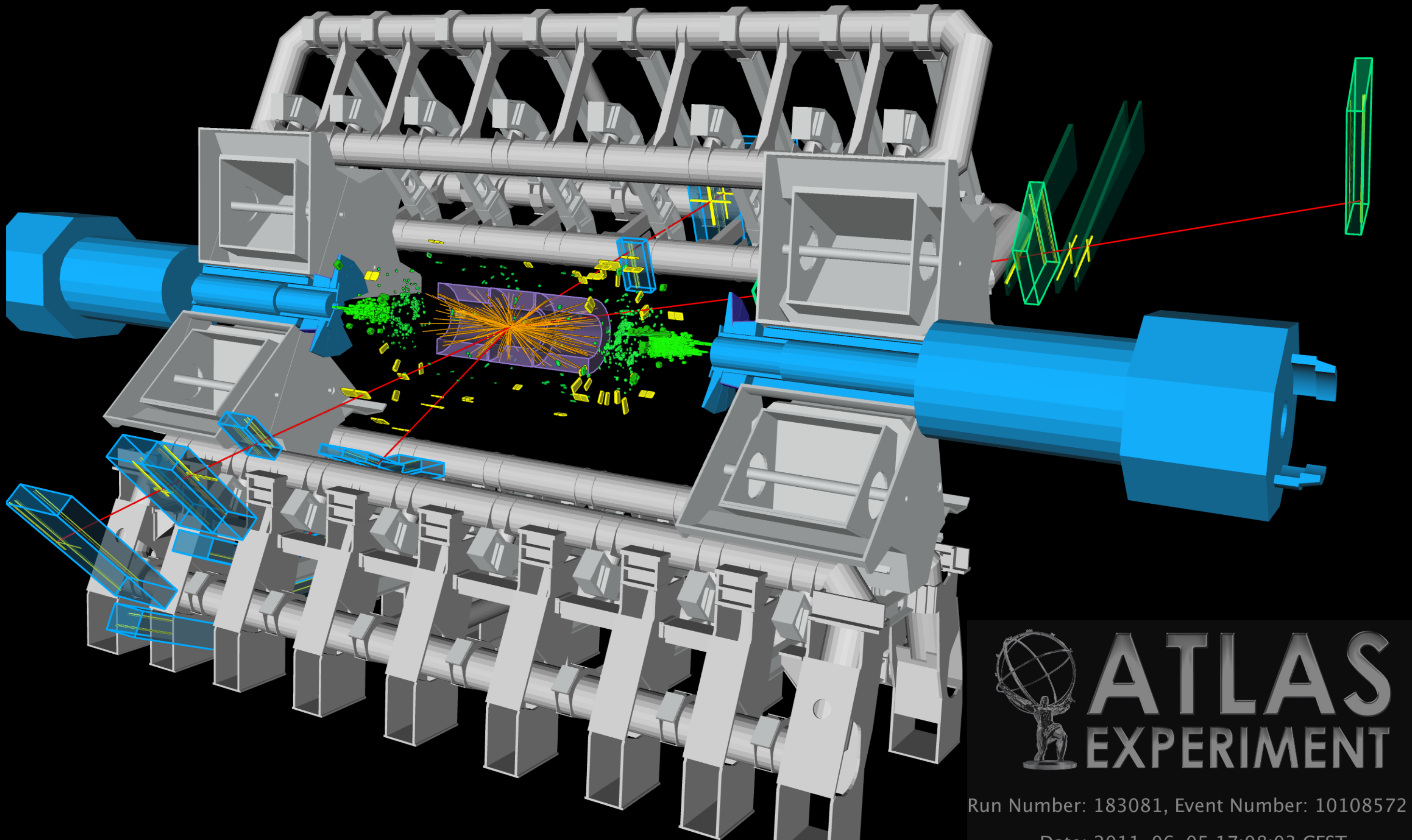
Polarisation Measurements in ATLAS

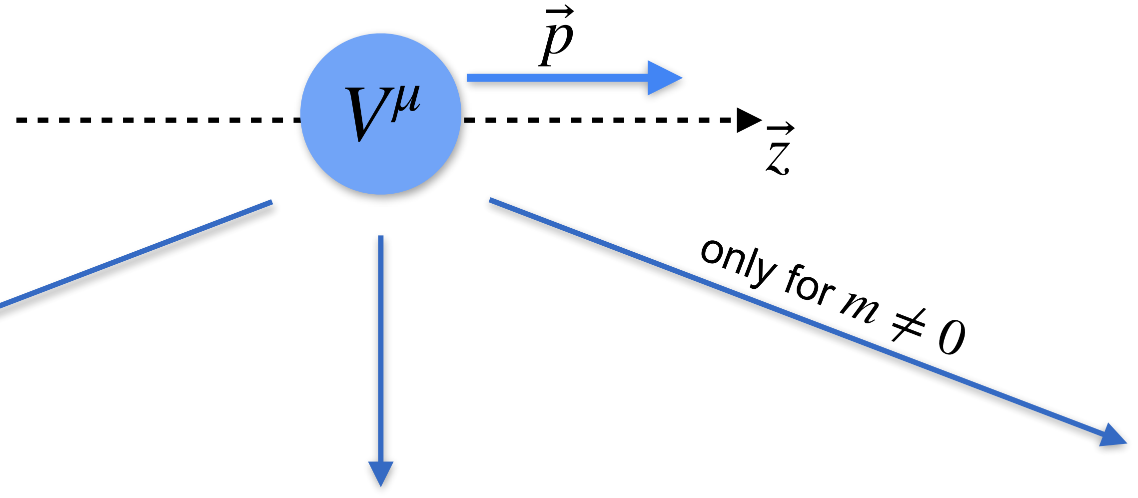
COMETA VB Polarisation Workshop
23/09/2024

Max Stange, IKTP (TU Dresden)



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayStandAlone

What is Boson Polarisation?



$\epsilon_R^\mu(\vec{p}) = (0,1,i,0)$

Right-handed (R)

$\epsilon_L^\mu(\vec{p}) = (0,1,-i,0)$

Left-handed (L)

Transverse (T)

$$\epsilon_0^\mu(\vec{p}) = \frac{1}{m}(|\vec{p}|,0,0,E)$$

Longitudinal (0)

Why Polarisation Measurement?

EWK Symmetry Breaking

$$(D_\mu\phi)^\dagger D^\mu\phi = \frac{1}{2}\partial_\mu h\partial^\mu h + \frac{1}{4}g_W^2 W_\mu^- W^{+\mu}(v+h)^2$$
$$+\frac{1}{8}\left(g_W^2 + g'^2\right) Z_\mu Z^\mu (v+h)^2$$

$$m_W = \frac{1}{2}g_w v \qquad m_Z = \frac{1}{2}v\sqrt{g_W^2 + g'^2}$$

Why Polarisation Measurement?

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$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1 + i\phi_2 \\ v + h + i\phi_4 \end{pmatrix}$$

Goldstone bosons

Z_0 W_0^+ W_0^-

[J. Manjarrés Ramos, LHCP2022]
[A. Denner, T. Hahn, 1997]

Why Polarisation Measurement?

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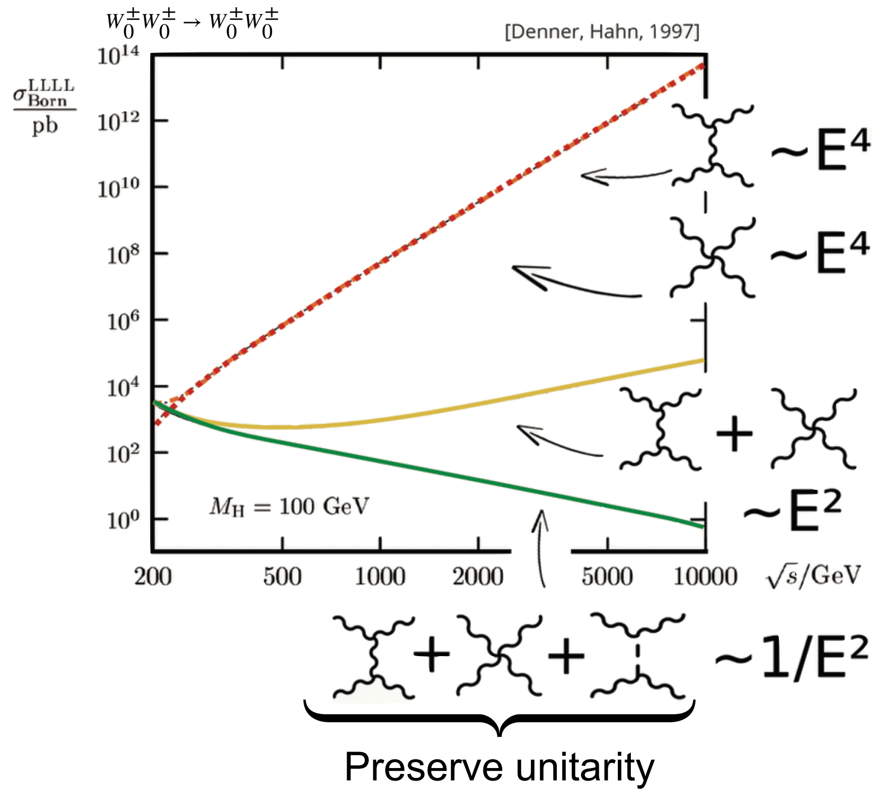

Why Polarisation Measurement?

EWK Symmetry Breaking

[J. Manjarrés Ramos, LHCP2022]
[A. Denner, T. Hahn, 1997]

$$(D_\mu\phi)^\dagger D^\mu\phi = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{1}{4} g_W^2 W_\mu^- W^{+\mu}(v+h)^2 + \frac{1}{8}\left(g_W^2 + g'^2\right) Z_\mu Z^\mu (v+h)^2$$

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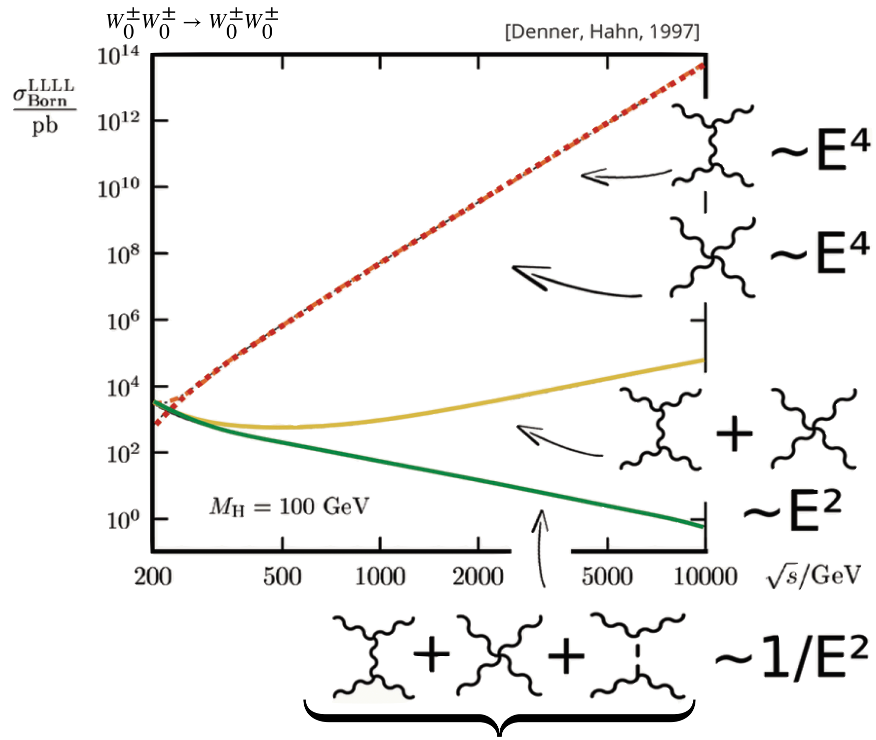


Preserve unitarity

$W_0^\pm W_0^\mp \to W_0^\pm W_0^\mp$	$W_0^\pm W_0^\pm \to W_0^\pm W_0^\pm$	$W_0^\pm Z_0 \to W_0^\pm Z_0$	$Z_0 Z_0 \to Z_0 Z_0$
Not studied	1 ATLAS analysis ongoing	2 ATLAS analyses published	1 ATLAS analysis published

ATLAS Polarisation Measurements

Overview

$W^{\pm}Z$ Polarisation

arXiv:2211.09435

- Single Polarisation $V_{pol}V$
- Joint Polarisation $V_{pol}V_{pol}$

$W^{\pm}Z$ Polarisation Kinematic

arXiv:2402.16365

- Energy Dependence $V_{pol}V_{pol}$
- RAZ Effect $V_{T}V_{T}$

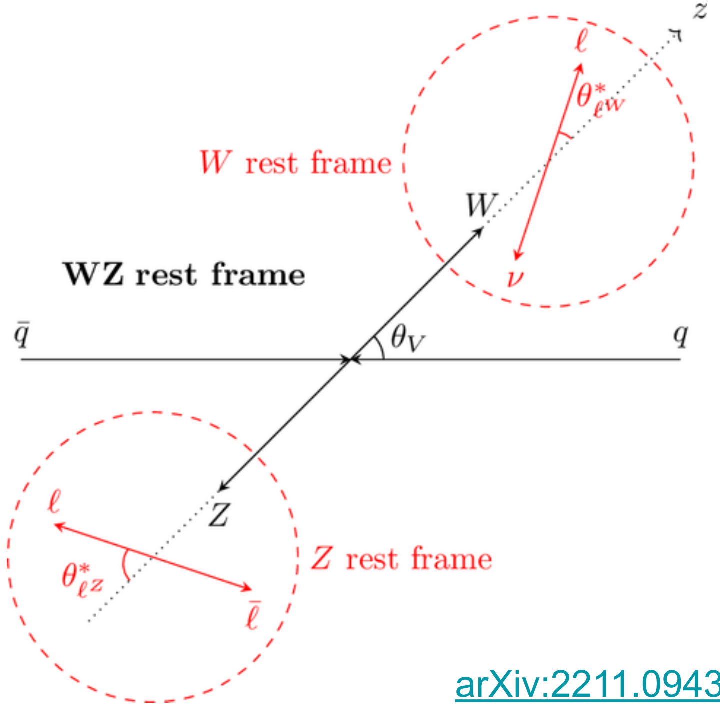
ZZ Analysis

arXiv:2310.04350

- Joint Polarisation $V_{pol}V_{pol}$
- CP Properties

ATLAS Polarisation Measurements

Access the Polarisation

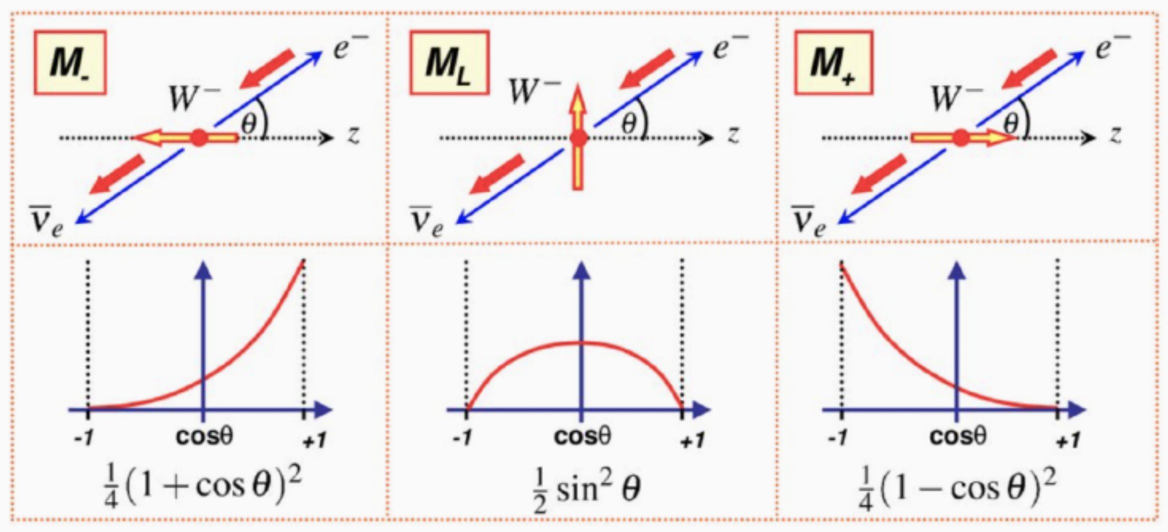


[arXiv:2211.09435]

Polarisation defined in VV reference frame

$$W^{\pm}: \frac{1}{\sigma}\frac{d\sigma}{d\cos\theta'_{lW}} = \frac{3}{8}(1 \mp \cos\theta'_{lW})^2 f_L + \frac{3}{8}(1 \pm \cos\theta'_{lW})^2 f_R + \frac{3}{4}\sin^2\theta'_{lW} f_0$$

$$Z: \frac{1}{\sigma}\frac{d\sigma}{d\cos\theta'_{lZ}} = \frac{3}{8}(1 + 2\alpha\cos\theta'_{lZ} + \cos^2\theta'_{lZ}) f_L + \frac{3}{8}(1 - 2\alpha\cos\theta'_{lZ} + \cos^2\theta'_{lZ}) f_R + \frac{3}{4}\sin^2\theta'_{lZ} f_0$$



[J. Manjarrés Ramos, LHCP2022]

ATLAS Polarisation Measurements

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Super fancy polarisation measurement in VBS from pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

Contents

1. Cut based analysis with high $VV \to VV$ purity
2. Get polarised samples
3. Deal with higher order effects
4. Study polarisation
   4.1 Machine learning
   4.2 Optional: Kinematic effects of polarisation
5. Statistical analysis

arXiv:2211.09435

$W^{\pm}Z$ Polarisation Measurement

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Phys. Lett. B 843 (2023) 137895
DOI: 10.1016/j.physletb.2023.137895

CERN-EP-2022-202
30th June 2023

Observation of gauge boson joint-polarisation states in $W^{\pm}Z$ production from pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

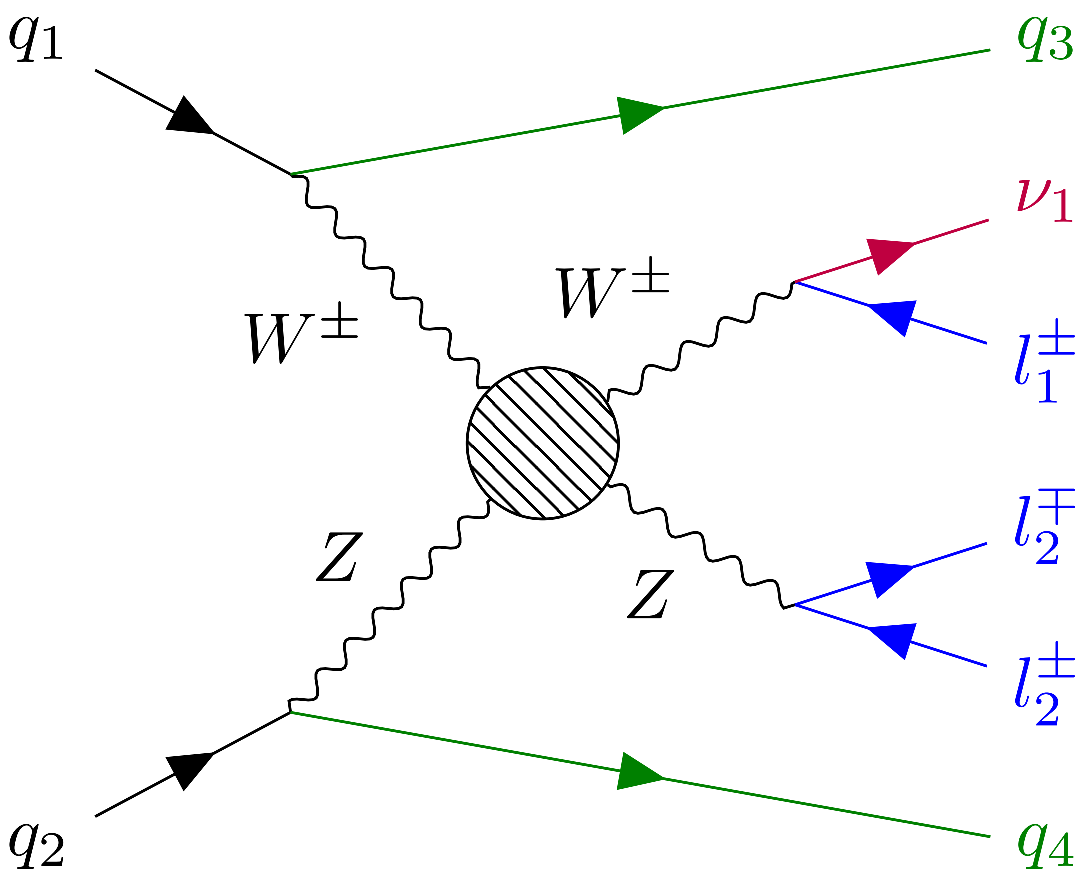
Measurements of joint-polarisation states of W and Z gauge bosons in $W^{\pm}Z$ production are presented. The data set used corresponds to an integrated luminosity of 139 fb^{-1} of proton–proton collisions at a centre-of-mass energy of 13 TeV recorded by the ATLAS detector at the CERN Large Hadron Collider. The $W^{\pm}Z$ candidate events are reconstructed using leptonic decay modes of the gauge bosons into electrons and muons. The simultaneous pair-production of longitudinally polarised vector bosons is measured for the first time with a significance of 7.1 standard deviations. The measured joint helicity fractions integrated over the fiducial region are $f_{00} = 0.067 \pm 0.010$, $f_{0\mathrm{T}} = 0.110 \pm 0.029$, $f_{\mathrm{T}0} = 0.179 \pm 0.023$ and $f_{\mathrm{TT}} = 0.644 \pm 0.032$, in agreement with the next-to-leading-order Standard Model predictions. Individual helicity fractions of the W and Z bosons are also measured and found to be consistent with joint helicity fractions within the expected amounts of correlation. Both the joint and individual helicity fractions are also measured separately in $W^{+}Z$ and $W^{-}Z$ events. Inclusive and differential cross sections for several kinematic observables sensitive to polarisation are presented.

arXiv:2211.09435

$W^{\pm}Z$ Polarisation Measurement

Analysis Goal

- Joint-polarisation
  - Measure f_{00}, f_{T0}, f_{0T}, and f_{TT}
- Single-polarisation
  - Individual polarisation of $W^{\pm}$ or Z boson
  - Measure f_0 and $f_L - f_R$

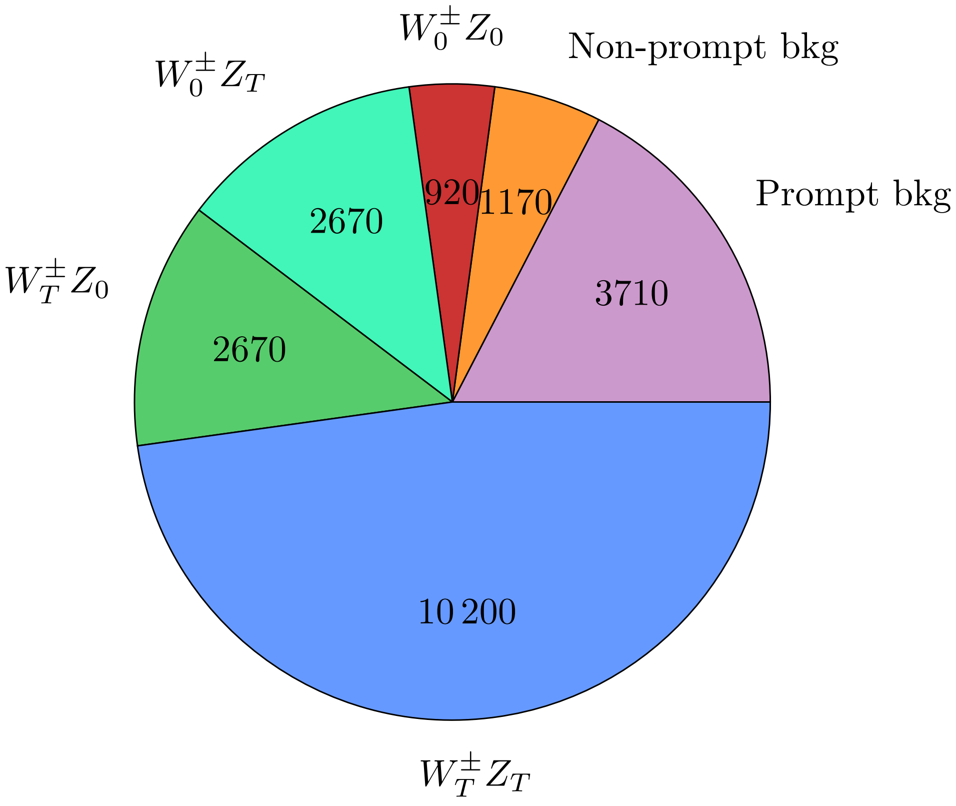


$W^{\pm}Z$ Polarisation Measurement

Phase Space

Inclusive event selection	
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)
Z leptons	Two same flavor oppositely charged leptons passing Z-lepton selection
Mass window	$\lvert M_{\ell\ell} - M_Z \rvert < 10$ GeV
W lepton	Remaining lepton passes W-lepton selection
W transverse mass	$m_T^W > 30$ GeV

21400 events



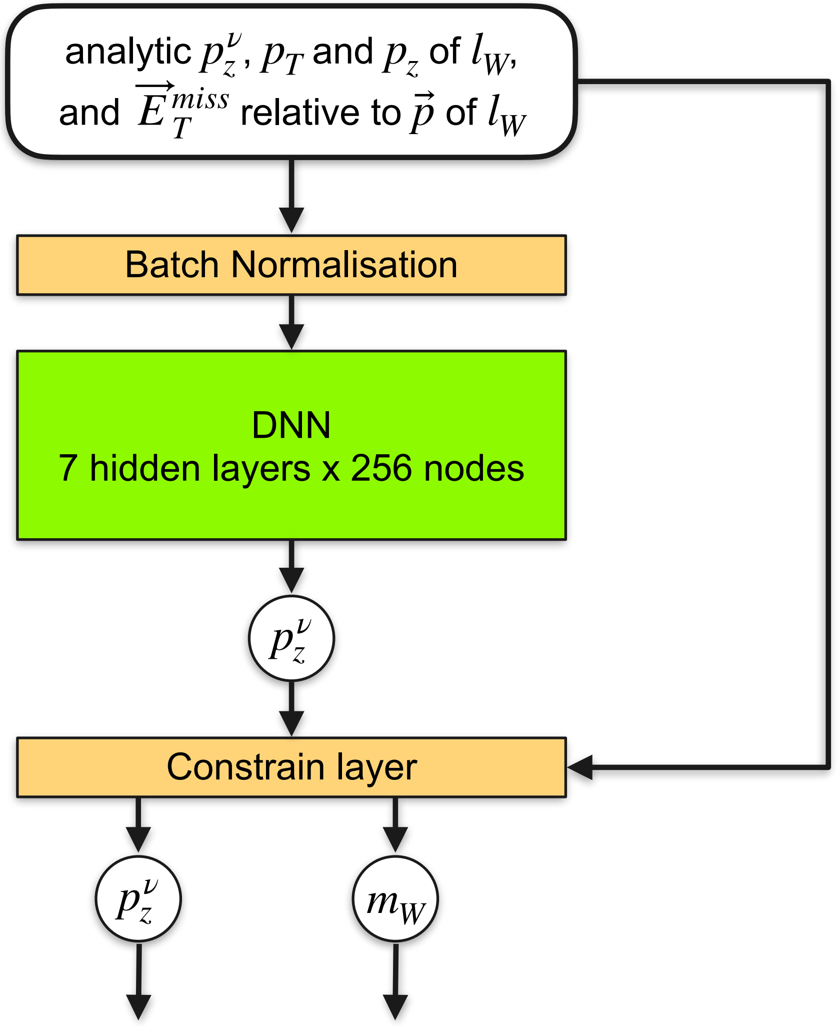
arXiv:2211.09435

$W^{\pm}Z$ Polarisation Measurement

DNN to Reconstruct Neutrino p_z

$\vec{p}_\nu$ required to access $W^{\pm}Z$ center of mass

- Improve analytic calculation of p_z^ν
- Regression DNN trained on inclusive Powheg+Pythia sample
- Introduce m_W constrain in last layer
- Better regression than analytic p_z^ν calculation



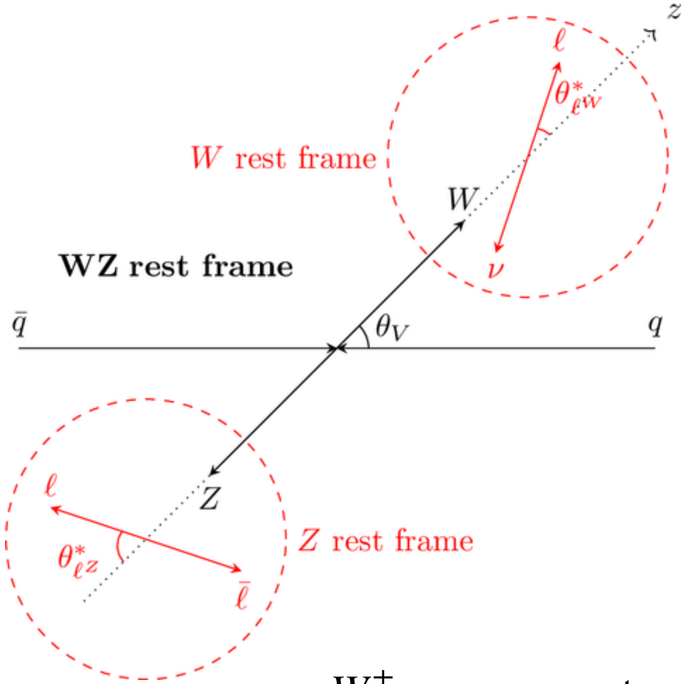
$$loss = MSE(p_z^\nu) + MSE(m_W)$$

arXiv:2211.09435

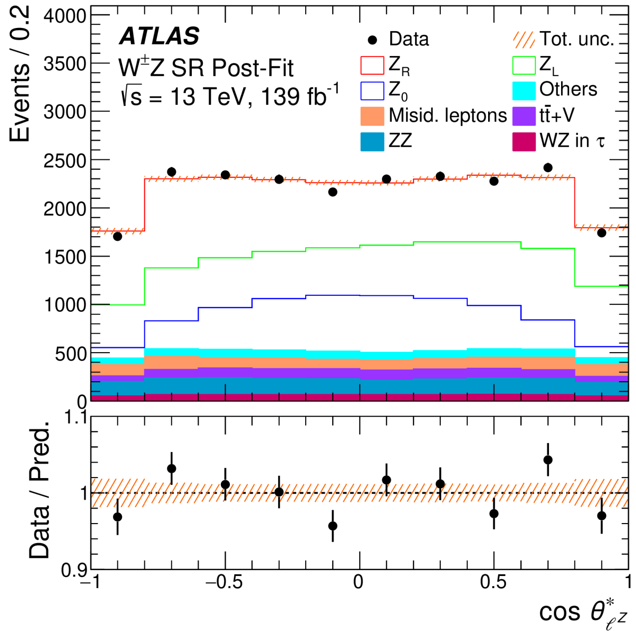
$W^{\pm}Z$ Single-Polarisation Measurement

Analysis Strategy

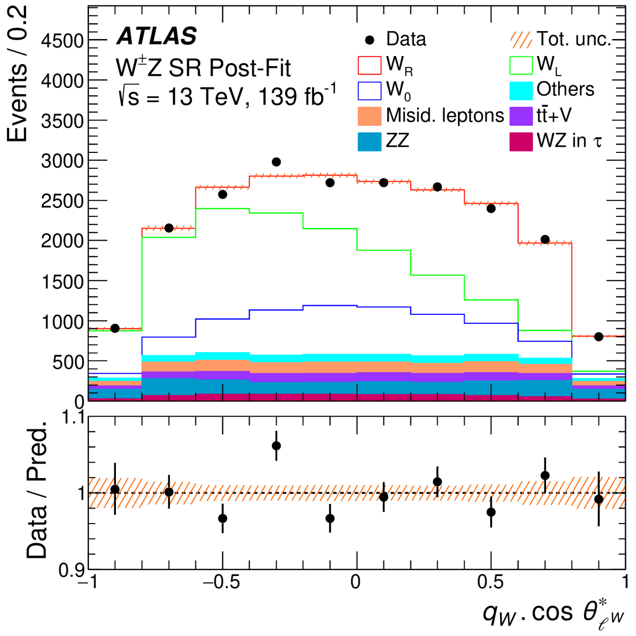
- Fit directly in $\cos\theta^*_{lW}$ and $\cos\theta^*_{lZ}$
- Reweight Powheg+Pythia (NLO-QCD) with corresponding $\cos\theta^*_{lV}$ distribution to get polarised sample
- Measure f_0 and $f_L - f_R$



Z measurement



$W^{\pm}$ measurement



arXiv:2211.09435

$W^{\pm}Z$ Single-Polarisation Measurement

Fit Results

- Good agreement with SM
- Dominated by statistical uncertainty
- Dominant systematic is modelling uncertainty

	f_0 Data	f_0 POWHEG+PYTHIA	$f_L - f_R$ Data	$f_L - f_R$ POWHEG+PYTHIA
W in W^+Z	0.23 ± 0.05	0.2044 ± 0.0024	0.071 ± 0.023	0.0990 ± 0.0015
W in W^-Z	0.19 ± 0.05	0.217 ± 0.004	0.026 ± 0.027	-0.0491 ± 0.0020
W in $W^{\pm}Z$	0.21 ± 0.04	0.2094 ± 0.0016	0.059 ± 0.016	0.0390 ± 0.0011
Z in W^+Z	0.223 ± 0.025	0.1971 ± 0.0019	-0.20 ± 0.10	-0.217 ± 0.006
Z in W^-Z	0.241 ± 0.029	0.2065 ± 0.0023	0.10 ± 0.13	0.092 ± 0.007
Z in $W^{\pm}Z$	0.231 ± 0.019	0.2009 ± 0.0014	-0.10 ± 0.08	-0.092 ± 0.005

arXiv:2211.09435

$W^{\pm}Z$ Joint-Polarisation Measurement

Simulate Polarisation at NLO-QCD

- Extensive study of polarisation simulation
  ⇒ only nominal strategy presented
- Use two samples:
  - Polarised MadGraph LO-QCD
  - Unpolarised Powheg NLO
- Train 4 binary classifier DNN for pol-sum MadGraph vs pol MadGraph

$$w_{pol}(X) = \frac{DDN_{pol}(X)}{1 - DDN_{pol}(X)}$$

- Use $w_{pol}(X)$ to introduce polarisation in Powheg NLO

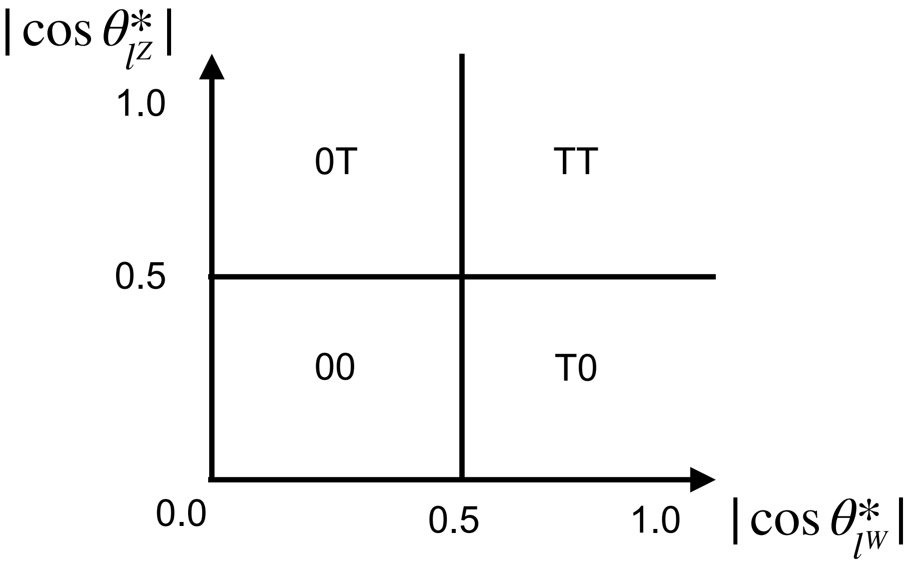
$W^{\pm}Z$ Joint-Polarisation Measurement

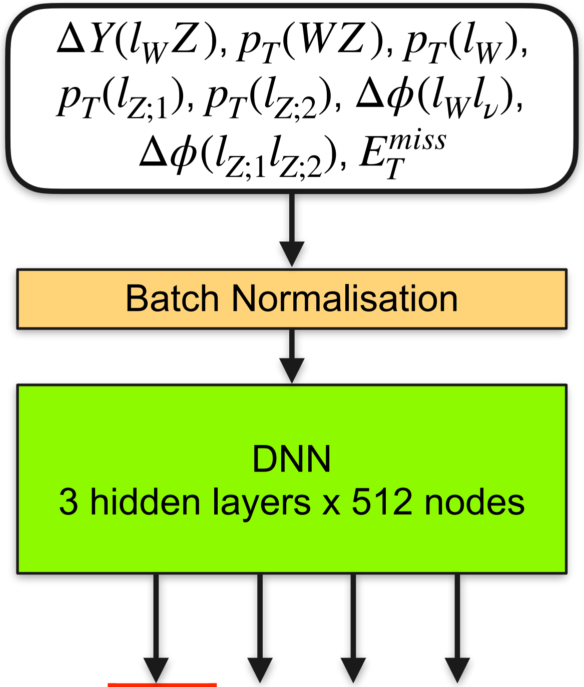
Multivariate Analysis

- Multiclass DNN trained on Madgraph-0,1j@LO
- Modify the 00-output node targets

➡ sufficient to separate 00, TT and mixed modes

- Combine DNN output with $\cos\theta^*_{lW}$ and $\cos\theta^*_{lZ}$





Polarisation mode	00	T0	0T	TT
00	1	0	0	0
T0	0.5	1	0	0
0T	0.5	0	1	0
TT	0	0	0	1

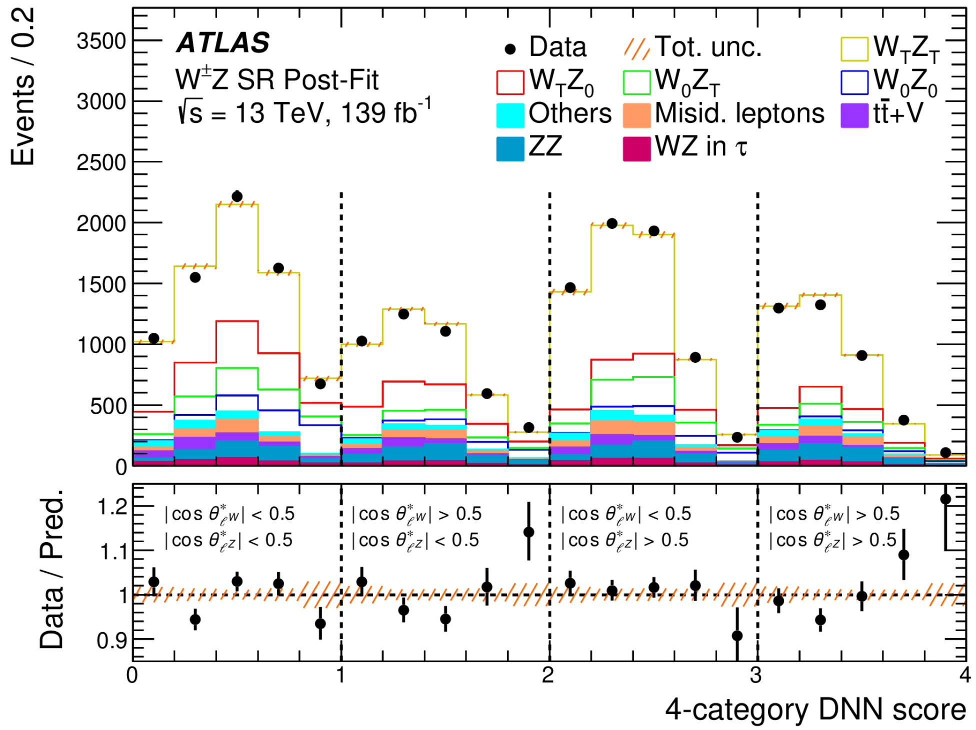
ATLAS EXPERIMENT

arXiv:2211.09435

$W^{\pm}Z$ Joint-Polarisation Measurement

Fit Results

- Measure f_{00}, f_{T0}, f_{0T}, and f_{TT}
- Statistic, QCD-scale and modelling have similar impact
- Modelling uncertainty mainly from polarisation at NLO-QCD



	Data	Powheg+Pythia	observed	expected
f_{00}	0.067 ± 0.010	0.0590 ± 0.0009	7.1σ	6.2σ
$f_{0\mathrm{T}}$	0.110 ± 0.029	0.1515 ± 0.0017	3.4σ	5.4σ
$f_{\mathrm{T}0}$	0.179 ± 0.023	0.1465 ± 0.0017	7.1σ	6.6σ
f_{TT}	0.644 ± 0.032	0.6431 ± 0.0021	11σ	9.7σ

Observation **Evidence**

$W^{\pm}Z$ Joint-Polarisation Measurement

Spin correlation

Single-polarisation measurement

Joint-polarisation measurement

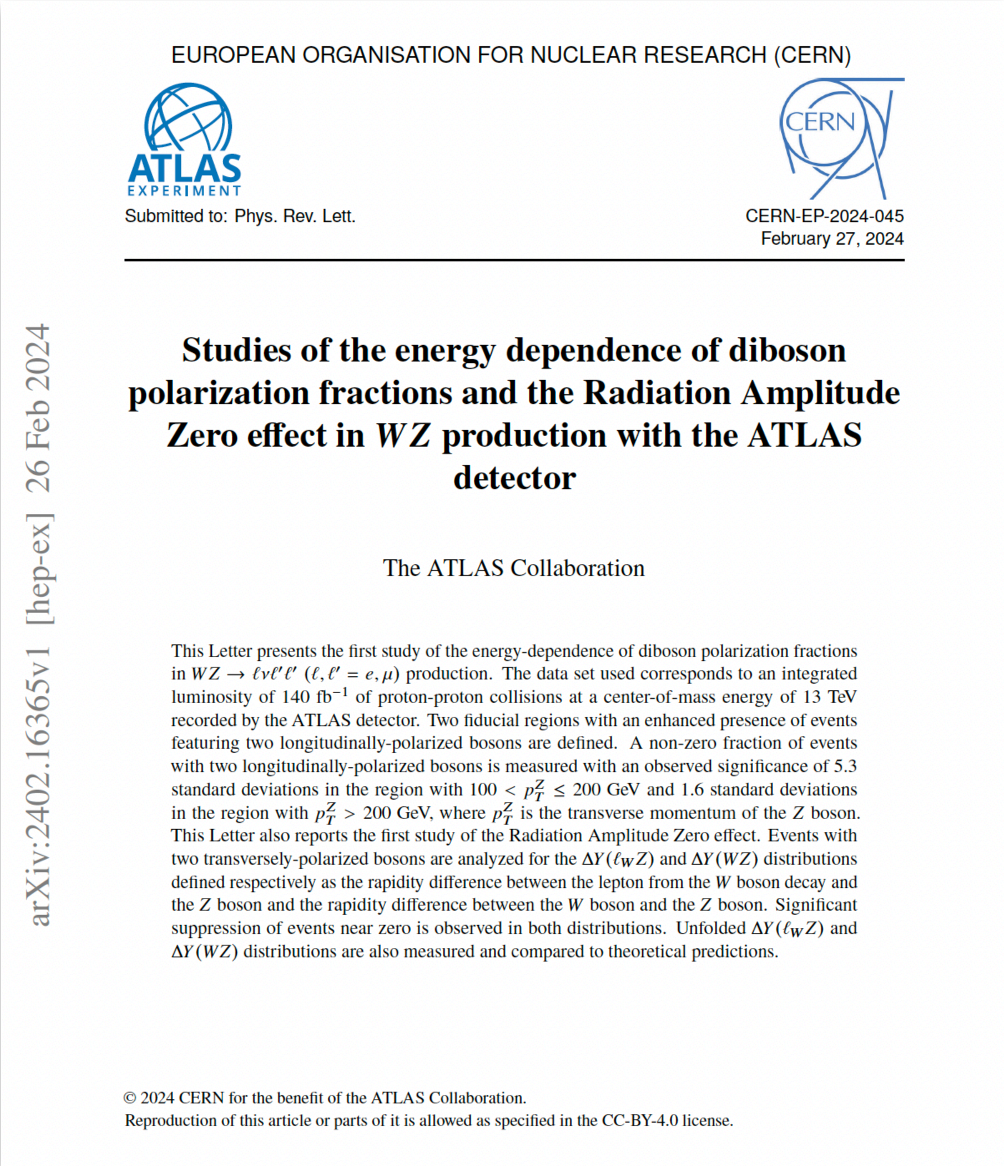
$$R_c = \frac{f_{00}}{f_0^W f_0^Z}$$

No correlation $R_c = 1$ and SM $R_c = 1.3$

$R_c = 1.54 \pm 0.35$ with 1.6σ against $R_c = 1$

arXiv:2402.16365

$W^{\pm}Z$ Polarisation Energy Dependency & RAZ



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Phys. Rev. Lett.

CERN-EP-2024-045
February 27, 2024

Studies of the energy dependence of diboson polarization fractions and the Radiation Amplitude Zero effect in WZ production with the ATLAS detector

The ATLAS Collaboration

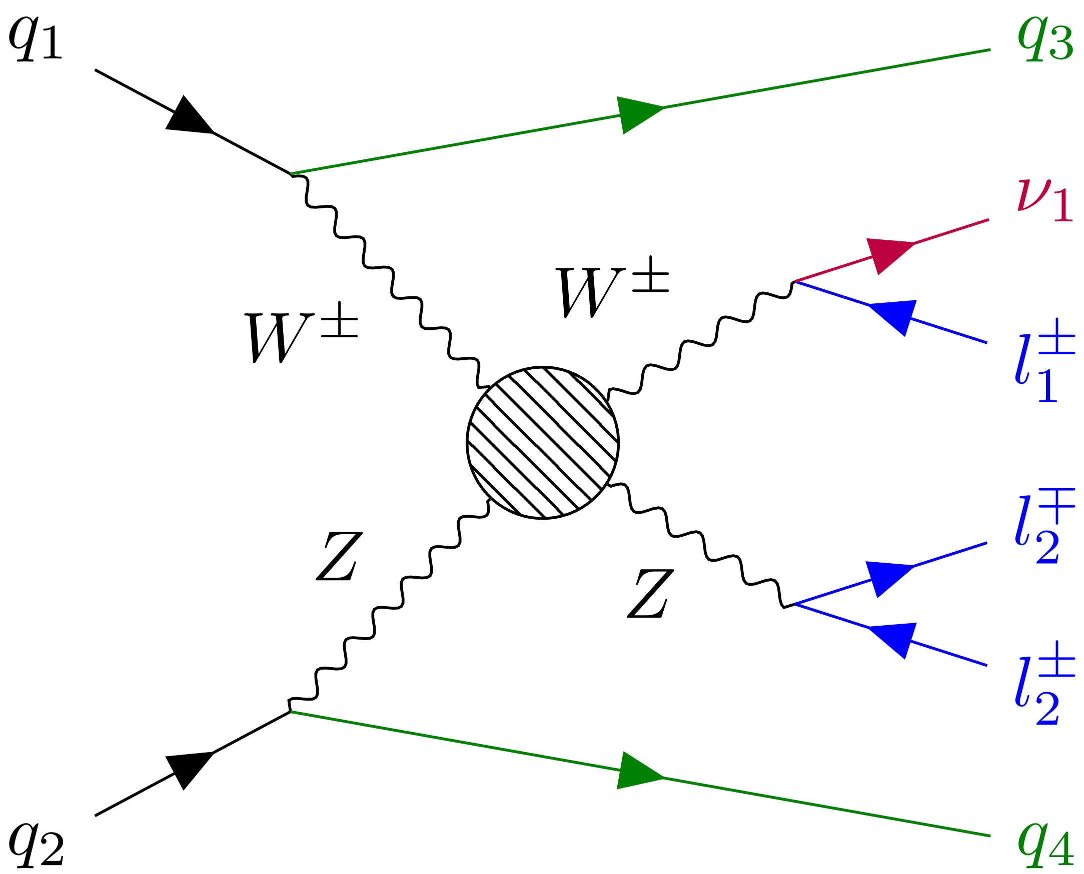
This Letter presents the first study of the energy-dependence of diboson polarization fractions in $WZ \to \ell\nu\ell'\ell'$ ($\ell, \ell' = e, \mu$) production. The data set used corresponds to an integrated luminosity of 140 fb^{-1} of proton-proton collisions at a center-of-mass energy of 13 TeV recorded by the ATLAS detector. Two fiducial regions with an enhanced presence of events featuring two longitudinally-polarized bosons are defined. A non-zero fraction of events with two longitudinally-polarized bosons is measured with an observed significance of 5.3 standard deviations in the region with $100 < p_T^Z \leq 200$ GeV and 1.6 standard deviations in the region with $p_T^Z > 200$ GeV, where p_T^Z is the transverse momentum of the Z boson. This Letter also reports the first study of the Radiation Amplitude Zero effect. Events with two transversely-polarized bosons are analyzed for the $\Delta Y(\ell_W Z)$ and $\Delta Y(WZ)$ distributions defined respectively as the rapidity difference between the lepton from the W boson decay and the Z boson and the rapidity difference between the W boson and the Z boson. Significant suppression of events near zero is observed in both distributions. Unfolded $\Delta Y(\ell_W Z)$ and $\Delta Y(WZ)$ distributions are also measured and compared to theoretical predictions.

arXiv:2402.16365

$W^{\pm}Z$ Polarisation Energy Dependency & RAZ

Analysis Goal

- Joint-polarisation at high p_T^Z
  - Measure f_{00}, $f_{T0} + f_{0T}$, and f_{TT}
  - Measure p_T^Z dependency with two distinct fits
- Radiation Amplitude Zero (RAZ) effect



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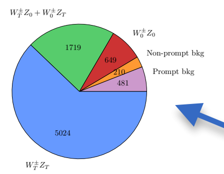
$W^{\pm}Z$ Polarisation Energy Dependency & RAZ

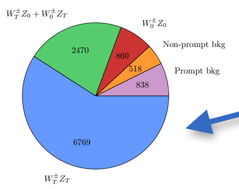
Phase Space

Inclusive WZ event selection	
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	$\lvert m_{\ell\ell} - M_Z \rvert < 10$ GeV
W lepton	Remaining lepton passes the W-lepton selection
W transverse mass	$m_T^W > 30$ GeV
ΔR	$\Delta R(\ell_Z^-, \ell_Z^+) > 0.2$, $\Delta R(\ell_Z, \ell_W) > 0.3$

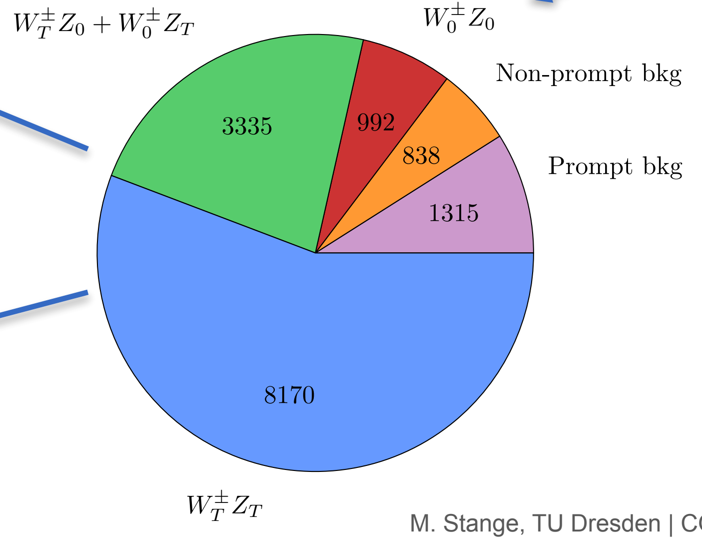
Signal regions

	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	

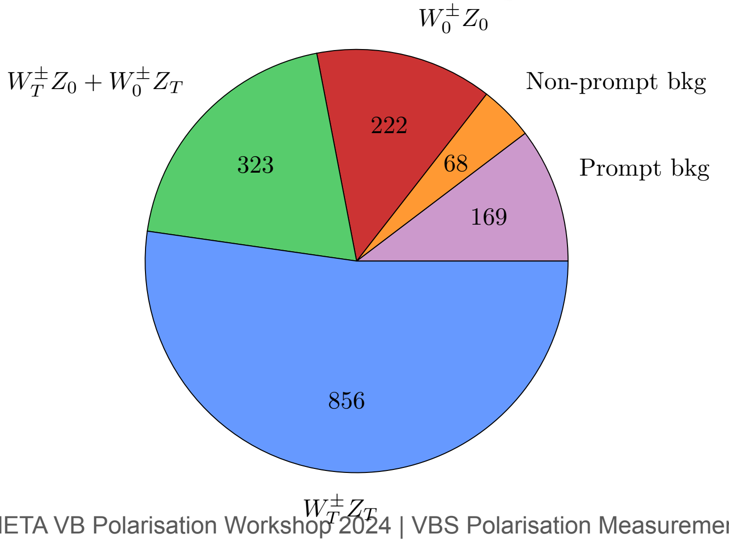




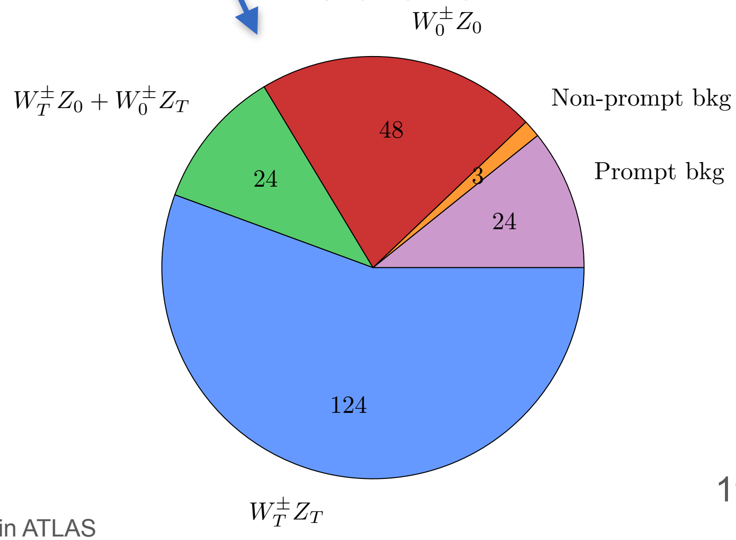
12500 events



1640 events



220 events



ATLAS EXPERIMENT

$W^{\pm}Z$ Polarisation Energy Dependency & RAZ

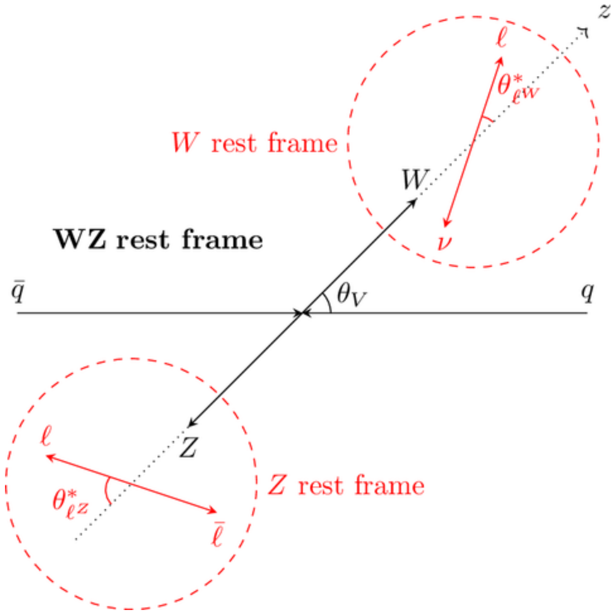
Polarisation Simulation

- Use MadGraph0,1j@LO to get NLO-QCD effects
- Compared with unpolarised NLO samples:
  - Powheg+Pythia8
  - MadGraph aMC@NLO
  - Sherpa
  - ➡ Sufficient NLO modelling
- Scale factor from data in inclusive multi-jet region for remaining NLO-QCD effects

arXiv:2402.16365

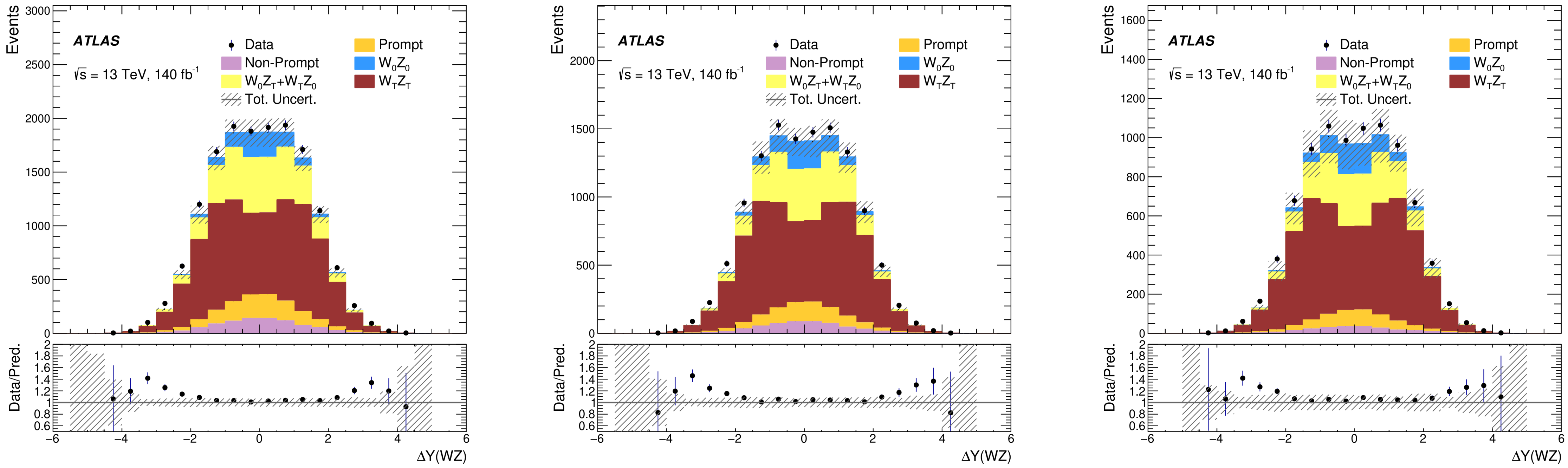
$W^{\pm}Z$ Polarisation Radiation Amplitude Zero

Analysis Strategy



- $\mathcal{M}_{WZ}^{TT} = 0$ at $\theta_V = \pi/2 \Rightarrow$ visible at $\Delta Y_{WZ} = |Y_W - Y_Z| = 0$
- Dip is filled by NLO-QCD contributions
- Split in 3 regions to suppress NLO-QCD

$p_T^{WZ} < 70\,GeV$	$p_T^{WZ} < 40\,GeV$	$p_T^{WZ} < 20\,GeV$
12500 events	10100 events	7390 events

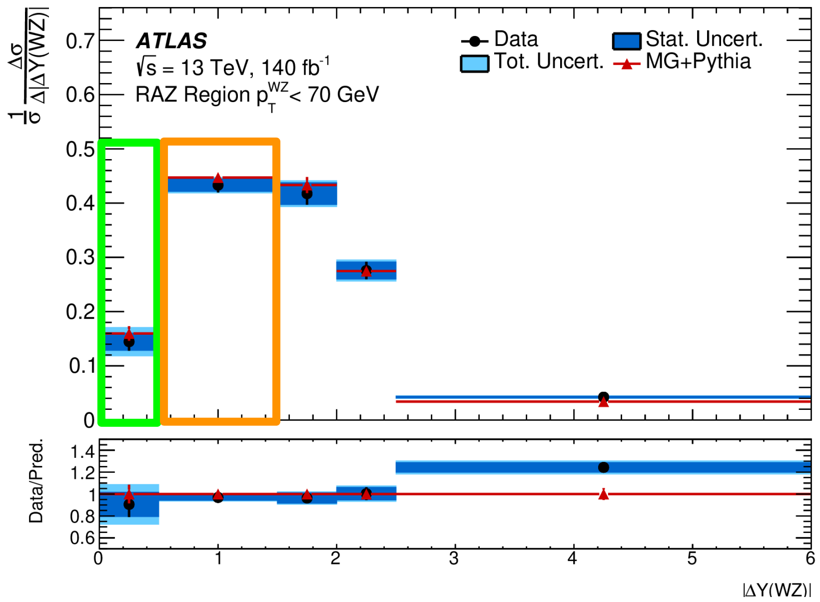


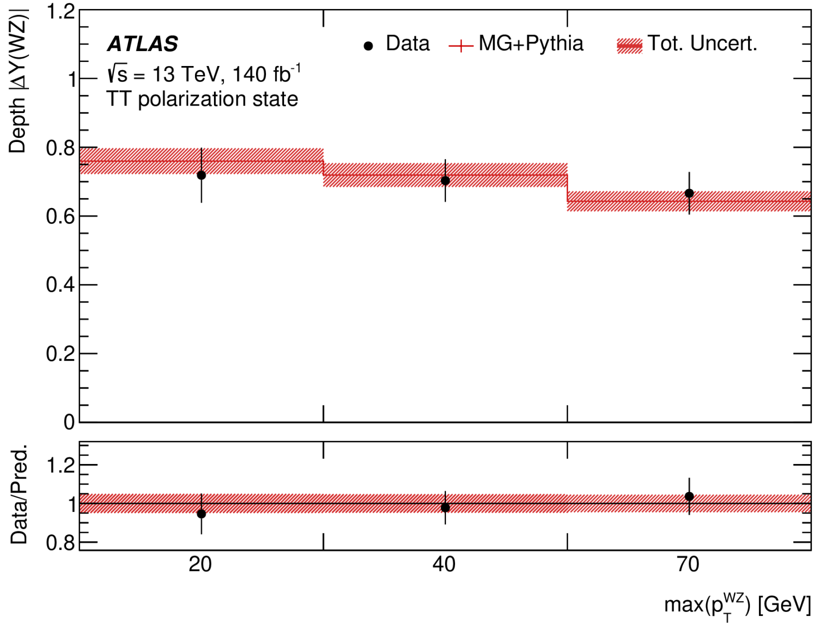
arXiv:2402.16365

$W^{\pm}Z$ Polarisation Radiation Amplitude Zero

Measurement

- Unfold $W^{\pm}_{T}Z_{T}$
- Depth variable $D = 1 - \frac{N_{central}}{N_{sides}/2}$
- Dominated by statistic
- Dominant systematic are NLO effects





arXiv:2402.16365

$W^{\pm}Z$ Polarisation Energy Dependency

Measurement

- Train BDTs for $W_0^{\pm}Z_0$ vs rest in two p_T^Z regions
- Perform 2 parameter and 3 parameter fit
- Dominated by statistic
- Dominant systematic are NLO effects

3 parameter:

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

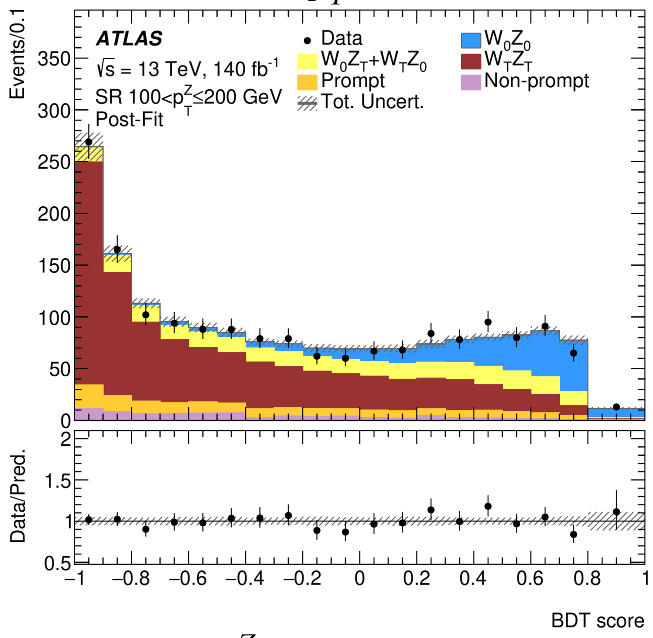
2 parameter:

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

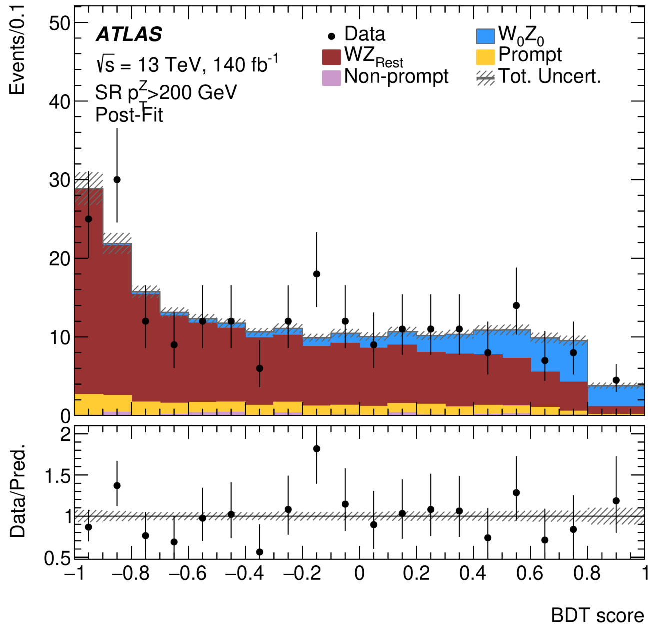
Observation 🎉

Evidence 🔎

$100\,\text{GeV} < p_T^Z \leq 200\,\text{GeV}$



$p_T^Z > 200\,\text{GeV}$



arXiv:2310.04350

ZZ Polarisation Measurement

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

JHEP 12 (2023) 107
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CERN-EP-2023-199
22nd February 2024

Evidence of pair production of longitudinally polarised vector bosons and study of CP properties in $ZZ \to 4\ell$ events with the ATLAS detector at $\sqrt{s} = 13$ TeV

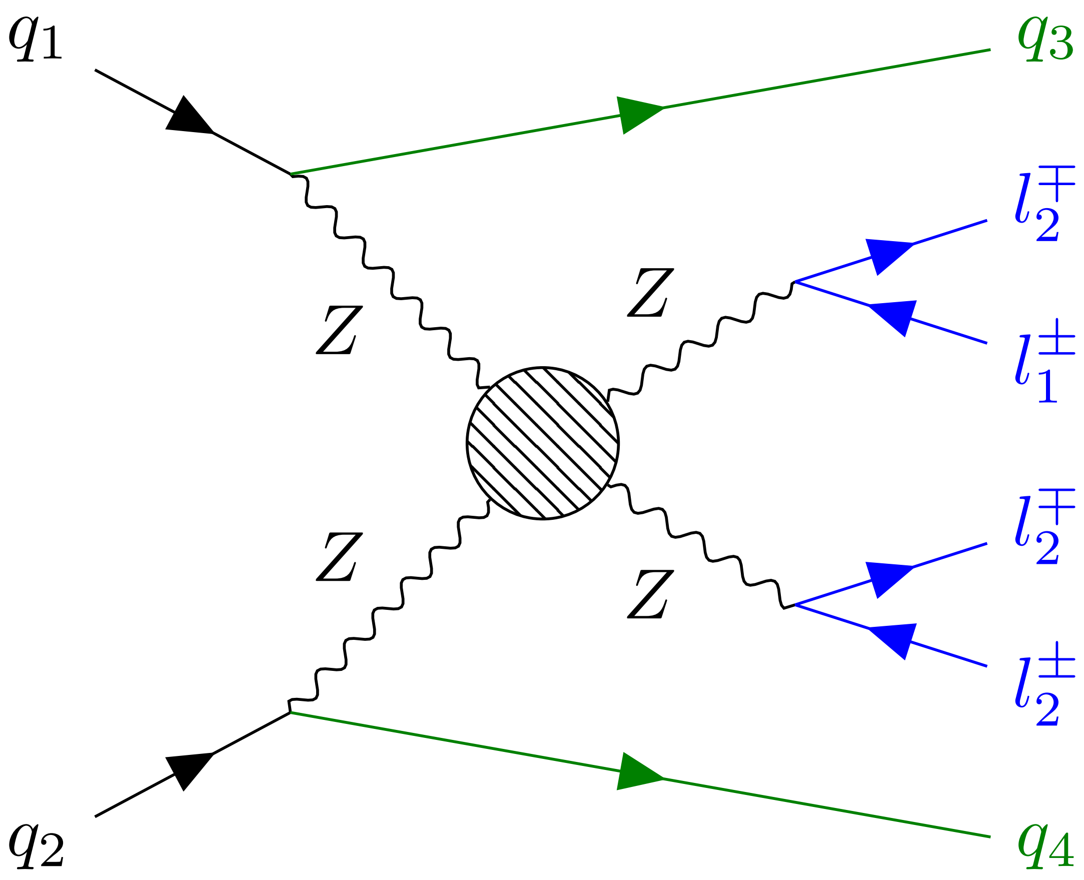
The ATLAS Collaboration

A study of the polarisation and CP properties in ZZ production is presented. The used data set corresponds to an integrated luminosity of 140 fb^{-1} of proton–proton collisions at a centre-of-mass energy of 13 TeV recorded by the ATLAS detector at the Large Hadron Collider. The ZZ candidate events are reconstructed using two same-flavour opposite-charge electron or muon pairs. The production of two longitudinally polarised Z bosons is measured with a significance of 4.3 standard deviations, and its cross-section is measured in a fiducial phase space to be 2.45 ± 0.60 fb, consistent with the next-to-leading-order Standard Model prediction. The inclusive differential cross-section as a function of a CP-sensitive angular observable is also measured. The results are used to constrain anomalous CP-odd neutral triple gauge couplings.

ZZ Polarisation Measurement

Analysis Goal

- Joint-polarisation
  - Cross-section of Z_0Z_0 and $Z_0Z_T + Z_TZ_0 + Z_TZ_T$
- CP-odd optimal variable
  $\Rightarrow$ not covered in this talk

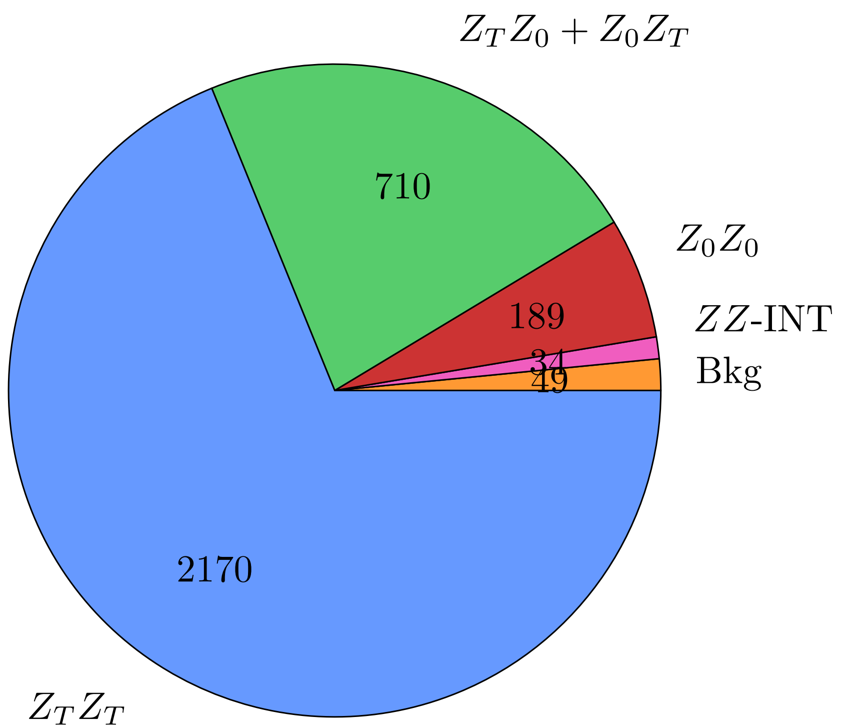


ZZ Polarisation Measurement

Phase Space

Category	Requirement
Event Preselection	Fire at least one lepton trigger ≥1 vertex with 2 or more tracks
Four-lepton signature Lepton kinematics Lepton separation J/ψ-Veto	At least 4 leptons (e, μ) $p_T > 20$ GeV for leading two leptons $\Delta R_{ij} > 0.05$ for any two leptons $m_{ij} > 5$ GeV for 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 (the quadruplet having the smallest $\lvert m_{Z_1} - m_{Z_{pole}}\rvert + \lvert m_{Z_2} - m_{Z_{pole}}\rvert$ is chosen)
On-shell ZZ pair	$m_{4l} > 180$ GeV
On-shell Z boson	$\lvert m_{ij} - m_Z\rvert$<10 GeV

3140 events

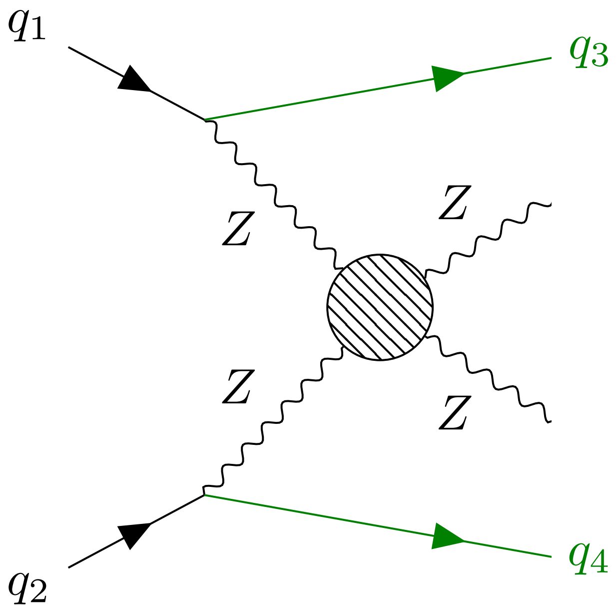


arXiv:2310.04350

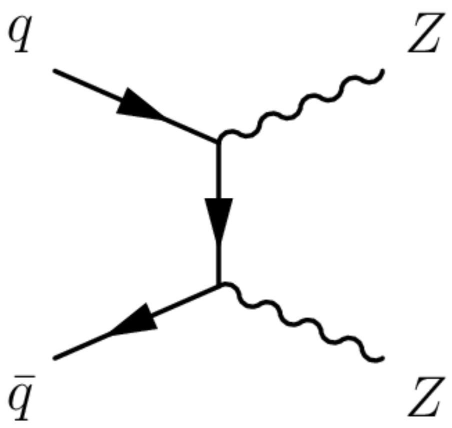
ZZ Polarisation Measurement

Polarisation Simulation

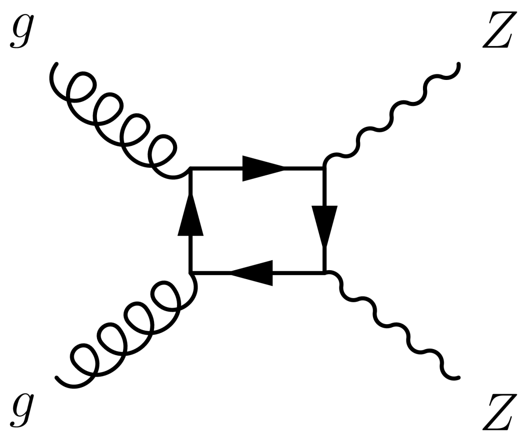
$qq \to ZZjj \to 4ljj$
MadGraph 2.7.3 + Pythia 8



$q\bar{q} \to ZZ \to 4l$



$gg \to ZZ \to 4l$



arXiv:2310.04350

ZZ Polarisation Measurement

Polarisation Simulation for $q\bar{q} \rightarrow ZZ \rightarrow 4l$

- MadGraph+Pythia8 at LO

1. **NLO correction** from analytic calculation [A. Denner, G. Pelliccioli, arXiv:2107.06579]

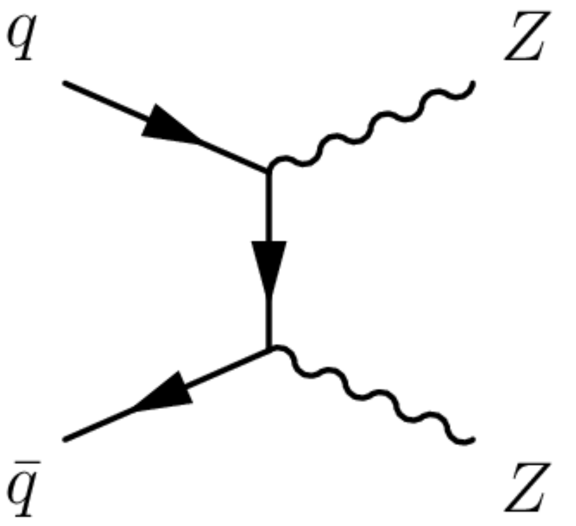
$$k = \underbrace{\frac{\text{MoCaNLO}^{Parton}_{pol}}{\text{MG012LO}^{Particle}_{pol}}}_{\text{NLO correction}} \times \underbrace{\frac{\text{Sh\_NLO}^{Particle}_{Incl}}{\text{MoCaNLO}^{Parton}_{Incl}}}_{\text{parton shower}} \text{ in } \cos\theta_1$$

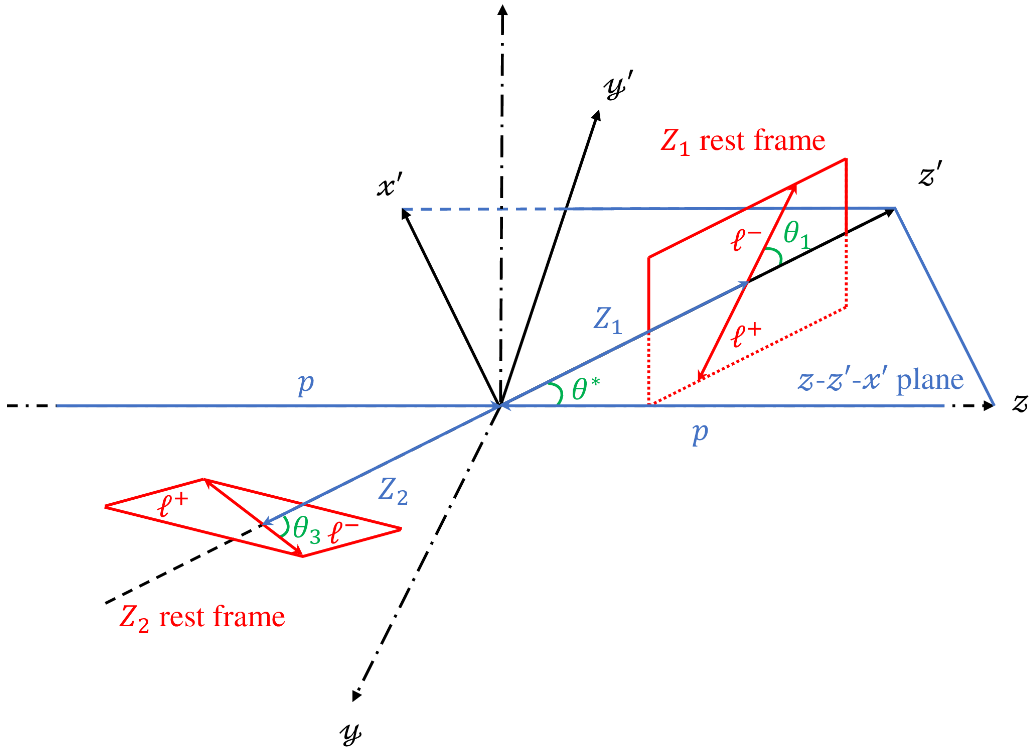
2. **Interference**

$$N^{int,Reco} = \left(1 - \frac{\sum_{pol} \text{MoCaNLO}^{Parton}_{pol}}{\text{MoCaNLO}^{Parton}_{Incl}}\right) \times \text{Sh\_NLO}^{Reco}_{Incl} \text{ in } \cos\theta_1$$

3. Correction for **residual higher-order effects**

$$c = \frac{\text{Sh\_NLO}^{Reco}_{Incl} - N^{int,Reco}}{\sum_{pol} N_{pol}} \text{ in } \cos\theta^* \text{ and } \Delta\phi_{l1l2}$$





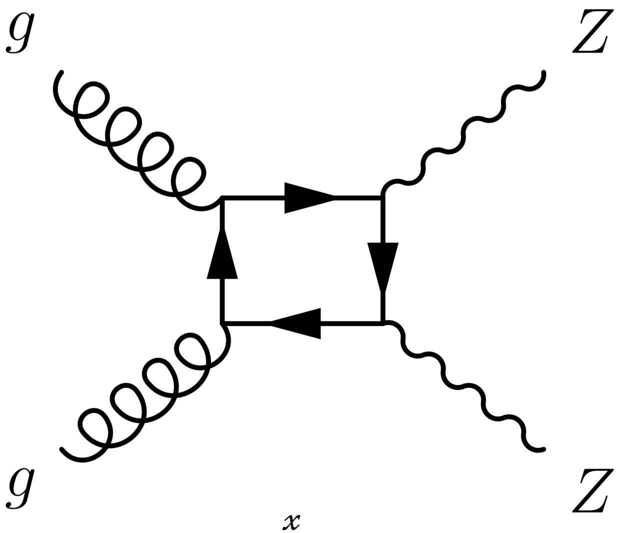
arXiv:2310.04350

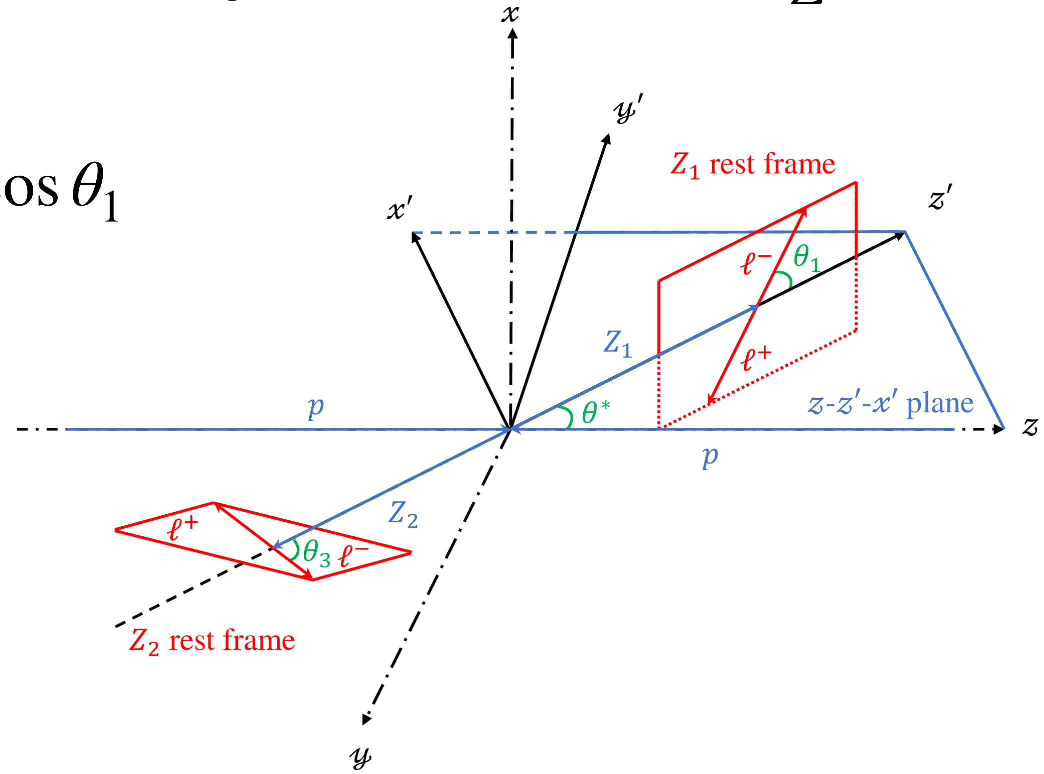
ZZ Polarisation Measurement

Polarisation Simulation for $gg \to ZZ \to 4l$

- MadGraph cannot directly simulate $gg \to ZZ \to 4l$ directly
- Unpolarised $gg \to ZZ \to 4l$ by Sherpa
- Introduce polarisation via analytic calculation
  [A. Denner, G. Pellicciolì, arXiv:2107.06579]

$$N^{ggZZ,reco}_{LO,pol} = \underbrace{\frac{\text{MoCaNLO}^{ggZZLO,Parton}_{pol}}{\text{MoCaNLO}^{ggZZLO,Parton}_{incl}}}_{\text{polarisation}} \times \text{Sh}^{ggZZ,reco}_{incl} \text{ in } \cos\theta_1$$





arXiv:2310.04350

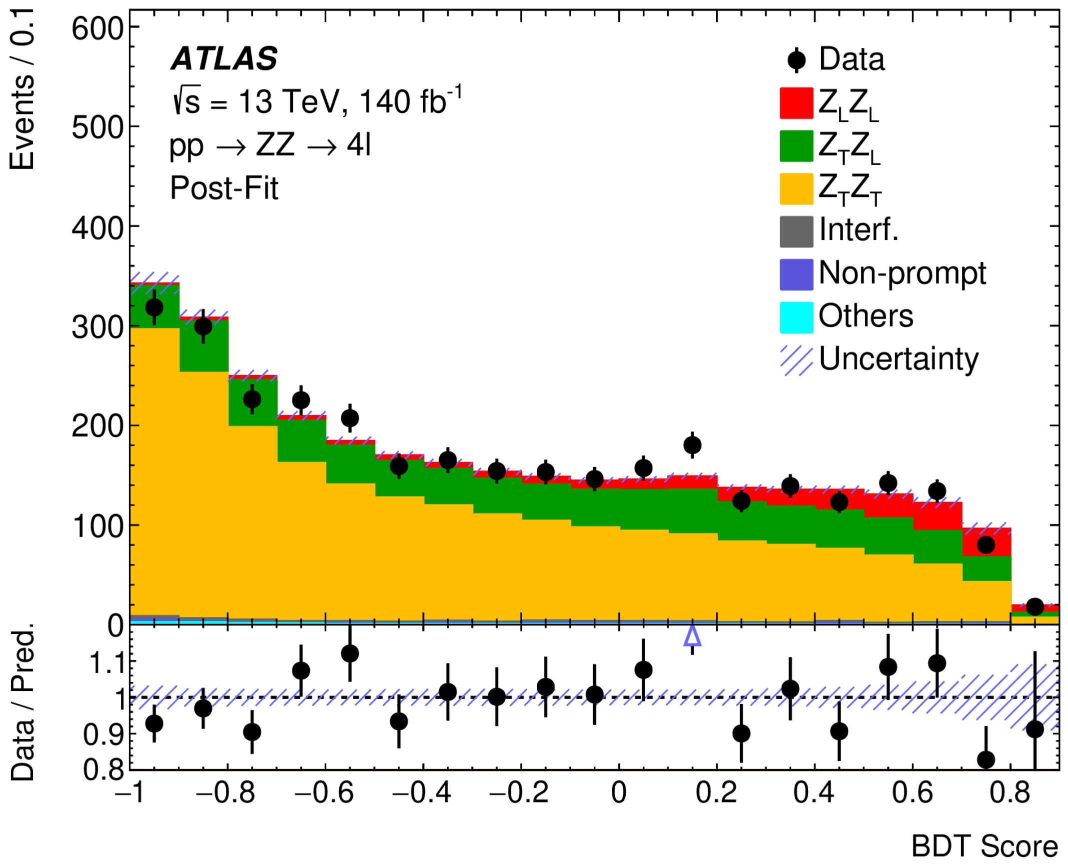
ZZ Polarisation Measurement

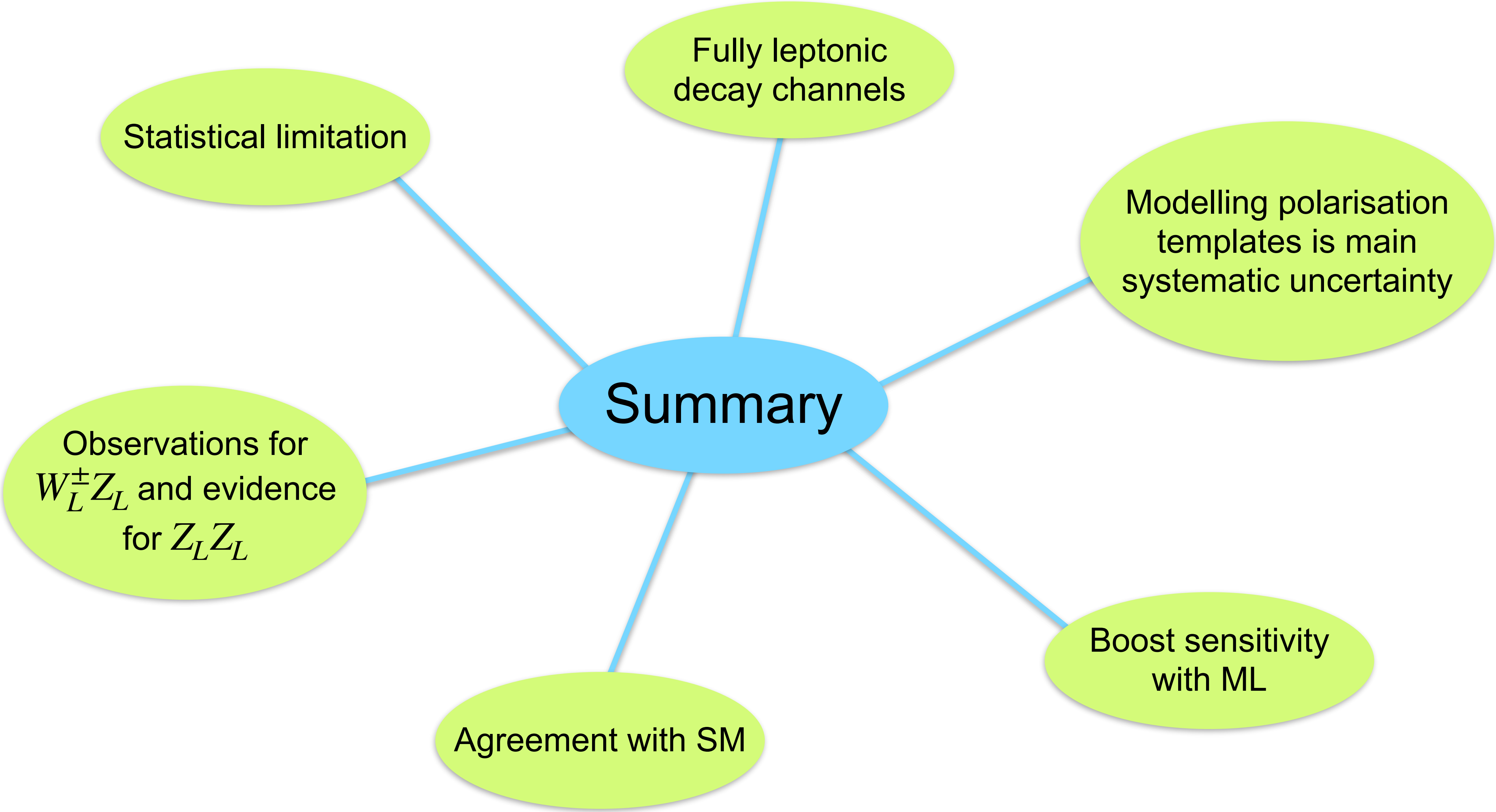
Measurement

- Train BDT on LO $q\bar{q} \rightarrow ZZ \rightarrow 4l$ to separate $Z_0 Z_0$ from rest
- Fit normalisation of $Z_0 Z_0$ and $Z_0 Z_T + Z_T Z_0 + Z_T Z_T$
- Dominated by statistic
- Dominant systematic from reweighting steps

σ_{00}^{obs}	$2.45 \pm 0.56\,(\text{stat}) \pm 0.21\,(\text{syst})$
$\sigma_{00}^{\text{pred.}}$	2.10 ± 0.09
f_{00} obs (exp) sig.	$4.3\sigma\ (3.8\sigma)$

Observation 🎉 Evidence 🔍



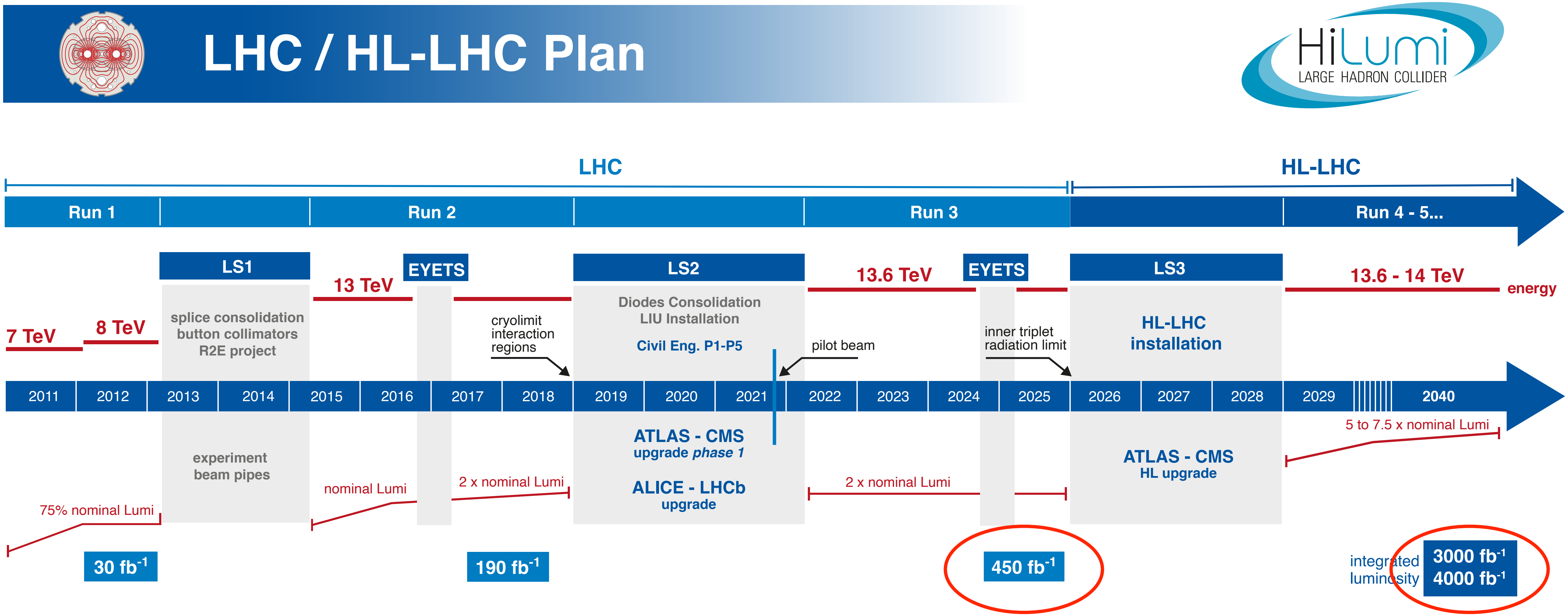

Summary
Fully leptonic decay channels
Statistical limitation
Modelling polarisation templates is main systematic uncertainty
Observations for $W^{\pm}_{L}Z_{L}$ and evidence for $Z_{L}Z_{L}$
Agreement with SM
Boost sensitivity with ML

Summary

- Statistical limitation
- Fully leptonic decay channels
- Modelling polarisation templates is main systematic uncertainty
- Observations for $W^{\pm}_{L}Z_{L}$ and evidence for $Z_{L}Z_{L}$
- Agreement with SM
- Boost sensitivity with ML

What's next?

Statistic



https://hilumilhc.web.cern.ch/content/hl-lhc-project

What's next?

Polarisation Simulation

Powheg-Box-Res+Pythia

[G. Pellicciol, G. Zanderighi, arXiv:2311.05220]

polarisation in VBS @NLO QCD + PS

Sherpa 3

[M. Hoppe, M. Schönherr, F. Siegert, arXiv:2310.14803]

VB polarisation @nLO QCD + PS and also interference

UFO model for gluon-loop induced VB

[M. Javurkova, R. Ruiz, R. Coelho Lopes de Sá, J. Sandesara, arXiv:2401.17365]

modify Feynman rules for polarisation in loop-induced processes

What's next?

Polarisation Reconstruction by ML

Amplitude-assisted tagging

[M. Grossi, M. Incudini, M. Pellen, G. Pelliccioli, arXiv:2306.07726]

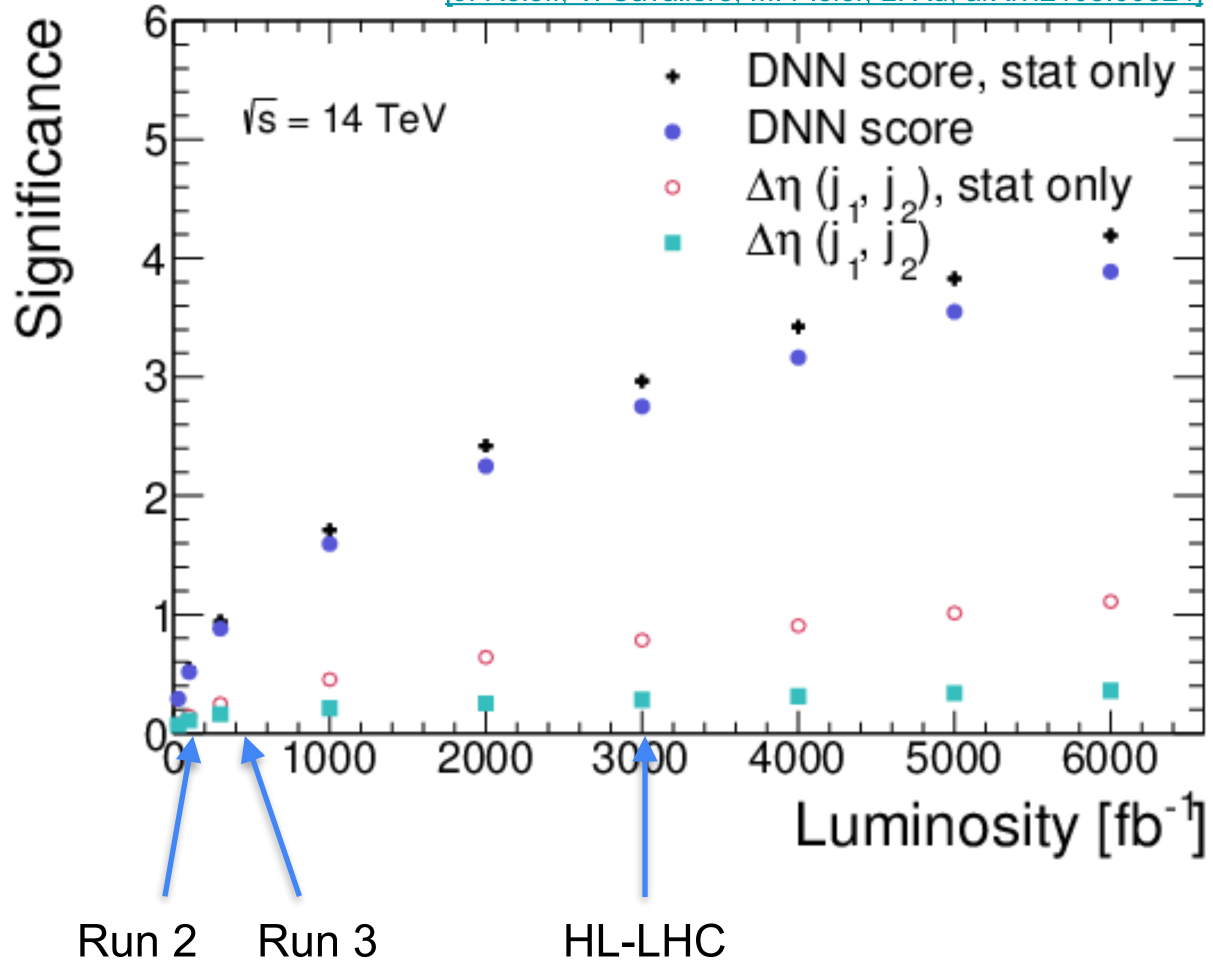
DNN access longitudinal polarisation on amplitude level

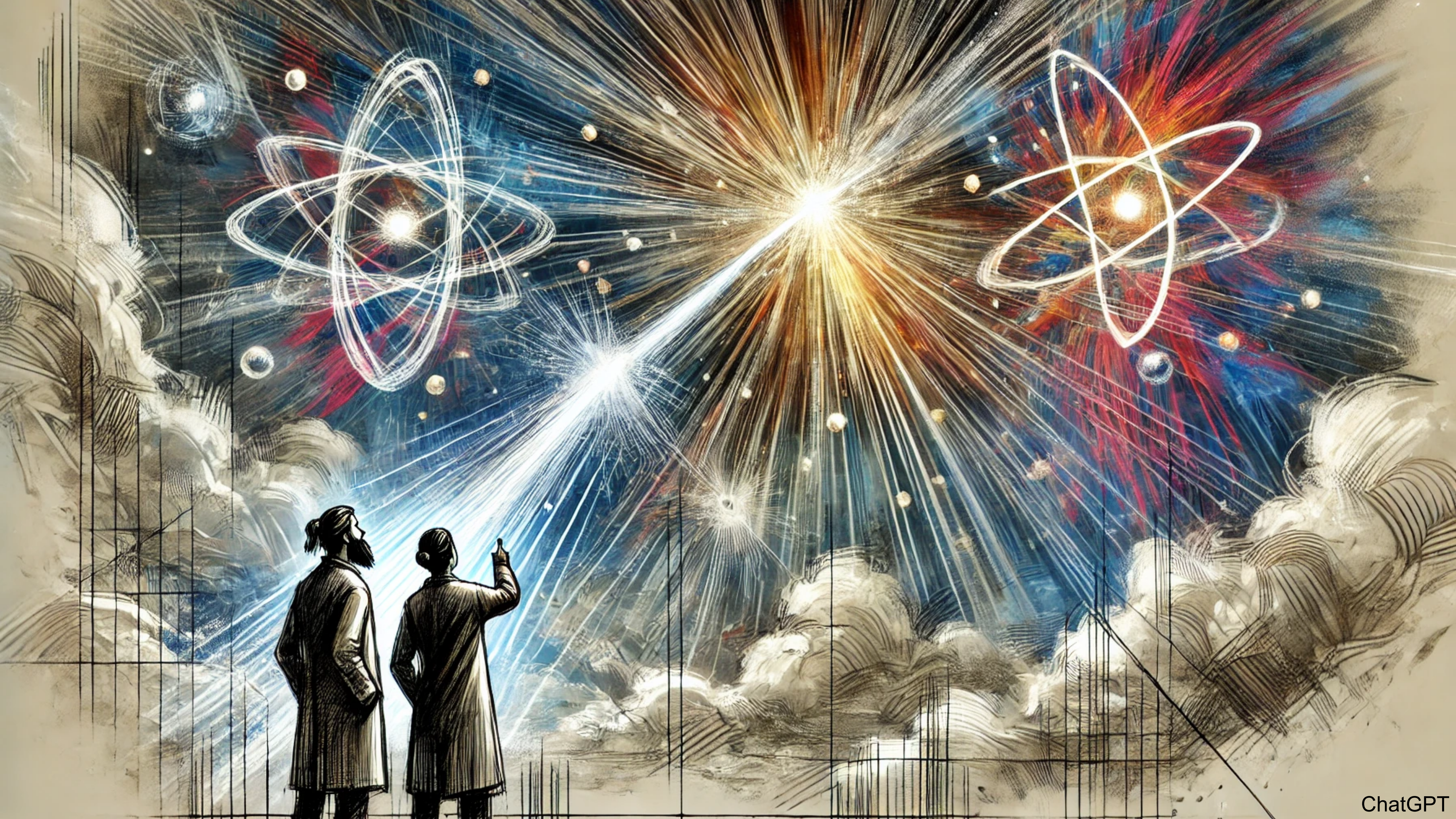
$$r_L = \frac{|\mathscr{M}_L|^2}{|\mathscr{M}|^2}$$

What's next?

$W_L^{\pm}V_L \rightarrow l^{\pm}\nu q\bar{q}$ with Semi-Leptonic Final State

[J. Roloff, V. Cavaliere, M. Pleier, L. Xu, arXiv:2108.00324]





ChatGPT

$W^{\pm}Z$ Polarisation Measurement

Object Selection

Electron object selection

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

Muon object selection

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

$W^{\pm}Z$ Polarisation Measurement

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	$p_T^{lead} > 25$ GeV (in 2015) or $p_T^{lead} > 27$ 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	$m_T^W > 30$ GeV

$W^{\pm}Z$ Polarisation Energy Dependency & RAZ

Event Selection

<table>
<tr><th colspan="2">Inclusive WZ event selection</th></tr>
<tr><td>Event cleaning</td><td>Reject LAr, Tile and SCT corrupted events and incomplete events</td></tr>
<tr><td>Primary vertex</td><td>Hard scattering vertex with at least two tracks</td></tr>
<tr><td>Triggers in 2015</td><td>HLT_e24_lhmedium_L1EM20VH || HLT_e60_lhmedium || HLT_e120_lhloose
HLT_mu20_iloose_L1MU15 || HLT_mu50</td></tr>
<tr><td>Triggers in 2016–2018</td><td>HLT_e26_lhtight_nod0_ivarloose || HLT_e60_lhmedium_nod0 || HLT_e140_lhloose_nod0
HLT_mu26_ivarmedium || HLT_mu50</td></tr>
<tr><td>ZZ veto</td><td>Less than 4 baseline leptons</td></tr>
<tr><td>N leptons</td><td>Exactly three leptons passing the Z lepton selection</td></tr>
<tr><td>Leading lepton p_{T}</td><td>$p_{\mathrm{T}}^{\mathrm{lead}} > 25$ GeV (in 2015) or $p_{\mathrm{T}}^{\mathrm{lead}} > 27$ GeV (in 2016-2018)</td></tr>
<tr><td>Z leptons</td><td>Two same flavor oppositely charged leptons passing the Z-lepton selection</td></tr>
<tr><td>Z lepton invariant mass</td><td>$|m_{\ell\ell} - M_Z| < 10$ GeV</td></tr>
<tr><td>W lepton</td><td>Remaining lepton passes the W-lepton selection</td></tr>
<tr><td>W transverse mass</td><td>$m_{\mathrm{T}}^{W} > 30$ GeV</td></tr>
<tr><td>ΔR</td><td>$\Delta R(\ell_Z^-, \ell_Z^+) > 0.2$, $\Delta R(\ell_Z, \ell_W) > 0.3$</td></tr>
</table>

<table>
<tr><th colspan="4">Signal regions</th></tr>
<tr><th></th><th>Radiation Amplitude Zero</th><th>00-enhanced region 1</th><th>00-enriched region 2</th></tr>
<tr><td>Pass inclusive WZ event selection</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>Transverse momentum of the Z boson (p_T^Z)</td><td>-</td><td>[100, 200] GeV</td><td>> 200 GeV</td></tr>
<tr><td>Transverse momentum of the WZ system (p_T^{WZ})</td><td>< 20, 40, 70 GeV</td><td colspan="2">< 70 GeV</td></tr>
</table>

ZZ Polarisation Measurement

Event Selection

Category	Requirement
Event Preselection	Fire at least one lepton trigger ≥1 vertex with 2 or more tracks
Four-lepton signature	At least 4 leptons (e, μ)
Lepton kinematics	$p_T >$ 20 GeV for leading two leptons
Lepton separation	$\Delta R_{ij} >$ 0.05 for any two leptons
J/ψ-Veto	$m_{ij} >$ 5 GeV for 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 (the quadruplet having the smallest $\lvert m_{Z_1} - m_{Z_{pole}}\rvert + \lvert m_{Z_2} - m_{Z_{pole}}\rvert$ is chosen)
On-shell ZZ pair	$m_{4l} >$ 180 GeV
On-shell Z boson	$\lvert m_{ij} - m_Z\rvert <$ 10 GeV

ATLAS EXPERIMENT

$W^{\pm}Z$ Polarisation Energy Dependency & RAZ

Measurement

	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

	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

$W^{\pm}Z$ Single-Polarisation Measurement

Uncertainties

	$W^{\pm}$ in $W^{\pm}Z$		Z in $W^{\pm}Z$	
	f_0	$f_L - f_R$	f_0	$f_L - f_R$
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_T^{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

$W^{\pm}Z$ Joint-Polarisation Measurement

Uncertainties

	f_{00}	f_{0T}	f_{T0}	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_T^{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

ATLAS EXPERIMENT

arXiv:2402.16365

$W^{\pm}Z$ Polarisation Radiation Amplitude Zero

Uncertainties

$p_T^Z < 70\,GeV$

Source	Impact [%] 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

$p_T^Z < 40\,GeV$

Source	Impact [%] TT state		Sum of polarizations	
Experimental	$\Delta Y(\ell_W Z)$	$\Delta Y(WZ)$	$\Delta Y(\ell_W Z)$	$\Delta Y(WZ)$
Luminosity	1.4	0.5	0.4	0.1
Electron calibration	1.1	0.6	1.2	0.4
Muon calibration	1.9	0.8	1.1	0.6
Jet energy scale and resolution	5.1	2.5	1.2	1.1
E_T^{miss} scale and resolution	1.0	1.1	1.7	1.8
Flavor-tagging inefficiency	0.0	0.0	0.1	0.0
Pileup modelling	0.3	0.6	3.3	0.2
Non-prompt background estimation	7.2	2.5	10.0	2.7
Modelling				
Background, other	4.9	1.7	6.5	1.8
Model statistical	2.4	1.2	4.3	2.0
NLO corrections	11.3	1.7	0.0	0.0
PDF, Scale and shower settings	9.0	4.3	0.6	0.3
Unfolding uncertainty	0.0	1.4	0.0	0.9
Experimental and modelling	18.0	6.5	13.3	4.5
Data statistical	13.3	5.9	26.0	10.3
Total	22.4	8.8	29.2	11.2

$p_T^Z < 20\,GeV$

Source	Impact [%] 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

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$W^{\pm}Z$ Polarisation Energy Dependency

Uncertainties

2 parameter fit

Source	Impact on f_{00} [%]	
Experimental	**$100 < p_T^Z \leq 200$ GeV**	**$p_T^Z > 200$ GeV**
Luminosity	0.1	0.1
Electron calibration	1.0	0.9
Muon calibration	0.6	0.6
Jet energy scale and resolution	3.1	4.8
E_T^{miss} scale and resolution	0.3	0.3
Flavor-tagging inefficiency	0.0	0.0
Pileup modelling	1.0	0.7
Non-prompt background estimation	3.6	0.6
Modelling		
Background, other	0.9	0.9
Model statistical	1.6	2.2
NLO QCD effects	3.7	9.1
NLO EW effects	0.9	7.5
Effect of additive vs multiplicative QCD+EW combination	0.5	1.7
Interference impact	2.4	1.4
PDF, Scales, and shower settings	4.0	4.0
Experimental and modelling	8.1	13.9
Data statistical	11.4	31.4
Total	14.0	34.4

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

ZZ Polarisation Measurement

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

ATLAS EXPERIMENT

ML Comparison

Variables

$W^{\pm}Z$ Polarisation

Variables
$\Delta Y(l_W Z)$
$p_T(WZ)$
$p_T(l_W)$
$p_T(l_{Z;1})$
$p_T(l_{Z;2})$
$\Delta\phi(l_W l_\nu)$
$\Delta\phi(l_{Z;1} l_{Z;2})$
E_T^{miss}

arXiv:2211.09435

$W^{\pm}Z$ Polarisation Kinematic

Variables
$\Delta Y(l_W Z)$
$p_T(WZ)$
$p_T(l_W)$
$p_T(l_{Z;2})$
$\cos\theta^*_{decay}(Z)$ in $W^{\pm}Z$-rest boosted in Z-rest
$\cos\theta^*_{decay}(W)$ in $W^{\pm}Z$-rest boosted in $W^{\pm}$-rest
E_T^{miss}

arXiv:2402.16365

ZZ Analysis

Variables
$\Delta\phi(l_1 l_2)$ in ZZ-rest
$\Delta\phi(l_3 l_4)$ in ZZ-rest
$\cos\theta^*(Z_1)$ in ZZ-rest
$\cos\theta^*_{decay}(Z_1)$ in ZZ-rest
$\cos\theta^*_{decay}(Z_2)$ in ZZ-rest

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