

# SMEFT IN THE EWK SECTOR IN ATLAS

LHC EFT WG (CERN 15-17 Nov)

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# HIGHLIGHTS (DIM-6)

## Older results:

### SMEFT HIGGS+EWK

[ATL-PHYS-PUB-2022-037]

- Optimal sensitivity to effects from dim-6 SMEFT operators of these operators

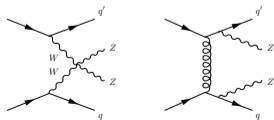
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \mathcal{O}(\Lambda^{-4})$$

## New results (this year):

### VBS ZZjj PRODUCTION

[STDM-2020-02]

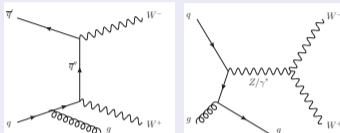
- Sensitive to aQGC



### WW + jets CROSS-SECTIONS

[JHEP 06 (2021) 003]

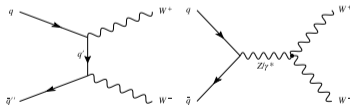
- Sensitive to aTGCs
- Interference resurrection



### WW JET INCLUSIVE

[ATLAS-CONF-2023-012]

- Sensitive to aTGC



### VBF Z PRODUCTION

[Eur. Phys. J. C 81 (2021) 163]

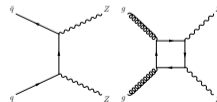
- Sensitive to aTGCs
- Sensitive to interference between SM and CP-odd amplitudes  
→ Test of CP invariance



### ZZ PRODUCTION @ 13.6 TeV

[ATLAS-CONF-2023-062]

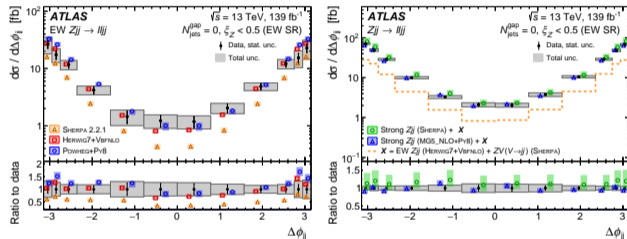
- Sensitive to neutral aTGCs



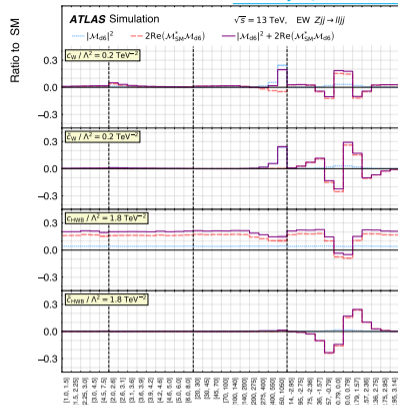


# VBF $Z$ PRODUCTION CROSS-SECTIONS

- First differential cross-section measurements for the EWK  $Z(\rightarrow \ell\ell)jj$  production ( $139 \text{ fb}^{-1}$ ), sensitive to VBF prod.
  - Probe WWZ TGC  $\rightarrow$  fundamental test of the SM EWK sector



- Constrain two CP-even ( $c_W$ ,  $c_{HWB}$ ) and two CP-odd ( $\tilde{c}_W$ ,  $\tilde{c}_{HWB}$ ) dim-6 operators
  - $\Delta\phi_{jj}$  very sensitive. Interference effects dominate
  - Used to constrain dim-6 operators in EWK  $Zjj$  SR
  - Stringent limits in linear-only fit



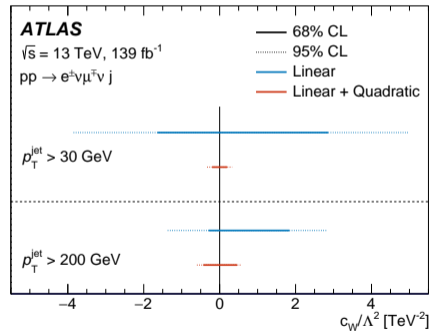
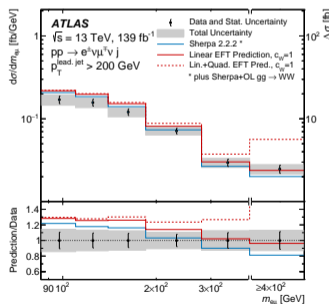
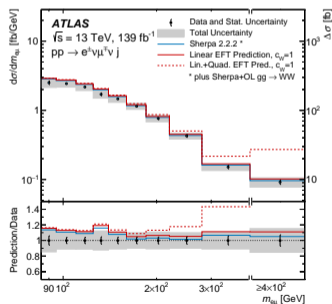
	$m_{jj}$ [TeV]	$ \Delta y_{jj} $	$p_{T,\perp}$ [GeV]	$\Delta\phi_{jj}$
Wilson coefficient	Includes $ M_{06} ^2$	95% confidence interval [TeV $^{-2}$ ]		$p$ -value (SM)
		Expected	Observed	
$c_W/\Lambda^2$	no	[-0.30, 0.30]	[-0.19, 0.41]	45.9%
	yes	[-0.31, 0.29]	[-0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	no	[-0.12, 0.12]	[-0.11, 0.14]	82.0%
	yes	[-0.12, 0.12]	[-0.11, 0.14]	81.8%
$c_{HWB}/\Lambda^2$	no	[-2.45, 2.45]	[-3.78, 1.13]	29.0%
	yes	[-3.11, 2.10]	[-6.31, 1.01]	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	[-1.06, 1.06]	[0.23, 2.34]	1.7%
	yes	[-1.06, 1.06]	[0.23, 2.35]	1.6%

# $W^+W^- \geq 1$ jets CROSS-SECTION MEASUREMENTS

- Unexplored  $pp \rightarrow e^\pm \nu \mu^\mp \nu + \text{jets}$  ( $139 \text{ fb}^{-1}$ ) topology up to 5 jets.
- Fiducial integrated and differential cross-sections in good agreement with SM within 10% unct.
- Dim-6  $\mathcal{O}_W$  operator constrained also in high- $p_T^{\text{lead. jet}}$  phase space using unfolded  $m_{e\mu}$  cross-section

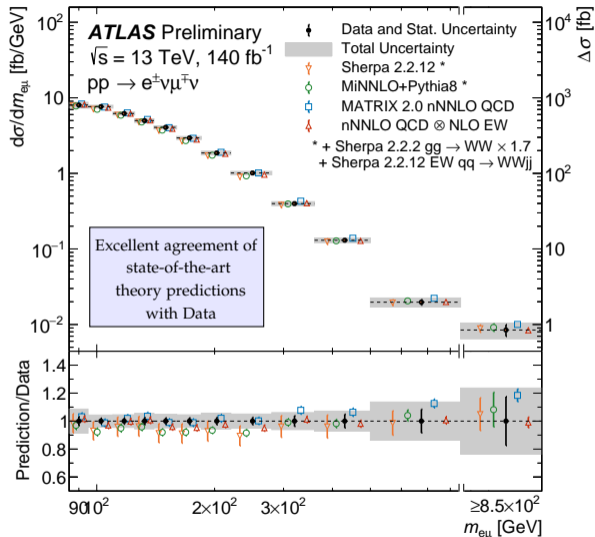
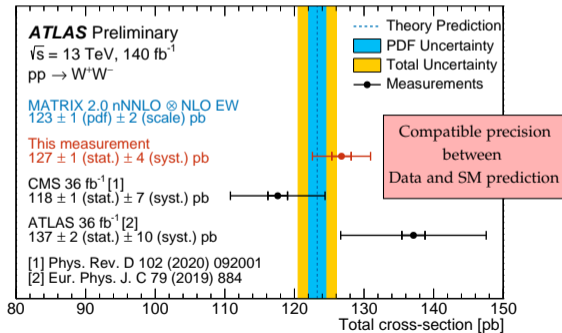
High- $p_T^{\text{jet}}$  SR enhances the sensitivity to SM-EFT interference

Dominated by  $\mathcal{O}(\Lambda^{-4})$  terms



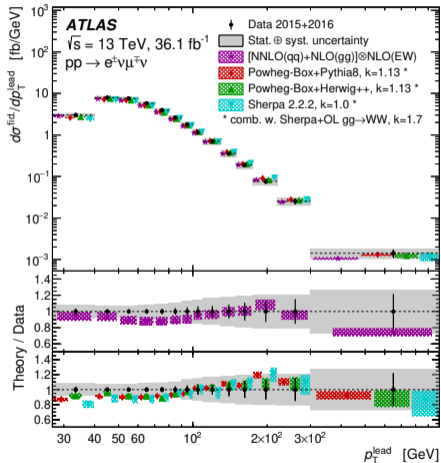
# $W^+W^-$ JET-INCLUSIVE: RESULTS

- Precision measurement of  $WW$  production in fully leptonic final state across 12 observables on lepton, jet and  $E_T^{\text{miss}}$  kinematics
- **Fiducial** (integrated and differential) and **total cross-sections**
- **Precision of 3.1%**, dominated by top modelling and fake background estimate



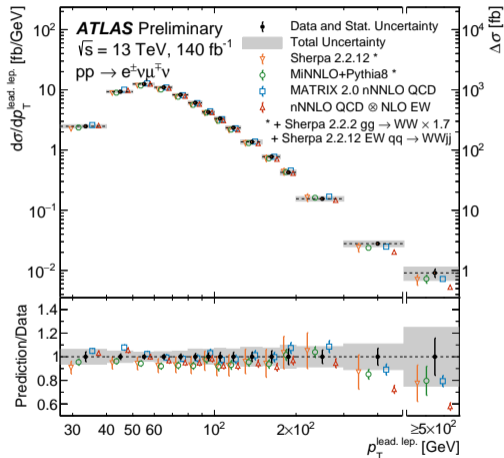
# PRECISION IN $W^+W^-$ PRODUCTION

$W^+W^- + 0 \text{ jets } (36 \text{ fb}^{-1})$



[Eur.Phys.J.C 79(2019)884]

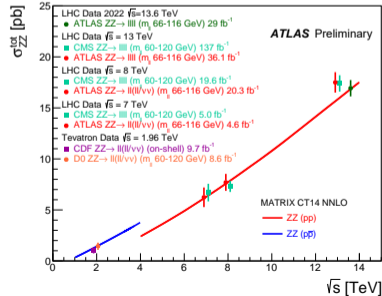
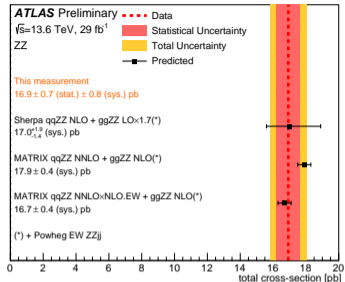
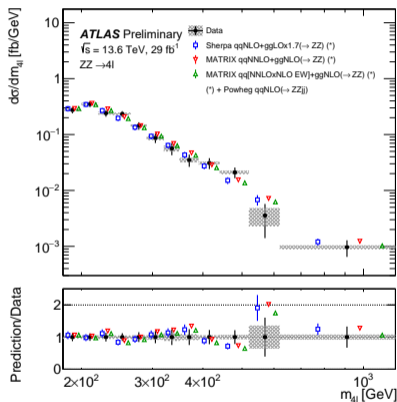
$W^+W^- \text{ jet inclusive } (140 \text{ fb}^{-1})$



NEW! [ATLAS-CONF-2023-012]

# ZZ PRODUCTION CROSS-SECTIONS @ 13.6 TeV

- First integrated and differential fiducial cross-section measurements
  - ▶ Using 2022 data ( $29 \text{ fb}^{-1}$ )
  - ▶  $ZZ \rightarrow 4\ell$  and  $ZZ \rightarrow 2\ell 2\nu$ , including  $H \rightarrow ZZ$  and EWK production
  - ▶ Two observables sensitive aTGCs:  $m_{4\ell}, p_{T,4\ell}$
- Good agreement with SM predictions



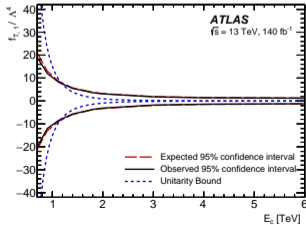
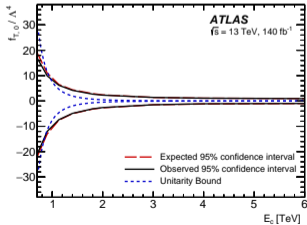


# VBS $ZZjj$ PRODUCTION

- Differential cross-section measurements of  $Z(\ell\ell)Z(\ell\ell)jj$ .

Observables:

- VBS-sensitive:  $m_{4\ell}, p_{T,4\ell}, m_{jj}, \Delta y_{jj}, p_{T,jj}$
- Polarization and CP structure of WWZ and WWZZ self-interactions:  $\cos\theta_{12}^*, \cos\theta_{34}^*, m_{jj}, \Delta\phi_{jj}, p_{T,jj}$
- Sensitive to extra QCD emission:  $p_{T,4\ell jj}, S_{T,4\ell jj}$
- Constrains on **CP-odd dim-6 operators** using  $\Delta\phi_{jj}$  dist. (large asymmetric effects for SM-EFT int.).
- 95% CL intervals for **dim-8 operators** as a function of cut-off energy ( $m_{4\ell} < E_c$ ) using 2D ( $m_{jj}, m_{4\ell}$ ) fit.

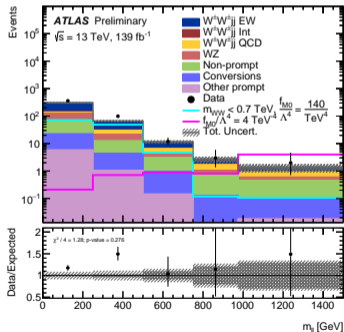


Wilson coefficient	$ \mathcal{M}_{d6} ^2$ Included	95% confidence interval [TeV <sup>-2</sup> ] Expected	95% confidence interval [TeV <sup>-2</sup> ] Observed
$c_W/\Lambda^2$	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-32, 32]	[-37, 28]
$c_{\bar{W}}/\Lambda^2$	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-17, 17]*	[0, 30]*
$c_{HWB}/\Lambda^2$	yes	[-16, 7]	[-16, 6]
	no	[-12, 12]	[-15, 10]
$c_{H\bar{W}B}/\Lambda^2$	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-67, 67]*	[-25, 130]*
$c_{HB}/\Lambda^2$	yes	[-13, 13]	[-12, 12]
	no	[-38, 38]	[-38, 38]
$c_{H\bar{B}}/\Lambda^2$	yes	[-13, 13]	[-12, 12]
	no	[-420, 420]*	[-200, 790]*

Wilson coefficient	$ \mathcal{M}_{d8} ^2$ Included	95% confidence interval [TeV <sup>-4</sup> ] Expected	95% confidence interval [TeV <sup>-4</sup> ] Observed
$f_{T,0}/\Lambda^4$	yes	[-0.98, 0.93]	[-1.00, 0.97]
	no	[-23, 17]	[-19, 19]
$f_{T,1}/\Lambda^4$	yes	[-1.2, 1.2]	[-1.3, 1.3]
	no	[-160, 120]	[-140, 140]
$f_{T,2}/\Lambda^4$	yes	[-2.5, 2.4]	[-2.6, 2.5]
	no	[-74, 56]	[-63, 62]
$f_{T,5}/\Lambda^4$	yes	[-2.5, 2.4]	[-2.6, 2.5]
	no	[-79, 60]	[-68, 67]
$f_{T,6}/\Lambda^4$	yes	[-3.9, 3.9]	[-4.1, 4.1]
	no	[-64, 48]	[-55, 54]
$f_{T,7}/\Lambda^4$	yes	[-8.5, 8.1]	[-8.8, 8.4]
	no	[-260, 200]	[-220, 220]
$f_{T,8}/\Lambda^4$	yes	[-2.1, 2.1]	[-2.2, 2.2]
	no	[-4.6, 3.1]×10 <sup>4</sup>	[-3.9, 3.8]×10 <sup>4</sup>
$f_{T,9}/\Lambda^4$	yes	[-4.5, 4.5]	[-4.7, 4.7]
	no	[-7.5, 5.5]×10 <sup>4</sup>	[-6.4, 6.3]×10 <sup>4</sup>

# ONE LAST HIGHLIGHT (DIM-8): EWK $W^\pm W^\pm jj$ PRODUCTION

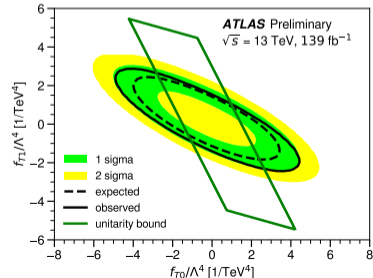
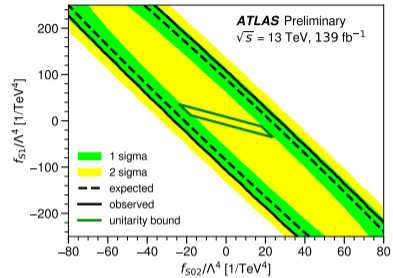
- Fiducial and differential production cross-sections for inclusive and EWK-enhanced phase space



Optimized  $m_{\ell\ell}$ -dist binning to extract dim-8 SMEFT limits on dim-8 Wilson coeffs.

Constrains as a function of  $m_{WW}$  cut-off also reported

Coefficient	Type	No unitarisation cut-off [ $\text{TeV}^{-4}$ ]
$f_{M0}/\Lambda^4$	exp.	[-3.9, 3.8]
	obs.	[-4.1, 4.1]
$f_{M1}/\Lambda^4$	exp.	[-6.3, 6.6]
	obs.	[-6.8, 7.0]
$f_{M7}/\Lambda^4$	exp.	[-9.3, 8.8]
	obs.	[-9.8, 9.5]
$f_{S02}/\Lambda^4$	exp.	[-5.5, 5.7]
	obs.	[-5.9, 5.9]
$f_{S1}/\Lambda^4$	exp.	[-22.0, 22.5]
	obs.	[-23.5, 23.6]
$f_{T0}/\Lambda^4$	exp.	[-0.34, 0.34]
	obs.	[-0.36, 0.36]
$f_{T1}/\Lambda^4$	exp.	[-0.158, 0.174]
	obs.	[-0.174, 0.186]
$f_{T2}/\Lambda^4$	exp.	[-0.56, 0.70]
	obs.	[-0.63, 0.74]



# CONCLUSIONS

- Measurements of EWK vector boson production at the LHC provide unprecedented sensitivity to both anomalous triple and quartic gauge couplings.
- Global ATLAS EFT interpretations including Higgs, EWK and LEP/SLC precision observables available
  - ▶ Robust framework and growing up!
- Many interesting EWK results released/coming using
  - ▶ Full Run 2 dataset @ 13 TeV
  - ▶ Collected Run 3 dataset @ 13.6 TeV

**Stay tune for oncoming results!**

SMEFT Higgs+EWK(+EWPD)

[[ATL-PHYS-PUB-2022-037](#)]

$WW$  + jets CROSS-SECTIONS

[[JHEP 06 \(2021\) 003](#)]

VBF  $Z$  PRODUCTION

[[Eur. Phys. J. C 81 \(2021\) 163](#)]

VBS  $ZZjj$  PRODUCTION

NEW! [[STDM-2020-02](#)]

$WW$  JET INCLUSIVE

NEW! [[ATLAS-CONF-2023-012](#)]

$ZZ$  PRODUCTION @ 13.6 TeV

NEW! [[ATLAS-CONF-2023-062](#)]

EWK  $W^\pm W^\pm jj$  PRODUCTION

NEW! [[ATLAS-CONF-2023-023](#)]

# Backup slides



# RELATIVE IMPACT OF LINEAR SMEFT TERMS WITH WILSON COEFFS

