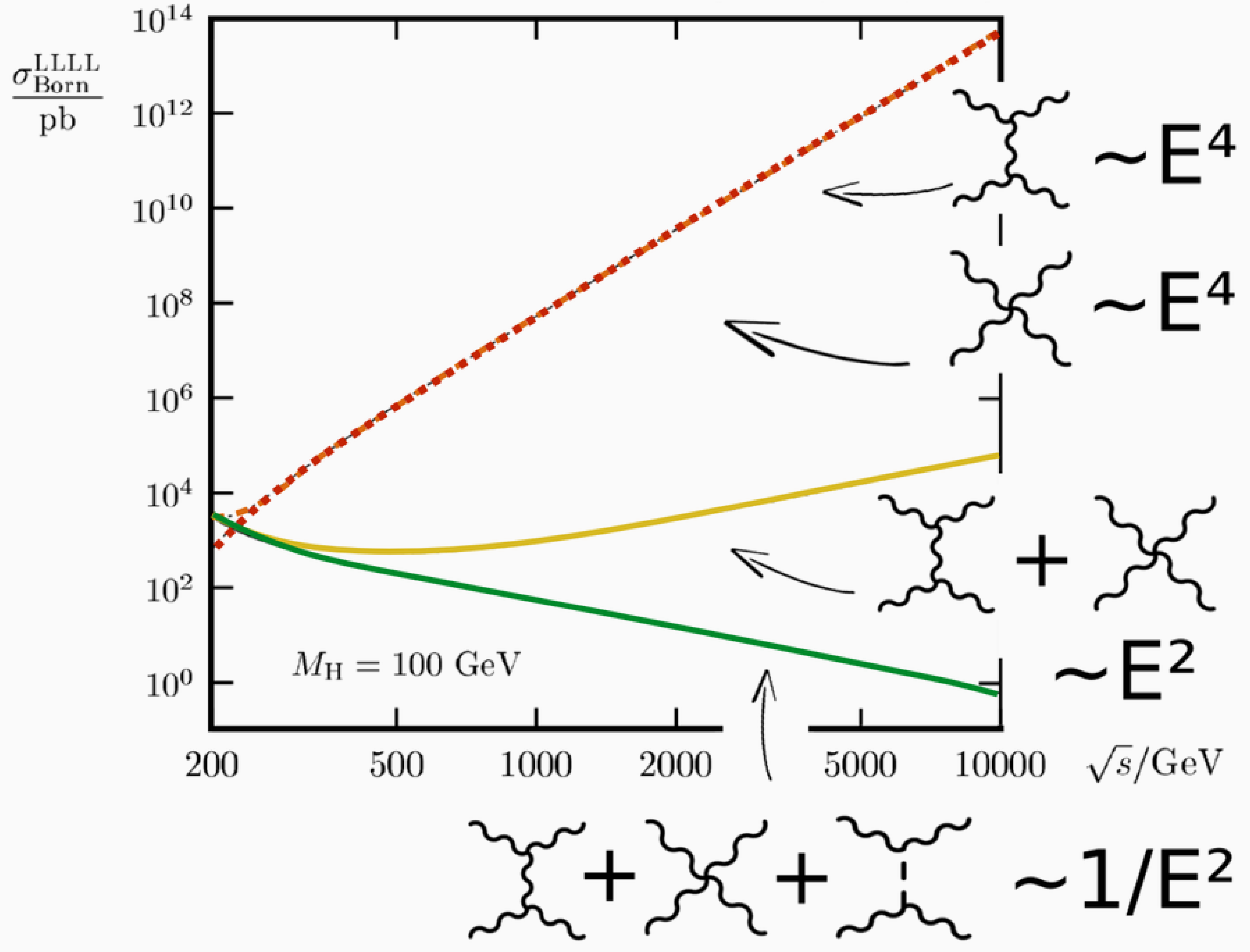
Polarization Measurements in ATLAS and CMS

Erik Bachmann, on behalf of the ATLAS and CMS Collaborations
LHC EW WG General Meeting, 11 July 2024

Motivation

- Longitudinal polarization of electroweak gauge bosons is a direct consequence of the EWSB
- **Important test of the Higgs mechanism**
- Particularly interesting: **longitudinal VBS**

[Denner, Hahn, 1997]



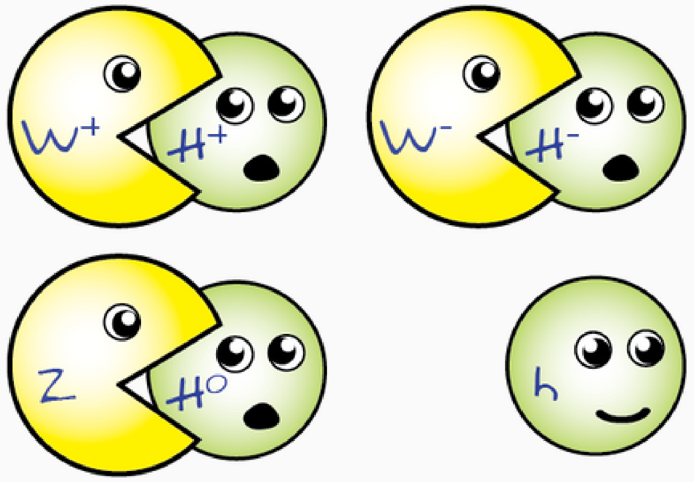
[J. Manjarrés Ramos, LHCP2022]

Higgs mechanism

Massive W and Z bosons

Longitudinal polarization allowed

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

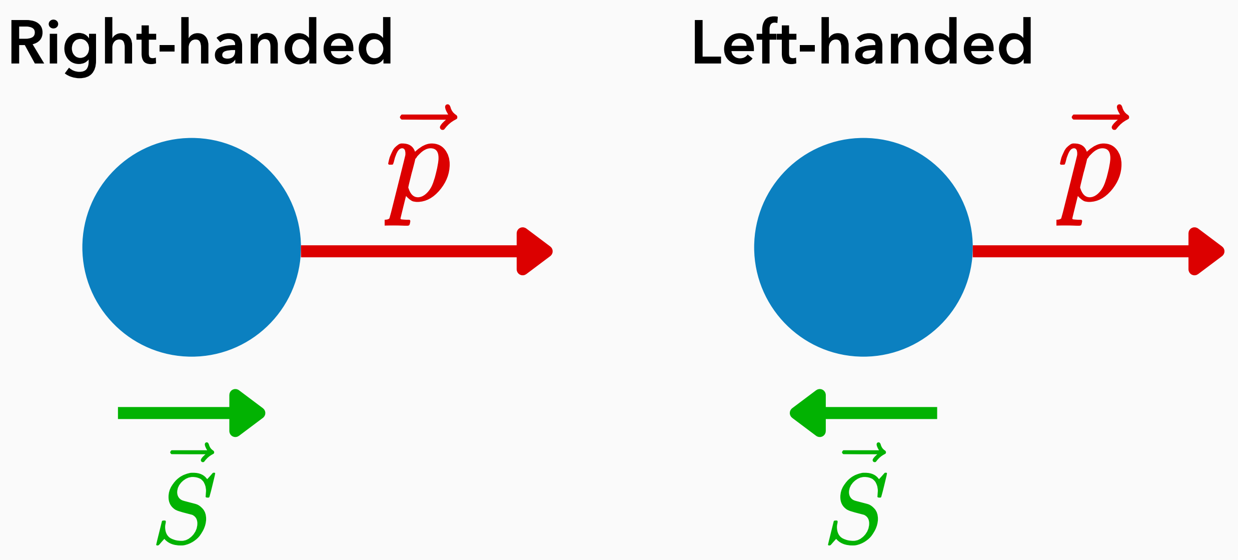


[quantumdiaries.org]

Vector boson polarization

What is vector boson polarization?

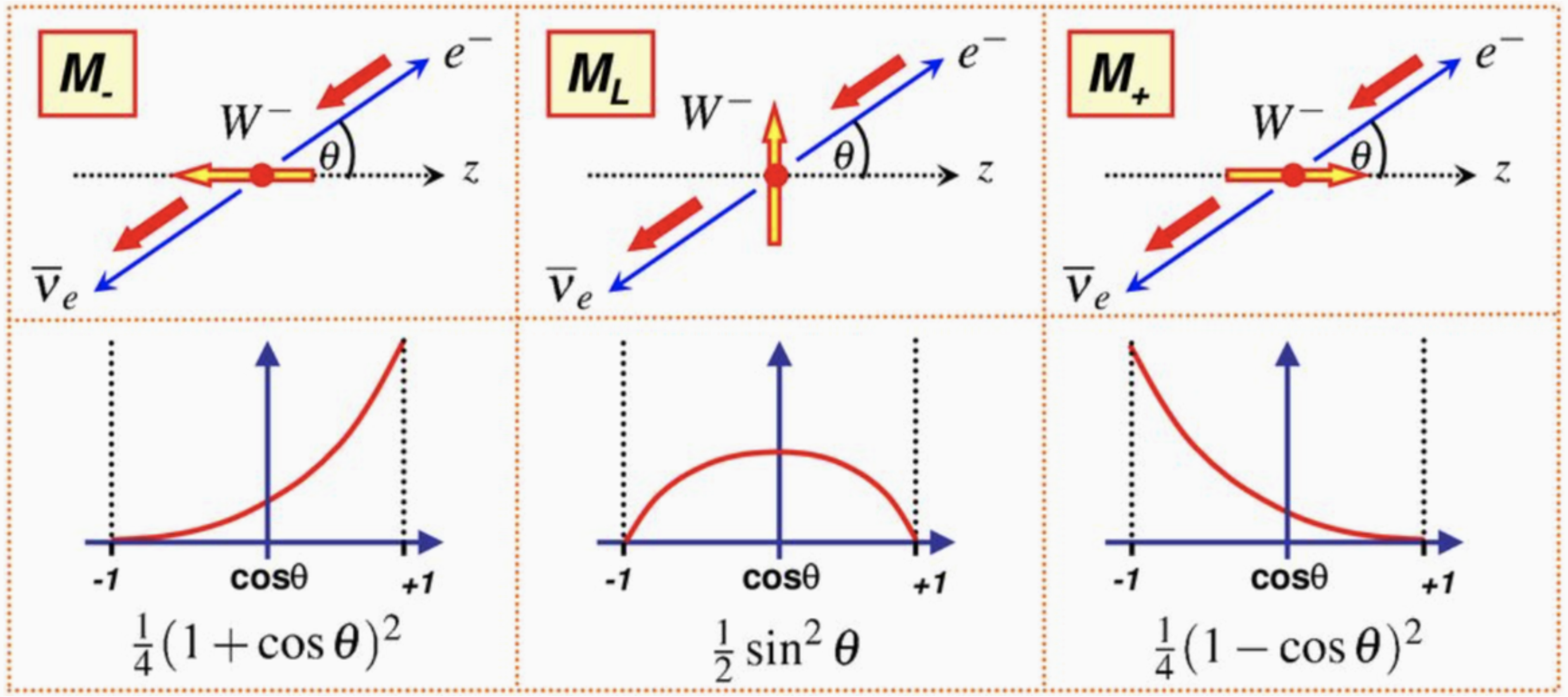
- **Alignment** of a particle's **spin** with its **momentum**
- Helicity: $h = \vec{S} \cdot \frac{\vec{p}}{|\vec{p}|}$
  - **Transverse** polarization (T): (anti-)aligned ($h = \pm 1$)
  - **Longitudinal** polarization (0/L): orthogonal ($h = 0$)
- Helicity is not Lorentz-invariant
  - **reference-frame** needs to be defined for all polarization measurements



How to measure vector boson polarization?

- Parity violation in weak interactions
  $\longrightarrow$ **effects on decay products**
- Analytical distribution of **decay angle** is known at born-level
- In practise: **polarized templates**

$$\frac{d\sigma}{dX} = f_L \frac{d\sigma_L}{dX} + f_R \frac{d\sigma_R}{dX} + f_0 \frac{d\sigma_0}{dX} \left(+ f_{\text{int.}} \frac{d\sigma_{\text{int.}}}{dX} \right)$$



Polarized templates

Monte-Carlo event generators

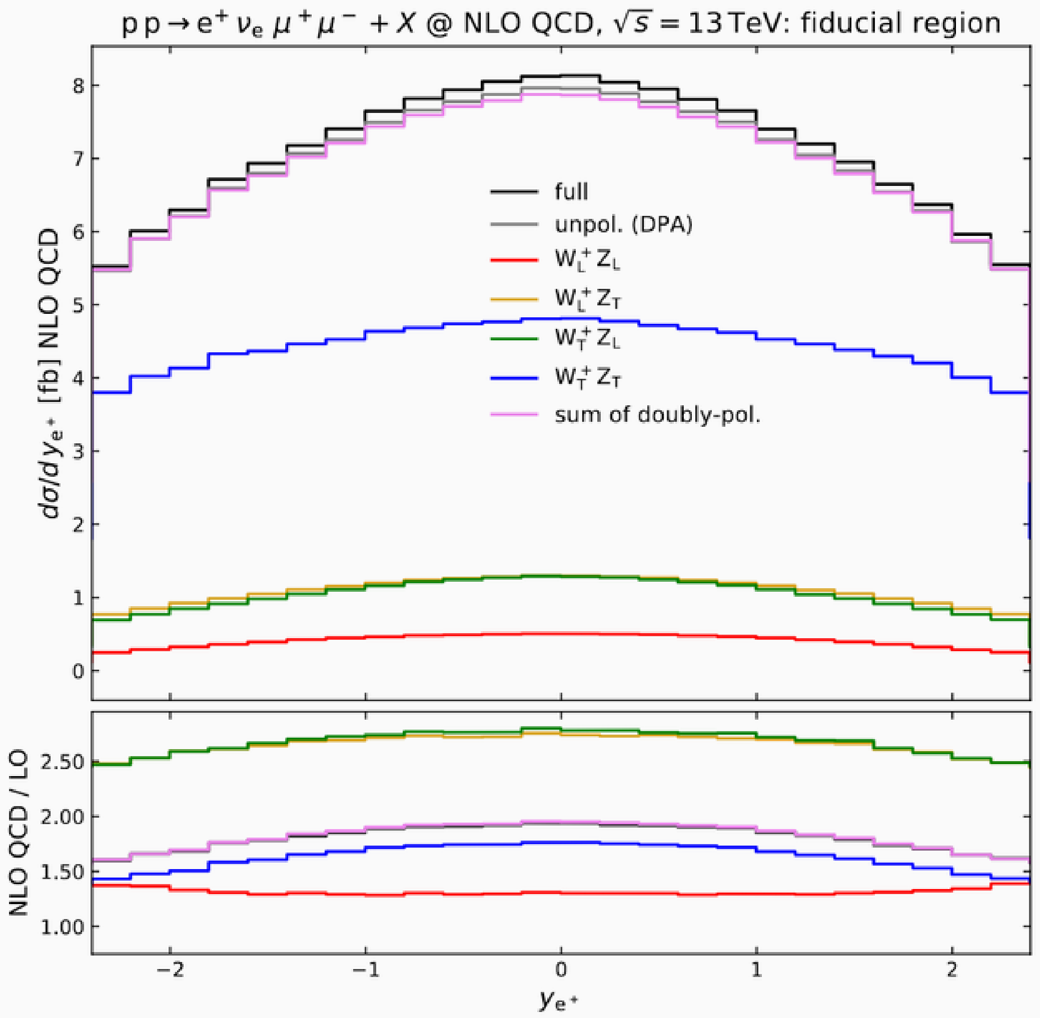
- Several generators available:
  - Phantom: 2→6 proceses at LO+PS [A. Ballestrero et al. 2008, 2017]
  - MG5_aMC@NLO: arbitrary processes at LO+PS, multi-jet merging [D. Buarque Franzosi et al. 2020]
  - Sherpa: arbitrary processes at nLO QCD + PS, multi-jet merging [M. Hoppe et al. 2023]
  - POWHEG BOX RES: diboson processes at NLO QCD + PS [G. Pelliccioli, G. Zanderighi 2023]
- **Only Madgraph used so far by the collaborations**

Fixed-order calculations

- fixed-order calculations show **large, polarization-dependent NLO corrections**

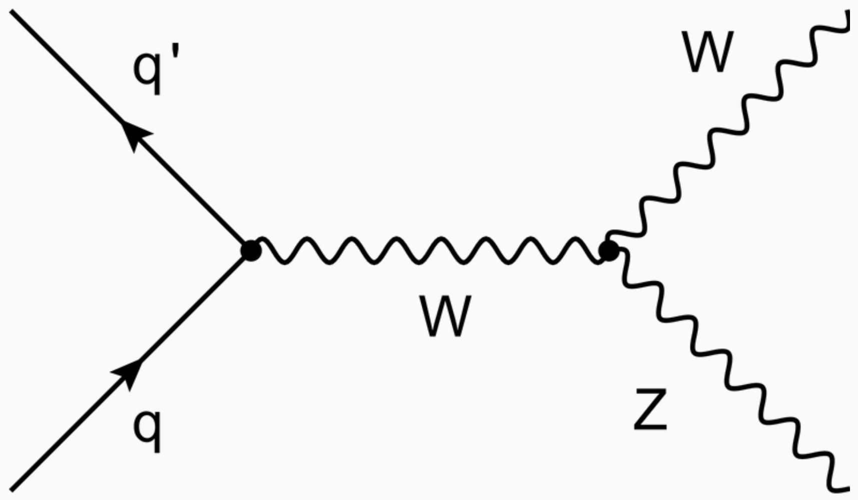
Process	LO	NLO	NLO EW	NNLO
pp → WW	X	X	X	X
pp → ZZ	X	X	X	
pp → WZ	X	X	X	
pol. VBS	X	X		

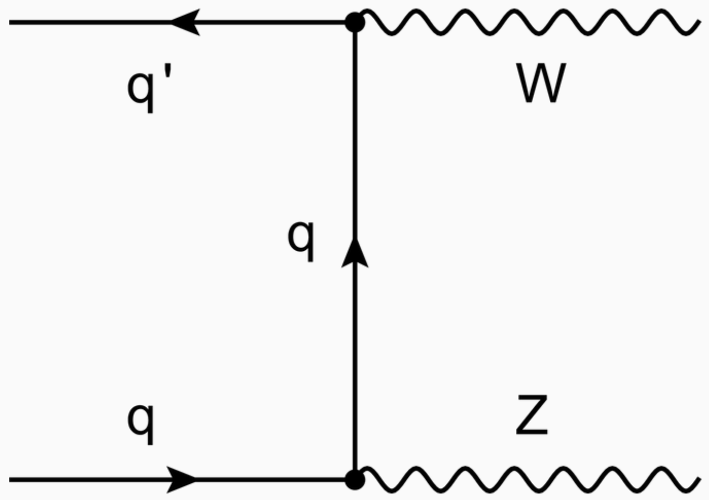
[R. Poncelet, 1st COMETA General Meeting]

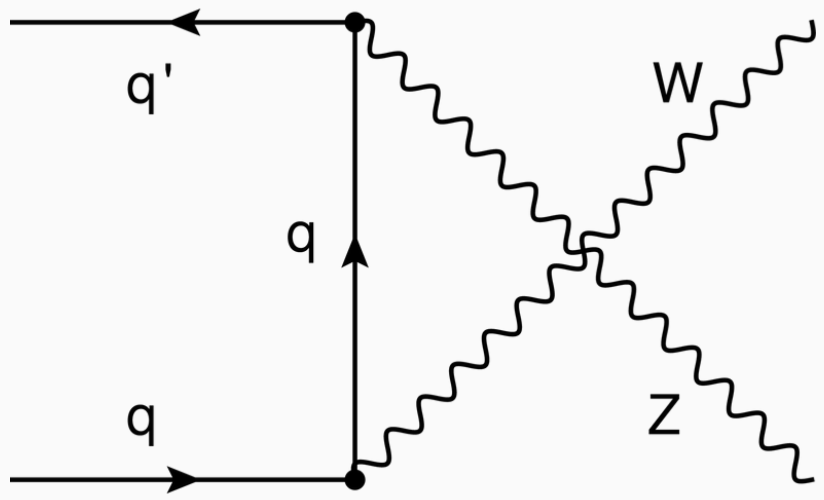


[A. Denner, G. Pelliccioli 2020]

Polarization measurements in WZ



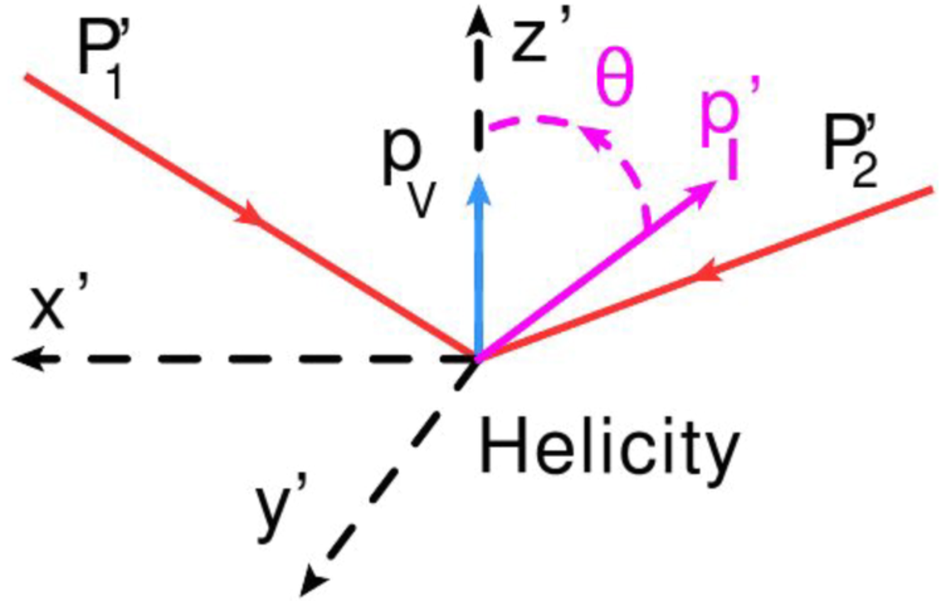




CMS polarization measurement in WZ

Analysis target

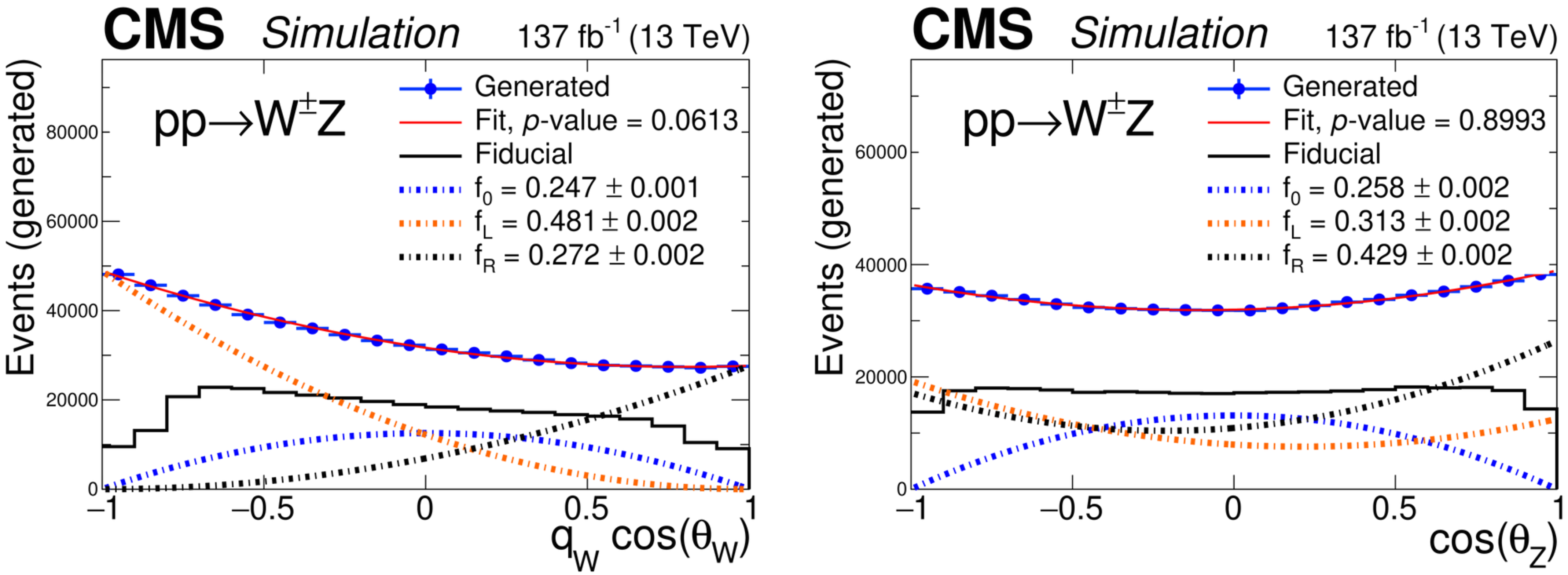
- Singly-polarized states:
  - W-polarization: $\mathrm{W_L Z}$, $\mathrm{W_R Z}$, $\mathrm{W_0 Z}$
  - Z-polarization: $\mathrm{W Z_L}$, $\mathrm{W Z_R}$, $\mathrm{W Z_0}$



Reference frame: laboratory frame

Polarized templates

- Reweighting of inclusive Powheg NLO-QCD sample using generator-level $\cos\theta_V$ distribution



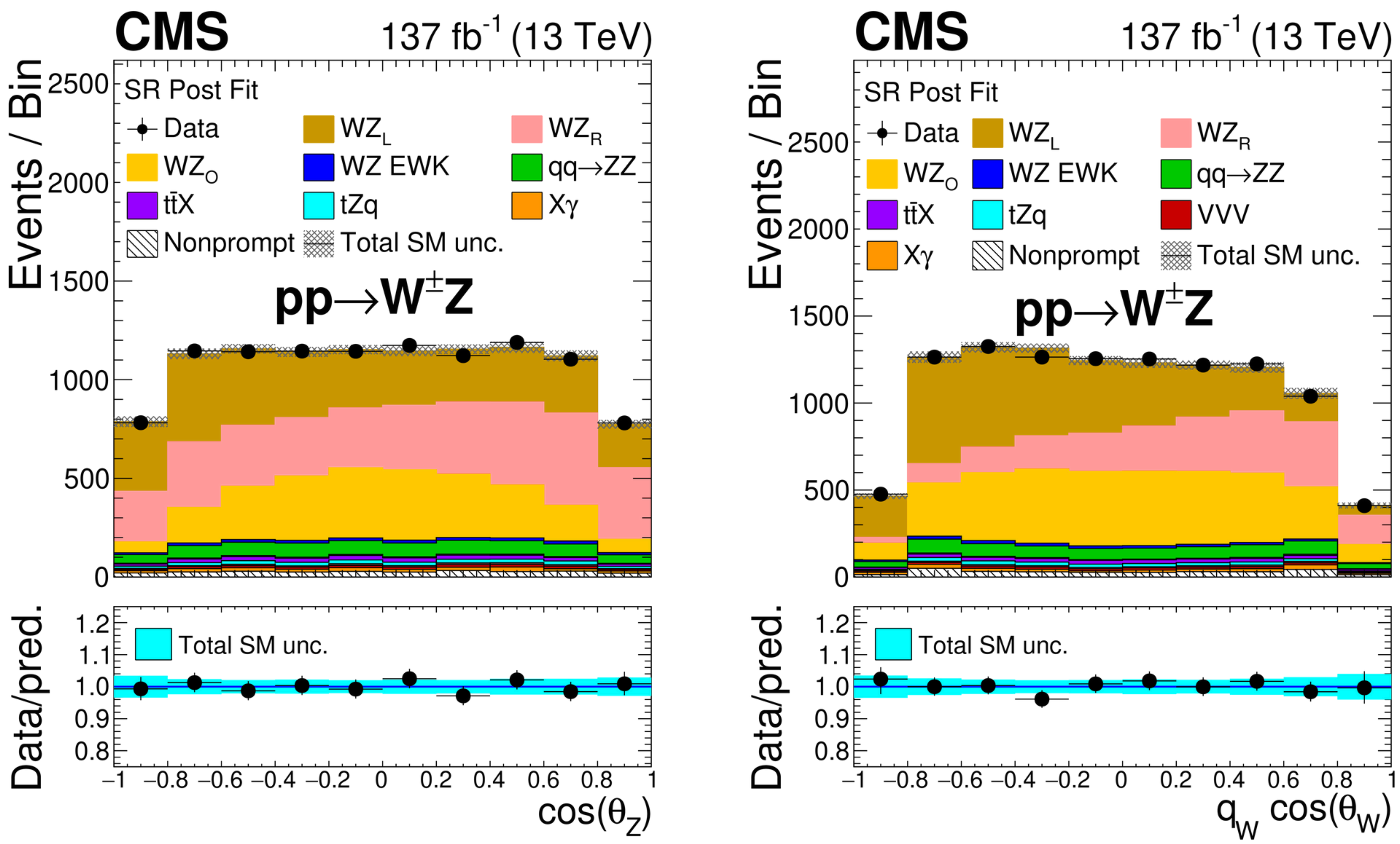
JHEP 07 (2022) 032

CMS polarization measurement in WZ

Region	N_ℓ	$p_T\{\ell_{Z1}, \ell_{Z2}, \ell_W, \ell_4\}$	N_{OSSF}	$\lvert M(\ell_{Z1}, \ell_{Z2}) - m_Z \rvert$	p_T^{miss}	$N_{b\ tag}$	$\min(M(\ell\ell'))$	$M(\ell_{Z1}, \ell_{Z2}, \ell_W)$
SR	$=3$	$>\{25, 10, 25, —\}$ GeV	≥ 1	<15 GeV	>30 GeV	$=0$	>4 GeV	>100 GeV
CR-ZZ	$=4$	$>\{25, 10, 25, 10\}$ GeV	≥ 1	<15 GeV	—	$=0$	>4 GeV	>100 GeV
CR-$t\bar{t}$Z	$=3$	$>\{25, 10, 25, —\}$ GeV	≥ 1	<15 GeV	>30 GeV	>0	>4 GeV	>100 GeV
CR-conv	$=3$	$>\{25, 10, 25, —\}$ GeV	≥ 1	—	≤ 30 GeV	$=0$	>4 GeV	<100 GeV

Statistical Analysis

- Cut-based event selection
- CR for ZZ, top and photon conversion
- $\cos\theta_V$ fitted separately for W and Z in charge-inclusive and charged ($W^+Z\,/\,W^-Z$) channels
- free parameters: μ, f_0, $f_L - f_R$

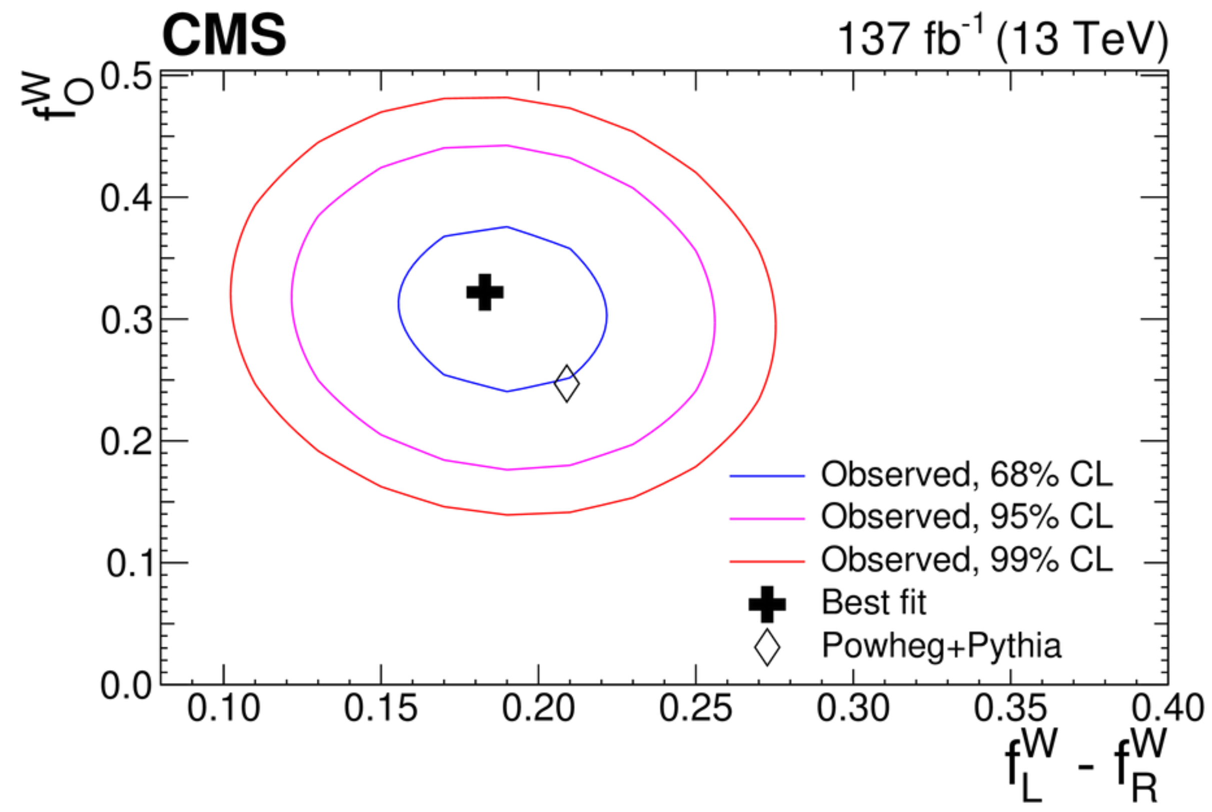


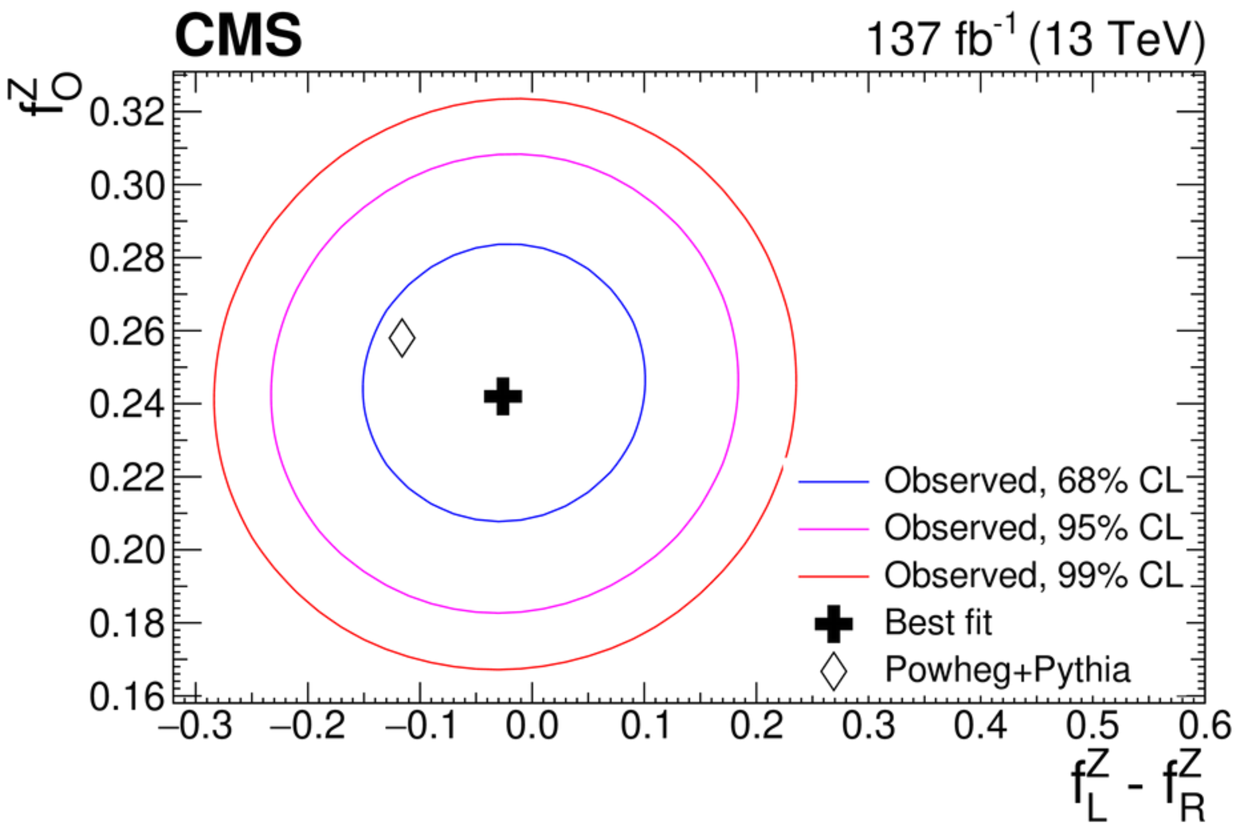
CMS polarization measurement in WZ

First observation of longitudinally polarized W-bosons in WZ: 5.6σ(4.3σ)

Significance for longitudinally polarized Z-bosons way above five standard deviations

Category	Observable	Observed	POWHEG expected	MATRIX expected
W, inclusive	f_0	$0.322^{+0.080}_{-0.077}$	$0.2470^{+0.0003}_{-0.0003}$	$0.248^{+0.003}_{-0.003}$
	f_{LR}	$0.183^{+0.032}_{-0.032}$	$0.209^{+0.002}_{-0.002}$	$0.210^{+0.006}_{-0.006}$
W, plus	f_0	$0.358^{+0.100}_{-0.096}$	$0.2294^{+0.0003}_{-0.0003}$	$0.237^{+0.004}_{-0.004}$
	f_{LR}	$0.288^{+0.041}_{-0.042}$	$0.305^{+0.003}_{-0.003}$	$0.293^{+0.007}_{-0.007}$
W, minus	f_0	$0.361^{+0.118}_{-0.128}$	$0.2782^{+0.0007}_{-0.0007}$	$0.268^{+0.005}_{-0.005}$
	f_{LR}	$0.010^{+0.055}_{-0.049}$	$0.056^{+0.002}_{-0.002}$	$0.076^{+0.007}_{-0.007}$
Z, inclusive	f_0	$0.245^{+0.024}_{-0.024}$	$0.2583^{+0.0003}_{-0.0003}$	$0.253^{+0.003}_{-0.003}$
	f_{LR}	$-0.038^{+0.078}_{-0.078}$	$-0.116^{+0.002}_{-0.002}$	$-0.120^{+0.006}_{-0.006}$
Z, plus	f_0	$0.236^{+0.030}_{-0.030}$	$0.2710^{+0.0003}_{-0.0003}$	$0.263^{+0.004}_{-0.004}$
	f_{LR}	$0.039^{+0.101}_{-0.101}$	$-0.073^{+0.003}_{-0.003}$	$-0.083^{+0.007}_{-0.007}$
Z, minus	f_0	$0.266^{+0.037}_{-0.037}$	$0.2392^{+0.0005}_{-0.0005}$	$0.238^{+0.004}_{-0.004}$
	f_{LR}	$-0.164^{+0.121}_{-0.121}$	$-0.179^{+0.003}_{-0.003}$	$-0.178^{+0.007}_{-0.007}$





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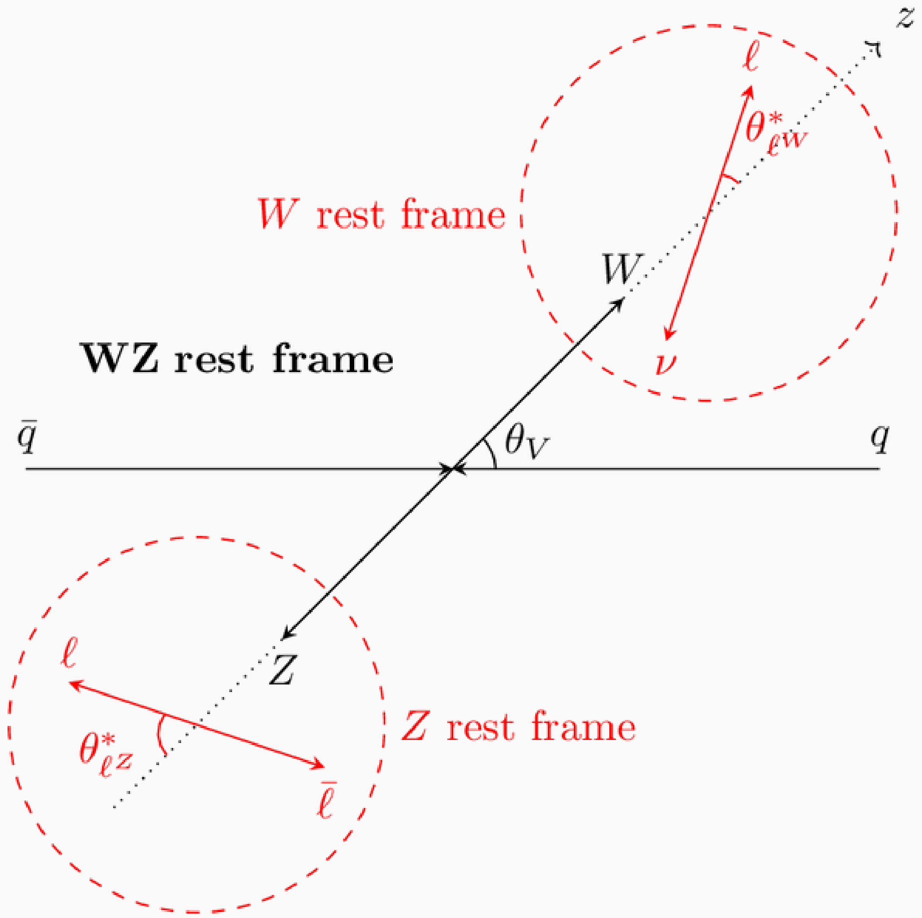
ATLAS polarization measurement in WZ

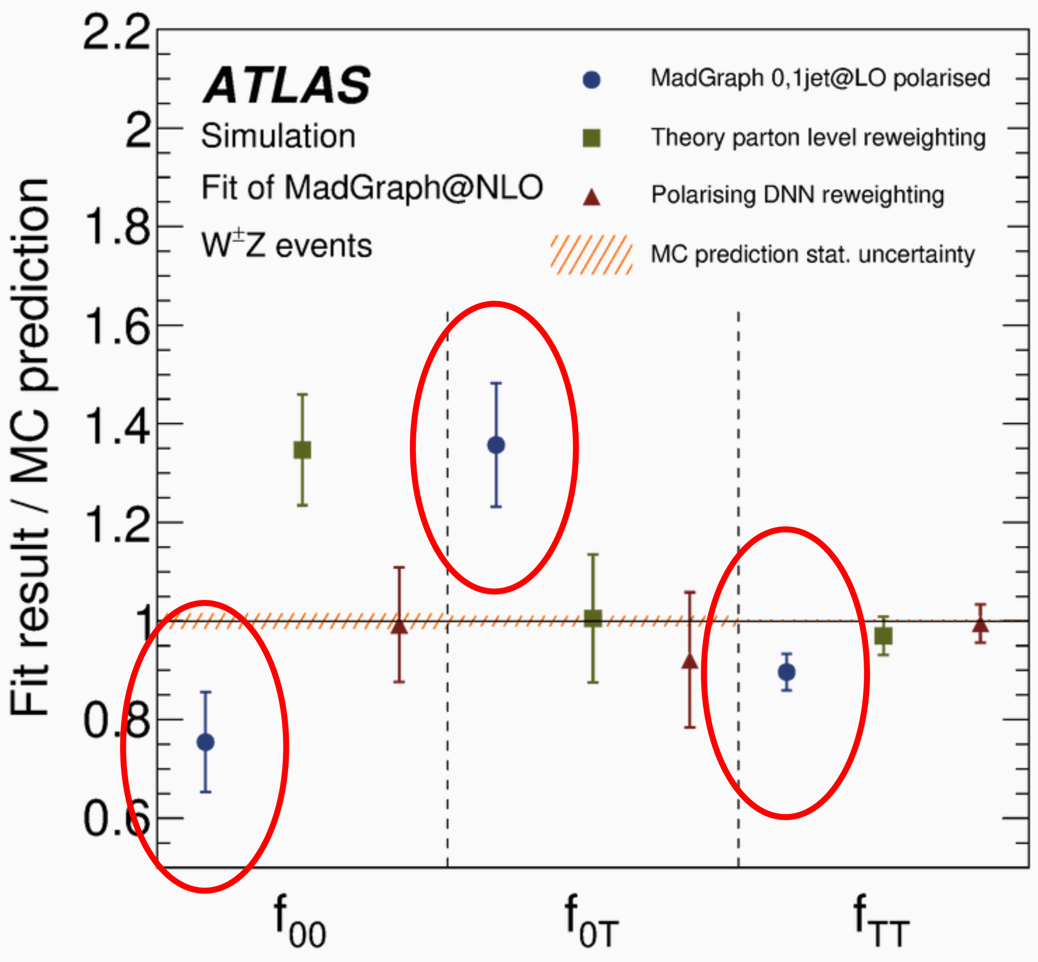
Analysis target

- Joint-polarization states $W_0 Z_0$, $W_T Z_0$, $W_0 Z_T$, $W_T Z_T$
- Singly-polarized states



Reference frame: WZ rest frame

⟶ *minimizes correlation between 00 and TT modes*



Polarization templates

- Events generated with MadGraph 2.7.3 + Pythia 8 in 0,1j@LO merged setup

⟶ **observed bias in extracted polarization fractions, up to 50% of fraction value!**

Phys. Lett. B 843 (2023) 137895

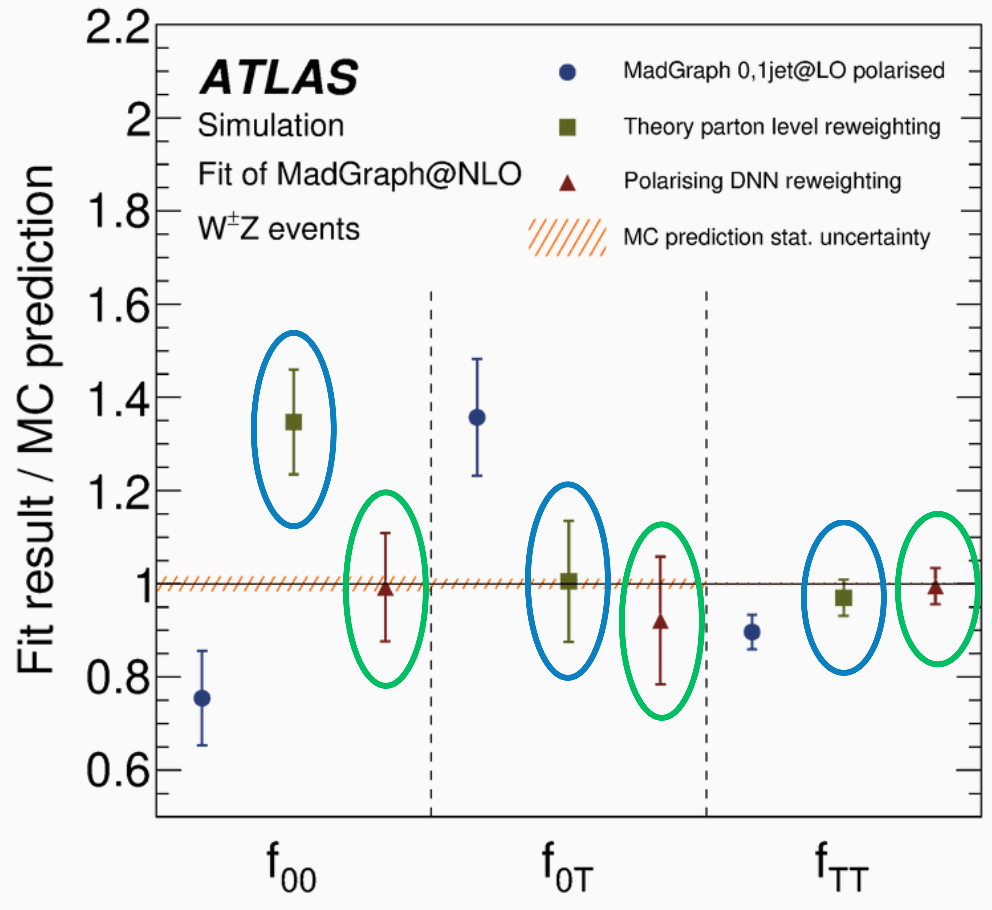
Joint-polarization measurement in WZ

Templates Challenge: multiple reweighting methods to obtain templates at NLO-QCD

- **Full phase-space reweighting** of Powheg NLO-QCD with DNN [arXiv:1907.08209]
  - factorization assumption: $p_{\mathrm{NLO}}(\vec{x}, i, j) \propto p_{0,1\mathrm{j@LO}}(\vec{x}) \cdot p(i, j|\vec{x}) \cdot p_{0,1\mathrm{j@LO} \to \mathrm{NLO}}(\vec{x})$
  - MadGraph 0,1j@LO: $p_{0,1\mathrm{j@LO}}(\vec{x}, i, j) \propto p_{0,1\mathrm{j@LO}}(\vec{x}) \cdot p(i, j|\vec{x})$
  - Powheg NLO-QCD: $p_{\mathrm{NLO}}(\vec{x}) \propto p_{0,1\mathrm{j@LO}}(\vec{x}) \cdot p_{0,1\mathrm{j@LO} \to \mathrm{NLO}}(\vec{x})$

⟶ **learn $\mathbf{p(i, j|\vec{x})}$ by discriminating (i, j) polarization against sum of polarizations**

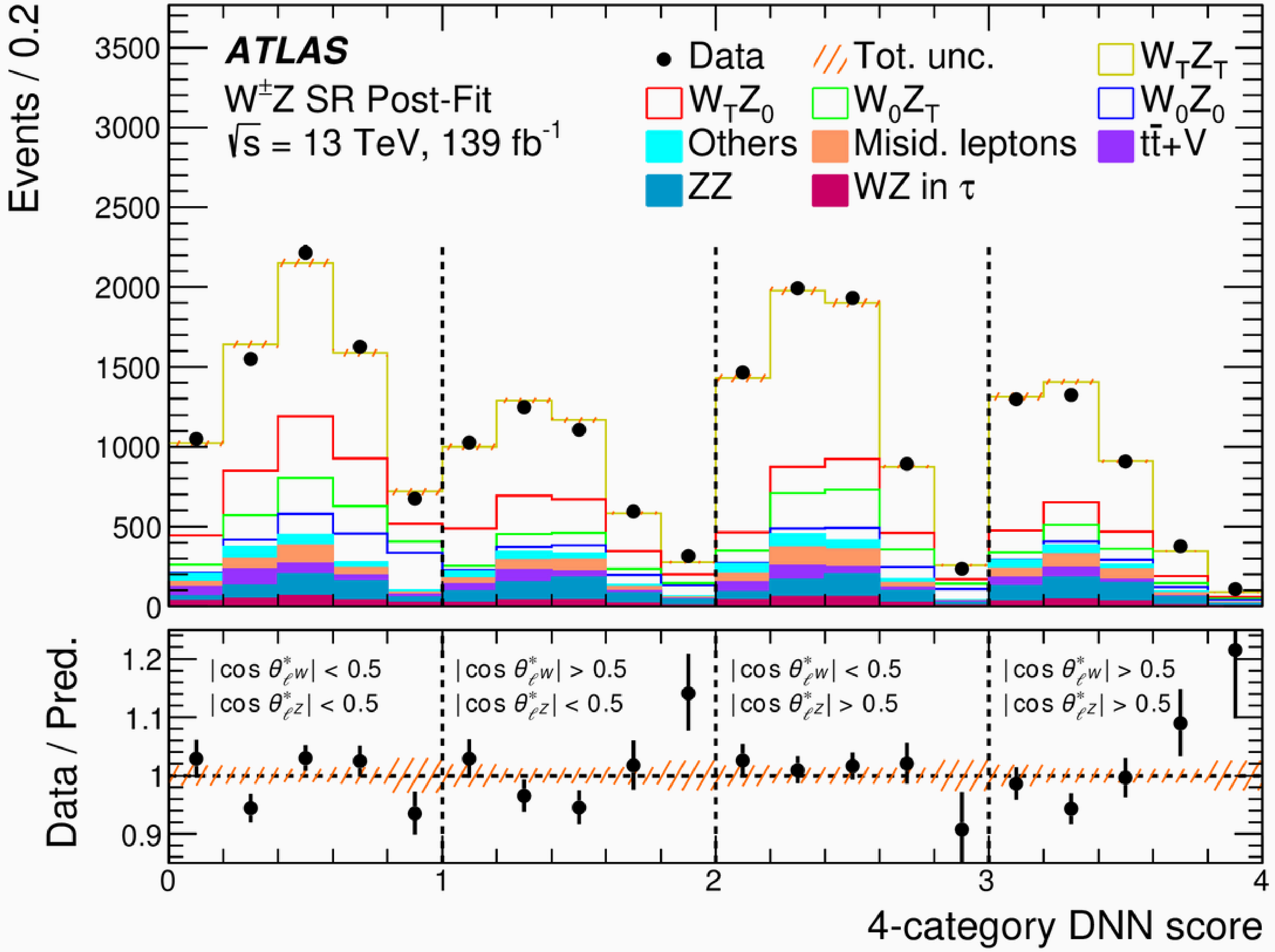
- **Binned reweighting of DNN score** based on polarized fixed-order NLO-QCD calculations (MoCaNLO) [A. Denner, G. Pelliccioli, arXiv:2010.07149]
  - used to assess modelling uncertainties



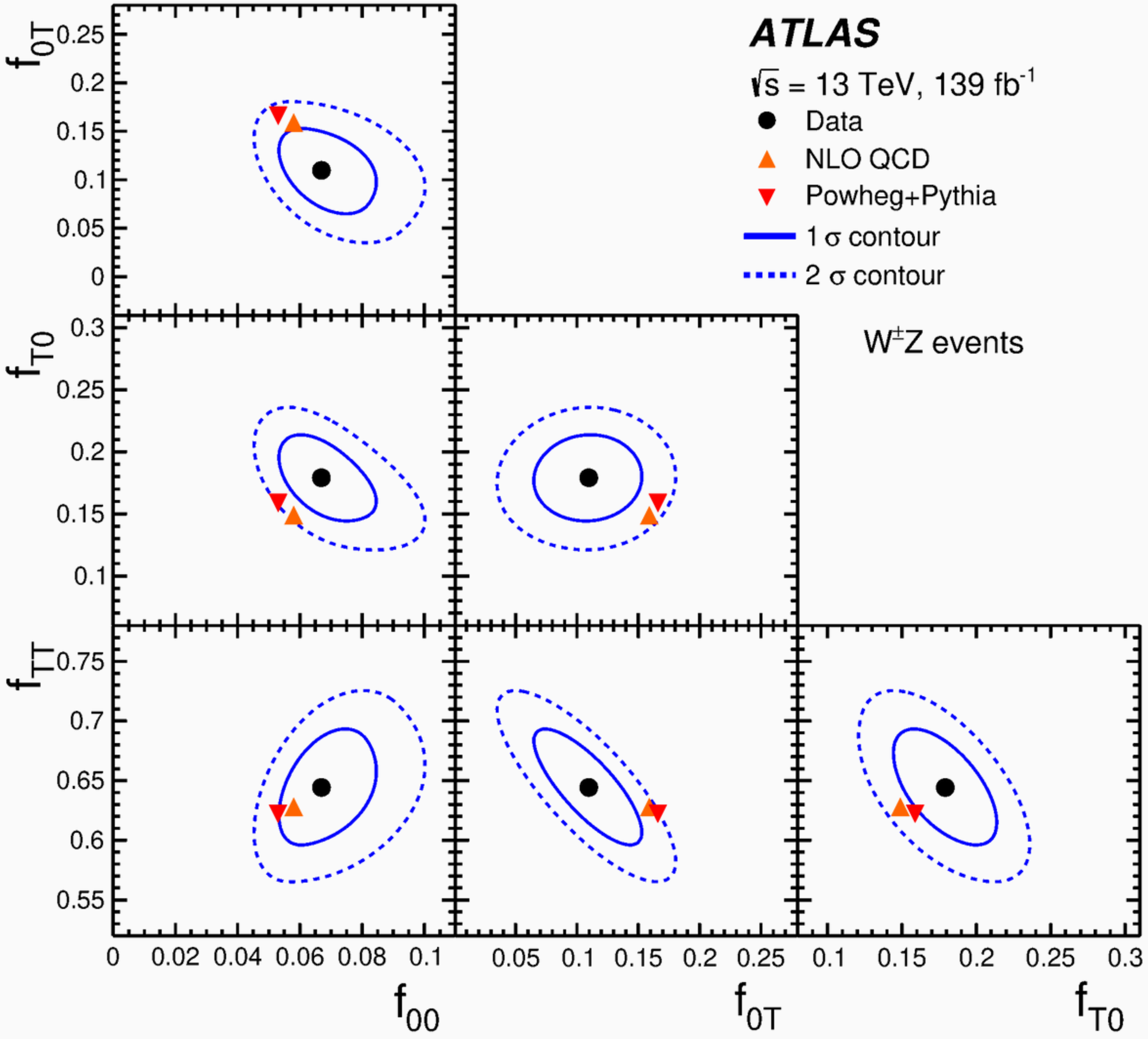
Joint-polarization measurement in WZ

Statistical Analysis

- Free parameters: μ, f_{00}, f_{T0}, f_{TT}
- DNN multiclass classifier trained on MadGraph 0,1j@LO polarized samples
  - inputs: $p_T^{\ell^W}$, $p_T^{\ell_1^Z}$, $p_T^{\ell_2^Z}$, E_T^{miss}, $|y_Z - y_{\ell^W}|$, $\Delta\phi(l^W, \nu)$, $\Delta\phi(\ell_1^Z, \ell_2^Z)$, p_T^{WZ}
- p_{00}^{DNN} distribution fitted in four decay angle categories to separate 0T and T0 states
- Statistical uncertainties at the same level as systematic uncertainties
  - Modelling uncertainty on DNN reweighting and choice of templates
  - QCD scale
  - Jets / E_T^{miss} reconstruction, calibration



Joint-polarization measurement in WZ



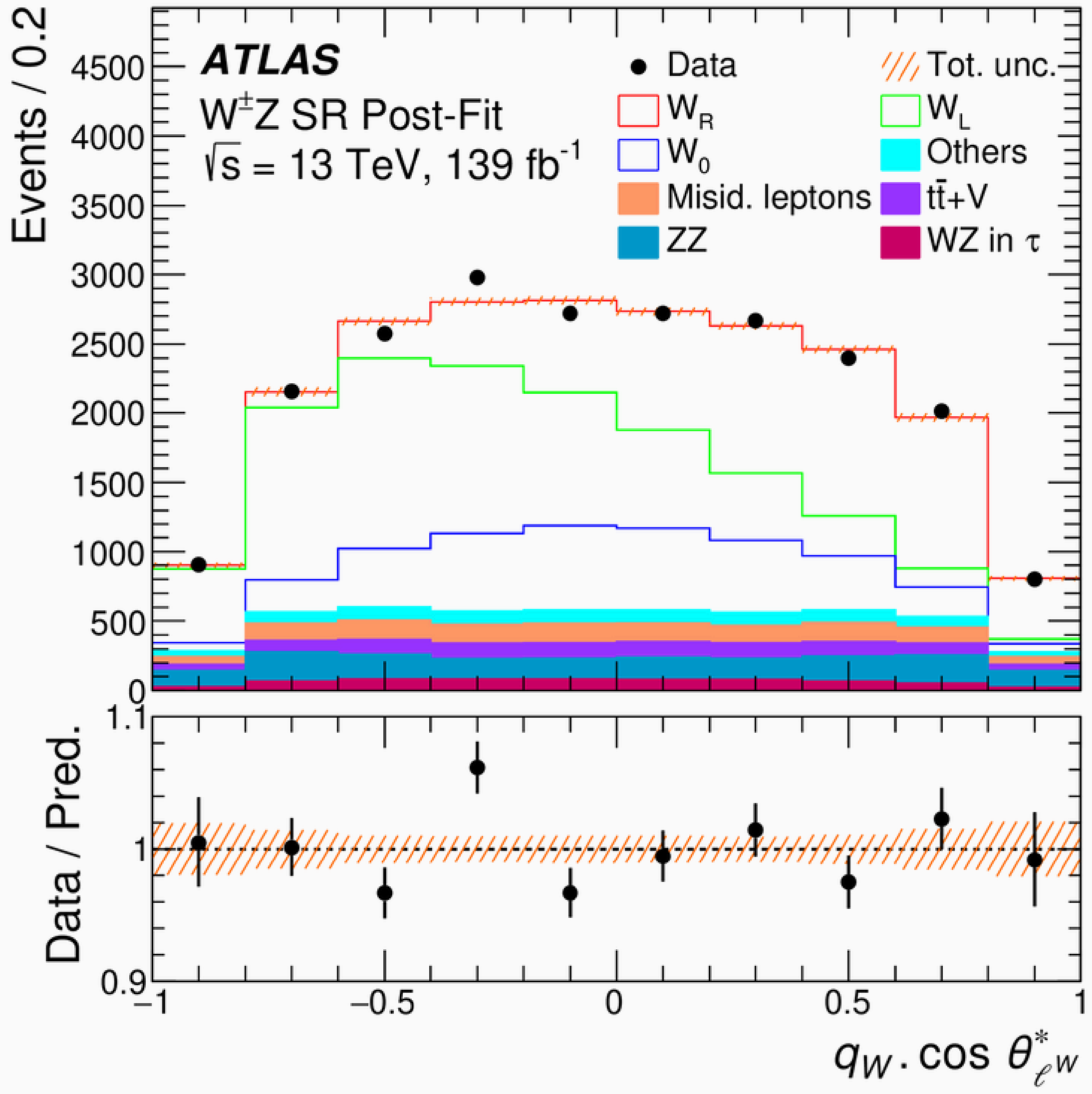
First observation of simultaneous pair-production of longitudinally-polarised VB

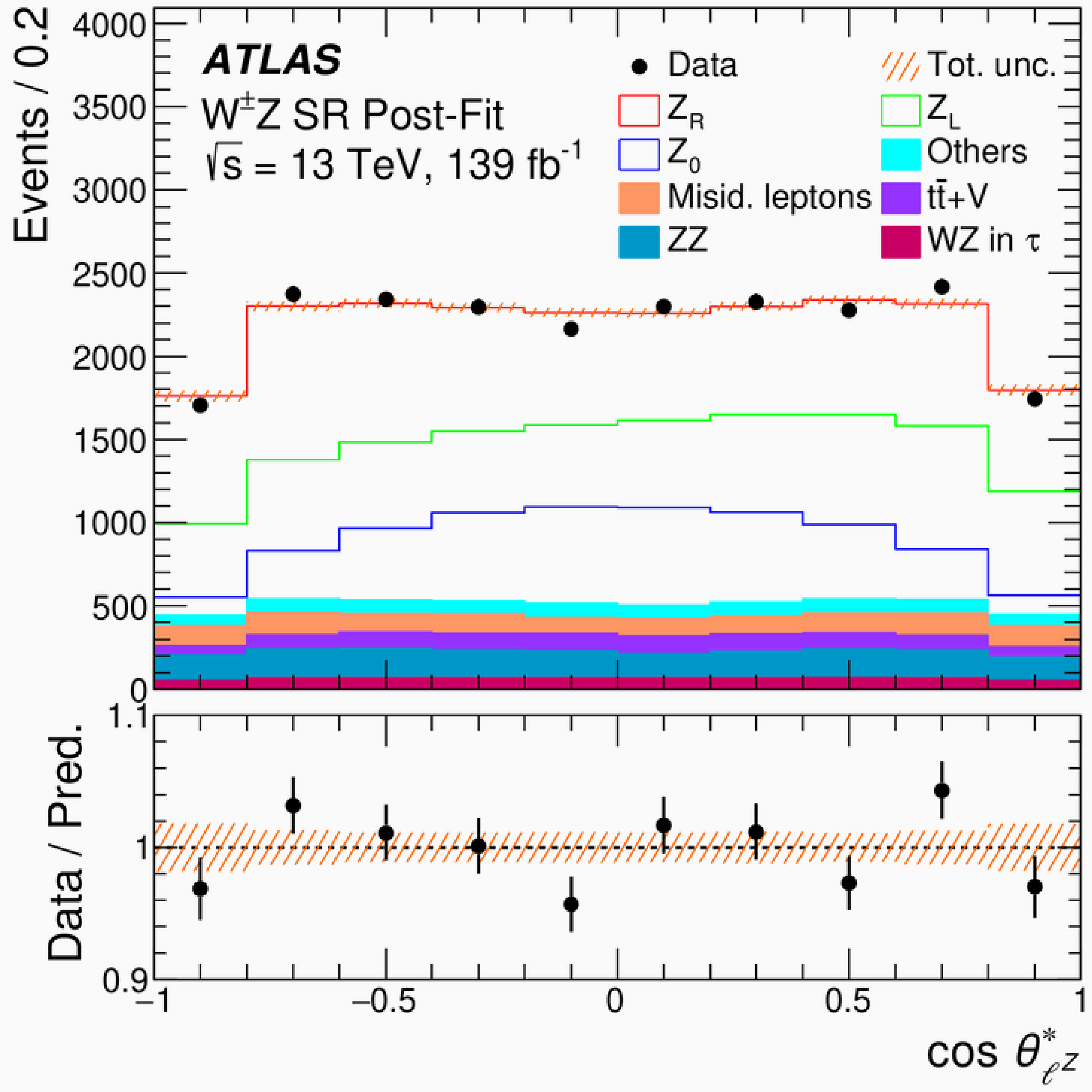
- significance of 7.1σ (6.2σ) for f_{00}
- significance for f_{T0} and f_{TT} >5σ

	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

Single boson polarization in WZ

- Measured f_0 and $f_L - f_R$ for W and Z bosons in charge inclusive and both charged final states
- Polarization templates of $\cos\theta^*_V$ from analytical reweighting of Powheg NLO-QCD
- **Spin correlation:** measured $R_c = \dfrac{f_{00}}{f_0^W f_0^Z} = 1.54 \pm 0.35$ (SM: 1.3)





	f_0 Data	f_0 POWHEG+PYTHIA
W in W^+Z	0.23 ± 0.05	0.2044 ± 0.0024
W in W^-Z	0.19 ± 0.05	0.217 ± 0.004
W in $W^\pm Z$	0.21 ± 0.04	0.2094 ± 0.0016
Z in W^+Z	0.223 ± 0.025	0.1971 ± 0.0019
Z in W^-Z	0.241 ± 0.029	0.2065 ± 0.0023
Z in $W^\pm Z$	0.231 ± 0.019	0.2009 ± 0.0014

	$f_L - f_R$ Data	$f_L - f_R$ POWHEG+PYTHIA
W in W^+Z	0.071 ± 0.023	0.0990 ± 0.0015
W in W^-Z	0.026 ± 0.027	-0.0491 ± 0.0020
W in $W^\pm Z$	0.059 ± 0.016	0.0390 ± 0.0011
Z in W^+Z	-0.20 ± 0.10	-0.217 ± 0.006
Z in W^-Z	0.10 ± 0.13	0.092 ± 0.007
Z in $W^\pm Z$	-0.10 ± 0.08	-0.092 ± 0.005

ATLAS measurement of energy dependence of WZ polarization fractions and RAZ effect

Analysis target

- Joint-polarization states at high p_T^Z : W_0Z_0, W_TZ_0, W_0Z_T, W_TZ_T
    - **first measurement to probe the energy dependence of polarization fractions**
- Radiation Amplitude Zero (RAZ) effect in WZ production

00-enhanced signal regions

- Cuts on p_T^Z to increase 00-fraction ⟶ **up to 23%!**
- Cut on p_T^{WZ} to reduce jet activity

⟶ **more LO-like phase space**

	Prediction	
	100 < p_T^Z ≤ 200 GeV	**p_T^Z > 200 GeV**
f_{00}	0.152 ± 0.006	0.234 ± 0.007
f_{0T}	0.120 ± 0.002	0.062 ± 0.002
f_{T0}	0.109 ± 0.001	0.058 ± 0.001
f_{TT}	0.619 ± 0.007	0.646 ± 0.008

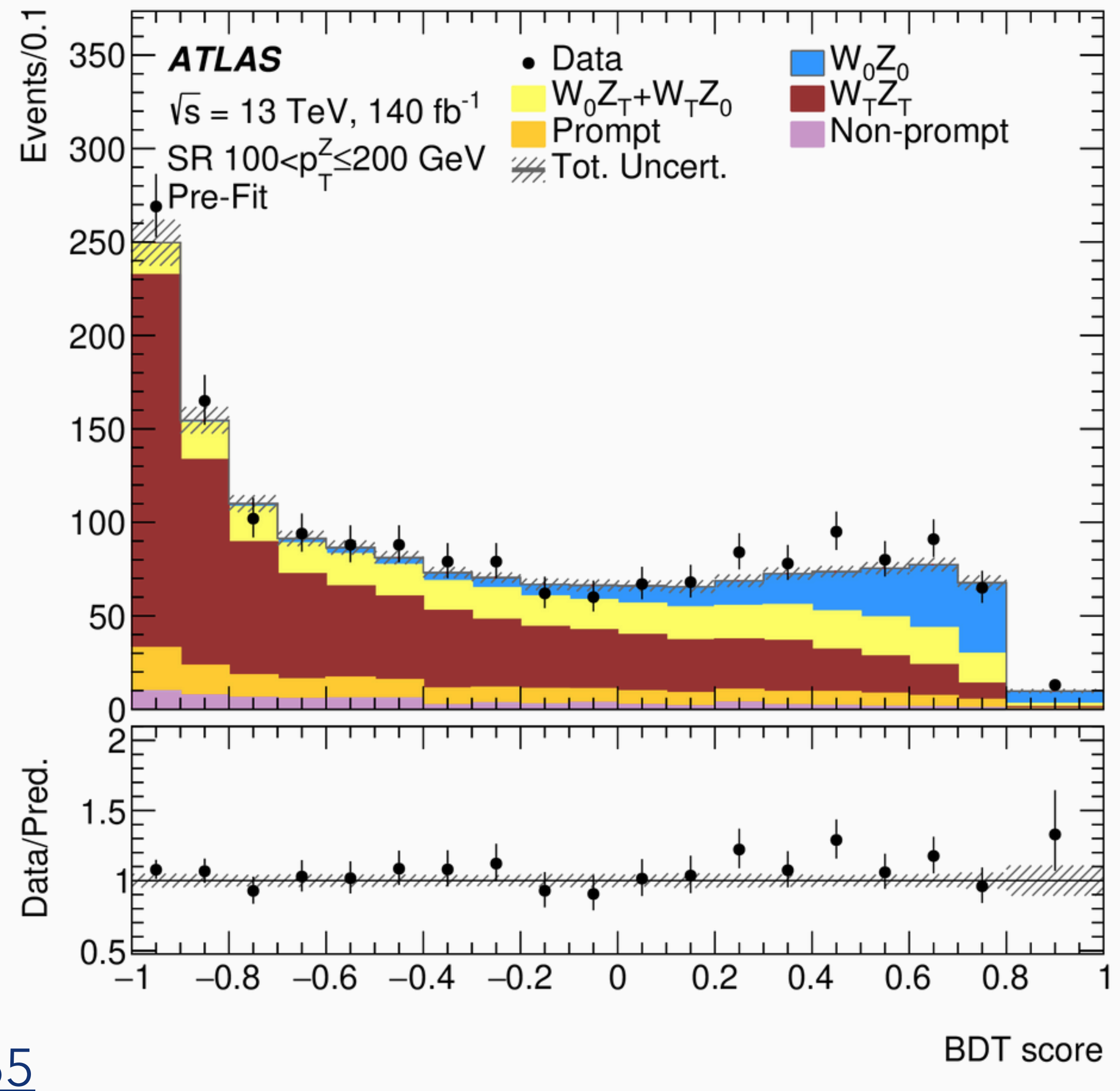
	Signal regions	
	00-enhanced region 1	**00-enriched region 2**
Pass inclusive WZ event selection	✓	✓
Transverse momentum of the Z boson (p_T^Z)	[100, 200] GeV	> 200 GeV
Transverse momentum of the WZ system (p_T^{WZ})	< 70 GeV	

arXiv:2402.16365

Energy dependence of WZ polarization fractions

Polarization modelling

- MadGraph LO+0,1j
- Uncertainties from NLO QCD+EW fixed-order calculations (G. Pelliccioli, Duc Ninh Le)



Discriminant variable

- Dedicated BDTs trained in each p_T^Z bin to discriminate W_0Z_0 vs rest

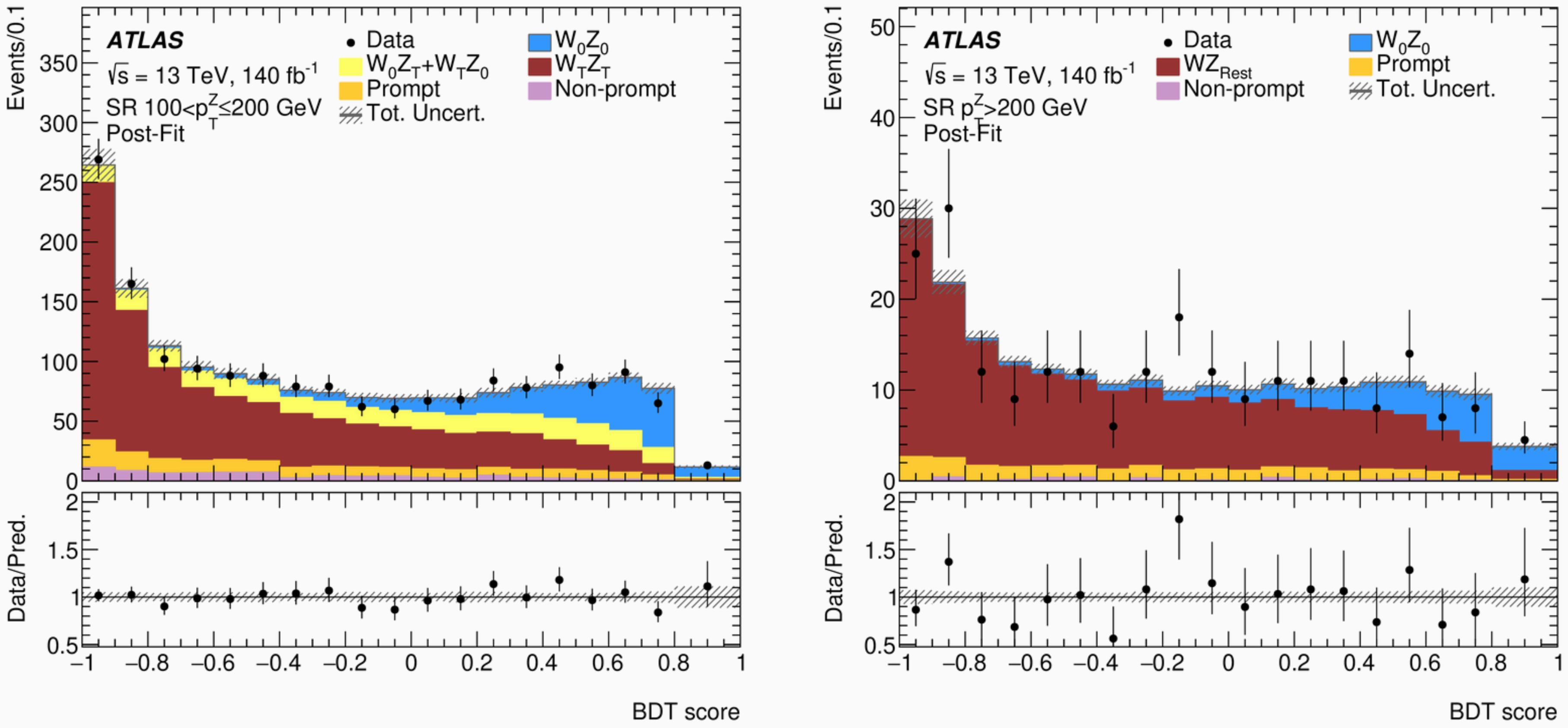
Training variable	Definition
$\Delta Y(\ell_W Z)$	Rapidity difference between the W lepton and Z boson
p_T^{WZ}	Transverse momentum of the WZ system
$p_T(\ell_W)$	Transverse momentum of the W lepton
$p_T(\ell_2^Z)$	Transverse momentum of the subleading Z lepton
E_T^{miss}	Missing transverse momentum
$\cos\theta_{\ell_Z}$	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

Statistical analysis

- 2 fit configurations
  - 3 parameters: μ, f_{00}, $f_{T0}+f_{0T}$
  - 2 parameters: μ, f_{00}
- Dominated by statistical uncertainties
- NLO QCD uncertainties subleading

arXiv:2402.16365

Energy dependence of WZ polarization fractions



3 parameter fit

	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

2 parameter fit

	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

5 sigma observation for f_{00} in $100 < p_T^Z \leq 200$ GeV region

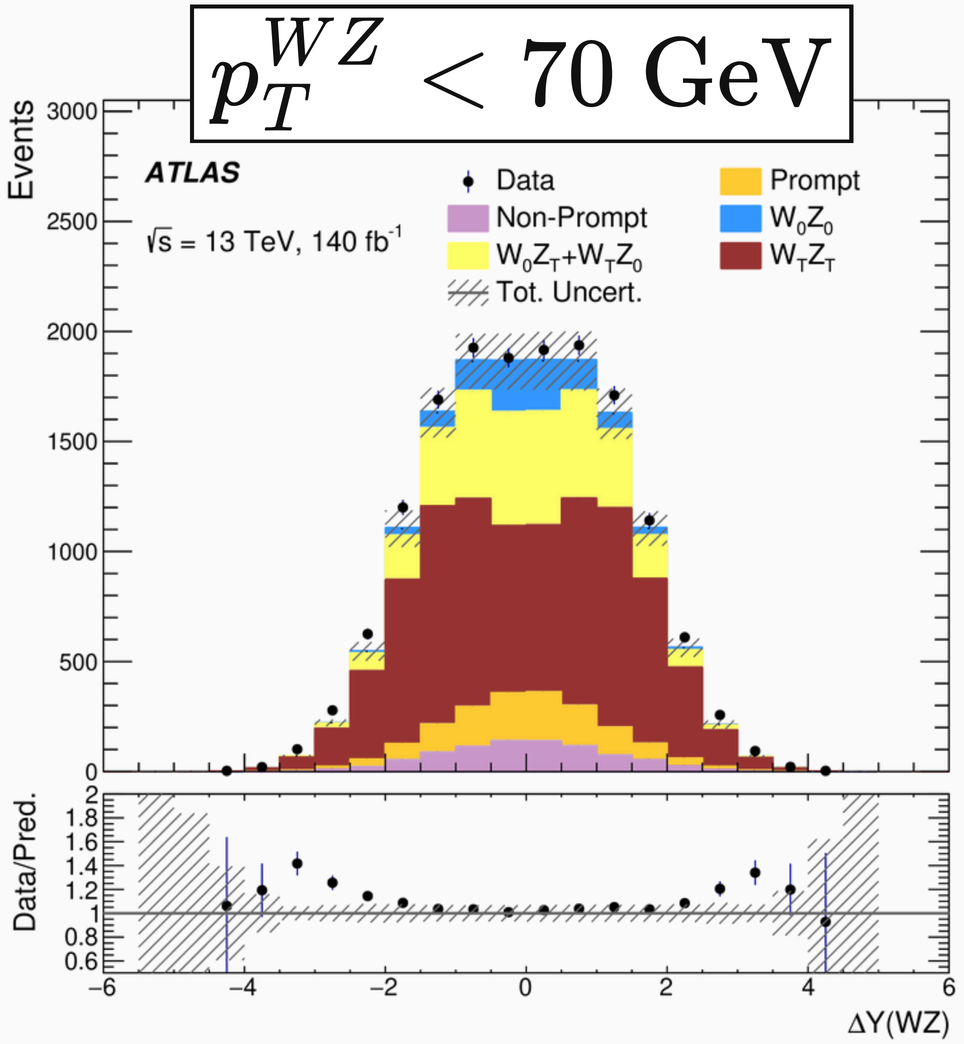
Evidence for f_{00} in $p_T^Z > 200$ GeV region for 2 parameter fit

arXiv:2402.16365

RAZ effect in WZ

Radiation Amplitude Zero effect

- At LO: TT cross-section drops to zero when $\cos\theta_V$ approaches zero
  ⟶ **observable as dip in $\mathbf{\Delta Y(WZ)}$ and $\mathbf{\Delta Y(\ell_W Z)}$**
- Diluted by NLO QCD effects
  ⟶ **reduce jet activity with $\mathbf{p_T^{WZ}}$ cuts**



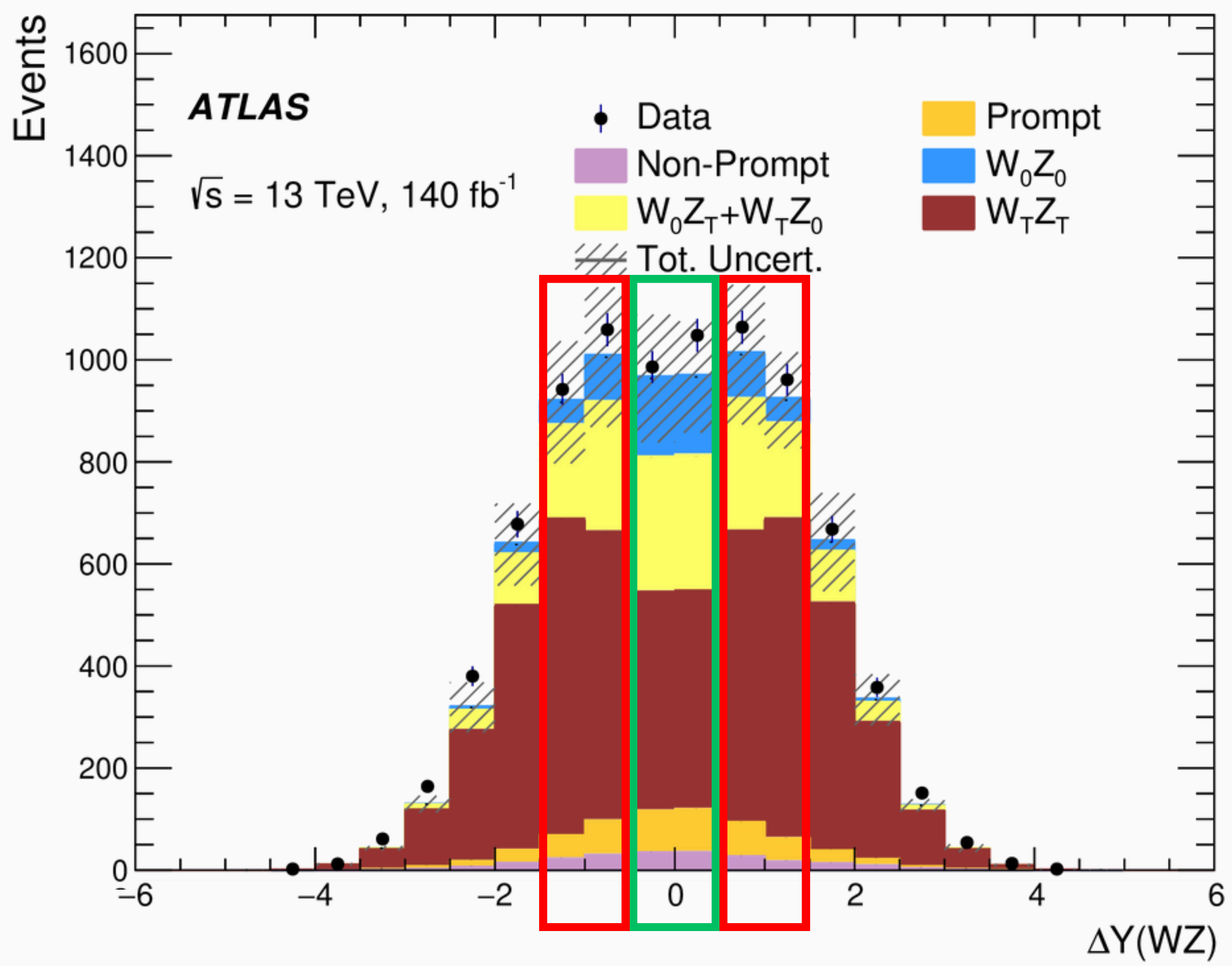
arXiv:2402.16365

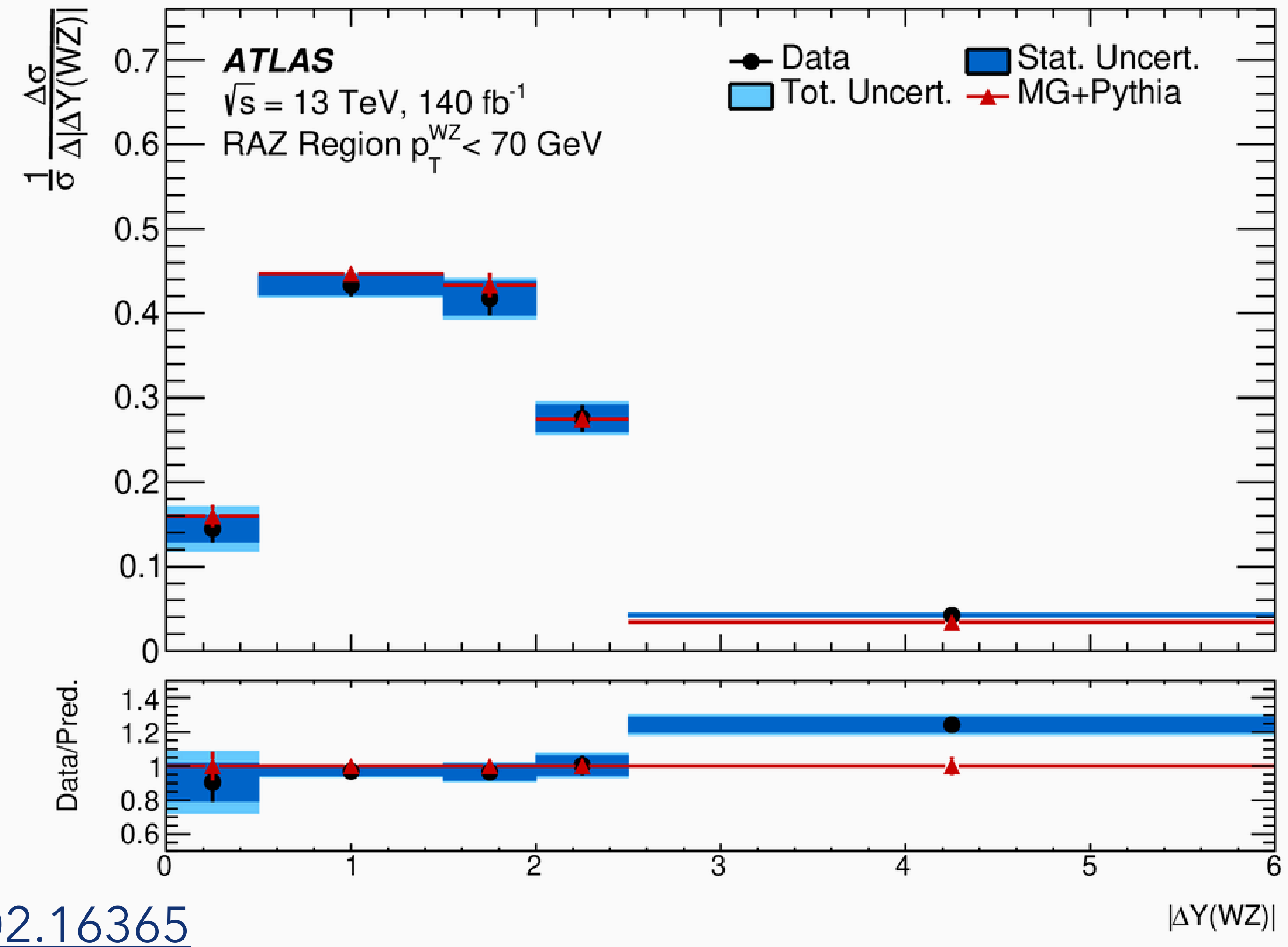
RAZ effect in WZ

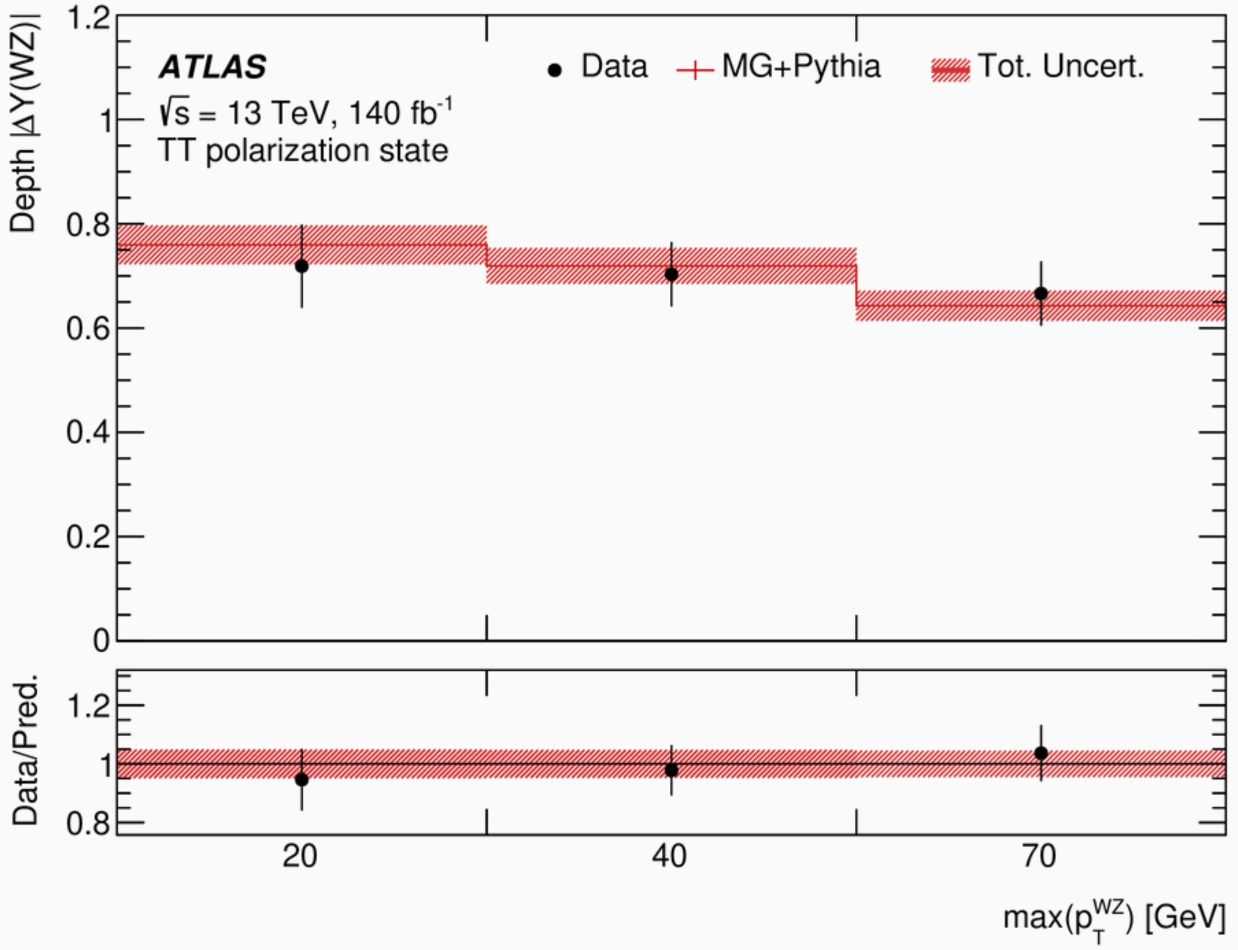
Depth variable to quantify dip

$$D = 1 - \frac{N(|\Delta Y| < 0.5)}{N(0.5 < |\Delta Y| < 1.5)/2}$$

Measure depth using unfolded TT-only distributions for different p_T^{WZ} cuts



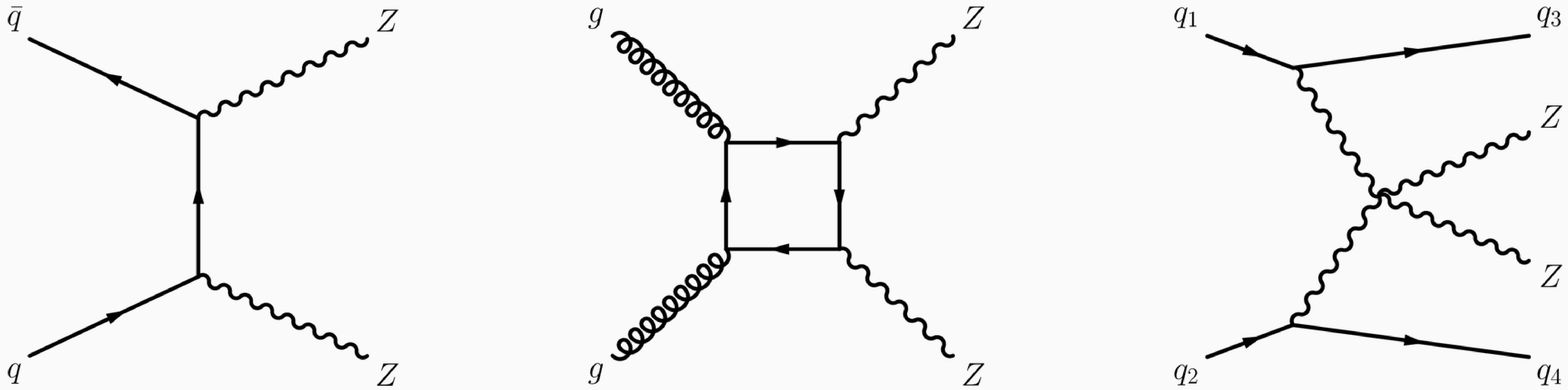




RAZ dip is clearly visible!

arXiv:2402.16365

Polarization measurements in ZZ



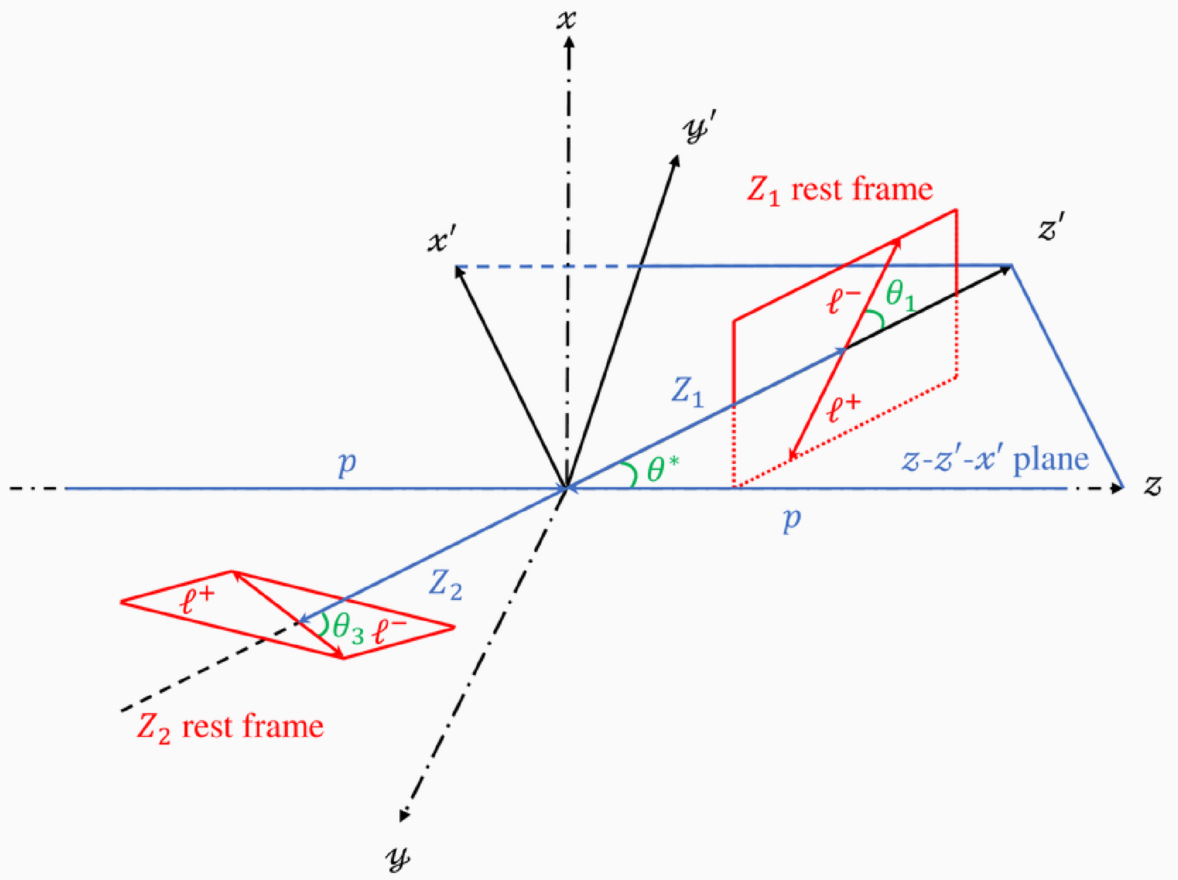
ATLAS polarization measurement in ZZ

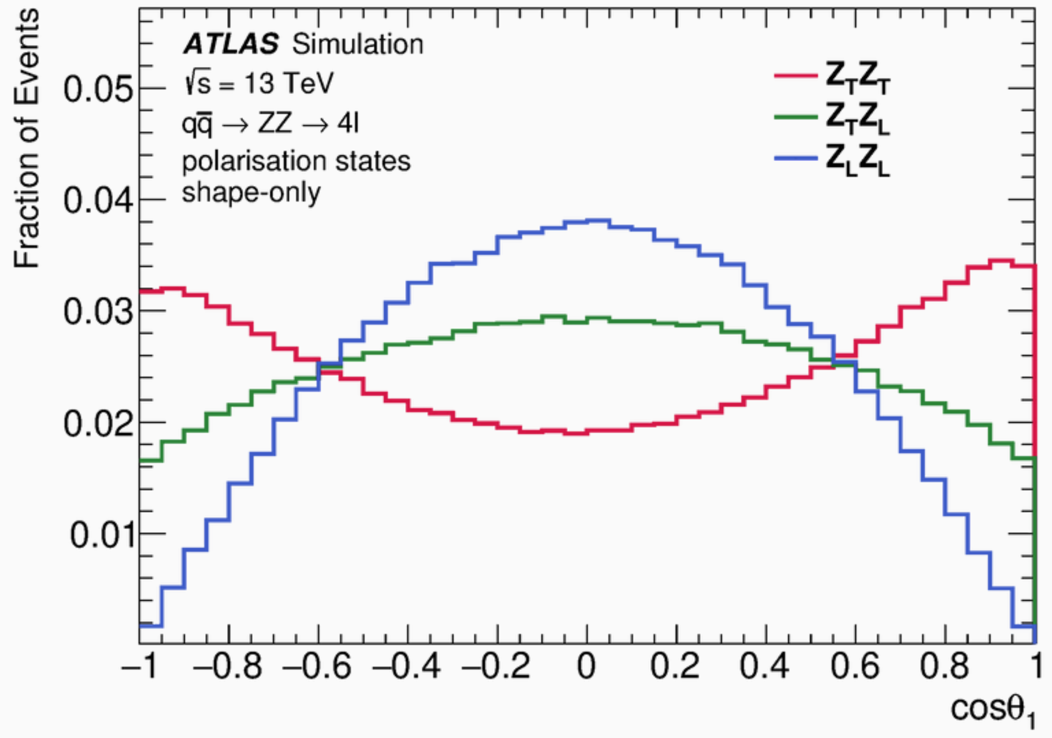
Analysis target: joint-polarization states $Z_L Z_L$ and $Z_T Z_X$

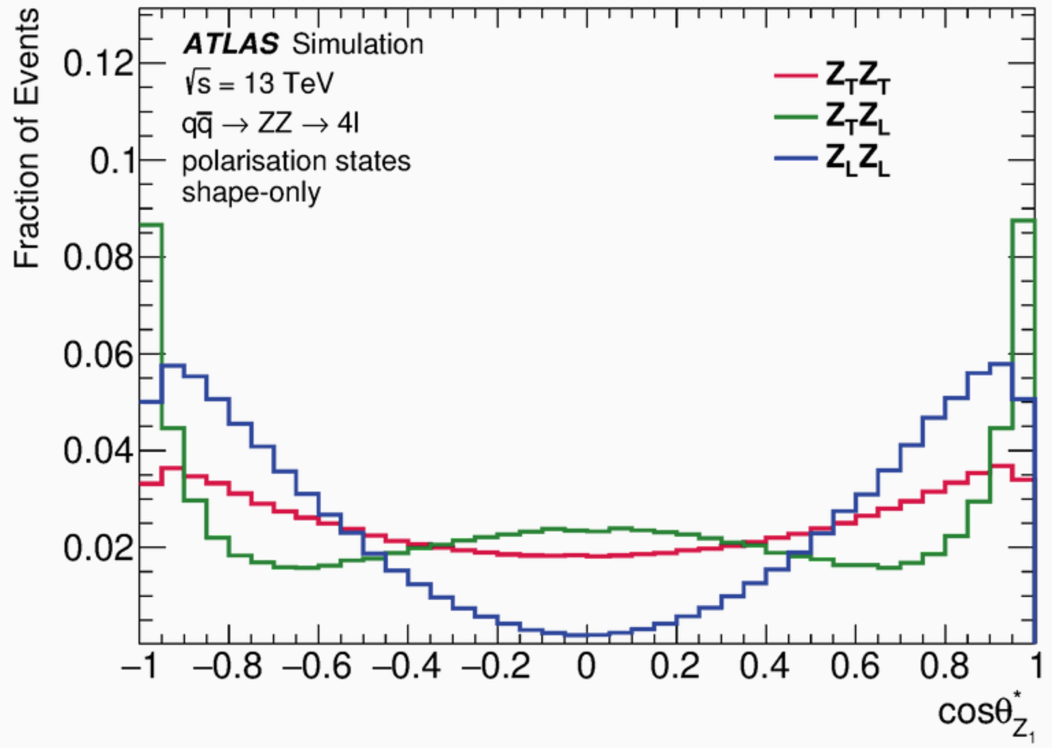
Reference frame: ZZ rest frame

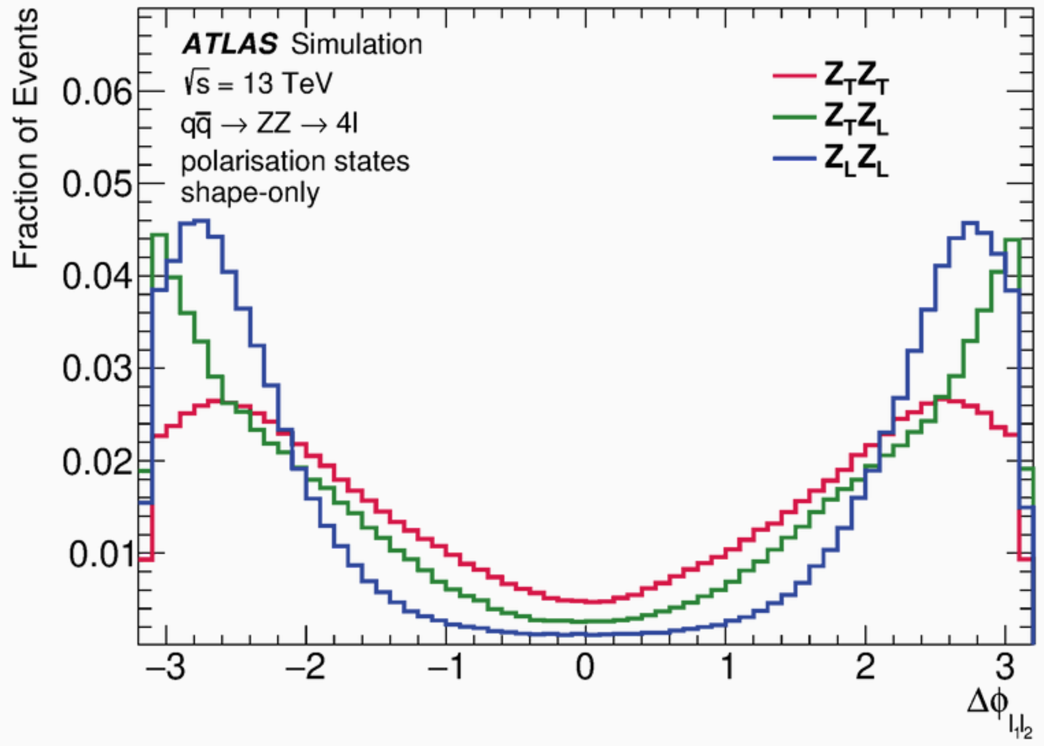
Discriminant variable

- BDT trained to separate $Z_L Z_L$ from $Z_T Z_X$
  - inputs: $\cos\theta_1,\ \cos\theta_3,\ \cos\theta^*_{Z_1},\ \Delta\phi^*_{\ell_1\ell_2},\ \Delta\phi^*_{\ell_3\ell_4}$









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ATLAS polarization measurement in ZZ

Templates challenge

- MadGraph 2.7.3 + Pythia 8 for **polarized QCD qq → ZZ+0,1,2j** and **EWK qq → ZZjj**
- **Reweight QCD samples** based on **polarized NLO QCD+EW** corrections (MoCaNLO):

[JHEP10 (2021) 097]

1. $k_{\text{pol}} = \dfrac{\text{MoCaNLO}^{\text{parton}}_{\text{pol}}}{\text{MG\_012jLO}^{\text{particle}}_{\text{pol}}} \times \dfrac{\text{Sh\_NLO}^{\text{particle}}_{\text{inc}}}{\text{MoCaNLO}^{\text{parton}}_{\text{inc}}}$

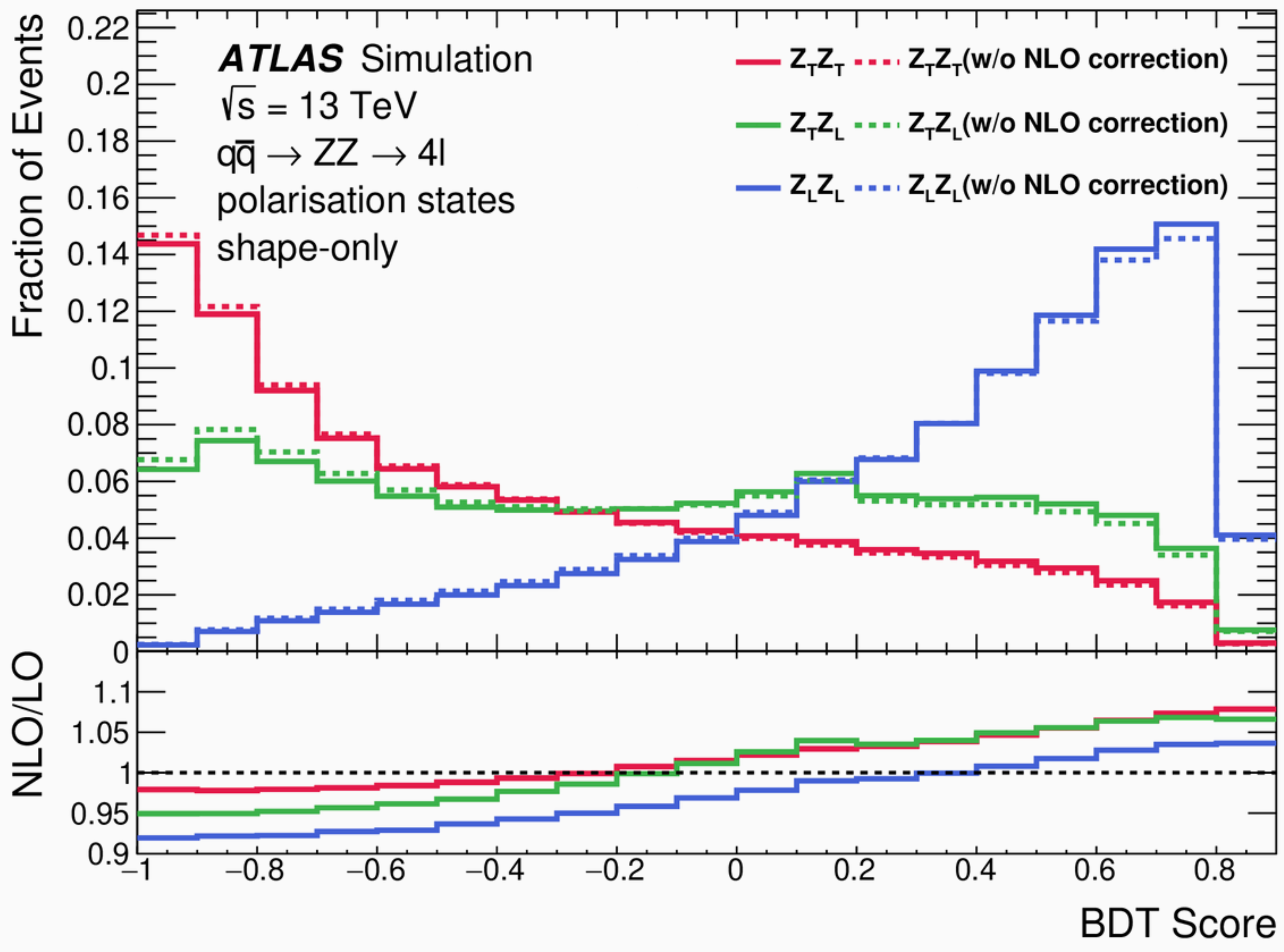
   as a function of $\cos\theta_1$ or $|\Delta Y_{ZZ}|$

2. $N^{\text{reco}}_{\text{int}} = \dfrac{\text{MoCaNLO}^{\text{parton}}_{\text{inc}} - \sum_{\text{pol}} \text{MoCaNLO}^{\text{parton}}_{\text{pol}}}{\text{MoCaNLO}^{\text{parton}}_{\text{inc}}} \times \text{Sh\_NLO}^{\text{reco}}_{\text{inc}}$

   as a function of $\cos\theta_1$ or $|\Delta Y_{ZZ}|$

3. $k_{\text{res}} = \dfrac{\text{Sh\_NLO}^{\text{reco}}_{\text{inc}} - N^{\text{reco}}_{\text{int}}}{\sum_{\text{pol}} N_{\text{pol}}}$

   as a function of $\cos\theta^*_{Z_1}$ and $\Delta\phi^*_{\ell_1\ell_2}$



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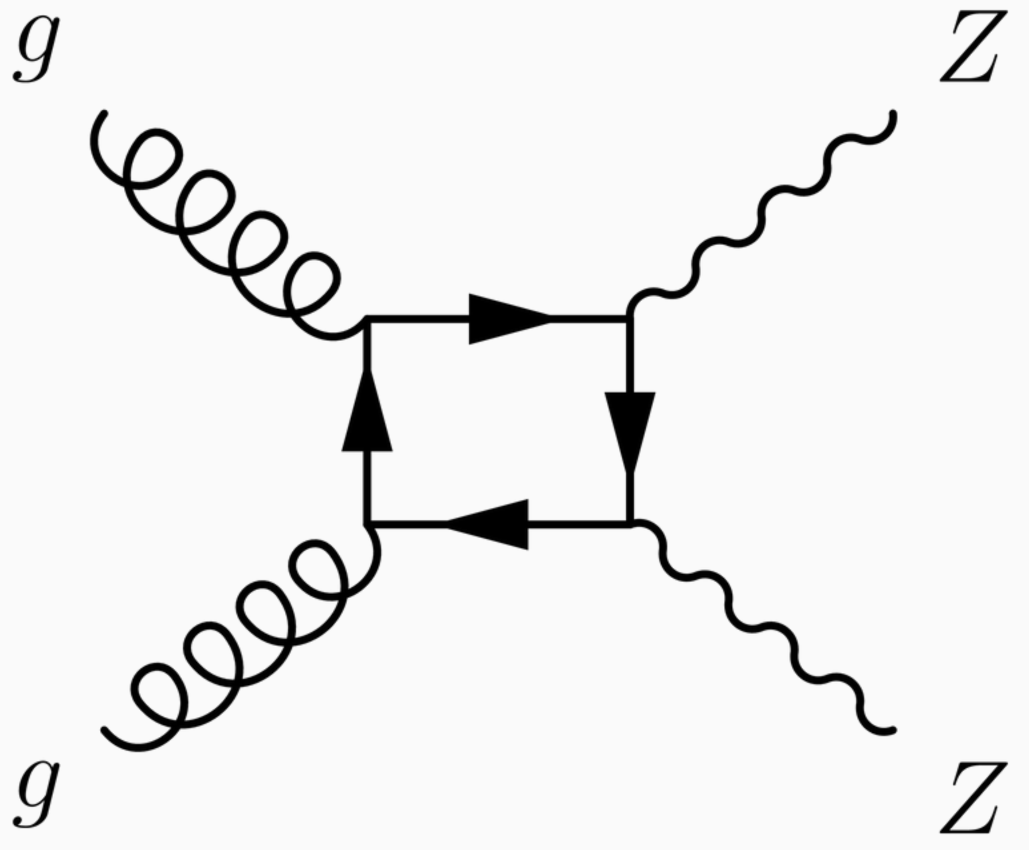
ATLAS polarization measurement in ZZ

Templates challenge

- Polarized templates for **gg-loop induced ZZ** from **inclusive ggZZ** sample (Sherpa 2.2.2) and **polarized leading order calculation** (MoCaNLO)
  - $N_{\text{pol}}^{\text{ggZZ,reco}} = \dfrac{\text{MoCaNLO}_{\text{pol}}^{\text{ggZZ,parton}}}{\text{MoCaNLO}_{\text{inc}}^{\text{ggZZ,parton}}} \times \text{Sh}_{\text{inc}}^{\text{ggZZ,reco}}$

    as a function of $\cos\theta_1$
  - interference negligible
  - 2D reweighting as for qqZZ



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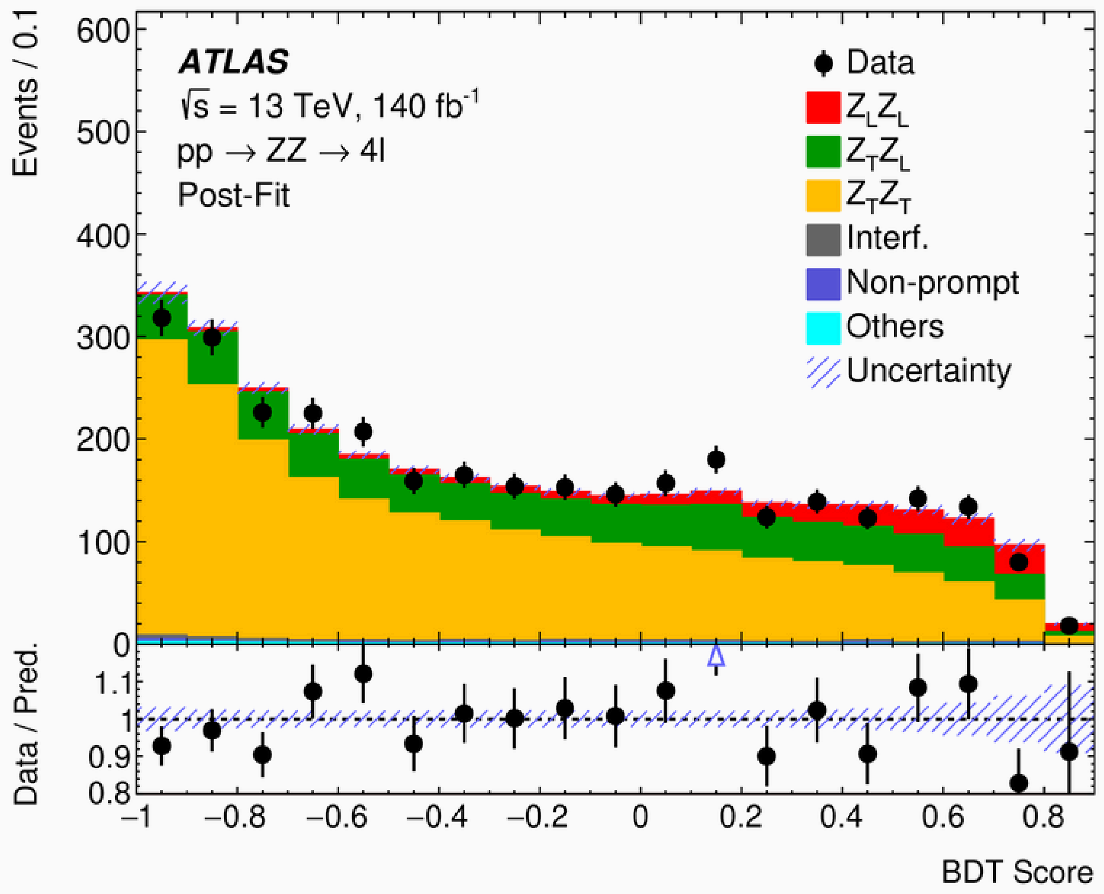
ATLAS polarization measurement in ZZ

ATLAS EXPERIMENT

Statistical analysis

- Free parameters: $\mu_{LL}, \mu_{LT} + \mu_{TL} + \mu_{TT}$
- **Evidence for doubly-longitudinal ZZ with 4.3σ (3.8σ)**
- Measured cross-section in agreement with SM prediction:
  - $\sigma^{\text{obs.}}_{\text{Z}_\text{L}\text{Z}_\text{L}} = 2.45 \pm 0.56(\text{stat.}) \pm 0.21(\text{syst.})\ \text{fb}$
  - $\sigma^{\text{pred.}}_{\text{Z}_\text{L}\text{Z}_\text{L}} = 2.10 \pm 0.09\ \text{fb}$



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

Measurement limited by statistical power

Theoretical systematics dominated by reweighting uncertainties!

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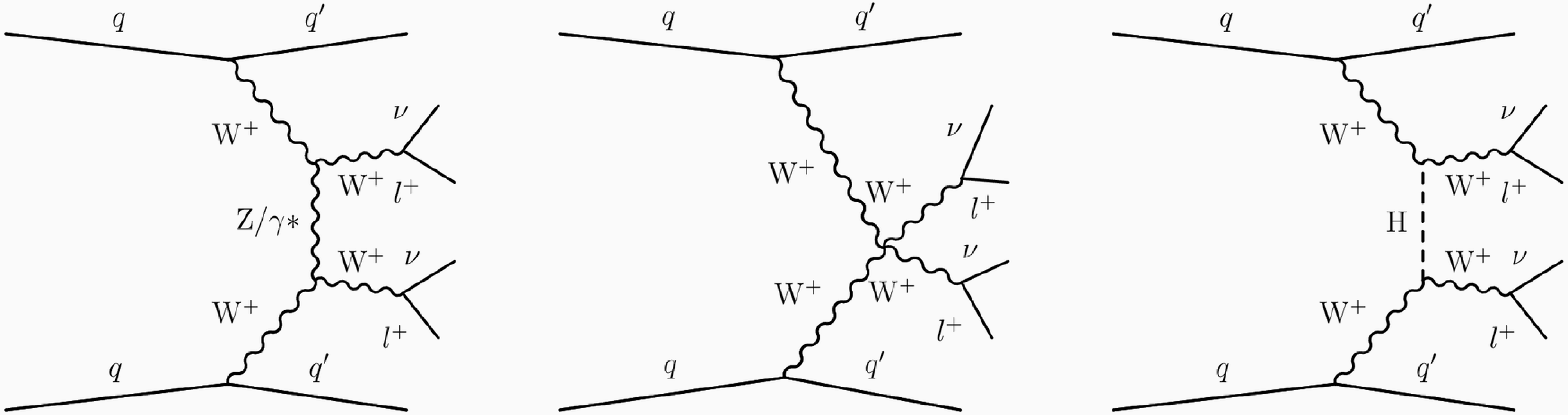
Polarization measurements in same-sign WW Vector Boson Scattering



CMS same-sign WW polarization measurement

Variable	Requirement
Leptons	Exactly 2 same-sign leptons, $p_T > 25/20$ GeV
p_T^j	>50 GeV
$\lvert m_{\ell\ell} - m_Z \rvert$	>15 GeV (ee)
$m_{\ell\ell}$	>20 GeV
p_T^{miss}	>30 GeV
b quark veto	Required
$\mathrm{Max}(z_\ell^*)$	<0.75
m_{jj}	>500 GeV
$\lvert \Delta\eta_{jj} \rvert$	>2.5

Analysis target

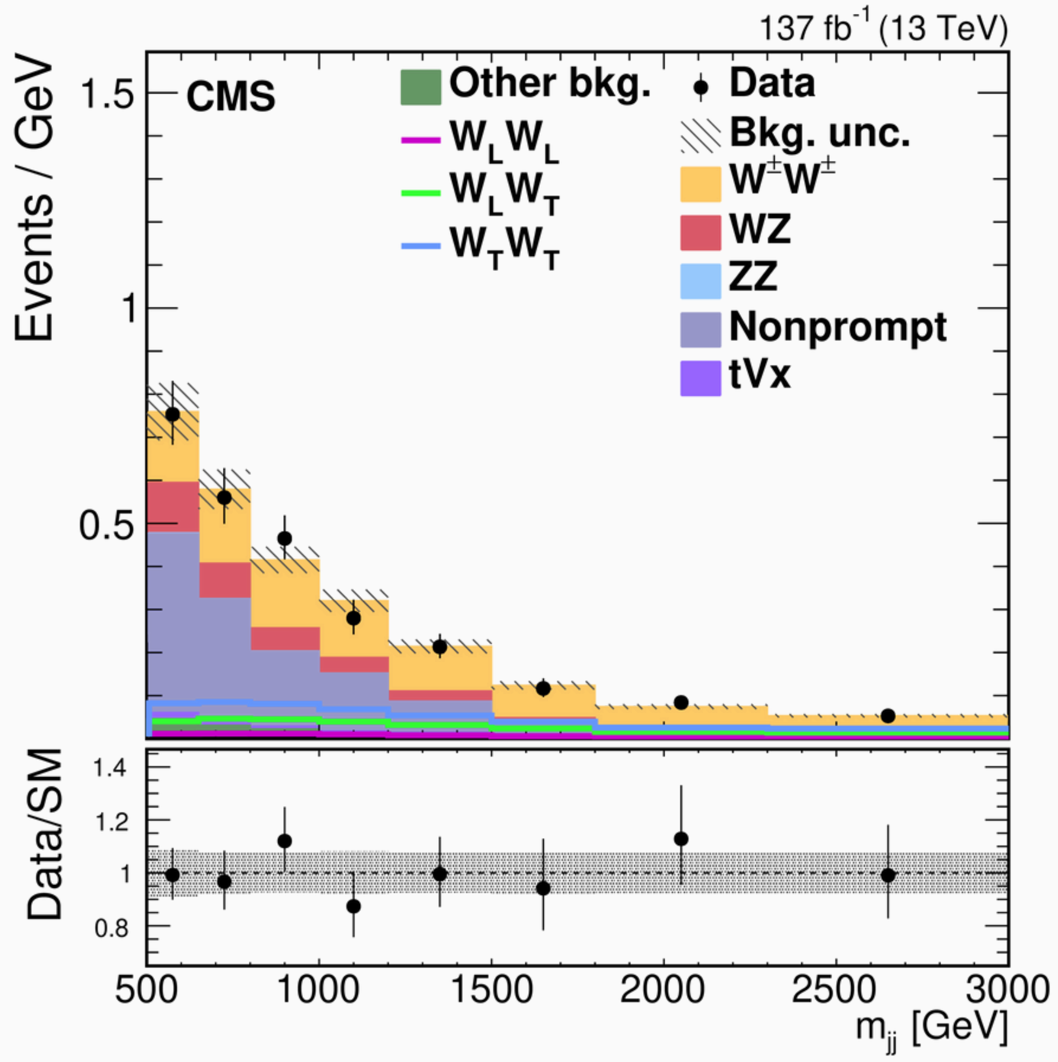
- Joint-polarization: $W_L^\pm W_L^\pm$, $W_T^\pm W_T^\pm$
- Singly-polarized states: $W_L^\pm W_X^\pm$, $W_T^\pm W_X^\pm$

Reference frame

- WW rest frame
- Initial state parton-parton rest frame

Analysis strategy

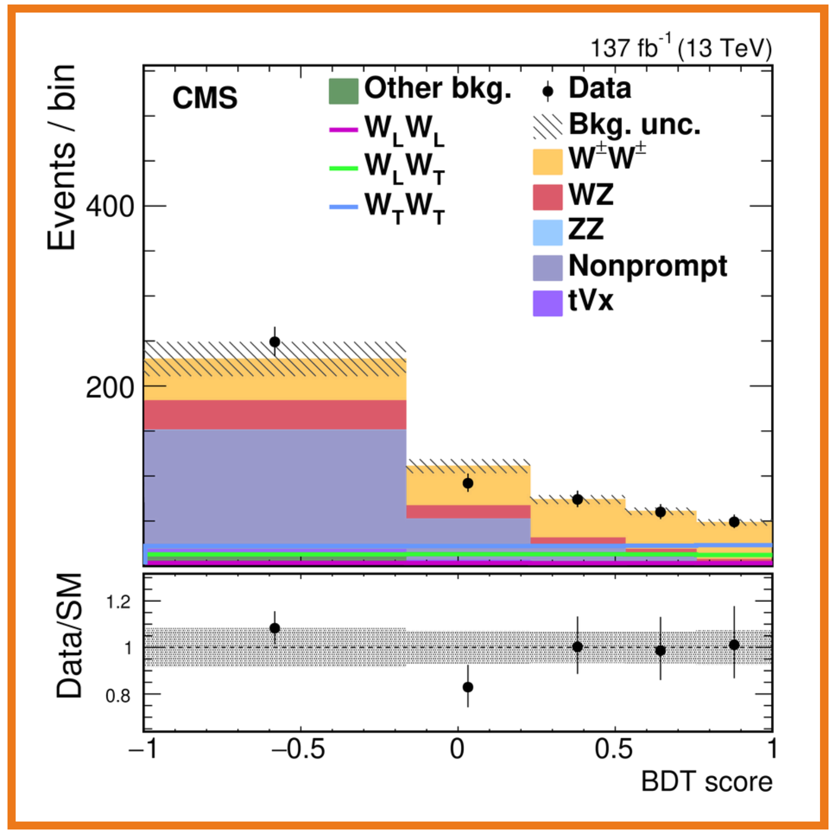
- Cut-based SR selection, leveraging VBS topology
- CRs to constrain WZ, nonprompt lepton, tZq and ZZ backgrounds



CMS same-sign WW polarization measurement

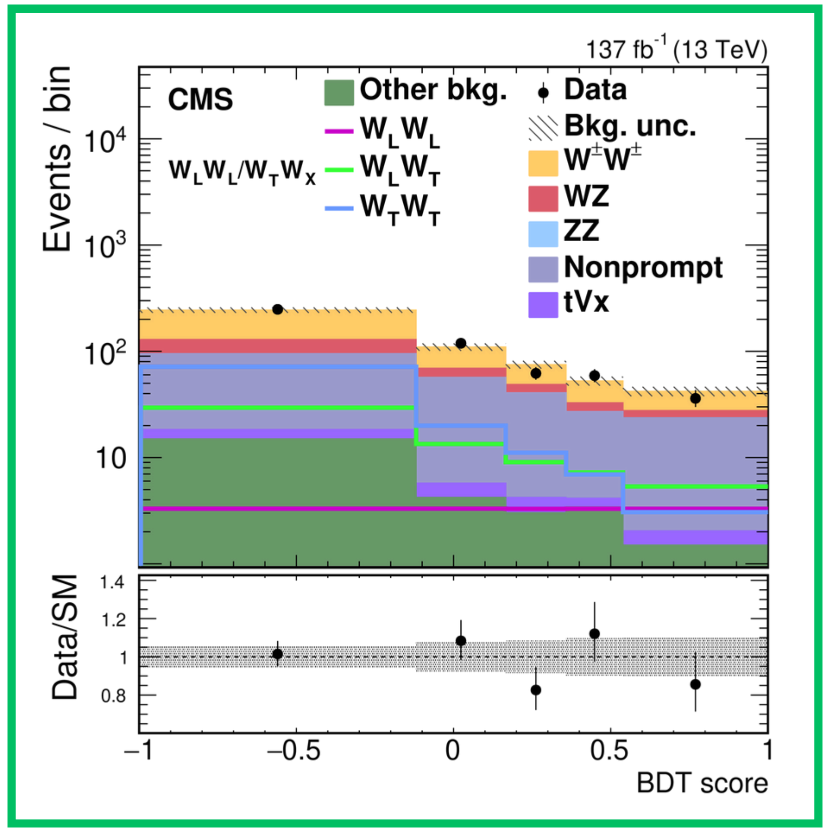
Discriminant variable

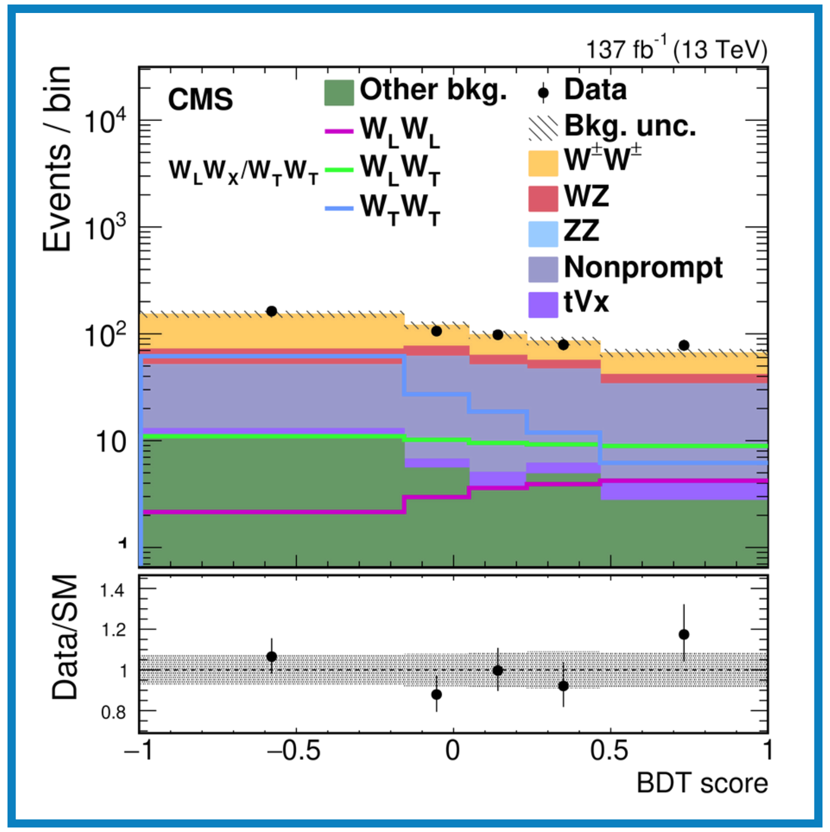
- Inclusive BDT: $W^{\pm}W^{\pm}$ vs bkg.
- Two signal BDTs per frame:
  - $W_L^{\pm}W_L^{\pm}$ vs $W_T^{\pm}W_X^{\pm}$
  - $W_L^{\pm}W_X^{\pm}$ vs $W_T^{\pm}W_T^{\pm}$



Polarization modelling

- pol. MadGraph LO
- NLO QCD+EW corrections from inclusive fixed-order calculations





BDT input variables

signal BDT	inclusive BDT
m_{jj}	$\Delta\phi_{jj}$
$\lvert\Delta\eta_{jj}\rvert$	p_T^{j1}
$\Delta\phi_{jj}$	p_T^{j2}
p_T^{j1}	$p_T^{\ell_1}$
p_T^{j2}	$p_T^{\ell_2}$
$p_T^{\ell_1}$	$\Delta\phi_{\ell\ell}$
$p_T^{\ell\ell}$	$m_{\ell\ell}$
$z^*_{\ell_1}$	$p_T^{\ell\ell}$
$z^*_{\ell_2}$	m_T^{WW}
p_T^{miss}	$z^*_{\ell_1}$
	$z^*_{\ell_2}$
	$\Delta R_{j1,\ell\ell}$
	$\Delta R_{j2,\ell\ell}$
	$(p_T^{\ell_1}p_T^{\ell_2})/(p_T^{j1}p_T^{j2})$
	p_T^{miss}

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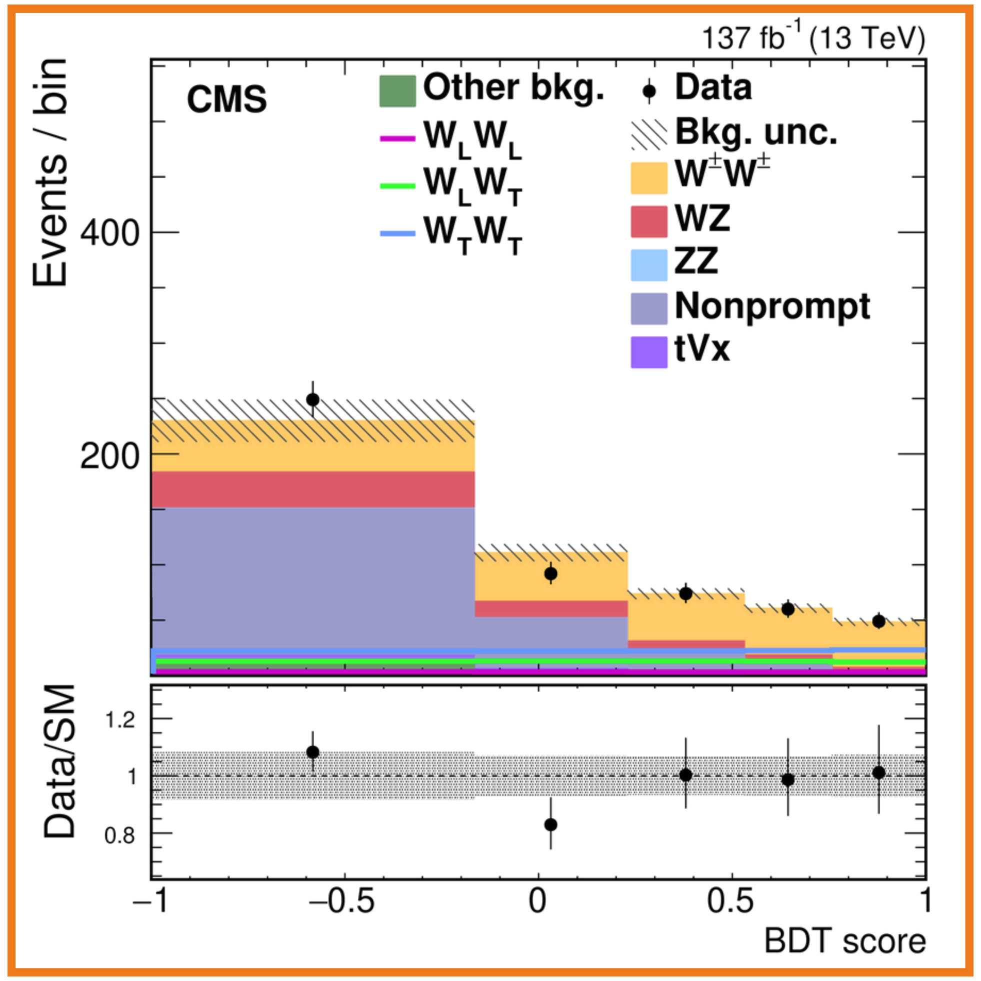
CMS same-sign WW polarization measurement

Statistical Analysis

- One fit per signal hypothesis
  - $W_L^{\pm}W_L^{\pm}$ and $W_T^{\pm}W_X^{\pm}$: Inclusive BDT × "LL vs TX" BDT (5x5 bins)
  - $W_L^{\pm}W_L^{\pm}$ and $W_T^{\pm}W_X^{\pm}$: Inclusive BDT × "LX vs TT" BDT (5x5 bins)
- Free parameters: $\mu_{LL}, \mu_{LT} + \mu_{TL} + \mu_{TT}$ / $\mu_{TT}, \mu_{LL} + \mu_{LT} + \mu_{TL}$



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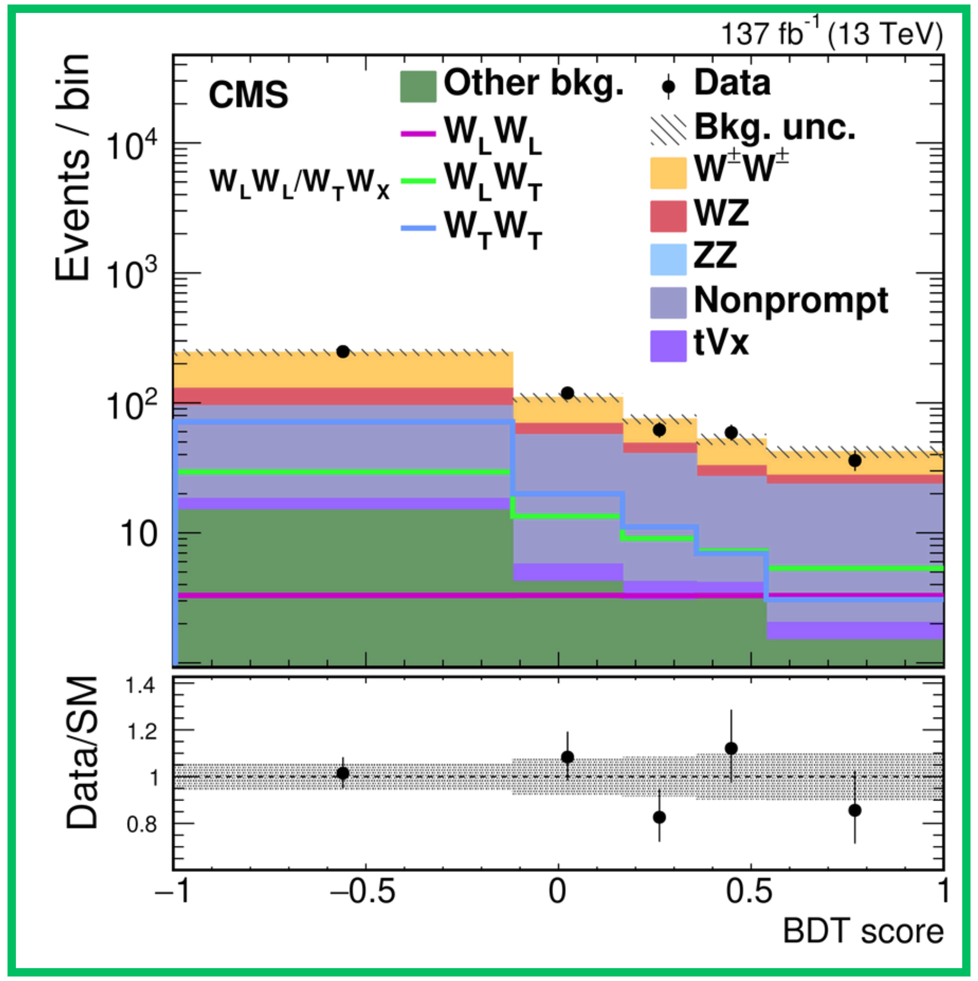
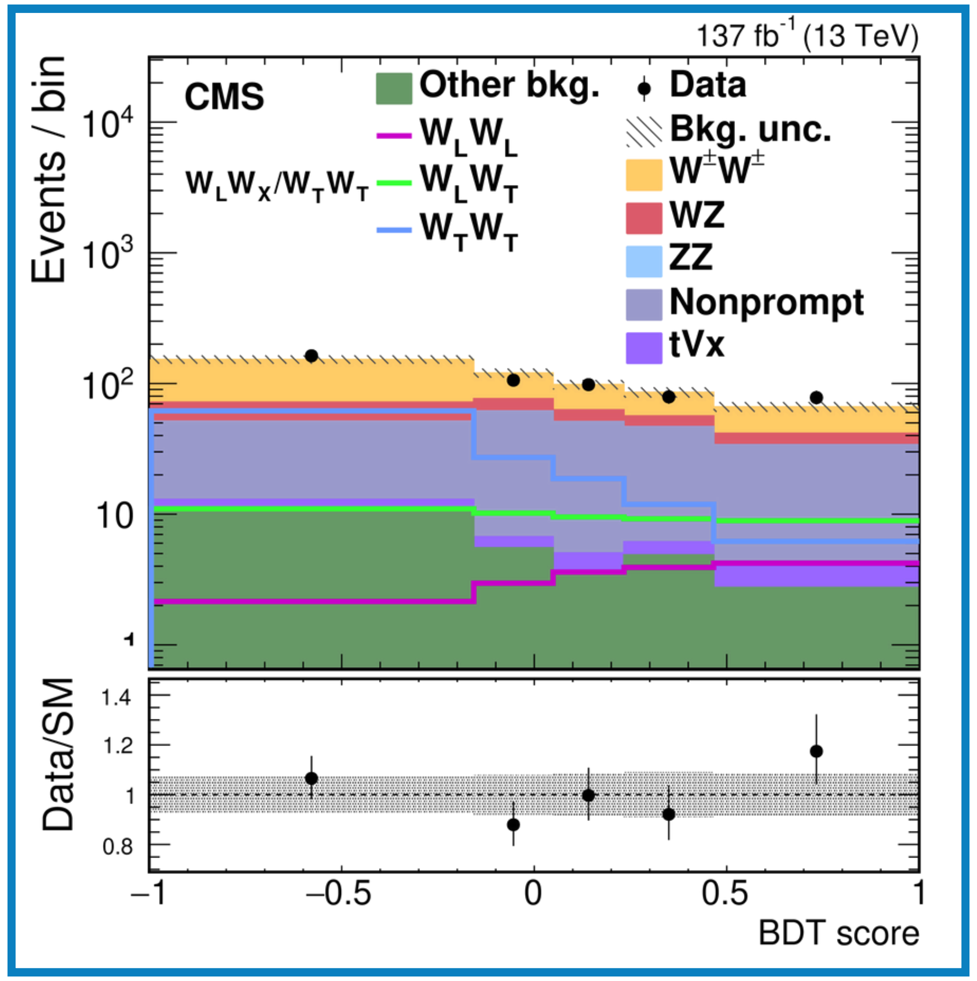


or



CMS same-sign WW polarization measurement

WW-frame

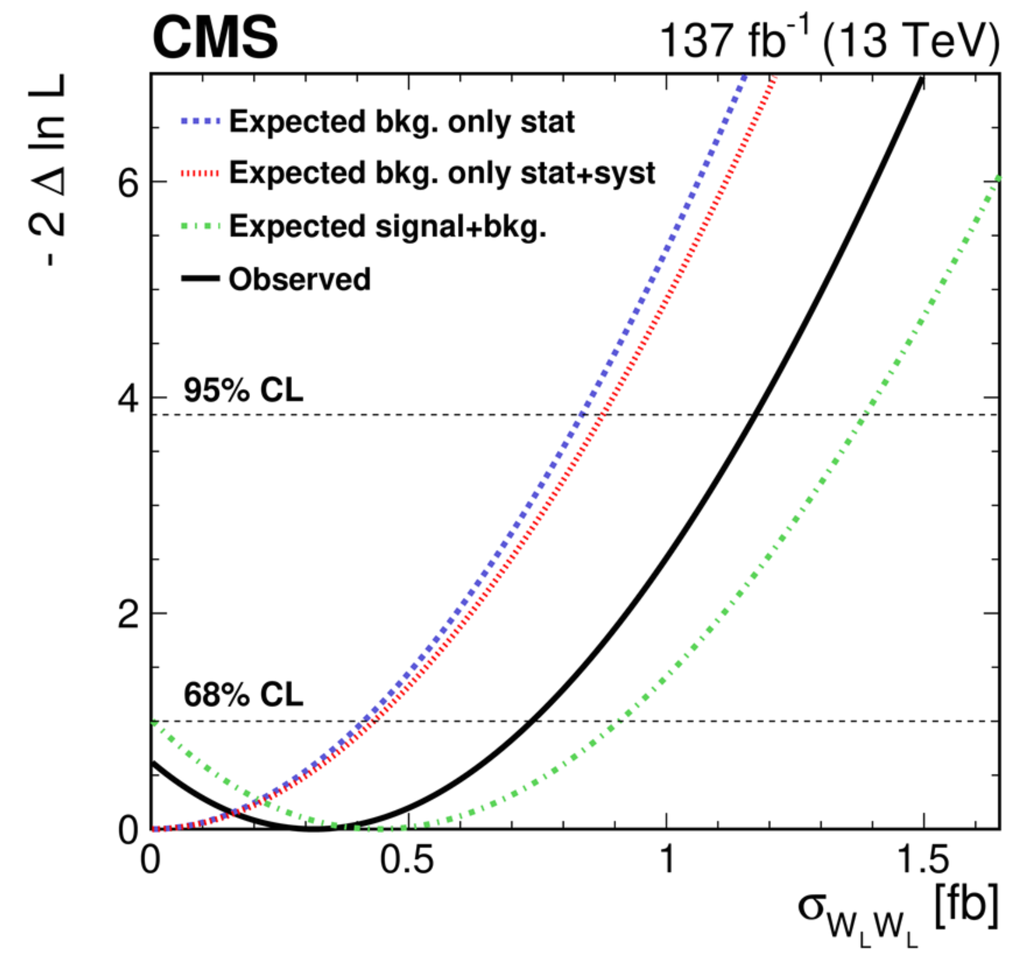
- Significance for $W_L^{\pm}W_X^{\pm}$ production of 2.3σ (3.1σ)
- 95% CL upper limit on $W_L^{\pm}W_L^{\pm}$: 1.17 (0.88) fb

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

pp-frame

- Significance for $W_L^{\pm}W_X^{\pm}$ production of 2.6σ (2.9σ)
- 95% CL upper limit on $W_L^{\pm}W_L^{\pm}$: 1.06 (0.85) fb

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



Measurement strongly dominated by statistical uncertainties!

Phys. Lett. B 812 (2020) 136018

Conclusion

Summary

- Weak boson polarization is a useful tool to
  - probe the inner workings of the EWSB
  - look for physics beyond the Standard Model
- First observation of joint-longitudinally polarized VB in WZ, evidence in ZZ, with Run 2 dataset
  - Modelling of polarization templates is the main systematic uncertainty
  - Interference contribution may not be negligible

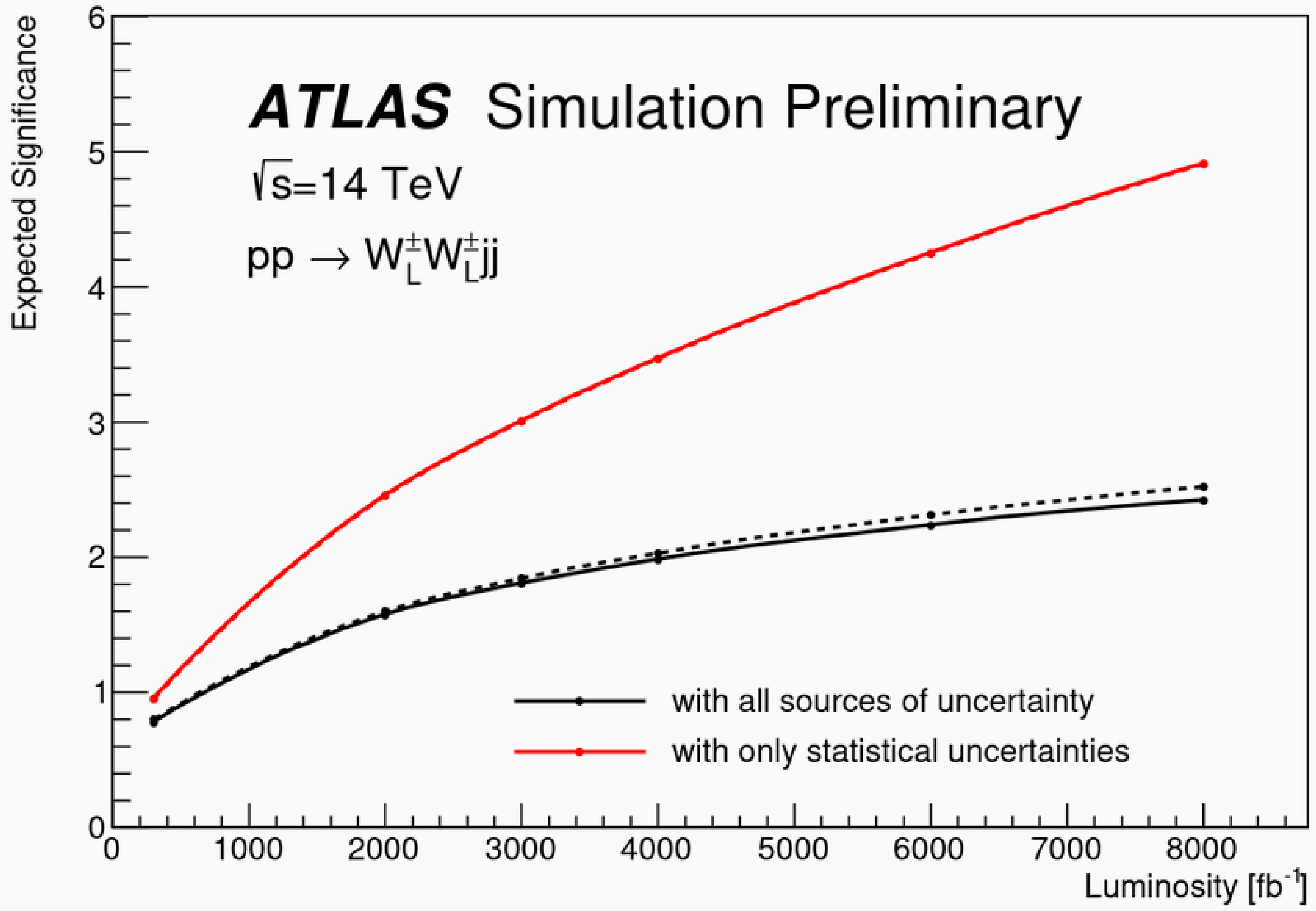
  $\longrightarrow$ Careful selection of observables, decorrelation from ϕ^*_V, and / or interference templates necessary

Outlook

- Recent advancements in Monte-Carlo generators:
  - Powheg-Box-Res+Pythia: **inclusive VV @NLO QCD+PS** [G. Pelliccioli, G. Zanderighi 2023]
  - Sherpa 3: **arbitrary processes @nLO QCD+PS**, multi-jet merging, **interference templates** [M. Hoppe, M. Schönherr, F. Siegert 2023]
  - **polarized gluon-loop induced processes** via UFO model [M. Javurkova et al. 2024]
- Recent interest in **semi-leptonic decay channels**
  - higher statistical power, but larger backgrounds
- New developments in machine learning techniques
  - first steps towards a polarization tagger: **"Amplitude-assisted tagging"** [arXiv:2306.07726]
- Study of BSM sensitivity in polarized analyses
  - **EFT via UFO models** should be possible in MadGraph and Sherpa

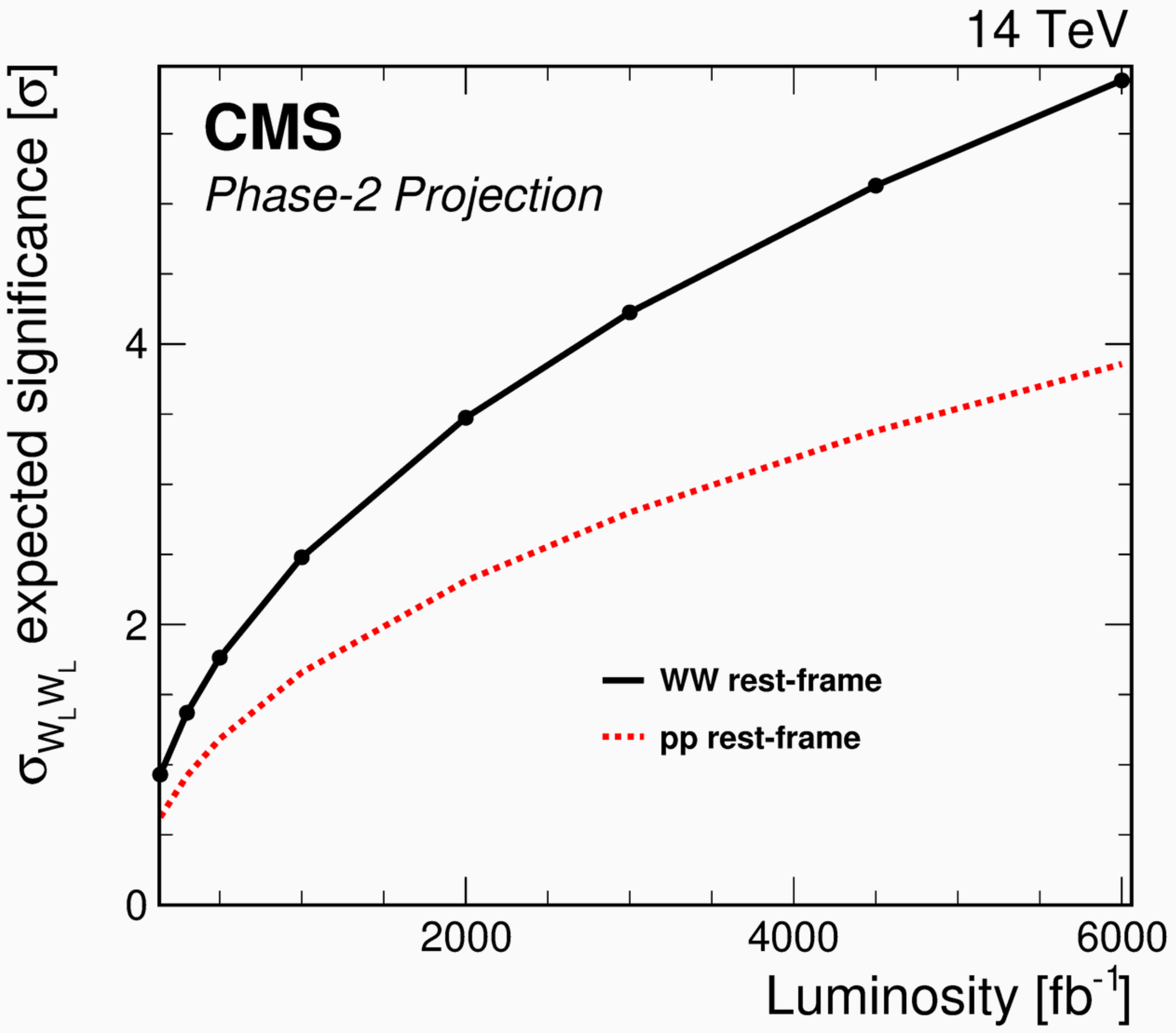
Outlook

- Projections for measurement of joint-longitudinal $W_L^{\pm}W_L^{\pm}$ at the HL-LHC presented in the Yellow Report



ATL-PHYS-PUB-2018-052

- Cut based analysis



CMS-PAS-FTR-21-001

- Almost the same analysis as presented before

Open questions

- Interpretation of template-based polarization measurements
  - inherently model-dependent ⟶ **alternative approach?**
  - in the meantime: **as many polarization fractions as possible!**
- Best reference frame to use
  - agreed-upon standard choice not yet defined
- Optimal definition of polarised-boson signals
  - clear guidelines for the experiments are needed

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Backup

CMS polarization measurement in WZ

Yields

Process	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$	Inclusive
Nonprompt	19 ± 8	48 ± 16	45 ± 15	143 ± 39	255 ± 46
ZZ	42.9 ± 1.4	73 ± 7	188 ± 6	363 ± 10	668 ± 15
Xγ	25 ± 3	5.5 ± 0.9	98 ± 10	33 ± 4	161 ± 11
t$\bar{t}$X	12.6 ± 1.3	24 ± 3	47 ± 5	98 ± 11	181 ± 13
VVV	8 ± 3	14 ± 6	30 ± 12	60 ± 24	111 ± 28
VH	3.1 ± 0.6	8.7 ± 1.6	19 ± 4	37 ± 7	68 ± 8
tZq	11.2 ± 1.9	21 ± 4	45 ± 8	88 ± 16	165 ± 19
WZ EWK	8.5 ± 1.3	16 ± 2	35 ± 5	72 ± 11	132 ± 12
Total background	130 ± 10	211 ± 20	507 ± 26	894 ± 54	1741 ± 64
WZ	561 ± 15	1122 ± 24	2328 ± 39	4974 ± 82	8985 ± 95
Total expected	691 ± 18	1333 ± 28	2835 ± 43	5868 ± 89	10726 ± 95
Observed	739	1286	2849	5855	10729

CMS polarization measurement in WZ

Uncertainties

Source	Combined	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$
Electron efficiency	0.6	3.2	1.8	0.9	—
Muon efficiency	1.2	—	0.5	1.0	1.5
Electron energy scale	0.1	0.3	0.1	0.1	0.0
Muon energy scale	0.1	0.0	0.0	0.1	0.1
Trigger efficiency	0.7	0.7	0.8	0.7	0.7
Jet energy scale	0.9	0.8	0.7	1.0	0.9
b tagging	1.6	1.8	1.7	1.8	1.6
Pileup	0.9	1.0	1.2	0.8	0.7
ISR	0.2	0.2	0.2	0.2	0.2
Nonprompt normalization	0.6	0.7	0.8	0.6	0.7
Nonprompt shape	1.0	1.2	1.0	0.9	0.9
VVV normalization	0.5	0.6	0.5	0.5	0.5
VH normalization	0.2	0.1	0.2	0.2	0.2
WZ EWK normalization	0.2	0.2	0.2	0.2	0.2
ZZ normalization	0.3	0.3	0.3	0.3	0.3
$t\bar{t}Z$ normalization	0.3	0.4	0.4	0.4	0.3
tZq normalization	0.4	0.4	0.4	0.4	0.4
Xγ normalization	0.2	0.5	0.1	0.5	0.1
Total systematic uncertainties	2.8	4.3	3.7	3.0	3.0
Integrated luminosity	2.1	2.2	2.2	2.1	2.1
Statistical uncertainty	1.5	5.0	3.4	2.5	2.0
PDF+scale	0.9	0.9	0.9	0.9	0.9

ATLAS Polarization measurement in WZ

Object selection

Muon object selection			
Selection	Baseline selection	Z selection	W selection
$p_{\mathrm{T}} > 5$ GeV	✓	✓	✓
$\|\eta\| < 2.7$	✓	✓	✓
Loose quality	✓	✓	✓
$\|d_0^{\mathrm{BL}}/\sigma(d_0^{\mathrm{BL}})\| < 3$ *(for $\|\eta\| < 2.5$ only)*	✓	✓	✓
$\|\Delta z_0^{\mathrm{BL}} \sin\theta\| < 0.5$ mm *(for $\|\eta\| < 2.5$ only)*	✓	✓	✓
PflowLoose_FixedRad isolation	✓	✓	✓
μ-jet Overlap Removal		✓	✓
$p_{\mathrm{T}} > 15$ GeV		✓	✓
$\|\eta\| < 2.5$		✓	✓
Medium quality		✓	✓
$p_T > 20$ GeV			✓
Tight quality			✓
PflowTight_FixedRad isolation			✓

Electron object selection			
Selection	Baseline selection	Z selection	W selection
$p_{\mathrm{T}} > 5$ GeV	✓	✓	✓
Electron object quality	✓	✓	✓
$\|\eta^{\mathrm{cluster}}\| < 2.47$, $\|\eta\| < 2.5$	✓	✓	✓
LooseLH+BLayer identification	✓	✓	✓
$\|d_0^{\mathrm{BL}}/\sigma(d_0^{\mathrm{BL}})\| < 5$	✓	✓	✓
$\|\Delta z_0^{\mathrm{BL}} \sin\theta\| < 0.5$ mm	✓	✓	✓
Loose_VarRad isolation	✓	✓	✓
e-to-μ and e-to-e overlap removal	✓	✓	✓
e-to-jets overlap removal		✓	✓
$p_T > 15$ GeV		✓	✓
Exclude $1.37 < \|\eta^{\mathrm{cluster}}\| < 1.52$		✓	✓
MediumLH identification		✓	✓
HighPtCaloOnly isolation		✓	✓
$p_T > 20$ GeV			✓
TightLH identification			✓
Tight_VarRad isolation			✓
Unambiguous author			✓
DFCommonAddAmbiguity ≤ 0			✓

ATLAS Polarization measurement in WZ

Event selection

Inclusive event selection	
Event cleaning	Reject LAr, Tile and SCT corrupted events and incomplete events
Primary vertex	Hard scattering vertex with at least two tracks
Trigger 2015	HLT_e24_lhmedium_L1EM20VH || HLT_e60_lhmedium || HLT_e120_lhloose HLT_mu20_iloose_L1MU15 || HLT_mu50
Trigger 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}	$p_{\mathrm{T}}^{\mathrm{lead}} > 25$ GeV (in 2015) or $p_{\mathrm{T}}^{\mathrm{lead}} > 27$ GeV (in 2016)
Z leptons	Two same flavor oppositely charged leptons passing Z-lepton selection
Mass window	$\|M_{\ell\ell} - M_Z\| < 10$ GeV
W lepton	Remaining lepton passes W-lepton selection
W transverse mass	$m_{\mathrm{T}}^{W} > 30$ GeV

ATLAS Polarization measurement in WZ

Yields

	Signal Region Pre-fit	Signal Region 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
$W_\mathrm{T}Z_0$	2670 ± 60	3100 ± 400
$W_\mathrm{T}Z_\mathrm{T}$	10200 ± 230	10900 ± 600
Total MC	21400 ± 500	21950 ± 170
Data	—	21936

	ZZ Control Region Pre-fit	ZZ Control Region Post-fit
WZ unpol.	35.6 ± 1.9	35.6 ± 1.9
ZZ	2030 ± 150	2290 ± 50
$t\bar{t}+V$	153 ± 23	143 ± 21
Misid. leptons	14 ± 4	15 ± 4
Others	32 ± 8	33 ± 8
Total MC	2260 ± 150	2510 ± 50
Data	—	2554

ATLAS Polarization measurement in WZ

Predicted and measured fractions

	Data	POWHEG+PYTHIA	NLO QCD
		$W^{\pm}Z$	
f_{00}	0.067 ± 0.010	0.0590 ± 0.0009	0.058 ± 0.002
$f_{0\mathrm{T}}$	0.110 ± 0.029	0.1515 ± 0.0017	0.159 ± 0.003
$f_{\mathrm{T}0}$	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
		$W^{+}Z$	
f_{00}	0.072 ± 0.016	0.0583 ± 0.0012	0.057 ± 0.002
$f_{0\mathrm{T}}$	0.119 ± 0.034	0.1484 ± 0.0022	0.155 ± 0.003
$f_{\mathrm{T}0}$	0.152 ± 0.033	0.1461 ± 0.0022	0.147 ± 0.003
f_{TT}	0.66 ± 0.04	0.6472 ± 0.0026	0.635 ± 0.004
		$W^{-}Z$	
f_{00}	0.063 ± 0.016	0.0600 ± 0.0014	0.059 ± 0.002
$f_{0\mathrm{T}}$	0.11 ± 0.04	0.1560 ± 0.0027	0.166 ± 0.003
$f_{\mathrm{T}0}$	0.21 ± 0.04	0.1470 ± 0.0027	0.152 ± 0.003
f_{TT}	0.62 ± 0.05	0.6370 ± 0.0033	0.618 ± 0.004

	f_0	
	Data	POWHEG+PYTHIA
W in $W^{+}Z$	0.23 ± 0.05	0.2044 ± 0.0024
W in $W^{-}Z$	0.19 ± 0.05	0.217 ± 0.004
W in $W^{\pm}Z$	0.21 ± 0.04	0.2094 ± 0.0016
Z in $W^{+}Z$	0.223 ± 0.025	0.1971 ± 0.0019
Z in $W^{-}Z$	0.241 ± 0.029	0.2065 ± 0.0023
Z in $W^{\pm}Z$	0.231 ± 0.019	0.2009 ± 0.0014

	$f_{\mathrm{L}} - f_{\mathrm{R}}$	
	Data	POWHEG+PYTHIA
W in $W^{+}Z$	0.071 ± 0.023	0.0990 ± 0.0015
W in $W^{-}Z$	0.026 ± 0.027	-0.0491 ± 0.0020
W in $W^{\pm}Z$	0.059 ± 0.016	0.0390 ± 0.0011
Z in $W^{+}Z$	-0.20 ± 0.10	-0.217 ± 0.006
Z in $W^{-}Z$	0.10 ± 0.13	0.092 ± 0.007
Z in $W^{\pm}Z$	-0.10 ± 0.08	-0.092 ± 0.005

ATLAS Polarization measurement in WZ

Uncertainties

	f_{00}	$f_{0\mathrm{T}}$	$f_{\mathrm{T}0}$	f_{TT}
Relative uncertainty [%]				
e energy scale and id. efficiency	0.34	0.6	0.8	0.31
μ energy scale and id. efficiency	0.8	0.23	0.23	0.13
$E_{\mathrm{T}}^{\mathrm{miss}}$ and jets	3.3	1.3	1.2	0.4
Pile-up	0.6	0.17	0.4	0.15
Misidentified lepton background	2.3	1.6	0.8	0.26
ZZ background	0.9	0.17	0.32	0.07
Other backgrounds	3.0	1.6	1.3	0.4
Parton Distribution Function	0.5	1.8	0.09	0.5
QCD scale	0.19	8	0.9	2.0
Modelling	9	4	2.9	1.2
Total systematic uncertainty	14	15	8	4
Luminosity	0.35	0.24	0.15	0.05
Statistical uncertainty	13	10	12	3.0
Total	19	18	14	5

	$W^\pm$ in $W^\pm Z$		Z in $W^\pm Z$	
	f_0	$f_{\mathrm{L}} - f_{\mathrm{R}}$	f_0	$f_{\mathrm{L}} - f_{\mathrm{R}}$
Relative uncertainty [%]				
e energy scale and id. efficiency	1.4	0.8	1.3	0.7
μ energy scale and id. efficiency	2.1	5	0.8	0.5
$E_{\mathrm{T}}^{\mathrm{miss}}$ and jets	1.9	2.8	0.28	3.0
Pile-up	1.4	4	1.2	3.1
Misidentified lepton background	3.4	0.8	1.6	1.2
ZZ background	0.7	0.6	0.6	2.5
Other backgrounds	0.9	1.3	0.7	1.3
Parton Distribution Function	0.5	2.9	0.05	0.5
QCD scale	6	6	0.22	5
Modelling	12	3.1	2.2	19
Total systematic uncertainty	14	11	3.5	21
Luminosity	0.25	0.09	0.06	0.19
Statistical uncertainty	13	40	9	90
Total	19	40	10	90

ATLAS measurement of energy dependence of WZ polarization fractions and RAZ effect

Event selection

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	$p_T^{lead} > 25$ GeV (in 2015) or $p_T^{lead} > 27$ GeV (in 2016-2018)
Z leptons	Two same flavor oppositely charged leptons passing the Z-lepton selection
Z lepton invariant mass	$\|m_{\ell\ell} - M_Z\| < 10$ 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	

ATLAS measurement of energy dependence of WZ polarization fractions and RAZ effect

Yields

Process	$100 < p_T^Z \leq 200$ GeV		$p_T^Z > 200$ GeV	
	Pre-fit	Post-fit	Pre-fit	Post-fit
W_0Z_0	222 ± 5	290 ± 60	47.6 ± 1.5	28 ± 19
$W_0Z_T + W_TZ_0$	323 ± 12	280 ± 140	23.7 ± 0.8	50 ± 40
W_TZ_T	856 ± 31	920 ± 100	124 ± 4	132 ± 29
Prompt background	169 ± 18	166 ± 18	24.1 ± 2.7	24.2 ± 2.7
Non-prompt background	68 ± 29	80 ± 40	2.8 ± 1.1	2.8 ± 1.1
Total Expected	1640 ± 60	1740 ± 40	222 ± 8	236 ± 15
Data	1740		236	

ATLAS measurement of energy dependence of WZ polarization fractions and RAZ effect

Predicted and measured fractions

3 parameter fit

	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

2 parameter fit

	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}	$0.17 \pm^{0.02}_{0.02}$ (stat) $\pm^{0.01}_{0.02}$ (syst)	$0.16 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.02}_{0.03}$ (syst)	f_{00}	0.152 ± 0.006	0.234 ± 0.007
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_{0T}	0.120 ± 0.002	0.062 ± 0.002
f_{00} obs (exp) sig.	7.7 (6.9) σ	3.2 (4.2) σ	f_{T0}	0.109 ± 0.001	0.058 ± 0.001
			f_{TT}	0.619 ± 0.007	0.646 ± 0.008

ATLAS measurement of energy dependence of WZ polarization fractions and RAZ effect

Uncertainties

3 parameter fit

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

$p_T^{WZ} < 20$ GeV

	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	1.2	0.5	0.3	0.1
Electron calibration	1.3	0.7	0.7	0.2
Muon calibration	1.9	0.7	1.1	0.8
Jet energy scale and resolution	8.1	3.6	2.0	1.0
E_T^{miss} scale and resolution	0.3	0.8	0.4	1.0
Flavor-tagging inefficiency	0.0	0.0	0.0	0.0
Pileup modelling	1.3	1.3	2.7	0.4
Non-prompt background estimation	4.2	1.4	5.7	1.7
Modelling				
Background, other	4.0	1.4	4.9	1.5
Model statistical	2.3	1.3	4.1	2.2
NLO corrections	13.3	3.5	0.0	0.0
PDF, Scale and shower settings	13.1	5.4	0.7	0.5
Unfolding uncertainty	0.0	4.4	0.0	0.8
Experimental and modelling	21.5	9.1	9.3	3.7
Data statistical	13.3	6.5	24.1	11.7
Total	25.3	11.1	25.9	12.3

ATLAS Polarization measurement in ZZ

Yields

		Pre-fit	Post-fit
ZZ	$Z_L Z_L$	189.3 ± 8.7	220 ± 54
	$Z_T Z_L$	710 ± 29	711 ± 29
	$Z_T Z_T$	2170 ± 120	2147 ± 60
	Interference	33.7 ± 2.8	33.4 ± 2.7
Non-prompt		18.7 ± 7.1	18.5 ± 7.0
Others		20.0 ± 3.7	19.9 ± 3.7
Total		3140 ± 150	3149 ± 57
Data		3149	3149

ATLAS Polarization measurement in ZZ

Uncertainties

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

CMS same-sign WW polarization measurement

Yields

Process	Yields in $W^{\pm}W^{\pm}$ SR
$W_L^{\pm}W_L^{\pm}$	16.0 ± 18.3
$W_L^{\pm}W_T^{\pm}$	63.1 ± 10.7
$W_T^{\pm}W_T^{\pm}$	110.1 ± 18.1
QCD $W^{\pm}W^{\pm}$	13.8 ± 1.6
Interference $W^{\pm}W^{\pm}$	8.4 ± 0.6
WZ	63.3 ± 7.8
ZZ	0.7 ± 0.2
Nonprompt	213.7 ± 52.3
tVx	7.1 ± 2.2
Other background	26.9 ± 9.9
Total SM	522.9 ± 60.7
Data	524

CMS same-sign WW polarization measurement

Uncertainties

Source of uncertainty	$W^{\pm}_{L}W^{\pm}_{L}$ (%)	$W^{\pm}_{X}W^{\pm}_{T}$ (%)	$W^{\pm}_{L}W^{\pm}_{X}$ (%)	$W^{\pm}_{T}W^{\pm}_{T}$ (%)
Integrated luminosity	3.2	1.8	1.9	1.8
Lepton measurement	3.6	1.9	2.5	1.8
Jet energy scale and resolution	11	2.9	2.5	1.1
Pileup	0.9	0.1	1.0	0.3
b tagging	1.1	1.2	1.4	1.1
Nonprompt lepton rate	17	2.7	9.3	1.6
Trigger	1.9	1.1	1.6	0.9
Limited sample size	38	3.9	14	5.7
Theory	6.8	2.3	4.0	2.3
Total systematic uncertainty	44	6.6	18	7.0
Statistical uncertainty	123	15	42	22
Total uncertainty	130	16	46	23