Electroweak Measurements of Multiboson Production with the ATLAS Experiment

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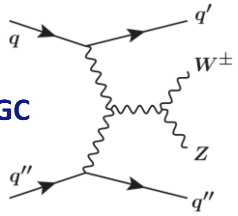
ATLAS EXPERIMENT

Introduction

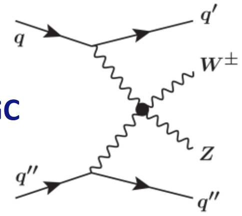
Multiboson studies probe the SM EW symmetry breaking mechanism

- Study of vector boson **self-couplings**
  - ⇒ Vector boson self-interactions determined by the gauge symmetry of the EW theory
  - ⇒ **VBS** of particular interest due to its sensitivity to triple and quartic gauge couplings

TGC



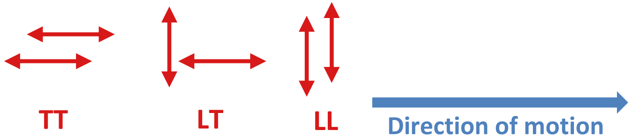
QGC



  - ⇒ Search for anomalous gauge couplings in context of an **EFT interpretation**

$$\underbrace{\mathcal{L}_{\text{eff}}}_{\text{EFT}} = \underbrace{\mathcal{L}_{\text{SM}}}_{\text{SM}} + \underbrace{\cancel{\sum_i \frac{f_i^{(6)}}{\Lambda_i^2} O_i^{(6)}}}_{\text{aTGC}} + \underbrace{\sum_i \frac{f_i^{(8)}}{\Lambda_i^4} O_i^{(8)}}_{\text{aQGC}} + \ldots$$

- Study of vector boson **polarisation states**
  - ⇒ Vector bosons obtain through the EW symmetry breaking mechanism longitudinally polarised states



  - ⇒ Deviations of the cross-section of the longitudinal polarisation state indicates physics beyond the SM

Introduction

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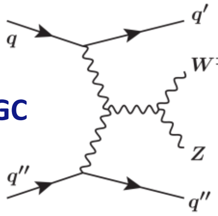

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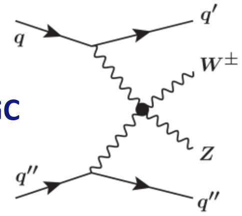

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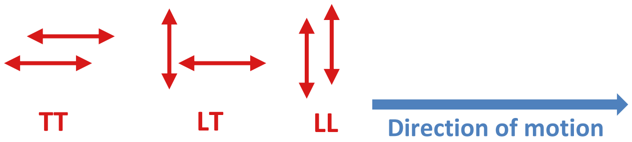


  - ⇒ Deviations of the cross-section of the longitudinal polarisation state indicates physics beyond the SM

ATLAS analyses presented in this talk

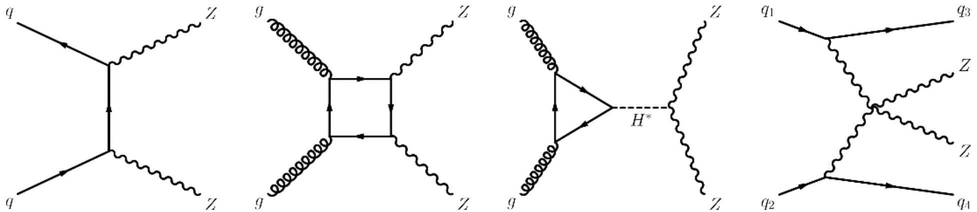
New energy:	ZZ at 13.6 TeV	
Polarisation:	ZZ polarisation & CP	WZ polarisation at high p_{T}
VBS:	$W^{\pm}Zjj$ $W^{\pm}W^{\pm}jj$	$W\gamma jj$

ZZ at 13.6 TeV

13.6 TeV 29 fb^{-1} Partial Run-3

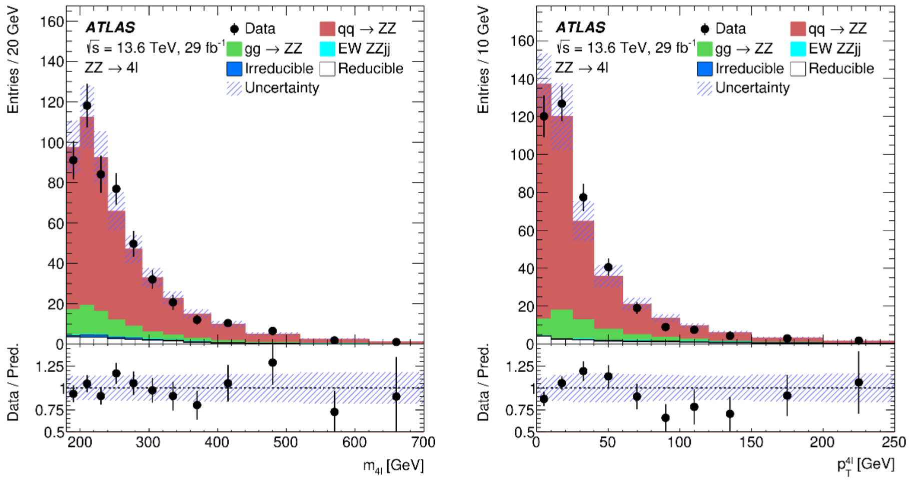
Phys. Lett. B 855 (2024) 138764

- **First Run-3 ZZ cross-section measurement!**
- Rarest diboson process but attractive due to high signal-to-background ratio in fully-leptonic channels
- Key channel for aTGCs searches & studying off-shell Higgs boson production
- **Signal**: 2 SFOC lepton pairs (e, μ) with on-shell Z requirements
- $q\bar{q} \rightarrow ZZ$ dominant process
- Irreducible backgrounds from $t\bar{t}Z$ & triboson
- Non-prompt lepton background
- Comparison of results to state-of-art MC simulation and fixed-order calculations (NNLO QCD & NL EW)



$q\bar{q} \rightarrow ZZ$ $gg \rightarrow ZZ$ $q\bar{q} \rightarrow ZZ2j$

Good data/MC agreement!



ZZ at 13.6 TeV

13.6 TeV 29 fb^{-1} Partial Run-3

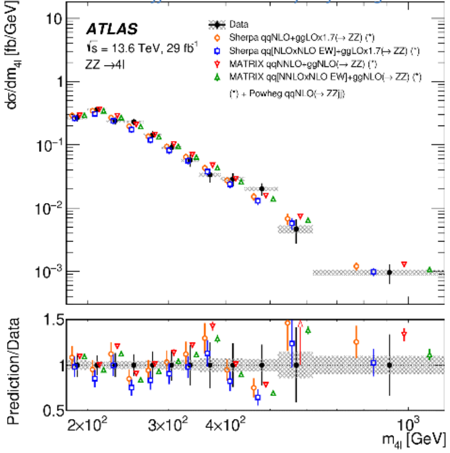
Cross-section measurements:

- Inclusive measurement & extrapolation to a total phase space with $66 < m_Z < 116\text{GeV}$

	Measurement	MC prediction	MATRIX prediction
Fiducial	$36.7 \pm 1.6(\text{stat}) \pm 1.5(\text{syst}) \pm 0.8(\text{lumi})$ fb	$36.8\ ^{+4.3}_{-3.5}$ fb	36.5 ± 0.7 fb
Total	$16.8 \pm 0.7(\text{stat}) \pm 0.7(\text{syst}) \pm 0.4(\text{lumi})$ pb	$17.0\ ^{+1.9}_{-1.4}$ pb	16.7 ± 0.5 pb

- Differential measurements

Detector effects corrected by unfolding



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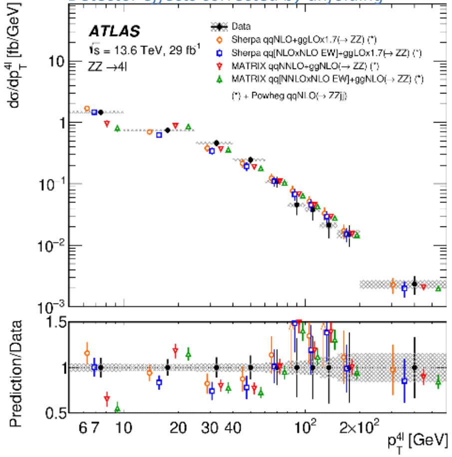
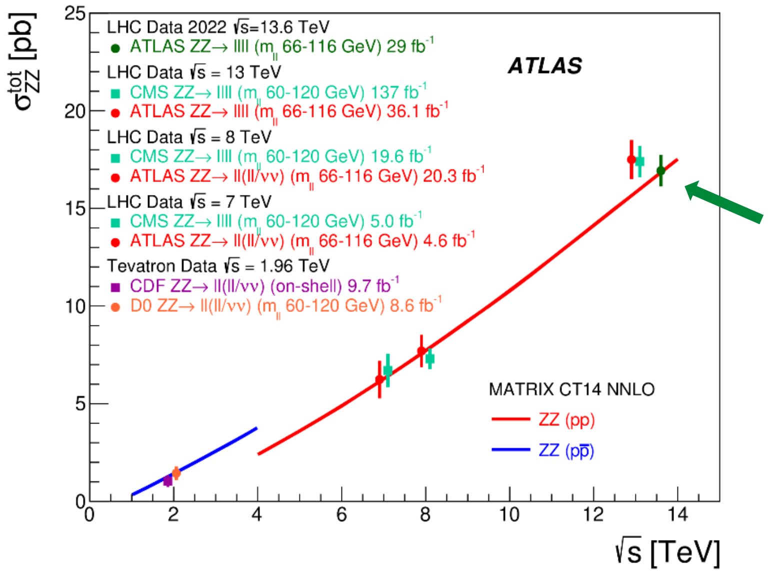


ZZ at 13.6 TeV in a historical context:

- Extension of diboson studies to a **new centre-of-mass energy**



All results well described by SM predictions!

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ZZ polarisation & CP

13 TeV 140 fb^{-1} Full Run-2

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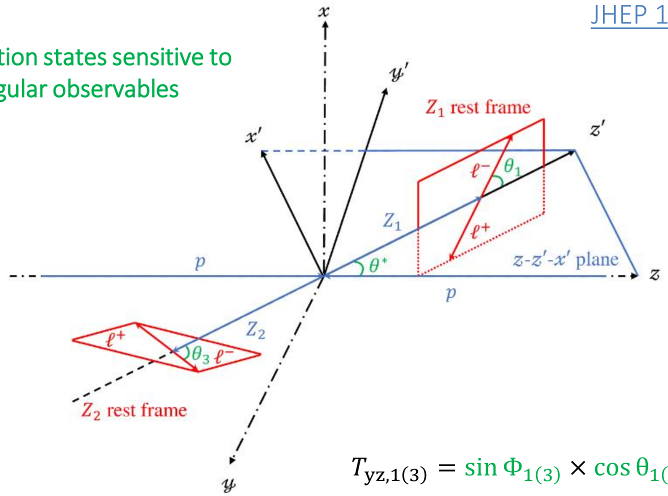
- **Signal**: $q\bar{q} \to ZZ,\ gg \to ZZ,\ qq \to ZZjj$
- 2 SFOC e or μ pairs, on-shell with $|m_{ll} - m_Z| < 10$ GeV
- Prompt lepton background from $t\bar{t}Z$ & triboson
- Non-prompt lepton background

Polarisation states sensitive to angular observables



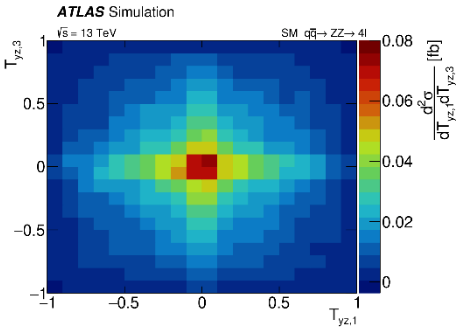
- 3 helicity states: $Z_L Z_L$, $Z_L Z_T$, $Z_T Z_T$
- $Z_L Z_L$ signal extraction by profile likelihood fit on BDT distribution
- Additional reweighting of MC templates to account for NLO/LO corrections of ZZ polarisation states

CP-odd aNTGC

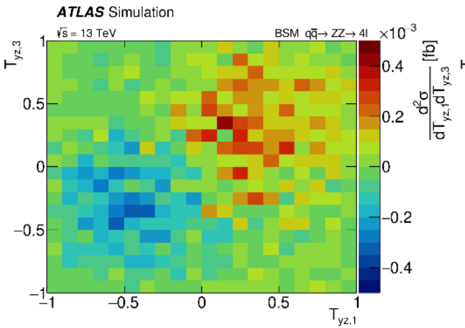
- **aNTGC** cross-section: $\sigma^i = \sigma^i_{\mathrm{SM}} + \boxed{c\sigma^i_{\mathrm{interference}}} + \cancel{c^2\sigma^i_{\mathrm{quadratic}}}$

$$T_{yz,1(3)} = \sin\Phi_{1(3)} \times \cos\theta_{1(3)}$$

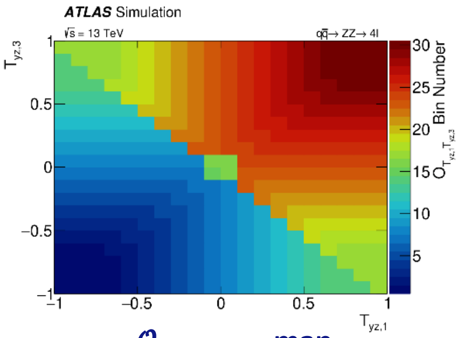
- Construction of an observable $\mathcal{O}_{T_{yz,1}T_{yz,3}}$ to improve sensitivity to CP-odd aNTGC



Symmetric SM prediction



Presence of aNTGC



$\mathcal{O}_{T_{yz,1}T_{yz,3}}$ map

ZZ polarisation & CP

13 TeV 140 fb^{-1} Full Run-2

Polarisation measurements:

$$\sigma^{obs}_{Z_L Z_L} = 2.45 \pm \underbrace{0.56}_{\text{stat}} \pm \underbrace{0.21}_{\text{syst}} \text{ fb with } 4.3\sigma \text{ significance}$$

- $Z_L Z_L$-polarisation cross-section consistent with SM prediction
- Measurement limited by data statistic & polarisation modelling

Study of the CP property :

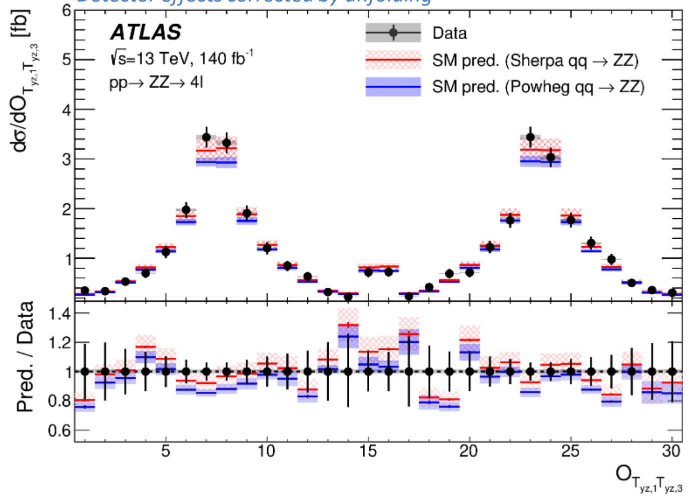
- Inclusive ($Z_L Z_L$+$Z_L Z_T$+$Z_T Z_T$) differential cross-section measurement for $\mathcal{O}_{T_{yz,1}\, T_{yz,3}}$
- $\mathcal{O}_{T_{yz,1}\, T_{yz,3}}$ asymmetric for CP-odd aNTGC

CP-odd aNTGC:

- Constraints on ZZZ & $ZZ\gamma$ coupling parameters f_Z^4, f_γ^4 at 95% CL using the differential cross-section distribution
- First constraints using only linear interference terms
- **No significant deviations from SM**

Good data/MC agreement!

Detector effects corrected by unfolding



CP-odd aNTGC **with $\sigma^i_{\text{quadratic}}$**

aNTGC parameter	Interference only Expected	Interference only Observed	Full Expected	Full Observed
f_Z^4	[−0.16, 0.16]	[−0.12, 0.20]	[−0.013, 0.012]	[−0.012, 0.012]
f_γ^4	[−0.30, 0.30]	[−0.34, 0.28]	[−0.015, 0.015]	[−0.015, 0.015]

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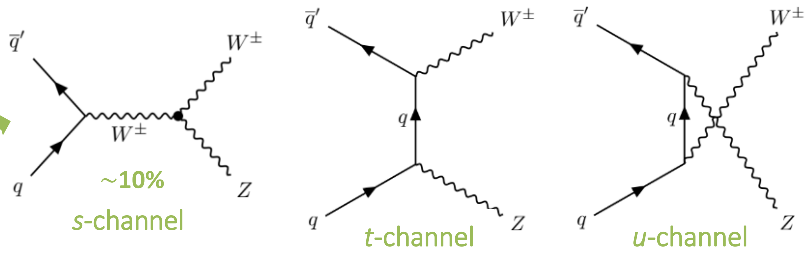
WZ polarisation at high p_T

13 TeV 140 fb^{-1} Full Run-2

arXiv:2402.16365

- **Signal**: $Z \rightarrow l'l'$ (SFOC) with $|m_{ll} - m_Z| < 10$ GeV
  $W \rightarrow l\nu$ with $m_T^W > 30$ GeV
  $l = e, \mu$

Measurement in **s-channel** to obtain a sufficient contribution of 00 WZ polarisation states



- Selection of 2 fiducial regions such to enhanced prevalence for the 2 longitudinally-polarised (00) bosons for the measurement of **diboson polarisation fractions** $f_{00}, f_{0T}, f_{T0}, f_{TT}$ $\Rightarrow$ **high p_T^Z**
- Exploit **Radiation Amplitude Zero (RAZ) effect in WZ**
  - $\Rightarrow$ Dominant helicity amplitude of the TT-polarised bosons becomes zero when the scattering angle of the W boson to the incoming antiquark $\bar{q}$ approaches 90° in the WZ restframe
  - $\Rightarrow$ NLO QCD corrections dilute effect

Reduced jet activity for the observation of the RAZ

Reduced TT contribution and increase of f_{00} from 5-7% to 20-30%

	Signal regions		
	Radiation Amplitude Zero	**00-enhanced region 1**	**00-enriched region 2**
Pass inclusive WZ event selection	✓	✓	✓
Transverse momentum of the Z boson (p_T^Z)	-	[100, 200] GeV	> 200 GeV
Transverse momentum of the WZ system (p_T^{WZ})	< 20, 40, 70 GeV	< 70 GeV	

WZ polarisation at high p_T

13 TeV 140 fb^{-1} Full Run-2

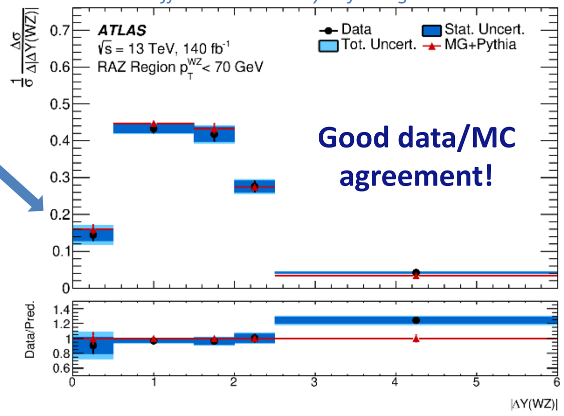
RAZ effect in WZ:

- **First-time study in WZ**
- Evaluation of the 00+0T+T0-subtracted $|\Delta Y(l_W Z)|$ & $|\Delta Y(WZ)|$ distributions for TT events
- Evaluation of the dip depth

$$\mathcal{D} = 1 - 2\frac{N^{\text{unf}}_{\text{central}}}{N^{\text{unf}}_{\text{sides}}} > 0 \text{ indicates dip}$$

Dip indicates RAZ

Detector effects corrected by unfolding

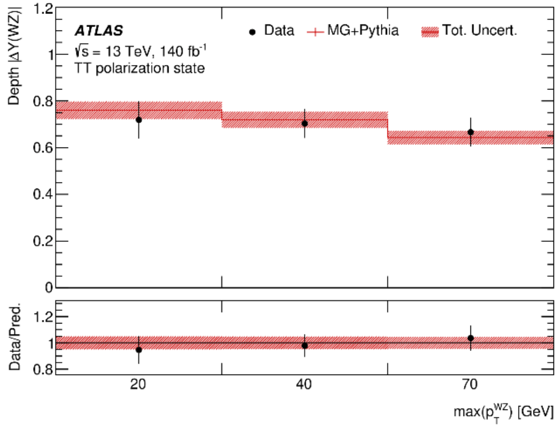


Good data/MC agreement!

Energy dependence of diboson polarisation fractions

- Signal extraction from maximum-likelyhood fit on BDT score distribution
- **f_{00} observation in agreement with SM prediction**

	Measurement	
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
f_{00}	$0.19\ \pm^{0.03}_{0.03}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	$0.13\ \pm^{0.09}_{0.08}$ (stat) $\pm^{0.02}_{0.02}$ (syst)
f_{0T+T0}	$0.18\ \pm^{0.07}_{0.08}$ (stat) $\pm^{0.05}_{0.06}$ (syst)	$0.23\ \pm^{0.17}_{0.18}$ (stat) $\pm^{0.06}_{0.10}$ (syst)
f_{TT}	$0.63\ \pm^{0.05}_{0.05}$ (stat) $\pm^{0.04}_{0.04}$ (syst)	$0.64\ \pm^{0.12}_{0.12}$ (stat) $\pm^{0.06}_{0.06}$ (syst)
f_{00} obs (exp) sig.	5.2 (4.3) σ	1.6 (2.5) σ



arXiv:2402.16365

$W^{\pm}Zjj$

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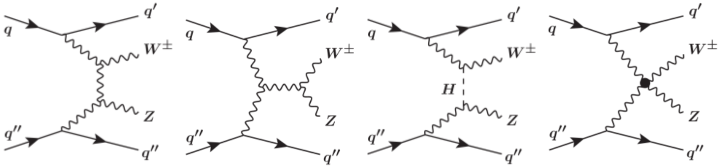
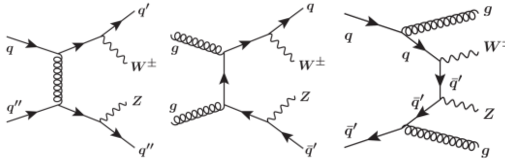
- **VBS** not independently gauge invariant, therefore study with same final-state processes required
  - $\Rightarrow$ Exclusively **EW** $\sim \alpha_{EW}^{6}$
  - $\Rightarrow$ **QCD** $\sim \alpha_S^2\, \alpha_{EW}^4$
  - $\Rightarrow$ EW-QCD interference $\sim \boldsymbol{\alpha_S\, \alpha_{EW}^5}$

VBS



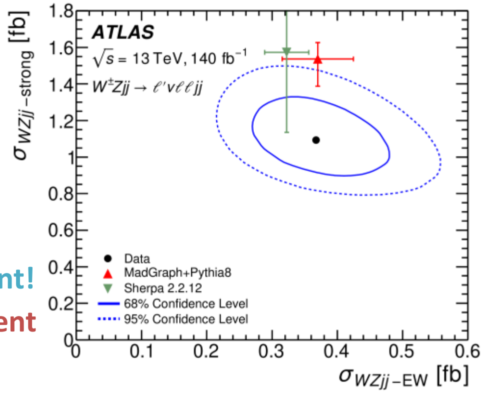
QCD



- **Signature**: $WZ \rightarrow l'\nu ll$ & $\geq 2\, j$
- SR with enhanced **VBS**: $m_{jj} > 500$ GeV, $N_{b-\text{quark}} = 0$
- Main irreducible background from ZZ & $t\bar{t}$V
- Background from misidentified leptons

EW & QCD cross-section measurements

- Multivariate discriminant constructed from BDT to separate **EW** from **QCD**
- **Most precise EW $W^{\pm}Zjj$ cross-section measurement to date!**



Good EW agreement!

▲**1.8σ QCD agreement**

$W^{\pm}Zjj$

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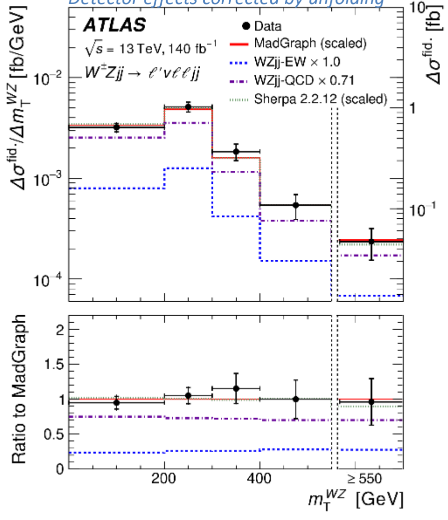
EW & QCD differential cross-section measurements

- In bins of N_{jets}, m_{jj}
- **2σ EW agreement** in all SR sub-categories
- **QCD** mis-modelling by MADGRAPH+PYTHIA8 or SHERPA 2.2.12 for events with exactly 2 jets of $p_{\mathrm{T}} > 25$ GeV or with $500 < m_{jj} < 1300$ GeV

Detector effects corrected by unfolding



$W^{\pm}Zjj$ inclusive differential cross-section measurements

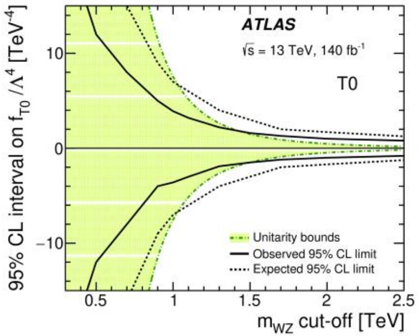
- For several kinematic observables
- Statistical uncertainties dominant

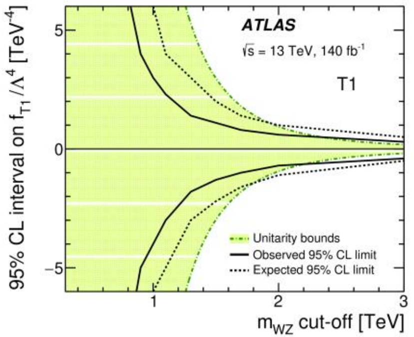
aQGC

- BDT score & m_{T}^{WZ} to search for aQGC
- 95% CL limits D-8 EFT operators indicating **no deviation from 0**

	Expected [TeV $^{-4}$]	Observed [TeV $^{-4}$]
$f_{\mathrm{T0}}/\Lambda^4$	[-0.80, 0.80]	[-0.57, 0.56]
$f_{\mathrm{T1}}/\Lambda^4$	[-0.52, 0.49]	[-0.39, 0.35]
$f_{\mathrm{T2}}/\Lambda^4$	[-1.6, 1.4]	[-1.2, 1.0]
$f_{\mathrm{M0}}/\Lambda^4$	[-8.3, 8.3]	[-5.8, 5.6]
$f_{\mathrm{M1}}/\Lambda^4$	[-12.3, 12.2]	[-8.6, 8.5]
$f_{\mathrm{M7}}/\Lambda^4$	[-16.2, 16.2]	[-11.3, 11.3]
$f_{\mathrm{S02}}/\Lambda^4$	[-14.2, 14.2]	[-10.4, 10.4]
$f_{\mathrm{S1}}/\Lambda^4$	[-42, 41]	[-30, 30]

- Evaluation of relevant limits as a function of the unitarisation cut-off





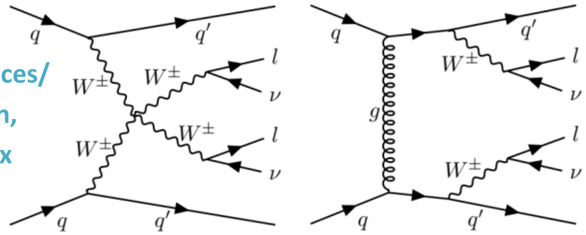
$W^{\pm}W^{\pm}jj$

13 TeV 139 fb[-1] Full Run-2

- Largest **EW** to **QCD** production ratio among final states sensitive to **VBS**
- Triboson production with 1 hadronic decay suppressed in EW VBS phase space region ($\rightarrow m_{\mathrm{jj}}$)

EW

VBS with triple/quartic vertices/ exchange of a higgs boson, no s-channel triple vertex & non-VBS

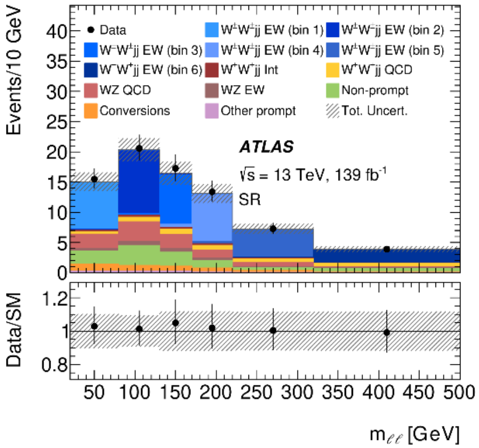


QCD

w/o qg & gg initial states

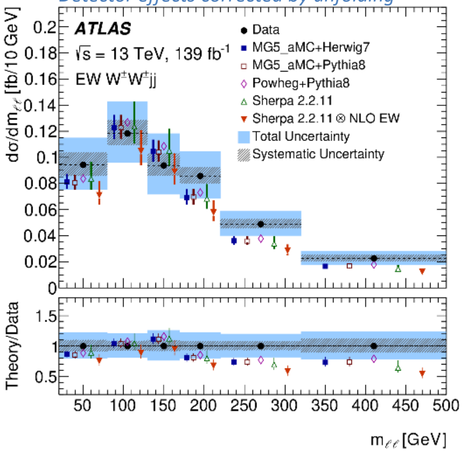
- **Clean signature**: 2 same-charged leptons (e,μ), $\geq 2j$ (high m_{jj} & $|\Delta y_{\mathrm{jj}}|$) & $E_{\mathrm{T}}^{\mathrm{miss}}$
- Dominant WZ/γ^{*} and non-prompt lepton background

Very good data/MC agreement!



EW $W^{\pm}W^{\pm}jj$

Detector effects corrected by unfolding



EW $W^{\pm}W^{\pm}jj$ & inclusive cross-section measurements

- Cross-section from maximum likelihood fits with signal strength of SR & WZ CR (m_{jj} reduced) as free parameter
- **Most precise $W^{\pm}W^{\pm}jj$ fiducial measurements to date!**

$\sigma_{\mathrm{fid}}^{\mathrm{EW}}$ [fb]	$\sigma_{\mathrm{fid}}^{\mathrm{EW+Int+QCD}}$ [fb]
$2.92 \pm 0.22\,(\mathrm{stat.}) \pm 0.19\,(\mathrm{syst.})$	$3.38 \pm 0.22\,(\mathrm{stat.}) \pm 0.19\,(\mathrm{syst.})$

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aQGC

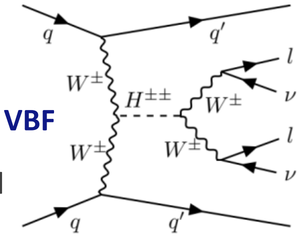
- Limits on 9 relevant D-8 EFT operators at 95% CL from the m_{ll} distribution in both SR & CRs

Coefficient	Type	No unitarisation cut-off [TeV^{-4}]	Lower, upper limit at the respective unitarity bound [TeV^{-4}]
f_{M0}/Λ^4	Exp.	[-3.9, 3.8]	-64 at 0.9 TeV, 40 at 1.0 TeV
	Obs.	[-4.1, 4.1]	-140 at 0.7 TeV, 117 at 0.8 TeV
f_{M1}/Λ^4	Exp.	[-6.3, 6.6]	-25.5 at 1.6 TeV, 31 at 1.5 TeV
	Obs.	[-6.8, 7.0]	-45 at 1.4 TeV, 54 at 1.3 TeV
f_{M7}/Λ^4	Exp.	[-9.3, 8.8]	-33 at 1.8 TeV, 29.1 at 1.8 TeV
	Obs.	[-9.8, 9.5]	-39 at 1.7 TeV, 42 at 1.7 TeV
f_{S02}/Λ^4	Exp.	[-5.5, 5.7]	-94 at 0.8 TeV, 122 at 0.7 TeV
	Obs.	[-5.9, 5.9]	–
f_{S1}/Λ^4	Exp.	[-22.0, 22.5]	–
	Obs.	[-23.5, 23.6]	–
f_{T0}/Λ^4	Exp.	[-0.34, 0.34]	-3.2 at 1.2 TeV, 4.9 at 1.1 TeV
	Obs.	[-0.36, 0.36]	-7.4 at 1.0 TeV, 12.4 at 0.9 TeV
f_{T1}/Λ^4	Exp.	[-0.158, 0.174]	-0.32 at 2.6 TeV, 0.44 at 2.4 TeV
	Obs.	[-0.174, 0.186]	-0.38 at 2.5 TeV, 0.49 at 2.4 TeV
f_{T2}/Λ^4	Exp.	[-0.56, 0.70]	-2.60 at 1.7 TeV, 10.3 at 1.2 TeV
	Obs.	[-0.63, 0.74]	–

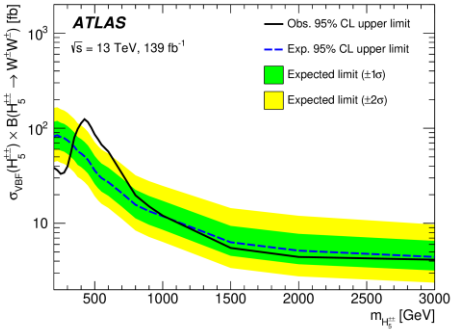
- Evaluation of limits as a function of the unitarisation cut-off excludes zero-values for f_{M0}, f_{S1}, f_{S02}, f_{T0} for clipping scales below ~ 1 TeV at 95% CL
- Additional 2D limits on operator pairs

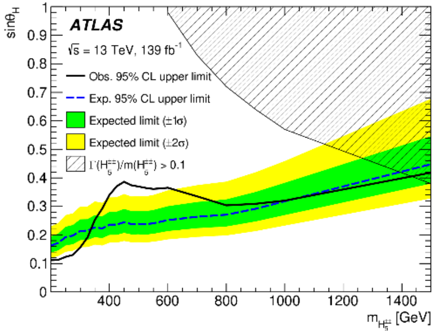
Search for doubly-charged Higgs boson production

VBF



- Evaluation of the m_T distribution in context of the Georgi-Machacek model
- Upper limits on $\sin\Theta_H$ & $\sigma_{VBF}(H_5^{\pm\pm}) \times B(H_5^{\pm\pm} \to W^{\pm}W^{\pm})$ at 95% CL
- $\sin\Theta_H$ > 0.11-0.42 excluded for 200 GeV $< m_{H_5^{\pm\pm}} <$ 1500 GeV
- Local excess of events for $m_{H_5^{\pm\pm}}$ = 450 GeV at 2.5σ



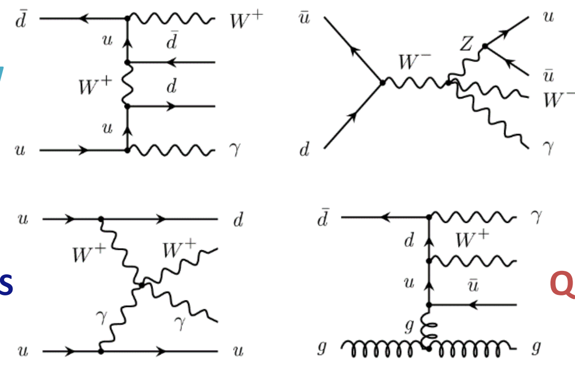


JHEP 04 (2024) 026

Wγjj

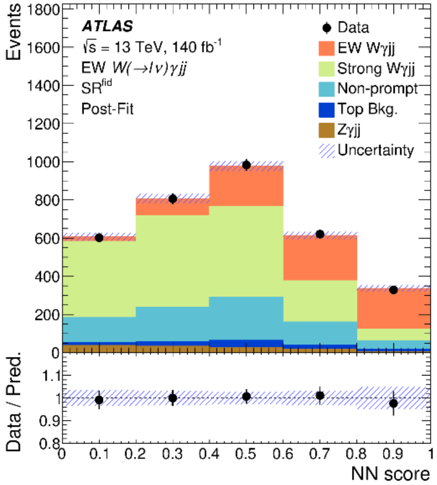
arXiv:2403.02809

- High precision for differential **EW** $W\gamma jj$ cross-section measurements compared to other **VBS** processes (large production cross-section)
- Combined measurement of **EW** $W\gamma jj$ processes in region with enhanced **VBS**



- **Clean signature**: 1e/μ, p_T^{miss}, ≥ 1γ, ≥ 2*j* (high m_{jj} & $|\Delta y_{jj}|$)
- **QCD** *Wγjj* dominant prompt background
- Background from misidentified leptons and photons

- Multivariate techniques including a Neural Network to isolate **EW** $W\gamma jj$ from **QCD** $W\gamma jj$
- SR & CRs separated by N_{jets}^{gap} & $\xi_{l\gamma}$



Good data/MC agreement!

EW *Wγjj* fiducial cross section measurement

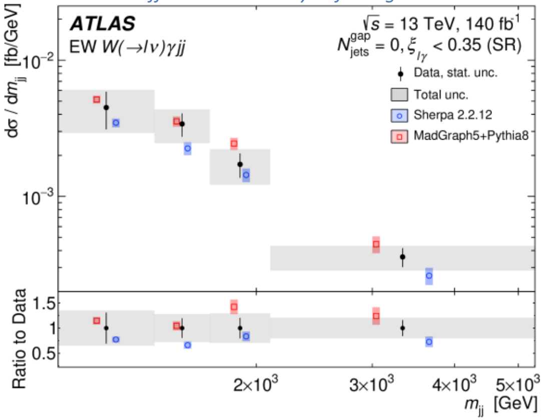
$$\sigma_{EW} = 13.2 \pm 2.5 \text{ fb with} \gg 6\sigma \text{ significance } (6.3\sigma \text{ expected})$$

- MADGRAPH5+PYTHIA8 in agreement with data within uncertainties
- $\sim 2\sigma$ underestimation by SHERPA 2.2.12 from the 3rd parton in the SHERPA matrix element

EW *Wγjj* differential cross section measurements

- Differential measurements for a set of variables sensitive to QGC or the CP violation structure of $WW\gamma\gamma$ & $WW\gamma Z$
- Reasonable agreement of data & LO SM prediction
- Slight overestimation of the measurement by MADGRAPH5+PYTHIA8 at high m_{jj} & high p_{T}^{jj}
- Good shape agreement for SHERPA 2.2.12 but tendency to underestimate

Detector effects corrected by unfolding



Search for $WW\gamma\gamma$ & $WW\gamma Z$ (aQGC)

arXiv:2403.02809

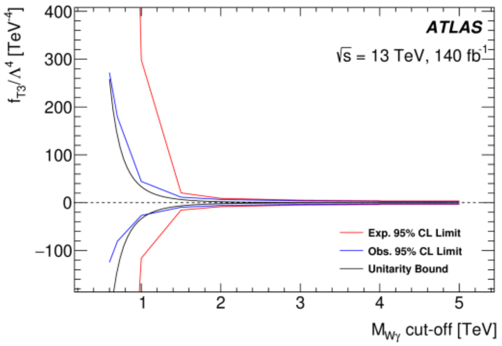
- 95% CL limits on EFT D-8 operators

Observable most sensitive to tensor-type operators

Observable most sensitive to mixed scalar operators

Coefficients [TeV^{-4}]	Observable	Expected [TeV^{-4}]	Observed [TeV^{-4}]
f_{T0}/Λ^4	p_{T}^{jj}	[-2.4, 2.4]	[-1.8, 1.8]
f_{T1}/Λ^4	p_{T}^{jj}	[-1.5, 1.6]	[-1.1, 1.2]
f_{T2}/Λ^4	p_{T}^{jj}	[-4.4, 4.7]	[-3.1, 3.5]
f_{T3}/Λ^4	p_{T}^{jj}	[-3.3, 3.5]	[-2.4, 2.6]
f_{T4}/Λ^4	p_{T}^{jj}	[-3.0, 3.0]	[-2.2, 2.2]
f_{T5}/Λ^4	p_{T}^{jj}	[-1.7, 1.7]	[-1.2, 1.3]
f_{T6}/Λ^4	p_{T}^{jj}	[-1.5, 1.5]	[-1.0, 1.1]
f_{T7}/Λ^4	p_{T}^{jj}	[-3.8, 3.9]	[-2.7, 2.8]
f_{M0}/Λ^4	p_{T}^{l}	[-28, 28]	[-24, 24]
f_{M1}/Λ^4	p_{T}^{l}	[-43, 44]	[-37, 38]
f_{M2}/Λ^4	p_{T}^{l}	[-10, 10]	[-8.6, 8.5]
f_{M3}/Λ^4	p_{T}^{l}	[-16, 16]	[-13, 14]
f_{M4}/Λ^4	p_{T}^{l}	[-18, 18]	[-15, 15]
f_{M5}/Λ^4	p_{T}^{l}	[-17, 14]	[-14, 12]
f_{M7}/Λ^4	p_{T}^{l}	[-78, 77]	[-66, 65]

- Additional constraints with unitarity preservation are obtained by applying the clipping technique
- **First LHC constraints on f_{T3} and f_{T4}**



Summary

- Several exciting results by the 6 ATLAS analyses presented!

ZZ at 13.6 TeV

- Extension of diboson studies to a new centre-of-mass energy
- Good agreement with SM predictions!

ZZ polarisation & CP

- Observation of $Z_L Z_L$ at 4.3σ
- First constraints on CP-odd aNTGC (SM-EFT interference)

WZ polarisation at high p_T

- First time study of RAZ effect in WZ
- Observation of 00 WZ polarisation at 5.2σ in $100 < p_T^Z < 200$ GeV

$W^\pm Zjj$

- Most precise $W^\pm Zjj$ EW cross-section measurement
- Constraints on aQGC

$W^\pm W^\pm jj$

- Constraints on aQGC
- Search for $H^{\pm\pm}$

$W\gamma jj$

- Constraints on aQGC
- First LHC constraints on the f_{T3} & f_{T4} operators of the EFT framework

Backup

ZZ at 13.6 TeV

13.6 TeV 29 fb^{-1} Partial Run-3

Source	Relative uncertainty(%)
Data statistical uncertainty	4.2
MC statistical uncertainty	0.3
Luminosity	2.2
Lepton momentum	0.2
Lepton efficiency	3.7
Background	1.6
Theoretical uncertainty	1.0
Total	6.3

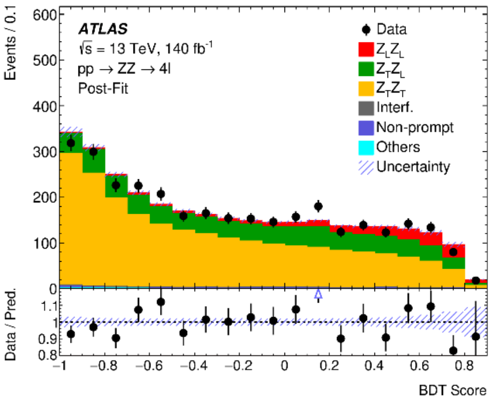
Phys. Lett. B 855 (2024) 138764, STDM-2022-17

ZZ polarisation & CP

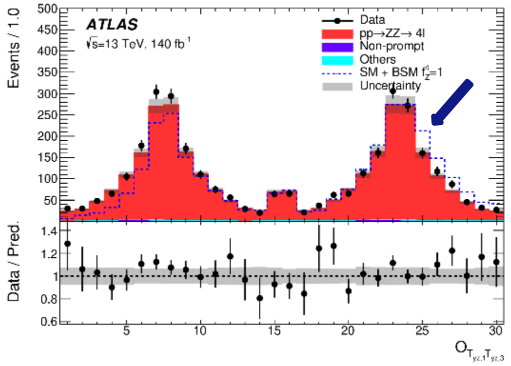
13 TeV 140 fb^{-1} Full Run-2

Contribution	Relative uncertainty [%]
Total	24
Data statistical uncertainty	23
Total systematic uncertainty	8.8
MC statistical uncertainty	1.7
Theoretical systematic uncertainties	
$q\bar{q} \to ZZ$ interference modelling	6.9
NLO reweighting observable choice for $q\bar{q} \to ZZ$	3.7
PDF, α_s and parton shower for $q\bar{q} \to ZZ$	2.2
NLO reweighting non-closure	1.0
QCD scale for $q\bar{q} \to ZZ$	0.2
NLO EW corrections for $q\bar{q} \to ZZ$	0.2
$gg \to ZZ$ modelling	1.4
Experimental systematic uncertainties	
Luminosity	0.8
Muons	0.6
Electrons	0.4
Non-prompt background	0.3
Pile-up reweighting	0.3
Triboson and $t\bar{t}Z$ normalisations	0.1

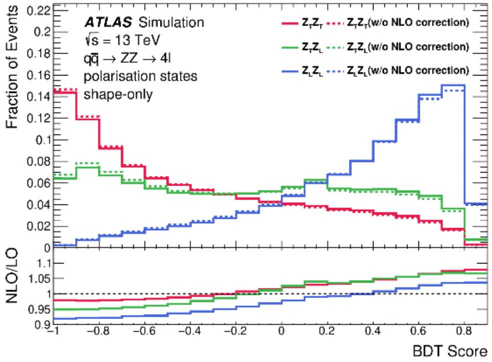
BDT distribution



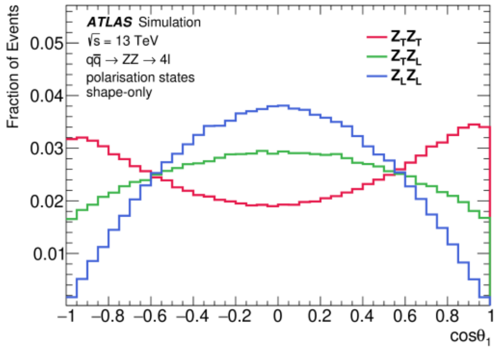
Asymmetric prediction



Impact of NLO corrections



Detector-level distribution to train BDT



JHEP 12 (2023) 107,STDM-2021-05

WZ polarisation at high p_T

13 TeV 140 fb^{-1} Full Run-2

(RAZ) effect in *WZ*

p_T^{WZ}<70 GeV	Impact [%]			
Source	TT state		Sum of polarizations	
Experimental	$\Delta Y(\ell_W Z)$	$\Delta Y(WZ)$	$\Delta Y(\ell_W Z)$	$\Delta Y(WZ)$
Luminosity	1.5	0.6	0.5	0.1
Electron calibration	0.9	0.5	1.7	0.4
Muon calibration	1.6	0.8	1.4	0.5
Jet energy scale and resolution	3.4	1.9	1.8	1.2
E_T^{miss} scale and resolution	1.3	1.0	2.2	1.4
Flavor-tagging inefficiency	0.0	0.0	0.1	0.0
Pileup modelling	0.0	0.4	3.4	0.4
Non-prompt background estimation	9.5	3.6	13.5	3.7
Modelling				
Background, other	5.7	2.1	8.0	2.1
Model statistical	2.4	1.3	4.6	2.0
NLO corrections	9.2	1.0	0.0	0.0
PDF, Scale and shower settings	7.5	3.9	0.7	0.2
Unfolding uncertainty	0.0	2.3	0.0	2.6
Experimental and modelling	17.0	6.8	17.2	5.7
Data statistical	12.8	6.2	27.0	10.3
Total	21.3	9.3	32.0	11.8

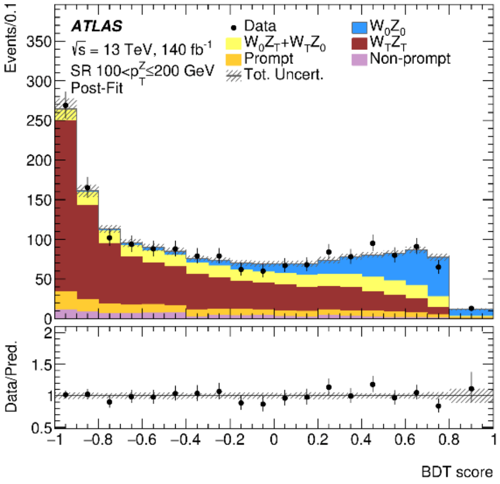
Energy dependence of diboson polarisation fractions

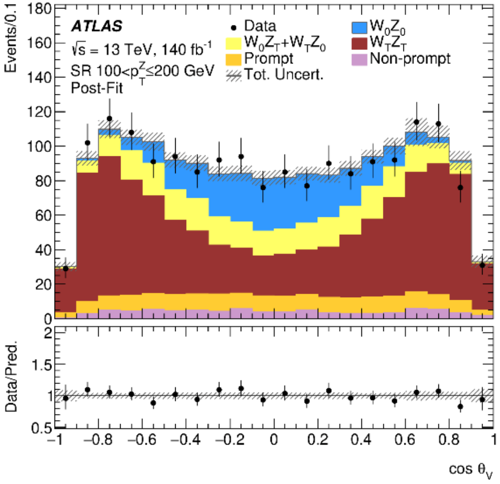
Source	Impact on f_{00} [%]	
Experimental	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
Luminosity	0.1	0.2
Electron calibration	1.0	0.9
Muon calibration	1.1	1.3
Jet energy scale and resolution	5.9	9.0
E_T^{miss} scale and resolution	1.0	0.6
Flavor-tagging inefficiency	0.1	0.2
Pileup modelling	1.6	1.1
Non-prompt background estimation	5.8	0.8
Modelling		
Background, other	1.4	1.6
Model statistical	2.5	5.6
NLO QCD effects	6.8	8.2
NLO EW effects	1.1	3.3
Effect of additive vs multiplicative QCD+EW combination	1.3	3.8
Interference impact	1.4	0.7
PDF, Scales, and shower settings	3.5	9.2
Experimental and modelling	12.1	17.7
Data statistical	18.0	64.5
Total	21.7	66.9

arXiv:2402.16365, STDM-2020-01

WZ polarisation at high p_T

13 TeV 140 fb^{-1} Full Run-2



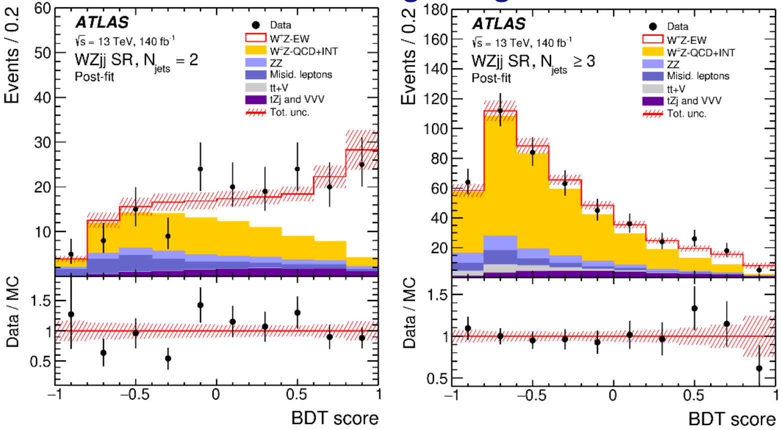


arXiv:2402.16365, STDM-2020-01

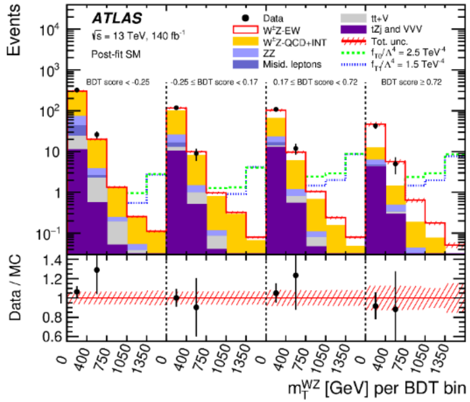
$W^{\pm}Zjj$

Source	$\frac{\Delta\sigma_{WZjj-\mathrm{EW}}}{\sigma_{WZjj-\mathrm{EW}}}$ [%]	$\frac{\Delta\sigma_{WZjj-\mathrm{strong}}}{\sigma_{WZjj-\mathrm{strong}}}$ [%]
$WZjj$–EW theory modelling	7	1.8
$WZjj$–QCD theory modelling	2.8	8
$WZjj$–EW and $WZjj$–QCD interference	0.35	0.6
PDFs	1.0	0.06
Jets	2.3	5
Pile-up	1.1	0.6
Electrons	0.8	0.8
Muons	0.9	0.9
b-tagging	0.10	0.11
MC statistics	1.9	1.2
Misid. lepton background	2.3	2.3
Other backgrounds	0.9	0.23
Luminosity	0.7	0.9
All systematics	16	12
Statistics	10	6
Total	19	13

BDT score distribution in the signal regions



2D combination of BDT score and m_{T}^{WZ} to obtain the EFT limits



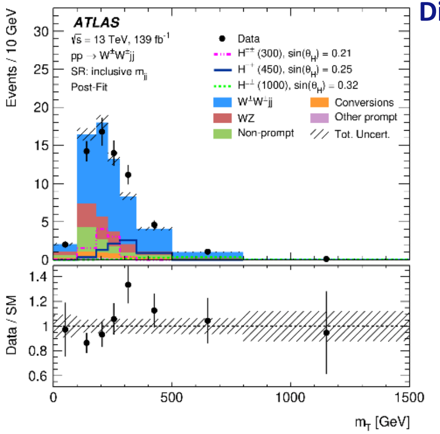
[JHEP 06 (2024) 192](), [STDM-2018-35]()

$W^{\pm}W^{\pm}jj$

13 TeV 139 fb^{-1} Full Run-2

JHEP 04 (2024) 026, STDM-2018-32

Source	Impact [%]
Experimental	4.6
Electron calibration	0.4
Muon calibration	0.5
Jet energy scale and resolution	1.9
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale and resolution	0.2
b-tagging inefficiency	0.7
Background, misid. leptons	3.4
Background, charge misrec.	1.0
Pile-up modelling	0.1
Luminosity	1.9
Modelling	4.5
EW $W^{\pm}W^{\pm}jj$, shower, scale, PDF & α_s	0.7
EW $W^{\pm}W^{\pm}jj$, QCD corrections	1.9
EW $W^{\pm}W^{\pm}jj$, EW corrections	0.9
Int $W^{\pm}W^{\pm}jj$, shower, scale, PDF & α_s	0.6
QCD $W^{\pm}W^{\pm}jj$, shower, scale, PDF & α_s	2.6
QCD $W^{\pm}W^{\pm}jj$, QCD corrections	0.8
Background, WZ scale, PDF & α_s	0.3
Background, WZ reweighting	1.5
Background, other	1.3
Model statistical	1.8
Experimental and modelling	6.4
Data statistical	7.4
Total	9.8

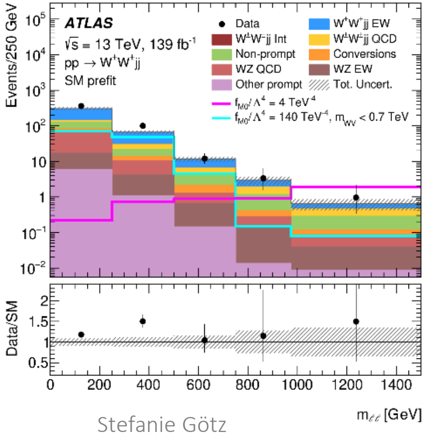


Distribution for $H_5^{\pm\pm}$ search

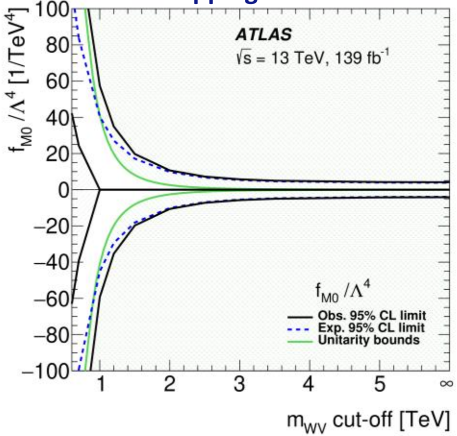
- The differential measurements are for all parameters except m_{T} well described

Variable	EW $W^{\pm}W^{\pm}jj$ χ^2/N_{dof}	EW $W^{\pm}W^{\pm}jj$ p-value	Inclusive $W^{\pm}W^{\pm}jj$ χ^2/N_{dof}	Inclusive $W^{\pm}W^{\pm}jj$ p-value	Max. value in data
$m_{\ell\ell}$	4.5/6	0.605	7.34/6	0.291	1081 GeV
m_{T}	13.0/6	0.043	16.33/6	0.012	1270 GeV
m_{jj}	7.6/6	0.266	8.67/6	0.193	6328 GeV
$N_{\mathrm{gap\ jets}}$	2.5/2	0.282	2.53/2	0.282	5
ξ_{j3}	4.2/5	0.517	4.93/5	0.424	1.74

Distribution for aQGC limits



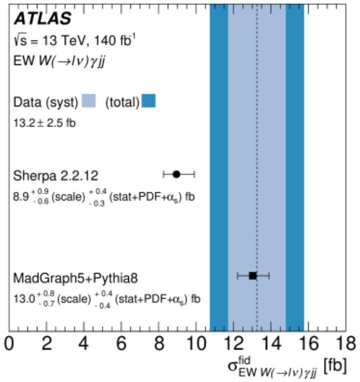
Example of 1D limit on D-8 EFT operators vs clipping scale



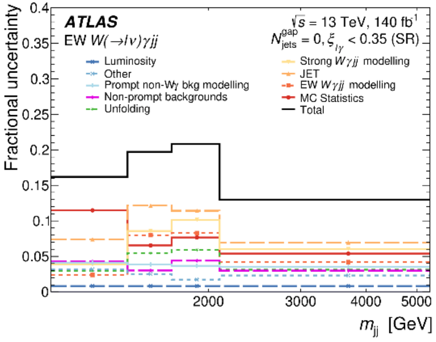
$W\gamma jj$

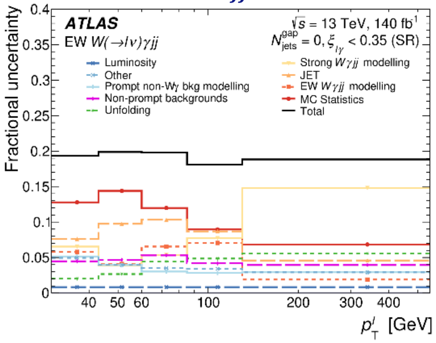
Uncertainty Source	Fractional Uncertainty [%]
MC Statistics	11
Jets	8
Lepton, photon, pile-up	8
EW $W\gamma jj$ modelling	7
Data Statistics	6
Strong $W\gamma jj$ modelling	6
Non-prompt background	2
Luminosity	2
Other Background modelling	2
$E_{\mathrm{T}}^{\mathrm{miss}}$	1

Fiducial cross-section	$\mathrm{SR}^{\mathrm{fid}}$		$\mathrm{CR}^{\mathrm{fid}}$	
	$N_{\mathrm{jets}}^{\mathrm{gap}} = 0$		$N_{\mathrm{jets}}^{\mathrm{gap}} > 0$	
Differential cross-section	SR	$\mathrm{CR_A}$	$\mathrm{CR_B}$	$\mathrm{CR_C}$
$m_{jj} > 1$ TeV	$N_{\mathrm{jets}}^{\mathrm{gap}} = 0$, $\xi_{l\gamma} < 0.35$	$N_{\mathrm{jets}}^{\mathrm{gap}} > 0$, $\xi_{l\gamma} < 0.35$	$N_{\mathrm{jets}}^{\mathrm{gap}} > 0$, $0.35 < \xi_{l\gamma} < 1$	$N_{\mathrm{jets}}^{\mathrm{gap}} = 0$, $0.35 < \xi_{l\gamma} < 1$

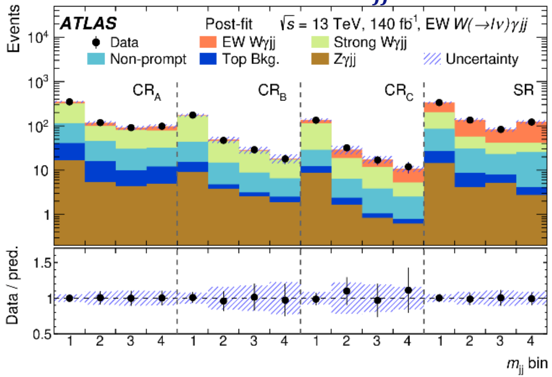


Fractional uncertainties as a function of m_{jj} & p_{T}^{l}





Distribution for predicted and observed yields as a function of m_{jj}



arXiv:2403.02809, STDM-2018-31