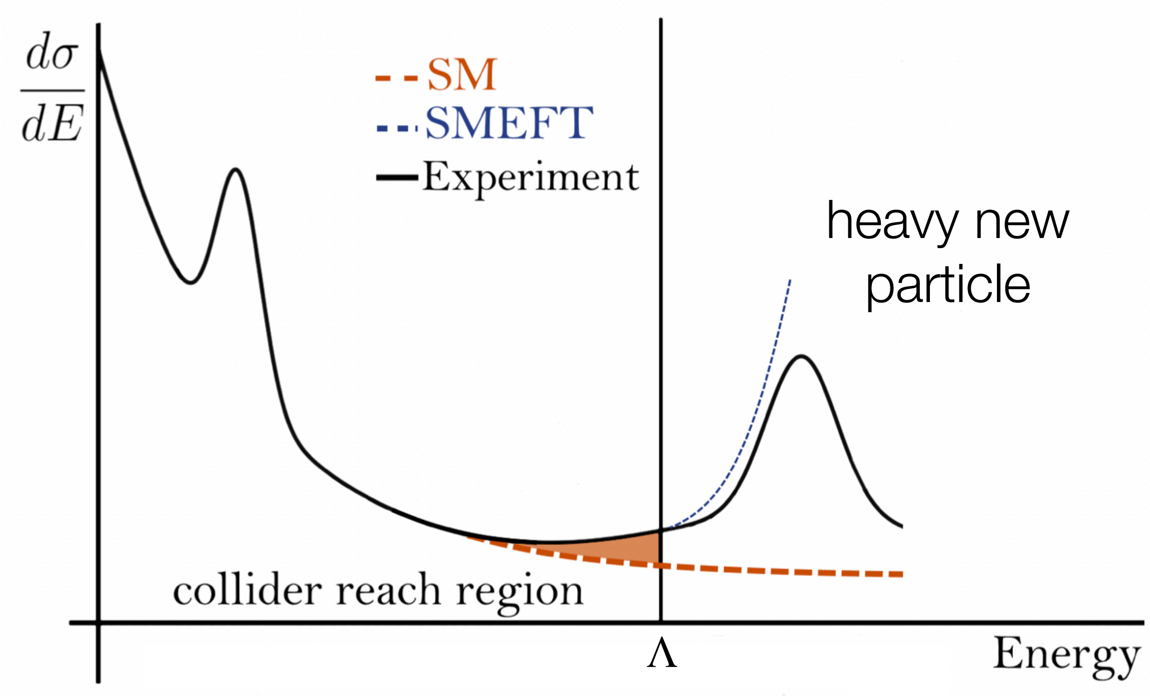
SMEFT predictions for triboson

Based on a work with Gauthier Durieux, Ken Mimasu, Eleni Vryonidou

Joint WG1+WG3 meeting on triple vector-boson production,
COMETA COST action,
10/04/24

Eugenia Celada
University of Manchester

The SMEFT



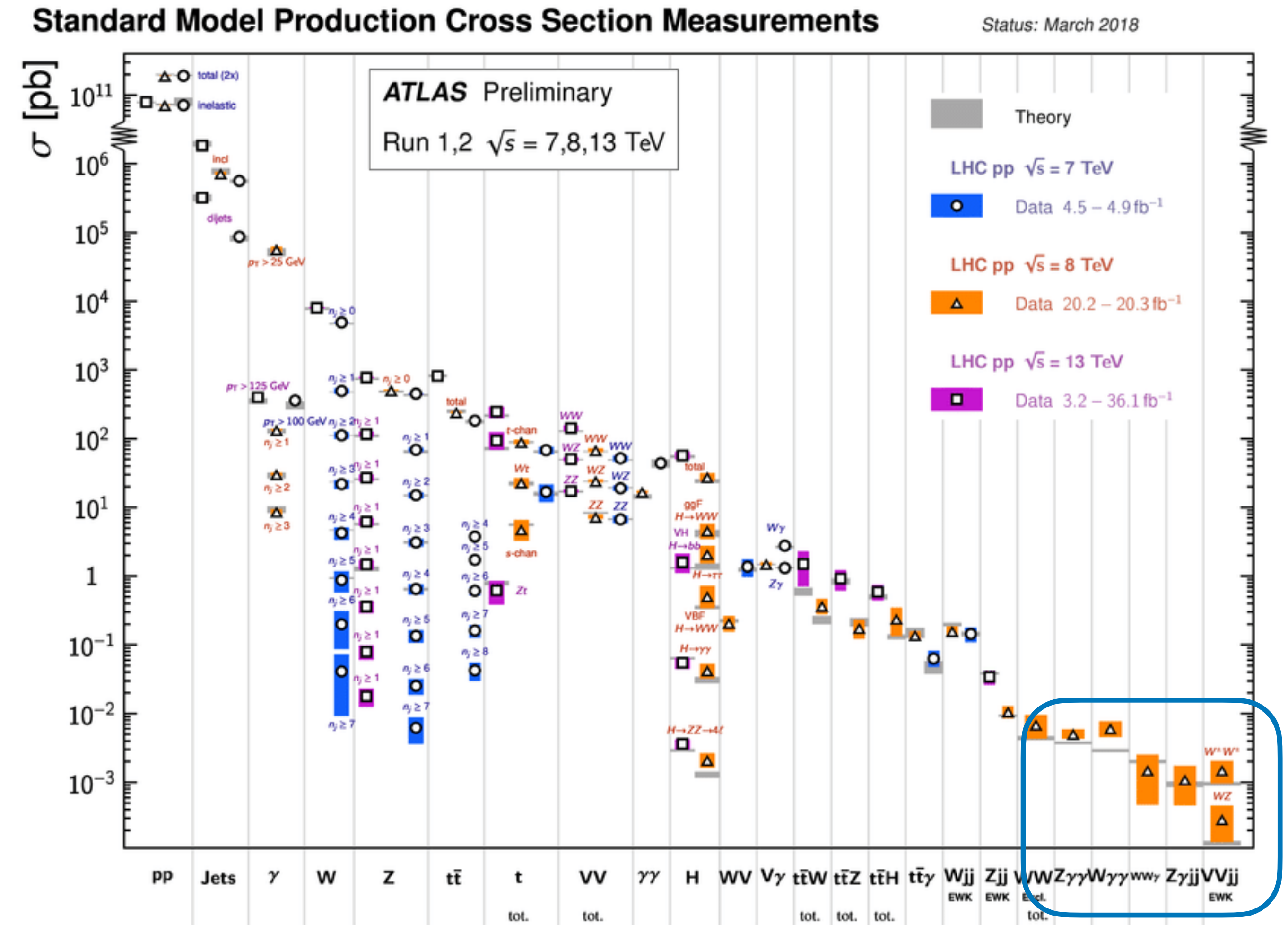
Original fig. by C. Severi, M. Thomas, E. Vryonidou

Dimension-6 operators Warsaw basis

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

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

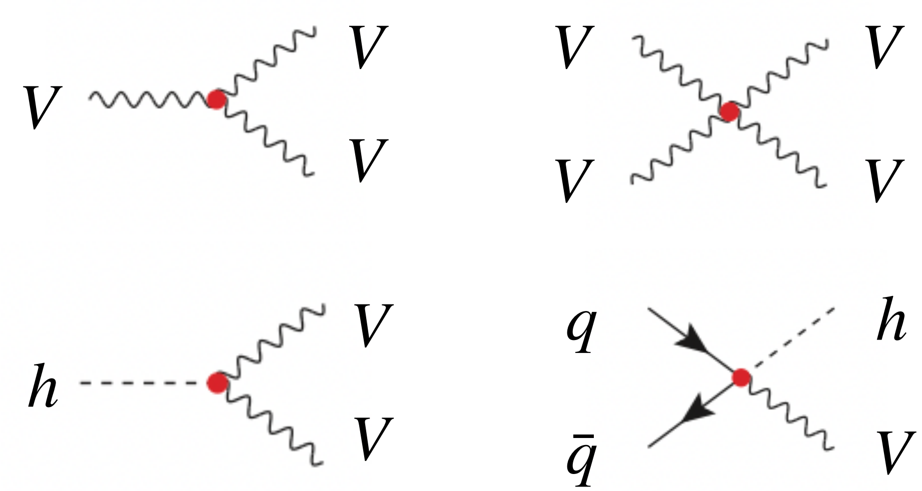
Triboson production at the LHC



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

Why triboson?

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



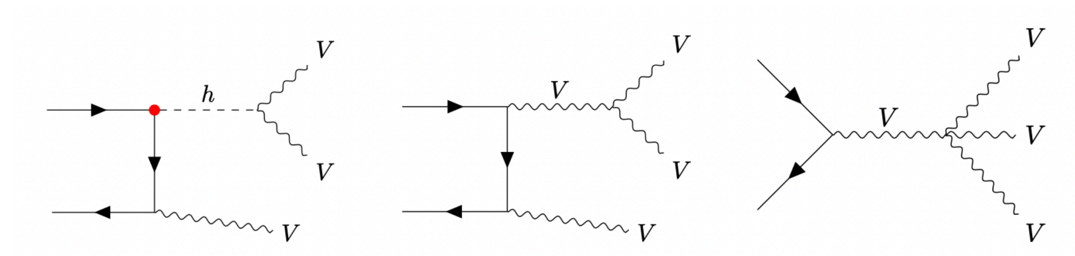
What information?

Sensitivity to light quark Yukawa in longitudinal VVV production

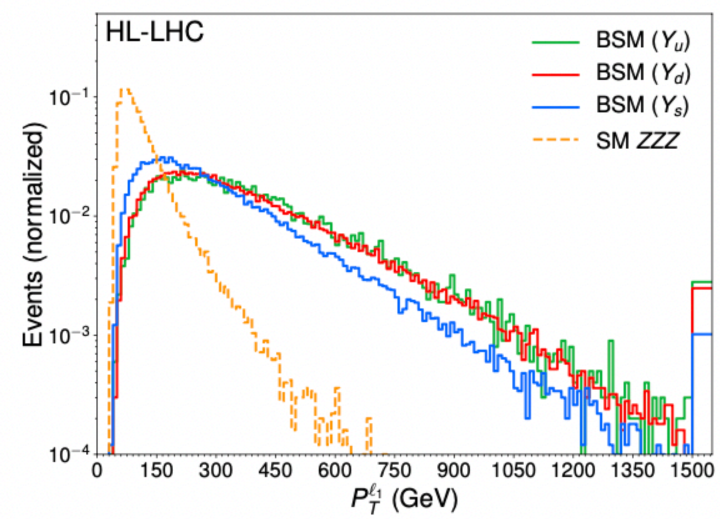
[Falkowski et al.; 2011.09551]

- off-shell Higgs production in WWW and ZZZ

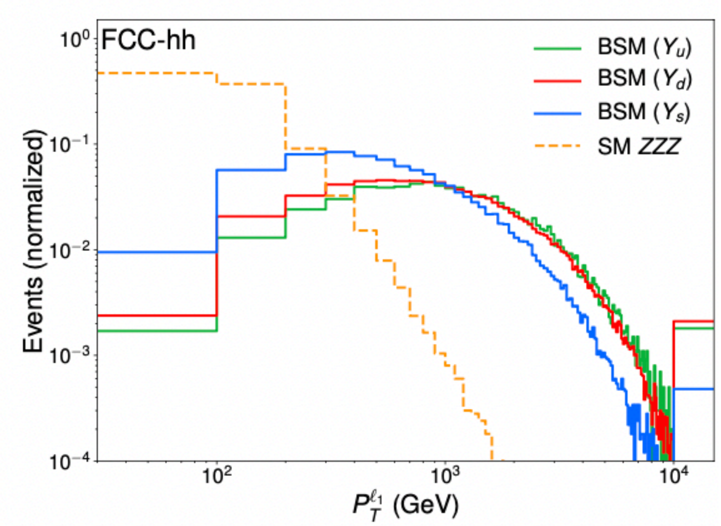
$$\mathcal{L} \supset -\frac{h}{v} \sum_{q=u,d,s} m_q (1+\delta y_q) \bar{q} q \qquad \boxed{\delta y_q = -\frac{Y_q}{y_q^{\rm SM}}}$$



- 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



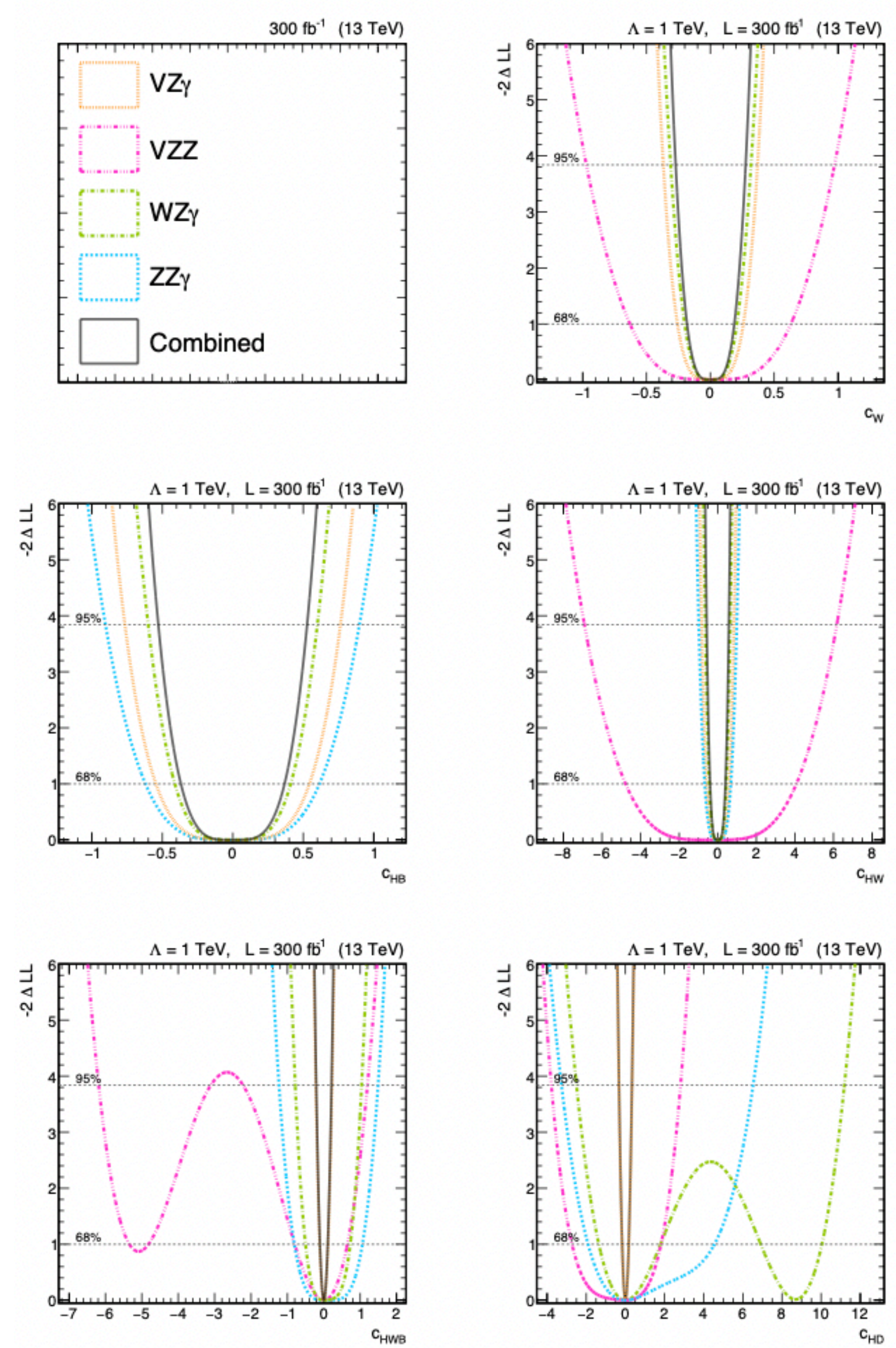
What information?

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]



Triboson in global fits

- Triboson is sensitive to a variety of anomalous effects
- Sensitivity studies are promising compared to other probes
- … time to go global!
- We incorporate triboson in a global EW fit

What's triboson constraining power?

Any 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	
$\mathcal{O}^{(1)}_{\phi q}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{q}\gamma^\mu q)$
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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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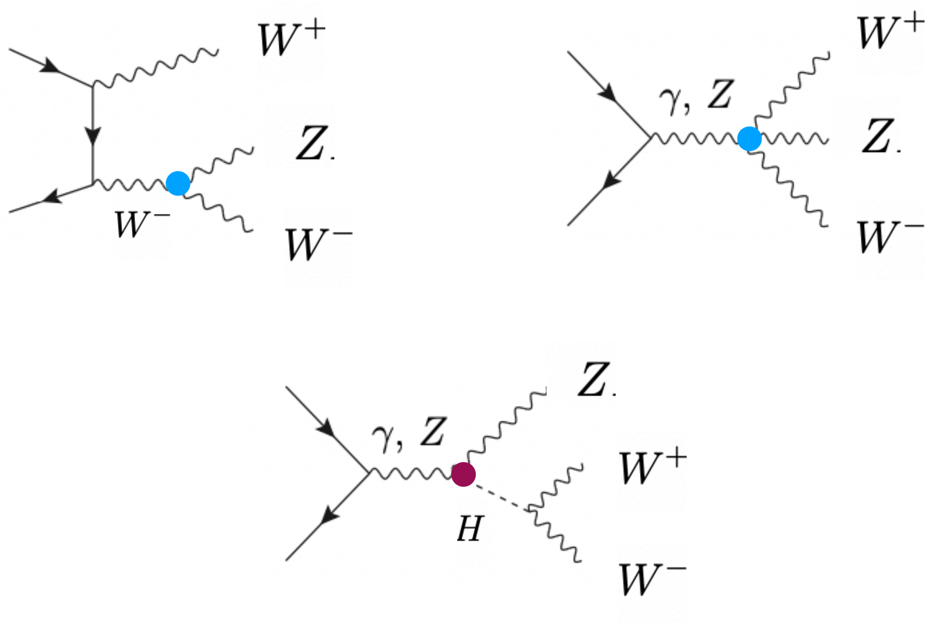
$$pp \to W^+W^-Z$$



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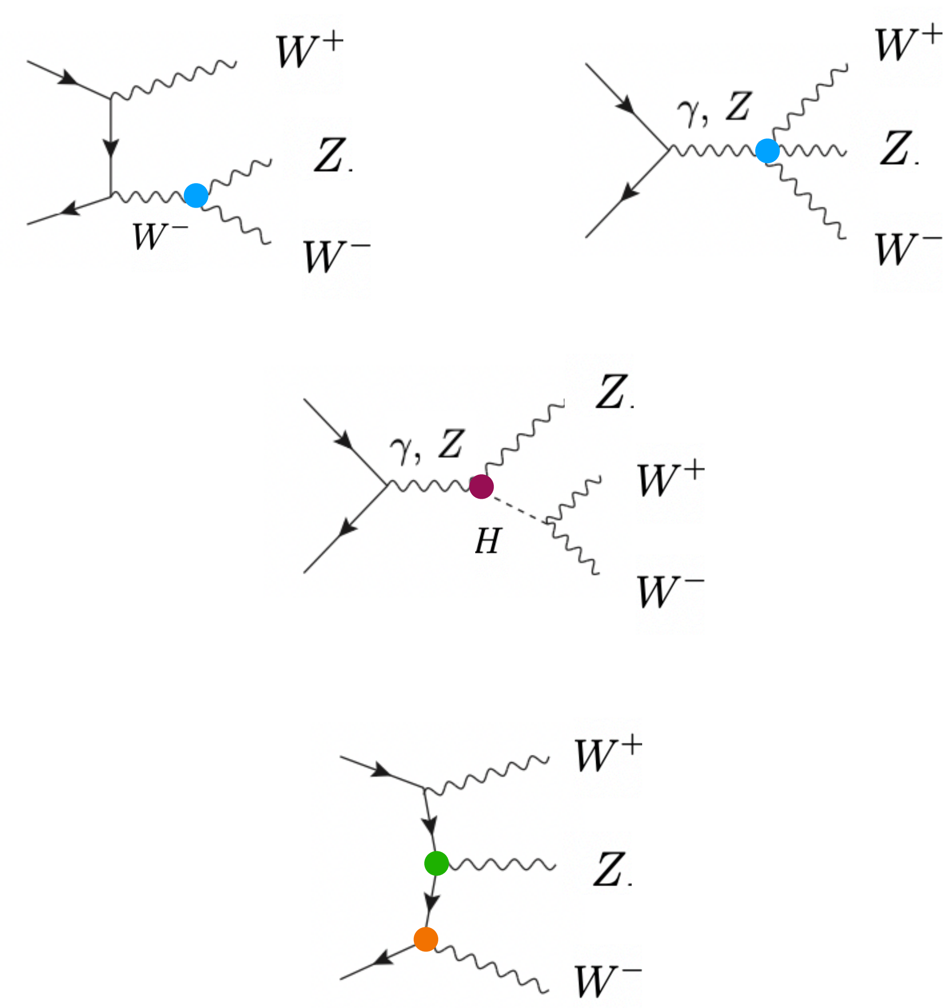

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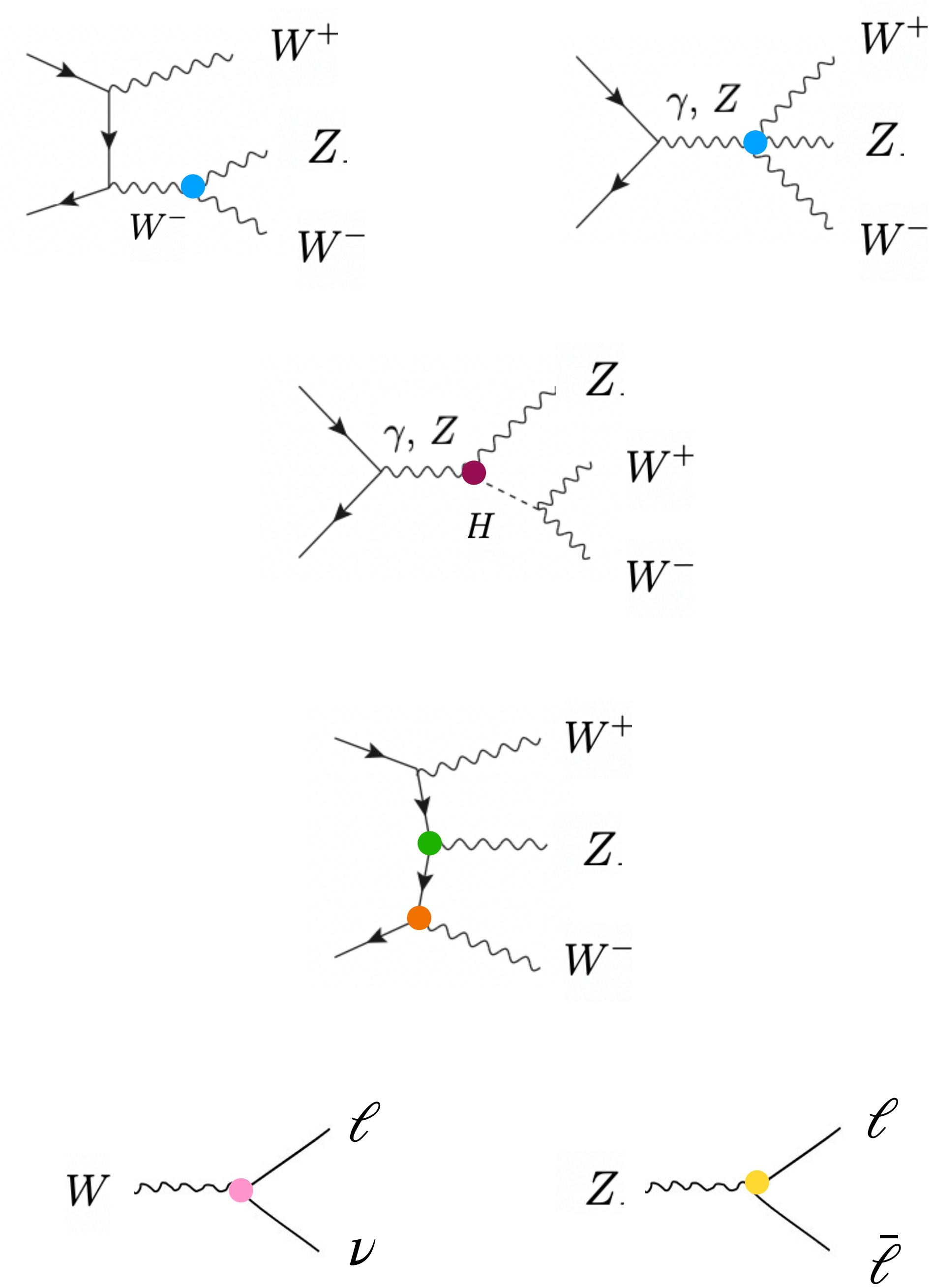

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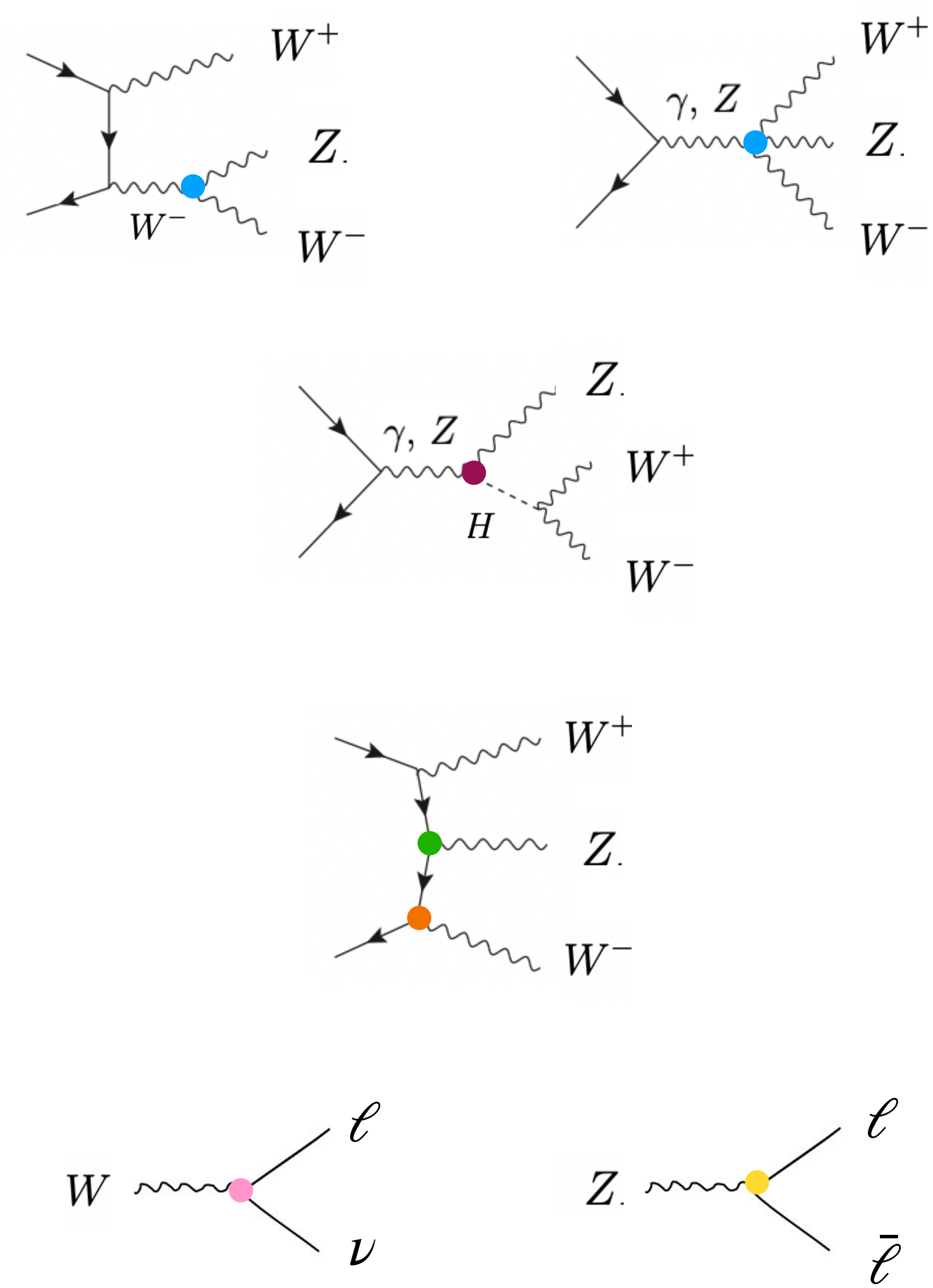
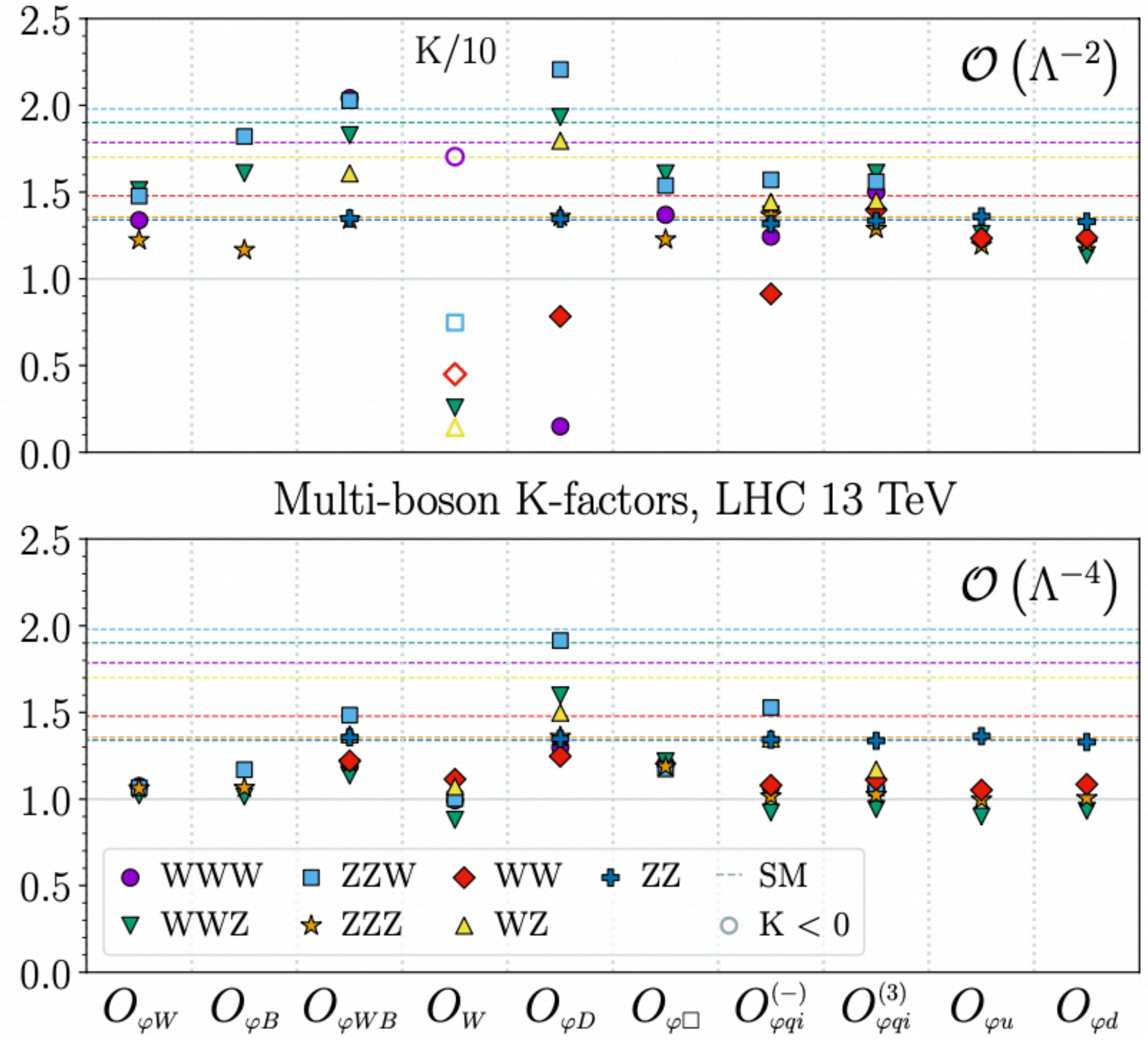


[EC, Durieux, Mimasu, Vryonidou; to appear]

Going NLO

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

[Degrande et al.; 2008.11743]



- NLO QCD effects are seizable in VV and VVV: $K \sim 1 - 2$
- significant variations between operators, processes and EFT orders
- $K(O_W/\Lambda^{-2}) \sim \mathcal{O}(10)$: LO suppression lifted at NLO

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

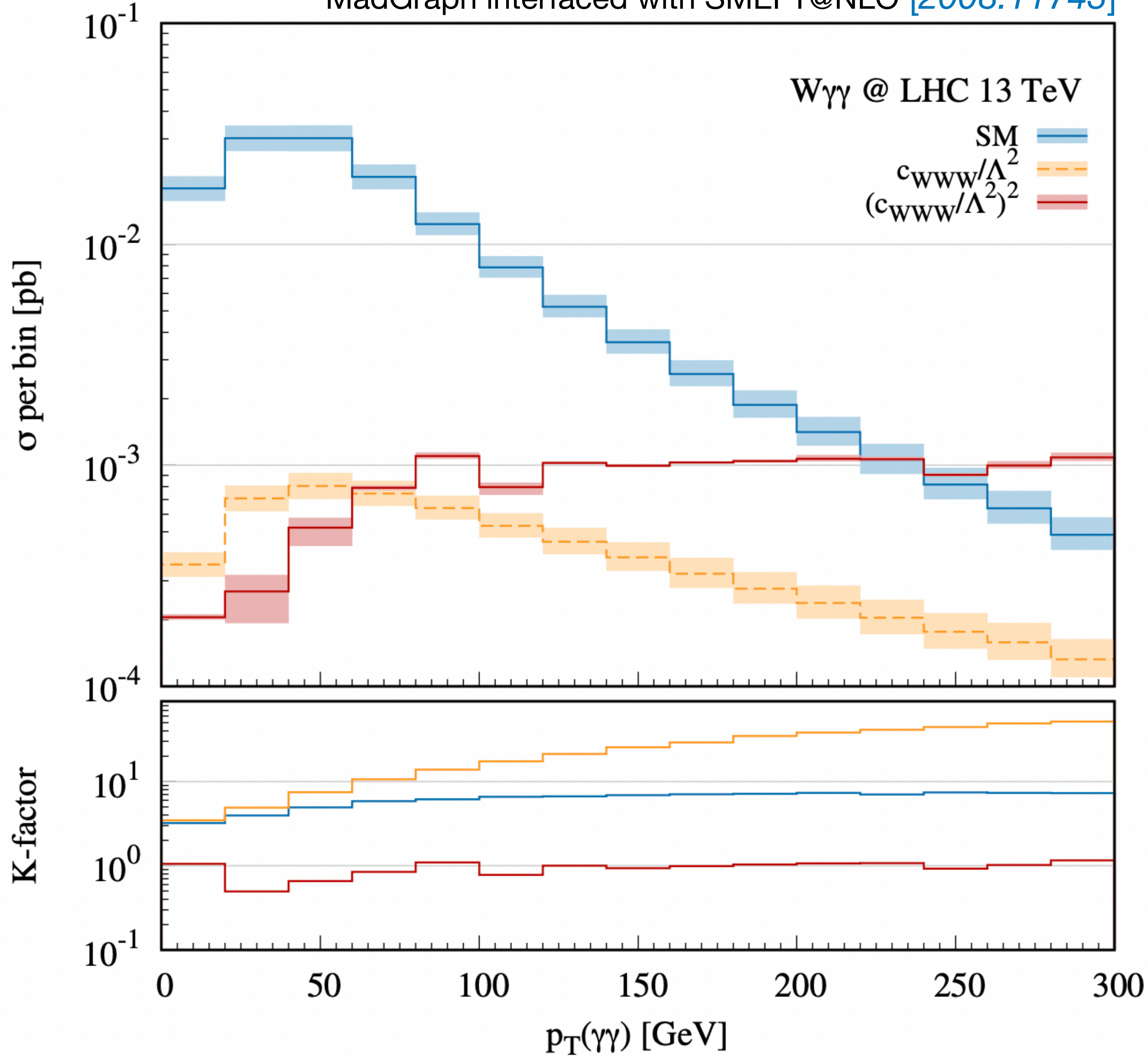
Going NLO

NLO QCD corrections are large in triboson processes

$W\gamma\gamma$	
σ(fb)	K-factor
σ_{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}	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

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

MadGraph interfaced with SMEFT@NLO [2008.11743]



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

Operators and observables

EWPOs and α_{EW} $\sqrt{s} = m_Z$

$$\Gamma_Z = 2.495 \pm 0.0023 \text{ GeV}$$
$$\sigma_{\text{had.}} = 41.54 \pm 0.0037 \text{ nb}$$
$$R^0_\ell = 20.77 \pm 0.025$$
$$A^\ell_{FB} = 0.00171 \pm 0.001$$
$$A_\ell(\text{SLD}) = 0.147 \pm 0.003$$
$$A_\ell(\text{Pt}) = 0.151 \pm 0.002$$
$$R^0_b = 0.2163 \pm 0.0007$$
$$A^b_{FB} = 0.099 \pm 0.0016$$
$$A_b = 0.923 \pm 0.02$$
$$R^0_c = 0.172 \pm 0.003$$
$$A^c_{FB} = 0.0707 \pm 0.0035$$
$$A_c = 0.67 \pm 0.027$$

[LEP; 0509008]

$$\left.\frac{\alpha(M_Z)}{\alpha(M_Z)_{SM}}\right|_{\overline{MS}} = 0.998 \pm 0.0011$$

[PDG; 20-21]

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

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

[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

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

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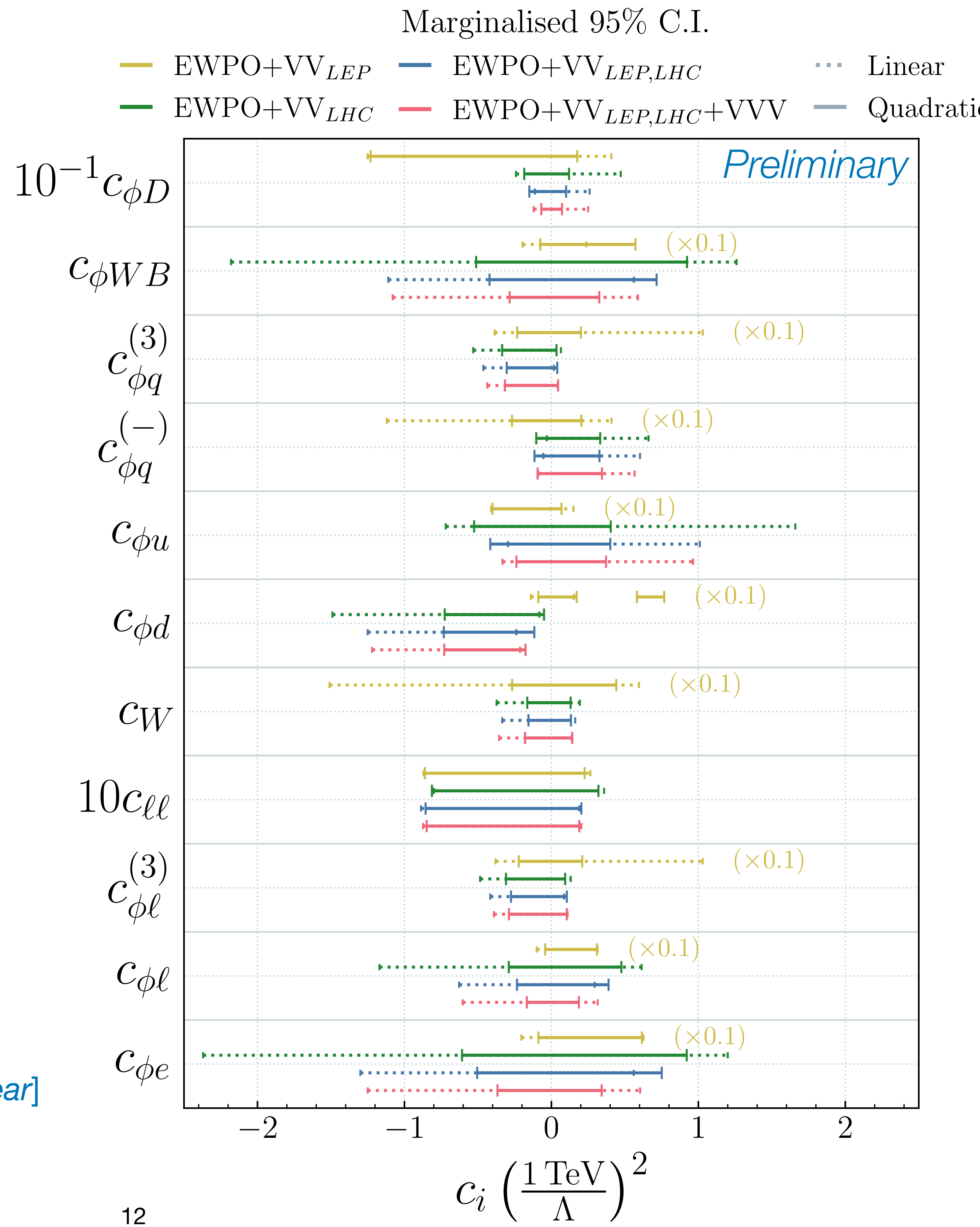
$\mathcal{O}_{\phi e}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{e}\gamma^\mu e)$	✓	✓	✓	✓
	four-fermion				
$\mathcal{O}_{\ell\ell}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma^\mu \ell)$	✓	✓	✓	✓

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

Fit results

- LHC VV & VVV appear to improve significantly the bounds from EWPOs & LEP VV
- Biggest impact from LHC VV compared to LEP VV
- 50% improvement from VVV wrt VV on $c_{\phi D}\, ,c_{\phi WB}\, ,c_{\phi \ell}\, ,c_{\phi e}$
- Bounds dominated by quadratic

Fitmaker [*Ellis et al.; 2012.02779*]



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

Interpretation

- Two 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

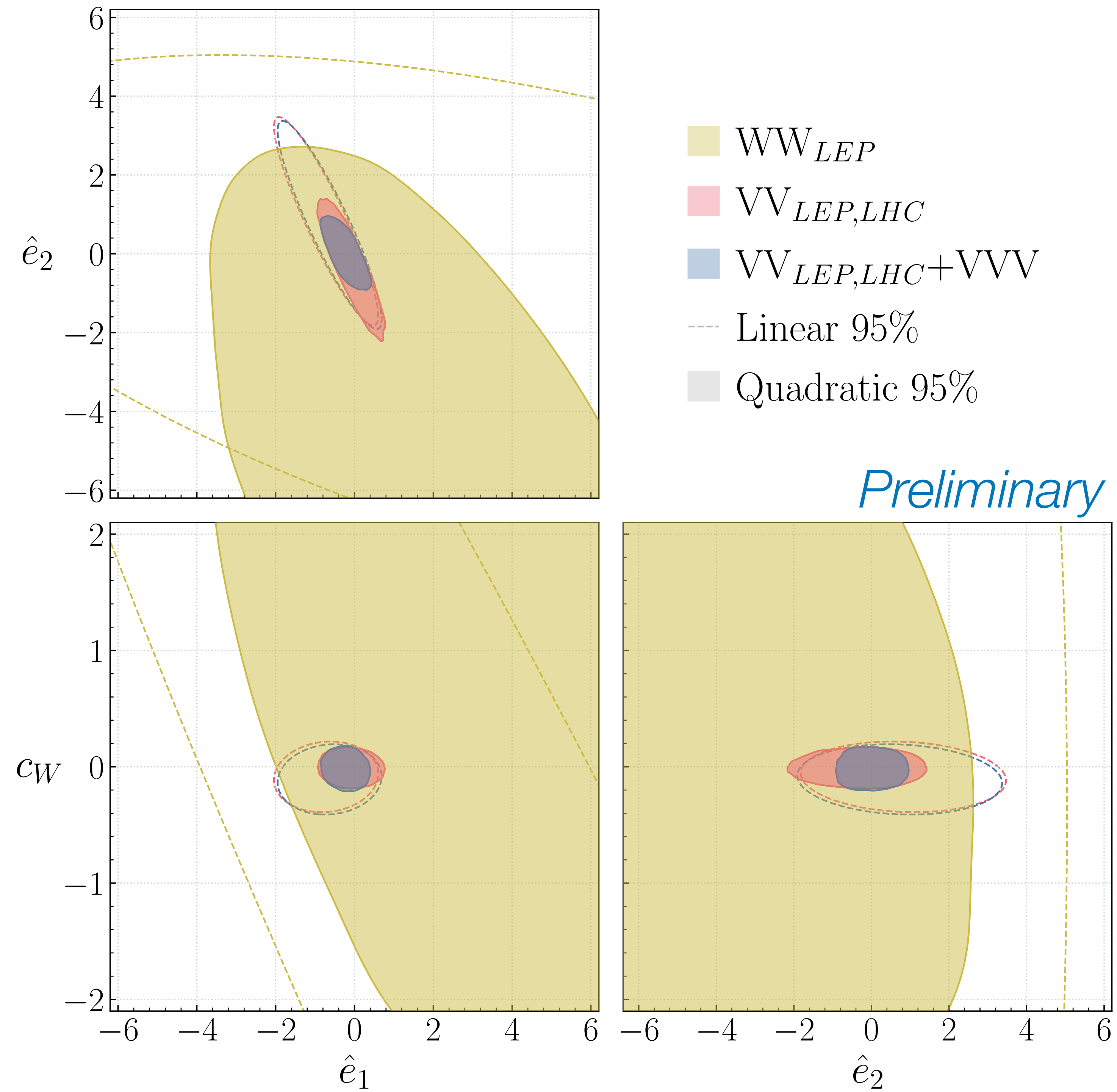
1. constraints in EWPOs blind space + marginalisation
2. genuine effect of higher sensitivity in all directions

Where do VV & VVV help?

Three EWPOs unconstrained parameters: $\hat{e}_1, \hat{e}_2, c_W$

- 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 the $\{\hat{e}_1, \hat{e}_2\}$ space

- Quadratic corrections are important
- VVV improves in EWPOs flat directions

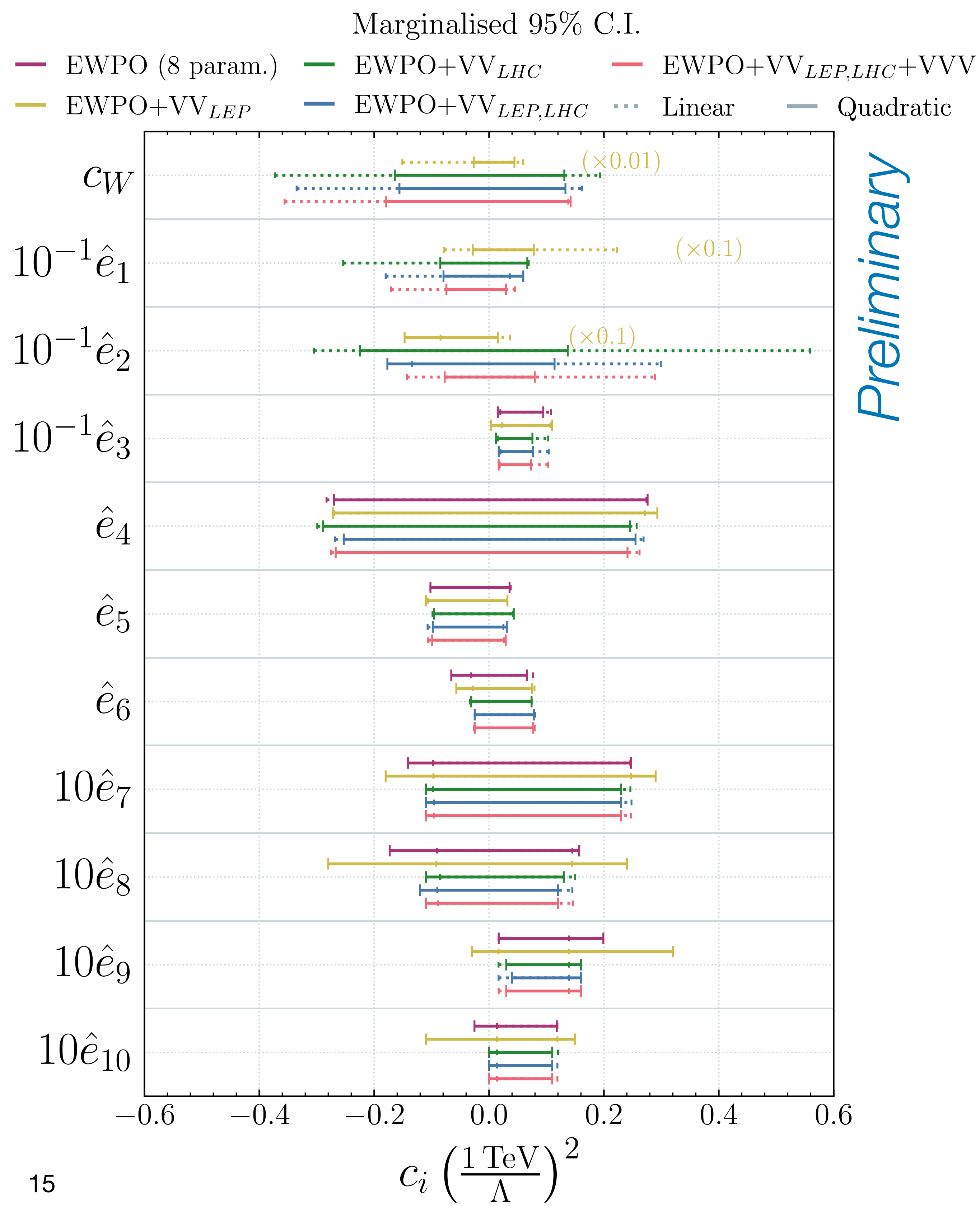


[EC, Durieux, Mimasu, Vryonidou; to appear]

What about the other directions?

Does multiboson help EWPOs in the directions orthogonal to $\{\hat{e}_1, \hat{e}_2, O_{WWW}\}$?

- in general, EWPOs constraints are dominant



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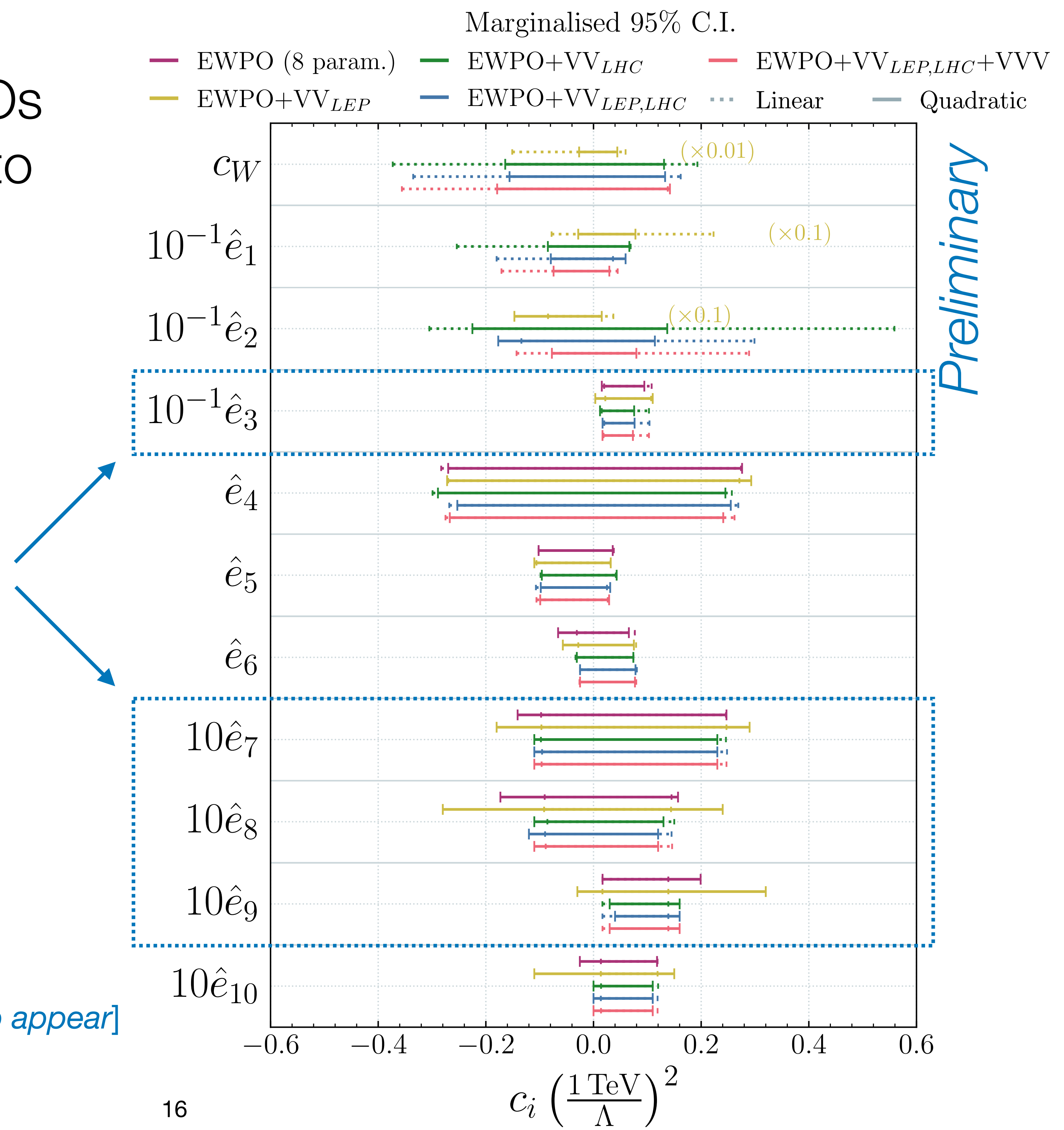
- mild improvement from quadratics (even EWPOs) on some directions



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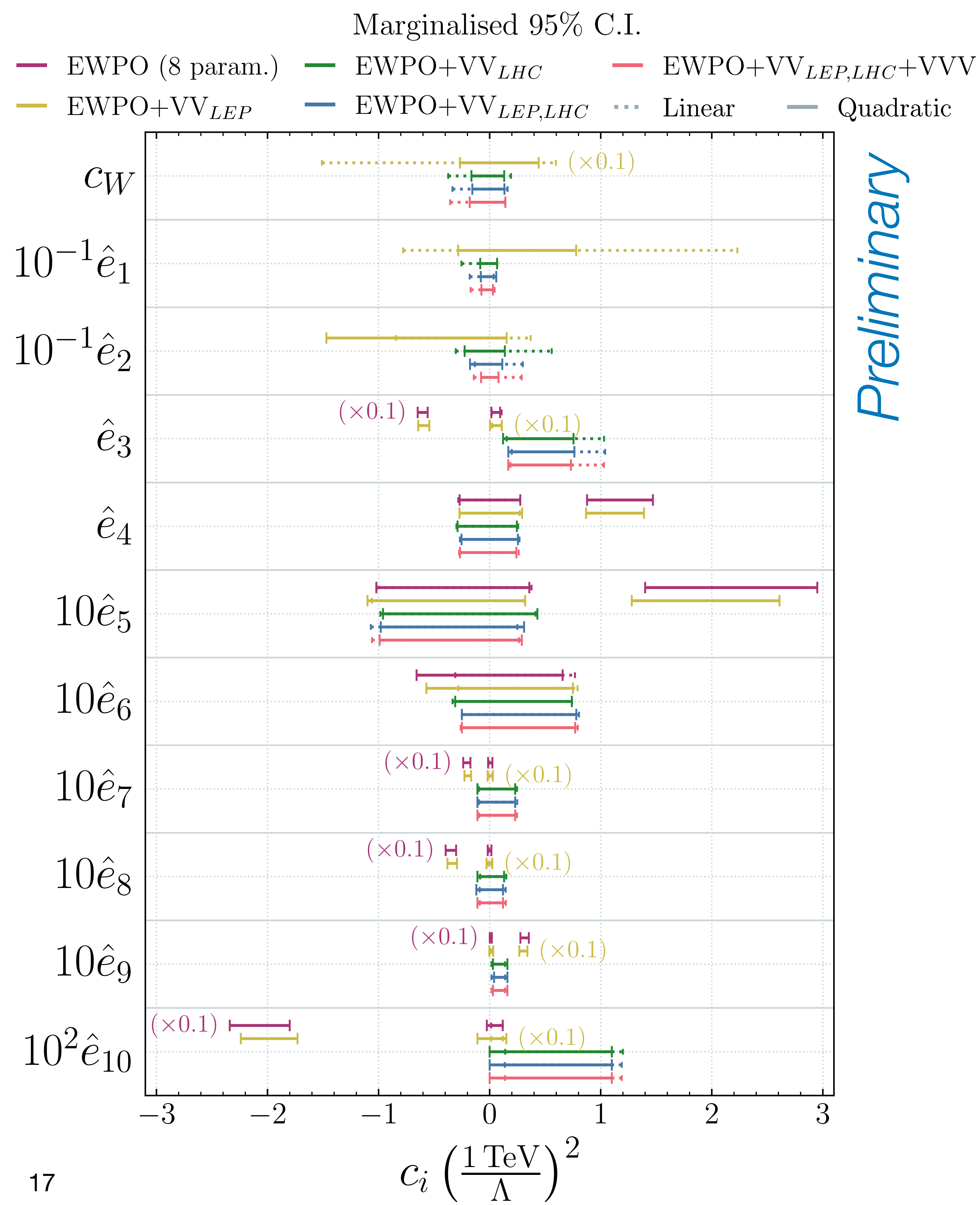
- in general, EWPOs constraints are dominant
- mild improvement from quadratics (even EWPOs) on some directions
- secondary minima in EWPOs+LEP lifted by LHC VV

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



Summary & conclusions

- Multiboson is multi-purpose: sensitivity to TGC, Higgs-gauge and light quark Yukawa couplings

- Complementarity to EWPOs

- Triboson improves the bounds of up to a factor 2 compared to diboson in directions unconstrained by EWPOs

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