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Measurements of polarization and CP properties in $ZZ \rightarrow 4l$ production with full Run2 data at ATLAS

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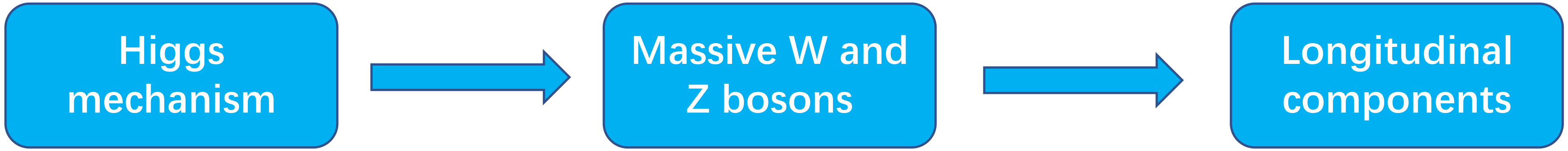
Outline

- Motivation
- Measurement of ZZ joint longitudinal polarization
- Measurement of CP properties in ZZ production
- Summary

Motivation



- The longitudinally polarization measurement of massive W and Z bosons is a direct way to probe the EWSB mechanism.

- The first observation of joint longitudinal polarization states of two vector bosons using WZ production process [2211.09435].

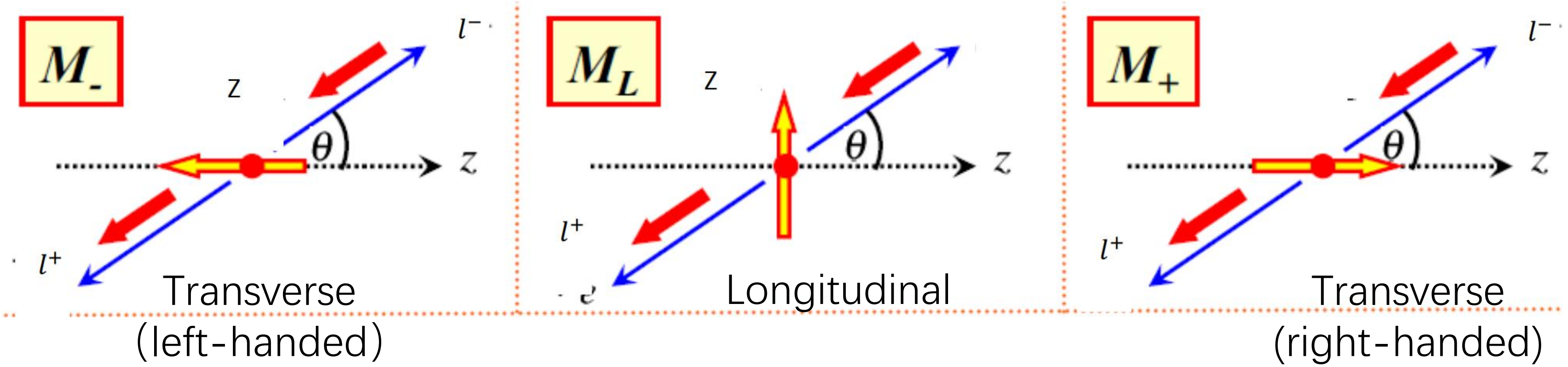
- Expected to establish the first evidence of joint longitudinal polarization states of ZZ bosons in ATLAS.

- Measurement of CP-sensitive observables in ZZ production can be used to explore the new source of CP violation in gauge boson sector.

Measurement of ZZ joint longitudinal polarization

Introduction

- Goal: Establish the first evidence of joint longitudinal polarization states of ZZ bosons in ATLAS.
- Phase space: On-shell ZZ region
  - m_{4l}> 180 GeV && $|m_{ij}$-$m_Z|$ <10 GeV
- Signal: Longitudinal longitudinal components (LL) in the ZZ events
  - The polarization is defined in the ZZ rest frame.
- Background: TT (Both Z bosons are transverse), TL (One Z boson is transverse and another is longitudinal polarized), ttZ, triboson (ZWW, ZZZ, ZZW) and fake(Zjets/ttbar)



Analysis strategy

① To improve the sensitivity

- ➢Multivariate Analysis (MVA) Method: Boost decision tree (BDT) to enhance the separation power between signal and bkg

② To improve the accuracy of qqZZ polarized samples

- ➢**NLO** polarized samples are **not** available
- ➢Reweighted to the lastest MoCaNLO program calculation (JHEP10(2021)097)
  - NLO QCD and EW correction on the qqZZ polarized samples.
  - Loop induced ggZZ correction

③ To get the final results (signal strength and significance)

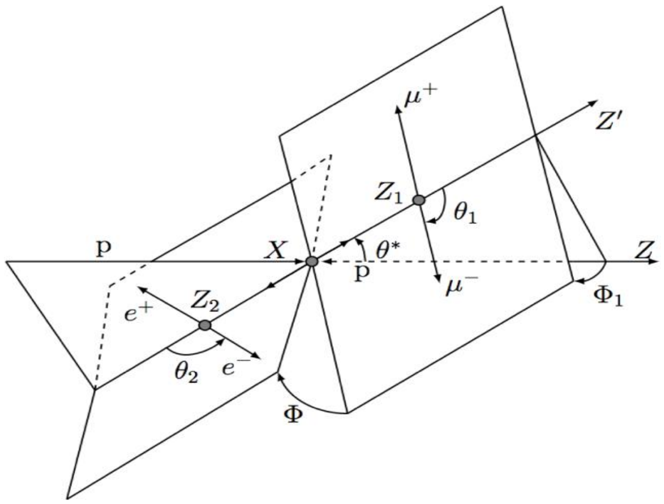
- ➢Tool: TRExFitter

Multivariate Analysis

- Due to limited statistics, very challenging to extract the LL component

- Started with BDT method
  - Signal: LL
  - Background: TT+TL

- Input variables: 5 purely angular observables

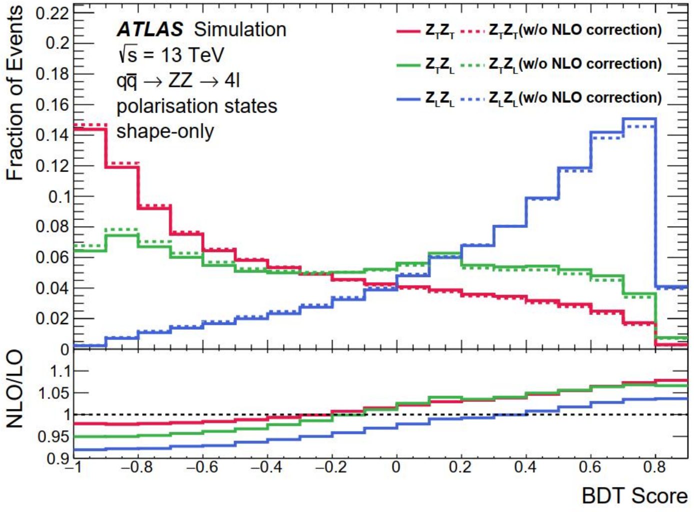


Input observables of MVA for polarization study	
$\cos\theta_{1,\mathrm{ZREST}}$	Decay angles
$\cos\theta_{2,\mathrm{ZREST}}$	
$\cos\theta^*_{Z_1,\mathrm{ZZREST}}$	Production angles
$\Delta\phi_{\ell_1\ell_2,\mathrm{ZZREST}}$	Azimuthal angles
$\Delta\phi_{\ell_3\ell_4,\mathrm{ZZREST}}$	

- Largely improve the sensitivity
  - Significance (LO, LL vs TT+TL, stat only): 4.38 σ
  - For comparison, single angular variable: 2.58 σ

The higher order polarized samples

- Only LO polarized qqZZ and inclusive ggZZ samples available
- A three steps reweighting method is established to incorporate the higher order correction using MoCaNLO program (JHEP10(2021)097)
  - Step1: 1D reweighting for each individual polarization state
  - Step2: 1D reweighting for the interference effect
  - Step3: 2D reweighting for the residual higher order corrections
- The BDT distribution comparison before and after reweighting procedure



The shape impact from this reweighting procedure on each polarized state with a maximum variation of about 10% for qqZZ sample

NLO correction and interference effect

➢ A three steps reweighting method is used to consider the NLO correction

- Step1: 1D reweighting for each individual polarization state

✓ qqZZ process:

☐ Reweighting as a function of $\cos\theta_1$

$$qqZZ^{reco}_{polarized} = \frac{MoCaNLO^{parton}_{polarized}}{MG012LO^{particle}_{polarized}} * \frac{MC_{NLO}{}^{particle}_{Inclusive}}{MoCaNLO^{parton}_{Inclusive}} * MG012LO^{reco}_{polarized}$$

K-factor

Parton shower correction

qqZZ MG LO reco sample

⋆ “MoCaNLO”: differential xs from theorists’ calculation

☐ The impact of the 1D reweighting corrections on the BDT discriminant is mostly of about 20% on the normalisation, and the shape variation is only of 2 − 4%.

☐ The difference induced by different reweighting variables is treated as a systematic uncertainty

NLO correction and interference effect

- Step2: 1D reweighting for the interference effect
  - ✓ The simulated polarized samples do not consider the interference effects which is not negligible
  - ✓ Interference effect:
    - ☐ Reweighting as a function of cosθ_1

$$\mathrm{InterfNLO}^{\mathrm{reco}} = \frac{\mathrm{MoCaNLO}_{\mathrm{incl}}^{\mathrm{parton}} - \sum_{\mathrm{pol}} \mathrm{MoCaNLO}_{\mathrm{pol}}^{\mathrm{parton}}}{\mathrm{MoCaNLO}_{\mathrm{incl}}^{\mathrm{parton}}} \times \mathrm{SherpaNLO}_{\mathrm{incl}}^{\mathrm{reco}}$$

    - ☐ The difference caused by reweighting variable choice is not negligible and considered as modeling uncertainty
- Step3: 2D reweighting for the residual higher order corrections
  - ✓ To consider NLO correction modelling effect (reweighting with 1 variable can hardly catch full structure of high-order contributions)
  - ✓ Reweighting as a function of cosθ_Z^* and $\Delta\phi_{l1l2}$

$$\mathrm{NLO_{final}}_{\mathrm{pol}}^{\mathrm{reco}} = \frac{\mathrm{SherpaNLO} - \mathrm{InterfNLO}}{\sum_{\mathrm{pol}} \mathrm{NLO}_{\mathrm{pol}}^{\mathrm{reco}}} \times \mathrm{NLO}_{\mathrm{pol}}^{\mathrm{reco}}$$

  - ✓ The impact of this 2D reweighting on the BDT discriminant is mostly on the shape with a maximum variation of about 10%.

The difference between unpolarized and inclusive sample is treated as residual modeling uncertainty

ggZZ polarized sample and other NLO uncertainty

- ggZZ polarized samples
  - Reweighting the inclusive ggZZ samples to get different polarization states
  - Differential fraction for each component is taken from theorists' work

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

  - Interference effect is negligible for ggZZ process
  - Alternative way: reweighting like the qqZZ, the difference taken as systematic uncertainty

$$ggZZ_{LO,polarized}^{reco} = \frac{MoCaNLO_{Polarized}^{ggZZLO,Parton}}{MadGraph012LO_{Polarized}^{qqZZ,Particle}} \times \frac{Sherpa\_NLO_{Inclusive}^{Particle}}{MoCaNLO_{Inclusive}^{Parton}} \times MadGraph012LO_{Polarized}^{qqZZ,Reco}$$

- NLO theoretical uncertainties:
  - Besides the systematics mentioned in NLO correction procedure, still theoretical uncertainties for NLO polarized samples (inputs also from theorists' work):
    - NLO EW: difference between multiplicative & additive methods
    - NLO QCD for qqZZ and ggZZ: 7-point variation with NLO correction

Systematics uncertainties

➢Experimental uncertainties

- Lepton ID, reconstruction and isolation efficiency
- Trigger efficiency
- Lepton resolution and scale
- Pileup scale
- Luminosity

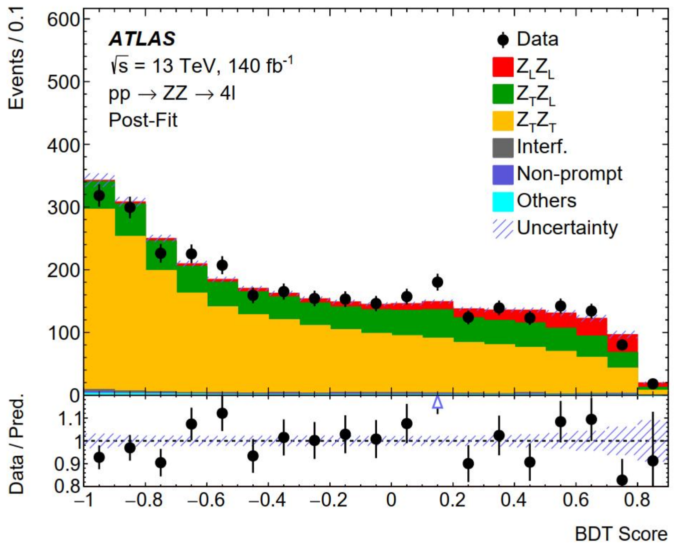
➢Theoretical uncertainties

- QCD sclale
- PDF+α_S
- Parton shower
- ttV and VVV cross-section variation
- Variation related to NLO k-factor variation for ggZZ
- Fake related uncertainties
- Variation related to EWK NLO reweighting for inclusive qqZZ
- Uncertainties related to the higher order correction
  - Interference modeling
  - NLO redicual non-closure uncertainties
  - NLO EW uncertainty
  - NLO reweighting observable choice
  - ggZZ modeling uncertainty

Results

- Signal strength:
  - μ_{LL} = 1.15 ± 0.27(stat.) ± 0.11(syst.)
- Significance: **4.3 σ** (3.8 σ)

→ **Evidence established**



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

- The fiducial cross-section of Z_LZ_L process is measured as 2.44 ± 0.59 fb, consistent with SM prediction 2.09 ± 0.10 fb.

This analysis still dominant by statistical uncertainty

Measurement of CP properties in ZZ production

Introduction

- Goal: Search for CP-violation in ZZ(4l) on-shell events

- Focus on aTGC which appears at dim-8 and onward
  - aTGC: ZZZ, yZZ (PLB817(2021)136311)
    - ✓ CP-conserving: $f_{5\gamma}, f_{5Z}, h_{3Z}, h_{4Z}$
    - ✓ CP-violating: $f_{4\gamma}, f_{4Z}, h_{1Z}, h_{2Z}$

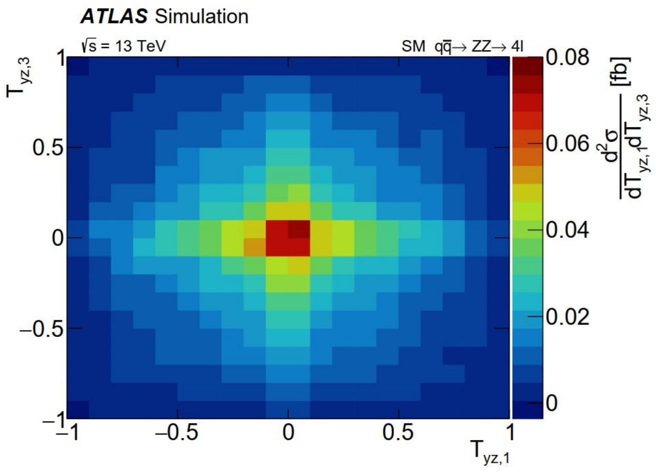
- "f" operators predominately sensitive in on-shell ZZ region

- Only interference term considered to constrain anomalous CP-odd neutral triple gauge couplings ($f_{4\gamma}$ and f_{4z})
  - Quadratic term will violates the unitarity and will also not induce asymmetries in the discriminating variable

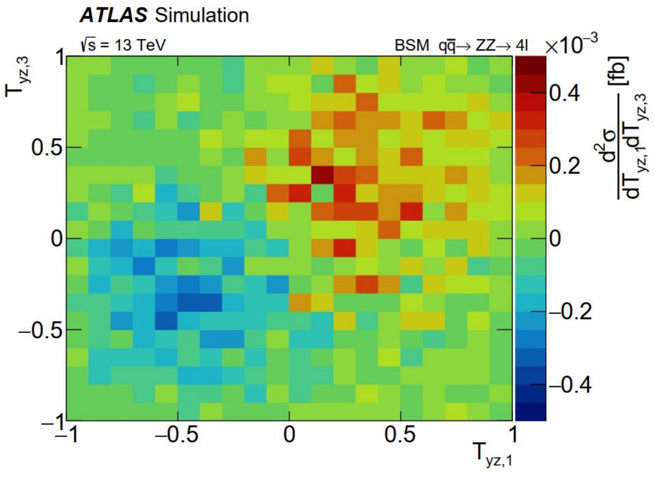
- Use CP odd sensitive observable to do the constraint ★

Analysis strategy

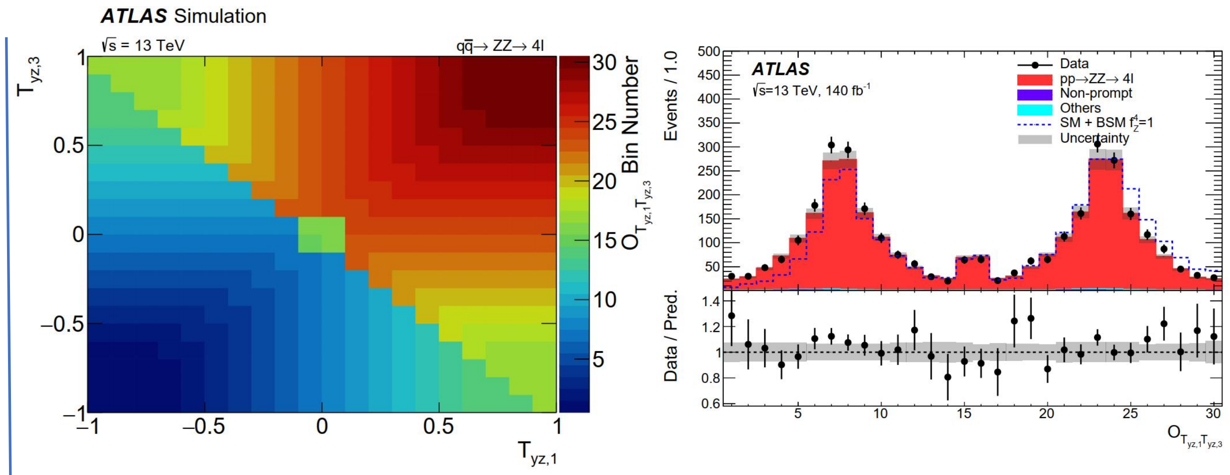
- Construct **CP sensitive angular observable** ($o_{T_{yz,1}T_{yz,3}}$) with the polar and azimuthal angles of Z boson
  - Angular observable: $T_{yz,1(3)}$=sin$\emptyset_{1(3)}$* cos$\theta_{1(3)}$



SM prediction



f_{4Z} prediction

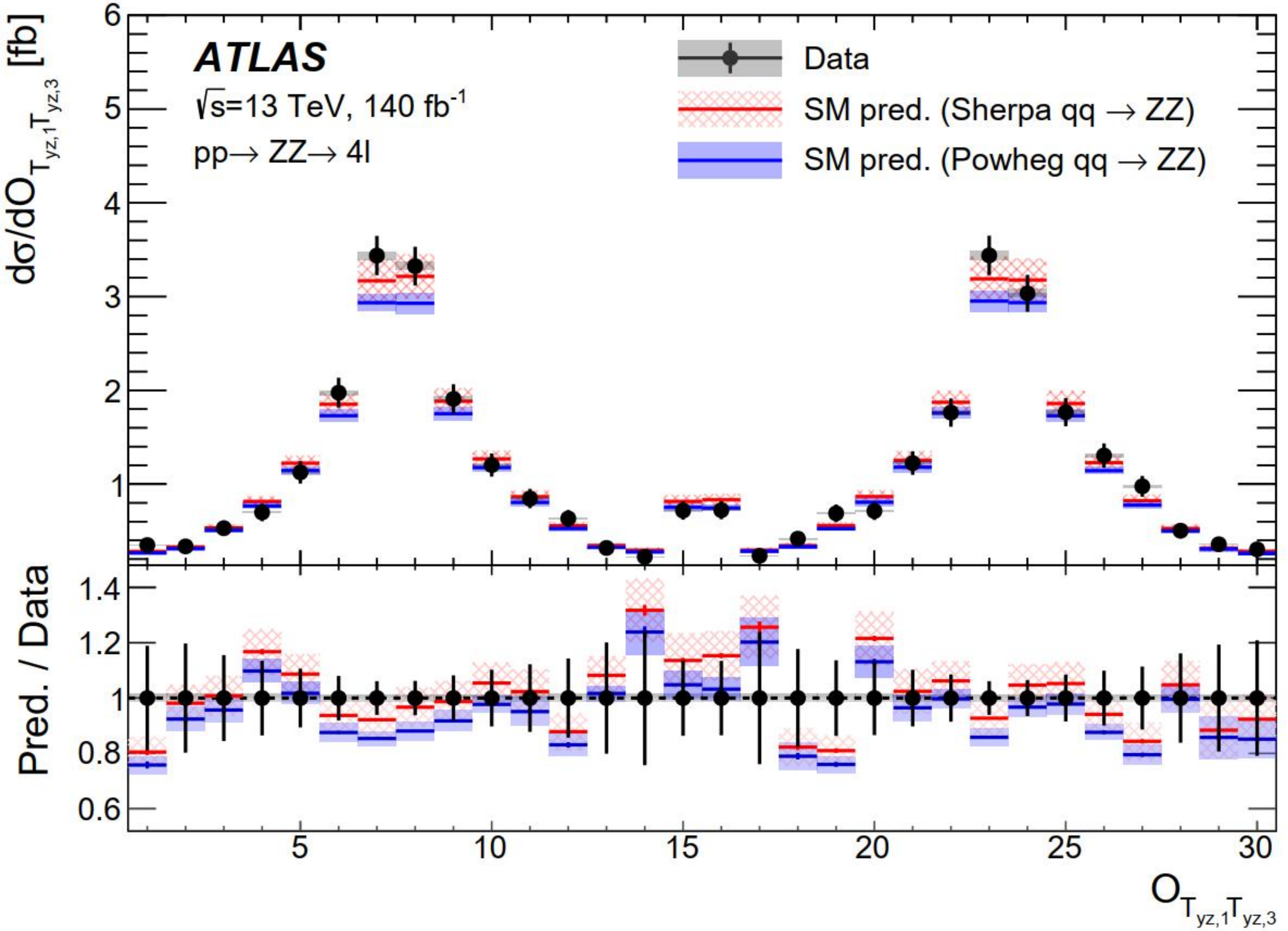


The $2D \rightarrow 1D$ mapping

- Use unfolding to correct the detector effects
  - Bayesian iteration unfolding method
  - Iteration number 2 is used

- The measured data agree closely with the prediction at the reco level
- The bins 1 to 7 and 24 to 30 are the most sensitivity bins

Results



- The measured cross-section from the data agrees closely with both SM predicted cross-sections (Sherpa and Powheg)
- The differential cross-section of a CP-sensitive angular observable ($o_{T_{yz1}T_{yz2}}$) used to constrain anomalous CP-odd neutral triple gauge couplings.

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

The first constraints on CP-odd aNTGC parameters using only linear interference terms with a dedicated CP-sensitive observable

Summary

- The polarization and CP properties in ZZ $\rightarrow$ 4l production are measured with full Run2 data at ATLAS
- **Established the first evidence of joint longitudinal polarization states of ZZ bosons in ATLAS.**
  - Signal strength:

$$\mu_{LL} = 1.15 \pm 0.27(\text{stat.}) \pm 0.11(\text{syst.})$$

  - Significance: **4.3 σ** (3.8 σ)
- The differential cross-section of a CP sensitive angular observable ($o_{T_{yz1}T_{yz2}}$) used to constrain anomalous CP-odd neutral triple gauge couplings (f_{4Z} and $f_{4\gamma}$).

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

Stay tuned for new Run 3 results!

Backup

Phase space and samples

- Data: Full Run2 dataset @13 TeV
- MC Samples:

LO

$qq \to ZZ \to 4l$		Generator	DSID	Cross-section (fb)
TT 0 or 1 jet	inclusive	MadGraph + Pythia 8	502354	20.486
TT 2 jets	inclusive	MadGraph + Pythia 8	502357	3.1879
TT 2 jets EW	inclusive	MadGraph + Pythia 8	502360	0.32478
TL 0 or 1 jet	inclusive	MadGraph + Pythia 8	502355	7.4671
TL 2 jets	inclusive	MadGraph + Pythia 8	502358	1.7441
TL 2 jets EW	inclusive	MadGraph + Pythia 8	502361	0.1552
LL 0 or 1 jet	inclusive	MadGraph + Pythia 8	502356	1.7441
LL 2 jets	inclusive	MadGraph + Pythia 8	502359	0.2829
LL 2 jets EW	inclusive	MadGraph + Pythia 8	502362	0.0438

qqZZ

Process		Generator	DSID	Cross-section fb (k-factor if not 1)
$gg (\to H^{(*)}) \to ZZ^{(*)} \to 4\ell$	inclusive, $m_{4\ell} > 130$ GeV	Sherpa 2.2.2	345706	10.091 (1.7)
$pp \to W^{(*)}W^{(*)}Z^{(*)} \to 4\ell 2\nu$	inclusive	Sherpa 2.2.2	364243	1.7973
$pp \to W^{(*)}Z^{(*)}Z^{(*)} \to 5\ell 1\nu$	inclusive	Sherpa 2.2.2	364245	0.18812
$pp \to Z^{(*)}Z^{(*)}Z^{(*)} \to 6\ell$	inclusive	Sherpa 2.2.2	364247	0.014458
$pp \to Z^{(*)}Z^{(*)}Z^{(*)} \to 4\ell 2\nu$	inclusive	Sherpa 2.2.2	364248	0.38556
$pp \to t\bar{t} + \ell\ell$	$t\bar{t}Z$, $m_{\ell\ell} > 5$ GeV	Sherpa 2.2.0	410142	113.09 (1.09)

ggZZ & Other bkg

- Event selection

Category	Requirement
Event Preselection	Fire at least one lepton trigger ≥1 vertex with 2 or more tracks
Four-lepton signature Lepton kinematics	At least 4 leptons (e, μ) $p_T > 20$ GeV for leading two leptons
Lepton separation J/ψ-Veto	$\Delta R_{ij} > 0.05$ for any two leptons $m_{ij} > 5$ GeVfor all SFOS pairs
Trigger matching	Baseline leptons matched to at least one lepton trigger
Quadruplet formation	At least one quadruplet with 2 Same-Flavor, Opposite-Sign (SFOS) pairs
On-shell ZZ pair	$m_{4l} > 180$ GeV
On-shell Z boson	$\lvert m_{ij} - m_Z \rvert < 10$ GeV

On Shell

The definition of angular variables

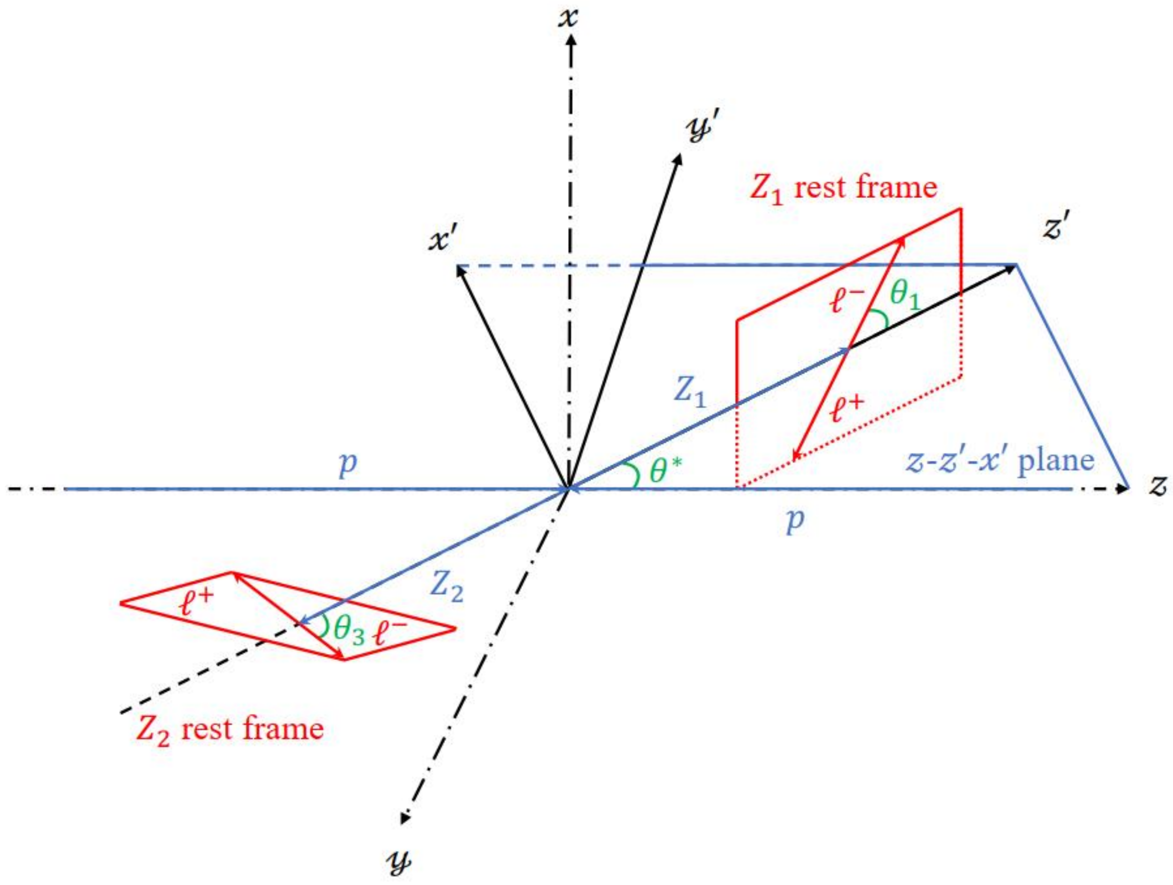
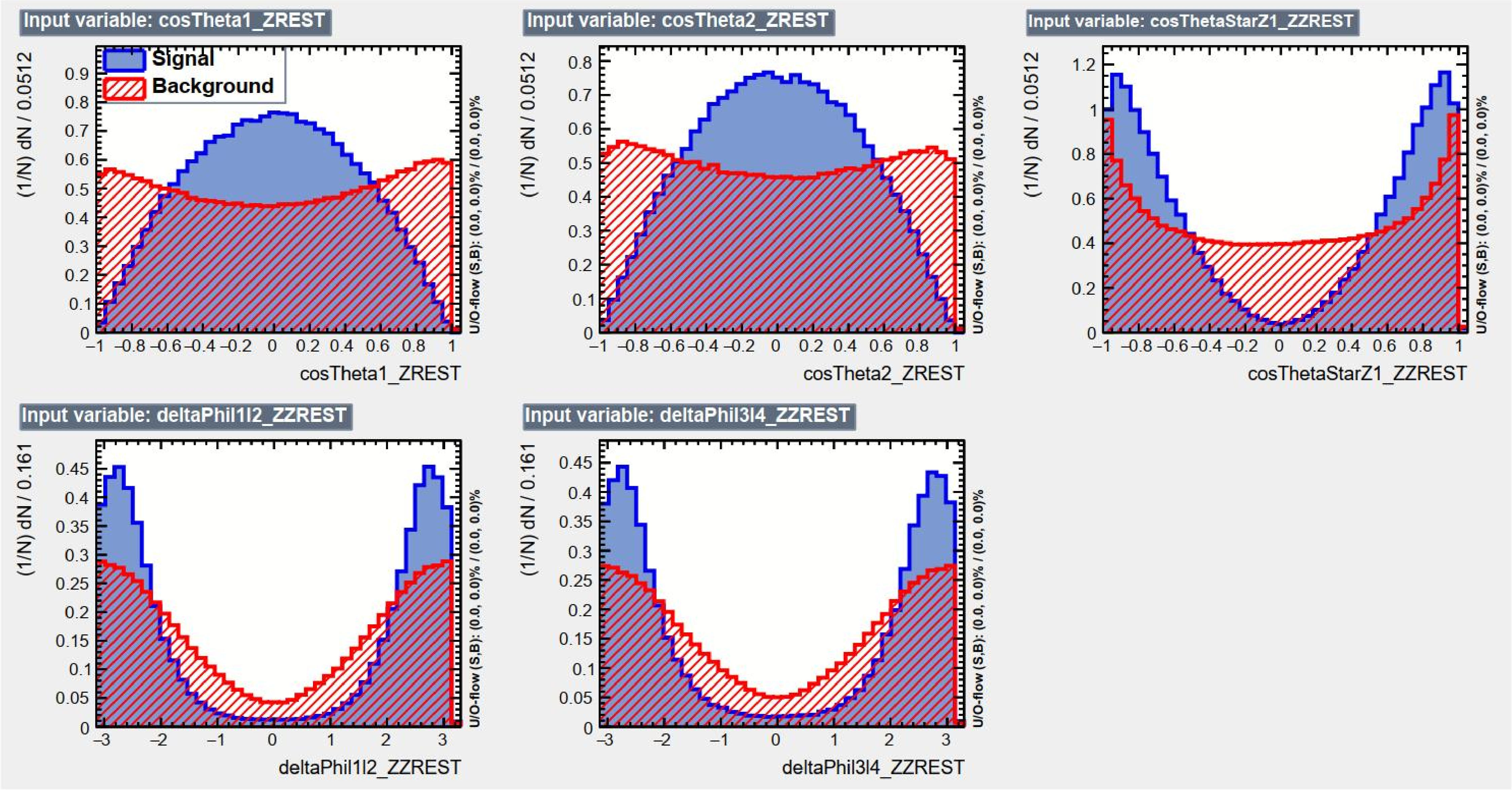


Figure 2: Definition of the angles used for the polarisation measurement and the reference frame used to define the CP-sensitive angles. The xyz-frame (dot-dashed) is the laboratory frame with the z-axis along the beam direction. The $x'y'z'$-frame (solid) is a new frame used to define the CP-sensitive angles. The z'-axis is defined as the direction of motion of the Z_1 boson in the four-lepton rest frame. The x'-axis defines the reaction plane containing the laboratory z-axis and the z'-axis. The right-hand rule gives the y'-axis.

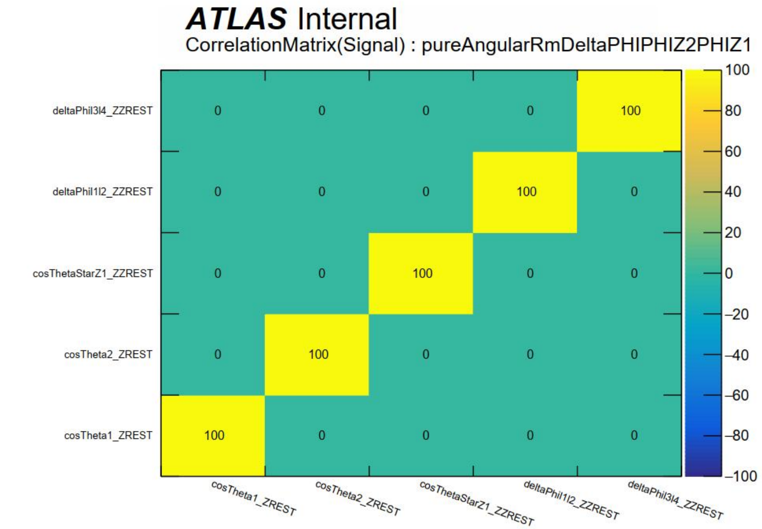
Multivariate Analysis



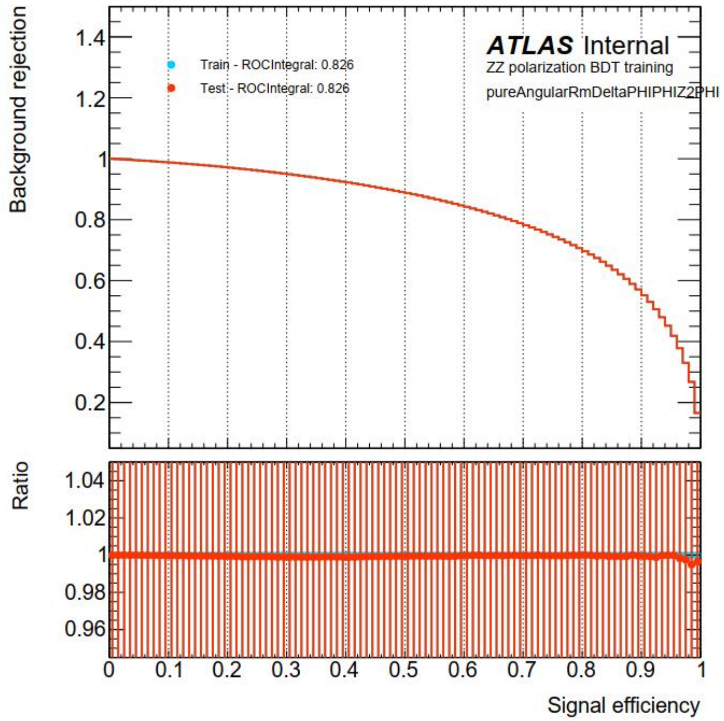
Multivariate Analysis

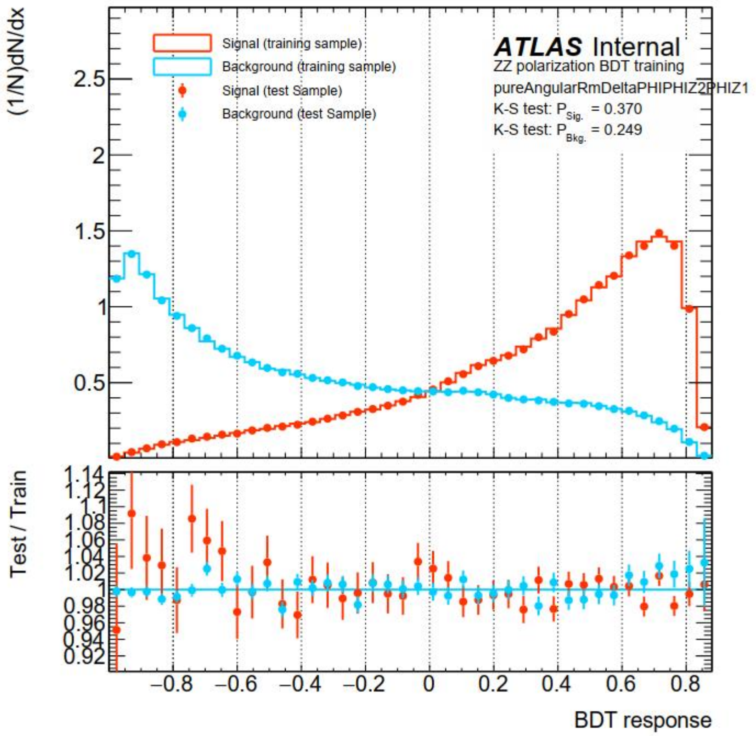
Rank	BDT observables	Importance
1	$\Delta\phi_{\ell_3\ell_4,\mathrm{ZZREST}}$	2.231×10^{-1}
2	$\Delta\phi_{\ell_1\ell_2,\mathrm{ZZREST}}$	2.212×10^{-1}
3	$\cos\theta^*_{Z_1,\mathrm{ZZREST}}$	2.086×10^{-1}
5	$\cos\theta_{1,\mathrm{ZREST}}$	1.806×10^{-1}
6	$\cos\theta_{2,\mathrm{ZREST}}$	1.665×10^{-1}

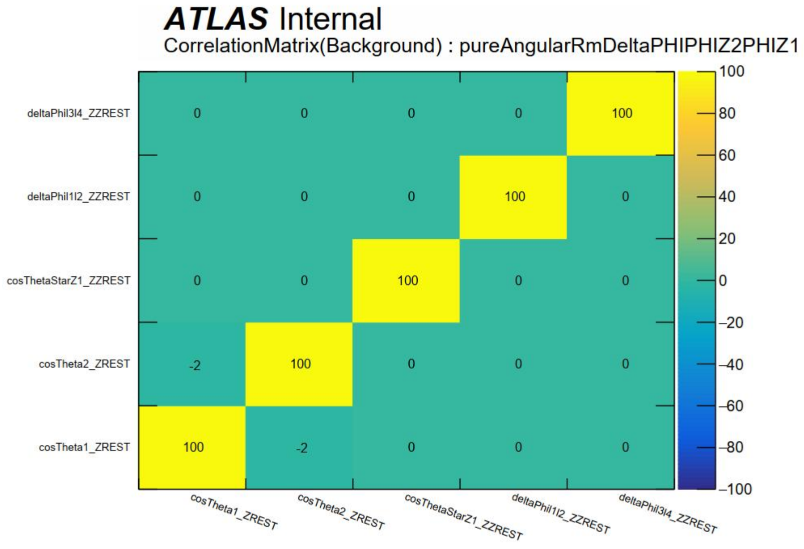
BDT parameters	value
NTrees	850
MaxDepth	3
MinNodeSize	1%
nCuts	100
Shrinkage	0.1



(a) correlation among observables in signal







(b) correlation among observables in background

Systematics uncertainties

- Theoretical systematics on SM MC samples
  - QCD scale
    - envelope of variation of μ_R, μ_F to 0.5 and 2 scale
  - PDF+α_s
    - envelope of σ of 100 NNPDF3.0 variations and MMHT & CT14NNLOPDF
  - Parton Shower uncertainty for qqZZ
    - comparing the truth-born distributions of the nominal SHERPA and alternative POWHEG samples
  - ttV and VVV cross-section variation
    - a conservative flat 15% variation for ttV cross-section from the measurement
    - a conservative flat 40% variation for VVV cross-sections from the measurement
  - Variation related to EWK NLO reweighting for qqZZ
    - virtual EW correction k-factor applied on qqZZ sample
    - to account for non-factorizing effects for high QCD active events, as the size of correction
  - Variation related to NLO k-factor variation for ggZZ
    - uncertainty of NLO k-factor reweighting on ggZZ sample

Zjj analysis

- Data: Full Run2 dataset @13 TeV
- $\Delta\phi_{jj}$ variable is used to search for anomalous weak-boson self-interactions using dimention-six EFT

Wilson coefficient	Includes $\|\mathcal{M}_{d6}\|^2$	95% confidence interval [TeV^{-2}]		p-value (SM)
		Expected	Observed	
c_W/Λ^2	No	[−0.30, 0.30]	[−0.19, 0.41]	45.9%
	Yes	[−0.31, 0.29]	[−0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	No	[−0.12, 0.12]	[−0.11, 0.14]	82.0%
	Yes	[−0.12, 0.12]	[−0.11, 0.14]	81.8%
c_{HWB}/Λ^2	No	[−2.45, 2.45]	[−3.78, 1.13]	29.0%
	Yes	[−3.11, 2.10]	[−6.31, 1.01]	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	No	[−1.06, 1.06]	[0.23, 2.34]	1.7%
	Yes	[−1.06, 1.06]	[0.23, 2.35]	1.6%

The results are almost unaffected with/without the pure dimension-six contributions.