Multiboson Production and Polarisation Measurements With the ATLAS Detector

Muhammad Alhroob

On Behalf of the ATLAS Collaboration

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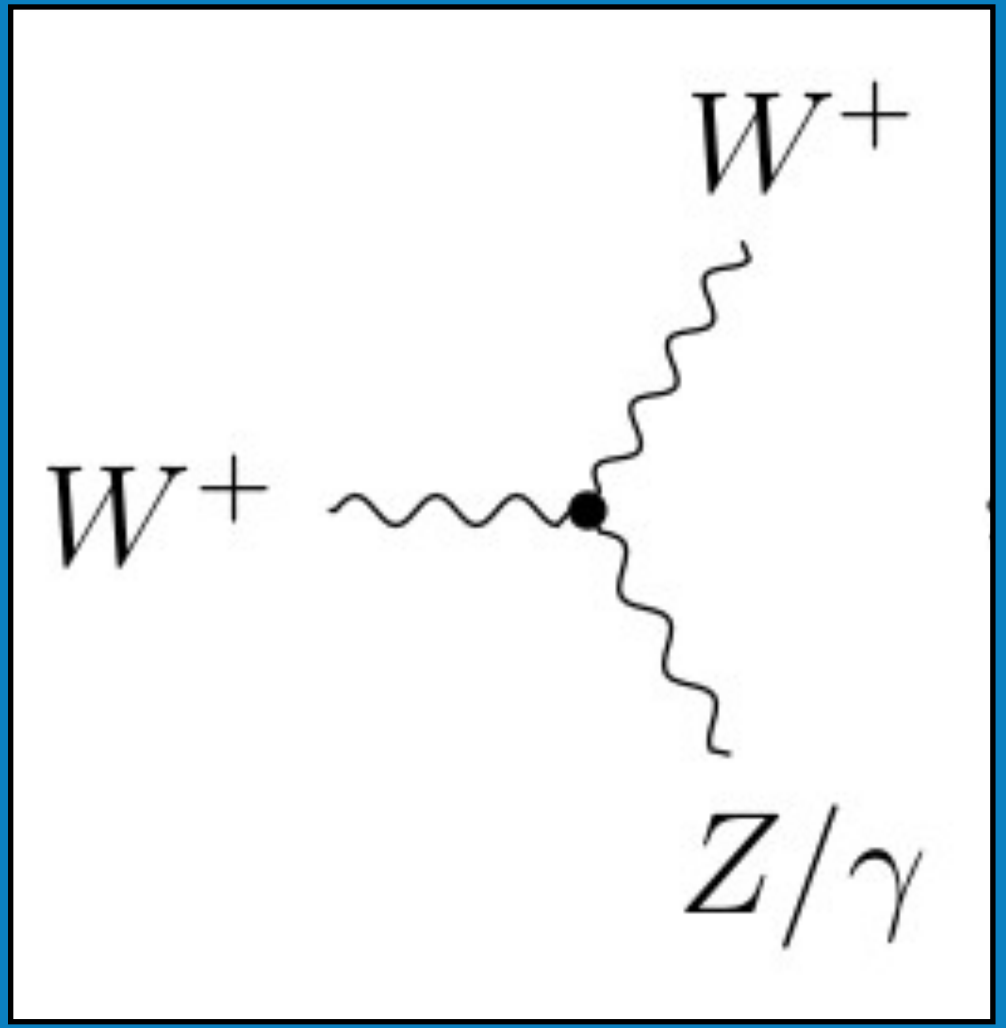
Outline

- Motivation
- $W Z\gamma$ results at 13 TeV using 140 fb^{-1} of Run2
- $W\gamma\gamma$ results at 13 TeV using 140 fb^{-1} of Run2
- ZZ production at 13.6 TeV using 29 fb^{-1} of Run3
- ZZ polarization and CP results at 13 TeV using 140 fb^{-1} of Run2
- WZ polarisation at high-P_T^Z using 13 TeV using 140 fb^{-1} of Run2
- Summary

Motivation

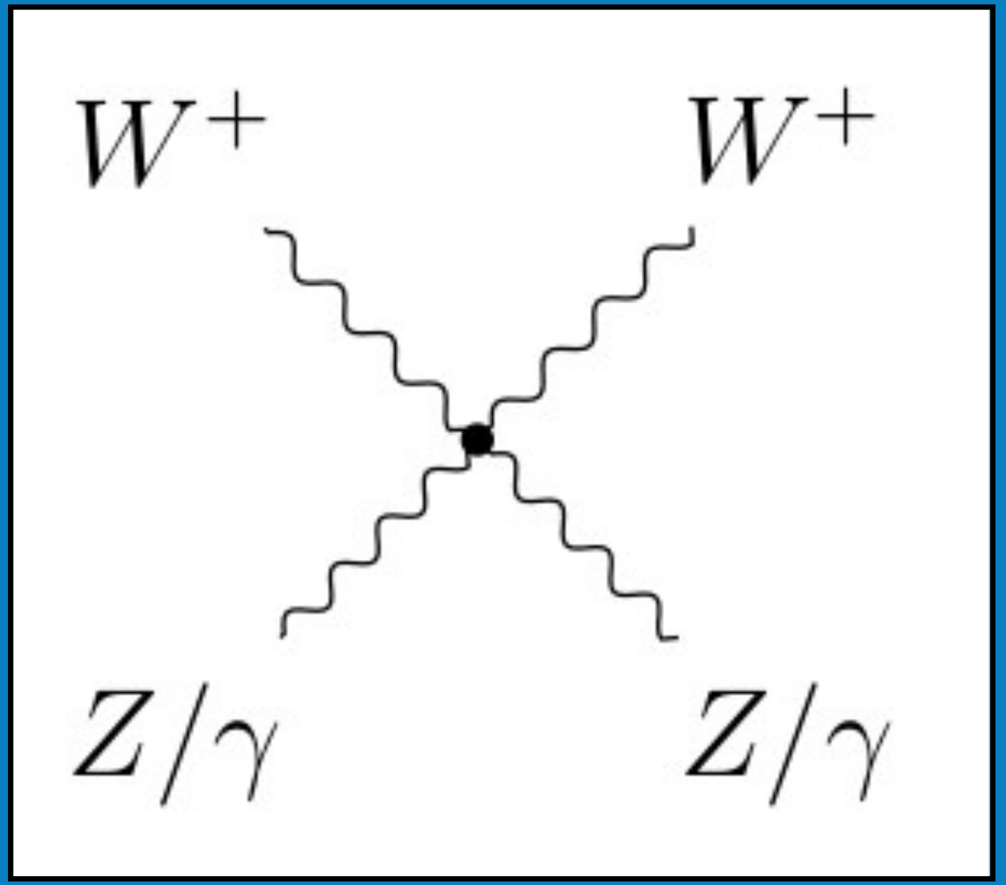
Investigate the SM Electroweak Sector:

- Measurements of multiboson processes provide an important test of the SM
- Study non-abelian structures through triple and quartic gauge couplings
- Deviations from predictions provide evidence of new physics
  - Set limits on anomalous quartic gauge couplings via interpretations: EFT and resonant searches



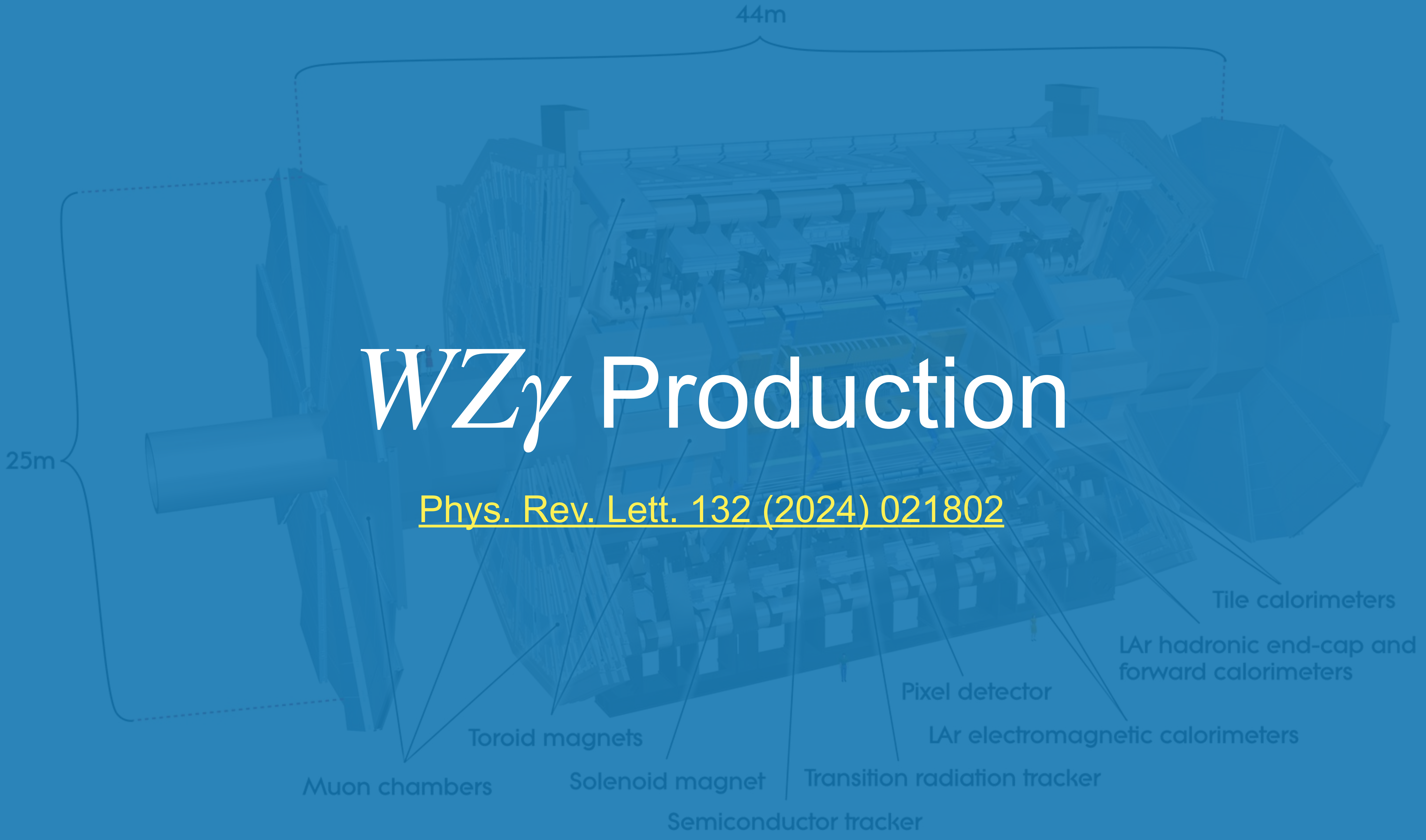
Longitudinal polarisation:

- Directly probes the Electroweak Symmetry Breaking mechanism
- Sensitive to new physics
- The first step toward longitudinal VBS



$WZ\gamma$ Production

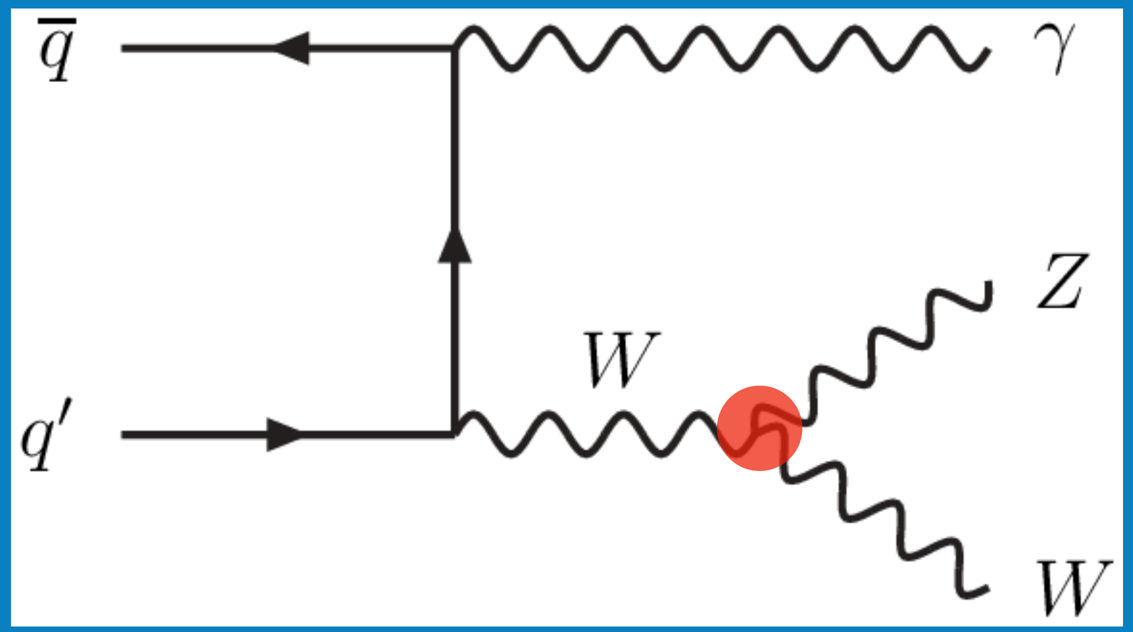
Phys. Rev. Lett. 132 (2024) 021802

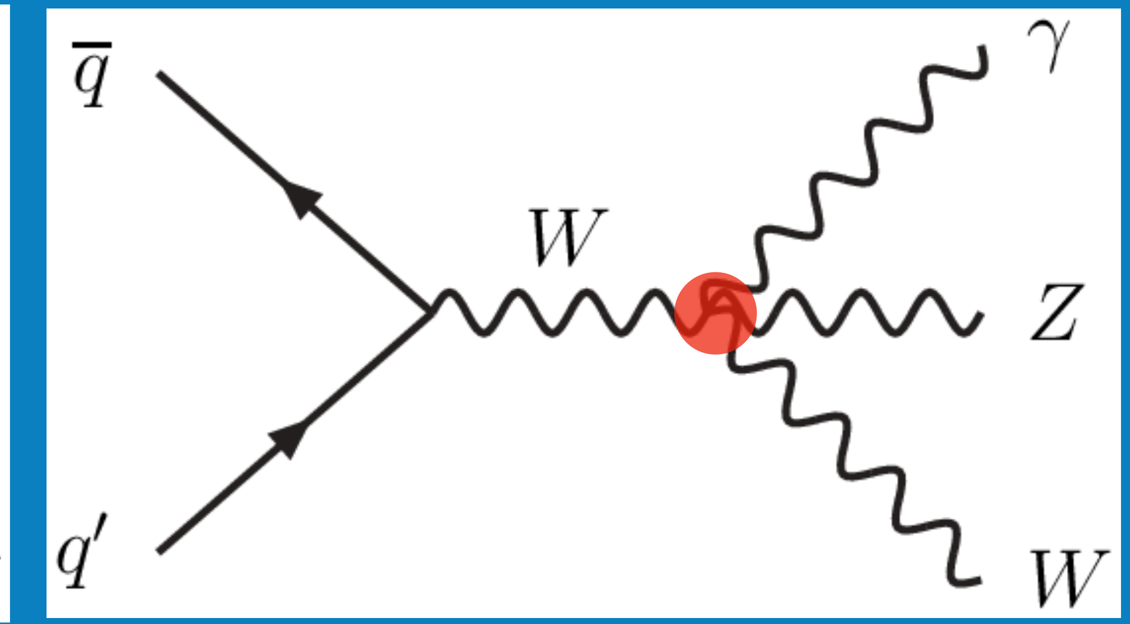


$WZ\gamma$ Process

Targeting the $WWZ\gamma$ quartic gauge coupling:

- 3 leptons (e, μ): $P_T > 30, 20, 20$ GeV
- Z lepton pair with $m_{\ell\ell} > 80$ GeV
- $E_T^{miss} > 20$ GeV
- 1 photon, $P_T > 15$ GeV





	SR definition	$ZZ\gamma$ CR definition	$ZZ(e\to\gamma)$ CR definition
Lepton veto	no additional leptons with $p_T^{\ell_4} > 10$ GeV	one additional lepton with $p_T^{\ell_4} > 10$ GeV	same as SR
Z-leptons assignment	smallest $\lvert m_{\ell\ell} - m_Z\rvert$	same as SR	same as SR
ΔR	$\Delta R(\ell,\gamma) > 0.4, \quad \Delta R(\mu, e) > 0.2$	same as SR	same as SR
$ZZ(e \to \gamma)$ rejection	$\lvert m(e_W, \gamma) - m_Z\rvert > 10$ GeV	same as SR	$\lvert m(e_W, \gamma) - m_Z\rvert < 10\,GeV$
Missing p_T	$E_T^{miss} > 20$ GeV	no requirement	$E_T^{miss} < 20$ GeV
Z candidate mass	$m_{\ell\ell} > 81\,GeV$	$m_{\ell\ell} > 40\,GeV$	same as SR

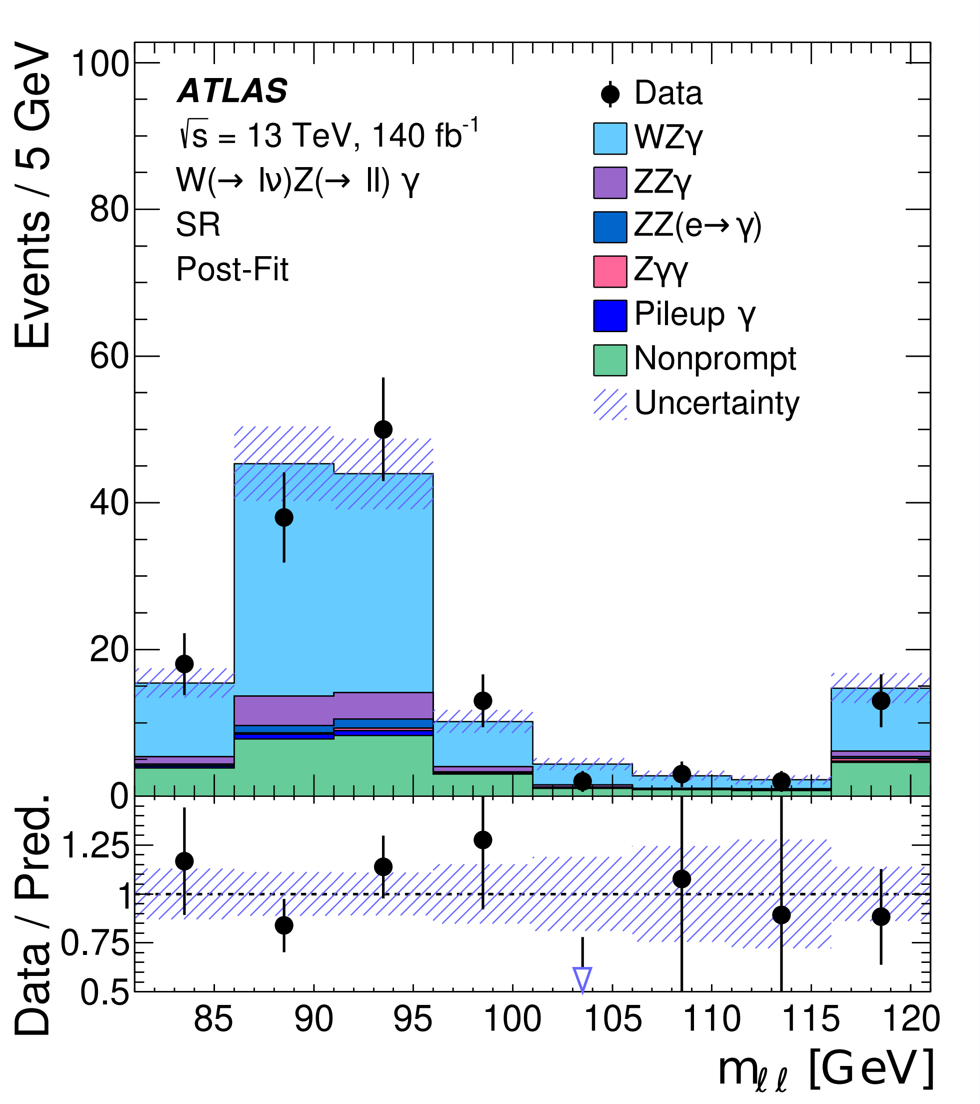
Reject FSR

- Non-prompt bkg. (WZ, ZZ, $Z\gamma$, $t\bar{t}\gamma$): estimated using a data-driven “Fake Factor” method
- Prompt bkg. ($ZZ\gamma$): estimated using MC samples and CRs

$WZ\gamma$ Observation

- A profile-likelihood fit is performed on three bins to extract the signal and $ZZ/ZZ\gamma$ backgrounds
- $WZ\gamma$ process observed (expected) with 6.3σ (5σ)
  - consistent with the SM prediction within 1.5σ

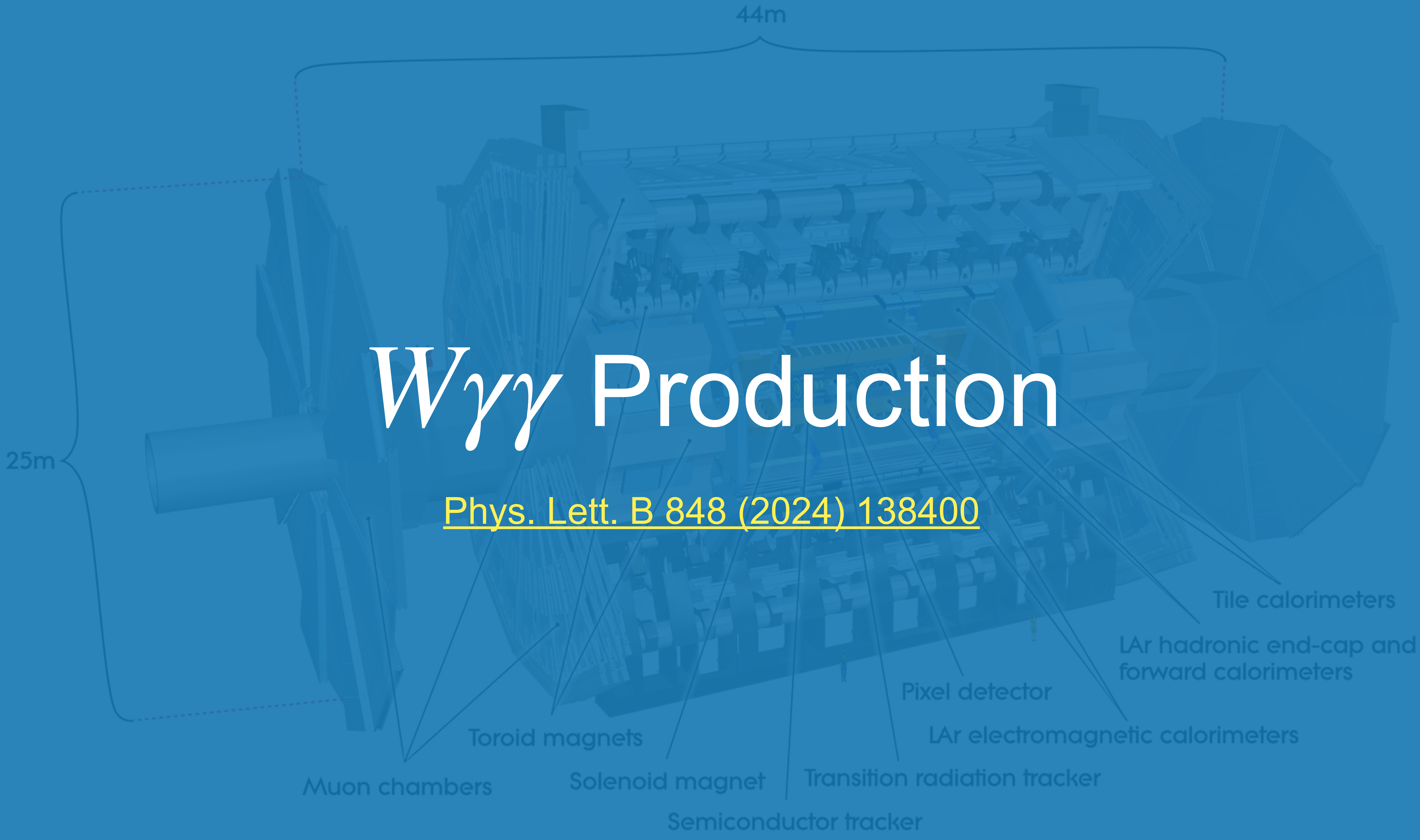
Process	SR	$ZZ\gamma$ CR	$ZZ(e \to \gamma)$ CR
$WZ\gamma$	92 ± 15	0.21 ± 0.07	0.56 ± 0.14
$ZZ\gamma$	10.7 ± 2.3	23 ± 5	1.8 ± 0.4
$ZZ(e \to \gamma)$	3.0 ± 0.6	0.028 ± 0.020	30 ± 6
$Z\gamma\gamma$	1.05 ± 0.32	0.15 ± 0.06	0.29 ± 0.10
Nonprompt background	30 ± 6	-	-
Pileup γ	1.9 ± 0.7	-	-
Total yield	139 ± 12	23 ± 5	33 ± 6
Data	139	23	33



- $\mu_{WZ\gamma}$ = 1.34 ± 0.20 (stat.) ± 0.10 (syst.) ± 0.07 (theory)
- $\sigma^{Fid}_{WZ\gamma}$ = 2.01 ± 0.30 (stat.) ± 0.16 (syst.) fb
  - Photon identification and isolation are the biggest systematic uncertainties

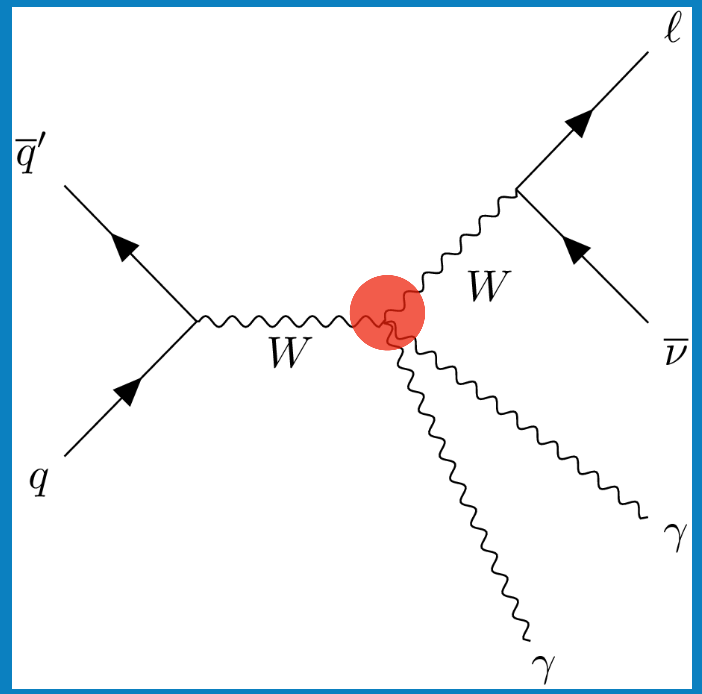
$W\gamma\gamma$ Production

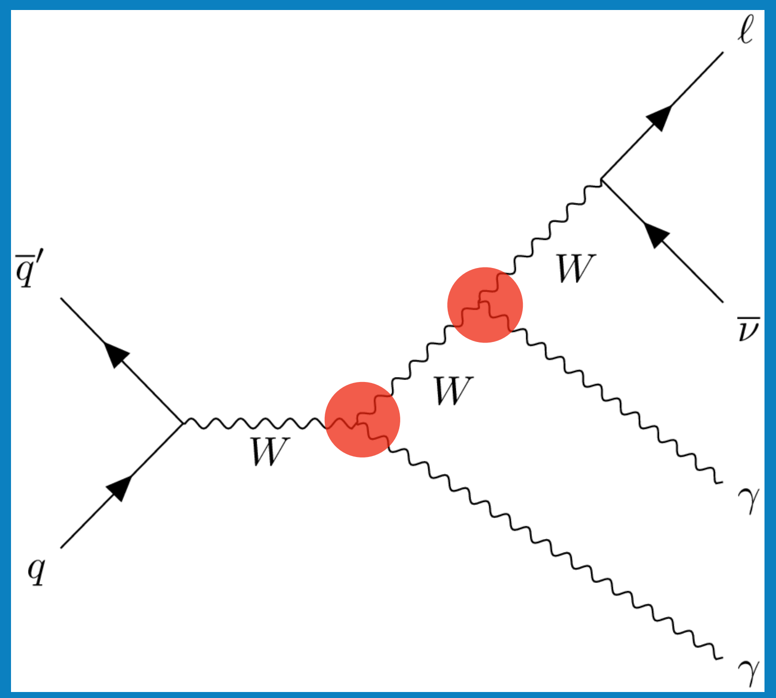
Phys. Lett. B 848 (2024) 138400



$W\gamma\gamma$ Process

- Sensitive to the $WW\gamma\gamma$ and $WW\gamma$ gauge coupling
- An important background for $WH \rightarrow W\gamma\gamma$



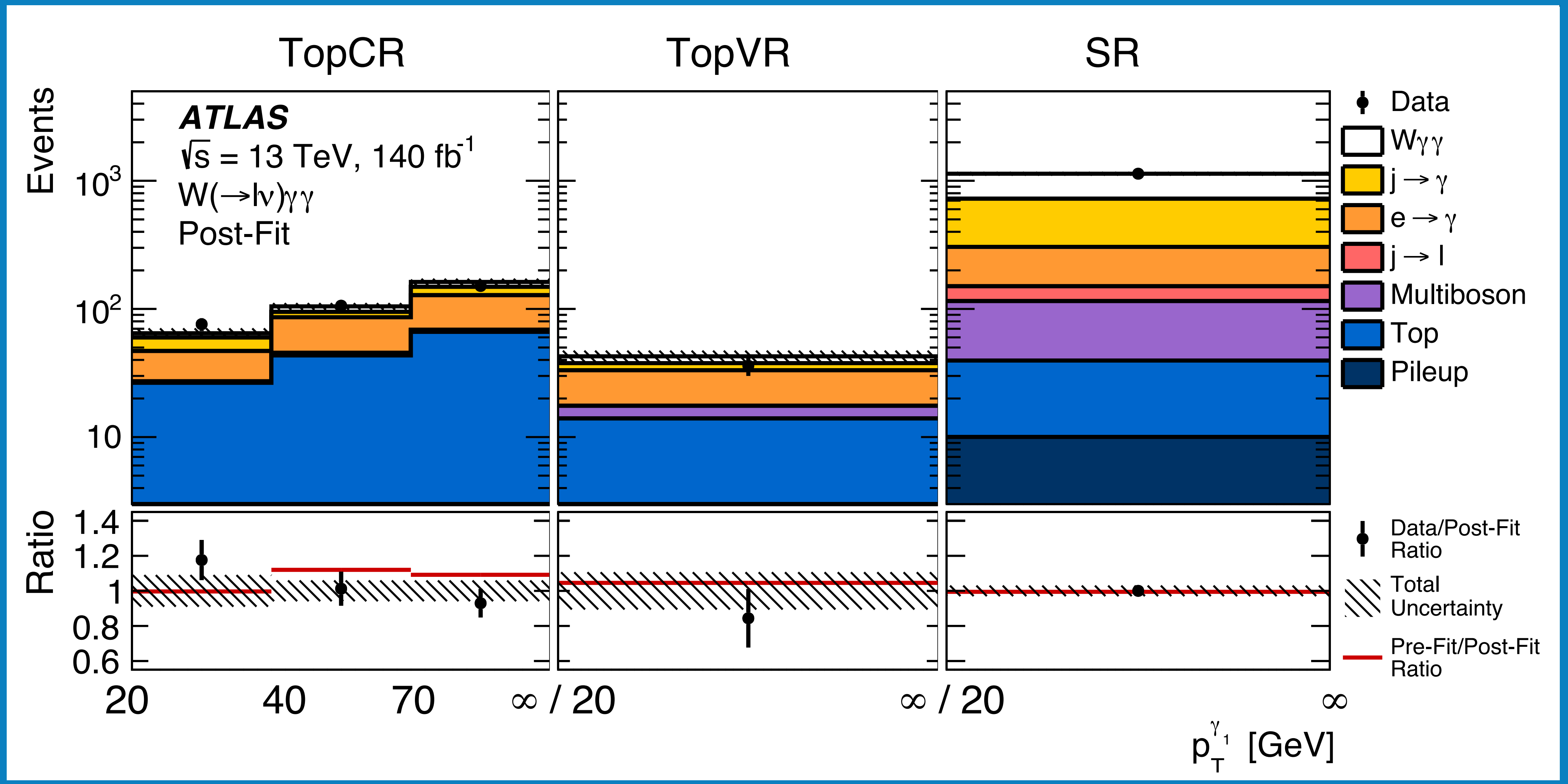


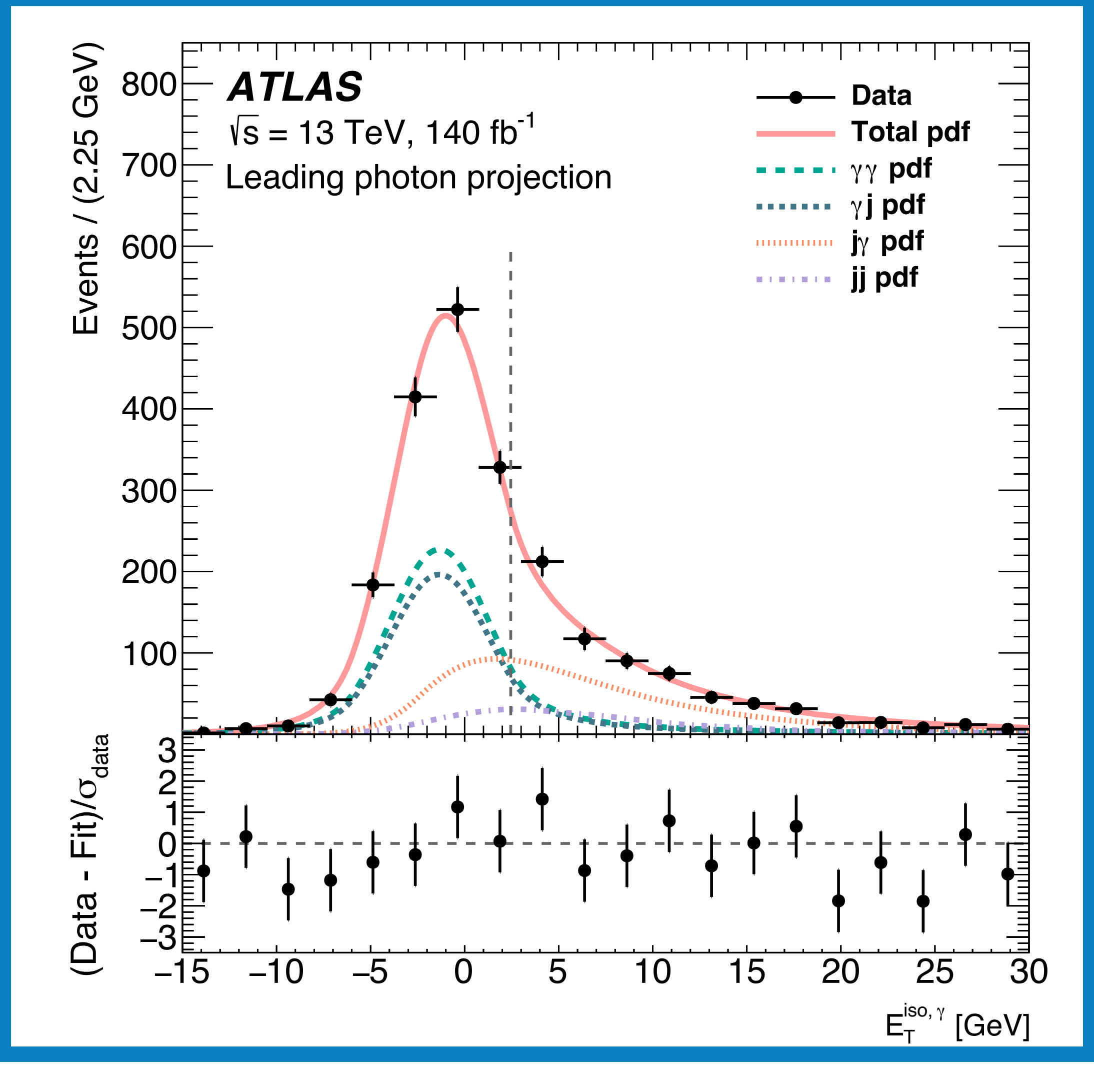
Event selection:

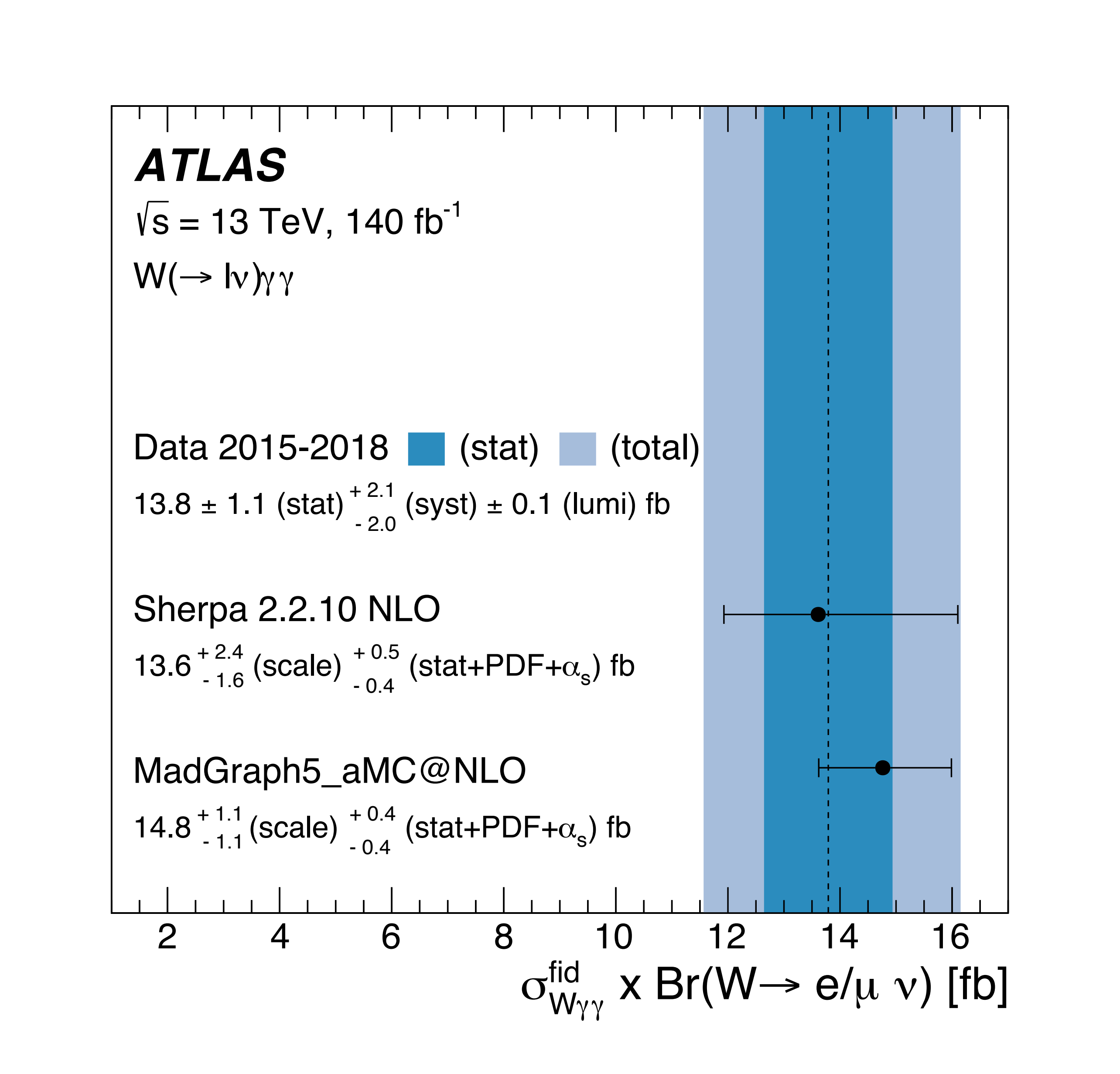
- 2 isolated photons, $P_T > 20$ GeV
- 1 isolated electron (muon), $P_T > 20$ (25) GeV
- E_T^{miss} > 25 GeV && $m_T(W)$ > 40 GeV
- $Z\gamma$ veto:
  $m(l\gamma)$, $m(l\gamma\gamma) \notin$ [82,100] GeV
  && $pT(l\gamma\gamma) > 30$ GeV

Source	SR	TopCR
$W\gamma\gamma$	410 ± 60	28 ± 5
Non-prompt $j \rightarrow \gamma$	420 ± 50	42 ± 20
Misidentified $e \rightarrow \gamma$	155 ± 11	120 ± 9
Multiboson ($WH(\gamma\gamma)$, $WW\gamma$, $Z\gamma\gamma$)	76 ± 13	5.2 ± 1.7
Non-prompt $j \rightarrow \ell$	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

$W\gamma\gamma$ Observation



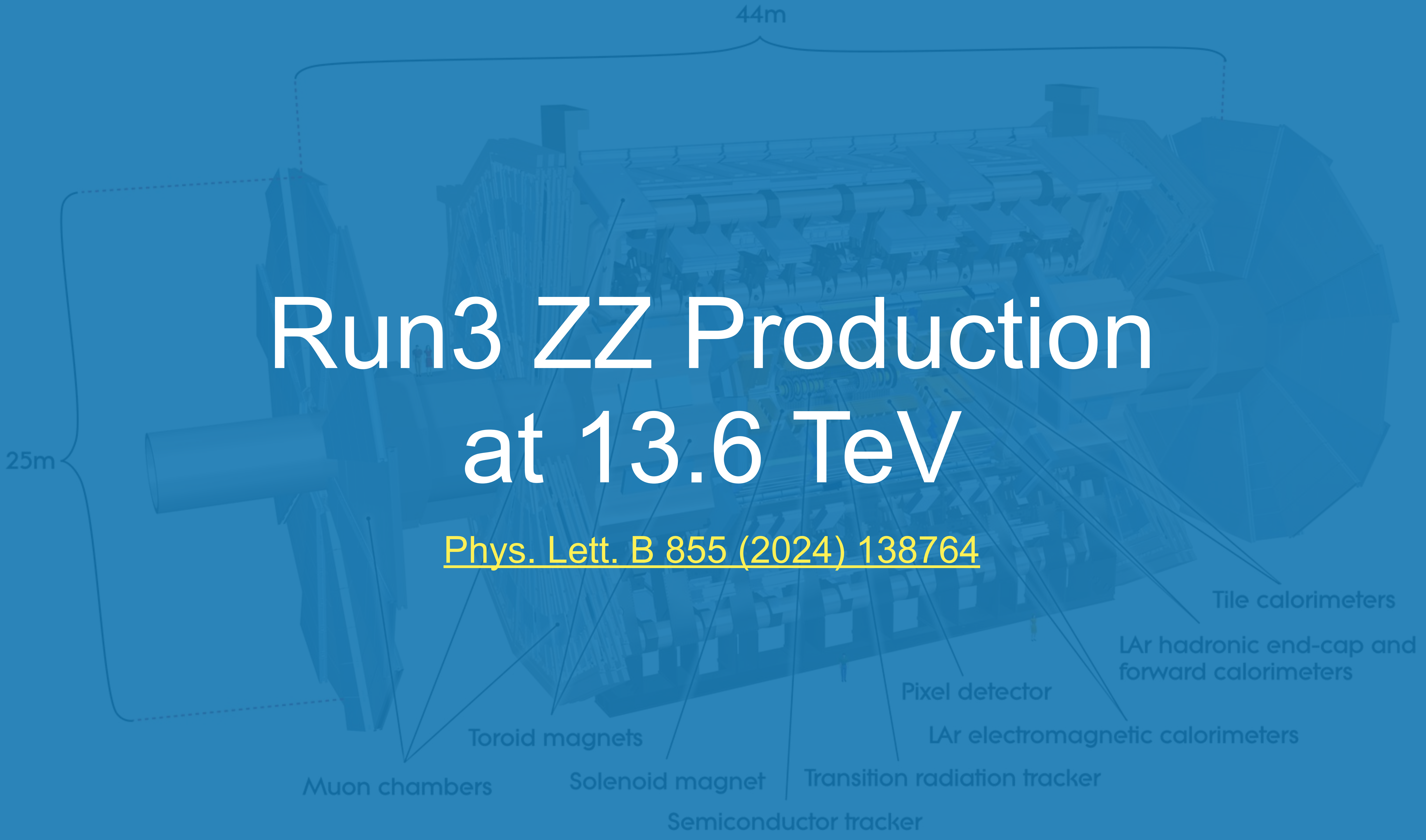




- A profile-likelihood fit is performed on SR and TopCR
- $W\gamma\gamma$ observed significance with 5.6σ
- The fiducial cross section is measured for $W \rightarrow e\nu/\mu\nu$ with a total 17% uncertainty
  - The $j \rightarrow \gamma$ background estimate is the dominant systematic uncertainty

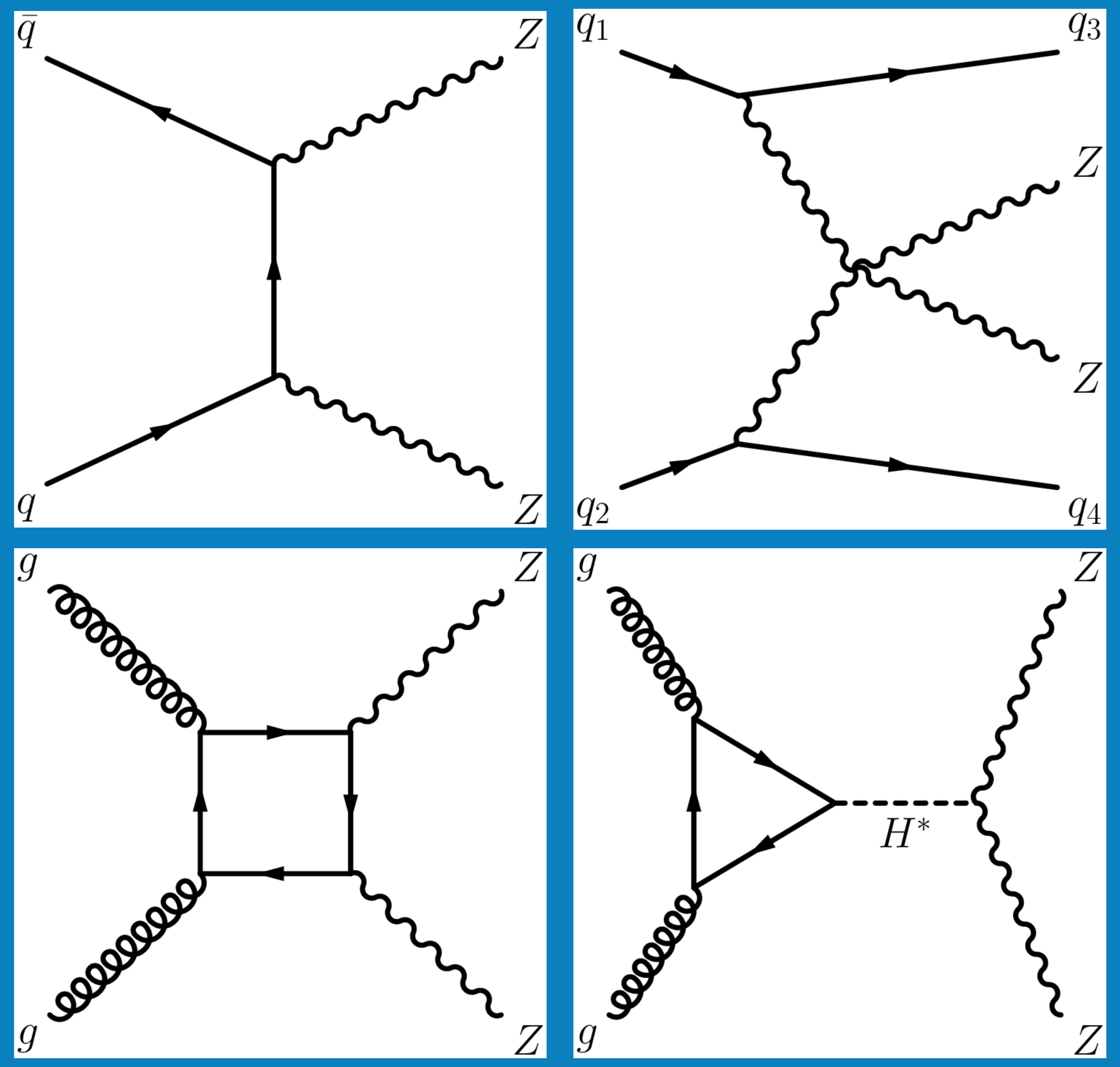
Run3 ZZ Production at 13.6 TeV

Phys. Lett. B 855 (2024) 138764



ZZ @ 13.6 TeV

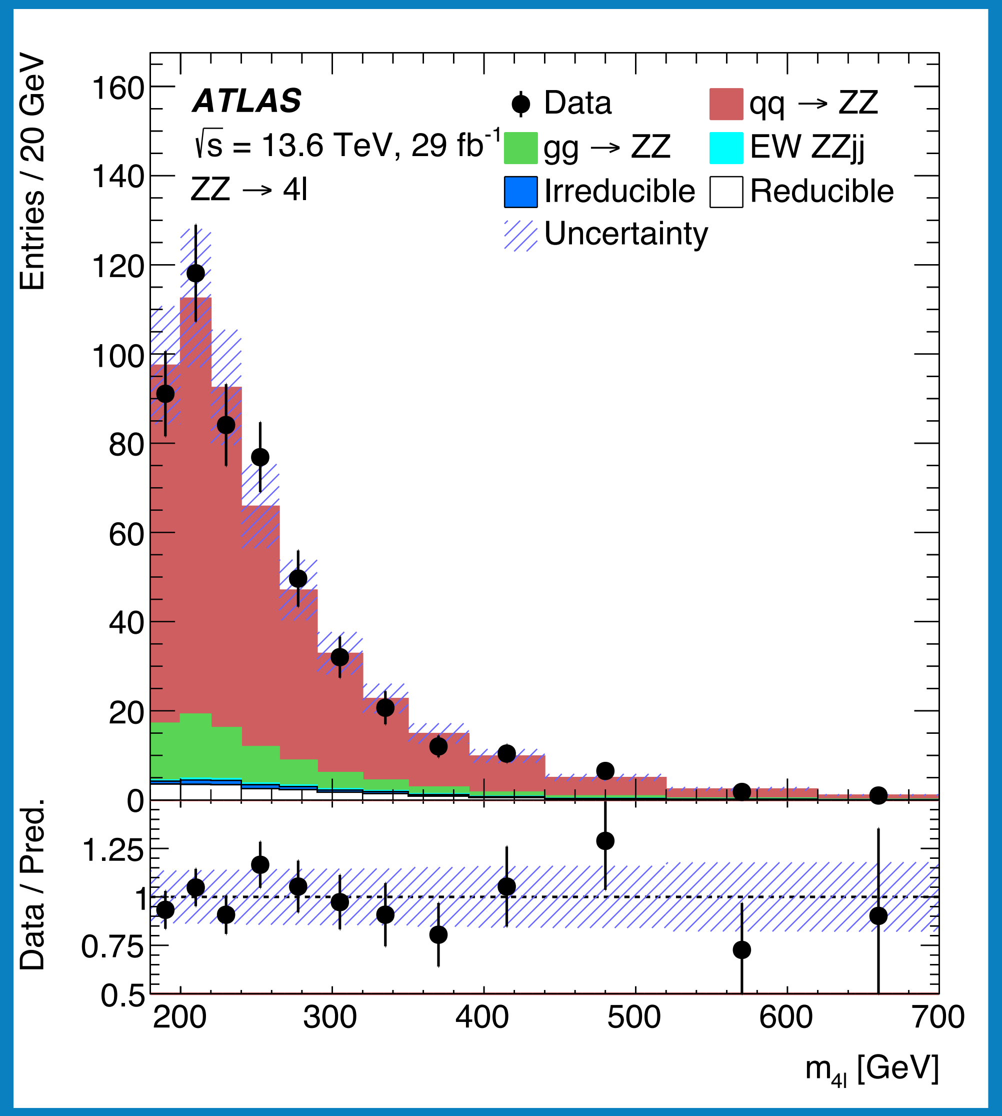
- Key channel to search anomalous neutral TGCs (aTGCs)
- Study the off-shell Higgs boson production



Fiducial and differential cross-sections are measured in 4 lepton final states

- 4 isolated leptons (e, μ), $P_T > 27, 10, 10, 10$ GeV
- 2 Z-lepton pairs
  - 66 < $m_{\ell\ell}$ < 116 GeV for both pairs
- $m_{4\ell}$ > 180 GeV

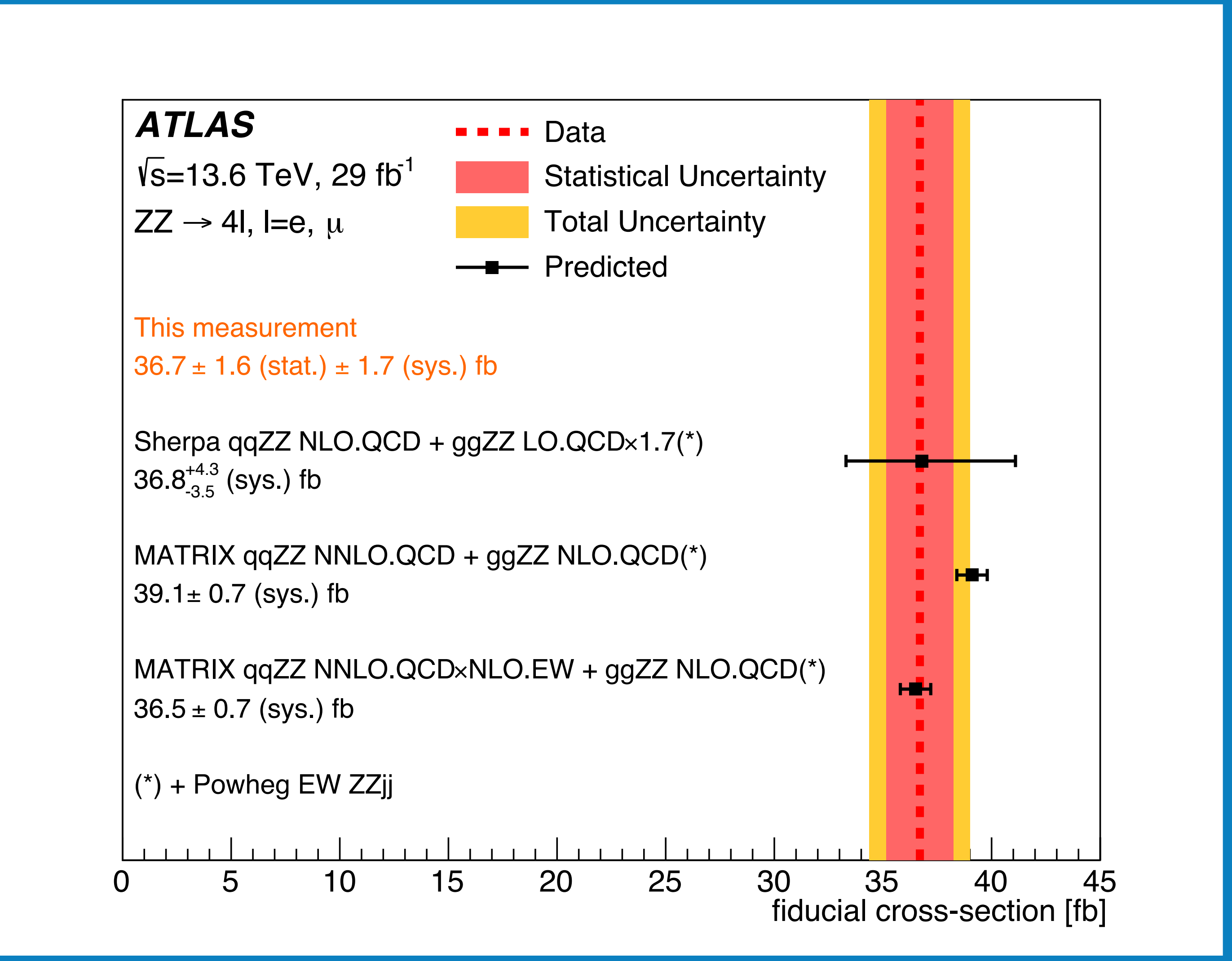
Process	$q\bar{q} \to ZZ$	$gg \to ZZ$	EW $qq \to ZZ + 2j$	$t\bar{t}Z$	VVV	Reducible	Total	Data
Yield	515 ± 50	74 ± 44	4.7 ± 1.0	5.5 ± 0.8	2.1 ± 0.2	25.4 ± 8.1	626 ± 88	625



- Prompt back.: triboson and $t\bar{t}Z$
- Non-prompt back. : Z+jets, WZ, $t\bar{t}$ using the data-driven “Fake Factor” method

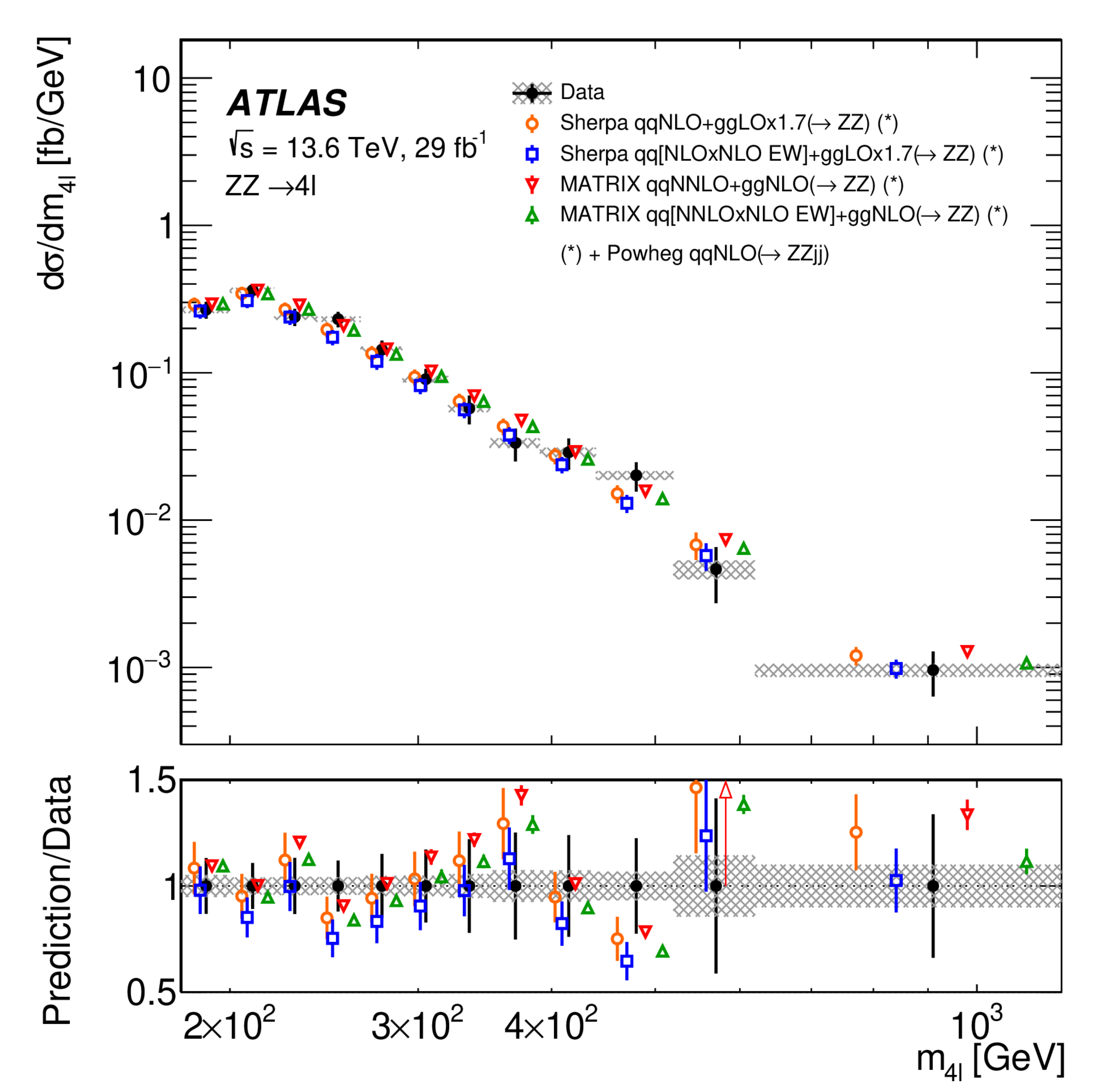
ZZ @ 13.6 TeV

- A single bin is used to extract the fiducial cross section
- Extrapolated to the total cross section with
  $66 < m_Z < 116$ GeV for both Z bosons



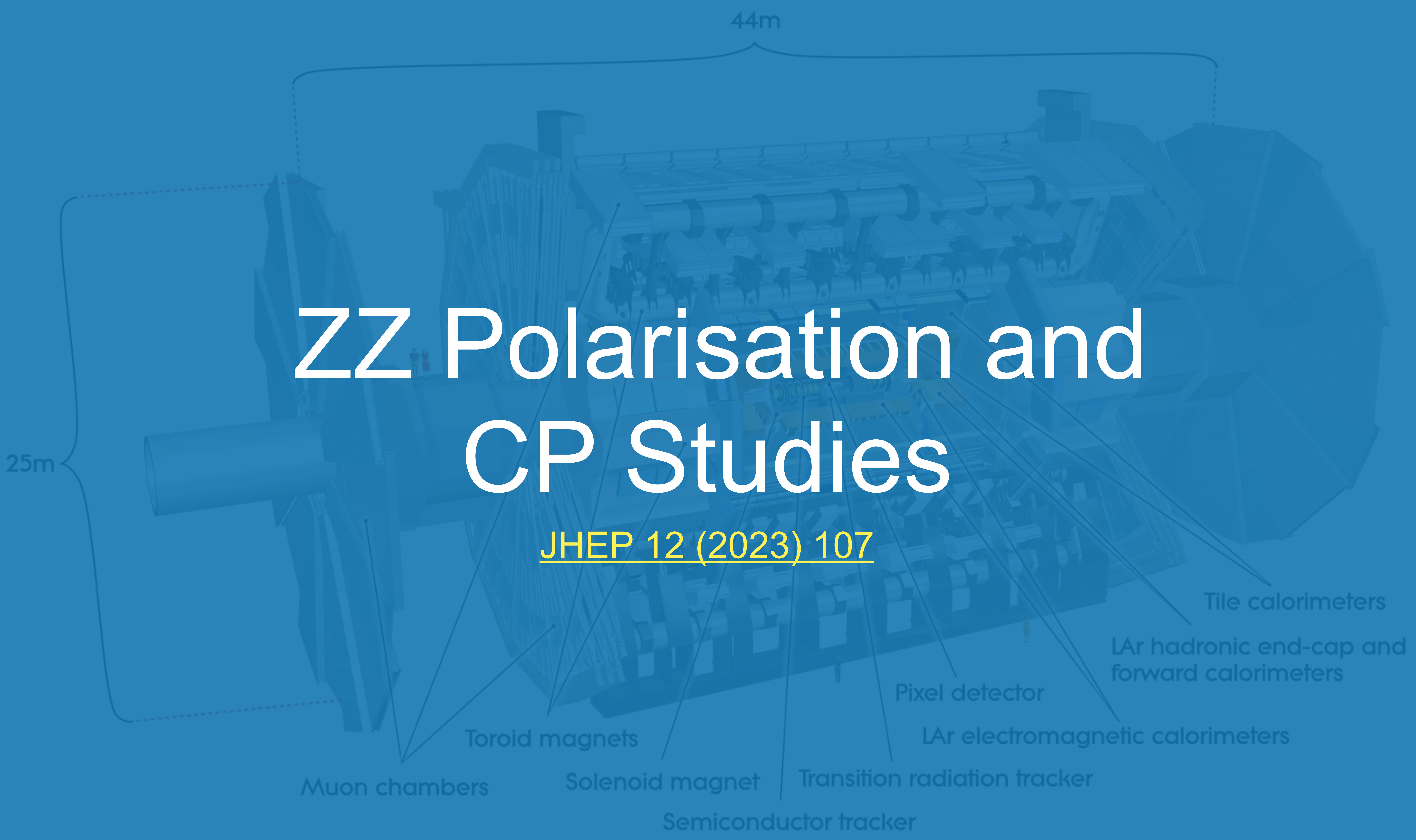
	Measurement	MC prediction	MATRIX prediction
Fiducial	$36.7 \pm 1.6(\mathrm{stat}) \pm 1.5(\mathrm{syst}) \pm 0.8(\mathrm{lumi})$ fb	$36.8\ ^{+4.3}_{-3.5}$ fb	36.5 ± 0.7 fb
Total	$16.8 \pm 0.7(\mathrm{stat}) \pm 0.7(\mathrm{syst}) \pm 0.4(\mathrm{lumi})$ pb	$17.0\ ^{+1.9}_{-1.4}$ pb	16.7 ± 0.5 pb

Iterative Bayesian unfolding: $m_{4\ell}$ and $P_T(4\ell)$



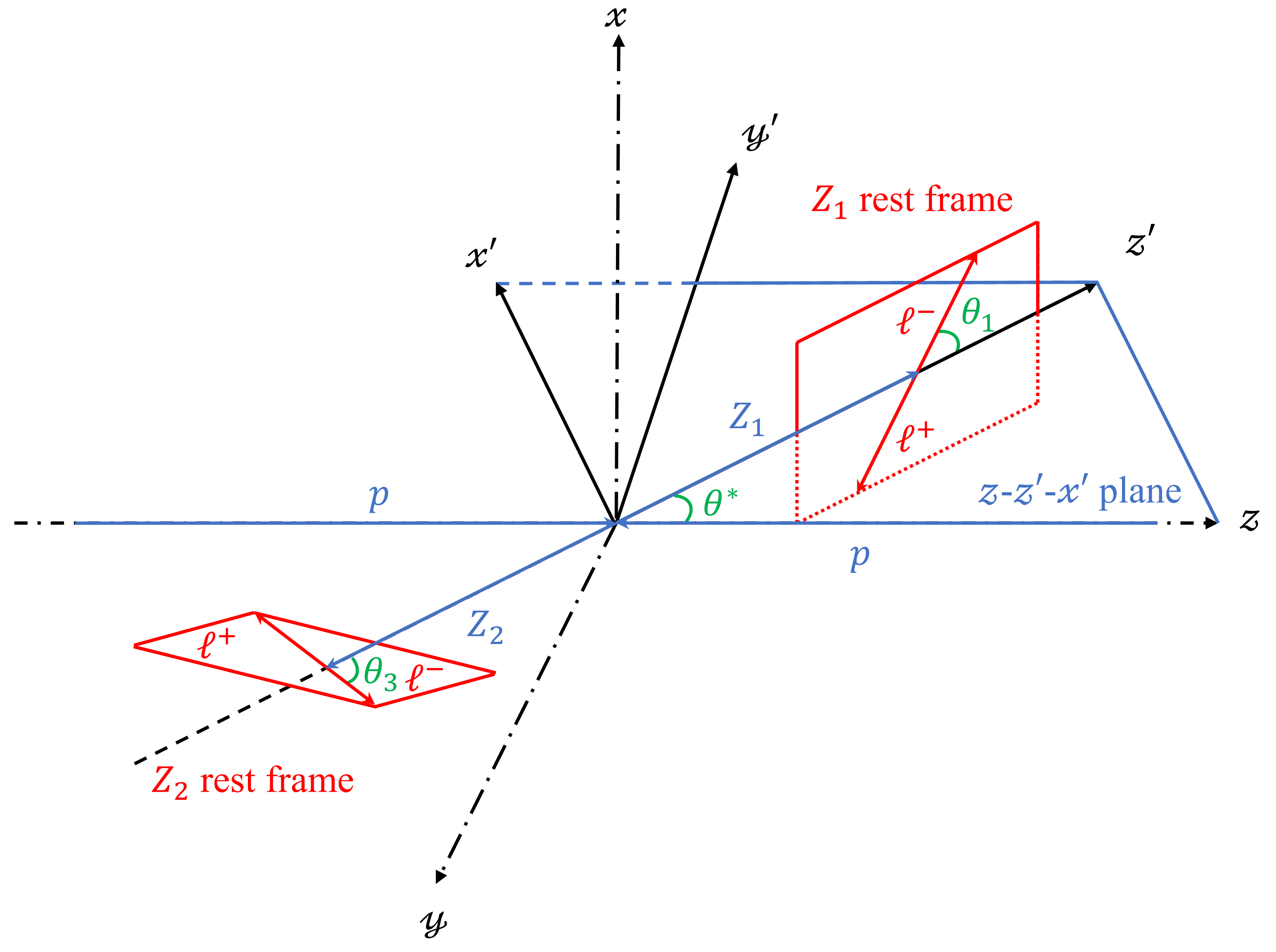
ZZ Polarisation and CP Studies

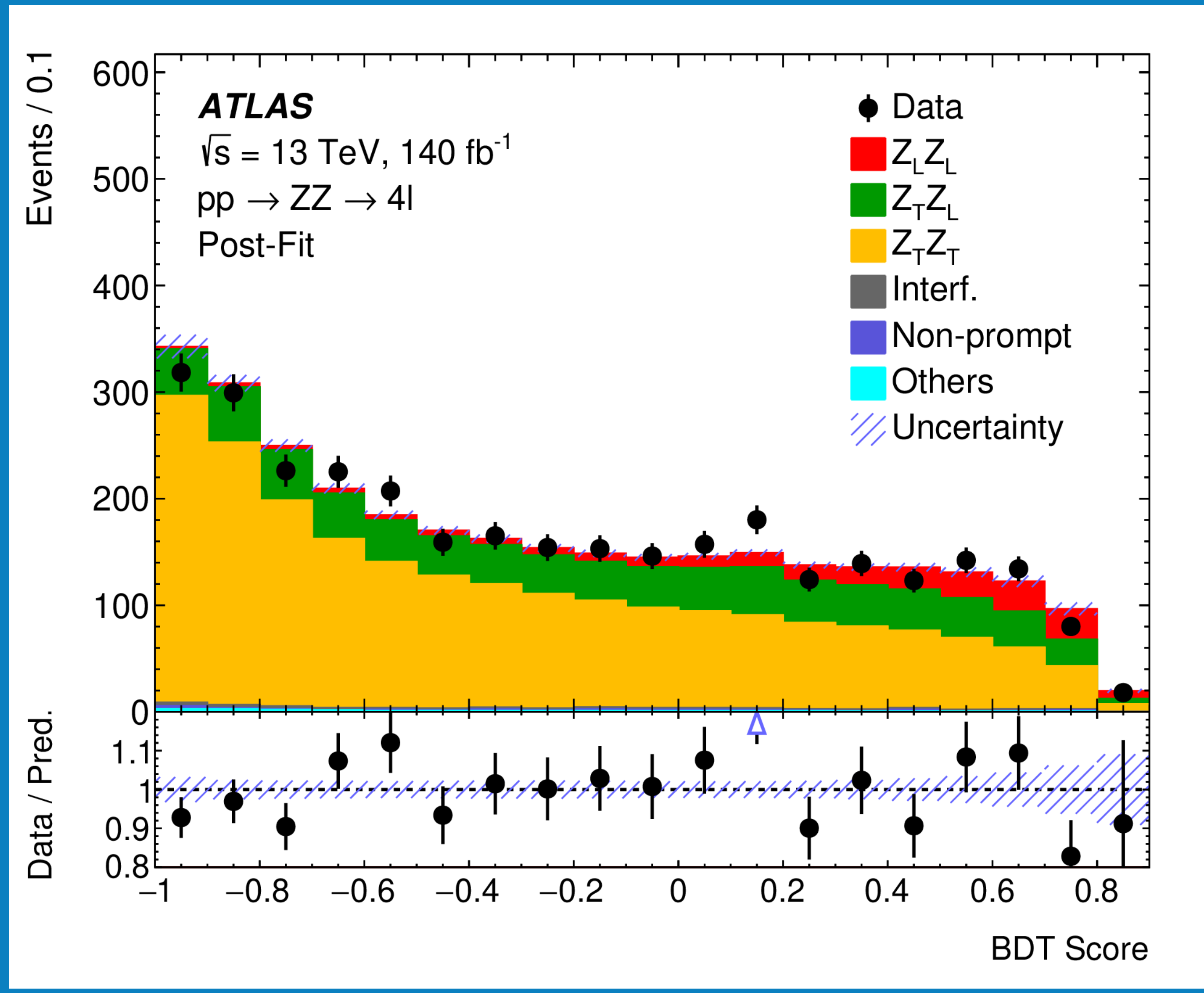
JHEP 12 (2023) 107



ZZ Polarisation at 13 TeV

- The polarisation measurement of massive weak bosons directly probes the Electroweak Symmetry-Breaking mechanism
  - Provides unique sensitivity to physics BSM
- Measurement of longitudinally polarised $Z_L Z_L$ bosons in $ZZ \rightarrow 4\ell$ final states ($\ell = e, \mu$)
- BDT is trained to distinguish the $Z_L Z_L$ from $Z_L Z_T$ and $Z_T Z_T$ polarisation components



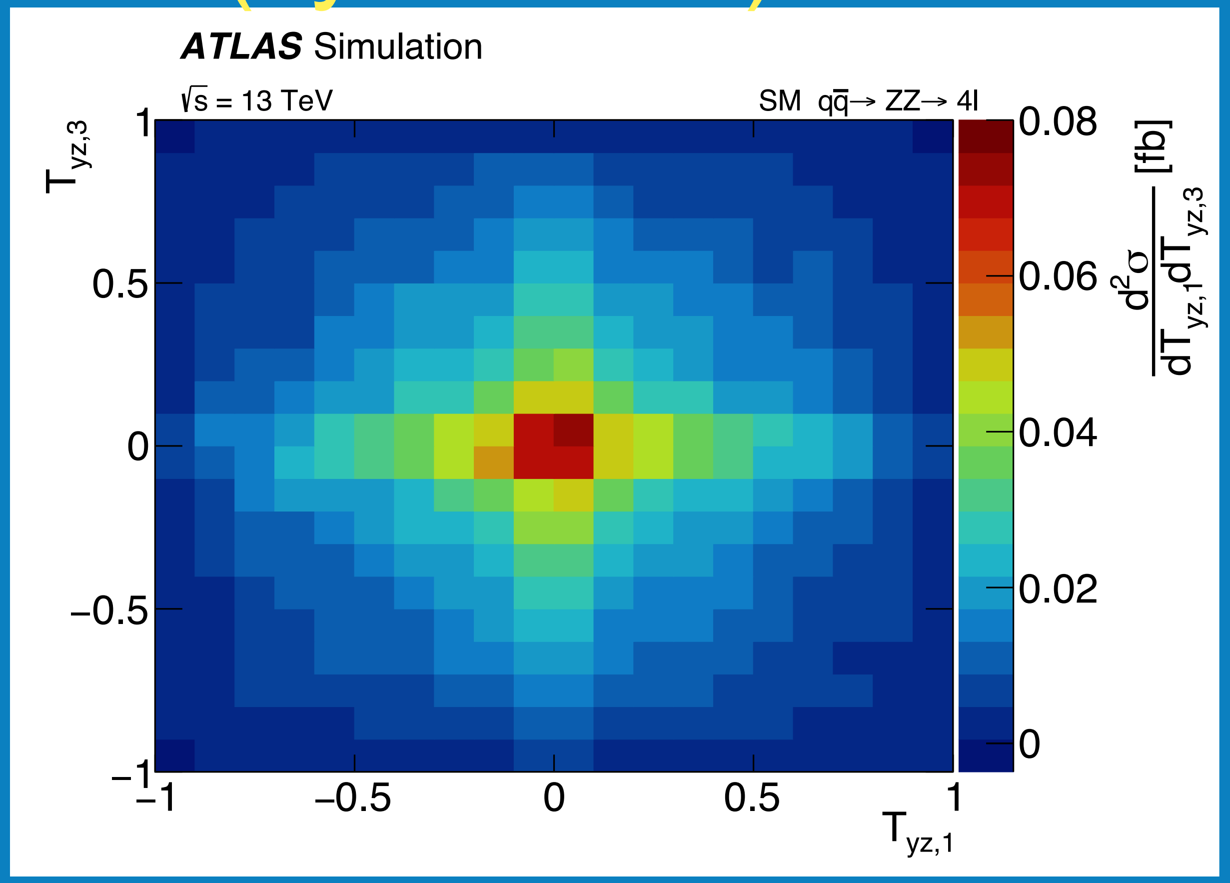


- $\mu_{Z_L Z_L}$ = 1.15 ± 0.27(stat.) ± 0.11 (syst.) with 4.3σ (3.8σ) significance
- Fiducial cross section = 2.45 ± 0.60 fb
- Interferences and modelling are the largest systematic uncertainties

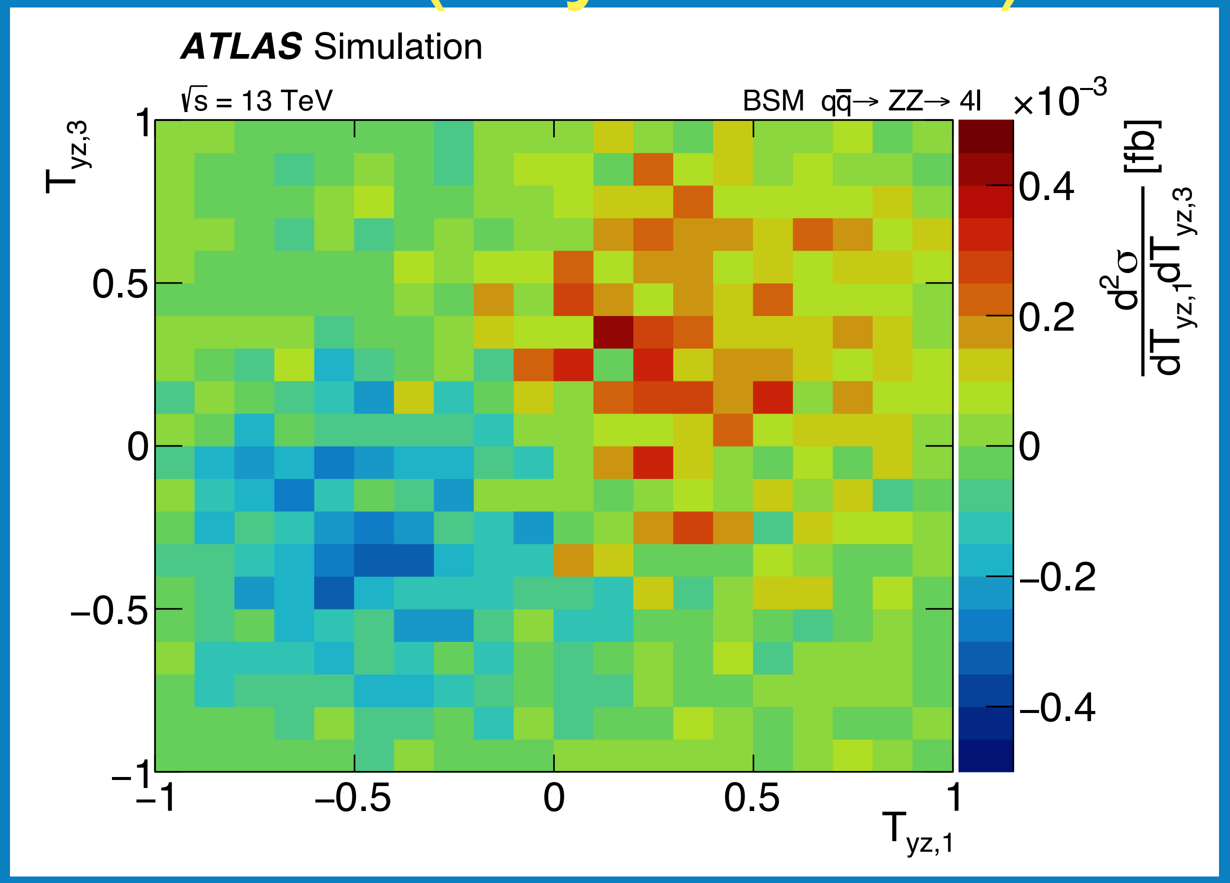
ZZ CP Properties

- Differential cross-section as a function of Optimal CP-sensitive observable
  - $T_{yz,1(3)} = sin(\Phi_{1(3)}) \times cos(\theta_{1(3)})$
  - Symmetric in the SM, but asymmetry in the presence of a CP-odd anomalous triple gauge coupling (aNTGC)

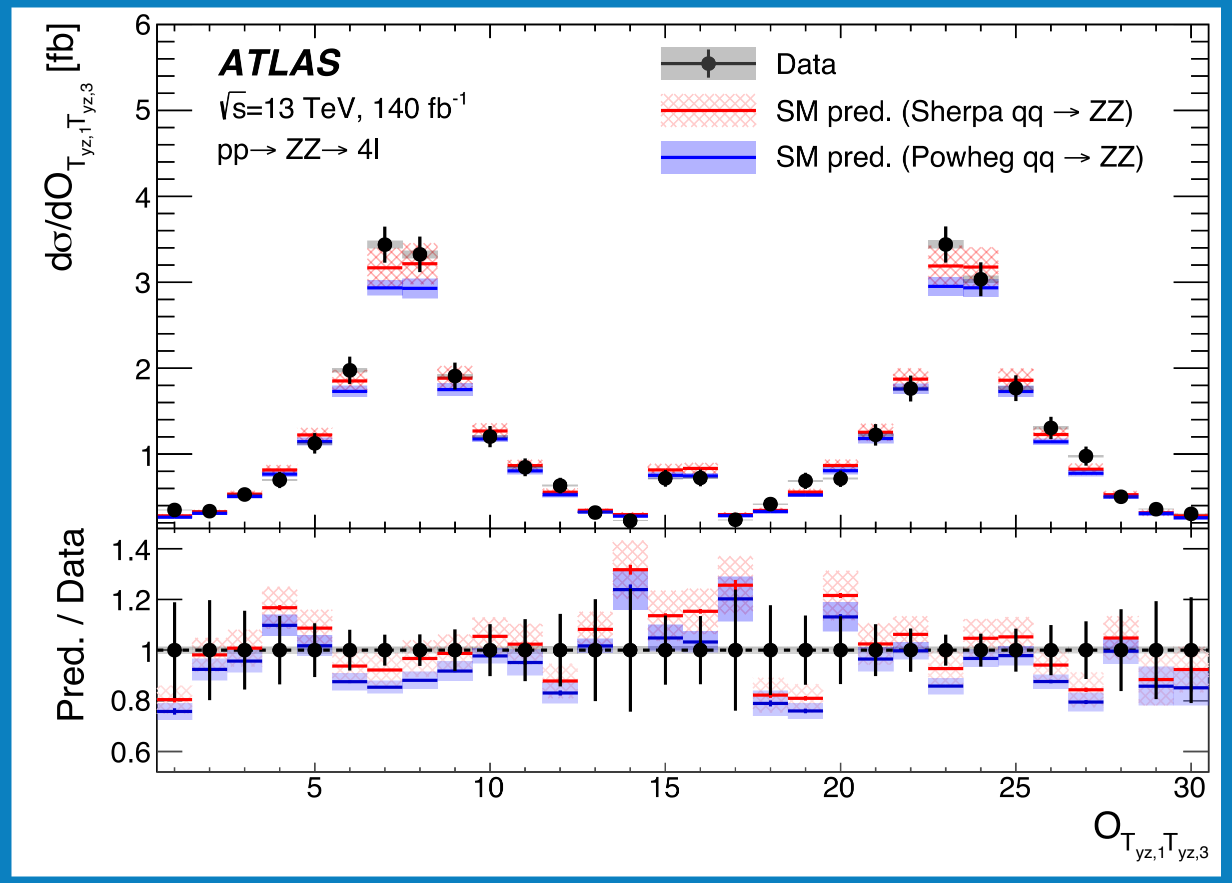
SM (symmetric)



aNTGC (asymmetric)



Unfolded distribution



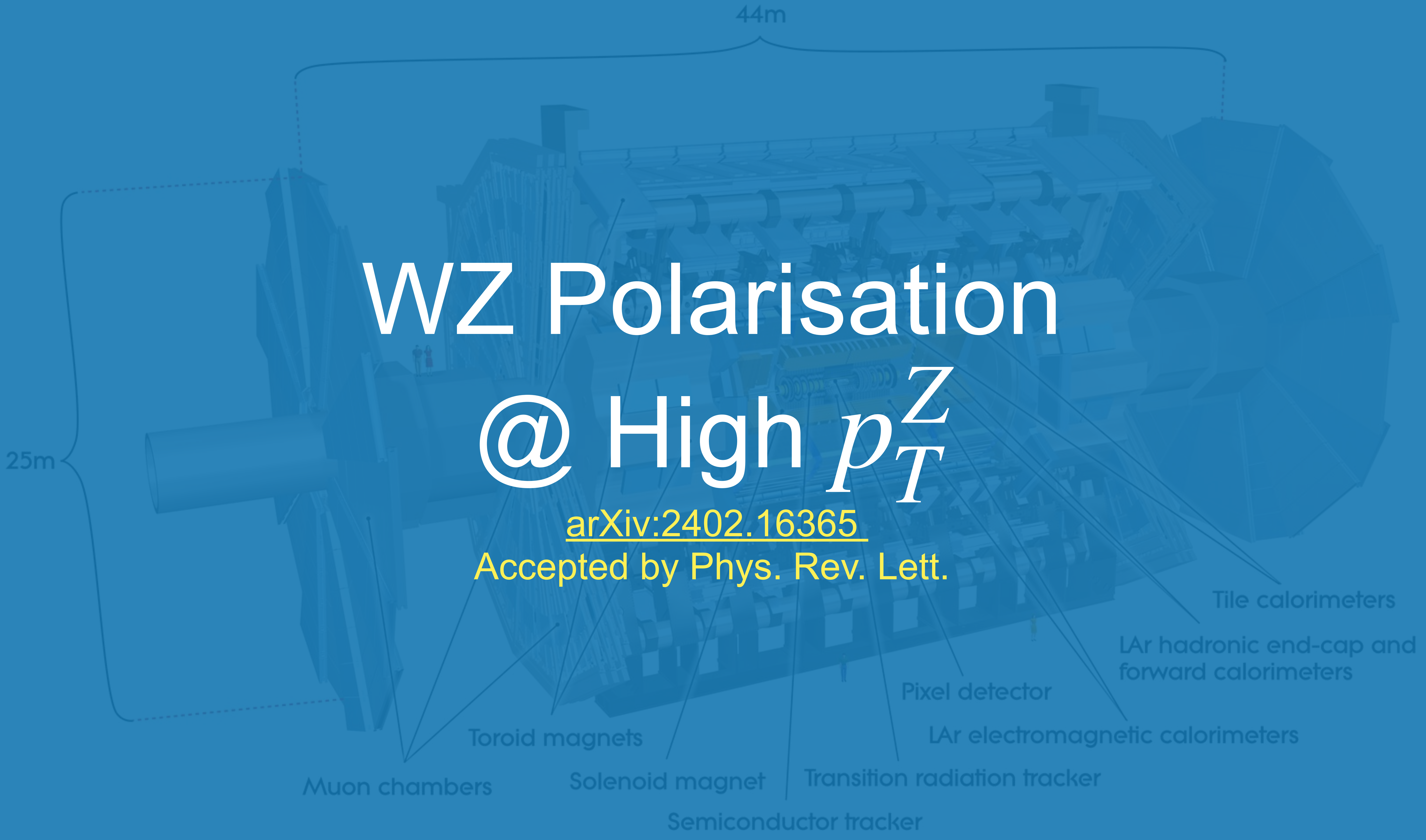
First limits @ 95% CL on aNTGC

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 Polarisation @ High p_T^Z

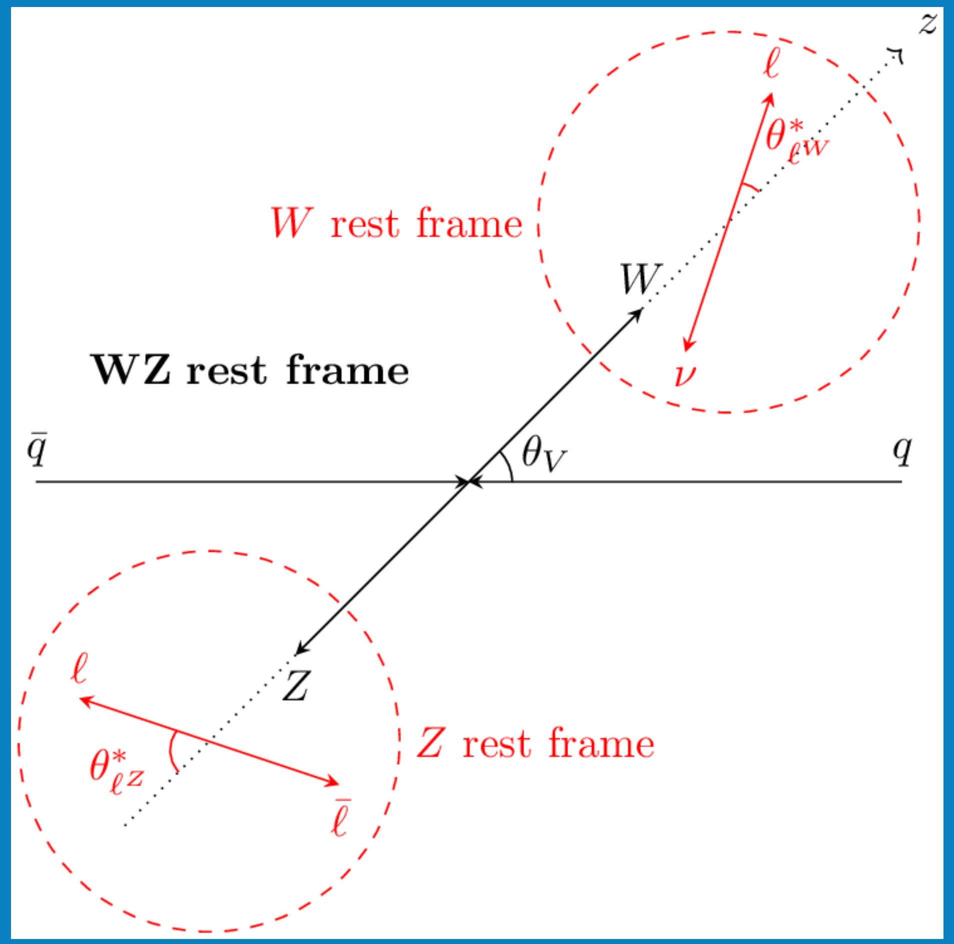
arXiv:2402.16365

Accepted by Phys. Rev. Lett.



WZ Polarisation @ High p_T^Z

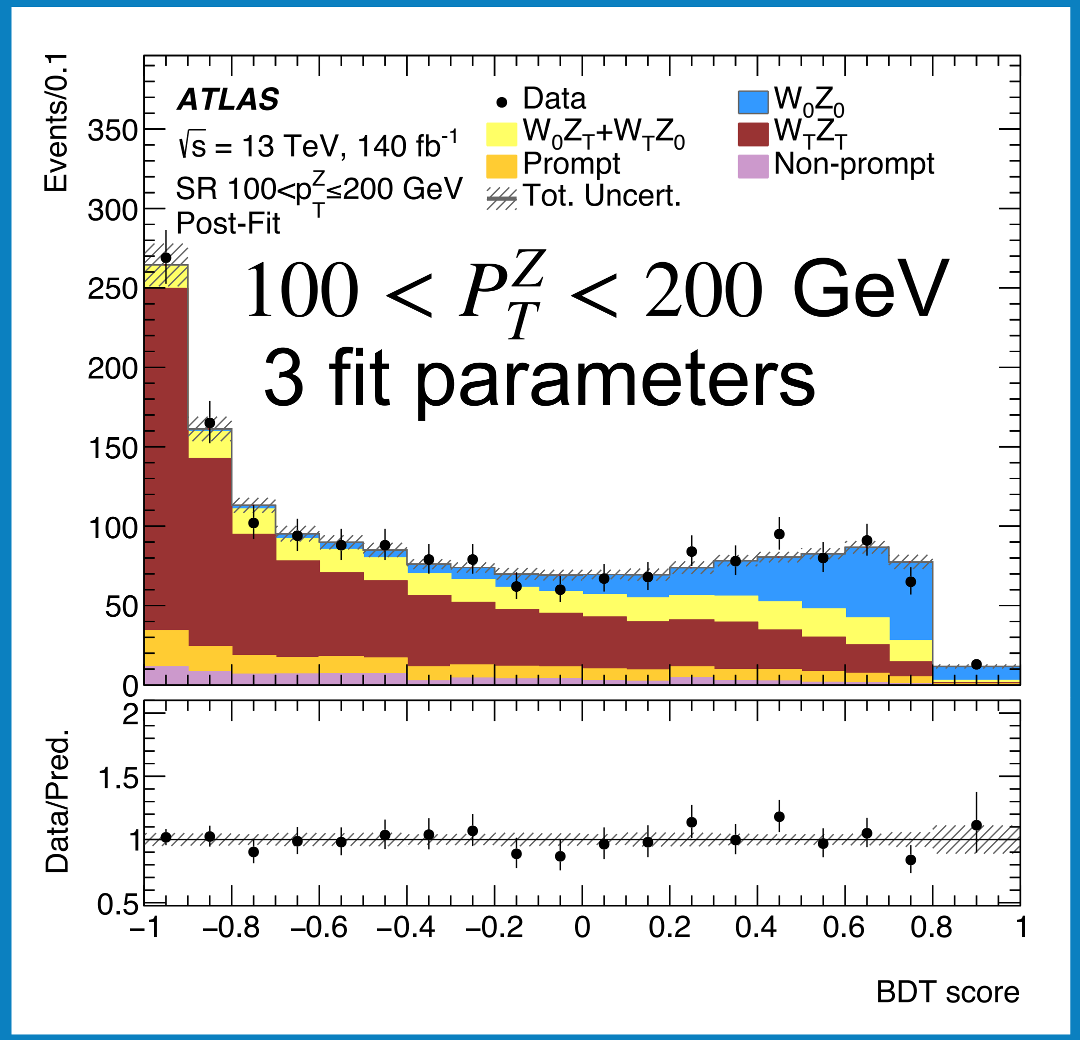
- Measure joint-polarisation states at a high P_T^Z :W_0Z_0, W_0Z_T, W_TZ_0, W_TZ_T)
  - The first study to probe the energy dependence of polarisation fractions
- Radiation Amplitude Zero (RAZ) effect in WZ production

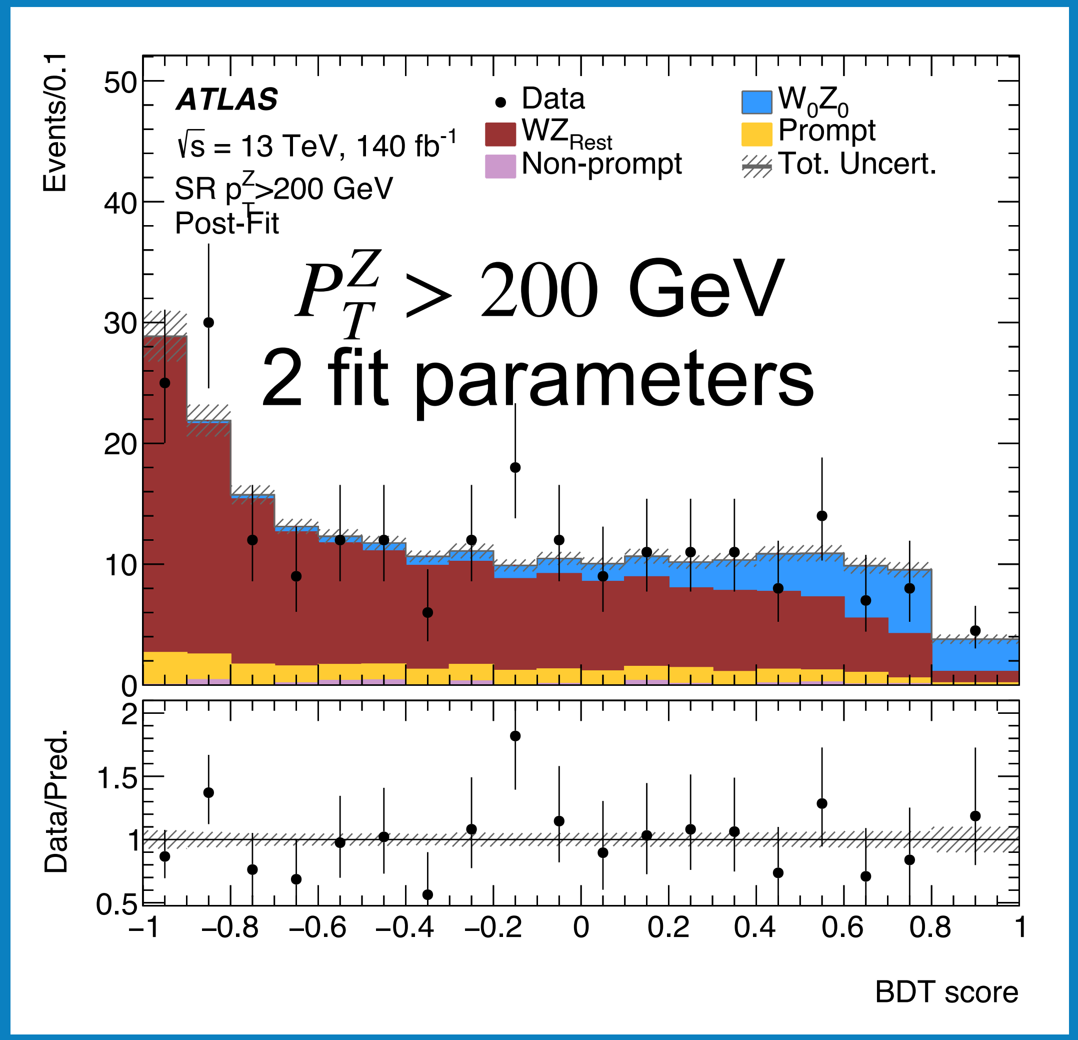


Dedicated BDTs trained in each of the two P_T^Z regions to discriminate W_0Z_0 from the rest

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

WZ Polarisation @ High p_T^Z





3 parameters fit configurations: f_{00}, $f_{0T} + f_{T0}$, f_{TT}

	Measurement	
	$100 < p_T^Z \leq 200$ 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_{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_{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_{00} obs (exp) sig.	5.2 (4.3) σ	1.6 (2.5) σ

- 5.2σ observation of f_{00} in the $100 < P_T^Z < 200$ GeV region
- 3.2σ evidence of f_{00} in the $P_T^Z > 200$ GeV region using 2 parameters fit
- Leading systematic uncertainty from QCD higher order effects

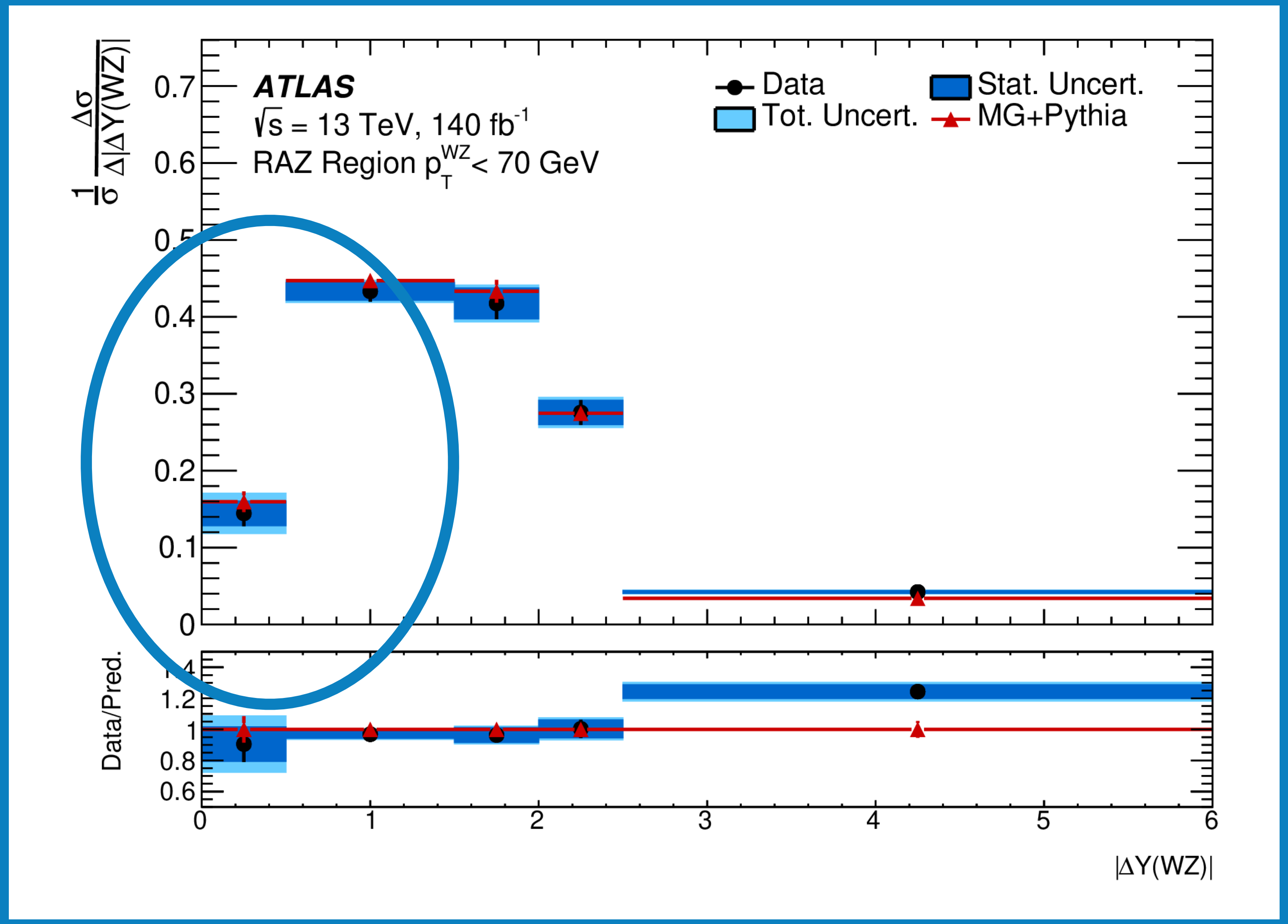
2 parameters fit configurations: f_{00}, f_{xx}

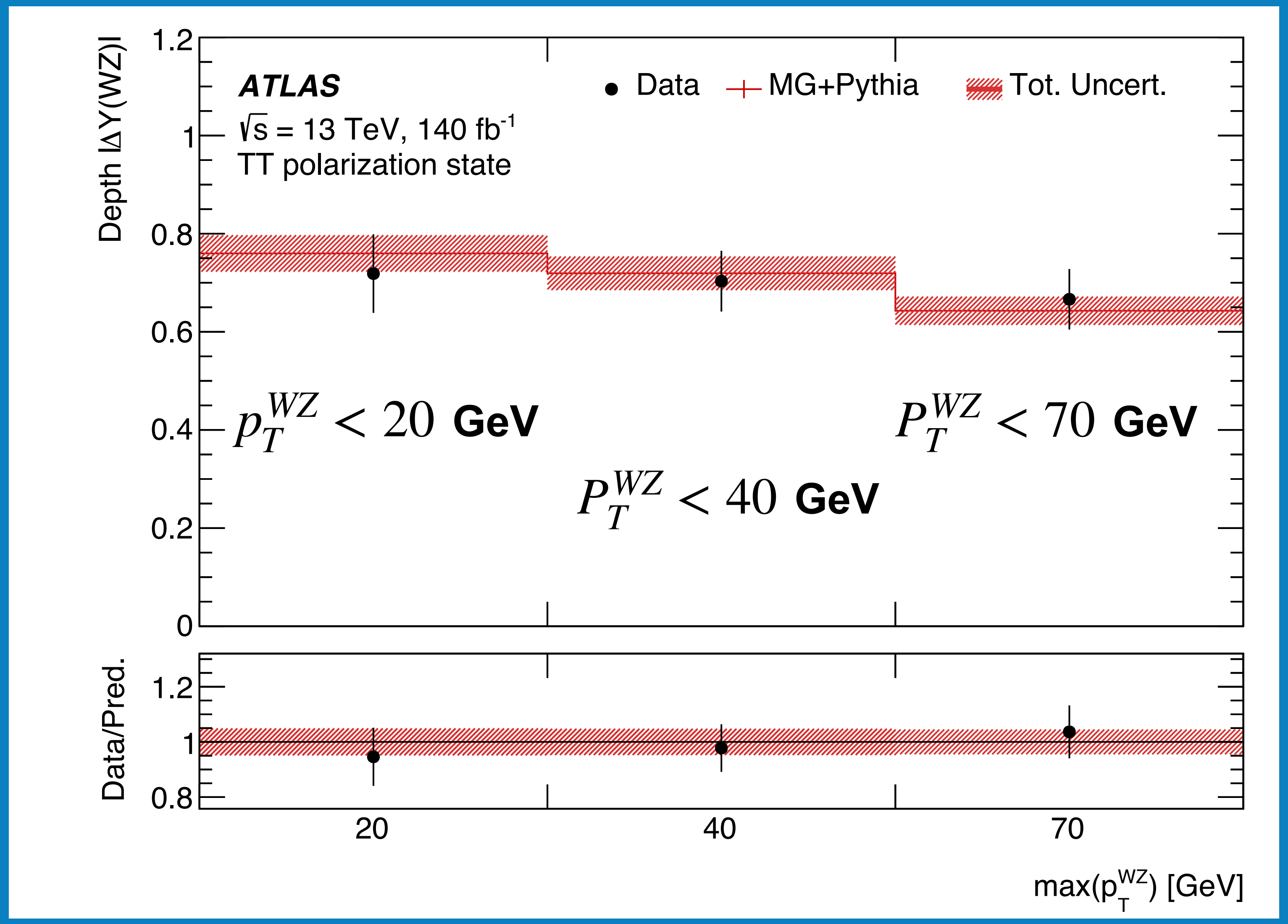
	Measurement	
	$100 < p_T^Z \leq 200$ GeV	**$p_T^Z > 200$ GeV**
f_{00}	$0.17 \pm^{0.02}_{0.02}$ (stat) $\pm^{0.01}_{0.02}$ (syst)	$0.16 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.02}_{0.03}$ (syst)
f_{XX}	$0.83 \pm^{0.02}_{0.02}$ (stat) $\pm^{0.02}_{0.01}$ (syst)	$0.84 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.03}_{0.02}$ (syst)
f_{00} obs (exp) sig.	7.7 (6.9) σ	3.2 (4.2) σ

Radiation Amplitude Zero Effect

- At LO, $W_T Z_T$ the cross-section drops to zero when θ_V approaches $\pi/2$
  - The scattering angle of the W in the WZ rest frame relative to the incoming antiquark direction
- Observed in $\Delta Y(WZ)$ and $\Delta Y(l_W Z)$
- Depth variable to quantify dip: $D = 1 - 2 \cdot \frac{N(|\Delta Y| < 0.5)}{N(0.5 < |\Delta Y| < 1.5)}$

$D > 0$, indicates the existence of a dip





Observed in the P_T^{WZ} regions

Summary

- Measurements of multiboson production processes test gauge interactions within the SM electroweak theory and its symmetry-breaking mechanism
- Multiboson production processes have relatively small cross sections at the LHC and is sensitive to new physics and anomalous triple and quartic gauge couplings
- Presented results are consistent with the SM predictions