ATLAS diboson polarisation studies

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On behalf of the ATLAS Collaboration

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Motivation for polarisation measurement

Higgs mechanism

$W^{\pm}$ and Z bosons are massive

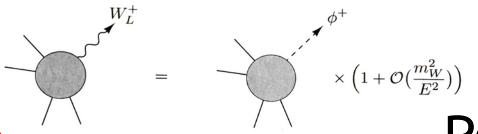
Longitudinal polarisation allowed

$V_0V_0 \rightarrow V_0V_0$ Vector Boson Scattering

New physics visible in polarisation measurement ?

Goldstone equivalence theorem

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



VBS $\mathbf{V_0V_0 \rightarrow V_0V_0}$ beyond reach for now

➔ $W^{\pm}Z$ bosons joint-polarisation state in inclusive selection as **a first step**

Polarisation as a **handle to new physics**

– Resurrection of interference term with EFT in angular variables [arXiv:1708.07823]

Recent polarised theoretical calculations

➔ Check predictions at NLO QCD or NLO QCD+EW

➔ ***e.g. WZ:*** NLO QCD in 2020 [arXiv:2010.07149], NLO QCD+EW in 2022 [arXiv:2203.01470]

Previous measurements at LEP

Only **diboson process** accessible for such measurements: **$e^+ e^- \rightarrow W^+W^-$**

Single W boson polarisation measurements:

➔ **L3** [arXiv:0301027], **OPAL** [arXiv:0312047], **DELPHI** [arXiv:0801.1235]

Joint-polarisation measurements:

➔ **L3** [arXiv:0501036]: **only correlations** between bosons polarisation (decay planes)

➔ **OPAL** [arXiv:0009021]: **almost 3σ** for f00, but **tension** with Standard Model

➔ **DELPHI** [arXiv:0908.1023]: **not sensitive** enough to f00

	Measured	Expected
$\sigma_{\mathrm{TT}}/\sigma_{\mathrm{total}}$	$0.781 \pm 0.090 \pm 0.033$	0.572 ± 0.010
$\sigma_{\mathrm{LL}}/\sigma_{\mathrm{total}}$	$0.201 \pm 0.072 \pm 0.018$	0.086 ± 0.008
$\sigma_{\mathrm{TL}}/\sigma_{\mathrm{total}}$	$0.018 \pm 0.147 \pm 0.038$	0.342 ± 0.016

OPAL results

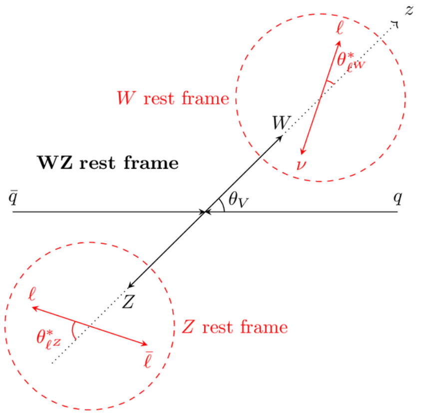
$$\bar{\rho}_{TT} = (67 \pm 8)\%,$$
$$\bar{\rho}_{LT} = (30 \pm 8)\%,$$
$$\bar{\rho}_{LL} = (3 \pm 7)\%.$$

DELPHI results

Previous measurements at LHC

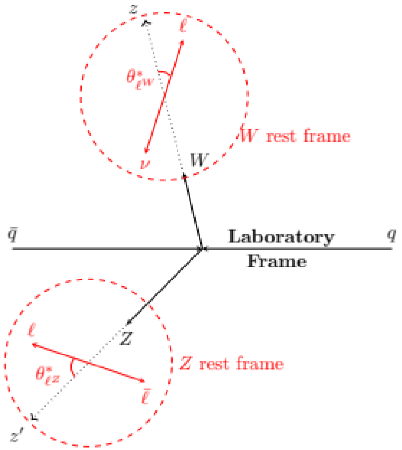
Single boson polarisation in WZ production

- **ATLAS** : in WZ rest frame, L = **36 fb^{-1}** [arXiv:1902.05759]
- **CMS** : in Laboratory frame, L = **137 fb^{-1}** [arXiv:2110.11231]



Newest measurement by ATLAS [CDS:ATLAS-CONF-2022-053]
in WZ production with full Run 2 dataset, 139 fb^{-1}

- Joint-polarisation fractions in WZ
- Single boson polarisation fractions
- Differential cross sections



First observation ever of longitudinal-longitudinal joint-polarisation state in diboson events

Challenges of this analysis

Method : Generate **polarisation templates** and extract polarisation fractions through a **template fit**

- **Polarisation definition :** Not Lorentz invariant ! Need to **define a frame**, template yields define **pseudo-cross sections**

- **Low statistics :** Expected yield for WZ leptonic signal events with full Run-2 : ~ 17 000 events
  - ➔ Around 0.2 for f_0 of W or Z : **~3500 events**
  - ➔ Around 0.2x0.2 = 0.04 for f_{00} : **~ 1000 events**

- **Discriminating variable :** should distinguish for **both bosons polarisation at once**
  - ➔ 3 x 3 =9 configurations, reduced to 4 by merging ***Left*** and ***Right*** in ***Transverse*** polarisation

- **NLO template :** many efforts to obtain **polarised** templates **at NLO, unbiased**

- **Consistency :** **Single** and **Double** boson polarisation **fits should agree**

Definition of polarisation fractions

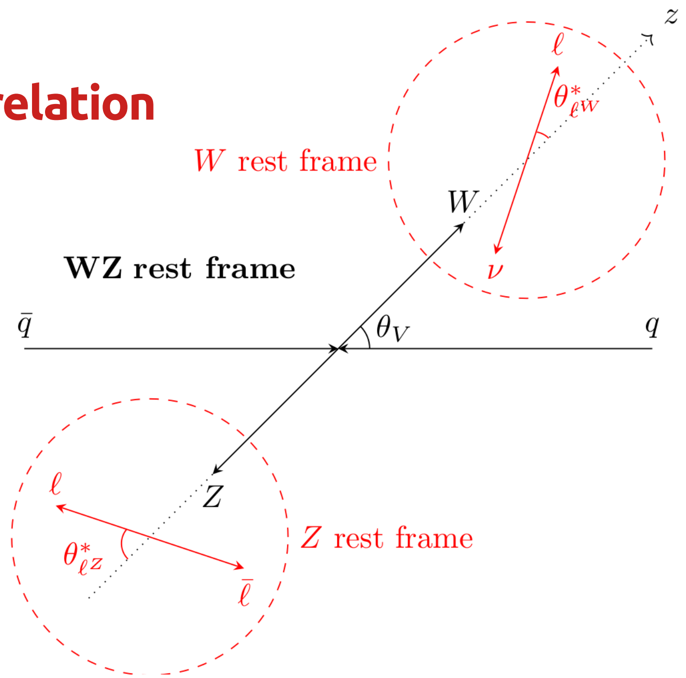
Polarisation fractions are **NOT Lorentz invariant**

➔ Need to **choose a frame**

WZ rest frame for joint-polarisation and single boson polarisation *(so-called Modified Helicity frame)*

– Allow to meaningfully **compare** both

– **Longitudinal fractions** of both bosons have **maximum decorrelation**



Defined from the joint spin density matrix:

$$\rho_{\lambda_W \lambda'_W \lambda_Z \lambda'_Z} \equiv \frac{1}{C} \times \sum_{\mu_q \mu_{\bar{q}}} F^{(\mu_q \mu_{\bar{q}})}_{\lambda_W \lambda_Z} F^{(\mu_q \mu_{\bar{q}})*}_{\lambda'_W \lambda'_Z} \qquad C = \sum_{\mu_q \mu_{\bar{q}} \lambda_W \lambda_Z} \left| F^{(\mu_q \mu_{\bar{q}})}_{\lambda_W \lambda_Z} \right|^2$$

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

WZ inclusive selection

Experimental signature : $$p\,p \rightarrow \ell\,\bar{\ell}\,\ell'\,\nu_{\ell'} + X$$

ℓ ***= electron or muon***

Variable	Total	Fiducial inclusive
Lepton $\|\eta\|$	—	< 2.5
p_T of ℓ_Z, p_T of ℓ_W [GeV]	—	> 15, > 20
m_Z range [GeV]	66 – 116	$\|m_Z - m_Z^{PDG}\| < 10$
m_T^W [GeV]	—	> 30
$\Delta R(\ell_Z^-, \ell_Z^+)$, $\Delta R(\ell_Z, \ell_W)$	—	> 0.2, > 0.3

Cross section and polarisation fractions extracted in the Fiducial phase space

Trigger	At least one of five single lepton triggers fired
Leading lepton p_T	$p_T^{lead} > 27\,\text{GeV}$
Event cleaning	Reject corrupted or incomplete events and events with non-collision background jet
Primary vertex	Hard scattering vertex with at least two tracks
ZZ veto	Strictly less than 4 baseline leptons
N leptons	Exactly 3 leptons passing the Z-lepton selection
Z leptons	2 same flavor oppositely charged leptons passing Z-lepton selection
Mass window	$\|m_{\ell\ell} - M_Z\| < 10\,\text{GeV}$
W lepton	Remaining lepton passes W-lepton selection
W transverse mass	$m_T^W > 30\,\text{GeV}$

Signal Region event selection

– **Leptons** reconstruction

➔ 3 increasingly tight selections : ***baseline***, ***Z-lepton*** and ***W-lepton***

– p_z^ν reconstruction:

➔ **New DNN-based** method

Backgrounds

Irreducible (with 3 or more leptons): **18% of selected events**

➔Estimated from **Monte Carlo generation**

- **ZZ: 7.5%** of selected events, main background *(include QCD and EW production)*
  - ➔ MC rescaled during the fit by **~1.13** using a Control Region
- **ttV: 4%** of selected events
  - ➔Total MC yield rescaled by **1.3** from Control Region estimation
- **WZ→ τ ll → lν ll: 3%** of selected events.
  - ➔Scaled with the WZ signal post-fit event yields using fixed fraction of such events from MC
- Others: **t+Z**, Triboson **VVV**, Vector Boson Scaterring WZ production **WZ EW**[6], **Migrating γ*** (from outside the total phase space $M_Z < 66$ or $M_Z > 116$)

Reducible (with at least 1 fake lepton): **5% of selected events**

- ***« Misidentified Leptons »*** background mainly from **Z+γ, t tbar, Z+jets**

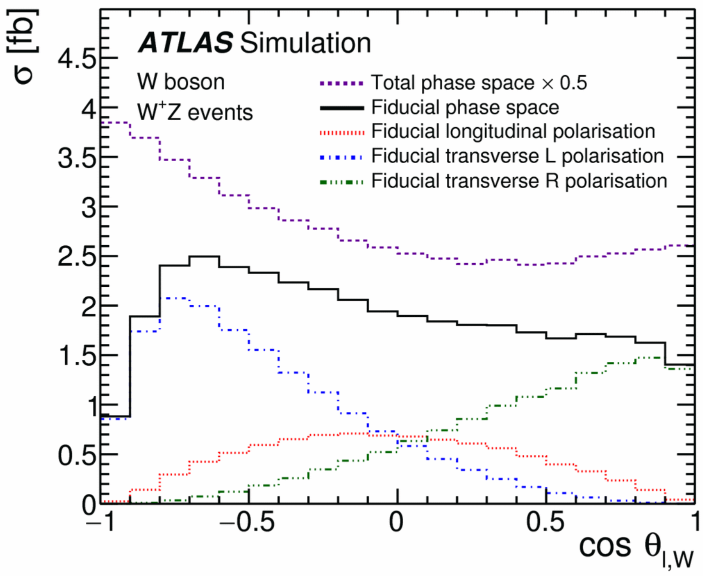
➔ Estimated by a **data driven matrix method**

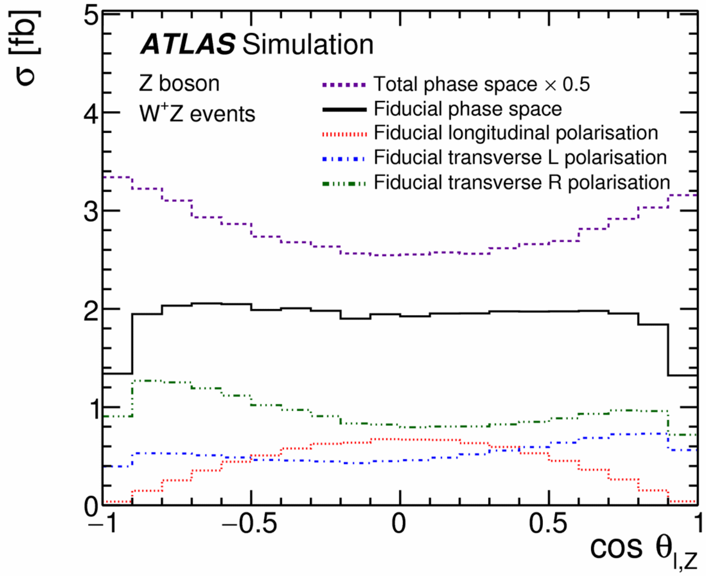
Discriminating variable for the fit

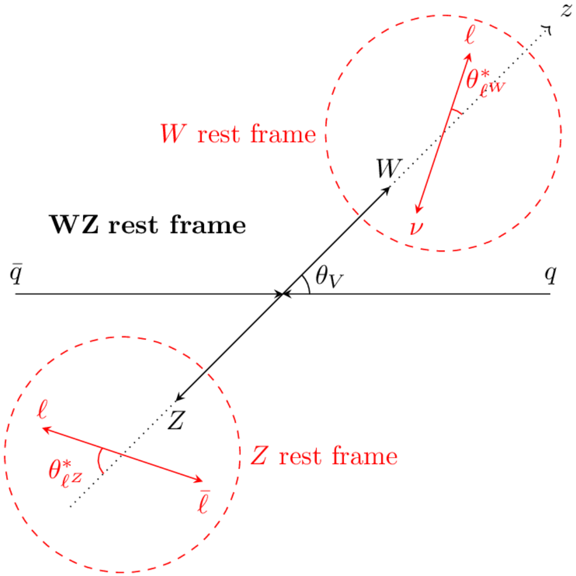
Goal: Perform a **binned maximum likelihood template fit** to extract simultaneously polarisation fractions

➔ Need for a **discriminating variable** to be fitted

Single boson polarisation fraction measurement: **$\cos\theta^*_W$** and **$\cos\theta^*_Z$**







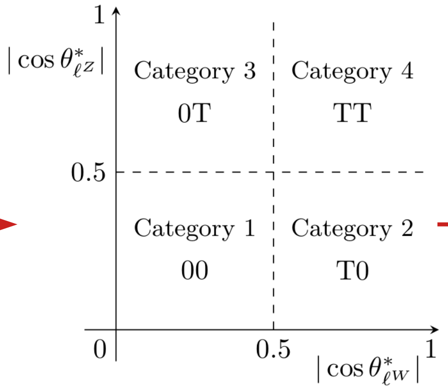
Templates from 36 fb⁻¹ measurement [arXiv:1902.05759]

Variable for the joint-polarisation

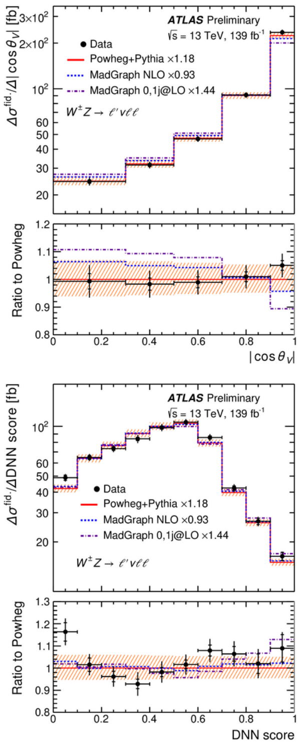
Joint-polarisation fraction measurement:

- Analytical variable **$|\cos\theta_V|$** not discriminant enough
- **Classification DNN** between all 4 joint-polarisation states: still **poorly discriminant between 0T and T0**
- Split DNN score for 00 in **4 categories** based on $\cos\theta^*$

DNN score →



→ ***4-categories DNN score***



Classification DNN input variables
(by importance)

- $|y_{l,W} - y_Z|$
- P_T^{WZ}
- $P_T^{l,W}$
- $\Delta\varphi(l^W, \nu)$
- $\Delta\varphi(l1^Z, l2^Z)$
- E_T^{miss}
- $P_T^{l2,Z}$
- $P_T^{l1,Z}$

Obtaining MC polarisation templates

Need for NLO accurate templates

Polarisation templates directly from polarised MC generation

– Madgraph at **LO + 0,1 jet** (NLO real corrections) *MG0,1jet*

– Generate templates for 00, 0T, T0 and TT joint-polarisation states
➔ No **Left** and **Right** polarisation states: **not used for single boson** polarisation

Bias study:

– Perform **detector level fit** on various **NLO inclusive pseudo-data MC** samples using **a polarisation template set**

– Compare to the **truth values** of the fractions from MC

➔ **Bias found** (10% to 50% on fraction value) using **MG0,1jet templates**

Need for NLO accurate polarisation templates

Methods for NLO accurate templates

Analytical reweighting

➔ Method used in previous single boson polarisation measurement

A new method: Multi-dimensionnal reweighting with DNN output:

➔ Possibility to reweight a distribution using a DNN output [arXiv: 1907.08209]

Reweight using theoretical predictions

– Collaboration with theorists Ansgar Denner & Giovanni Pelliccioli

➔ Used our fiducial phase space and predictions for our classification DNN

Analytical reweighting

Use the analytical expression of the **angular differential cross section** of the decay of a **Spin 1** particle (angular momentum conservation)

→ Fit of inclusive MC prediction allows to extract **polarisation fractions**

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{8}\left[f_R(1+\cos^2\theta^* + 2C_W\cos\theta^*) + f_L(1+\cos^2\theta^* - 2C_W\cos\theta^*) + 2f_0\left(1-\cos^2\theta^*\right)\right]$$

Reweight NLO inclusive sample event-by-event to obtain polarised NLO accurate samples

→ Reweight the distribution of variable $\mathbf{V_1}$: use **fractions in bins** of $\mathbf{V_1}$

→ **WARNING:** $\mathbf{V_1}$ must be **independent** of **cosθ*** (bosonic variable) such that bin cuts don't distort cosθ* distribution → **validity of the fit formula**

$$\mathbb{P}\left(V_1\left(v_1\right) \cap H = h_0\right) = \mathbb{P}\left(H = h_0 | V_1\left(v_1\right)\right)\mathbb{P}\left(V_1\left(v_1\right)\right)$$

*Distribution of **variable** $\boldsymbol{V_1}$ for a boson with **polarisation** $\boldsymbol{H=h_0}$*

***Polarisation fraction** $\boldsymbol{f_{h0}(v_1)}$ in bin around v_1 for variable V_1 = **applied weight** !*

*Distribution of **variable** $\boldsymbol{V_1}$ for an **unpolarised** boson*

Limits of analytical reweighting

Warning : a variable **V_1** needs to be in the **conditional part of the weight** to have its reweighted distribution correctly modified to correspond to a polarised sample !

$$\mathbb{P}\left(H = h | \underbrace{V_1\left(v_1\right), V_2\left(v_2\right), \ldots}_{\text{Conditional part}}\right) \equiv f_h\left(v_1, v_2, \ldots\right)$$

- If completely **independent** from the conditional part, then distribution **unmodified**
- If completely **determined** by the conditional part, the distribution is **correctly modified**

Each variable in the conditional part = **new segmentations** of the Phase space

- To **keep enough statistics** for the fits extracting fractions : choose **only one variable** V_1
  - ➔ **Here $|\cos\theta_V|$**, better variables could exist
- Polarised distribution of cosθ* **already known**
  - ➔ incorporated without any more work or additional uncertainty thanks to **Bayes formula**

$$w_{W_0^+}\left(\cos\theta^*_{\ell W}, v_1\right) = \frac{f_0(v_1)\frac{3}{4}\left(1-\cos^2\theta^*_{\ell W}\right)}{f_0(v_1)\frac{3}{4}\left(1-\cos^2\theta^*_{\ell W}\right) + f_{\mathrm{L}}(v_1)\frac{3}{8}\left(1-\cos\theta^*_{\ell W}\right)^2 + f_{\mathrm{R}}(v_1)\frac{3}{8}\left(1+\cos\theta^*_{\ell W}\right)^2}$$

Use of analytical reweighting

Compared to direct MC generation:

- Possible to have Left and Right polarisation templates
- NLO accurate, almost no bias
- Can only reweight the distribution of one discriminating variable (in addition to $\cos\theta^*_W$ and $\cos\theta^*_Z$) for lack of statistic in MC samples
- Ony reweights bosonic variables: cannot use the classification DNN

Used in single boson polarisation

➔ **cosθ*** as discriminating variables

In joint-polarisation can't be used:

➔ **Classification DNN** needed to have **sensitivity**

➔ |cosV| in 4 categories of cos* used at fiducial level for theory predictions from MC

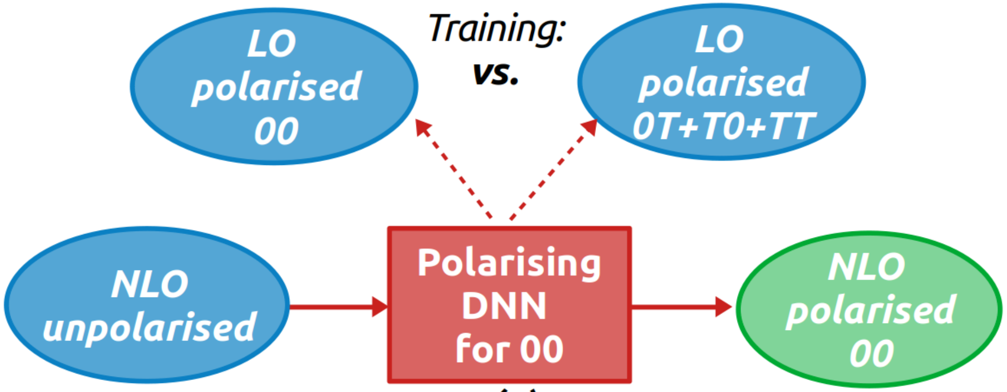
DNN reweighting

Acts as a **multi-dimensionnal reweighting** of the input MC sample

This **new method** relies on two **assumptions**:

- Possibility to **reweight with the used DNN** [arXiv: 1907.08209]
- **Factorisation** of NLO effect and polarisation effects

4 DNN **trained on polarised MG0,1jet** to discriminate one joint-polarisation states against the rest : event-by-event output used in **reweighting**



w(x)= DNN(x) / (1 – DNN(x))

$\lvert y_{\ell,W} - y_Z \rvert$
$p_T^{\ell,W}$
E_T^{miss}
$\Delta\phi(\ell^W, \ell^\nu)$
p_T^{WZ}
$p_T^{\ell 1,Z}$
$p_T^{\ell 2,Z}$
$\Delta\phi(\ell 1^Z, \ell 2^Z)$
m_{WZ}
$\cos(\theta^*_{\ell W})$
$\cos(\theta^*_{\ell^Z_{ss}})$
$\cos(\theta_V)$

Reweighting DNNs input variables

DNN reweighting assumption

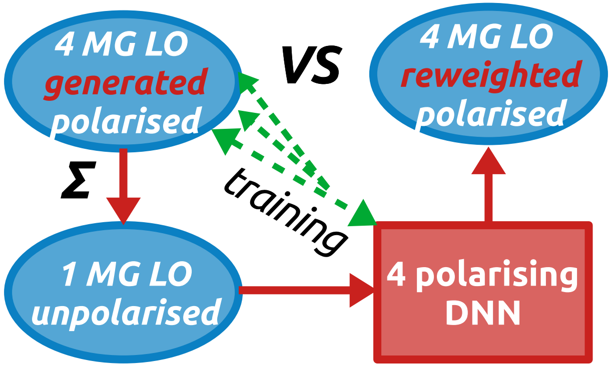
Possibility to reweight **event x** using a DNN trained to discriminate between type A *(DNN(x) = 1)* and type B *(DNN(x) = 0)*

➔ $$w(x) = \frac{\mathrm{DNN}(x)}{1 - \mathrm{DNN}(x)} \approx \frac{p_B(x)}{p_A(x)}$$: morph distribution of A in B

➔ **Two closure tests** to validate this assumption

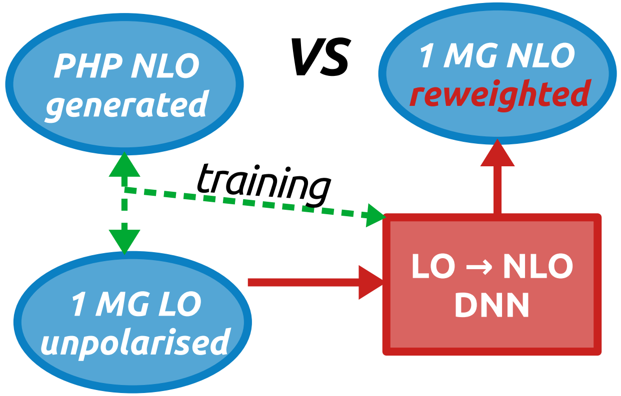
A DNN to discriminate 1 polarised MadGraph against the 3 others

➔ **Weight from unpolarised to polarised**



A DNN to discriminate between inclusive **LO** MadGraph and **NLO** Powheg+Pythia samples

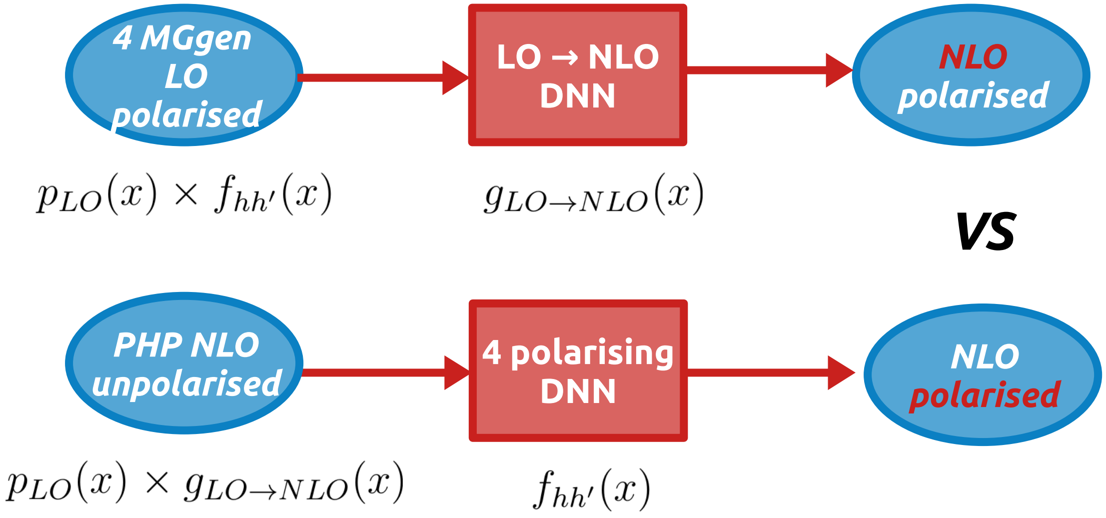
➔ Weight **from LO to NLO**



Validation of factorisation assumption

Applying polarising DNN weight to a **NLO inclusive** sample turns it in a **NLO polarised** sample if the distribution ***p(x)*** can be factorised :

$$p^{hh'}_{NLO}(x) \propto p_{LO}(x) \times f_{hh'}(x) \times g_{LO\to NLO}(x)$$



Two ways to obtain **NLO polarised** sample

– Comparison provides a test of the factorisation assumption

➔ **Test passed !**

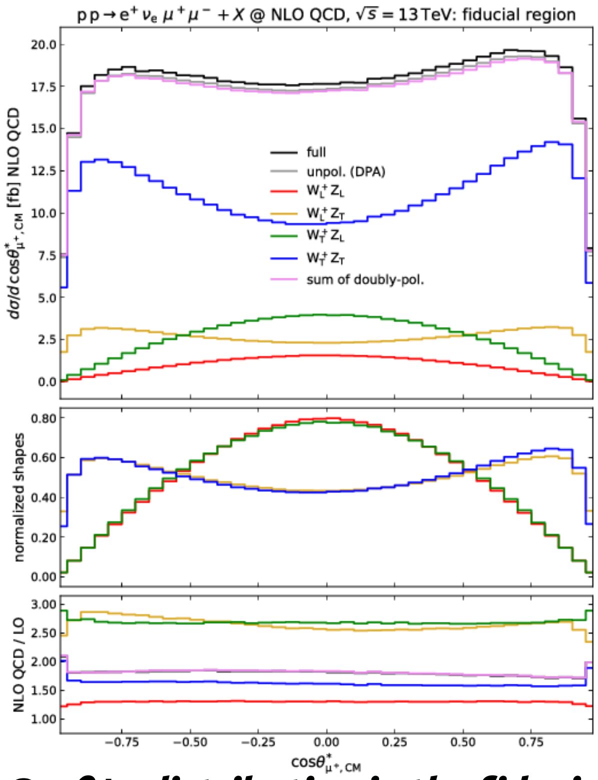
Reweighting to theory prediction

In collaboration with theorists **A. Denner, G. Pelliccioli** :
Theoretical calculations performed in the fiducial phase space [arXiv:2010.07149]

- **NLO polarised** predictions for **our classification DNN score**

➔ **Reweight** MG0,1jet polarised to NLO at parton level event-by-event with *k*-factor:

$$K_{\mathrm{MG\,p.s.}} = \frac{\mathrm{MoCaNLO}^{parton}_{\mathrm{pol.}}}{\mathrm{MadGraph}^{parton}_{ref,\mathrm{pol.}}}$$



Cosθ*$_z$ distribution in the fiducial phase space.
From [2010.07149]

Joint-polarisation measurement

Choice of NLO accurate template set

Direct polarised Monte Carlo generation:

➔ Big **bias**, from **10% to 50%** of the fraction values

Analytical reweighting:

➔ Cannot be used with the **Classification DNN**

Reweighting MG polarised predictions to theoretical predictions

– Still some **bias**, but **reduced to ~10%** of the fraction value

➔ Used as **Modelling uncertainty** for **alternative polarisation template** set choice

Multi-dimensionnal reweighting with DNN output:

– Found to be the **least biased method** of all tried (almost no bias)

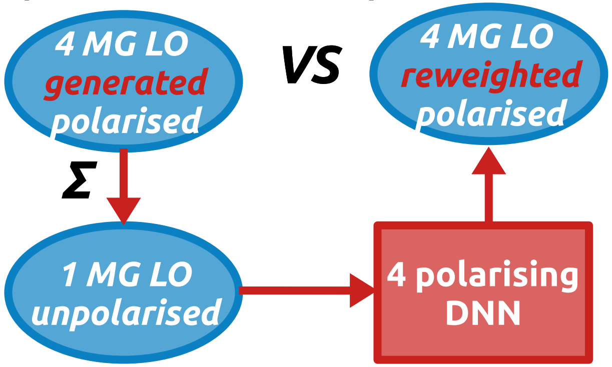
➔ **Used as baseline**

DNN reweighting uncertainty

DNN reweighting uncertainty:

– **Sum** MG0,1jet at LO polarised to obtain an **inclusive MG0,1jet** at LO sample

– Reweight it with DNN to repolarise and compare



➔ Small **non-closure** used as systematic uncertainty

Joint-polarisation Template Fit

Perform template fit on data at detector level with :

- DNN reweighted NLO accurate polarisation templates
- All backgrounds MC samples and associated systematic uncertainties
- Particle reconstruction systematic uncertainty
- Modelling uncertainties
- PDF and QCD scale (7 point variations) systematic uncertainties for polarisation templates and ZZ background

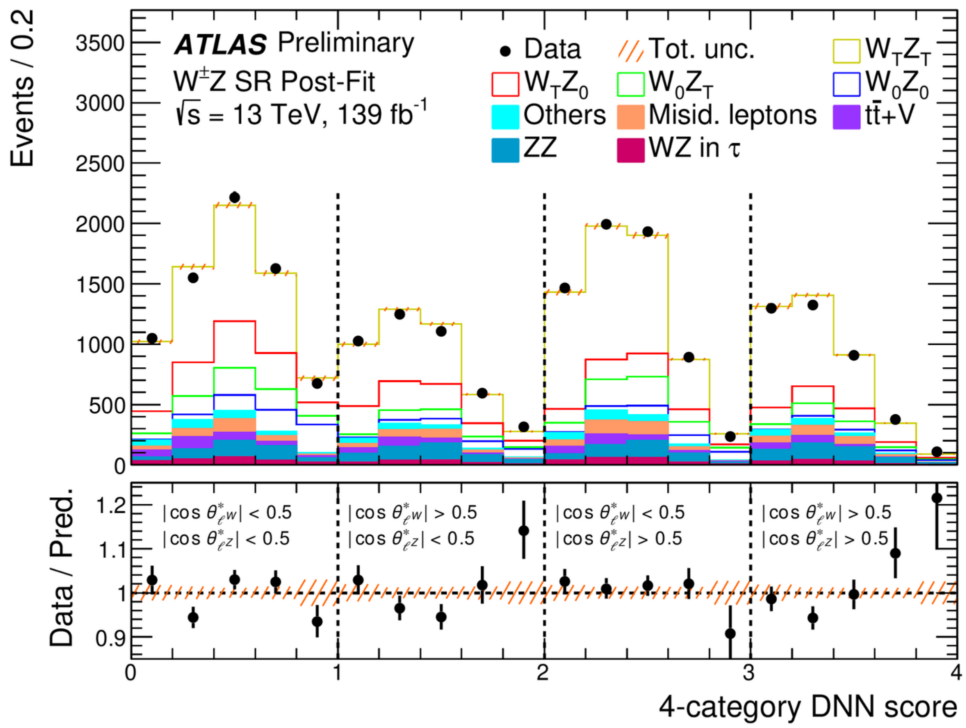
➔ ZZ Control region (reverse 4 baseline lepton veto) to constrain ZZ theory systematic uncertainties

Fit parameters of interest are $\mathbf{f_{00}}$, $\mathbf{f_{0T}}$, $\mathbf{f_{TT}}$ and $\mathbf{N_{tot}}$ the number of signal event extracted at particle level in the fiducial phase space

➔ **Decouple overall normalisation from polarisation fraction shape effects**

➔ $\mathbf{f_{T0} = 1 - f_{00} - f_{0T} - f_{TT}}$

Joint-polarisation Template Fit



	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	830 ± 120
Misid. leptons	1170 ± 230	1010 ± 220
Others	800 ± 90	790 ± 90
W_0Z_0	920 ± 40	1190 ± 160
W_0Z_T	2670 ± 50	1900 ± 500
W_TZ_0	2670 ± 60	3100 ± 400
W_TZ_T	10200 ± 230	10900 ± 600
Total MC	21400 ± 600	21950 ± 170
Data	—	21936

	ZZ Control Region Pre-fit	ZZ Control Region Post-fit
WZ	35.6 ± 1.9	35.9 ± 1.9
ZZ	2030 ± 150	2290 ± 50
$t\bar{t}+V$	153 ± 23	144 ± 22
Misid. leptons	8.5 ± 3.4	8.7 ± 3.4
Others	38 ± 8	39 ± 8
Total MC	2260 ± 160	2510 ± 50
Data	—	2554

➔ **Correct agreement** of the fitted templates with data

➔ ZZ CR **rescales** and **constrain** uncertainty on ZZ background

Joint-polarisation fractions

Theory predictions

	Data	POWHEG+PYTHIA	NLO QCD Denner&Pellicciolі [arXiv:2010.07149]
	$W^{\pm}Z$		
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
$f_{\mathrm{T}0}$	0.153 ± 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

All joint-polarisation states observed

- Significance on f_{00} at **7.1σ**
- Significance on f_{TT} and f_{T0} **>5σ**

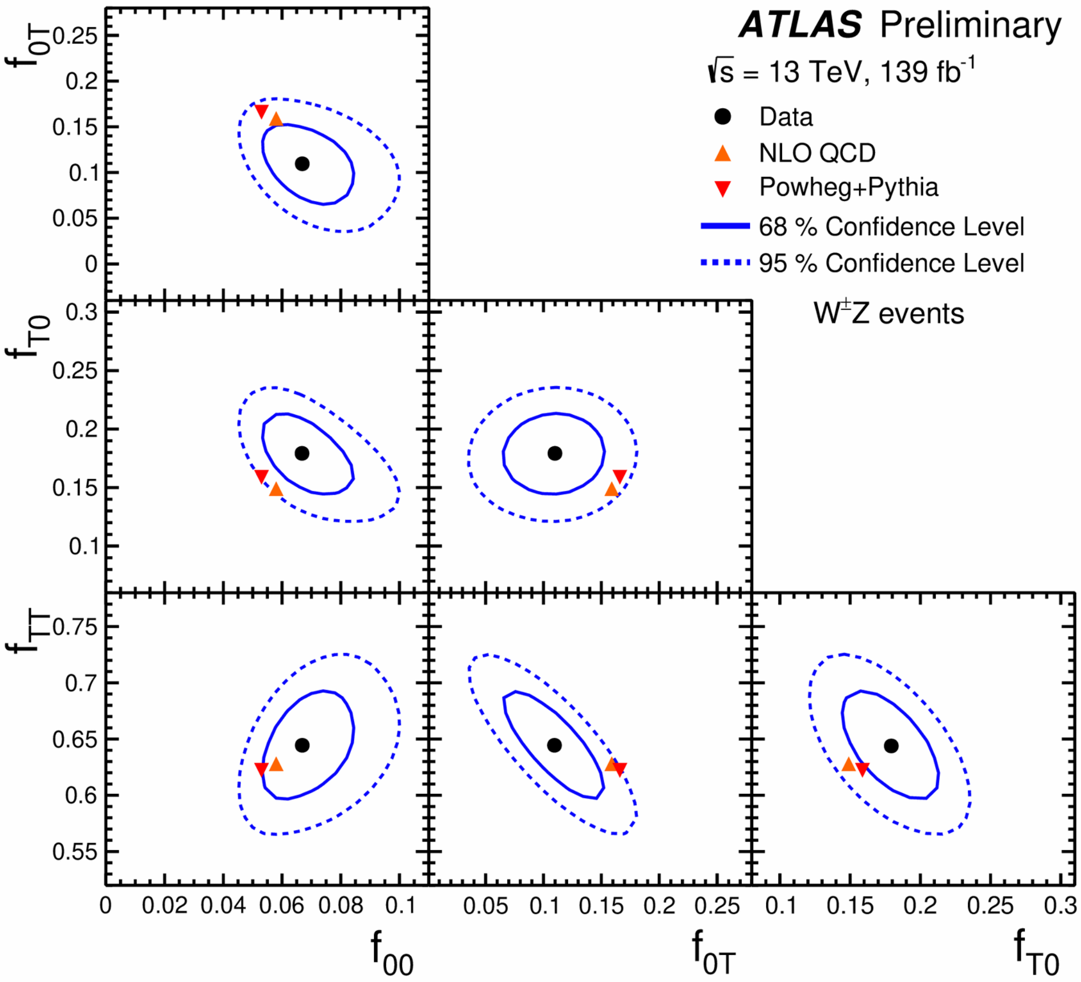
Measurement performed as well separating by the W charge

- Significance on f_{00} at **6.9σ in W+Z**
- Significance on f_{00} at **4.1σ in W-Z**

No major difference visible in the charge break down

(baring 1σ difference in fT0/f0T)

Joint-polarisation CL regions



Strong correlations between simultaneously extracted fractions

- ➔ Confidence Level regions represented for fractions 2 by 2
- ➔ **No tension** with theory: better than **2σ** agreement

Test of independence of fractions of W and Z by reparametrising :

$$f_{0\mathrm{T}} = f_0^W - f_{00},$$
$$f_{\mathrm{T}0} = f_0^Z - f_{00},$$
$$f_{\mathrm{TT}} = 1 + f_{00} - f_0^W - f_0^Z$$

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

➔ $\mathbf{R_c = 1.54 \pm 0.35}$ (if independent, R_c=1)

Uncertainty breakdown

	f_{00}	$f_{0\mathrm{T}}$	$f_{\mathrm{T}0}$	f_{TT}
e energy scale and id. efficiency	0.00019	0.0009	0.0012	0.0020
μ energy scale and id. efficiency	0.0004	0.0004	0.0004	0.0008
$E_{\mathrm{T}}^{\mathrm{miss}}$ and jets	0.0017	0.0021	0.0020	0.0023
Pile-up	0.00031	0.00026	0.0007	0.0010
Misidentified lepton background	0.0012	0.0026	0.0013	0.0016
ZZ background	0.0004	0.00027	0.0005	0.0004
Other backgrounds	0.0016	0.0026	0.0021	0.0025
Parton Distribution Function	0.00017	0.0029	0.00014	0.0028
QCD scale	0.00010	0.014	0.0014	0.012
Modelling	0.005	0.007	0.005	0.008
Total systematic uncertainty	0.005	0.017	0.006	0.016
Luminosity	0.00015	0.00026	0.0004	0.00004
Statistical uncertainty	0.007	0.016	0.019	0.019
Total	0.010	0.029	0.023	0.032

NLO QCD modelling

Background estimation

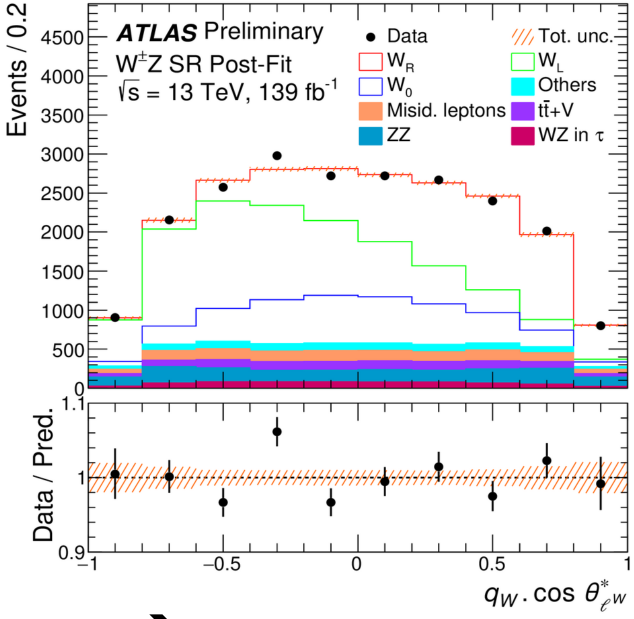
Statistical uncertainties at the same level as systematic uncertainties

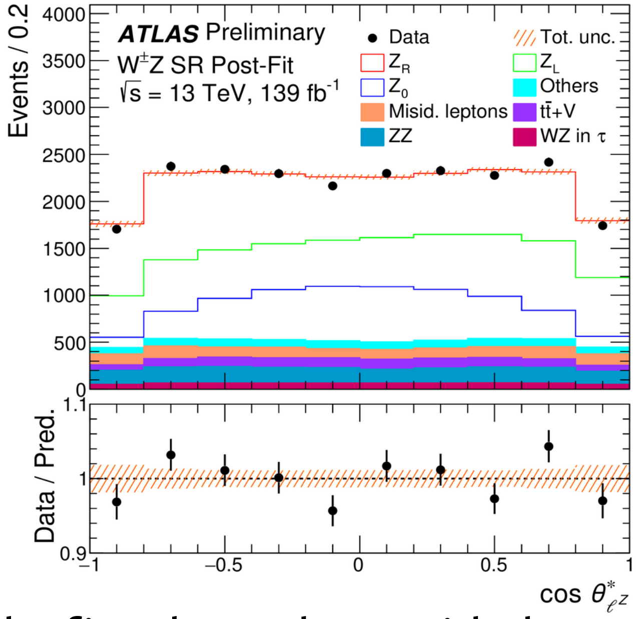
Single boson polarisation measurement

Single boson template fit

Template fit on data at detector level as for joint-polarisation

- Discriminating variables **$\cos\theta^*_W$** and **$\cos\theta^*_Z$**, polarisation templates from **analytical reweighting**
- **Modelling uncertainties**
  - Alternative Monte Carlo Sherpa
  - Reweighting uncertainty (similar to joint-polarisation DNN reweighting uncertainty)





➔**Correct agreement** of the fitted templates with data

Single boson polarisation fractions

	f_0		Denner&Pellicciolli [arXiv:2010.07149]	$f_L - f_R$	
	Data	POWHEG+PYTHIA	NLO QCD	Data	POWHEG+PYTHIA
W in W^+Z	0.23 ± 0.05	0.2044 ± 0.0024	0.211 ± 0.002	0.071 ± 0.023	0.0990 ± 0.0015
W in W^-Z	0.19 ± 0.05	0.217 ± 0.004	0.225 ± 0.001	0.026 ± 0.027	-0.0491 ± 0.0020
W in $W^{\pm}Z$	0.22 ± 0.04	0.2094 ± 0.0016	0.217 ± 0.001	0.059 ± 0.016	0.0390 ± 0.0011
Z in W^+Z	0.223 ± 0.025	0.1971 ± 0.0019	0.206 ± 0.002	-0.20 ± 0.10	-0.217 ± 0.006
Z in W^-Z	0.240 ± 0.029	0.2065 ± 0.0023	0.211 ± 0.001	0.10 ± 0.13	0.092 ± 0.007
Z in $W^{\pm}Z$	0.231 ± 0.019	0.2009 ± 0.0014	0.208 ± 0.001	-0.10 ± 0.08	-0.092 ± 0.005

f_0 and f_L-f_R measured for W and Z boson

– **f_0** mesured with **5σ** significance even in charge break-down

–**No tension** with theory

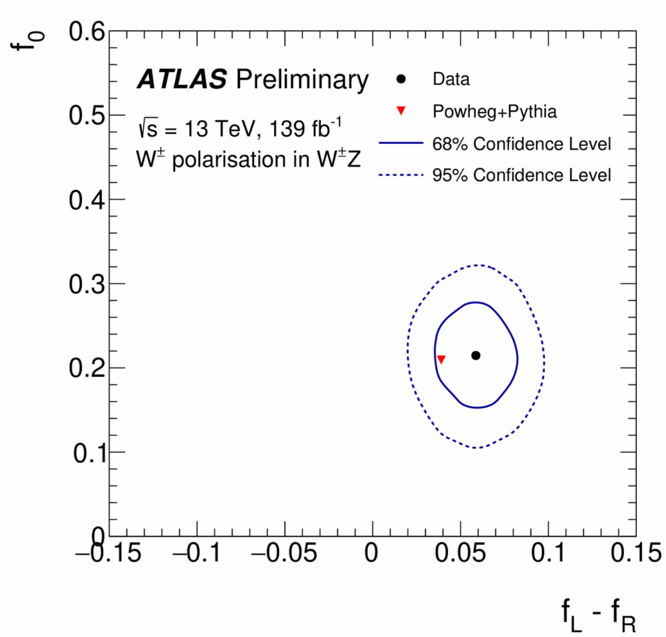
➔ Small tension for f_L-f_R in W-Z at **2.8σ**

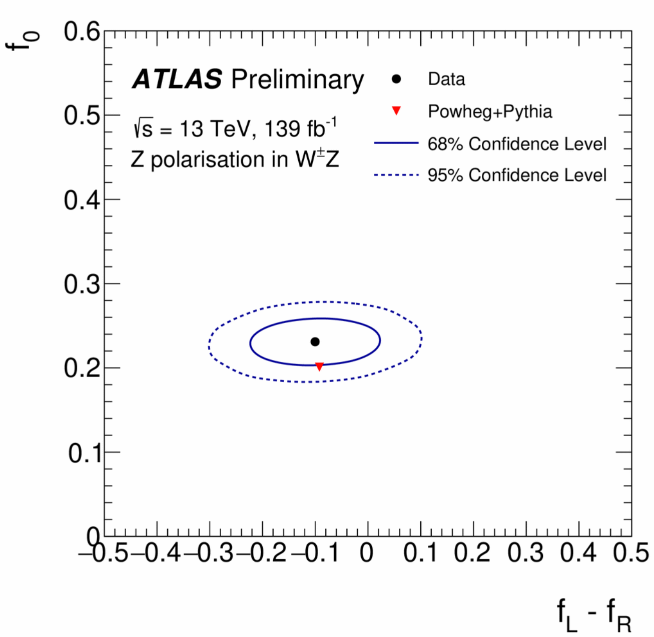
The **charge of the W** impacts **significantly f_L-f_R**, less so for f_0

➔ Less than **1σ** difference for **f_0**

➔ More than **2σ** difference for **f_L-f_R**

Single boson polarisation CL region





Consistency check:

– $\mathbf{f_0^W}$ and $\mathbf{f_0^Z}$ measured using reparametrisation in joint-polarisation fit

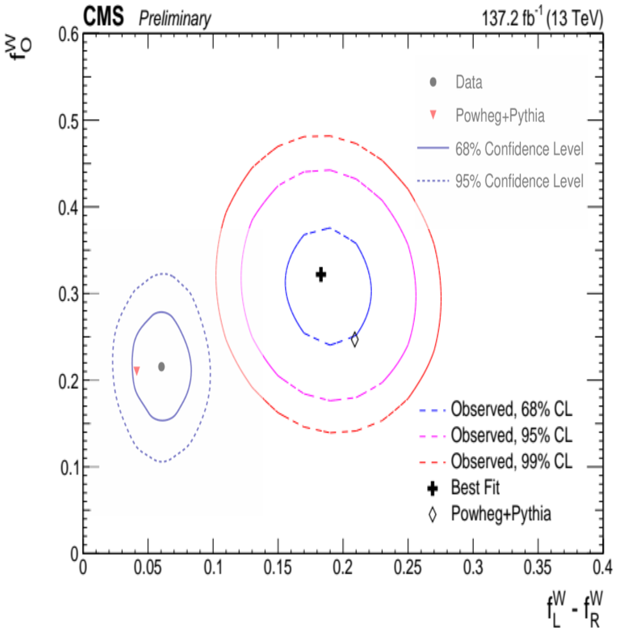
➔ Agreement within **1σ** with the **single boson polarisation fit**

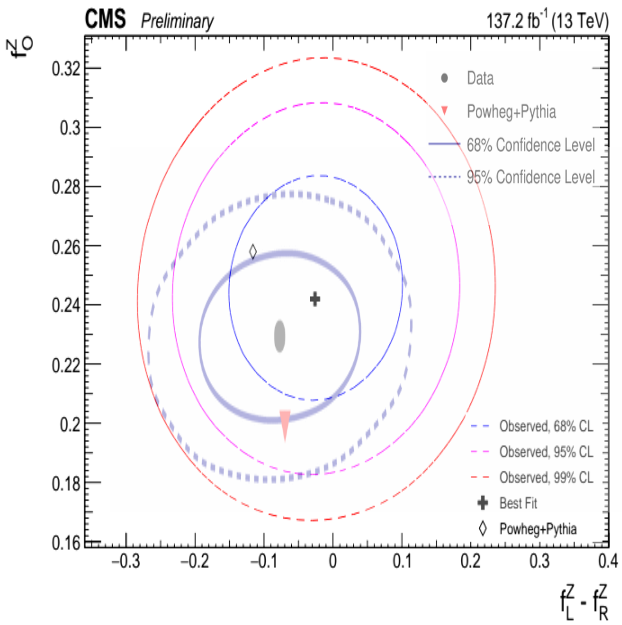
$$f_{0\mathrm{T}} = f_0^W - f_{00},$$
$$f_{\mathrm{T}0} = f_0^Z - f_{00},$$
$$f_{\mathrm{TT}} = 1 + f_{00} - f_0^W - f_0^Z$$

CMS results

CMS published results on **full Run 2 data** for **single boson polarisation fractions**

- Not the same frame: **central values not comparable**
- Uncertainties somewhat smaller for W fractions in ATLAS, similar sensitivity for Z fractions
- Again, **no tension with theory**





CMS results for W (left) and Z (right)
Previously presented CL regions in transparency

Uncertainty Breakdown

	$W^{\pm}$ in $W^{\pm}Z$ f_0	$W^{\pm}$ in $W^{\pm}Z$ $f_L - f_R$	Z in $W^{\pm}Z$ f_0	Z in $W^{\pm}Z$ $f_L - f_R$
e energy scale and id. efficiency	0.0029	0.00030	0.0027	0.0005
μ energy scale and id. efficiency	0.004	0.0018	0.0015	0.0007
$E_{\mathrm{T}}^{\mathrm{miss}}$ and jets	0.004	0.0011	0.0006	0.0027
Pile-up	0.0029	0.0015	0.0024	0.0029
Misidentified lepton background	0.007	0.00033	0.0033	0.0013
ZZ background	0.0010	0.00028	0.0012	0.0025
Other backgrounds	0.0018	0.0005	0.0014	0.0011
Parton Distribution Function	0.0011	0.0011	0.00010	0.0005
QCD scale	0.012	0.0025	0.0004	0.005
Modelling	0.025	0.0012	0.004	0.018
Total systematic uncertainty	0.030	0.004	0.007	0.019
Luminosity	0.0018	0.00004	0.00007	0.00018
Statistic uncertainty	0.028	0.015	0.018	0.08
Total	0.04	0.016	0.019	0.08

f_0^W systematic at the same level as **statistical**

Others statistically dominated:

- ➔ f_L-f_R very small, hard to extract
- ➔ Better controlled systematics for Z boson (no neutrino)

Conservative modelling uncertainty as **main** uncertainty

Unfolding of polarisation sensitive variable

Unfolded distributions

Cross section of inclusive WZ production in the fiducial phase space with leptonic decay :

➔ Obtained from $\mathbf{N_{tot}}$ parameter of the fit, at the **Born level**

$$\sigma^{\text{fid.}}_{W^\pm Z \to \ell' \nu \ell \ell} = 64.6 \pm 2.1 \text{ fb}$$

VS **NNLO QCD SM prediction** $= 64.0^{+1.5}_{-1.3}$ fb

With MATRIX [arXiv:1703.09065]

➔ **Perfect agreement, similar precision**

Iterative bayesian unfolding of **polarisation sensitive variables:**

➔ $\cos\theta^*_W$, $\cos\theta^*_Z$, $|\cos\theta_V|$

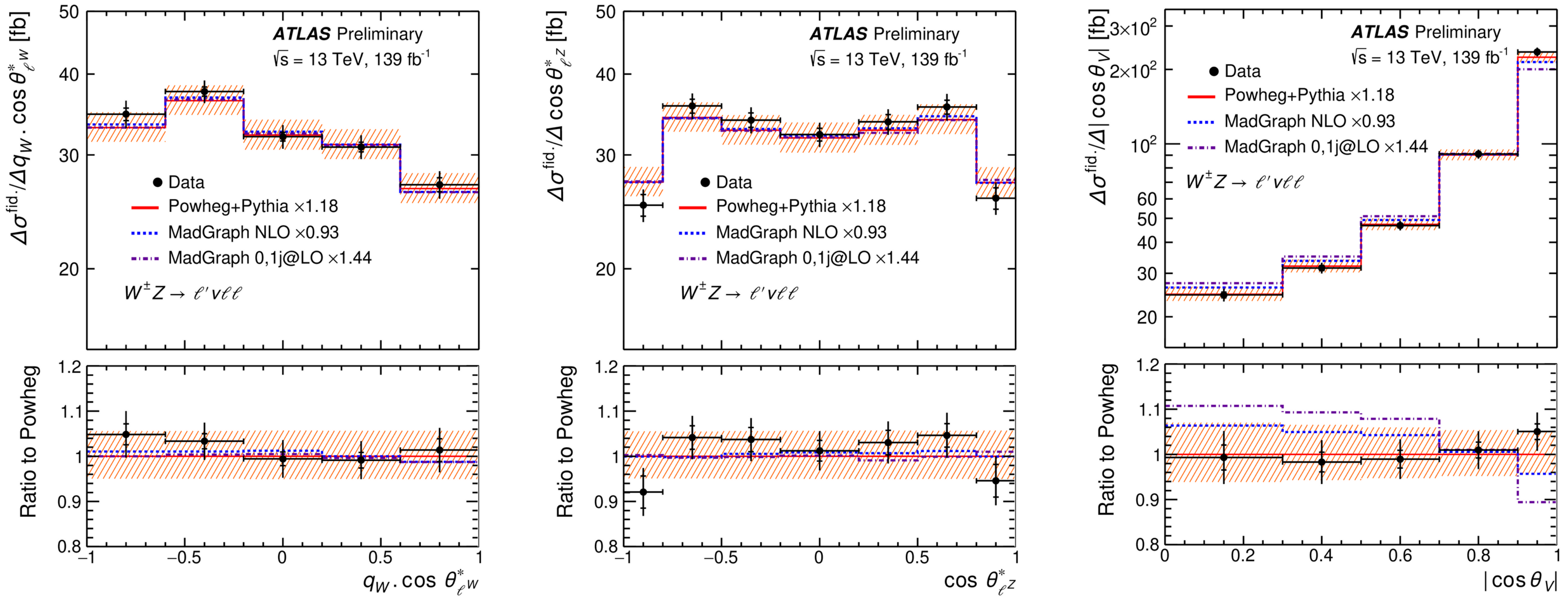
Compared to Born level **predictions** from

– **NLO inclusive MC** sample: Powheg+Pythia and MadGraph5_aMC@NLO+Pythia

– **Sum of LO polarised MC** MG0,1jet samples

➔ All **rescaled to integral NNLO QCD** cross section prediction

Unfolded distributions



– **Good agreement** of data with NLO MC

– MG0,1jet at **LO** fails with |cosV| because it has strong **NLO** dependence (Denner&Pellicciolі theoretical calculations)

Unfolding the DNN

Classification DNN **to be made public**

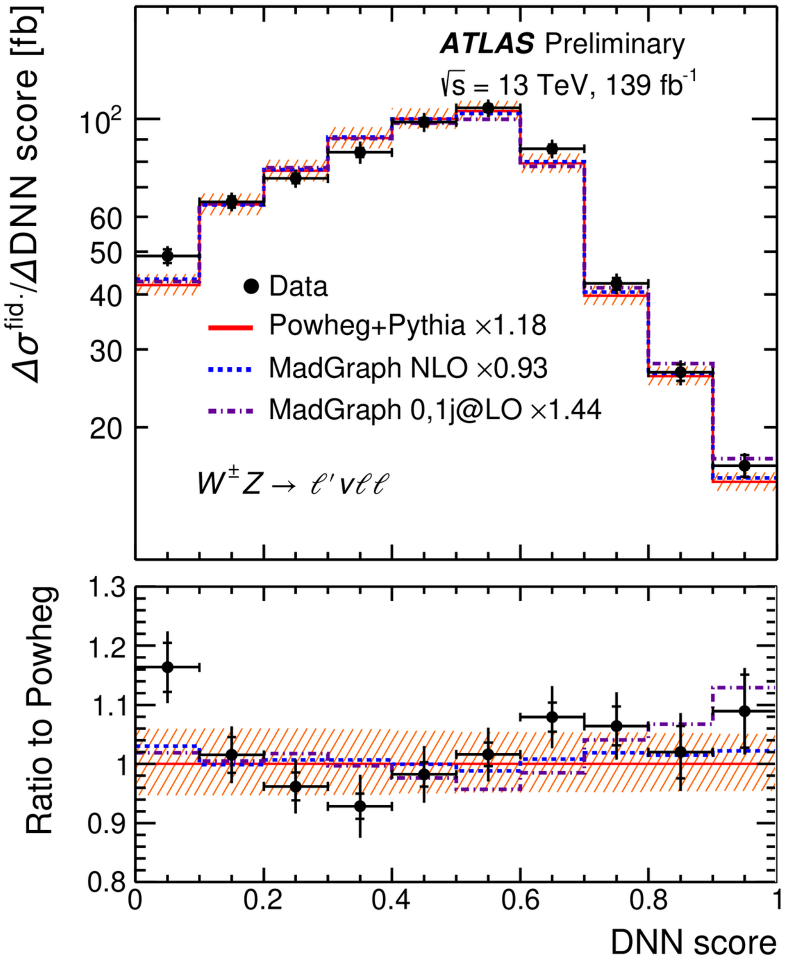
–**Classification DNN** trained at detector level on Madgraph polarised samples

– Uses **low level variables, not p_z^{ν} related**, to be independent from the method chosen for its reconstruction

➔ Used by theorist Denner&Pellicciolі to **compute particle level predictions**

Unfolded differential cross section

➔ Particle level DNN score feeds the same DNN with particle level variables



CONCLUSION

Pioneering methods have been developped

- **Classification DNN** used by **theorist for calculation** and **unfolded**
- **DNN reweighting method** found very promising

➔ Could be used in other diboson studies

Allowing this measurement:

- **First observation** ever of **all four joint-polarisation states** in diboson events
- **Evidence** for **correlation** between the two bosons polarisations
- **Improvement** on the **single boson polarisation fractions** measurement
- **Unfolded distributions** for **polarisation sensitive variables**

PROSPECTS

Apply these methods to **other diboson processes**

➔ ZZ, same sign WW

Perform the same measurement in **more restrictive phase spaces, with high p_T^Z**

– 00 enhanced phase space + Radiation Zero Amplitude effect

– Enhanced sensibility to dimension 6 EFT operators

Ultimately: Longitudinal-Longitudinal **Vector Boson Scattering** observation