Triboson production in the SMEFT

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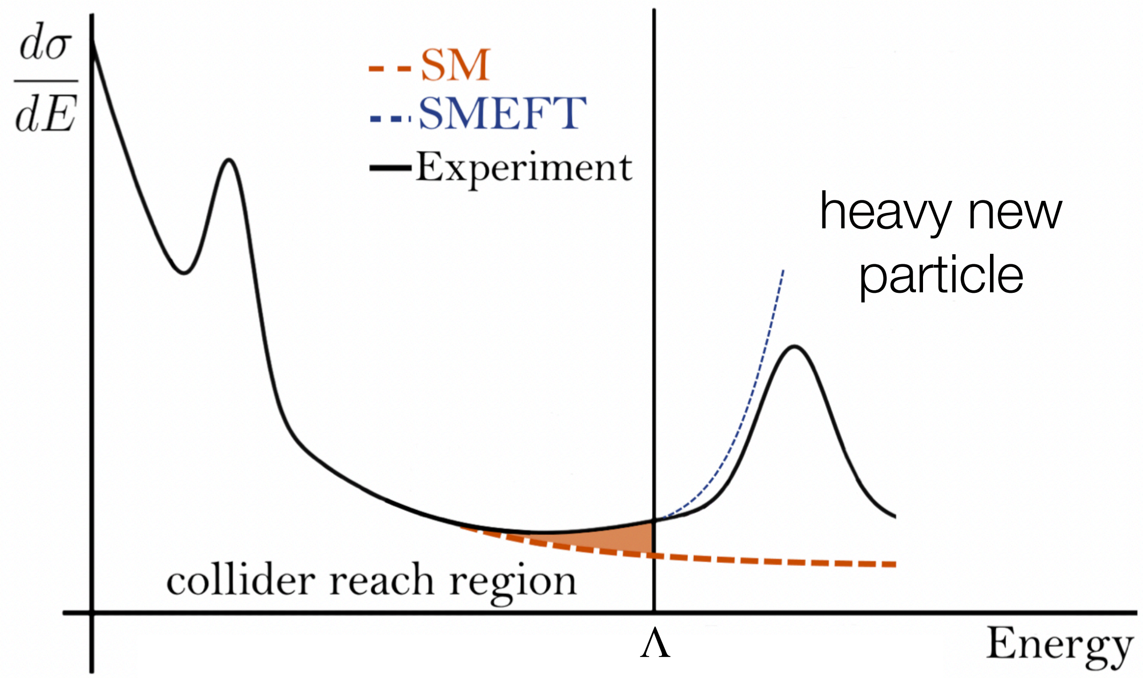
The SMEFT



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

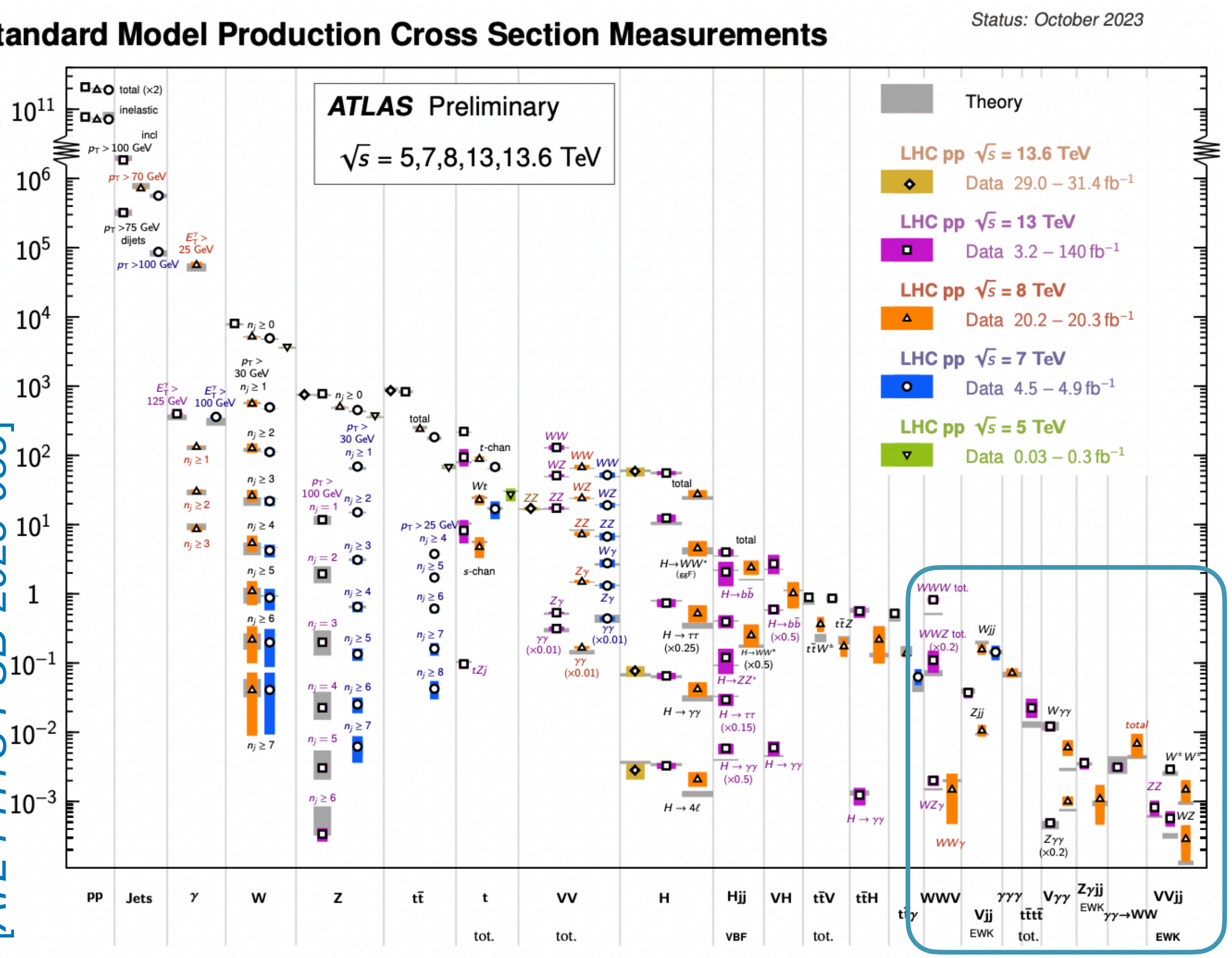
Dimension-6 operators Warsaw basis

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

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

Triboson production at the LHC

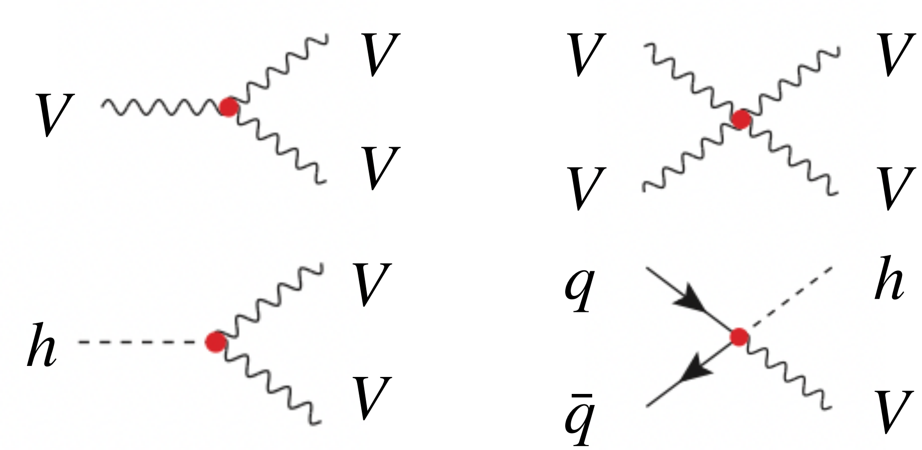
- Triboson have small cross sections, only accessible with LHC run 2 (total rates, mainly fully leptonic)



[ATL-PHYS-PUB-2023-039]

Why triboson?

- Tree-level access to TGC and QGC
- Interplay with the Higgs sector



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

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
$\mathcal{O}^{(1)}_{\phi q}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{q}\gamma^\mu q)$
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$\mathcal{O}_{\phi e}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{e}\gamma^\mu e)$
	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; to appear]

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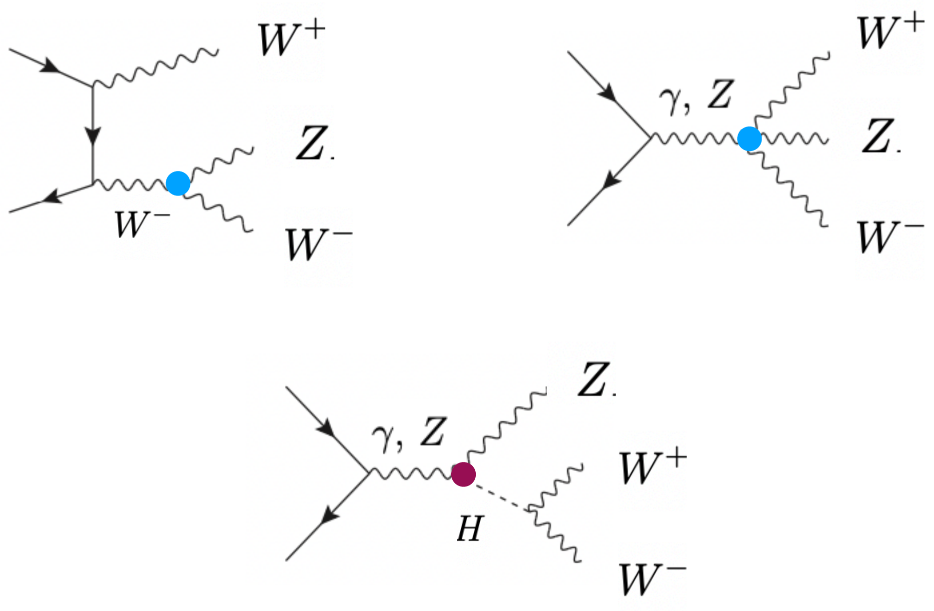
$$pp \to W^+W^-Z$$



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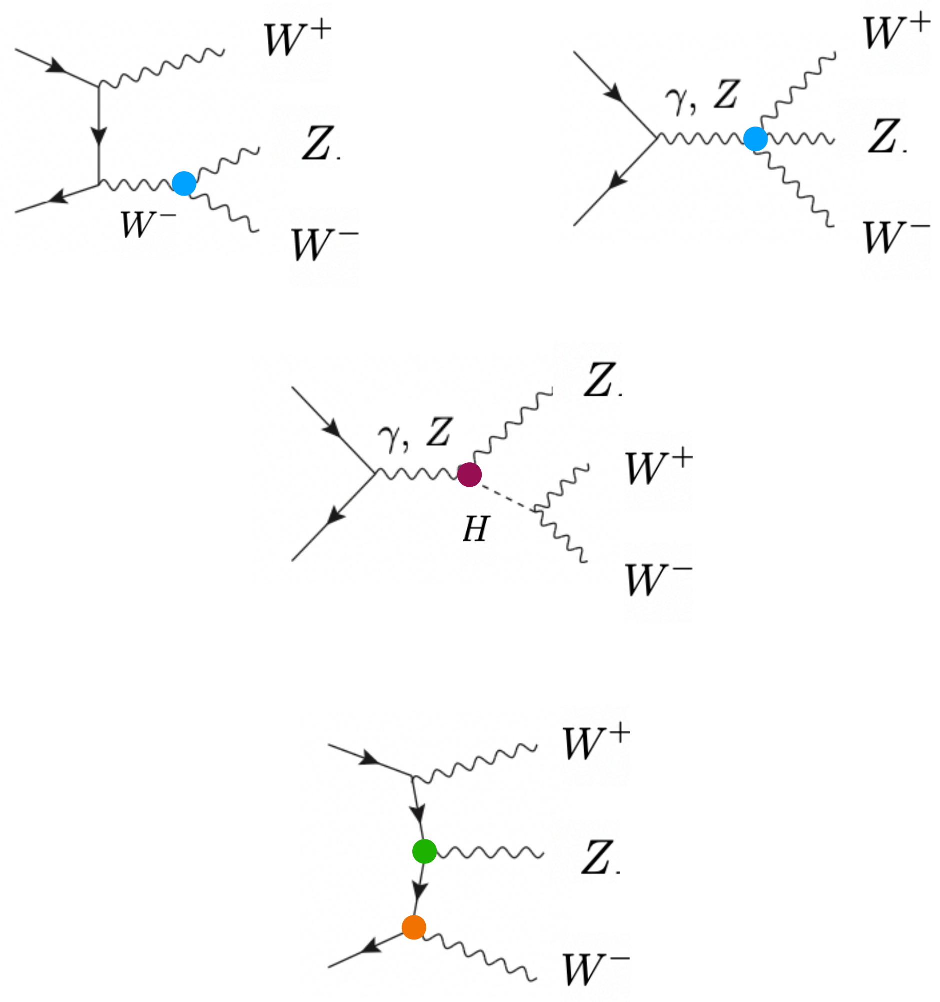

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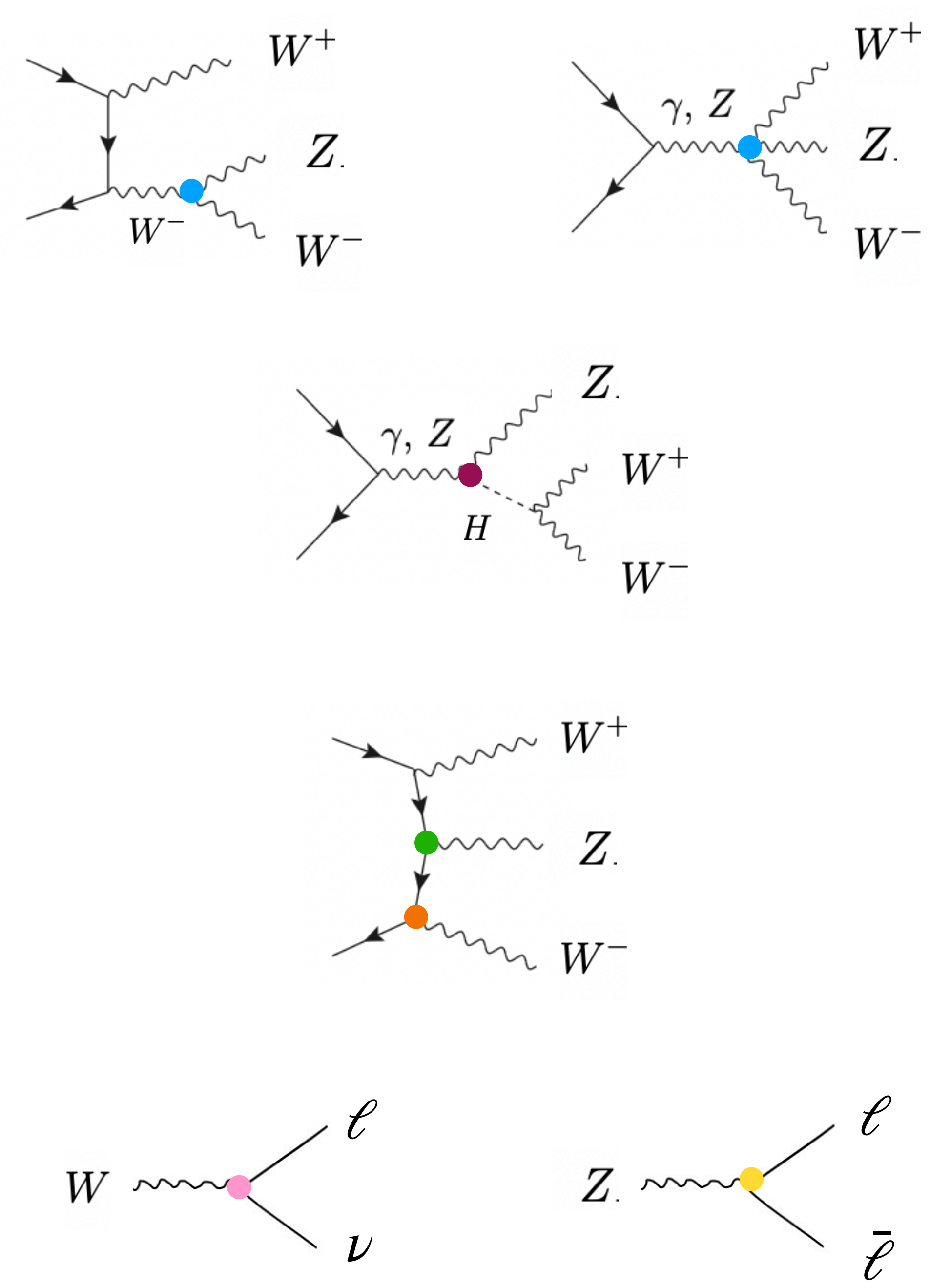

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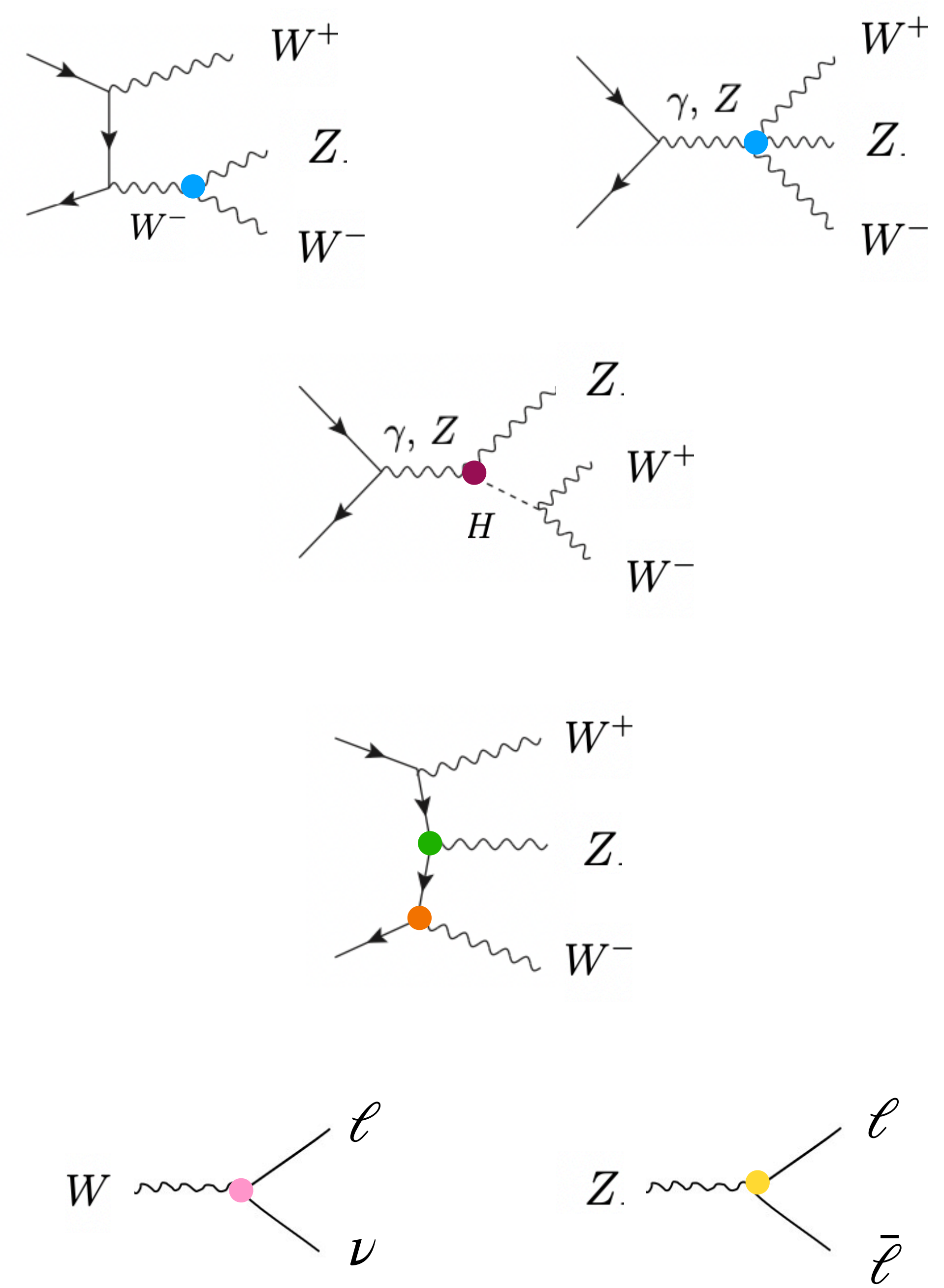


[EC, Durieux, Mimasu, Vryonidou; to appear]

Going NLO - inclusive

NLO QCD corrections are large in triboson processes

[Degrande et al.; 2008.11743]

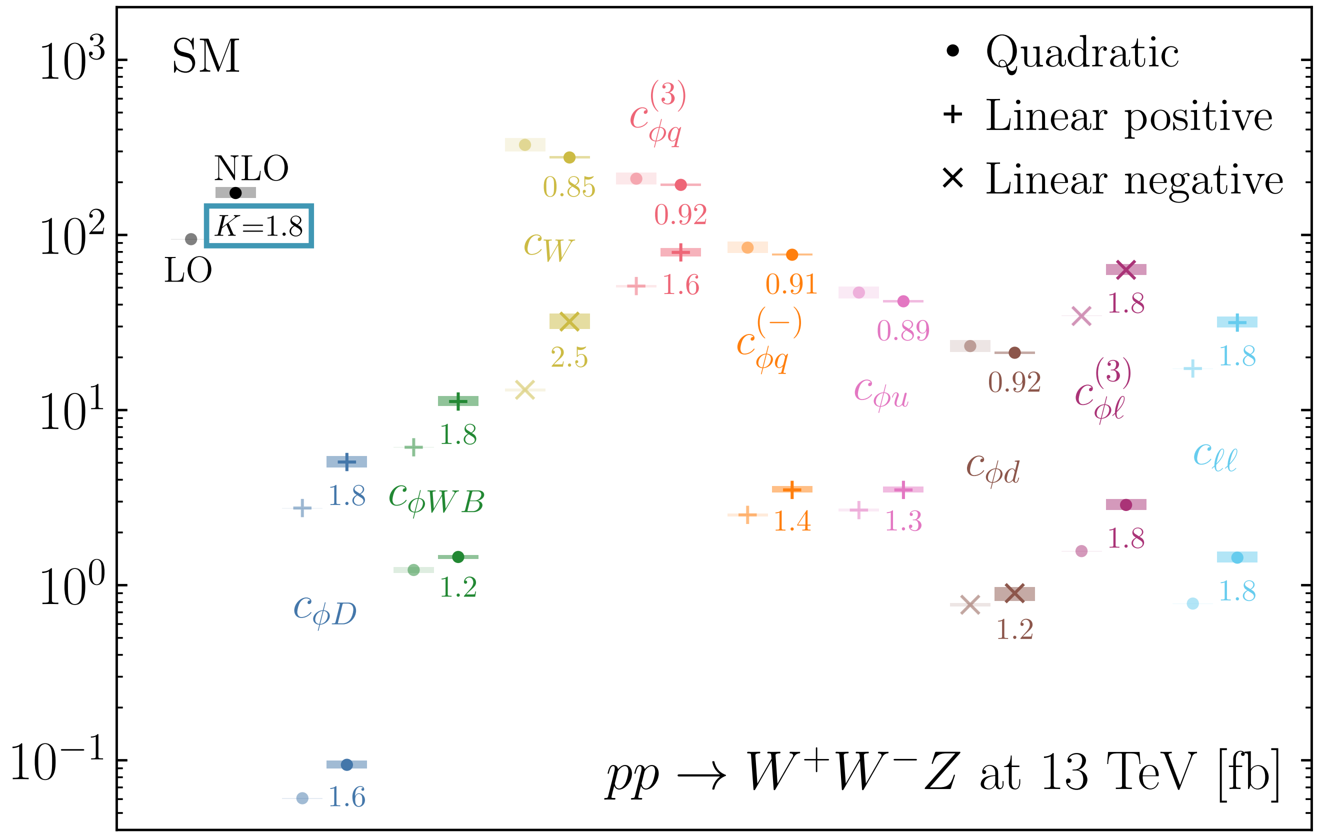
- giant K-factors (in SM) for photonic processes

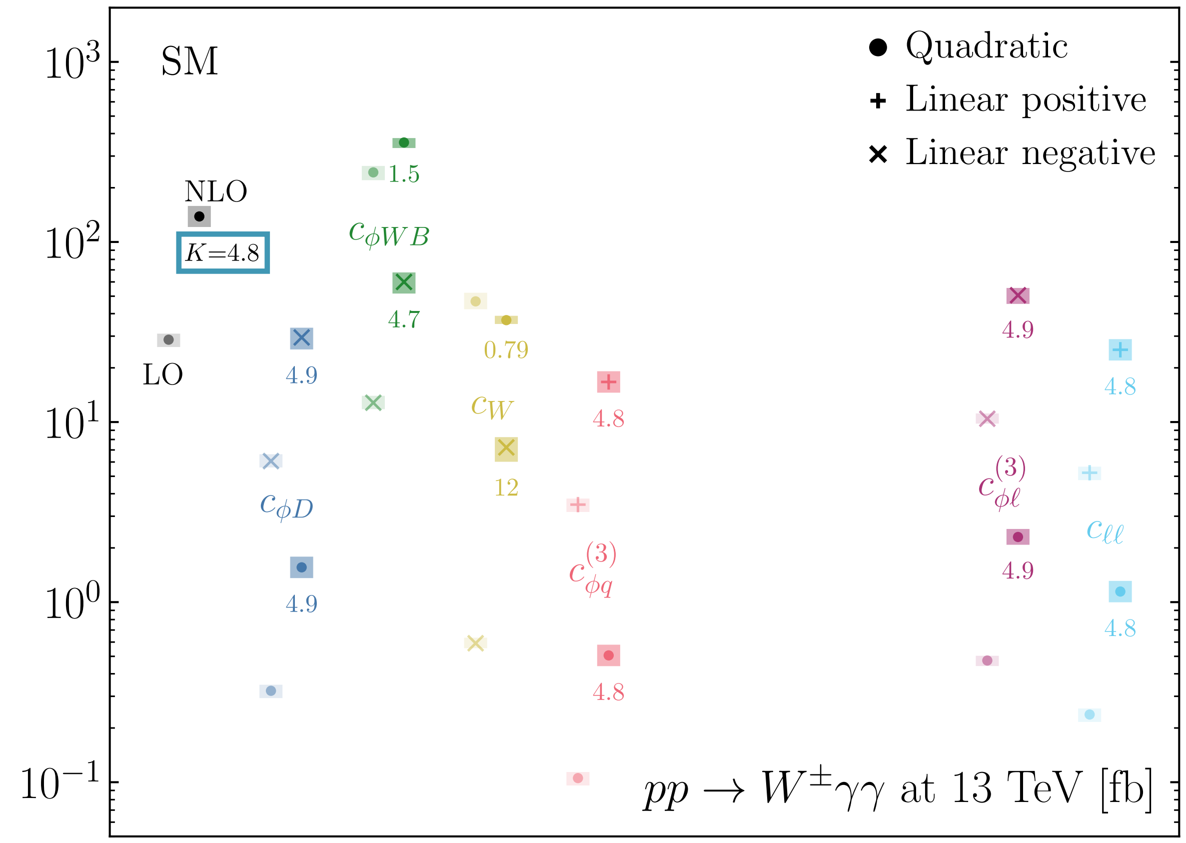
[Bozzi et al.; Phys. Rev. D 83 (2011) 114035]

- most EFT K-factors similar to the SM

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

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





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see Matteo's talk

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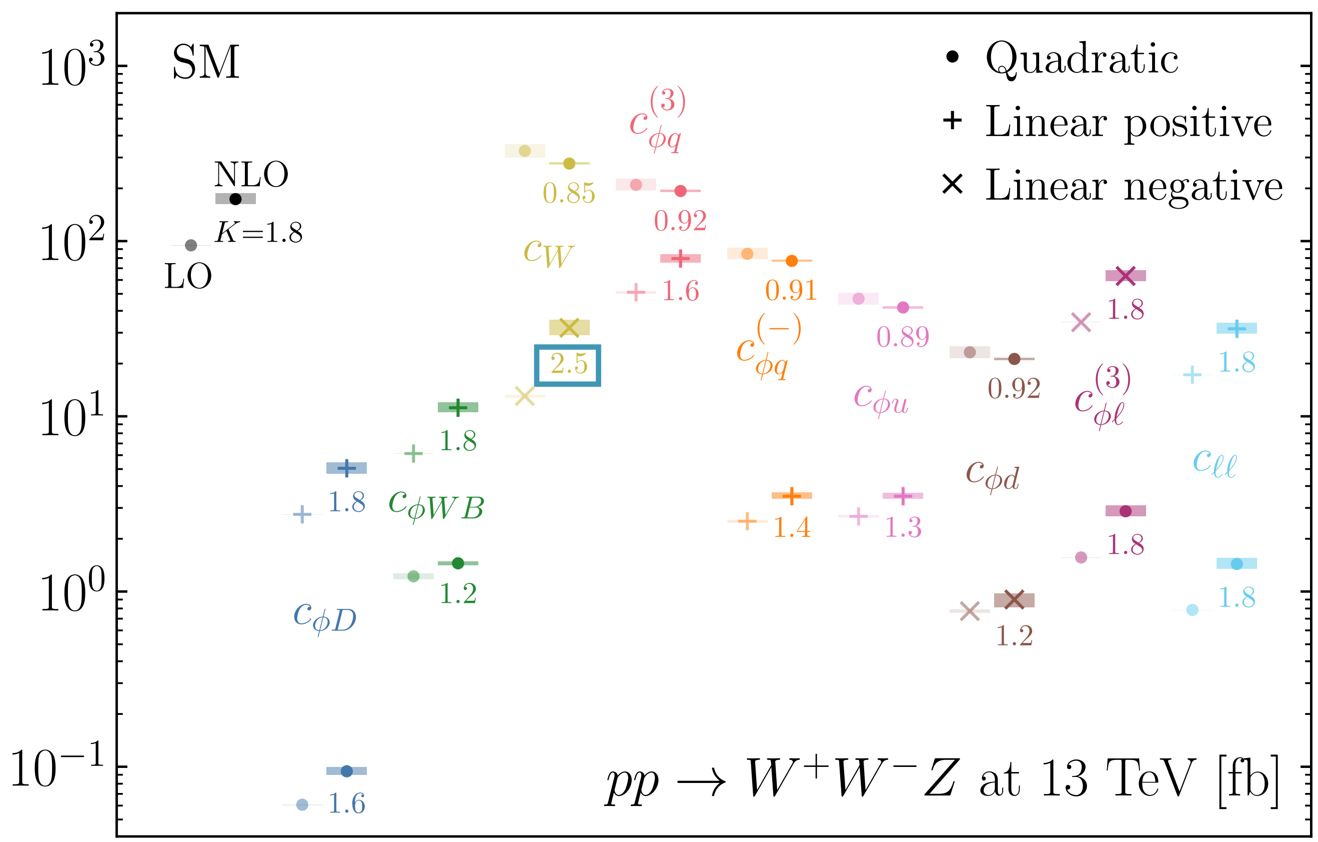
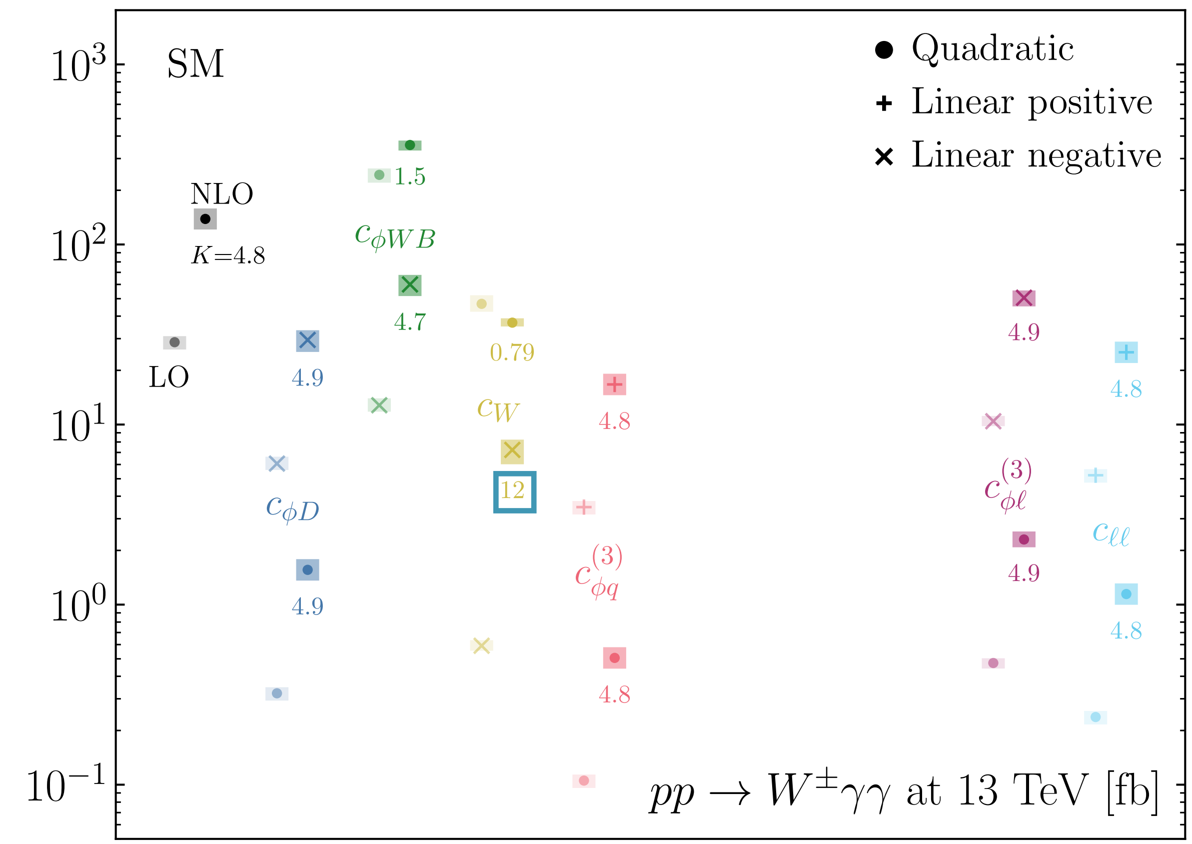




[EC, Durieux, Mimasu, Vryonidou; to appear]

Going NLO - differential

Non trivial NLO QCD corrections: impact in size and shape

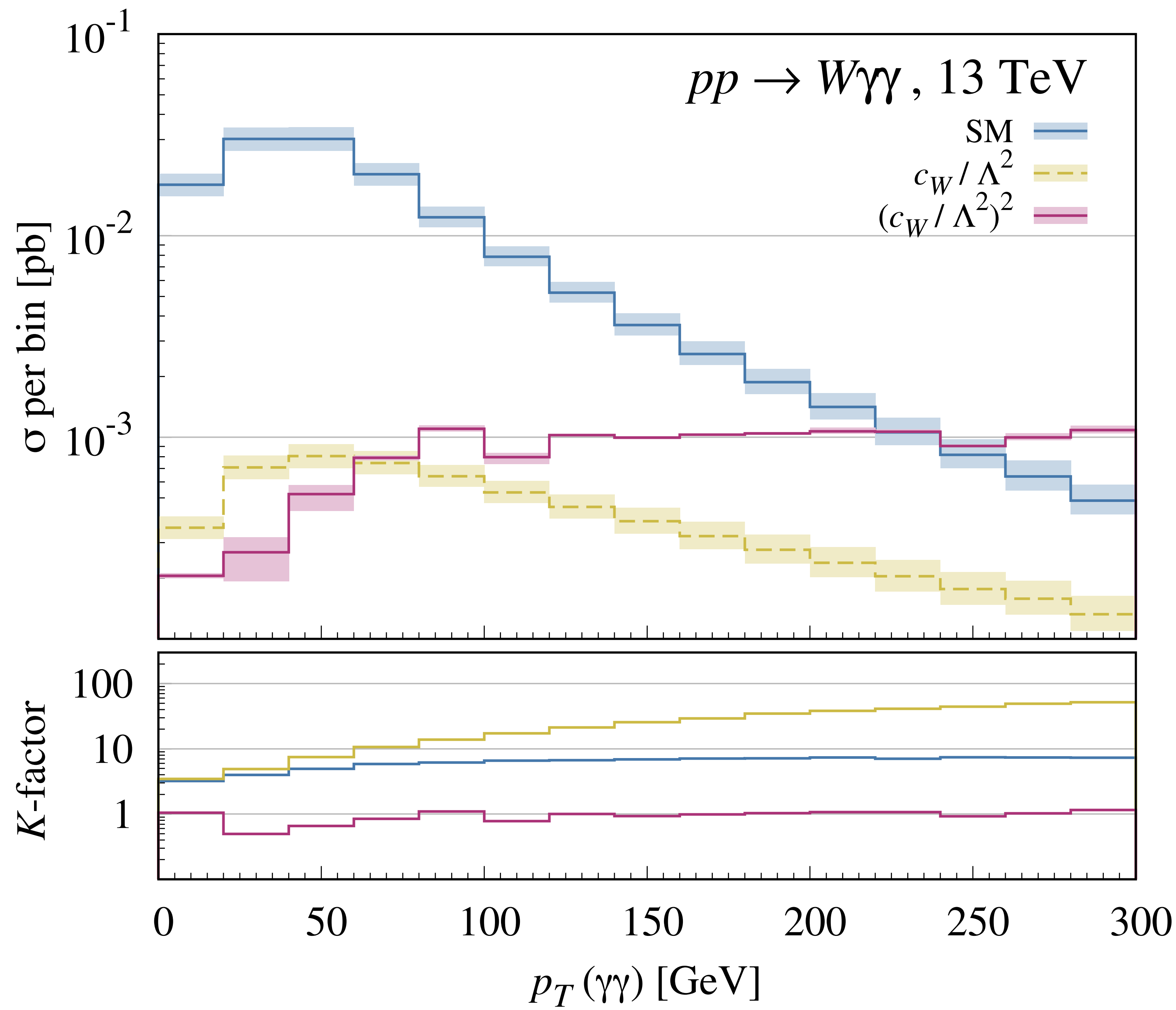
- high SM K-factor:
  soft V emission from a jet resembles EW corrections

  [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

- $\mathcal{O}(\Lambda^{-2})$ and $\mathcal{O}(\Lambda^{-4})$ harder than SM



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

Fit: operators and observables

EWPOs and $\alpha_{\text{EW}}\ \sqrt{s} = m_Z$

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

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

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

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

[LEP; 1302.3415]

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

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

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

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

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

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

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

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

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				
$\mathcal{O}^{(1)}_{\phi q}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{q}\gamma^\mu q)$	✓		✓	✓
$\mathcal{O}^{(3)}_{\phi q}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi)(\bar{q}\gamma^\mu \tau^I q)$	✓	✓	✓	✓
$\mathcal{O}_{\phi u}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{u}\gamma^\mu u)$	✓		✓	✓
$\mathcal{O}_{\phi d}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{d}\gamma^\mu d)$	✓		✓	✓
$\mathcal{O}^{(1)}_{\phi \ell}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{\ell}\gamma^\mu \ell)$	✓	✓	✓	✓
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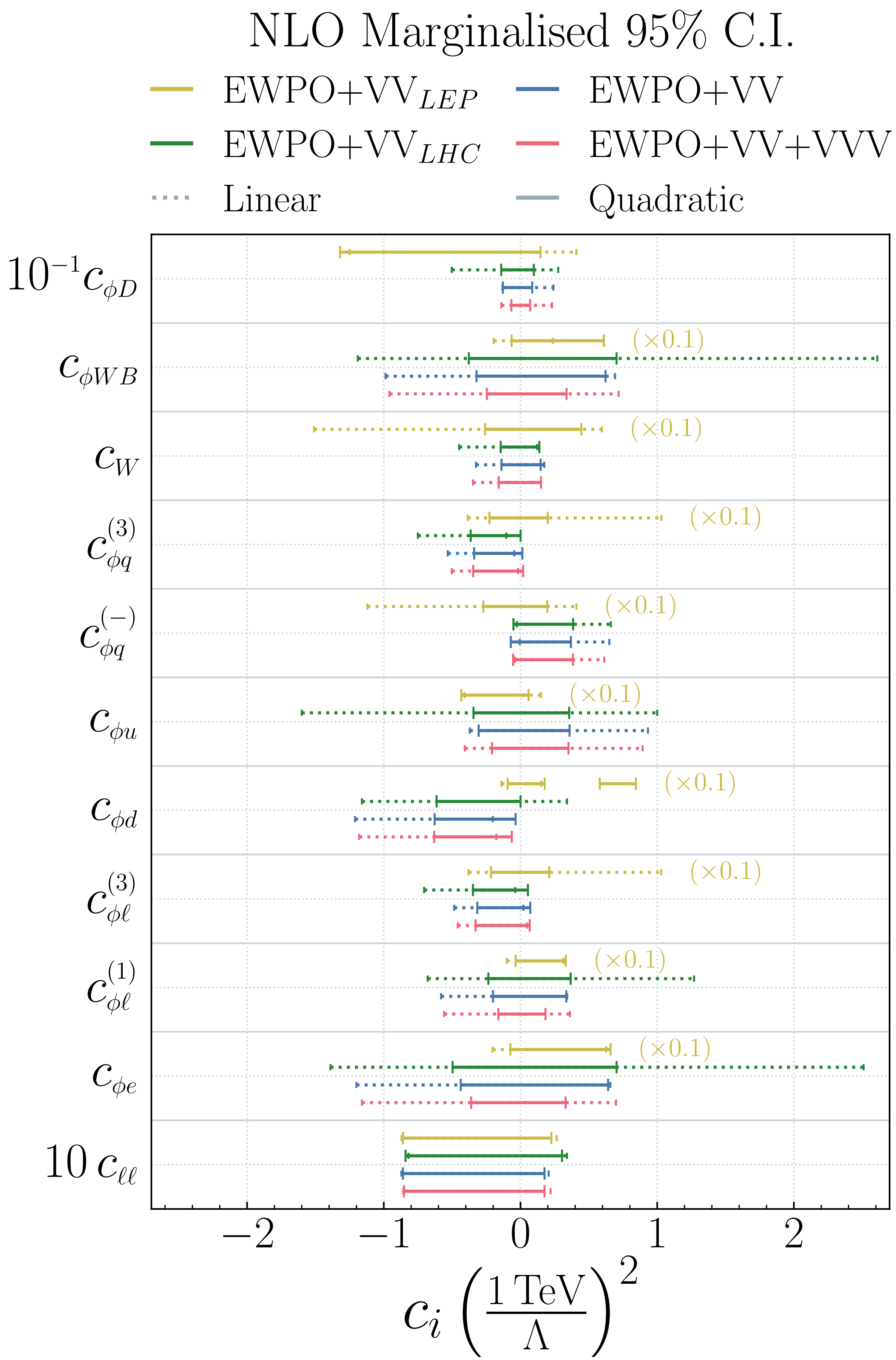
	four-fermion				
$\mathcal{O}_{\ell\ell}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma^\mu \ell)$	✓	✓	✓	✓

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

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 $c_{\phi D}\,, c_{\phi WB}\,, c_{\phi \ell}^{(1)}\,, c_{\phi e}$
- Bounds dominated by quadratic

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

EWPOs eigenbasis

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

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

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

[Brivio and Trott; 1701.06424]

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

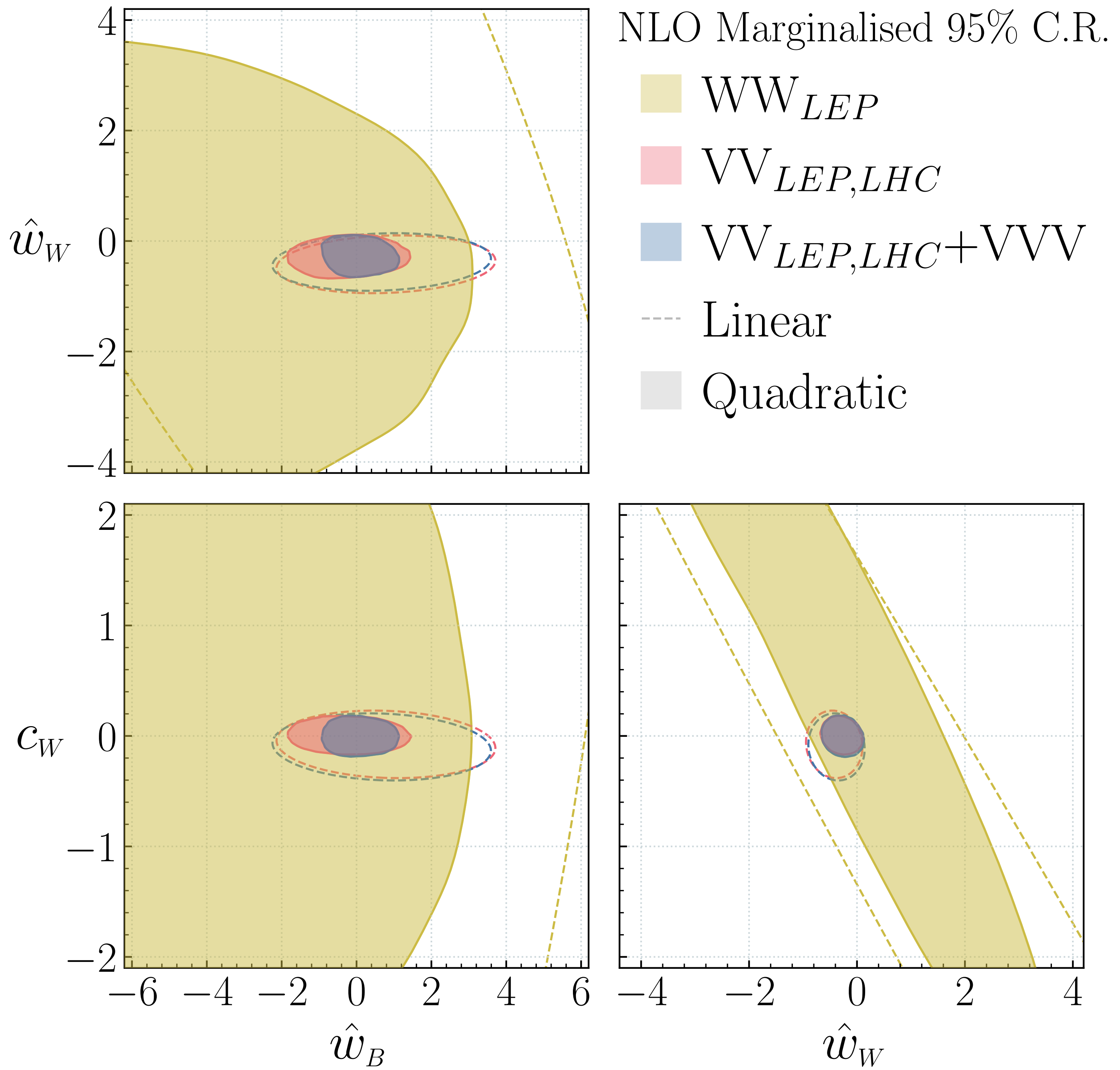
2 possible origins of the improvement

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

Where do VV & VVV help?

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

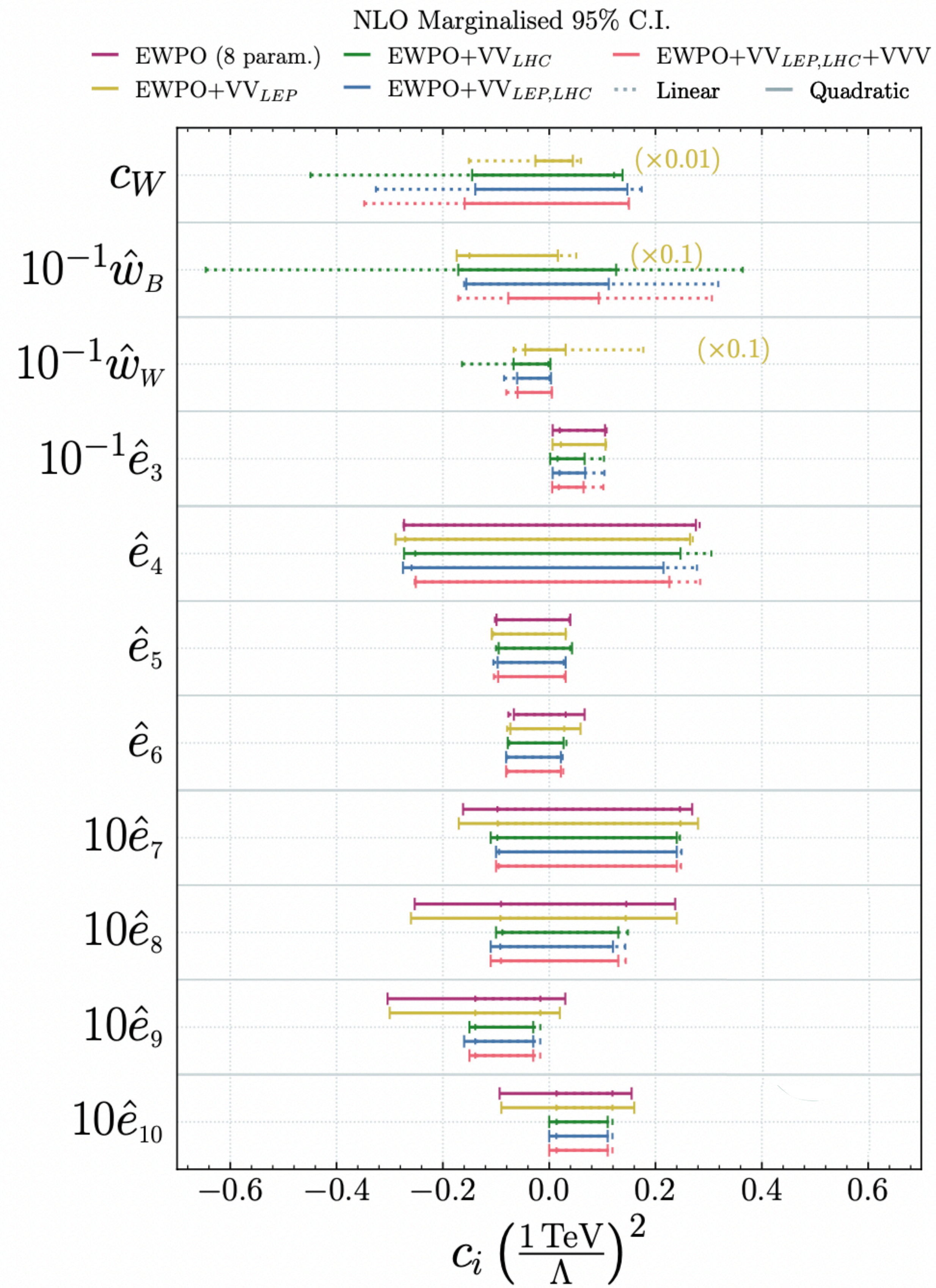


[EC, Durieux, Mimasu, Vryonidou; to appear]

What about the other directions?

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

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



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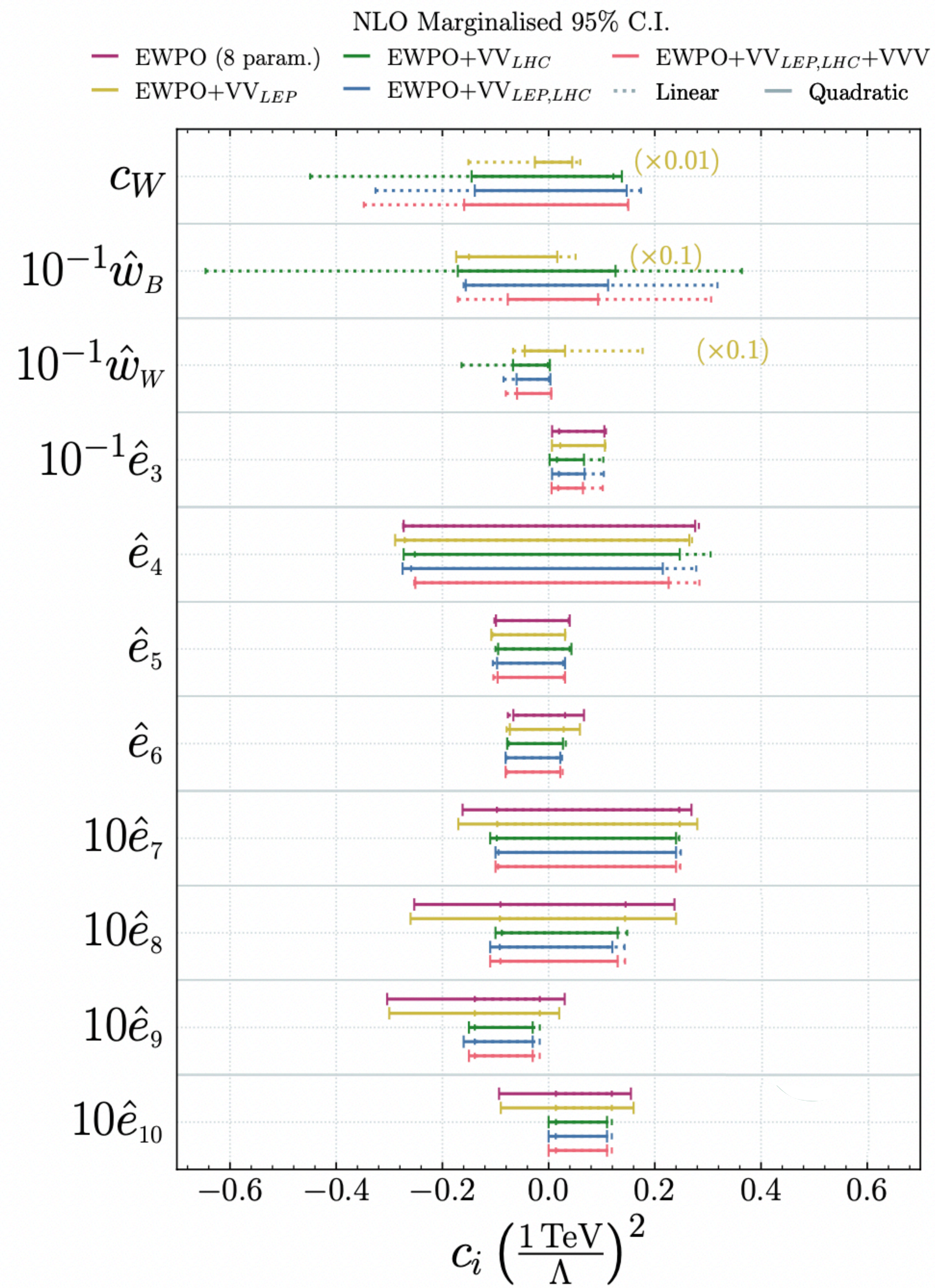
- mild improvement from quadratics (even EWPOs) on some directions



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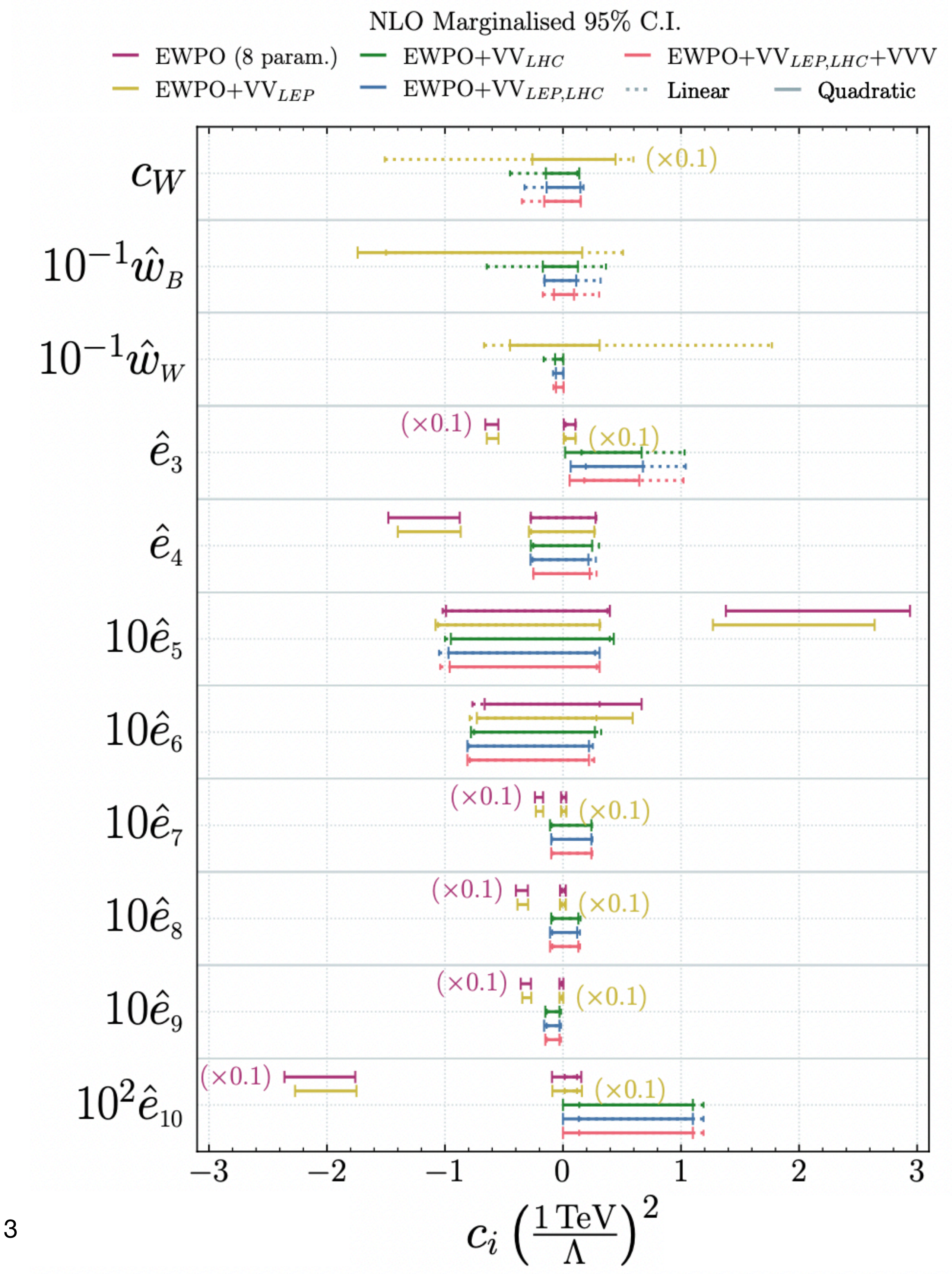
- mild improvement from quadratics (even EWPOs) on some directions
- secondary minima in EWPOs+LEP VV lifted by LHC VV

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



Summary & conclusions

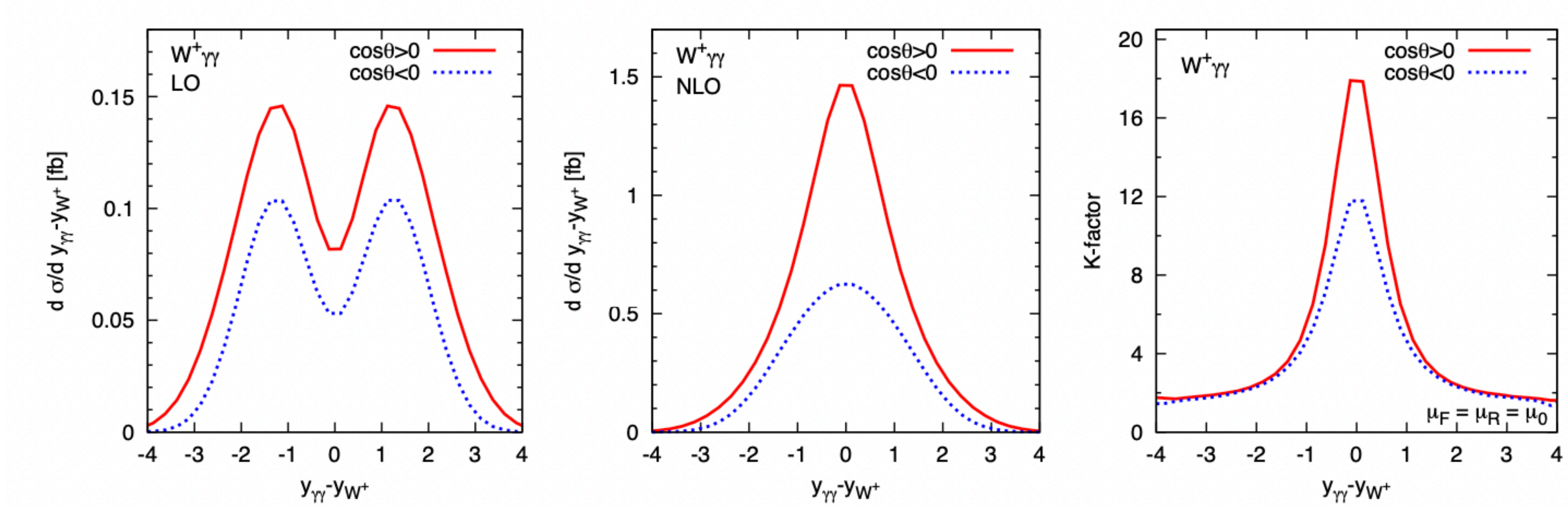
- QCD corrections have significant impact in LHC VV&VVV
- Quadratic EFT contributions are sizeable for all the processes, from EWPO leading to secondary minima, to LEP diboson, and the LHC VV&VVV
- Triboson already improves electroweak SMEFT reach beyond EWPOs and diboson (improvement in EWPOs blind space)

Backup

Giant SM K-factors

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

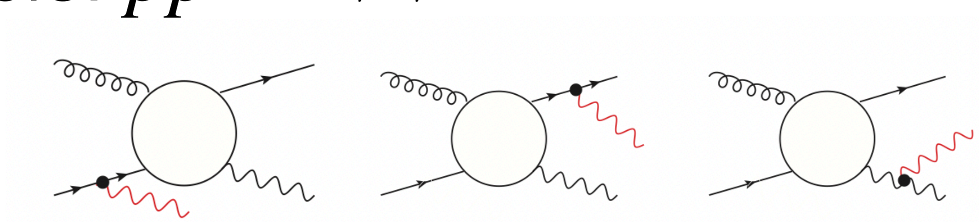
- partial LO cancellation between qq-induced amplitudes
- no cancellation in qg-channels (dominating the NLO cross section)



[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: $pp \to VV$



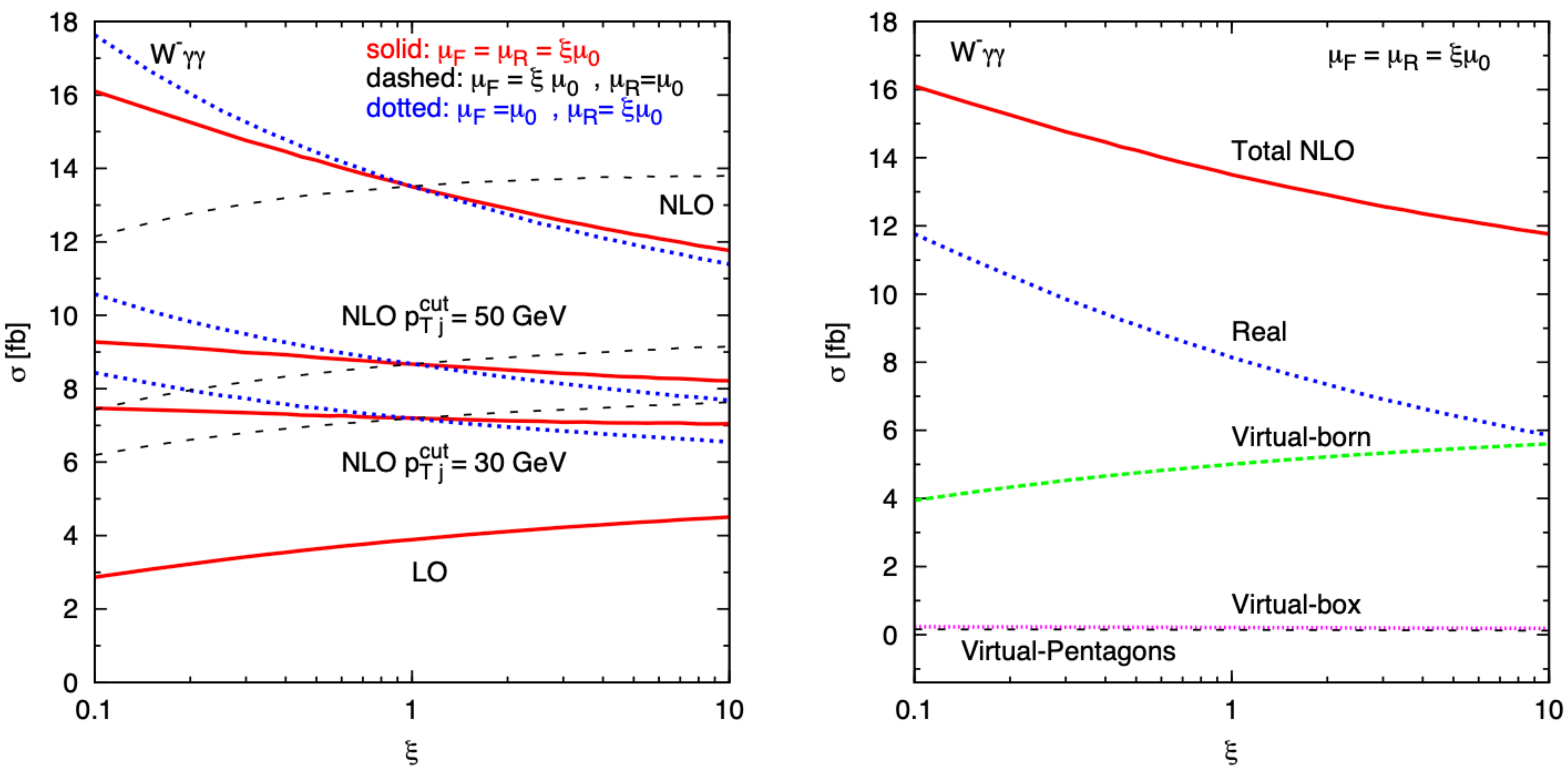
$$\frac{d\sigma^{V(V)j}}{d\sigma^{\mathrm{LO}}_{VV}} \propto \alpha_{\mathrm{S}} \log^2\left(\frac{Q^2}{M_W^2}\right)$$

[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



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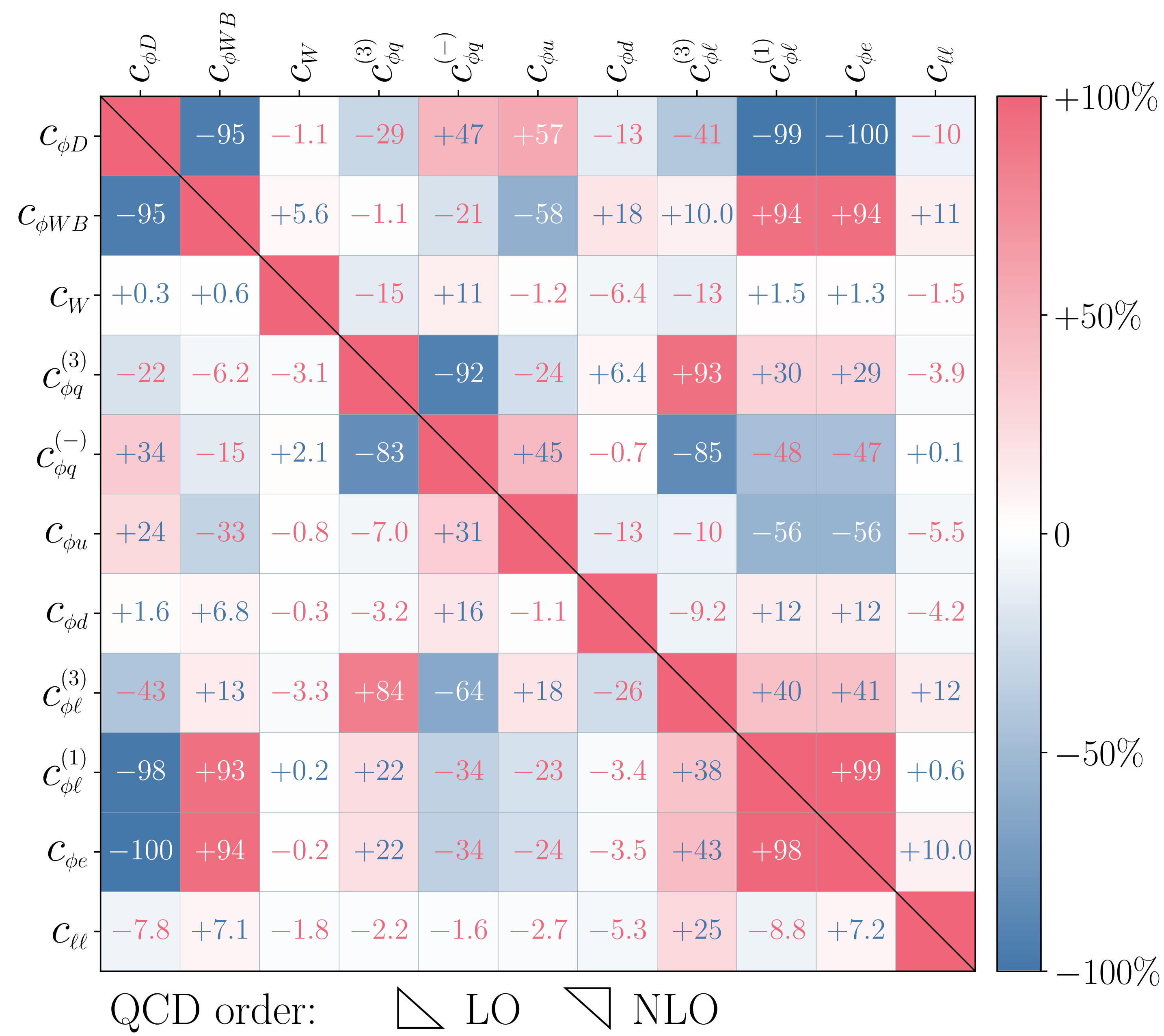
LO vs NLO: correlation matrix

EWPO+VV+VVV fit

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



LO vs NLO: posteriors

LO bounds are better than NLO

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