Inclusive $W^{\pm}Z$ production at $\sqrt{s}$ = 13 TeV with the ATLAS detector

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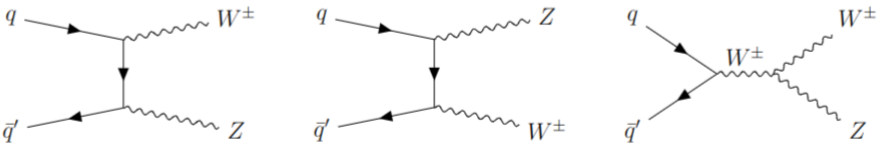
Inclusive *WZ*



First step toward probing the EWSB through the scattering of EW gauge bosons.

This work completes previous partial Run 2 inclusive $W^\pm Z$ analysis:

- Reduced statistical uncertainty
- Comparison with state-of-the-art SM fixed-order calculations
- EFT interpretations

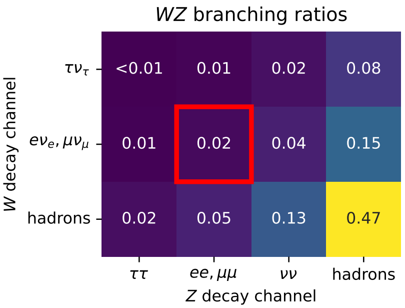
Leptonic decay channel

Fiducial cross-section extrapolated to the total phase space (EPJC **79** (2019) 535):

$$\sigma^{\text{tot.}}_{W^\pm Z} = 51.0 \pm 2.4 \text{ pb}$$

$\rightarrow 7 \times 10^6$ events expected with 140 fb^{-1}.

Sensitive to choice of **leptonic decay channels (e, μ)** for precision measurement.
$\rightarrow 1 \times 10^5$ events

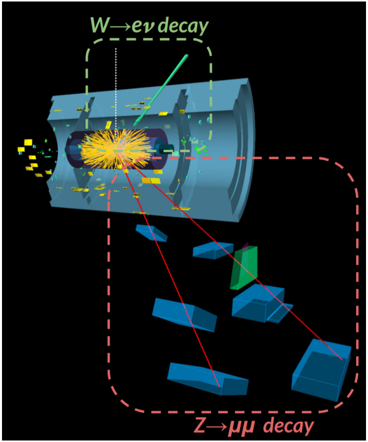


Lepton and event selection

Selection in 3 steps, from least to most stringent:

- Baseline (Loose ID, p_T > 5 GeV)
- Z selection (Medium ID, p_T > 15 GeV)
- W selection (Tight ID, p_T > 20 GeV)

Inclusive event selection	
N leptons	Exactly 3 leptons passing baseline selection
Z leptons	2 same flavour, opposite charge leptons passing Z-lepton selection
Mass window	$\|m_{\ell\ell} - m_Z\| < 10$ GeV
W lepton	Remaining lepton passes W-lepton selection
W transverse mass	$m_T^W > 30$ GeV

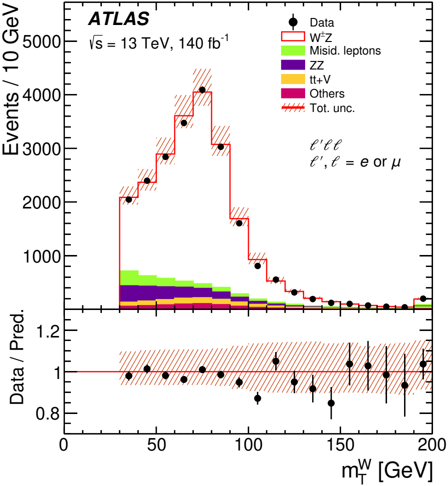


ATLAS public event displays

Irreducible: ≥ 3 real leptons

- $ZZ \rightarrow$ dedicated CR (≥ 4 baseline leptons)
- $t\bar{t}V \rightarrow$ dedicated CR (≥ 2 b-jets)
- tZ, VVV, electroweak $W^{\pm}Zjj$ $\rightarrow$ MC estimation

Reducible: ≥ 1 "fake" lepton
$Z\gamma$, $Z+j$, $t\bar{t}$
$\rightarrow$ data-driven method



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Fixed-order calculations

MATRIX framework computes matrix elements up to:

- NNLO in QCD
- NLO in EW

Two main schemes applicable, accounting for EW corrections differently:

NNLO QCD + EW

$$d\sigma = d\sigma_{\text{LO}}(1 + \delta_{\text{QCD}} + \delta_{\text{EW}}) + d\sigma_{\text{LO}}^{gg}$$

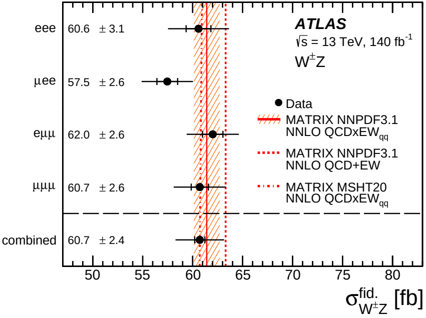
NNLO QCD $\times$ EW$_{qq}$

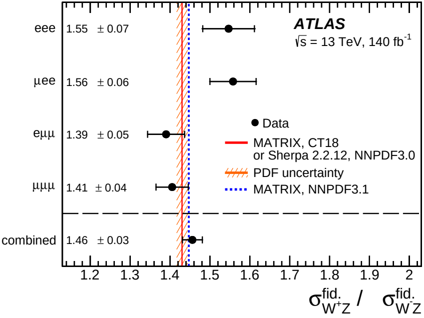
$$d\sigma = \left[d\sigma_{\text{LO}}^{q\bar{q}}(1 + \delta_{\text{QCD}}^{q\bar{q}}) + d\sigma_{\text{LO}}^{\gamma\gamma}\right](1 + \delta_{\text{EW}}) + d\sigma_{\text{LO}}^{gg}$$

Inclusive cross-section measurement

Measurement by decay channel $\rightarrow \chi^2$ combination.

$$\sigma^{\text{fid.}}_{W^\pm Z\rightarrow \ell' \nu \ell\ell} = 60.7 \pm 0.5\,(\text{stat.}) \pm 2.3\,(\text{syst.}) \pm 0.6\,(\text{lumi.})\ \text{fb.}$$





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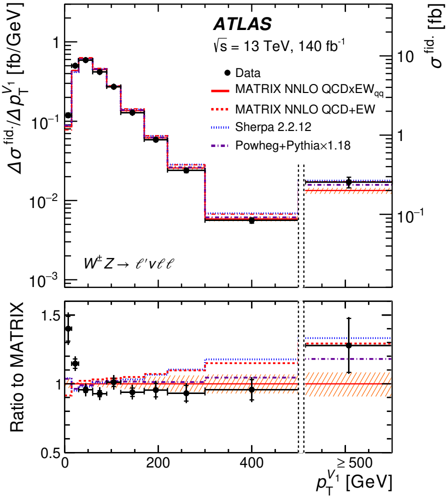
Sensitive to the **choice of PDF** and **MATRIX EW scheme**.

Differential cross-sections



V_1: vector boson with leading p_T

- Low energy:
  differences due to soft QCD effects not accounted for in the calculation.
- High energy:
  Better description of data by multiplicative scheme.

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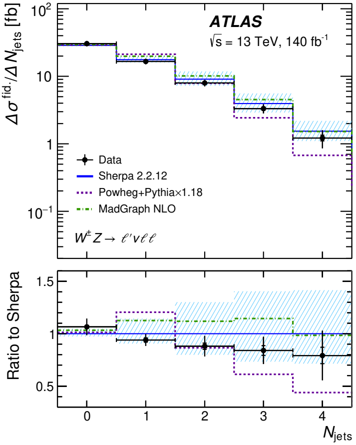
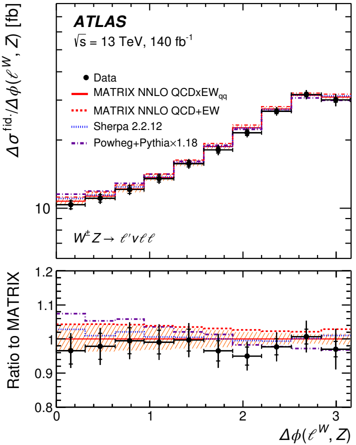
SHERPA2.2.12 describes fairly the jet mutliplicity.
SHERPA2.2.12 and MATRIX describe $\Delta\phi(\ell^W, Z)$ reasonably well.





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EFT interpretation

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{n-4}} \left(\sum_i c_i^{(n)} \mathcal{O}_i^{(n)} \right)$$

$c_i^{(n)}$ Wilson coefficients, Λ new physics energy scale.

- $n = 5$: non conservation of L, not considered
- **$n = 6$: dominant term**

Operator type	Wilson coefficient	Operator	CP
X^3	c_W	$\mathcal{O}_W = \varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	even
	$c_{\tilde{W}}$	$\mathcal{O}_{\tilde{W}} = \varepsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	odd
X^2H^2	c_{HWB}	$\mathcal{O}_{HWB} = \phi^\dagger \sigma^I \phi W^I_{\mu\nu} B^{\mu\nu}$	even
	$c_{H\tilde{W}B}$	$\mathcal{O}_{HWB} = \phi^\dagger \sigma^I \phi \tilde{W}^I_{\mu\nu} B^{\mu\nu}$	odd
H^4D^2	c_{HD}	$\mathcal{O}_{HD} = (D^\mu \phi^\dagger \phi)(\phi^\dagger D^\mu \phi)$	even
ψ^2H^2D	$c_{Hq}^{(1)}$	$\mathcal{O}_{Hq}^{(1)} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{q}\gamma^\mu q)$	even
	$c_{Hq}^{(3)}$	$\mathcal{O}_{Hq}^{(3)} = (\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi)(\bar{q}\sigma^I\gamma^\mu q)$	even

Fit at detector level

Decomposition method:

$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + \sum_i \frac{c_i}{\Lambda^2} 2\Re\left\{\mathcal{M}_{\mathrm{SM}}^* \mathcal{M}_{i,6}\right\} + \sum_i \frac{c_i^2}{\Lambda^4} |\mathcal{M}_{i,6}|^2$$

Maximum likelihood fit to constrain floating parameter of interest c_i/Λ^2.

Fit at detector level:

- **SM** prediction: Sherpa2.2.12 (**NLO QCD**)
- **EFT** predictions: MadGraph5+Pythia8 interfaced with SMEFTsim (**LO QCD**)
- Backgrounds
- Uncertainties on each component

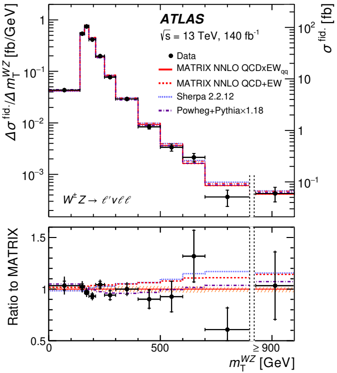
No EFT generator available at NLO QCD for the decomposition method.
$\rightarrow$ EFT simulations generated in the **merged 0+1j scheme**.

Decomposition method:

$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + \sum_i \frac{c_i}{\Lambda^2} 2\Re\left\{\mathcal{M}^*_{SM}\mathcal{M}_{i,6}\right\} + \sum_i \frac{c_i^2}{\Lambda^4}|\mathcal{M}_{i,6}|^2$$

CP-even: all terms lead to $\Delta\sigma \neq 0$, choice based on sensitivity to EFT in high energy tails.
$\rightarrow m_T^{WZ}$ binning optimised.

$$\left(m_T^{WZ}\right)^2 = \left(\sum_{\ell=1}^{3} p_T^\ell + E_T^{miss}\right)^2 - \left(\sum_{\ell=1}^{3} p_x^\ell + E_x^{miss}\right)^2 - \left(\sum_{\ell=1}^{3} p_y^\ell + E_y^{miss}\right)^2$$



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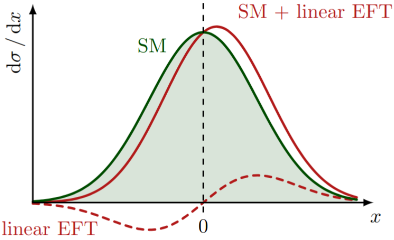
EFT: CP-violating case

Decomposition method:

$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + \sum_i \frac{c_i}{\Lambda^2} 2\Re\left\{\mathcal{M}_{\mathrm{SM}}^* \mathcal{M}_{i,6}\right\} + \sum_i \frac{c_i^2}{\Lambda^4} |\mathcal{M}_{i,6}|^2$$

CP-odd: bosonic operators only.
$\rightarrow \Delta\sigma_{\mathrm{int}} = 0$
Choice of variable based on the **asymmetry** of the interference.



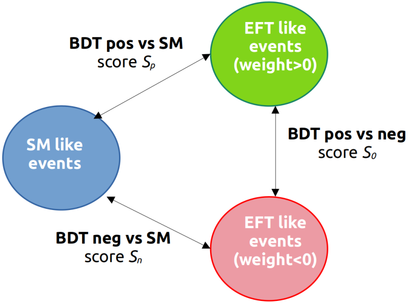
To exploit CP-odd variables properties, events classified in 3 categories:
SM, interference ($w > 0$), interference ($w < 0$).

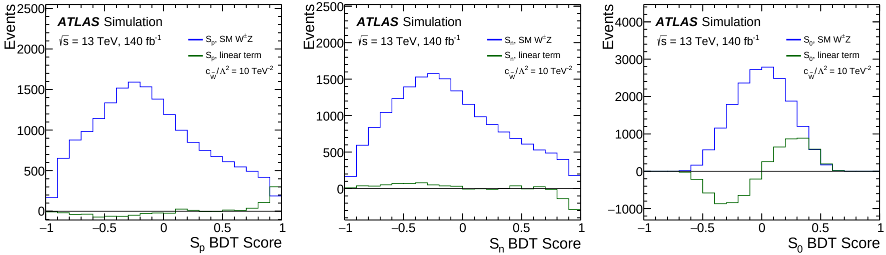
Multivariate approach

Enhance asymmetry with a set of Boosted Decision Trees using `TMVA`.

Three BDT acting each as binary classifier, three BDT scores S_p, S_n, S_o for each operator.

S_o most sensitive to CP-violation.





($c_{\tilde{W}}$ interference vs SM)

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Multivariate approach

Variable	$S_{p,n}$	S_0
r_{21}	✓	
m_{T}^{WZ}	✓	✓
m_{T}^{W}		✓
p_{T}^{WZ}	✓	
$E_{\mathrm{T}}^{\mathrm{miss}}$	✓	
$p_\perp(\sum p^z, Z, \ell^W)$	✓	✓
$p_\perp(W, \ell^+, \ell^W)$	✓	✓
$p_\perp(W, \ell^-, \ell^W)$	✓	✓
$p_\perp(\ell^{-,z}, \ell^W, \ell^+)$		✓
$p_\perp(\ell^{+,z}, \ell^-, \ell^W)$		✓
ϕ_Z^*	✓	✓
ϕ_W^*		✓
$\lvert\cos\theta_V\rvert$	✓	✓
$\cos\theta_W^*$	✓	✓
$\cos\theta_Z^*$		✓
$\cos\chi$		✓
$\Delta\phi(\ell^W, \ell^Z)^{ss}$	✓	
$\Delta\phi(\ell^W, Z)$		✓
$\lvert y_Z - y_{\ell,W}\rvert$	✓	✓

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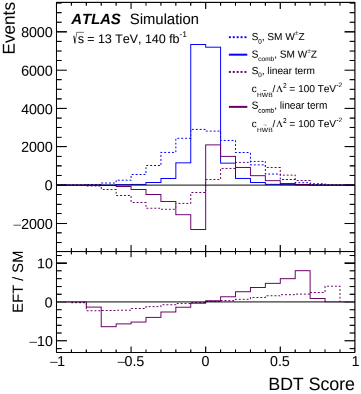
- $r_{21} = p_{\mathrm{T}}^{V_1}/p_{\mathrm{T}}^{V_2}$
- ϕ_W^*, $\cos\theta_W^*$, ϕ_Z^*, $\cos\theta_Z^*$: angles of ℓ^W and ℓ^{Z-} in the modified helicity frame.
- Triple products: $p_\perp(A,B,C) = \vec{p}_A \cdot \frac{\vec{p}_B\times\vec{p}_C}{|\vec{p}_B\times\vec{p}_C|}$
- χ: angle between W and Z decay planes
- θ_V: angle between $\vec{p}_V$ and z-axis in WZ rest frame

Multivariate approach

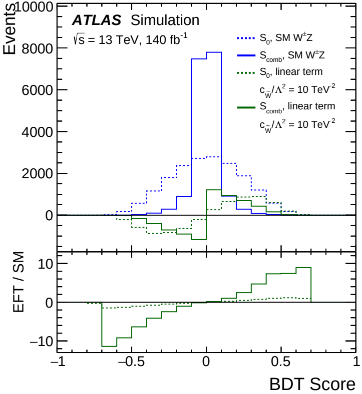
Enhance SM vs EFT separation by combining the scores:

$$S_{\text{comb}}(c_i) = S_{\text{o}}(c_i)\,\frac{1+S_p(c_i)}{2}\,\frac{1+S_n(c_i)}{2}$$

$S_{\text{comb}}(c_{H\tilde{W}B})$



$S_{\text{comb}}(c_{\tilde{W}})$



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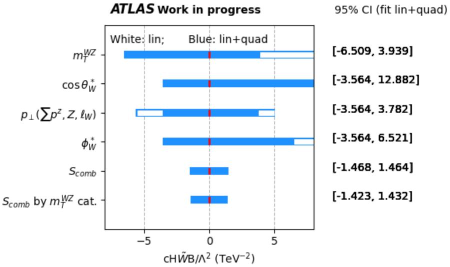
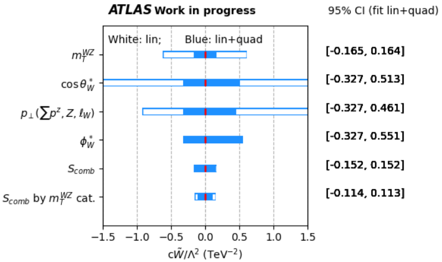
Multivariate approach

Expected sensitivity (Asimov fit, stat. only)

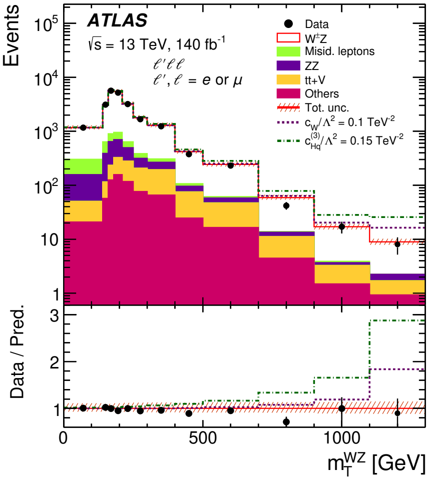


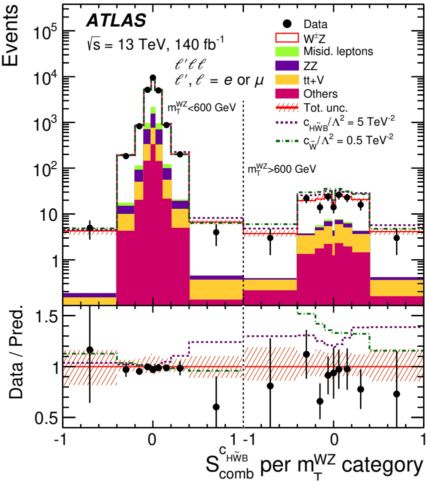


Improvement of expected limits by a factor up to 3 with respect to best single observable for $c_{H\tilde{W}B}$.

Splitting $S_{\text{comb}}(c_i)$ by $m_{\text{T}}^{WZ} \lessgtr 600$ GeV categories brings sensitivity to quadratic term.

Wilson coefficient limits





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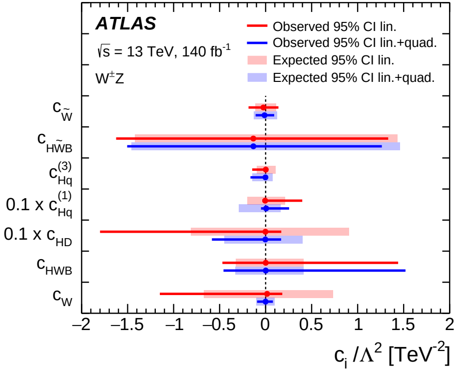
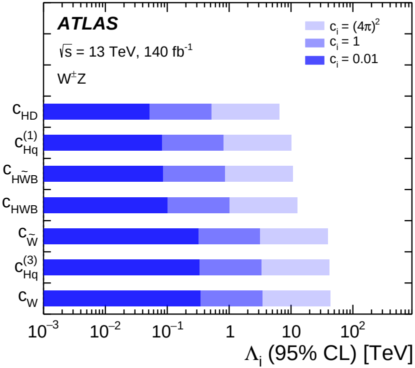
Wilson coefficient limits

Limits driven by the EFT linear term, except for CP-even c_W and c_{HD}.





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Measurement dominated by statistical uncertainties.

Comparison to existing CP-odd limits

Limits on CP-violating operators competitive with existing analyses.

Process	Observable	$c_{H\tilde{W}B}$ 95% CL	$c_{\tilde{W}}$ 95% CL
$H \to ZZ^*$	Optimal Observable	$[-0.82, 0.31]$	—
$H \to WW^*$	$\Delta\phi_{jj}$	$[-1.15, 1.14]$	—
$W\gamma$	p_T^{γ}	—	$[-0.45, 0.45]$
EW-Zjj	$\Delta\phi_{jj}$ vs p_T^H	$[0.23, 2.35]$	$[-0.11, 0.14]$
$W^{\pm}Z$	S_{comb}	$[-1.51, 1.26]$	$[-0.11, 0.09]$

red: CMS blue: ATLAS

Conclusion

Inclusive cross-section measurement agrees with SM prediction.

Differential cross-section measurements enable testing different schemes for the combination of NNLO QCD and NLO EW corrections.

Novel MVA approach to enhance sensitivity to CP-odd EFT interference terms.

Limits on c_i at 95% confidence level competitive with existing limits, **compatible with Standard Model scenario**.

Input for **incoming combination** of all ATLAS CP-odd coefficients measurements.

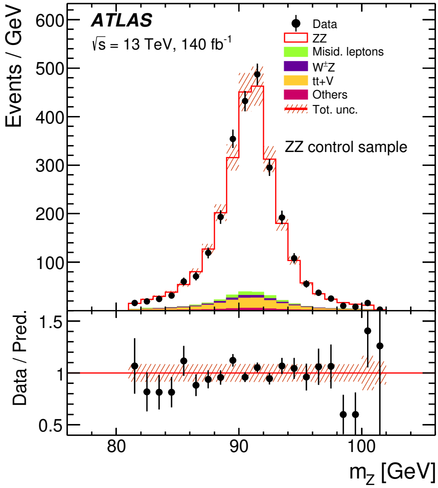
Back-up

Criteria	Baseline selection	Z selection	W selection
p_T cut	> 5 GeV	> 15 GeV	> 20 GeV
$\|\eta\|$ cut	< 2.7	< 2.5	< 2.5
Identification WP	`Loose`	`Medium`	`Tight`
$\|d_0^{BL}/\sigma(d_0^{BL})\|$ cut[1]	< 3	< 3	< 3
$\|\delta z_0^{BL} \sin\theta\|$ cut[1]	< 0.5 mm	< 0.5 mm	< 0.5 mm
Isolation WP	`PflowLoose_FixedRad`	`PflowLoose_FixedRad`	`PflowLoose_FixedRad`
Overlap removal	None	μ-jet	μ-jet

Electrons:

Criteria	Baseline selection	Z selection	W selection
p_T cut	> 5 GeV	> 15 GeV	> 20 GeV
$\|\eta\|$ cut	< 2.5	< 2.5	< 2.5
$\|\eta_{BE2}\|$ cut	< 2.47	$\in [0, 1.37] \cup [1.52, 2.47]$	$\in [0, 1.37] \cup [1.52, 2.47]$
Identification WP	`LooseAndBLayer`	`Medium`	`Tight`
$\|d_0^{BL}/\sigma(d_0^{BL})\|$ cut	< 5	< 5	< 5
$\|\delta z_0^{BL} \sin\theta\|$ cut	< 0.5 mm	< 0.5 mm	< 0.5 mm
Isolation WP	`Loose_VarRad`	`HighPtCaloOnly`	`Tight_VarRad`
Overlap removal	e-to-μ, e-to-e	e-to-μ, e-to-e, e-to-jets	e-to-μ, e-to-e, e-to-jets
Ambiguous author	Accepted	Accepted	Rejected
`DFCommonAddAmbiguity`	No cut	No cut	≤ 0

ZZ **CR**: inclusive selection with ≥ 4 baseline leptons



Fit uncertainties

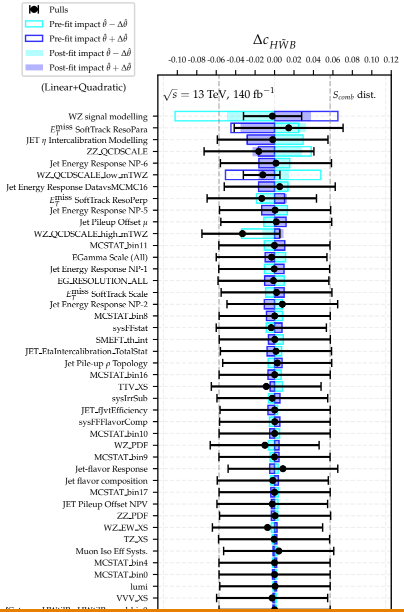
Merged 0+1j EFT samples to emulate real corrections

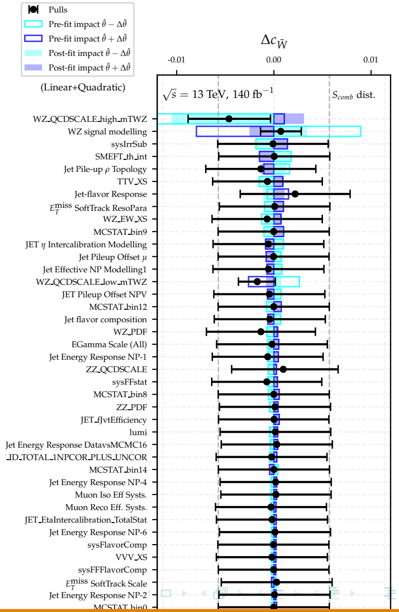
Theory uncertainty on EFT predictions taken as $\frac{\Delta(\mathrm{LO},\, 0+1\mathrm{j})}{2}$

SM signal modelling uncertainty:

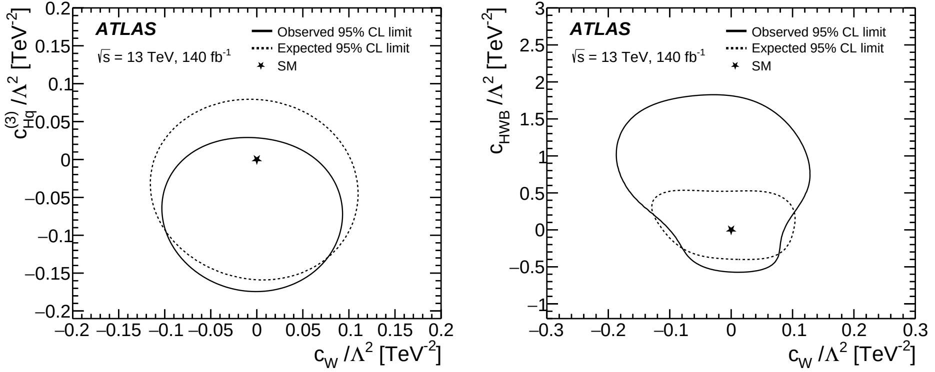
$$|\mathrm{SH}_k - \mathrm{PHP}_k| - \sqrt{\delta_k^{stat}\mathrm{SH}_k^2 + \delta_k^{stat}\mathrm{PHP}_k^2} \text{ or } 0$$

Uncertainties





ML fit with 2 simultaneously floating POI (CP-even):



For comparison, 1D limits at 95% confidence level:

$c_W/\Lambda^2 \in [-0.093, 0.079]$ TeV^{-2}

$c_{HWB}/\Lambda^2 \in [-0.458, 1.520]$ TeV^{-2}

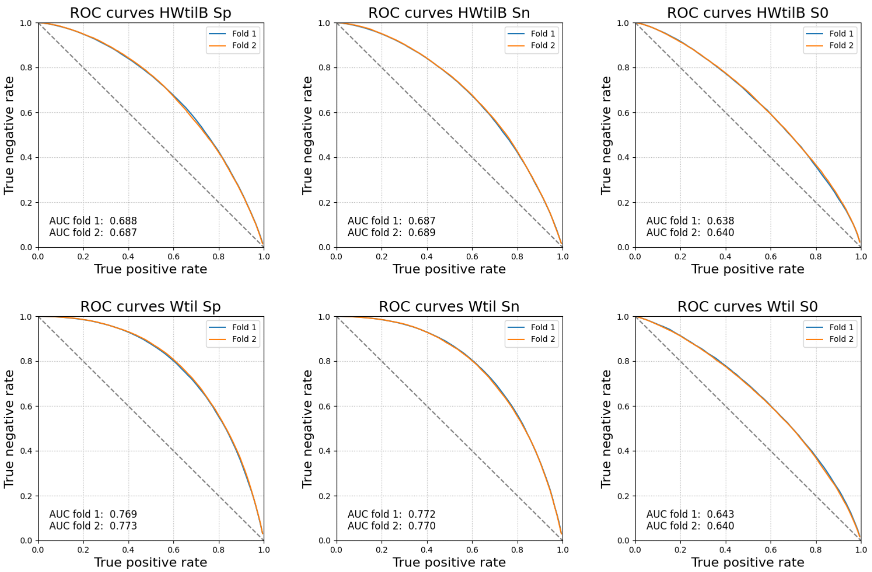
$c_{Hq}^{(3)}/\Lambda^2 \in [-0.165, 0.015]$ TeV^{-2}

Existing ATLAS limits

anomalous TGC: *WZ* complementary to other EFT studies in Vector Boson Fusion (VBF) and Scattering (VBS) processes:

Process	Observable	$c_{H\tilde{W}B}$ 95% CL	$c_{\tilde{W}}$ 95% CL
$H \to \tau\tau$	$\Delta\Phi_{jj}$	[-2.5, 5.1]	—
$H \to WW^*$	$\Delta\Phi_{jj}$	[-1.2, 1.1]	—
Electroweak *Zjj*	$\Delta\Phi_{jj}$	[0.23, 2.35]	[-0.11, 0.14]
$W^{\pm}Z$	S_{comb}	**[-1.51, 1.26]**	**[-0.11, 0.09]**

BDT performance



BDT variables importance

Rank	$S_p(c_{H\tilde{W}B})$ input	Separation
1	m_{T}^{WZ}	5.620e-02
2	r_{21}	3.945e-02
3	$\lvert\cos\theta_V\rvert$	2.411e-02
4	$\Delta\phi(\ell^W,\ell^Z)^{ss}$	2.358e-02
5	p_{T}^{WZ}	1.903e-02
6	$E_{\mathrm{T}}^{\mathrm{miss}}$	1.591e-02
7	$p_\perp(\sum p^z, Z, \ell^W)$	1.243e-02
8	$p_\perp(W,\ell^-,\ell^W)$	9.407e-03
9	$p_\perp(W,\ell^+,\ell^W)$	8.869e-03
10	$\cos\theta_W^*$	3.763e-03
11	$\lvert y_Z - y_{\ell,W}\rvert$	3.537e-03
12	ϕ_Z^*	2.215e-03

Rank	$S_n(c_{H\tilde{W}B})$ input	Separation
1	m_{T}^{WZ}	5.364e-02
2	r_{21}	3.722e-02
3	$\lvert\cos\theta_V\rvert$	2.419e-02
4	$\Delta\phi(\ell^W,\ell^Z)^{ss}$	2.310e-02
5	p_{T}^{WZ}	1.913e-02
6	$E_{\mathrm{T}}^{\mathrm{miss}}$	1.509e-02
7	$p_\perp(\sum p^z, Z, \ell^W)$	1.190e-02
8	$p_\perp(W,\ell^-,\ell^W)$	9.703e-03
9	$p_\perp(W,\ell^+,\ell^W)$	7.590e-03
10	$\lvert y_Z - y_{\ell,W}\rvert$	3.905e-03
11	$\cos\theta_W^*$	3.889e-03
12	ϕ_Z^*	2.357e-03

Rank	$S_o(c_{H\tilde{W}B})$ input	Separation
1	$p_\perp(\sum p^z, Z, \ell^W)$	2.427e-02
2	$p_\perp(W,\ell^-,\ell^W)$	2.087e-02
3	$p_\perp(W,\ell^+,\ell^W)$	1.611e-02
4	$\Delta\phi(\ell^W, Z)$	1.079e-02
5	ϕ_W^*	9.083e-03
6	$p_\perp(\ell^{+,z},\ell^-,\ell^W)$	2.582e-03
7	ϕ_Z^*	1.715e-03
8	$p_\perp(\ell^{-,z},\ell^W,\ell^+)$	1.670e-03
9	m_{T}^{W}	3.927e-04
10	$\cos\theta_Z^*$	3.751e-04
11	m_{T}^{WZ}	3.751e-04
12	$\cos\chi$	3.184e-04
13	$\cos\theta_W^*$	3.078e-04
14	$\lvert\cos\theta_V\rvert$	2.851e-04
15	$\lvert y_Z - y_{\ell,W}\rvert$	2.270e-04

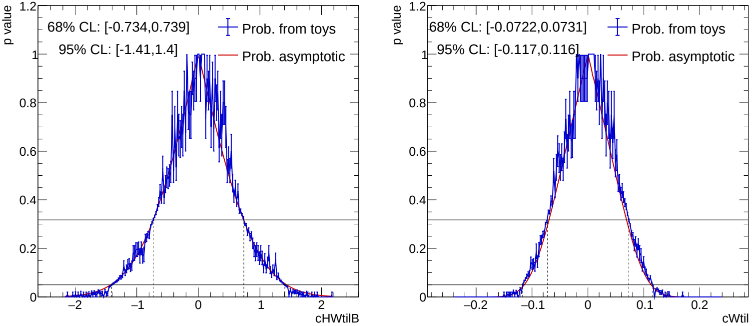
(Work in progress)

$$\mathcal{S} = w_{\mathrm{parent}} Q_{\mathrm{parent}} - w_{\mathrm{left}} Q_{\mathrm{left}} - w_{\mathrm{right}} Q_{\mathrm{right}}$$

$$Q = p_S(1-p_S) = \frac{n_S n_B}{(n_S+n_B)^2}$$ the Gini index of a node

Toys extracted limits

10^4 pseudo-experiments per scan point (Asimov fit, stat. only)



(Work in progress)

Operator	Asymptotic 95% CL	Toys 95% CL
$c_{H\tilde{W}B}$	[-1.423, 1.432]	[-1.407, 1.404]
$c_{\tilde{W}WW}$	[-0.114, 0.113]	[-0.117, 0.116]

CP-odd Uncertainties

	$c_{H\tilde{W}B}$ 95% CL	$c_{\tilde{W}}$ 95% CL
Stat.	**[-1.296, 1.137]**	**[-0.087, 0.076]**
Stat. + ZZ th.	[-1.304, 1.212]	[-0.088, 0.077]
Stat. + EFT th.	[-1.297, 1.154]	[-0.087, 0.076]
Stat. + exp.	[-1.459, 1.220]	[-0.094, 0.082]
Stat. + WZ th.	[-1.486, 1.250]	[-0.108, 0.091]
Stat. + syst.	**[-1.505, 1.263]**	**[-0.109, 0.093]**

(Work in progress)

Dominated by **statistical uncertainties**, followed by WZ theory uncertainties.

- WZ theory:
  MC modelling, α_S and PDF
- ZZ theory:
  α_S and PDF
- Experimental:
  objects[a], bkg, luminosity
- EFT theory:
  LO vs 0+1j difference

[a] Pruned if low impact on EFT pred.

Comparison to existing limits

Limits on CP-conserving operators globally not as stringent as those from direct H production measurements.

Process	Observable	$c_{Hq}^{(1)}$ 95% CL	$c_{Hq}^{(3)}$ 95% CL
High p_T $VH(\to b\bar{b})$	m_J	$[-0.15, 0.10]$	$[-0.17, 0.04]$
$VH(\to b\bar{b})$	STXS(p_T^V)	$[-0.19, 0.10]$	$[-0.23, -0.18]$ $\cup [-0.005, 0.04]$
This work	S_{comb}	$[-0.37, 3.98]$	$[-0.15, 0.02]$

red: CMS blue: ATLAS