Polarisation measurements in diboson final states

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On behalf of the ATLAS & CMS Collaboration

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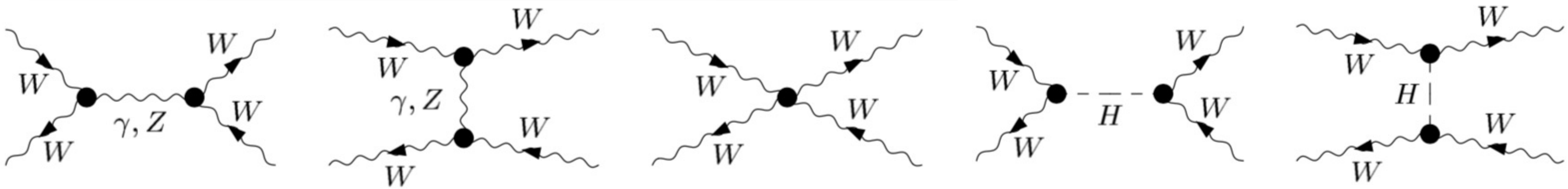
Polarisation measurements in diboson final states

Outline

- **Motivations**
- **How to measure "polarisation"**
- **Polarisation templates**
- **Measurements in ATLAS and CMS**
  - *** Single boson polarisation in WZ**
  - *** Joint polarisation in WZ and ZZ**
  - *** Polarisation in Vector Boson Scattering $W^{\pm}W^{\pm}jj$**
- **Conclusion and outlook**

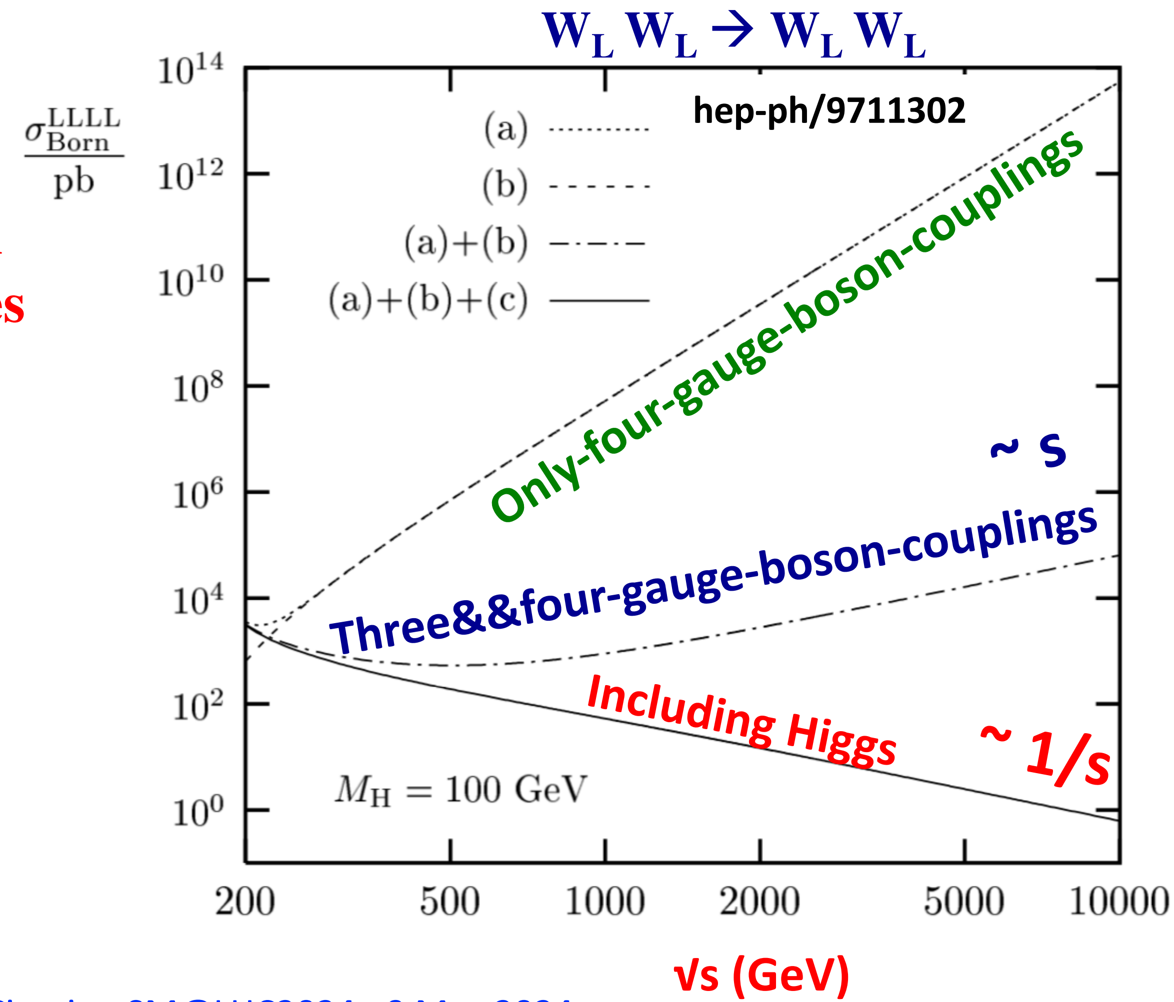
Motivation : probe EWSB in Vector Boson Scattering



- The scattering of polarised gauge bosons (VBS) probes the EWSB mechanism

- Unitarity cancellation ensures that σ_{LLLL} decreases @ high energies

L = longitudinal
T = transverse



Motivation: New Physics effects in diboson inclusive

- **Different behaviors of amplitudes with different diboson polarisations**

	SM	BSM
$q_{L,R}\bar{q}_{L,R} \to V_L V_L(h)$	~ 1	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_L(h)$	$\sim m_W/E$	$\sim m_W E/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\pm$	$\sim m_W^2/E^2$	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\mp$	~ 1	~ 1

$V \equiv W, Z$

$V\pm \equiv V_T$

L = longitudinal

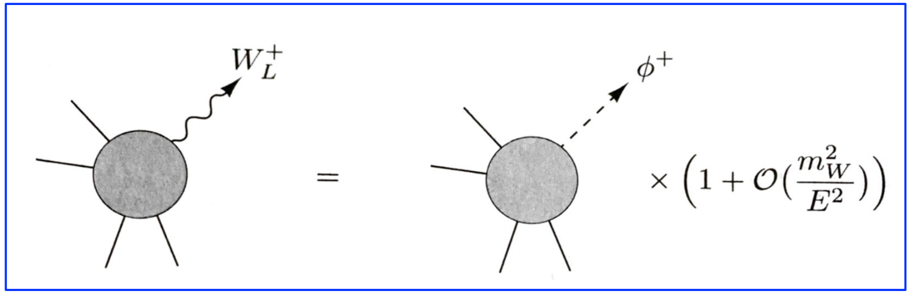
T = transverse

arXiv:1712.01310

- **Even if BSM small :**
  → **Probe new theories via SM - BSM Interference**
  → **interesting limits on New Physics parameters**

NB: Expect similar $W_L Z_L$ and $W_L h$ cross sections at higher energies

Goldstone Theorem



"Introduction to QFT", M.E.Peskin, D. V. Schroeder

Single and joint boson polarisation measurements @LHC

- **Inclusive VV**

  $pp \to W^{\pm}Z$

  ATLAS @13 TeV 36 fb^{-1} Eur. Phys. J. C 79 (2019) 535 → Single only (Z first obs)

  CMS @13 TeV 137 fb^{-1} JHEP 07 (2022) 032 → Single only (W first obs)

  ATLAS @13 TeV 139 fb^{-1} Phys. Lett. B 843 (2023) 137895 → Single & joint (first obs)

  ATLAS @13 TeV 139 fb^{-1} arXiv:2402.16365 → Joint @high p_T^Z Radiation Zero Amplitude

  time

  $pp \to ZZ$

  ATLAS @13 TeV 140 fb^{-1} JHEP 12 (2023) 107 → Single & joint(evidence)

- **Vector Boson Scattering VVjj**

  $pp \to W^{\pm}W^{\pm}jj$

  CMS @13TeV 137 fb^{-1} Phys. Lett. B 812 (2020) 13601

- **In all cases: leptonic final states (e, μ) considered**

- **All Run 2 measurements: data statistics is important !**

Very active field !

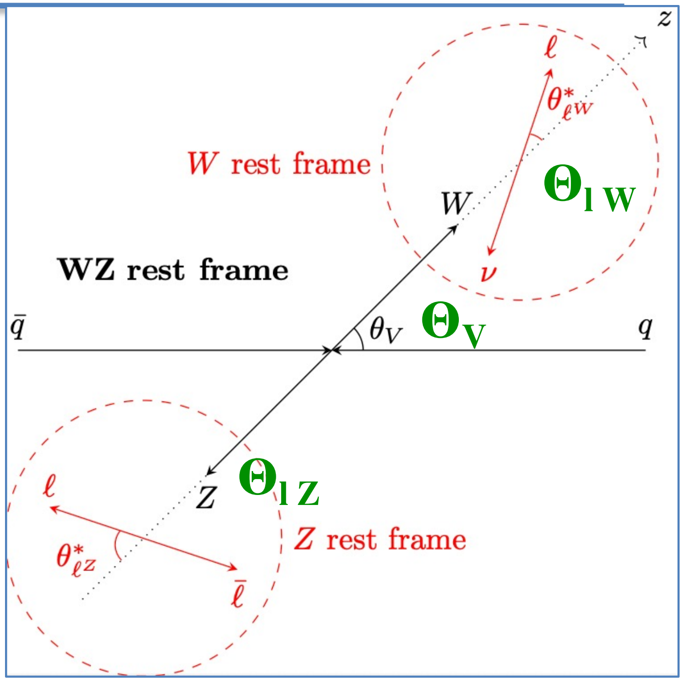
How polarisation is measured

- **Choose a reference frame :**
  the value of the "polarised cross sections" is frame dependent ("pseudo cross section")

- **Devise variables (BDT, DNN combinations of decay, production angles and variables) discriminating among final states with bosons in a given helicity state**

- **Fit these variables to polarised templates**

  One of the main challenges



Phys. Lett. B 843 (2023) 137895

- **Extract "polarised cross sections" or polarisation fractions f**

For singly-polarised: σ_X (X = L, R, 0),
f_L, f_R, f_0 $\quad f_X = \sigma_X / \sigma$ tot

For joint polarisation: σ_{XY} (XY = LL, LT, TL, TT)
$f_{00}, f_{0T}, f_{T0}, f_{TT}$ $\quad f_{XY} = \sigma_{XY} / \sigma$ tot

L = left } T
R = right }
0 or L = longitudinal

(see also backup)

Polarisation templates

- **Use Monte Carlo + (complex) reweighting techniques**

  So far polarised templates from MADGRAPH LO (+PS) (arXiv: 1912.01725)

  Alternatives :

  POWHEG-BOX-RES: NLO QCD+PS
  (EPJC 84 (2024) 16)

  SHERPA: nLO QCD + PS (JHEP 04 (2024), 001)

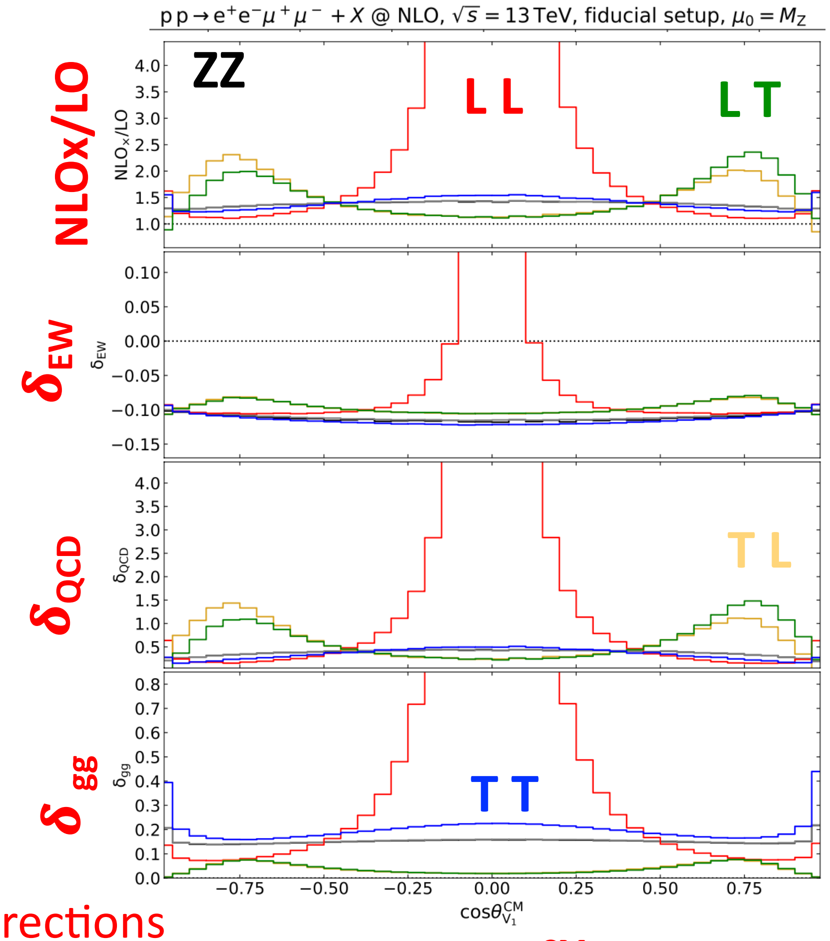
  PHANTOM (2→6) : LO+PS (arXiv: 0801.3359)

- **Fixed-order calculations (MoCaNLO polarised) + POWHEG, SHERPA unpolarised for higher order (HO) reweight**

- **Templates: sources of main systematic uncertainties**

  (also take care of interference among polarisations, minimize non resonant contributions)

MoCaNLO JHEP 2021, 97 (2021)



HO Corrections depend on polarisation

$\cos\theta^{CM}_{V1}$

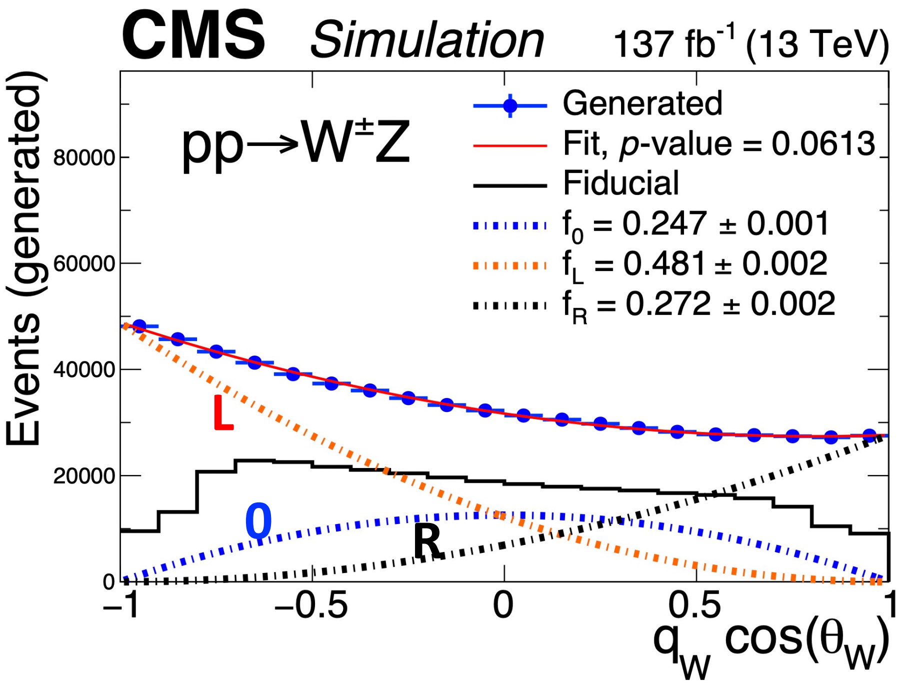
Polarisation measurements of a single boson in WZ final states

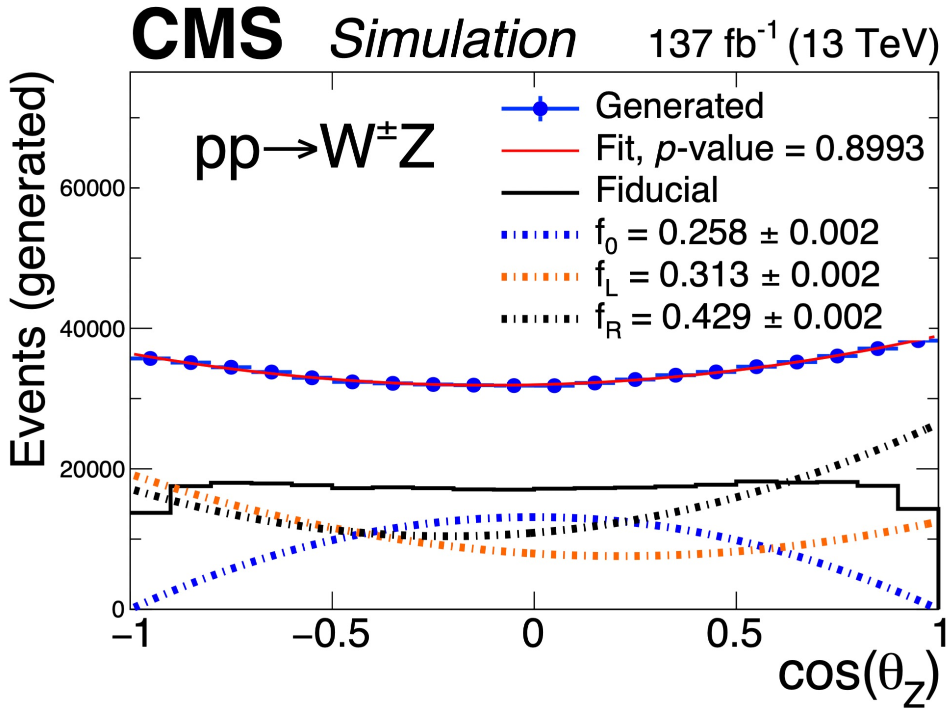
Single boson polarisation measurements in WZ

Phys. Lett. B 843 (2023) 137895

JHEP 07 (2022) 032

- Polarisation templates obtained by reweighting an unpolarised POWHEG+Pythia sample by $\cos(\theta_V)$ (V=Z,W)



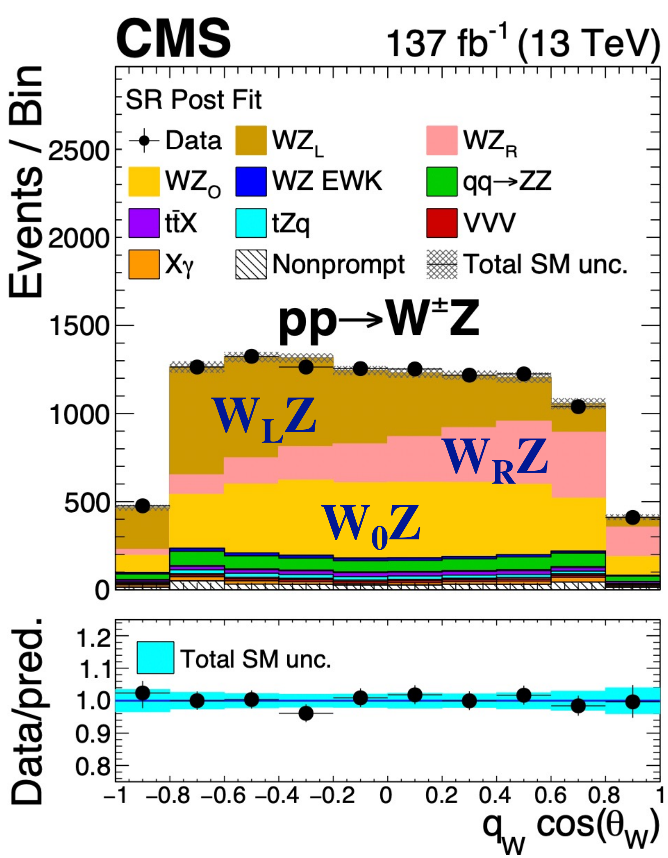


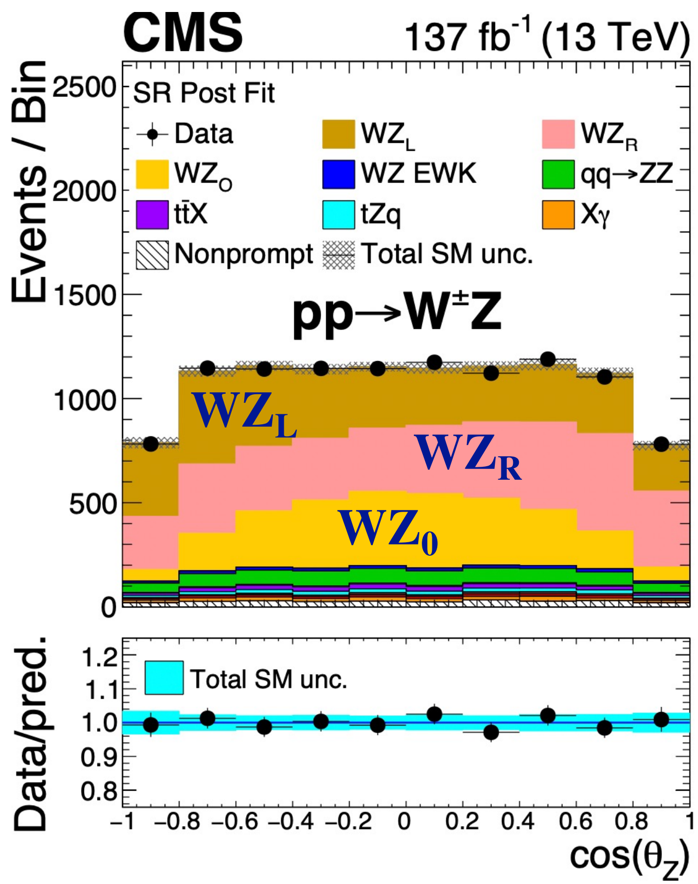
In CMS: θ_V (V=W, Z) is the angle between the momentum of the decay lepton in the rest frame of the massive boson V and the momentum of its parent in the laboratory frame.

Single boson polarisation measurements in WZ

JHEP 07 (2022) 032

- W reconstructed using PDG W mass constrain
- Cut-based Signal Region selection
- Three Control Regions for ZZ, top and photon conversions

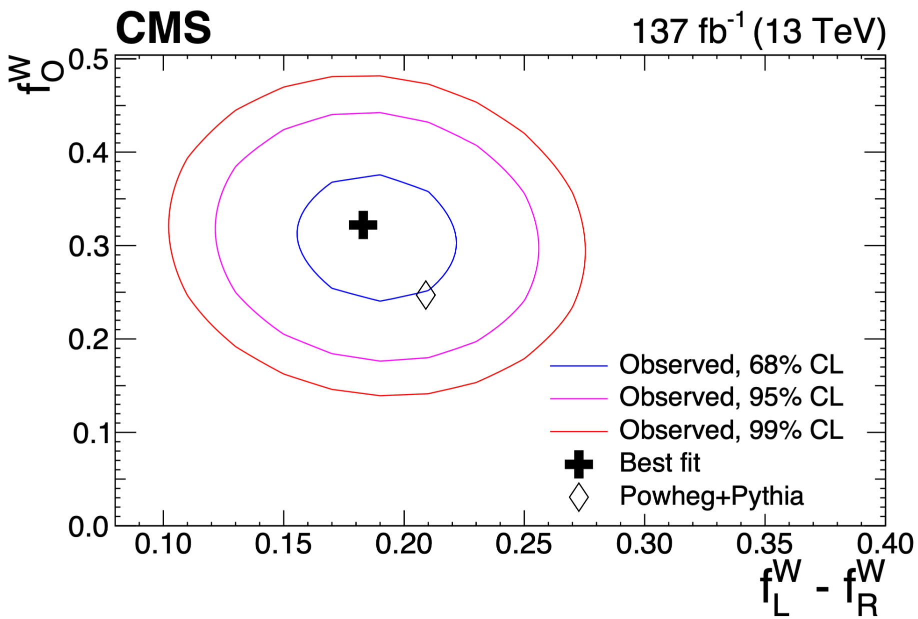


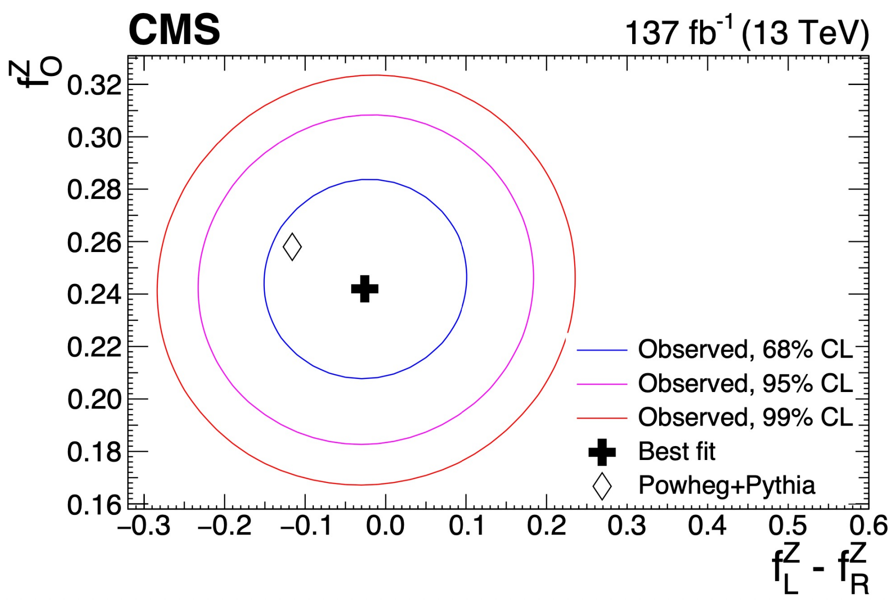


Results : single boson polarisation measurements in WZ

JHEP 07 (2022) 032

f = polarisation fractions $f_0 + f_L + f_R = 1$ → Only 2 f are independent





$f_0^W =$ 0.32 + 0.08

- **Observed significance for longitudinally polarized W bosons of 5.6 σ (4.3 σ).**

  First observation of longitudinally polarized W bosons in WZ events

- **Results consistent between observations and predictions**

Comparison with ATLAS results in backup

Joint polarisation measurements in diboson final states: WZ and ZZ

Joint polarisation measurements in WZ

Phys. Lett. B 843 (2023) 137895

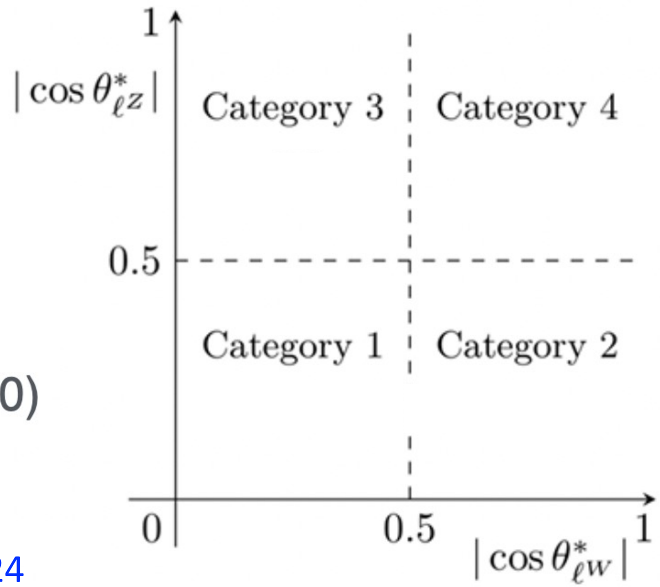
- First joint polarisation observations: W_0Z_0 , W_TZ_0 , W_TZ_T
  The polarisation of each single boson is also measured.

- Joint polarised templates:
  Madgraph LO (0-1jet): bias ~ 10-50% from NLO-QCD effects

  - 2 techniques to obtain templates @ NLO-QCD:
    * Multidimensional reweighting DNN-based [arXiv:1907.08209] using Madgraph LO (0-1jet) and POWHEG+Pythia unpolarised
    * Fixed order calculations (+ PS) reweighting

- A DNN variable is used to discriminate among polarisations, then events are split in 4 categories using the lepton decay angles cosθ*

0)



Joint polarisation measurements in WZ

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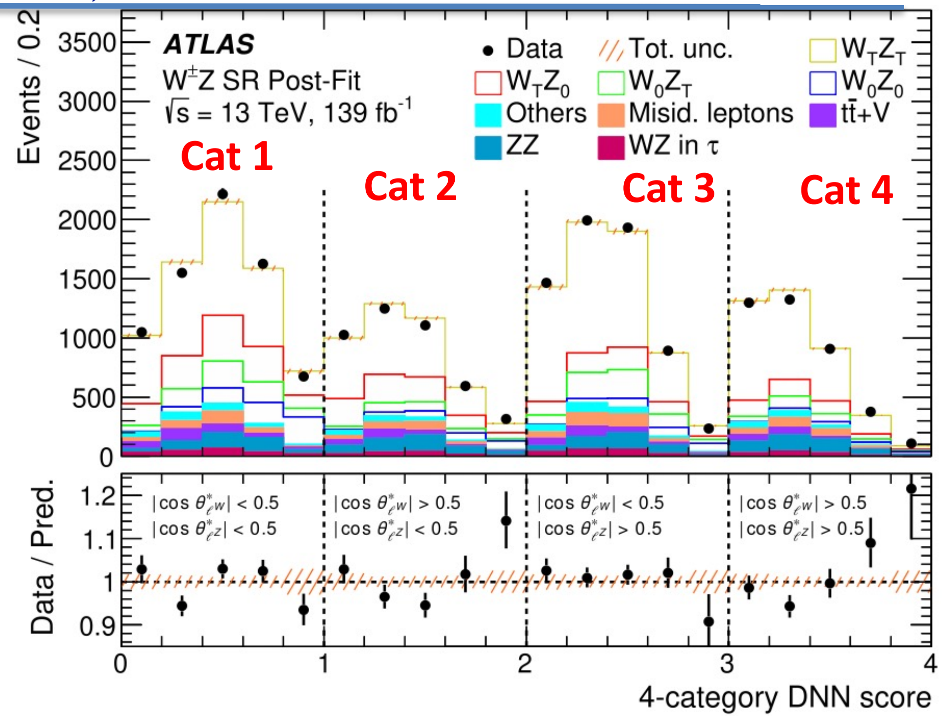
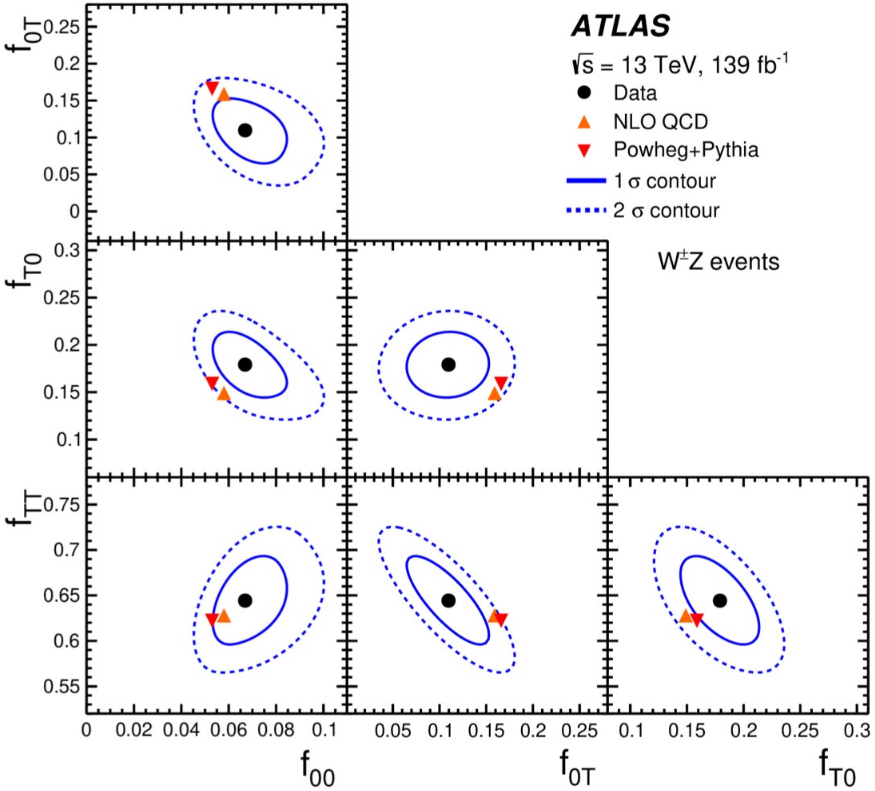
- **Simultaneous fit of the 4 categories**
- **Systematic uncertainties on f_{00} :**
  - * Modelling
  - * E_T^{miss}





	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

Significance on f_{00} at 7.1σ (6.2 σ)

Significance on f_{TT} and f_{T0} > 5σ

→ First joint polarisation observations

WZ polarisation in specific phase spaces: results

arXiv:2402.16365

- Polarisation in 00-enriched region: cut on p_T^Z → f_{00} increases

  → Investigate p_T^Z dependence of the polarisation
- Discriminating variable : BDT (00 against 0T+T0, TT or 00 against all)
- Polarised templates: MadGraph LO 0,1 j polarised + reweight

Results of a 3-parameter fit. In $100 < p_T^Z < 200$ GeV f_{00} : 5.2 σ (4.3 σ)

	Measurement $100 < p_T^Z \leq 200$ GeV	Measurement $p_T^Z > 200$ GeV		Prediction $100 < p_T^Z \leq 200$ GeV	Prediction $p_T^Z > 200$ 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

- Results consistent with SM within uncertainties
- As expected, f_{00} is higher than in the inclusive phase space :

  @ $100 < p_T^Z < 200$ GeV: $f_{00} = 0.19$ (wrt 0.067)
- Uncertainties: ~ 22 % on f_{00} @ $100 < p_T^Z < 200$ GeV

  * Statistically dominated

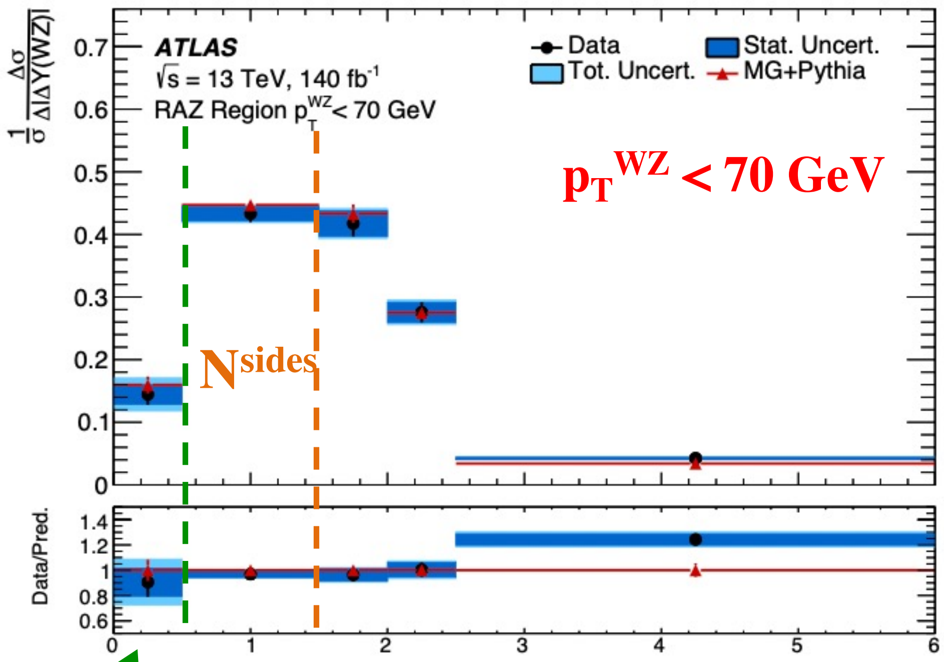
  * Systematics mainly from QCD higher order effects

Radiation Zero Amplitude Effect (RAZ) observation

arXiv:2402.16365

- **@ LO strong gauge cancellations make a dip in the TT cross-section (WZ and Wγ) in ΔY_{WZ} → cut on p_T^{WZ} (approach LO phase space)**

Backgrounds and 0T, T0 & 00 contributions subtracted unfolded and normalised

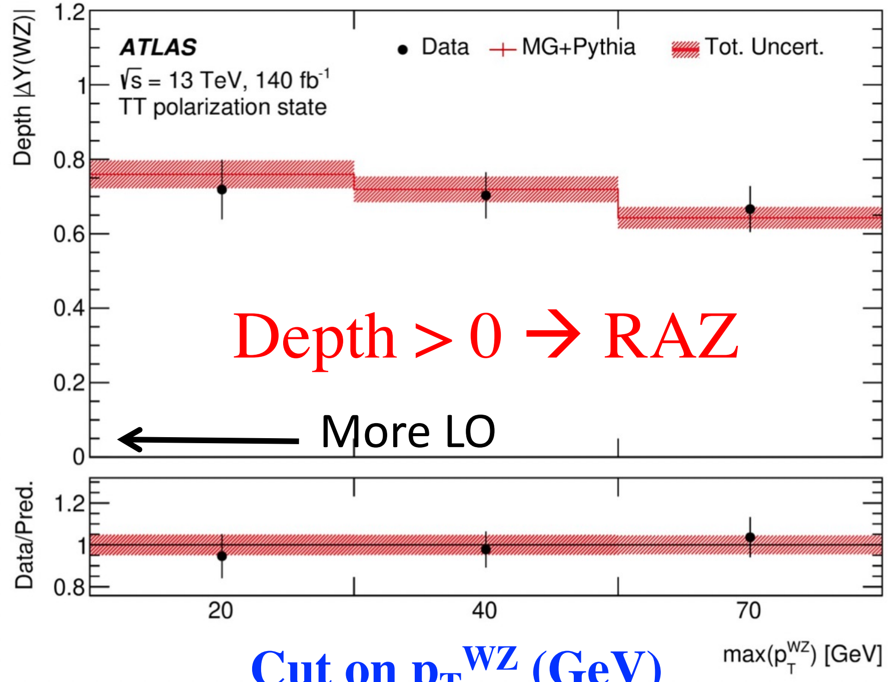


$|\Delta Y_{WZ}|$

$N^{central}$

Depth = 1 - 2 * $N^{central}$ / N^{sides}

Depth of the unfolded $|\Delta Y_{WZ}|$ deep



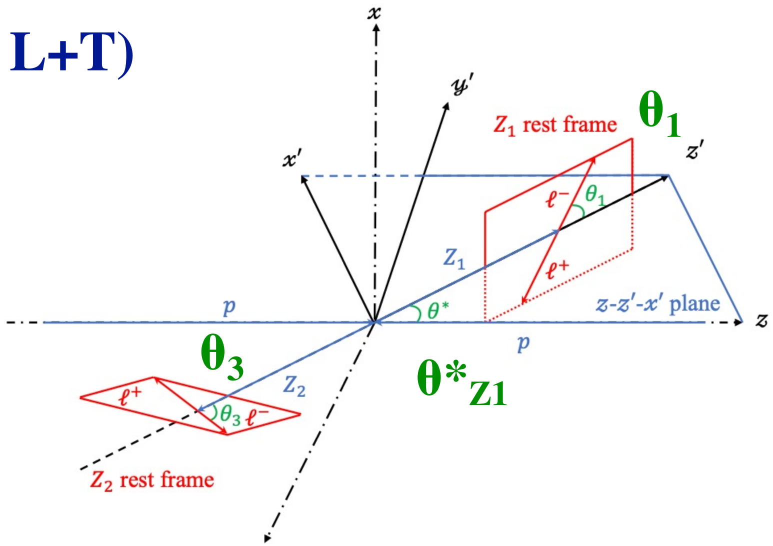
Cut on p_T^{WZ} (GeV)

- **Results consistent with SM**

Polarisation measurements in ZZ

JHEP 12 (2023) 107

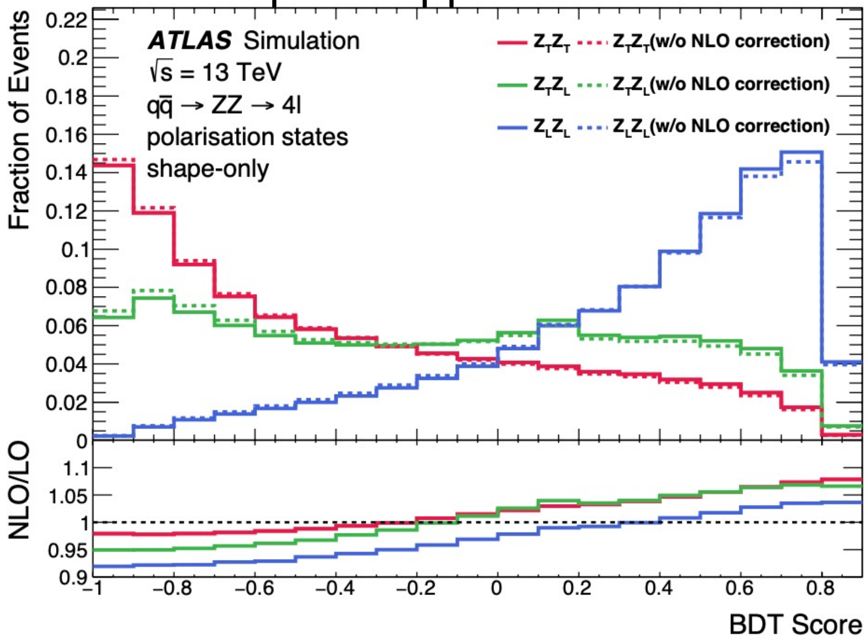
- **Joint polarisation & singly : $Z_L Z_L$, $Z_T Z_X$ (X = L+T)**
  In ZZ rest frame



- **Polarised templates + reweight:**
  * Madgraph LO (0,1j) polarised for qq→ZZ & EW-ZZ
  * Unpolarised Sherpa NLO/fixed order LO polarised for gg→ ZZ

➢ **Three steps reweighting:**
  * 1D fixed order polarised(+PS) reweight NLO QCDxEW along $\cos\theta_1$
  * 1D Interference term reweight $qq \rightarrow ZZ$ by (unpolarised – Σ polarised)
  * 2D reweighting for residual high order along $\cos\theta^*_{Z1}$ and $\Delta\phi_{l1\,l2}$

Templates qq→ZZ: NLO effects



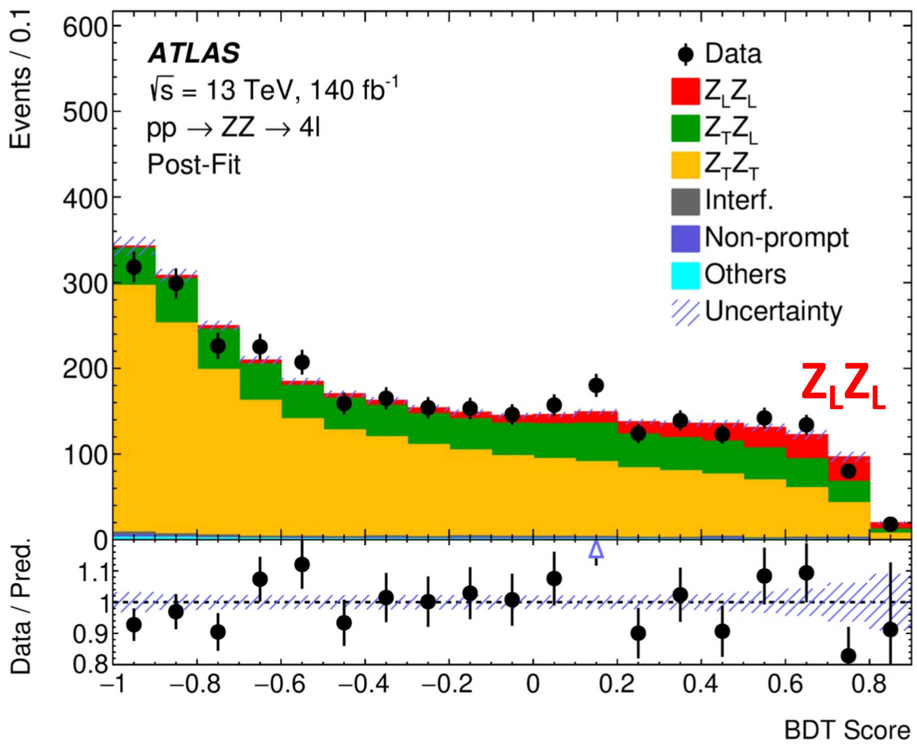
- **Boosted Decision Tree:**
  $\cos\theta_1$, $\cos\theta_3$, $\cos\theta^*_{Z1}$, $\Delta\phi_{l1\,l2}$, $\Delta\phi_{l3\,l4}$

Results: polarisation measurements in ZZ

- **Fit using 2 free parameters: fractions of $Z_L Z_L$ and $Z_T Z_X$ (X=T, L)**

$$\sigma^{\text{obs.}}_{Z_L Z_L} = 2.45 \pm 0.56(\text{stat.}) \pm 0.21(\text{syst.})\ \text{fb}$$

- **Evidence for $Z_L Z_L$ with 4.3σ (3.8σ exp.)**
- **Main uncertainties from statistics, 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

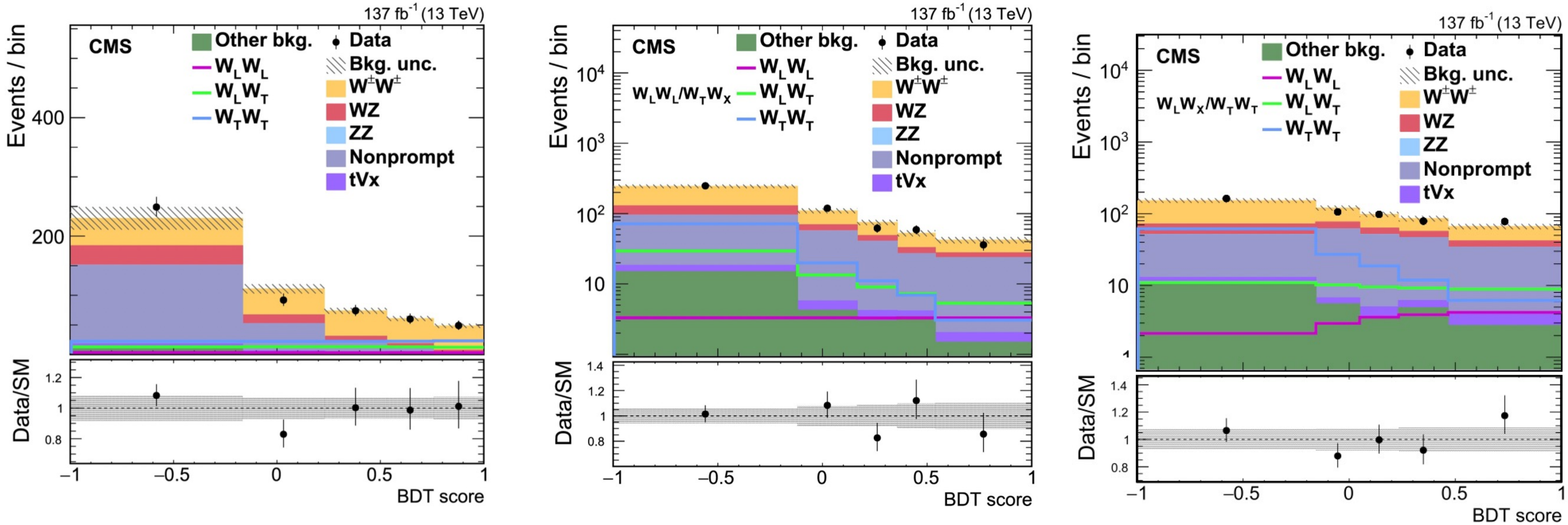
Polarisation measurements in Vector Boson Scattering process $W^{\pm}W^{\pm}jj$

Polarisation measurements with $W^{\pm}W^{\pm}jj$

Phys. Lett. B 812 (2020) 136018

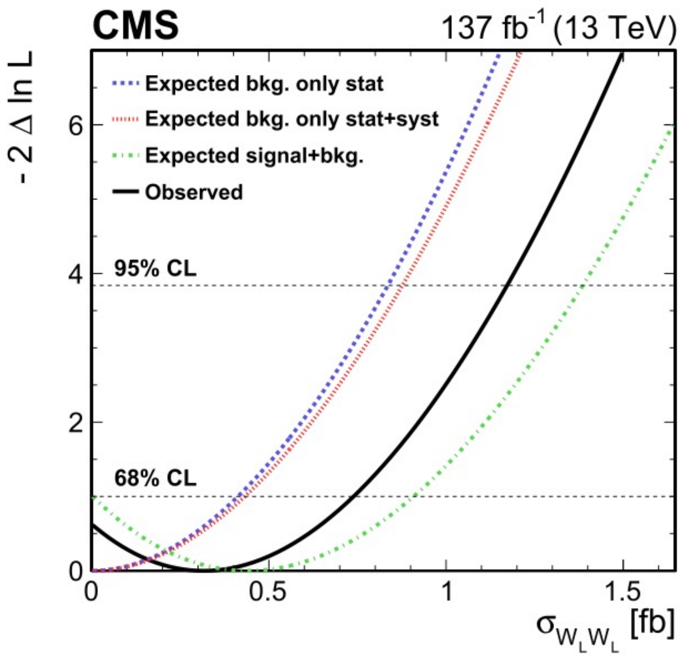
- **First polarisation studies in Vector Boson Scattering process (VBS)**
  Joint and single boson polarisation is measured
- **Challenging:**
  - * low cross section
  - * separation Signal vs Background (Nonprompt, WZ) & between polarisations
- **Three BDTs are trained, 2 fits:**

Inclusive BDT ssWW signal vs background | **LL vs the rest for W_LW_L & W_TW_X** | **TT vs the rest for W_LW_X & W_TW_T**



VBS Results: Polarisation measurements with $W^\pm W^\pm jj$

Phys. Lett. B 812 (2020) 136018



Diboson c.o.m. frame

Significance for LX production at **2.3σ** (3.1σ expected)

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^\pm_L W^\pm_L$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W^\pm_X W^\pm_T$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W^\pm_L W^\pm_X$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W^\pm_T W^\pm_T$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

Parton-parton c.o.m. frame

Significance for LX production at **2.6σ** (2.9σ expected)

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^\pm_L W^\pm_L$	$0.24^{+0.40}_{-0.37}$	0.28 ± 0.03
$W^\pm_X W^\pm_T$	$3.25^{+0.50}_{-0.48}$	3.32 ± 0.37
$W^\pm_L W^\pm_X$	$1.40^{+0.60}_{-0.57}$	1.71 ± 0.19
$W^\pm_T W^\pm_T$	$2.03^{+0.51}_{-0.50}$	1.89 ± 0.21

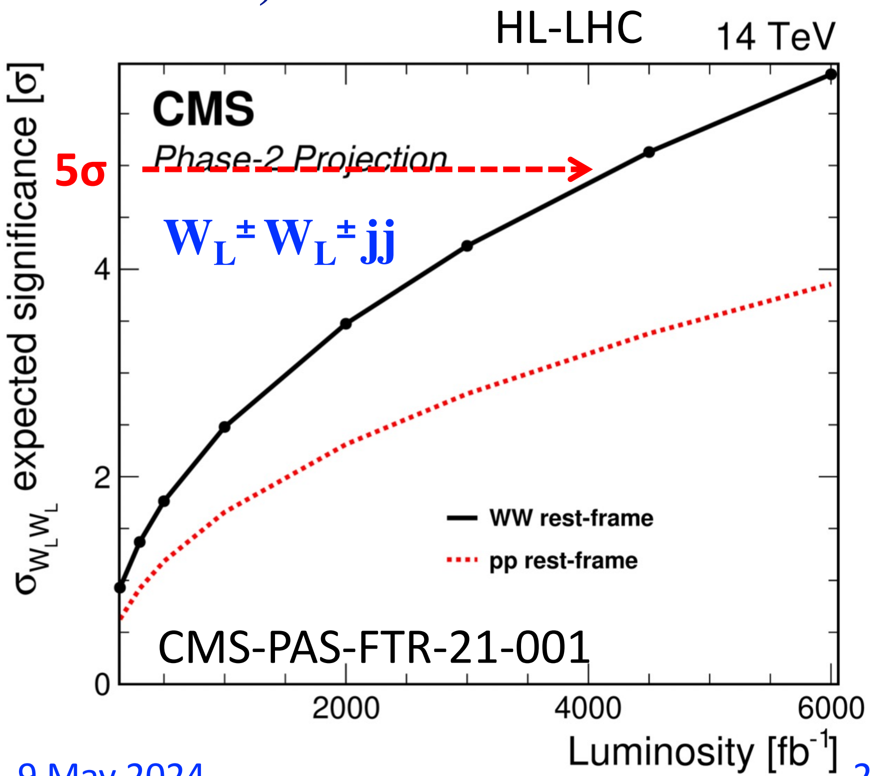
- **Statistical uncertainty dominant**
- **Significant improvements expected from Run 3 and HL-LHC before systematics start to become a significant issue**

Conclusion and Outlook

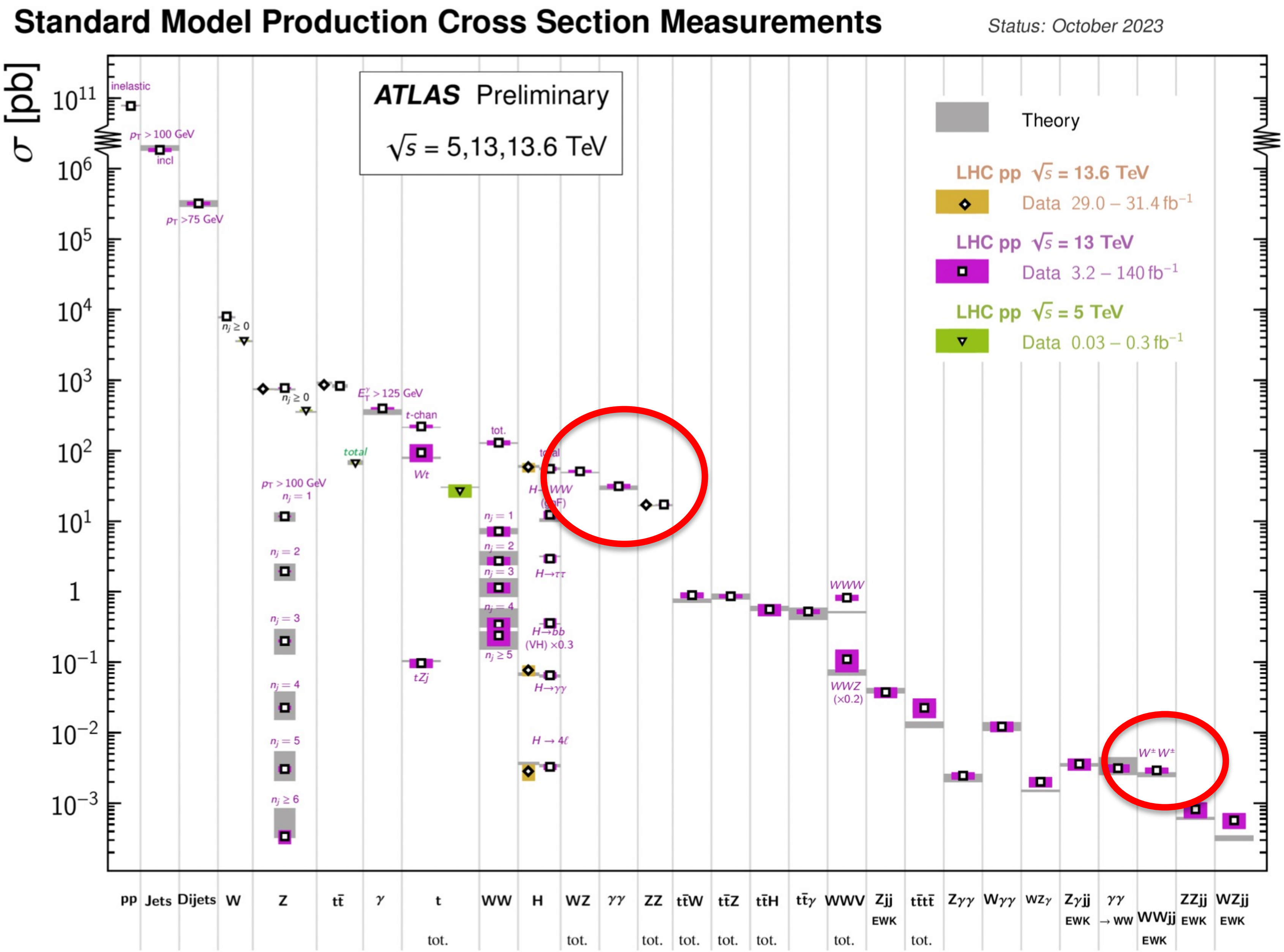
- **Polarisation measurements in diboson is a very interesting & active field**
  - ✓ **Probe the EWSB at high √s and New Physics**
  - ✓ **Important for EFT interpretation (no results yet)**

- **VV inclusive : with Run 2 first observations and evidence in (single and joint) → Need statistics (Run 3 and HL-LHC)**
  - ✓ **Main limiting factor: modelling of the polarization templates → theorists – experimentalists studies important**

- **VBS diboson process :**
  - ✓ **severely limited by data statistics**
  - ✓ **important study at HL-LHC, complementary to HH**



Backup


Standard Model Production Cross Section Measurements
Status: October 2023
ATLAS Preliminary
√s = 5,13,13.6 TeV
σ [pb]
Theory
LHC pp √s = 13.6 TeV
Data 29.0 – 31.4 fb⁻¹
LHC pp √s = 13 TeV
Data 3.2 – 140 fb⁻¹
LHC pp √s = 5 TeV
Data 0.03 – 0.3 fb⁻¹
pp
Jets
Dijets
W
Z
tt̄
γ
t
WW
H
WZ
γγ
ZZ
tt̄W
tt̄Z
tt̄H
tt̄γ
WWV
Zjj EWK
tt̄tt̄
Zγγ
Wγγ
WZγ
Zγjj EWK
γγ → WW
WWjj EWK
ZZjj EWK
WZjj EWK
tot.

Spin Density Matrix: $\varrho_{\lambda_W \lambda'_W \lambda_Z \lambda'_Z}$

hep-ph/9403248

$\mu_q, \mu_{\bar{q}} = \pm 1/2$ initial state helicities

$\lambda_{W,Z}$ helicity of W or Z

$$\rho_{\lambda_W \lambda'_W \lambda_Z \lambda'_Z} \equiv \frac{1}{C} \times \sum_{\mu_q \mu_{\bar{q}}} F^{(\mu_q \mu_{\bar{q}})}_{\lambda_W \lambda_Z} F^{(\mu_q \mu_{\bar{q}})*}_{\lambda'_W \lambda'_Z}$$

$$C = \sum_{\mu_q \mu_{\bar{q}} \lambda_W \lambda_Z} \left| F^{(\mu_q \mu_{\bar{q}})}_{\lambda_W \lambda_Z} \right|^2$$

F **= Helicity amplitudes**

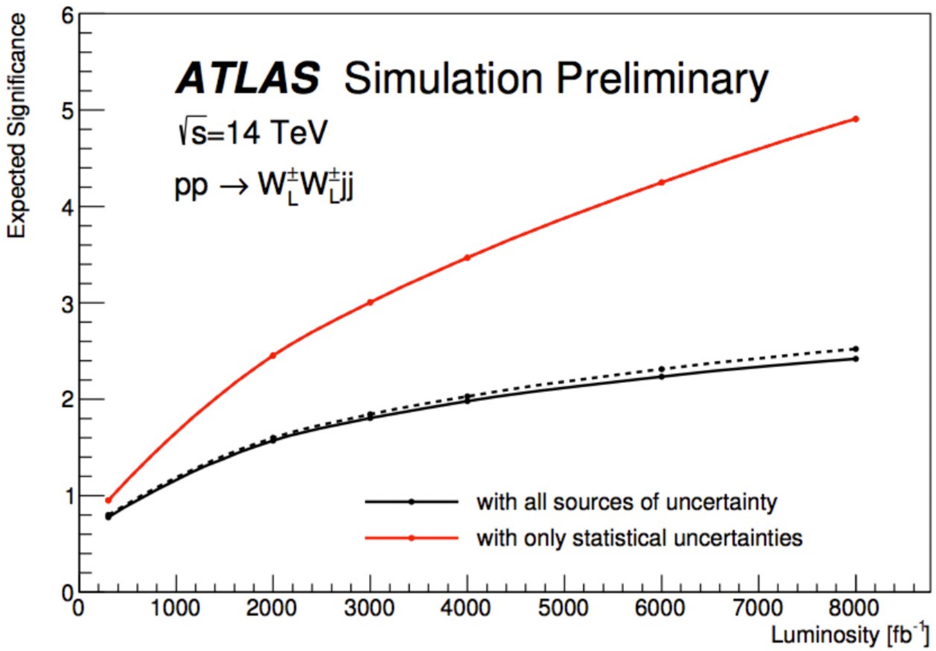
Helicity or polarisation fractions f_{XX} (**X=T,0**)

$$\begin{aligned} f_{00} &= \rho_{0000}\,, \\ f_{TT} &= \rho_{++--} + \rho_{--++} + \rho_{----} + \rho_{++++}\,, \\ f_{0T} &= \rho_{00--} + \rho_{00++}\,, \\ f_{T0} &= \rho_{--00} + \rho_{++00}\,. \end{aligned}$$

For a single boson : $\rho_{\lambda\lambda'}$ Sum over the helicities of one boson

f_X , X=L, R, 0 the diagonal elements of the $\varrho_{\lambda\lambda'}$ matrix

projection studies for polarisation measurements in the HL-LHC in the Yellow Report (https://e-publishing.cern.ch/index.php/CYRM/article/view/950)



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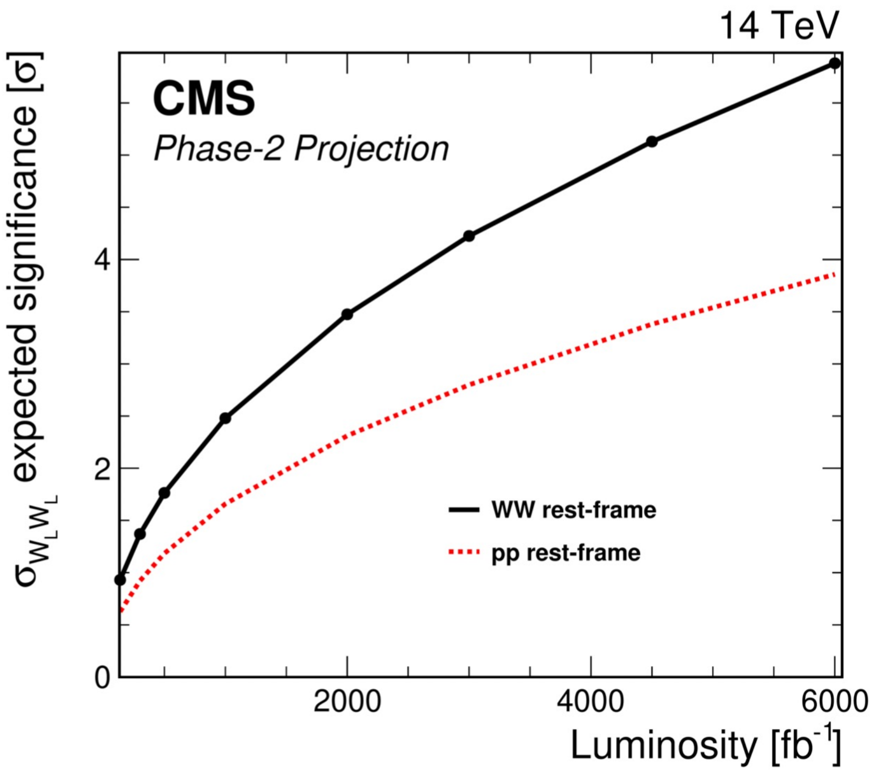

CMS-PAS-FTR-21-001

Single boson Polarization measurements in WZ

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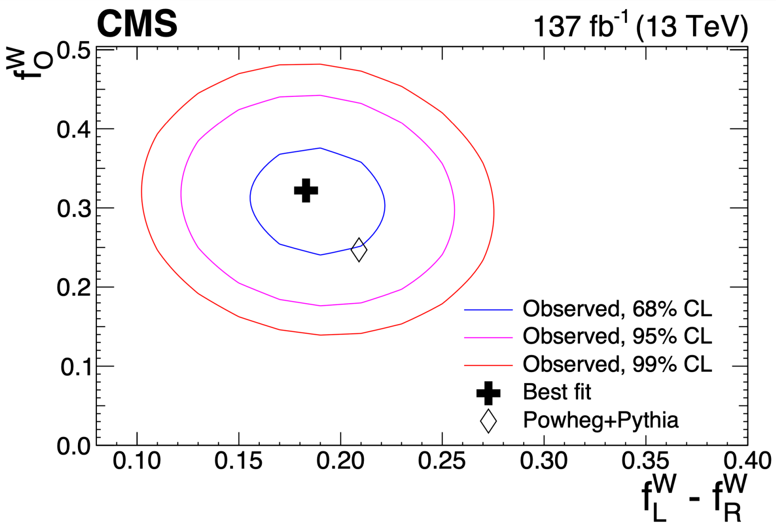
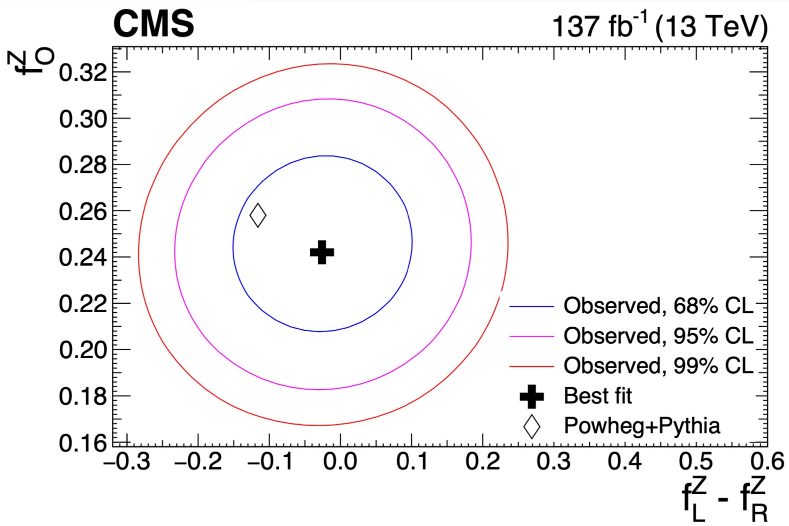
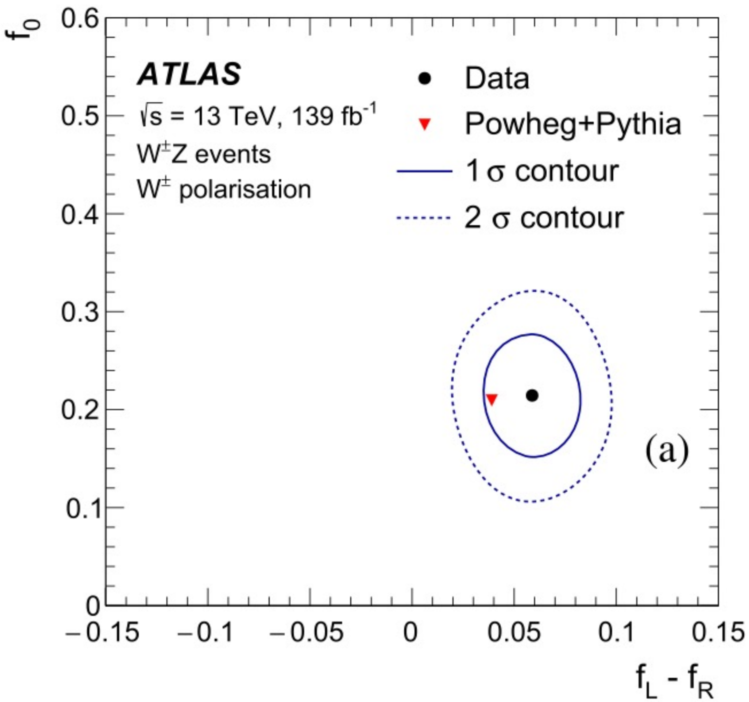
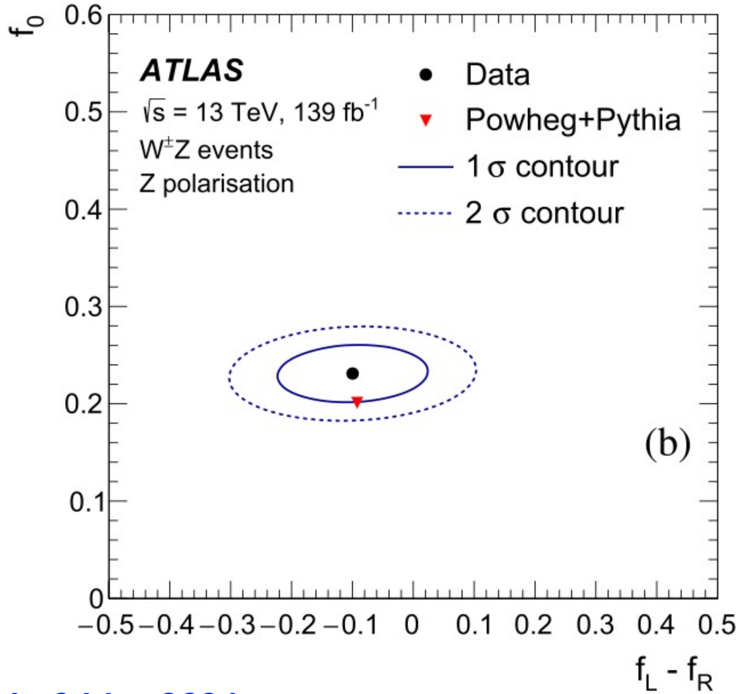
JHEP 07 (2022) 032









Single boson Polarization measurements in WZ

In ATLAS:

θ^*_{lV} (V=W,X) is angle between the momentum of the decay lepton in the rest frame of the massive boson and the momentum of its parent in the WZ rest Frame (modified helicity frame)

In CMS:

θ_V (V=W,X)) is angle between the momentum of the decay lepton in the rest frame of the massive boson and the momentum of its parent in the laboratory frame.

Joint polarisation measurements in WZ

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- **eight variables are used as inputs to the DNN for the statistical analysis:**

4 the transverse momenta of the three leptons and of the neutrino, ,
1 the absolute difference between the rapidities of the Z boson and the lepton from the W decay
2 the azimuthal angle difference between the two leptons of each W and Z-boson decay,
1 the transverse momentum of the W Z system

Are the polarization correlated between the two bosons?

$$R_c = \frac{f_{00}}{f_0^W f_0^Z}$$

SM → 1.3

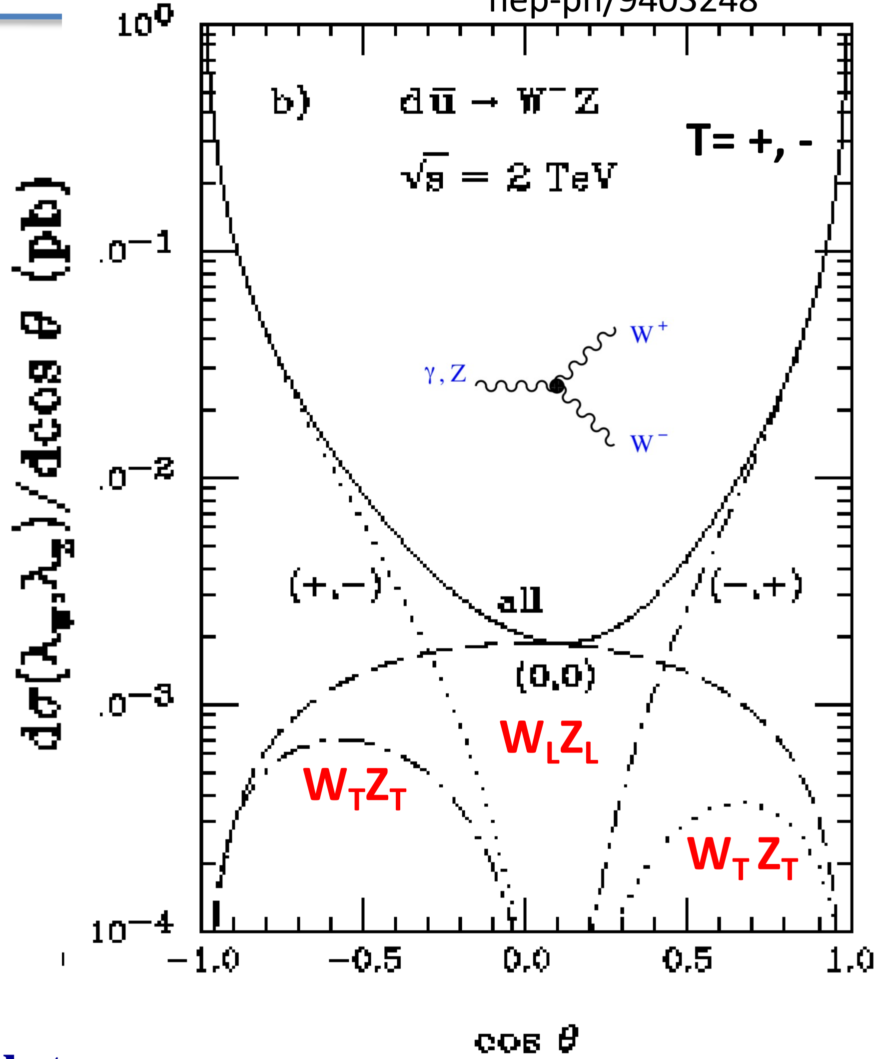
Measurement: Rc = 1.54 ± 0.35
(Obs. Significance 1.6σ wrt Rc = 1 hypothesis)

Unique for WZ (and Wγ): Approximate Amplitude Zero

- The SM amplitude for $q\bar{q} \to W^{\pm}Z$ @ Born-level exhibits an approximate zero @ $\cos\theta = (g_{f1} + g_{f2})/(g_{f1} - g_{f2})$ @ high energy

g_{fi} (i = 1, 2) LH couplings of the Z-boson to fermions
θ is the scattering angle of the W-boson w.r.t. quark

hep-ph/9403248



- This results from an exact zero in the dominant helicity amplitudes M(±, ∓) and strong gauge cancellations in the remaining amplitudes ($s \gg M^2_V$)

- For non-SM WWZ couplings these cancellations no longer occur
→ Sensitivity to NP

BUT the NLO spoil the effect: hope to profit a bit from it with appropriate cuts