Triboson production in the SMEFT

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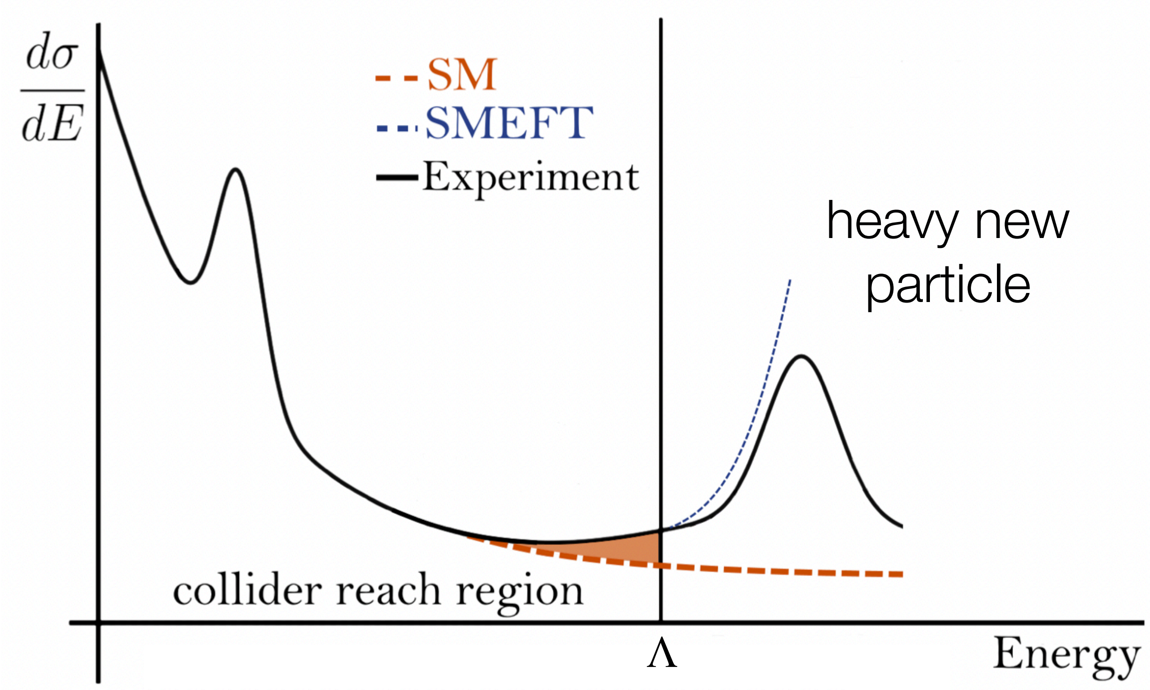
The SMEFT



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

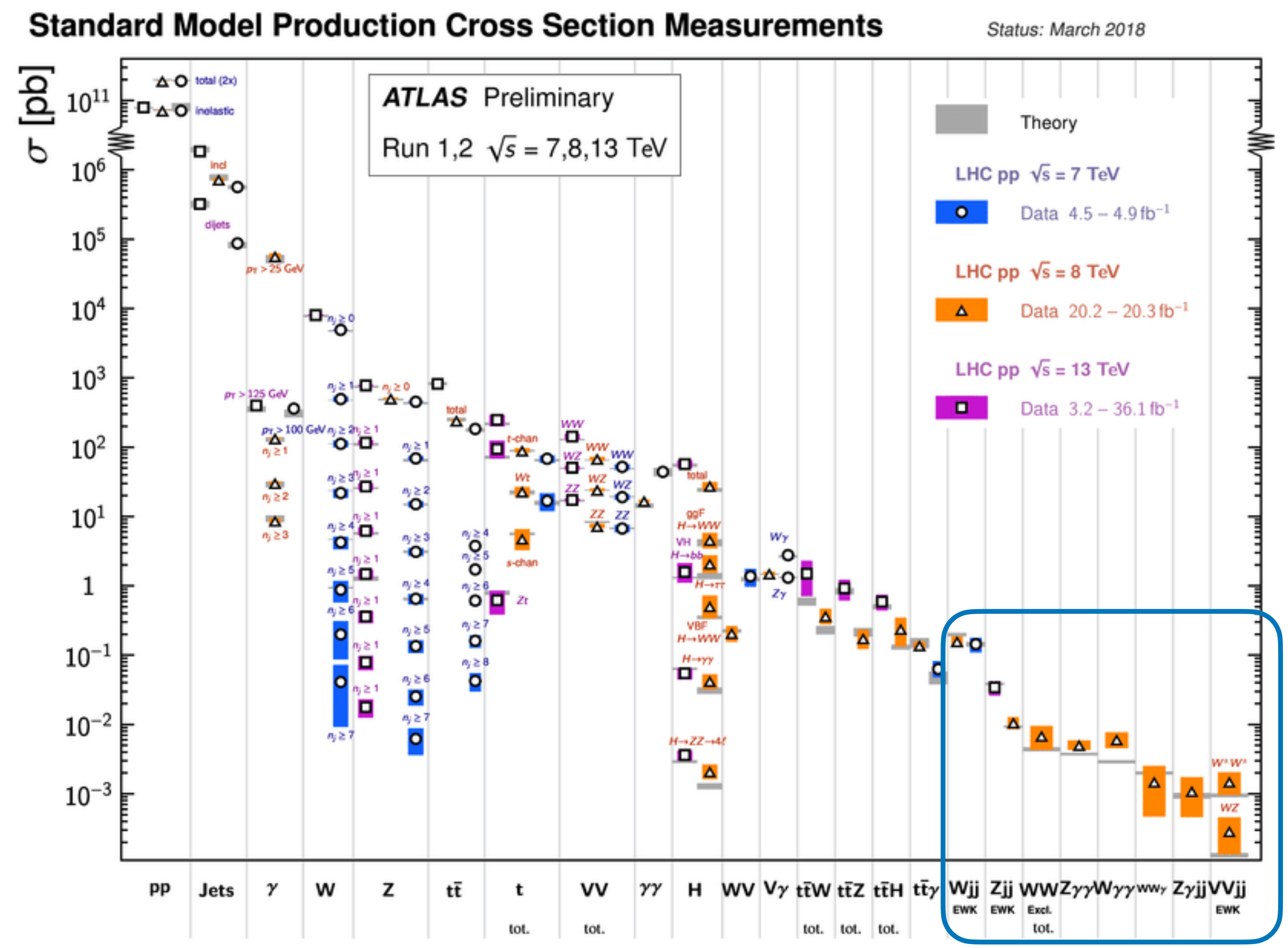
Dimension-6 operators Warsaw basis

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

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

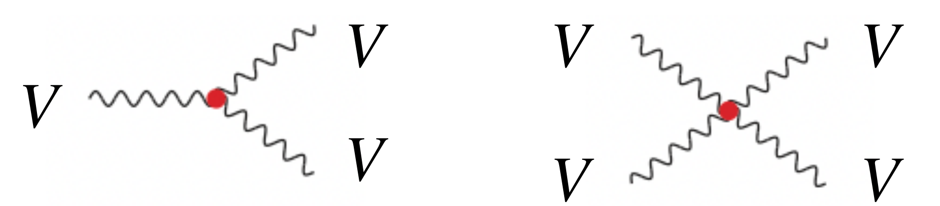
Triboson production at the LHC

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



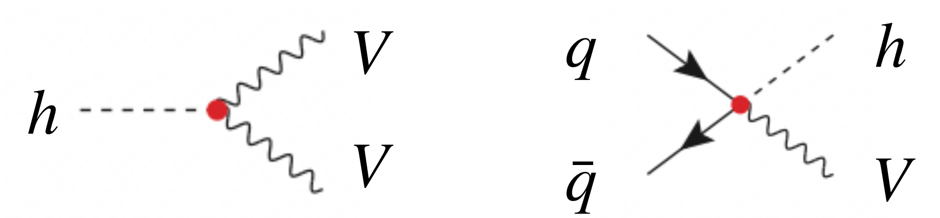
Why triboson?

- Tree-level access to TGC and QGC



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

- Interplay with the Higgs sector



[Falkowski et al.; JHEP 04 (2021) 023]

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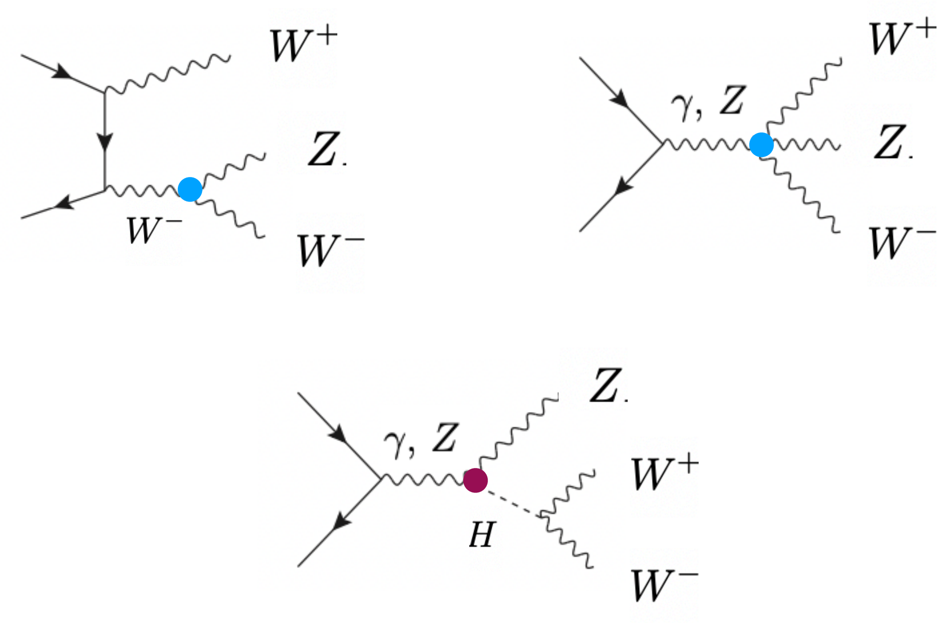
$pp \to W^+W^-Z$



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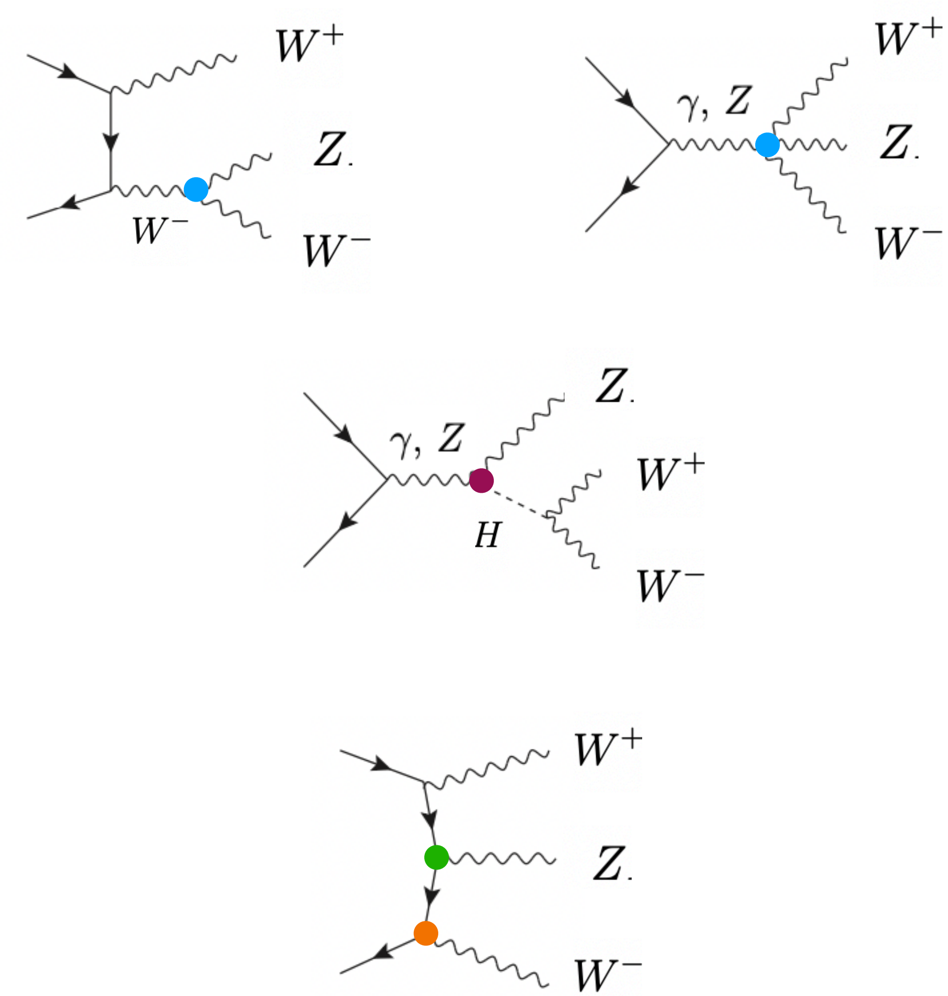

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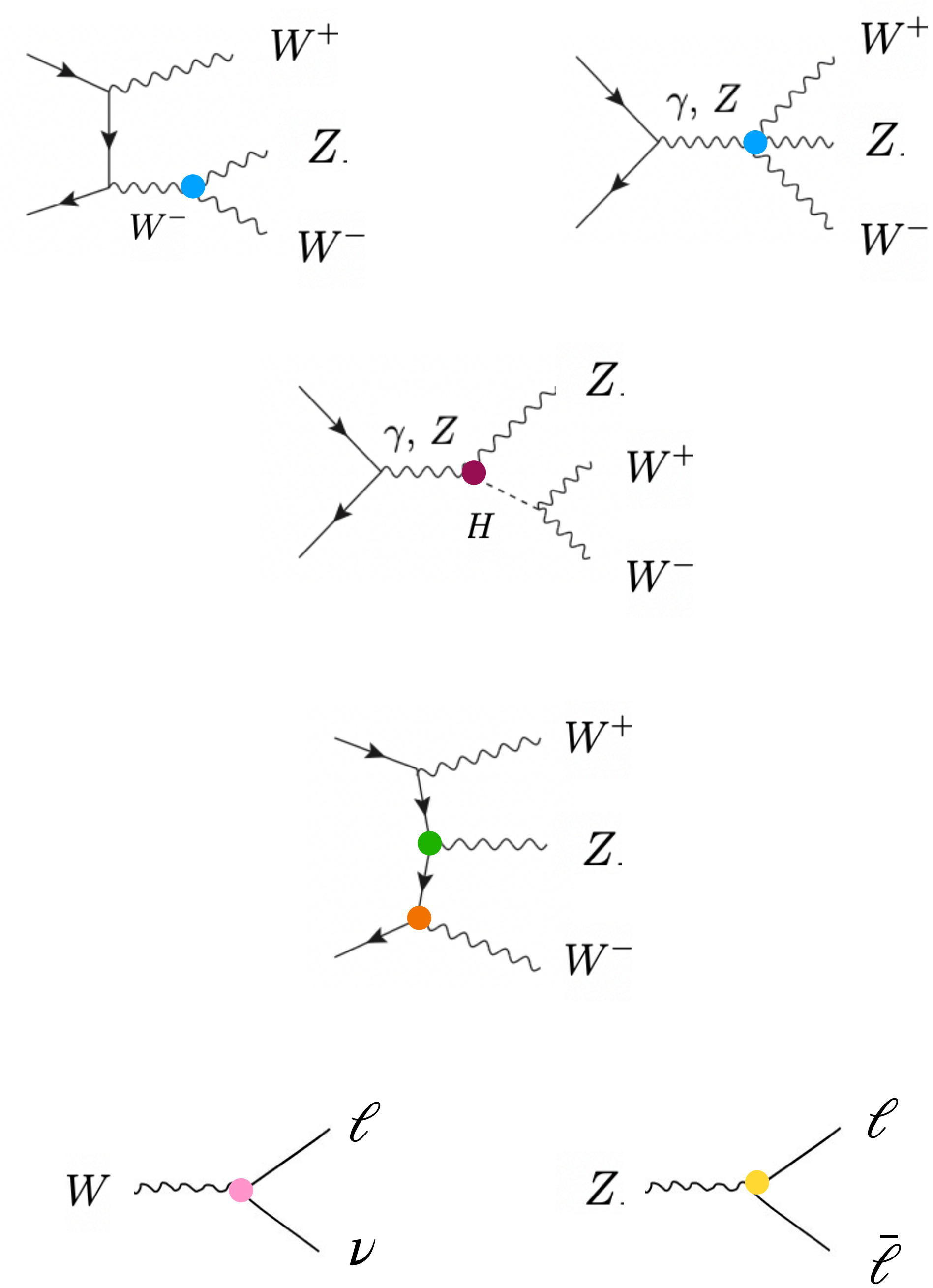

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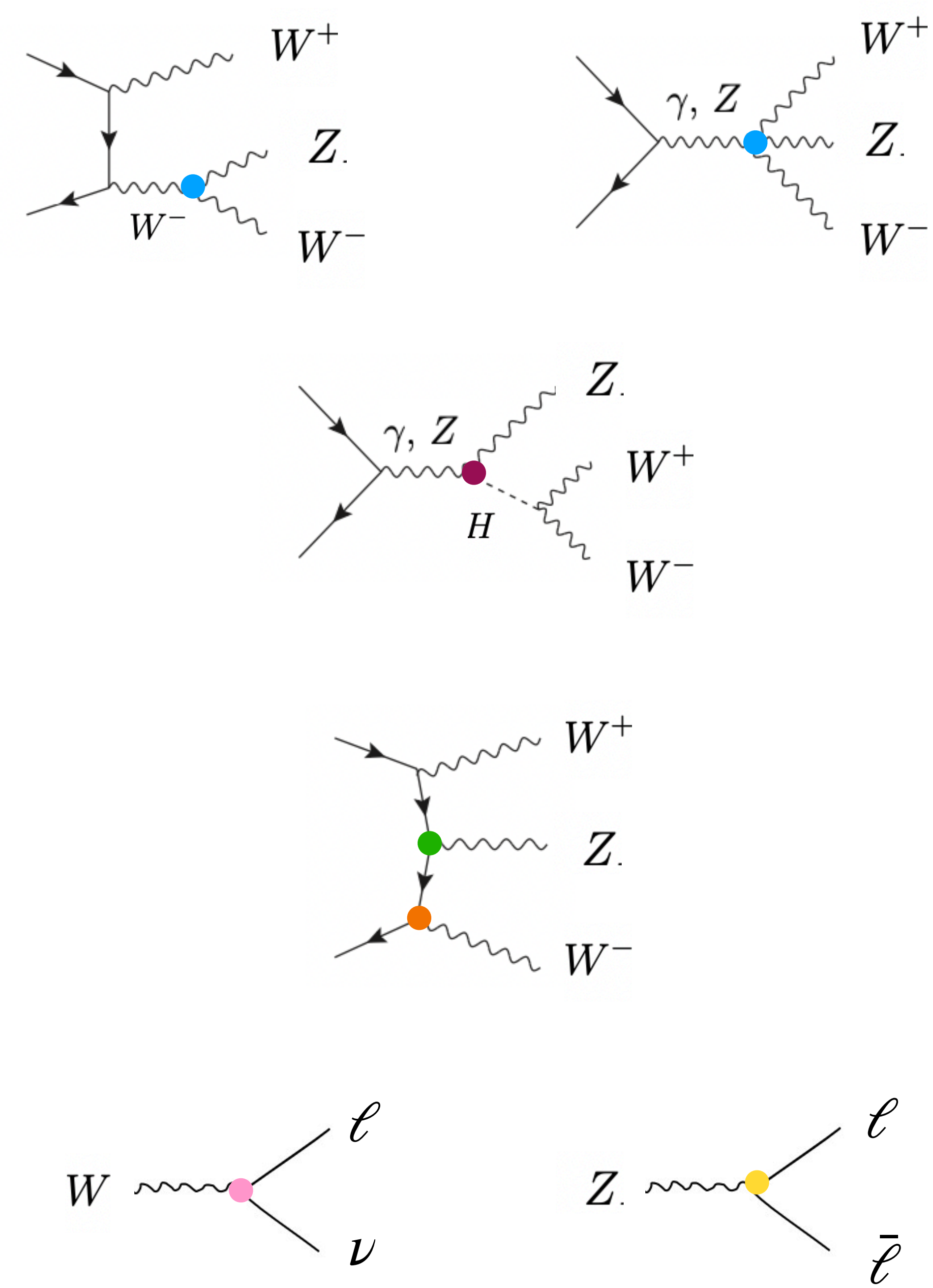


[EC, Durieux, Mimasu, Vryonidou; to appear]

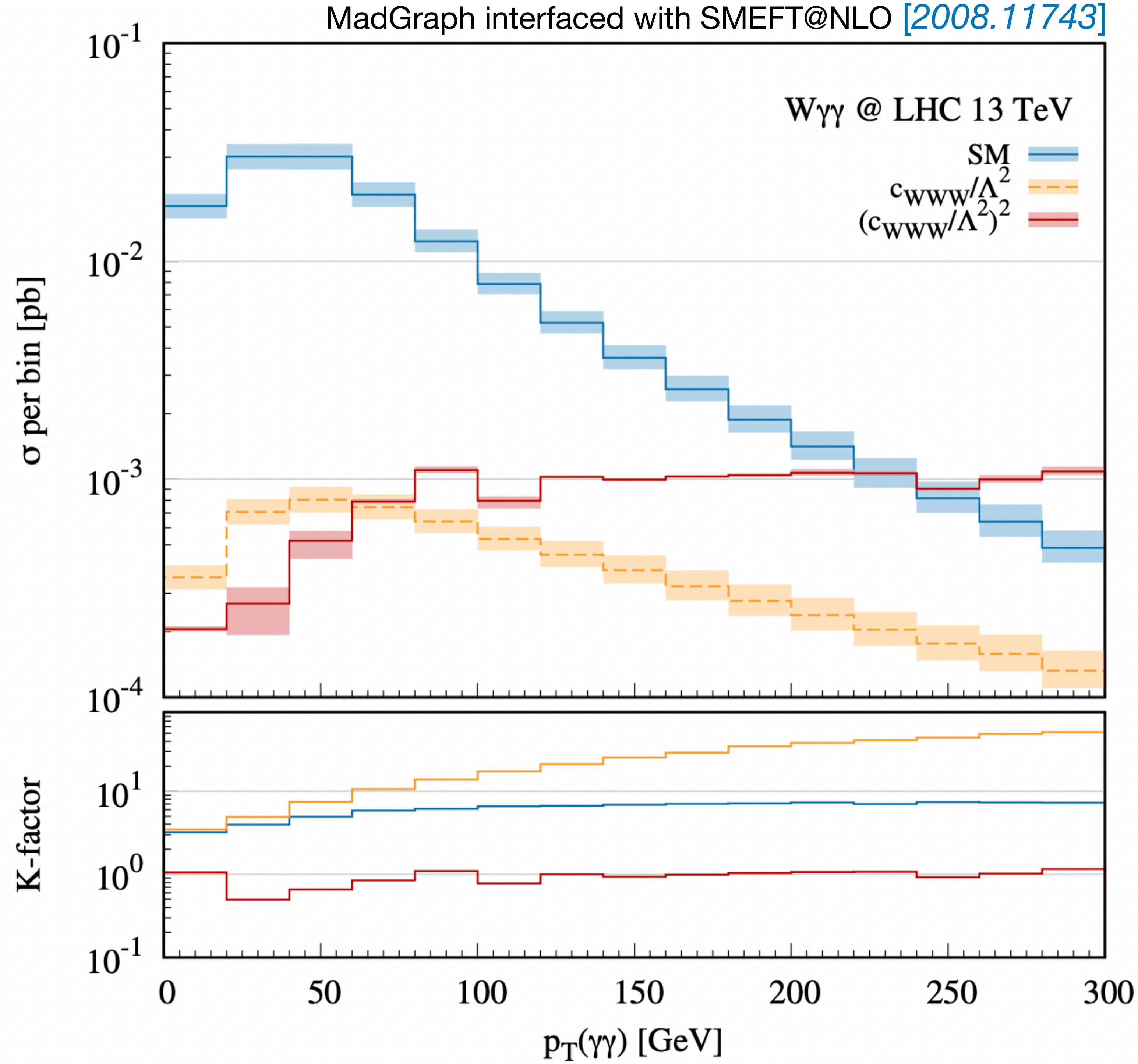
Going NLO

NLO QCD corrections are large in triboson processes [Degrande et al.; 2008.11743]

$W\gamma\gamma$	
$\sigma(\text{fb})$	K-factor
$\sigma_{\rm SM}$	4.84
$\sigma_{\phi D}$	4.86
$\sigma_{\phi D,\phi D}$	4.86
$\sigma_{\phi WB}$	4.70
$\sigma_{\phi WB,\phi WB}$	1.47
σ_{WWW}	$\boxed{12.24}$
$\sigma_{WWW,WWW}$	0.79
$\sigma_{\phi\ell^{(3)}}$	4.85
$\sigma_{\phi\ell^{(3)},\phi\ell^{(3)}}$	4.85
$\sigma_{\phi q^{(3)}}$	4.80
$\sigma_{\phi q^{(3)},\phi q^{(3)}}$	4.80
$\sigma_{\ell\ell}$	4.82
$\sigma_{\ell\ell,\ell\ell}$	4.82

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

MadGraph interfaced with SMEFT@NLO [2008.11743]



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

Operators and observables

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

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

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

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

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

[LEP; 1302.3415]

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

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

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

$\dfrac{d\sigma}{d\Delta\phi_{jj}}(Zjj \to \ell\ell jj)$ [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]

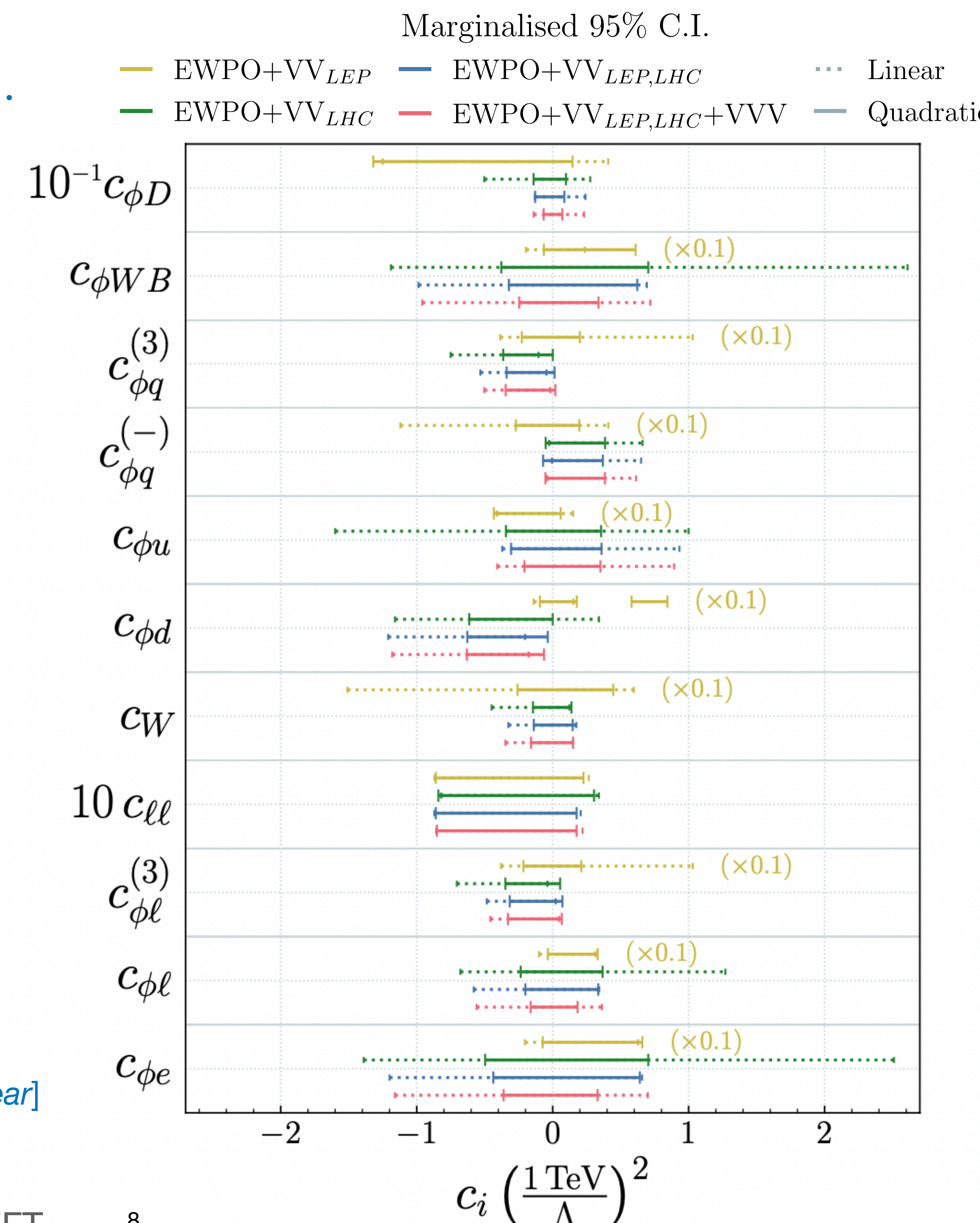
Operators and observables

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; 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 $c_{\phi D}\,,c_{\phi WB}\,,c_{\phi\ell}\,,c_{\phi e}$
- Bounds dominated by quadratic

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

Interpretation

- Three EWPOs unconstrained directions: $w_B, w_W + c_W$

$$g_1^2\, w_B = g_1^2 \frac{\bar{v}_T^2}{\Lambda^2}\left(-\frac{1}{3}C_{Hd} - C_{He} - \frac{1}{2}C_{Hl}^{(1)} + \frac{1}{6}C_{Hq}^{(1)} + \frac{2}{3}C_{Hu} + 2C_{HD} - \frac{1}{2t_{\hat{\theta}}}C_{HWB}\right),$$

$$g_2^2\, w_W = g_2^2 \frac{\bar{v}_T^2}{\Lambda^2}\left(\frac{C_{Hq}^{(3)} + C_{Hl}^{(3)}}{2} - \frac{t_{\bar{\theta}}}{2}C_{HWB}\right).$$

[Brivio and Trott; 1701.06424]

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

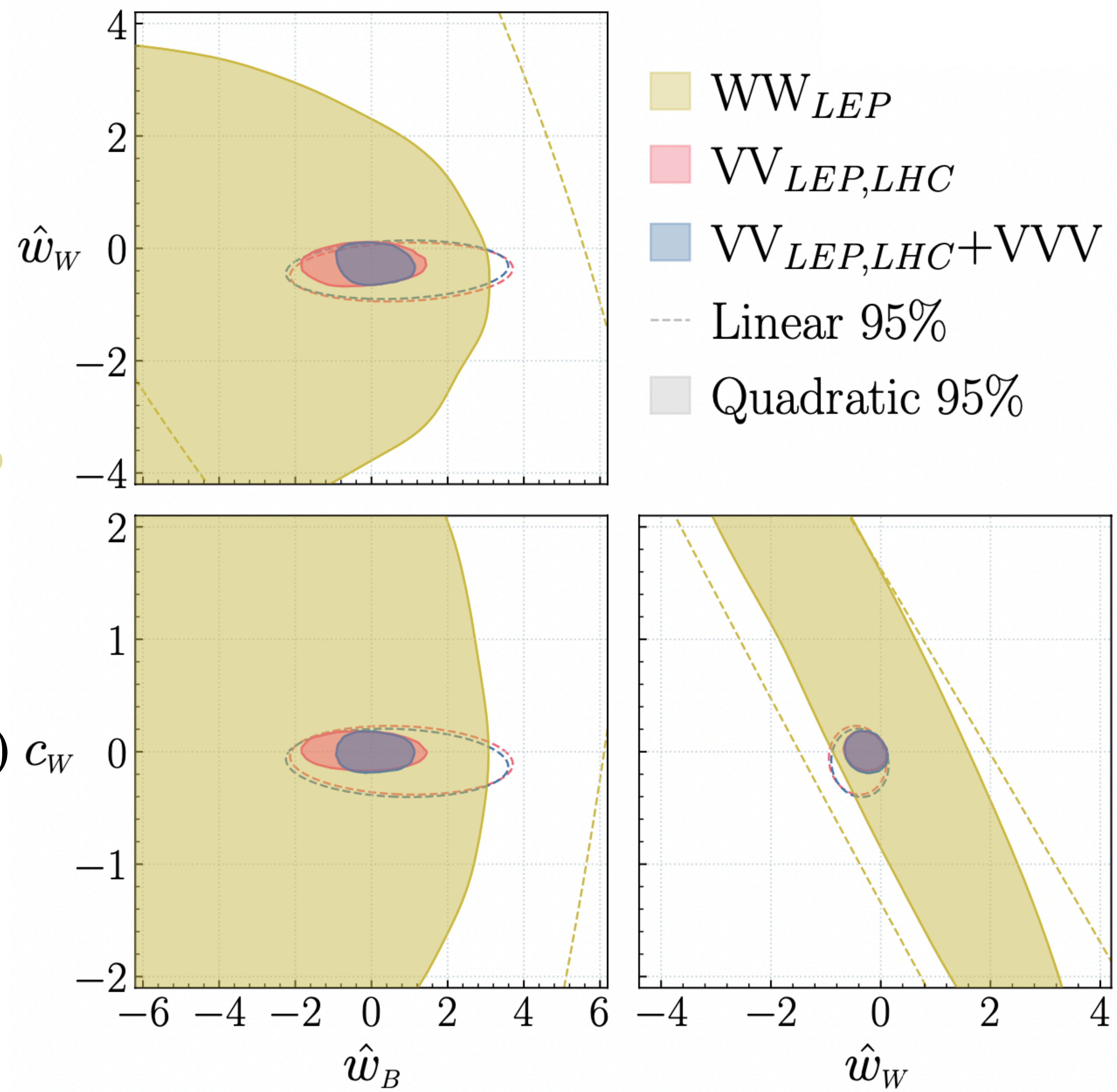
2 possible origins of the improvement

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

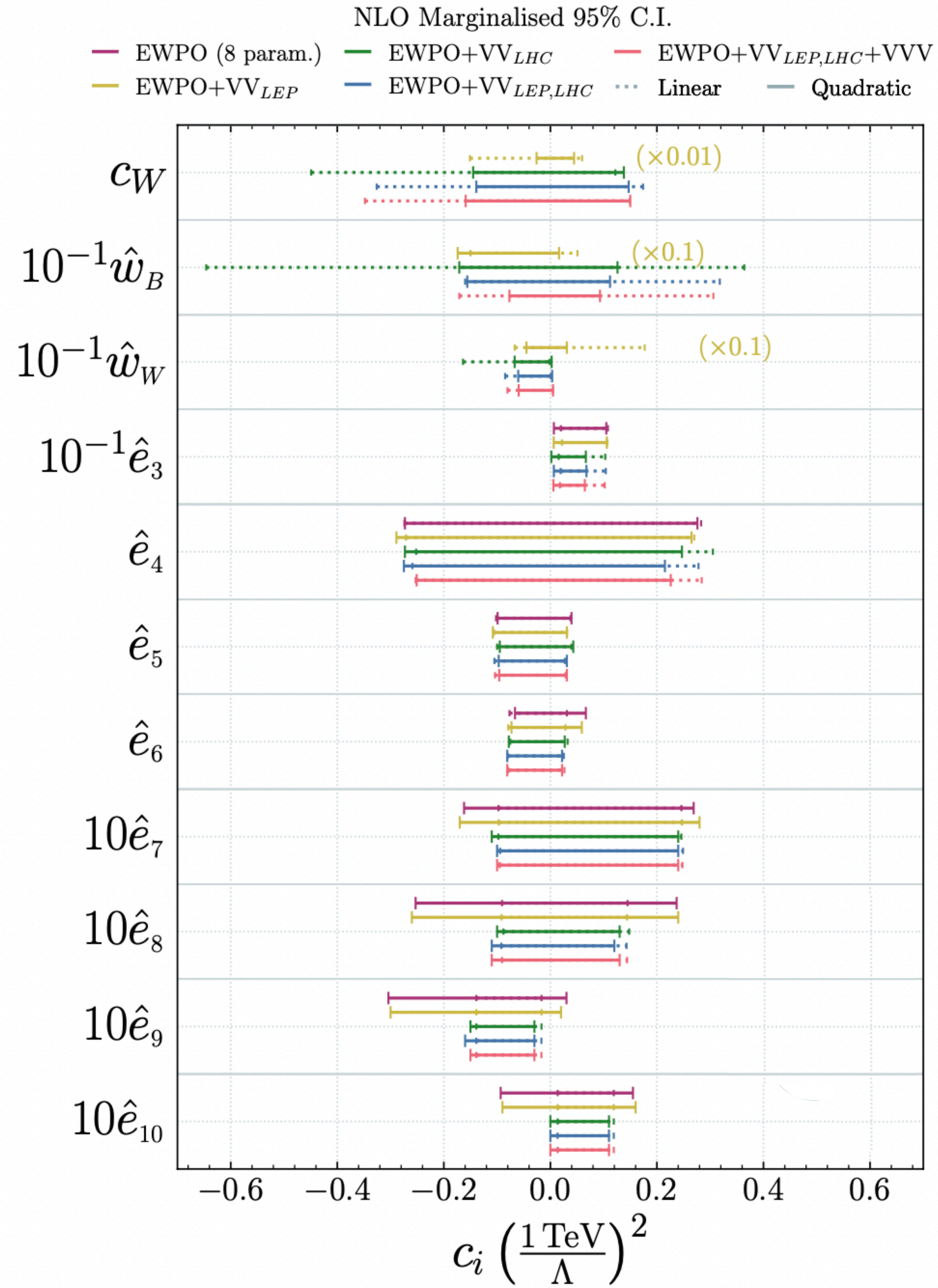


[EC, Durieux, Mimasu, Vryonidou; to appear]

What about the other directions?

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

- in general, EWPOs constraints are dominant



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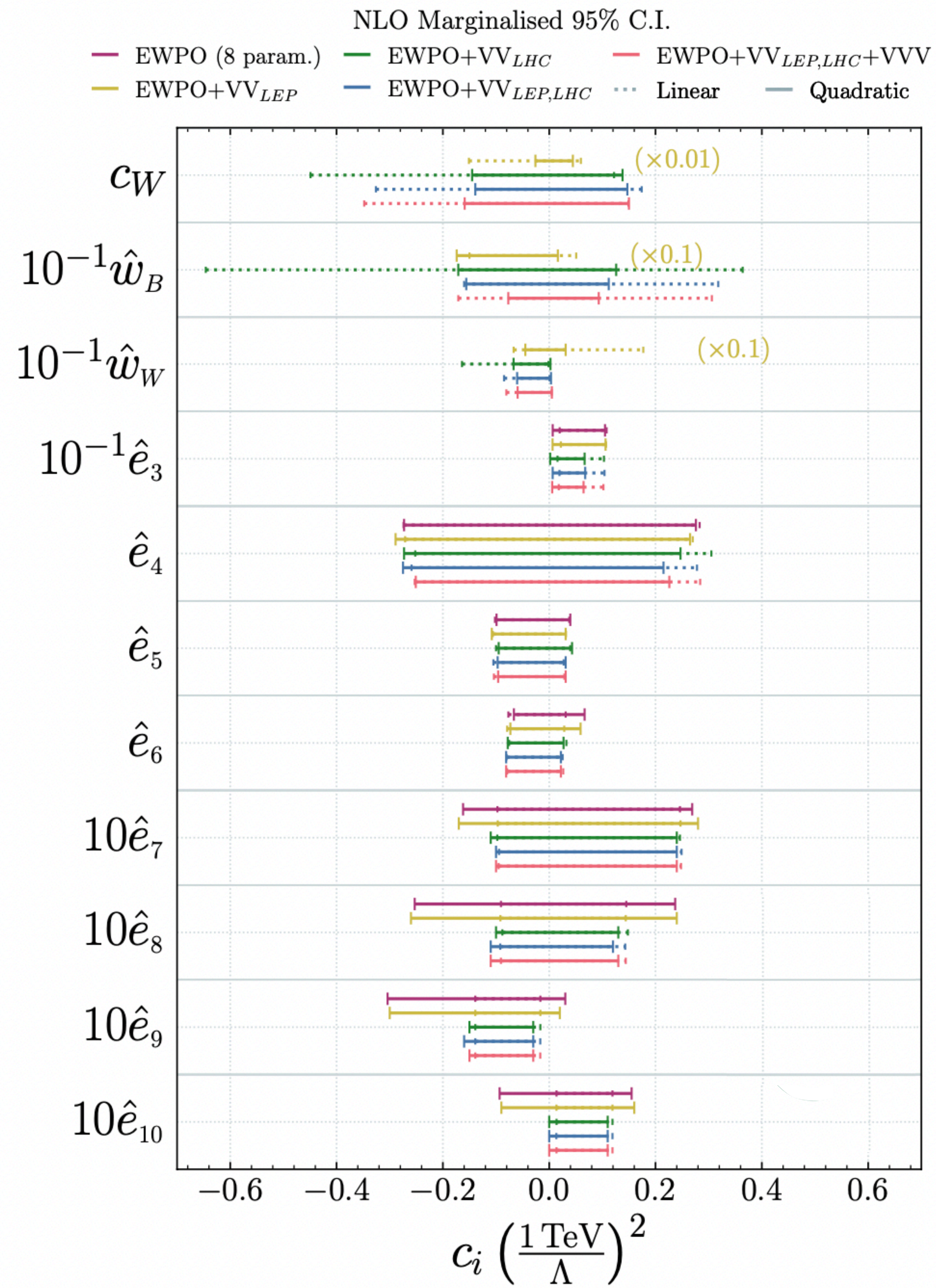
- mild improvement from quadratics (even EWPOs) on some directions



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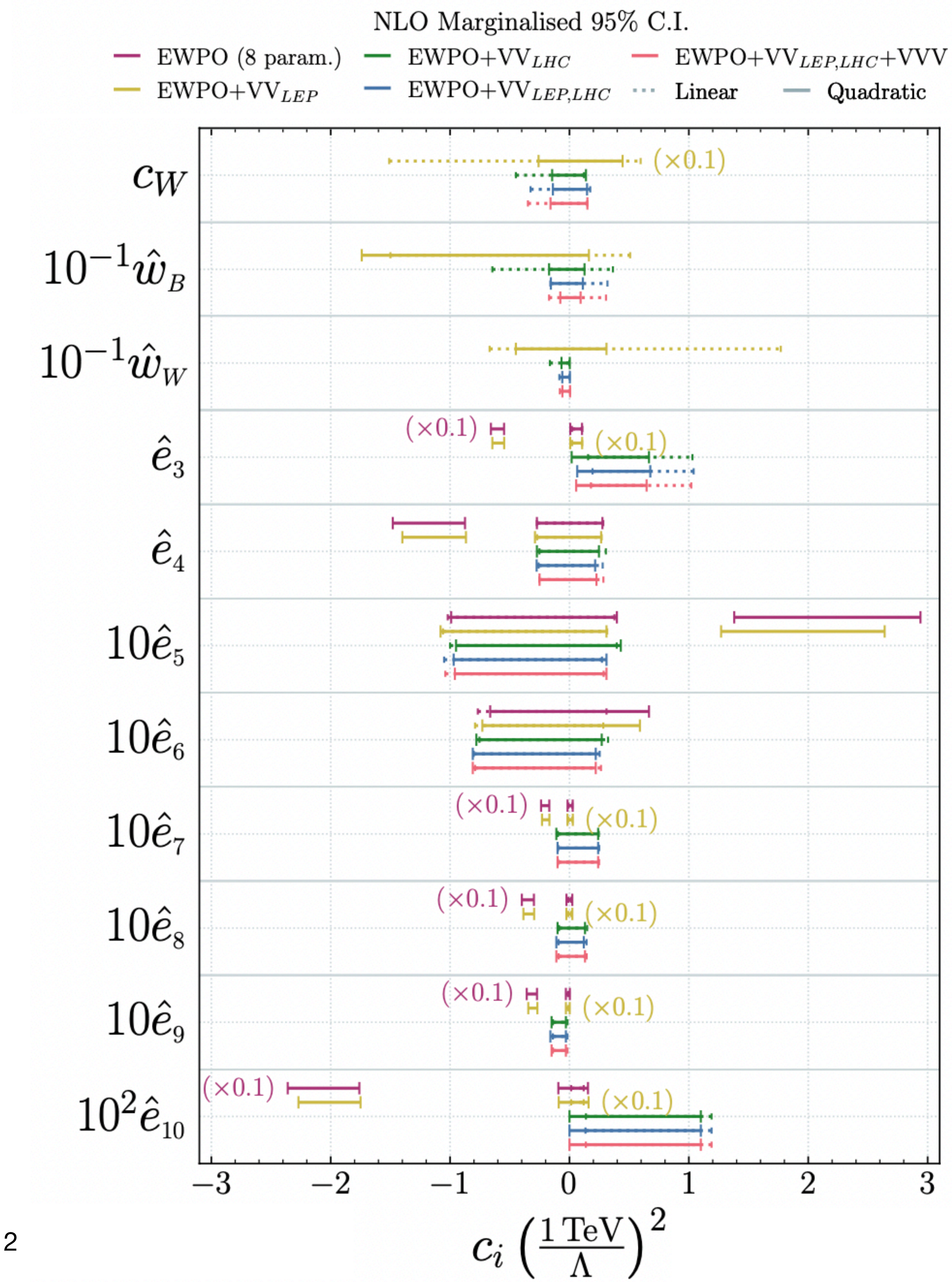
- in general, EWPOs constraints are dominant
- mild improvement from quadratics (even EWPOs) on some directions
- secondary minima in EWPOs+LEP VV lifted by LHC VV

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



Summary & conclusions

- QCD corrections have significant impact in LHC VV&VVV
- Multiboson production is complementary to EWPOs: triboson improves the bounds in EWPOs flat space
- Quadratic EFT contributions are sizeable for all the processes, from EWPO leading to secondary minima, to LEP diboson, and the LHC VV&VVV