Triboson production in the SMEFT

EC, Gauthier Durieux, Ken Mimasu, Eleni Vryonidou

based on JHEP12 (2024) 055 [arXiv: 2407.09600]

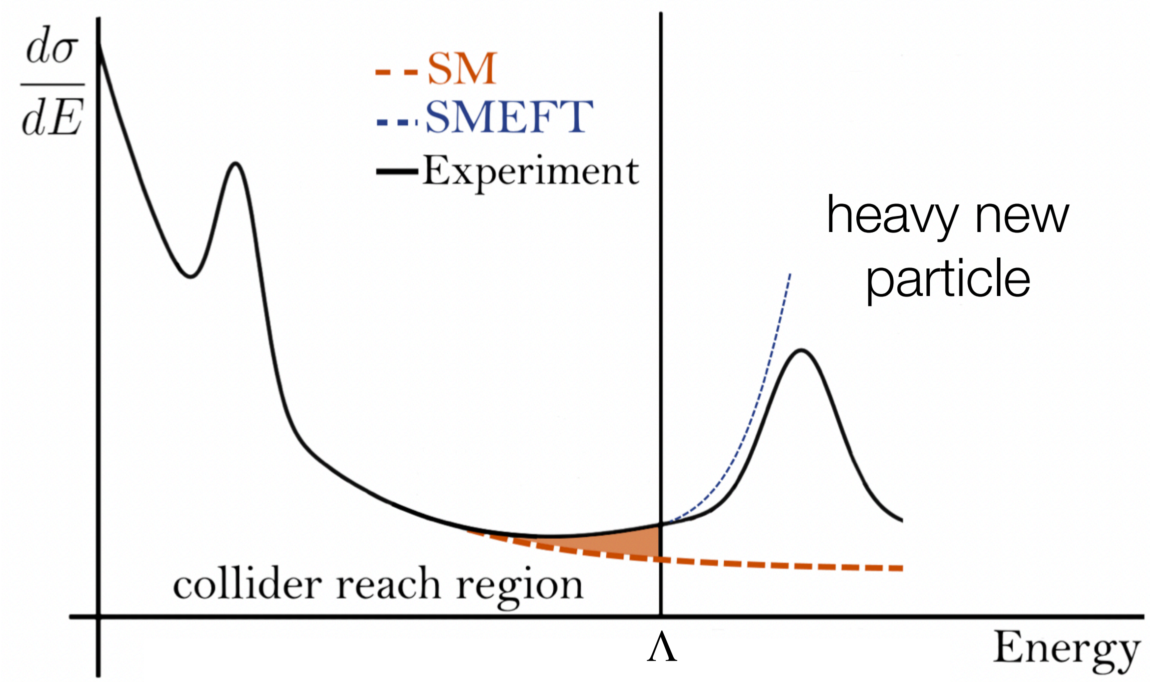
Milan Christmas meeting 2024

19/12/24, Milano, Italy

Eugenia Celada

University of Manchester

The SMEFT



Original fig. by C. Severi, M. Thomas, E. Vryonidou

Dimension-6 operators Warsaw basis

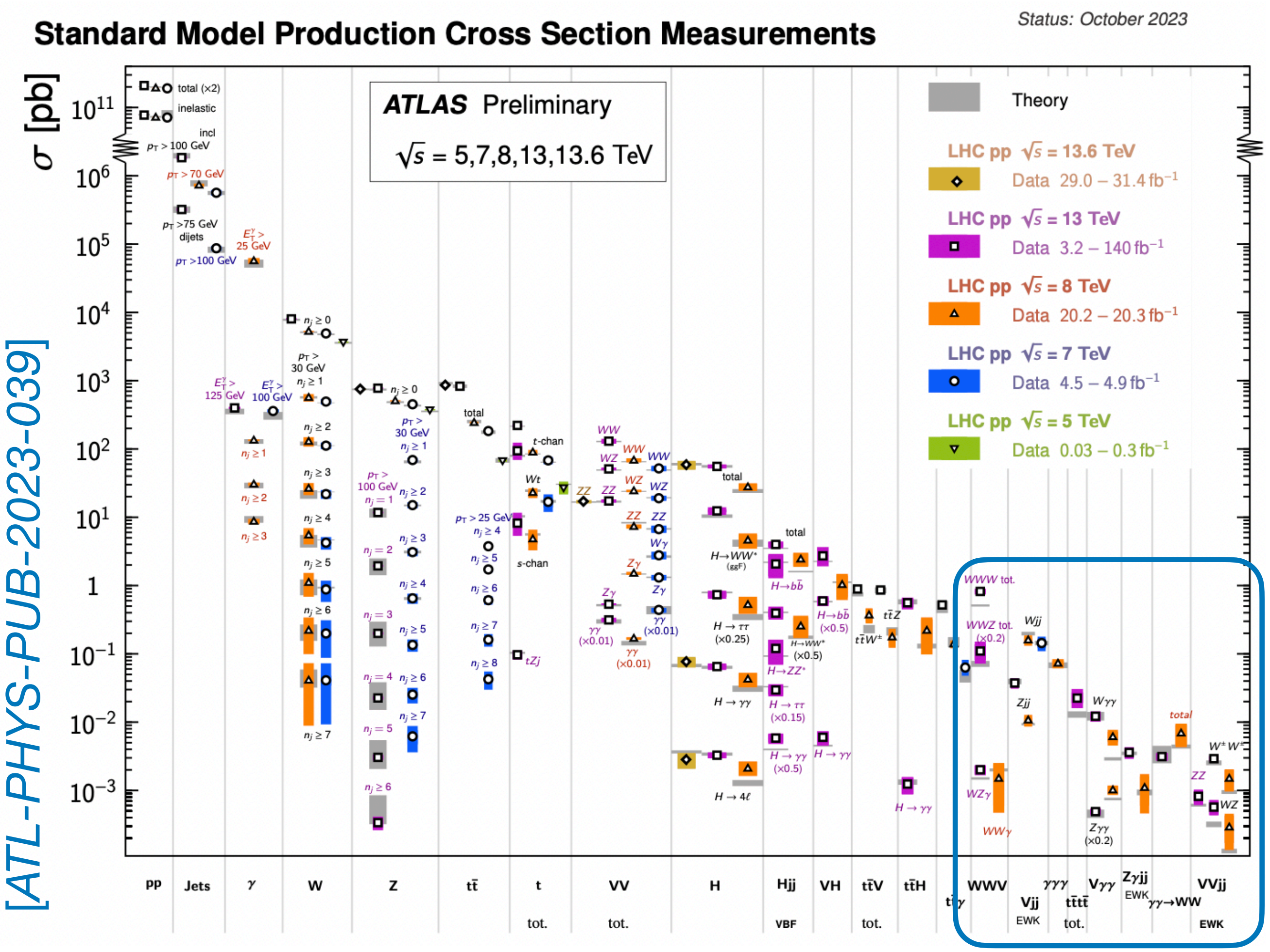
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \mathcal{O}(\Lambda^{-3})$$

$$\sigma \sim |\mathcal{M}_{\mathrm{SM}}|^2 + \frac{1}{\Lambda^2}\left(\sum c^{(6)}\, 2\mathrm{Re}[\mathcal{M}_{\mathrm{SM}}^* \mathcal{M}_{\mathrm{EFT}}^{(6)}]\right) + \frac{1}{\Lambda^4}\left(\sum c^{(6)} \mathcal{M}_{\mathrm{EFT}}^{(6)}\right)^2$$

Triboson production at the LHC

- Triboson have small cross sections, only accessible with LHC run 2 (mainly total rates, fully leptonic)

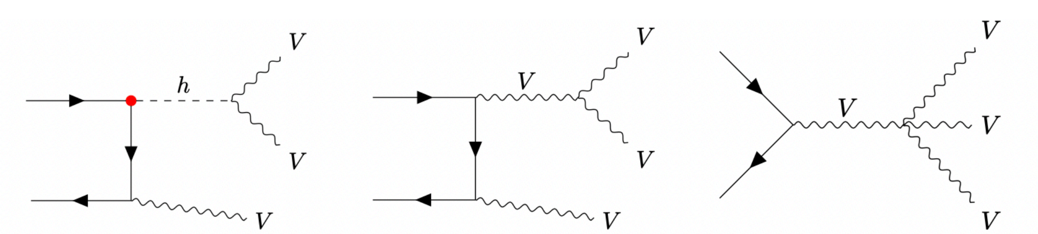
[ATL-PHYS-PUB-2023-039]



Why triboson?

- Tree-level access to TGC and QGC
- Interplay with the Higgs sector
- Sensitivity to light quark Yukawa in longitudinal VVV production

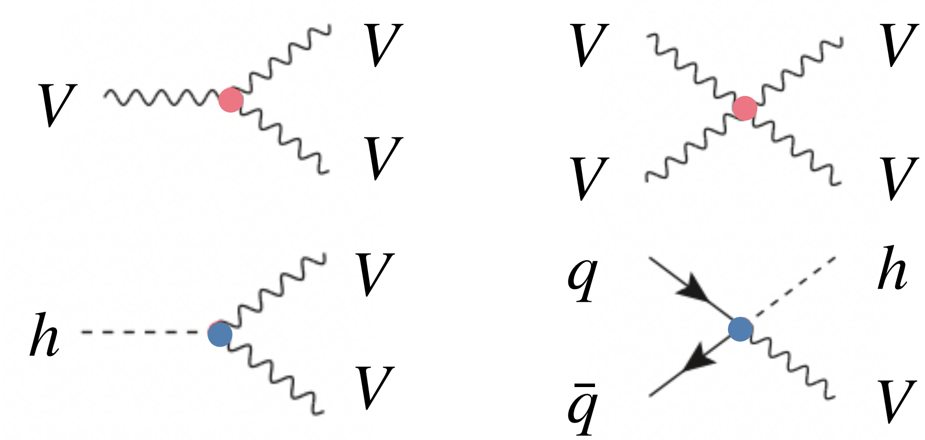
[Bellan et al.; JHEP 08 (2023) 158]



[Falkowski et al.; 2011.09551]

Triboson in global fits

- Triboson is sensitive to a variety of anomalous effects, including TGCs and Higgs-gauge couplings



- Sensitivity studies at LO showed promising results

[*Bellan et al.; JHEP 08 (2023) 158*]

- We incorporate triboson in a NLO global EW fit

Goal

1. First NLO SMEFT study of VVV
2. What's triboson constraining power? Additional information?

EW operators in Warsaw basis

Operator	Definition
bosonic	
$\mathcal{O}_{\phi D}$	$(\phi^\dagger D^\mu \phi)^\dagger(\phi^\dagger D_\mu \phi)$
$\mathcal{O}_{\phi WB}$	$(\phi^\dagger \tau_I \phi) B^{\mu\nu} W^I_{\mu\nu}$
$\mathcal{O}_{WWW}$	$\epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$
two-fermion	
$\mathcal{O}^{(1)}_{\phi q}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{q}\gamma^\mu q)$
$\mathcal{O}^{(3)}_{\phi q}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi)(\bar{q}\gamma^\mu \tau^I q)$
$\mathcal{O}_{\phi u}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{u}\gamma^\mu u)$
$\mathcal{O}_{\phi d}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{d}\gamma^\mu d)$
$\mathcal{O}^{(1)}_{\phi \ell}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{\ell}\gamma^\mu \ell)$
$\mathcal{O}^{(3)}_{\phi \ell}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi)(\bar{\ell}\gamma^\mu \tau^I \ell)$
$\mathcal{O}_{\phi e}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{e}\gamma^\mu e)$
four-fermion	
$\mathcal{O}_{\ell\ell}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma^\mu \ell)$

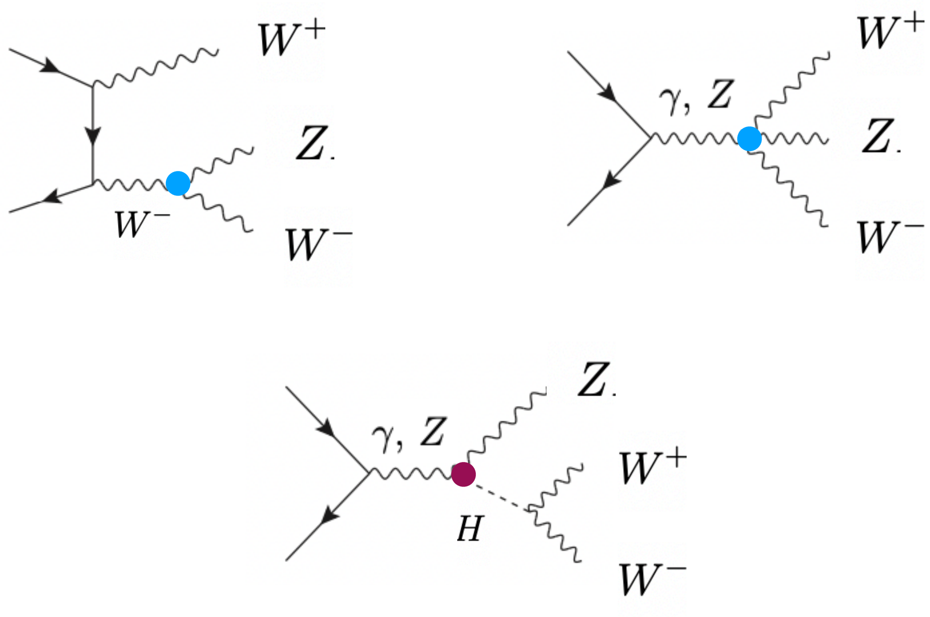
- Subset of 11 EW&Higgs operators
- flavour universality, $U(3)^5$

[*EC, Durieux, Mimasu, Vryonidou; JHEP* 12 (2024) 055]

EW operators in Warsaw basis

Operator	Definition
bosonic	
$\mathcal{O}_{\phi D}$	$(\phi^\dagger D^\mu \phi)^\dagger (\phi^\dagger D_\mu \phi)$
$\mathcal{O}_{\phi WB}$	$(\phi^\dagger \tau_I \phi) B^{\mu\nu} W^I_{\mu\nu}$
$\mathcal{O}_{WWW}$	$\epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_\rho$
two-fermion	
$\mathcal{O}^{(1)}_{\phi q}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{q}\gamma^\mu q)$
$\mathcal{O}^{(3)}_{\phi q}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi)(\bar{q}\gamma^\mu \tau^I q)$
$\mathcal{O}_{\phi u}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{u}\gamma^\mu u)$
$\mathcal{O}_{\phi d}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{d}\gamma^\mu d)$
$\mathcal{O}^{(1)}_{\phi \ell}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{\ell}\gamma^\mu \ell)$
$\mathcal{O}^{(3)}_{\phi \ell}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi)(\bar{\ell}\gamma^\mu \tau^I \ell)$
$\mathcal{O}_{\phi e}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{e}\gamma^\mu e)$
four-fermion	
$\mathcal{O}_{\ell\ell}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma^\mu \ell)$

$$pp \to W^+W^-Z$$

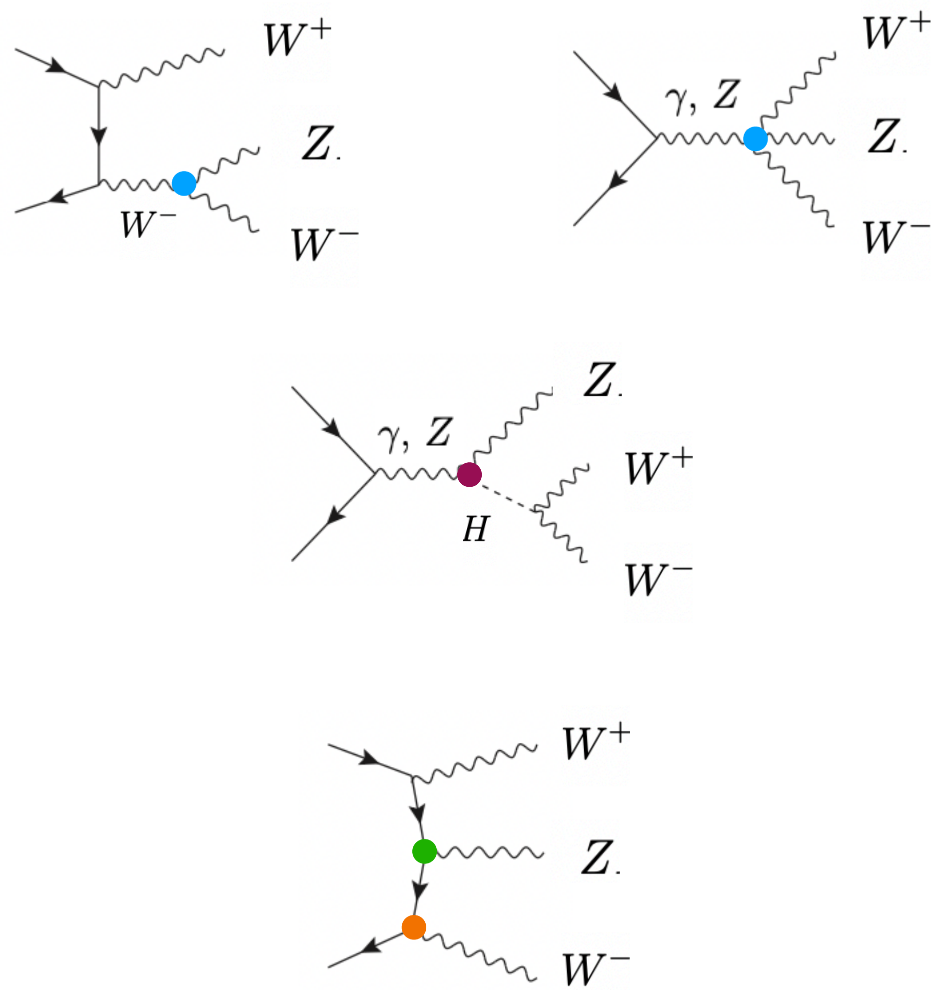


[EC, Durieux, Mimasu, Vryonidou; *JHEP* 12 (2024) 055]

EW operators in Warsaw basis

Operator	Definition
bosonic	
$\mathcal{O}_{\phi D}$	$(\phi^\dagger D^\mu \phi)^\dagger(\phi^\dagger D_\mu \phi)$
$\mathcal{O}_{\phi WB}$	$(\phi^\dagger \tau_I \phi) B^{\mu\nu} W^I_{\mu\nu}$
$\mathcal{O}_{WWW}$	$\epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_\rho$
two-fermion	
$\mathcal{O}^{(1)}_{\phi q}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{q}\gamma^\mu q)$
$\mathcal{O}^{(3)}_{\phi q}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi)(\bar{q}\gamma^\mu \tau^I q)$
$\mathcal{O}_{\phi u}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{u}\gamma^\mu u)$
$\mathcal{O}_{\phi d}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{d}\gamma^\mu d)$
$\mathcal{O}^{(1)}_{\phi \ell}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{\ell}\gamma^\mu \ell)$
$\mathcal{O}^{(3)}_{\phi \ell}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi)(\bar{\ell}\gamma^\mu \tau^I \ell)$
$\mathcal{O}_{\phi e}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{e}\gamma^\mu e)$
four-fermion	
$\mathcal{O}_{\ell\ell}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma^\mu \ell)$

$$pp \to W^+W^-Z$$

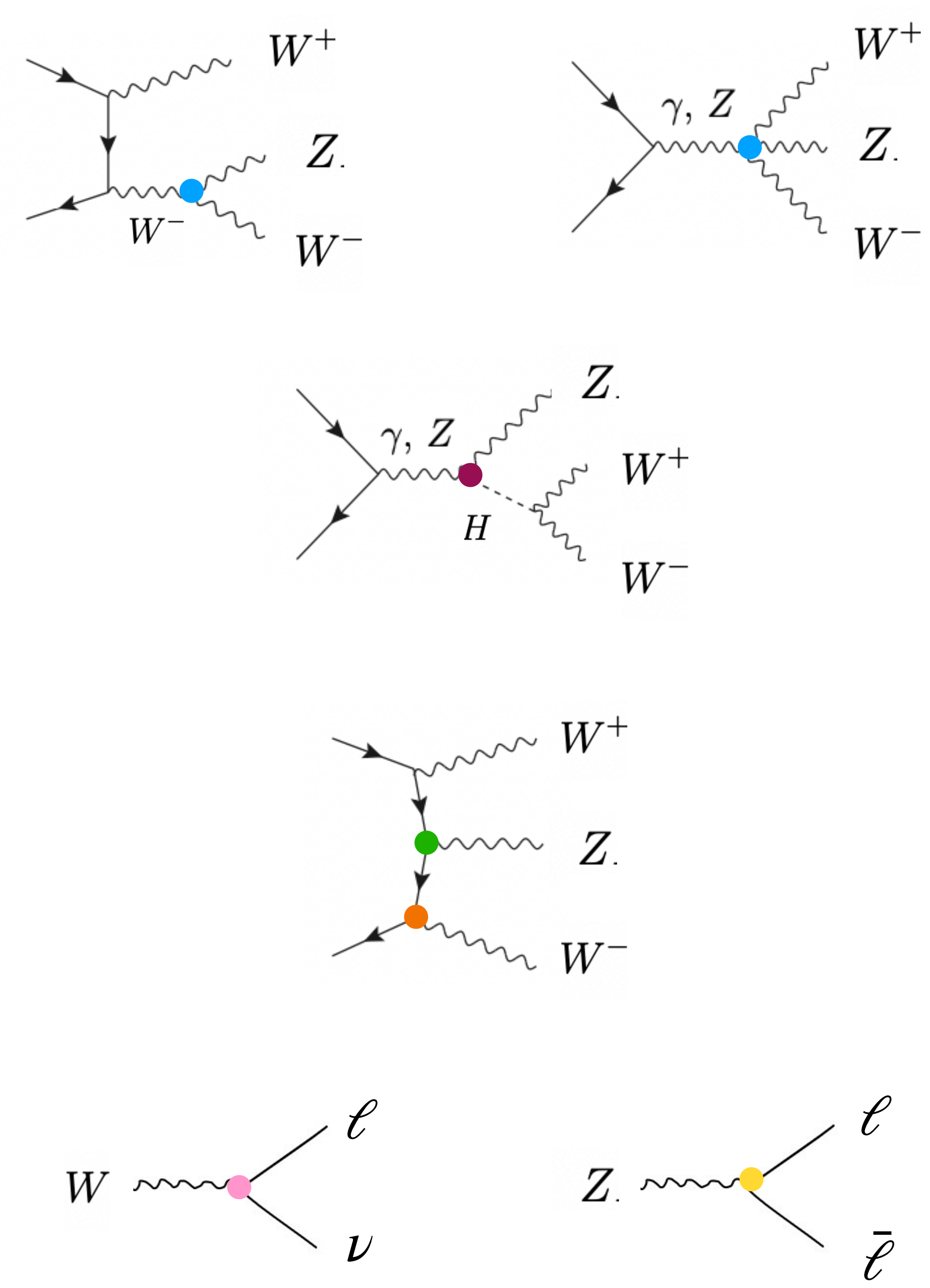


[*EC, Durieux, Mimasu, Vryonidou; JHEP* 12 (2024) 055]

EW operators in Warsaw basis

Operator	Definition
bosonic	
$\mathcal{O}_{\phi D}$	$(\phi^\dagger D^\mu \phi)^\dagger(\phi^\dagger D_\mu \phi)$
$\mathcal{O}_{\phi WB}$	$(\phi^\dagger \tau_I \phi) B^{\mu\nu} W^I_{\mu\nu}$
$\mathcal{O}_{WWW}$	$\epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$
two-fermion	
$\mathcal{O}^{(1)}_{\phi q}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{q}\gamma^\mu q)$
$\mathcal{O}^{(3)}_{\phi q}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi)(\bar{q}\gamma^\mu \tau^I q)$
$\mathcal{O}_{\phi u}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{u}\gamma^\mu u)$
$\mathcal{O}_{\phi d}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{d}\gamma^\mu d)$
$\mathcal{O}^{(1)}_{\phi \ell}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{\ell}\gamma^\mu \ell)$
$\mathcal{O}^{(3)}_{\phi \ell}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi)(\bar{\ell}\gamma^\mu \tau^I \ell)$
$\mathcal{O}_{\phi e}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{e}\gamma^\mu e)$
four-fermion	
$\mathcal{O}_{\ell\ell}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma^\mu \ell)$

$pp \to W^+W^-Z$

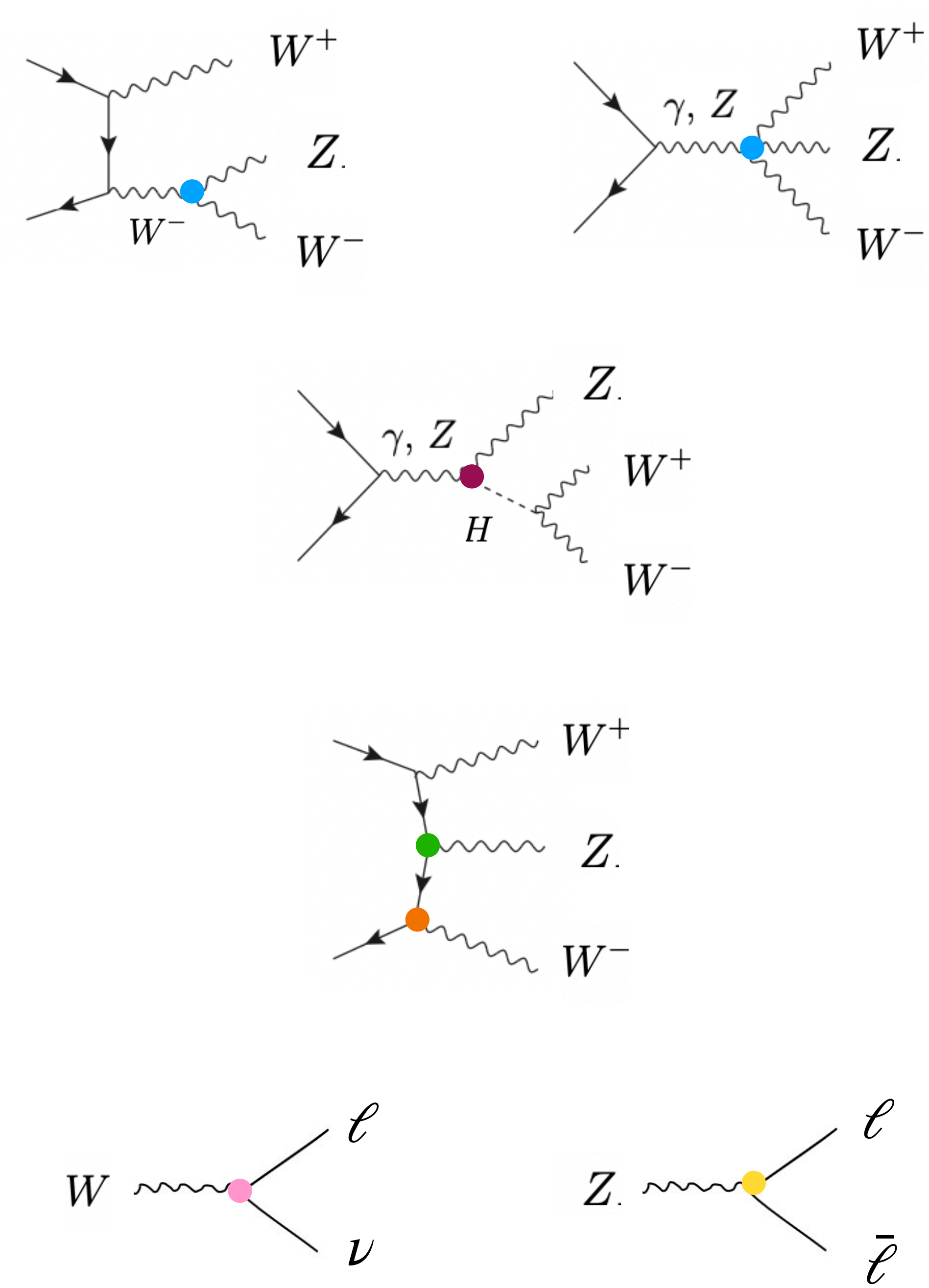


[EC, Durieux, Mimasu, Vryonidou; *JHEP* 12 (2024) 055]

EW operators in Warsaw basis

Operator	Definition	
bosonic		
$\mathcal{O}_{\phi D}$	$(\phi^\dagger D^\mu \phi)^\dagger(\phi^\dagger D_\mu \phi)$	
$\mathcal{O}_{\phi WB}$	$(\phi^\dagger \tau_I \phi) B^{\mu\nu} W^I_{\mu\nu}$	
$\mathcal{O}_{WWW}$	$\epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$	
two-fermion		
$\mathcal{O}^{(1)}_{\phi q}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{q}\gamma^\mu q)$	
$\mathcal{O}^{(3)}_{\phi q}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi)(\bar{q}\gamma^\mu \tau^I q)$	
$\mathcal{O}_{\phi u}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{u}\gamma^\mu u)$	
$\mathcal{O}_{\phi d}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{d}\gamma^\mu d)$	
$\mathcal{O}^{(1)}_{\phi \ell}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{\ell}\gamma^\mu \ell)$	
$\mathcal{O}^{(3)}_{\phi \ell}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi)(\bar{\ell}\gamma^\mu \tau^I \ell)$	G_F
$\mathcal{O}_{\phi e}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{e}\gamma^\mu e)$	
four-fermion		
$\mathcal{O}_{\ell\ell}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma^\mu \ell)$	G_F

$pp \to W^+W^-Z$



[EC, Durieux, Mimasu, Vryonidou; JHEP 12 (2024) 055]

Going NLO - inclusive

- K-factor quantifies the impact of NLO corrections

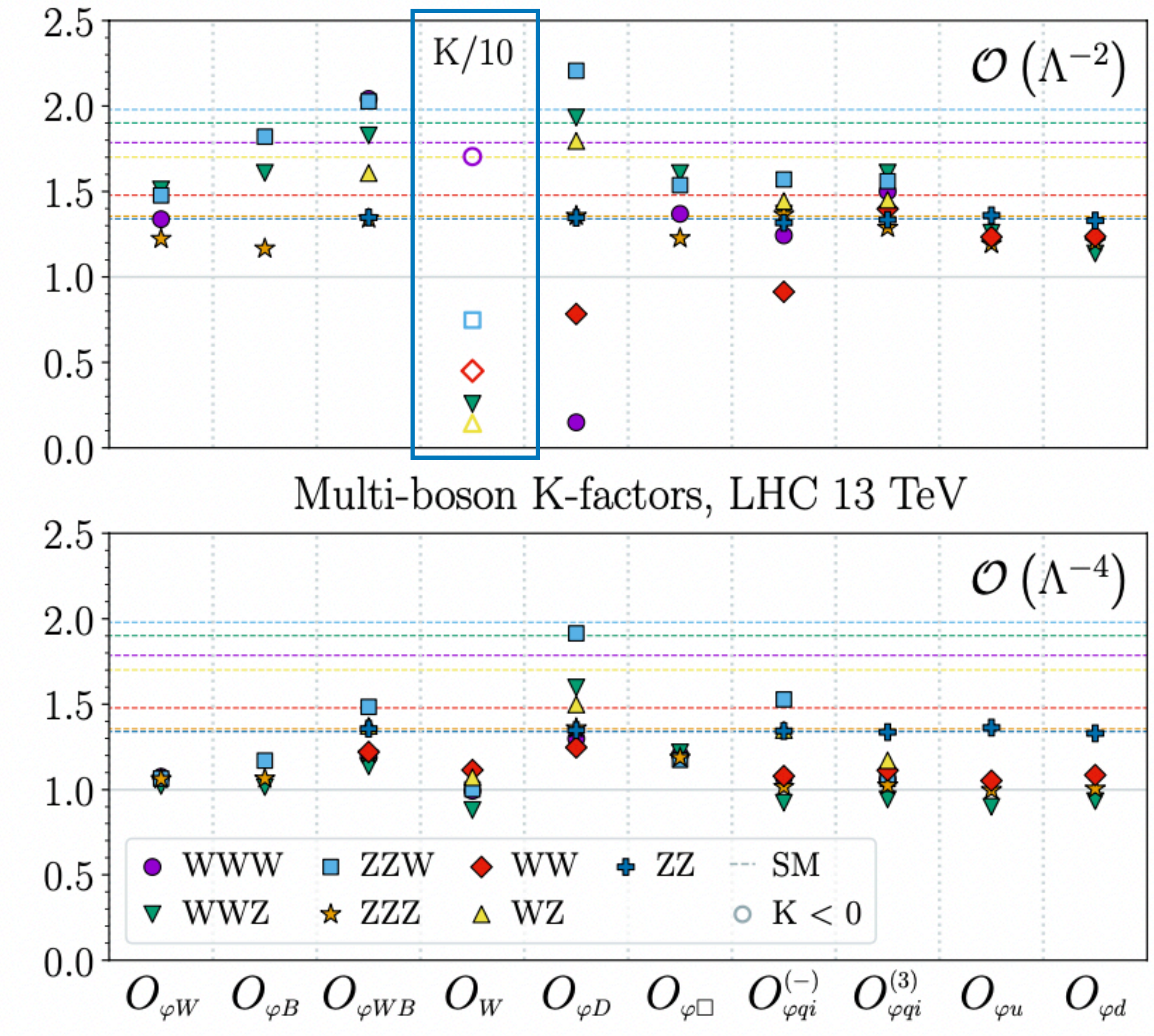
$$K = \frac{\sigma_{\text{NLO}}}{\sigma_{\text{LO}}}$$

- NLO QCD effects are sizeable in VV and VVV: $K \sim 1 - 2$

- For O_W $K(\Lambda^{-2}) \sim \mathcal{O}(10)$: LO suppression lifted at NLO

[Azatov et al.; 1607.05236]
[Dixon and Shadmi; 9312363]
[Degrande and Maltoni; 2012.06595, 2403.16894]

[Degrande et al.; 2008.11743]



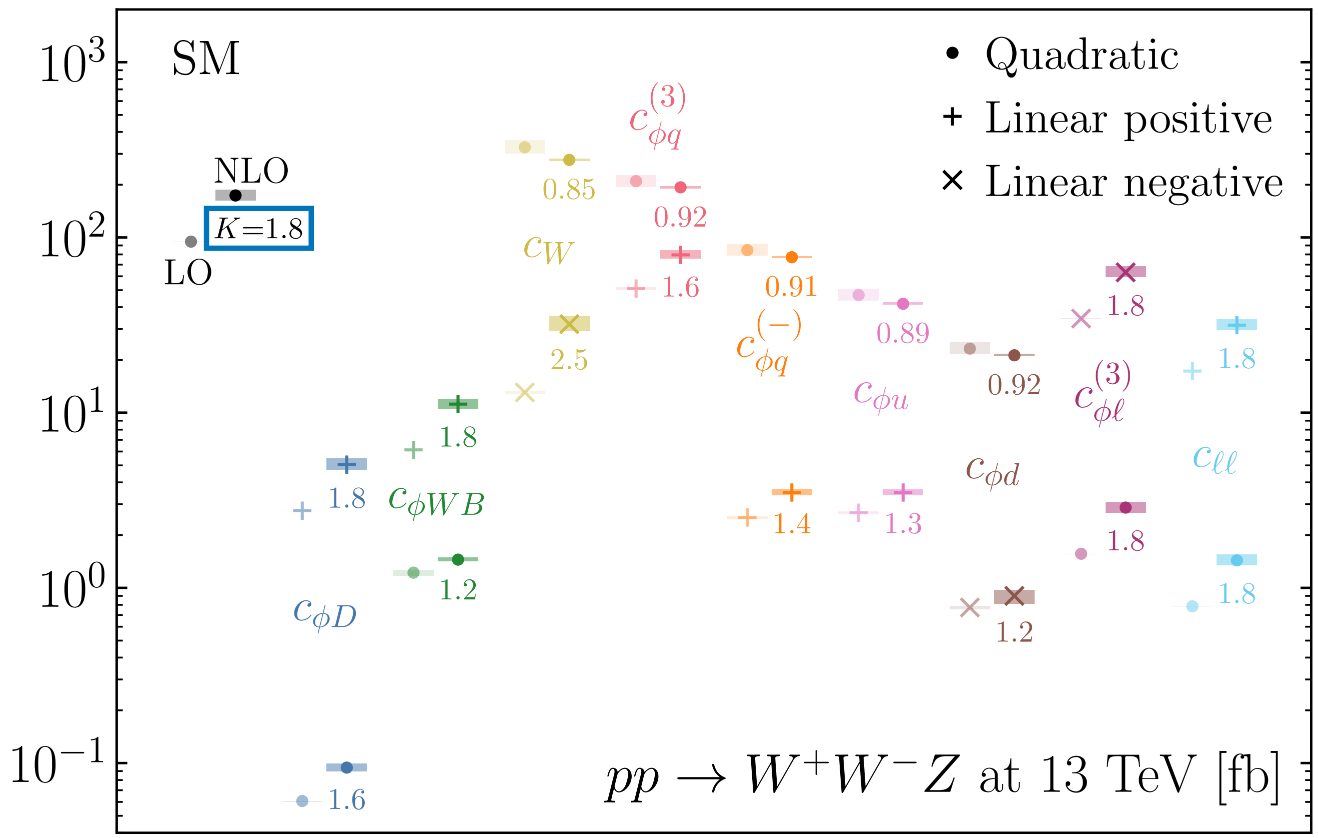
Going NLO - inclusive

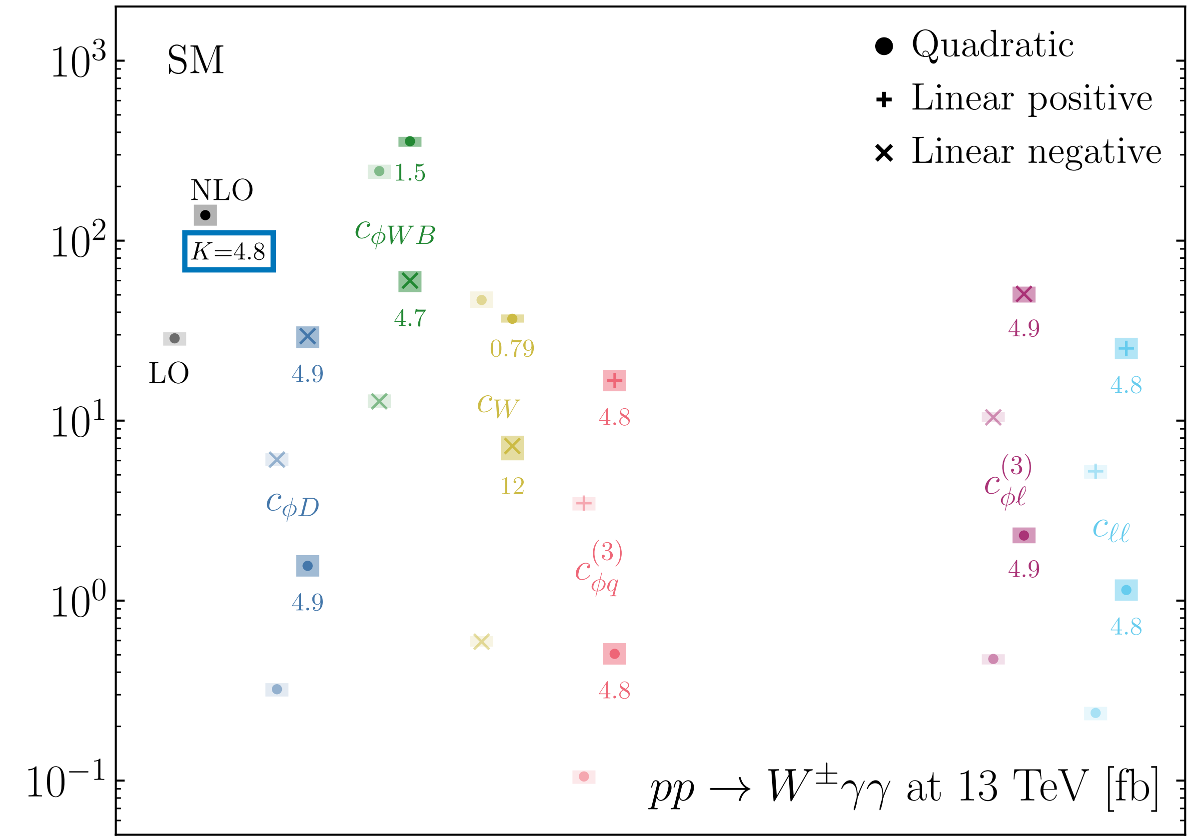
NLO QCD corrections are large in all triboson processes

- giant K-factors (in SM) for photonic processes (radiation zero)

[Bozzi et al.; Phys. Rev. D 83 (2011) 114035]

- most EFT K-factors similar to the SM
- very large linear c_W K-factor: LO suppression partly lifted at NLO





[EC, Durieux, Mimasu, Vryonidou; JHEP 12 (2024) 055]

Going NLO - inclusive

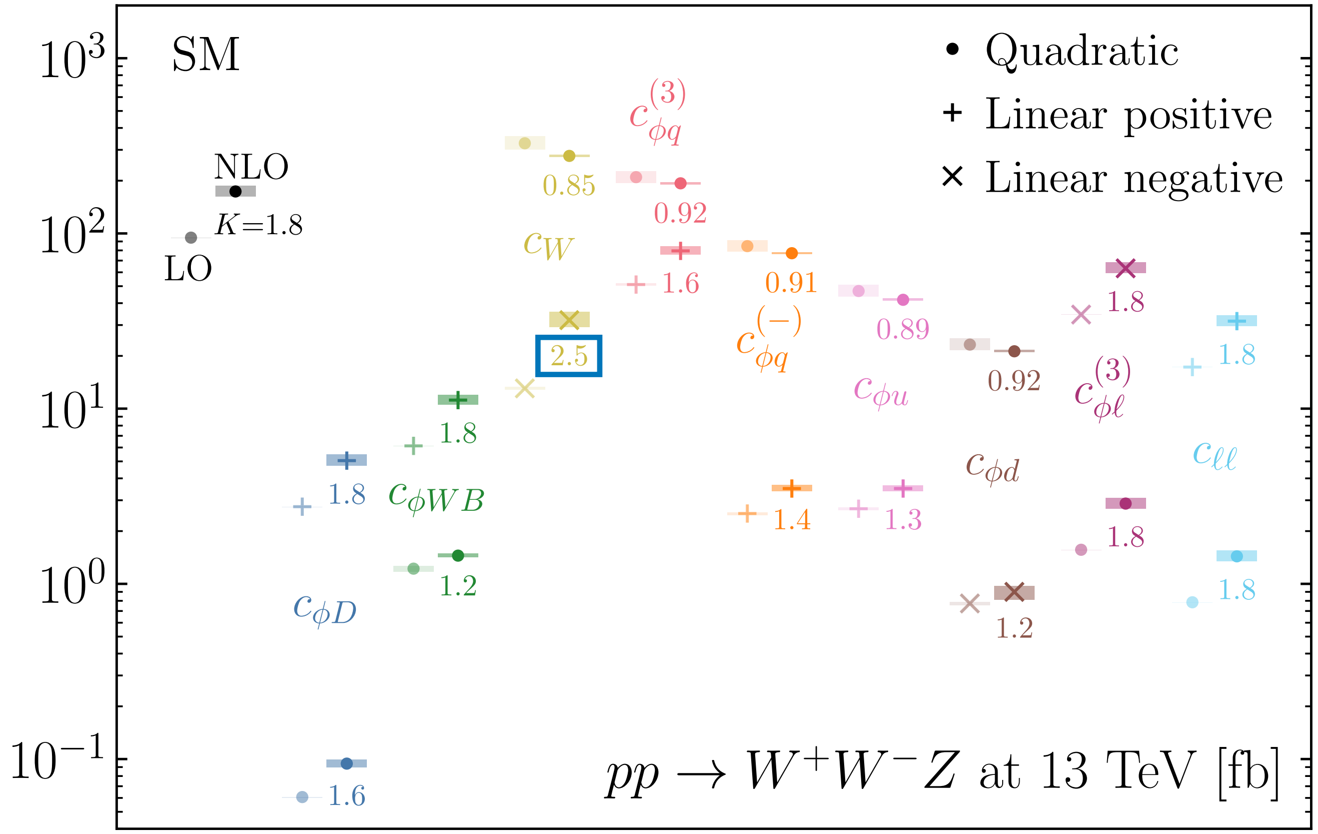
NLO QCD corrections are large in triboson processes

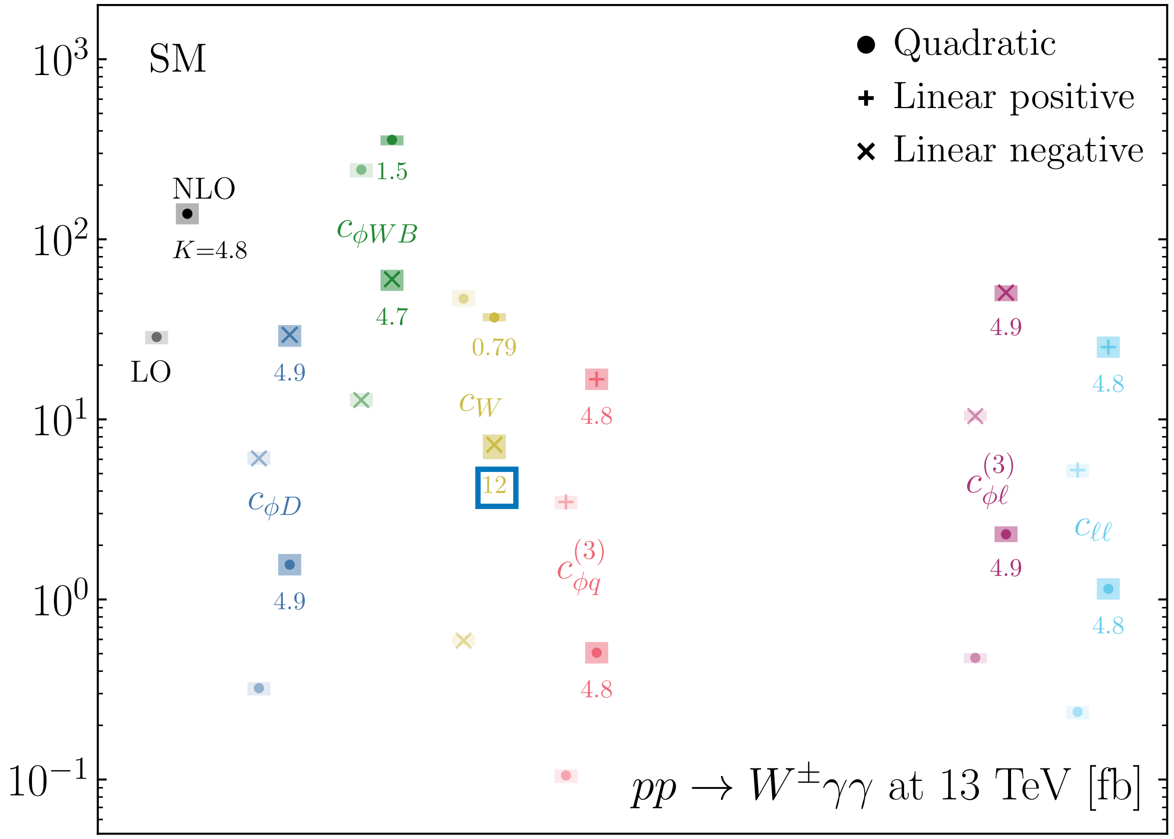
- giant K-factors (in SM) for photonic processes (radiation zero)

  [Bozzi et al.; Phys. Rev. D 83 (2011) 114035]

- most EFT K-factors similar to the SM

- very large linear c_W K-factor: LO suppression partly lifted at NLO





[EC, Durieux, Mimasu, Vryonidou; to appear]

Going NLO - differential

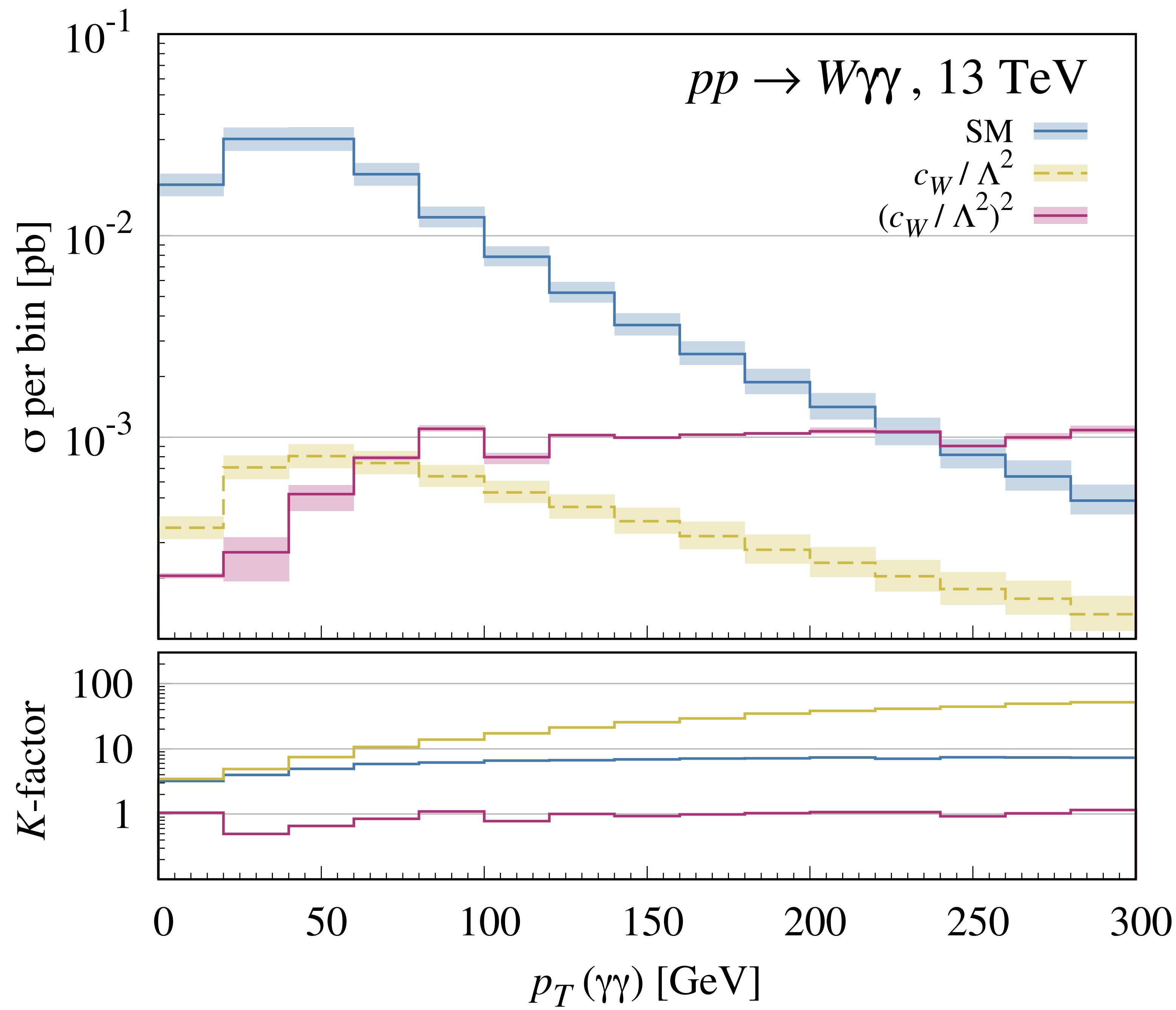
Non trivial NLO QCD corrections: impact in size and shape

- high SM K-factor:
  - radiation zero ($W\gamma\gamma$)
  - soft V emission from a jet resembles EW corrections

  [Grazzini at al.; 1912.00068]
  [Rubin at al.; 1006.2144]

- high linear K-factor:
  LO suppression partly lifted at NLO

- quadratic K-factor$\sim\mathcal{O}(1)$:
  EFT topology limits Sudakov-like contributions



 [EC, Durieux, Mimasu, Vryonidou; JHEP 12 (2024) 055]

Fit: operators and observables

EWPOs and α_{EW} $\sqrt{s} = m_Z$

$\Gamma_Z, \sigma^0_{\mathrm{had}}, R^0_\ell, A^\ell_{FB}, A_\ell(\mathrm{SLD}), R^0_b, R^0_c, A^b_{FB}, A^c_{FB}, A_b, A_c$ [LEP; 0509008]

$\alpha_{EW}(m_Z)$ [PDG; 20-21]

LEP WW $\sqrt{s} = 183 - 209$ GeV

$\sigma(WW \to \ell\nu\ell\nu, qqqq)$ $\frac{d\sigma}{d\cos(\theta)}(WW \to \ell\nu qq)$

[LEP; 1302.3415]

LHC VV $\sqrt{s} = 13$ TeV

$\frac{d\sigma}{dm_{e\mu}}(WW \to e\nu\mu\nu)$ [ATLAS; 1905.04242]

$\frac{d\sigma}{dp_T{}^Z}(WZ \to \ell\nu\ell\nu)$ [ATLAS; 1902.05759]

$\frac{d\sigma}{d\Delta\phi_{jj}}(Zjj \to \ell\ell jj)$ [ATLAS; 2006.15458]

LHC VVV $\sqrt{s} = 13$ TeV

$\sigma(WWW, WWZ, WZZ, WZ\gamma, WW\gamma, W\gamma\gamma, Z\gamma\gamma)$

[ATLAS; 2201.13045, 2305.16994, 2308.03041]
[CMS; 2006.11191, 2310.05164, 2105.12780]

 [EC, Durieux, Mimasu, Vryonidou; JHEP 12 (2024) 055]

Fit: operators and observables

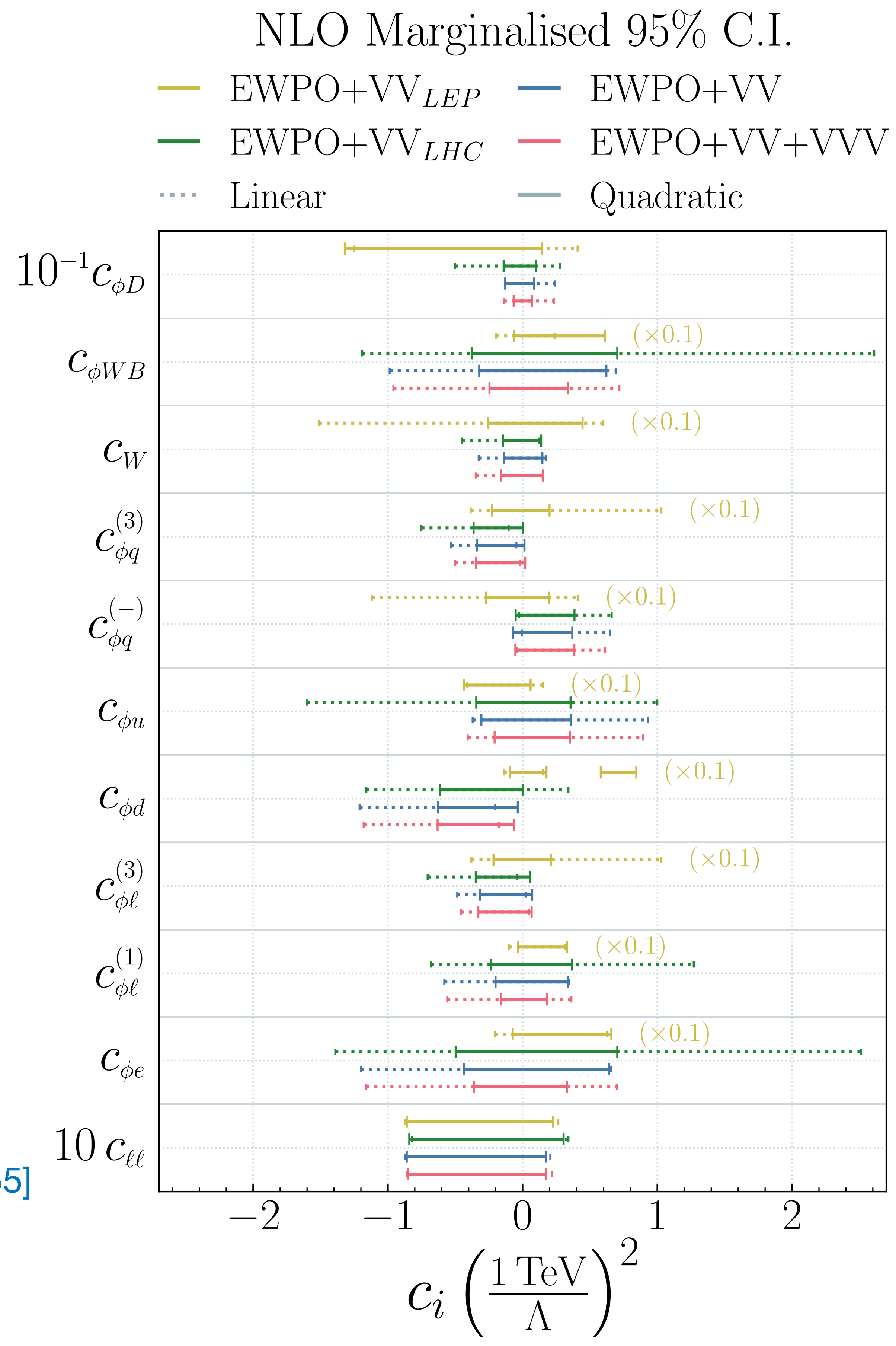
Operator	Definition	EWPOs	LEP WW	LHC VV	$VVV, VV\gamma, V\gamma\gamma$
	bosonic				
$\mathcal{O}_{\phi D}$	$(\phi^\dagger D^\mu \phi)^\dagger (\phi^\dagger D_\mu \phi)$	✓	✓	✓	✓
$\mathcal{O}_{\phi WB}$	$(\phi^\dagger \tau_I \phi) B^{\mu\nu} W^I_{\mu\nu}$	✓	✓	✓	✓
$\mathcal{O}_{WWW}$	$\epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$		✓	✓	✓
	two-fermion				
$\mathcal{O}^{(1)}_{\phi q}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{q}\gamma^\mu q)$	✓		✓	✓
$\mathcal{O}^{(3)}_{\phi q}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi)(\bar{q}\gamma^\mu \tau^I q)$	✓	✓	✓	✓
$\mathcal{O}_{\phi u}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{u}\gamma^\mu u)$	✓		✓	✓
$\mathcal{O}_{\phi d}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{d}\gamma^\mu d)$	✓		✓	✓
$\mathcal{O}^{(1)}_{\phi \ell}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{\ell}\gamma^\mu \ell)$	✓	✓	✓	✓
$\mathcal{O}^{(3)}_{\phi \ell}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi)(\bar{\ell}\gamma^\mu \tau^I \ell)$	✓	✓	✓	✓
$\mathcal{O}_{\phi e}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{e}\gamma^\mu e)$	✓	✓	✓	✓
	four-fermion				
$\mathcal{O}_{\ell\ell}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma^\mu \ell)$	✓	✓	✓	✓

[*EC, Durieux, Mimasu, Vryonidou; JHEP* 12 (2024) 055]

Fit results

Fitmaker [*Ellis et al.*; *2012.02779*]

- LHC VV & VVV appear to improve significantly the bounds from EWPOs & LEP VV
- Quadratic fit: 50% improvement from VVV wrt VV on $c_{\phi D}\,, c_{\phi WB}\,, c^{(1)}_{\phi\ell}\,, c_{\phi e}$
- Bounds dominated by quadratic



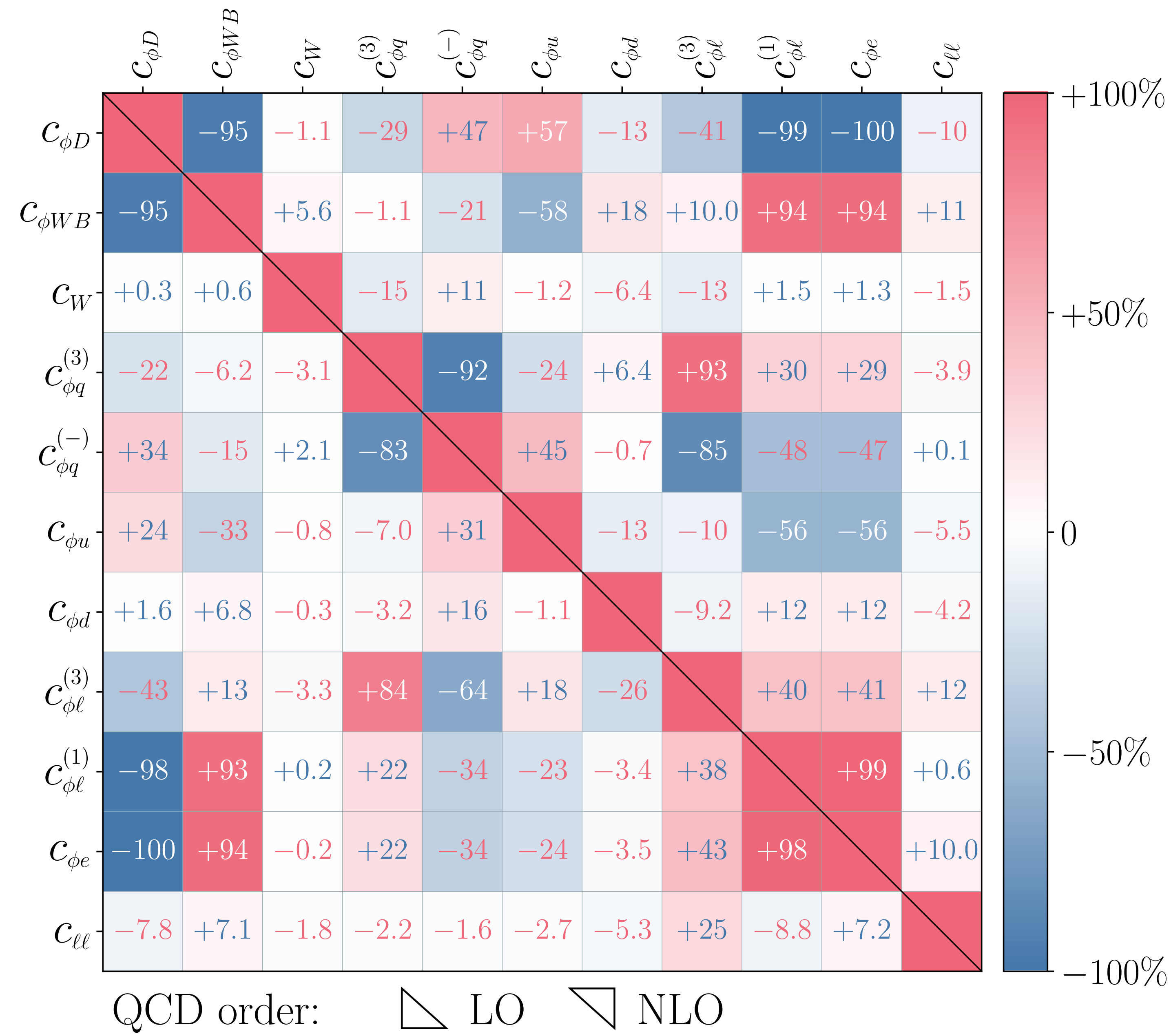
[*EC, Durieux, Mimasu, Vryonidou; JHEP* 12 (2024) 055]

Correlation matrix

EWPO+VV+VVV fit

The correlation matrix suggests a common origin of the observed improvement

- $c_{\phi WB}, c^{(1)}_{\phi \ell}, c_{\phi e}$ strongly correlated (>0.9)
- $c_{\phi WB}, c^{(1)}_{\phi \ell}, c_{\phi e}$ strongly anti-correlated with $c_{\phi D}$
- $c_{\ell \ell}, c_{\phi d}, c_W$ uncorrelated



 [EC, Durieux, Mimasu, Vryonidou; *JHEP* 12 (2024) 055]

EWPOs eigenbasis

- Two EWPOs unconstrained directions: $\hat{w}_B, \hat{w}_W + c_W$

$$w_B = \frac{v^2}{\Lambda^2}\left(-\frac{1}{3}c_{\phi d} - c_{\phi e} - \frac{1}{2}c_{\phi\ell}^{(1)} + \frac{1}{6}c_{\phi q}^{(-)} + \frac{2}{3}c_{\phi u} + 2c_{\phi D} - \frac{1}{2t_\theta}c_{\phi WB}\right)$$

$$w_W = \frac{v^2}{\Lambda^2}\left(\frac{1}{2}c_{\phi\ell}^{(3)} + \frac{1}{2}c_{\phi q}^{(3)} - \frac{1}{2}c_{\phi q}^{(-)} - \frac{t_\theta}{2}c_{\phi WB}\right)$$

[Brivio and Trott; 1701.06424]

- 3/11 directions unconstrained in a EWPOs only fit
- additional data is needed (multiboson)

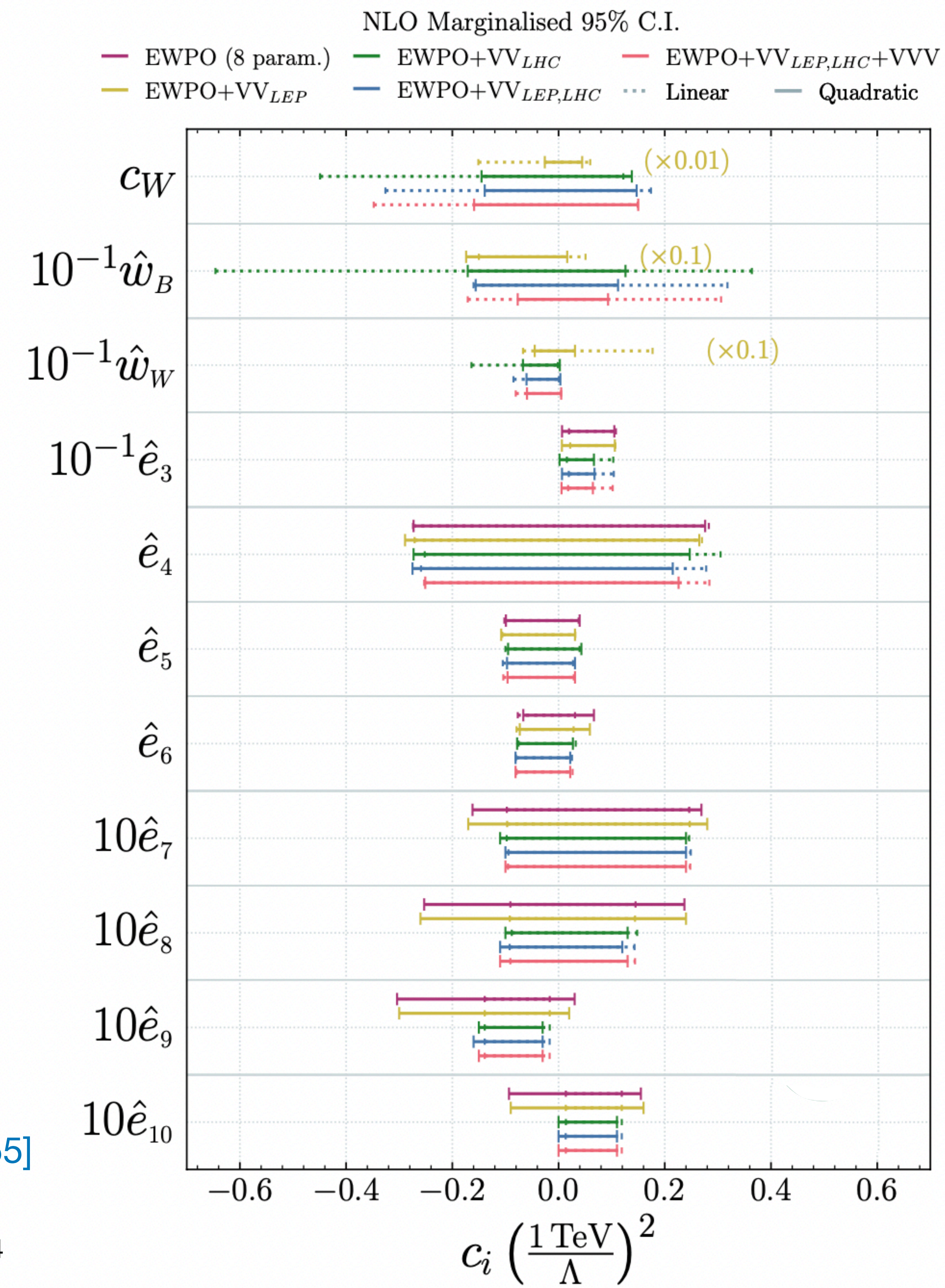
2 possible origins of the improvement

1. constraints in EWPOs blind space + marginalisation
2. genuine effect of higher sensitivity in all directions

Where do VV & VVV help?

Does multiboson help EWPOs in the directions orthogonal to $\{\hat{w}_B, \hat{w}_W, c_W\}$?

- LHC VVV impact is negligible on $\{\hat{e}_{3..10}\}$

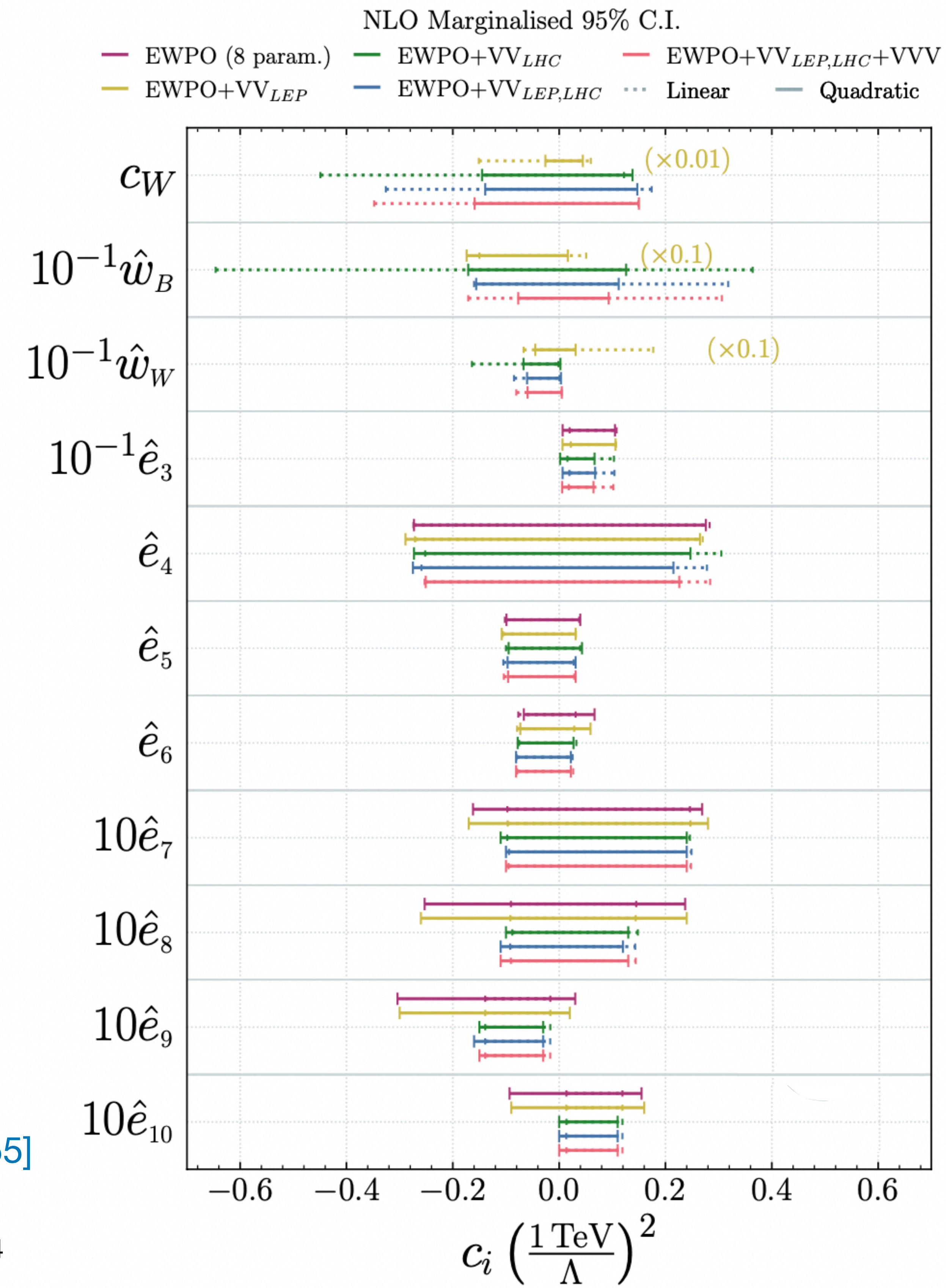


[EC, Durieux, Mimasu, Vryonidou; JHEP 12 (2024) 055]

Where do VV & VVV help?

Does multiboson help EWPOs in the directions orthogonal to $\{\hat{w}_B, \hat{w}_W, c_W\}$?

- LHC VVV impact is negligible on $\{\hat{e}_{3..10}\}$
- mild improvement from quadratics (even EWPOs) on some directions



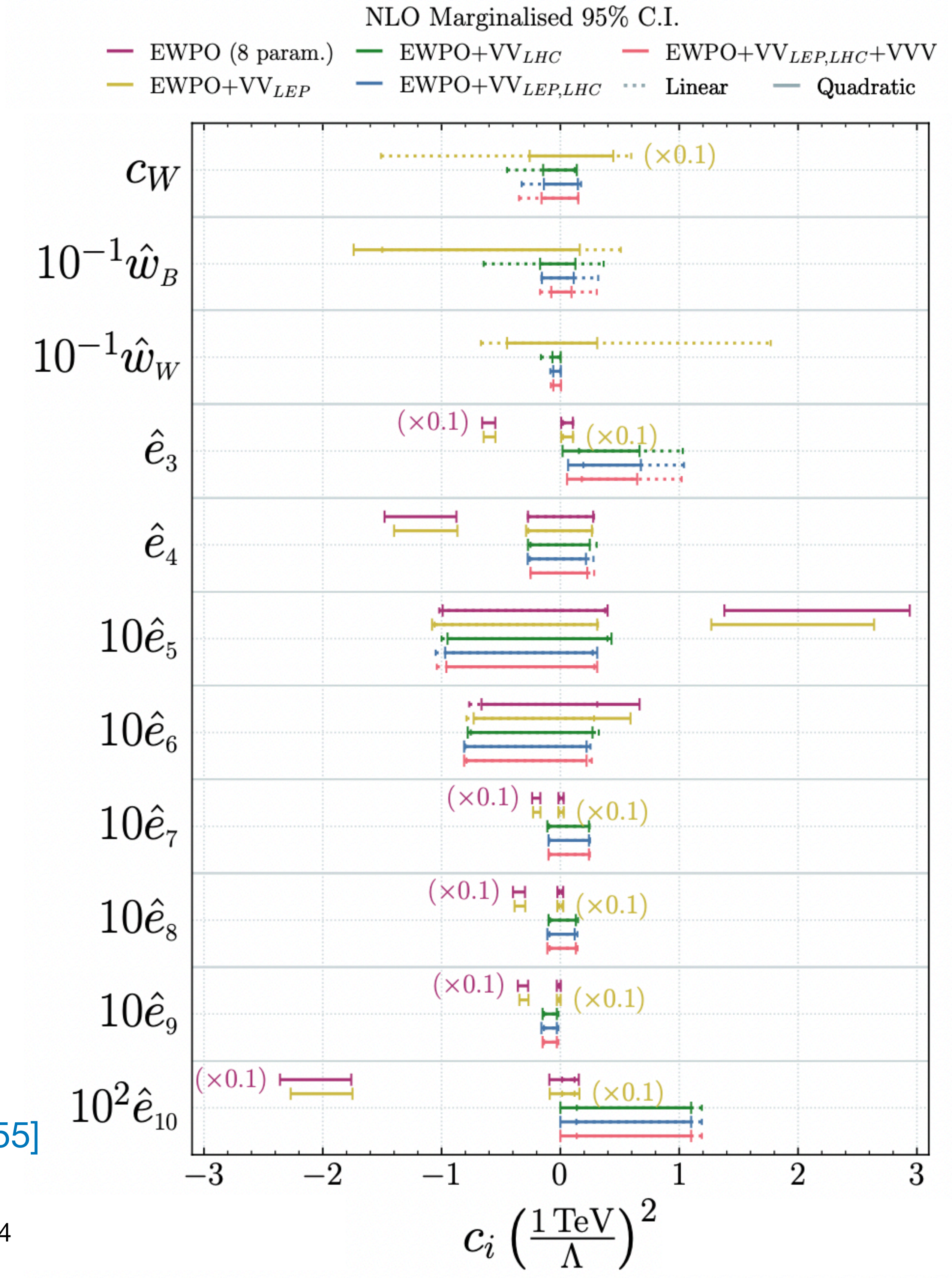
[EC, Durieux, Mimasu, Vryonidou; JHEP 12 (2024) 055]

Where do VV & VVV help?

Does multiboson help EWPOs in the directions orthogonal to $\{\hat{w}_B, \hat{w}_W, c_W\}$?

- LHC VVV impact is negligible on $\{\hat{e}_{3..10}\}$
- mild improvement from quadratics (even EWPOs) on some directions
- secondary minima in EWPOs+LEP VV lifted by LHC VV

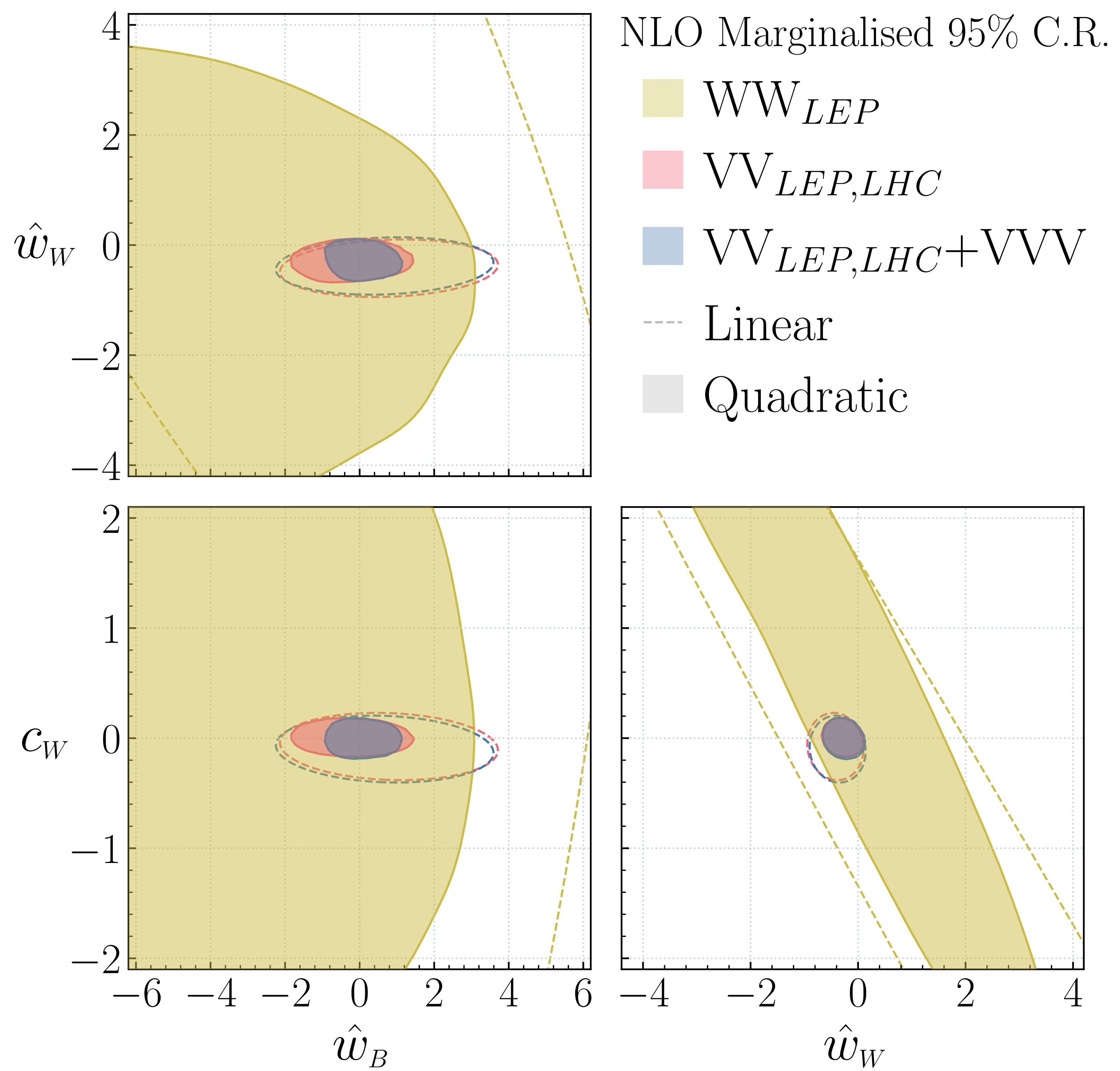
[EC, Durieux, Mimasu, Vryonidou; JHEP 12 (2024) 055]



EWPOs blind directions

Three EWPOs unconstrained parameters: $\hat{w}_B, \hat{w}_W, c_W$

- Large $\mathcal{O}(\Lambda^{-4})$ effect (also for LEP VV!)
- LHC VV dominates over LEP
- VVV at $\mathcal{O}(\Lambda^{-2})$ doesn't help
- VVV constrains $\hat{w}_B$ at $\mathcal{O}(\Lambda^{-4})$
- Bulk of the SMEFT improvement (resonant Higgs in $W\gamma\gamma, Z\gamma\gamma$ experimental selections)



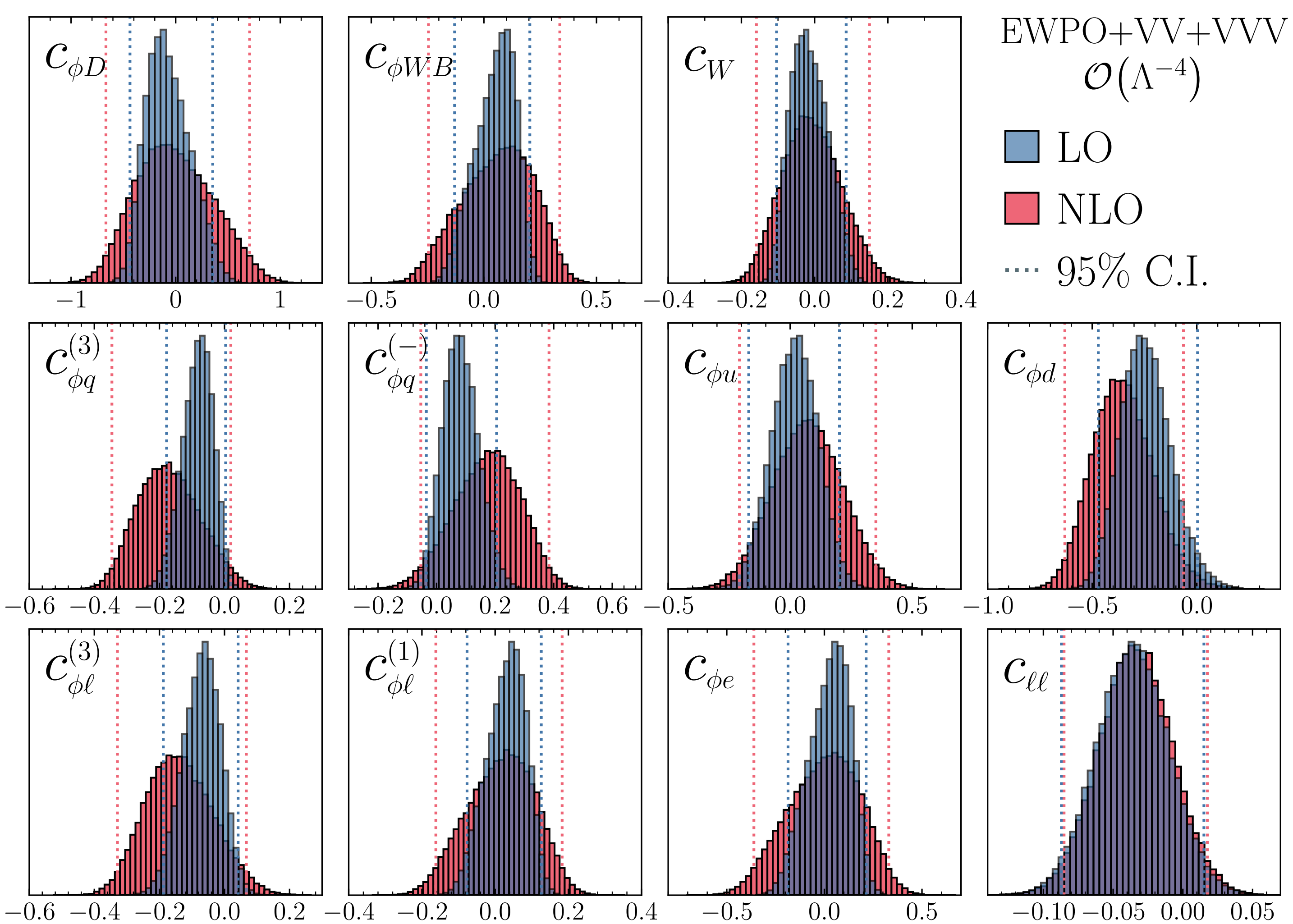
 [EC, Durieux, Mimasu, Vryonidou; JHEP 12 (2024) 055]

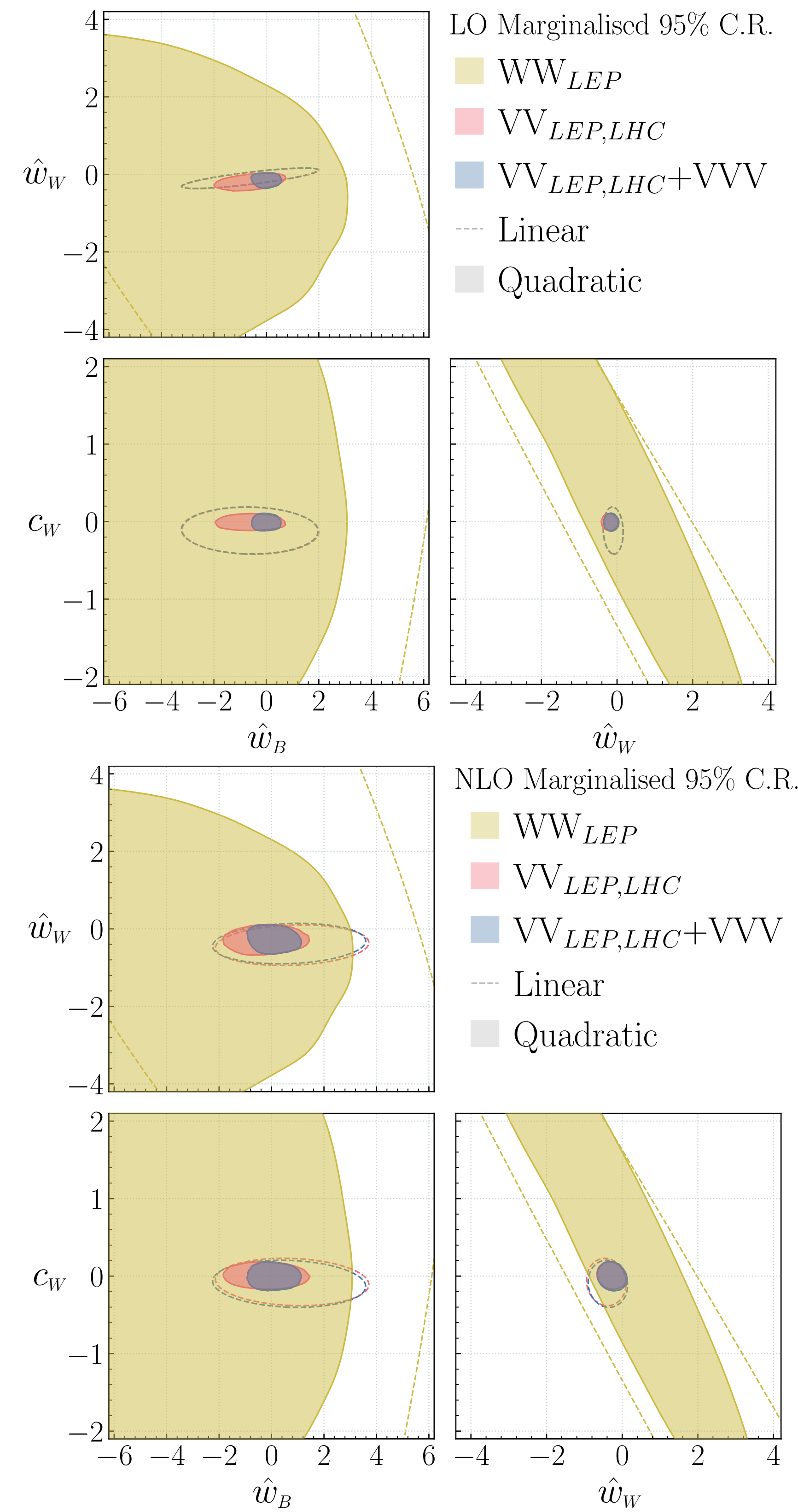
LO vs NLO

LO bounds are better than NLO

- driven by LHC diboson high-pT tails
- sensitivity “diluted” by real QCD radiation

[*Campanario et al.; Phys. Rev. D* ***91*** *(2015) 054039*]





Summary & conclusions

- Large QCD corrections in LHC VV&VVV: important for a fair assessment of their constraining power

- Quadratic EFT contributions are sizeable for all the processes, from EWPO leading to secondary minima, to LEP diboson, and the LHC VV&VVV

- The resonant Higgs contributions in $V\gamma\gamma$ play a dominant role

- Outlook: full understanding of the VVV sensitivity requires a global Higgs&EW fit

Backup

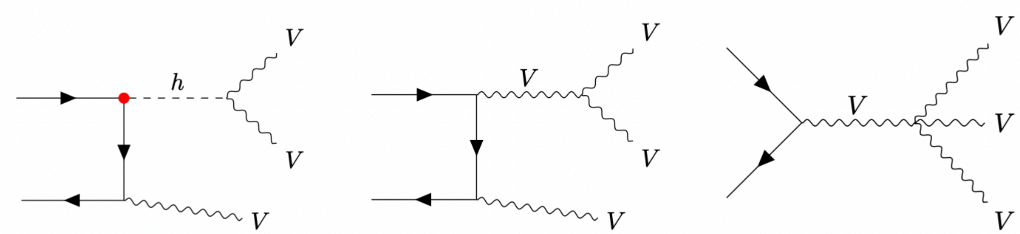
Light quark Yukawa in VVV

Sensitivity to light quark Yukawa in longitudinal VVV production

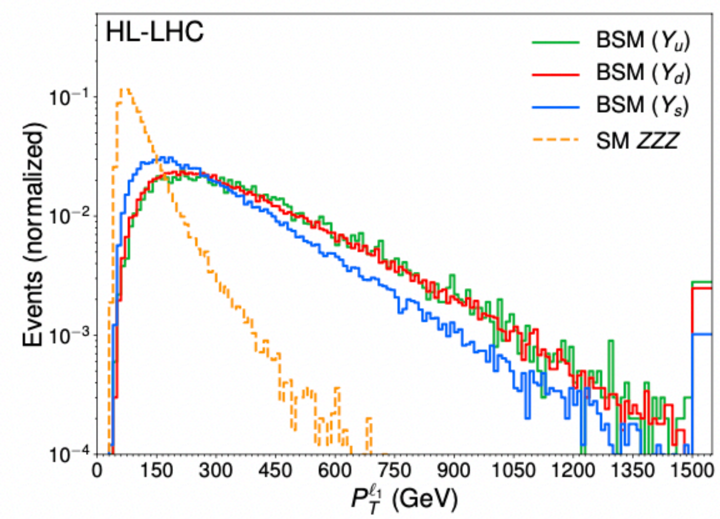
[Falkowski et al.; 2011.09551]

- off-shell Higgs production in WWW and ZZZ

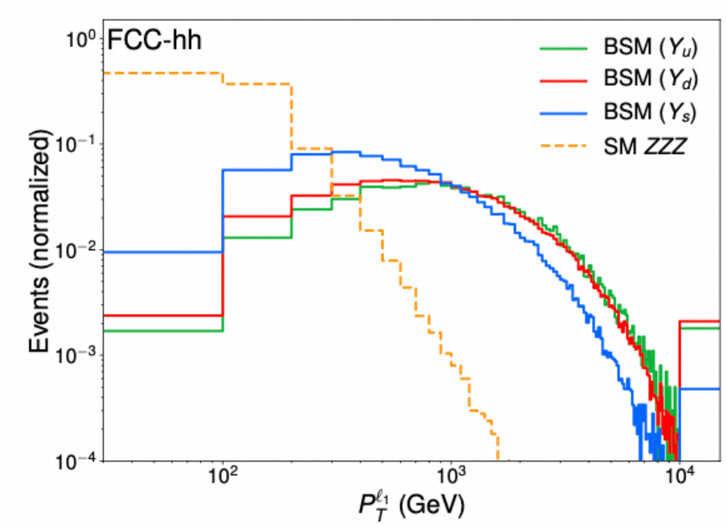
$$\mathcal{L} \supset -\frac{h}{v} \sum_{q=u,d,s} m_q (1 + \delta y_q) \bar{q} q \qquad \boxed{\delta y_q = -\frac{Y_q}{y_q^{\rm SM}}}$$



- energy enhancements of the longitudinally polarised cross sections in the high-energy limit: $\sigma(qq \to V_L V_L V_L) \sim s$



- projected sensitivity at HL-LHC and FCC-hh in triboson channel comparable to total Higgs signal strength

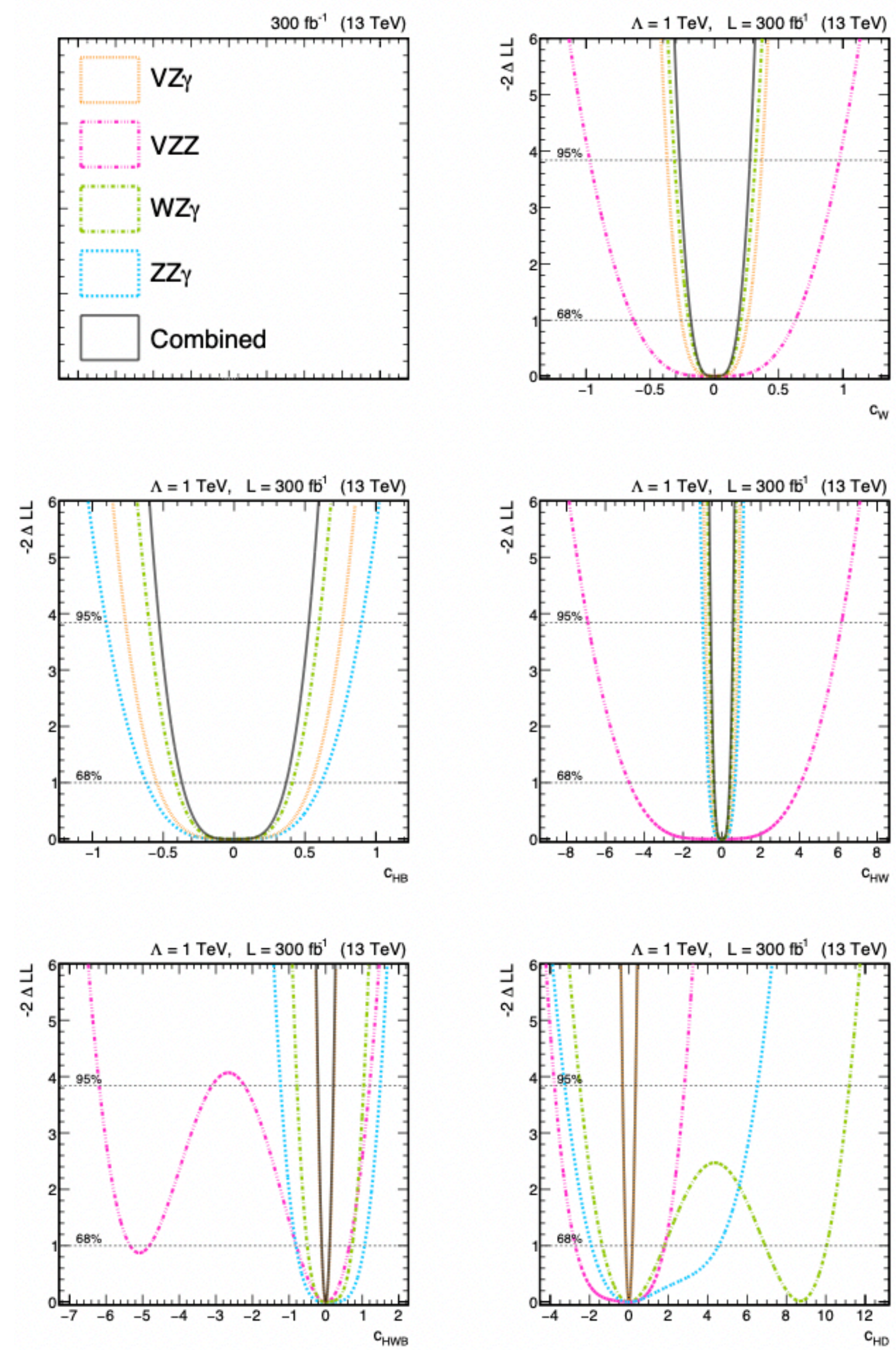


LO sensitivity study

Sensitivity to TGC and Higgs-gauge couplings [Bellan et al.; 2303.18215]

- Differential analysis
- Large quadratic contribution (secondary minima)
- Highest sensitivity in semileptonic $VZ\gamma$
- Individual bounds competitive with VBS

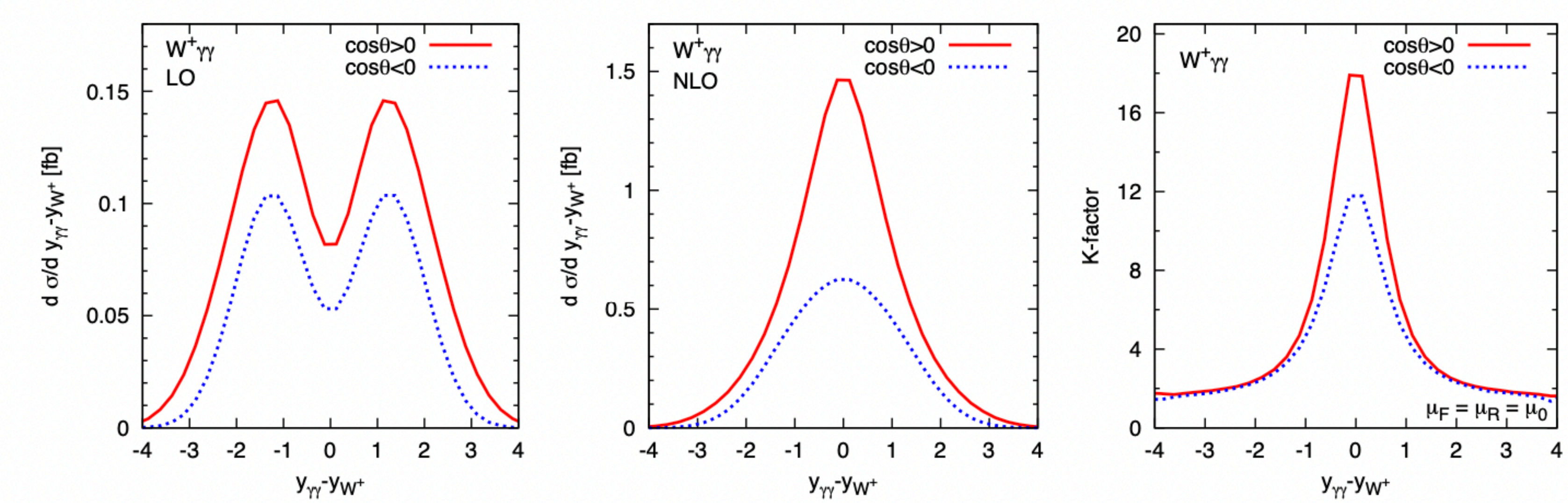
↓ Processes	Operators →	Q_W	Q_{HB}	Q_{HW}	Q_{HWB}	Q_{HD}
Combination	68% C.L.	[-0.18,0.19]	[-0.37,0.37]	[-0.40,0.40]	[-0.11,0.11]	[-0.17,0.17]
	95% C.L.	[-0.27,0.28]	[-0.53,0.53]	[-0.57,0.57]	[-0.21,0.21]	[-0.33,0.33]
VBS	95% C.L.	[-0.19,0.18]	-	[-1.02,1.08]	[-1.34,0.96]	[-1.98,1.74]



Giant SM K-factors

Approximate **radiation zero** effect in $pp \to W\gamma\gamma$

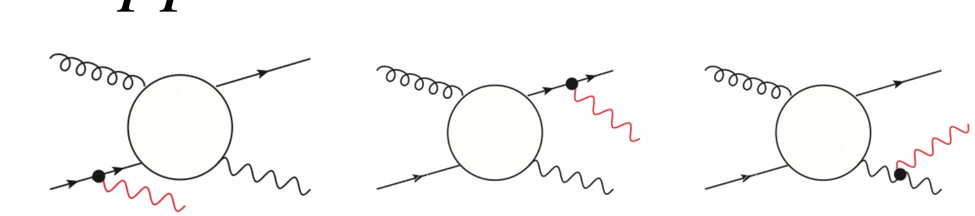
- partial LO cancellation between qq-induced amplitudes
- no cancellation in qg-channels (dominating the NLO cross section)



[Bozzi et al.; Phys. Rev. D 83 (2011) 114035]

Log enhancements in QCD corrections to VV&VVV processes

- Soft-boson radiation off a hard jet ~ Sudakov logs
- Example: $pp \to VV$



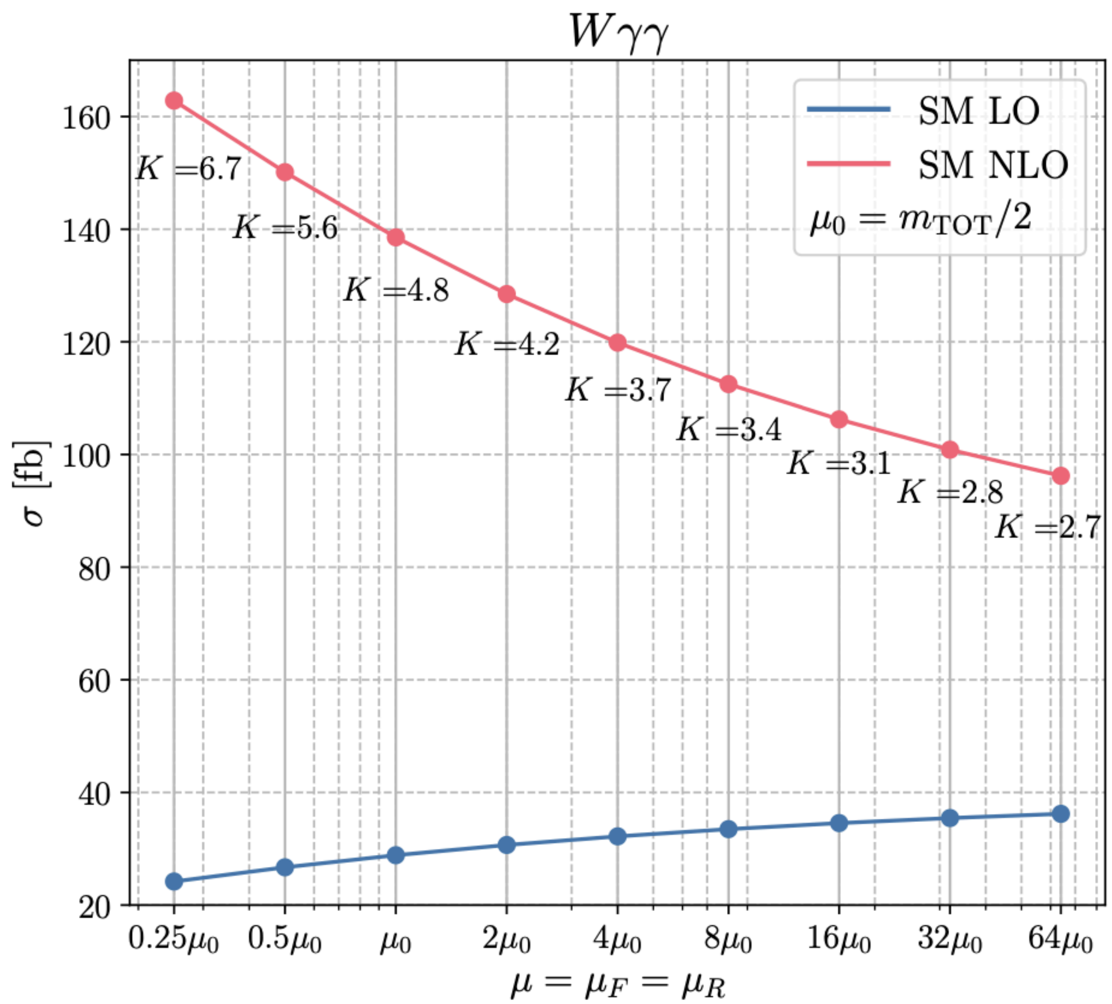
$$\frac{d\sigma^{V(V)j}}{d\sigma^{\mathrm{LO}}_{VV}} \propto \alpha_{\mathrm{S}} \log^2\left(\frac{Q^2}{M_W^2}\right)$$

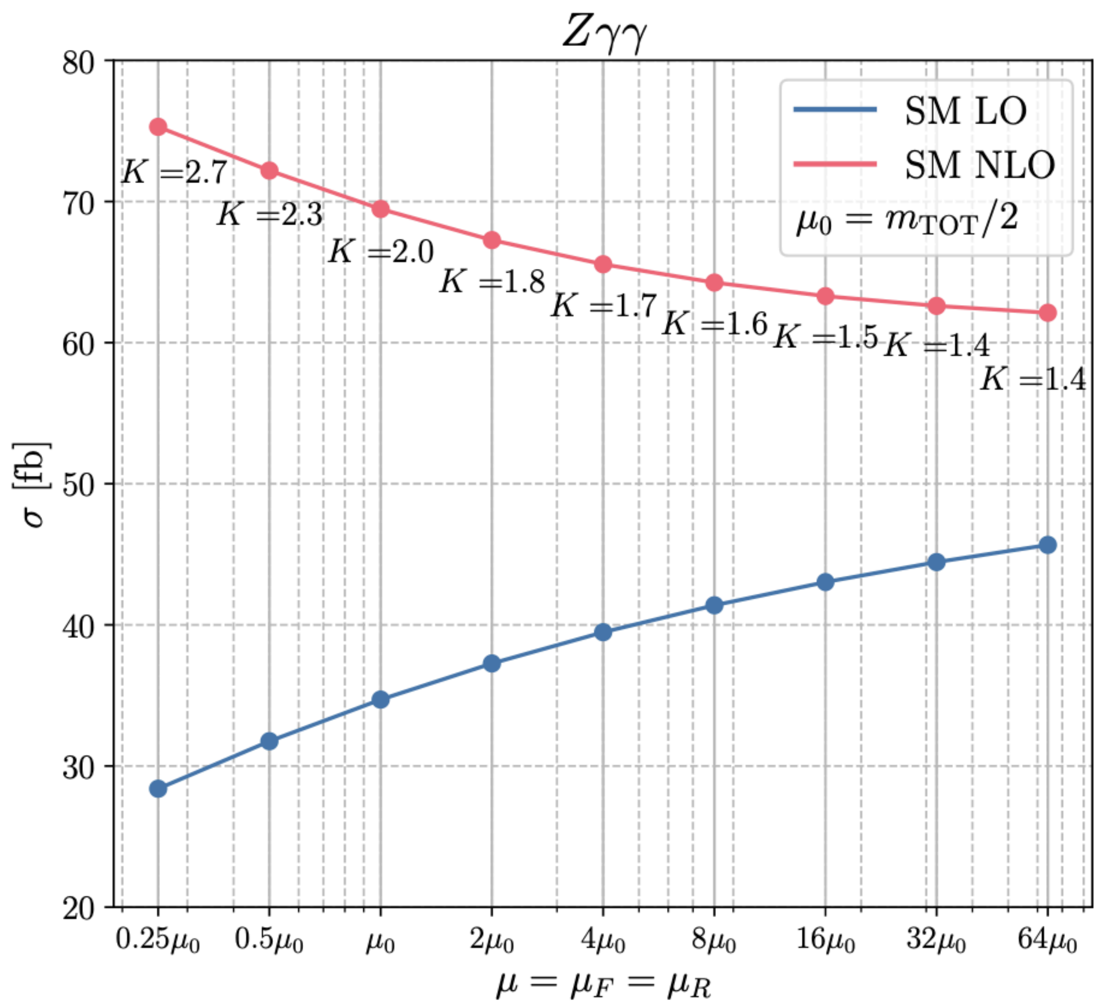
[Grazzini et al.; 1912.00068]

Scale dependence in $W\gamma\gamma$

Scale variation around $\mu_0 = m_{W\gamma\gamma}$

- the NLO scale uncertainty is ~10% for $\mu_0/2 < \mu < 2\mu_0$
- the K-factor is decreasing as the scale increases





[*EC, Durieux, Mimasu, Vryonidou; JHEP* 12 (2024) 055]