SMEFT fits

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Les Rencontres de Physique de la Vallée d'Aoste, La Thuile

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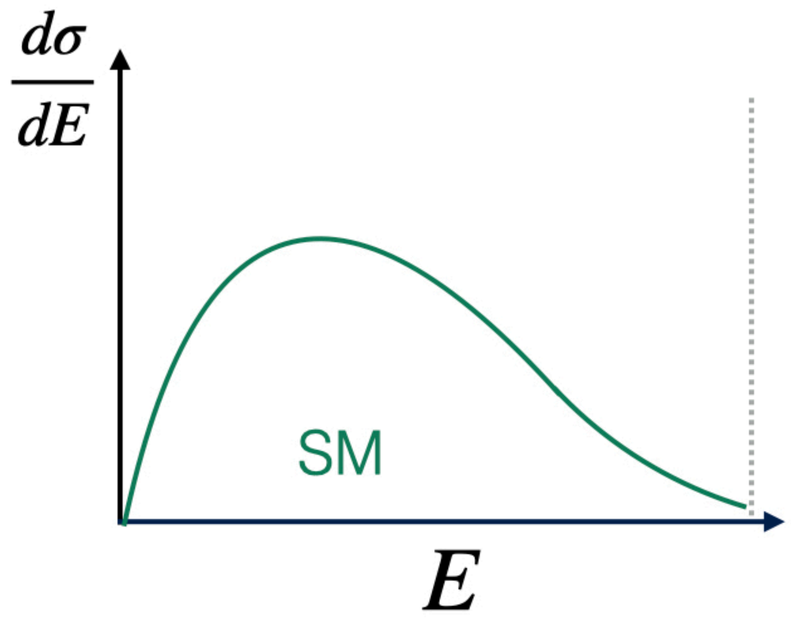
Science and Technology Facilities Council

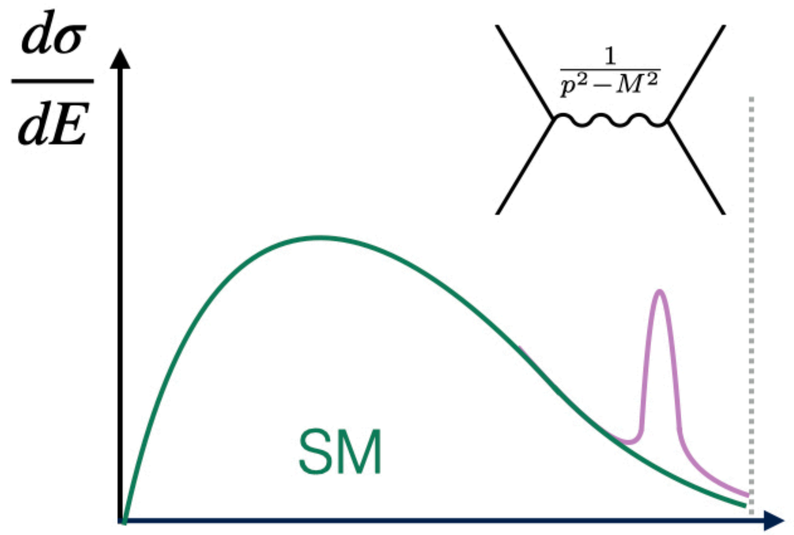
University of Southampton

Energy & precision for BSM



Energy & precision for BSM

2010s: energy
Direct (bumps)

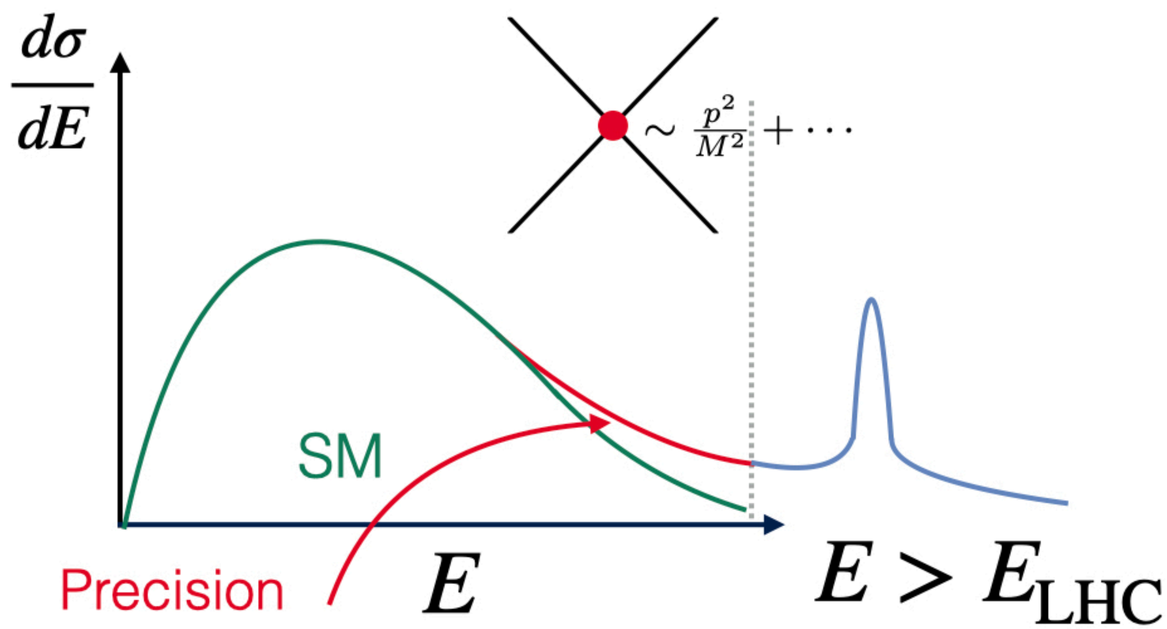


Energy & precision for BSM

2010s: energy
Direct (bumps)

2020s: intensity
Indirect (tails/precision)

⇒ New physics is heavy



measurements

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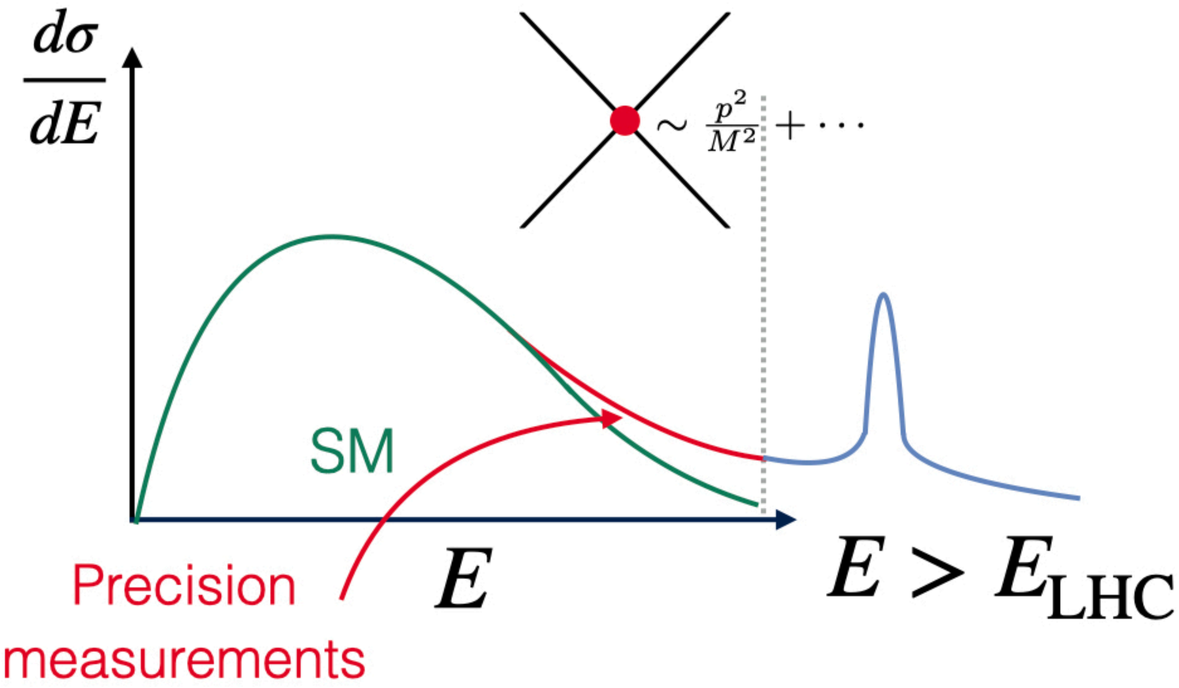

measurements

Heavy new physics
Precision measurements
High energy

Effective Field Theory (EFT)

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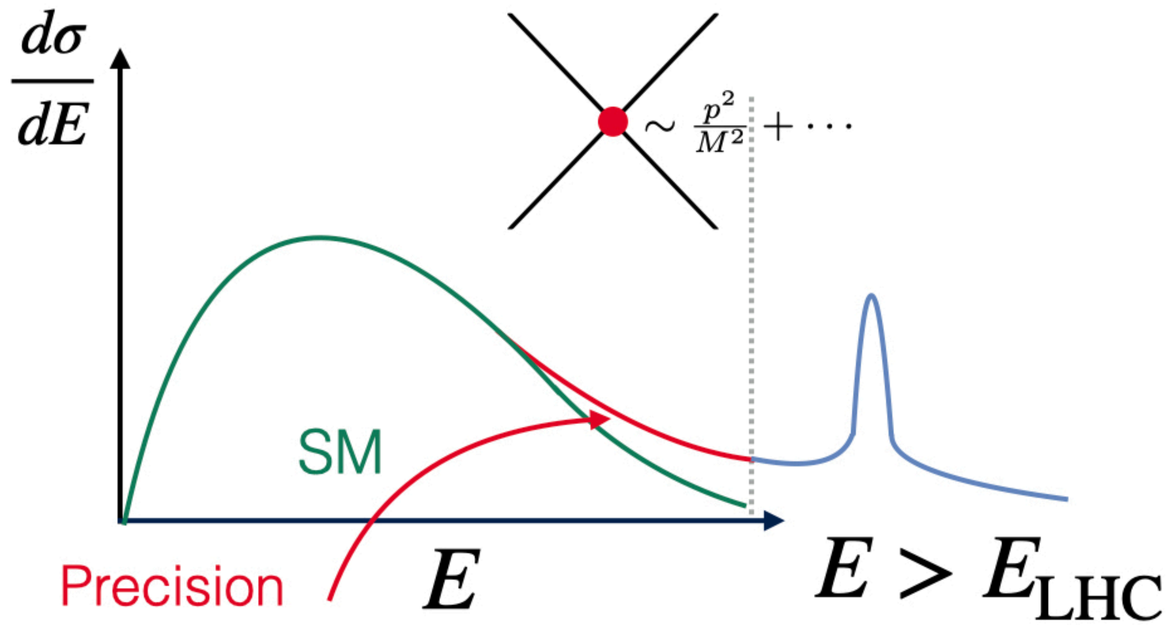

measurements

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Effective Field Theory (EFT)

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

SMEFT: SM v2.0

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

$(\varphi^\dagger\varphi)^3$

$(\bar{f}\gamma_\mu f)(\bar{F}\gamma^\mu F)$

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

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

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

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BSM particle masses M $\Leftrightarrow$ *Generic new physics scale* Λ

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

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

Low energy (SM) fields & symmetries

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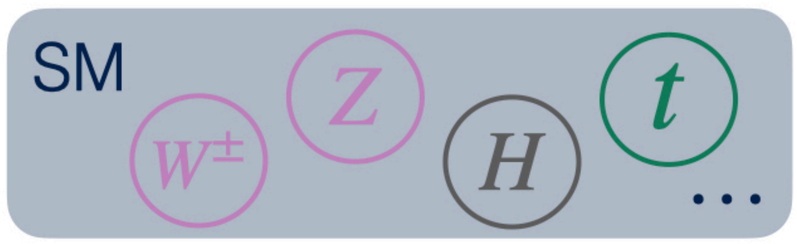
$\mathcal{O}_i^{(D)} \supset$ 

Low energy (SM) fields & symmetries

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

measure g_i : new physics model parameters

"Matching"

measure c_i : coupling strengths of new BSM interactions

SMEFT is…

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

Model independent

- Underlying assumptions

Heavy new physics: M > E_{exp}
SM field content & gauge symmetries
Linear EWSB: Higgs = doublet

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Systematically improvable

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

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

SMEFT interpretation (fits)

o_n *observables*

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

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Improving new physics reach means improving…

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Identify patterns & correlations in fits

Exploit energy-growth

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Experiment:
Best measurements & understanding of uncertainties and correlations

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

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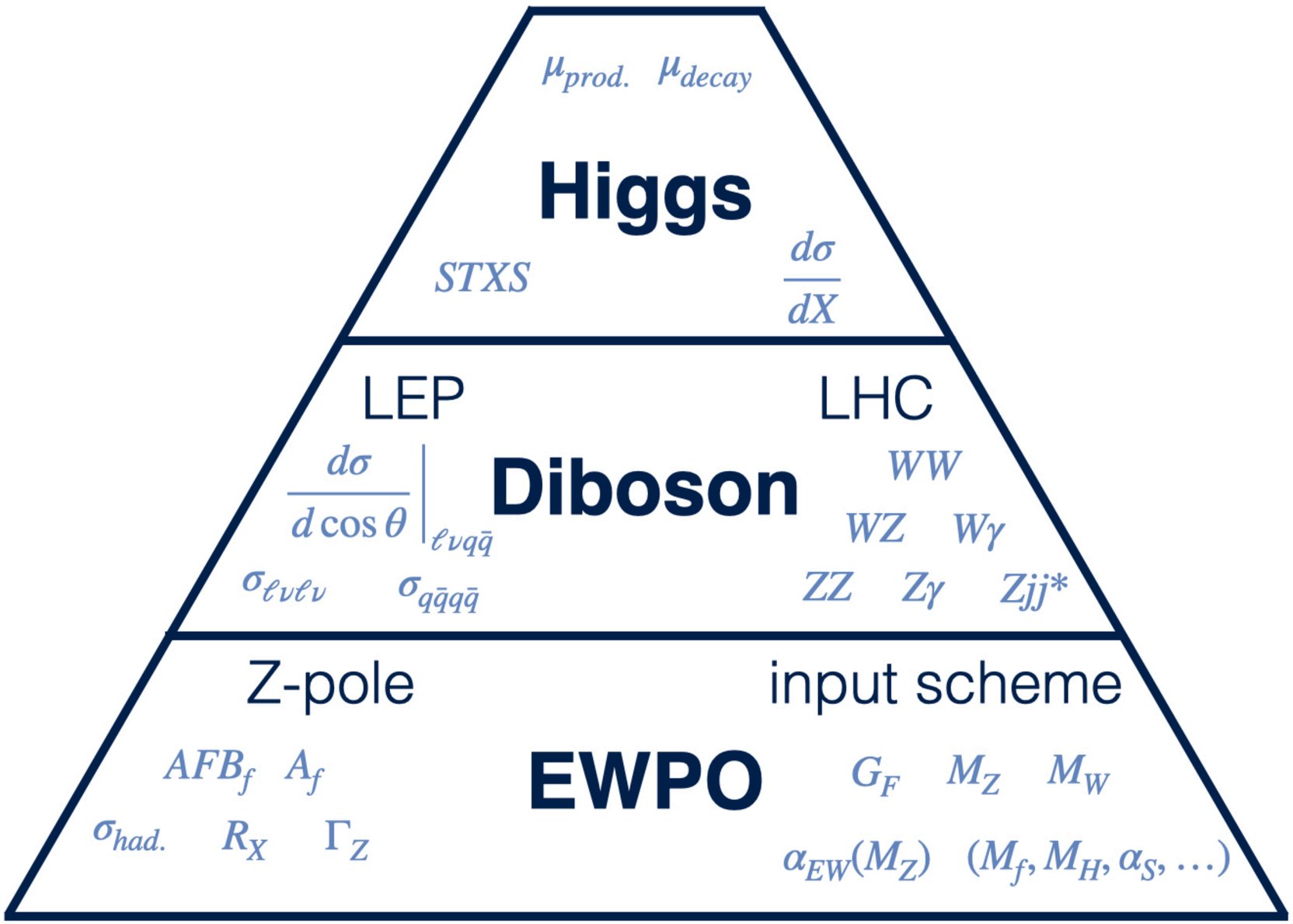
Interpretation

Relies on accurate knowledge of the size & correlation among a_i

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

Datasets


$\mu_{prod.}$ μ_{decay}
Higgs
$STXS$
$\frac{d\sigma}{dX}$
LEP
LHC
$\frac{d\sigma}{d\cos\theta}\Big|_{\ell\nu q\bar{q}}$
Diboson
WW
WZ $W\gamma$
$\sigma_{\ell\nu\ell\nu}$ $\sigma_{q\bar{q}q\bar{q}}$
ZZ $Z\gamma$ Zjj^*
Z-pole
input scheme
AFB_f A_f
EWPO
G_F M_Z M_W
$\sigma_{had.}$ R_X Γ_Z
$\alpha_{EW}(M_Z)$ $(M_f, M_H, \alpha_S, \ldots)$

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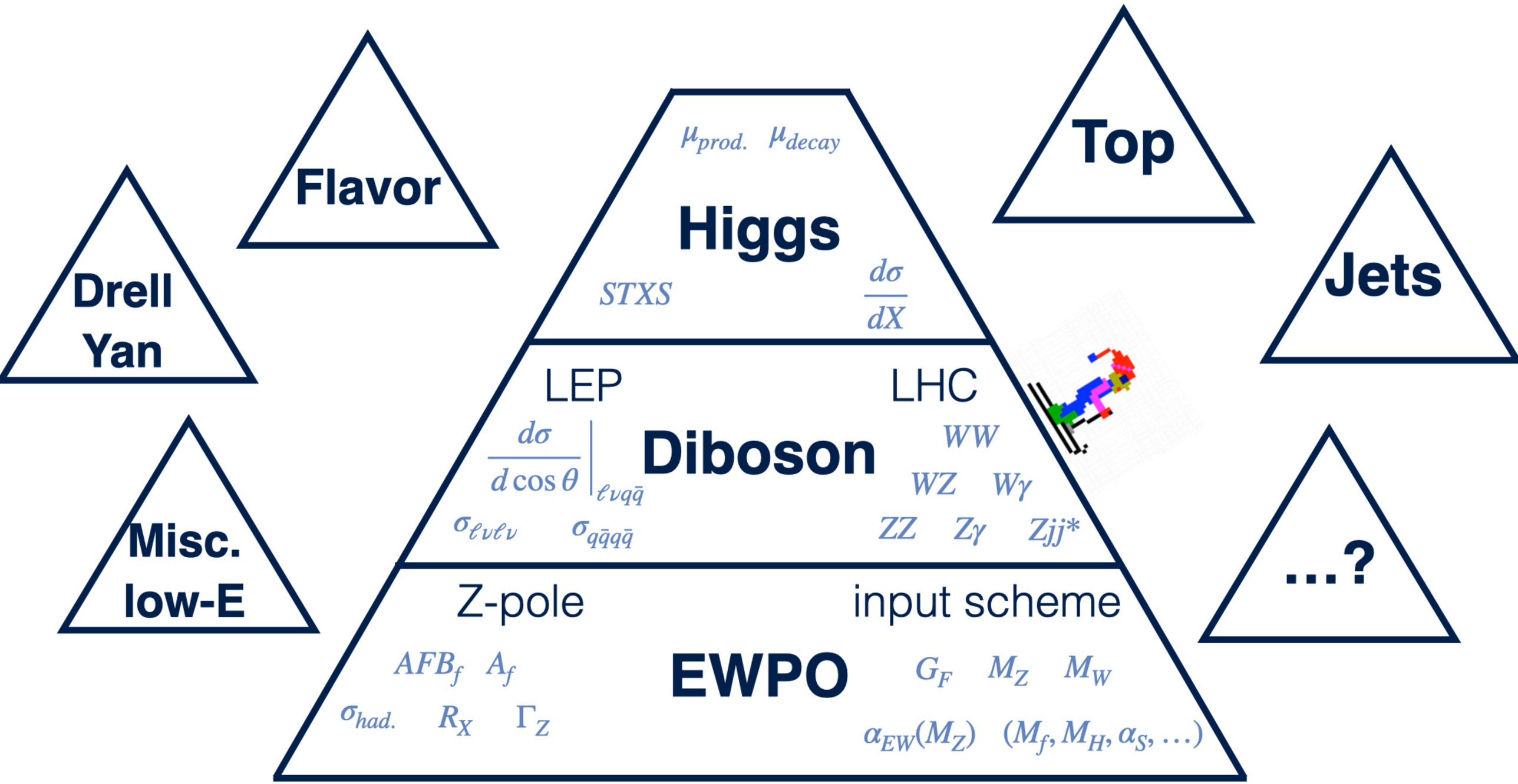
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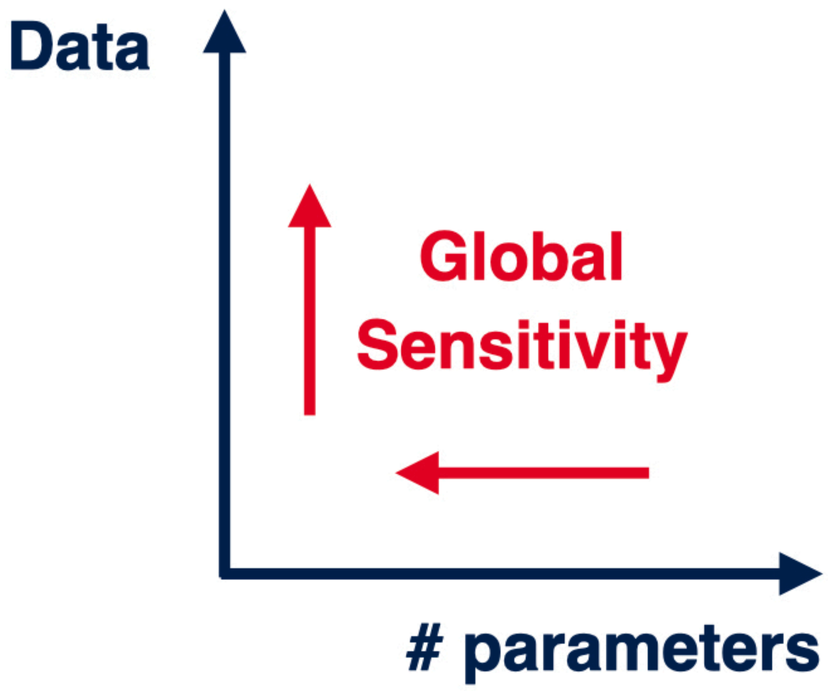
Breadth and sensitivity



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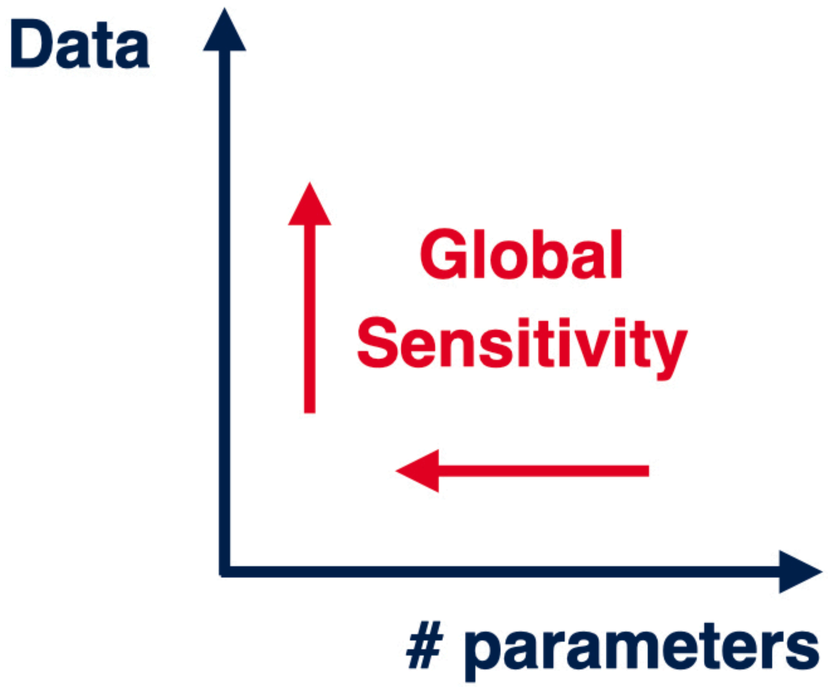

[Buchmuller & Wyler; Nucl. Phys. B 268 (1986) 621]

Dimension-6 SMEFT *[Grzadkowski et al.; 1008.4884]*

- O(3000) parameters (independent operators)

Symmetry assumptions

- B/L conservation
- CP conservation
- Flavor symmetries

$U(3)_L \times U(3)_Q \times U(3)_e \times U(3)_u \times U(3)_d$

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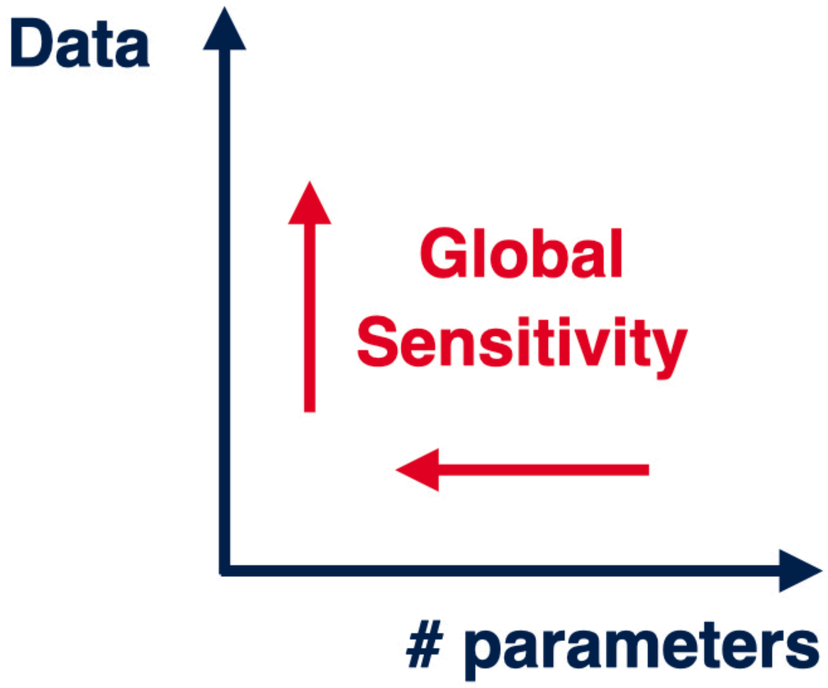

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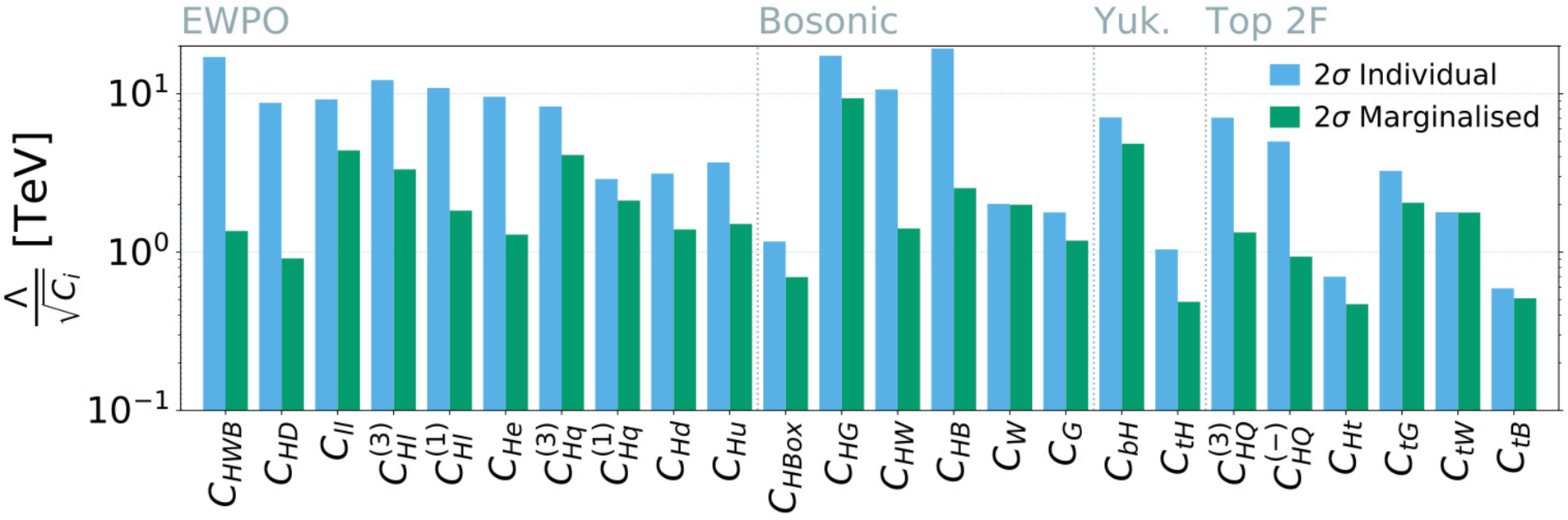

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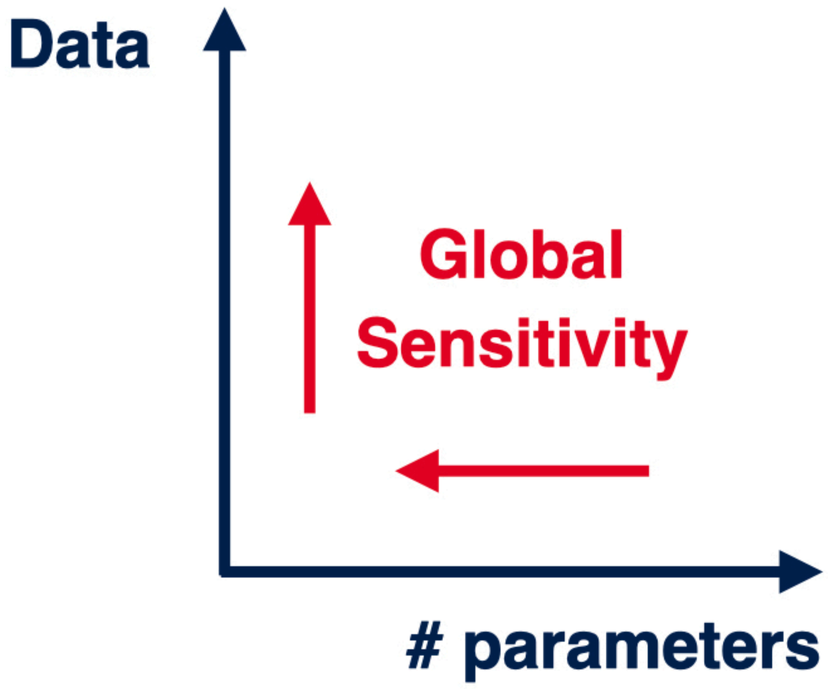

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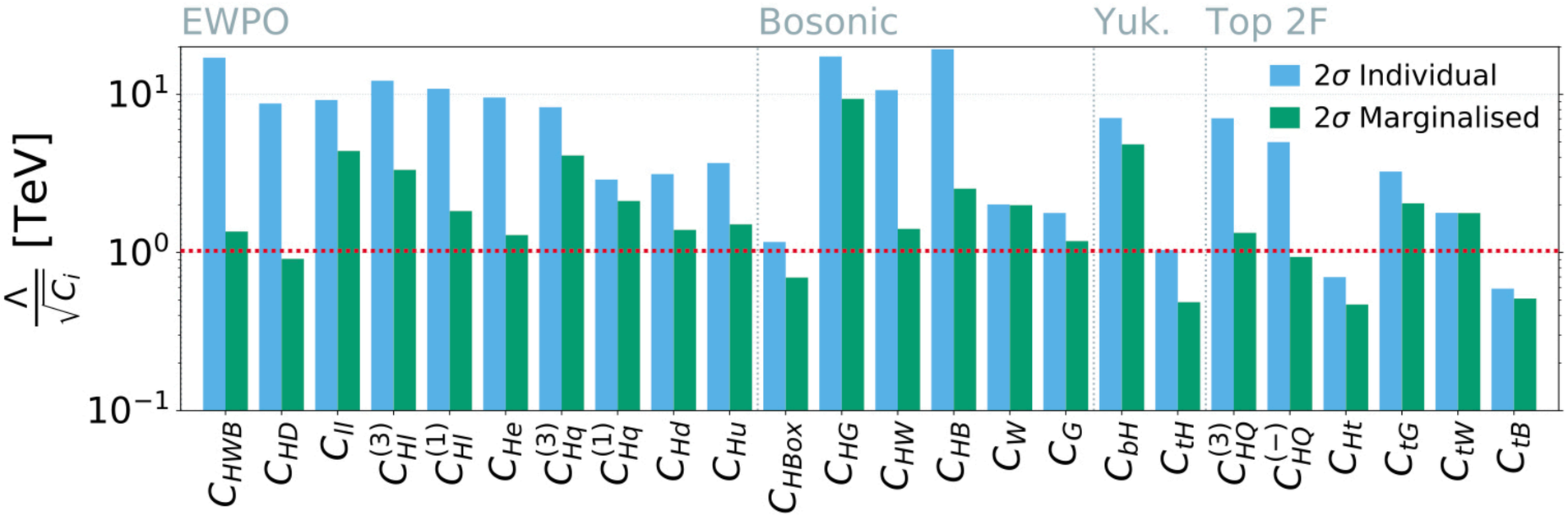
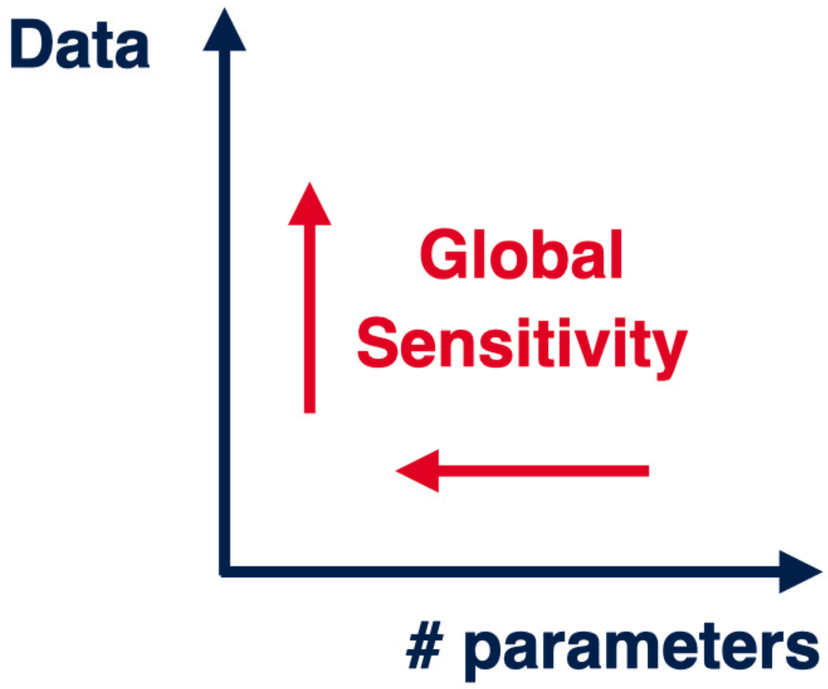


TeV-scale new physics

Breadth and sensitivity



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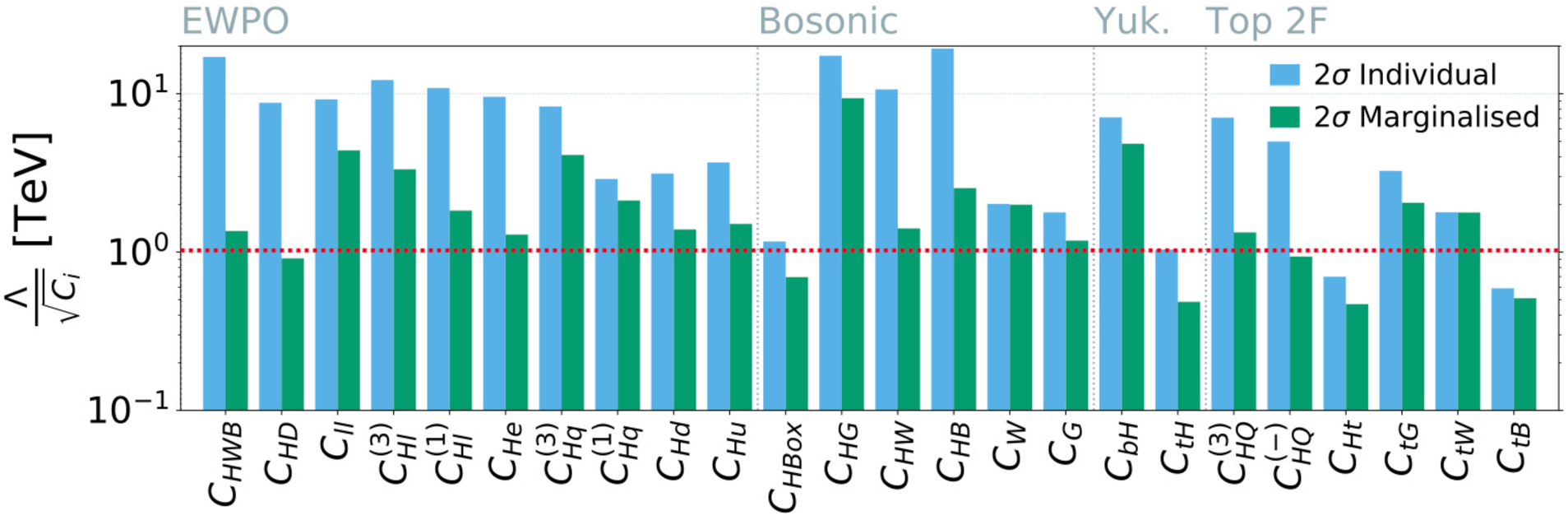


TeV-scale new physics

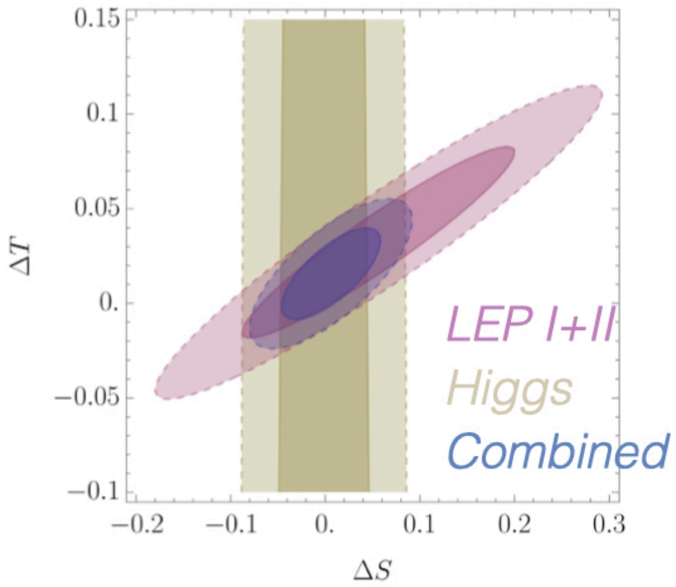
Hierarchies in sensitivity

EWPO $\gtrsim$
Diboson/Higgs $>$
Top

Interplay

Higgs & EWPO

[Ellis et al.; 1803.03252]



Top & Higgs (EWPO, Diboson)

fitmaker: [Ellis et al.; 2012.02779]
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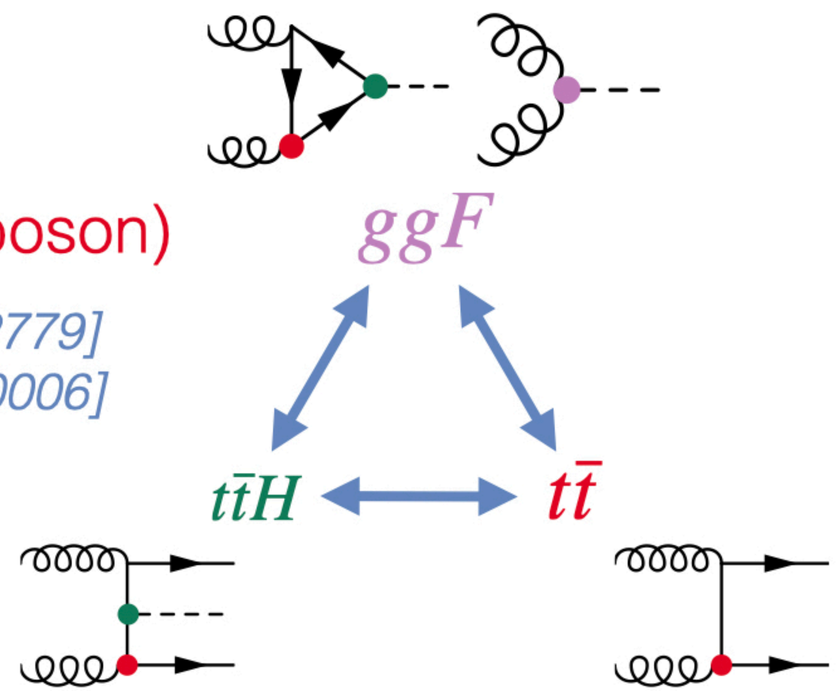
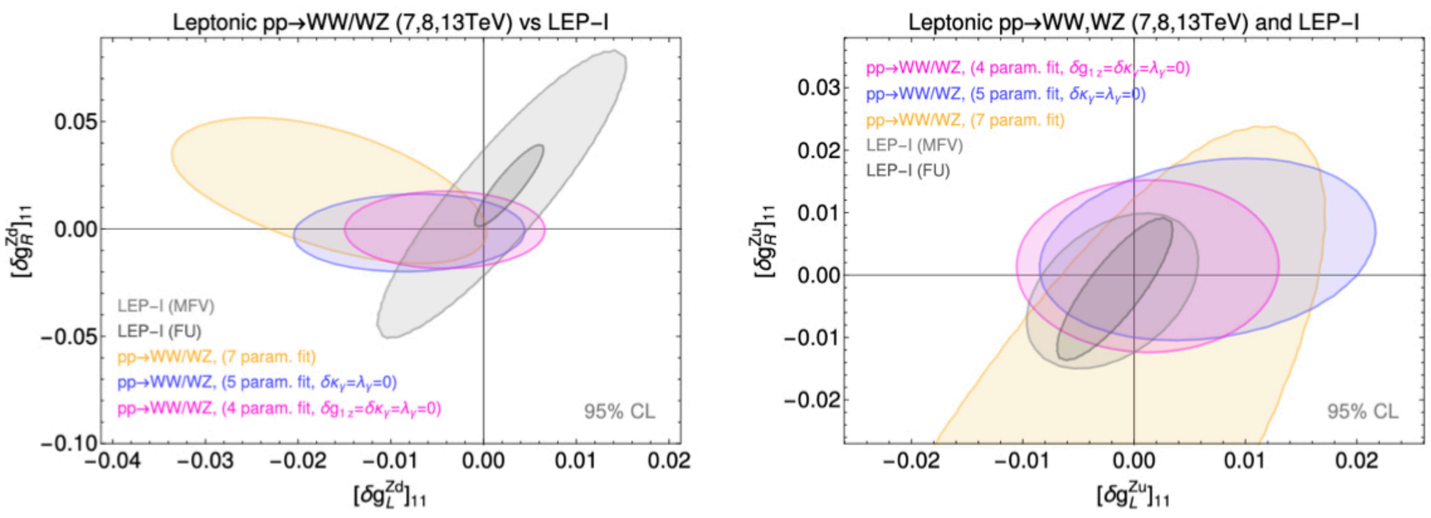


Where does being global matter?

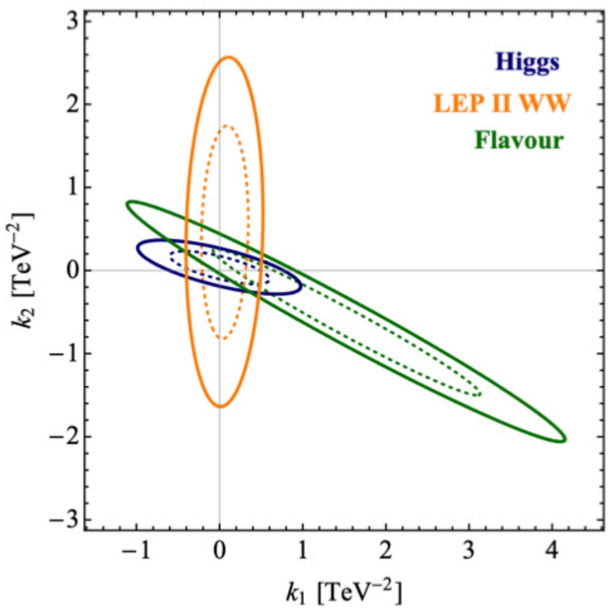
Diboson & EWPO

[Grojean, Montull & Riembau; 1810.05149]



Flavor, LEP II & Higgs

[Aoude, Hurth, Renner & Shepherd; 2003.05432]

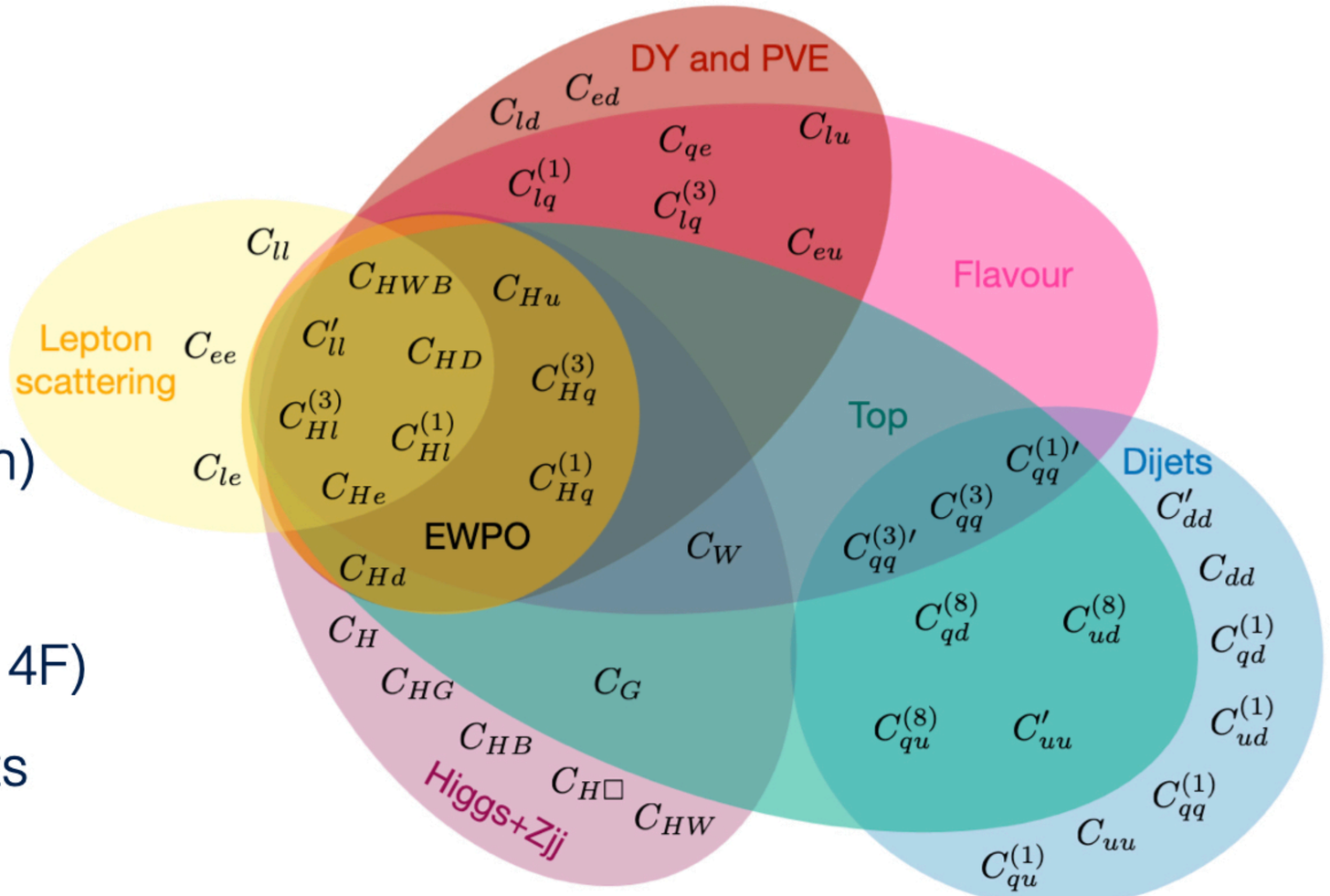


[Bartocci, Biekötter & Hurth; 2311.04963]

MFV fit

Global fit to the MFV SMEFT

- Exact $U(3)^5$: 41 operators (CP even)
- No LR interactions (Yukawa/dipole)
- Flavour universal interactions (2F & 4F)
- Synthesis of many public fit datasets



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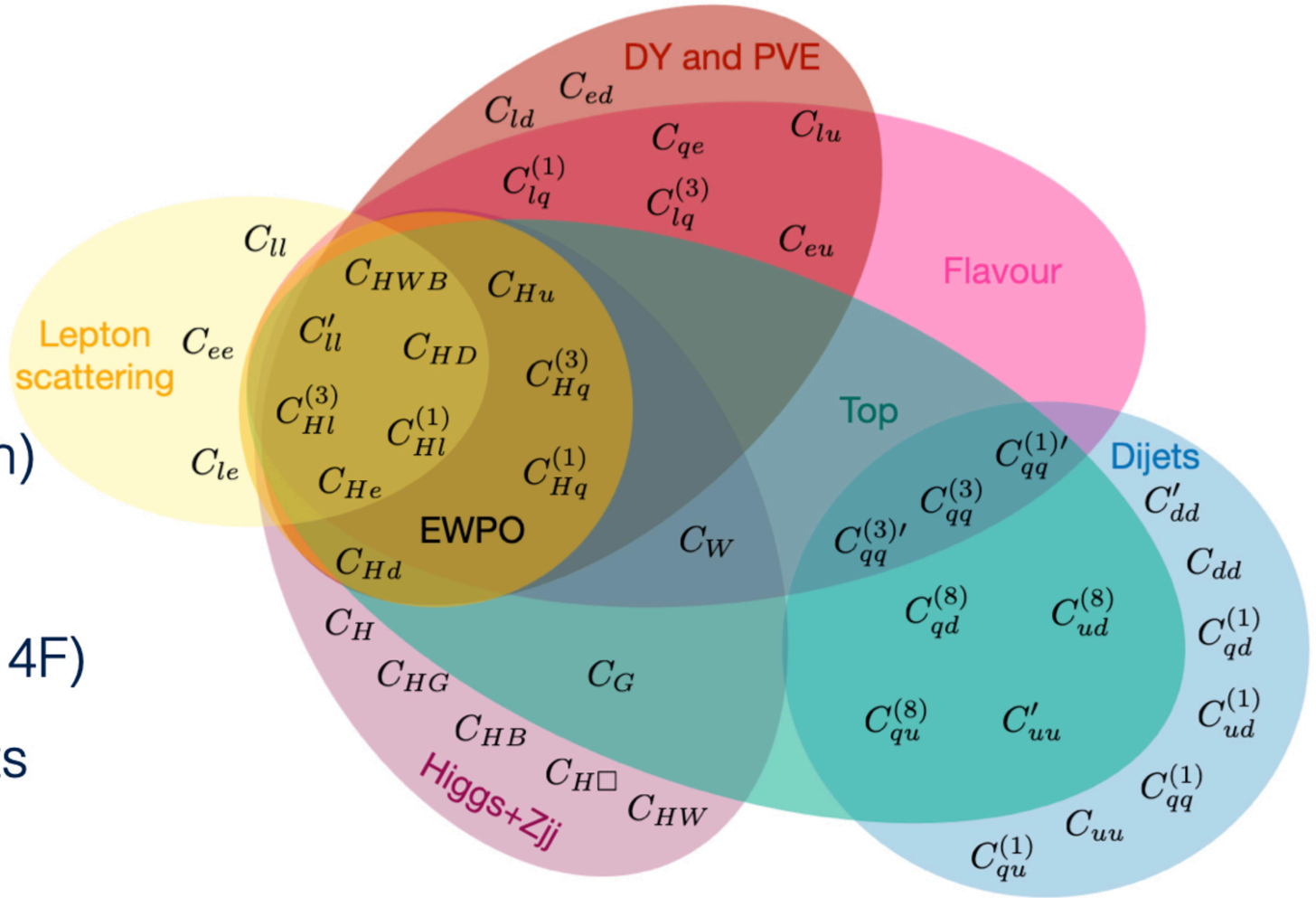
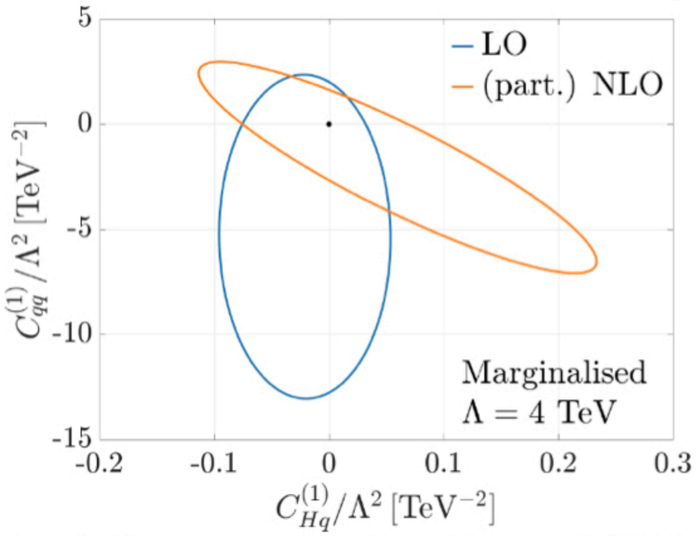
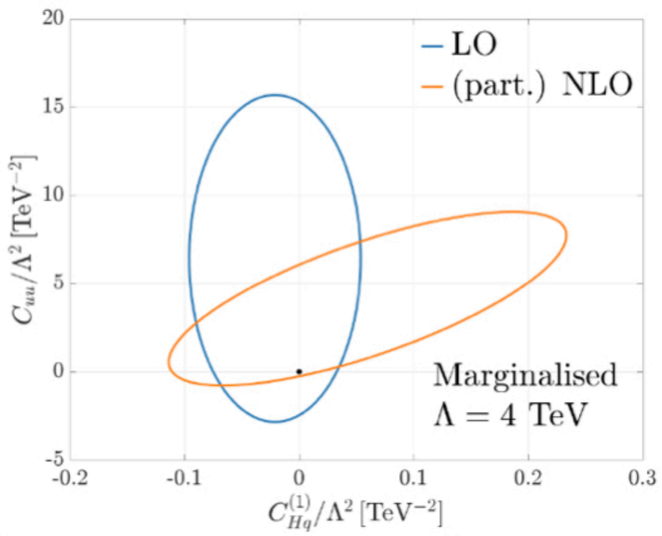


Partial NLO results

- EWPO (QCD & EW) *[Dawson & Giardino; 1909.02000, 2201.09887]*
- Selected Top/Higgs *SMEFiT: [Ethier et al; 2105.00006]* *[Alasfar, de Blas & Gröber; 2202.02333]*





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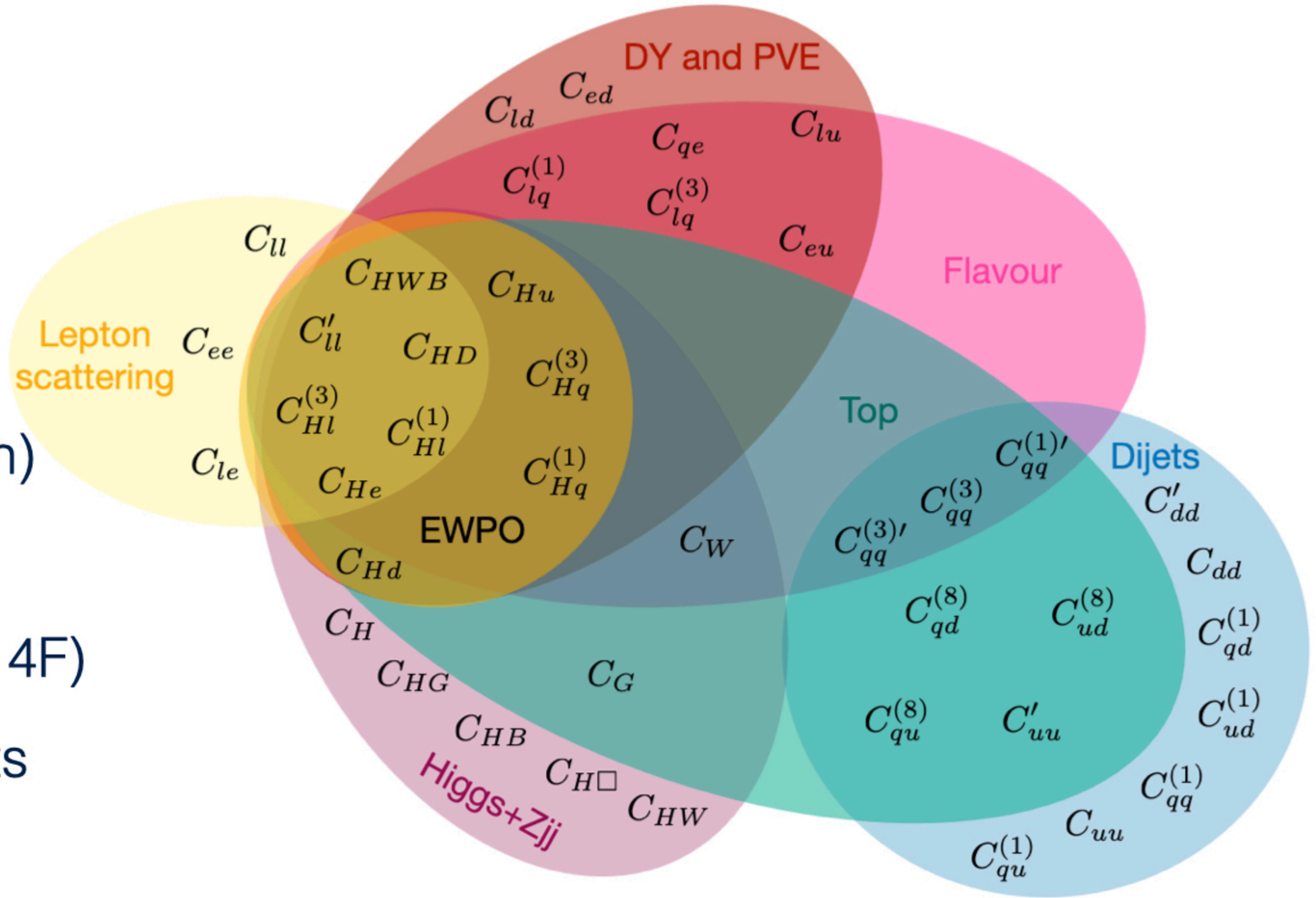

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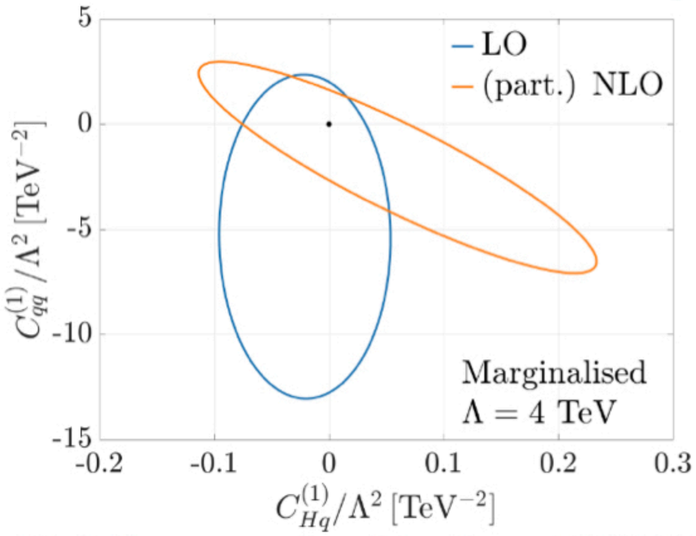
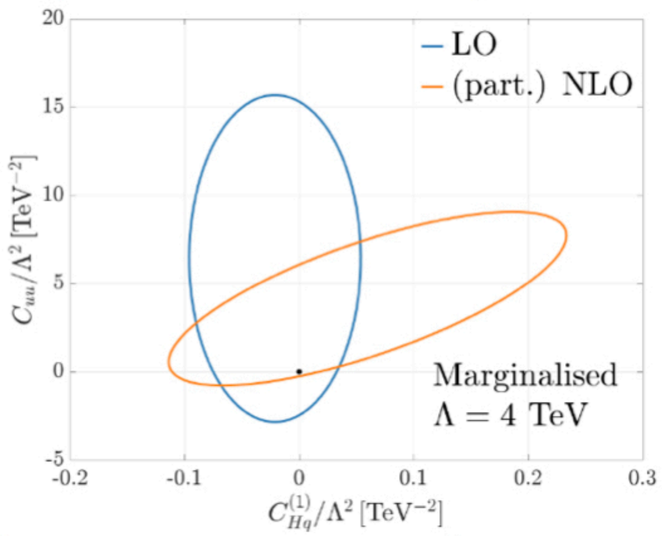
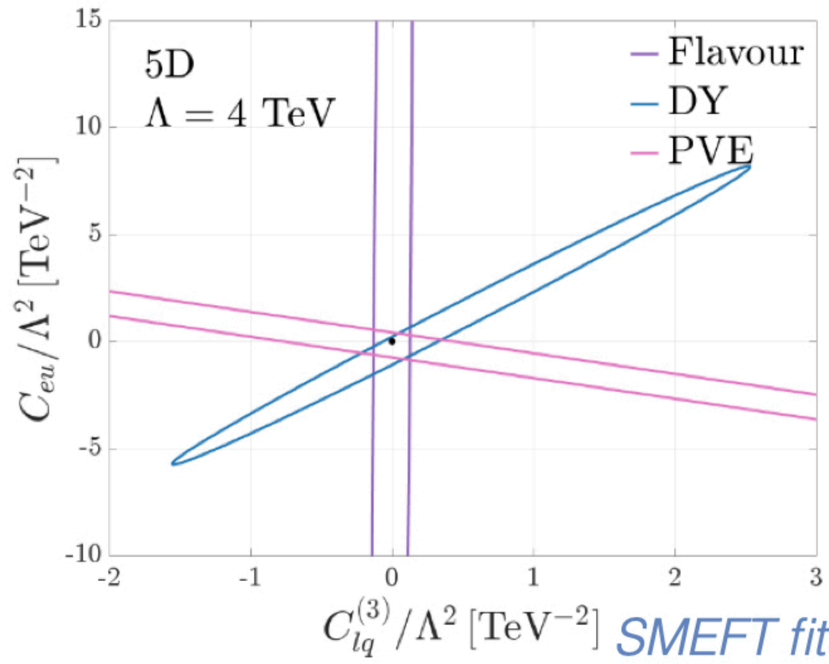




Low/high p_T interplay



[ATLAS-PHYS-PUB-2022-037]

Experimental fits

Z-pole @ LEP + Diboson @ LHC & Higgs STXS

- First experimental SMEFT combination of LHC & EWPO
- External inputs from theoretical literature
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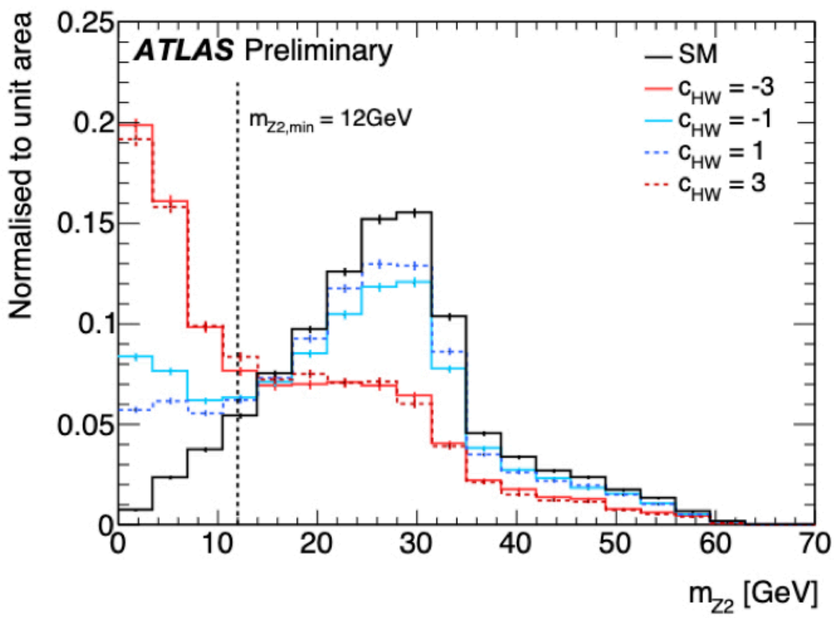

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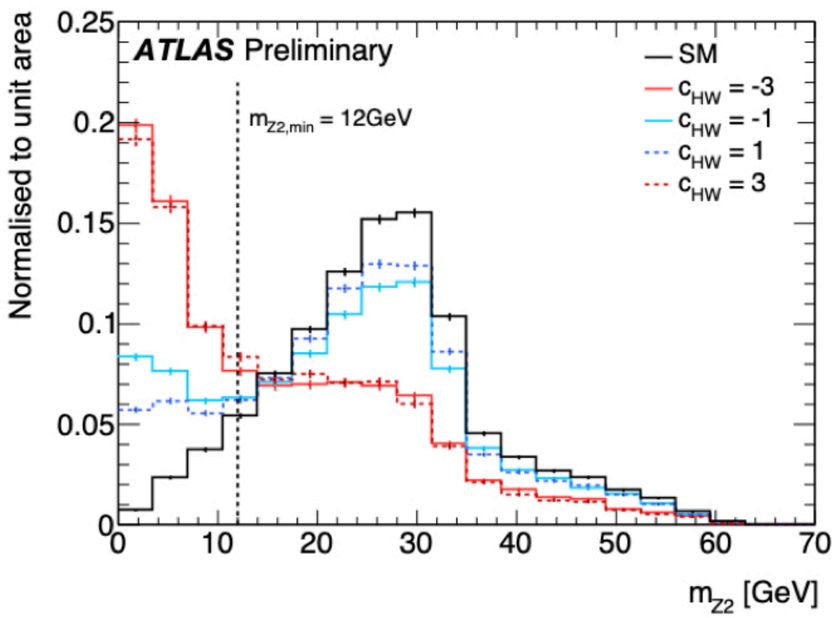

Under-constrained

⇓

Principal component analysis

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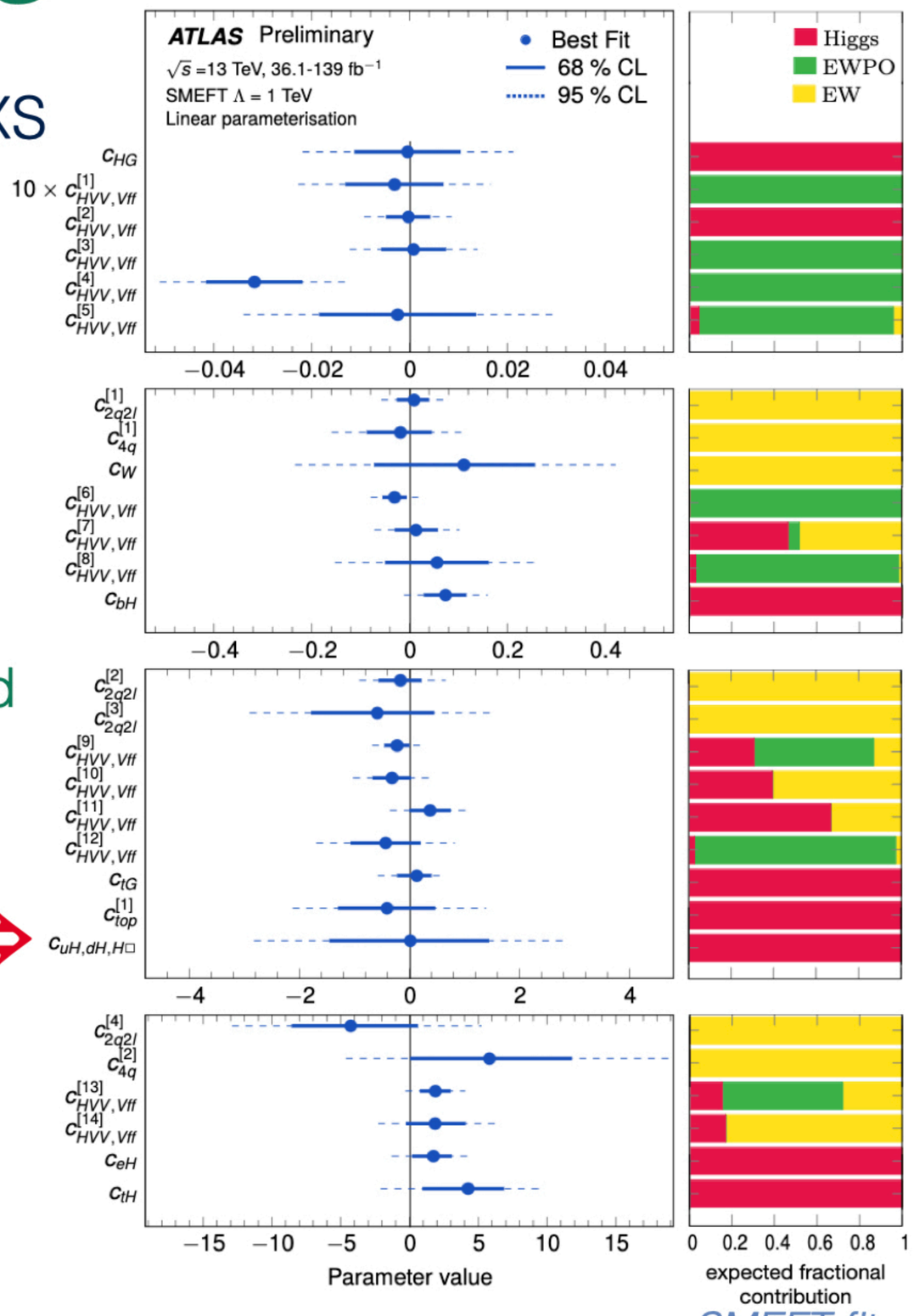

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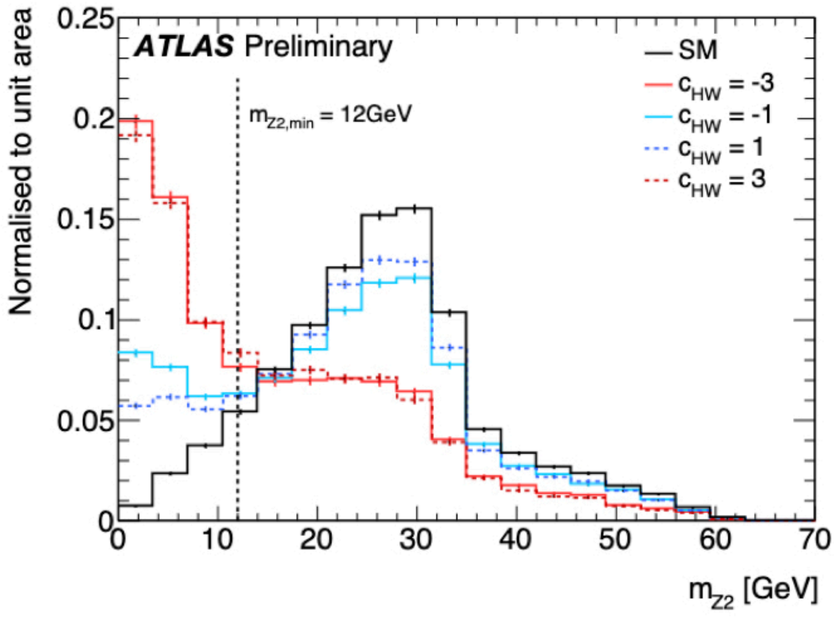


Under-constrained

⇓

Principal component analysis

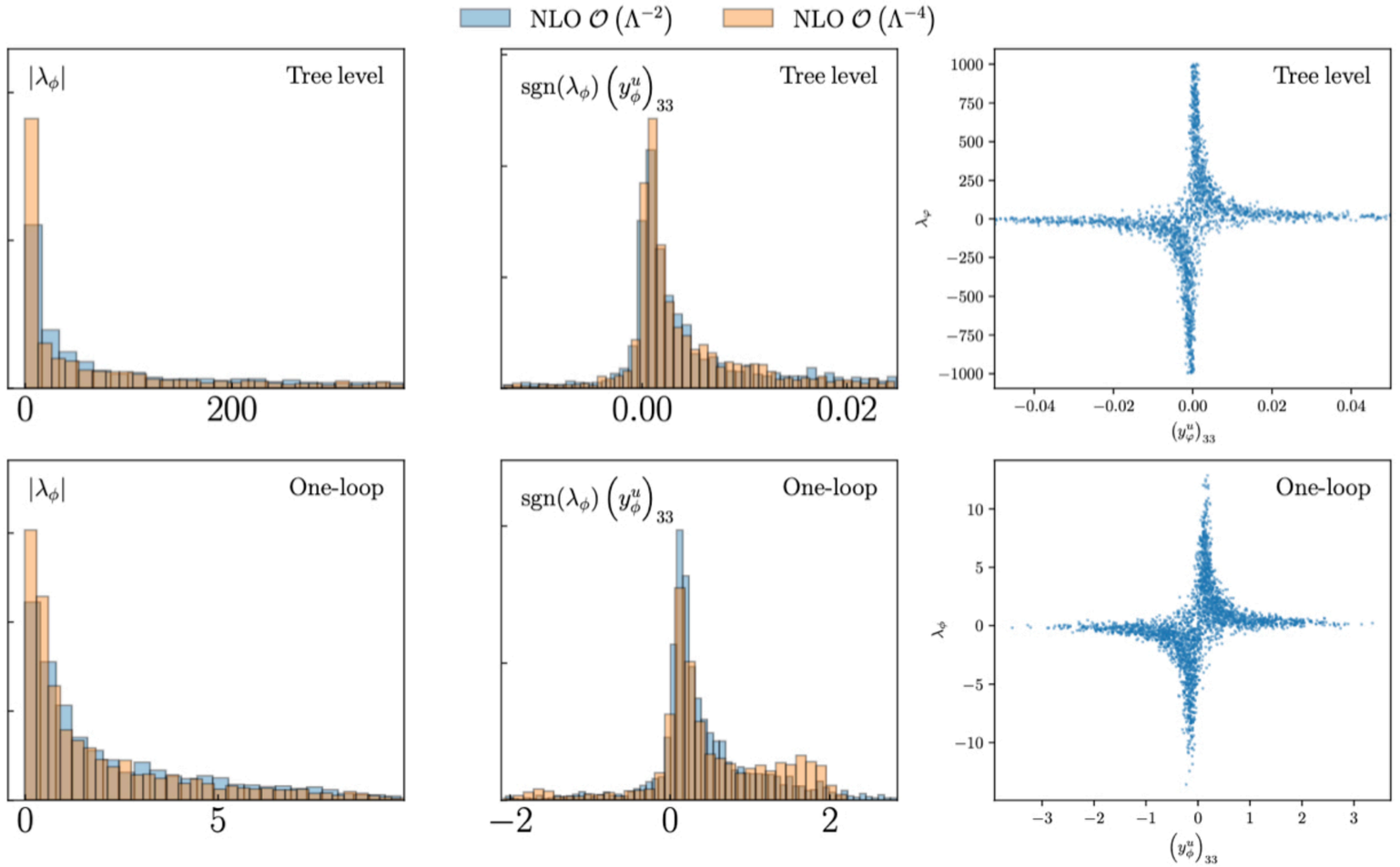
⇒

Automated UV connection

matchmakereft ⇒ **match2fit** ⇒ SMEFiT

[Carmona et al.; 2112.10787] [Giani et al.; 2302.06660]

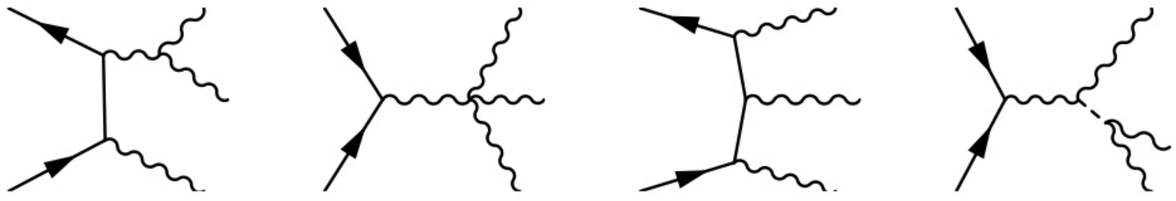
$$\mathcal{L}_{\rm UV} = \mathcal{L}_{\rm SM} + |D_\mu \phi|^2 - m_\phi^2 \phi^\dagger \phi - \Big((y_\phi^e)_{ij}\, \phi^\dagger \bar{e}_R^i \ell_L^j + (y_\phi^d)_{ij}\, \phi^\dagger \bar{d}_R^i q_L^j + (y_\phi^u)_{ij}\, \phi^\dagger i\sigma_2 \bar{q}_L^{T,i} u_R^j + \lambda_\phi\, \phi^\dagger \varphi |\varphi|^2 + \text{h.c.} \Big)$$



[E. Celada, G. Durieux, KM, E. Vryonidou; WIP]

Triboson in the SMEFT

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



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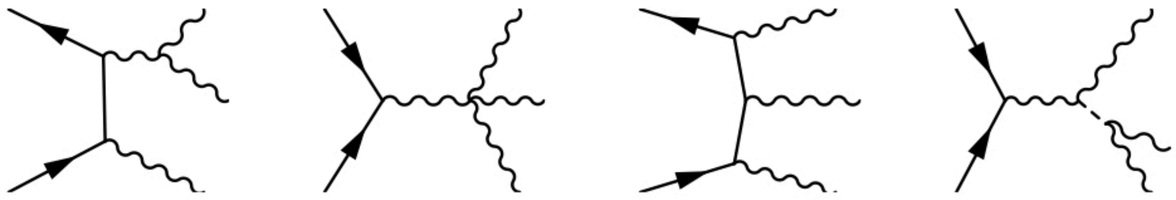

Many VVV processes measured in recent years

- Sensitivity to many (B)SM couplings in production & decay [Degrande et al; 2008.11743] [Bellan et al; 2303.18215]
- So far, only $\sigma_{tot.}$ in leptonic W/Z channels with 20-100% precision

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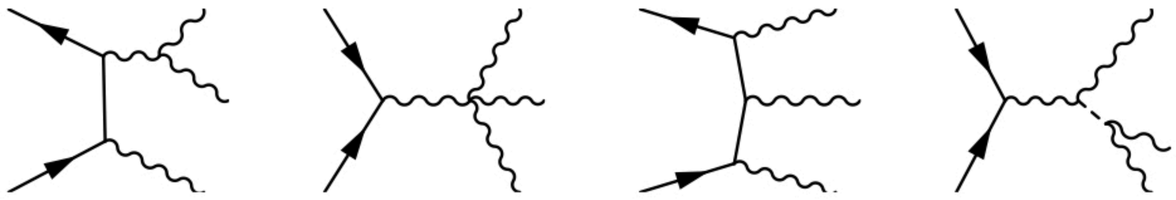

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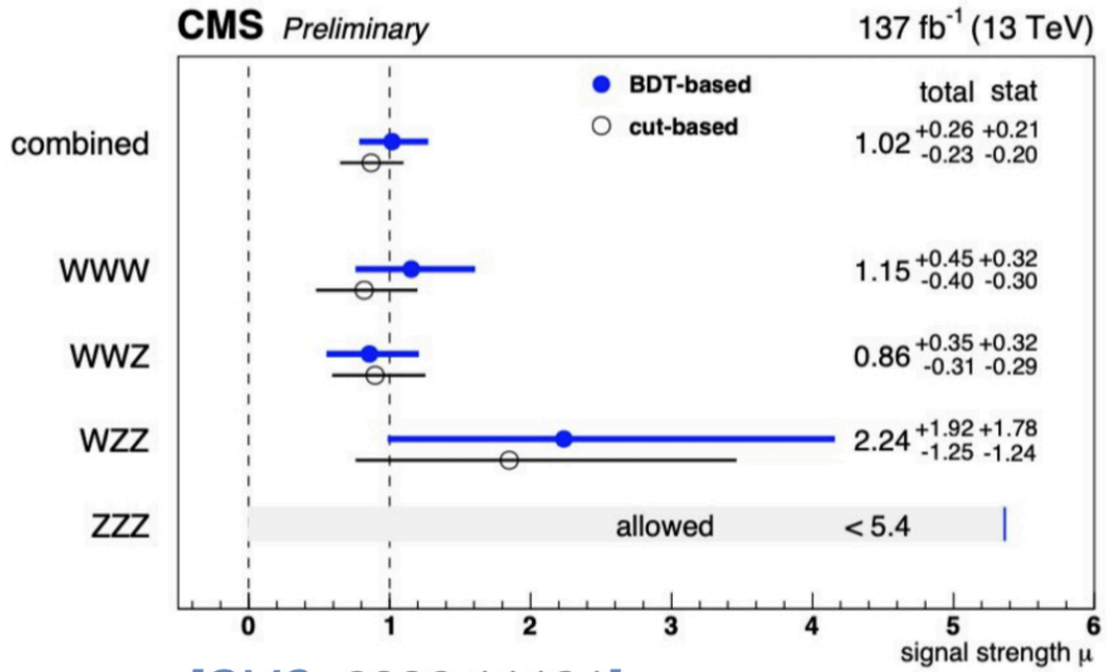

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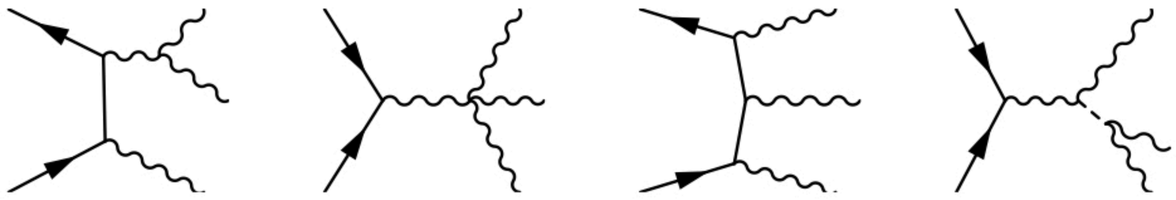

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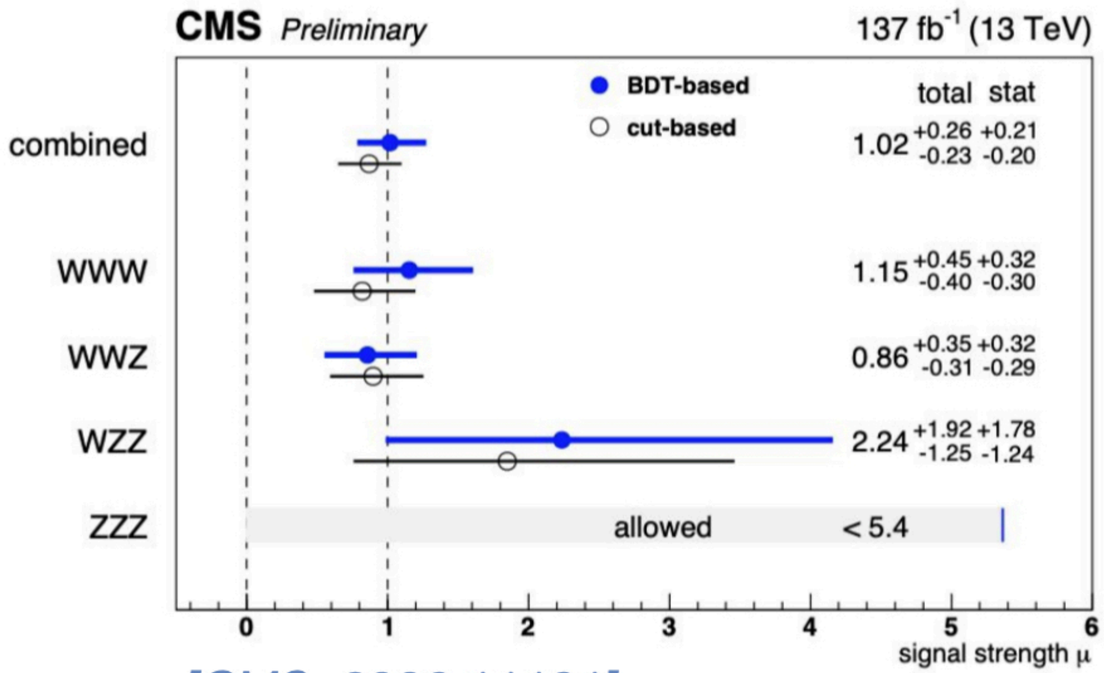

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$\mu_{WWW} = 1.61 \pm 0.19 \pm 0.16$ *[ATLAS; 2201.13045]*

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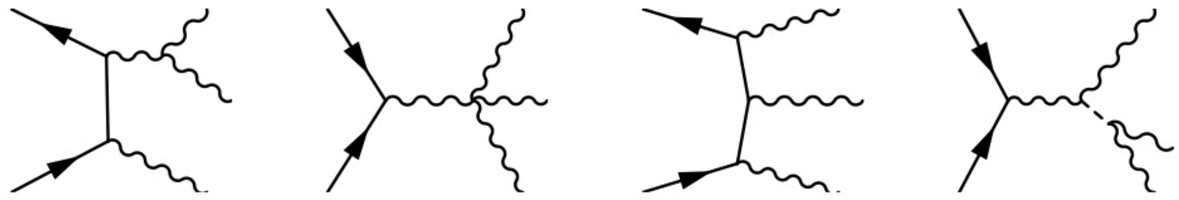

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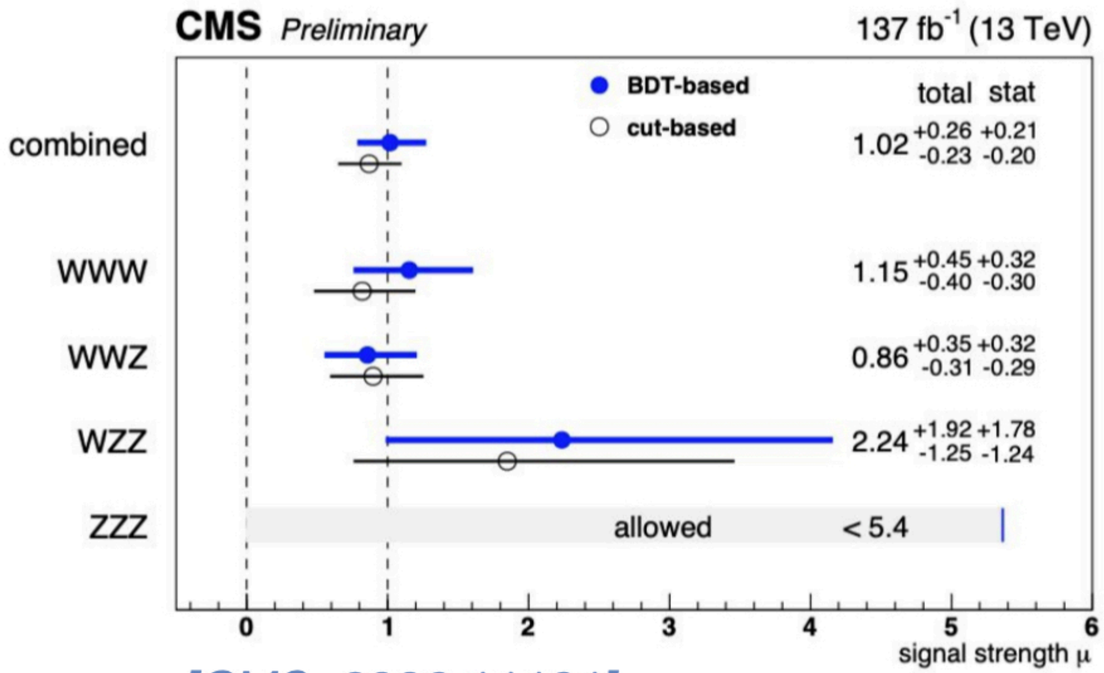

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What information do they bring to global SMEFT analyses?

Not very much…?

[E. Celada, G. Durieux, KM, E. Vryonidou; WIP]

1,2 & 3 bosons: data

Sensitivity baseline: EWPO & LEP/LHC diboson

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

$$\Gamma_Z = 2.495 \pm 0.0023 \text{ GeV}$$
$$\sigma_{\text{had.}} = 41.54 \pm 0.0037 \text{ nb}$$
$$R_\ell^0 = 20.77 \pm 0.025$$
$$A_{FB}^\ell = 0.00171 \pm 0.001$$
$$A_\ell(\text{SLD}) = 0.147 \pm 0.003$$
$$A_\ell(\text{Pt}) = 0.151 \pm 0.002$$
$$R_b^0 = 0.2163 \pm 0.0007$$
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[LEP; hep-ex/0509008]

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

[PDG 2020-2021]

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[PDG 2020-2021]

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

$$\sigma(WW \to \ell\nu\ell\nu, qqqq)$$

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

[L3; hep-ex/0409016]
[OPAL; 0708.1311]
[ALEPH; CERN-PH-EP-2004-012]
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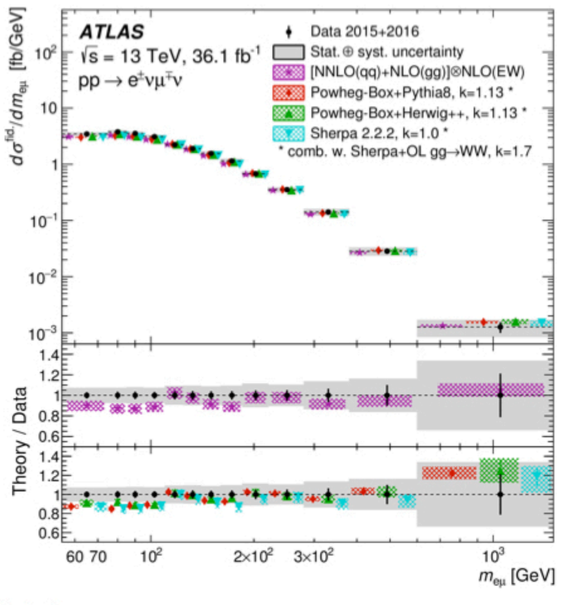
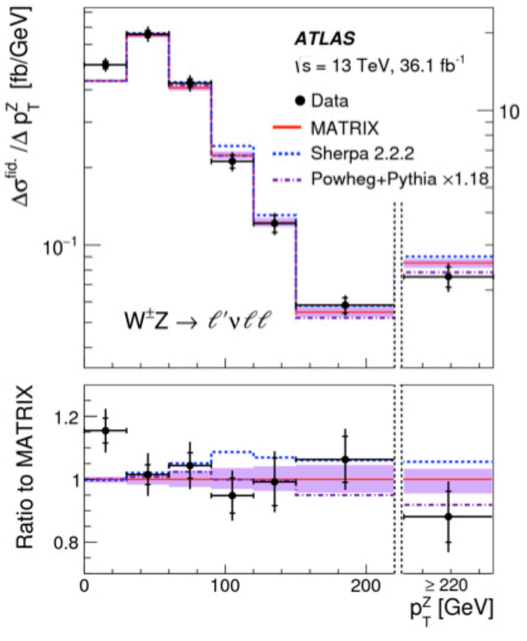
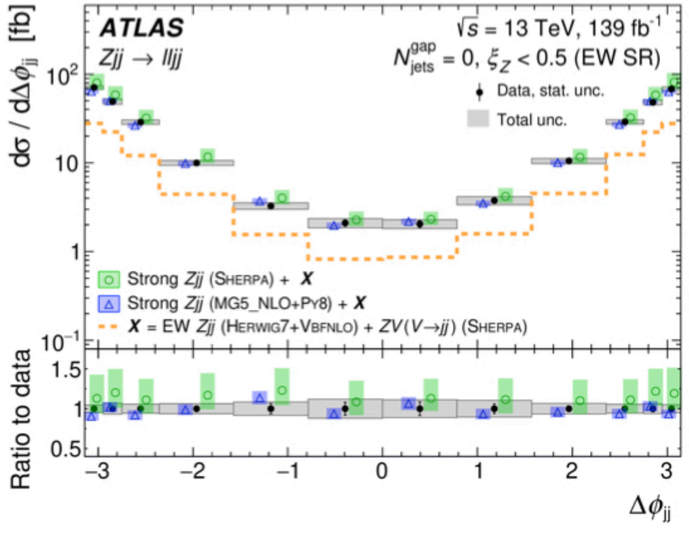
[LEP; 1302.3415]

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







[ATLAS;1905.04242] [ATLAS;1902.05759] [ATLAS; 2006.15458]

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Complete overlap between VVV & EWPO + VV

$\delta_{EWPO} \sim 1 - 0.1\,\%$ $\delta_{VV} \sim 10\,\%$

$\delta_{VVV} \sim 100\,\%$

VVV relatively poorly measured

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	four-fermion				
$\mathcal{O}_{\ell\ell}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma^\mu \ell)$	✓	✓	✓	✓

Complete overlap between VVV & EWPO + VV

$\delta_{EWPO} \sim 1 - 0.1\,\%$ $\delta_{VV} \sim 10\,\%$

$\delta_{VVV} \sim 100\,\%$

VVV relatively poorly measured

Expectations:

1) Minor gain from VVV
2) Significant quadratic effects of $O(\Lambda^{-4})$
3) Linear approx. $O(\Lambda^{-2})$ good for EWPO

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

[E. Celada, G. Durieux, KM, E. Vryonidou; WIP]

Results

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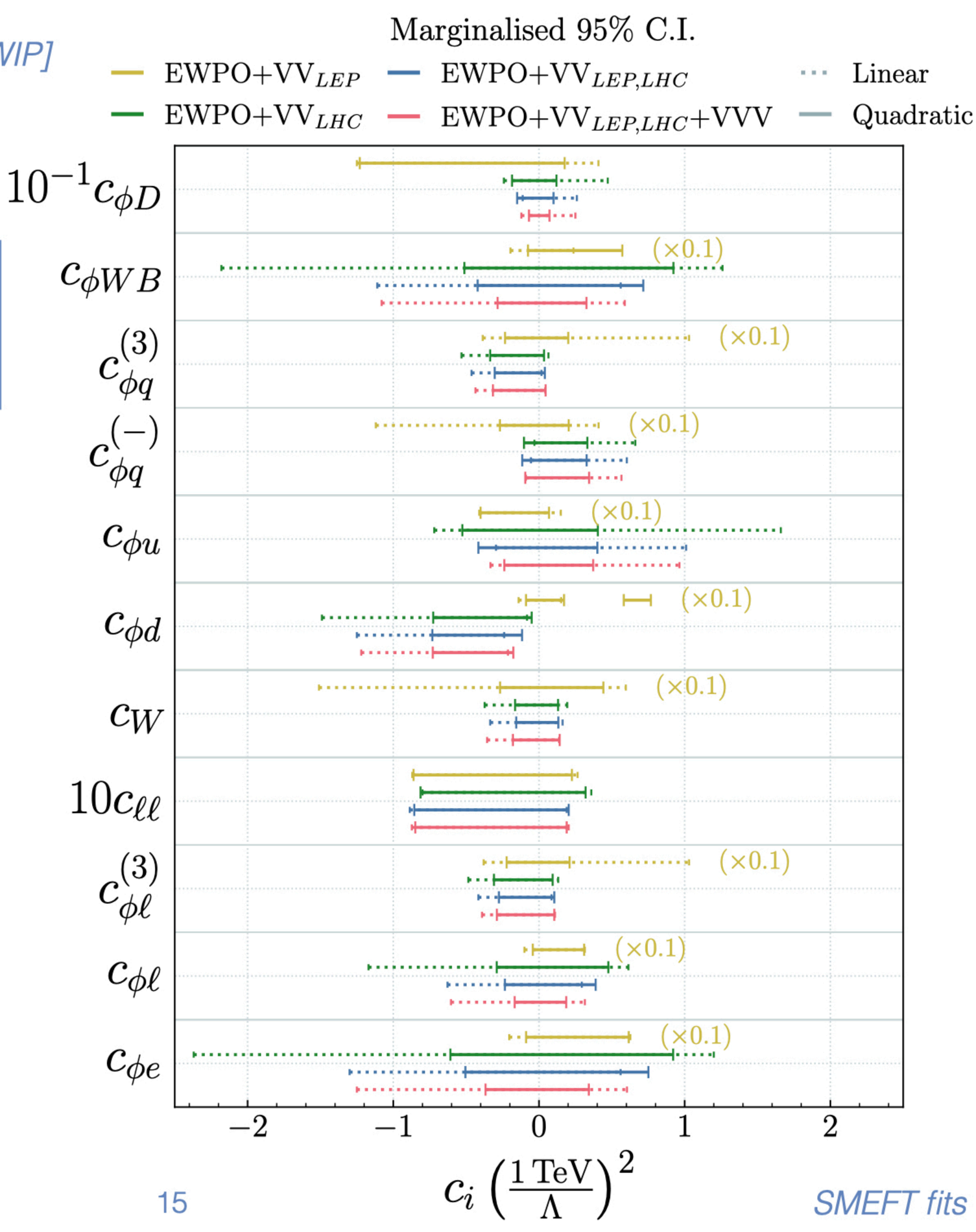

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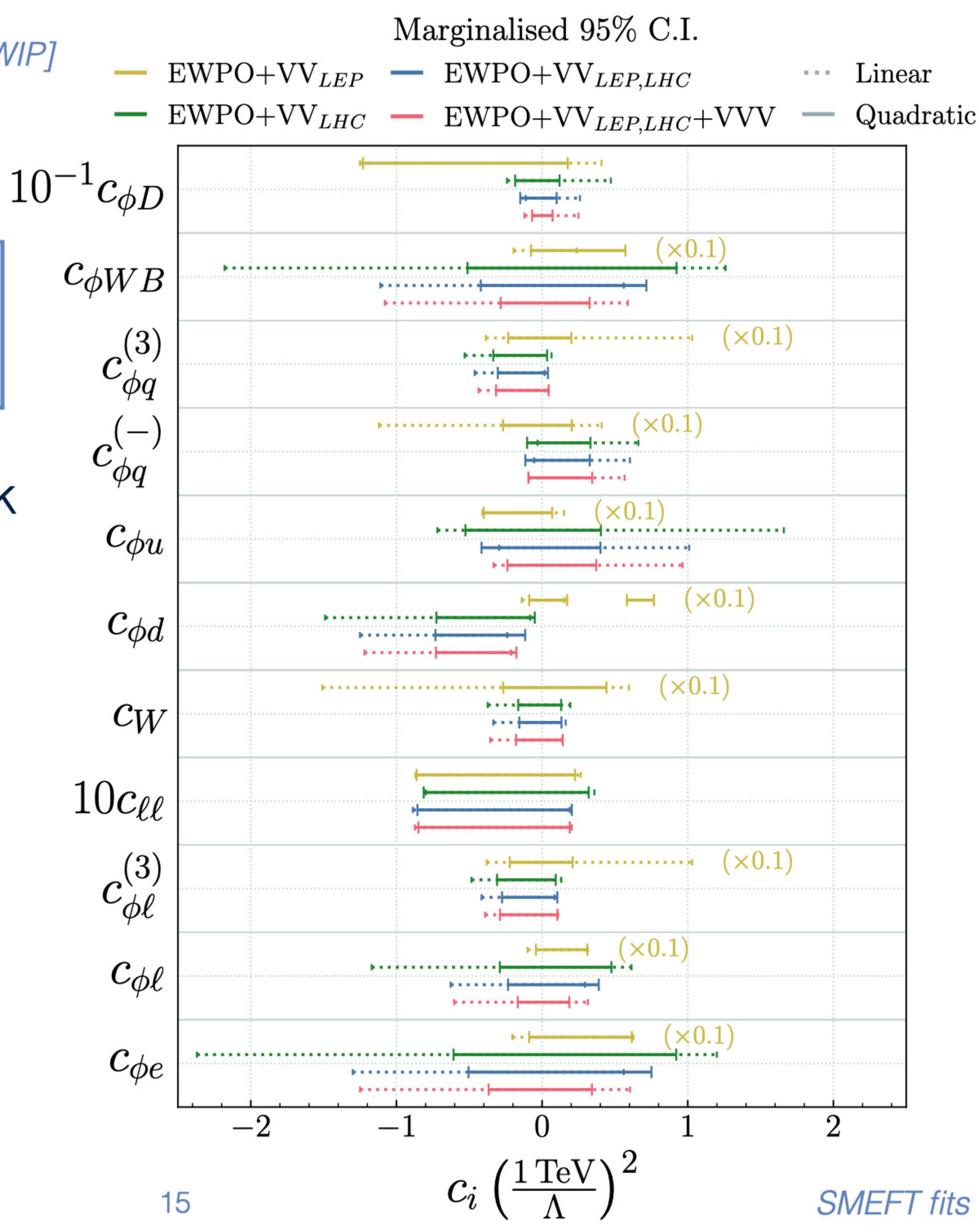
LEP WW bounds are weak

- Significant quadratic effects



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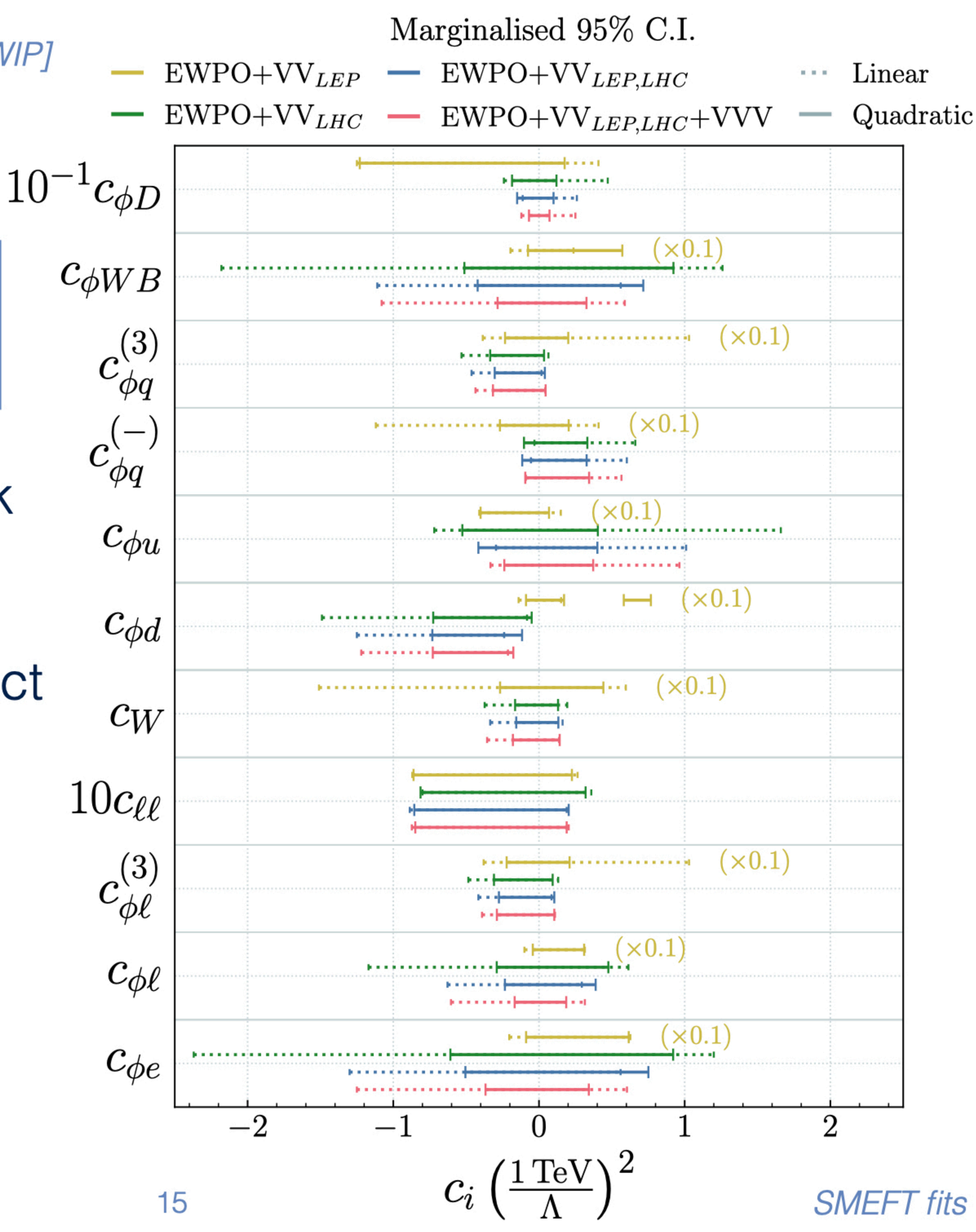
LHC VV has biggest impact

- Dominates VV combination



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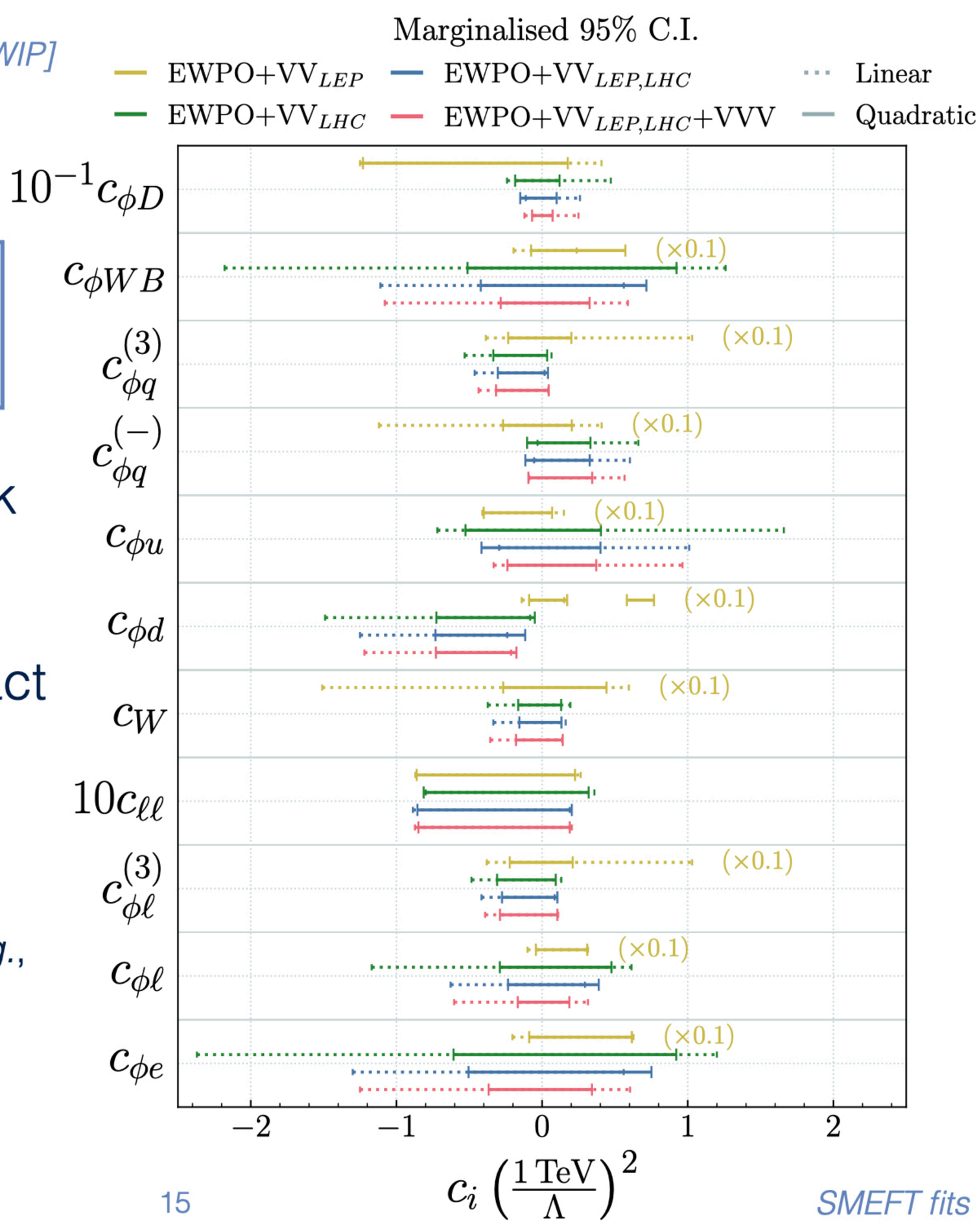
VVV makes a difference

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



[E. Celada, G. Durieux, KM, E. Vryonidou; WIP]

Interpretation

Why not look at EWPO only? We can't…

- Not sensitive to O_W & has 2 flat directions *[De Rujula et al.; Nucl. Phys. B 384 (1992) 3-58]*
- Constrains 8 out of 11 combinations of C_i *[Degrande et al.; 1205.4231]*
  [Efrati, Falkowsi & Soreq; 1503.07282]
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[E. Celada, G. Durieux, KM, E. Vryonidou; WIP]

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

$$g_2^2\, w_W = g_2^2 \frac{\bar{v}_T^2}{\Lambda^2}\left(\frac{C_{Hq}^{(3)} + C_{Hl}^{(3)}}{2} - \frac{t_{\bar{\theta}}}{2}C_{HWB}\right). \quad \textit{[Brivio \& Trott; 1701.06424]}$$

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

- Unconstrained directions: $\hat{e}_{1,2} = a_{1,2}\,\hat{\omega}_B + b_{1,2}\,\hat{\omega}_B$
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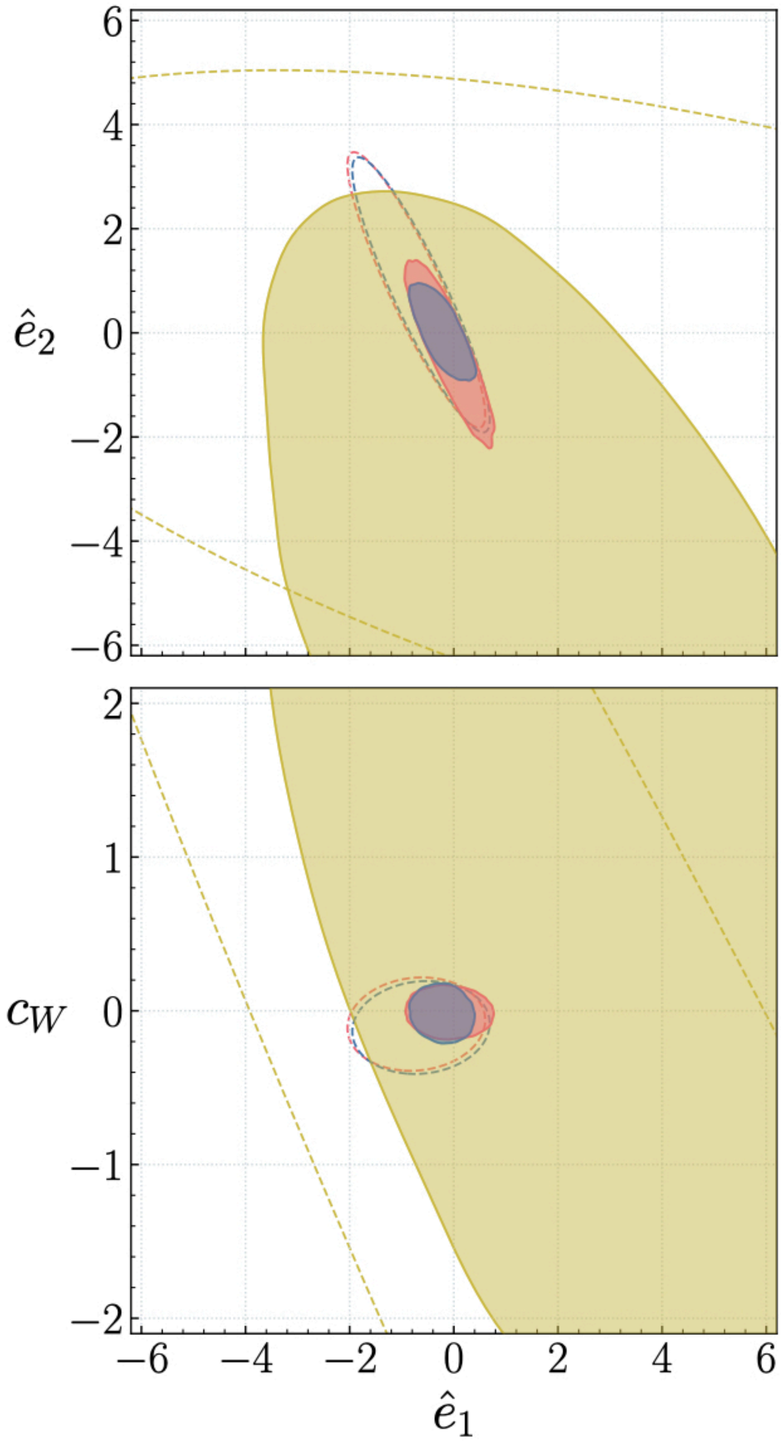
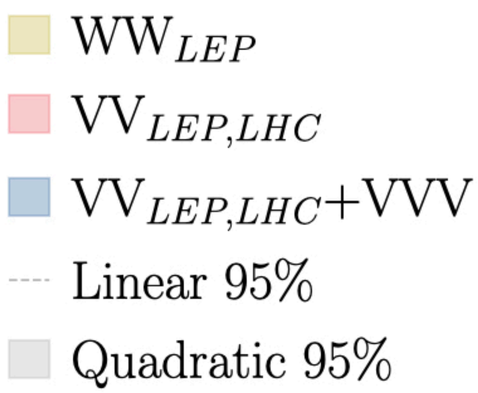
In a global analysis, bounds are limited by the sensitivity of the additional data

[E. Celada, G. Durieux, KM, E. Vryonidou; WIP]

EWPO blind space





Sufficient to study 3D space

- c_W + 2 flat directions, $\hat{e}_{1,2}$
- Emphasise the huge strength of LHC VV *w.r.t* LEP WW
- Non-negligible impact of VVV

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

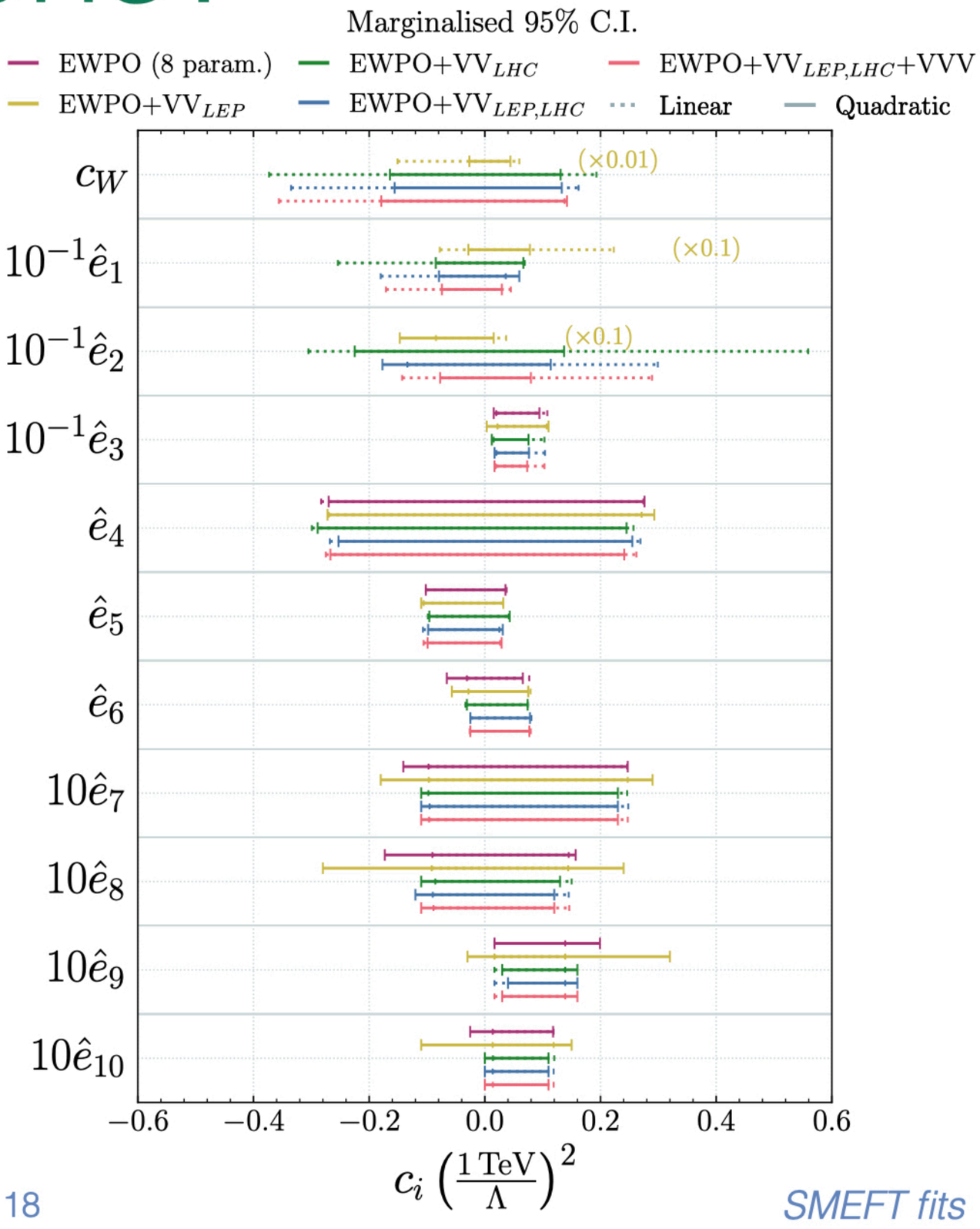
- Significant quadratics everywhere
- Propagate into any global analysis that combines EWPO with other things
- EFT validity…

[E. Celada, G. Durieux, KM, E. Vryonidou; WIP]

Other directions?

Rotated results to eigenbasis

- Compare to 8 parameter EWPO fit



[E. Celada, G. Durieux, KM, E. Vryonidou; WIP]

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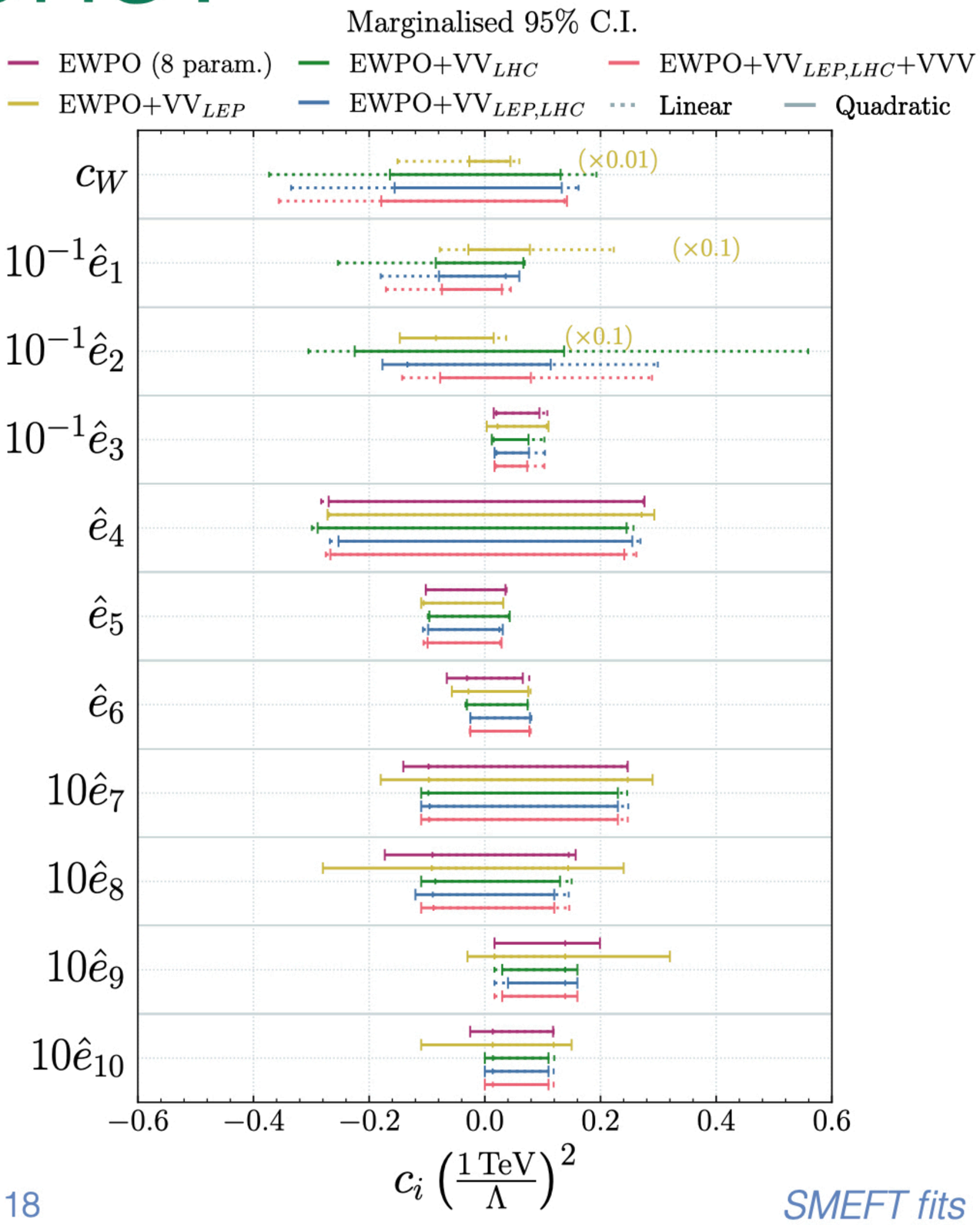
- Secondary minima (not shown) are lifted by VV data



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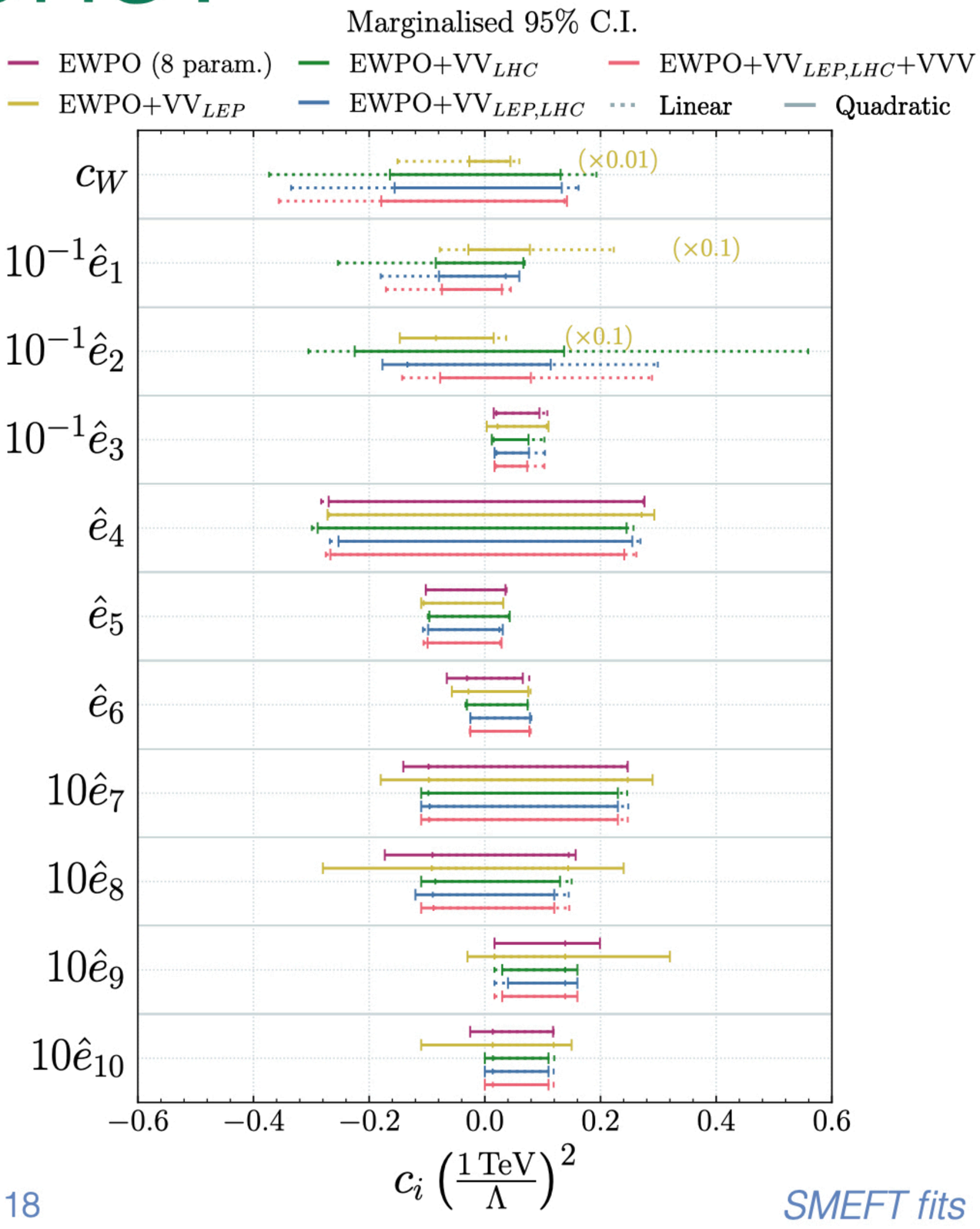
Mild improvements from LHC VV

- Nothing else from LEP WW & VVV
- Linear approximation is safe in these directions once extra data is added



Conclusions

Global SMEFT fits: key ingredient in quest for BSM

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- Bridge between explicit heavy new physics models and HEP datasets

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Frontiers (also many things I couldn't mention)

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- NLO & RGE effects important
- Interesting cross talk between many new sectors (flavor, PVE, DY, dijet)
- Automated UV matching frameworks

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- Automated UV matching frameworks

VVV has a role to play in global SMEFT analyses

- Revisited the combination EWPO with VV/VVV - significant $O(\Lambda^{-4})$
- Flat directions quantify the impact of adding data
- Next step:incorporate into bigger global fits

Backup

Notable omissions

New physics in top/3rd generation

[Grunwald et al.; 2304.12837]
[Garosi et al.; 2310.00047]
[Allwicher et al.; 2311.00020]

- Nice interplay between top/EWPO/flavor physics

Using full-likelihood information

[Elmer et al.; 2312.12502]

- Experiments publishing statistical likelihoods e.g. pyHF format
- Allows taking into account yields in signal & backgrounds
- More complex BDT/NN outputs?

New ALP bounds from ALP-SMEFT mixing

[Biekötter et al.; 2307.10372]

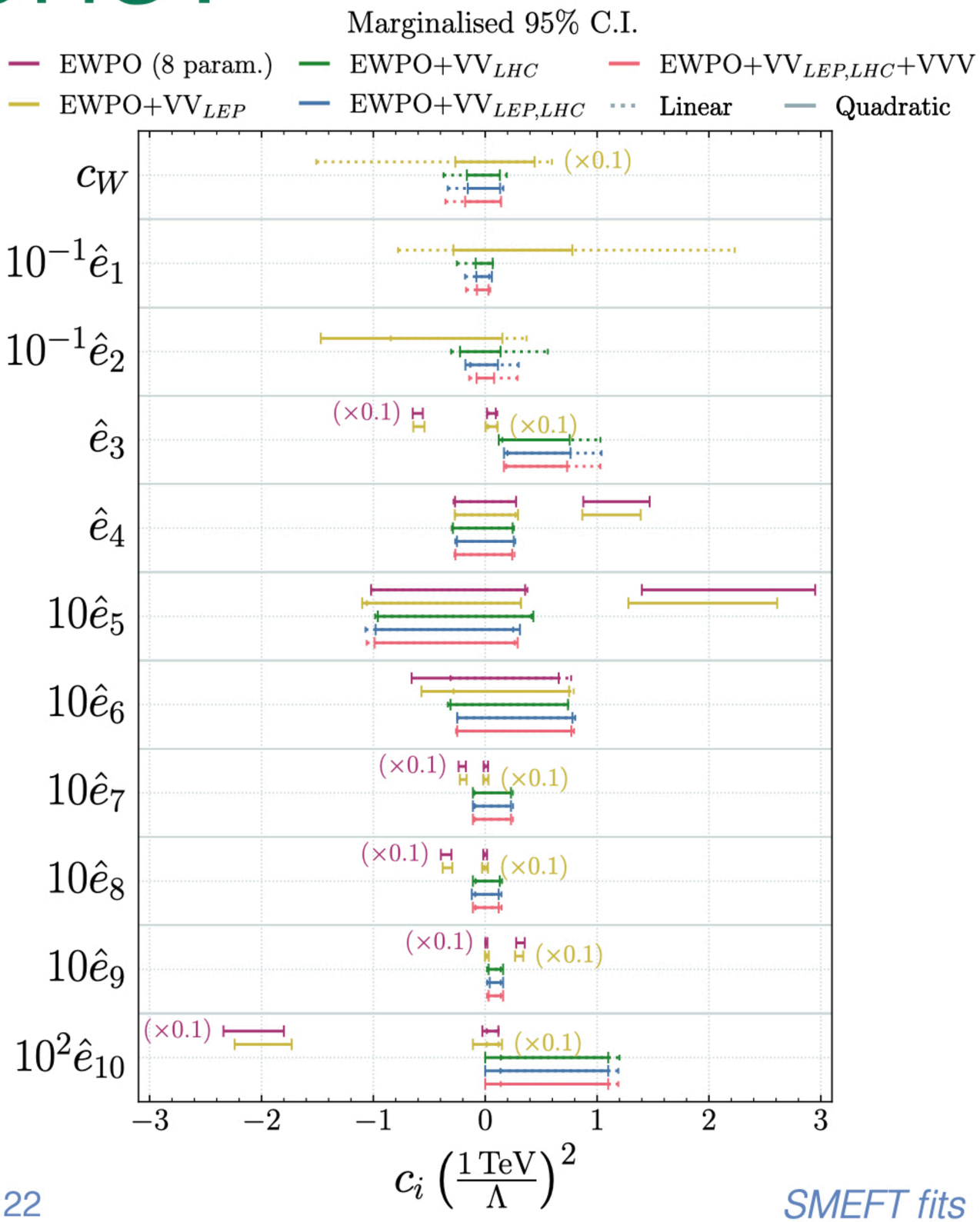
- D=5 ALP interactions mix into SMEFT operators at $O(1/f_a^2)$
- Pure SMEFT fits competitively constrain ALP couplings!
- Bounds are ~independent of ALP mass

[E. Celada, G. Durieux, KM, E. Vryonidou; WIP]

Other directions?

EWPO secondary minima

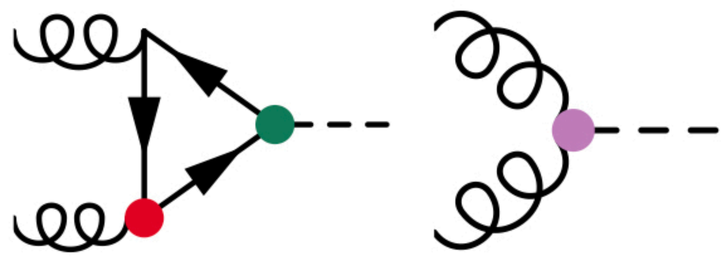
- Related to secondary minimum in $C_{\phi d}$ in Warsaw basis results
- Big quadratic effects in EWPO constrained directions
- New data, even though less precise, is crucial to lift degeneracies and return a better-behaved fit.

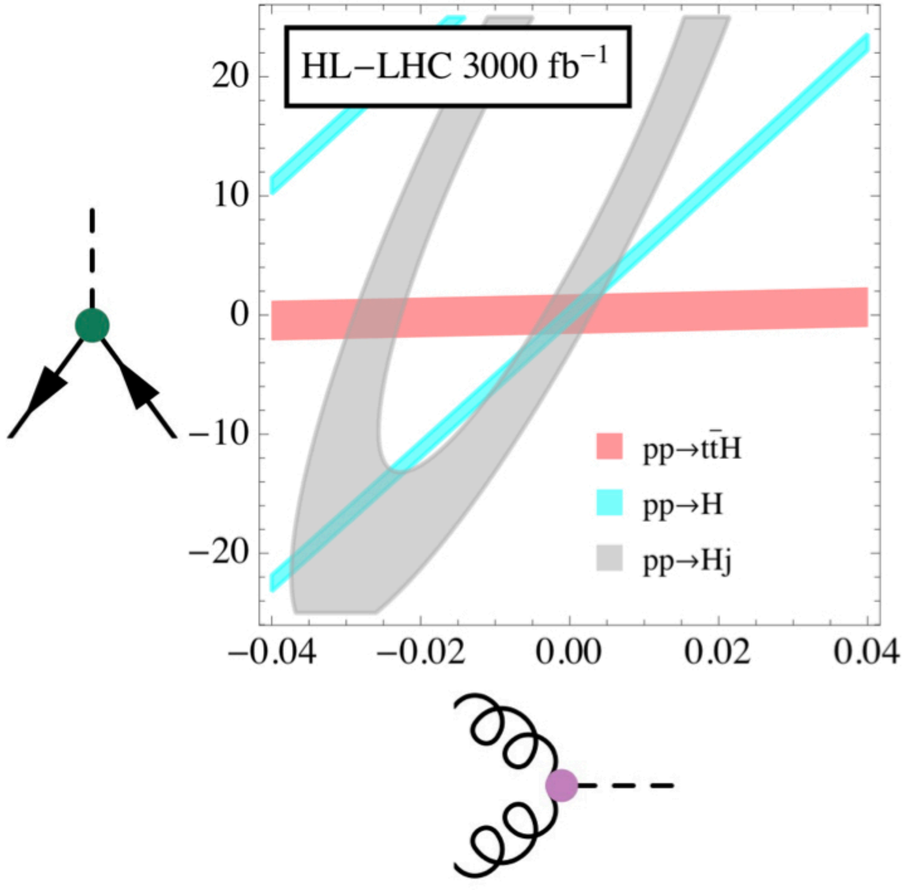


Top-Higgs interplay

Top data indirectly improves Higgs coupling measurements

- $gg \to h$ has 3 relevant new interactions
- Yukawa, dipole & contact term
- Degeneracy in coefficient/theory space

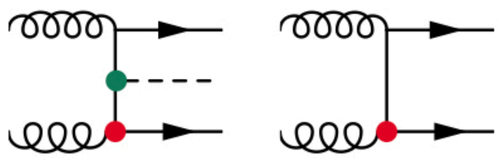




[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]

ggF is well measured, yet…

Cannot rule out heavy particles in the loop

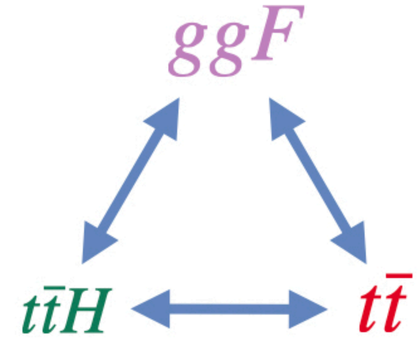


$t\bar{t}$ and $t\bar{t}h$ data can help

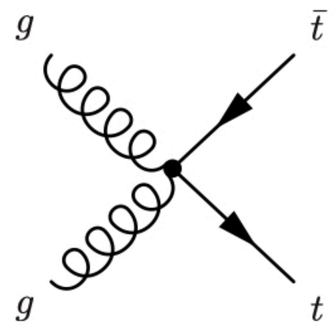
- Constrain dipole & Yukawa

What about 4 fermion ops.?

- Do they limit ultimate sensitivity?

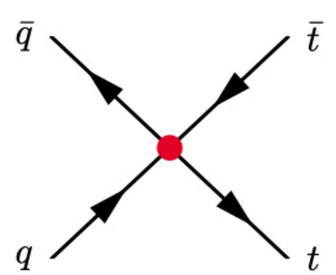


The role of top data



✓ $t\bar{t}$ cross section measurements constrain C_{tG}

- Indirectly improve bounds on C_{HG} and C_{tH}



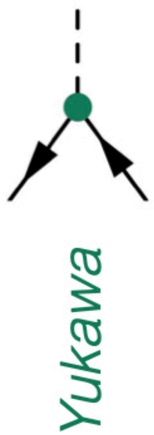
⚠ Several other new interactions can affect $t\bar{t}$

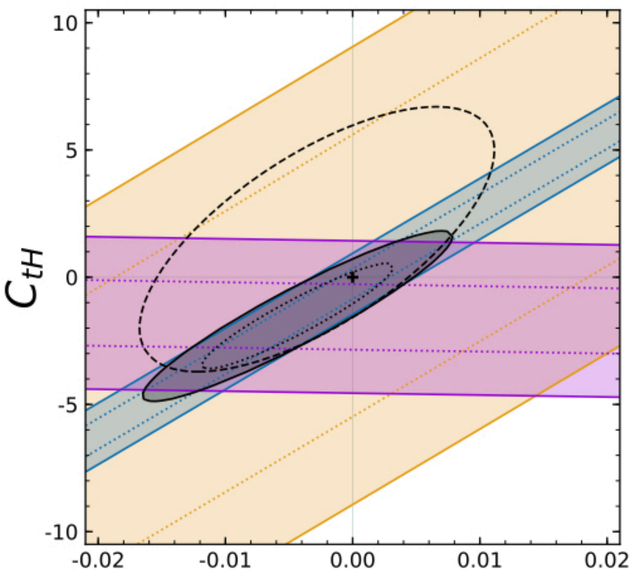
- Notably $qq\bar{t}\bar{t}$ operators, of which there are many (14)
- Also enter in $t\bar{t}h/Z/W/\gamma$
- To what extent do these limit ultimate NP sensitivity in top/Higgs sector?

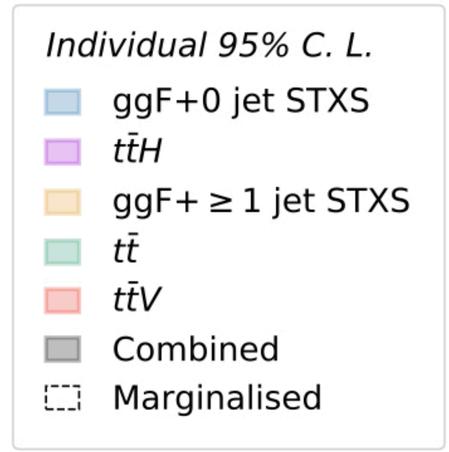
🔍 Can only be addressed in combined fit

- Beyond tree-level (at least for ggF) *[Degrande et al.; PRD 103 (2021) 9, 096024]* *http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO*
- Identify other cross-talk (non-trivial correlations)
- Crystallisation of knowledge gained after LHC Run 2/3
- Broaden range of applicability to UV models where the top is special

Top-Higgs interplay

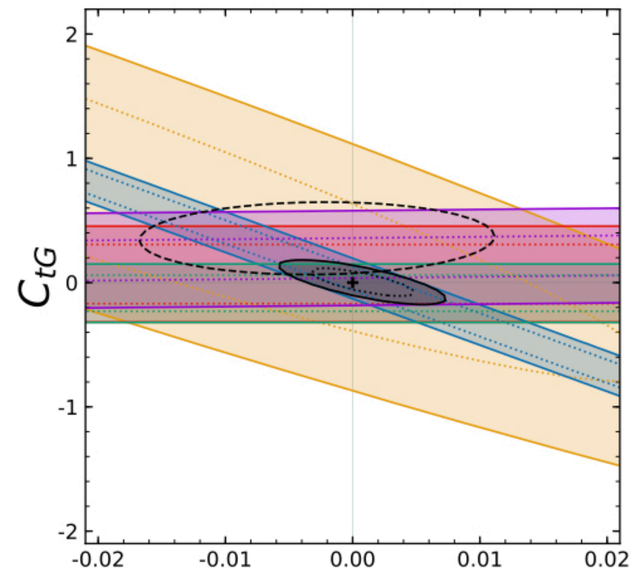


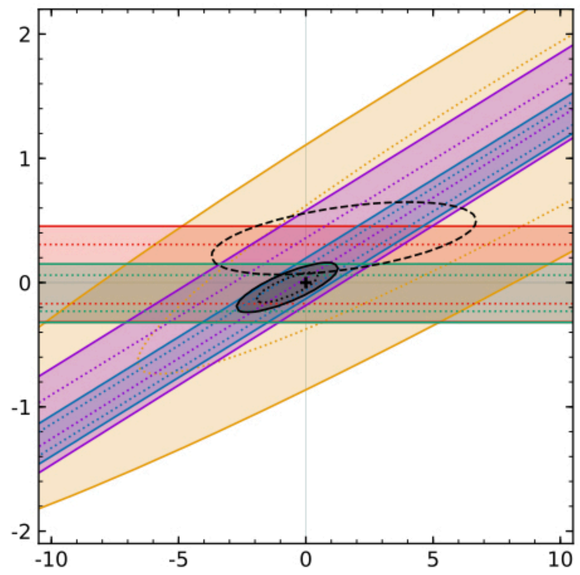


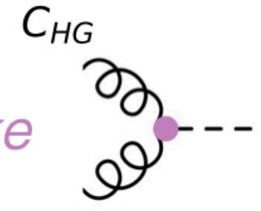


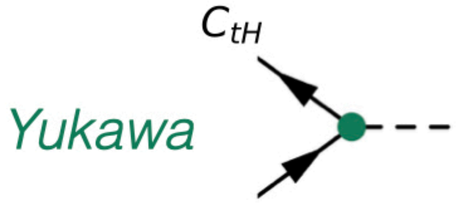
2D individual constraints

- All others set to 0
- $ggF/t\bar{t}H$ complementarity for (C_{HG}, C_{tH})
- H+jets STXS & $t\bar{t}V$ not yet competitive





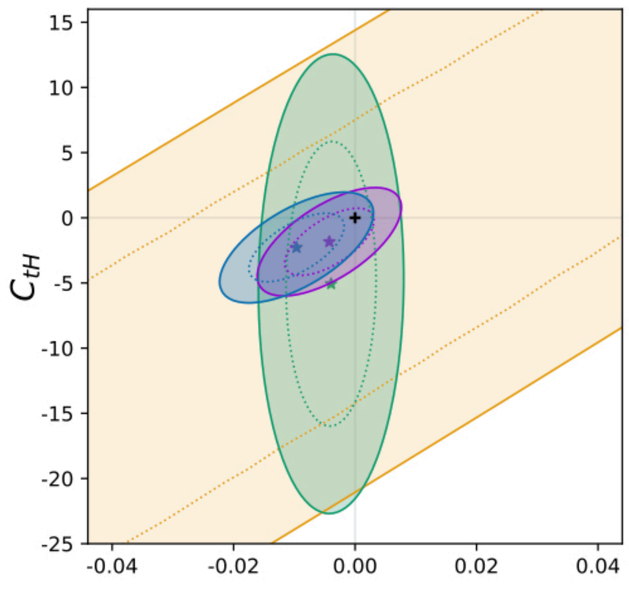


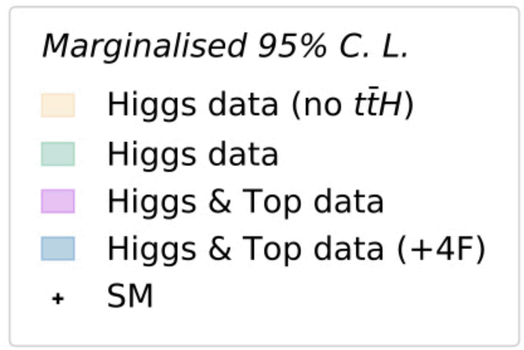


- Strong impact of $t\bar{t}$ evident for C_{tG}
- Tension with SM $\sim 2\sigma$
- Significant correlations remain
- Large marginalisation effects

What is the concrete impact of 4F?

Top-Higgs interplay



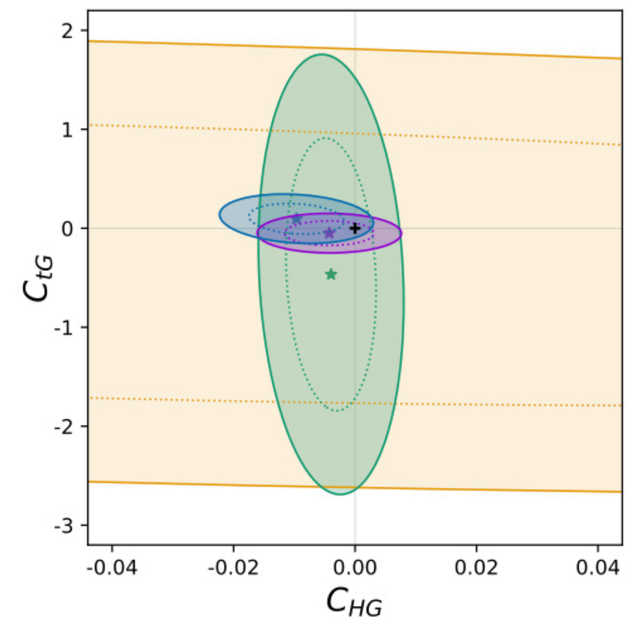


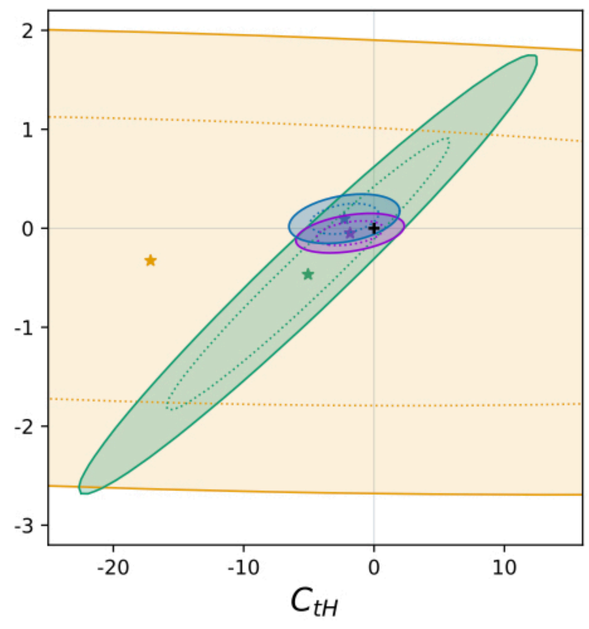
Fit: Higgs SS & STXS $\mathcal{O}(\Lambda^{-2})$

8 Higgs operators + C_{tG}

- Marginalised confidence regions
- Significant impact of $t\bar{t}H$ & $t\bar{t}(V)$

Now add in $t\bar{t}$ 4F operators





+ $C_{Qq}^{3,8}, C_{Qq}^{1,8}, C_{Qu}^{8}, C_{Qd}^{8}, C_{tq}^{8}, C_{tu}^{8}, C_{td}^{8}$

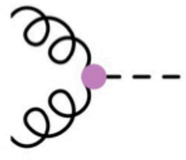
- Relatively mild impact
- Preferred $t\bar{t}$ phase space is different

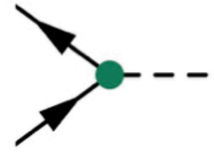
C_{tG} : low $m_{t\bar{t}}$

$4F$: high $m_{t\bar{t}}$

- Able to constrain them independently

Top data is crucial!



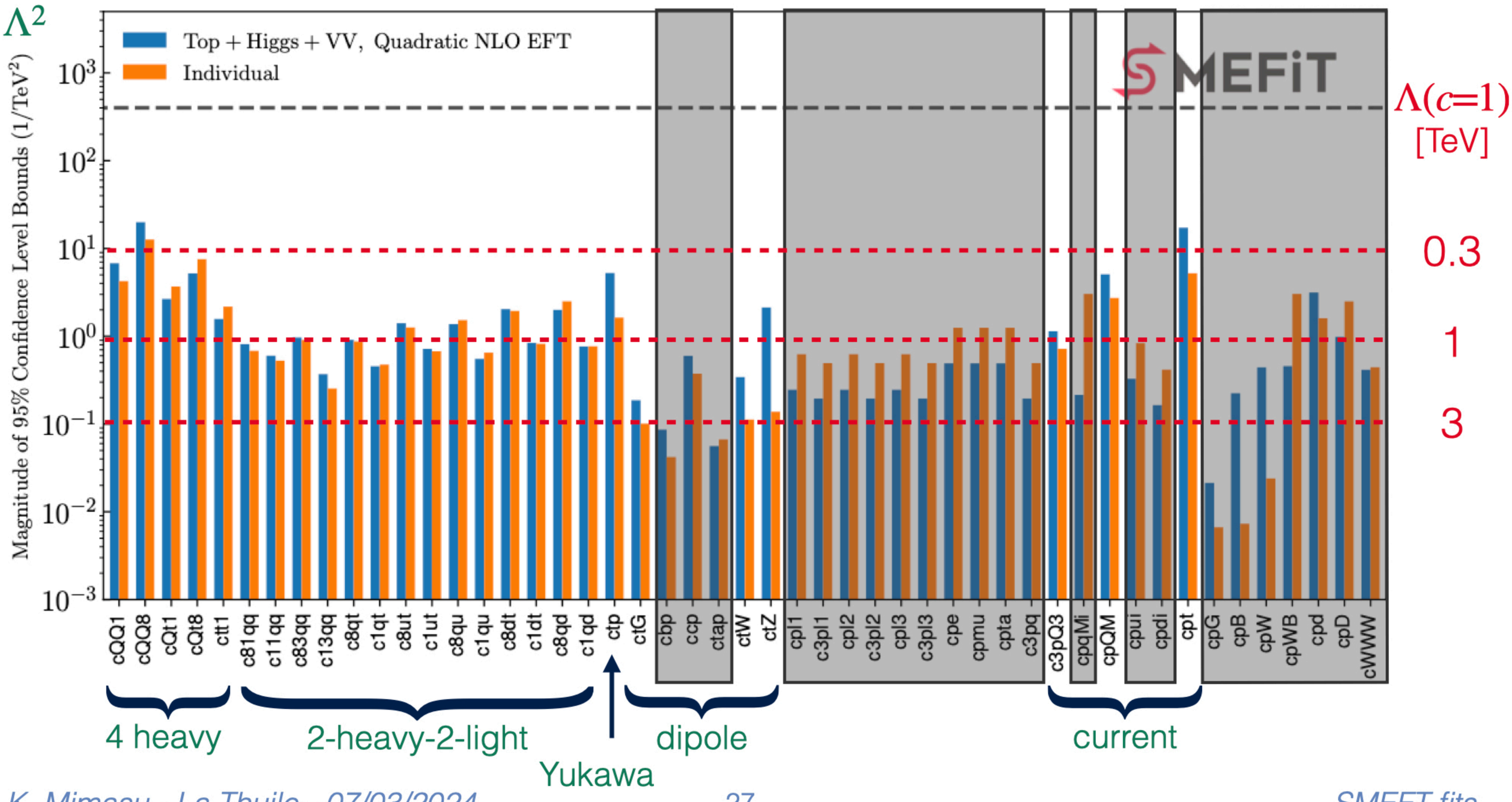


SMEFiT

[Ethier et al.; JHEP 11 (2021) 089]
see also: [Brivio et al.; JHEP 02 (2020) 131]
[Brown et al.; PoS ICHEP2020 (2021) 322]

Top, Higgs & Diboson w/ 'perfect' EWPO

- NLO QCD
- top loop sensitivity



Linear (Λ^{-2}) vs Quadratic (Λ^{-4})

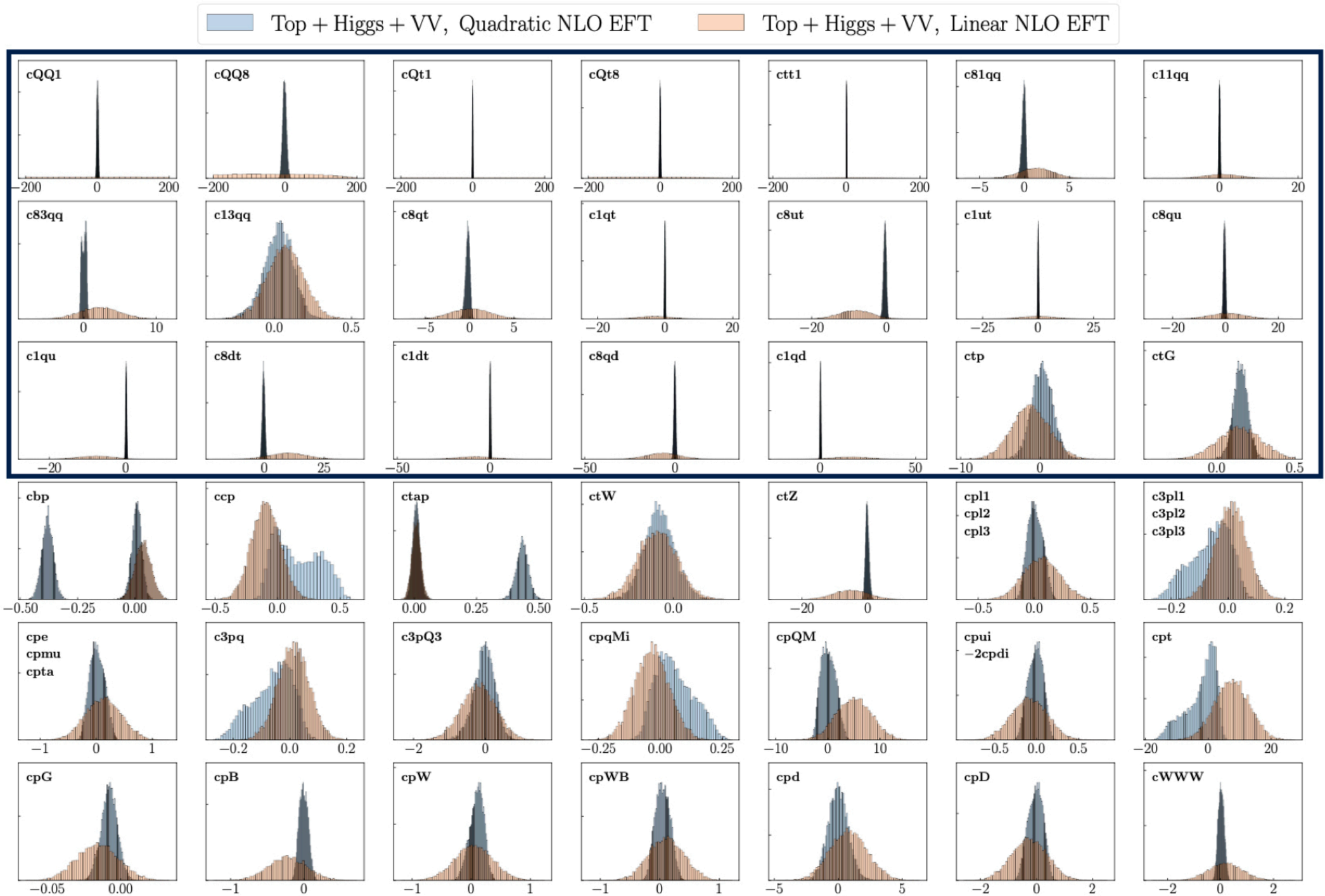
Some bounds purely $O(\Lambda^{-4})$

1) imprecise data

2) non-interference

Non-Gaussian posteriors: Quadratic effects important

Dim-8 effects? EFT validity?



[Ethier et al.; JHEP 11 (2021) 089]

NLO vs LO

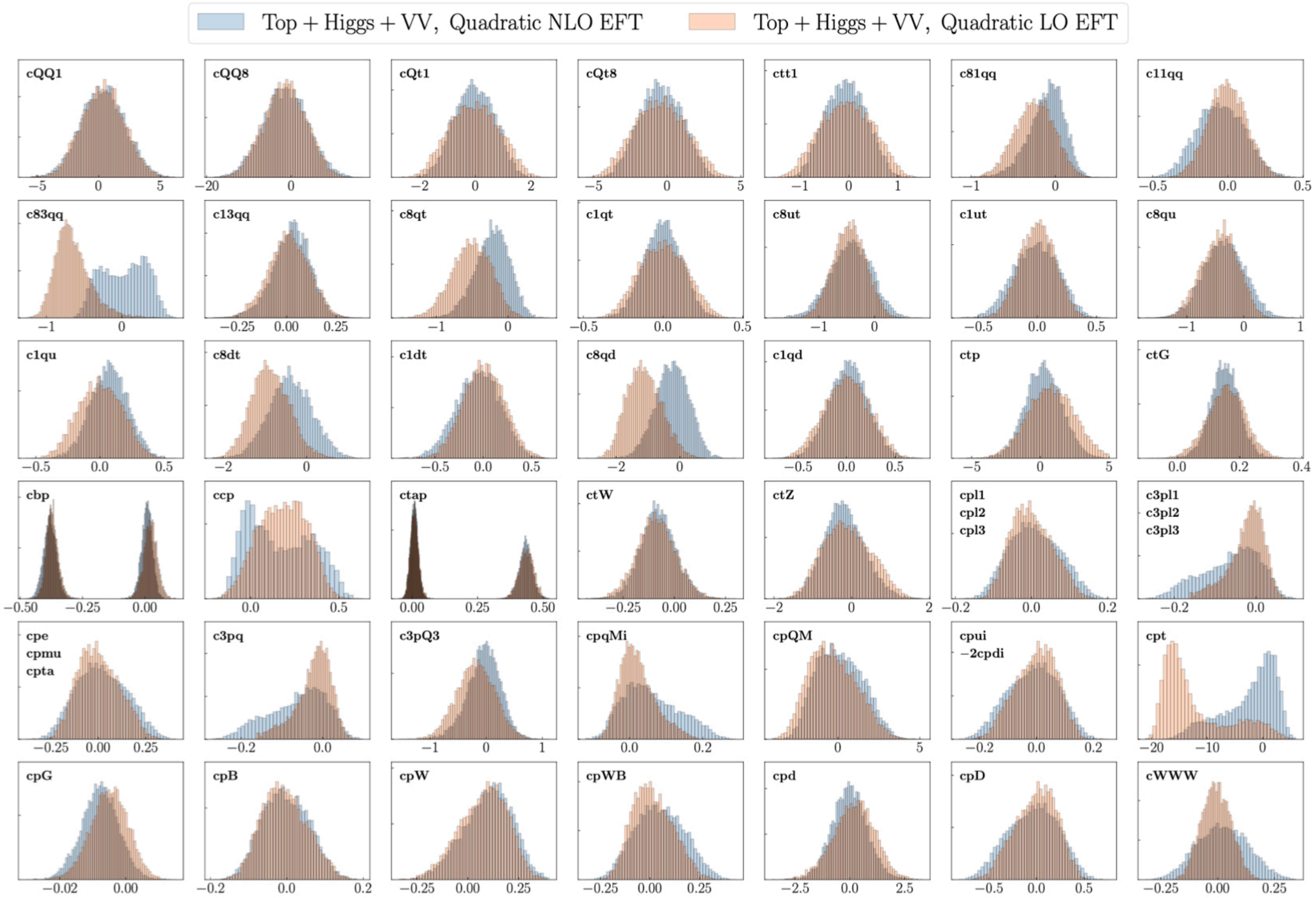
SMEFTatNLO

http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

[Degrande et al.; PRD 103 (2021) 9, 096024]

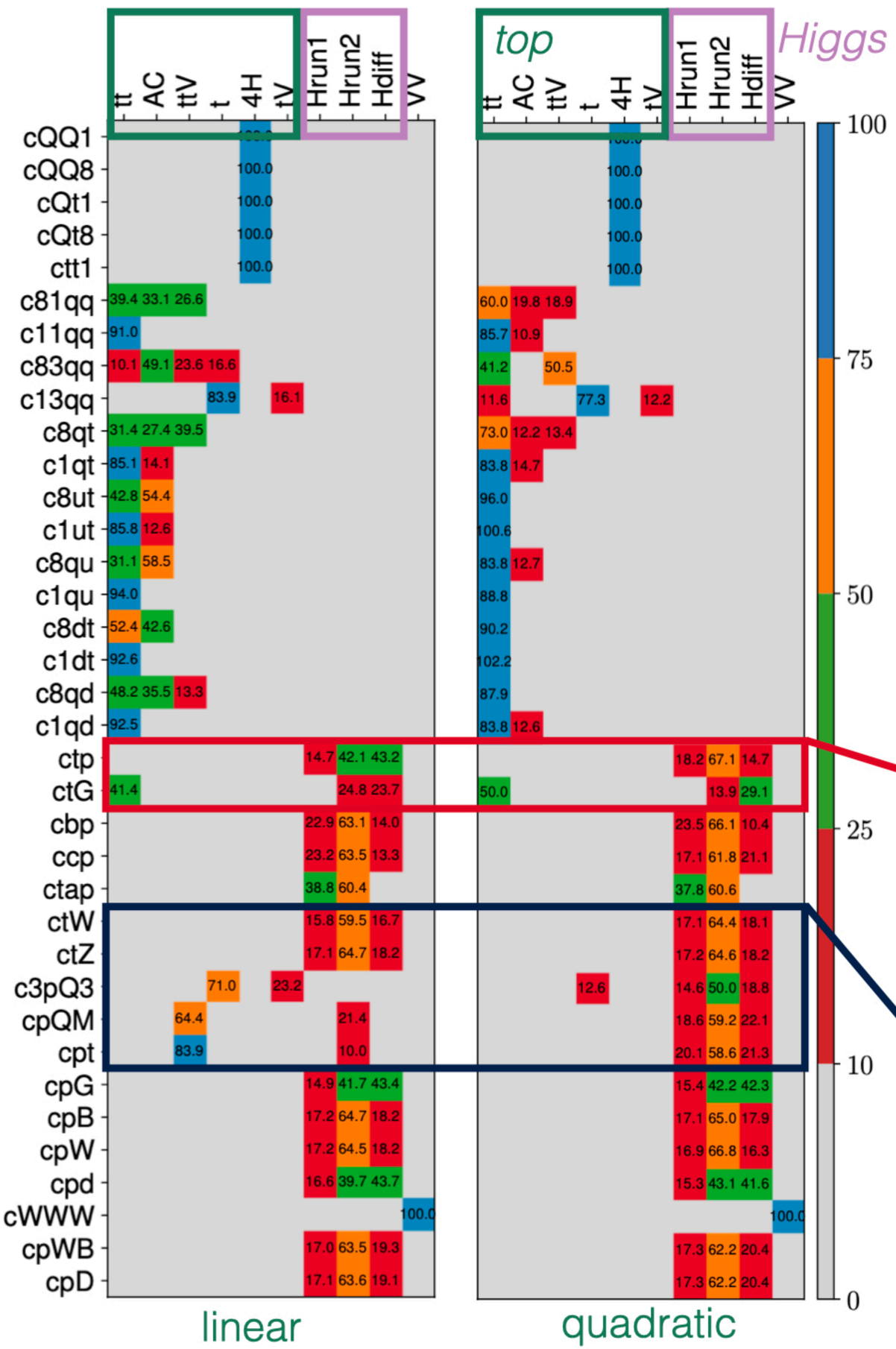
Top is coloured

Non-trivial QCD corrections



t/h interplay via loops

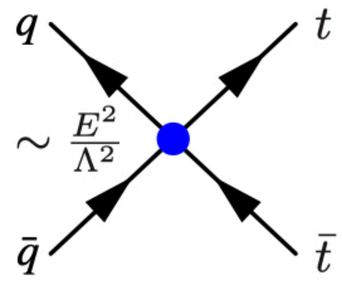
[Ethier et al.; JHEP 11 (2021) 089]



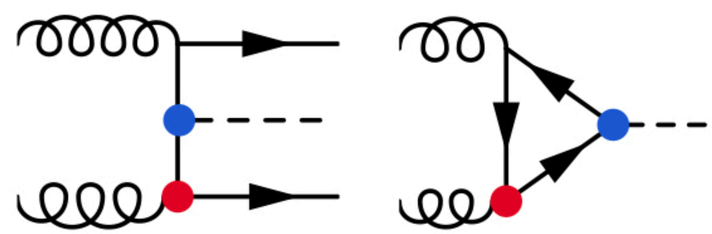
Fisher Information:

Hessian of Log-likelihood at the best-fit point

4F operators: mostly top data



Yukawa & Chromo-dipole



$t\bar{t}V$ couplings