



Polarisation measurements in WZ production

Luka SELEM

LHC EW WG
General Meeting

16/11/2022

Why study polarisation ?

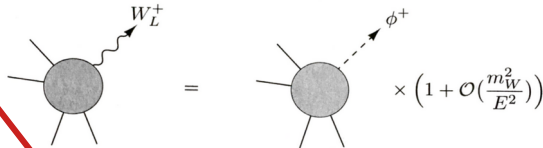
Higgs mechanism

W^\pm and Z bosons are massive

Longitudinal polarisation allowed

Goldstone equivalence theorem

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



**$V_0 V_0 \rightarrow V_0 V_0$
Vector Boson Scattering**

New physics visible in polarisation measurement?

VBS $V_0 V_0 \rightarrow V_0 V_0$ 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](https://arxiv.org/abs/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](https://arxiv.org/abs/2010.07149)], NLO QCD+EW in March 2022 [arXiv:[2203.01470](https://arxiv.org/abs/2203.01470)]

Status of polarisation in diboson systems

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)

→ DELPHI [arXiv:0908.1023]: **not sensitive** enough to f_{00}

→ OPAL [arXiv:0009021]: **almost 3σ** for f_{00} , but **tension** with Standard Model

$$\bar{\rho}_{TT} = (67 \pm 8)\%,$$

$$\bar{\rho}_{LT} = (30 \pm 8)\%,$$

$$\bar{\rho}_{LL} = (3 \pm 7)\%.$$

DELPHI results

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

OPAL results

Measurements at LHC

Diboson process chosen: $p p \rightarrow W^\pm Z$

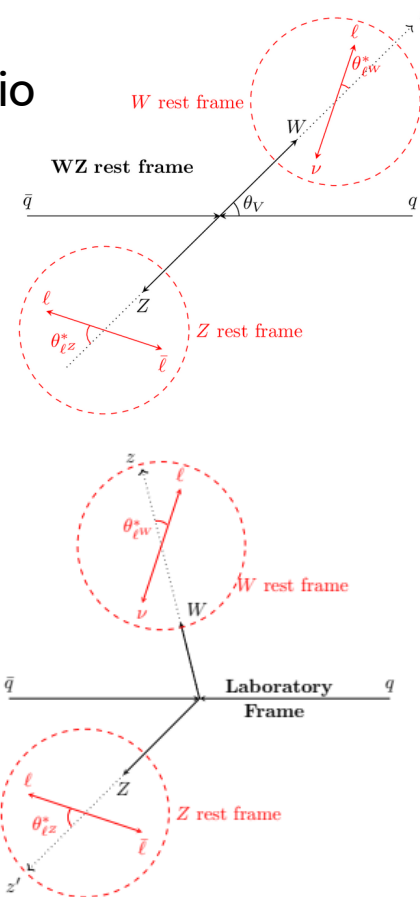
→ Best compromise between cross section and signal to background ratio

Single boson polarisation in WZ production

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

Recent ATLAS polarisation measurement :

- **Joint-polarisation** fractions in WZ
- Improvement on single boson polarisation fractions, $L = 139 \text{ fb}^{-1}$
- **First observation ever of longitudinal-longitudinal joint-polarisation state in diboson events**

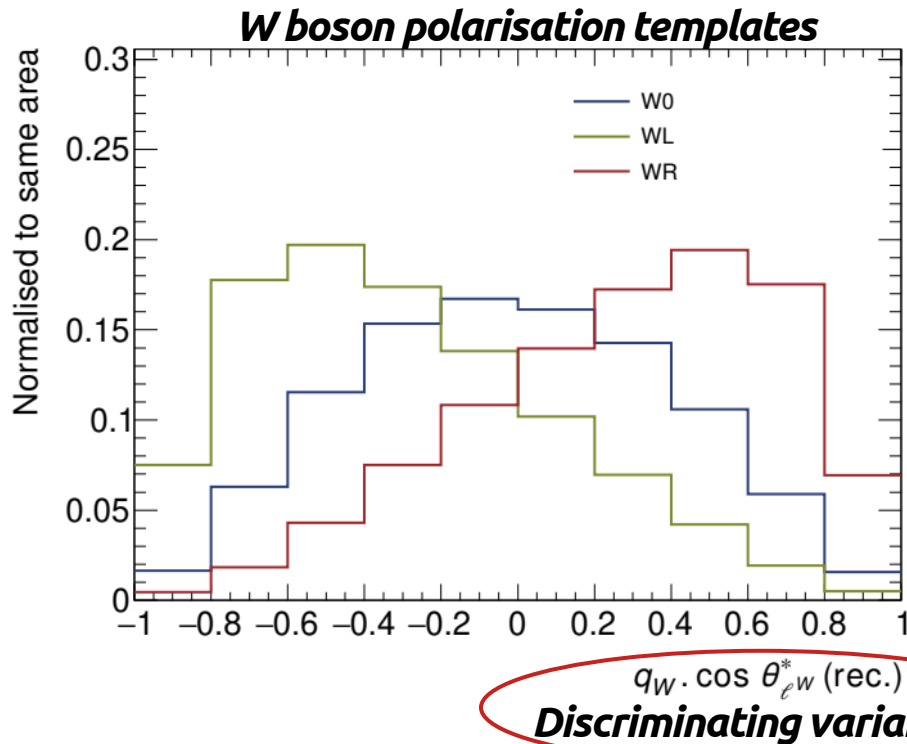


Single-boson polarisation measurement

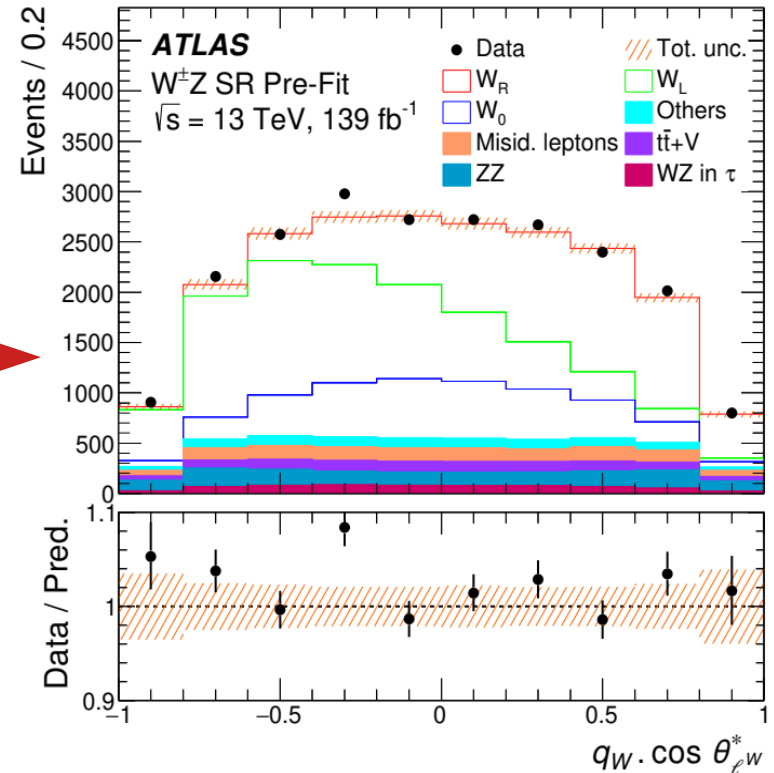
How to measure polarisation

Method: Here for single boson polarisation measurement

- Generate **polarisation templates** of a **discriminating variable**
- Extract polarisation fractions through a **template fit**



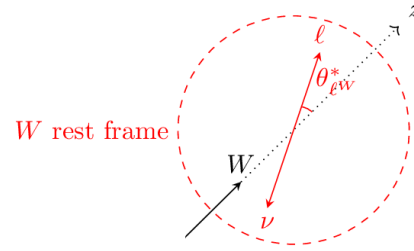
**Stacking
templates**



Polarisation templates

Discriminating variable

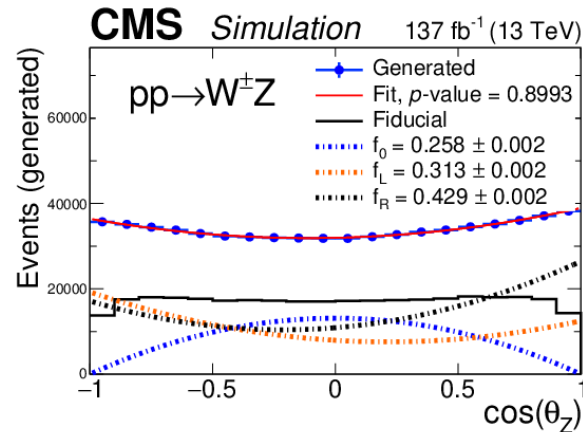
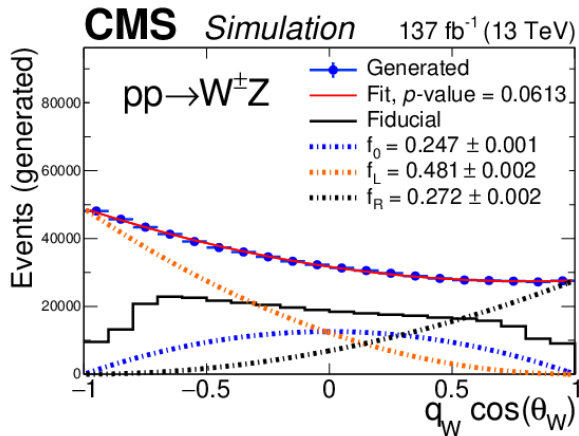
- W boson polarisation : $q_W \times \cos\theta_{\ell W}^*$
- Z boson polarisation : $\cos\theta^*_Z$



Detector-level templates

→ Analytical reweighting

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



$$w_{W_0^+}(\cos\theta_{\ell W}^*, v_1) = \frac{f_0(v_1) \frac{3}{4} (1 - \cos^2\theta_{\ell W}^*)}{f_0(v_1) \frac{3}{4} (1 - \cos^2\theta_{\ell W}^*) + f_L(v_1) \frac{3}{8} (1 - \cos\theta_{\ell W}^*)^2 + f_R(v_1) \frac{3}{8} (1 + \cos\theta_{\ell W}^*)^2}$$

ATLAS and CMS differences

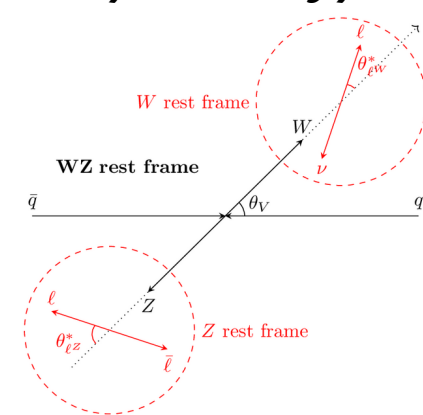
	<i>ATLAS</i>	<i>CMS</i>
Total p.s. (MC generation)	$66 < M_Z < 116$ [GeV]	$60 < M_Z < 120$ [GeV]
Measurement frame	Modified Helicity	Helicity
p_z^ν reconstruction	DNN-based	Analytical ($P_W^2 = M_W^2$)
Event yield	21936	10729
WZ signal/Backgrounds	≈ 4	≈ 5
Measured value p.s.	Fiducial	Total

ATLAS fiducial phase space

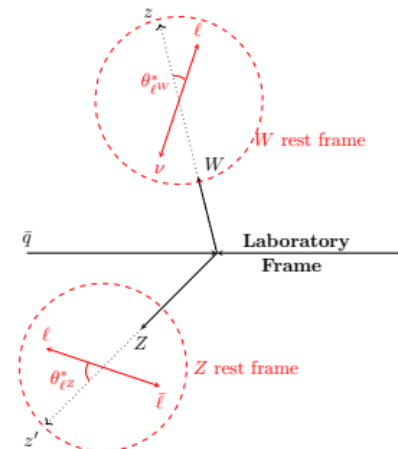
Variable	Fiducial inclusive
Lepton $ \eta $	< 2.5
p_T of ℓ_Z , p_T of ℓ_W [GeV]	$> 15, > 20$
m_Z range [GeV]	$ m_Z - m_Z^{\text{PDG}} < 10$
m_T^W [GeV]	> 30
$\Delta R(\ell_Z^-, \ell_Z^+)$, $\Delta R(\ell_Z, \ell_W)$	$> 0.2, > 0.3$

Different event selection

Modified Helicity frame



Helicity frame



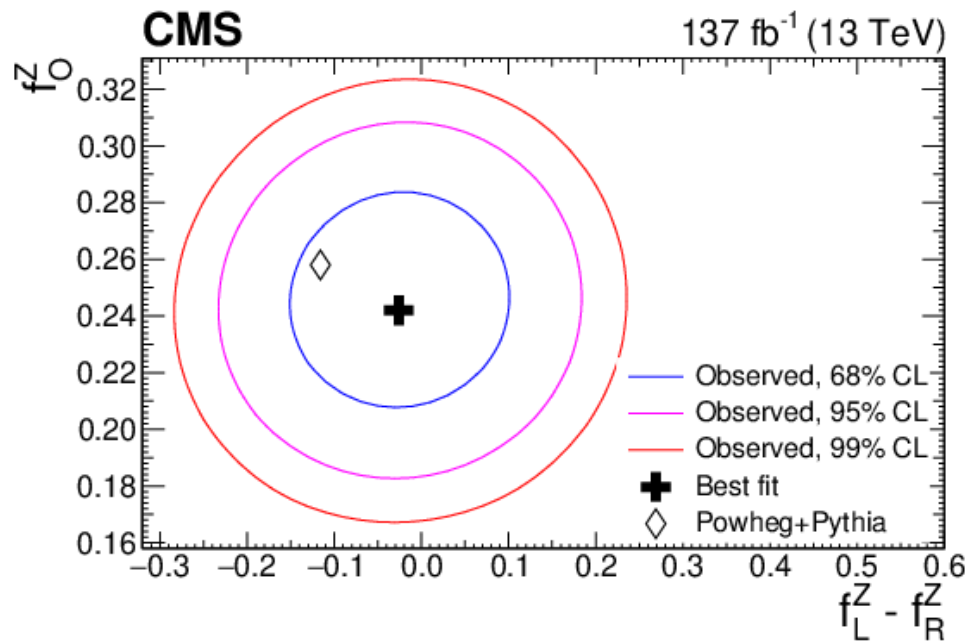
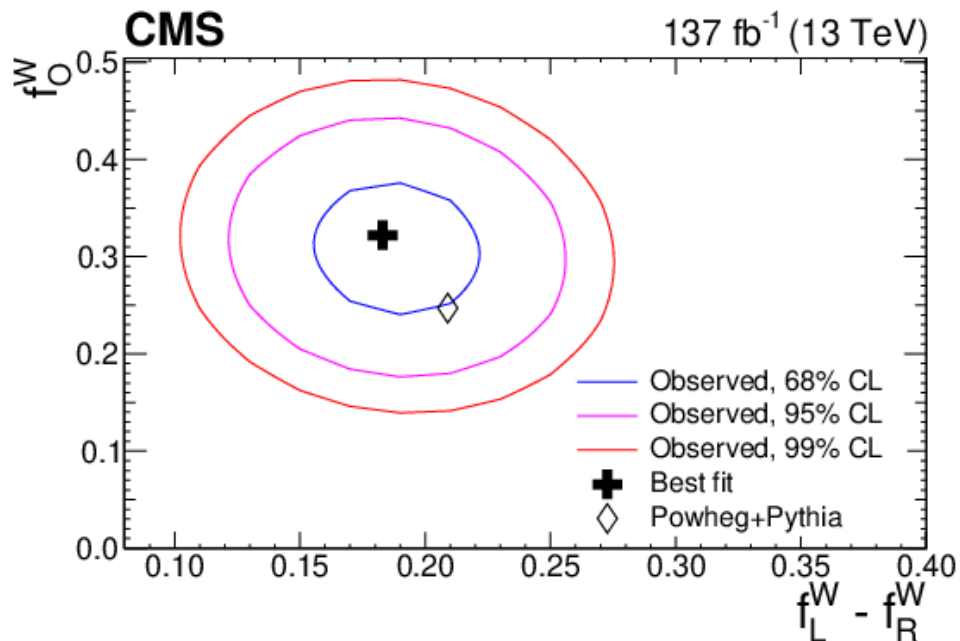
CMS results

Measurement in the **Helicity frame**:

→ Central values not comparable to ATLAS

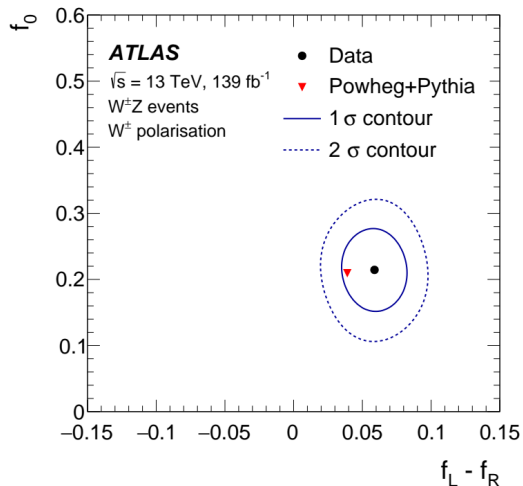
→ f_0^W and f_0^Z measured in $W\pm Z$ events and with charge separation (W+Z events, W-Z events)

Similar precision to ATLAS, **no tension with theory**

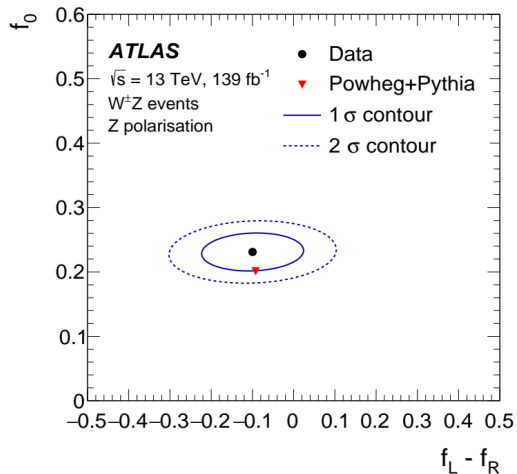


ATLAS results

W boson

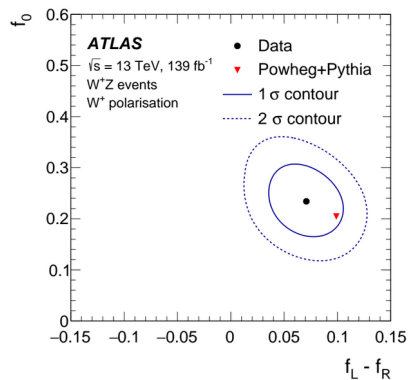


Z boson

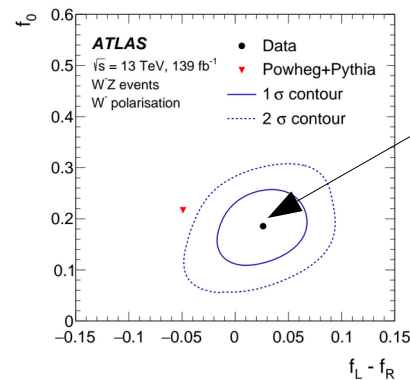


W charge break-down :

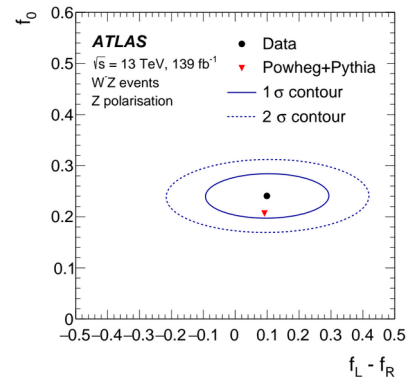
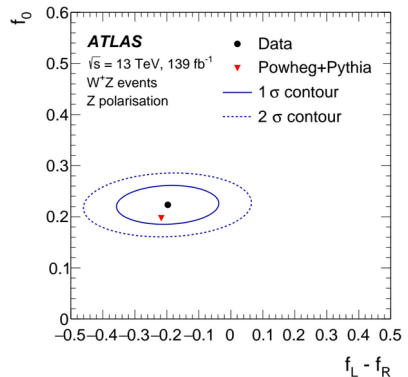
W⁺Z events



W⁻Z events



Tension at 2.3 σ



No significant tension with theory
 f_0 measured with 5 sigma in charge break-down

Joint-polarisation measurement in ATLAS

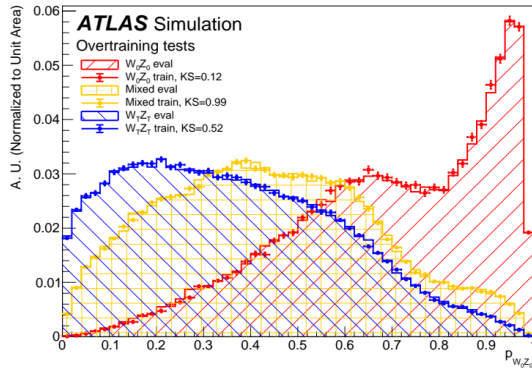
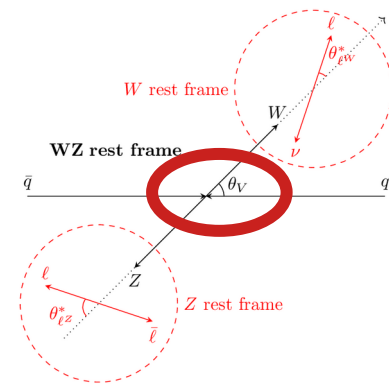
Challenges of this analysis

- **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 $0.2 \times 0.2 = 0.04$ for f_{00} : ~ **1000 events**
- **Discriminating variable** : should distinguish for **both bosons polarisation at once**
 - $3 \times 3 = 9$ configurations, reduced to 4 by merging **Left** and **Right** in **Transverse** polarisation
- **NLO template** : many efforts to obtain **polarised** templates **at highest possible QCD order**
 - **Unbiased measurement**

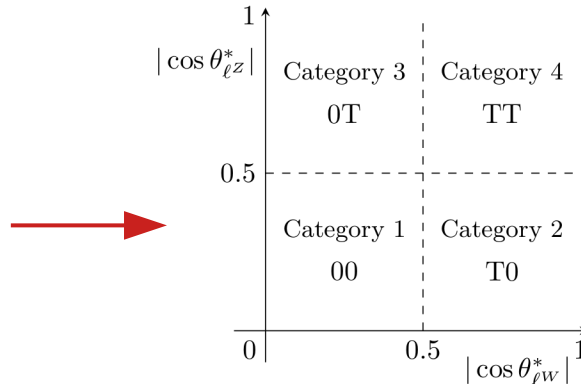
Variable for the joint-polarisation

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)**

$$|y_{lW} - y_{lZ}|$$

$$P_T^{WZ}$$

$$P_T^{lW}$$

$$\Delta\phi(l^W, \nu)$$

$$\Delta\phi(l_1^Z, l_2^Z)$$

$$E_T^{\text{miss}}$$

$$P_T^{l_2Z}$$

$$P_T^{l_1Z}$$

NLO accurate polarisation templates

Direct polarised generation with Madgraph 2.7.3

→ only **LO Matrix element** + real corrections (0,1 jets)

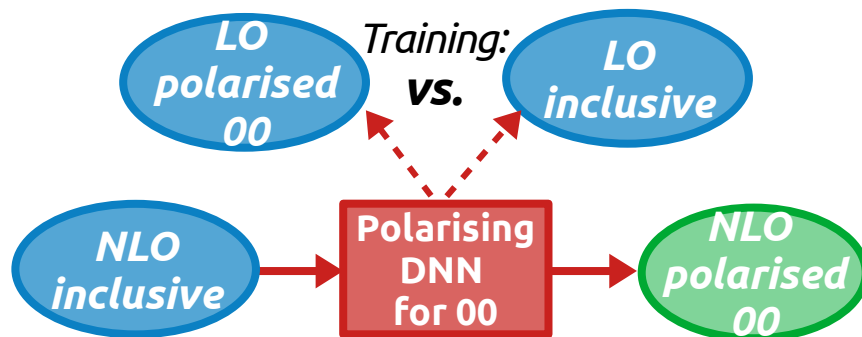
Reweighting to a calculation at NLO QCD

[Collaboration with theorists A. Denner & G. Pelliccioli arXiv:[2010.07149](https://arxiv.org/abs/2010.07149)]

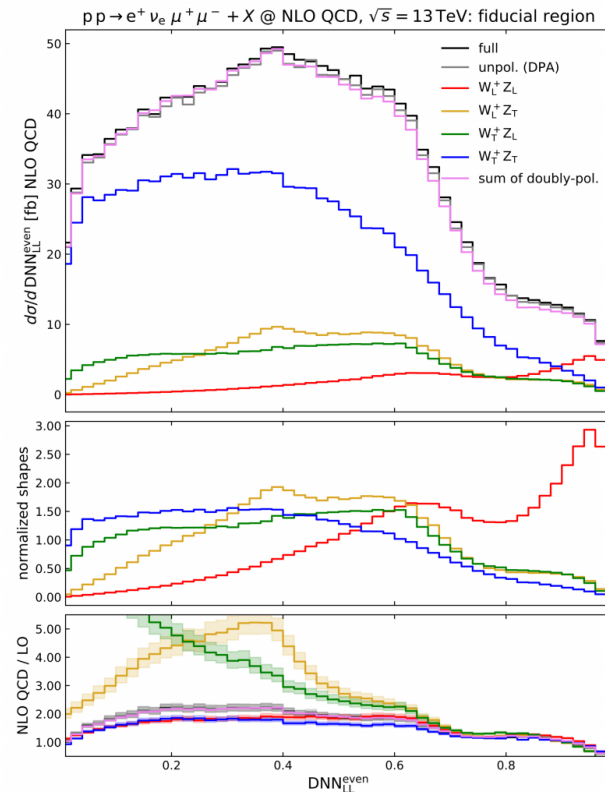
→ Parton level reweighting of Madgraph polarised samples

Reweighting using DNNs [arXiv:[1907.08209](https://arxiv.org/abs/1907.08209)]

→ Acts as some multi-dimensionnal reweighting



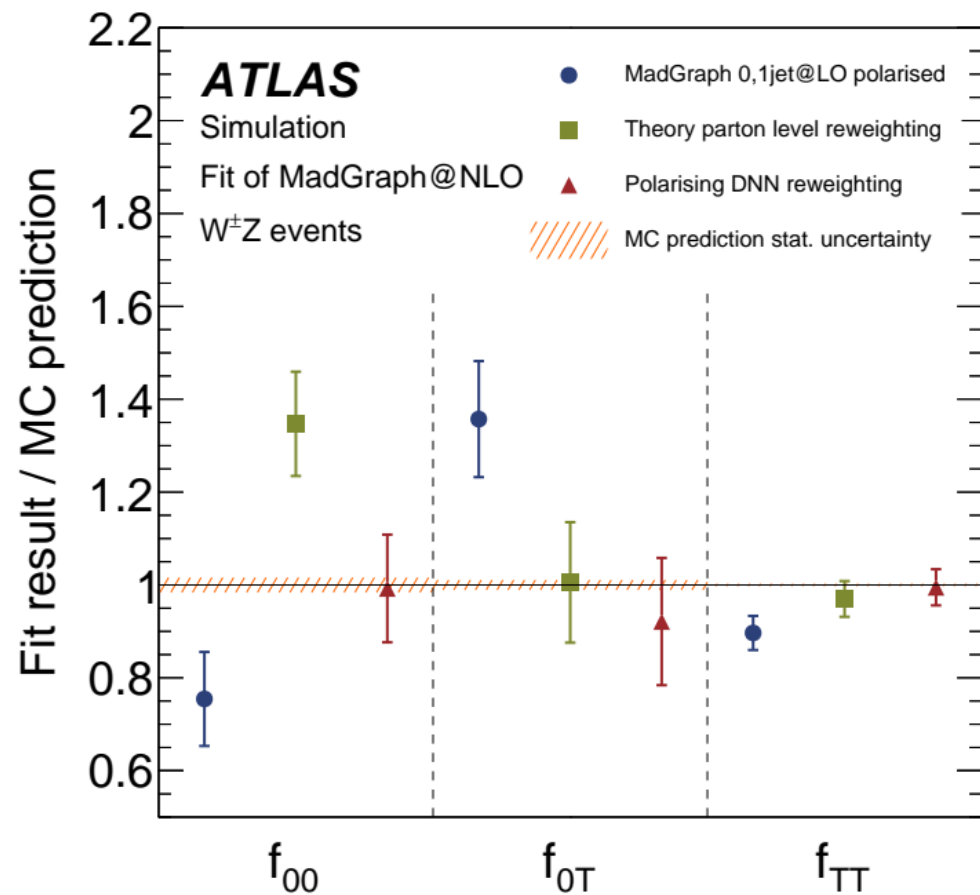
$$w(x) \sim DNN(x) / (1 - DNN(x))$$



Classification DNN p00
polarised distribution
at NLO QCD

[private communication from A. Denner, G. Pelliccioli]

Choice of NLO accurate template set



Madgraph polarised generation:

- Big **bias**, from **10% to 40%** of the fractions values

Analytical reweighting:

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

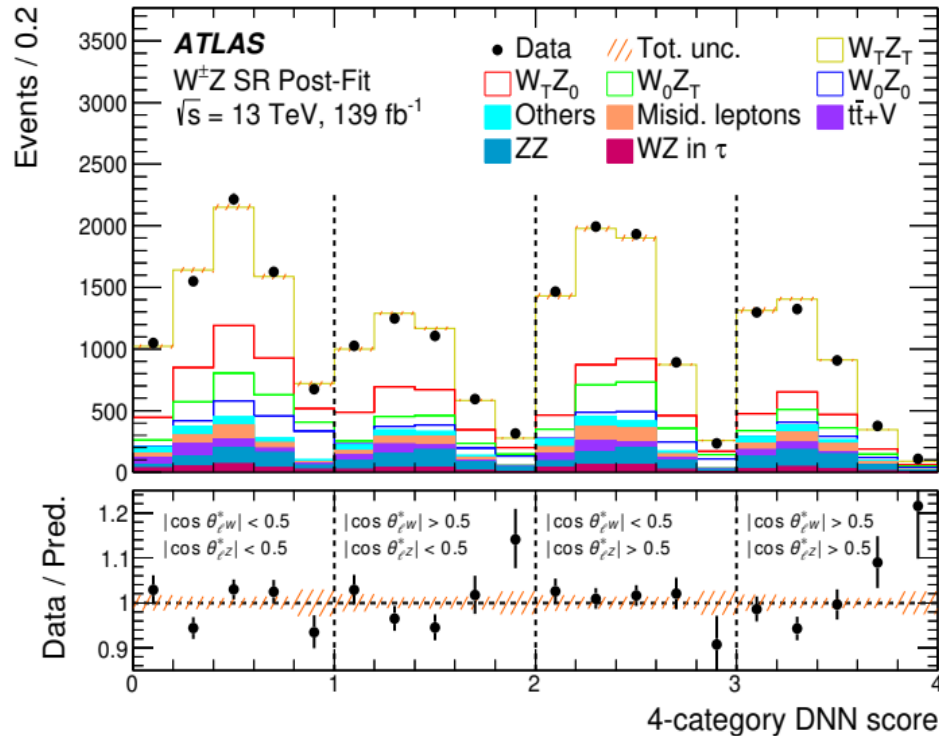
Theory parton level reweighting :

- Still some **bias**, but generally reduced **~15%** of the fractions values
- Used as the alternative method for modelling uncertainty

Polarising DNN reweighting :

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

Binned Maximum Likelihood Template Fit



Fit parameters of interest are f_{00} , f_{0T} , f_{TT} and

N_{tot} the number of signal event

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

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

Statistical uncertainties at the same level as **systematic** uncertainties, mainly

- Template modelling uncertainties
- QCD scale
- E_T^{miss} /jets object reconstruction

→ **Higher order QCD shape effects** on polarisation **templates**

Per charge of the W boson

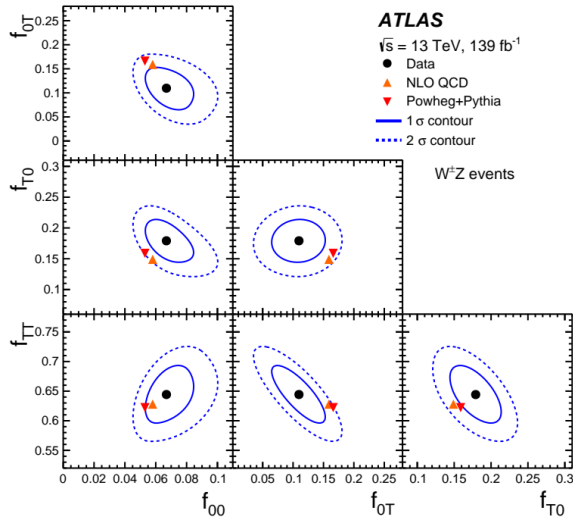
W+ Z & W- Z		W+ Z		W- Z	
f_{00}	0.067 ± 0.010	f_{00}	0.072 ± 0.016	f_{00}	0.063 ± 0.016
f_{0T}	0.110 ± 0.029	f_{0T}	0.119 ± 0.034	f_{0T}	0.11 ± 0.04
f_{T0}	0.179 ± 0.023	f_{T0}	0.153 ± 0.033	f_{T0}	0.21 ± 0.04
f_{TT}	0.644 ± 0.032	f_{TT}	0.66 ± 0.04	f_{TT}	0.62 ± 0.05

Measurement performed as well separating by the W charge

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

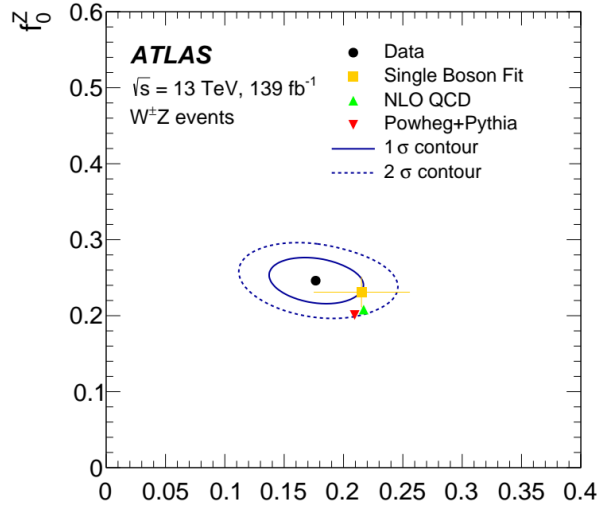
No major difference visible in the charge break down
(barring 1σ difference in f_{T0})

Analysing the results



All joint-polarisation states observed

- Significance on f_{00} at **7.1σ**
- Significance on f_{TT} and f_{T0} **>5σ**
- ➔ **1.4σ** global SM agreement

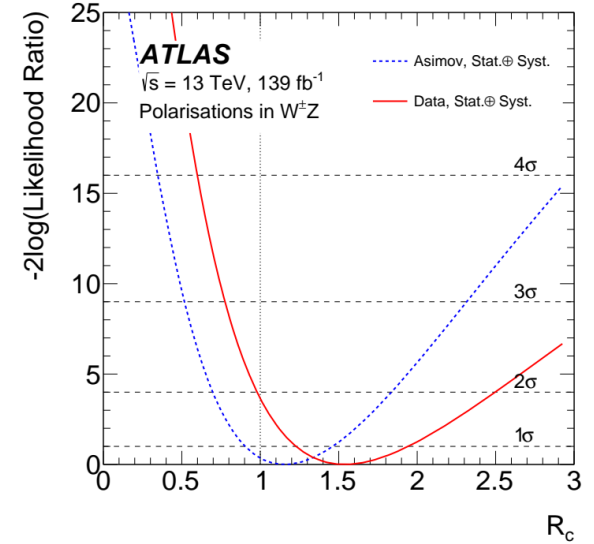


Consistency check of the joint-polarisation fit and the two single boson polarisation fits

$$f_{0T} = f_0^W - f_{00},$$

$$f_{T0} = f_0^Z - f_{00},$$

$$f_{TT} = 1 + f_{00} - f_0^W - f_0^Z$$



Evidence for correlation between bosons polarisation (independence: $R_c = 1$)

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

PROSPECTS

Pioneering methods have been developed :

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

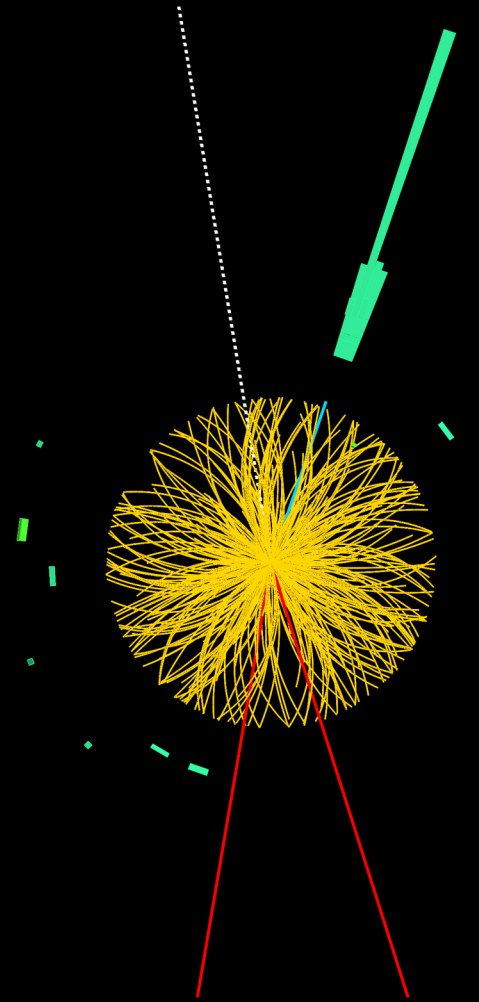
Apply these methods to **other diboson processes**: ZZ, WW

Perform the same measurement in **more restrictive phase spaces**:

- **Per Energy**: fractions in p_T^Z bins?
- Enhance the sensitivity to dimension 6 EFT operators at high energy

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

Thank you
for your attention !



WZ inclusive selection

Experimental signature: $p p \rightarrow \ell \bar{\ell} \ell' \nu_{\ell'} + X$ $\ell = \text{electron or muon}$

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^{\text{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**

Signal Region event selection

- **Leptons** reconstruction
 → 3 increasingly tight selections: **baseline**, **Z-lepton** and **W-lepton**
- **p_z^{ν}** reconstruction:
 → **New DNN-based** method

Trigger	At least one of five single lepton triggers fired
Leading lepton p_T	$p_T^{\text{lead}} > 27$ 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$ GeV
W lepton	Remaining lepton passes W-lepton selection
W transverse mass	$m_T^W > 30$ GeV

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 → lv 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 Scattering WZ production **WZ EW⁶**,
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

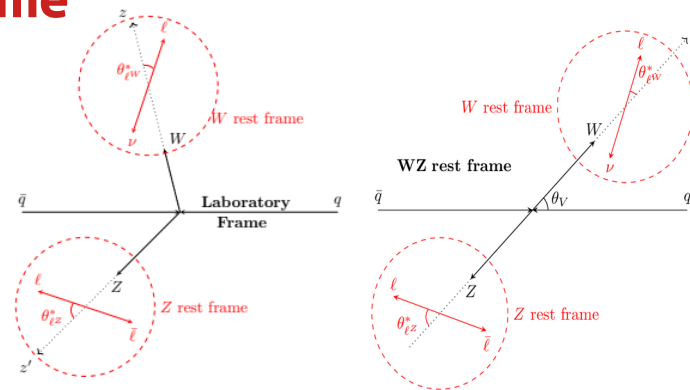
- « **Misidentified Leptons** » background mainly from **Z+ γ** , **t tbar**, **Z+jets**
- Estimated by a **data driven matrix method**

Frame choice

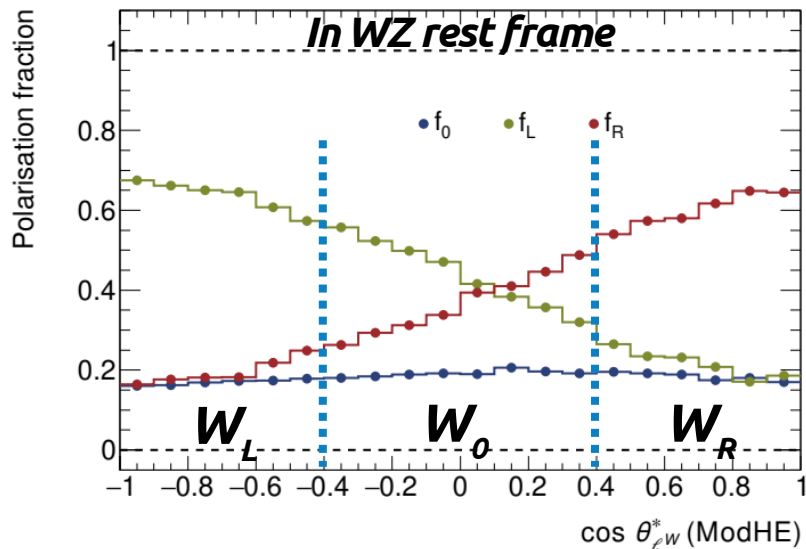
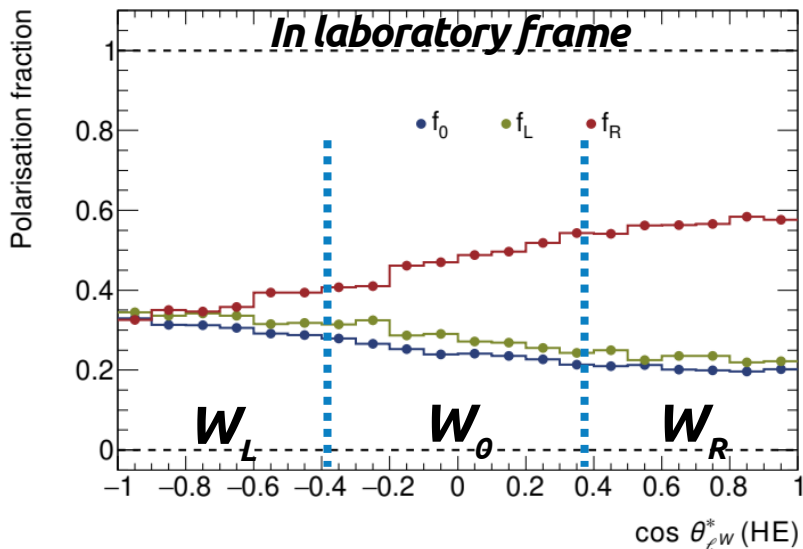
Polarisation fractions **NOT Lorentz invariant**: **choose a frame**

→ **WZ rest frame** chosen

- Allow to meaningfully **compare** single vs joint polarisation
- **Longitudinal fractions** of both bosons shown to have **maximum decorrelation**



Z boson polarisation fractions

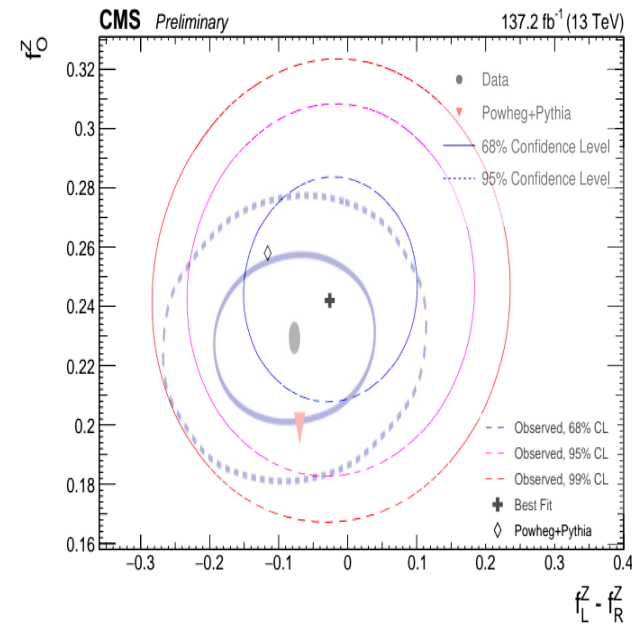
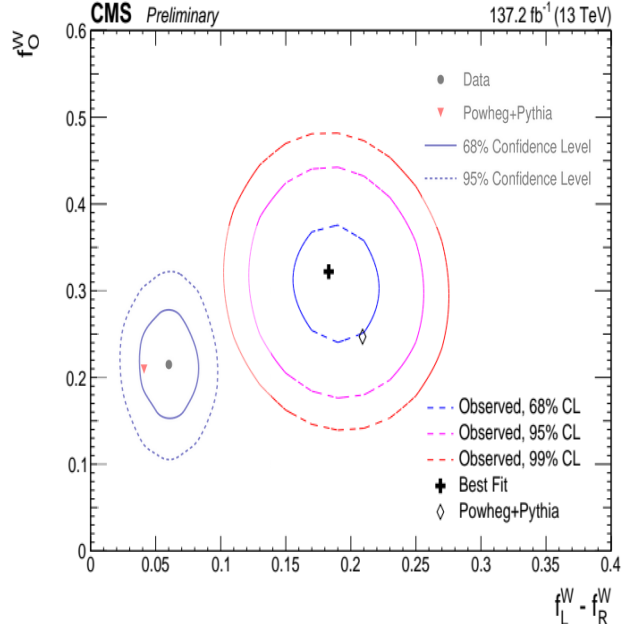


[From L. Selem thesis]

ATLAS and CMS comparison

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

Previous ATLAS measurement

36 fb⁻¹ results

	f_0	$f_L - f_R$
W ⁺ in W ⁺ Z	0.26 ± 0.08	-0.02 ± 0.04
W ⁻ in W ⁻ Z	0.32 ± 0.09	-0.05 ± 0.05
W [±] in W [±] Z	0.26 ± 0.06	-0.024 ± 0.033
Z in W ⁺ Z	0.27 ± 0.05	-0.32 ± 0.21
Z in W ⁻ Z	0.21 ± 0.06	-0.46 ± 0.25
Z in W [±] Z	0.24 ± 0.04	-0.39 ± 0.16

Compared to 36 fb⁻¹ single boson polarisation measurement: [arXiv:1902.05759]

- **Central value not comparable** for change of definition of $\cos\theta^*$
- Uncertainties roughly **divided by 2**
- Lower improvement for f_0^W who is not statistically dominated

139 fb⁻¹ results



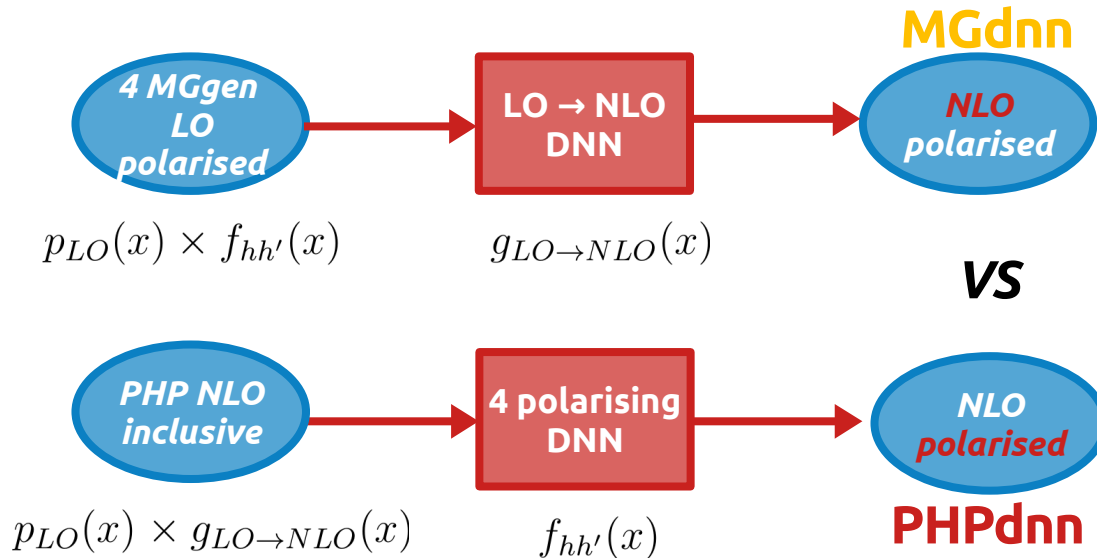
*~ x4 data,
~ /2 stat. uncertainties*

	f_0	$f_L - f_R$
W in W ⁺ Z	0.23 ± 0.05	0.071 ± 0.023
W in W ⁻ Z	0.19 ± 0.05	0.026 ± 0.027
W in W [±] Z	0.22 ± 0.04	0.059 ± 0.016
Z in W ⁺ Z	0.223 ± 0.025	-0.20 ± 0.10
Z in W ⁻ Z	0.240 ± 0.029	0.10 ± 0.13
Z in W [±] Z	0.231 ± 0.019	-0.10 ± 0.08

Validation of factorisation assumption

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

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

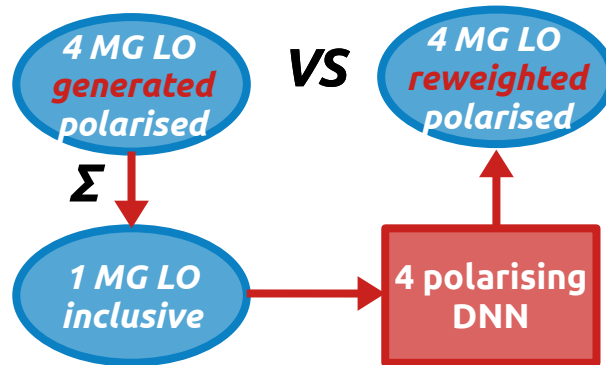


Two ways to obtain **NLO polarised** sample: Comparable results, **assumption validated**

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

Uncertainty breakdown

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

