Recent Di-boson & Polarization Measurement in ATLAS

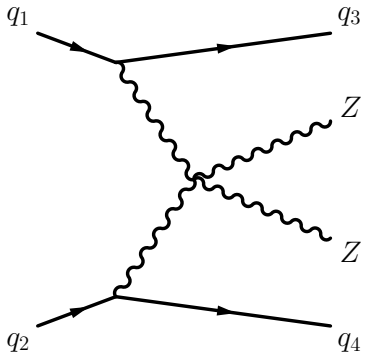
Prajita Bhattarai
on behalf of the ATLAS Collaboration

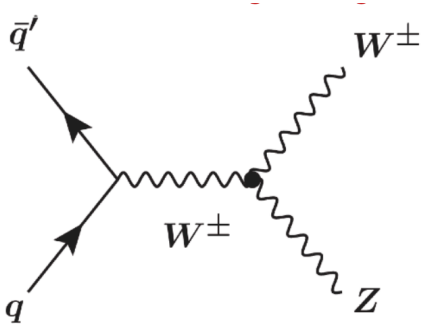
June 7, 2024

SLAC NATIONAL ACCELERATOR LABORATORY
ATLAS EXPERIMENT
Stanford University
U.S. DEPARTMENT OF ENERGY

Introduction

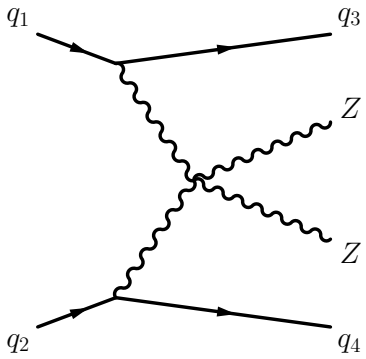
- Probe rare self-couplings between massive vector bosons in the Standard Model
  - Sensitive to new physics with anomalous gauge couplings

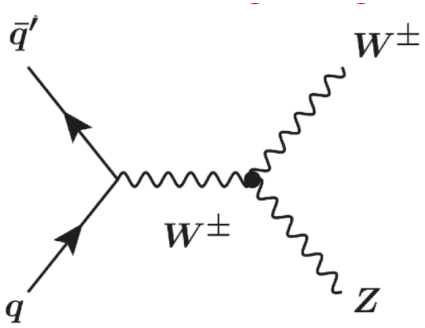




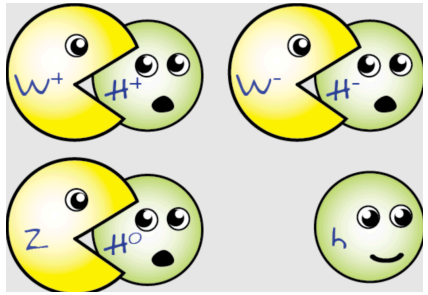
Introduction

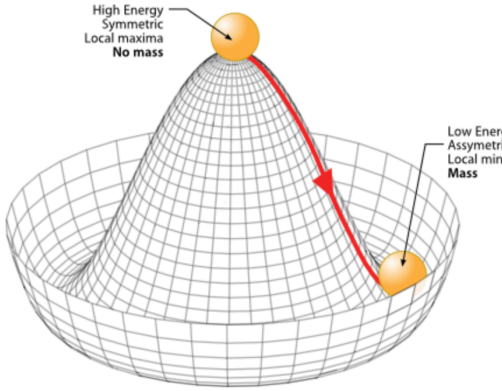
- Probe rare self-couplings between massive vector bosons in the Standard Model
  - Sensitive to new physics with anomalous gauge couplings





- Mass and longitudinal polarization of vector bosons from Higgs mechanism
  - Critical to measure cross-section of longitudinal polarization mode, any deviation hints of new physics

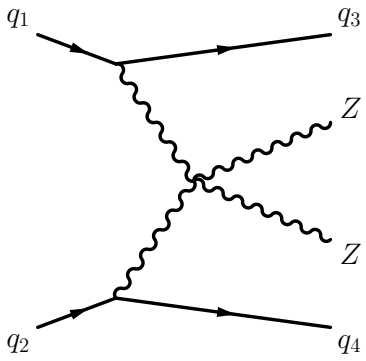


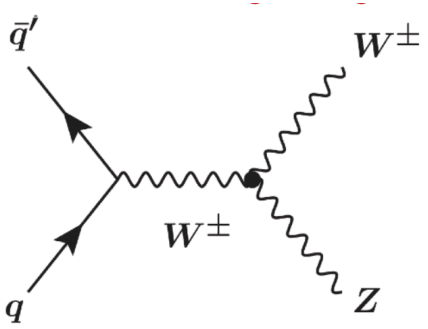


  - Sensitive to new physics with preferential coupling to certain polarization modes

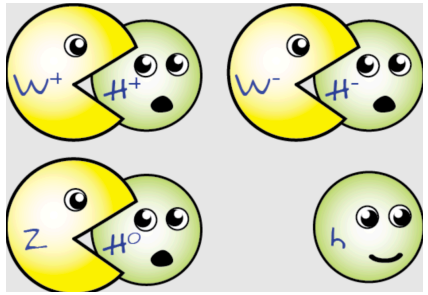
Introduction

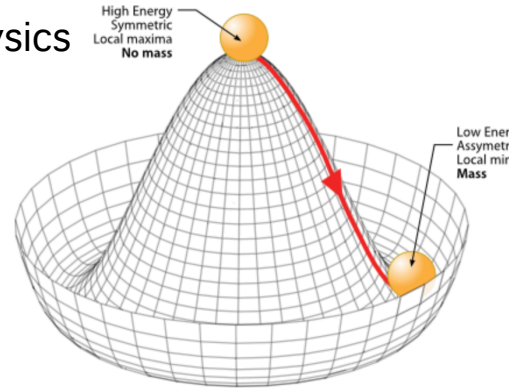
- Probe rare self-couplings between massive vector bosons in the Standard Model
  - Sensitive to new physics with anomalous gauge couplings





- Mass and longitudinal polarization of vector bosons from Higgs mechanism
  - Critical to measure cross-section of longitudinal polarization mode, any deviation hints of new physics





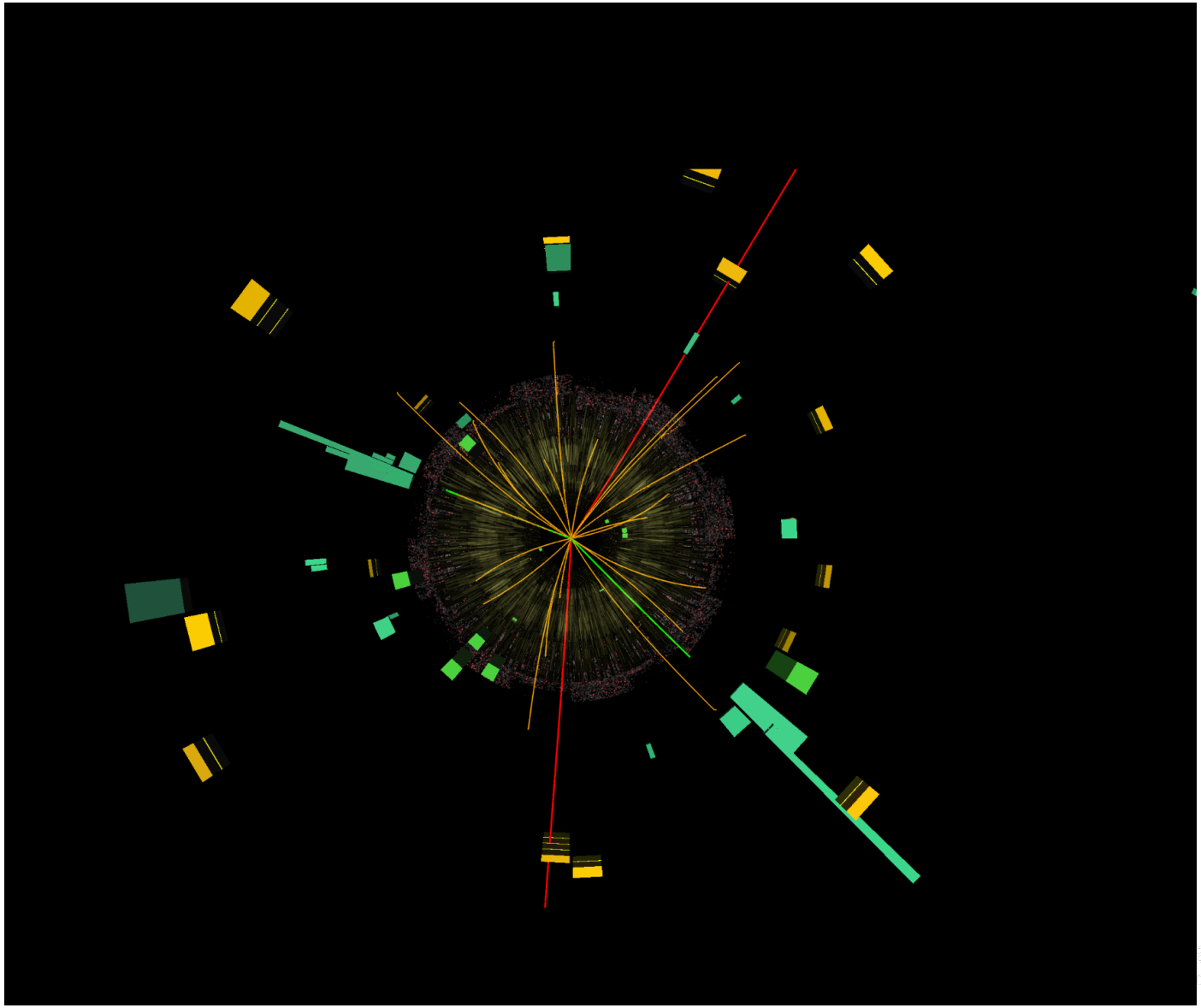
  - Sensitive to new physics with preferential coupling to certain polarization modes

- This talk focuses on 3 recent analyses from ATLAS with ZZ & WZ in leptonic final state
  - Clean detector signature with prompt leptons

  - 13.6 TeV ZZ measurement arXiv:2311.09715
  - 13 TeV measurement ZZ Polarization & CP violation search JHEP12(2023)107
  - 13 TeV measurement WZ Polarization at high pT arXiv:2402.16365

ZZ 13.6 TeV

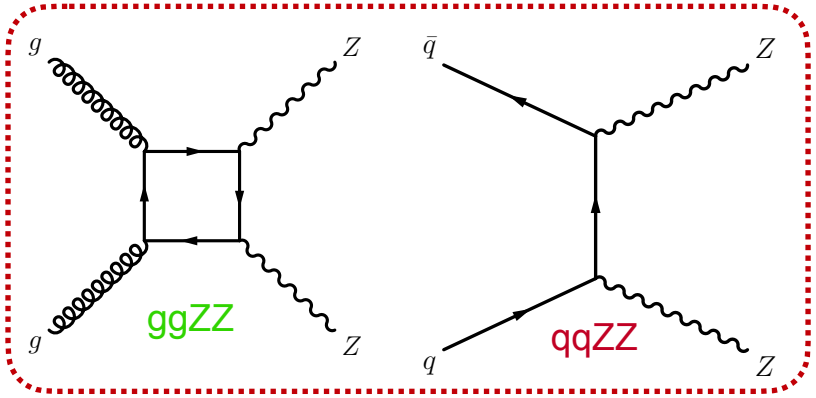
- First measurement of ZZ cross-section at 13.6 TeV
- Partial Run-3 29fb^{-1} of data

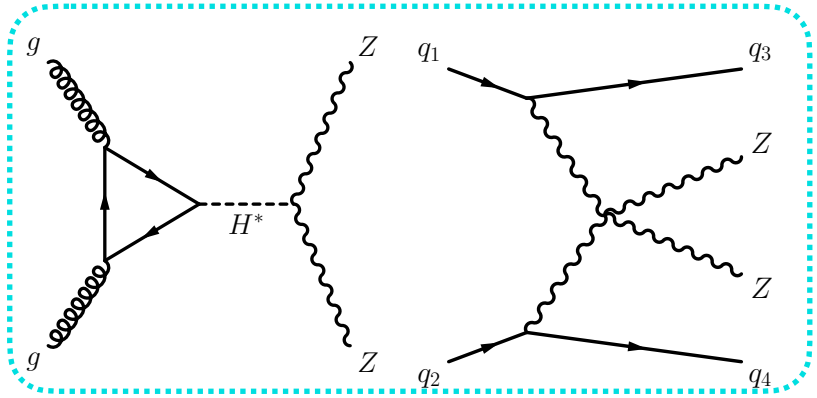


ZZ 13.6 TeV

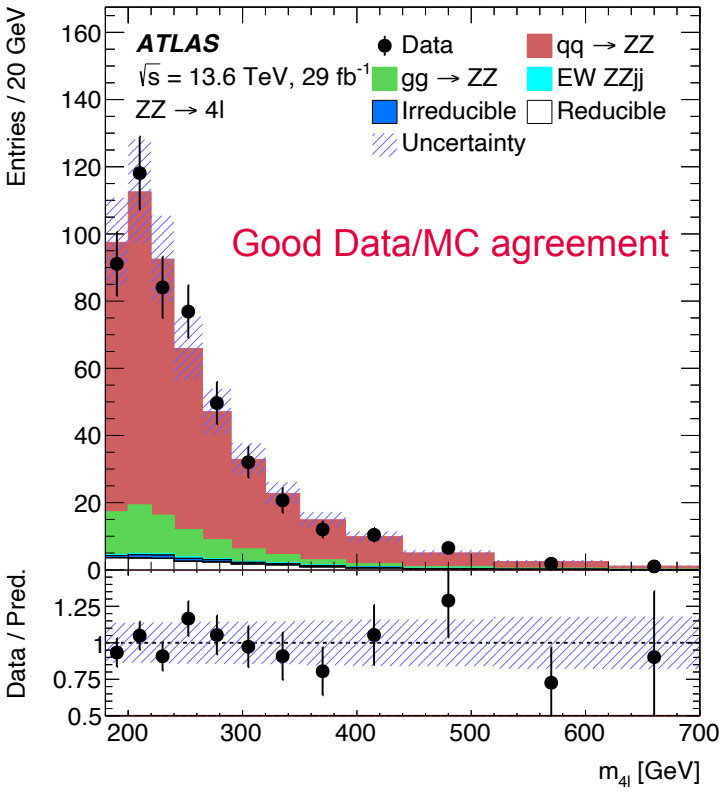
13.6 TeV Partial Run-3 29 fb^{-1} arXiv:2311.09715

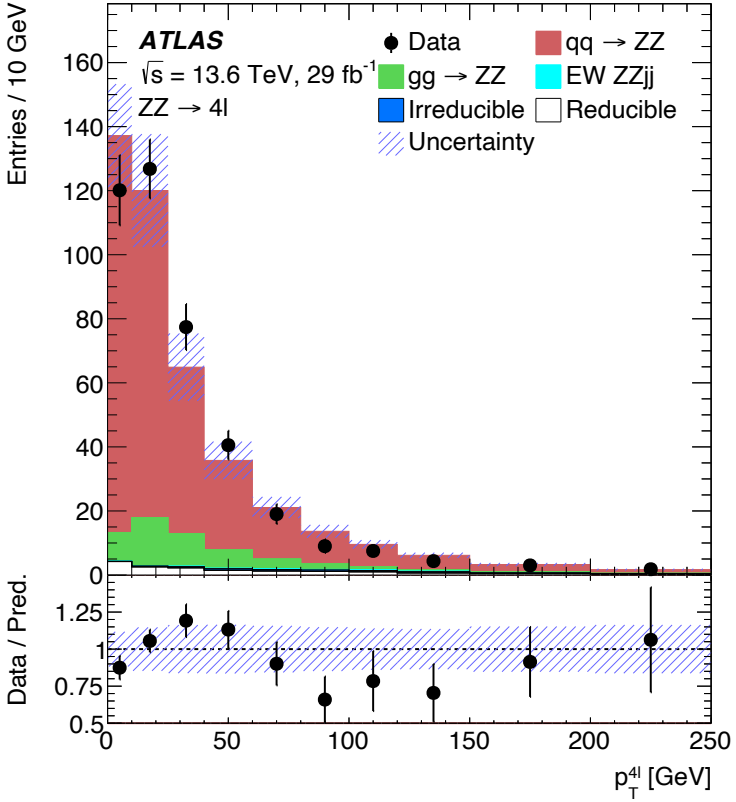
- QCD (dominant) & EWK production
- On-shell ZZ measurement





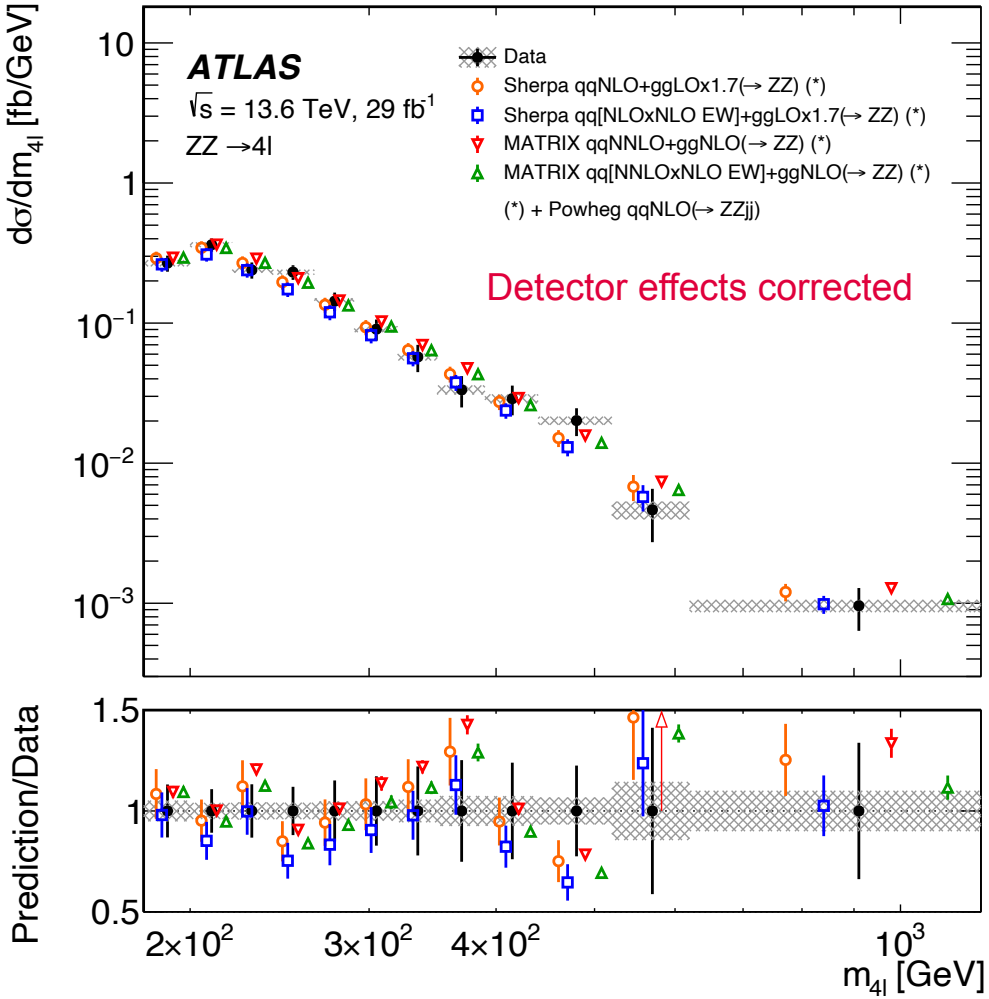
- Each Z decay to same flavor opposite sign lepton pairs
- Small fraction of irreducible (ttV & VVV) and non-prompt lepton background



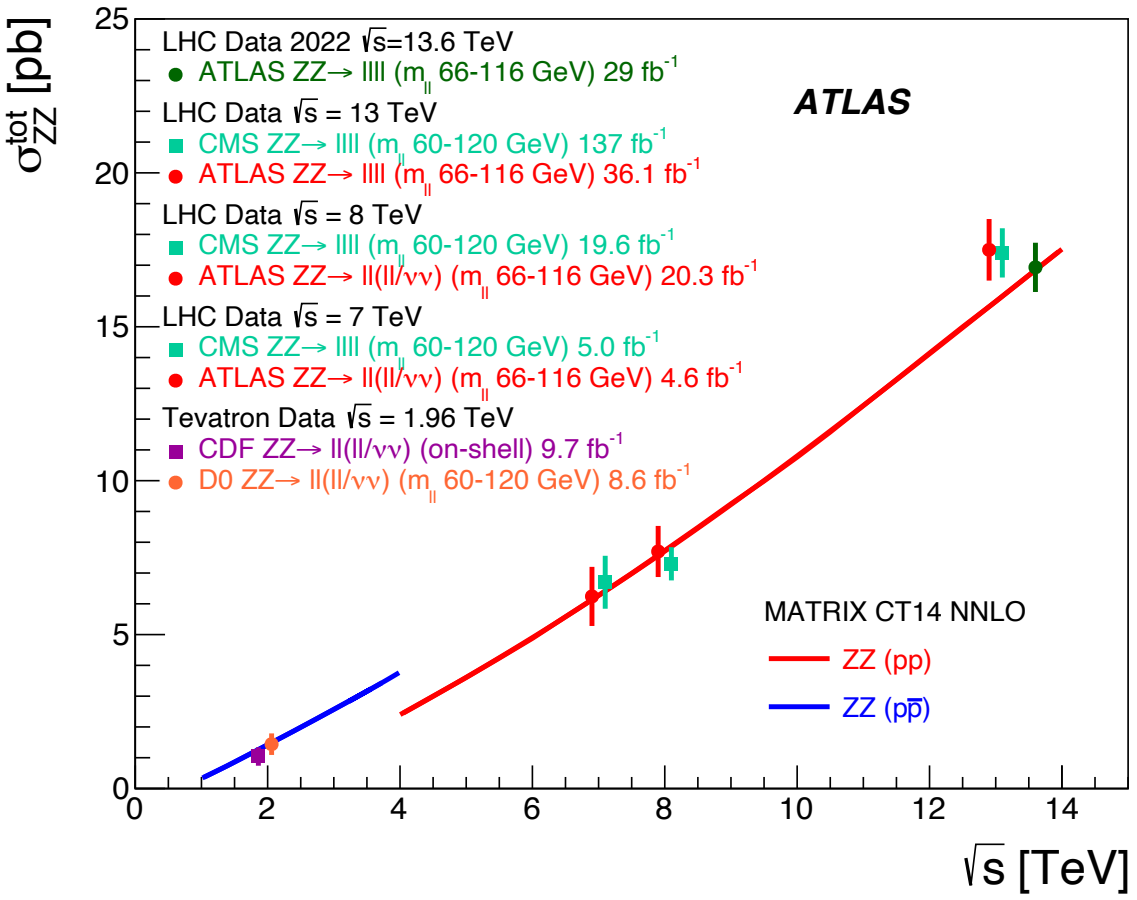


ZZ 13.6 TeV

- Inclusive & differential cross-section measurements with comparison to various state-of-the-art MC predictions

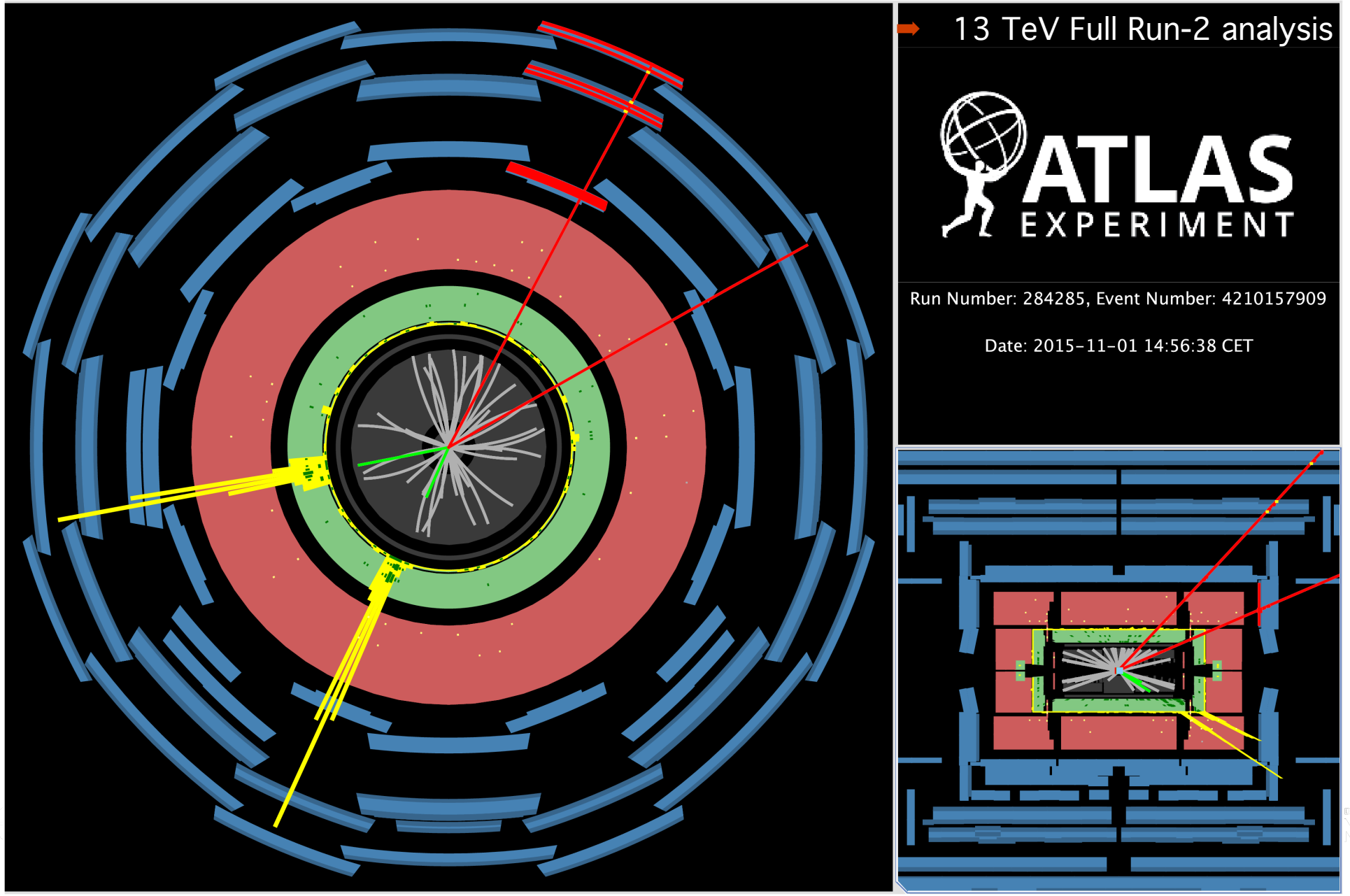


- ZZ(4l) total cross-section vs center of mass energy



- No deviation from Standard Model prediction

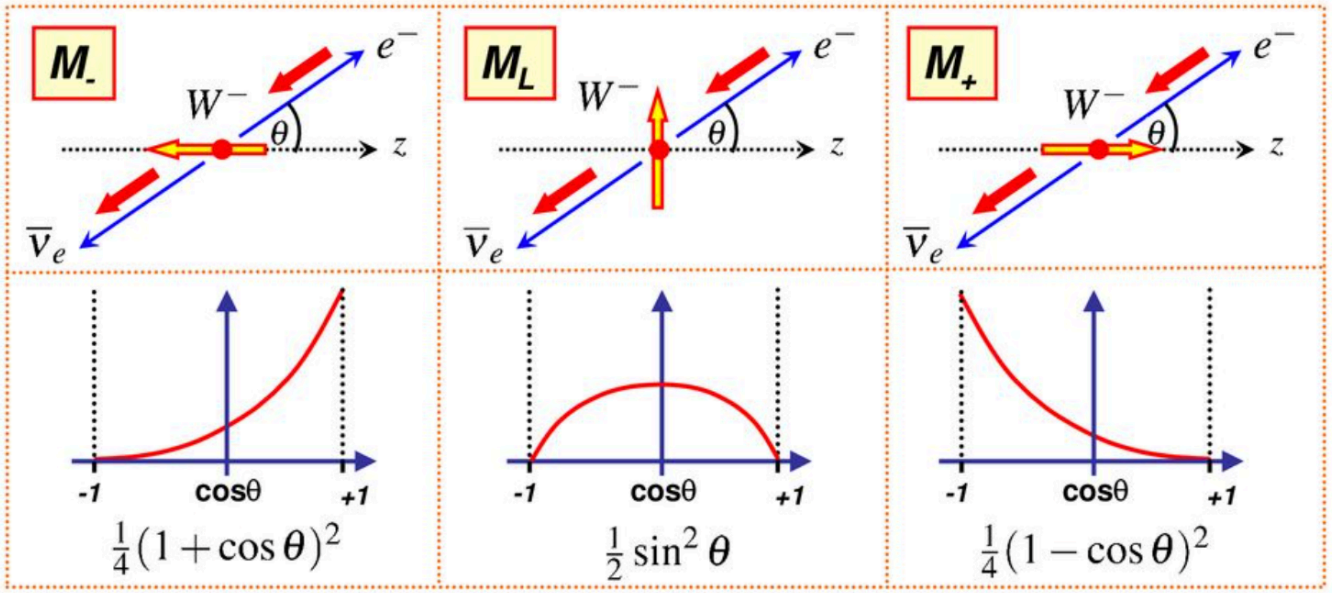
Full Run-2 13TeV ZZ Angular CP & Polarization



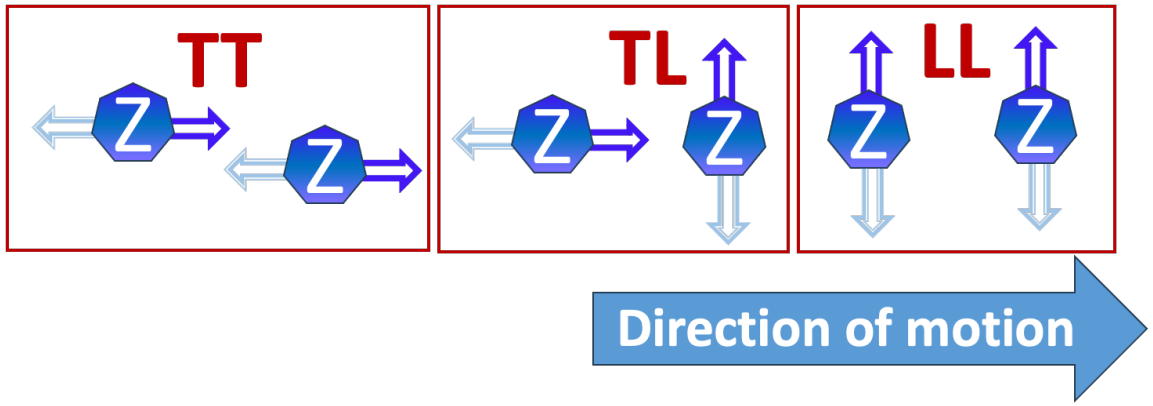
ZZ Angular CP & Polarization

- Reconstructed angular information for all final state particle, golden channel for polarization measurement
- Target to measure simultaneously longitudinally polarized ZZ & search for CP violation
- Due to conservation of angular momentum, vector bosons with different polarization states have different production & decay angular distributions

For single Vector boson decay

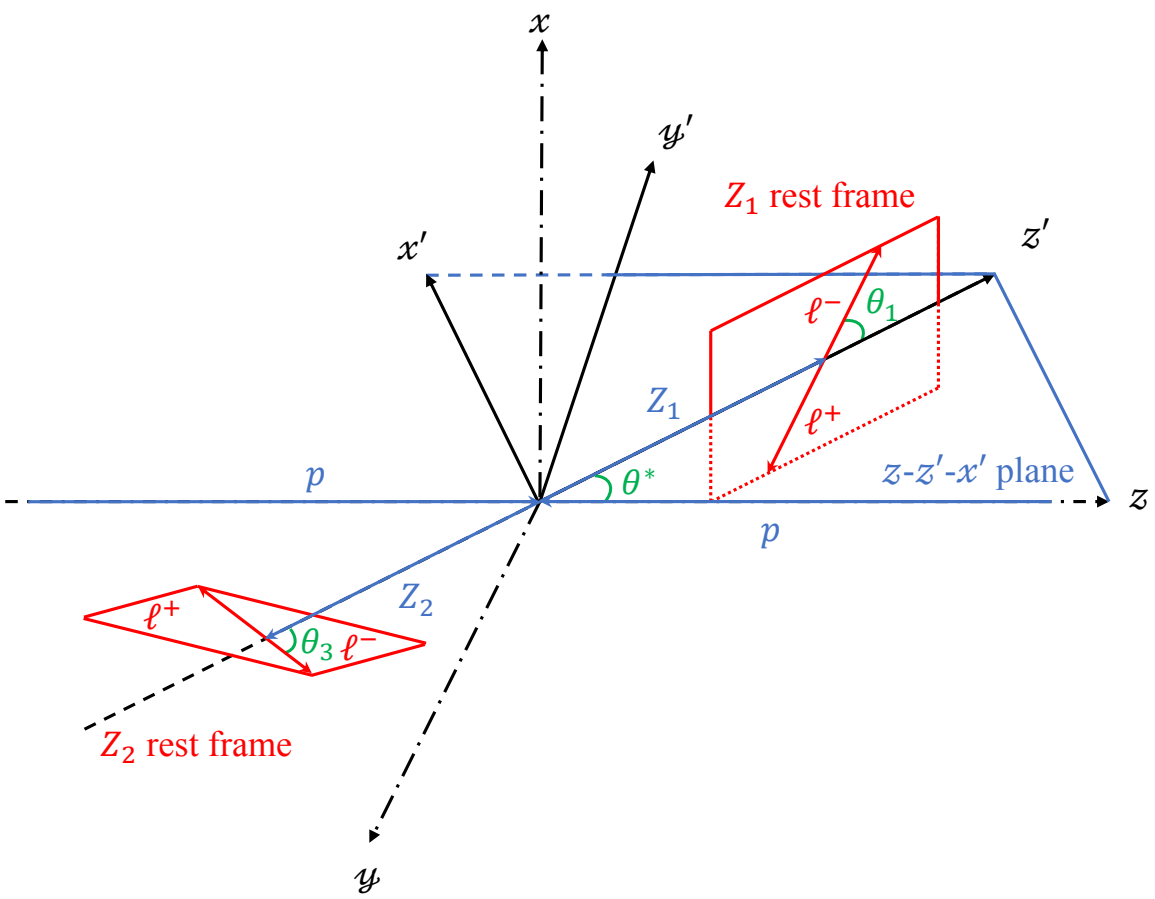


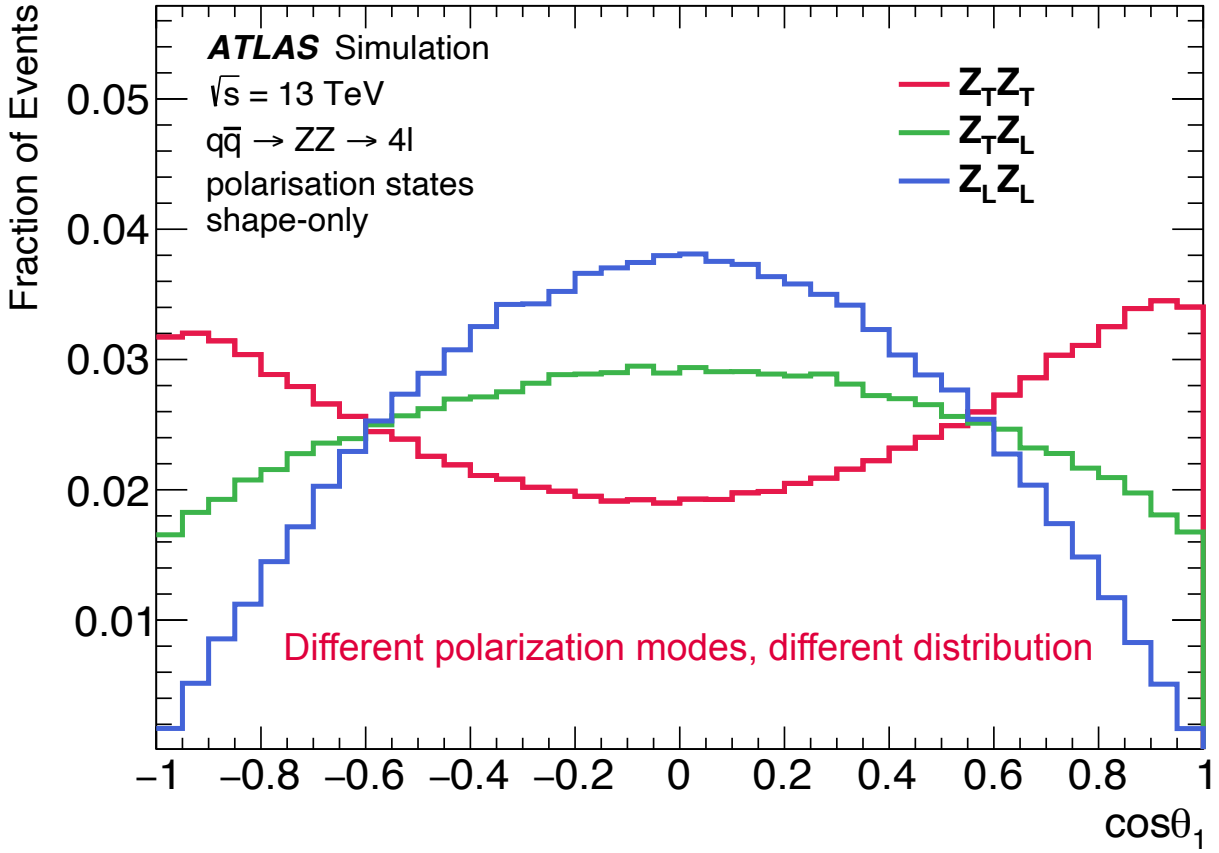
For two vector boson decay



ZZ Angular CP & Polarization

Angles defined in either ZZ or Z rest frames

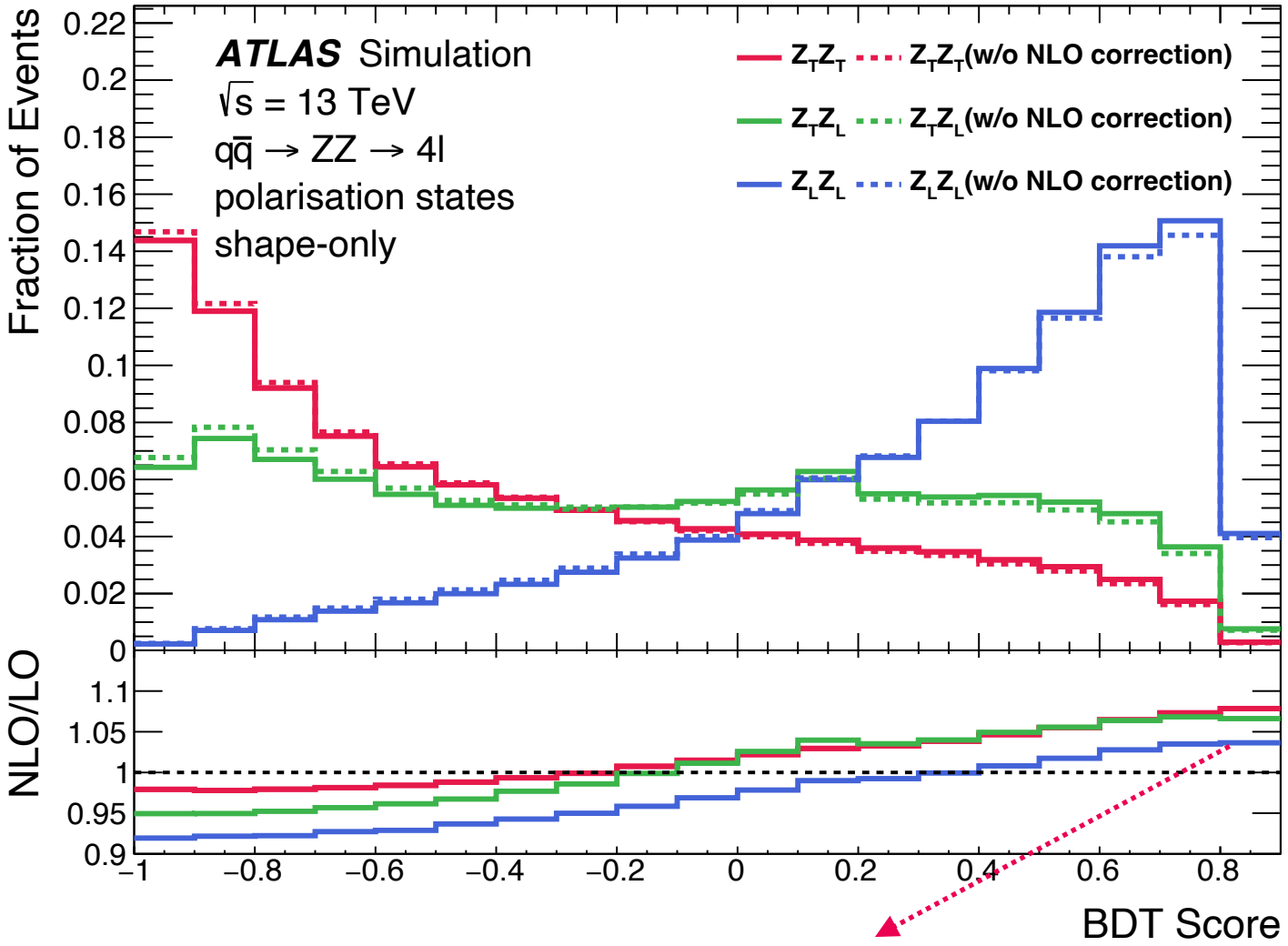




➡ MVA trained using angular observables to extract Z_LZ_L

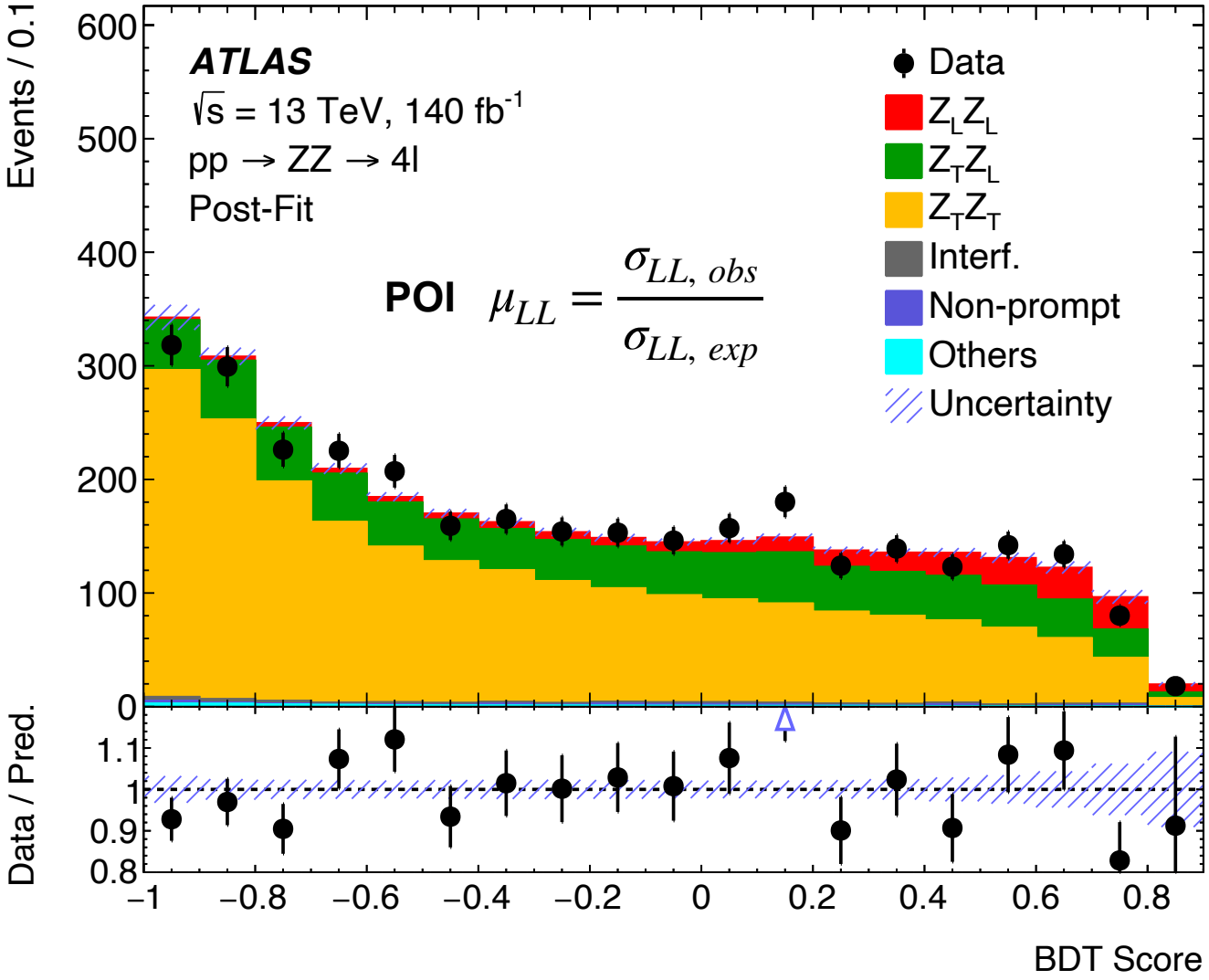
ZZ Angular CP & Polarization

- Main challenge, getting NLO corrected polarized template
- qqZZ LO template available, additional NLO correction
  - Correction applied using 1 & 2 dimensional reweighing process using numerical calculations from JHEP10(2021)097



NLO effects higher at high BDT score

ZZ Angular CP & Polarization



stat sys

$$\mu_{LL} = 1.15 \pm 0.27 \pm 0.11$$

First experimental 4.3σ evidence of $Z_L Z_L$

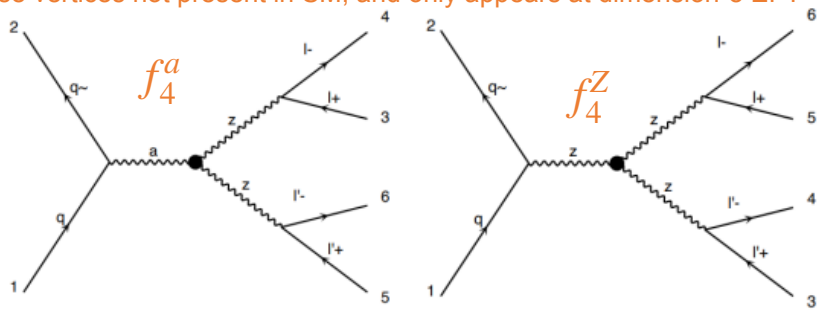
	σ [fb]
Observed	$2.45 \pm 0.56 \pm 0.21$
Expected	2.10 ± 0.09

➡ No deviation from Standard Model prediction

ZZ Angular CP & Polarization

- Model independent dimension-8 EFT to search for CP violation in diboson sector
- Consider two CP-odd operators

These vertices not present in SM, and only appears at dimension-8 EFT



CP odd & main target of the analysis

SM cross-section

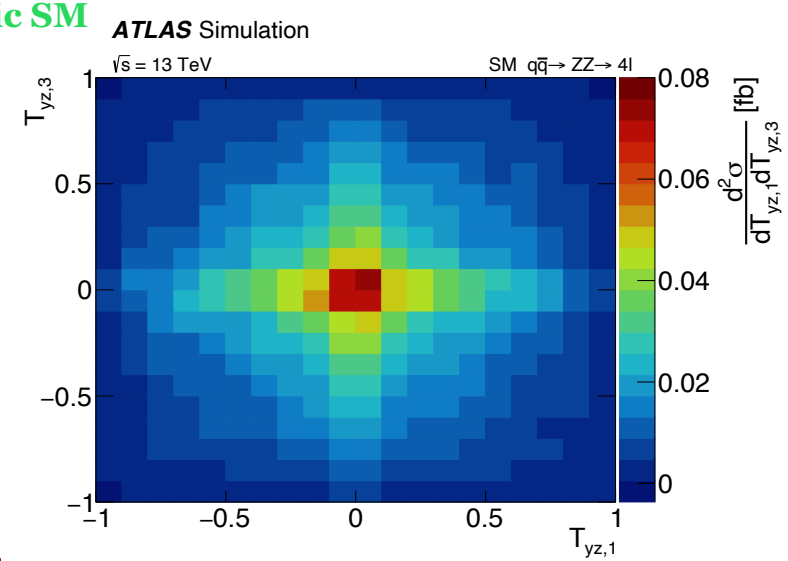
EFT only contribution

$$\sigma_{pred} = \sigma_{SM} + c \cdot \sigma_{interf} + c^2 \cdot \sigma_{quad}$$

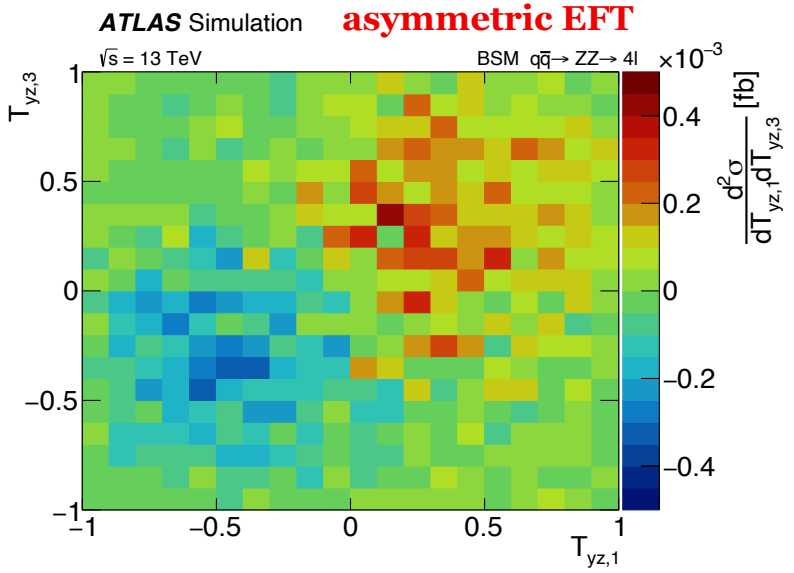
interference between SM & EFT

- Angular observable sensitive to CP violating effects, analysis constructs a observable to enhance sensitivity

Symmetric SM

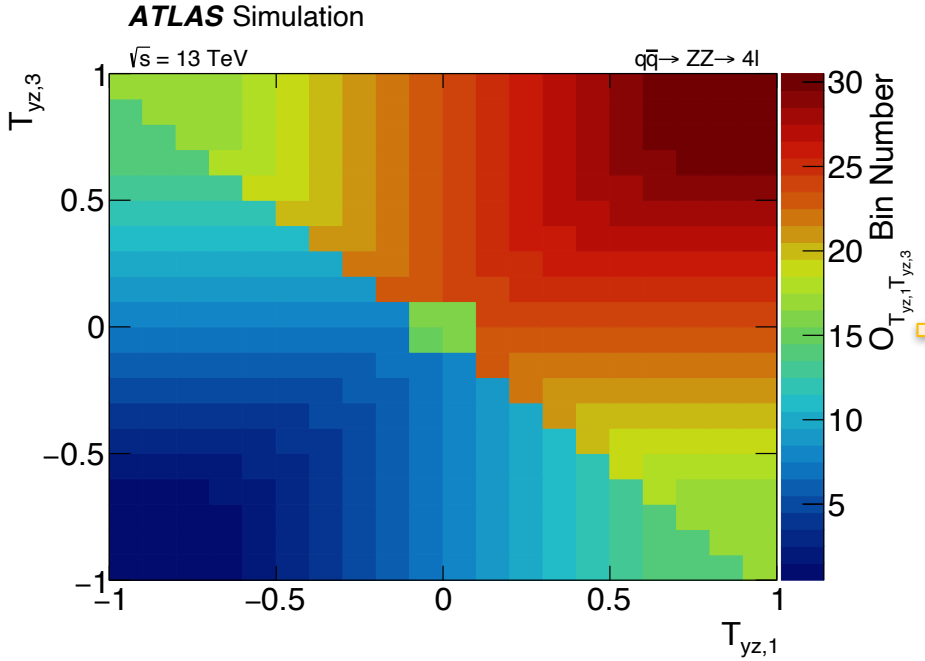


asymmetric EFT



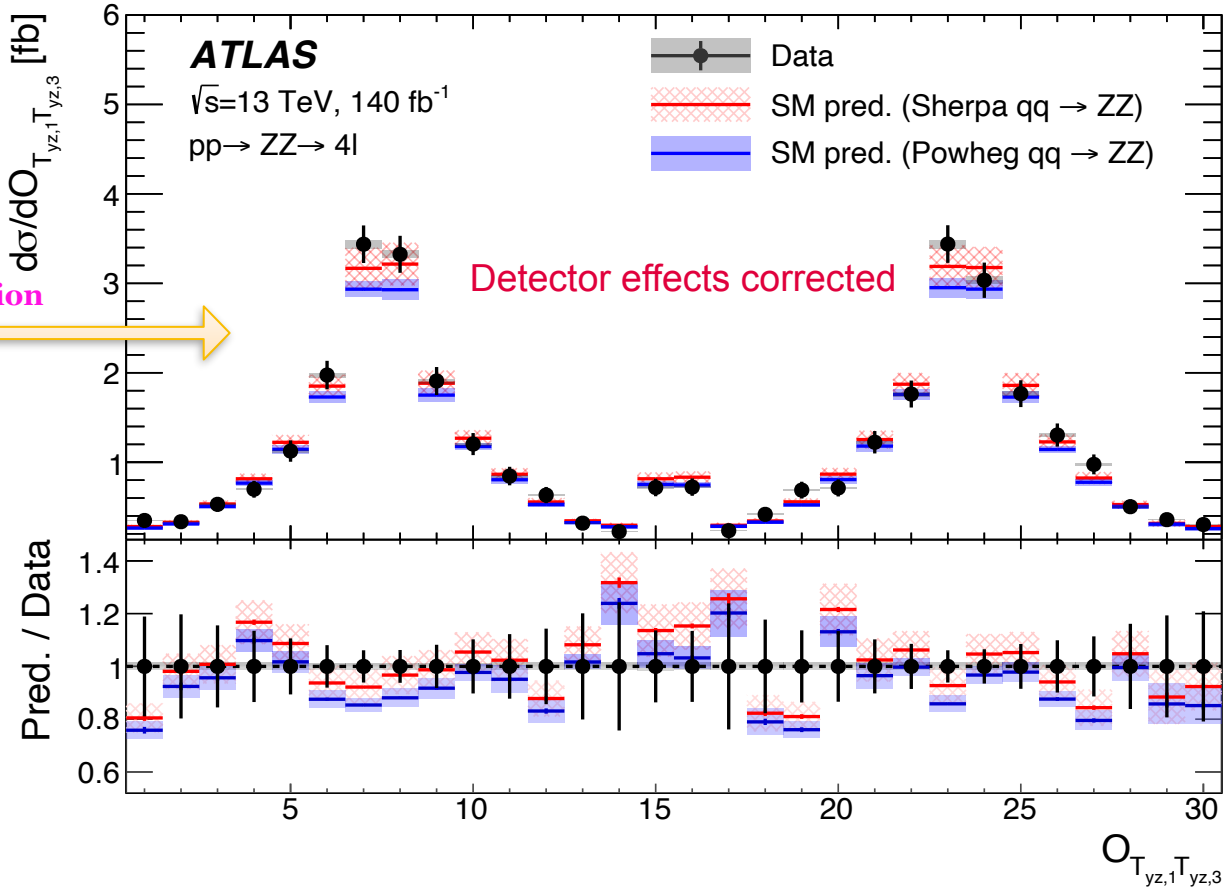
ZZ Angular CP & Polarization

- Construct 1D map observable based on 2D distribution



1D projection

- Unfolded differential cross-section of 1D map



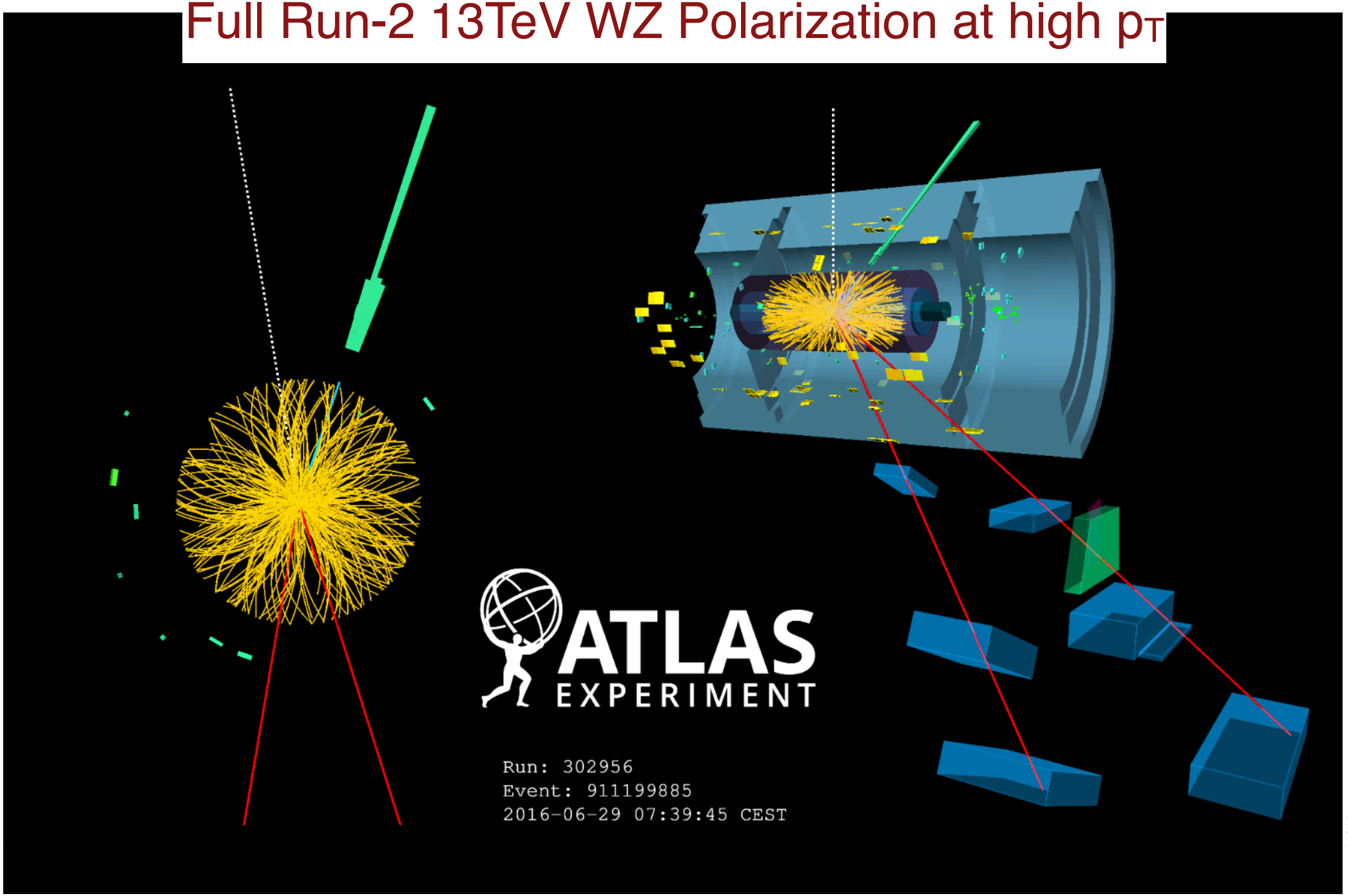
- Constraints on EFT operators using unfolded differential cross-section

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

10-30%

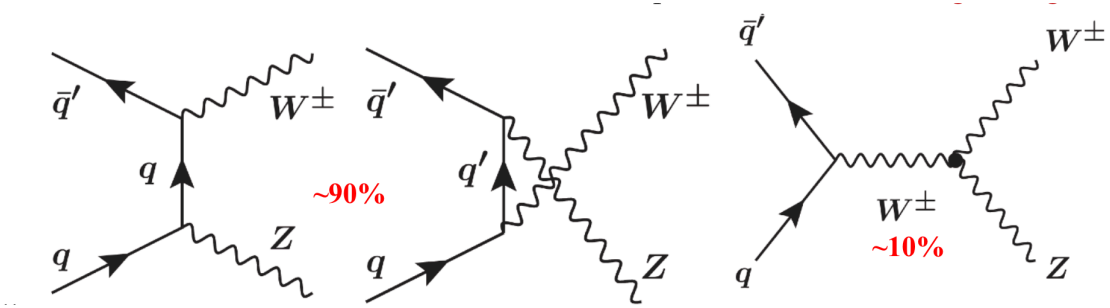
- No deviation from Standard Model prediction

Full Run-2 13TeV WZ Polarization at high p_T



WZ High pT Polarization

- LO inclusive WZ production

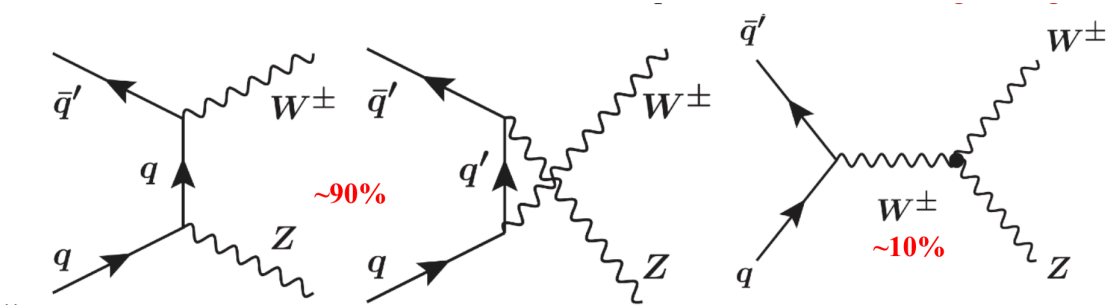


  - S-channel more interesting with self interactions

- Measurement of polarization fractions of WZ bosons in two fiducial regions to study energy dependence
  - Both bosons longitudinally polarized bosons ~6%

WZ High pT Polarization

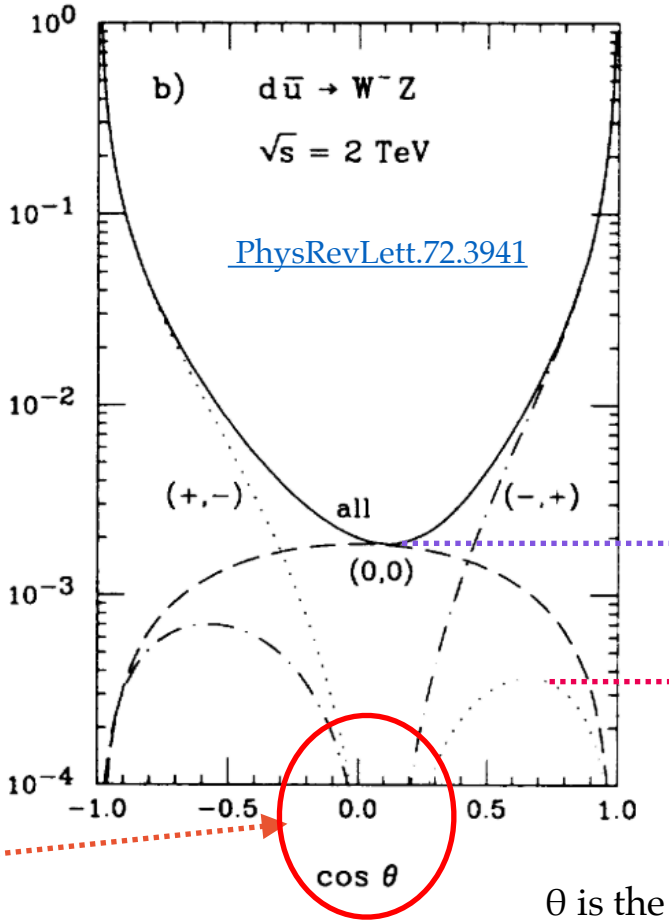
- L0 inclusive WZ production



  - S-channel more interesting with self interactions

- Measurement of polarization fractions of WZ bosons in two fiducial regions to study energy dependence
  - Both bosons longitudinally polarized bosons ~6%

- First study of Radiation Amplitude Zero (RAZ) effect in WZ
  - LO QCD effect in TT events
  - Destructive interference due to helicity resulting in 0 cross-sections at certain phase space



Total cross-section decreases

TT distribution

θ is the angle between the W boson and the incident fermion (d)

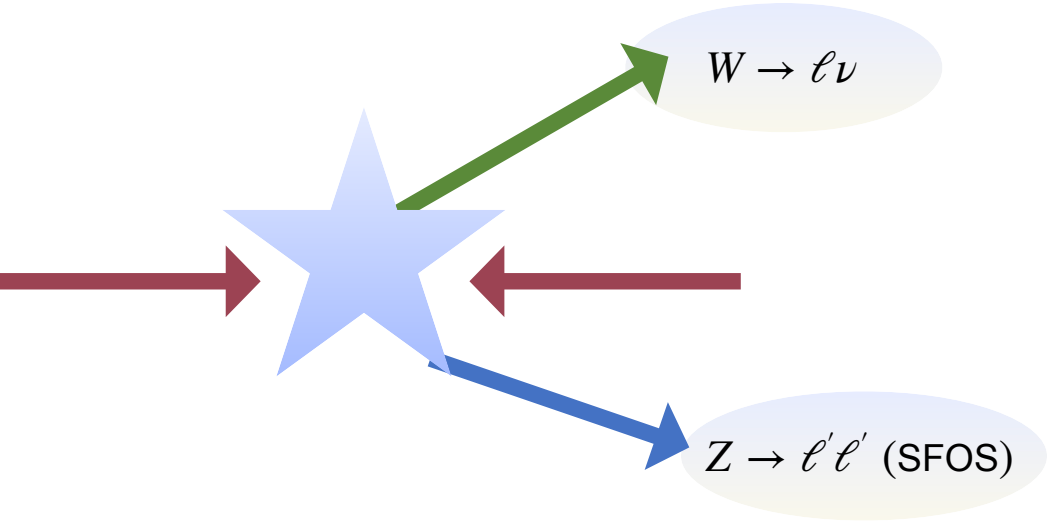
WZ High pT Polarization

Inclusive WZ selection

- $m_T^W > 30$ GeV
- $\Delta R(\ell'\ell) > 0.3$
- $\Delta R(\ell'^+\ell'^-) > 0.2$
- $|m_{\ell\ell} - m_Z| < 10$ GeV

	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	

Motivated to increase 00 fraction from 5-7% to 20-30%



- Four polarization fraction f_{00}, f_{T0}, $f_{0,T}$ & f_{TT}

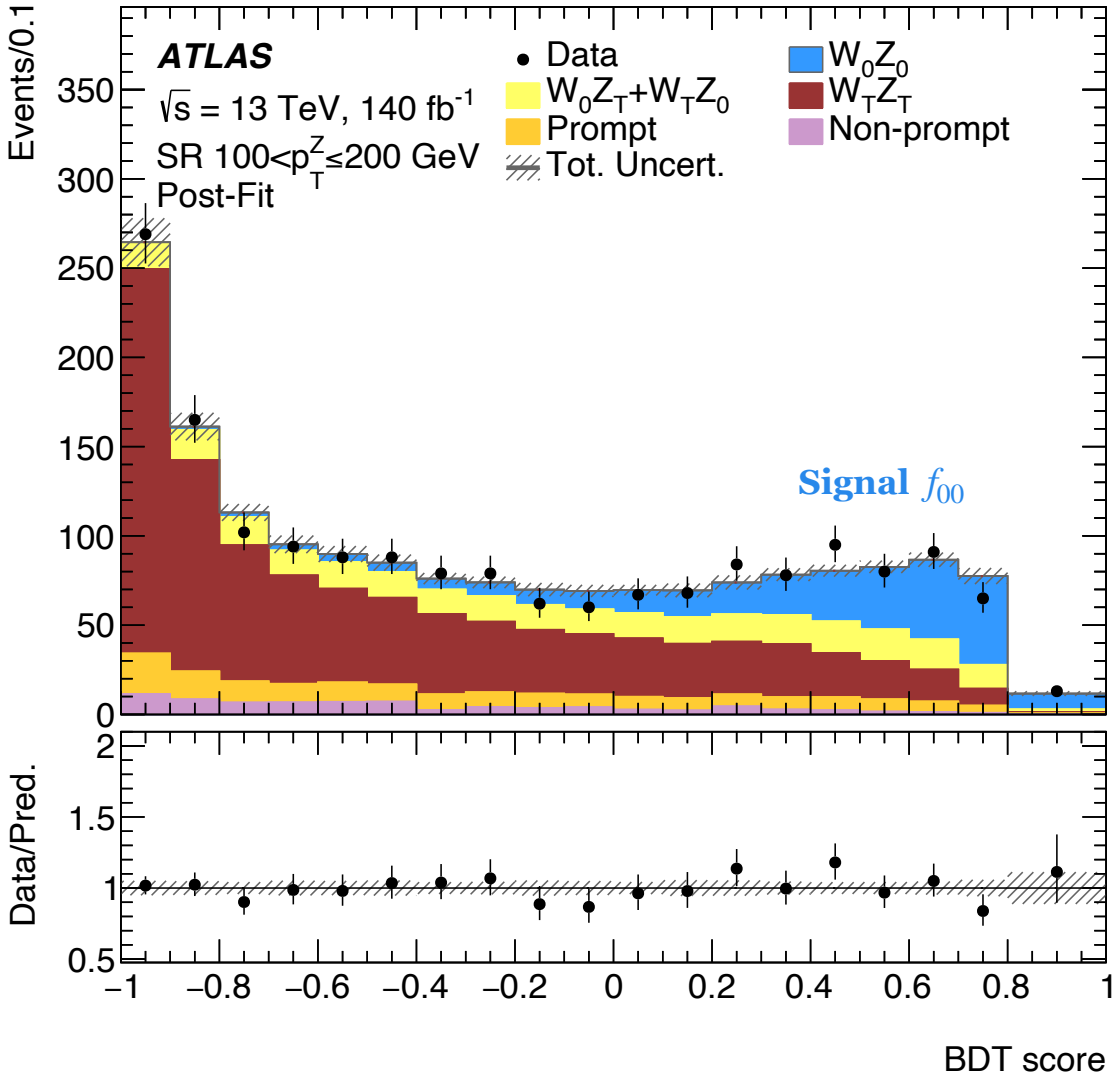
0 longitudinal polarization
T transverse

Signal f_{00}

- Similar to ZZ, NLO polarized templates unavailable, L0 WZ+0jets and WZ+1jet event generated with Madgraph to emulate NLO QCD effects
- BDT trained to separate longitudinally polarized events, separate for each SR

WZ High pT Polarization

- BDT trained to separate longitudinally polarized events, separate for each SR



	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 sigma observation in $100 < p_{T,Z} < 200$ **GeV for** f_{00}

Measurement limited by stat uncertainty

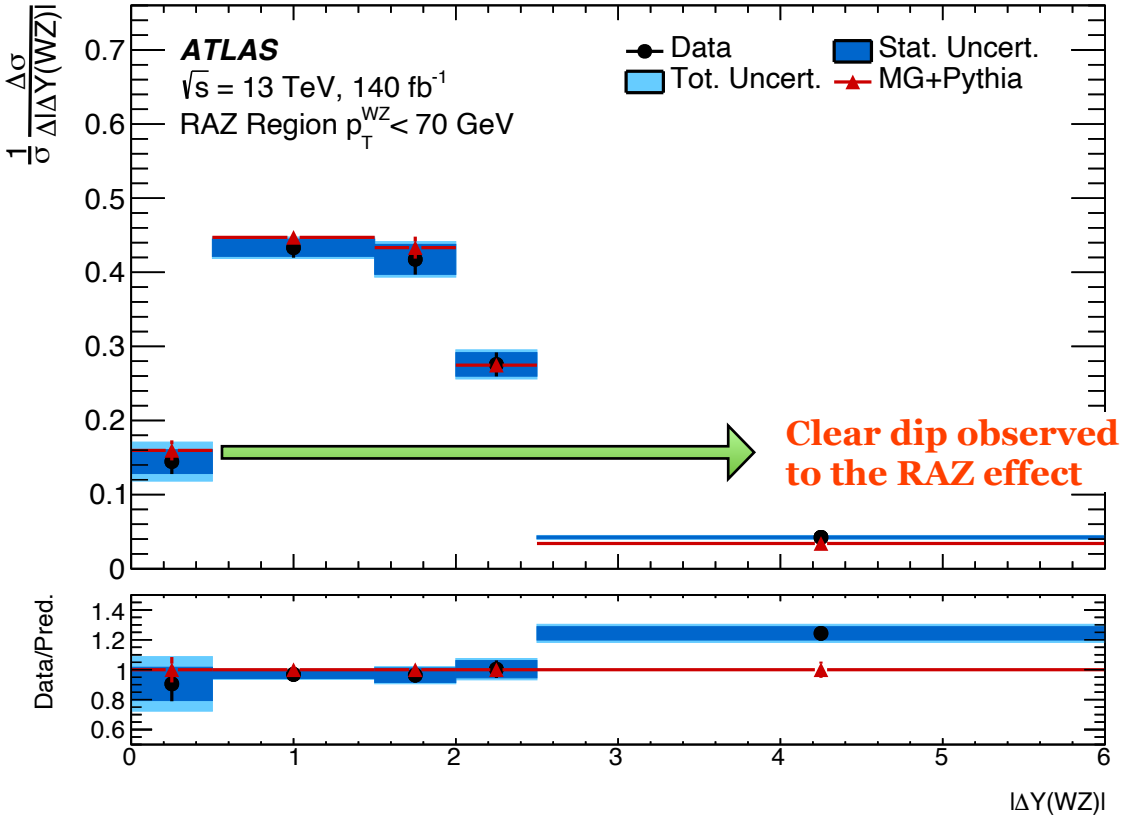
➡ No deviation from Standard Model prediction

WZ High pT Polarization

	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	

➡ Unfolded rapidity difference between W & Z $[\Delta Y(WZ)]$ for TT events

Motivated to suppress background events from WZ+jets



Clear dip observed corresponding to the RAZ effect

➡ Similar effects observed in all SR

Conclusion

➡ Presented 3 results from ATLAS

- 13.6 TeV ZZ measurement arXiv:2311.09715
- Inclusive & differential cross-section measurement of SM ZZ production & new center of mass energy
- No deviation from SM predictions

- ZZ Polarization & CP violation search JHEP12(2023)107
- First evidence @4.3 sigma for simultaneously longitudinally polarized ZZ
- Constraints on two CP odd dimension-8 effective field theory (EFT) giving anomalous neutral gauge couplings

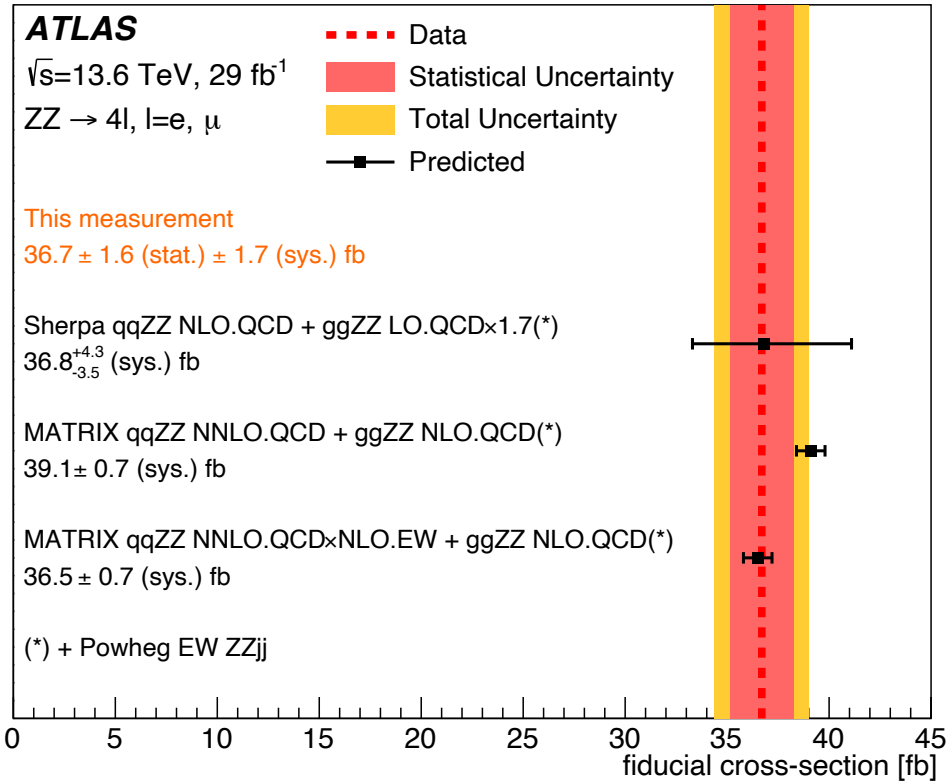
- WZ Polarization at high pT arXiv:2402.16365
- Measurement of diboson polarization fraction, 5.2 sigma effect for $100 < p_T^Z < 200$ GeV
- First study of Radiation Amplitude Zero (RAZ) effect in WZ, unfolded cross-section show decrease near 0 rapidity difference

Backup

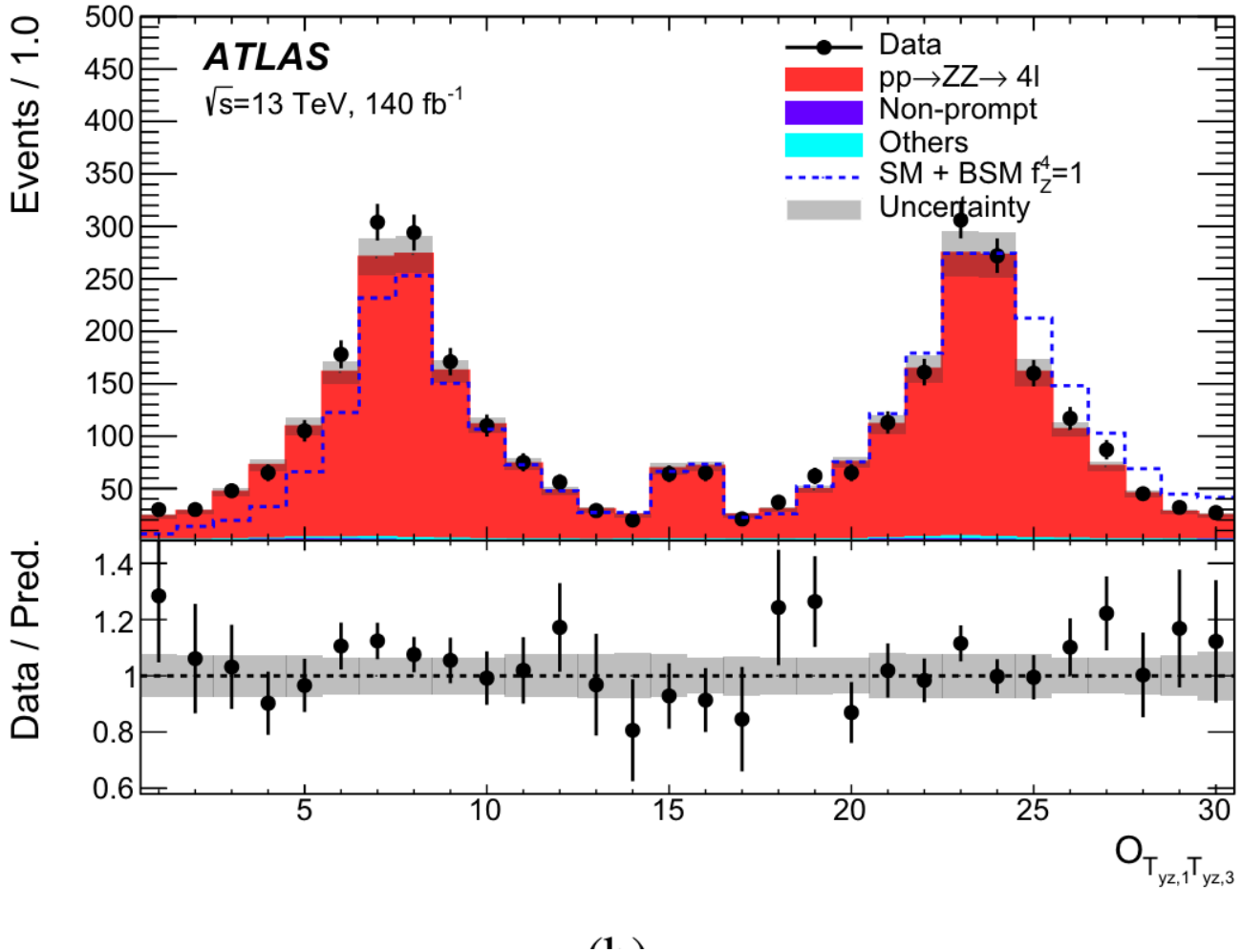
ZZ 13.6 TeV

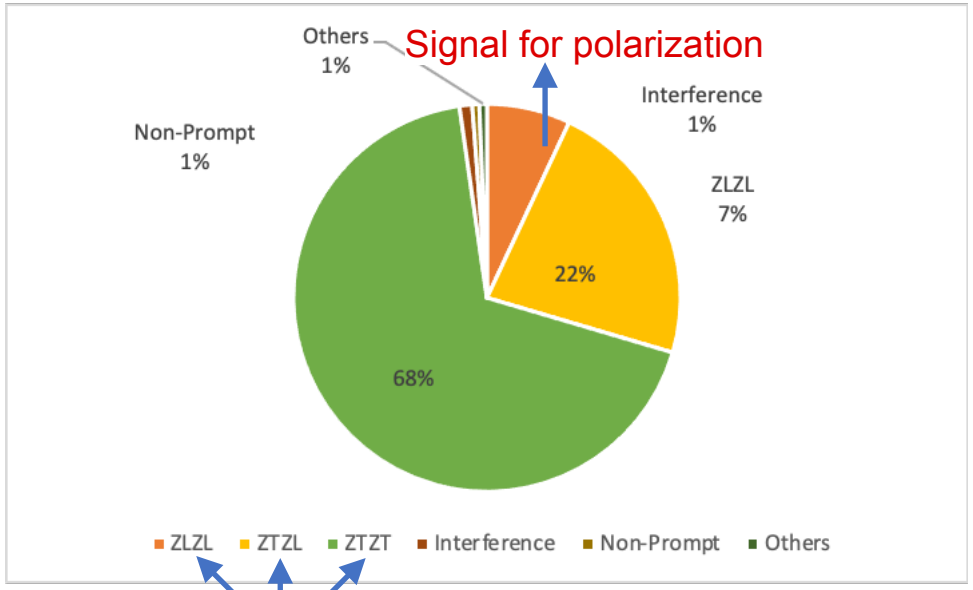
ATLAS-CONF-2023-012

Source	Relative uncertainty(%)
Data statistical uncertainty	4.2
MC statistical uncertainty	0.3
Luminosity	2.2
Lepton momentum	0.2
Lepton efficiency	3.7
Background	1.6
Theoretical uncertainty	1.0
Total	6.3



ZZ Angular CP & Polarisation



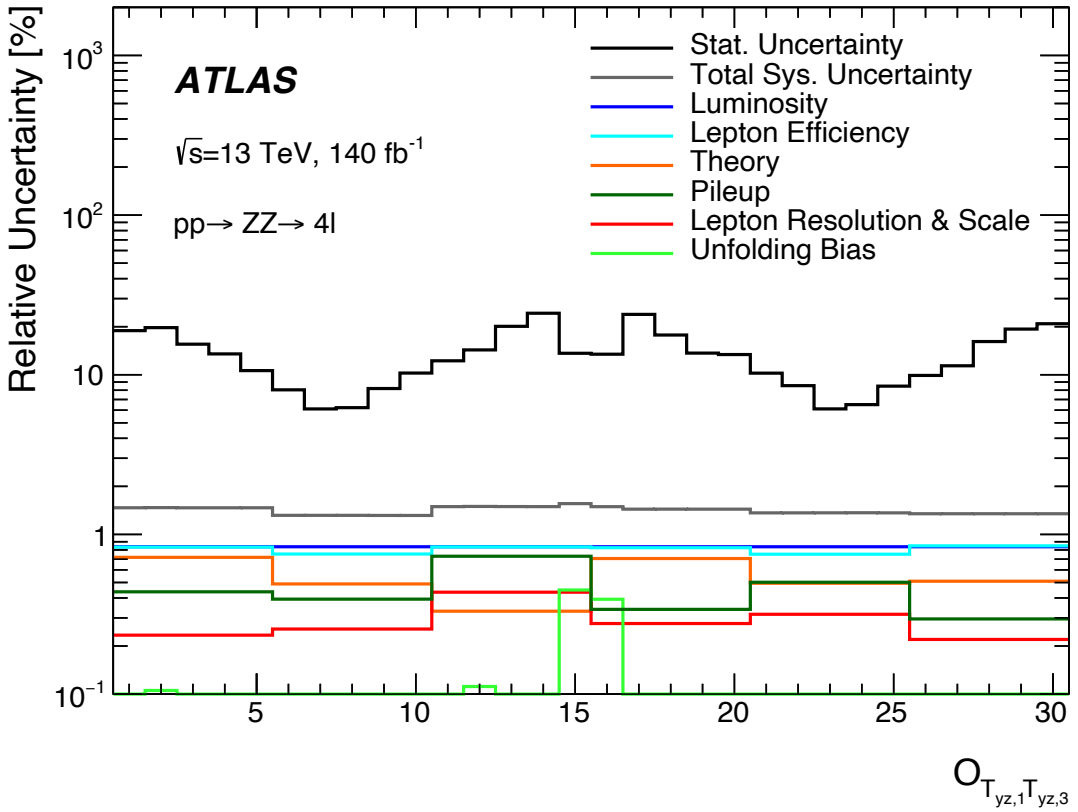


ZZ Angular CP & Polarisation

JHEP12(2023)107

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

$$\mathrm{ggZZ}_{\mathrm{pol}}^{\mathrm{reco}} = \frac{\mathrm{MoCaNLO}_{\mathrm{pol}}^{\mathrm{ggZZ,parton}}}{\mathrm{MoCaNLO}_{\mathrm{incl}}^{\mathrm{ggZZ,parton}}} \times \mathrm{Sherpa}_{\mathrm{incl}}^{\mathrm{ggZZ,reco}}$$

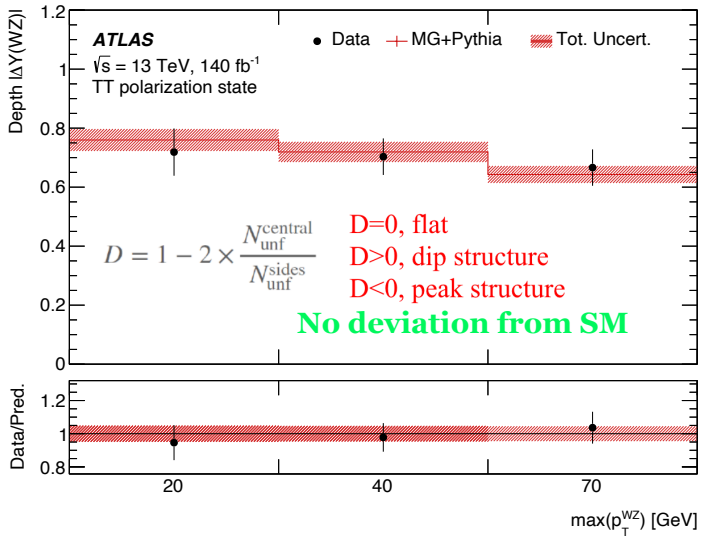


WZ High pT Polarization

arXiv:2402.16365

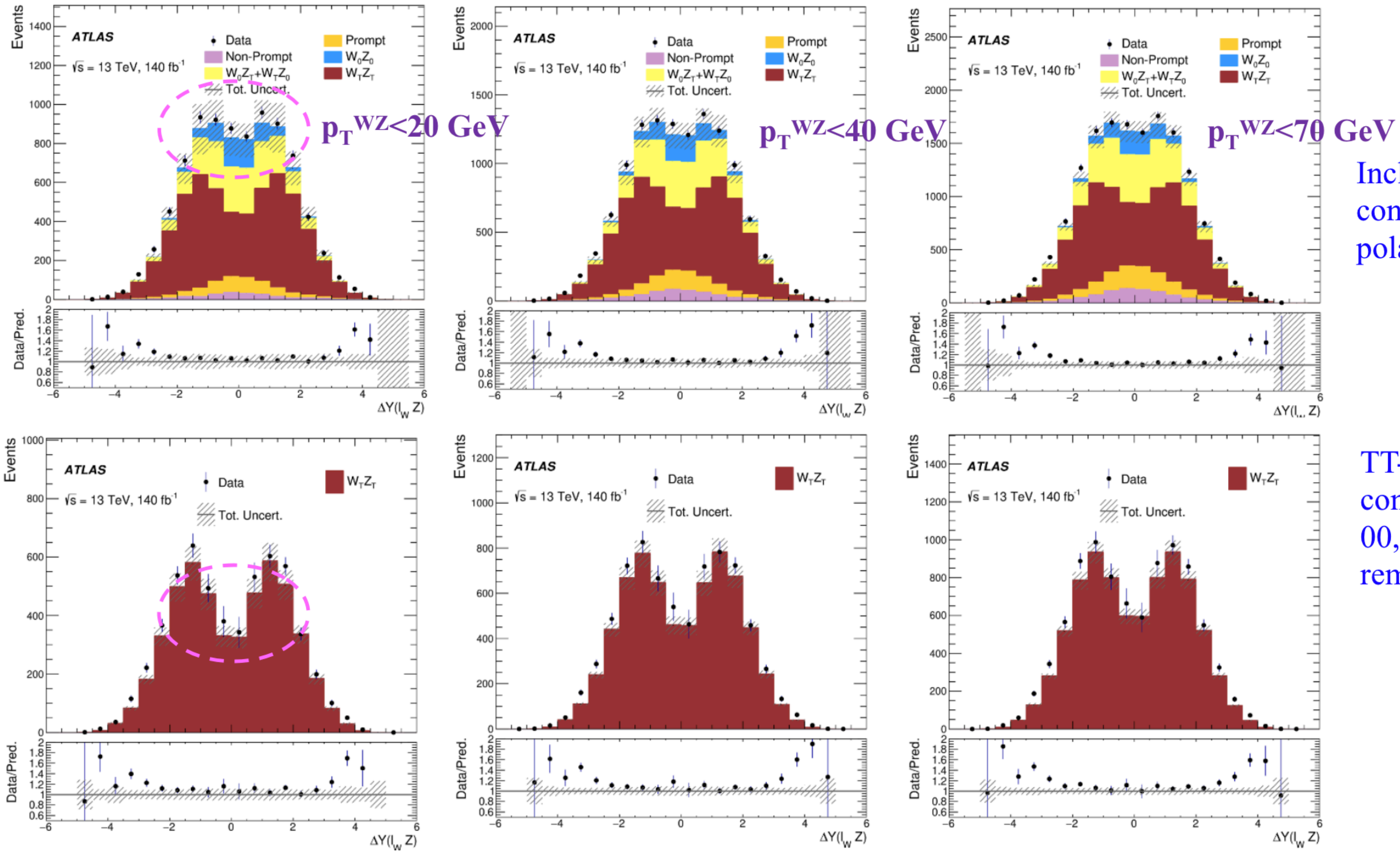
To Do: add systematic uncertainties & detail on reweighing

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



	Impact [%]			
Source	TT state		Sum of polarizations	
Experimental	$\Delta Y(\ell_W Z)$	$\Delta Y(WZ)$	$\Delta Y(\ell_W Z)$	$\Delta Y(WZ)$
Luminosity	1.5	0.6	0.5	0.1
Electron calibration	0.9	0.5	1.7	0.4
Muon calibration	1.6	0.8	1.4	0.5
Jet energy scale and resolution	3.4	1.9	1.8	1.2
E_T^{miss} scale and resolution	1.3	1.0	2.2	1.4
Flavor-tagging inefficiency	0.0	0.0	0.1	0.0
Pileup modelling	0.0	0.4	3.4	0.4
Non-prompt background estimation	9.5	3.6	13.5	3.7
Modelling				
Background, other	5.7	2.1	8.0	2.1
Model statistical	2.4	1.3	4.6	2.0
NLO corrections	9.2	1.0	0.0	0.0
PDF, Scale and shower settings	7.5	3.9	0.7	0.2
Unfolding uncertainty	0.0	2.3	0.0	2.6
Experimental and modelling	17.0	6.8	17.2	5.7
Data statistical	12.8	6.2	27.0	10.3
Total	21.3	9.3	32.0	11.8

WZ High pT Polarization



Inclusive events with contributions from al polarization states

TT-only events and contributions from 00, 0T, and T0 are removed