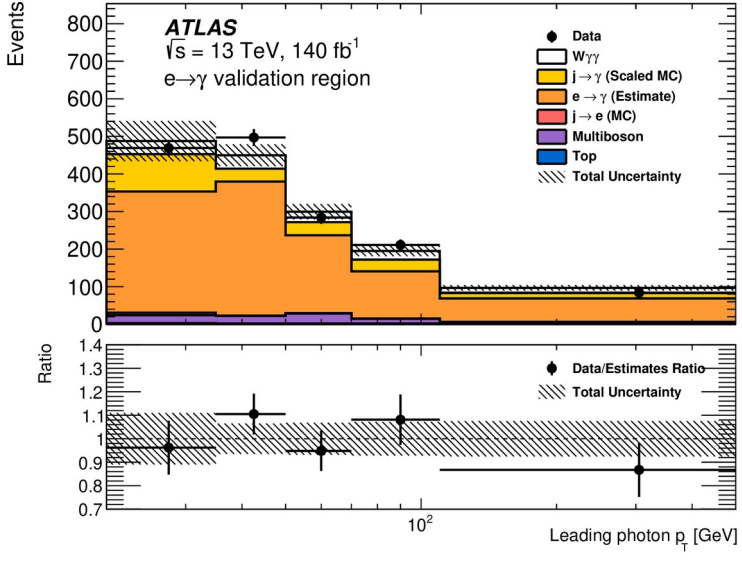
Template fit SR+ TopCR :

- Signal / background ~ **0.5**

➔ **Wγγ** observed with **5.6 σ**

Source	SR	TopCR
$W\gamma\gamma$	410 ± 60	28 ± 5
Non-prompt $j \to \gamma$	420 ± 50	42 ± 20
Misidentified $e \to \gamma$	155 ± 11	120 ± 9
Multiboson ($WH(\gamma\gamma)$, $WW\gamma$, $Z\gamma\gamma$)	76 ± 13	5.2 ± 1.7
Non-prompt $j \to \ell$	35 ± 10	–
Top ($tt\gamma$, $tW\gamma$, $tq\gamma$)	30 ± 7	136 ± 32
Pileup	10 ± 5	–
Total	$1\,136 \pm 34$	332 ± 18
Data	1 136	333



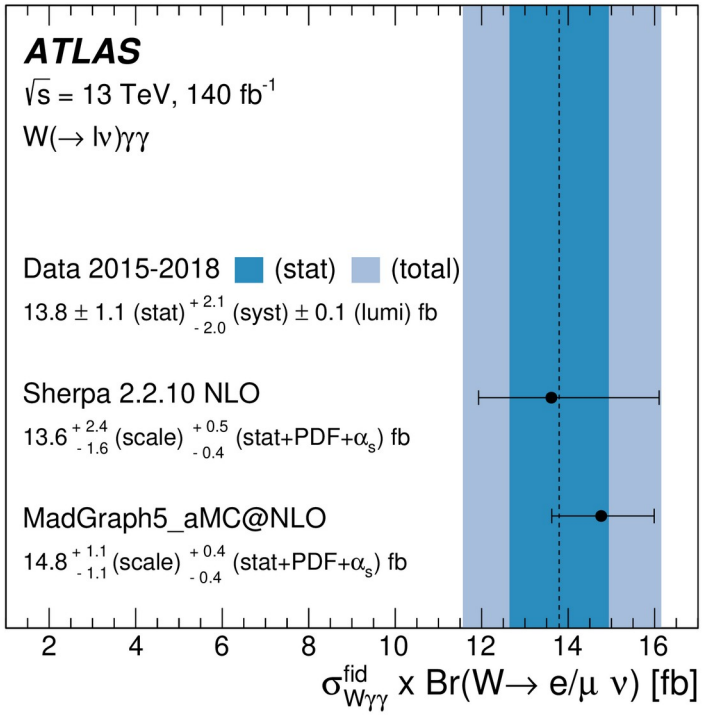


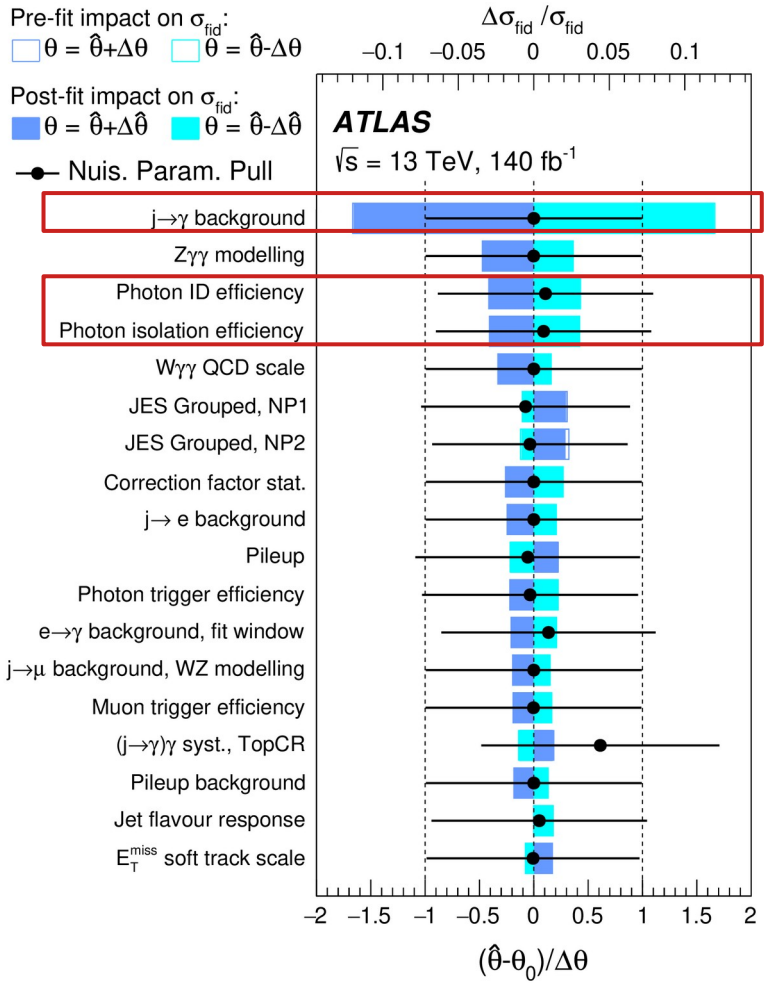
Wγγ inclusive cross section

No deviation from Standard Model

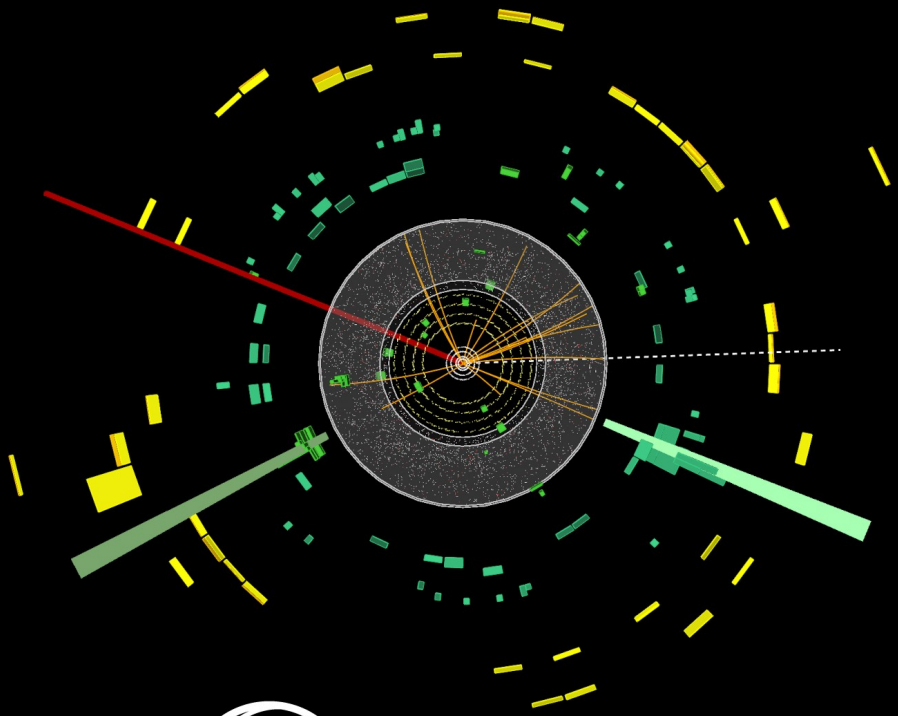
Systematic uncertainty **dominate**

– Main = Prompt photon identification : j→ y





Thank you for your attention



ATLAS EXPERIMENT

Extra

Inclusive WZ joint-polarisation

First joint-polarisation measurement : *arXiv:2211.09435*

Discriminating variable with a DNN score

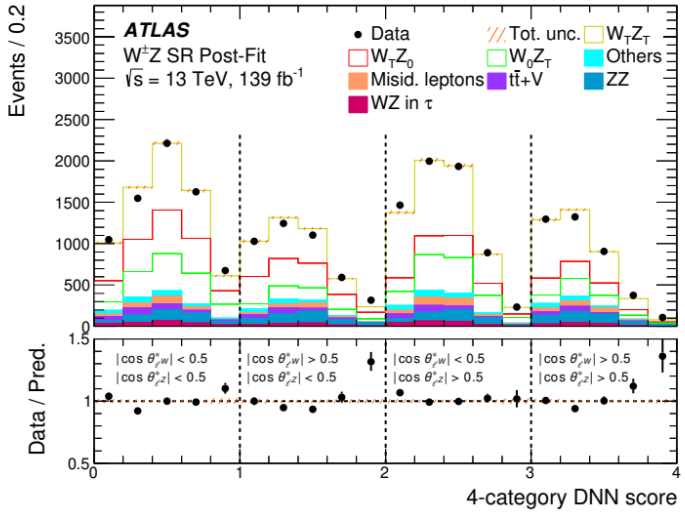
Extract 4 joint polarisation 00, 0T, T0, TT

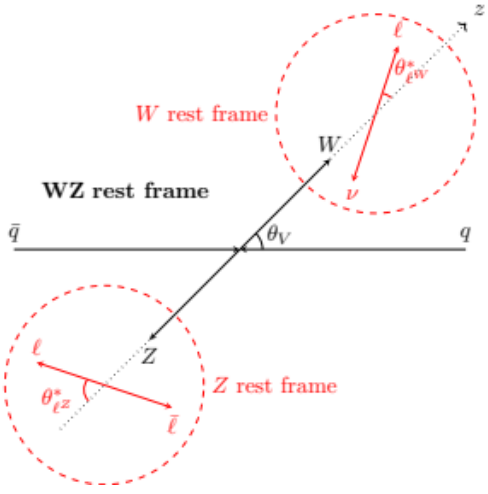
Templates at LO +0,1 jet polarised

Reweighted with DNN and parton level NLO QCD predictions

Modelling comparing both reweightings

Negligible interferences





	Data	POWHEG+PYTHIA	NLO QCD
		$W^{\pm}Z$	
f_{00}	0.067 ± 0.010	0.0590 ± 0.0009	0.058 ± 0.002
f_{0T}	0.110 ± 0.029	0.1515 ± 0.0017	0.159 ± 0.003
f_{T0}	0.179 ± 0.023	0.1465 ± 0.0017	0.149 ± 0.003
f_{TT}	0.644 ± 0.032	0.6431 ± 0.0021	0.628 ± 0.004

WZ event selection

Inclusive WZ event yield

	Signal Region	
	Pre-fit	Post-fit
WZ in τ	620 ± 60	630 ± 60
ZZ	1420 ± 120	1630 ± 50
$t\bar{t}+V$	870 ± 130	820 ± 120
Misid. leptons	1170 ± 230	1010 ± 220
Others	800 ± 90	780 ± 90
W_0Z_0	920 ± 40	1190 ± 160
W_0Z_T	2670 ± 50	1900 ± 500
W_TZ_0	2670 ± 60	3100 ± 400
W_TZ_T	10200 ± 230	10900 ± 600
Total MC	21400 ± 500	21950 ± 170
Data	—	21936

00-enriched event yield

Process	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
W_0Z_0	222 ± 5	47.6 ± 1.5
$W_0Z_T + W_TZ_0$	323 ± 12	23.7 ± 0.8
W_TZ_T	856 ± 31	124 ± 4
Prompt background	169 ± 18	24.1 ± 2.7
Non-prompt background	68 ± 29	2.8 ± 1.1
Total Expected	1640 ± 60	222 ± 8
Data	1740	236

Event selection

Signature: 3 leptons

Z Lepton pair

W lepton + MET

Inclusive WZ event selection	
Event cleaning	Reject LAr, Tile and SCT corrupted events and incomplete events
Primary vertex	Hard scattering vertex with at least two tracks
Triggers in 2015	`HLT_e24_lhmedium_L1EM20VH || HLT_e60_lhmedium || HLT_e120_lhloose` `HLT_mu20_iloose_L1MU15 || HLT_mu50`
Triggers in 2016–2018	`HLT_e26_lhtight_nod0_ivarloose || HLT_e60_lhmedium_nod0 || HLT_e140_lhloose_nod0` `HLT_mu26_ivarmedium || HLT_mu50`
ZZ veto	Less than 4 baseline leptons
N leptons	Exactly three leptons passing the Z lepton selection
Leading lepton p_T	$p_T^{\text{lead}} > 25$ GeV (in 2015) or $p_T^{\text{lead}} > 27$ GeV (in 2016-2018)
Z leptons	Two same flavor oppositely charged leptons passing the Z-lepton selection
Z lepton invariant mass	$\lvert m_{\ell\ell} - M_Z \rvert < 10$ GeV
W lepton	Remaining lepton passes the W-lepton selection
W transverse mass	$m_T^W > 30$ GeV
ΔR	$\Delta R(\ell_Z^-, \ell_Z^+) > 0.2, \Delta R(\ell_Z, \ell_W) > 0.3$

Signal regions			
	Radiation Amplitude Zero	00-enhanced region 1	00-enriched region 2
Pass inclusive WZ event selection	✓	✓	✓
Transverse momentum of the Z boson (p_T^Z)	-	[100, 200] GeV	> 200 GeV
Transverse momentum of the WZ system (p_T^{WZ})	< 20, 40, 70 GeV	< 70 GeV	