Indirect new physics searches with 1,2 & 3 bosons

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[E. Celada, G. Durieux, KM, E. Vryonidou; 240X.XXXXX]

CATCH22+2, DIAS, Dublin

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Science and Technology Facilities Council

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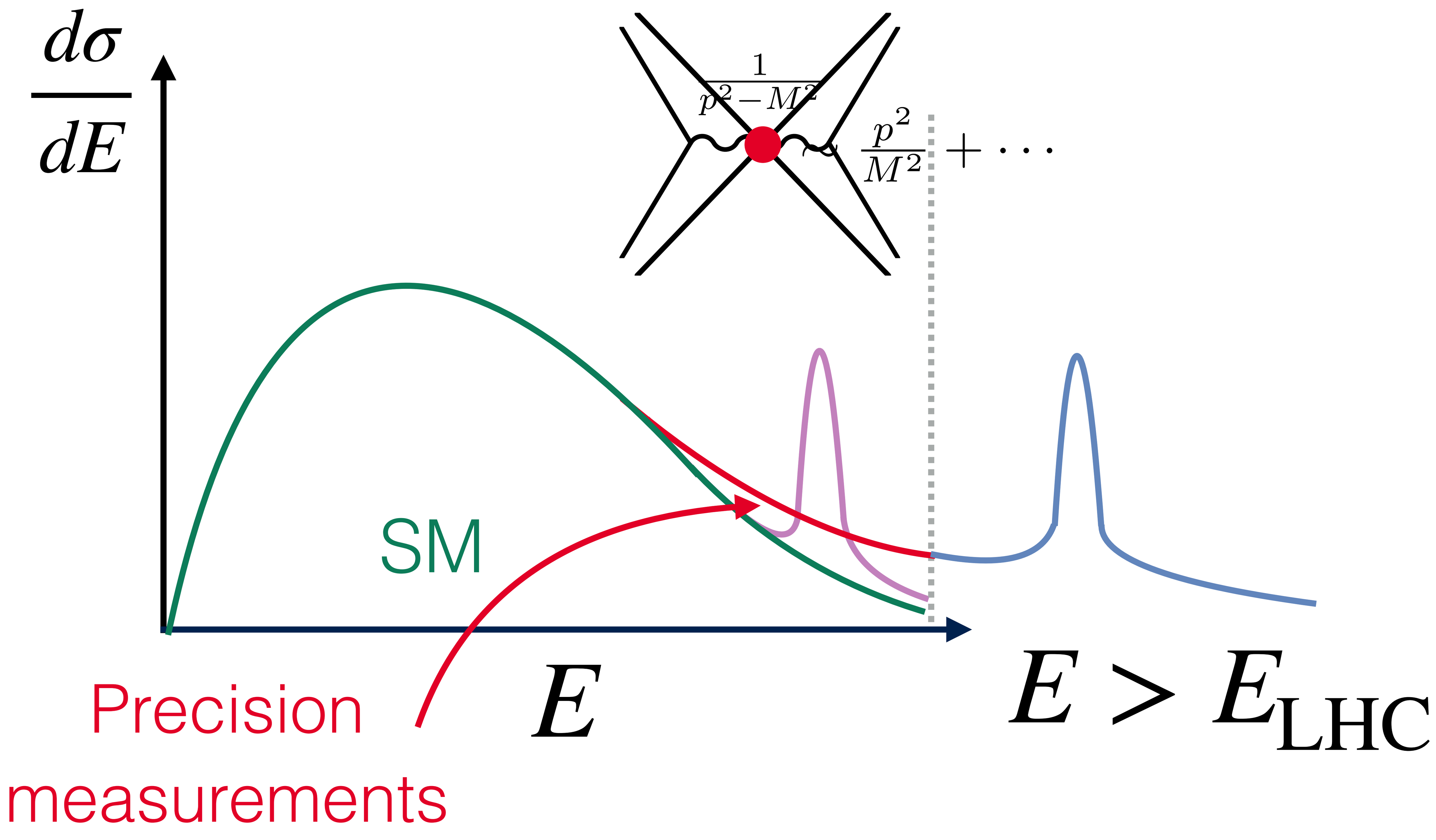
Energy & precision for BSM

2010s: energy
Direct (bumps)

2020s: intensity
Indirect (tails/precision)

⇒ New physics is heavy



Heavy new physics
Precision measurements
High energy

→ **Effective Field Theory (EFT)**

$$\mathcal{A}^n_{\mathrm{BSM}}(E, M) \sim E^{4-n}\left(a_0 + a_1\frac{E}{M} + a_2\frac{E^2}{M^2} + \cdots\right), \quad E \ll M$$

SMEFT is…

$$\mathcal{L}_{\rm eff} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$$

Model independent

- Underlying assumptions

Heavy new physics: $M > E_{exp}$

SM field content & gauge symmetries

Linear EWSB: Higgs = doublet

Systematically improvable

- Double expansion *higher dim.* $\frac{E^2}{\Lambda^2}$ *&* $\{g_S,\ g,\ g'\}$ *more loops*

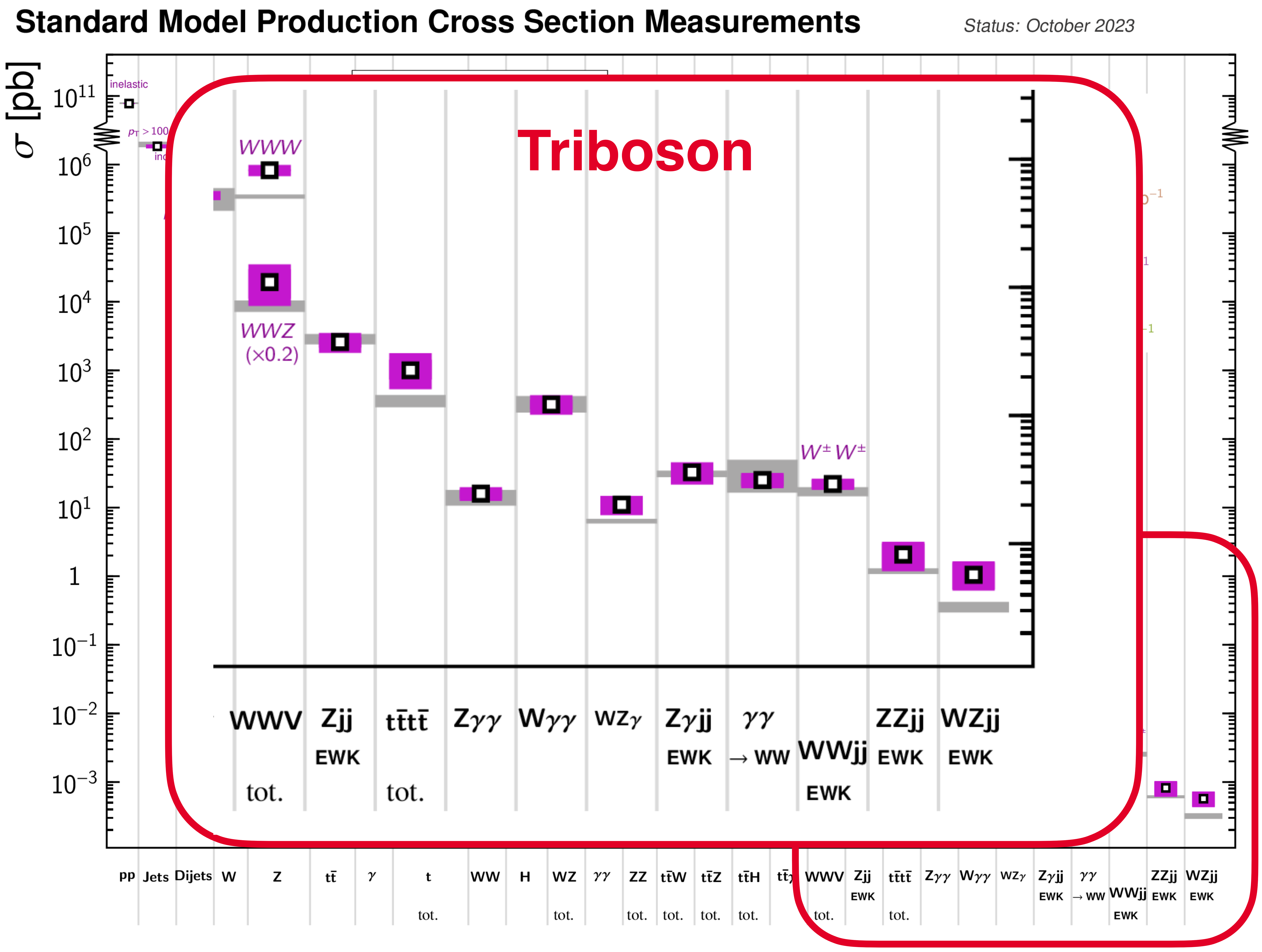
Global

- **Model independence:** we don't know what operators NP will generate
- Patterns & correlations among observables are key
- **Ultimate goal:** complete SMEFT likelihood confronted with HEP data

EWPO, Higgs, multiboson, top, DY, flavor,…

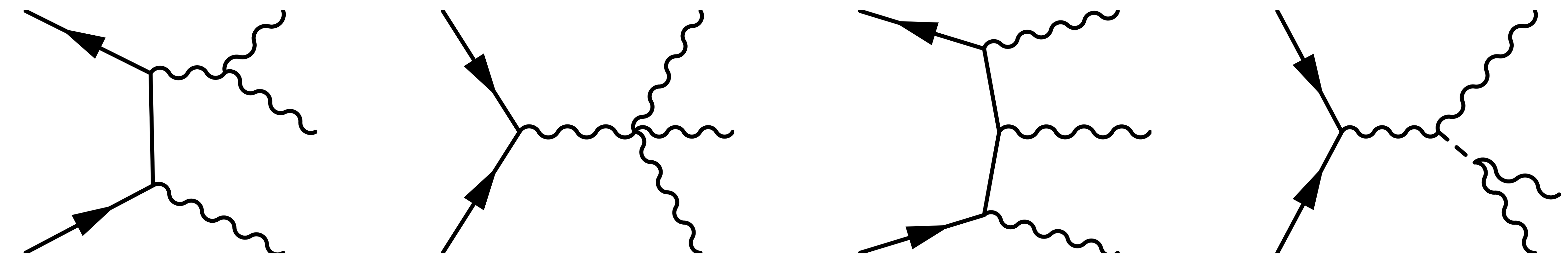
$\mathscr{L}(c_i) \Rightarrow$ **indirectly constrain many UV models**

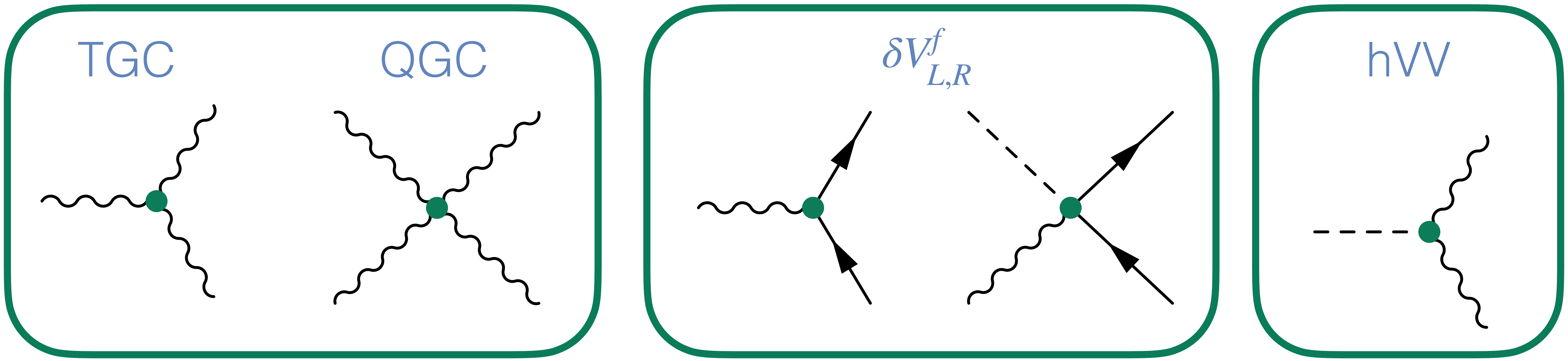
Energy & multiplicity

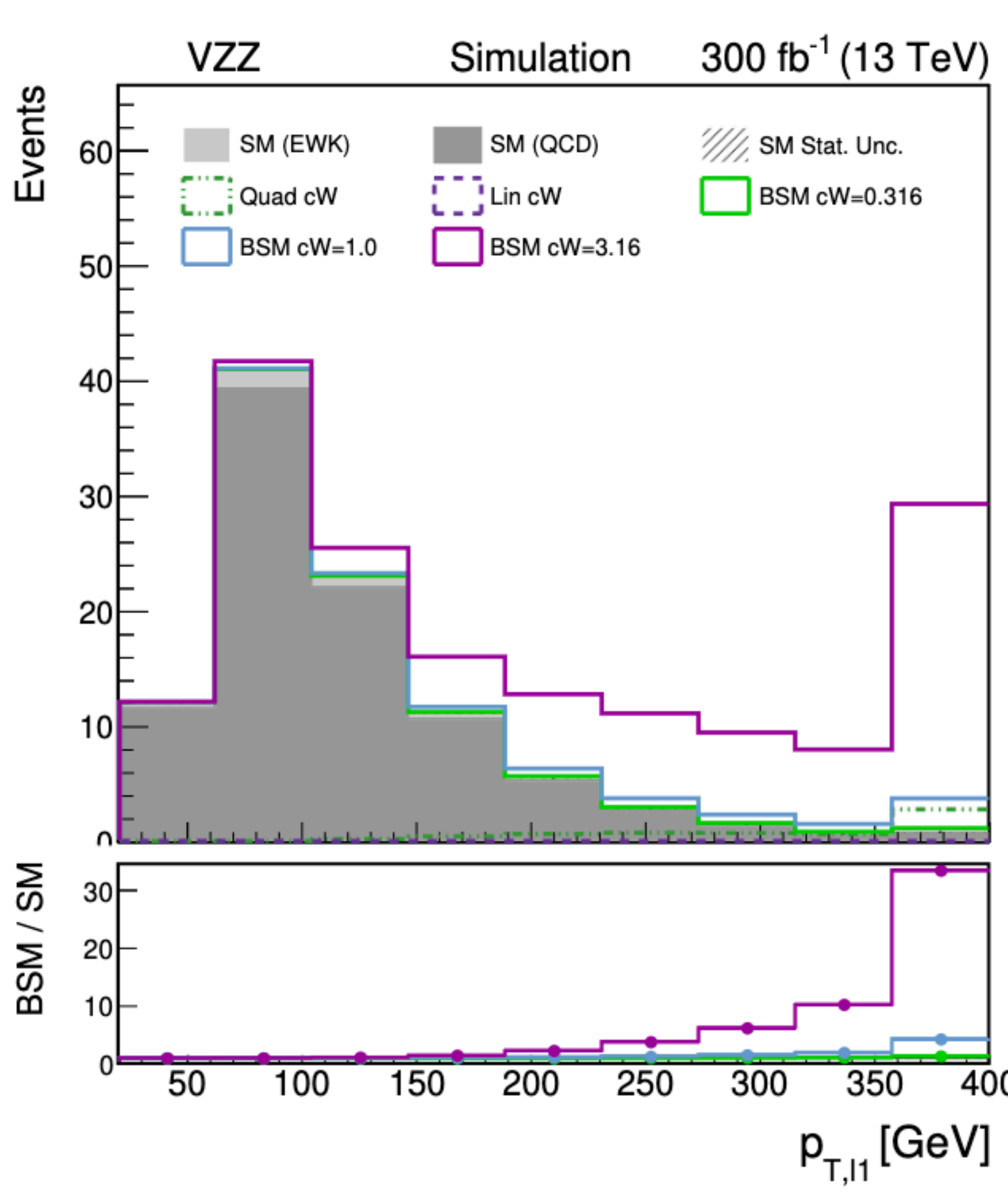


New physics probes with triboson

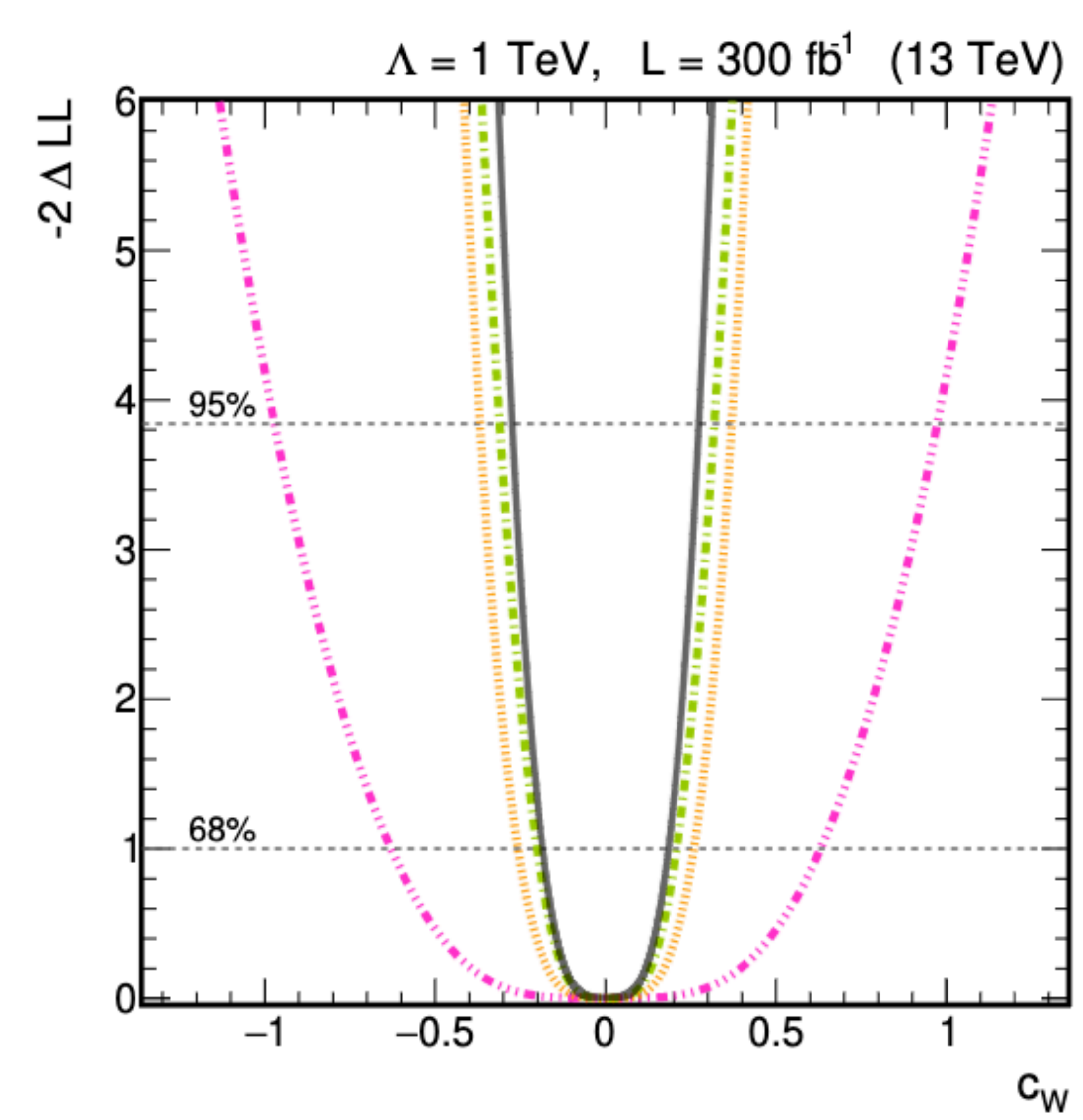
$pp \to VVV, \; V = W^{\pm}, Z, \gamma$





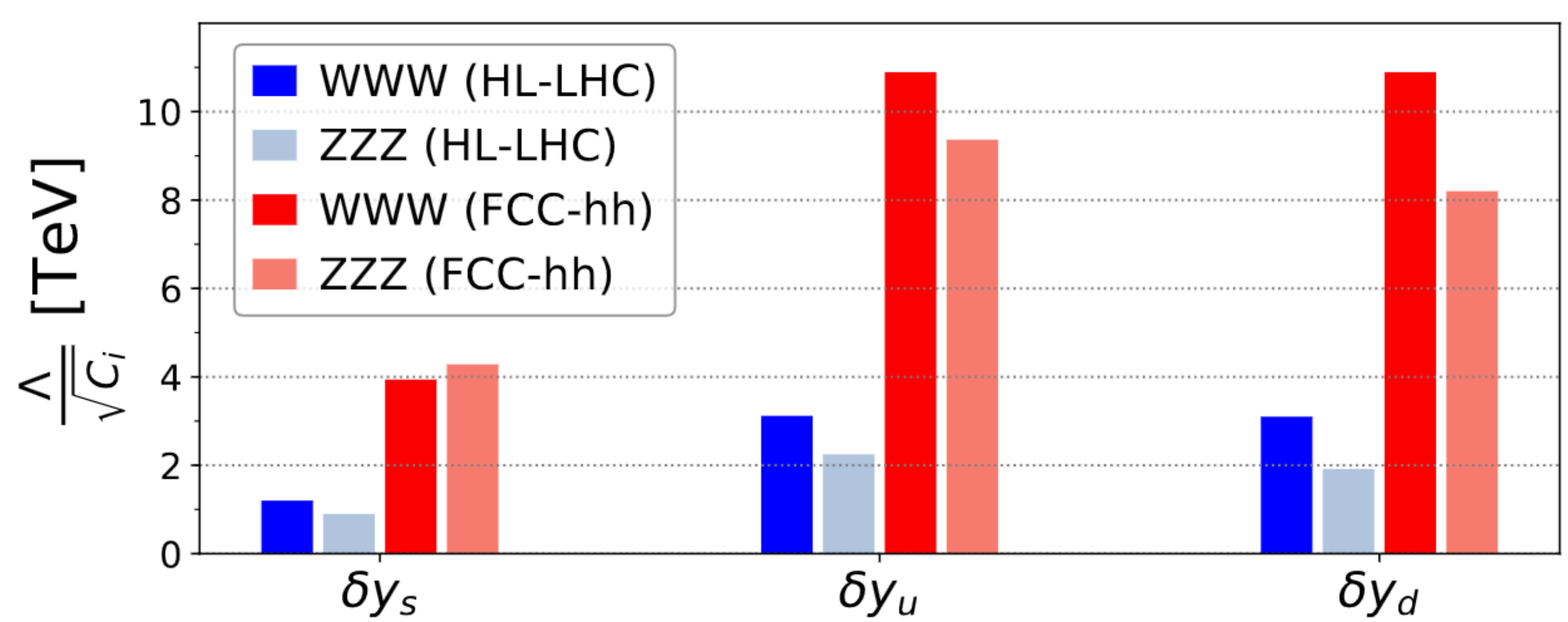


[Bellan et al; JHEP 08 (2023) 158]

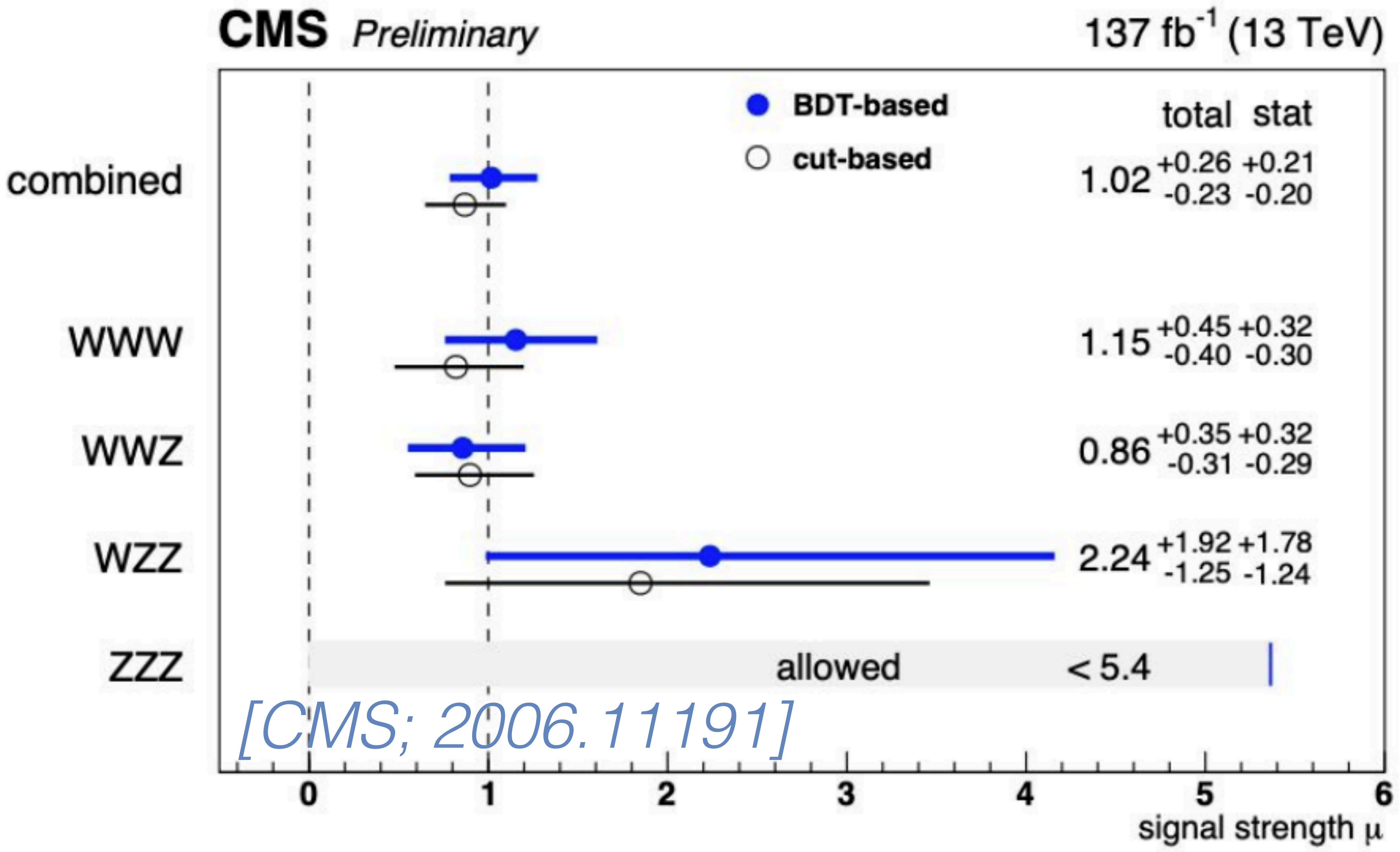


Light quark Yukawas

[Henning et al.; PRL 123 (2019) 181801]
[Falkowski et al; JHEP 04 (2021) 023]



Why now?



$\mu_{WWW} = 1.61 \pm 0.19 \pm 0.16$ [ATLAS; 2201.13045]

$\mu_{WZ\gamma} = 1.34 \pm 0.21 \pm 0.1$ [CMS; 2305.16994]

$\mu_{W\gamma\gamma} = 1.01 \pm 0.08 \pm 0.15$ [ATLAS; 2308.03041]

$\mu_{WW\gamma} = 1.31 \pm 0.17 \pm 0.21$ [CMS; 2310.05164]

σ_{tot} *in leptonic channels ~ 20-100% precision*

We have already constrained relevant new couplings

- EWPO, LHC & LEP diboson, Higgs programme $\delta_{EWPO} \sim 1-0.1\,\%$ $\delta_h \sim 10\,\%$
- Typically much more precise $\delta_{VV} \sim 10\,\%$ $\delta_{VVV} \sim 100\,\%$

What new information does triboson offer?

- Naively not much… do a fit to find out! [E. Celada, G. Durieux, KM, E. Vryonidou; WIP]

1,2 & 3 bosons: data

+ VVV signal strengths from before

EWPO $e^+e^- \,@\, \sqrt{s} \simeq M_Z$

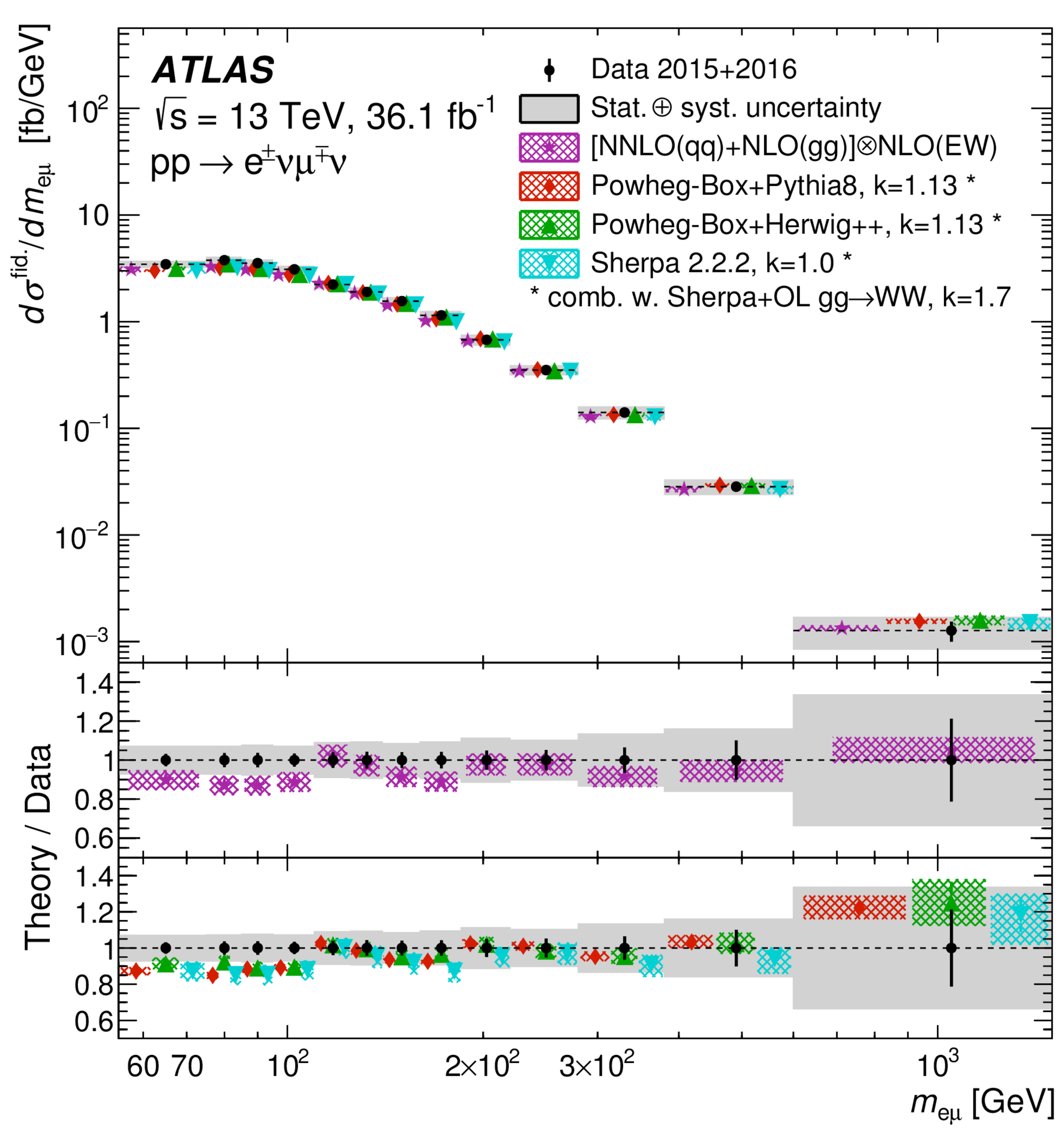
$$\{\ \Gamma_Z,\ \sigma_{had.},\ R^0_\ell,\ R^0_c,\ R^0_b,\ A^\ell_{FB},\ A^c_{FB},\ A^b_{FB},\ A_\ell,\ A_c,\ A_b\ \}$$

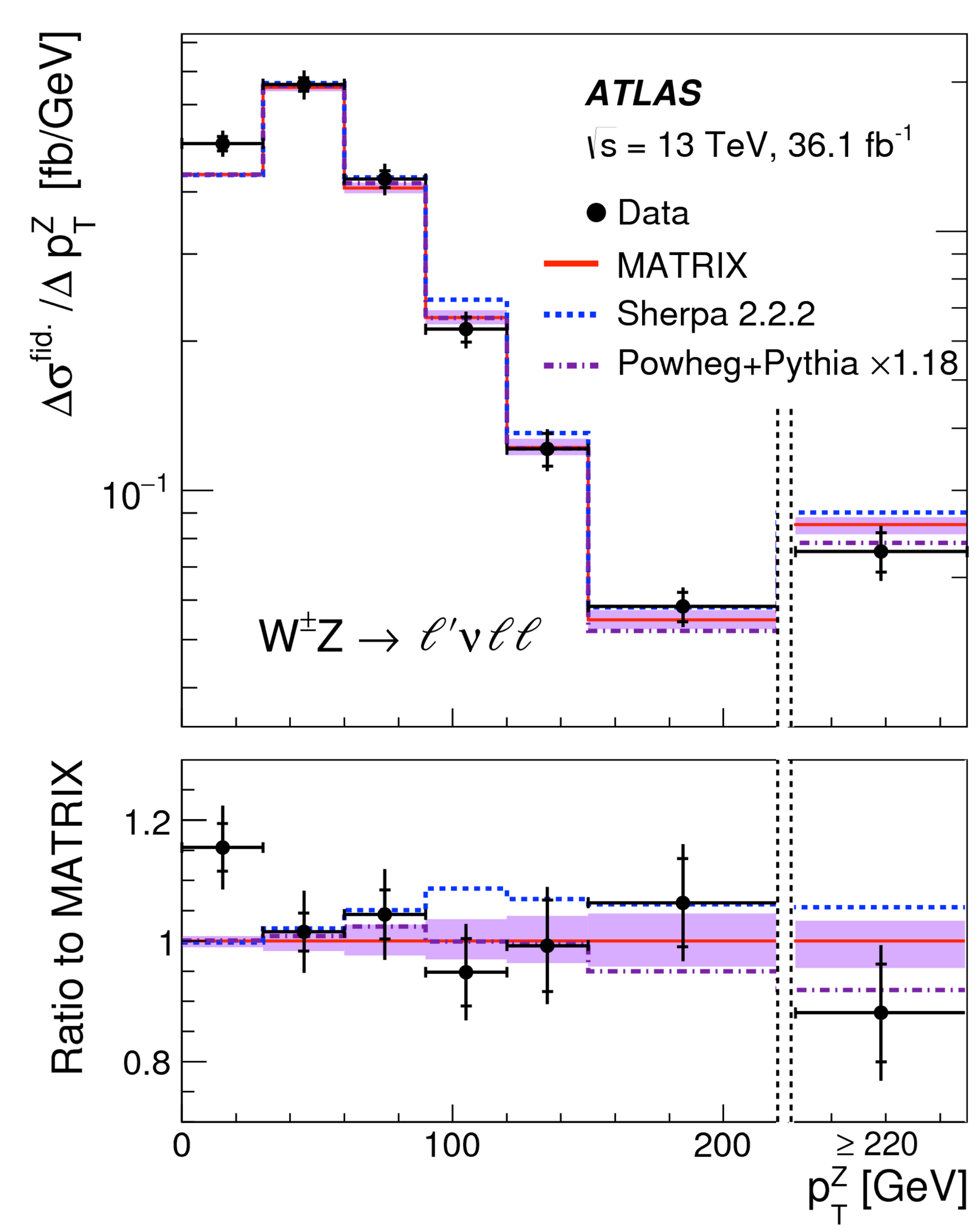
$+\ \alpha_{EW}(m_Z)$ ($\{m_Z, m_W, G_F\}$ input scheme)

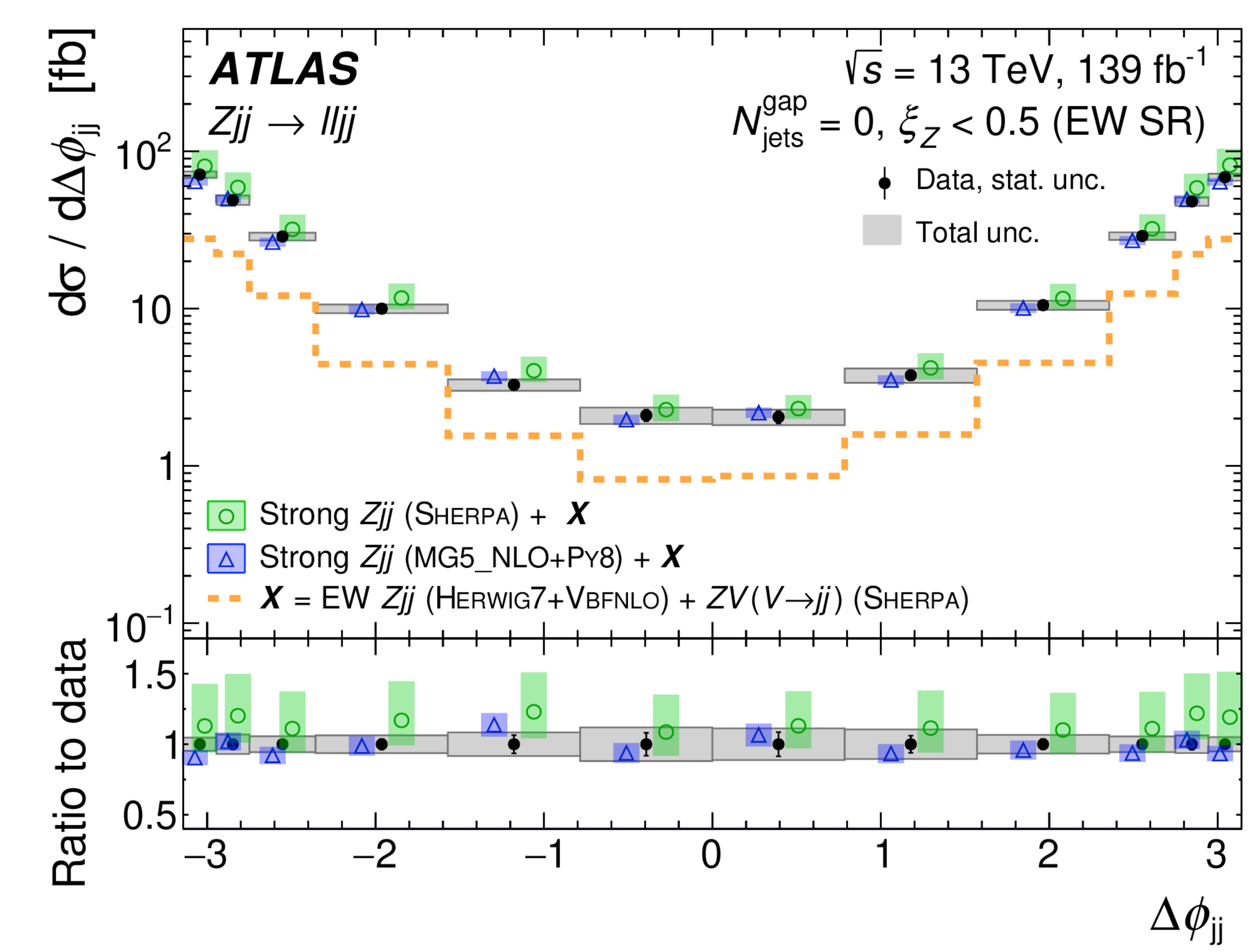
LEP WW $e^+e^- \,@\, \sqrt{s} = 183 - 209\ GeV$

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

LHC VV $pp \,@\, \sqrt{s} = 13\ TeV$ $\quad pp \to W^+W^-/WZ/Zjj$







$$\sigma = \sigma_{SM} + \sum_i \sigma_i \frac{C_i}{\Lambda^2} + \sum_{j \geq i} \sigma_{ij} \frac{C_i C_j}{\Lambda^4}$$

a) linear $O(\Lambda^{-2})$

b) quadratic $O(\Lambda^{-4})$

1,2 & 3 bosons: model

11 parameters

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

Results

$$\sigma = \sigma_{SM} + \sum_i \sigma_i \frac{C_i}{\Lambda^2} + \sum_{j\geq i} \sigma_{ij} \frac{C_i C_j}{\Lambda^4}$$

LEP WW bounds are weak

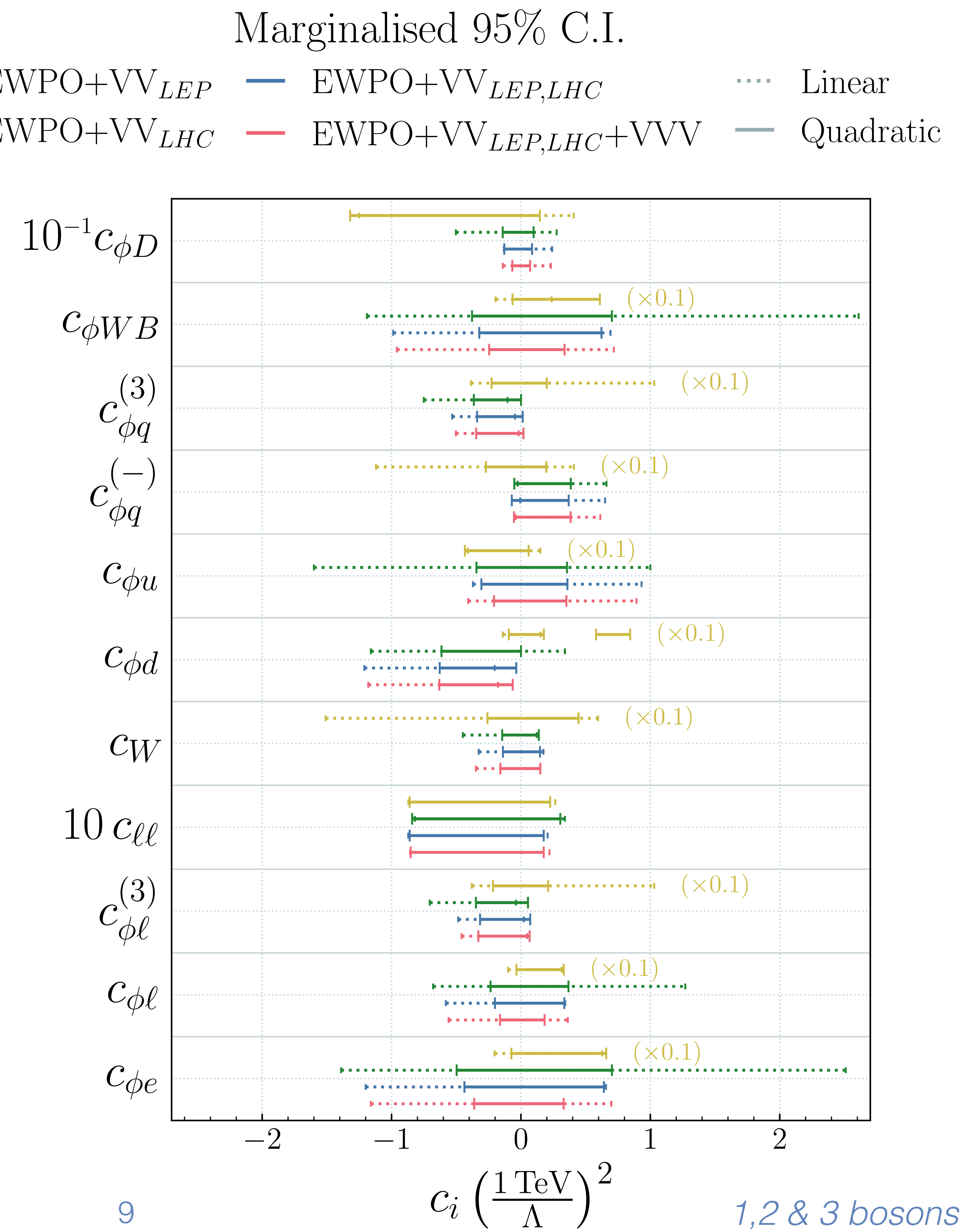
- Significant quadratic effects

LHC VV has biggest impact

- Dominates VV combination

VVV makes a difference

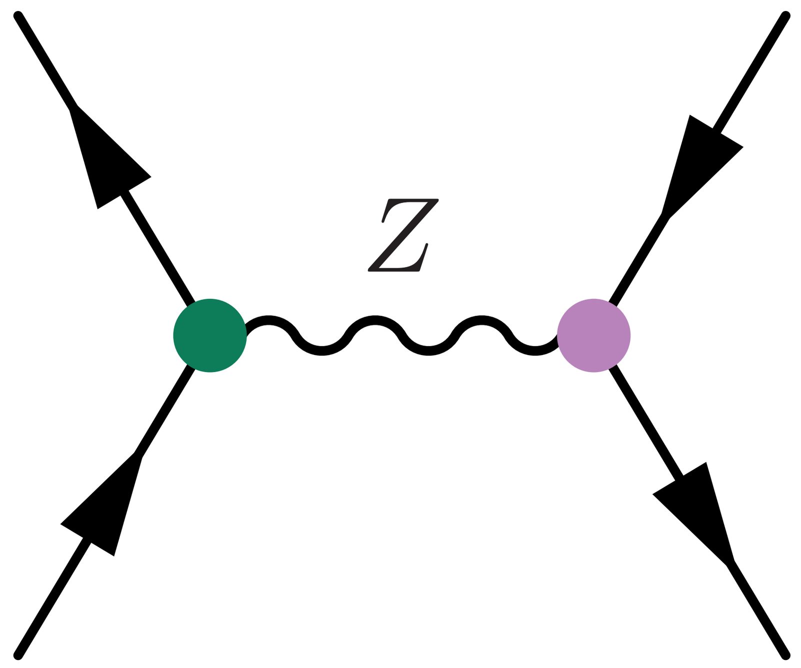
- Apparently $\sim 50\,\%$ effect in, *e.g.*, $c_{\phi D}$, $c_{\phi WB}$, $c_{\phi \ell}$, $c_{\phi e}$
- Quadratic only



Interpretation

[De Rujula et al.; Nucl. Phys. B 384 (1992) 3-58]
[Degrande et al.; 1205.4231]
[Efrati, Falkowsi & Soreq; 1503.07282]
…

“EWPO only” fit is not possible



- Not sensitive to TGC & has 2 additional flat directions
- Constrains 8 out of 11 combinations of C_i

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

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

[Brivio & Trott; 1701.06424]

Eigenvectors of the Fisher information, $\hat{e}_i$

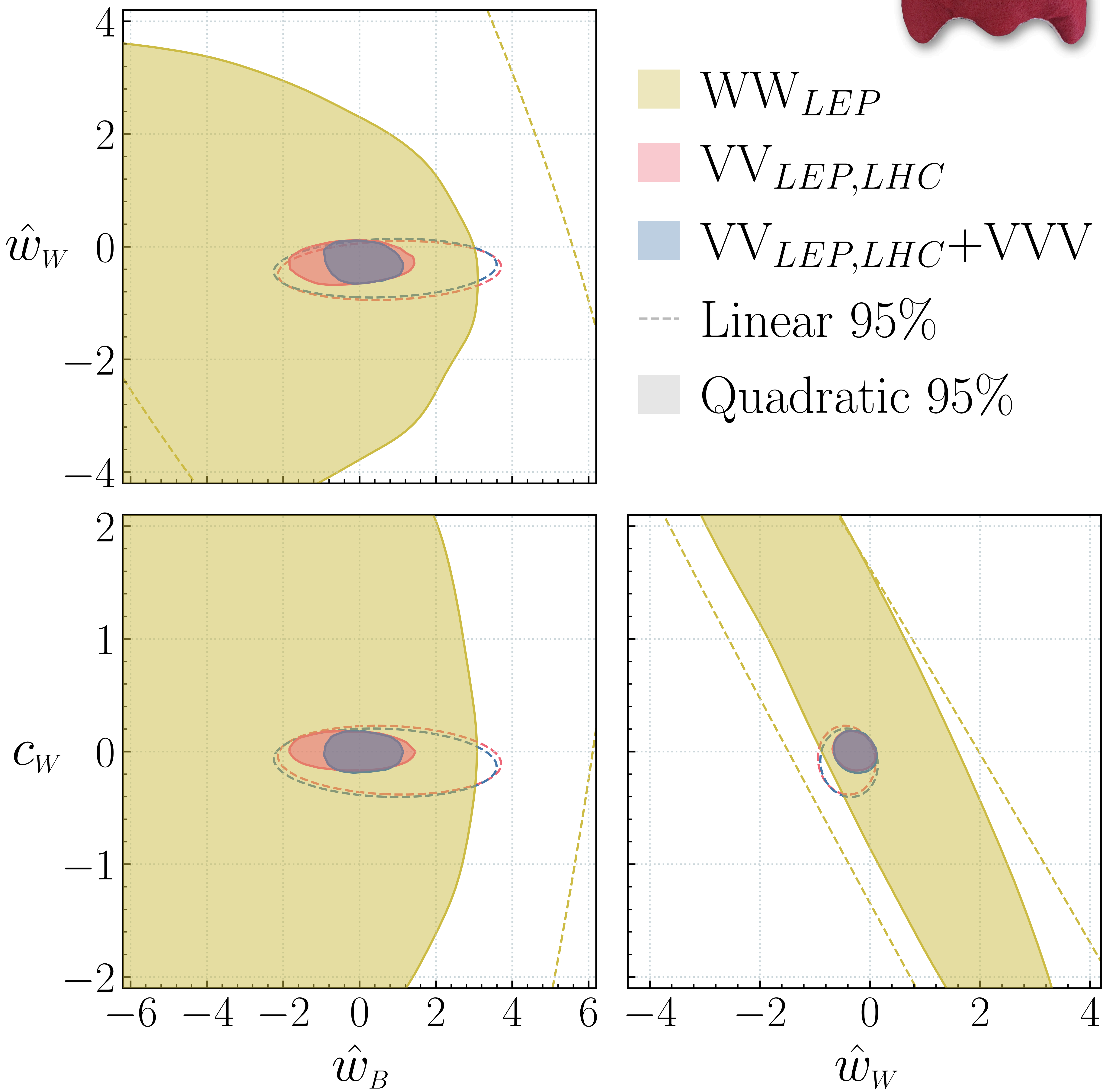
$$\vec{\mu} = \vec{\mu}_{SM} + \mathbf{H}\cdot\vec{c}$$

$$\mathbf{F} = \mathbf{H}^\top \cdot \mathbf{V}^{-1} \cdot \mathbf{H}$$

- Unconstrained directions: $\hat{e}_{1,2} = a_{1,2}\,\hat{\omega}_B + b_{1,2}\,\hat{\omega}_B$
- Additional datasets close the fit (LEP/LHC VV, VVV, Higgs…)

Global: bounds limited by the sensitivity of the extra data

EWPO blind space



Sufficient to study 3D space

- TGC + 2 flat directions
- Emphasise the strength of diboson
- Non-negligible impact of triboson
- No correlations in $\hat{w}_{B,W}$ vs. c_W

VVV: purely $O(\Lambda^{-4})$ effect

- Significant quadratics everywhere
- Propagate into any global analysis that combines EWPO with other things
- EFT validity?

Other $\hat{e}_i$?

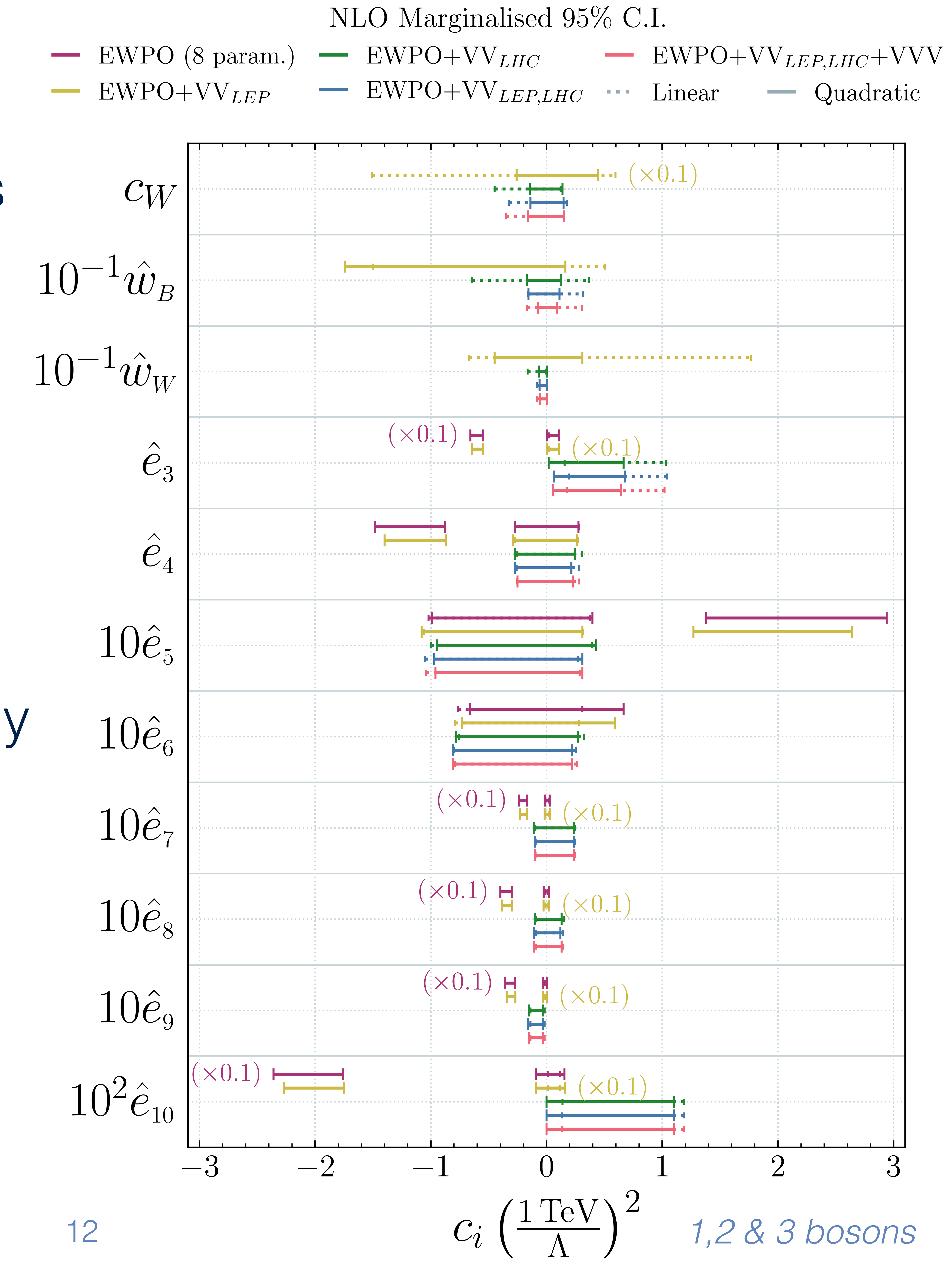
Rotated results to eigenbasis

- Compare to 8 parameter EWPO fit
- Significant quadratic effects
- Secondary minima

LEP WW has little impact

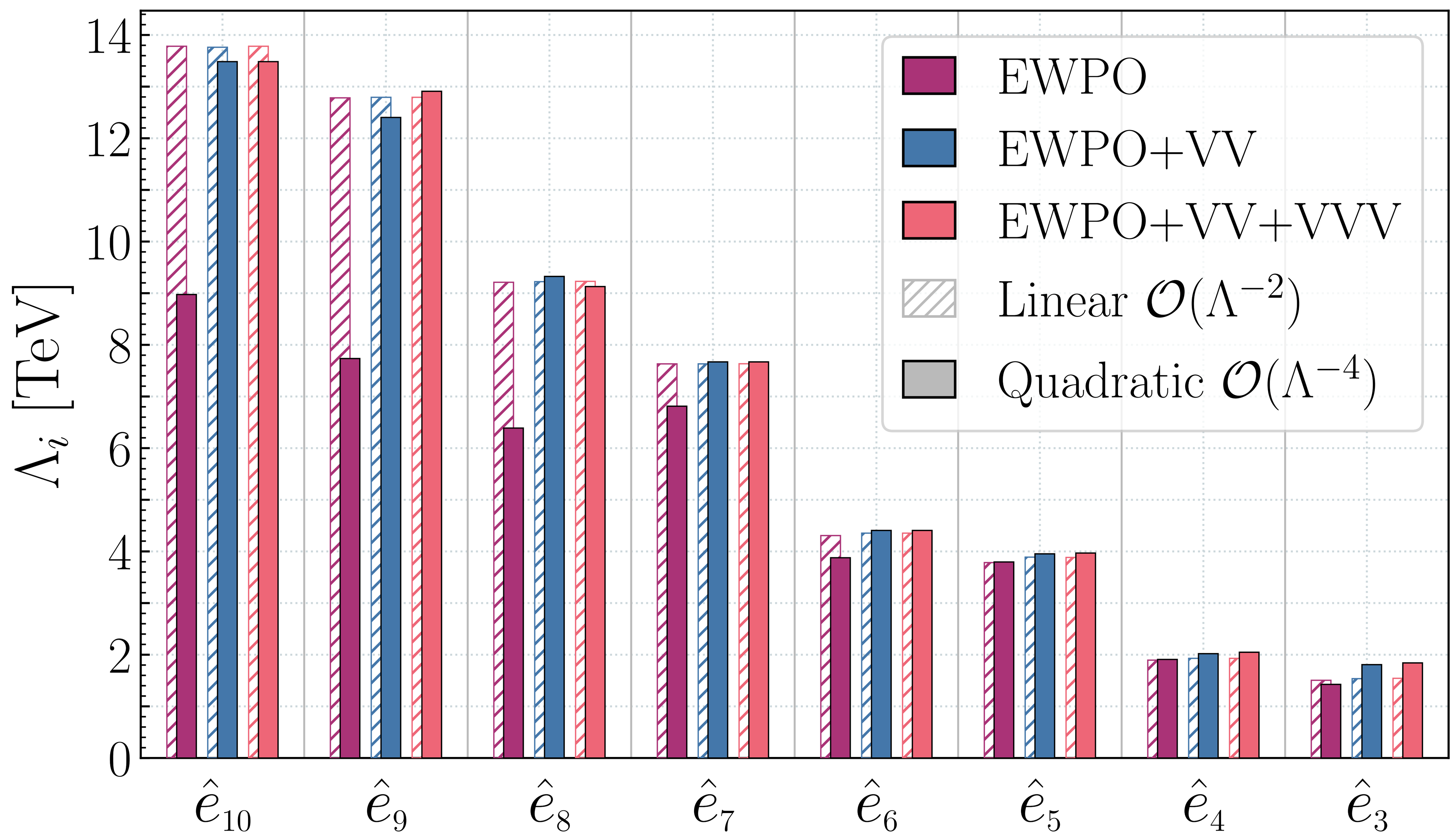
LHC VV improves significantly

- Lifts secondary minima
- No further impact from VVV

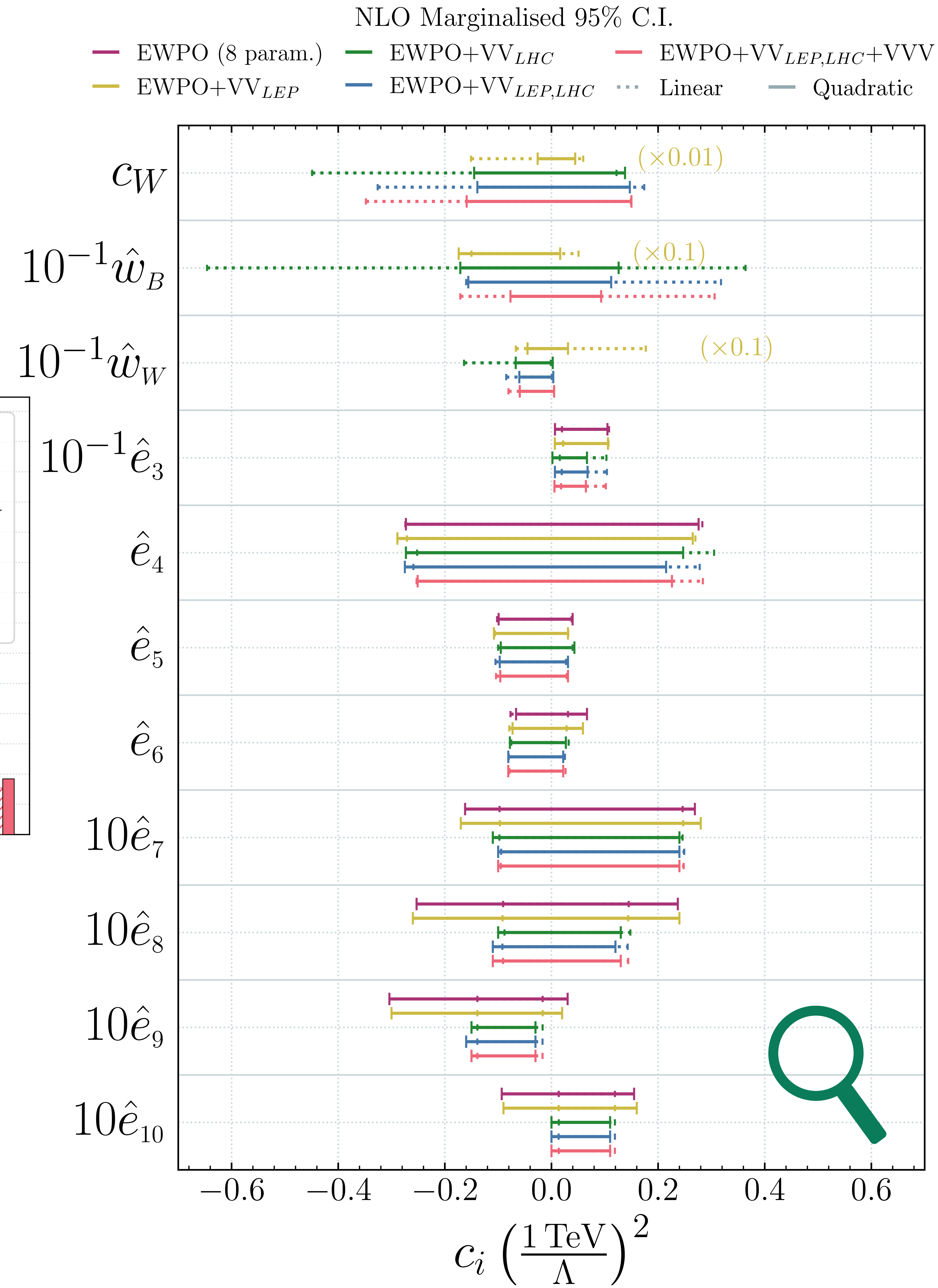


Other $\hat{e}_i$?

$$\Lambda_i = \left(\Delta\hat{e}_i^{95}\right)^{-\frac{1}{2}}$$



LHC data is crucial in solidifying the EFT validity in these directions



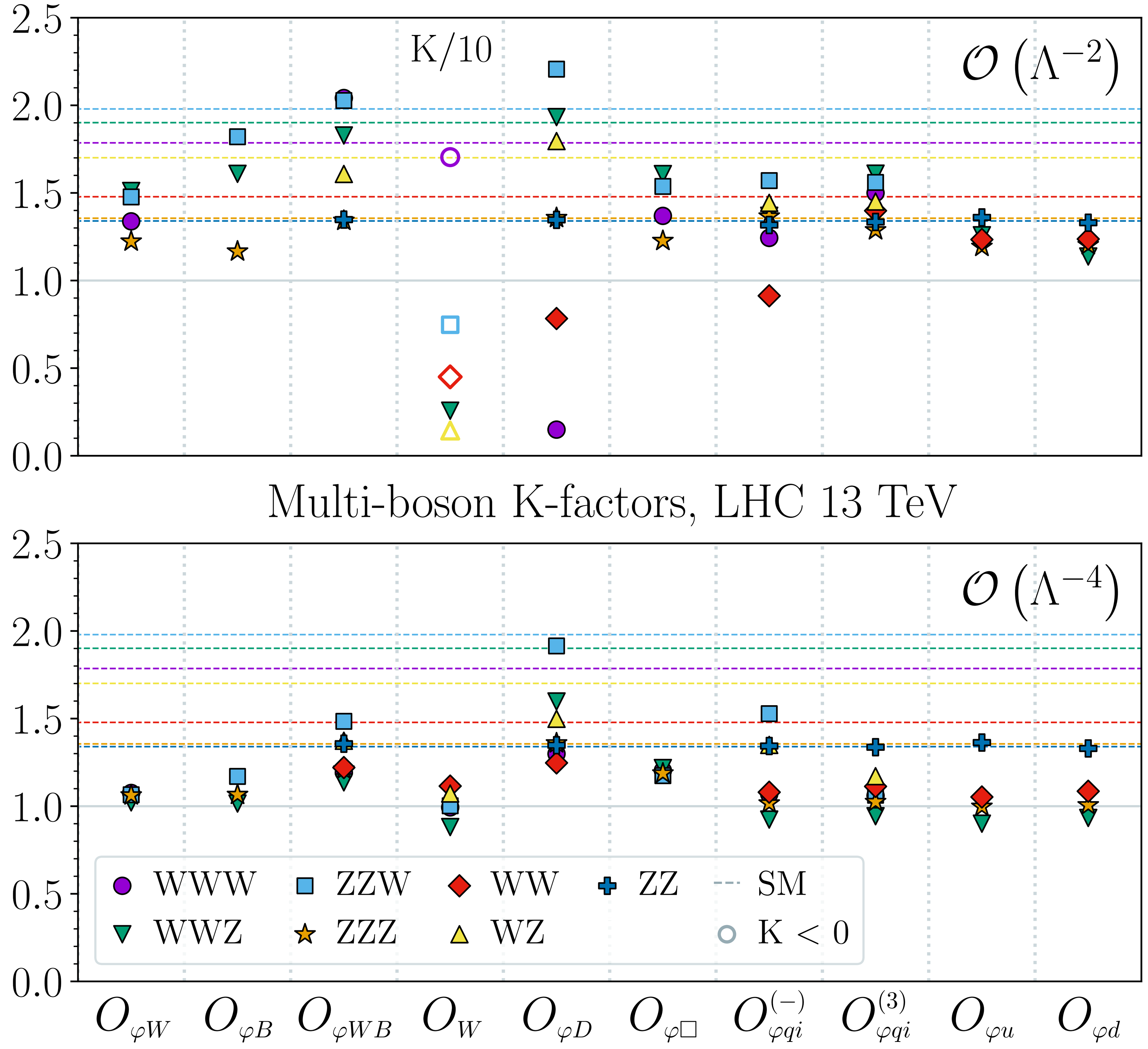
NLO vs LO

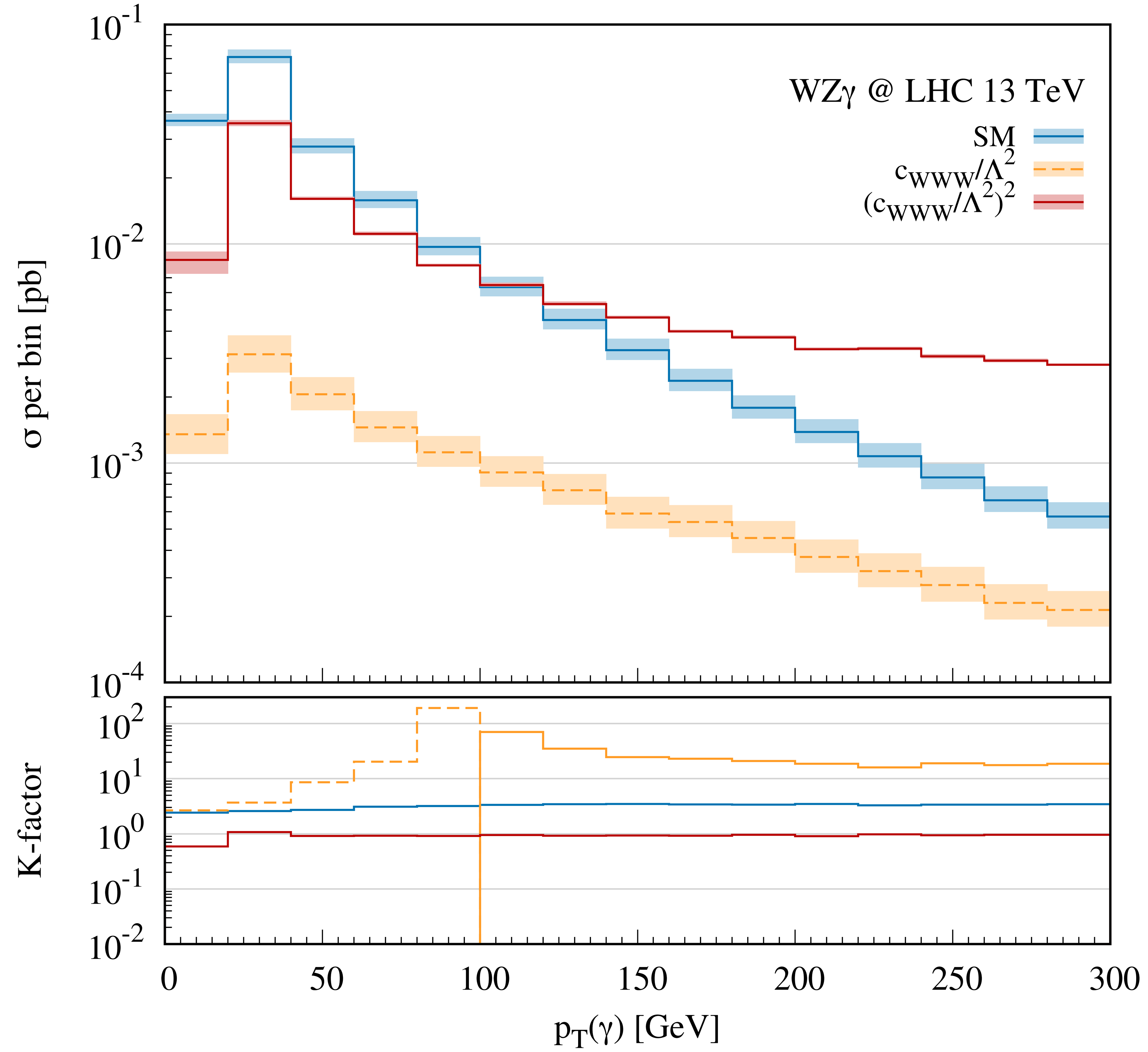
https://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO
[Degrande et al.; 2008.11743]

SMEFTatNLO: QCD corrections to SMEFT predictions

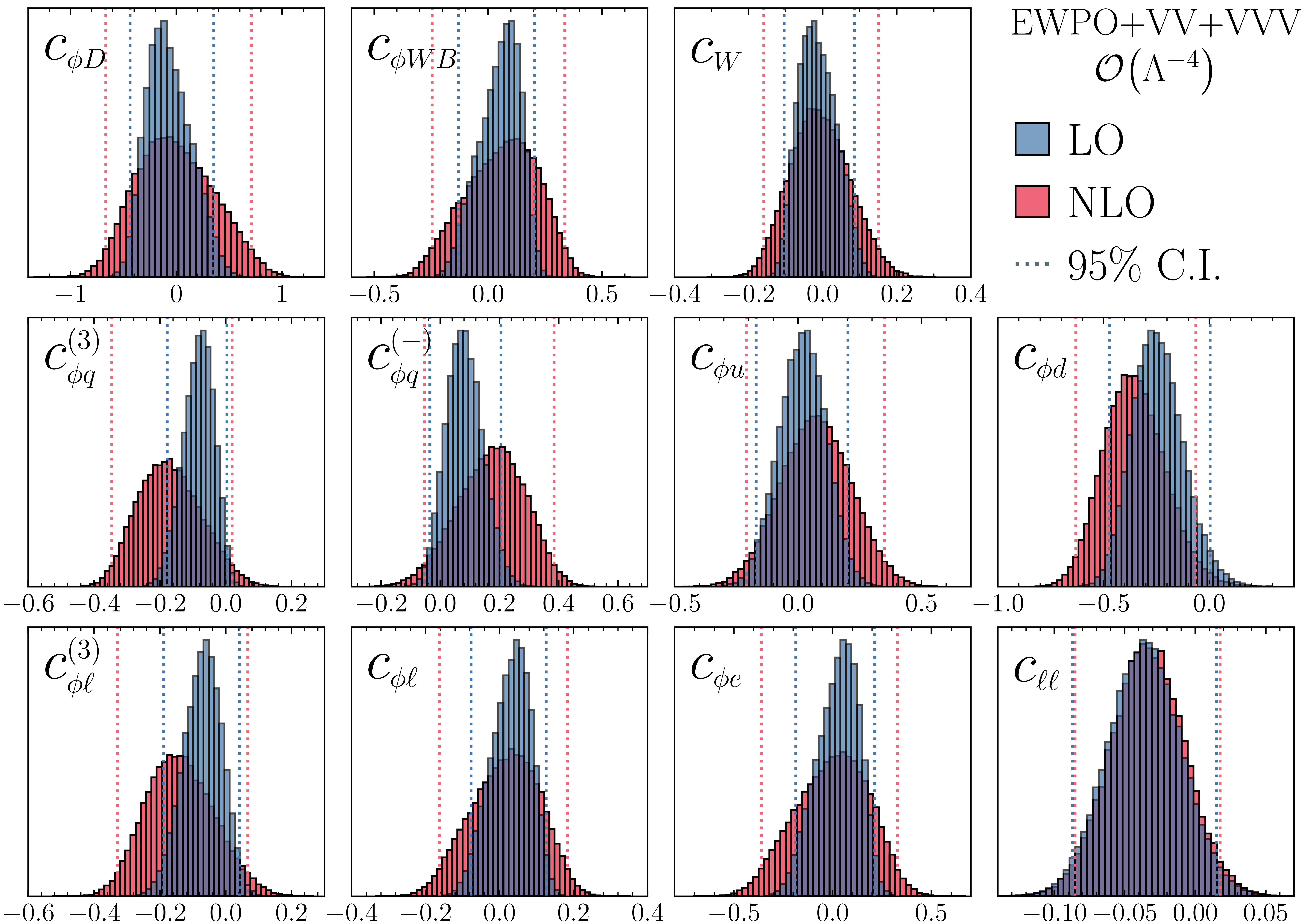
------ : SM K-factor ● : c_i K-factor

TGC operator: c_W



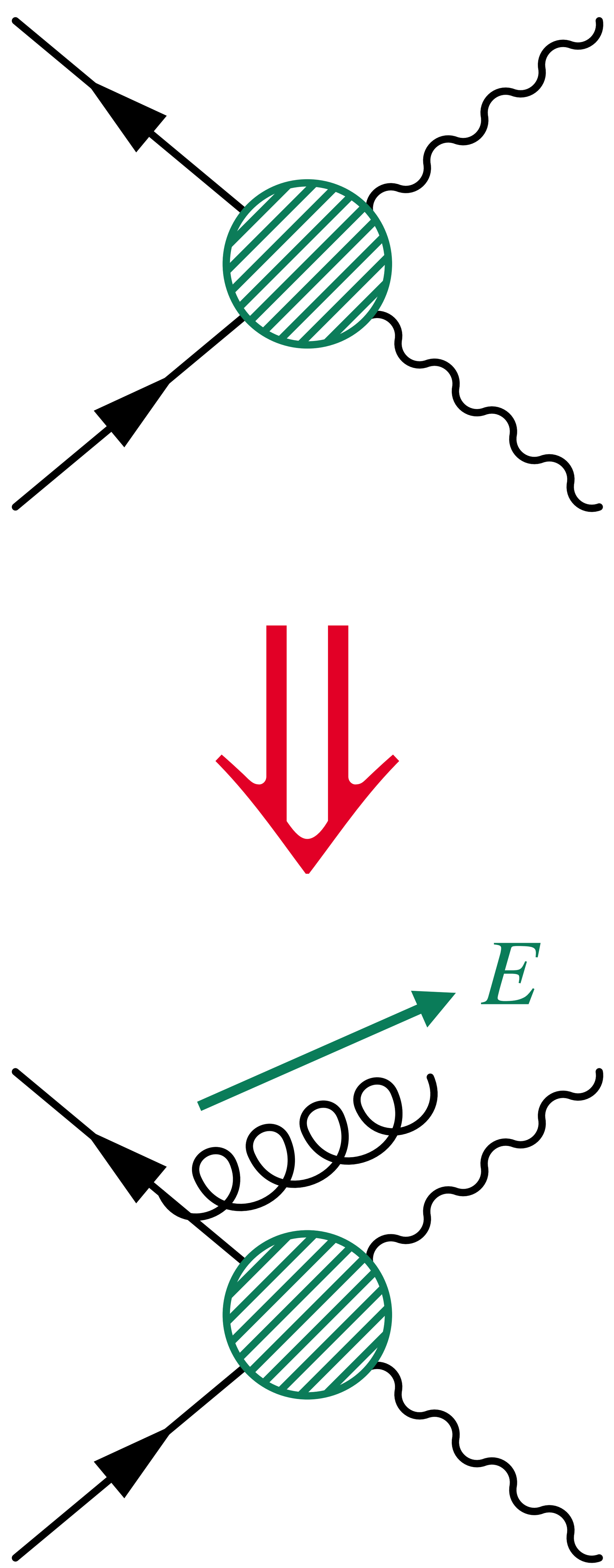


NLO vs LO


EWPO+VV+VVV
$\mathcal{O}(\Lambda^{-4})$
LO
NLO
95% C.I.
$c_{\phi D}$
$c_{\phi WB}$
c_W
$c_{\phi q}^{(3)}$
$c_{\phi q}^{(-)}$
$c_{\phi u}$
$c_{\phi d}$
$c_{\phi \ell}^{(3)}$
$c_{\phi \ell}$
$c_{\phi e}$
$c_{\ell\ell}$
−1 0 1
−0.5 0.0 0.5
−0.4 −0.2 0.0 0.2 0.4
−0.6 −0.4 −0.2 0.0 0.2
−0.2 0.0 0.2 0.4 0.6
−0.5 0.0 0.5
−1.0 −0.5 0.0
−0.6 −0.4 −0.2 0.0 0.2
−0.4 −0.2 0.0 0.2 0.4
−0.5 0.0 0.5
−0.10 −0.05 0.00 0.05

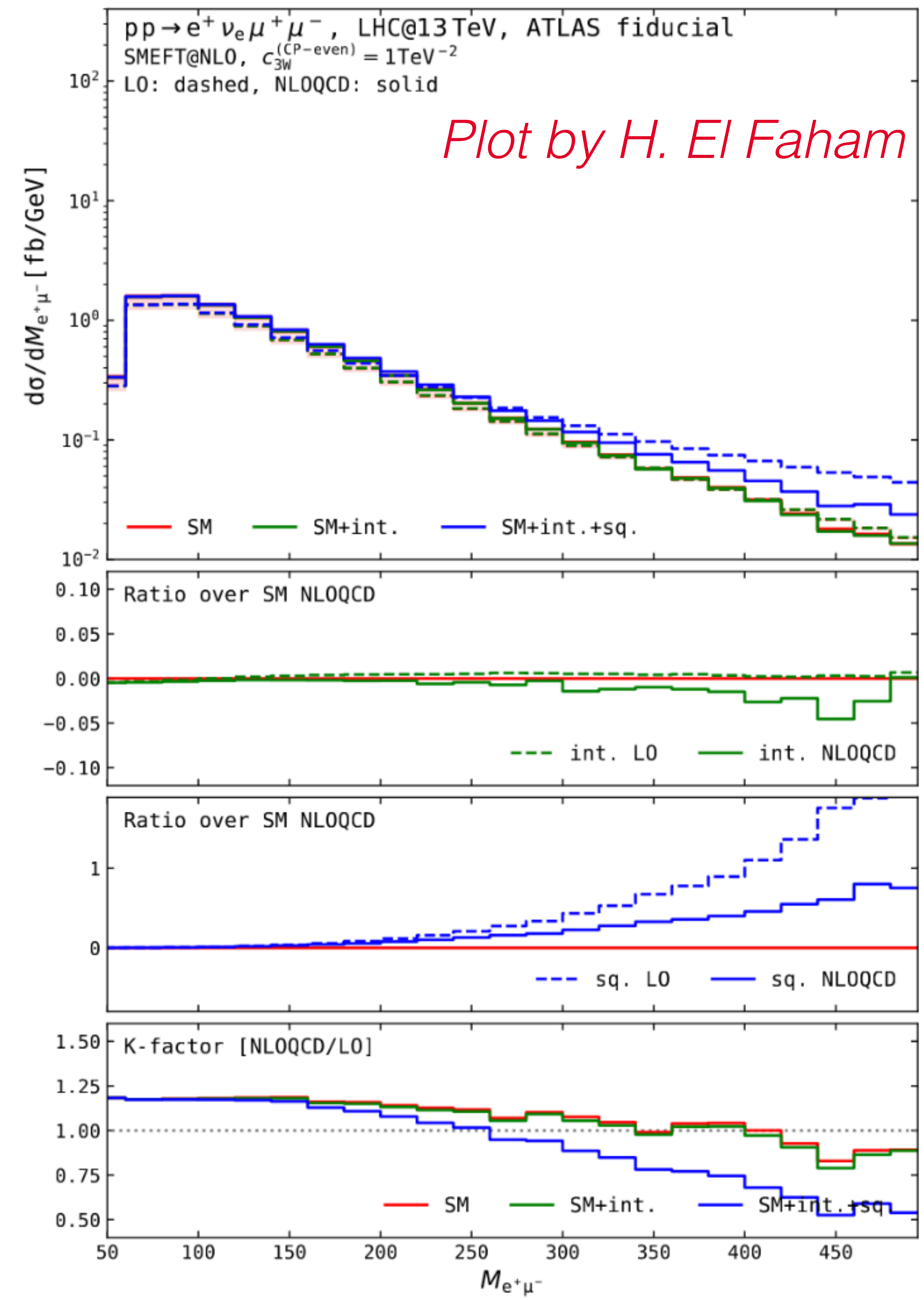
[Campanario, Englert & Spannowsky; PRD82 (2010) 054015 & PRD 83 (2011) 074009]
[Campanario, Roth & Zeppenfeld; PRD 91 (2015) 054039]
[Baglio et al.; PRD 101 (2020) 115004]

$pp \to VV$ @ NLO



$$\mathscr{A}_{EFT} \sim \frac{p_T^2}{\Lambda^2}$$

$$\mathscr{A}_{EFT} \sim \frac{q^2 < p_T^2}{\Lambda^2}$$



(b) ATLAS fiducial

Conclusions

Minimal global analysis of indirect NP sensitivity of triboson

- Reference sensitivity: EWPO & LEP & LHC diboson data
- Found significant impact at $O(\Lambda^{-4})$
- EFT validity is worse than expected, even for this small fit

EWPO flat space is a nice way to represent improvements

Large $O(\Lambda^{-4})$ effects in the EWPO constrained directions

- LHC diboson data crucial in lifting the secondary minima
- Improving EFT validity in these directions

QCD corrections to LHC diboson significantly impact bounds

- Important to not over-estimate our new physics reach

More data needed!

- Higgs, VBS, other rare EW processes?

Backup

SMEFT: SM v2.0

$(\bar{F}\sigma_{\mu\nu} f \tilde{\varphi})V^{\mu\nu}$ $(\varphi^\dagger\varphi)^3$

$(\bar{f}\gamma_\mu f)(\bar{F}\gamma^\mu F)$ $i(\varphi^\dagger \overleftrightarrow{D}^\mu \varphi)(\bar{f}\gamma^\mu f)$

$(\bar{F} f \tilde{\varphi})(\varphi^\dagger\varphi)$ $(\varphi^\dagger\varphi)V^{\mu\nu}V_{\mu\nu}$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_{i,D} \frac{c_i^{(D)}\mathcal{O}_i^{(D)}}{\Lambda^{D-4}}$$

BSM particle masses M ⇔ *Generic new physics scale* Λ

Taylor expansion of $\mathscr{A}_{BSM}$ ⇔ *Tower of operators* $\mathcal{O}_i^{(D)}$

$\mathcal{O}_i^{(D)} \supset$ SM $W^\pm$ Z H t …

Low energy (SM) fields & symmetries

Model parameters $\{g^i_{\rm BSM}, M_k\}$ ⇔ *Wilson coefficients* $\frac{c_j^{(D)}}{\Lambda^{D-4}}(g^i_{\rm BSM}, M_k)$

measure g_i *: new physics model parameters*

"Matching"

measure c_i *: coupling strengths of new BSM interactions*

SMEFT interpretation (fits)

Improving new physics reach means improving…

o_n
observables

$$\Delta o_n = o_n^{\mathrm{EXP}} - o_n^{\mathrm{SM}} = \sum_i \frac{a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu)}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

Global nature
As many observables as possible

Identify patterns & correlations in fits

Exploit energy-growth

Sensitivity
Experiment:
Best measurements & understanding of uncertainties and correlations

Theory:
Best available predictions for observables (NLO, NNLO, N3LO,…)

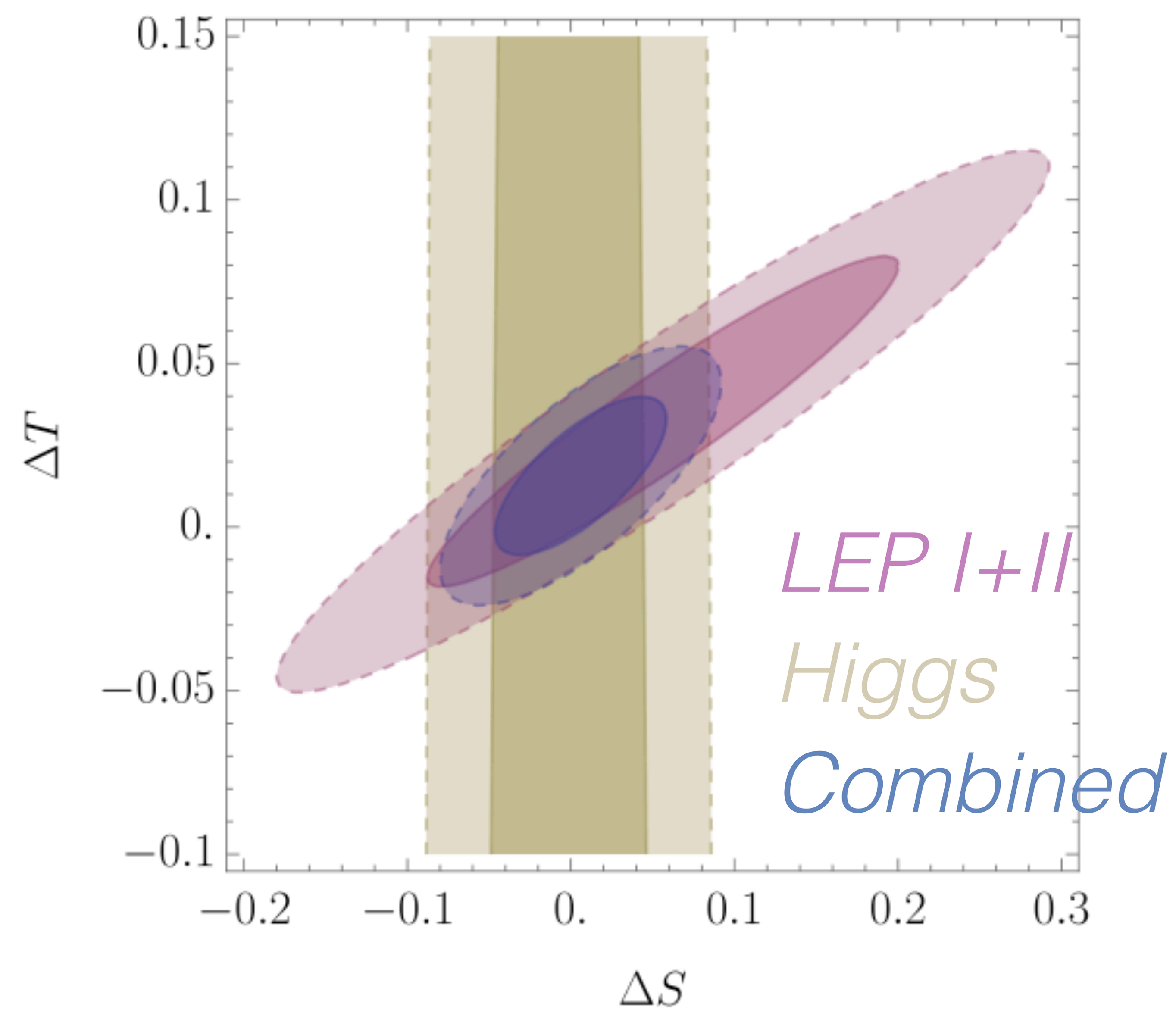
Interpretation
Relies on accurate knowledge of the size & correlation among a_i

Determining $c_i^{(6)}$ requires most precise available SMEFT predictions

Interplay

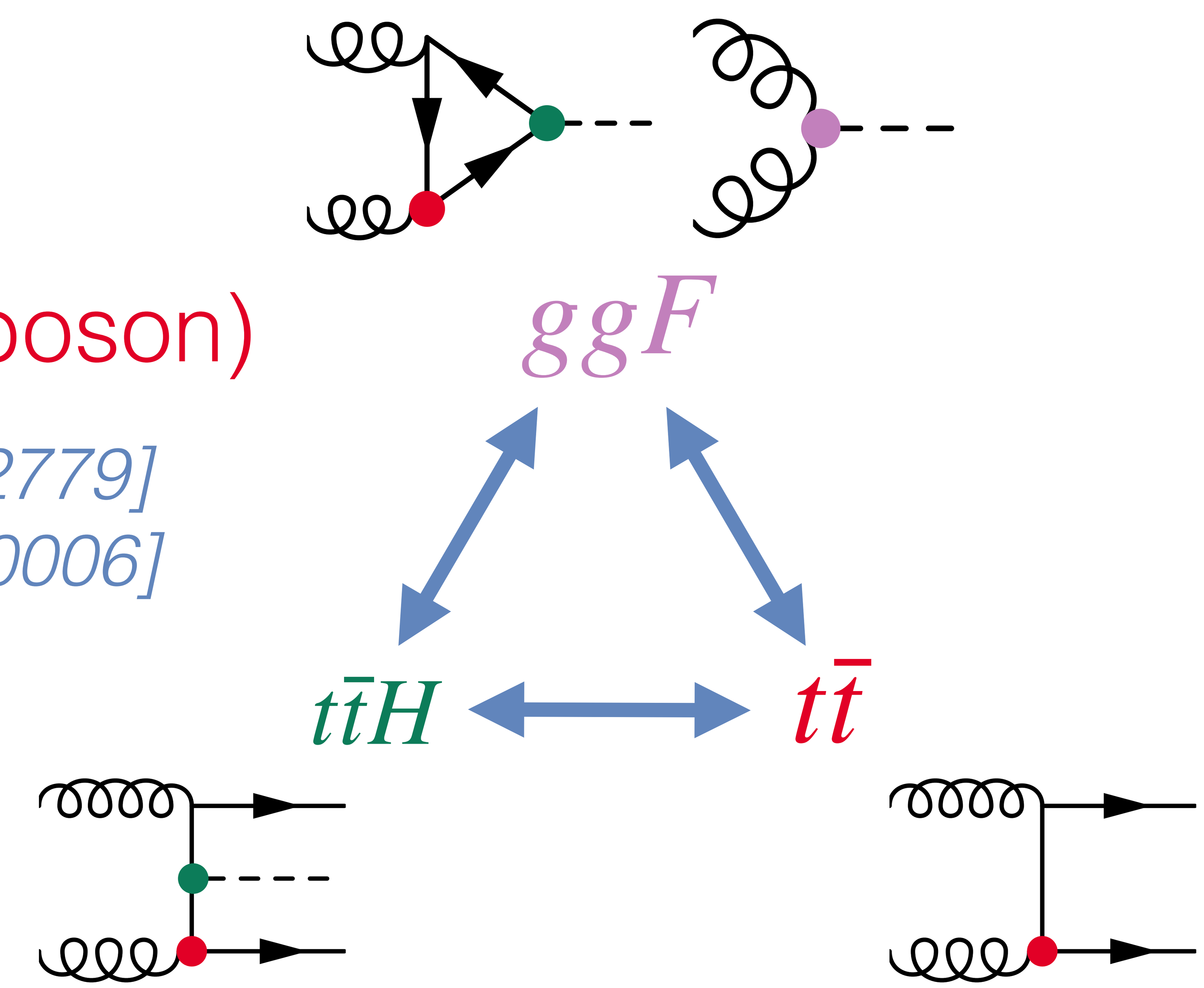
Higgs & EWPO

[Ellis et al.; 1803.03252]



Top & Higgs (EWPO, Diboson)

fitmaker: [Ellis et al.; 2012.02779]
SMEFiT: [Ethier et al; 2105.00006]



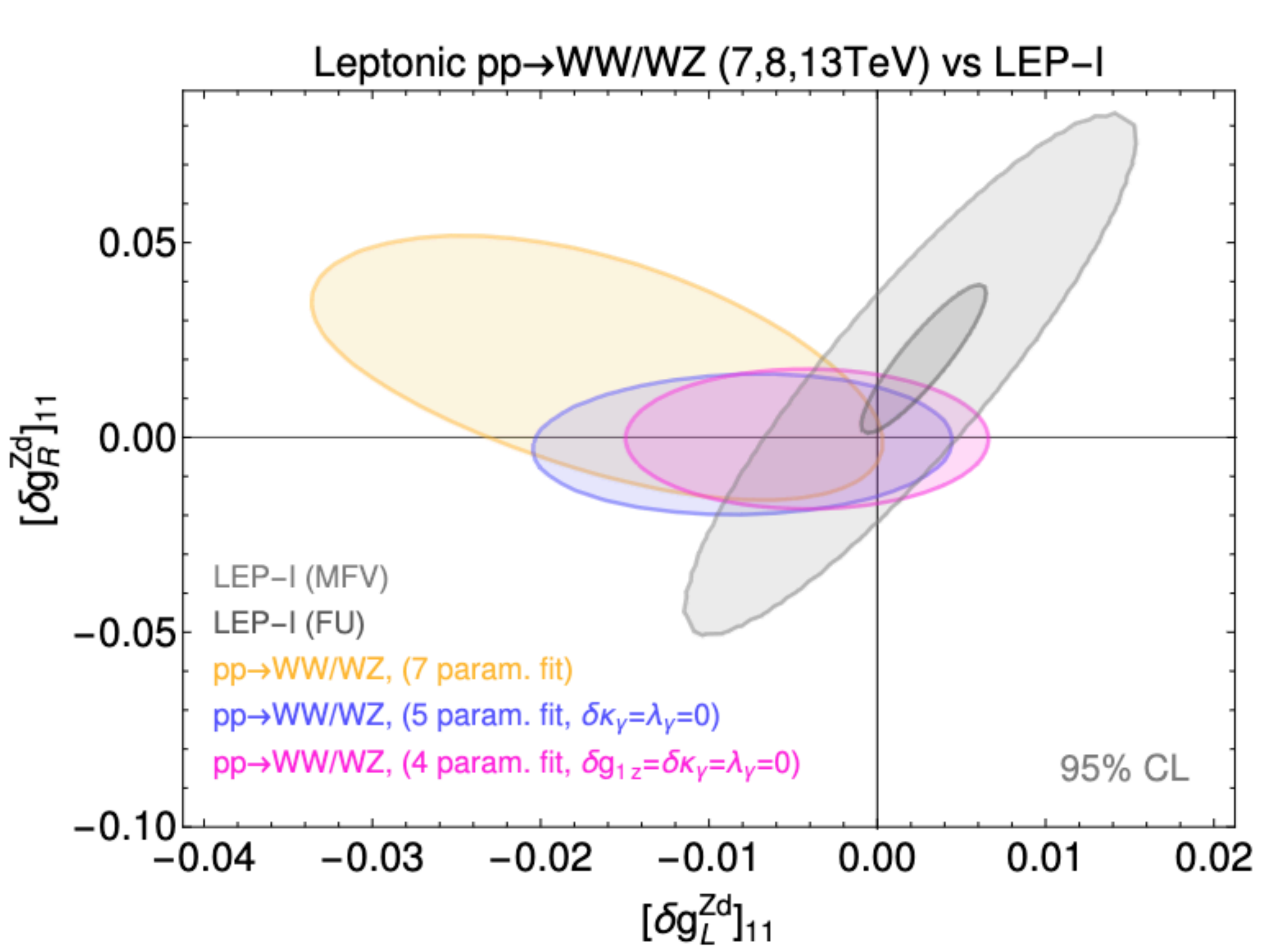
Where does being global matter?

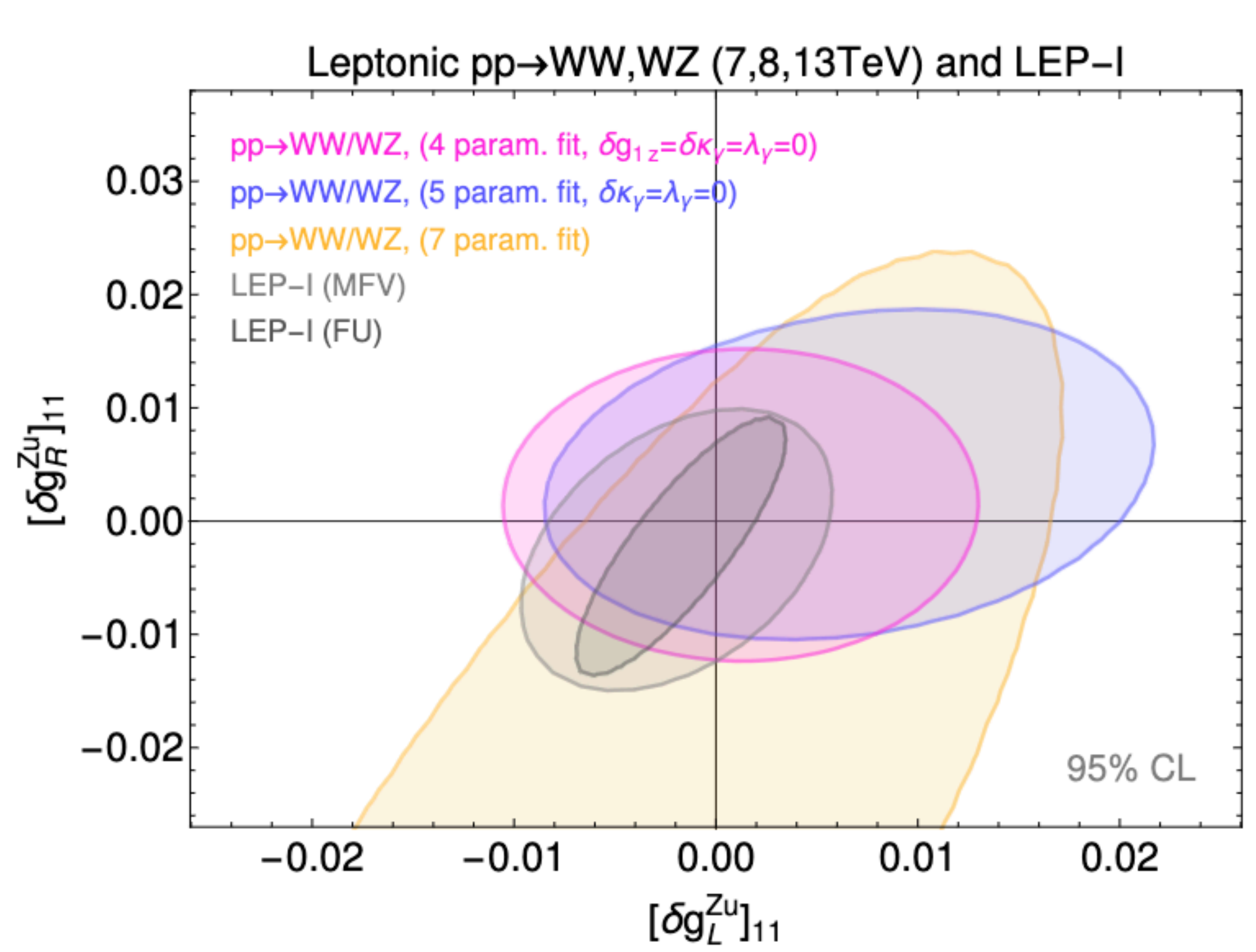
Flavor, LEP II & Higgs

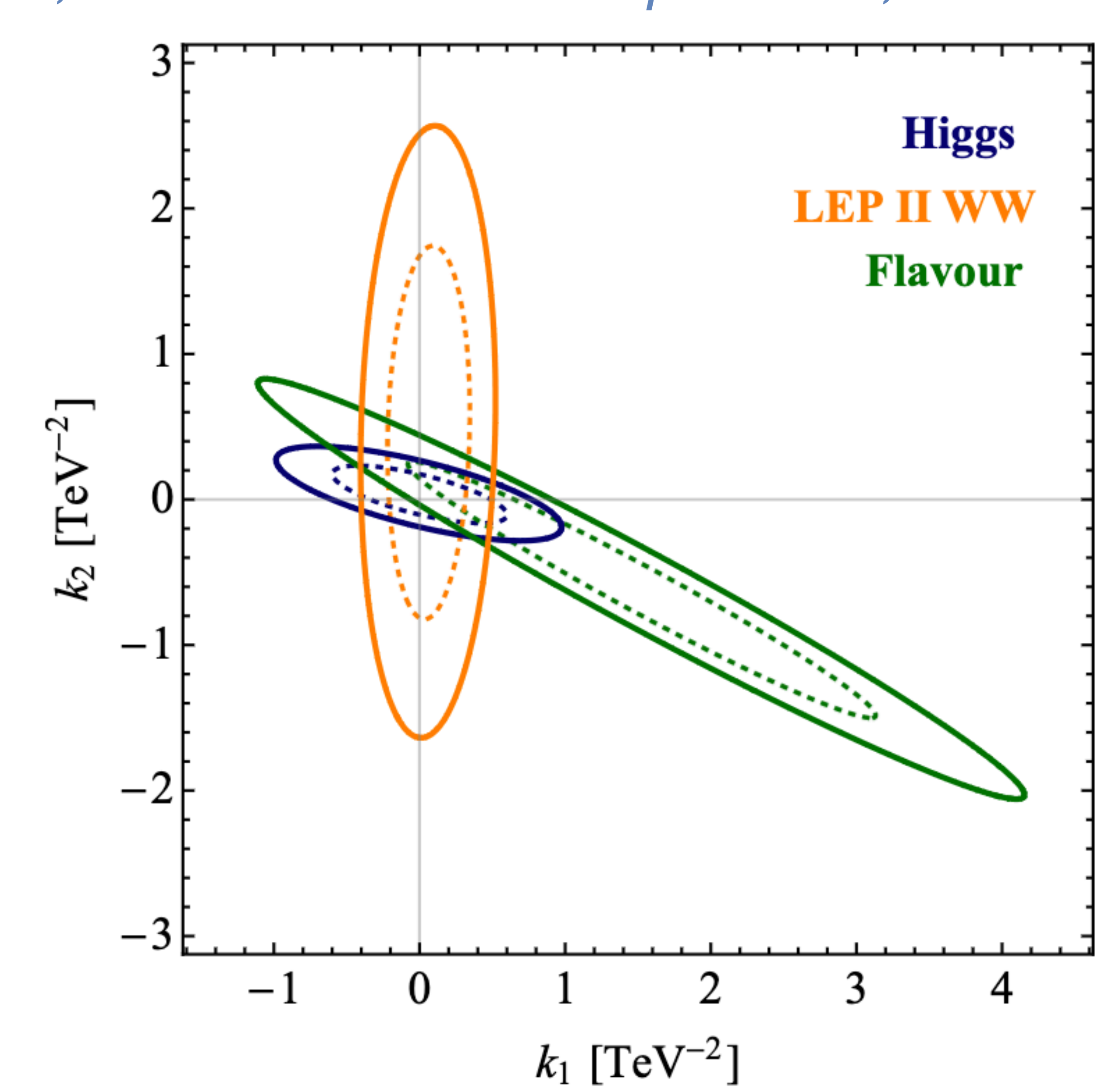
[Aoude, Hurth, Renner & Shepherd; 2003.05432]

Diboson & EWPO

[Grojean, Montull & Riembau; 1810.05149]

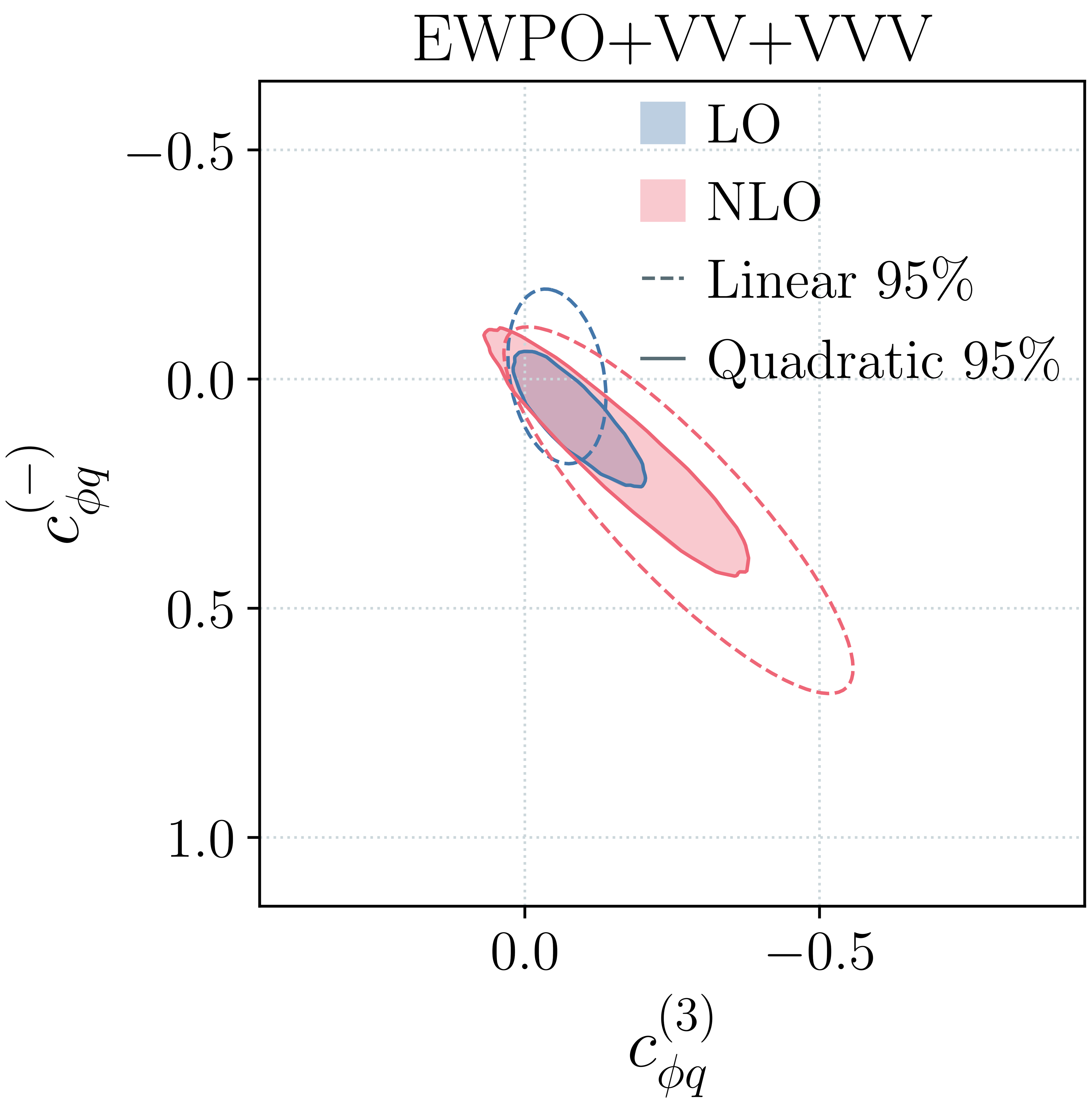




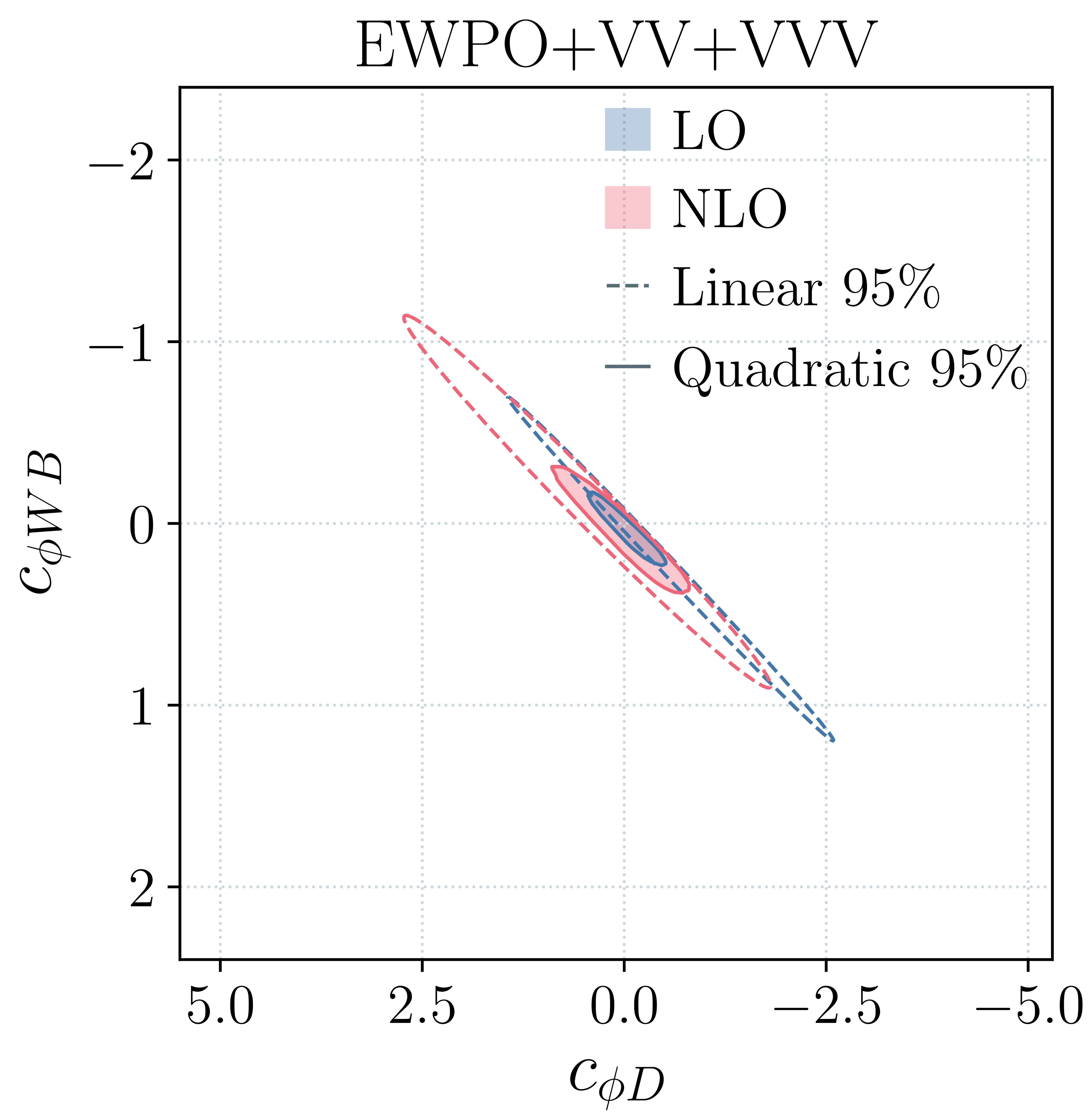


1,2 & 3 bosons

NLO vs LO



EWPO+VV+VVV
LO
NLO
Linear 95%
Quadratic 95%
−0.5
0.0
0.5
1.0
0.0
−0.5
$c_{\phi q}^{(-)}$
$c_{\phi q}^{(3)}$



EWPO+VV+VVV
LO
NLO
Linear 95%
Quadratic 95%
−2
−1
0
1
2
5.0
2.5
0.0
−2.5
−5.0
$c_{\phi WB}$
$c_{\phi D}$