Multi-boson production and diboson polarisation at ATLAS

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Introduction

Multi-boson processes as a **sensitive probe of Standard Model**

→ Electroweak **gauge coupling** sector

→ **Polarisation** of massive Spin 1 vector boson

Analysis presented here: ATLAS results using Run 2 data

– Measurements of Zγ+ jets differential cross sections in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector [ATLAS-CONF-2022-047]

– Combined effective field theory interpretation of Higgs boson and weak boson production and decay with ATLAS data and electroweak precision observables [ATL-PHYS-PUB-2022-037]

– Observation of gauge boson joint-polarisation states in $W^{\pm}Z$ production from pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector [ATLAS-CONF-2022-053]

Zγ+jets differential cross sections

[ATLAS-CONF-2022-047]

Zγ+jets events

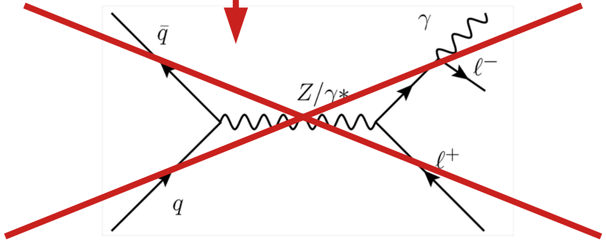
Study differential cross sections for Zγ+jets events

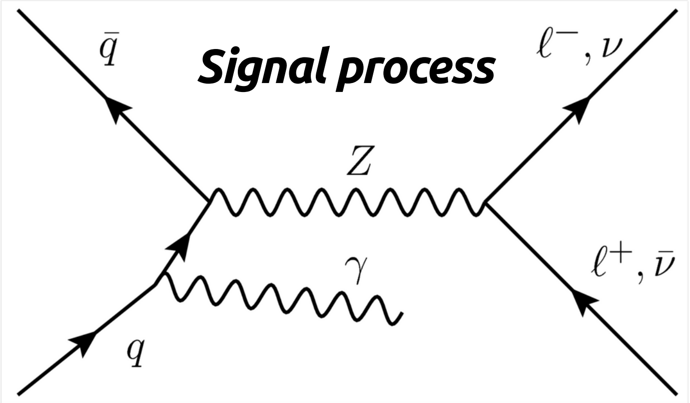
➔ Provide a **sensitive test of QCD predictions** (jet activity, parton shower predictions,…)

Event selection: select hard photon from **Initial State Radiation**

Observable	Signal Region	$t\bar{t}\gamma$ Control Region
Number of signal leptons	2 Opposite Sign, Same Flavour	2 Opposite Sign, Different Flavour
Lepton	$p_T(\ell_1) > 30$ GeV, $p_T(\ell_2) > 25$ GeV	
Photon	≥ 1 photon with $p_T^\gamma > 30$ GeV	
$m_{\ell\ell}$	> 40 GeV	
$m_{\ell\ell} + m_{\ell\ell\gamma}$	> 182 GeV	

~ $2\,M_Z$





Variables for differential cross section

Hard scale

Sensitive to perturbative QCD

Precise modelling needed for Zγjj EW search

1D Differential cross section

– **Z and γ variables:** p_T^{ll}, $\Delta R(l,l)$, $p_T^{ll}+p_T^{\gamma}$, $p_T^{ll}-p_T^{\gamma}$

– **Jet variables:** N_{jets}, p_T^{jet1}, p_T^{jet2}, p_T^{jet2}/p_T^{jet1}, $H_T=\Sigma$ all p_T, $p_T^{\gamma}/\sqrt{H_T}$, $\Delta\Phi(jet,\gamma)$, $p_T^{ll\gamma j}$, m_{jj}, $m_{ll\gamma j}$

Sensitive to QCD higher order & soft radiations

Sensitive to limits of PS effects and Sudakov resummation

Sensitive to PS corrections

– **Angular variables** sensitive to Z boson polarisation: $\cos\theta_{CS}$ and Φ_{CS} in bins of p_T^{ll}

2D Differential cross section:

➔ ***resolution* variable** in large bins of **hard scale** variable (different hard scale regime)

– Sudakov logarithm terms: $p_T^{ll\gamma}/m_{ll\gamma}$ in bins of $m_{ll\gamma}$

– Additionnal QCD emissions: $p_T^{ll}-p_T^{\gamma}$ in bins of $p_T^{ll}+p_T^{\gamma}$ and $p_T^{ll\gamma j}$ in bins of $p_T^{ll\gamma}$

Unfolding

Main backgrounds : **Z+jets**, **Pile-up**, **ttγ**

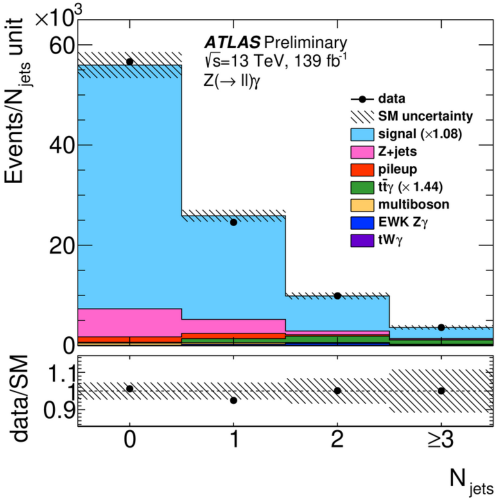
➔ Estimated with data driven methods

Differential cross sections: **unfolding** using an **Iterative Bayesian method**

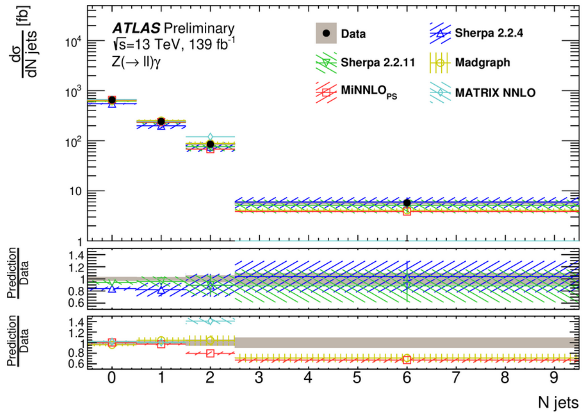
Main uncertainties from **backgrounds** and **jet** reconstruction

N_{Jet}	0	1	2	> 2
Source	Uncertainty [%]			
Electrons	1.0	0.9	0.8	0.8
Muons	0.3	0.3	0.3	0.4
Jets	1.7	1.7	4.5	8.8
Photons	1.4	1.3	1.3	1.2
Pile-up	2.1	0.8	0.2	0.3
Background	1.8	1.8	3.0	4.4
Stat. MC	0.1	0.2	0.3	0.4
Stat. data	0.8	1.5	1.8	1.9
Luminosity	1.7	1.7	1.7	1.7
Theory	0.6	0.2	1.4	1.0
Total	4.2	3.8	6.3	10.3

Detector level



Unfolded particle level



Theory predictions from 5 sources:

– Sherpa 2.2.4 and 2.2.11, Madgraph : **NLO/LO ME + PS**

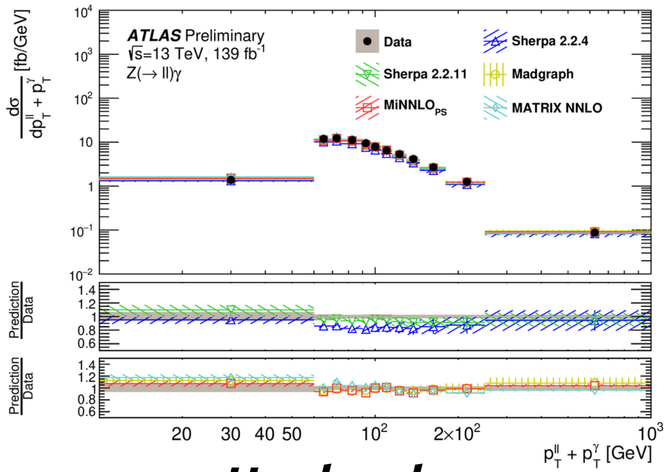
– MATRIX **NNLO fixed order** calculation

– Powheg NLO + **MiNNLO**

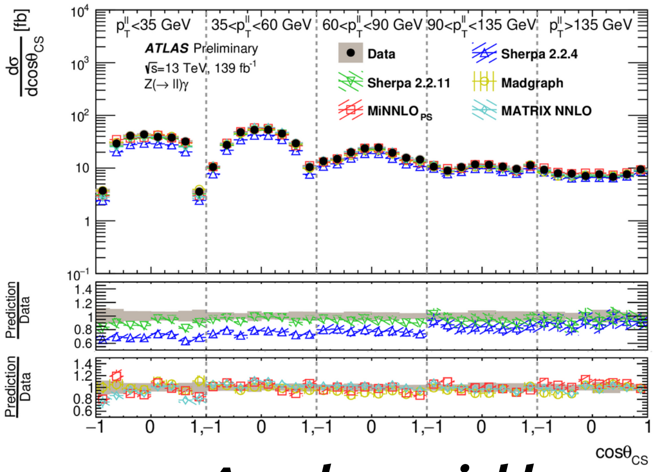
Results

No tension with theory in all differential cross sections

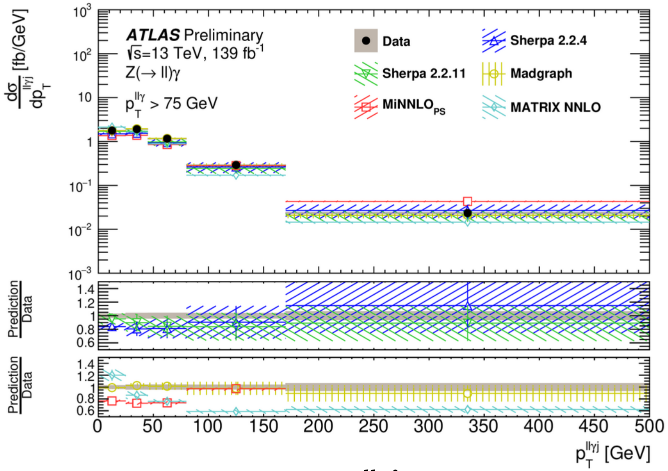
- **Jet activity generally well described**
- Act more as a test of the different theory prediction methods
  - Sherpa 2.2.11 better than Sherpa 2.2.4: benefits from NLO 0,1j ME
  - MiNNLO performs better than MATRIX, struggles in high energy bin



Hard scale
$p_T^{ll}+p_T^{\gamma}$



Angular variable
$\cos\theta_{CS}$



$p_T^{ll\gamma j}$
in highest bin of $p_T^{ll\gamma}$

Combined EFT interpretation

[ATL-PHYS-PUB-2022-037]

Effective Field Theory

Idea: Interpret **simultaneously** multiple measurements on **Higgs processes**, **multiboson processes**, and **electroweak precision observables** in term of **EFT**.

Effective Field Theory as an **extension** to the Standard: $\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \ldots$

- Only even terms conserve leptonic/baryonic number, **stop at dim 6**

Standard Model | *Linear term* | *Quadratic term* | *Dim 8 coefficients not considered*

$$|\mathcal{A}_{\text{SMEFT}}|^2 = |\mathcal{A}_{\text{SM}}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2\text{Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_{\text{SM}}^*\right) + \sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4} |\mathcal{A}_i^{(6)}|^2 + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2\text{Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_j^{(6)*}\right) + \sum_i \frac{c_i^{(8)}}{\Lambda^4} 2\text{Re}\left(\mathcal{A}_i^{(8)} \mathcal{A}_{\text{SM}}^*\right) + \mathcal{O}\left(\frac{1}{\Lambda^6}\right)$$

- With some additionnal symmetries (flavour, CP etc.) : **59 Wilson coefficients** considered

➔Any measured observable can be parametrised in term of Wilson coefficients:

$$O_b = O_b^{\text{SM}} \left(1 + \sum_i A_{bi} c_i + \sum_i B_{bi} c_i^2 + \sum_{i<j} C_{bij} c_i c_j\right)$$

- **Assumption**: Wilson coefficient do not affect acceptance, efficiency, backgrounds

➔ **Consider unfolded results**

Input measurements

Higgs processes: ATLAS Run 2 dataset

➔ Simplified Template Cross Section as a partition of the phase space of each Higgs production process

Decay channel	Target Production Modes
$H \to \gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$
$H \to ZZ^*$	ggF, VBF, $WH, ZH, t\bar{t}H\,(4\ell)$
$H \to WW^*$	ggF, VBF
$H \to \tau\tau$	ggF, VBF, $WH, ZH, t\bar{t}H\,(\tau_{\text{had}}\tau_{\text{had}})$
$H \to b\bar{b}$	WH, ZH VBF $t\bar{t}H$

MultiBoson electroweak processes: ATLAS (partial) Run 2 dataset

➔ Differential cross section of a given observable for each process

	Process	Important phase space requirements	Observable
WW	$pp \to e^{\pm}\nu\mu^{\mp}\nu$	$m_{\ell\ell} > 55\,GeV,\ p_T^{\text{jet}} < 35\,GeV$	$p_T^{\text{lead. lep.}}$
WZ	$pp \to \ell^{\pm}\nu\ell^{+}\ell^{-}$	$m_{\ell\ell} \in (81, 101)\,GeV$	m_T^{WZ}
ZZ	$pp \to \ell^{+}\ell^{-}\ell^{+}\ell^{-}$	$m_{4\ell} > 180\,GeV$	m_{Z2}
VBF Z	$pp \to \ell^{+}\ell^{-}jj$	$m_{jj} > 1000\,GeV,\ m_{\ell\ell} \in (81, 101)\,GeV$	$\Delta\phi_{jj}$

Electroweak Precision Observables: LEP and **SLC** data

➔ 8 precision observables

Observable
Γ_Z [MeV]
R_ℓ^0
R_c^0
R_b^0
$A_{FB}^{0,\ell}$
$A_{FB}^{0,c}$
$A_{FB}^{0,b}$
σ_{had}^0 [pb]

$$R_\ell^0 = \frac{\Gamma_{\text{had}}}{\Gamma_{\ell\ell}} \qquad R_q^0 = \frac{\Gamma_{qq}}{\Gamma_{\text{had}}}$$

$$A_{\text{FB}} = \frac{N_F - N_B}{N_F + N_B}$$

$$\sigma_{\text{had}}^0 = \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{\text{had}}}{\Gamma_Z^2}$$

Overlap:

➔ Only for **inclusive pp → 4l** vs **H → 4l** , dealt with cut on m_{4l} in inclusive

Statistical Model

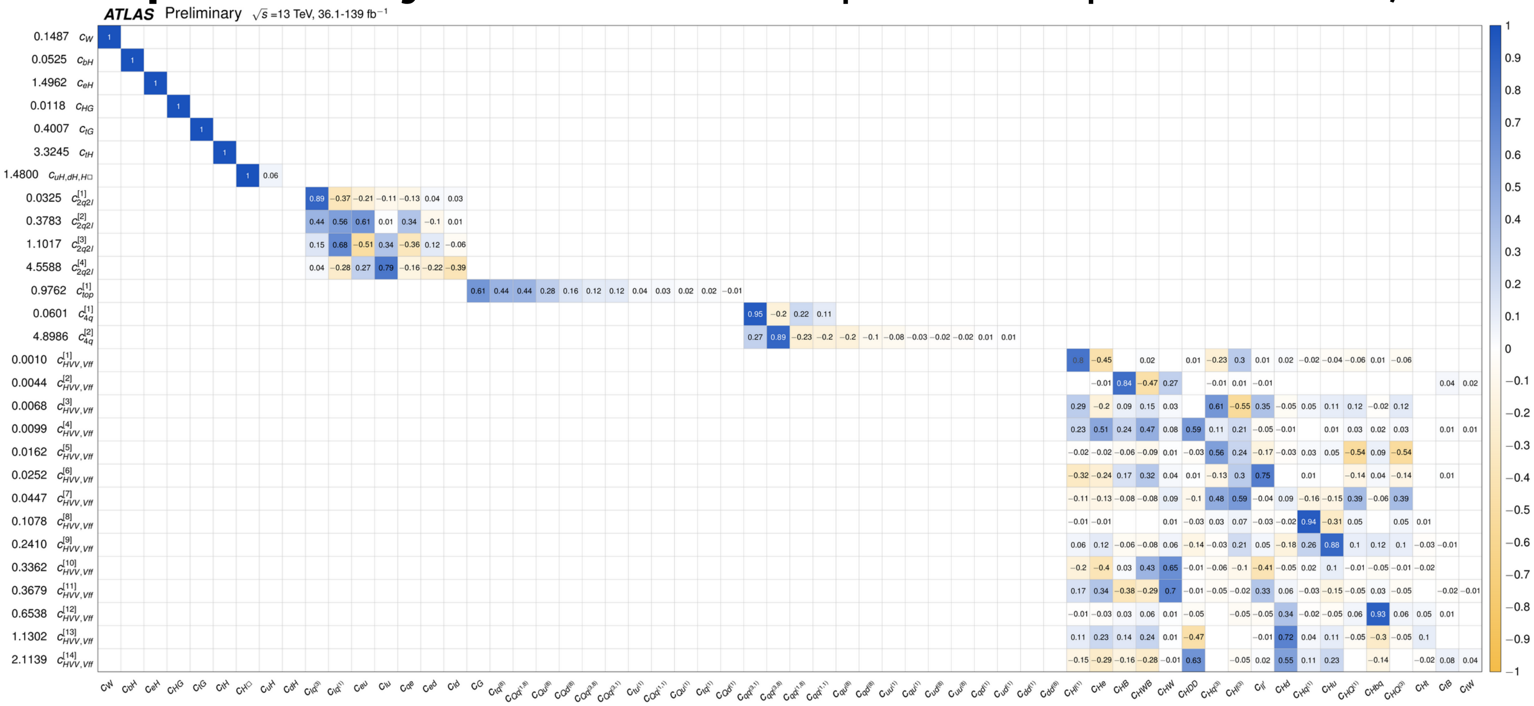
Combined Likelihood for all input measurements **parametrised by c_i**

$$O_b = O_b^{\mathrm{SM}} \left(1 + \sum_i A_{bi} c_i + \sum_i B_{bi} c_i^2 + \sum_{i<j} C_{bij} c_i c_j \right)$$

– Data **not enough to constrain all directions** in parameter space

➔ numerical problem for the fit

➔ **Principal component analysis: 28 directions** in parameter space identified, rest **set at 0**

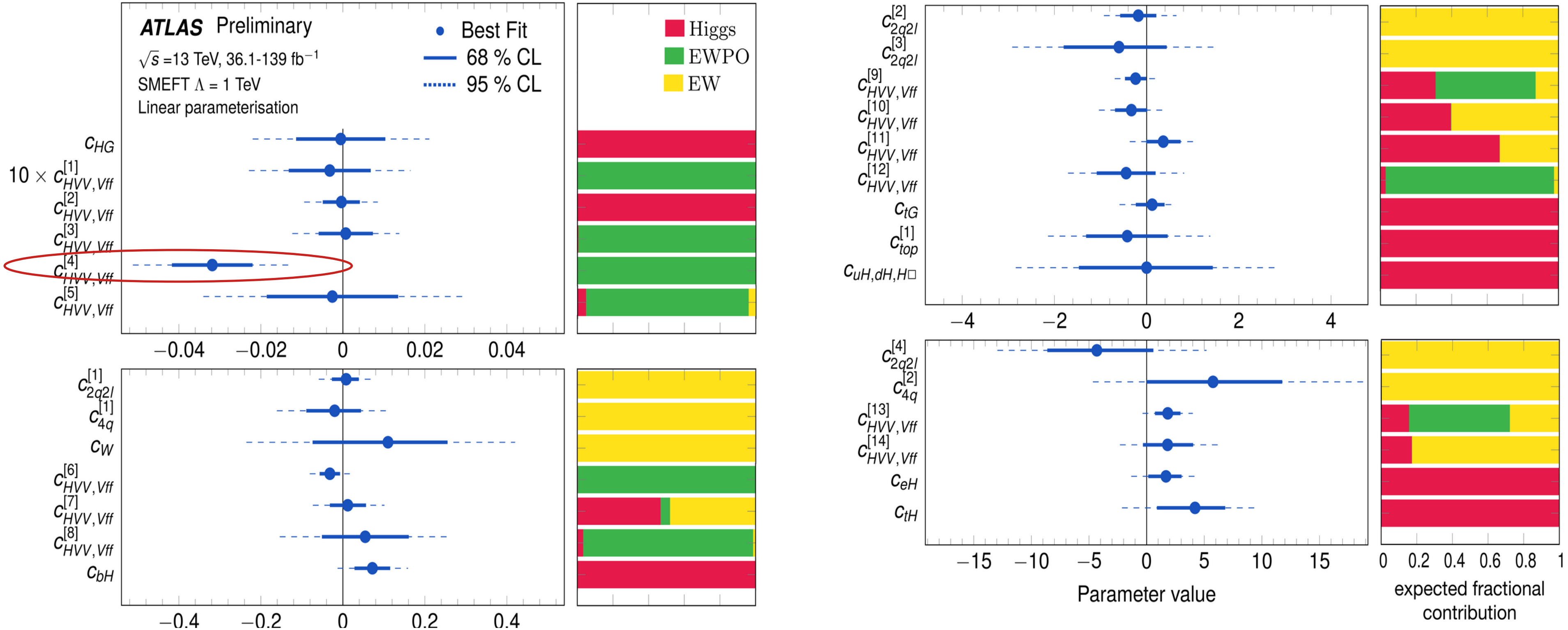


Results

With **linear parametrisation** only:

➔ Most coefficients agree within 2σ with SM expectation of 0

➔ $C^{[4]}_{HVV,Vff}$ driven by discrepancy $A_{FB}^{0,b}$ and $A_{FB}^{0,c}$ in LEP-SLC data



Joint-polarisation observation

[ATLAS-CONF-2022-053]

Diboson polarisation status

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: OPAL** [arXiv:0009021], **DELPHI** [arXiv:0908.1023]

➔ Never reached observation level sensitivity for longitudinal-longitudinal joint-polarisation

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}:**

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

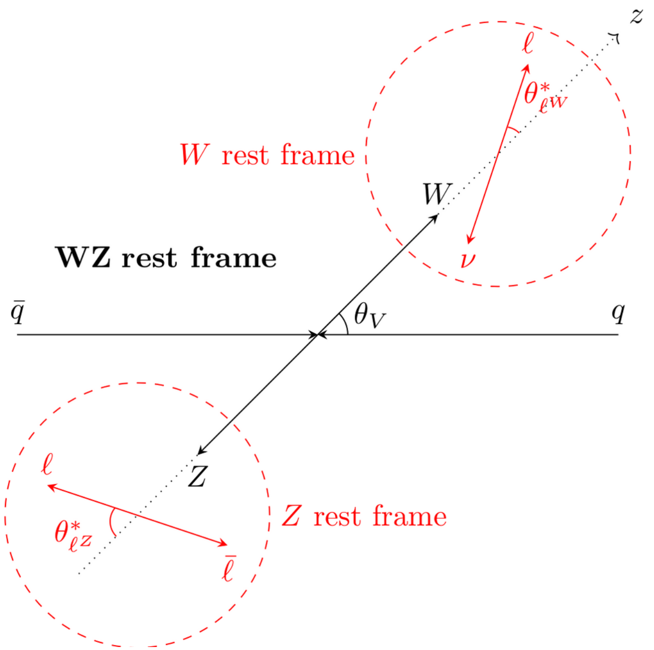
Polarisation fractions in WZ production

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

Polarisation defined from the joint spin density matrix:

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

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



Polarisation fractions are **NOT Lorentz invariant:**

➔ Need to **choose a frame**

WZ rest frame for joint-polarisation and single boson polarisation

– Allow to meaningfully **compare** both

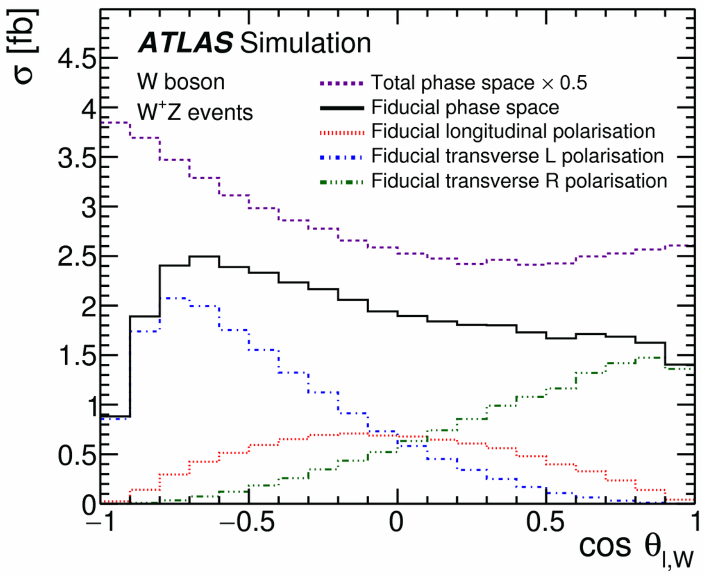
– **Longitudinal fractions** of both bosons have **maximum decorrelation**

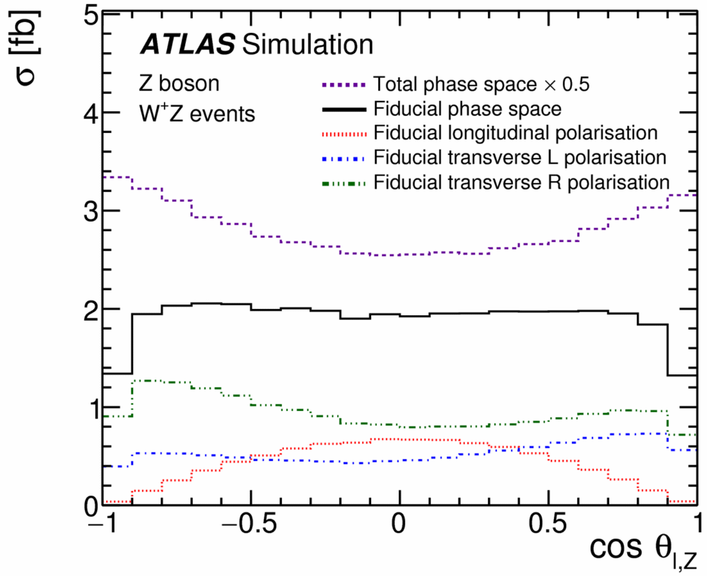
Discriminating variable for the fit

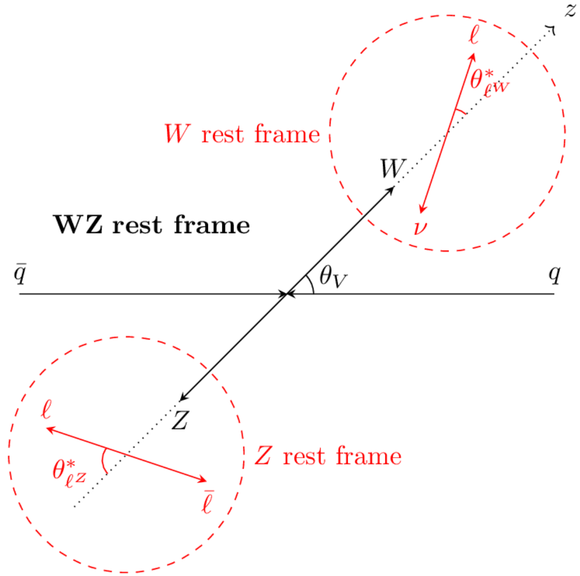
Goal: Perform a **binned maximum likelihood template fit** to extract simultaneously polarisation fractions

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

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







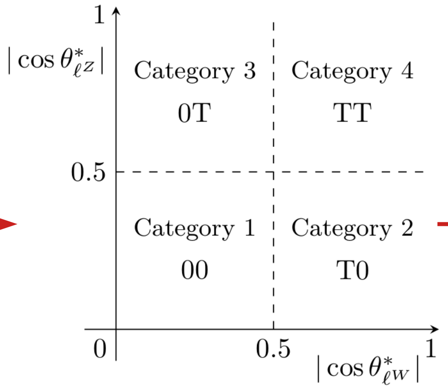
Fiducial level templates from 36 fb^{-1} measurement [arXiv:1902.05759]

Variable for the joint-polarisation

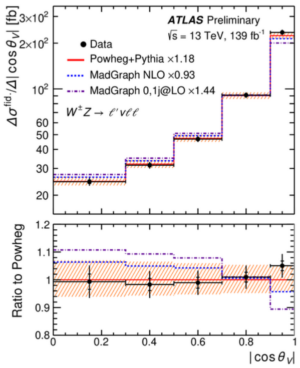
Joint-polarisation fraction measurement:

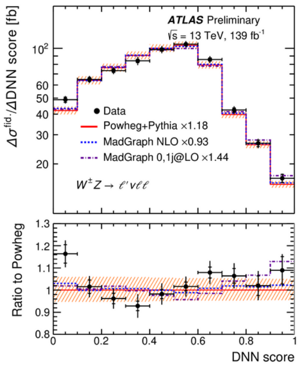
- Analytical variable **$|\cos\theta_V|$** not discriminant enough
- **Classification DNN** between all 4 joint-polarisation states: still **poorly discriminant between 0T and T0**
- Split DNN score for 00 in **4 categories** based on cosθ*

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}
- $P_T^{l2,Z}$
- $P_T^{l1,Z}$

NLO accurate polarisation templates

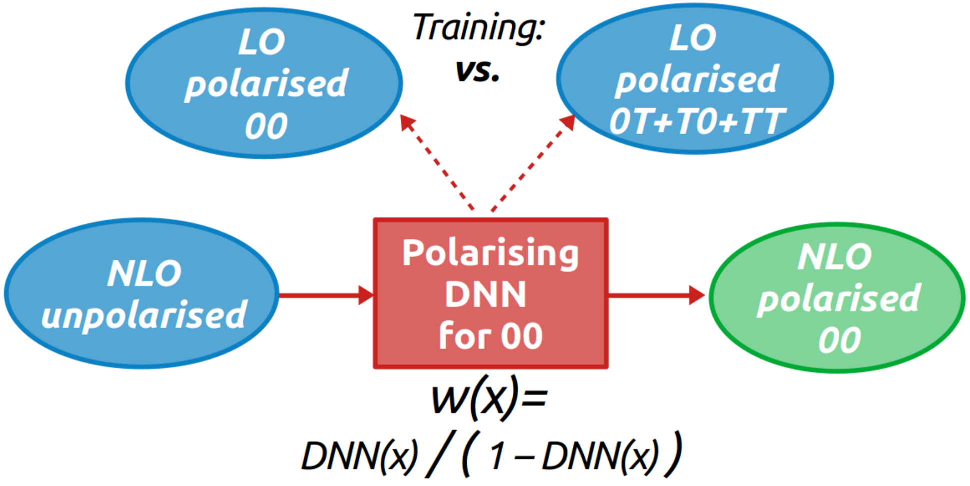
Direct polarised generation with Madgraph 2.7.3 **only at LO+real corrections**

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

Reweighting using DNNs (Baseline)

– Acts as some multi-dimensionnal reweighting [arXiv:1907.08209]

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



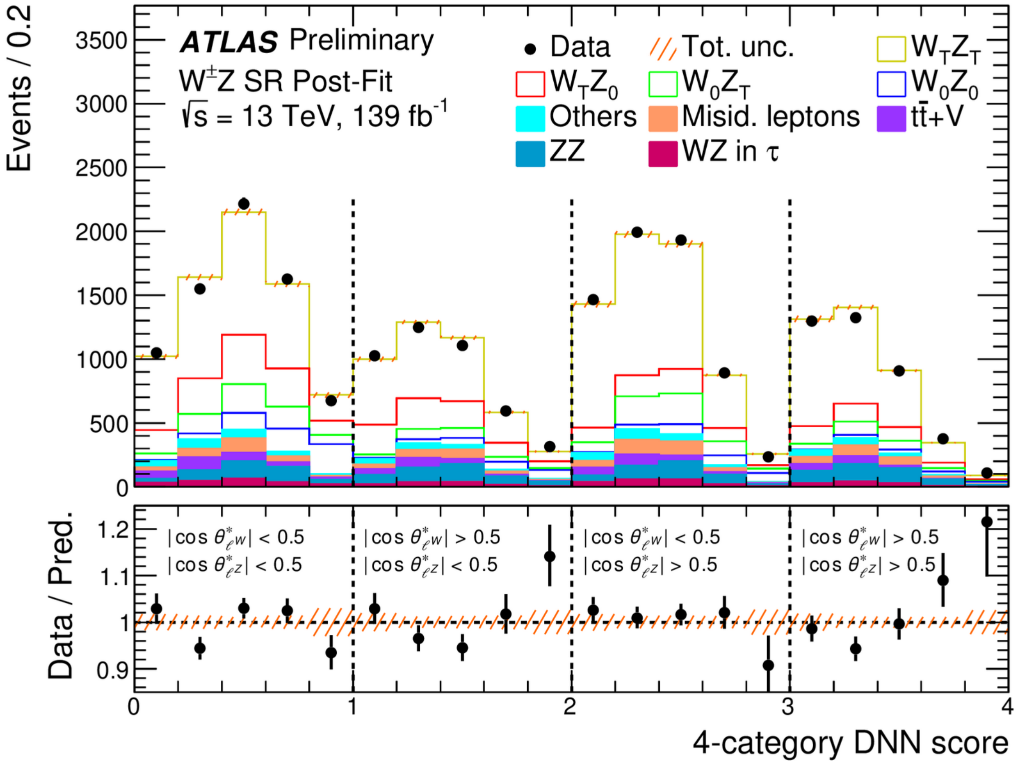
Reweighting to parton level calculation at NLO QCD of the classification DNN

[Collaboration with theorists A. Denner& G. Pelliccioli arXiv:2010.07149]

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

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

Binned Maximum Likelihood Template Fit



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**

	Data	POWHEG+PYTHIA	NLO QCD
		$W^{\pm}Z$	
f_{00}	0.067 ± 0.010	0.0590 ± 0.0009	0.058 ± 0.002
f_{0T}	0.110 ± 0.029	0.1515 ± 0.0017	0.159 ± 0.003
f_{T0}	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

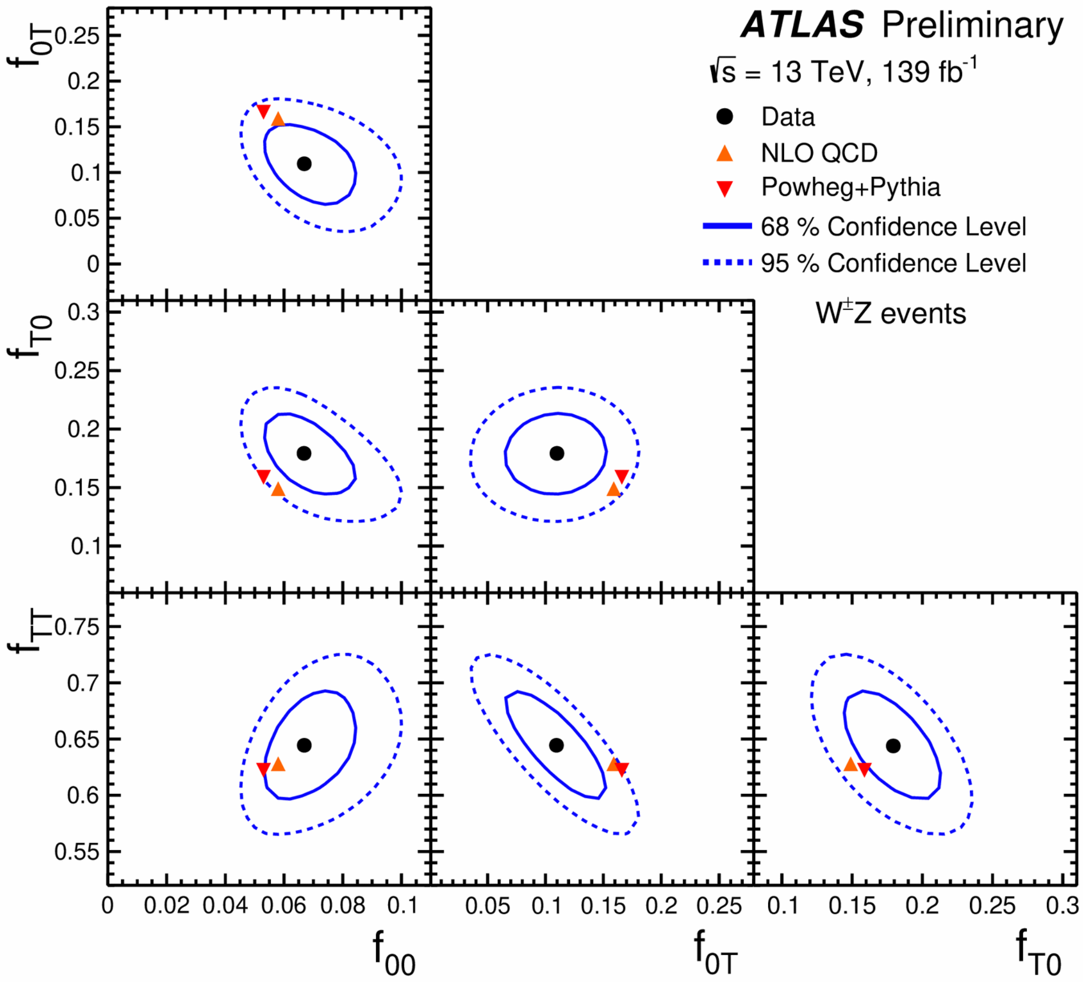
All joint-polarisation states observed:

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

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**

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 :

$$f_{0T} = f_0^W - f_{00},$$
$$f_{T0} = f_0^Z - f_{00},$$
$$f_{TT} = 1 + f_{00} - f_0^W - f_0^Z$$

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

➔ **R_c = 1.54 ± 0.35**

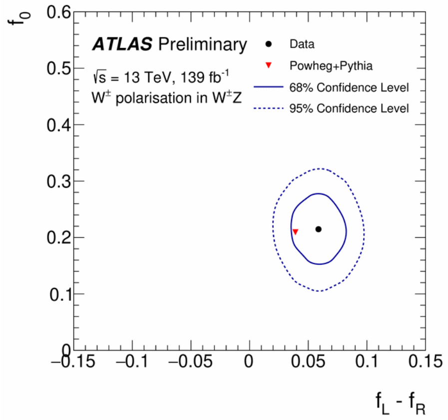
(if independent, R_c=1, theory predicts 1.3)

Other results

Single Boson polarisation: 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, except small tension for f_L-f_R in W-Z at **2.8σ**



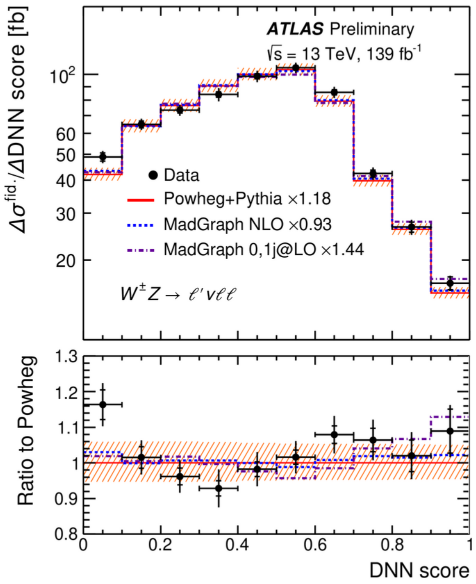
WZ **inclusive** production **cross section** at Born level:

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

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

With MATRIX [arXiv:1703.09065]

➔**Perfect aggreement, similar precision**



Differential cross sections of polarisation sensitive variables

➔ $\cos\theta^*_W$, $\cos\theta^*_Z$, $|\cos\theta_V|$, and **the DNN score**

CONCLUSION

Multi-boson processes studied through three different aspects

– **Differential cross sections** to test QCD predictions

➔ In Zγ+jets process, **good QCD description**, no tension

– Global **EFT fit** using multiboson processes along with Higgs production and electroweak precision observables

➔ **Constrained 28 directions** in parameter space

– **Polarisation** study in WZ production

➔ **Pioneering measurement** providing a new sensitive probe of Standard Model

Back-up

Zγ+jets backgrounds

Z+jet background: jet mistaken for a γ

➔ **Data driven** sideband method ("ABCD") with cuts on isolation and identification of the photon

Pile-up events: γ not from primary vertex

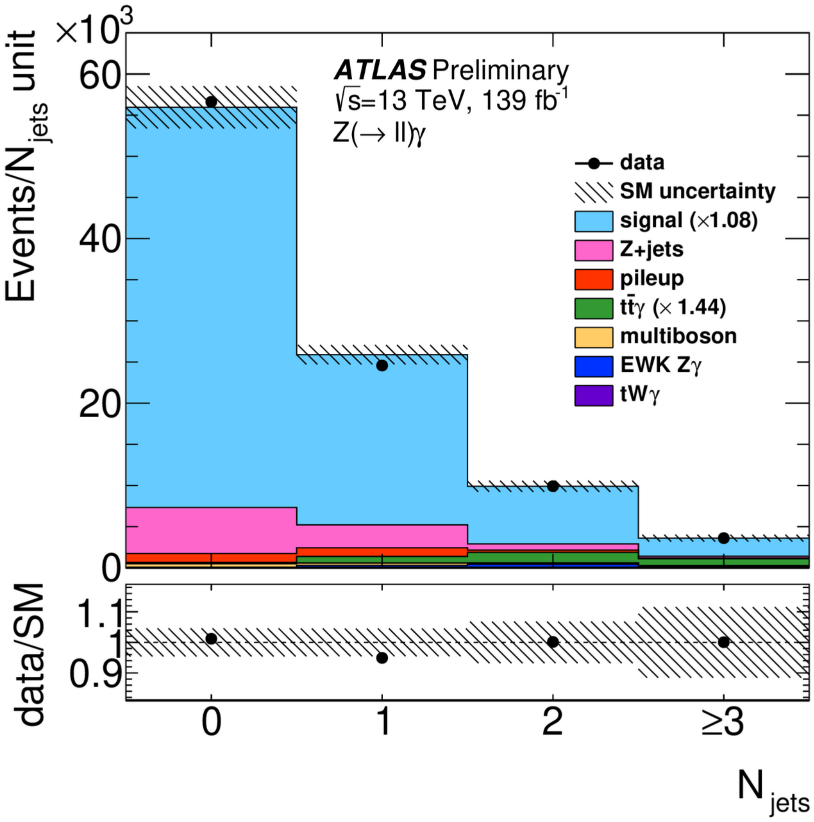
➔ Proportion of pile-up photon estimated from **photon converted** in tracker in e^+e^- pair and transferred to **unconverted photons**: **data driven**

ttγ background

➔ **Monte Carlo** sample scaled using a **control region**

Other backgrounds: VV, VVV

➔ Less than 1% of selected events, only from **Monte Carlo**



EFT Linear + Quadratic constraints

Using ATLAS data only, **linear + quadratic** constraint available

➔ No tension either