# Triple-gauge couplings in LHC diboson production: a SMEFT view from every angle

In collaboration with Giovanni Pelliccioli and Eleni Vryonidou, [arXiv:2405.19083]

Hesham El Faham
The University of Manchester



ICHEP, July 2024, Prague

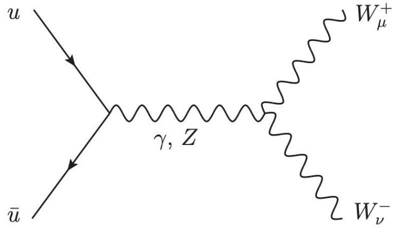
# Motivation for diboson at the LHC

- Important probe for EWSB
- Fully leptonic diboson production → **relatively clean signature at the LHC**
- With Run 3 and HL-LHC → **promising for precision and differential measurements**
- Irreducible background for Higgs analyses

At LO, production is dominated by quark-initial states and gluon-initiated ones are loop-induced

→ at **NLO in QCD, mixed channel opens up with enhancement from gluon luminosity**

# On diboson in the SMEFT




- Dominating quark-initiated channel is sensitive to dim-6 TGC

- At NLO QCD, **sensitivity to TGC is non-trivial and depends on phase-space setups**

- Dim-6 TGCs **non-trivially correlate with Vqq-induced ones** Grojean et al. [1810.05149]

- Linear **suppression is expected for 2 → 2** due to **helicity selection rules** Azatov et al. [1607.05236]

- A priori, one can not neglect dim-8 SMEFT insertions e.g. Degrande et al. [2303.10493]

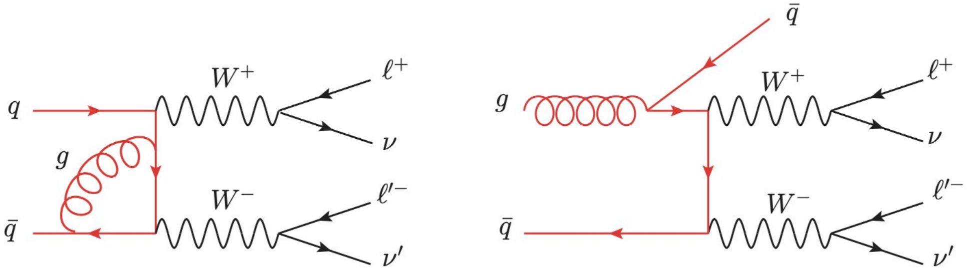
  → **dim-8 effects are not expected to alter the power induced by *purely* dim-6 TGC quadratic contributions** Corbett et al. [2304.03305]

# Goal

- Purely CP-even and CP-odd SMEFT coefficients in the Warsaw basis Grzadkowski et al. [1008.4884]

$$\epsilon_{ijk} W^{i}_{\mu\nu} W^{j,\nu\rho} W^{k,\mu}_{\rho}, \qquad \epsilon_{ijk} \tilde{W}^{i}_{\mu\nu} W^{j,\nu\rho} W^{k,\mu}_{\rho} \quad \Longleftrightarrow \quad \lambda_z = -c_W \frac{v}{\Lambda^2} \frac{3}{2} g, \qquad \tilde{\lambda}_z = -c_{\tilde{W}} \frac{v}{\Lambda^2} \frac{3}{2} g$$

- Full NLO in QCD, including the complete off-shell effects and spin correlations

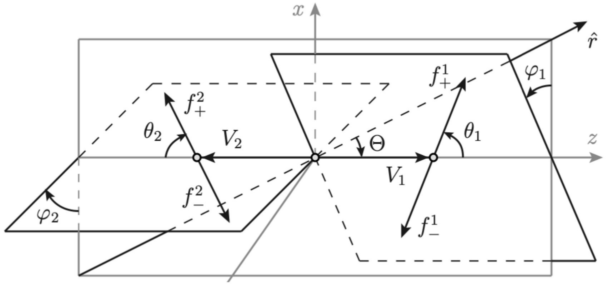


# Diboson analysis features

- $Z$ couples ~ equally to left and right-hand fermions → **can not identify helicities of final states**
- $W$ couples to left-hand fermions → **but neutrino reconstruction is problematic**

Interference suppression at 2 → 2 is lifted at 2 → 3 or 2 → 4

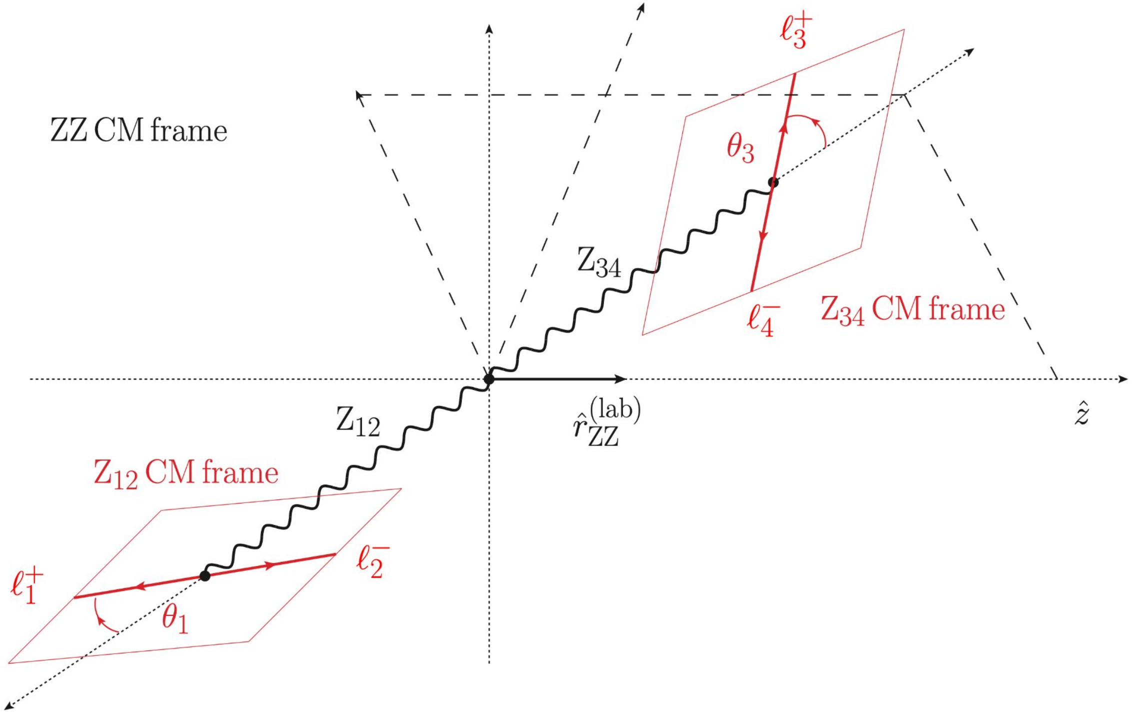
→ **the angle spanned by the decay products and/or real radiation 'restores' the interference**




$$\frac{d\sigma_{\text{int}}(q\bar{q} \to WZ \to 4\psi)}{d\phi_Z\, d\phi_W} \propto \cos(2\phi_Z) + \cos(2\phi_W)$$

Azatov et al. [1707.08060]; Panico et al. [1708.07823]

# Helicity coordinate system



# Questions to answer

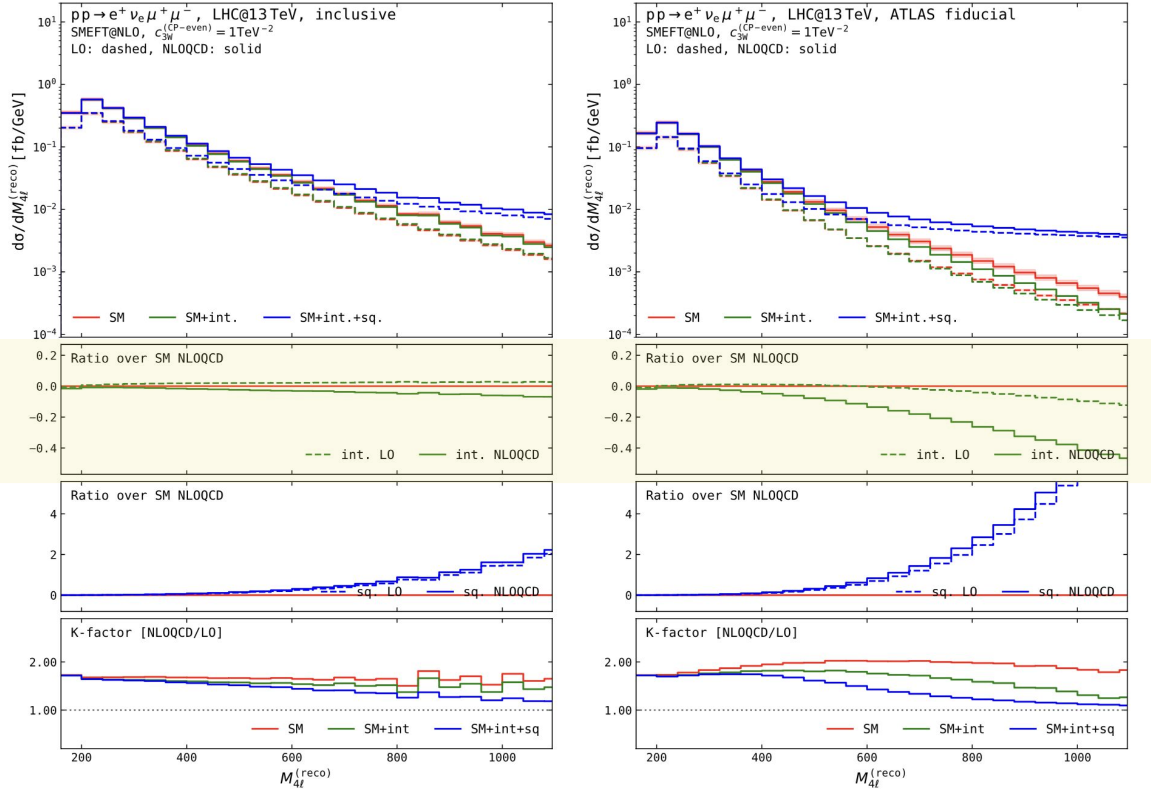
**→ Impact of different phase-space setups?**

**→ EFT effects on angular coefficients and observables?**

**→ Impact of NLO QCD?**

# Impact of NLO QCD and selection cuts

**interference 'restored' through selection cuts**




**Inclusive (left)**

→ Real NLO radiation restores the suppressed LO SMEFT interference

**Fiducial (right)**

→ The interference restoration is already manifest at LO due to the modulation from the cuts

→ **Non-trivial K-factors**



ATLAS fiducial setups [1902.05759, 2211.09435, 1905.04242]

# On polarisation fractions and angular terms

2-body decay rate of V boson + projections on spherical harmonics

→ inclusive angular coefficients and polarisation fractions

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*\,\mathrm{d}\phi^*} = \frac{3}{16\pi}\Big[1+\cos^2\theta^* + A_0\frac{1-3\cos^2\theta^*}{2} + A_1\sin 2\theta^*\cos\phi^* + \frac{1}{2}A_2\sin^2\theta^*\cos 2\phi^* + A_3\sin\theta^*\cos\phi^* + A_4\cos\theta^* + A_5\sin\theta^*\sin\phi^* + A_6\sin 2\theta^*\sin\phi + A_7\sin^2\theta^*\sin 2\phi^*\Big]$$

$$\xrightarrow{\text{azimuthal integral}}$$

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*} = \frac{3}{8}\Big[2 f_0 \sin^2\theta^* + f_L\left(1+\cos^2\theta^* - 2\,c_{LR}\cos\theta^*\right) + f_R\left(1+\cos^2\theta^* + 2\,c_{LR}\cos\theta^*\right)\Big]$$

$A_i$ coefficients modulate an angular term

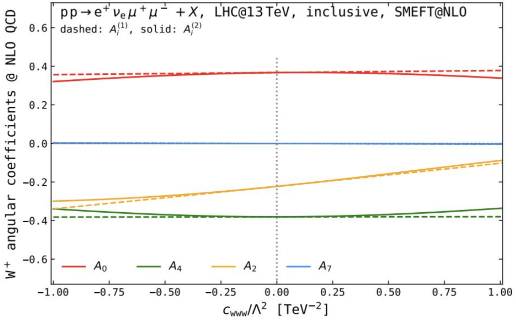
→ underly the **dynamics of the production and decay** process, the **polarisation states** of the particles, and **possible interference effects**

# Inclusive angular coefficients

**Inclusive setup**

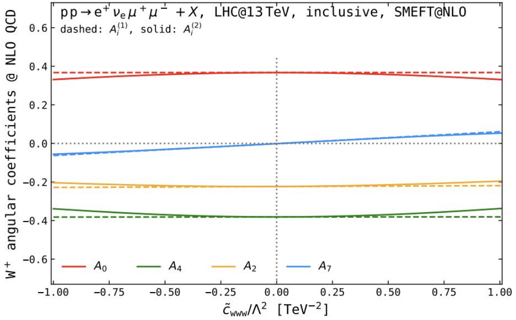
**W**

**CP-even**




(a)

**CP-odd**




(b)

**At the linear-level (dashed),**

→ polarisation fractions, A0 and A4, are barely distorted by CP-even and unaffected by the CP-odd modifications

$$A_0 = 2\, f_0\,, \qquad A_4 = 2\, c_{\rm LR}\,(f_{\rm R} - f_{\rm L})$$

**At the quadratic-level (solid),**

→ right handed and longitudinal fractions of the W are modified for CP-even and CP-odd

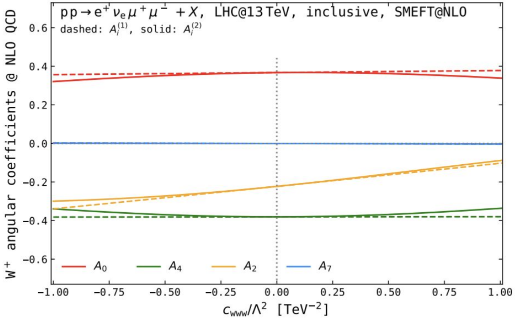
.. negligible effect on the left handed one

# Inclusive angular coefficients

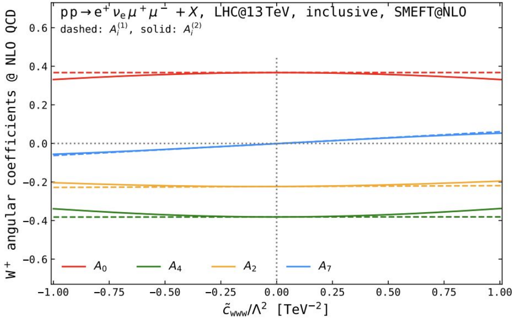
**Inclusive setup**

**CP-even** | **CP-odd**

**W**




(a)




(b)

**At the linear-level (dashed),**

→ polarisation fractions, A0 and A4, are barely distorted by CP-even and unaffected by the CP-odd modifications

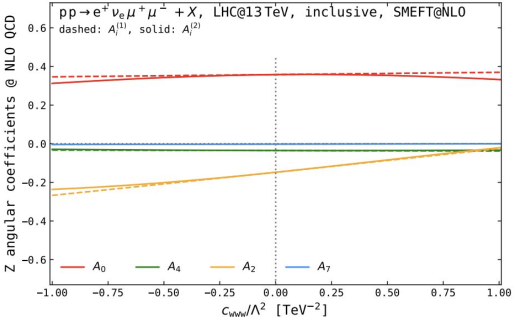
$$A_0 = 2\, f_0\,, \qquad A_4 = 2\, c_{\rm LR}\, (f_{\rm R} - f_{\rm L})$$

**At the quadratic-level (solid),**

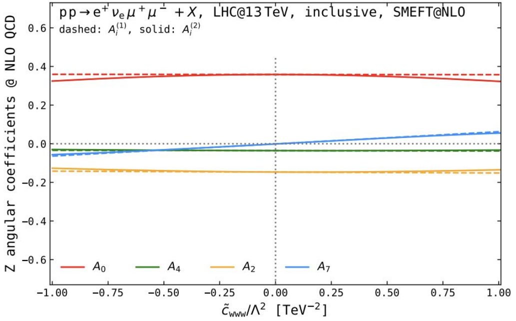
→ right handed and longitudinal fractions of the W are modified for CP-even and CP-odd

.. negligible effect on the left handed one

**Z**




(c)




(d)

**At the linear- and quadratic-levels,**

→ Longitudinal fraction of the Z behaves similarly to W

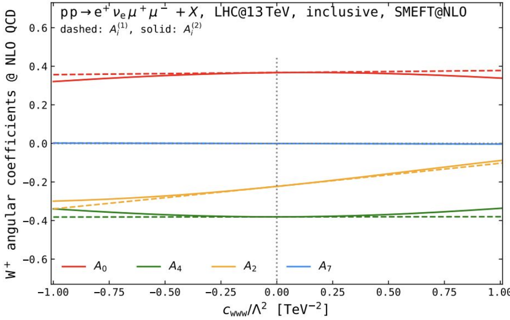
→ The very small absolute value of A4 for the Z manifest the left-right balance which is not altered by the EFT

# Inclusive angular coefficients

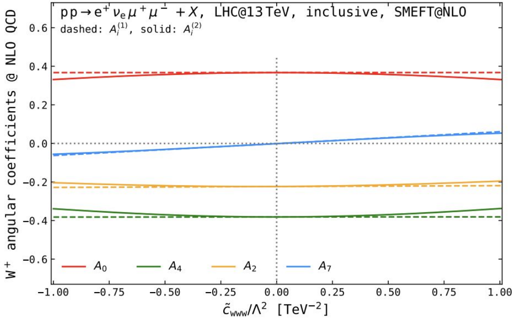
**Inclusive setup**

**CP-even** | **CP-odd**

**W**

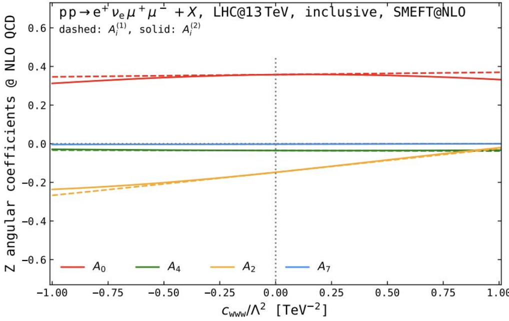



(a)

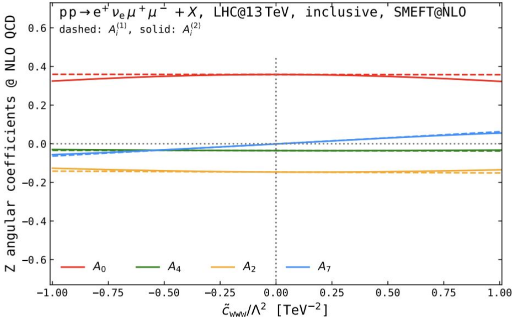



(b)

**Z**




(c)




(d)

**At the linear-level (dashed),**

→ polarisation fractions, A0 and A4, are barely distorted by CP-even and unaffected by the CP-odd modifications

$$A_0 = 2\, f_0\,, \qquad A_4 = 2\, c_{\rm LR}\,(f_{\rm R} - f_{\rm L})$$

**At the quadratic-level (solid),**

→ right handed and longitudinal fractions of the W are modified for CP-even and CP-odd

.. negligible effect on the left handed one

**At the linear- and quadratic-levels,**

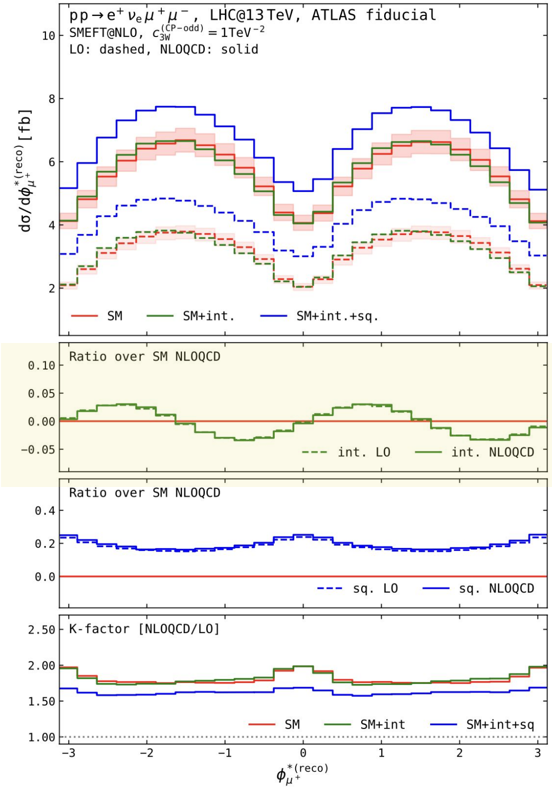
→ Longitudinal fraction of the Z behaves similarly to W

→ The very small absolute value of A4 for the Z manifest the left-right balance which is not altered by the EFT

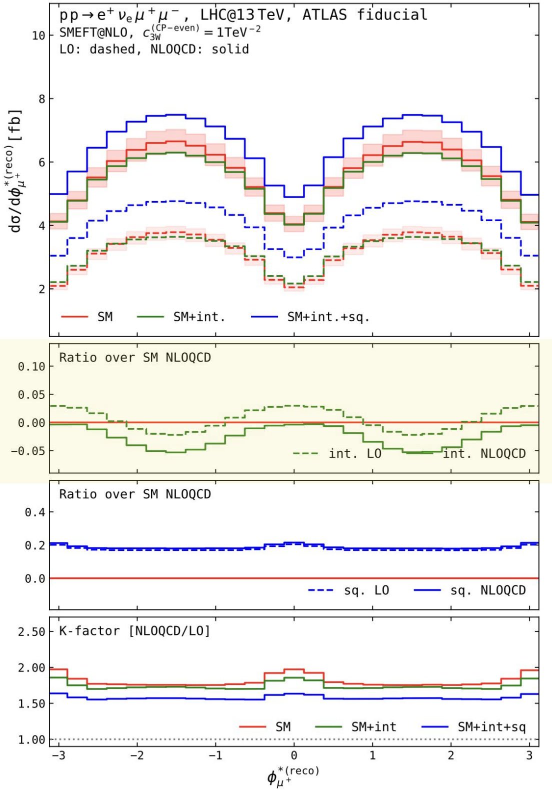
**A7 is parity odd sensitive**

# Differential angular observables

**CP-odd**




**CP-even**



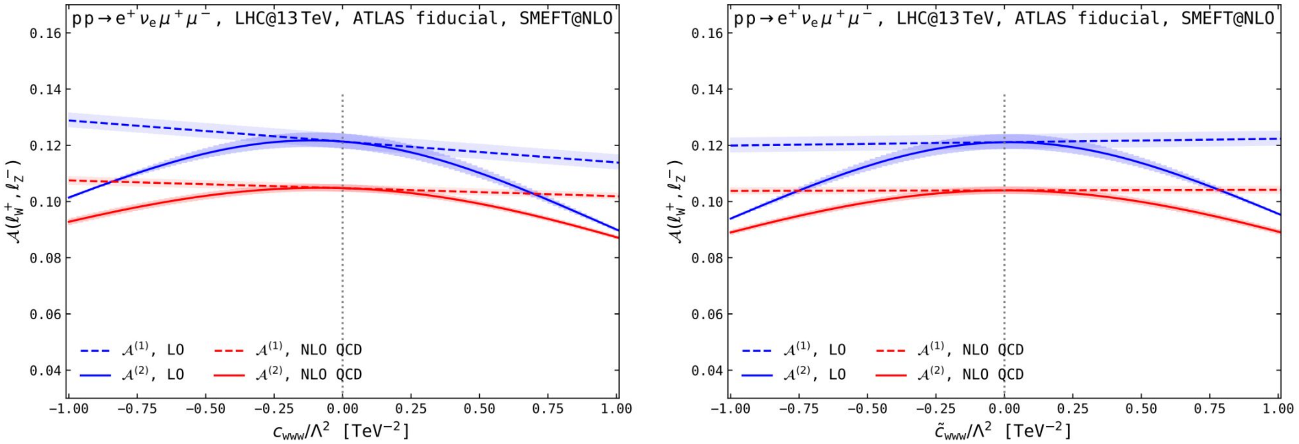

**Azimuthal variables are good probes for CP-properties**

→ Interference modulation maps the CP-property of TGC

→ Distortion due to selection cuts and neutrino reconstruction relative to SM is mild (inclusive setup not shown here)

# Boost asymmetries

$$\mathcal{A}(i,j) = \frac{\mathrm{d}\sigma(|y_i| > |y_j|) - \mathrm{d}\sigma(|y_i| < |y_j|)}{\mathrm{d}\sigma(|y_i| > |y_j|) + \mathrm{d}\sigma(|y_i| < |y_j|)}$$




(a) $\mathcal{A}(\ell_\mathrm{W}, \ell_\mathrm{Z}^-)$, CP even

(b) $\mathcal{A}(\ell_\mathrm{W}, \ell_\mathrm{Z}^-)$, CP odd

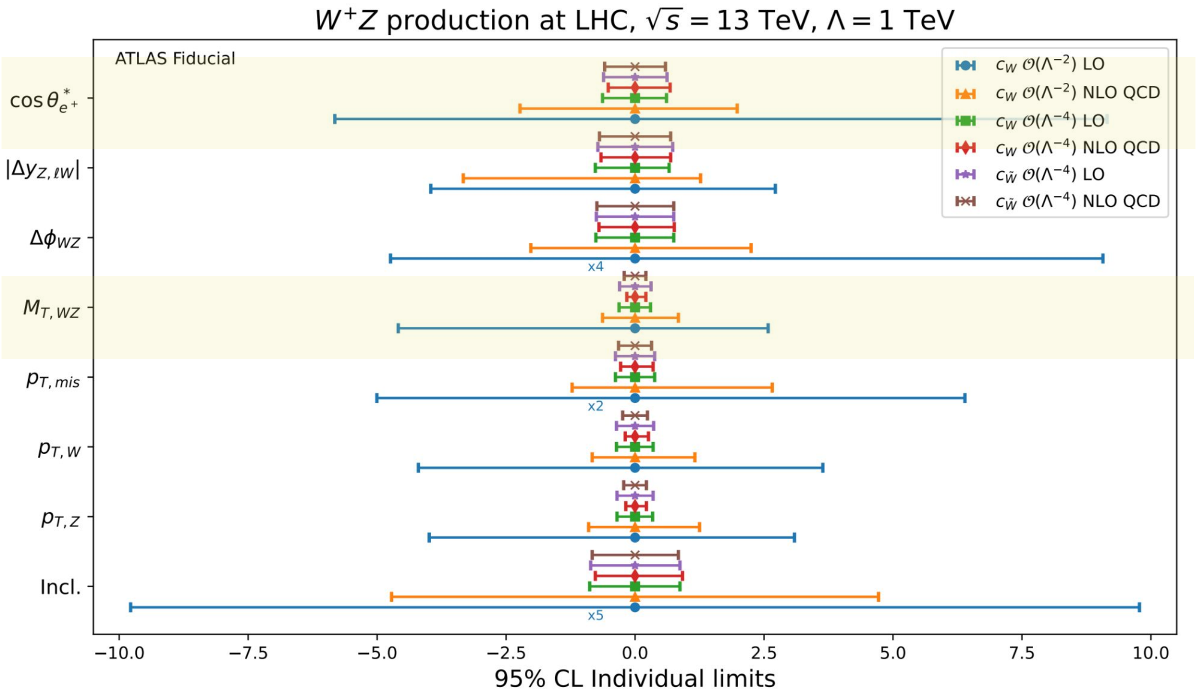
**WZ**

→ CP-even (left) modifies the right-handed fraction at linear and quadratic-levels

→ CP-odd (right) linear effects are negligible

**Differential measurements of boost asymmetries might be promising**

# Impact of NLO QCD on SMEFT WZ




→ dimensionful observables are the most stringent

→ polar decay angle is competitive in the dimensionless class

→ **NLO QCD** is key in constraining SMEFT



ATLAS fiducial setups [1902.05759, 2211.09435, 1905.04242]

# Summary

→ Impact of different phase-space setups?

→ EFT effects on angular coefficients and observables?

→ Impact of NLO QCD?

→ Analysis is sensitive to fiducial setup and interference suppression is lifted by cuts

→ Mild effects on angular coefficients; azimuthal-observables are interesting

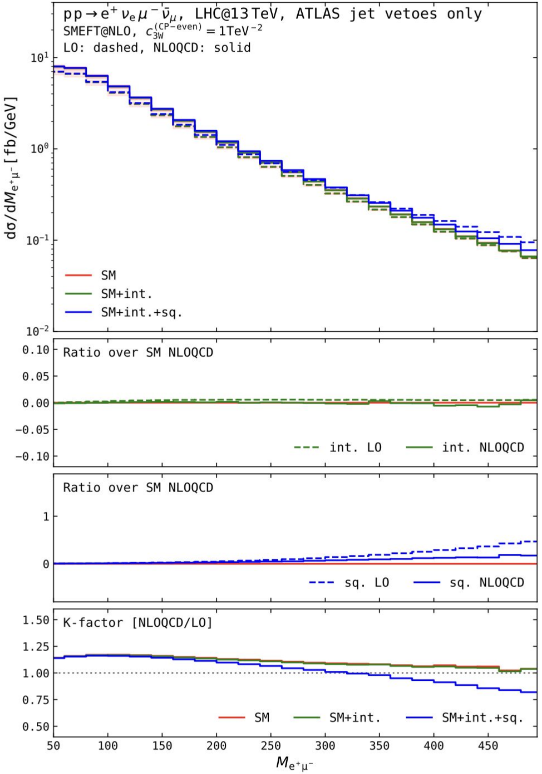
→ NLO effects lift the interference suppression and are key in constraining SMEFT

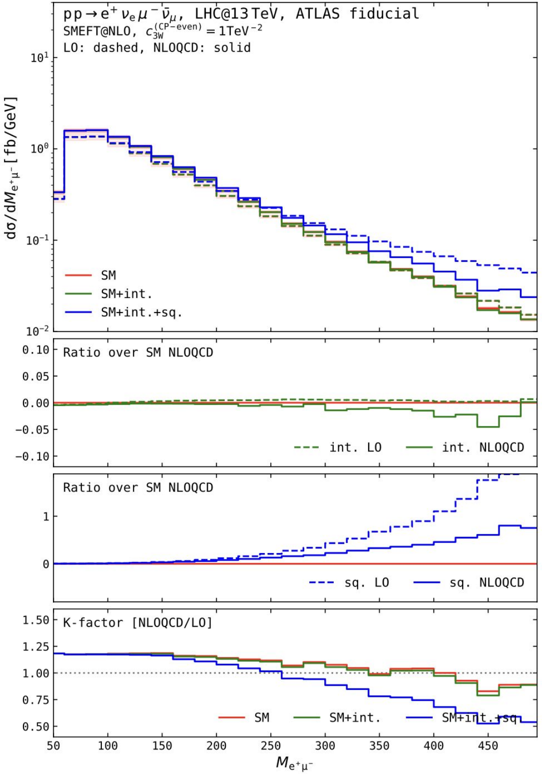
# Conclusions

- NLO QCD is key in diboson production; constraining SMEFT, resurrecting $2 \to 2$ suppressed interference, non trivial k-factors
- The angle spanned by decay products as well as selection cuts have significant impact on the interference behavior
- Angular observables are good probes for TGC CP-properties
- Differential leptonic boost asymmetries might be promising in constraining SMEFT

# Backup

# Impact of NLO QCD and selection cuts WW

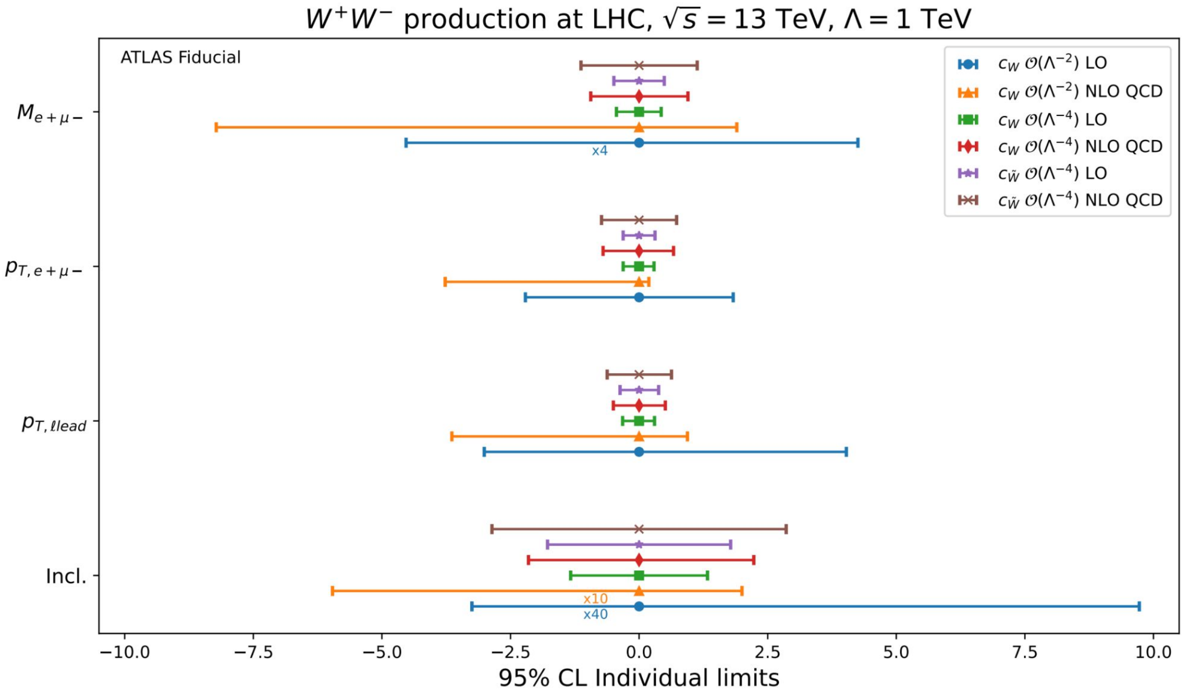



→ Selection cuts still enhances the interferences

→ WW is less-sensitive to TGC than WZ

# Impact of NLO QCD on SMEFT WW




→ similar conclusions to the WZ case

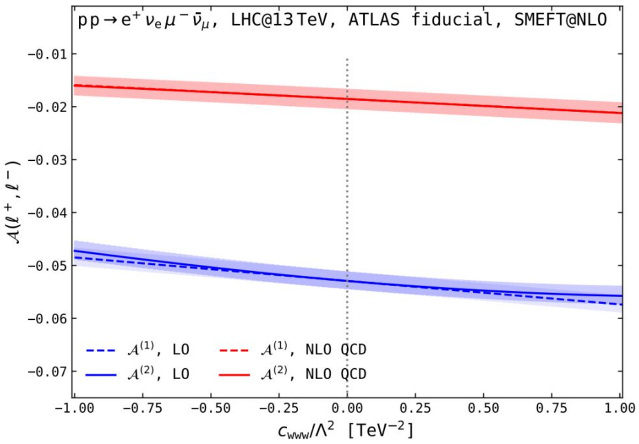
→ the different NLO QCD behaviour is manifest



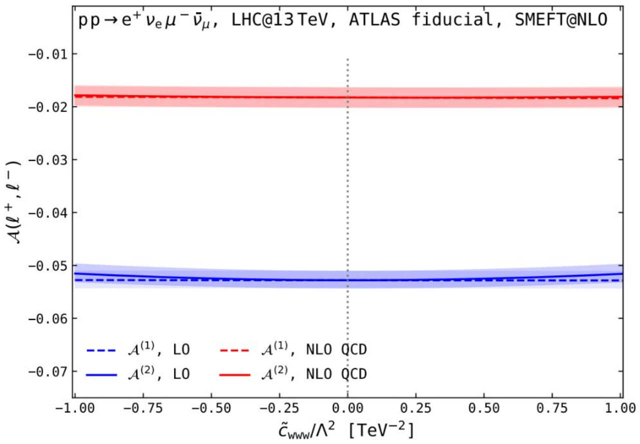
ATLAS fiducial setups [1902.05759, 2211.09435, 1905.04242]

# Boost asymmetries

$$\mathcal{A}(i,j) = \frac{\mathrm{d}\sigma(|y_i| > |y_j|) - \mathrm{d}\sigma(|y_i| < |y_j|)}{\mathrm{d}\sigma(|y_i| > |y_j|) + \mathrm{d}\sigma(|y_i| < |y_j|)}$$




(e) $\mathcal{A}(\ell^+, \ell^-)$, CP even



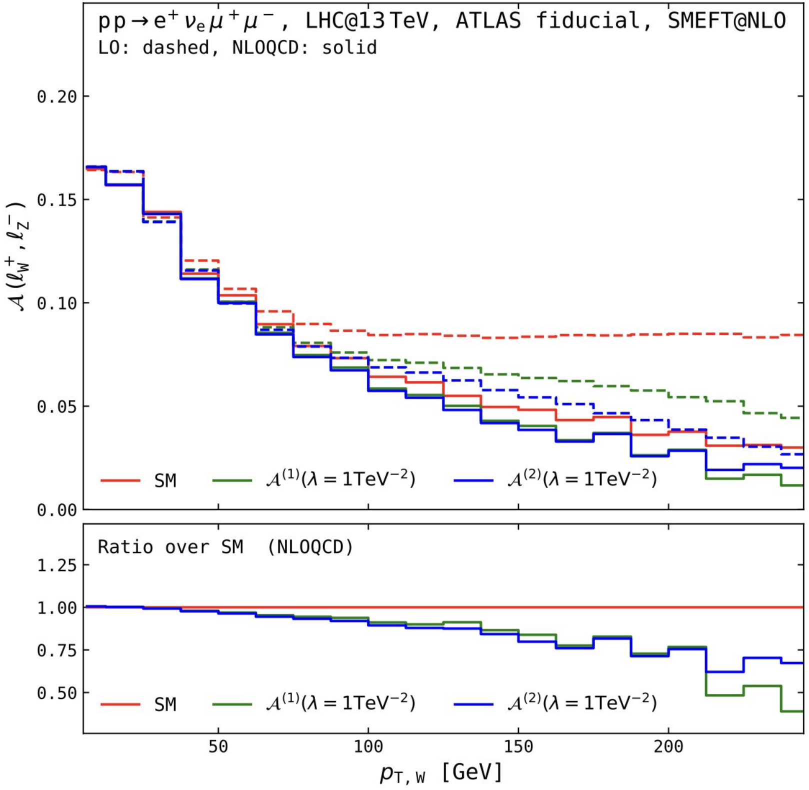

(f) $\mathcal{A}(\ell^+, \ell^-)$, CP odd

**WW**

→ Mild EFT effects on asymmetries

# Boost asymmetries WZ

CP-even




CP-odd