ATLAS multi-boson measurements

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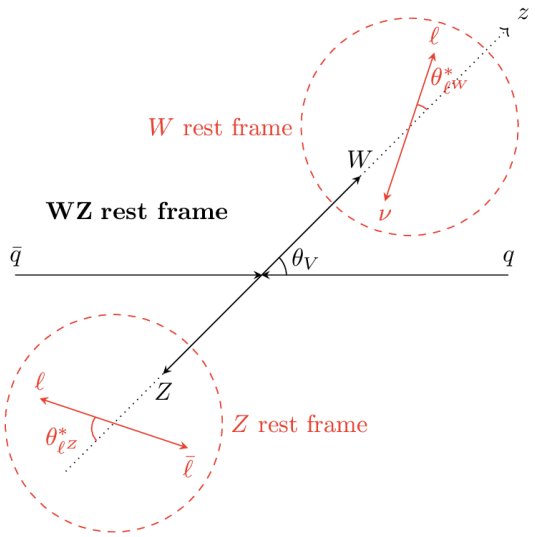
Presented here:

- First measurement of gauge boson joint-polarization states in $W^{\pm}Z$ production [ATLAS-CONF-2022-053]
- First ATLAS combined effective field theory interpretation: Higgs boson and weak boson production and decay with ATLAS data and electroweak precision observables [ATL-PHYS-PUB-2022-037]
- First measurements of Z γ +jets differential cross sections [ATLAS-CONF-2022-047]
- First measurement of Electroweak Z(vv)γjj production with large E_T^{γ} and limits on anomalous quartic gauge couplings

Joint WZ polarization measurement

- SM predicts transverse and longitudinal polarization of W/Z bosons
- So far: measurements of individual W/Z polarization in several processes,
- Now: **First measurement of joint WZ polarisation**
  - Compared to NLO QCD predictions (Phys.Lett.B 814 (2021) 136107)
  - Sensitive probe of BSM physics

Measurement performed using full Run2 data set, based on WZ leptonic final states, in fiducial phase space closely matching the detector acceptance



Measure combinations of combined spin-density matrix elements

long. + long.	f_{00}	=	ρ_{0000} ,
transv. + transv.	f_{TT}	=	$\rho_{++--} + \rho_{--++} + \rho_{----} + \rho_{++++}$,
long. + transv.	f_{0T}	=	$\rho_{00--} + \rho_{00++}$,
transv. + long.	f_{T0}	=	$\rho_{--00} + \rho_{++00}$.

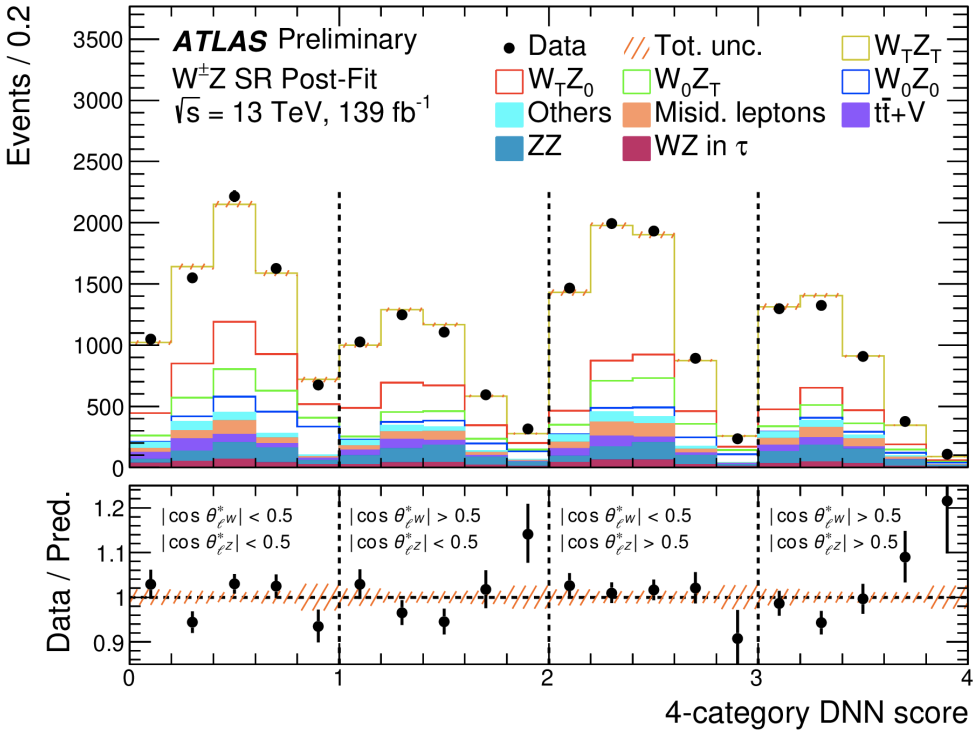
--> Probabilities of correlated helicity states

Joint WZ polarization measurement

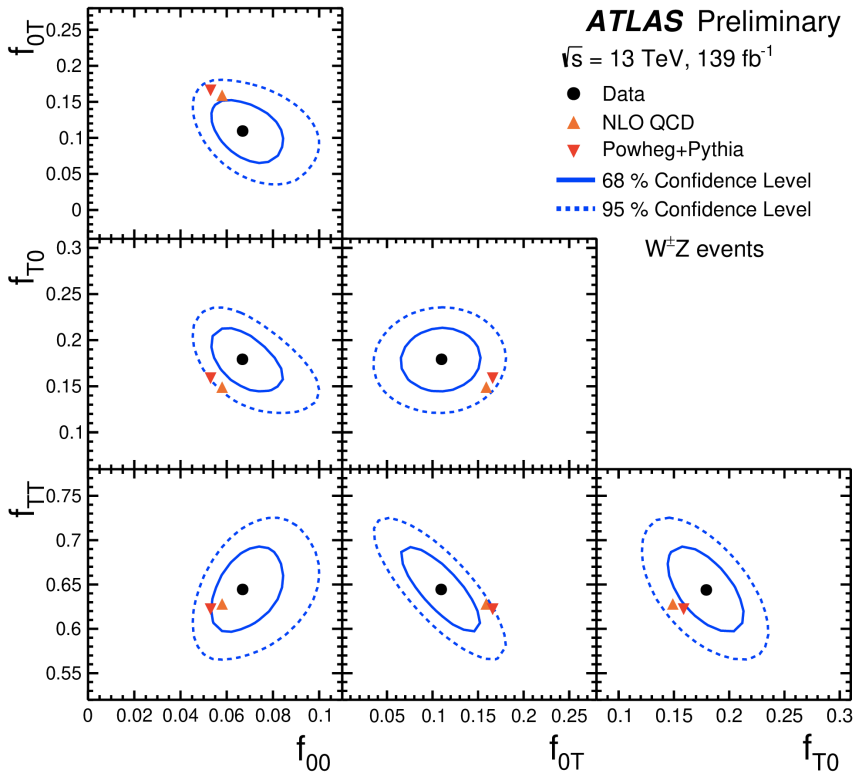
- Derive DNN sensitive to TT -- 0T/T0 – 00 in 4 categories of $|\cos\theta_{lW}| - |\cos\theta_{lZ}|$ using W, Z and WZ transverse momenta and angular variables

- Binned maximum LLH fit of polarization templates to the 4-category DNN score in WZ signal region and ZZ control region

- Major Uncertainties:
  - Statistical
  - MC modelling
  - $E_T$miss/jets



Joint WZ polarization measurement



	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

- Significance: measured (expected)
  - f_{00} : 7.1σ(6.2 σ)
  - f_{0T} : 3.4σ(5.4 σ)
  - f_{T0} : 7.1σ(6.6 σ)
  - f_{TT} : 11σ(9.7 σ)

- Measurements in agreement with SM predictions (Powheg+Pythia and NLO@QCD)
- Also measured and found in agreement with SM predictions:
  - Individual W/Z polarization
  - Inclusive fiducial cross section
  - Differential cross-sections of polarization-sensitive variables

ATLAS + EWPO combined EFT interpretation

Combined SMEFT analysis of measurements of:

- ATLAS Higgs production and decay in the STXS framework;
- ATLAS Differential cross-section measurements of weak boson production
- Electroweak precision observables (EWPO), measured at LEP and SLD.

SMEFT parametrization:

$$\sigma \sim |\mathcal{A}_{SM}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2\mathrm{Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_{SM}^*\right) + \sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4} \left|\mathcal{A}_i^{(6)}\right|^2 + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2\mathrm{Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_j^{(6)*}\right)$$

SM | SM- dim-6 interference leading, "linear term" | quadratic dim-6 | dim-6 operator interference

First ATLAS combined EFT fit

- Principal component analysis to reduce the dimensionality of the fit
- Combined Likelihood as a function of Wilson coefficients and experimental and MC modelling nuisance parameters
- ATLAS Higgs + EW only and combined ATLAS + EWPO fits

Shown here: Combined ATLAS + EWPO fits based on the linear term

Combined EFT interpretation: Inputs

ATLAS STXS Higgs (139/fb):

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
	$t\bar{t}H$

ATLAS EW boson cross-sections (VV and EW Zjj):

Process	Observable	$\mathcal{L}$ [fb^{-1}]
$pp \to e^{\pm}\nu\mu^{\mp}\nu$	$p_{\text{T}}^{\text{lead. lep.}}$	36
$pp \to \ell^{\pm}\nu\ell^{+}\ell^{-}$	m_{T}^{WZ}	36
$pp \to \ell^{+}\ell^{-}\ell^{+}\ell^{-}$	m_{Z2}	139
$pp \to \ell^{+}\ell^{-}jj$	$\Delta\phi_{jj}$	139

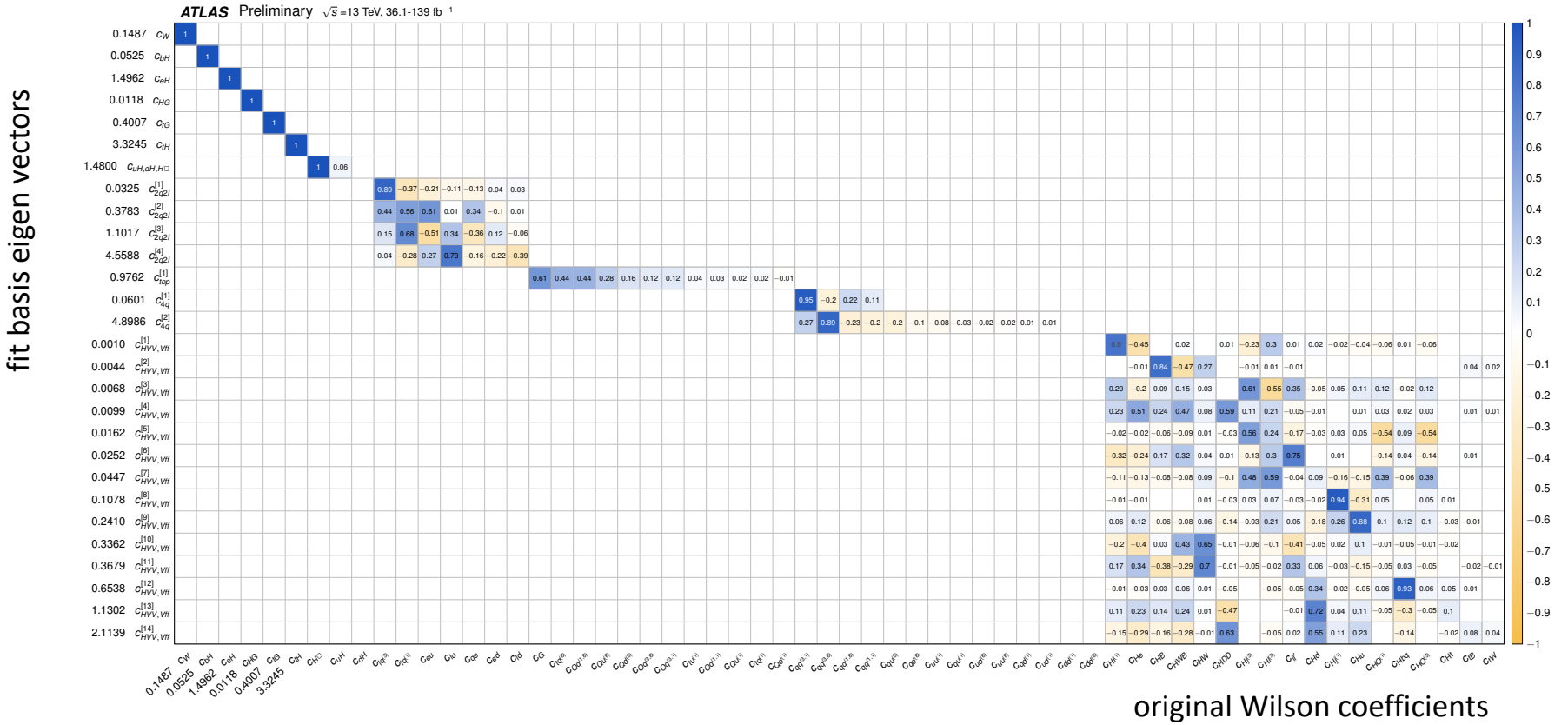
LEP/SLD EWPO:

Observable	
Γ_Z [MeV]	$A_{\text{FB}} = \frac{N_F - N_B}{N_F + N_B}$
R_ℓ^0	
R_c^0	
R_b^0	$R_\ell^0 = \frac{\Gamma_{\text{had}}}{\Gamma_{\ell\ell}}$ $\quad R_q^0 = \frac{\Gamma_{qq}}{\Gamma_{\text{had}}}$
$A_{\text{FB}}^{0,\ell}$	
$A_{\text{FB}}^{0,c}$	
$A_{\text{FB}}^{0,b}$	$\sigma_{\text{had}}^0 = \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{\text{had}}}{\Gamma_Z^2}$
σ_{had}^0 [pb]	

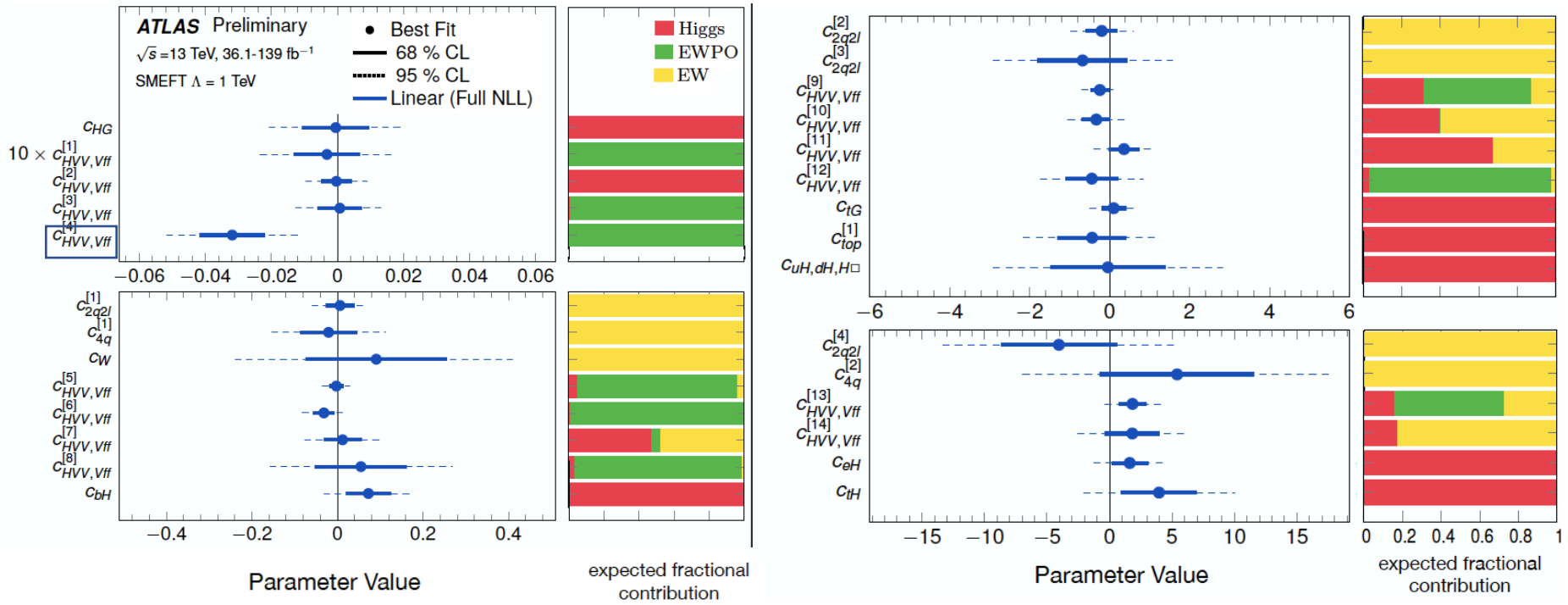
- Higgs production and decay factorize
- Acceptance corrected for EFT contribution
- Overlaps between Higgs and EW 4l and WW removed
- Take into account correlations between uncertainties (ATLAS PU, luminosity, some Jet energy scale components and WW modelling)
- Only linear EFT parametrization for EWPO

Combined EFT interpretation: Fit basis

- Fit basis of 28 eigenvectors from principal component analysis



Combined EFT interpretation: results

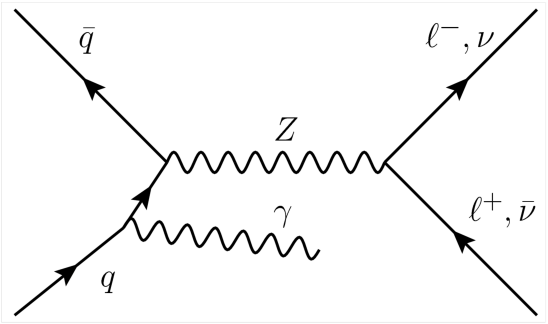


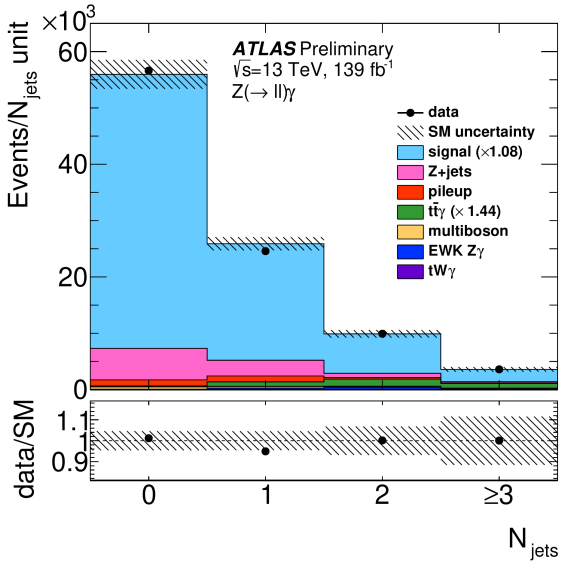
- Fits typically agree with the SM expectation of 0 (except for $c^{[4]}_{HVV}$, driven by the known LEP-SLD discrepancy)

ATLAS Zγ +jets differential cross sections

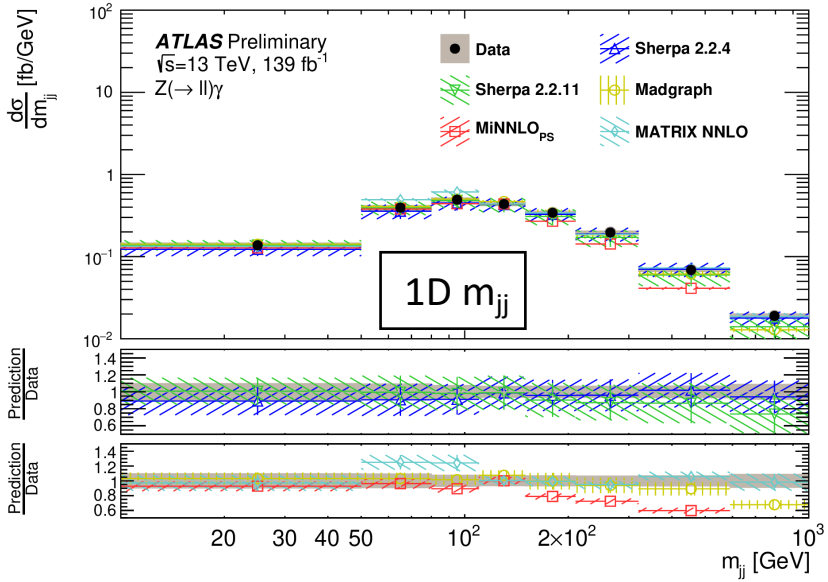
First measurement of Zγ +jets

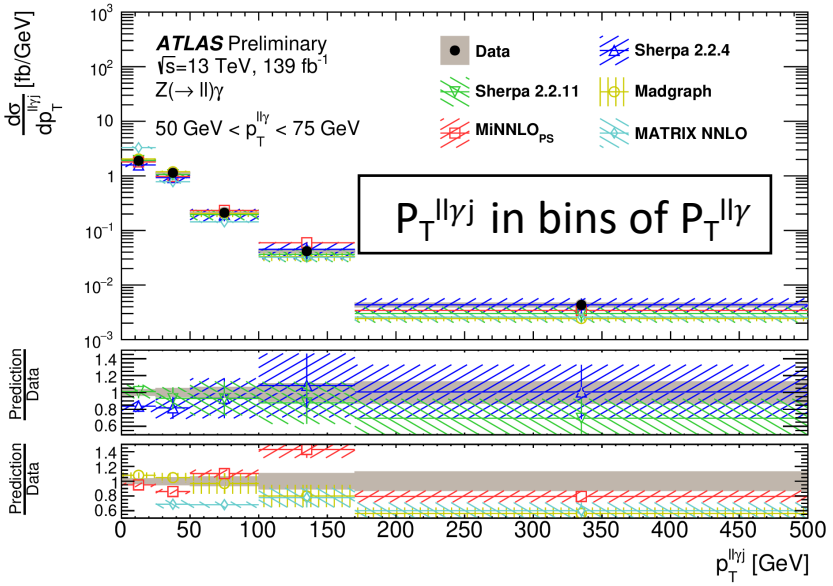
- Inclusive and differential fiducial cross sections:
  - N_{jet}, p_T^{j1}, p_T^{j2}, p_T^{j1}/p_T^{j2}, HT, $p_T(\gamma)$ and $p_T^{ll}/\sqrt{HT}$ $m_{ll\gamma j}$, m_{jj}, $\Delta R(ll), \Delta\phi(j,\gamma)$
  - QCD sensitive 2D observables:
    - $P_T^{ll\gamma}/m^{ll\gamma}$ in bins of $m^{ll\gamma}$,
    - $P_T^{ll} - P_T^{\gamma}$ in bins of $P_T^{ll} + P_T^{\gamma}$,
    - $P_T^{ll\gamma j}$ in bins of $P_T^{ll\gamma}$
  - Polarisation-sensitive 2D observables:
    - $\cos\theta_{CS}$ and ϕ_{CS} in bins of P_T^{ll}
- Main backgrounds data-driven (Z+Jets, Pile-up, ttγ)
- Uncertainties 4-10% (Jet energy scale, Bkg modelling)
- Compared with ME+PS multi-leg (all LO or 0,1j@NLO), Powheg + MiNNLO, MATRIX (NNLO)

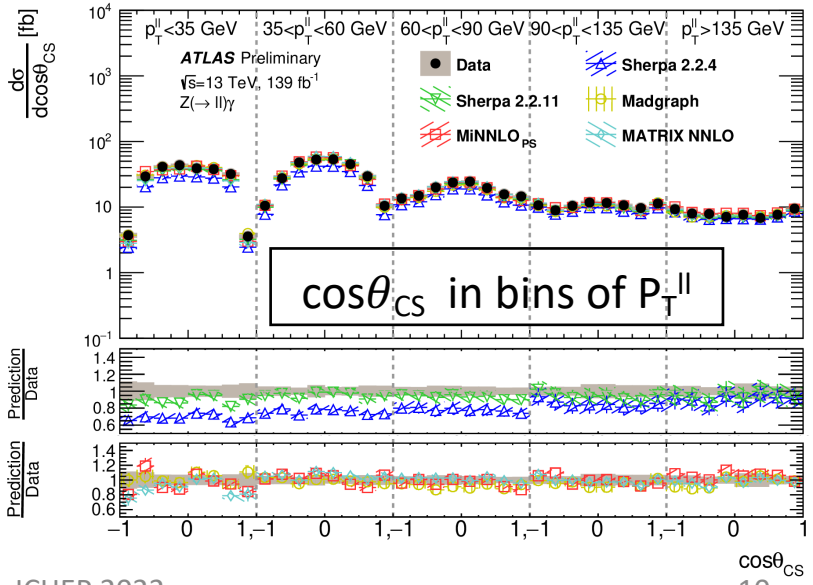




ATLAS Zγ +jets differential cross sections

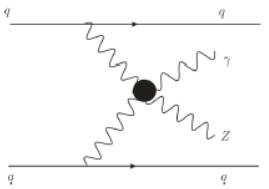




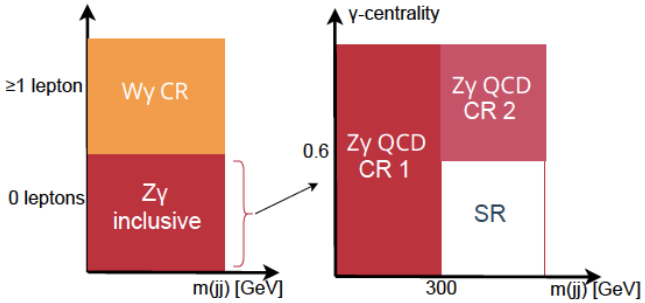


- Jet activity is in general well described
- Addition of NLO 0,1p in Sherpa improves description wrt ME+PS @LO
- MiNNLO underestimates cross sections in high-energetic bins

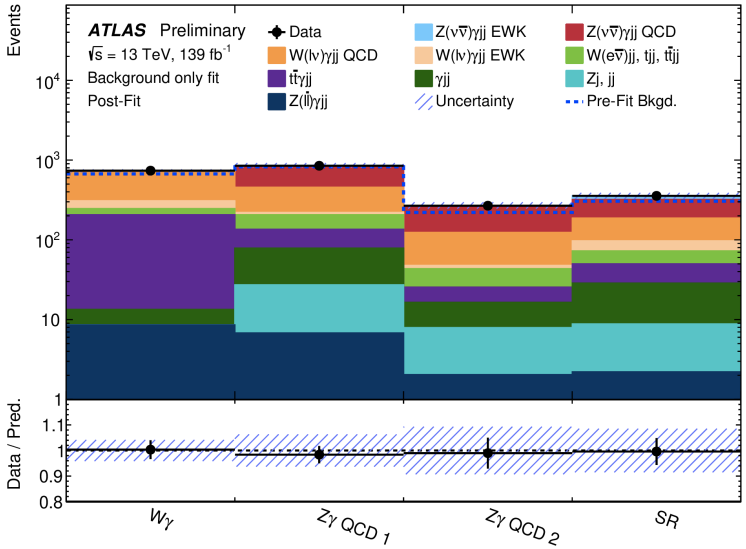
Electroweak Z(νν)γjj production and limits on anomalous quartic gauge couplings



- Sensitive to BSM aQGCs
- p_T^{γ} > 150 GeV → increase aQGC sensitivity
- SR: low γ centrality and high m(jj)



Main background from CR: QCD Zγjj , Wγjj, ttγjj



- Signal extracted via simultaneous binned maximum LLH fit to BDT in SR and mjj in CRs

→ Measured signal strength:

$$\mu_{Z\gamma EWK} = 0.78^{+0.25}_{-0.23}\,(\text{stat.})^{+0.21}_{-0.17}\,(\text{syst.}).$$

→ 3.2(3.7)σ observed (expected)

- Using prediction by MG_aMC+Py@NLO+VBFNLO

→ fiducial cross section:

$$\sigma_{Z\gamma EWK} = 0.77^{+0.34}_{-0.30}\ \text{fb}.$$

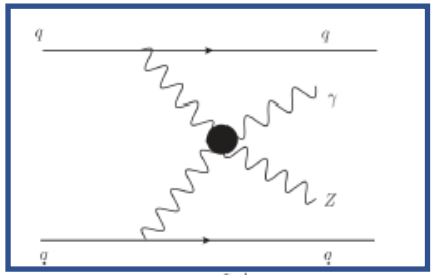
- Uncertainty: Sig/Bkg modelling, jet energy scale
- Combination with Eur. Phys. J. C 82 (2021) 105: p_T^{γ} < 110 GeV

Electroweak Z(vv)γjj production and limits on anomalous quartic gauge couplings

- limits on dim-8 operators in the EFT framework, via VBS component of electroweak process

$$\mathcal{L} = \mathcal{L}^{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \boxed{\sum_j \frac{f_j}{\Lambda^4} O_j,}$$

SM dim6 dim8



- aQGC = 0 for M(Zγ) > E_C to preserve unitarity
- Optimize E_T^{γ} threshold depending on E_C

f_{T8} and f_{T9} probed only by neutral vertices

Coefficient	E_c, TeV	Observed limit, TeV^{-4}	Expected limit, TeV^{-4}
f_{T0}/Λ^4	1.7	$[-8.7, 7.1] \times 10^{-1}$	$[-8.9, 7.3] \times 10^{-1}$
f_{T5}/Λ^4	2.4	$[-3.4, 4.2] \times 10^{-1}$	$[-3.5, 4.3] \times 10^{-1}$
f_{T8}/Λ^4	1.7	$[-5.2, 5.2] \times 10^{-1}$	$[-5.3, 5.3] \times 10^{-1}$
f_{T9}/Λ^4	1.9	$[-7.9, 7.9] \times 10^{-1}$	$[-8.1, 8.1] \times 10^{-1}$
f_{M0}/Λ^4	0.7	$[-1.6, 1.6] \times 10^{2}$	$[-1.5, 1.5] \times 10^{2}$
f_{M1}/Λ^4	1.0	$[-1.6, 1.5] \times 10^{2}$	$[-1.4, 1.4] \times 10^{2}$
f_{M2}/Λ^4	1.0	$[-3.3, 3.2] \times 10^{1}$	$[-3.0, 3.0] \times 10^{1}$

- Limits competitive with or more stringent than those previously published, especially those on *f_{T5}, f_{T8} and f_{T9}*