# Polarized WZ production observation by ATLAS

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On behalf of the ATLAS Collaboration

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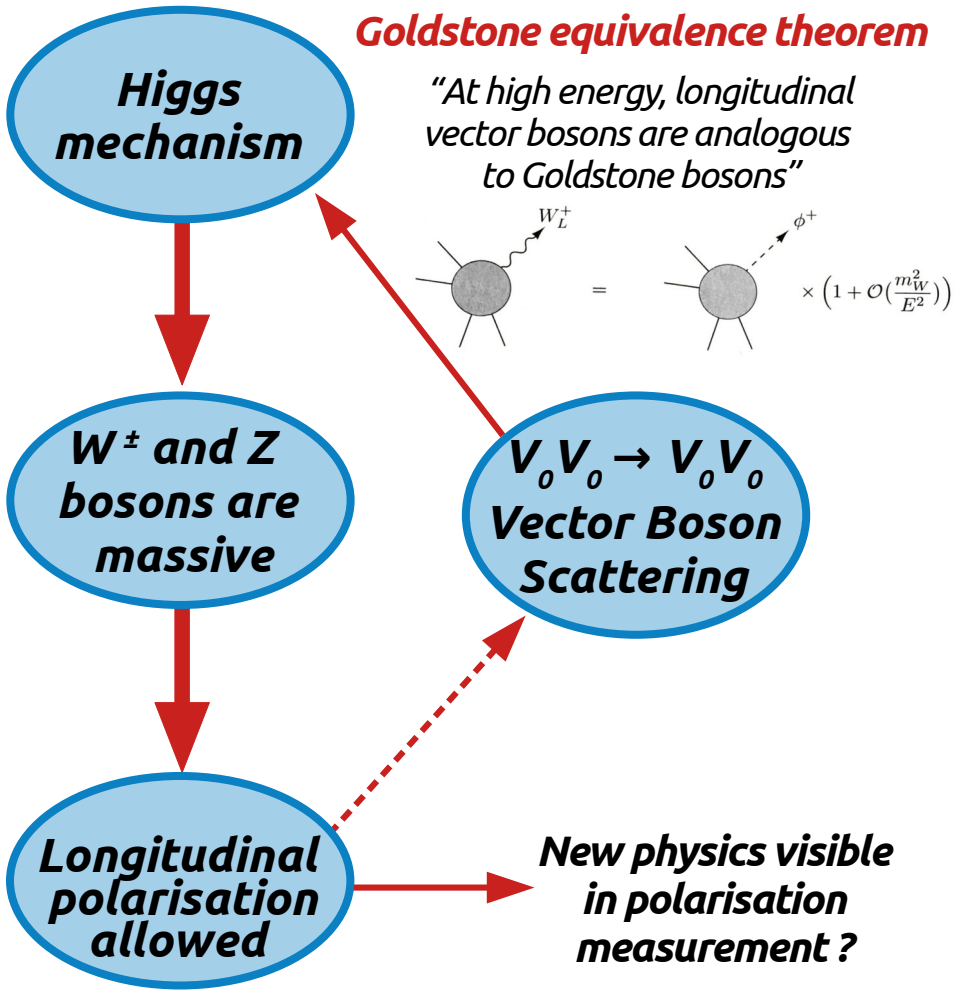
ATLAS EXPERIMENT

LAPP

LPSC
GRENOBLE | MODANE

# Why study polarisation ?




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 !

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

# Polarisation in diboson systems 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)
- **DELPHI** [arXiv:0908.1023]: **not sensitive** enough to $f_{00}$
- **OPAL** [arXiv:0009021]: **almost 3σ** for $f_{00}$, but **tension** with Standard Model

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

***DELPHI results***

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

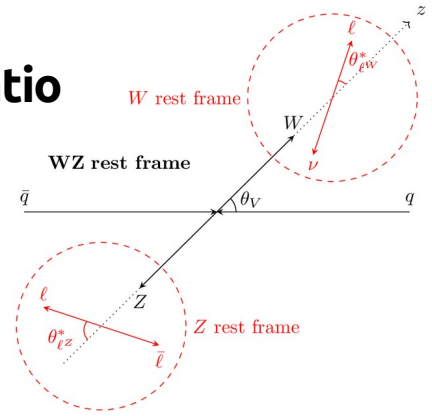
***OPAL results***

*Longitudinal here noted "L"*

# Measurements at LHC

**Diboson process favoured : p p → W± Z**

➔ Best compromise between **cross section** and **signal to background ratio**



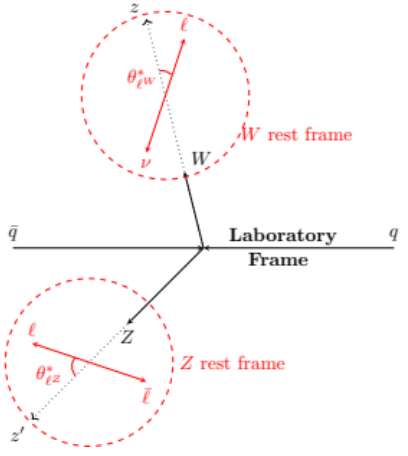

**Single boson polarisation in WZ production**

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

**Joint-polarisation fractions in WZ production, L = 139 fb-1**

- ATLAS result finally published in Phys. Lett. B 843 (2023) 137895
- Additional improvement on single boson polarisation fractions

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




**Other diboson channels are now being probed:**

➔ Recently released ATLAS result on joint-polarisation in **ZZ production** [arxiv:2310.04350]

# Polarisation in WZ pair production

# WZ inclusive production

**Experimental signature :** $pp \to \ell \bar{\ell} \ell' \nu_{\ell'} + X$ $\ell$ = ***electron or muon***

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

***ATLAS tracker available***
***Reduce background (fake) leptons***
***Reduce virtual photons γ* : on-shell Z***
***Select sizeable missing $E_T$ (neutrino)***
***Leptons isolation***

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

- **ZZ: 7.5%** , **ttZ and ttW: 4%** , others...

➔**Monte Carlo generation**

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

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

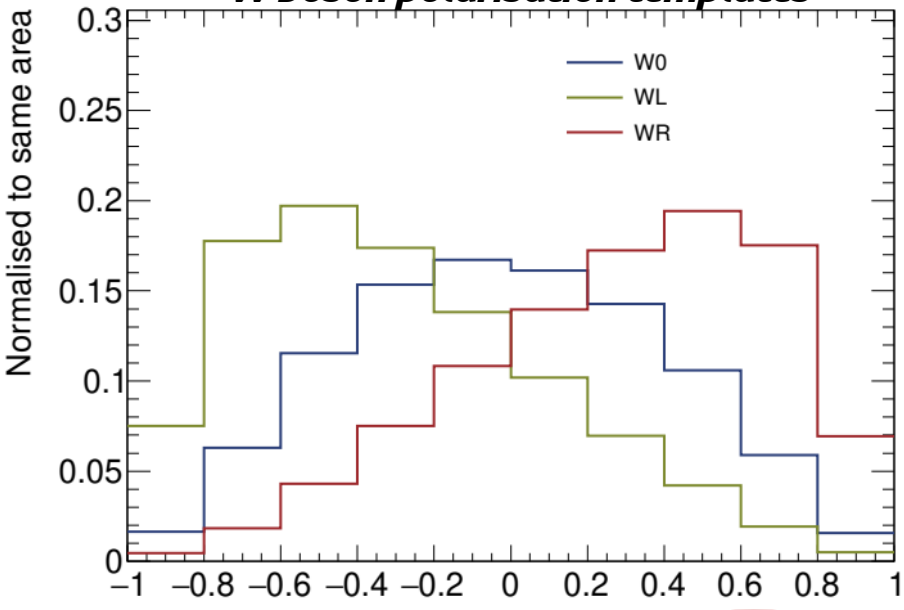
➔ **Data driven matrix method**

# How to measure polarisation

**Method :** *Here for single boson polarisation measurement*

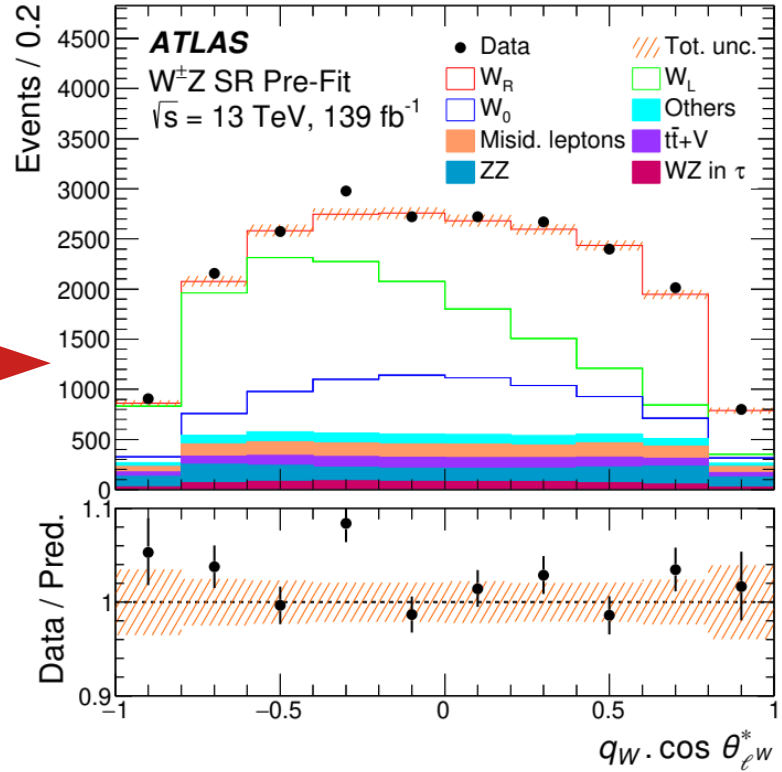
- Generate **polarisation templates** of a **discriminating variable**
- Extract polarisation fractions through a **template fit**

***W boson polarisation templates***




***Discriminating variable***

***Stacking templates***



# 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 0.2x0.2 = 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 highest possible QCD order**
  - ➔ **Unbiased measurement**

# Definition of polarisation fractions

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

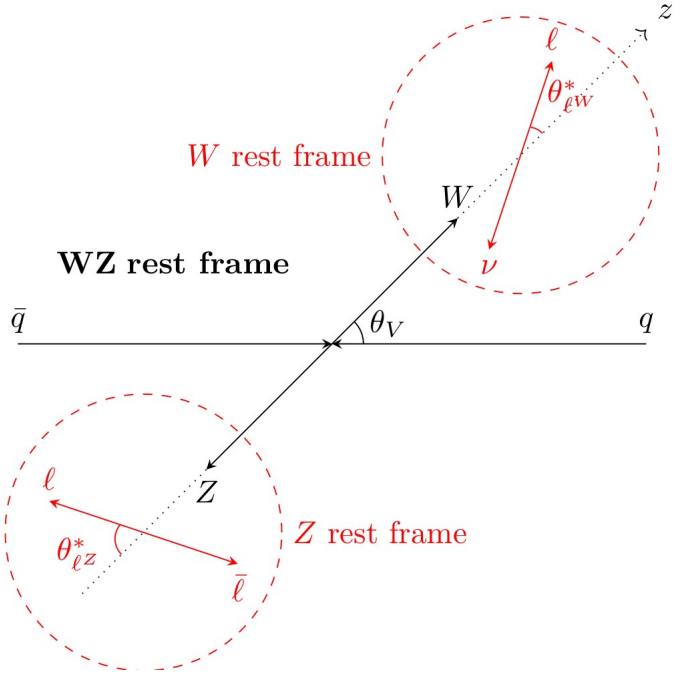
➔Defined from the **joint spin density matrix** :

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

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

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

- **Compare** single and joint
- **Single Longitudinal fractions** of bosons have **maximum decorrelation**

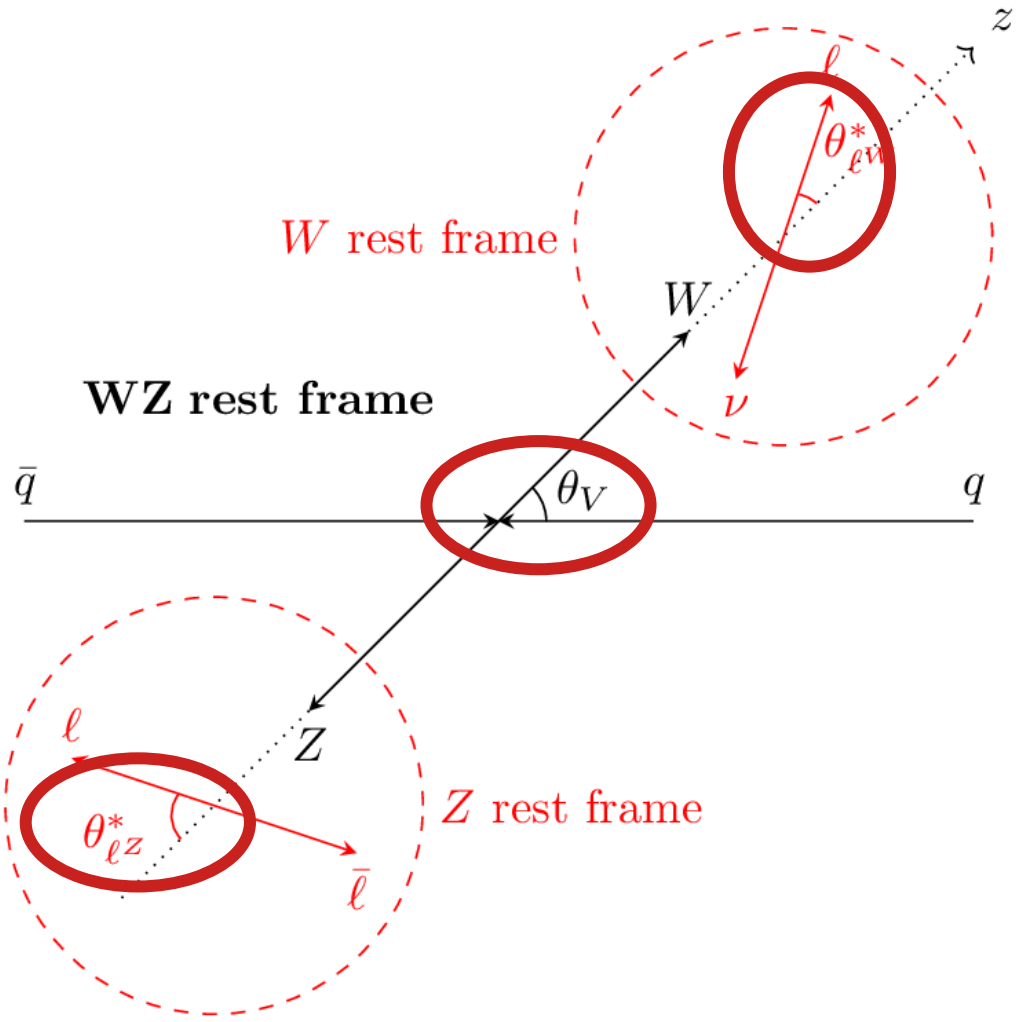


# Joint-polarisation templates

# Variable for the joint-polarisation

**Find a discriminating variable** for **both bosons polarisation at once**

➔ Analytical variable **$|\cos\theta_V|$** not discriminant enough



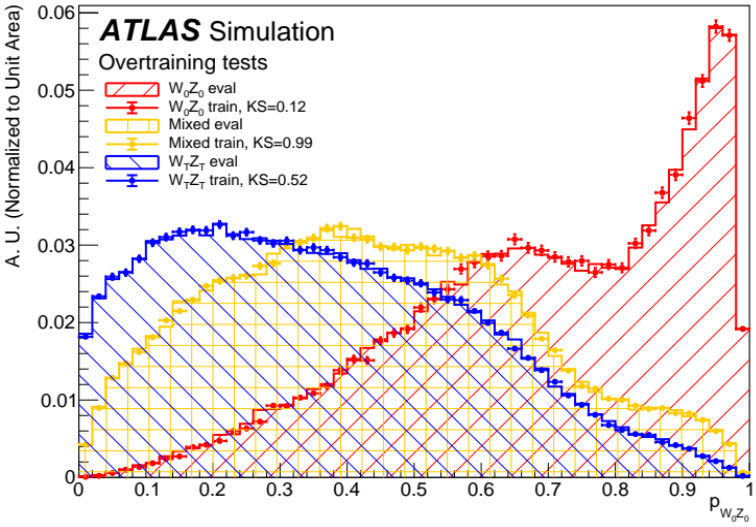
# The discriminating variable

**Classification DNN input variables**
*(by importance)*

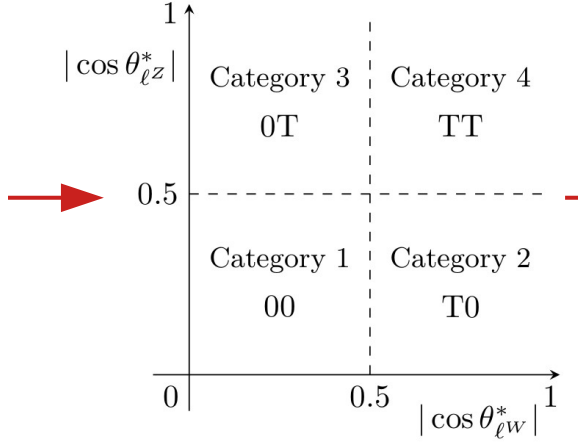
- $|y_{l,W} - y_Z|$ ~ $|\cos\theta_V|$
- $P_T^{WZ}$
- $P_T^{l,W}$
- $\Delta\varphi(l^W, v)$
- $\Delta\varphi(l1^Z, l2^Z)$
- $E_T^{miss}$
- $P_T^{l2,Z}$
- $P_T^{l1,Z}$

**Using a classification DNN:**

- **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 cosθ*

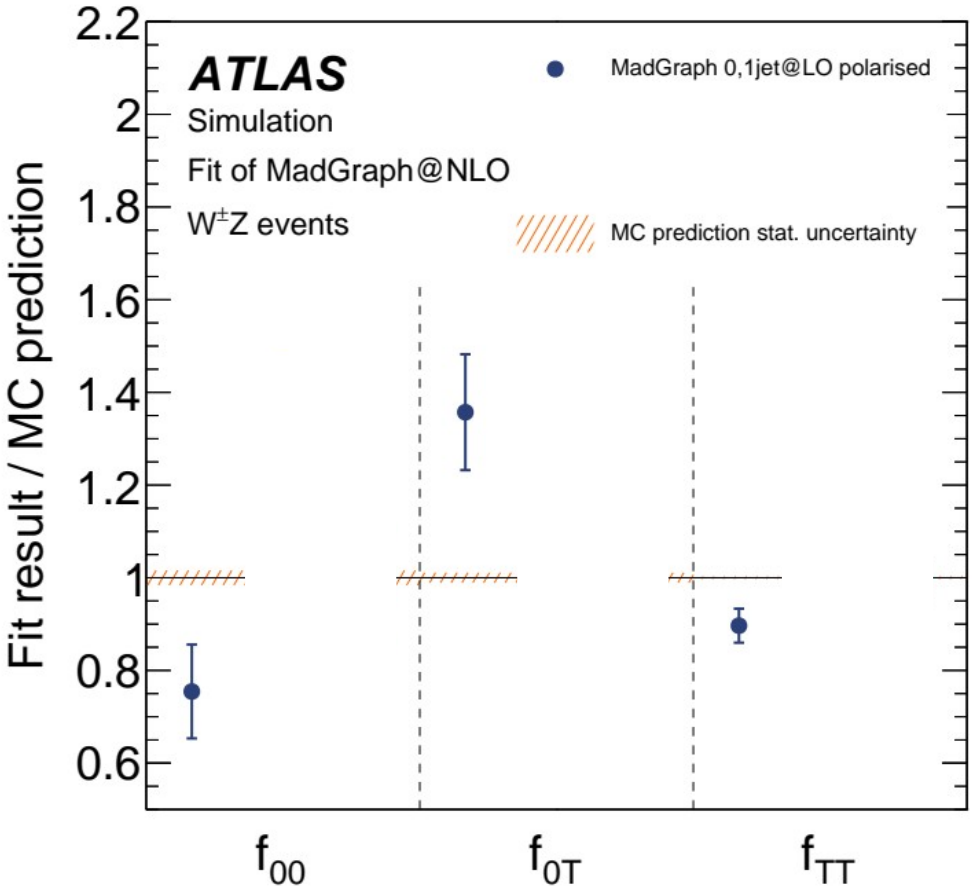



***DNN score for 00***




***4-categories DNN score***

# Need for NLO accurate templates




**Bias study:**

➔compare in pseudo data ...

**Detector level fit result** **vs** **Truth polarisation fraction**

**Direct polarised generation**

*Madgraph 2.7.3 LO Matrix element + real corrections (0,1 jets)*

➔ **Bias found** (10% to 50% on fraction value) using these **LO templates**

**Need for NLO accurate polarisation templates**

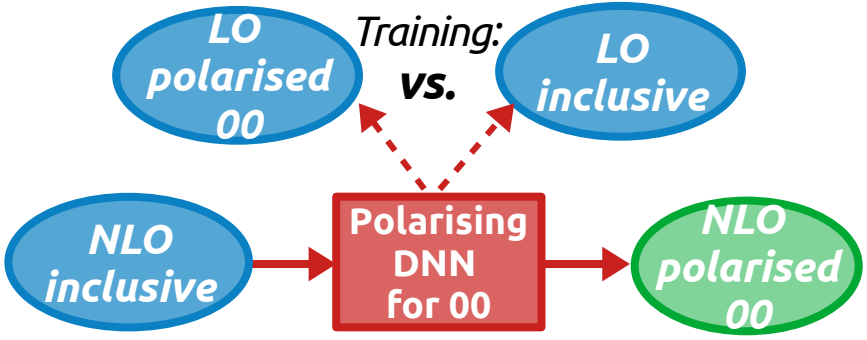
# NLO accurate polarisation templates

**Reweighting to a calculation at NLO QCD**
[Collaboration with theorists A. Denner& G. Pelliccioli arXiv:2010.07149]

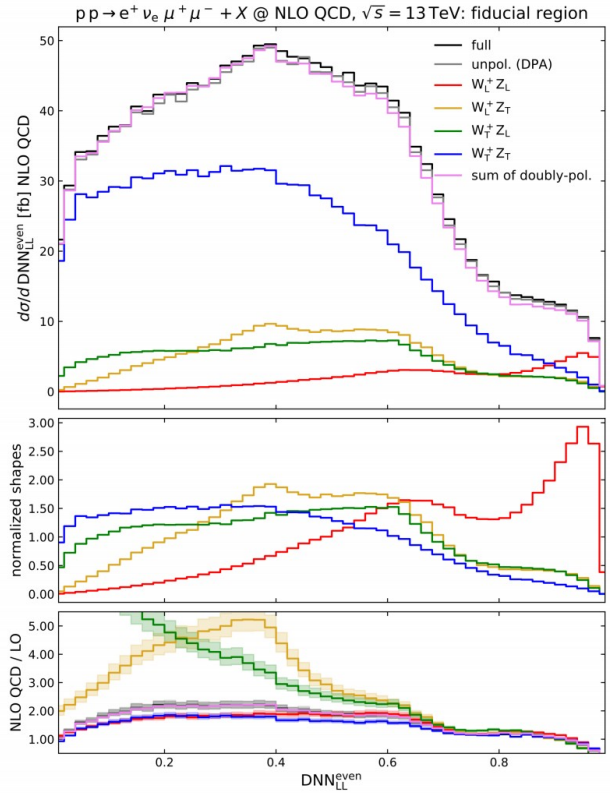
➔ Parton level reweighting of Madgraph polarised samples

**Reweighting using DNNs** [arXiv:1907.08209]

➔ Acts as some multi-dimensionnal reweighting



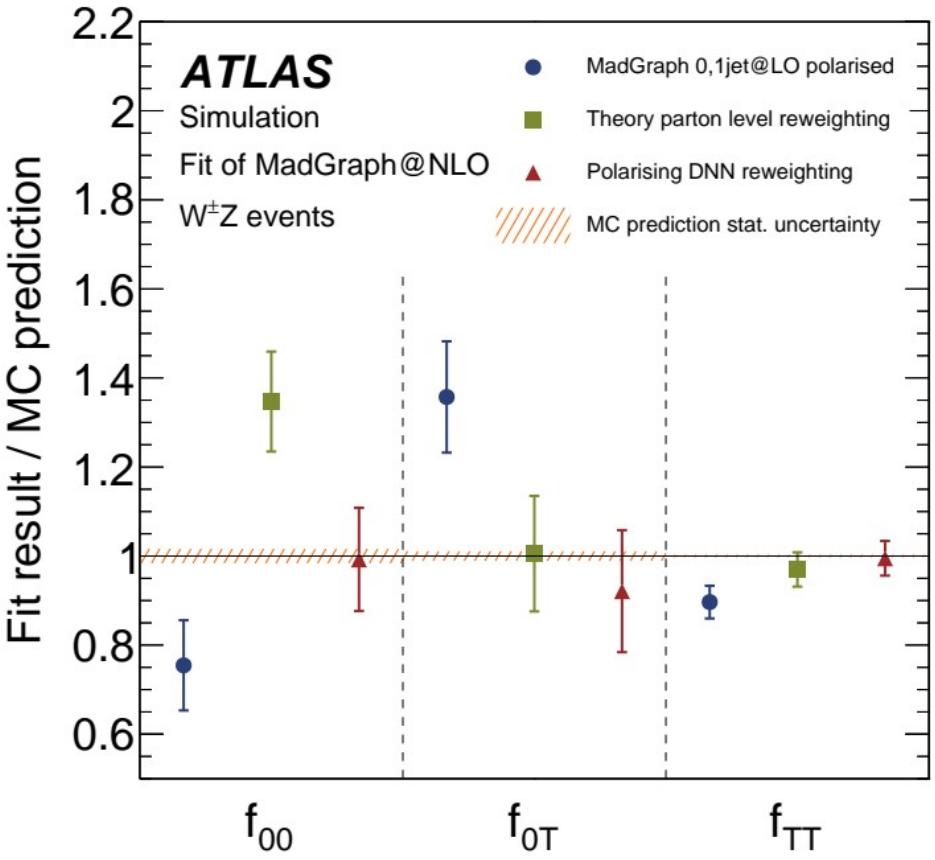

$w(x) \sim DNN(x) / ( 1 - DNN(x) )$




***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

**Theory parton level reweighting :**

- **biased**, reduced to **~15%** of the fractions values

➔ Alternative method for modelling **uncertainty**

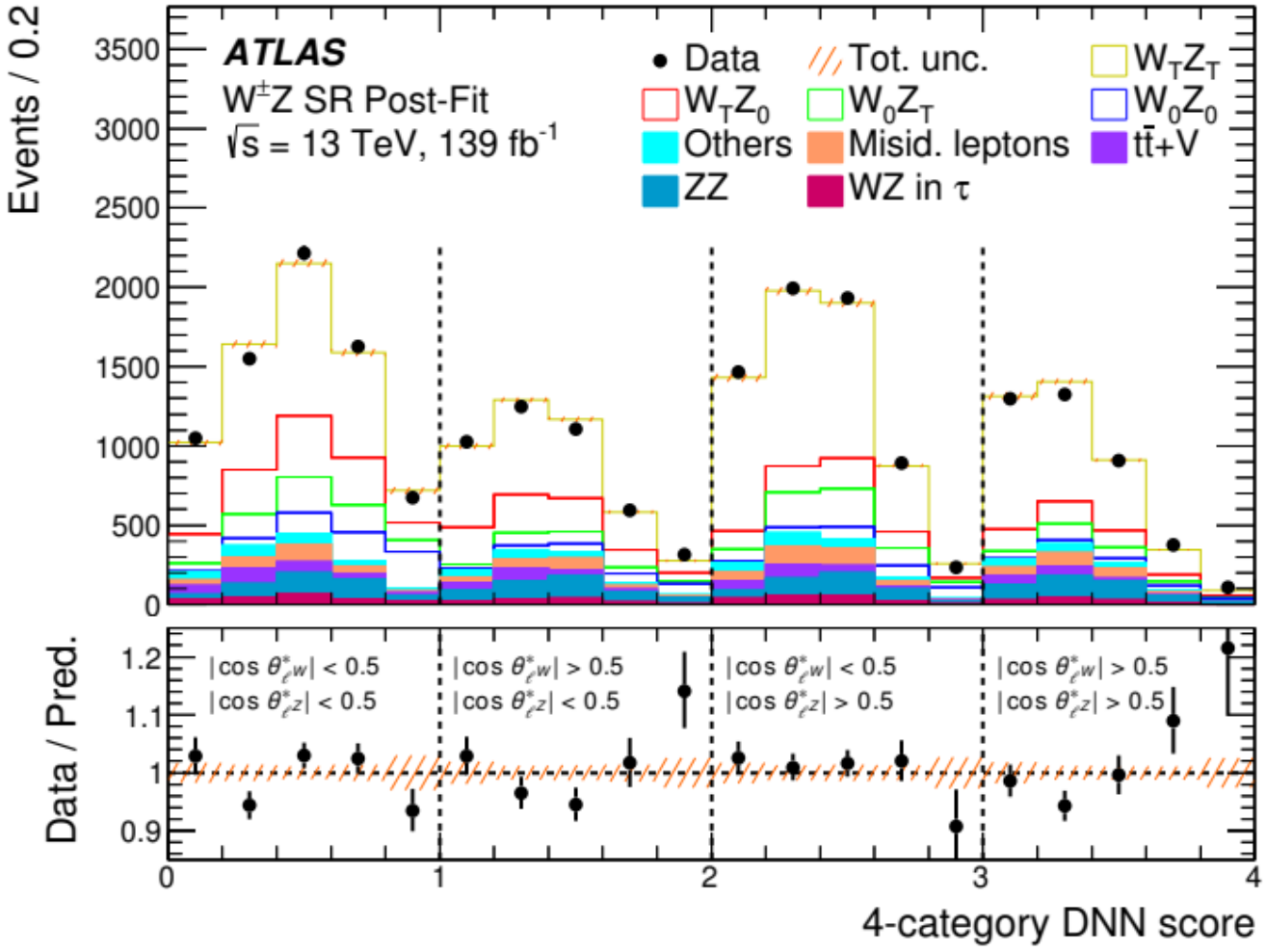
**Polarising DNN reweighting :**

- **Least biased method** (almost no bias)

➔ **Chosen one**

# Measurement of joint-polarisation

# 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**

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

# Per charge of the W boson

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

**All joint-polarisation states observed**

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

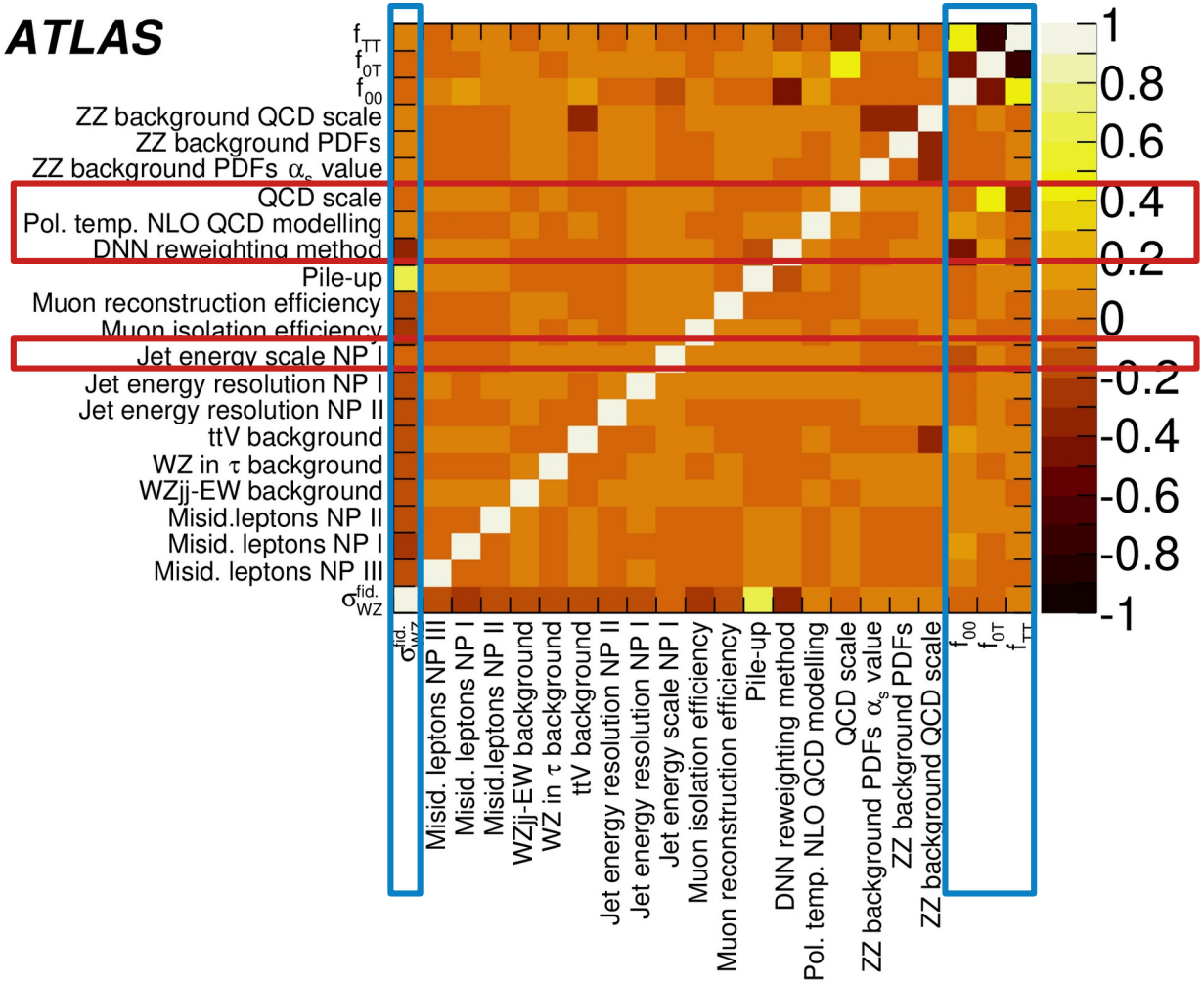
**Measurement performed as well separating by the W charge**

- 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 $f_{T0}$)*

# Fit parameters correlations



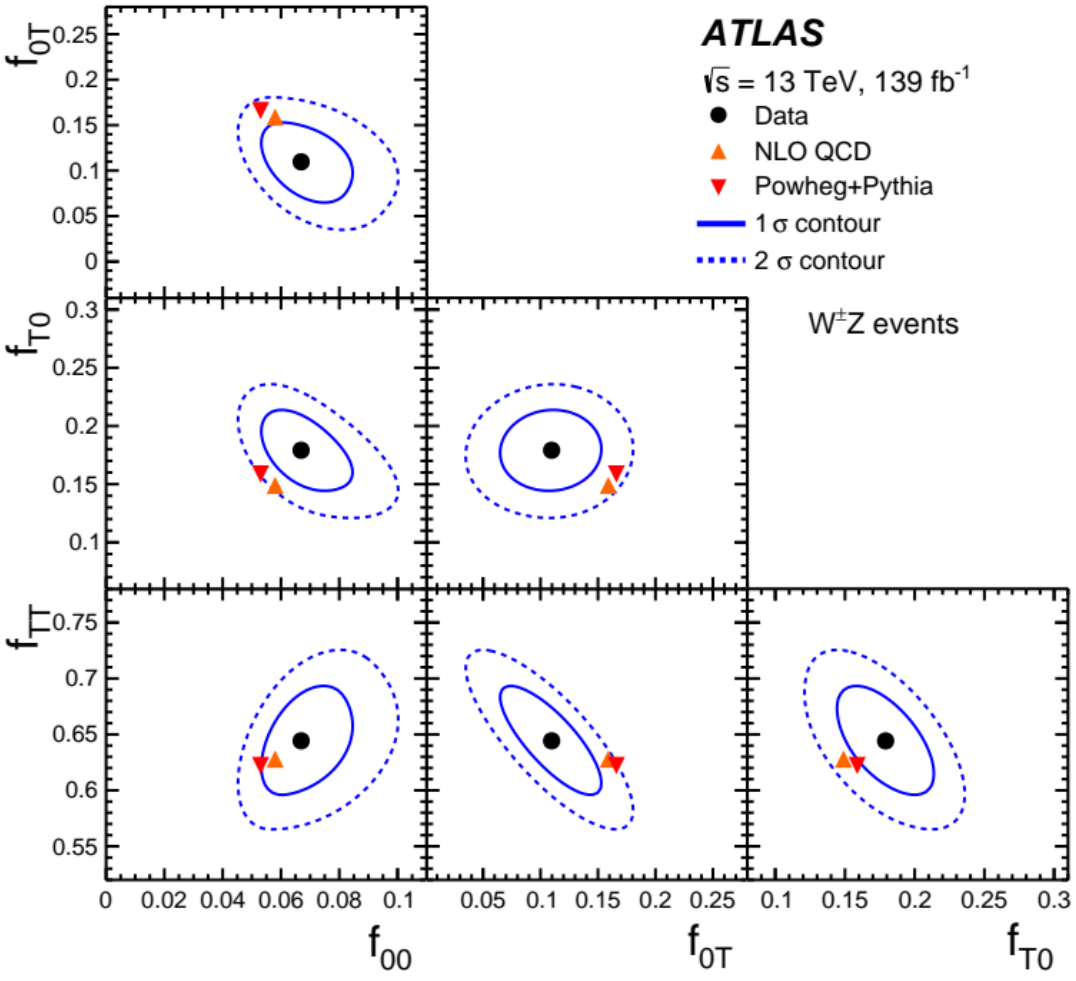

## Parameters of interest :

– **Decoupling** of normalisation and fractions parameters

## Main uncertainties :

– From **Higher order QCD shape effects** on polarisation **templates**

# Joint-polarisation CL regions

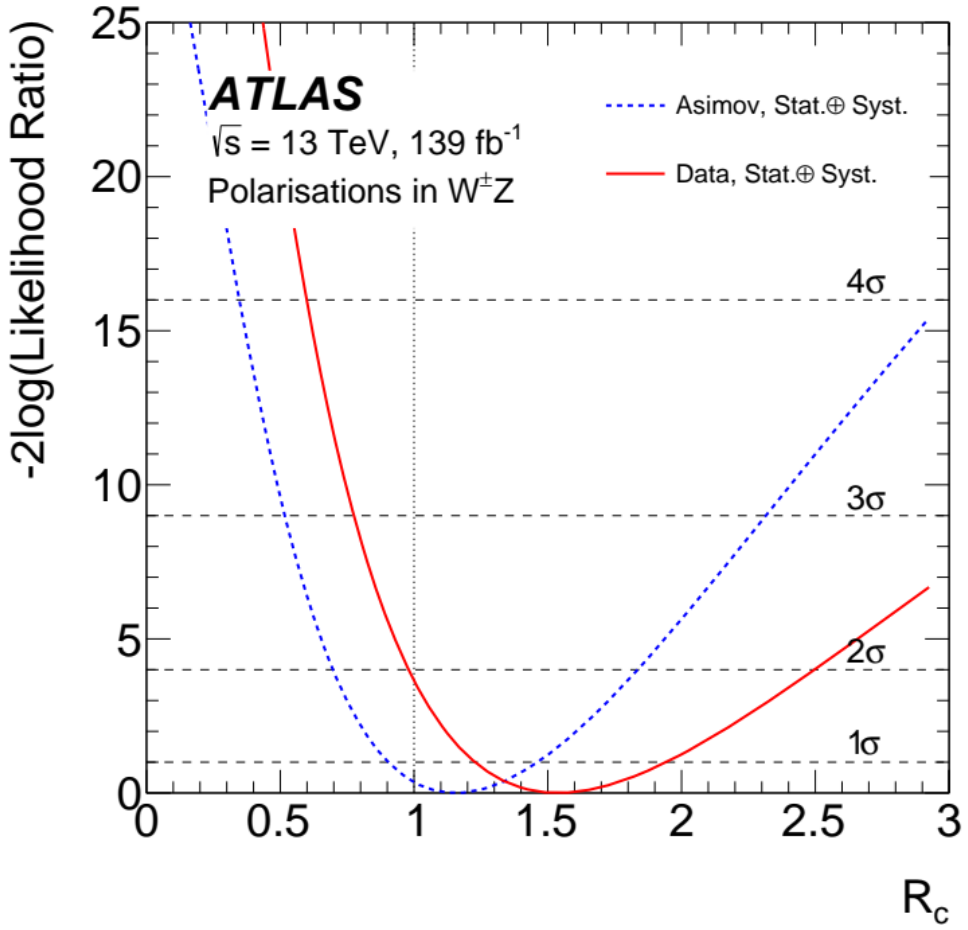



**Strong correlations** between simultaneously extracted fractions

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

➔ **1.4 σ** global agreement with SM

# Joint-polarisation CL regions




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

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

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

– If independent, $R_c$=1

– Theory predicts $R_c$ ~ 1.3

– Measurement gives **$R_c$ = 1.54 ± 0.35**

**Evidence for correlation between the bosons polarisations**

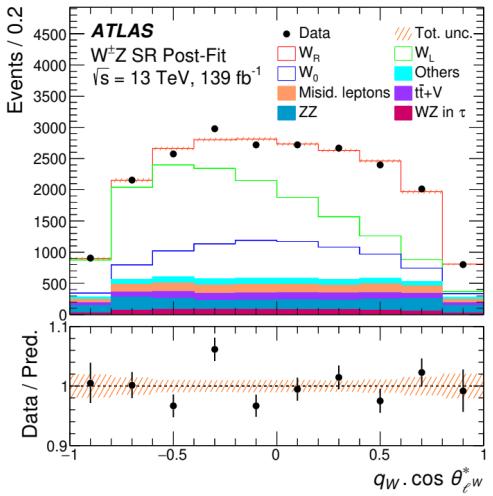
# Single boson template fit

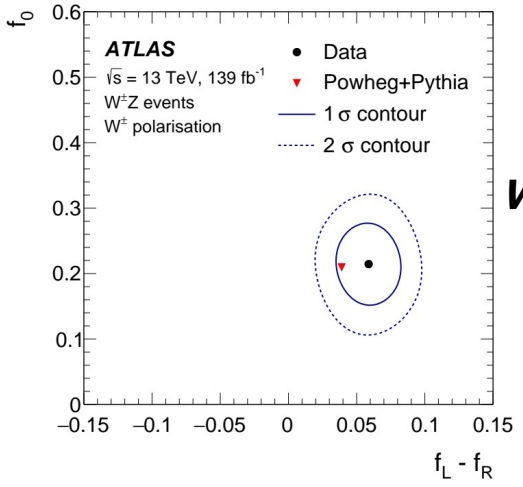
**Template fit on data at detector level as for joint-polarisation**

- Discriminating variables : **cosθ*$_w$** and **cosθ*$_z$**
- Polarisation templates: **analytical reweighting**

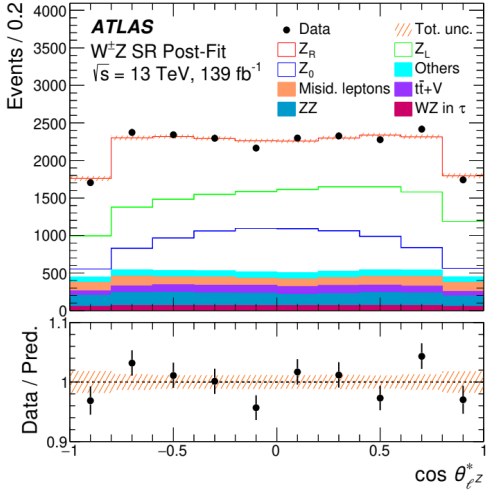
**No tension with theory**

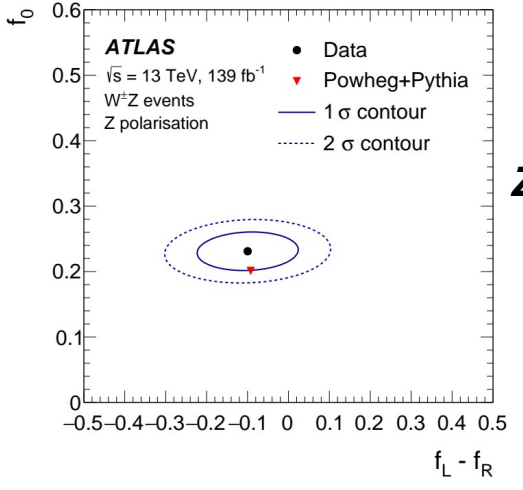
**$f_0$ mesured with 5 sigma in charge break-down**




***W boson***




***Z boson***

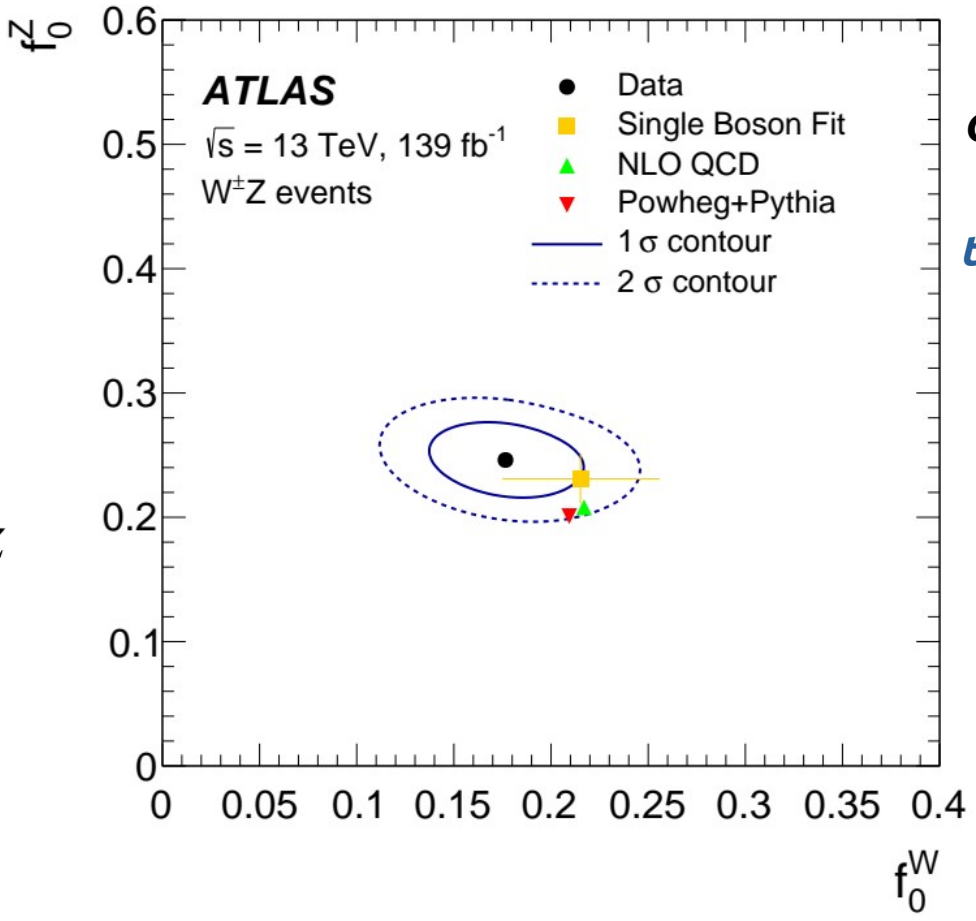
# Consistency with joint-polarisation

**Consistency check:**

– $f_0^W$ and $f_0^Z$ measured using reparametrisation in joint-polarisation fit

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

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




***Consistency check of***

***the joint-polarisation fit***

***and the two***

***single boson polarisation fits***

# PROSPECTS

**Pioneering methods** have been developed :

– 4 joint polarisations
➔ **Classification DNN** used by **theorist for calculation**

– High sensitivity to higher orders in QCD
➔ **DNN reweighting** method

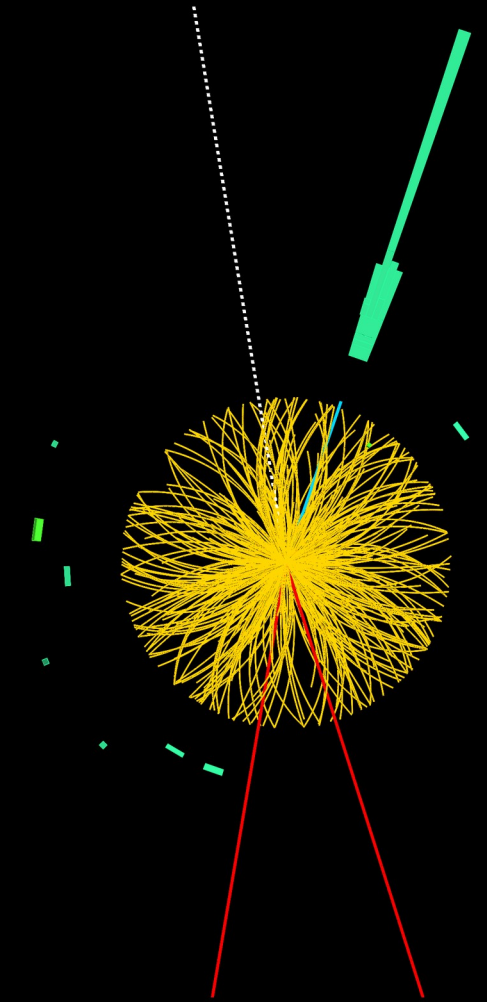
**Very active field:**

– ZZ joint-polarisation result released [arxiv:2310.04350]

– Efforts to look at polarisation in **more restrictive phase spaces** ($p_T^Z$ bins ?)
➔ Enhance the sensitivity to dimension 6 EFT operators at high energy

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

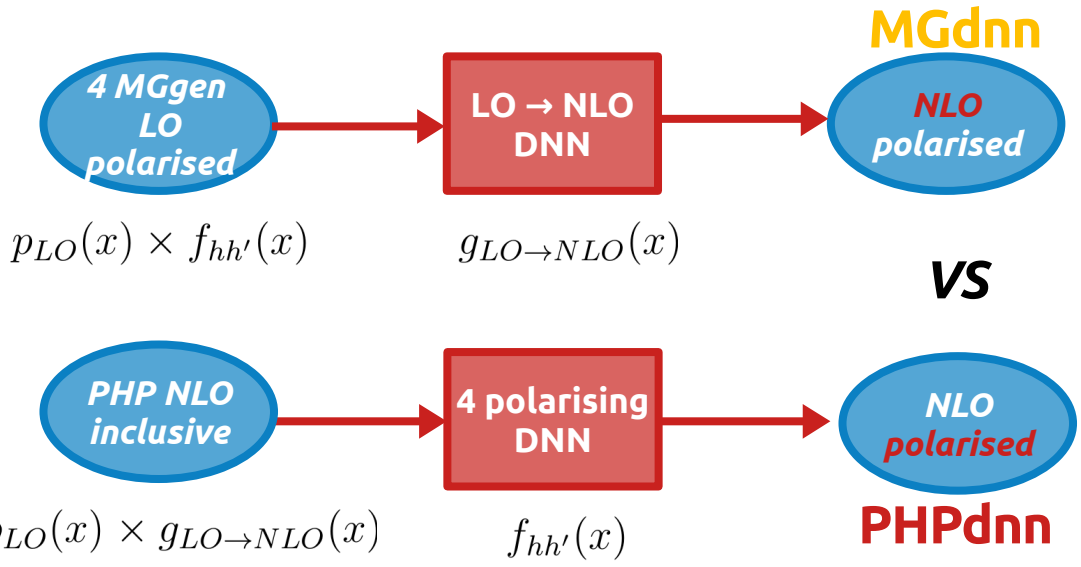
# Thank you
# for your attention !



# 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: Comparable results, assumption validated**

# Modelling uncertainties

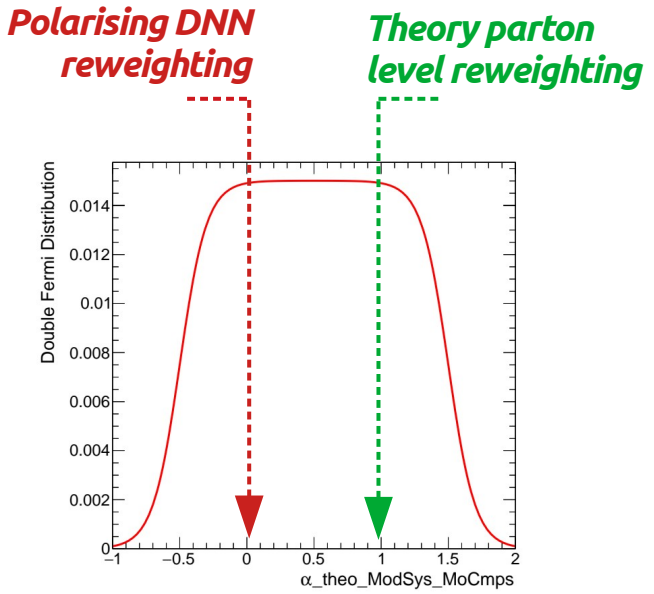
**NLO QCD polarisation template set choice** uncertainty:

- **Theory parton level reweighting** = 2nd least biased *(over all fractions)*, from a completely different method

➔ Shape uncertainty

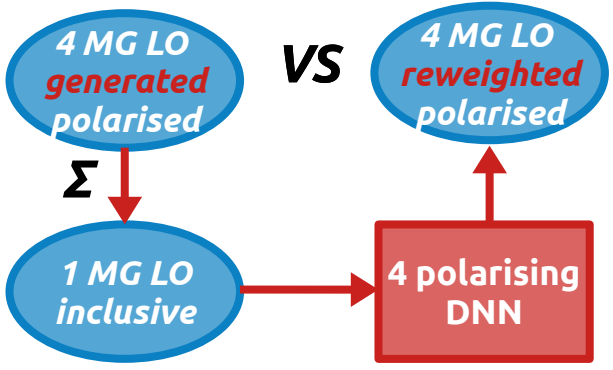
- Two point uncertainty, no privileged template

➔Constraint term to limit the range of the nuisance parameter to **the two only alternative template sets**




Uncertainty on the DNN **reweighting method:**

- Small non-closure used to extract uncertainty bands



# ATLAS and CMS differences

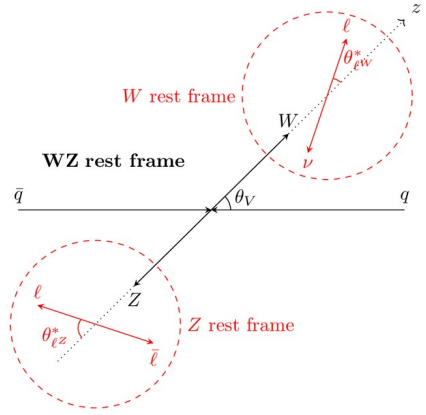
| | ATLAS | CMS |
|---|---|---|
| Total p.s. (MC generation) | $66 < M_Z < 116$ [GeV ] | $60 < M_Z < 120$ [GeV ] |
| Measurement frame | Modified Helicity | Helicity |
| $p_z^\nu$ reconstruction | DNN-based | Analytical ($P_W^2 = M_W^2$) |
| Event yield | 21936 | 10729 |
| $WZ$ signal/Backgrounds | $\approx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

***Different event selection***

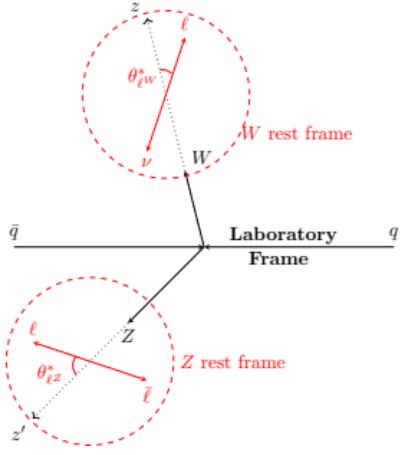
***ATLAS fiducial phase space***

| Variable | Fiducial inclusive |
|---|---|
| Lepton $\lvert\eta\rvert$ | $< 2.5$ |
| $p_{\mathrm{T}}$ of $\ell_Z$, $p_{\mathrm{T}}$ of $\ell_W$ [GeV | $> 15$, $> 20$ |
| $m_Z$ range [GeV] | $\lvert m_Z - m_Z^{\mathrm{PDG}}\rvert < 10$ |
| $m_{\mathrm{T}}^W$ [GeV] | $> 30$ |
| $\Delta R(\ell_Z^-, \ell_Z^+)$, $\Delta R(\ell_Z, \ell_W)$ | $> 0.2$, $> 0.3$ |

***Modified Helicity frame***



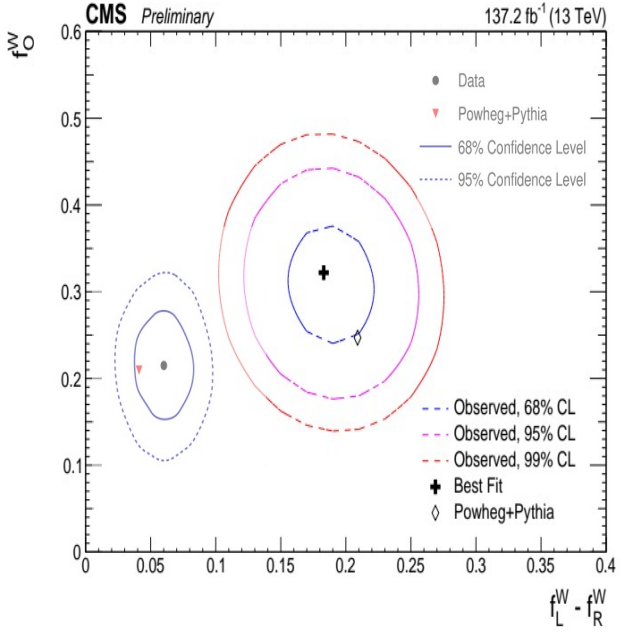

***Helicity frame***

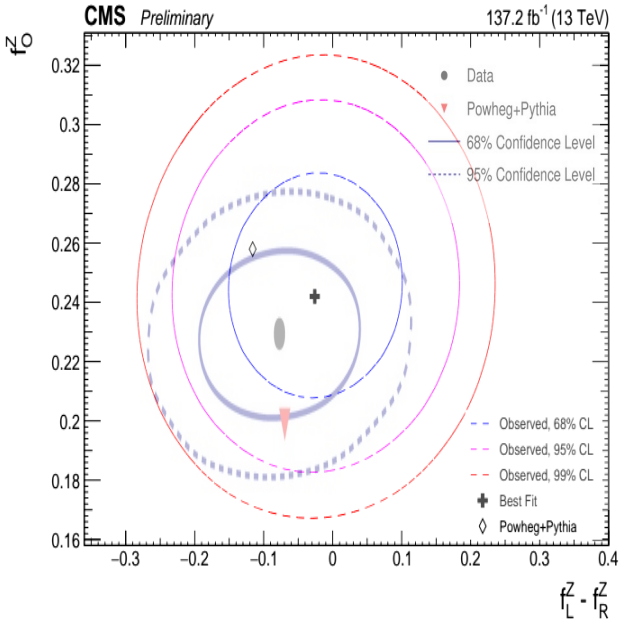


# ATLAS and CMS comparison

**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**

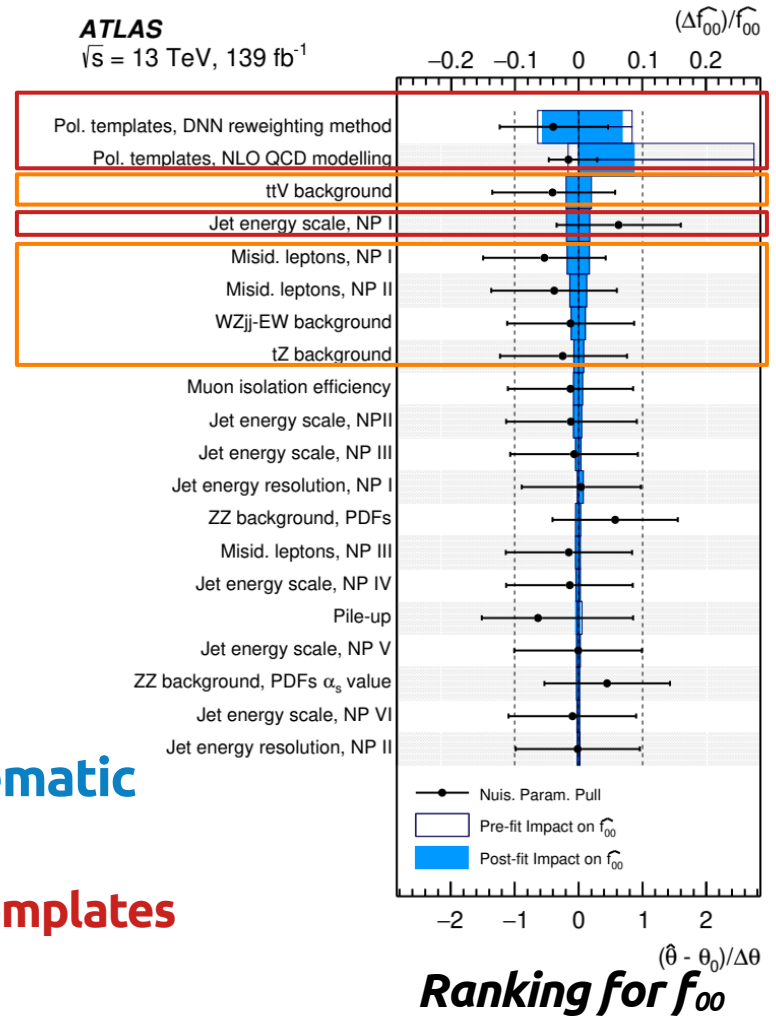



*CMS results for W (left) and Z (right)*
*Previously presented CL regions in transparency*

# Uncertainty breakdown

| | $f_{00}$ | $f_{0T}$ | $f_{T0}$ | $f_{TT}$ |
|---|---|---|---|---|
| Relative uncertainty [%] | | | | |
| $e$ energy scale and id. efficiency | 0.34 | 0.6 | 0.8 | 0.31 |
| $\mu$ 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 |




**Ranking for $f_{00}$**

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

- **Higher order QCD shape effects** on polarisation **templates**
- **Background estimation**

# 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 |
| $W^\pm$ in $W^\pm Z$ | 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 $W^\pm Z$ | 0.24 ± 0.04 | −0.39 ± 0.16 |

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

***139 fb$^{-1}$ results***

| | $f_0$ | $f_L - f_R$ |
|---|---|---|
| $W$ 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 $W^\pm Z$ | 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 $W^\pm Z$ | 0.231 ± 0.019 | -0.10 ± 0.08 |

**Compared to 36 fb$^{-1}$ single boson polarisation measurement:** [arXiv:1902.05759]

- **Central value not comparable** for change of definition of **cosθ***
- Uncertainties roughly **divided by 2**

➔ Lower improvement for **$f_0^W$ who is not statistically dominated**

# 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**

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

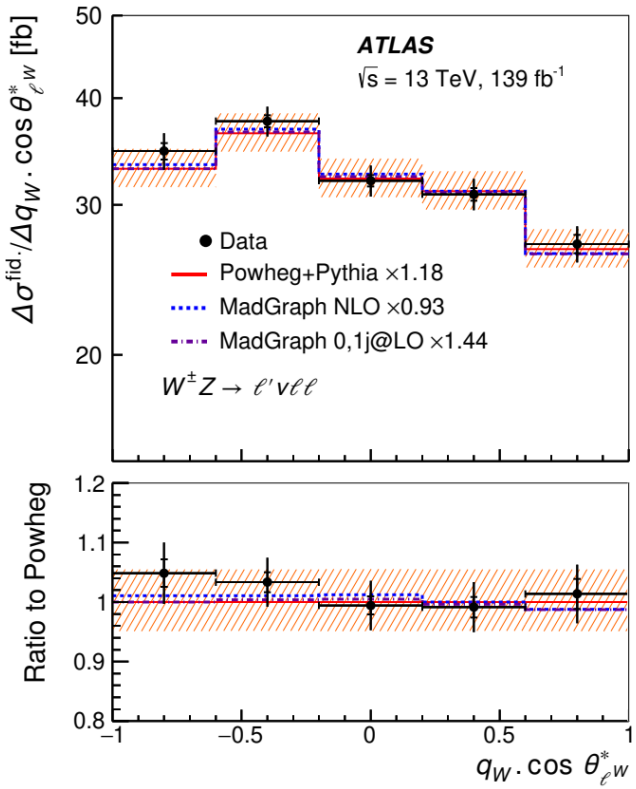
➔ $\cos\theta^*_W$ , $\cos\theta^*_Z$ , $|\cos\theta_V|$

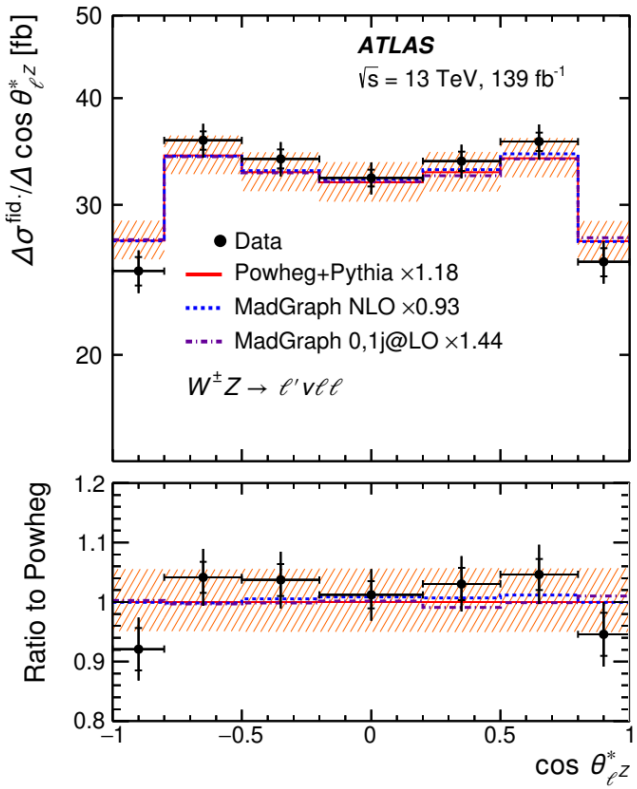
Compared to Born level **predictions** from

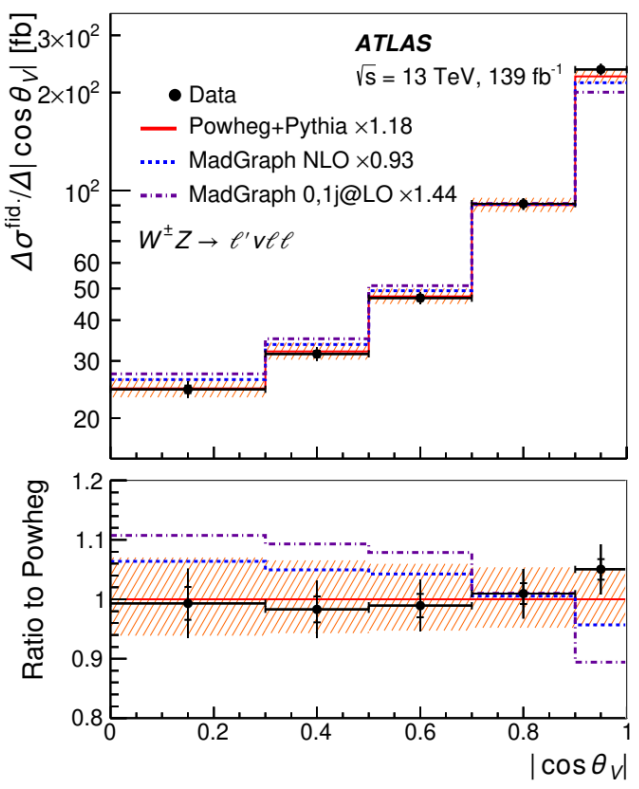
- **NLO inclusive MC** sample: Powheg+Pythia and MadGraph5_aMC@NLO+Pythia
- **Sum of LO polarised MC** MG0,1jet samples

➔ 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&Pellicioli 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 $p_z^{\nu}$ related**, to be independent from the method chosen for its reconstruction

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

**Unfolded differential cross section**

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