Observation of gauge boson joint-polarisation states in WZ production in ATLAS

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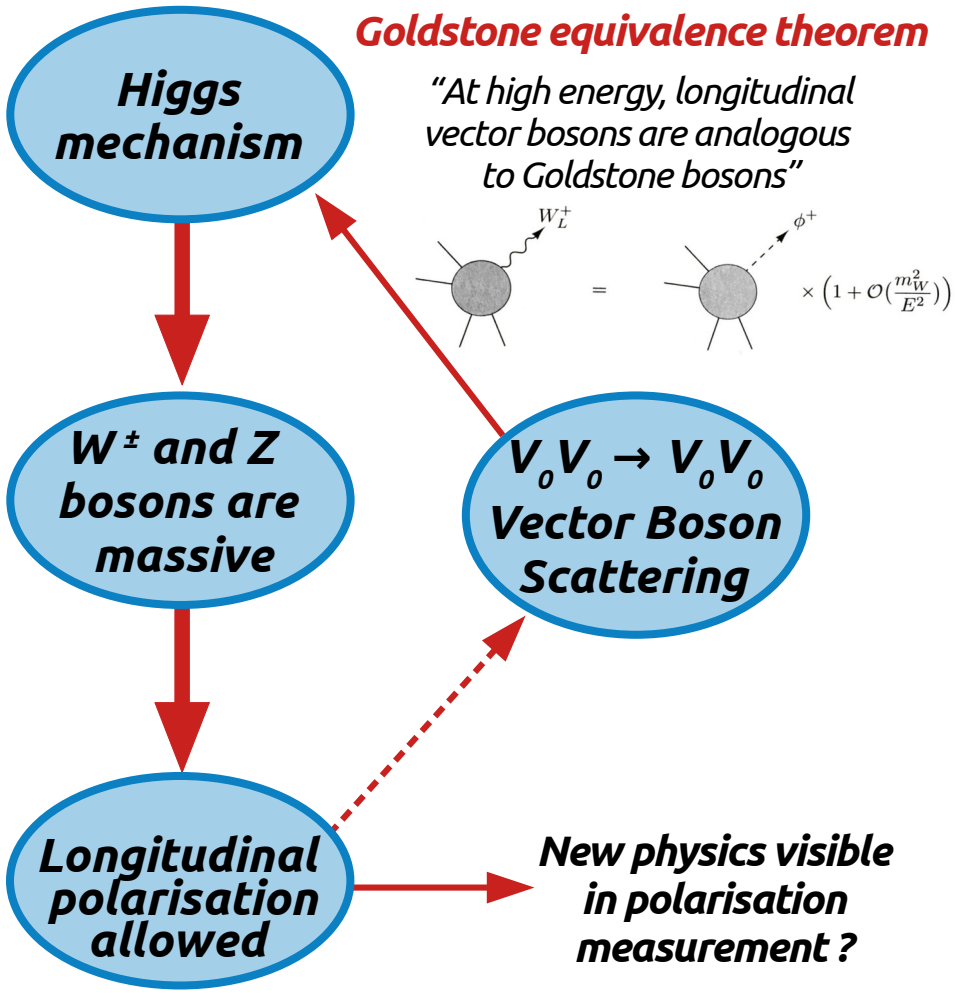
LHC EW WG - Multi Boson
Polarisation session
08/03/2023

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 at NLO QCD or NLO QCD+EW

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

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

DELPHI results

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

OPAL results

Longitudinal here noted "L"

Measurements at LHC

Diboson process chosen: p p → $W^{\pm}$ Z

➔ Best compromise between cross section and signal to background ratio

Single boson polarisation in WZ production

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

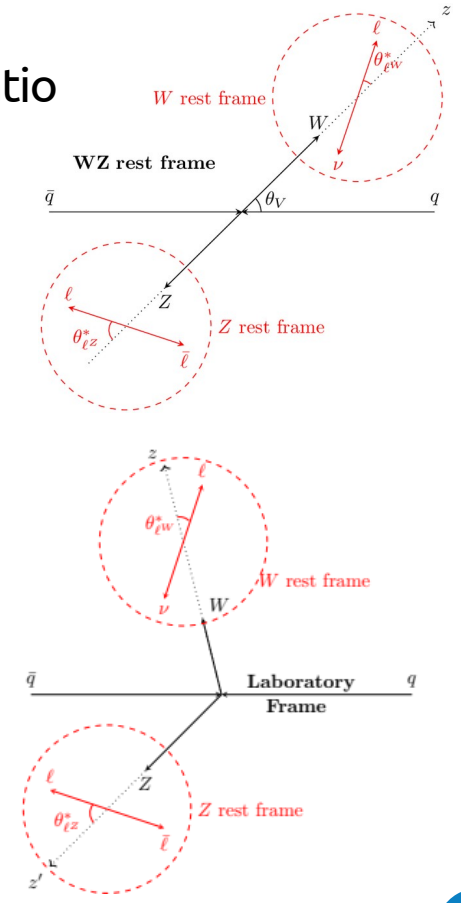
– **CMS** : in Laboratory frame, L = **137 fb^{-1}** [arXiv:2110.11231]

Recent ATLAS polarisation measurement [arXiv:2211.09435] :

– **Joint-polarisation** fractions in WZ

– Improvement on single boson polarisation fractions, L = **139 fb^{-1}**

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



Polarisation in WZ pair production

WZ inclusive production

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

Variable	Total	Fiducial inclusive
Lepton $\lvert\eta\rvert$	—	< 2.5
p_T of ℓ_Z, p_T of ℓ_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...

➔Estimated from **Monte Carlo generation**

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

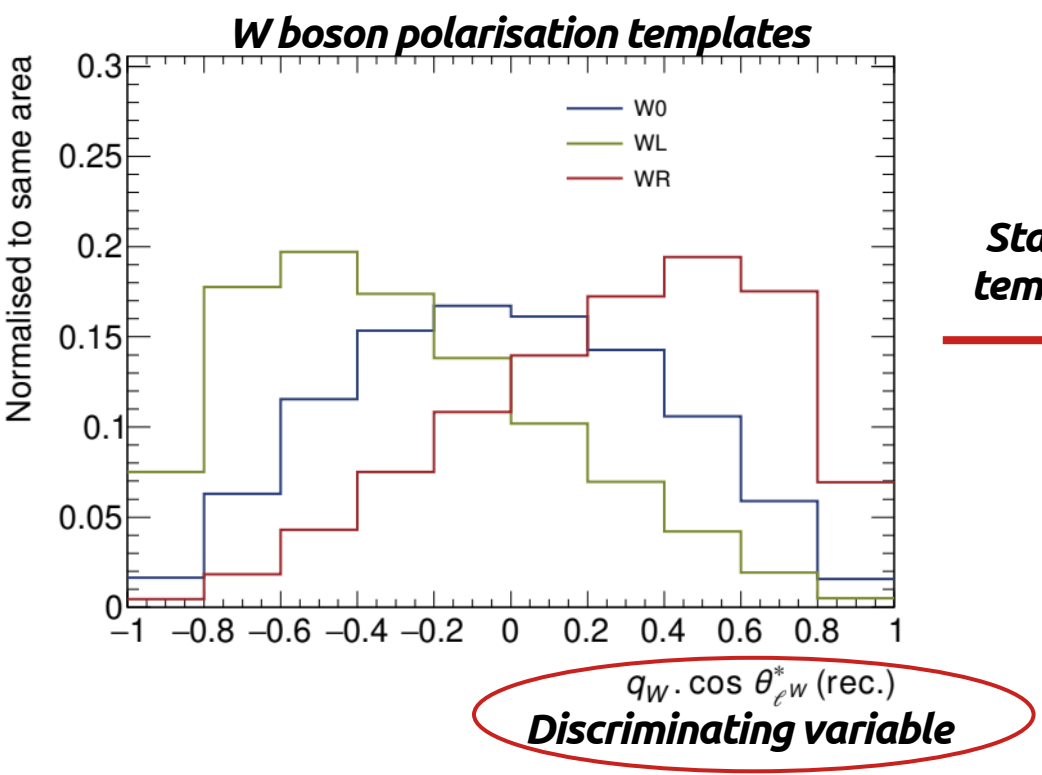
- ***« Misidentified Leptons »*** background mainly from **Z+γ, t tbar, Z+jets**

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

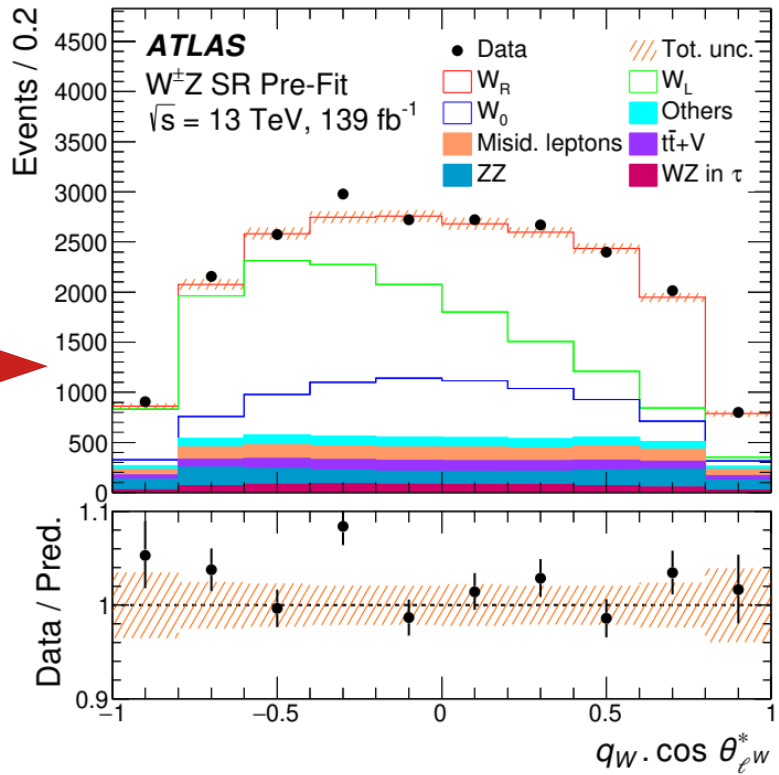
How to measure polarisation

Method : *Here for single boson polarisation measurement*

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



Stacking templates



Challenges of this analysis

- **Polarisation definition:** Not Lorentz invariant ! Need to **define a frame**

- **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**

➔ Need to **choose a frame**

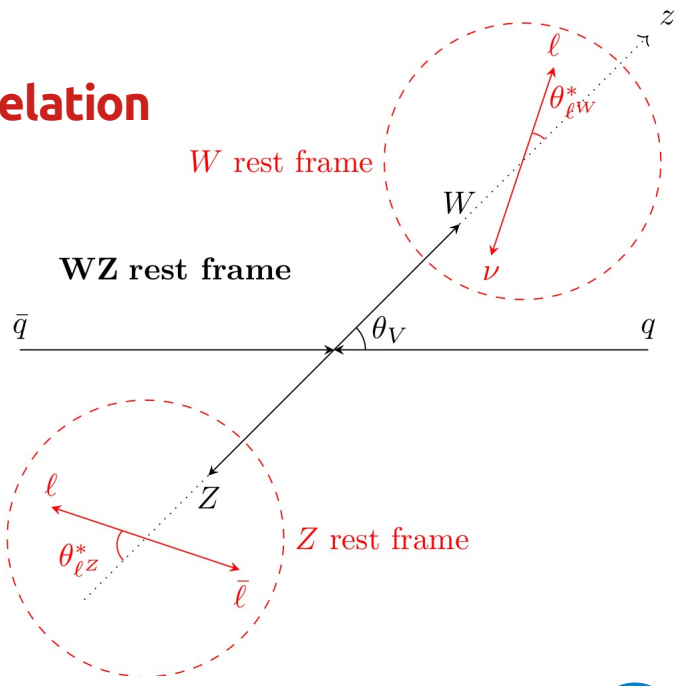
WZ rest frame for joint-polarisation and single boson polarisation *(so-called Modified Helicity frame)*

- Allow to meaningfully **compare** both
- **Longitudinal fractions** of both bosons have **maximum decorrelation**

Defined from the joint spin density matrix:

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

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

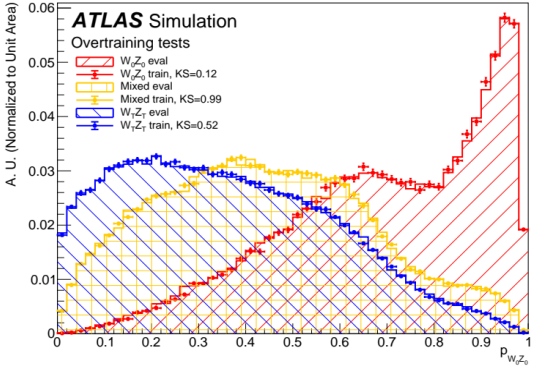


Joint-polarisation templates

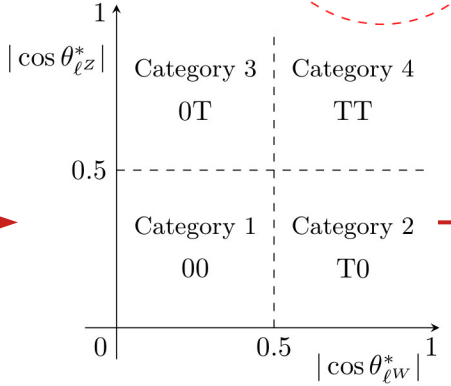
Variable for the joint-polarisation

Joint-polarisation fraction measurement:

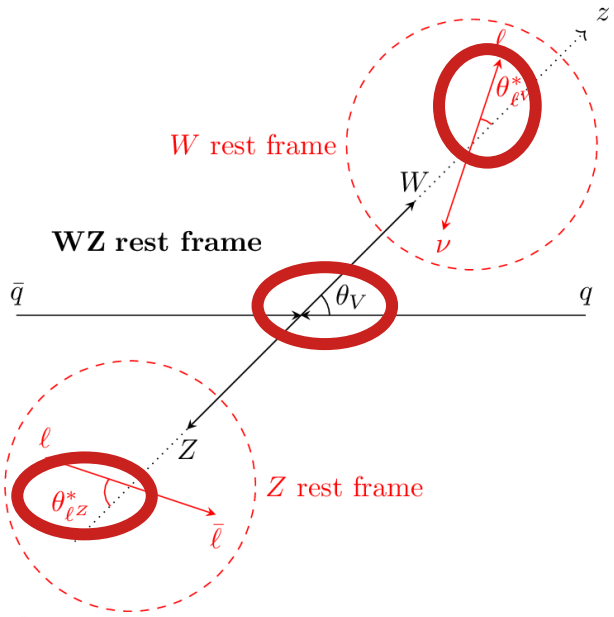
- Analytical variable **$|\cos\theta_V|$** not discriminant enough
- **Classification DNN** between all 4 joint-polarisation states: still **poorly discriminant between 0T and T0**
- Split DNN score for 00 in **4 categories** based on cosθ*



DNN score



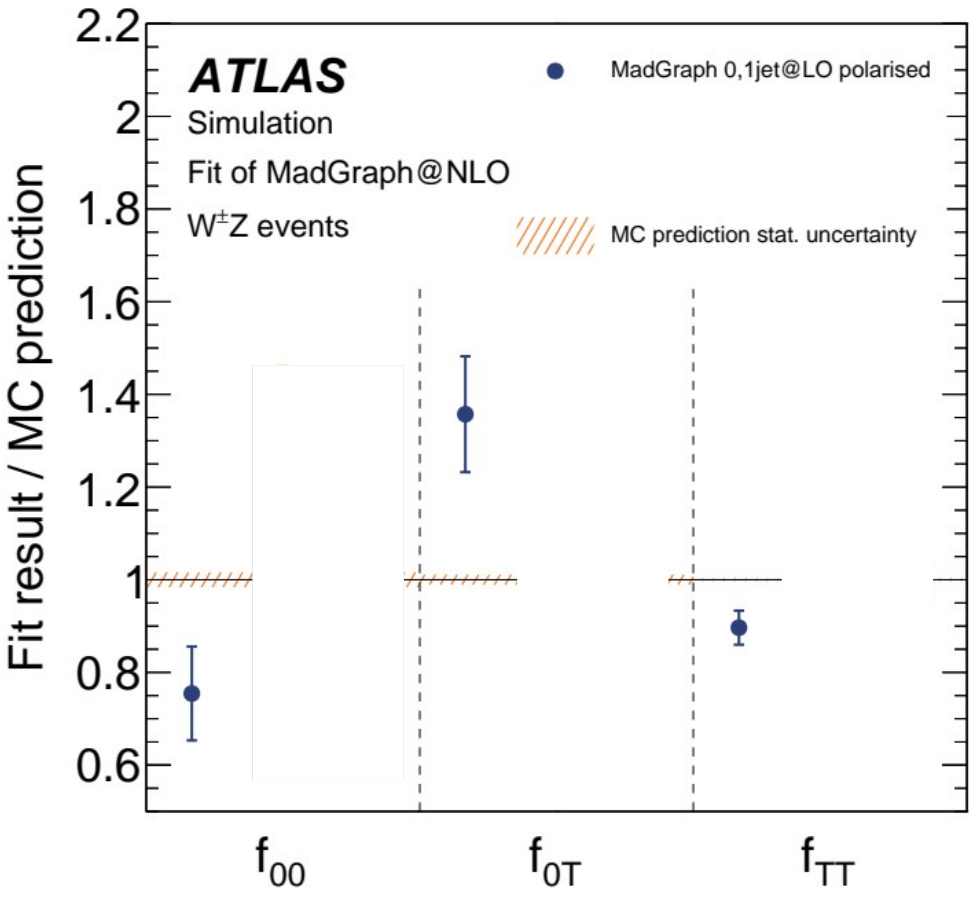
4-categories DNN score



Classification DNN input variables
(by importance)

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

Need for NLO accurate templates



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 **within the pseudo data**

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

Reweighting to theory prediction

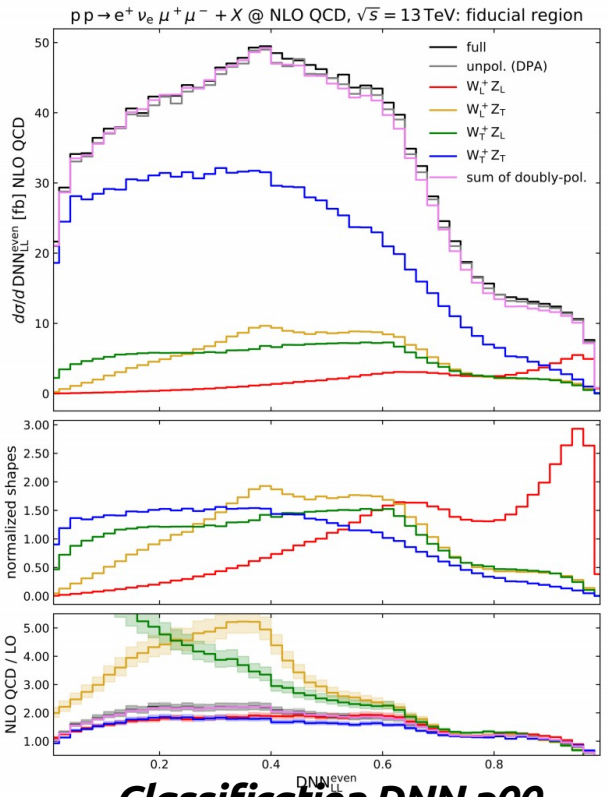
In collaboration with theorists **A. Denner, G. Pelliccioli :** Theoretical calculations [arXiv:2010.07149] performed

- in the analysis **fiducial phase** space
- **NLO QCD** polarised → at **parton level**,

➔ Several distributions including the analysis **classification DNN score**

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

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



Classification DNN p00 polarised distribution at NLO QCD

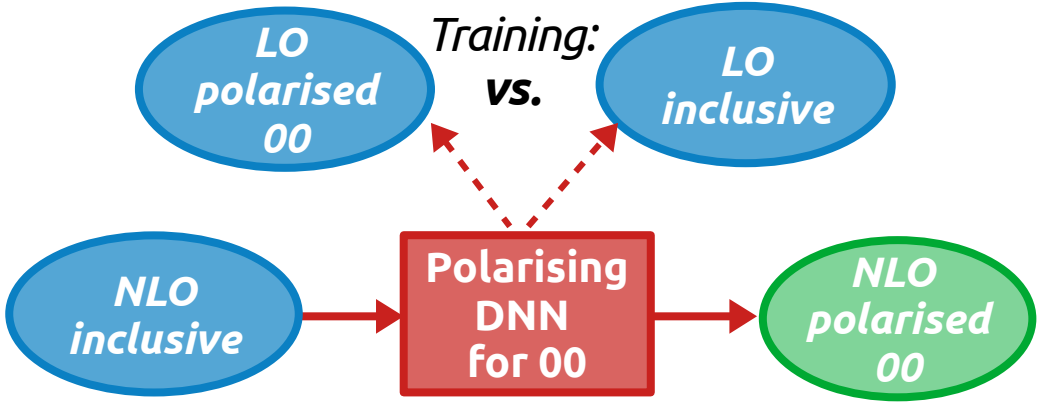
[private communication from A. Denner, G. Pelliccioli]

DNN reweighting

Possible to reweight a distribution using a DNN [arXiv:1907.08209]

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

4 DNN **trained on polarised Madgraph samples** to discriminate one joint-polarisation states against the inclusive : event-by-event output used in **reweighting**

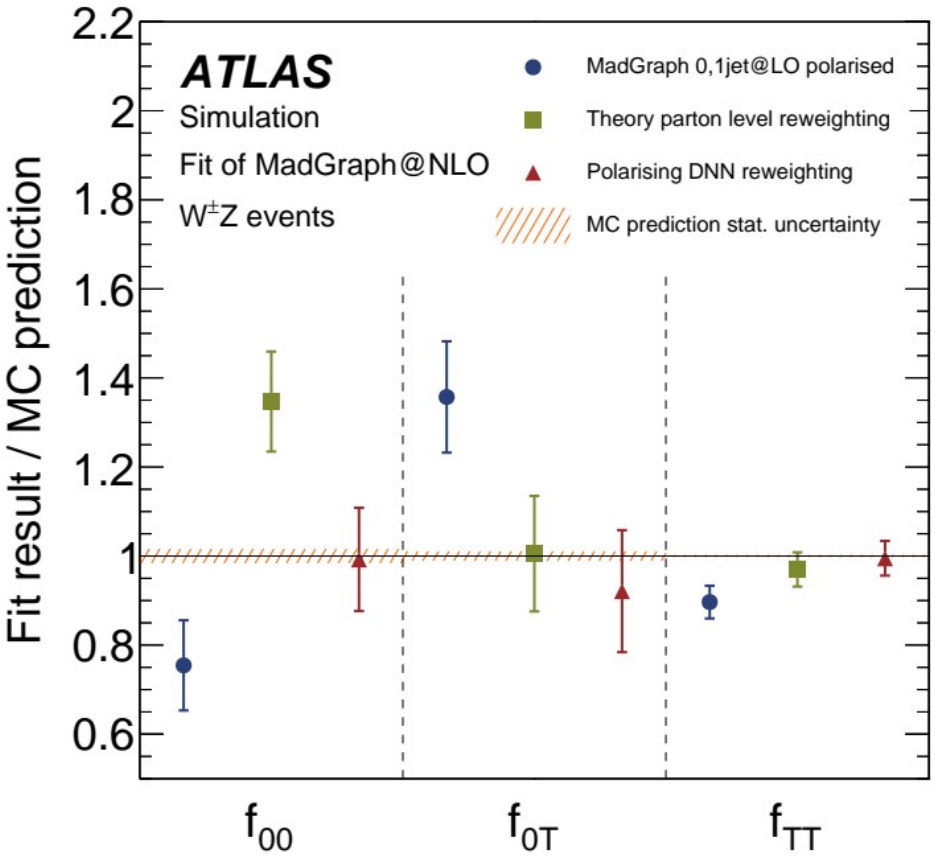


$w(x) \sim DNN(x) / (1 - DNN(x))$

$|y_{\ell,W} - y_Z|$
$p_T^{\ell,W}$
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

Choice of NLO accurate template set



Madgraph polarised generation:

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

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**

Modelling uncertainties

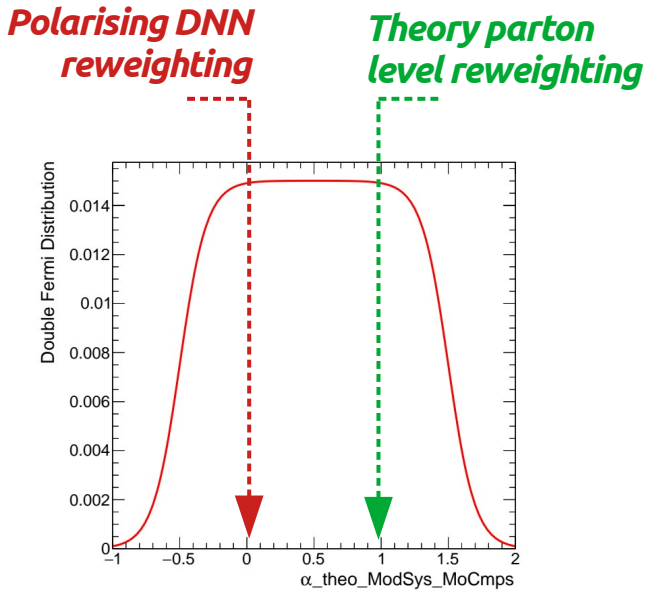
NLO QCD polarisation template set choice uncertainty:

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

➔ Shape uncertainty

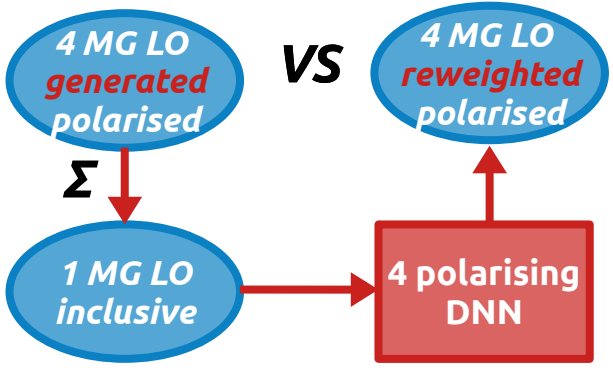
- Two point uncertainty, no privileged template

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



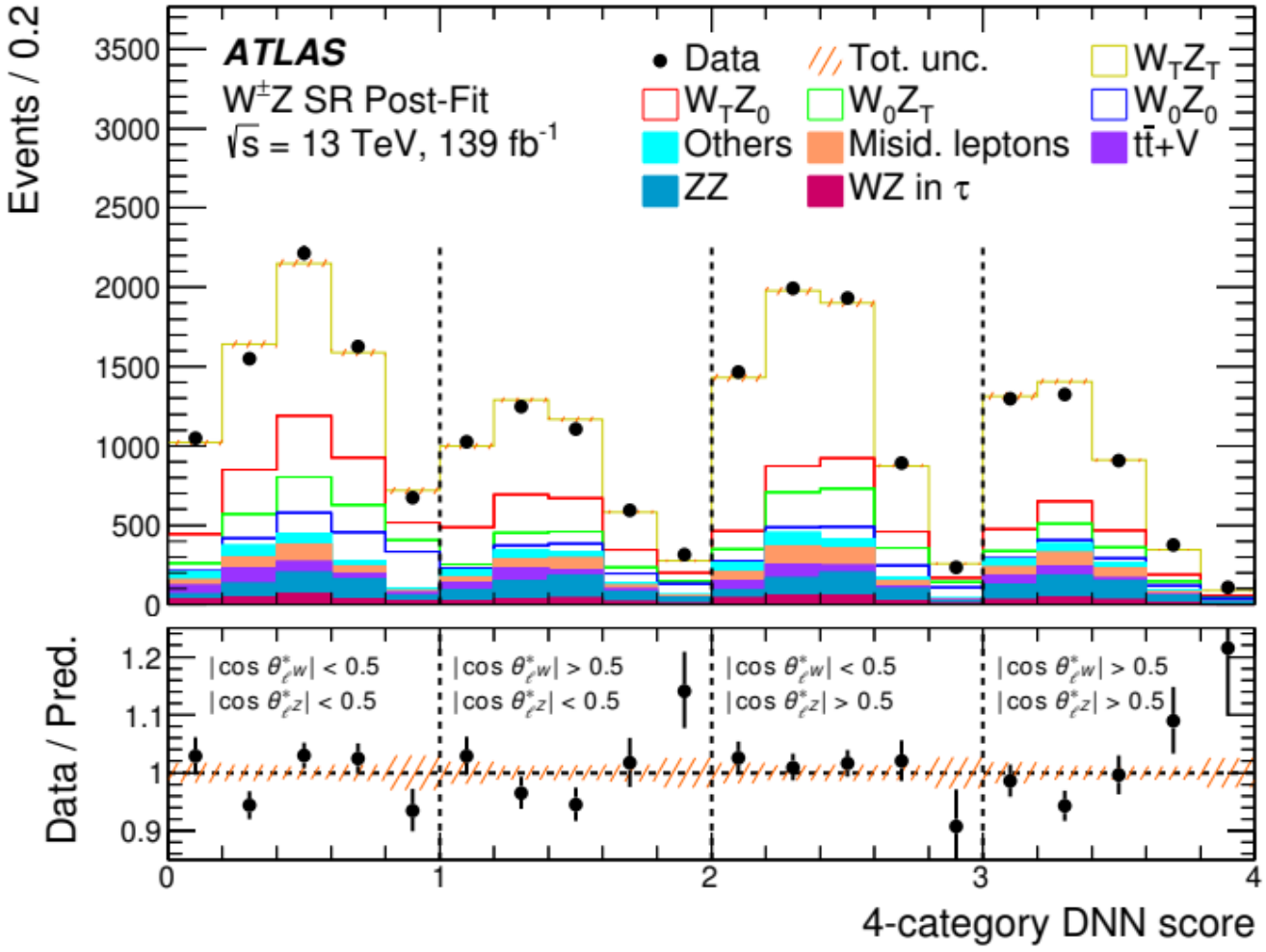
Uncertainty on the DNN **reweighting method:**

- Small non-closure used to extract uncertainty bands



Joint-polarisation measurement

Binned Maximum Likelihood Template Fit

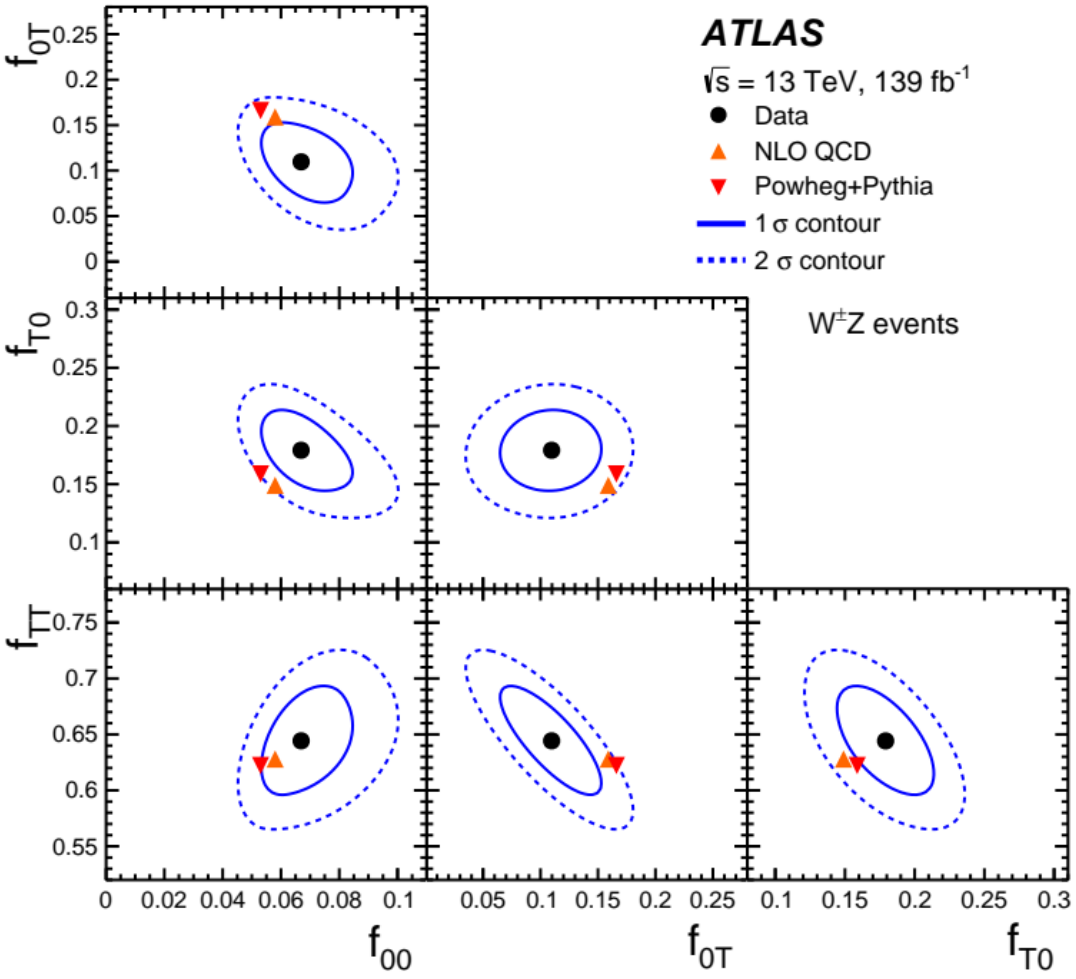


Fit parameters of interest are f_{00}, f_{0T}, f_{TT} and N_{tot} the number of signal event

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

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

Joint-polarisation CL regions



All joint-polarisation states observed

– Significance on f_{00} at **7.1σ**

– Significance on f_{TT} and f_{T0} **>5σ**

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

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

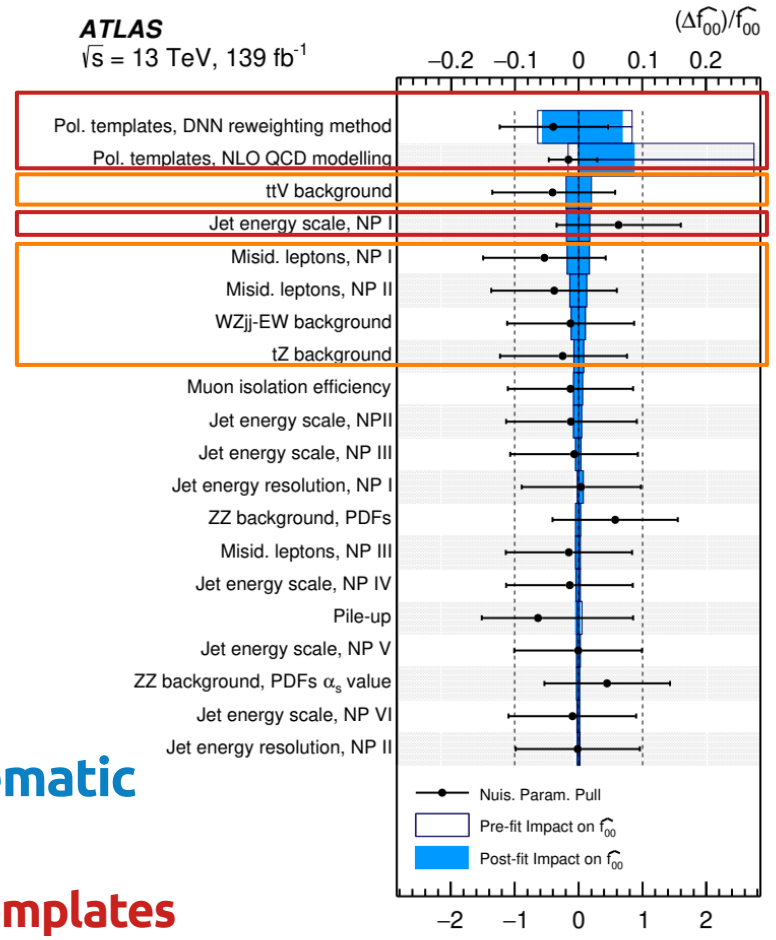
- Significance on f_{00} at **6.9σ in W+Z**
- Significance on f_{00} at **4.1σ in W-Z**

No major difference visible in the charge break down

(baring 1σ difference in f_{T0})

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
$E_{\mathrm{T}}^{\mathrm{miss}}$ 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

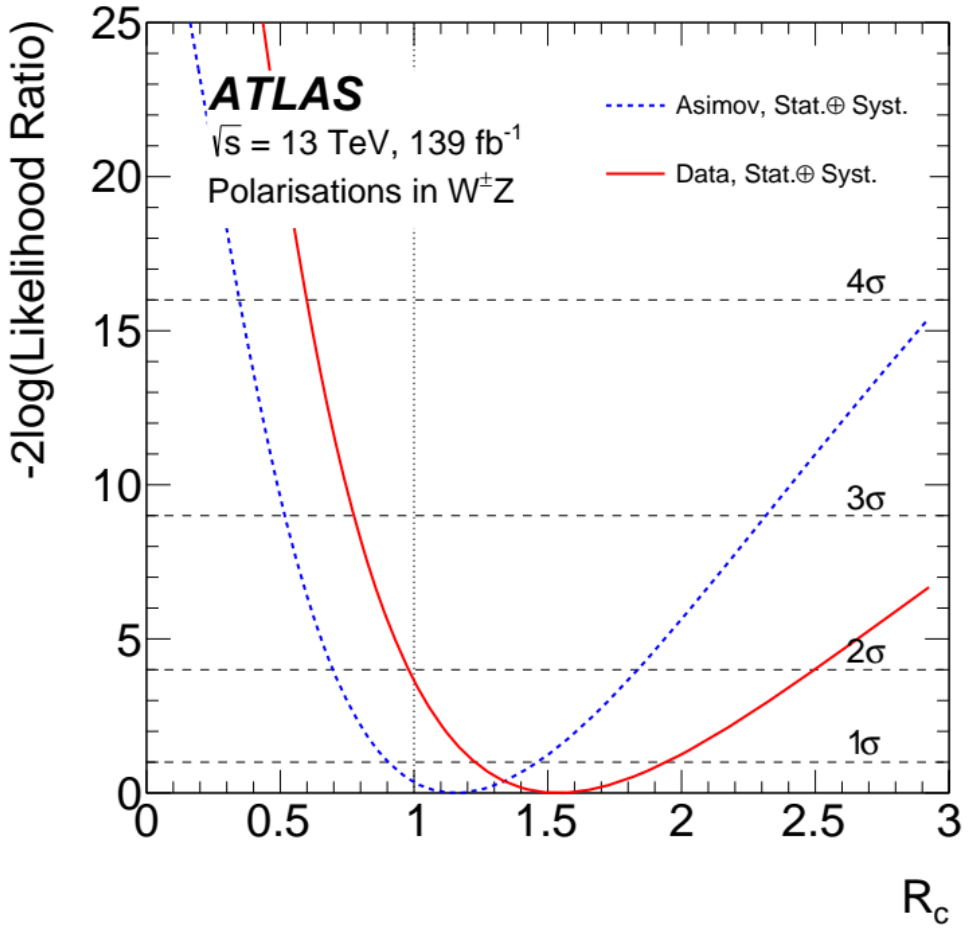


Ranking for f_{00}

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

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

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

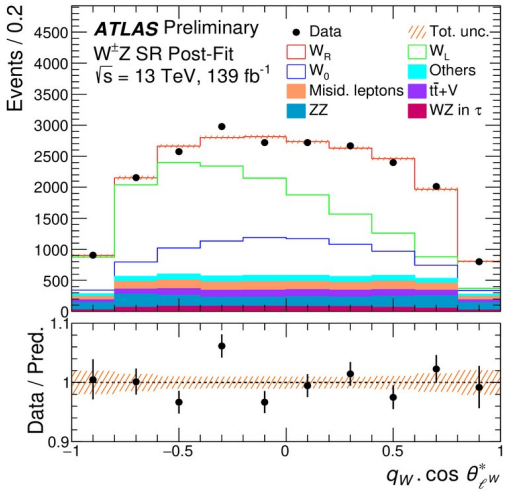
Template fit on data at detector level as for joint-polarisation

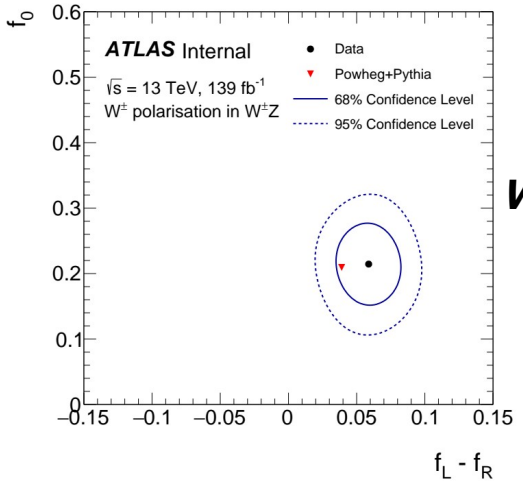
- Discriminating variables **cosθ*$_W$** and **cosθ*$_Z$**
- Polarisation templates from **analytical reweighting**

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

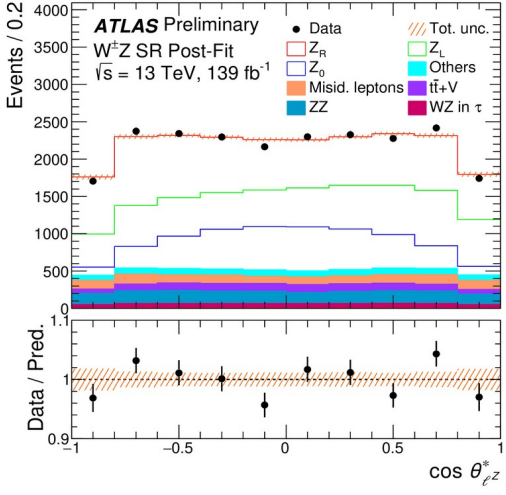
No tension with theory

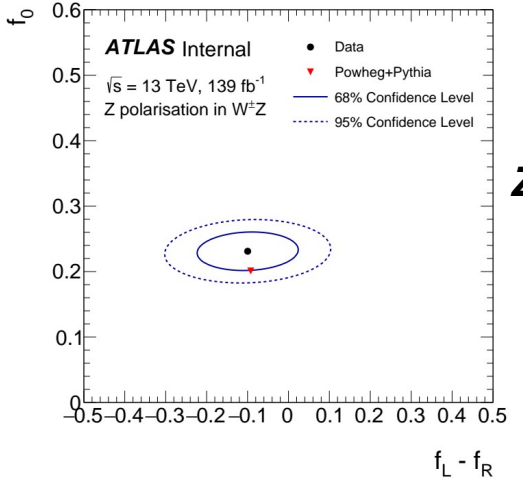
f_0 mesured with 5 sigma in charge break-down





W boson





Z boson

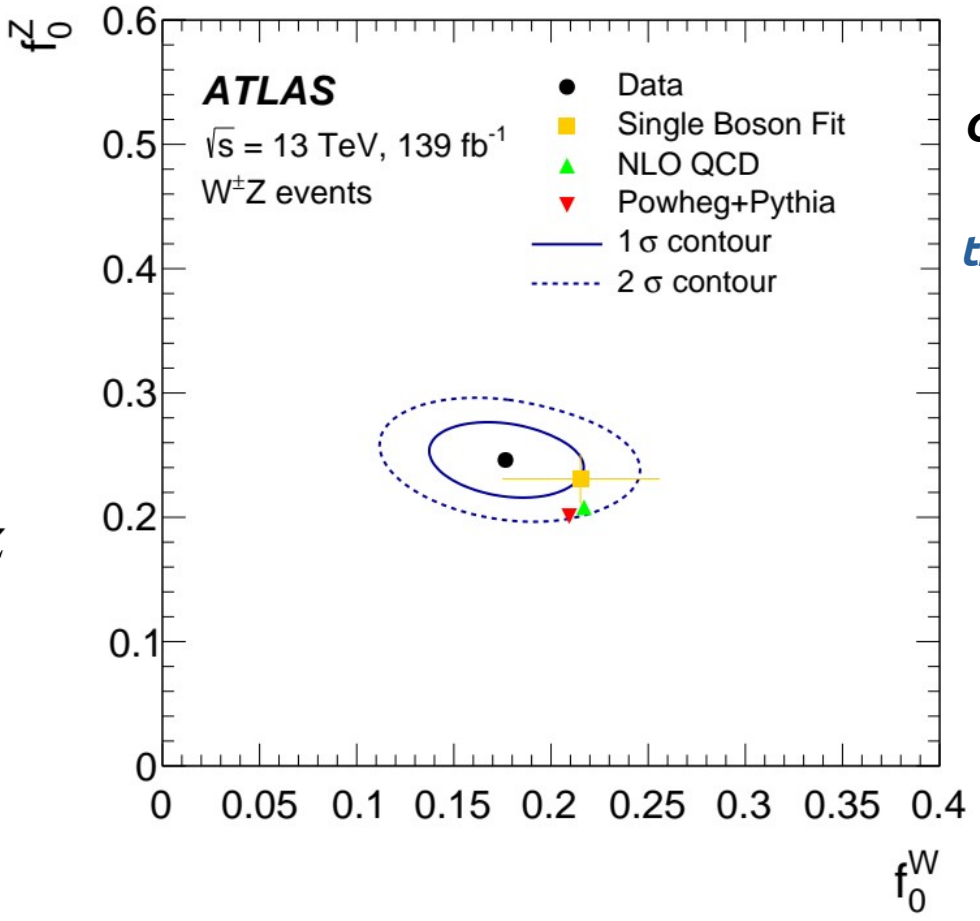
Consistency with joint-polarisation

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

CONCLUSION

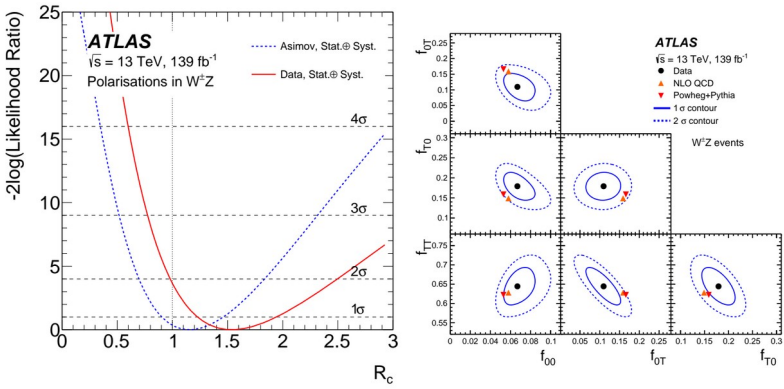
Need for **JOINT-polarisation** fraction

➔ **No independence** of single boson polarisation fractions

Need to evaluate **all fractions** simultaneously

➔ Strong **correlations between fractions**

Classification DNN

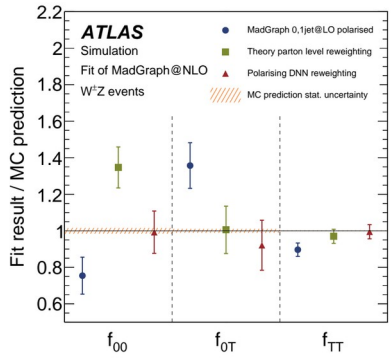


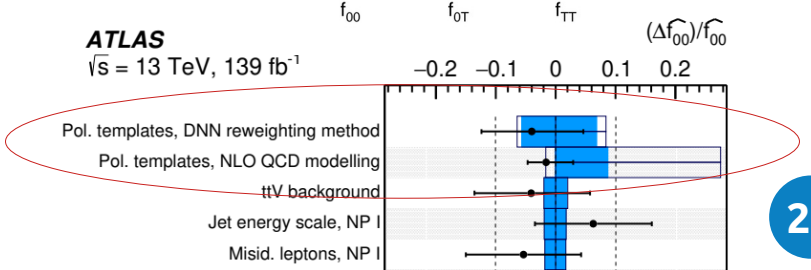
Need templates accurate to the **highest possible order in QCD**

➔ **Leading uncertainty**, bias of up to **50% on fractions values**

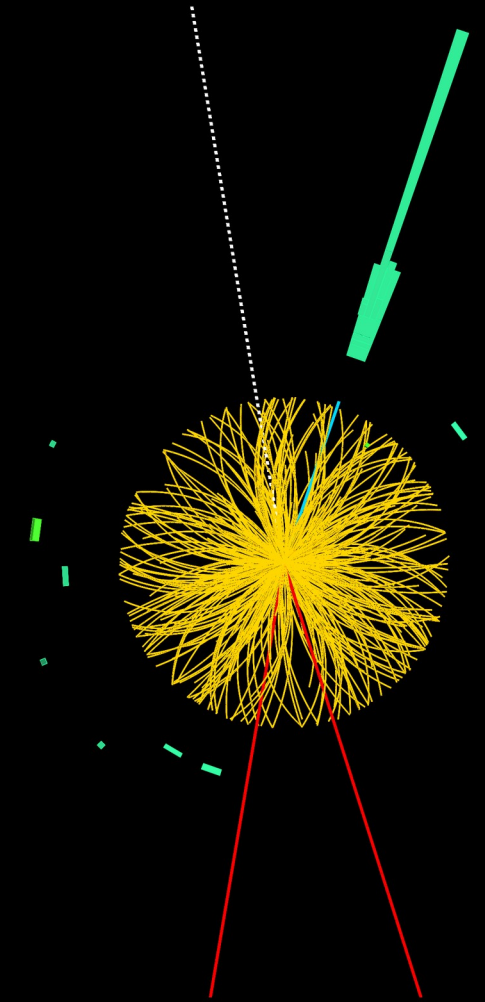
➔ Importance of the **modelling uncertainty** design

Polarising DNN reweighting





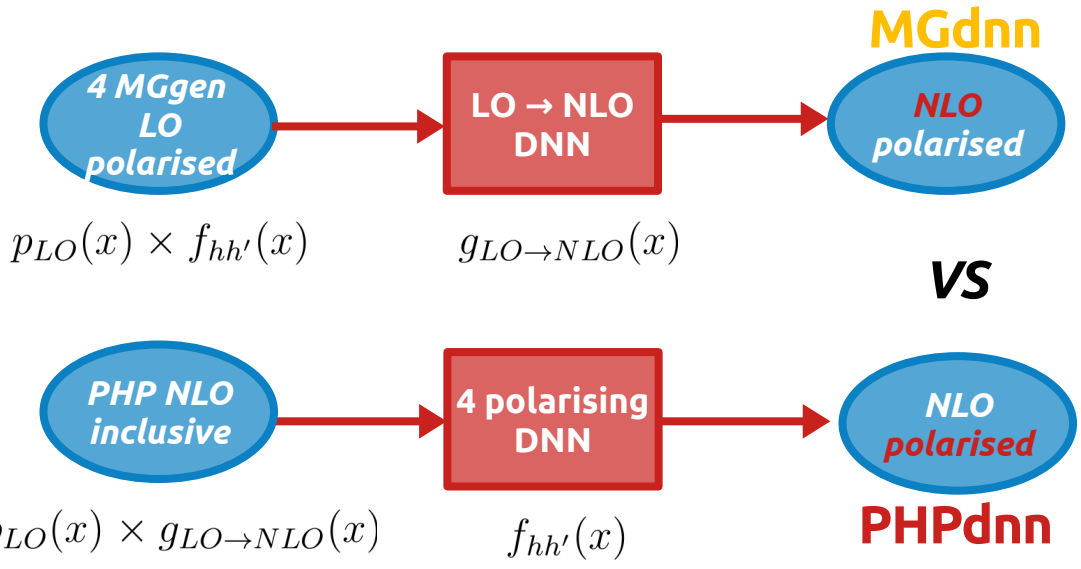
Thank you
for your attention !



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**

ATLAS and CMS differences

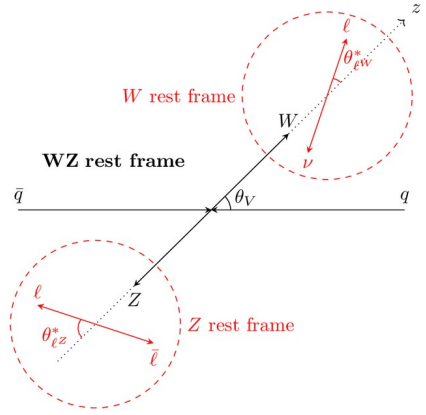
	ATLAS	CMS
Total p.s. (MC generation)	$66 < M_Z < 116$ [GeV]	$60 < M_Z < 120$ [GeV]
Measurement frame	Modified Helicity	Helicity
p_z^ν reconstruction	DNN-based	Analytical ($P_W^2 = M_W^2$)
Event yield	21936	10729
WZ signal/Backgrounds	≈ 4	≈ 5
Measured value p.s.	Fiducial	Total

Different event selection

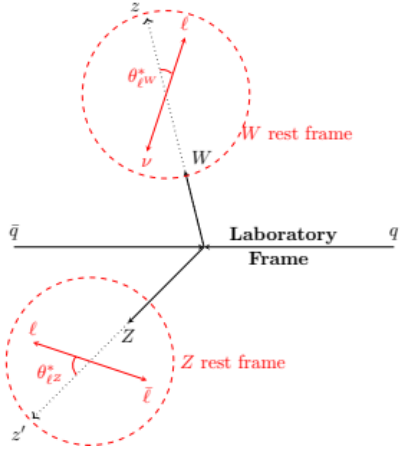
ATLAS fiducial phase space

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

Modified Helicity frame



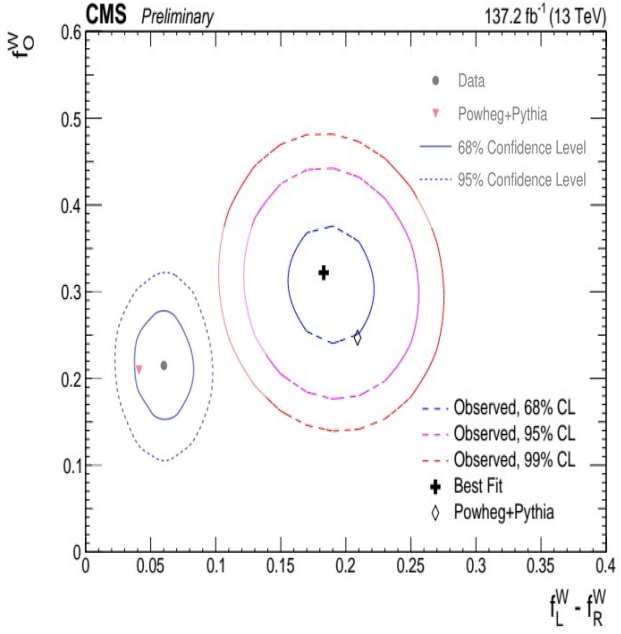
Helicity frame

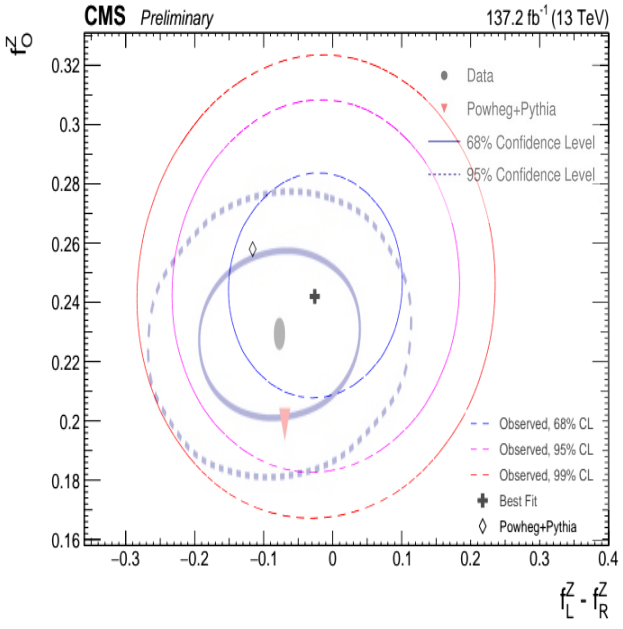


ATLAS and CMS comparison

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

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:**

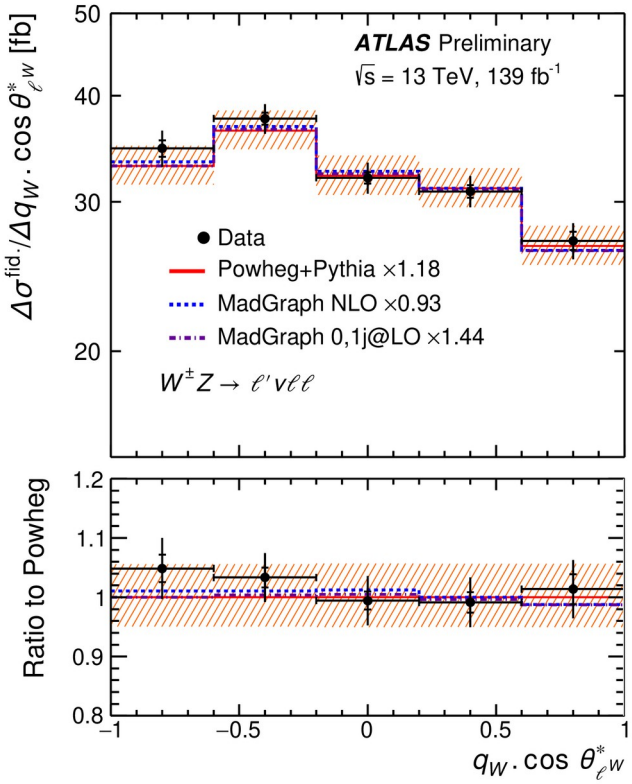
➔ $\cos\theta^*_W$, $\cos\theta^*_Z$, $|\cos\theta_V|$

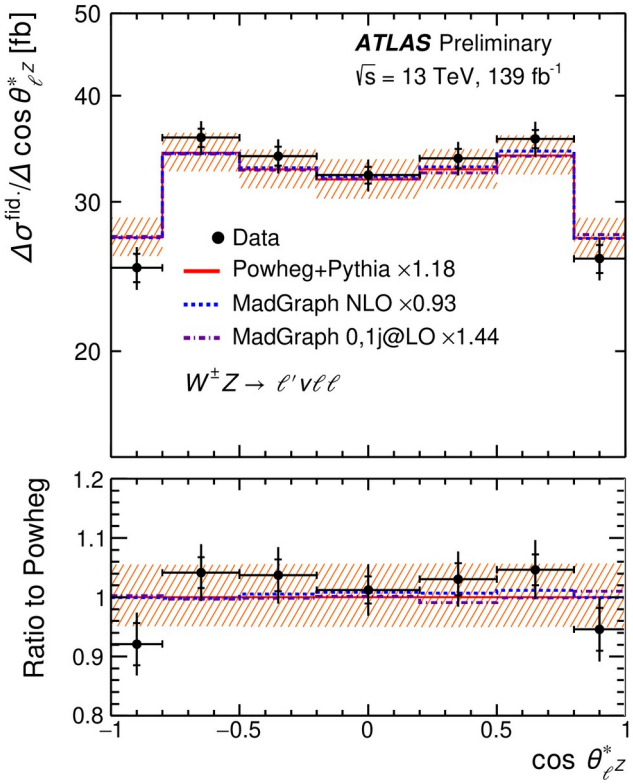
Compared to Born level **predictions** from

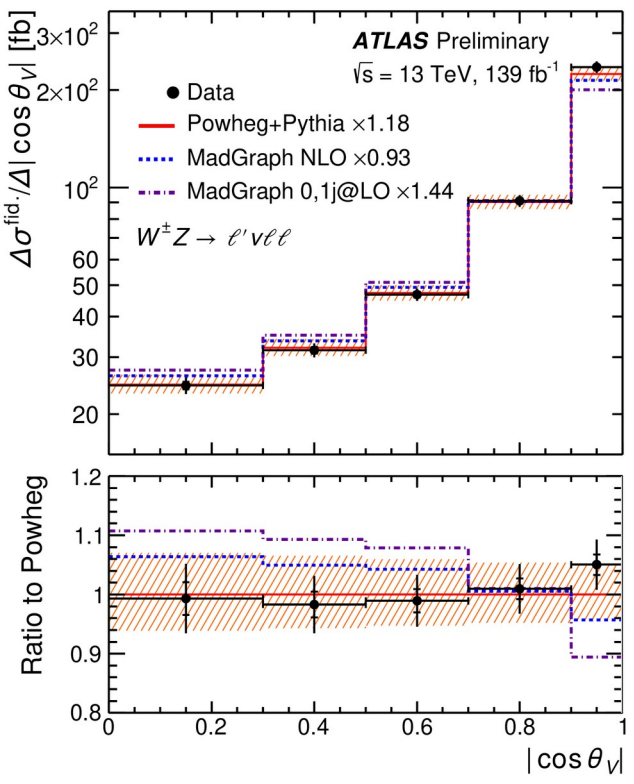
- **NLO inclusive MC** sample: Powheg+Pythia and MadGraph5_aMC@NLO+Pythia
- **Sum of LO polarised MC** MG0,1jet samples

➔ 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^{ν} 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