# SMEFT as a probe of New physics at colliders

Eleni Vryonidou
University of Cyprus

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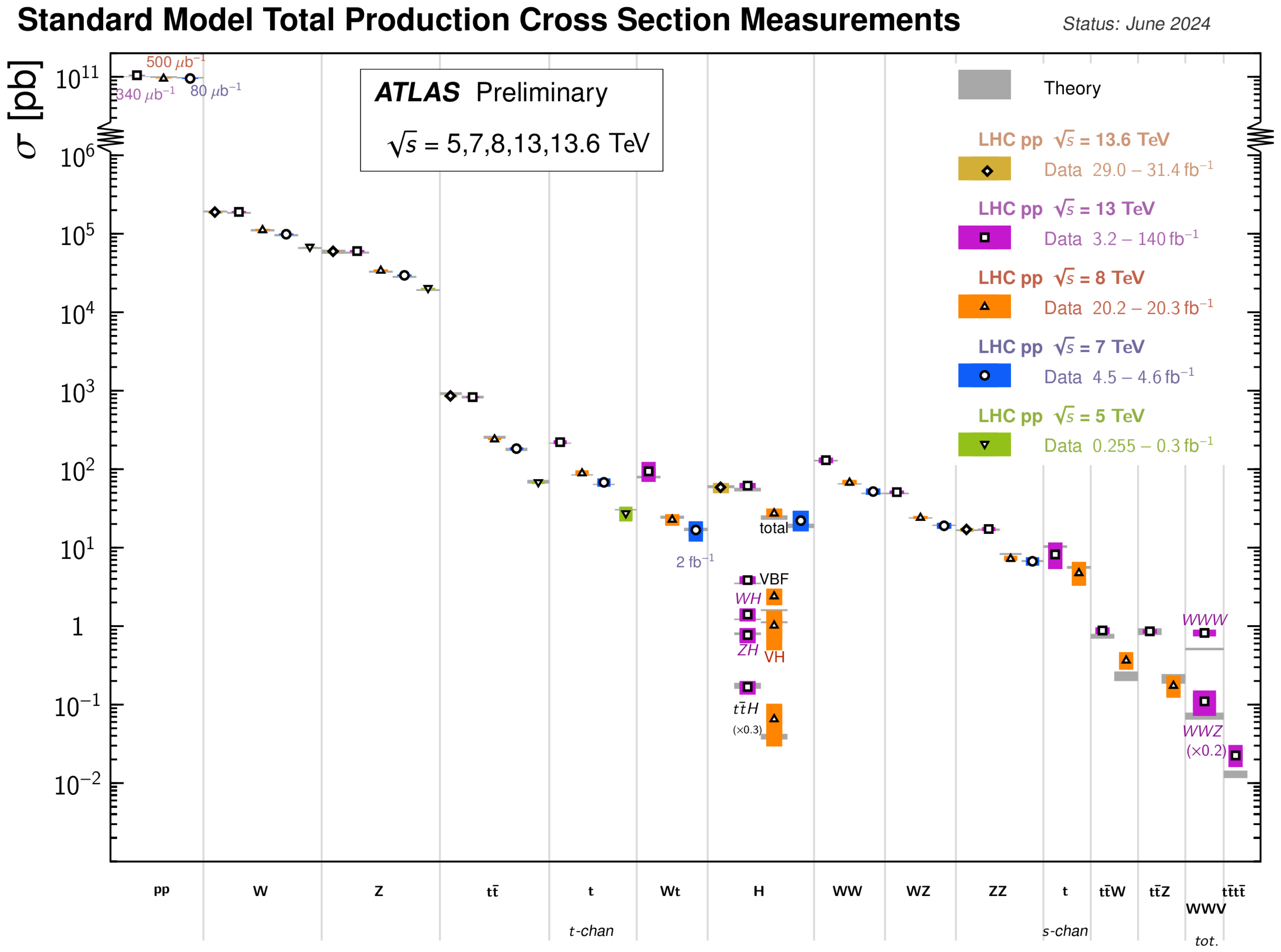
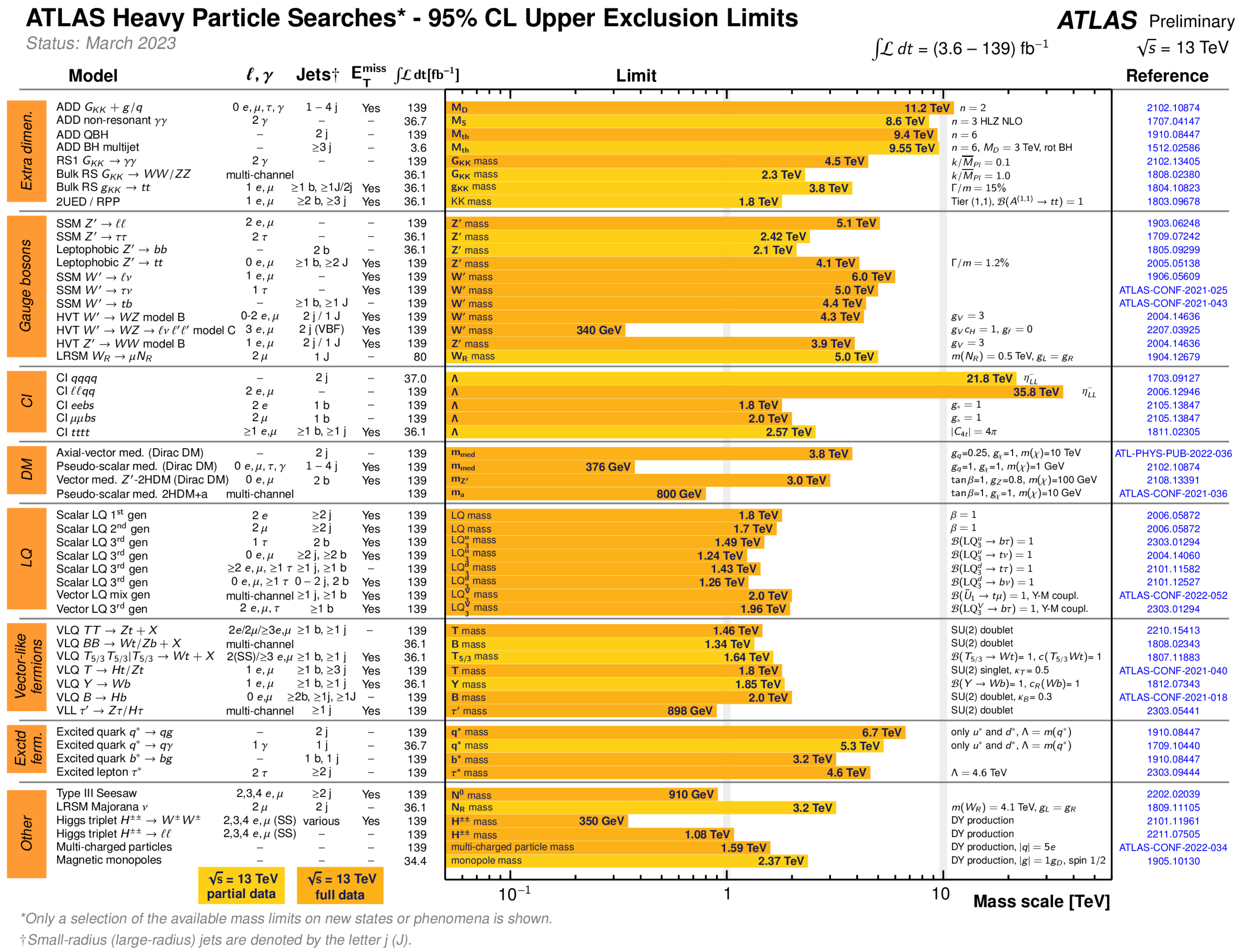
# LHC: the story so far

## Rediscovering the SM




## Searching for the unknown




**Good agreement with the SM predictions**

**No sign of new light particles**

# What can New Physics be?

Possibilities and how to deal with them:

Weakly coupled: Small rates means that more luminosity can help

Exotic: Need new ways to search for it, going beyond standard searches or even beyond high-energy colliders

Heavy: Not enough energy to produce it
Need indirect searches → SMEFT opens new directions

# Effective Field Theory

Energy

**UV physics (heavy particles)** $\mathcal{L}_{NP}(\phi, \underbrace{\boldsymbol{Z', X, Q, S}}_{\textbf{new}} \ldots)$

$\Lambda$

**Effective Field Theory** $\mathcal{L}_{SM}(\phi) \boxed{+ \mathcal{L}_{dim6}(\phi)} + \ldots$

**Standard Model** $\mathcal{L}_{SM}(\phi)$

Effective Field Theory reveals high energy physics through precise measurements at low energy.

# SMEFT basics

New Interactions of SM particles

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

Buchmuller, Wyler Nucl.Phys. B268 (1986) 621-653

Grzadkowski et al arXiv:1008.4884

## dim-6: 59 operators

| $X^3$ | | $\varphi^6$ and $\varphi^4 D^2$ | | $\psi^2\varphi^3$ | |
|---|---|---|---|---|---|
| $Q_G$ | $f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_\varphi$ | $(\varphi^\dagger\varphi)^3$ | $Q_{e\varphi}$ | $(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$ |
| $Q_{\widetilde{G}}$ | $f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_{\varphi\Box}$ | $(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$ | $Q_{u\varphi}$ | $(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$ |
| $Q_W$ | $\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | $Q_{\varphi D}$ | $(\varphi^\dagger D^\mu\varphi)^\star (\varphi^\dagger D_\mu\varphi)$ | $Q_{d\varphi}$ | $(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$ |
| $Q_{\widetilde{W}}$ | $\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | | | | |

| $X^2\varphi^2$ | | $\psi^2 X\varphi$ | | $\psi^2\varphi^2 D$ | |
|---|---|---|---|---|---|
| $Q_{\varphi G}$ | $\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eW}$ | $(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$ | $Q_{\varphi l}^{(1)}$ | $(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$ |
| $Q_{\varphi\widetilde{G}}$ | $\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eB}$ | $(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$ | $Q_{\varphi l}^{(3)}$ | $(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$ |
| $Q_{\varphi W}$ | $\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uG}$ | $(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$ | $Q_{\varphi e}$ | $(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$ |
| $Q_{\varphi\widetilde{W}}$ | $\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uW}$ | $(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W_{\mu\nu}^I$ | $Q_{\varphi q}^{(1)}$ | $(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$ |
| $Q_{\varphi B}$ | $\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$ | $Q_{uB}$ | $(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$ | $Q_{\varphi q}^{(3)}$ | $(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$ |
| $Q_{\varphi\widetilde{B}}$ | $\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$ | $Q_{dG}$ | $(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$ | $Q_{\varphi u}$ | $(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$ |
| $Q_{\varphi WB}$ | $\varphi^\dagger \tau^I \varphi\, W_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dW}$ | $(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$ | $Q_{\varphi d}$ | $(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$ |
| $Q_{\varphi\widetilde{W}B}$ | $\varphi^\dagger \tau^I \varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dB}$ | $(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$ | $Q_{\varphi ud}$ | $i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$ |

| $(\bar{L}L)(\bar{L}L)$ | | $(\bar{R}R)(\bar{R}R)$ | | $(\bar{L}L)(\bar{R}R)$ | |
|---|---|---|---|---|---|
| $Q_{ll}$ | $(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$ | $Q_{ee}$ | $(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$ | $Q_{le}$ | $(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$ | $Q_{uu}$ | $(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$ | $Q_{lu}$ | $(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$ | $Q_{dd}$ | $(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$ | $Q_{ld}$ | $(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$ | $Q_{eu}$ | $(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$ | $Q_{qe}$ | $(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$ | $Q_{ed}$ | $(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$ | $Q_{qu}^{(1)}$ | $(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$ |
| | | $Q_{ud}^{(1)}$ | $(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$ | $Q_{qu}^{(8)}$ | $(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$ |
| | | $Q_{ud}^{(8)}$ | $(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$ | $Q_{qd}^{(1)}$ | $(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$ |
| | | | | $Q_{qd}^{(8)}$ | $(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$ |

| $(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$ | | $B$-violating | |
|---|---|---|---|
| $Q_{ledq}$ | $(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$ | $Q_{duq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$ |
| $Q_{quqd}^{(1)}$ | $(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$ | $Q_{qqu}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$ |
| $Q_{quqd}^{(8)}$ | $(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$ | $Q_{qqq}^{(1)}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$ |
| $Q_{lequ}^{(1)}$ | $(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$ | $Q_{qqq}^{(3)}$ | $\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$ |
| $Q_{lequ}^{(3)}$ | $(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$ | $Q_{duu}$ | $\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$ |

# EFT pathway to New Physics

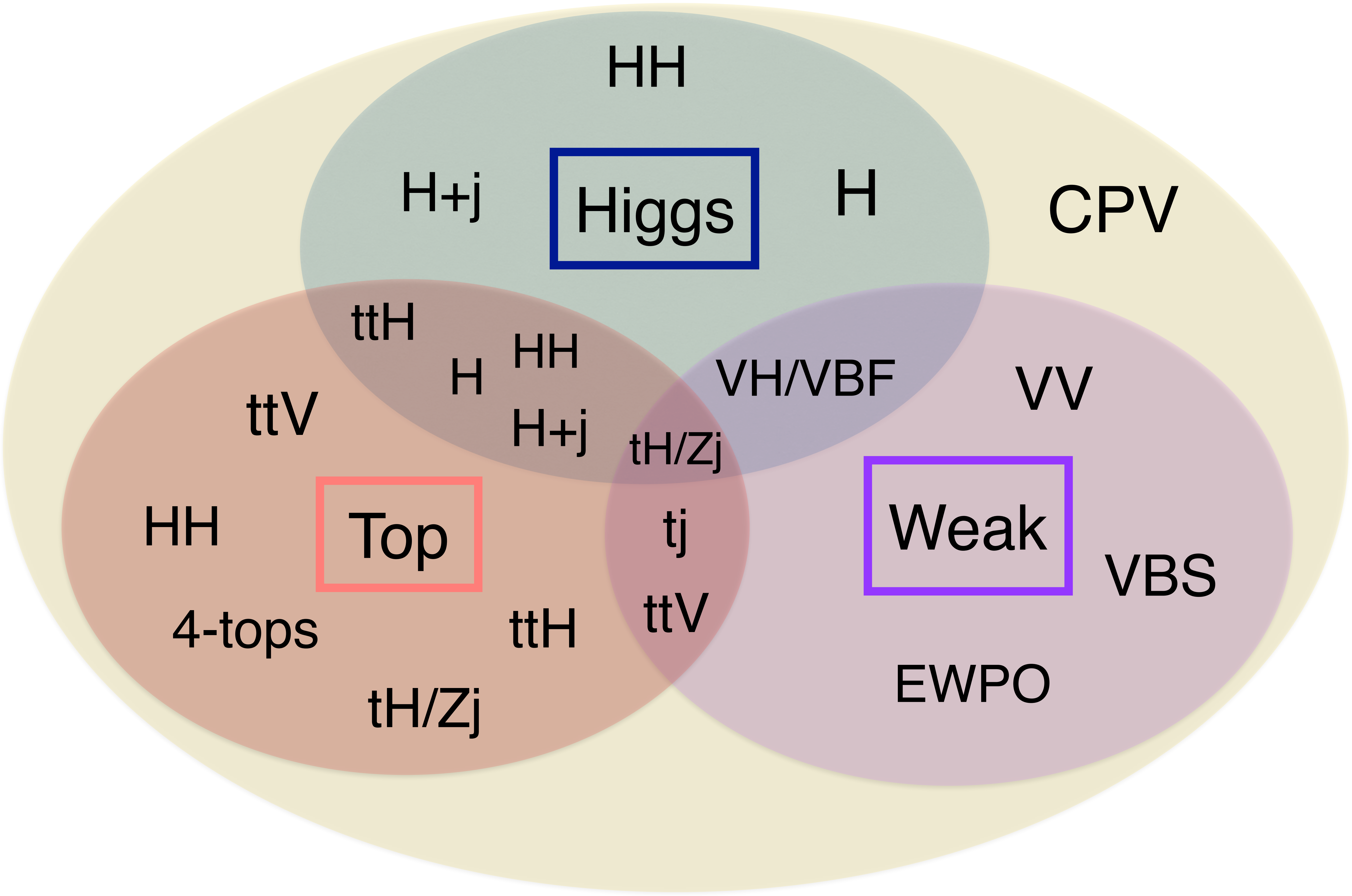
$$\Delta \text{Obs}_n = \text{Obs}_n^{\text{EXP}} - \text{Obs}_n^{\text{SM}} = \frac{1}{\Lambda^2} \sum_i c_i^6(\mu) a_{n,i}^6(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Precise EFT predictions

Precise SM predictions

Precise experimental measurements

# Global nature of EFT




Adapted from K. Mimasu

# Global fit Setup

## Theory

Accurate predictions for the SM and the EFT

SM: (N)NLO QCD + NLO EW

EFT: NLO QCD, linear and quadratics, with SMEFT@NLO
NNPDF4.0 no top

## Experimental data

445 data points from: Higgs, top, diboson (LHC) & EWPO (LEP).

Inclusive and differential: mostly parton level

Experimental uncertainties and their correlations as provided by experiments

SMEFiT

Giani, Magni, Rojo arXiv:2302.06660

## Methodology

Nested Sampling for quadratic fits
Analytic solution for linear fits
Faithful uncertainty estimate
Avoid under- and over-fitting, validated on pseudo-data (closure test)

## Output

Fit reports with bounds on coefficients, posterior distributions, PCA, Fisher information
Constraints on New Physics scale
Fit results can be used to bound specific UV complete models

# Current Data: Experimental input

**LEP & LHC**

| Category | Processes | $n_{\rm dat}$ SMEFiT3.0 |
|---|---|---|
| Top quark production | $t\bar{t}+X$ | 115 |
| | $t\bar{t}Z$, $t\bar{t}W$ | 21 |
| | $t\bar{t}\gamma$ | 2 |
| | single top (inclusive) | 28 |
| | $tZ, tW$ | 13 |
| | $t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$ | 12 |
| | **Total** | **191** |
| Higgs production and decay | Run I signal strengths | 22 |
| | Run II signal strengths | 36 (*) |
| | Run II, differential distributions & STXS | 71 |
| | **Total** | **129** |
| Diboson production | LEP-2 | 40 |
| | LHC | 41 |
| | **Total** | **81** |
| EWPOs | LEP-2 | 44 |
| Baseline dataset | **Total** | **445** |

SMEFiT3.0 Celada, Giani, Mantani, Rojo, Rossia, Thomas, EV, ter Hoeve arXiv:2404.12809

See also: de Blas et al arXiv:2507.06191 for a recent global fit

# Which operators?

Flavour assumption:

$\mathrm{U}(2)_q \times \mathrm{U}(3)_d \times \mathrm{U}(2)_u \times (\mathrm{U}(1)_\ell \times \mathrm{U}(1)_e)^3$ + Yukawa of bottom, charm and tau

| Operator | Coefficient | Definition | Operator | Coefficient | Definition |
|---|---|---|---|---|---|
| | | **3rd generation quarks** | | | |
| $\mathcal{O}_{\varphi Q}^{(1)}$ | $c_{\varphi Q}^{(1)}$ (*) | $i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{Q}\gamma^\mu Q)$ | $\mathcal{O}_{tW}$ | $c_{tW}$ | $i(\bar{Q}\tau^{\mu\nu}\tau_I t)\tilde{\varphi} W^I_{\mu\nu} + \text{h.c.}$ |
| $\mathcal{O}_{\varphi Q}^{(3)}$ | $c_{\varphi Q}^{(3)}$ | $i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{Q}\gamma^\mu \tau^I Q)$ | $\mathcal{O}_{tB}$ | $c_{tB}$ (*) | $i(\bar{Q}\tau^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu} + \text{h.c.}$ |
| $\mathcal{O}_{\varphi t}$ | $c_{\varphi t}$ | $i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t)$ | $\mathcal{O}_{tG}$ | $c_{tG}$ | $ig_S(\bar{Q}\tau^{\mu\nu} T_A t)\tilde{\varphi} G^A_{\mu\nu} + \text{h.c.}$ |
| $\mathcal{O}_{t\varphi}$ | $c_{t\varphi}$ | $(\varphi^\dagger\varphi)\bar{Q} t \tilde{\varphi} + \text{h.c.}$ | $\mathcal{O}_{b\varphi}$ | $c_{b\varphi}$ | $(\varphi^\dagger\varphi)\bar{Q} b \varphi + \text{h.c.}$ |
| | | **1st, 2nd generation quarks** | | | |
| $\mathcal{O}_{\varphi q}^{(1)}$ | $c_{\varphi q}^{(1)}$ (*) | $\sum_{i=1,2} i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{q}_i\gamma^\mu q_i)$ | $\mathcal{O}_{\varphi d}$ | $c_{\varphi d}$ | $\sum_{i=1,2,3} i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{d}_i\gamma^\mu d_i)$ |
| $\mathcal{O}_{\varphi q}^{(3)}$ | $c_{\varphi q}^{(3)}$ | $\sum_{i=1,2} i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{q}_i\gamma^\mu \tau^I q_i)$ | $\mathcal{O}_{c\varphi}$ | $c_{c\varphi}$ | $(\varphi^\dagger\varphi)\bar{q}_2 c \tilde{\varphi} + \text{h.c.}$ |
| $\mathcal{O}_{\varphi u}$ | $c_{\varphi u}$ | $\sum_{i=1,2} i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{u}_i\gamma^\mu u_i)$ | | | |
| | | **two-leptons** | | | |
| $\mathcal{O}_{\varphi \ell_i}$ | $c_{\varphi \ell_i}$ | $i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{\ell}_i\gamma^\mu \ell_i)$ | $\mathcal{O}_{\varphi\mu}$ | $c_{\varphi\mu}$ | $i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{\mu}\gamma^\mu \mu)$ |
| $\mathcal{O}_{\varphi \ell_i}^{(3)}$ | $c_{\varphi \ell_i}^{(3)}$ | $i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{\ell}_i\gamma^\mu \tau^I \ell_i)$ | $\mathcal{O}_{\varphi\tau}$ | $c_{\varphi\tau}$ | $i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{\tau}\gamma^\mu \tau)$ |
| $\mathcal{O}_{\varphi e}$ | $c_{\varphi e}$ | $i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{e}\gamma^\mu e)$ | $\mathcal{O}_{\tau\varphi}$ | $c_{\tau\varphi}$ | $(\varphi^\dagger\varphi)\bar{\ell}_3 \tau \varphi + \text{h.c.}$ |
| | | **four-leptons** | | | |
| $\mathcal{O}_{\ell\ell}$ | $c_{\ell\ell}$ | $(\bar{\ell}_1\gamma_\mu \ell_2)(\bar{\ell}_2\gamma^\mu \ell_1)$ | | | |

| DoF | Definition (in Warsaw basis notation) | DoF | Definition (in Warsaw basis notation) |
|---|---|---|---|
| $c_{QQ}^1$ | $2c_{qq}^{1(3333)} - \frac{2}{3}c_{qq}^{3(3333)}$ | $c_{QQ}^8$ | $8c_{qq}^{3(3333)}$ |
| $c_{Qt}^1$ | $c_{qu}^{1(3333)}$ | $c_{Qt}^8$ | $c_{qu}^{8(3333)}$ |
| $c_{Qq}^{1,8}$ | $c_{qq}^{1(i33i)} + 3c_{qq}^{3(i33i)}$ | $c_{Qq}^{1,1}$ | $c_{qq}^{1(ii33)} + \frac{1}{6}c_{qq}^{1(i33i)} + \frac{1}{2}c_{qq}^{3(i33i)}$ |
| $c_{Qq}^{3,8}$ | $c_{qq}^{1(i33i)} - c_{qq}^{3(i33i)}$ | $c_{Qq}^{3,1}$ | $c_{qq}^{3(ii33)} + \frac{1}{6}(c_{qq}^{1(i33i)} - c_{qq}^{3(i33i)})$ |
| $c_{tq}^8$ | $c_{qu}^{8(ii33)}$ | $c_{tq}^1$ | $c_{qu}^{1(ii33)}$ |
| $c_{tu}^8$ | $2c_{uu}^{(i33i)}$ | $c_{tu}^1$ | $c_{uu}^{(ii33)} + \frac{1}{3}c_{uu}^{(i33i)}$ |
| $c_{Qu}^8$ | $c_{qu}^{8(33ii)}$ | $c_{Qu}^1$ | $c_{qu}^{1(33ii)}$ |
| $c_{td}^8$ | $c_{ud}^{8(33jj)}$ | $c_{td}^1$ | $c_{ud}^{1(33jj)}$ |
| $c_{Qd}^8$ | $c_{qd}^{8(33jj)}$ | $c_{Qd}^1$ | $c_{qd}^{1(33jj)}$ |

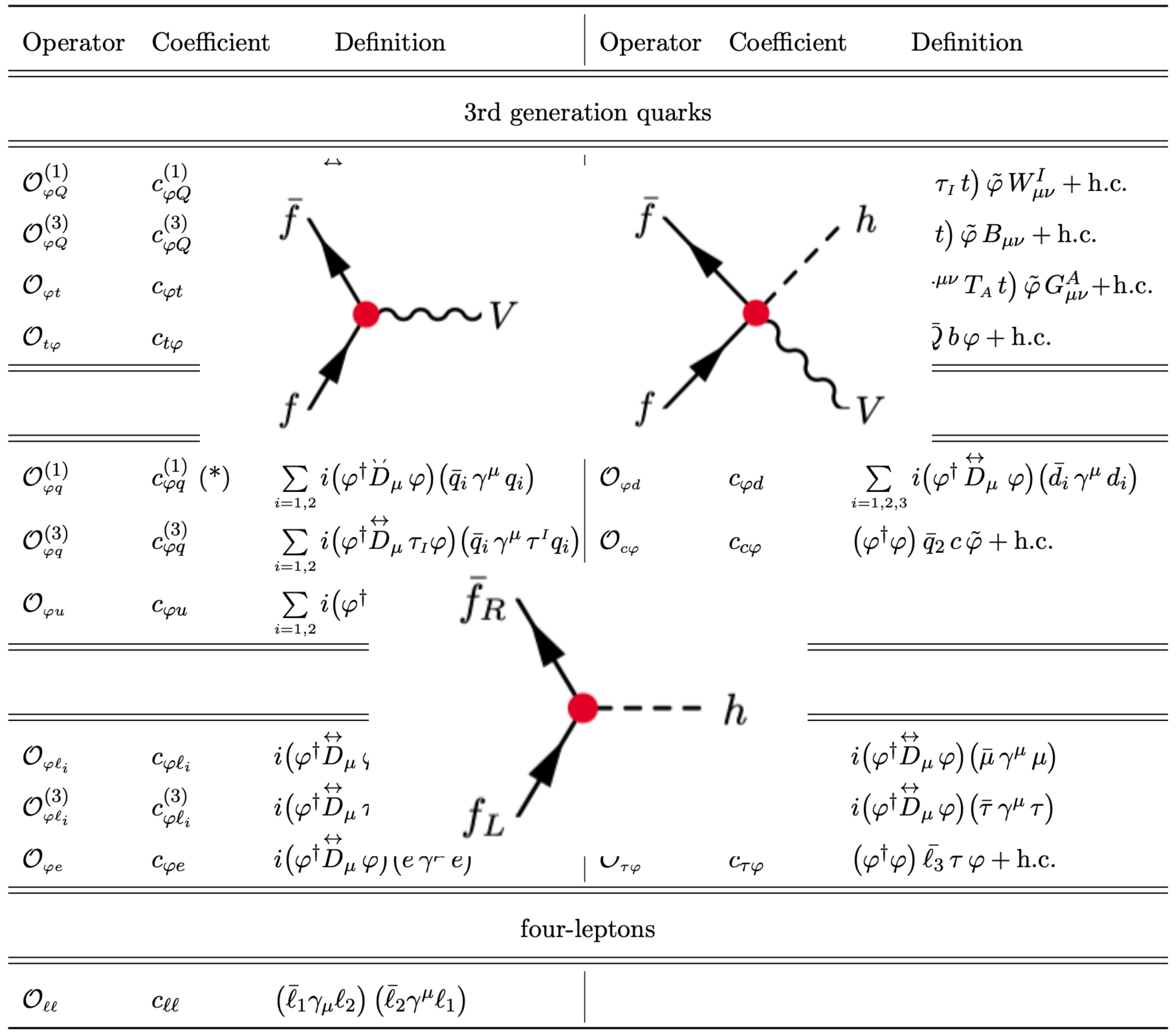
| Operator | Coefficient | Definition | Operator | Coefficient | Definition |
|---|---|---|---|---|---|
| $\mathcal{O}_{\varphi G}$ | $c_{\varphi G}$ | $(\varphi^\dagger\varphi) G_A^{\mu\nu} G^A_{\mu\nu}$ | $\mathcal{O}_{\varphi\Box}$ | $c_{\varphi\Box}$ | $\partial_\mu(\varphi^\dagger\varphi)\partial^\mu(\varphi^\dagger\varphi)$ |
| $\mathcal{O}_{\varphi B}$ | $c_{\varphi B}$ | $(\varphi^\dagger\varphi) B^{\mu\nu} B_{\mu\nu}$ | $\mathcal{O}_{\varphi D}$ | $c_{\varphi D}$ | $(\varphi^\dagger D^\mu\varphi)^\dagger(\varphi^\dagger D_\mu\varphi)$ |
| $\mathcal{O}_{\varphi W}$ | $c_{\varphi W}$ | $(\varphi^\dagger\varphi) W_I^{\mu\nu} W^I_{\mu\nu}$ | $\mathcal{O}_W$ | $c_{WWW}$ | $\epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_\rho$ |
| $\mathcal{O}_{\varphi WB}$ | $c_{\varphi WB}$ | $(\varphi^\dagger\tau_I\varphi) B^{\mu\nu} W^I_{\mu\nu}$ | | | |

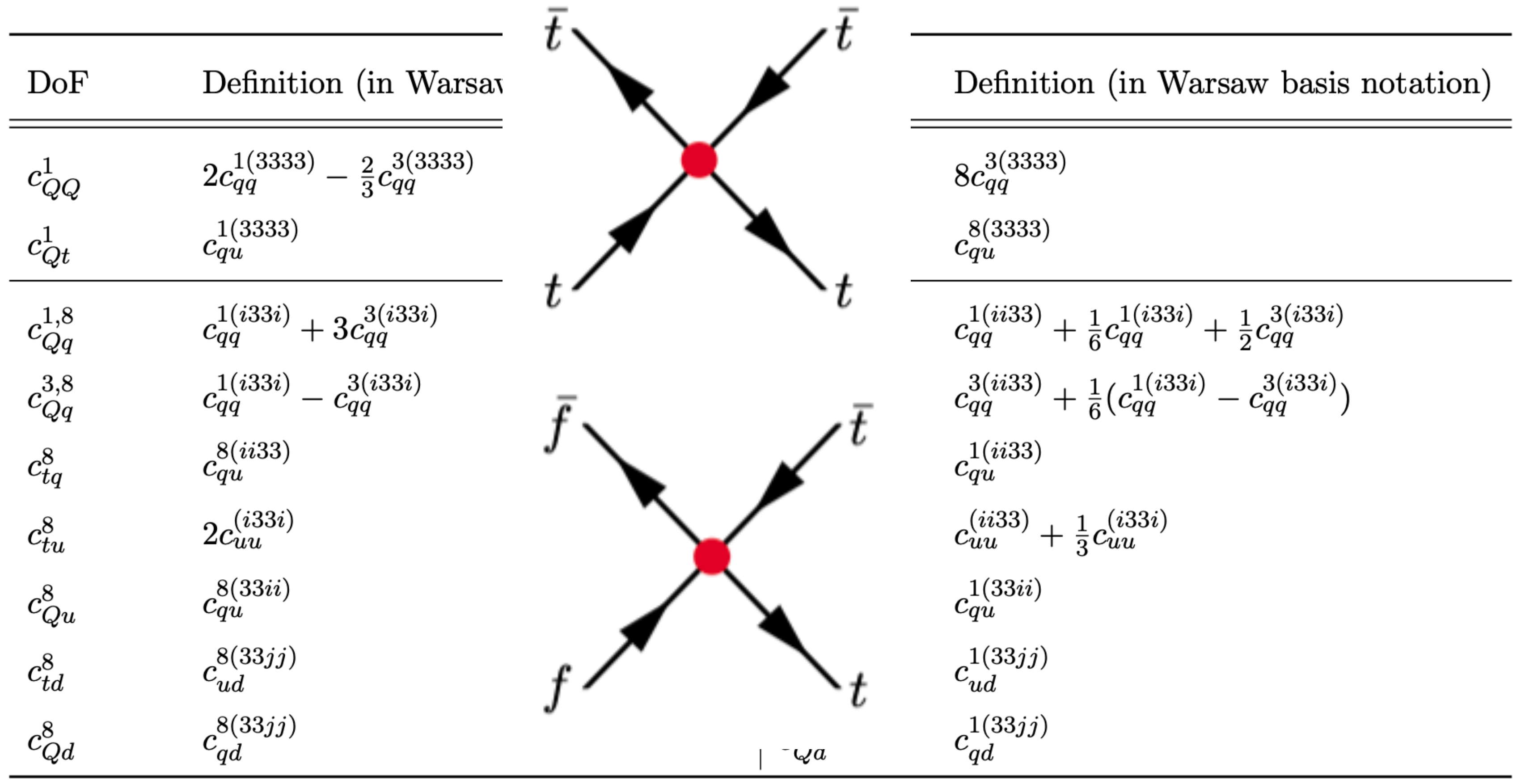
## 50 degrees of freedom

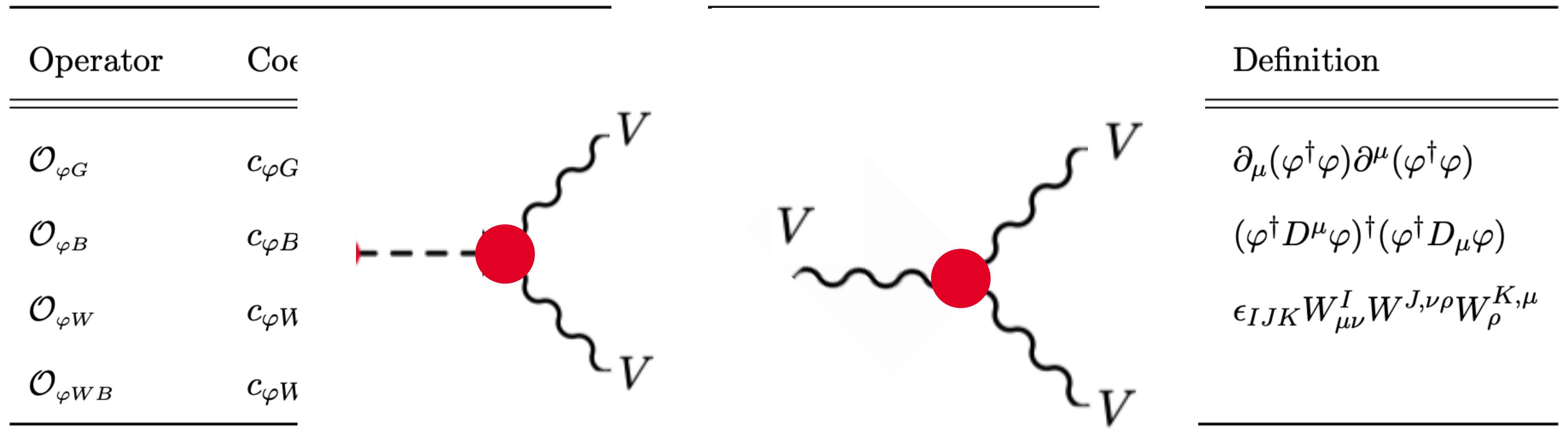
# Which operators?

## Flavour assumption:

$\mathrm{U}(2)_q \times \mathrm{U}(3)_d \times \mathrm{U}(2)_u \times (\mathrm{U}(1)_\ell \times \mathrm{U}(1)_e)^3$ + Yukawa of bottom, charm and tau

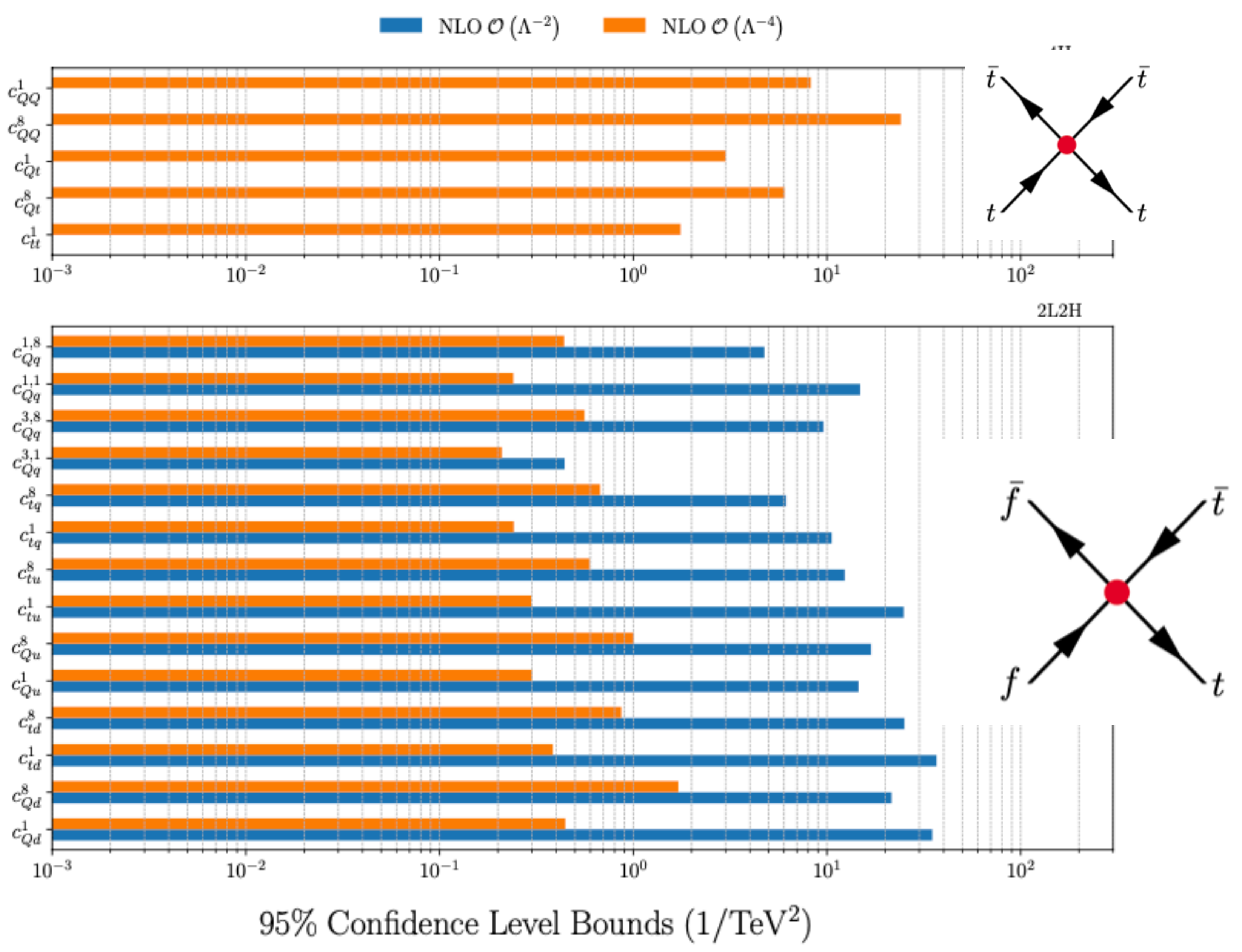


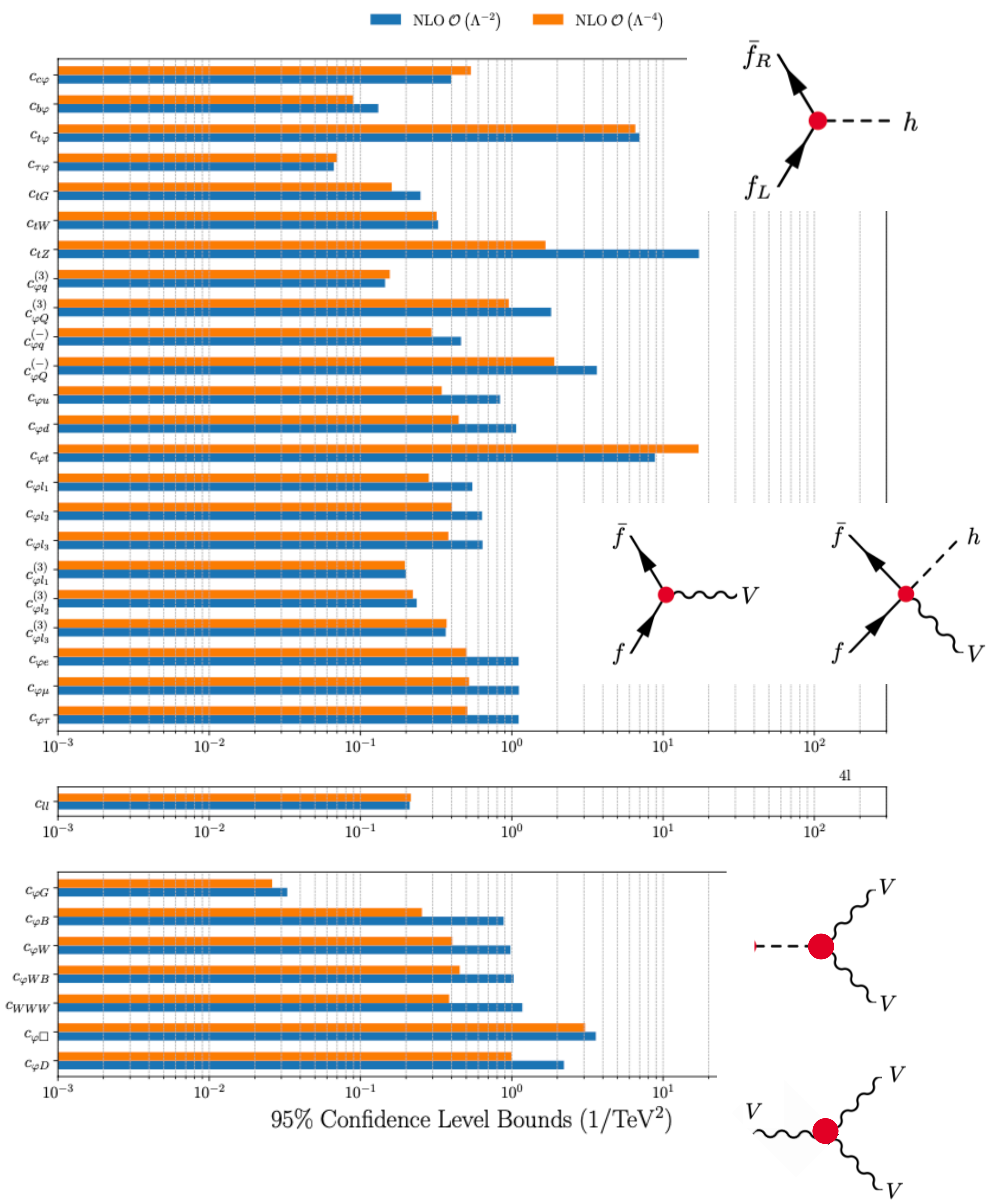




**50 degrees of freedom**

# Current global fit results

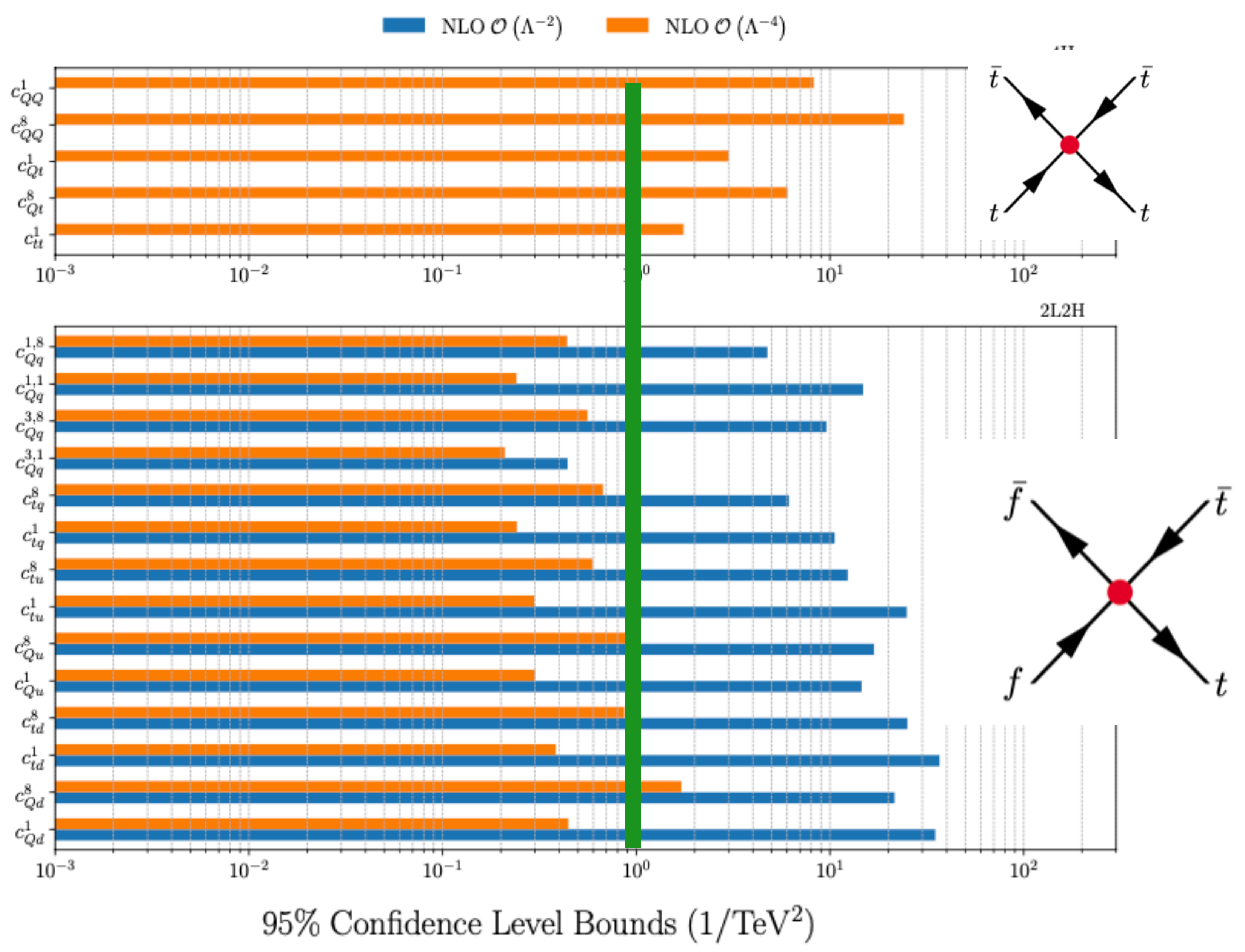


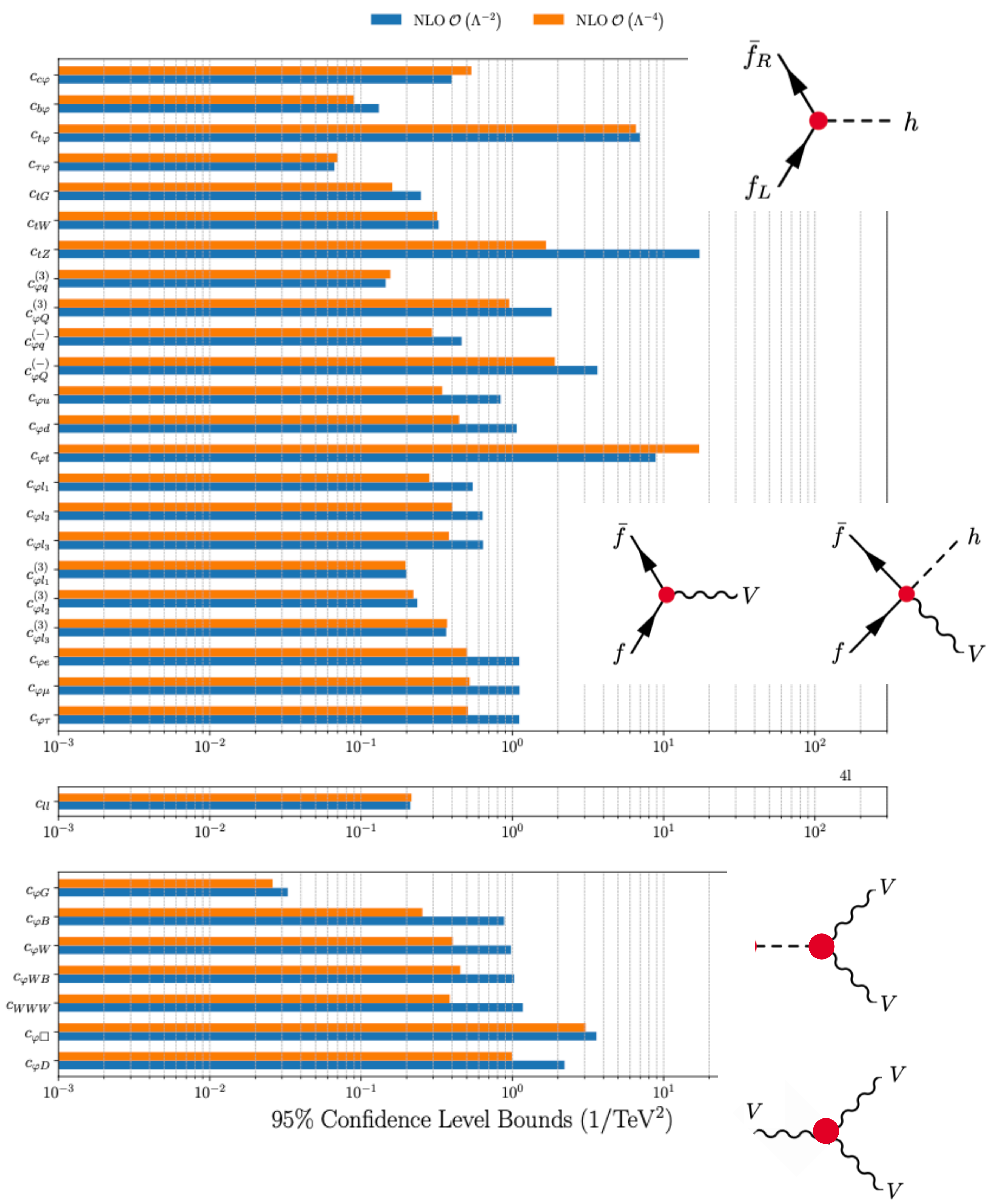




- Bounds varying between operators
- Most Wilson coefficient bounds below 1 for Λ=1 TeV
- Quadratic terms important (especially for 4-fermion operators)
- Least constrained coefficients are 4-top operators

Celada et al arXiv:2404.12809

# Current global fit results

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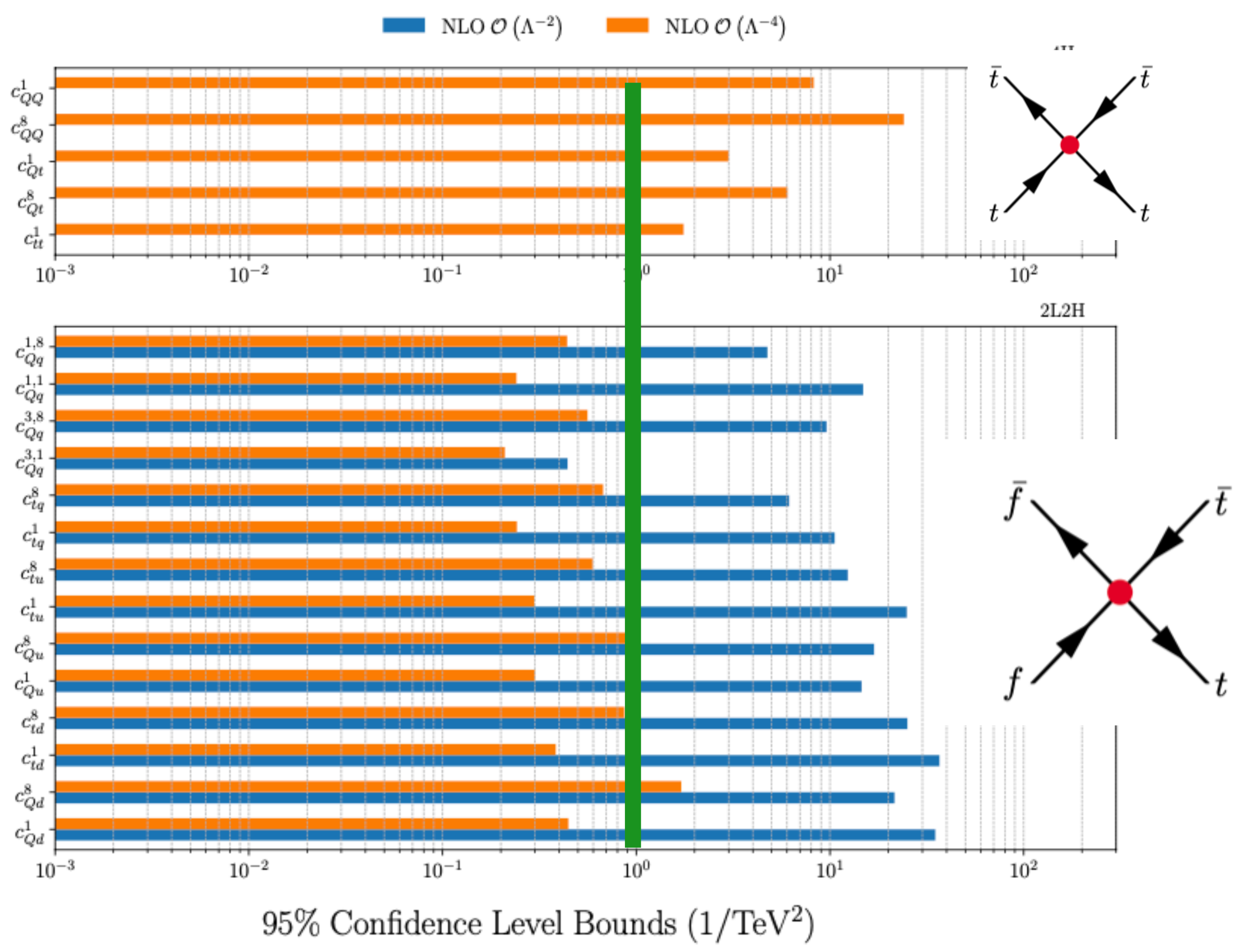


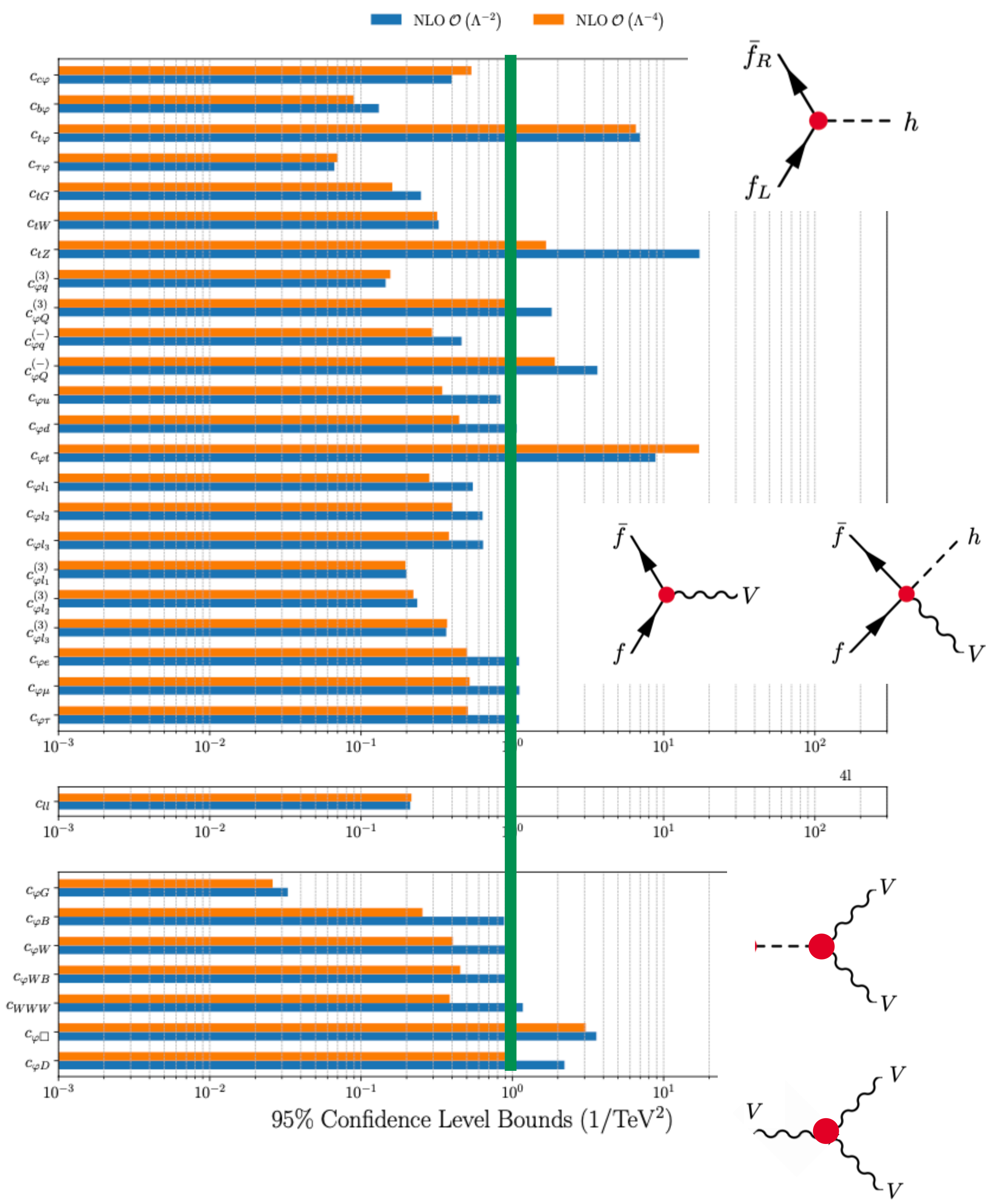


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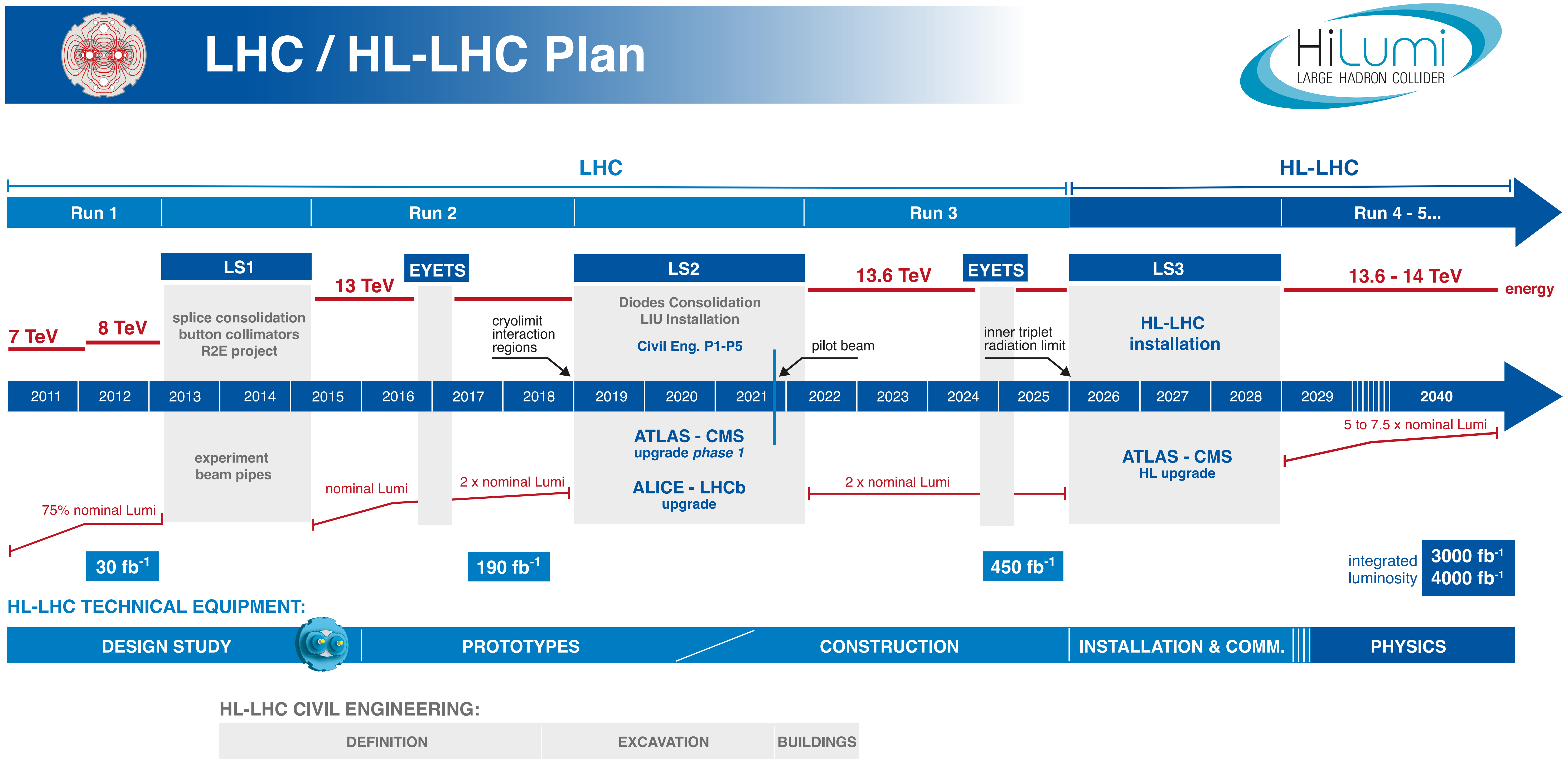
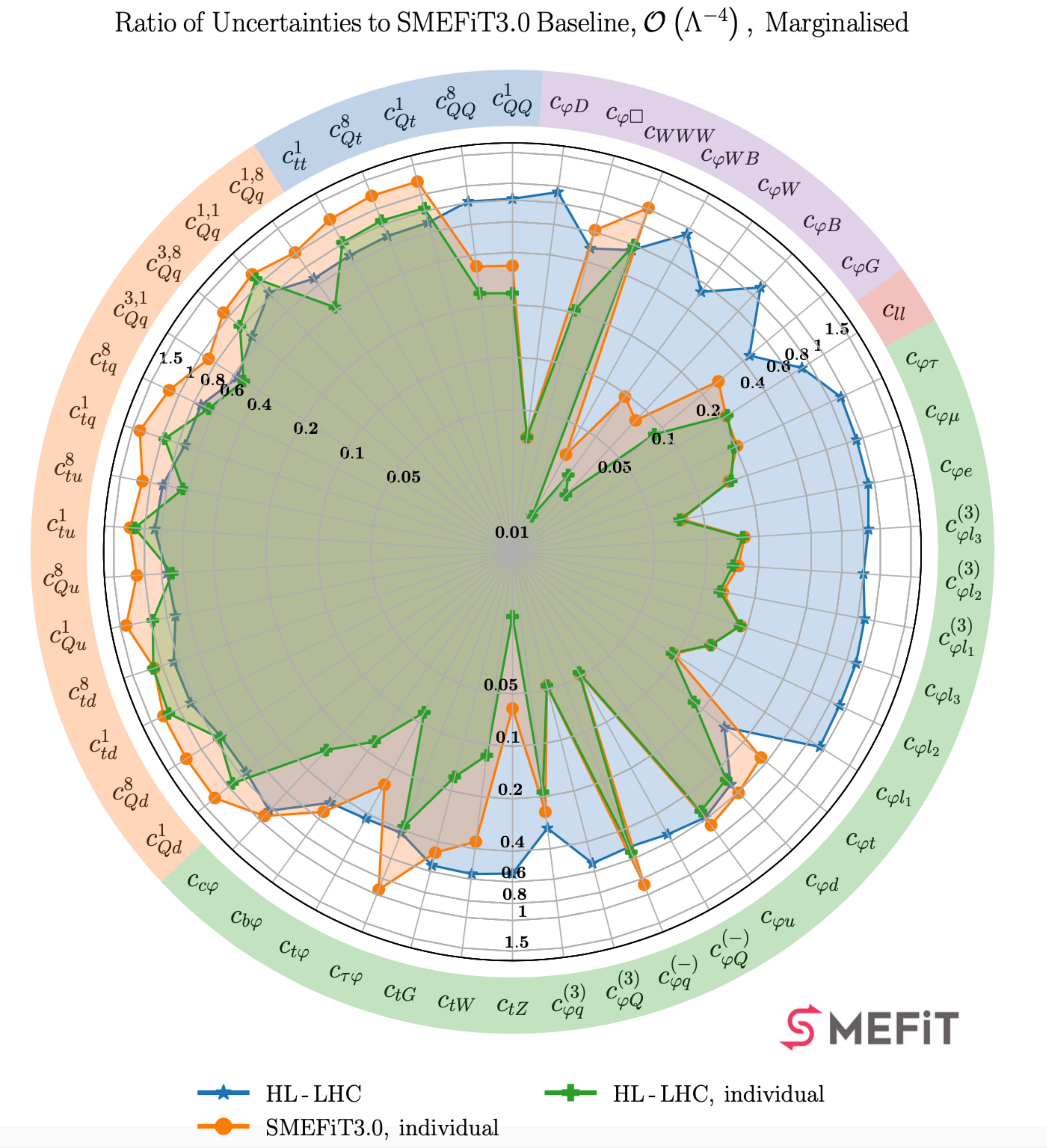
# How about the HL-LHC?




- HL-LHC will collect 3000ab$^{-1}$ over the next 20 years
- Any future project will come after that
- How will the constraints look at the end of the HL-LHC?

# Constraints at the HL-LHC

- We project all Run II datasets: one for each process and final state
- Scaling of uncertainties:
  - Statistical ones scaling with Luminosity
  - Systematics reduced by a factor of 2
- Explore relative improvement compared to current LHC fit
- We see an improvement ranging from 20% to a factor of 3 in the marginalised fit
- Improvement also through marginalisation
- No dedicated binning: Expect further improvement over LHC due to access to statistically limited high energy tails




Celada et al arXiv:2404.12809

# The future

# The future

HiLumi HL-LHC PROJECT

CLIC

International MUON Collider Collaboration

FCC hh ee he

CEPC

Linear Collider Vision

ilc international linear collider

# Future Circular Collider

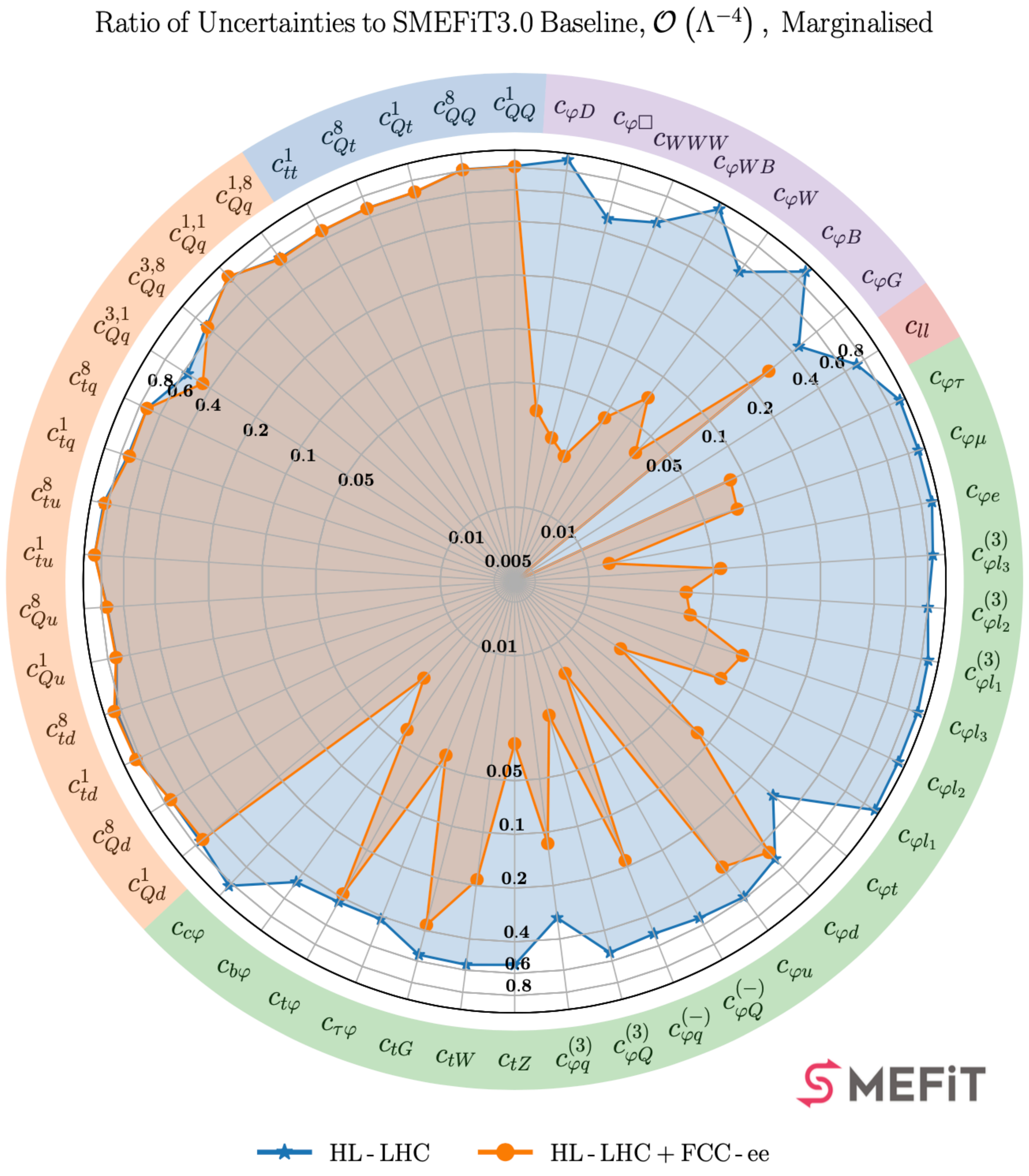
What will the FCC-ee measure?

- EWPOs at the Z-pole
- Light fermion pair prediction
- Higgsstrahlung and VBF
- W boson pair production
- Top-quark pair production (365GeV)

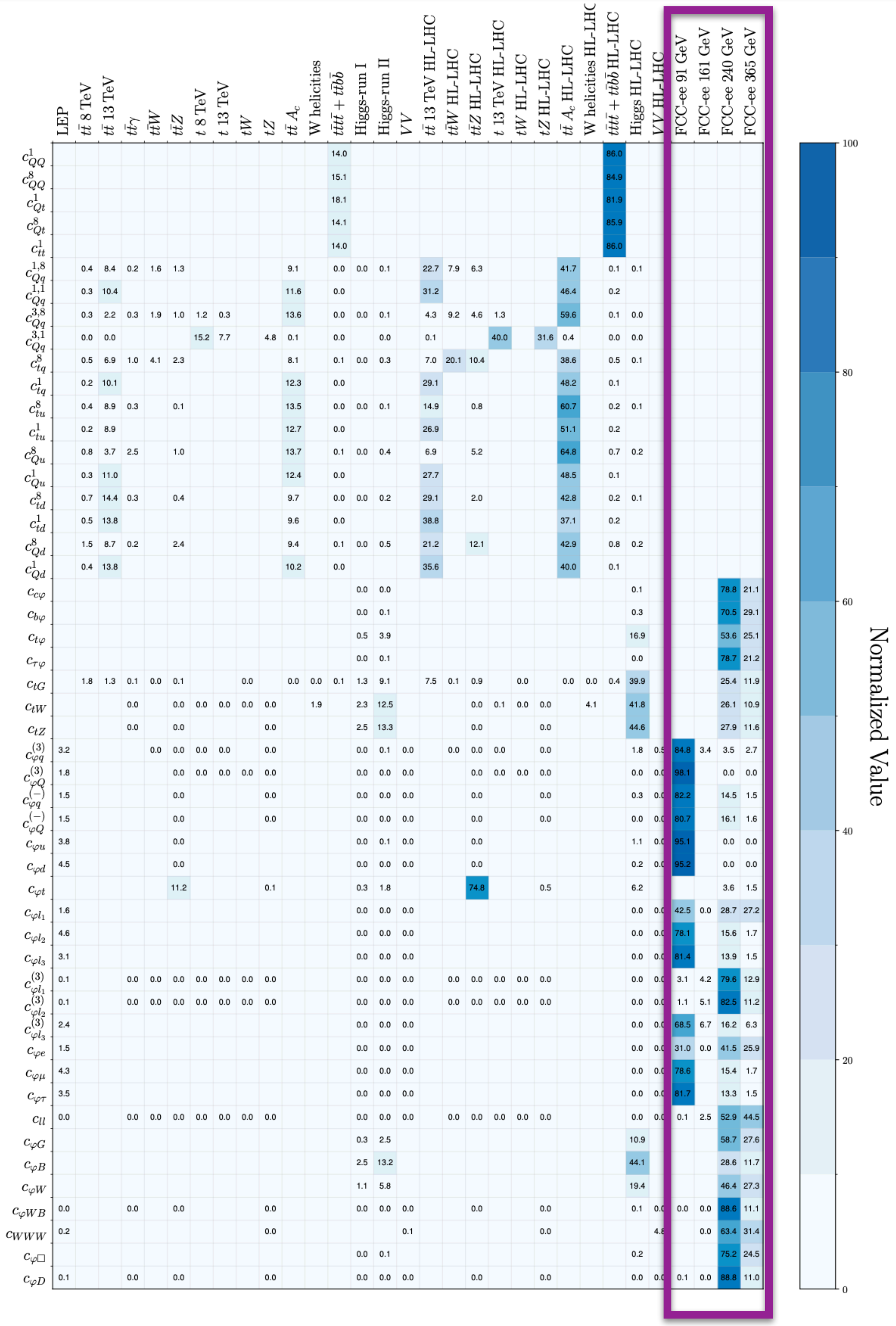
Uncertainty projections from Snowmass study: arXiv:2206.08326

Significant improvement for:

- gauge operators (up to 30 times)
- 2-fermion operators (up to 50 times)



# Fisher information




- Fisher information shows which process gives more sensitivity for a given operator
- Proxy for a linear individual fit
- FCC-ee dominates nearly all operators except for 4-quark operators, only accessible at in pp collisions (tree level)
- Global fit picture more complicated due to correlations
- Both Z-pole run and run at 240 GeV important to pin down 2-fermion and gauge operators

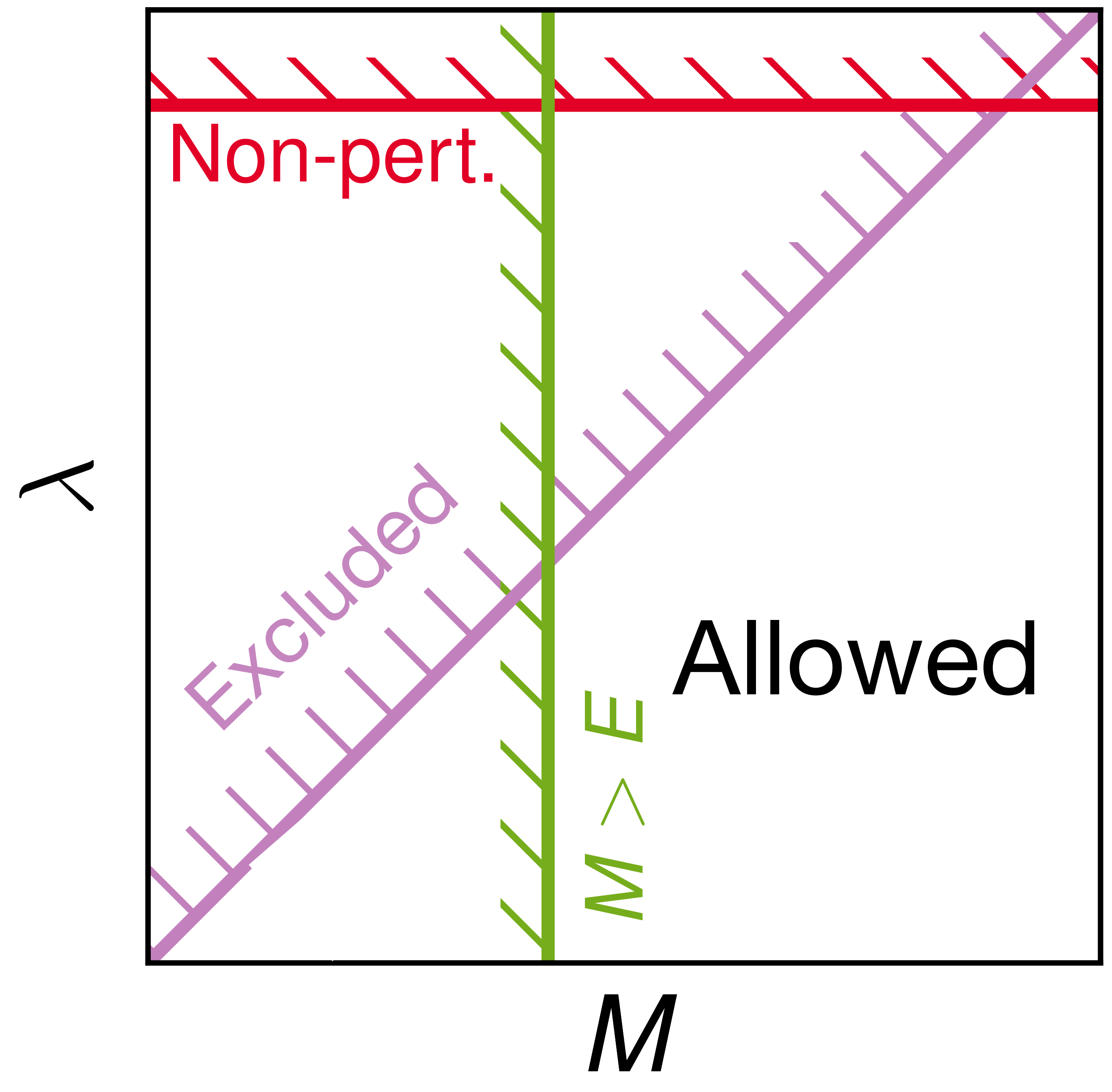
See also Maura, Stefanek, You arXiv:2412.14241

# What do we learn from global fits?

Bounds on new physics scale vary from 0.1 TeV (unconstrained) to 10s of TeV. Bounds depend on:

- the operator
- assumption of a strongly or weakly coupled theory
- individual or marginalised bounds (reality is somewhere in-between)
- linear or quadratic bounds

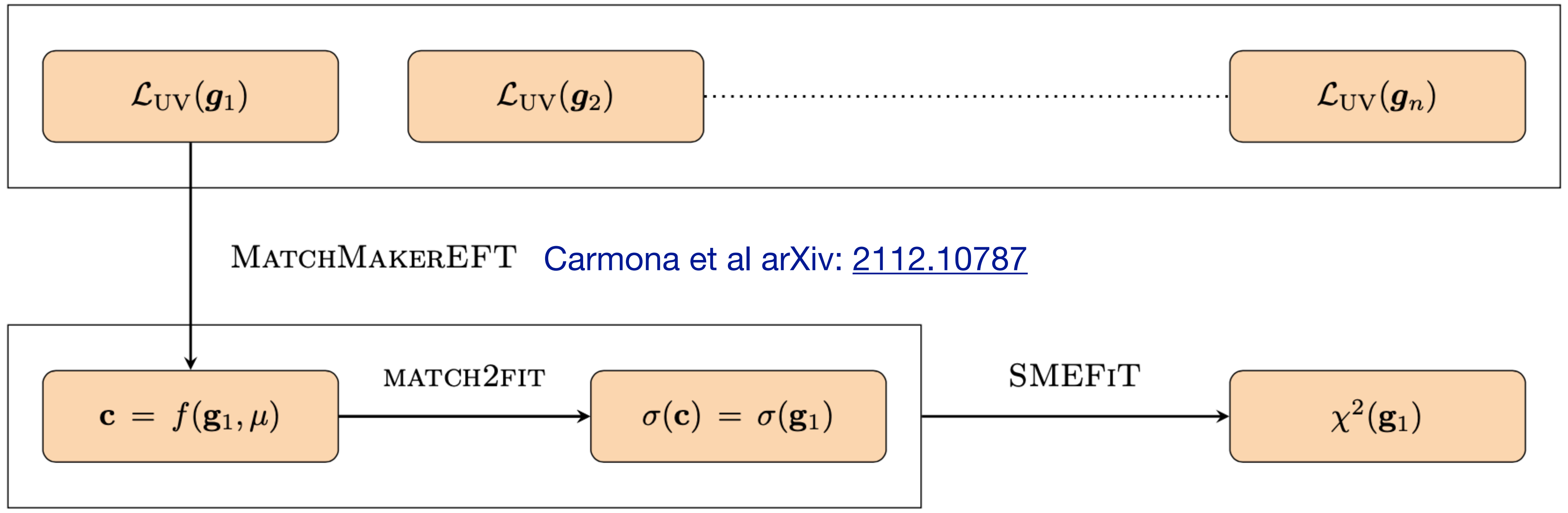
**constraint:** $$\frac{c_i^6(\mu)}{\Lambda^2} = \frac{\lambda^2}{M^2} < X$$



# From SMEFT to the UV

Global fit constrains parameters of UV models

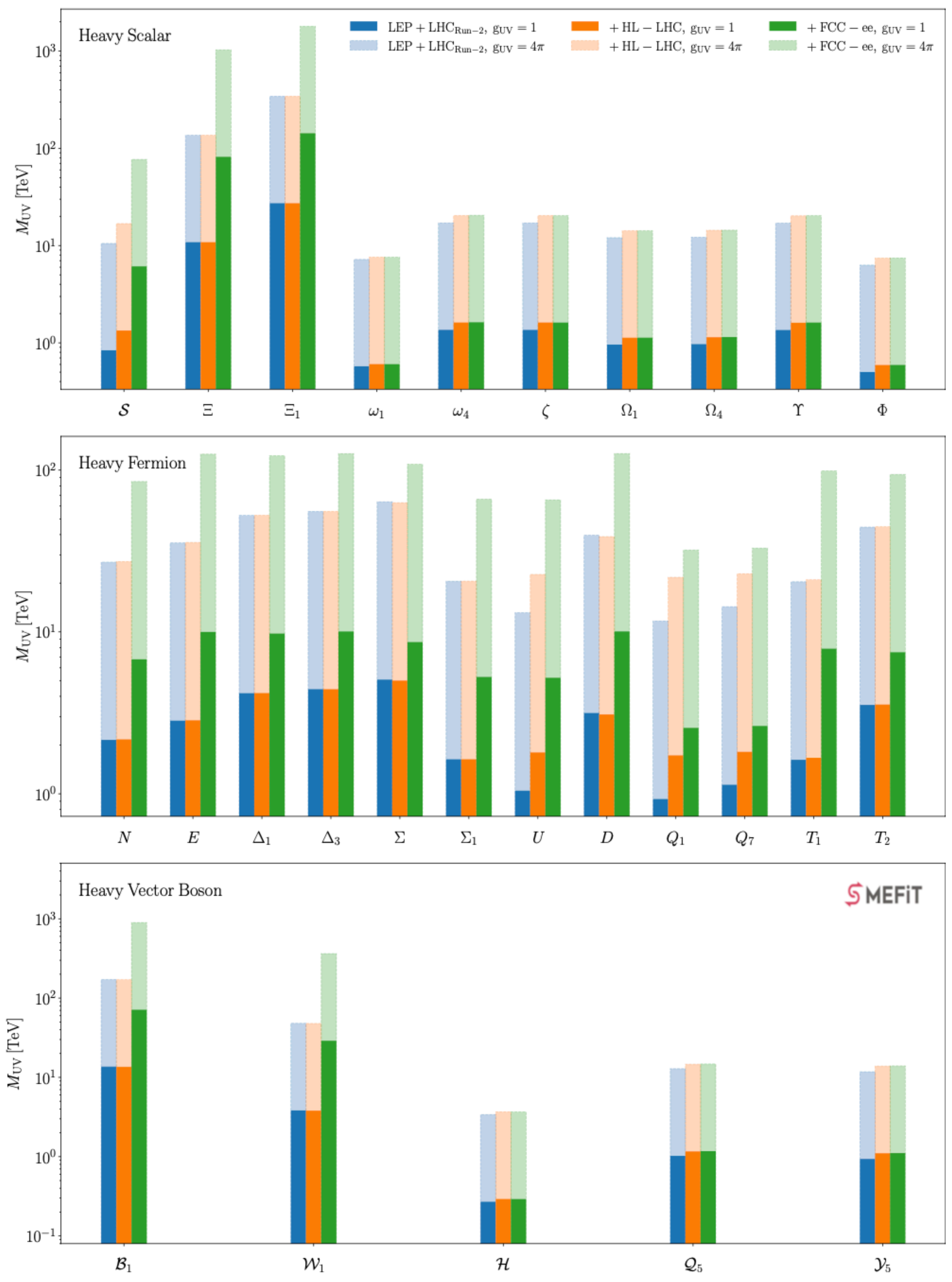
Matching condition ← $\frac{c_i^6(\mu)}{\Lambda^2} = \frac{\lambda^2}{M^2} < X$




- Automate chain with final output constraints on the UV parameters
- Simplest case: single-field extensions of the SM de Blas et al arXiv:1711.10391
- Assume mass, constrain the coupling or vice versa

ter Hoeve, Magni, Rojo, Rossia, EV arXiv: 2309.04523

# From SMEFT to the UV



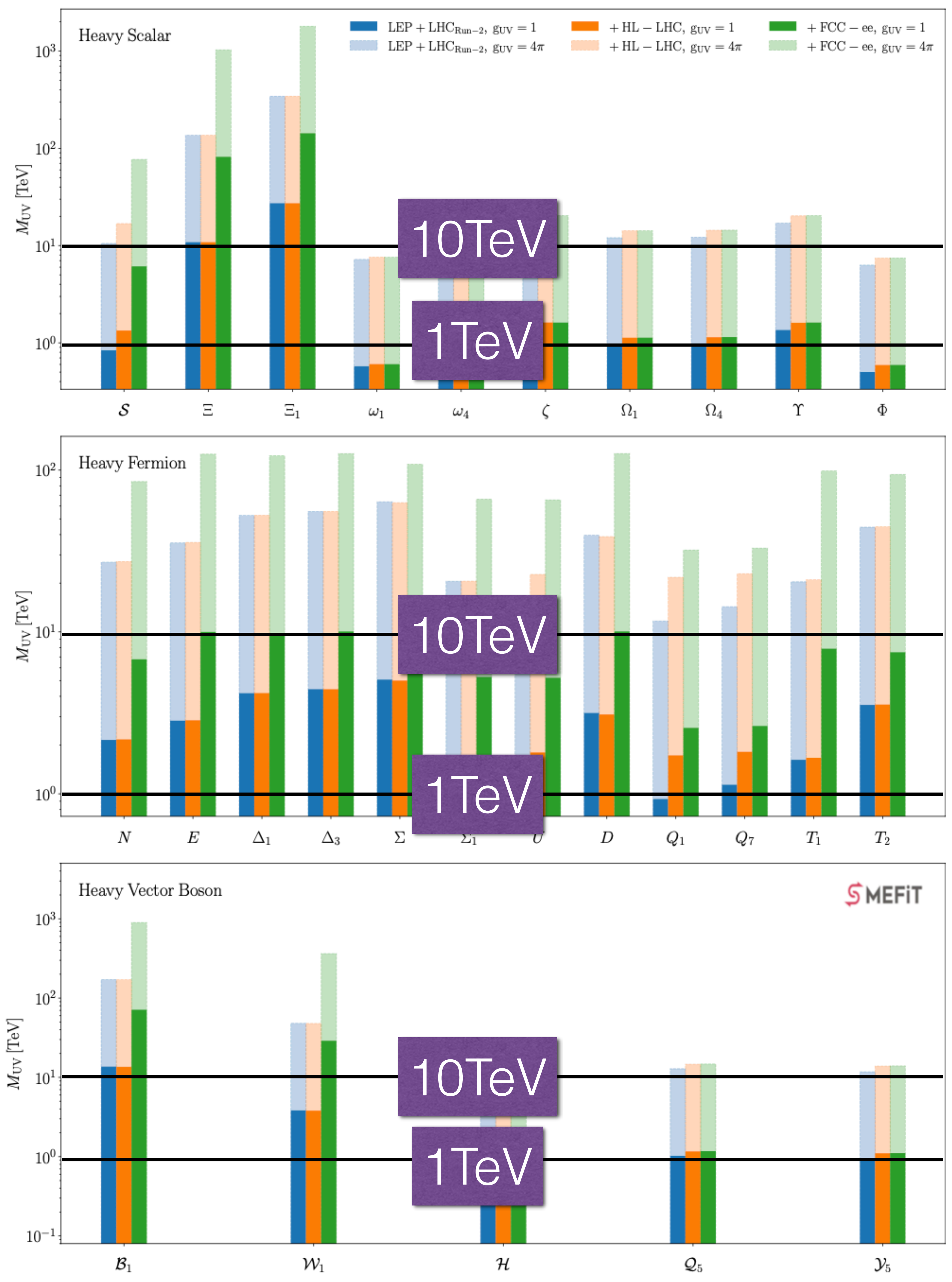

arXiv:2404.12809

| Scalars | | Fermions | | Vectors | |
|---|---|---|---|---|---|
| Particle | Irrep | Particle | Irrep | Particle | Irrep |
| $\mathcal{S}$ | $(1,1)_0$ | $N$ | $(1,1)_0$ | $\mathcal{B}$ | $(1,1)_0$ |
| $\mathcal{S}_1$ | $(1,1)_1$ | $E$ | $(1,1)_{-1}$ | $\mathcal{B}_1$ | $(1,1)_1$ |
| $\phi$ | $(1,2)_{1/2}$ | $\Delta_1$ | $(1,2)_{-1/2}$ | $\mathcal{W}$ | $(1,3)_0$ |
| $\Xi$ | $(1,3)_0$ | $\Delta_3$ | $(1,2)_{-3/2}$ | $\mathcal{W}_1$ | $(1,3)_1$ |
| $\Xi_1$ | $(1,3)_1$ | $\Sigma$ | $(1,3)_0$ | $\mathcal{G}$ | $(8,1)_0$ |
| $\omega_1$ | $(3,1)_{-1/3}$ | $\Sigma_1$ | $(1,3)_{-1}$ | $\mathcal{H}$ | $(8,3)_0$ |
| $\omega_4$ | $(3,1)_{-4/3}$ | $U$ | $(3,1)_{2/3}$ | $\mathcal{Q}_5$ | $(8,3)_0$ |
| $\zeta$ | $(3,3)_{-1/3}$ | $D$ | $(3,1)_{-1/3}$ | $\mathcal{Y}_5$ | $(\bar{6},2)_{-5/6}$ |
| $\Omega_1$ | $(6,1)_{1/3}$ | $Q_1$ | $(3,2)_{1/6}$ | | |
| $\Omega_4$ | $(6,1)_{4/3}$ | $Q_7$ | $(3,2)_{7/6}$ | | |
| $\Upsilon$ | $(6,3)_{1/3}$ | $T_1$ | $(3,3)_{-1/3}$ | | |
| $\Phi$ | $(8,2)_{1/2}$ | $T_2$ | $(3,3)_{2/3}$ | | |
| | | $Q_5$ | $(3,2)_{-5/6}$ | | |

- Large improvements in mass reach for models modifying EWPOs at the FCC
- Bounds reaching 100 TeV for some models at the FCC-ee
- HL-LHC improving models generating 4-quark operators (expect better improvement with dedicated HL-LHC analysis)

See also Allwicher, Mccullough, Renner 2408.03992 and Gargalionis, Quevillon, Vuong, You arXiv: 2412.01759

# From SMEFT to the UV




arXiv:2404.12809

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|---|---|---|---|---|---|
| Particle | Irrep | Particle | Irrep | Particle | Irrep |
| $\mathcal{S}$ | $(1,1)_0$ | $N$ | $(1,1)_0$ | $\mathcal{B}$ | $(1,1)_0$ |
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| $\Omega_4$ | $(6,1)_{4/3}$ | $Q_7$ | $(3,2)_{7/6}$ | | |
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| | | $Q_5$ | $(3,2)_{-5/6}$ | | |

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# Future of EFT predictions

- Missing Higher Orders in QCD and EW
  - EFT is a QFT, renormalisable order-by-order $1/\Lambda^2$

$$\mathcal{O}(\alpha_s, \alpha_{ew}) + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_s}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_{ew}}{\Lambda^2}\right)$$ → Does this matter?

- Renormalisation Group Running and mixing

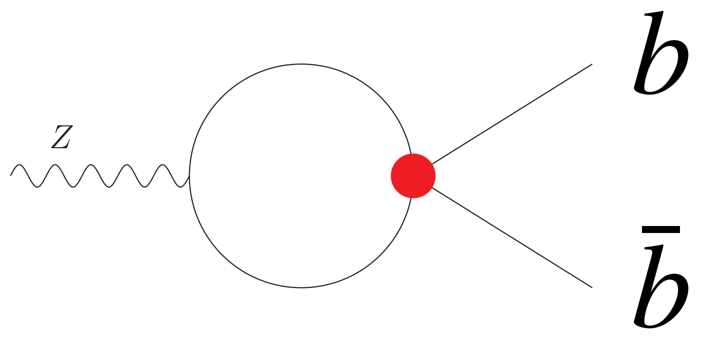
$$\Delta\text{Obs}_n = \text{Obs}_n^{\text{EXP}} - \text{Obs}_n^{\text{SM}} = \sum_i \frac{c_i^6(\mu)}{\Lambda^2} a_{n,i}^6(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$ How about this $\mu$?

- Matching to UV complete models at higher-loops: one-loop matching and efforts towards two loops

e.g. Guedes et al arXiv: 2303.16965, 2412.14253, Carmona et al 2112.10787, Fuentes Martin et al 2412.12270

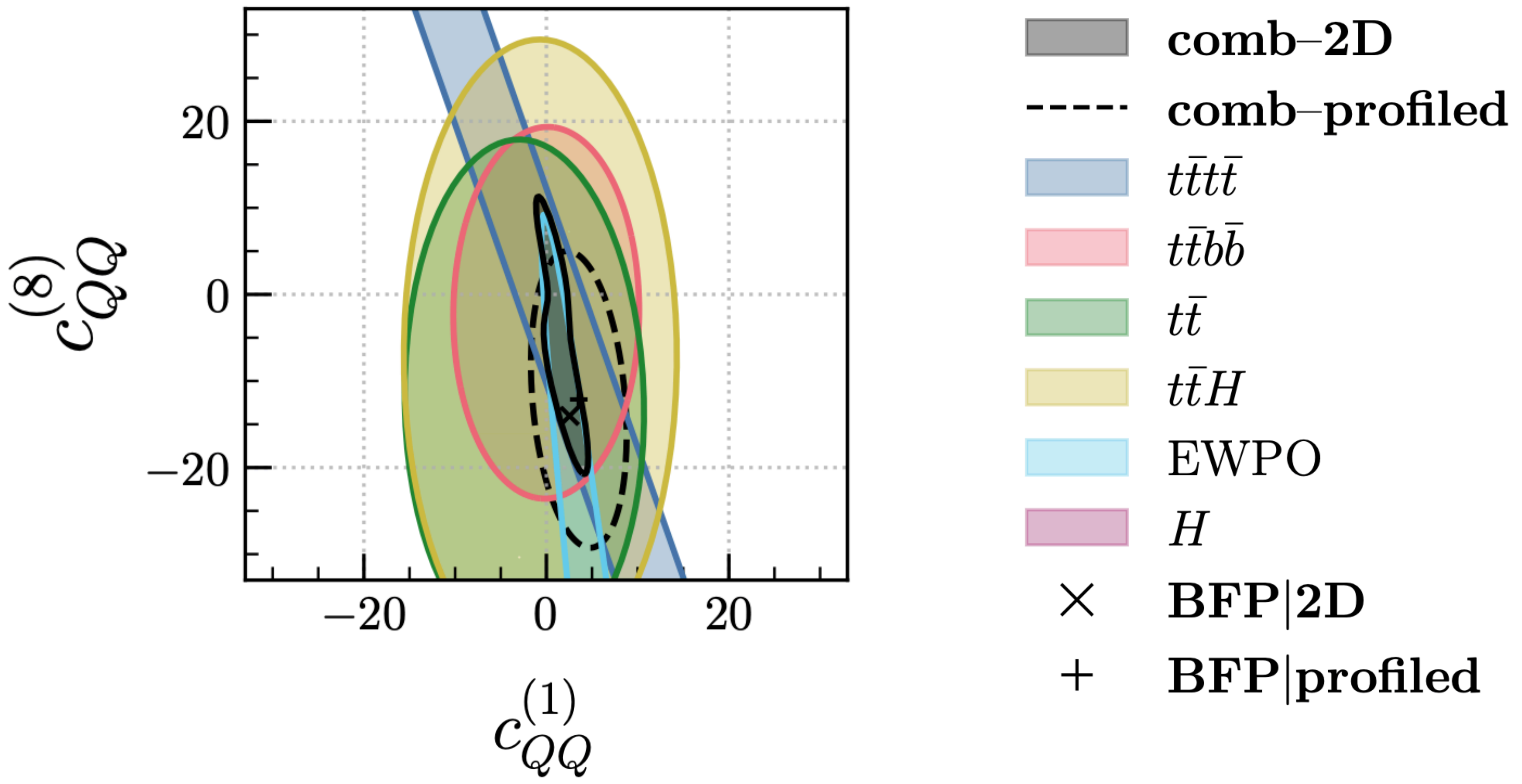
# Improved sensitivity due to EW loops

4-heavy operators in EWPO



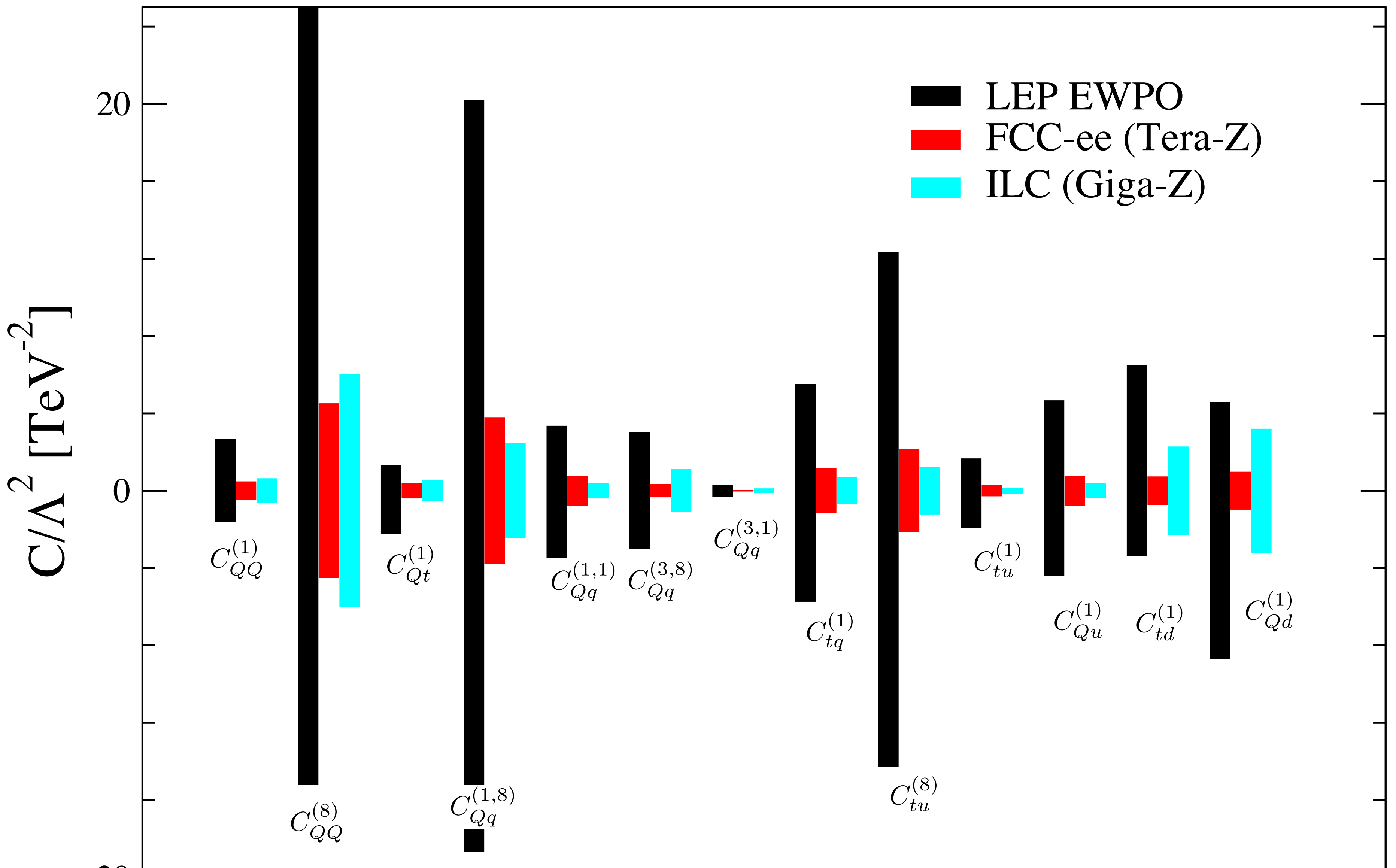

## Additional Sensitivity

95% CL — two-parameter scan (others = 0) + profiled ellipse — $\mathcal{O}(\Lambda^{-4})$



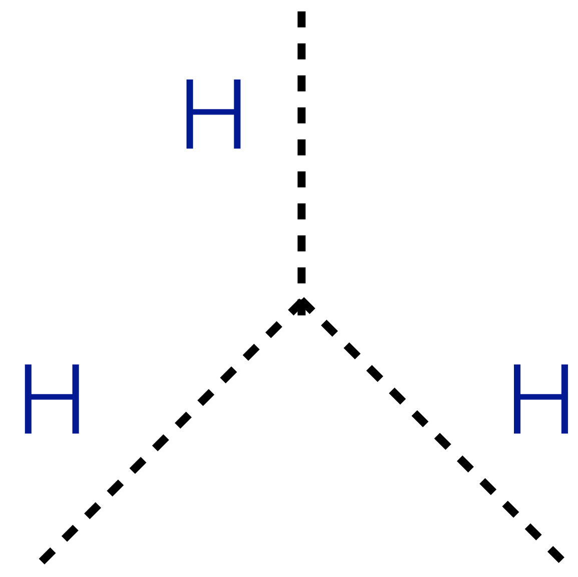

Di Noi, El Faham, Grober, Vitti, EV arXiv: 2507.01137

## Future prospects

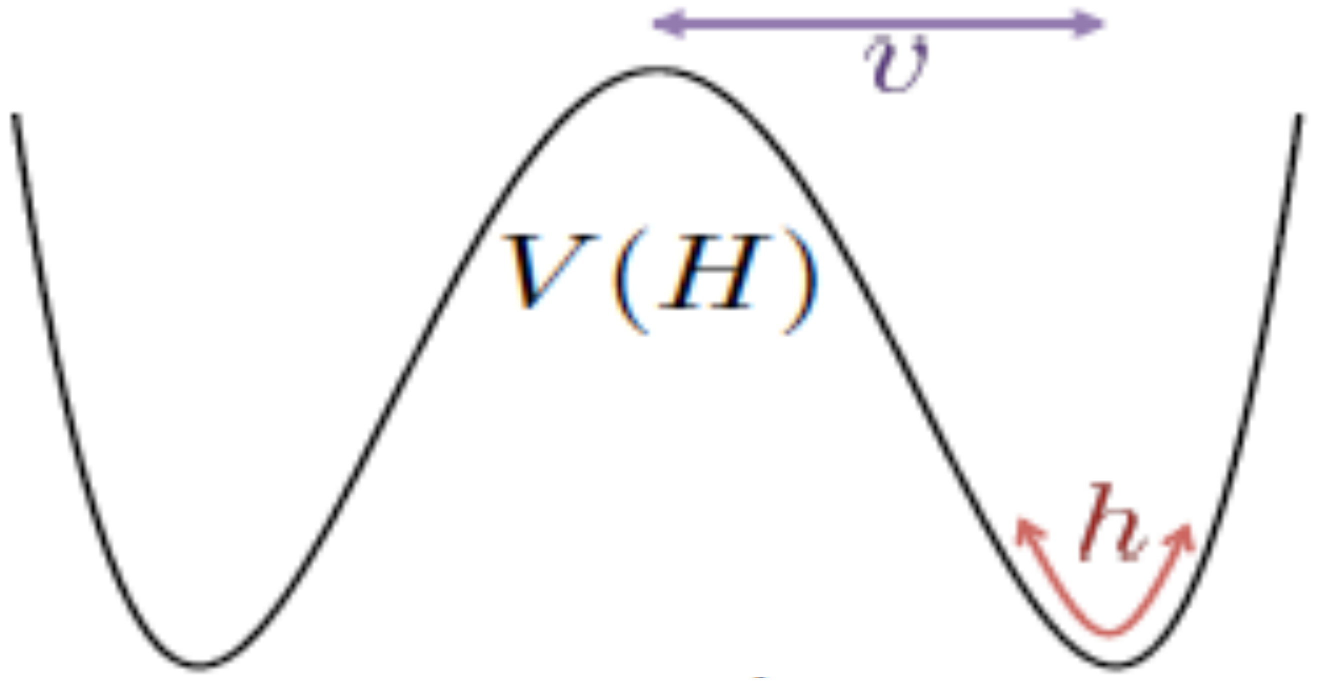



Dawson and Giardino arXiv: 2201.09887

# Focus: Higgs self-coupling




$\delta\lambda_{HHH}$?




$$V(H) = \frac{1}{2}M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4}\lambda_{HHHH} H^4$$

$$\lambda_{HHH} = \lambda_{HHHH} = \frac{M_H^2}{2v^2}$$

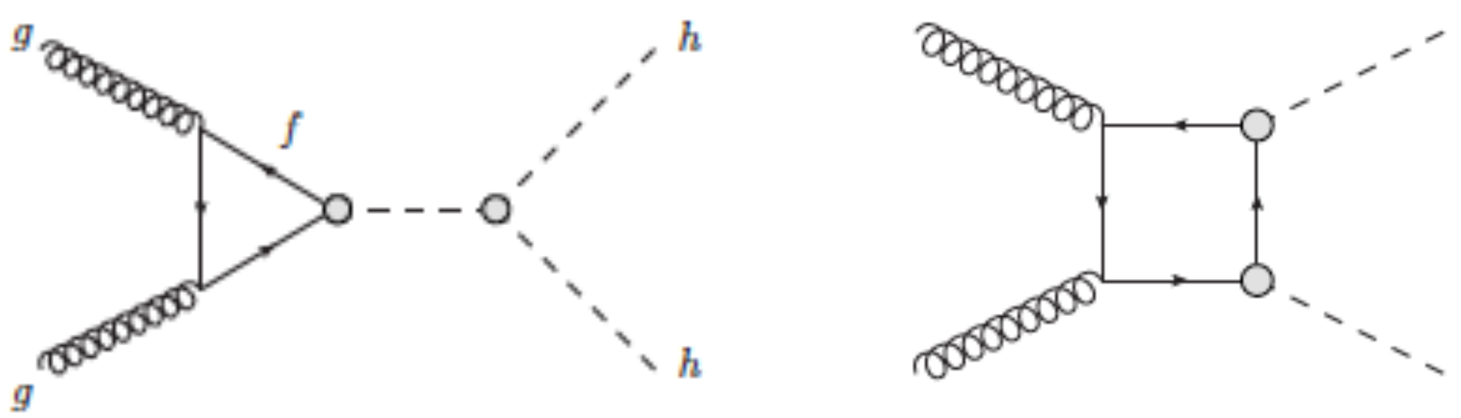
In the SMEFT:

$$\mathcal{O}_\varphi = \left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3 \supset v^3 h^3 + \frac{3}{2} v^2 h^4$$

$$\delta\kappa_3 = -\frac{2v^4}{m_h^2}\frac{c_\varphi}{\Lambda^2} + \frac{3v^2}{\Lambda^2}\left(c_{\varphi\Box} - \frac{1}{4}c_{\varphi D}\right)$$

# Higgs self-coupling probes

Hadron Collisions

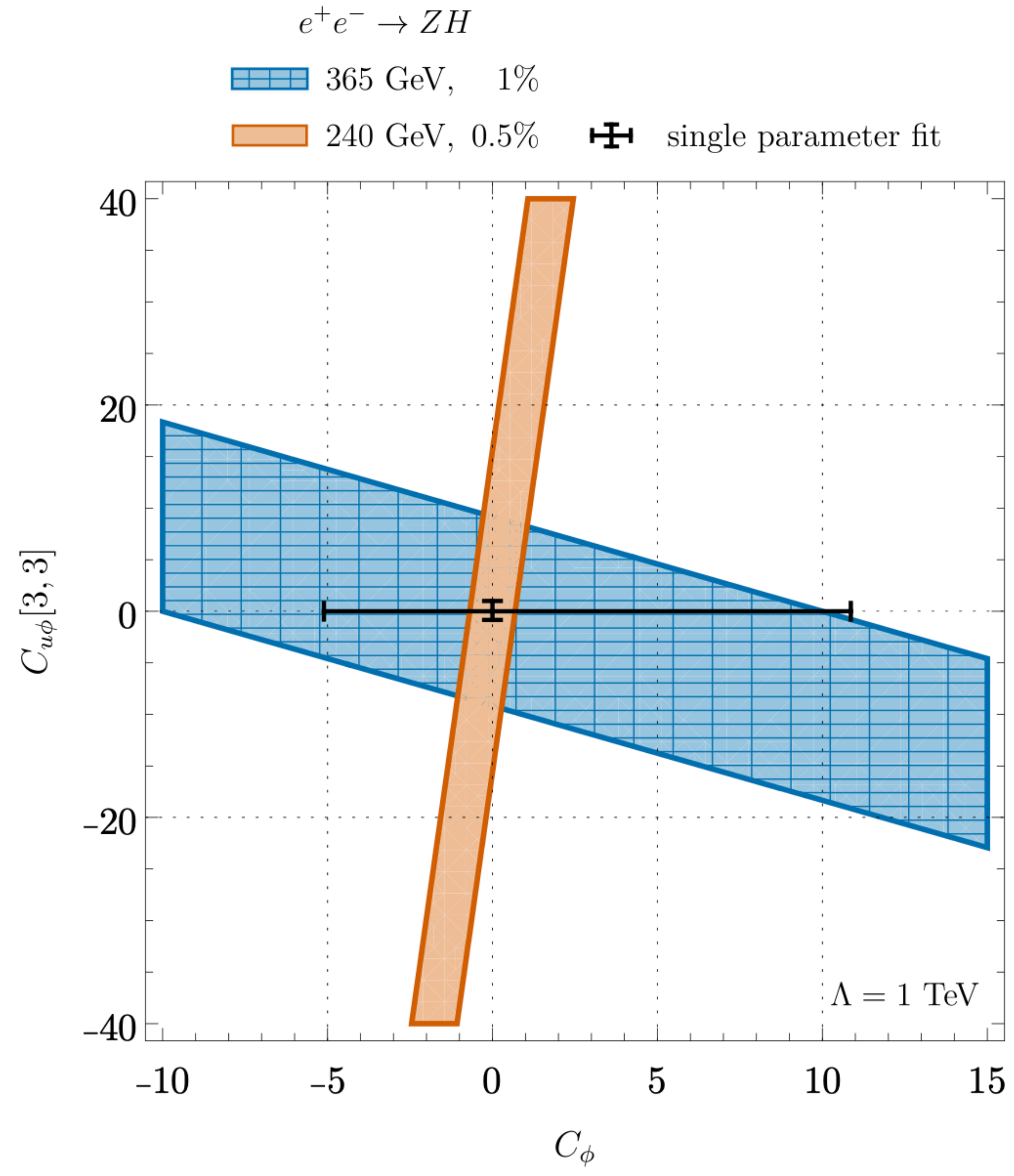



## HH projections for HL-LHC

| | 2 ab$^{-1}$ (S2) | | 3 ab$^{-1}$ (S2) | | 3 ab$^{-1}$ (S3) | |
|---|---|---|---|---|---|---|
| | ATLAS | CMS | ATLAS | CMS | ATLAS | CMS |
| | | | $HH$ statistical significance | | | |
| Combination | 3.7 | 3.5 | 4.3 | 4.2 | **4.5** | **4.5** |
| ATLAS+CMS | 6.0 | | 7.2 | | **7.6** | |
| | | | $\kappa_3$ 68% confidence interval | | | |
| Combination | [0.6, 1.5] | [0.4, 1.7] | [0.6, 1.5] | [0.5, 1.6] | **[0.6, 1.4]** | **[0.6, 1.5]** |
| ATLAS+CMS uncertainty | −32% / +37% | | −27% / +31% | | **−26% / +29%** | |

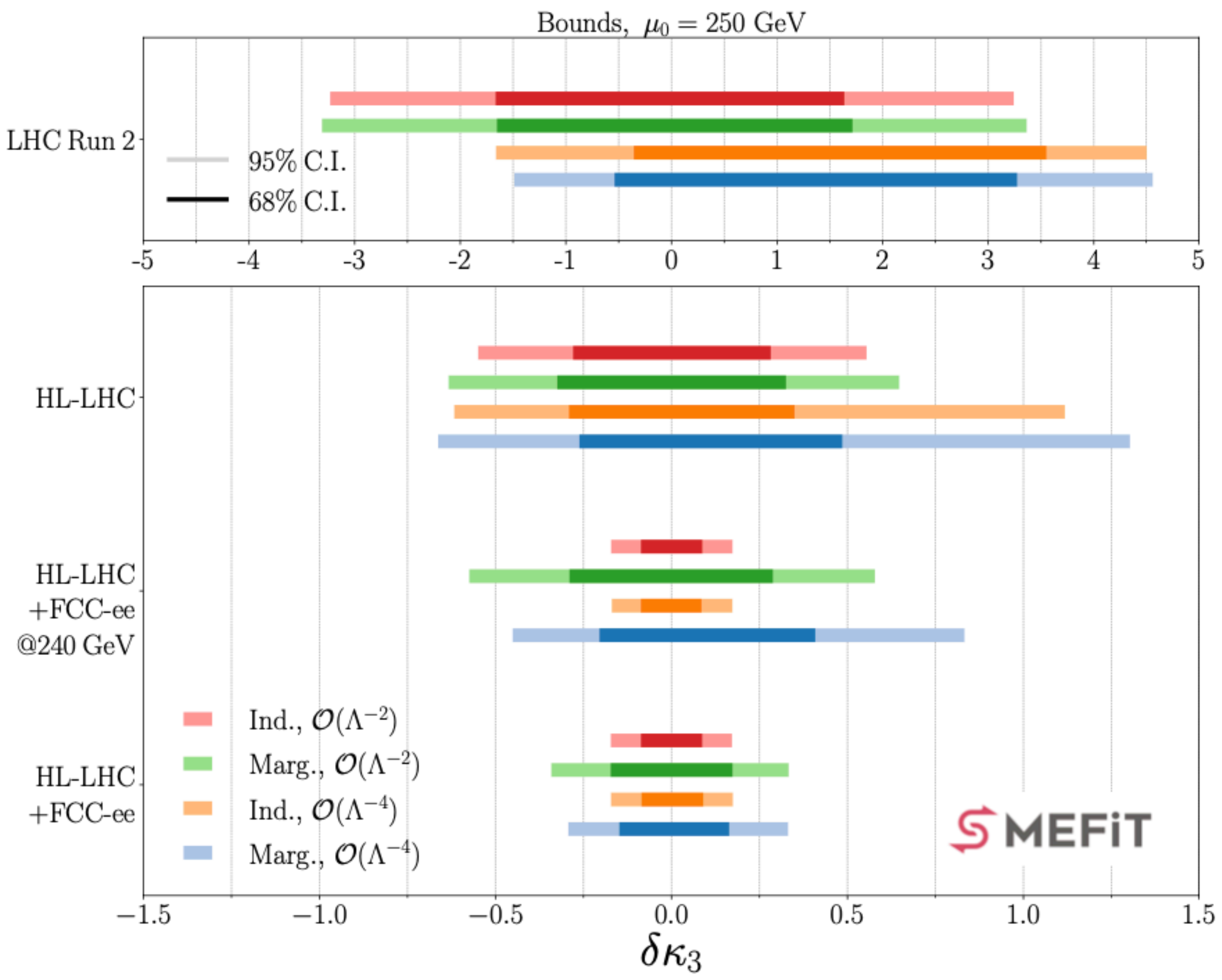
ESPPU26 projections: 2504.00672

Lepton Collisions (<500 GeV)


Asteriadis, Dawson, Giardino, Szafron arXiv:2406.03557

# How well can we know $\kappa_3$?




| Input Dataset | EFT | $\delta\kappa_3$ (68% C.I.) |
|---|---|---|
| LHC Run 2 | Linear | $[-1.68, 1.68]$ |
| | Quad. | $[-0.54, 3.27]$ |
| HL-LHC | Linear | $[-0.32, 0.32]$ |
| | Quad. | $[-0.26, 0.49]$ |
| HL-LHC & FCC-ee(240) | Linear | $[-0.29, 0.29]$ |
| | Quad. | $[-0.20, 0.41]$ |
| HL-LHC & FCC-ee | Linear | $[-0.17, 0.17]$ |
| | Quad. | $[-0.15, 0.16]$ |

ter Hoeve, Mantani, Rojo, Rossia EV arXiv: 2504.05974

Expect 15-20% accuracy at FCC-ee once 365 GeV is added
FCC-ee@240 not enough to improve over HL-LHC
Individual bounds and marginalised bounds can be significantly different

See also : Maura, Stefanek, You arXiv: 2503.13719

# RGE effects in global fit

$$\frac{dc_i(\mu)}{d\ln\mu} = \sum_{j=1}^{n_{\text{op}}} \gamma_{ij}^{(6)}(\bar{g})\, c_j(\mu)$$

1-loop RGE

(Alonso) Jenkins et al arXiv:1308.2627, 1310.4838, 1312.2014

$$c_i(\mu) = \sum_{j=1}^{n_{\text{op}}} \Gamma_{ij}(\mu,\mu_0;\bar{g}) c_j(\mu_0) \qquad \Gamma_{ij}(\mu,\mu_0;\bar{g}) = \exp\left(\int_{\mu_0}^{\mu} d\log(\mu')\gamma_{ij}^{(6)}(\bar{g}(\mu'))\right)$$

Evolution matrix through a SMEFiT interface to Wilson

Aebischer, Kumar, Straub arXiv:1804.05033

$$\begin{aligned} T_{\text{EFT}}(\boldsymbol{c}(\mu_0)/\Lambda^2) &= T_{\text{SM}} + \sum_{i,j=1}^{n_{\text{op}}} \kappa_i \Gamma_{ij} \frac{c_j(\mu_0)}{\Lambda^2} + \sum_{i,j,k,\ell=1}^{n_{\text{op}}} \widetilde{\kappa}_{ij} \Gamma_{ik}\Gamma_{j\ell} \frac{c_k(\mu_0) c_\ell(\mu_0)}{\Lambda^4}, \\ &= T_{\text{SM}} + \sum_{j=1}^{n_{\text{op}}} \kappa'_j \frac{c_j(\mu_0)}{\Lambda^2} + \sum_{k,\ell=1}^{n_{\text{op}}} \widetilde{\kappa}'_{k\ell} \frac{c_k(\mu_0) c_\ell(\mu_0)}{\Lambda^4}, \end{aligned}$$

Predictions parametrised as a function of $c_i(\mu_0)$ with $\mu_0$=5 TeV

# Scale choices

Each observable has an associated scale:

| Process | Scale Choice $\mu$ | Process | Scale Choice $\mu$ |
|---|---|---|---|
| Higgs (ggF) | $\sqrt{m_H^2 + (p_T^H)^2}$ | $t\bar{t}b\bar{b}$ | $2m_t$ |
| Higgs (VBF) | $\sqrt{m_H^2 + (p_T^H)^2}$ | $t\bar{t}V$ | $\sqrt{(2m_t + m_V)^2 + (p_T^V)^2}$ |
| $VH$ | $\sqrt{(m_V + m_H)^2 + (p_T^V)^2}$ | $tV$ | $m_t + m_V$ or $\sqrt{(m_t + m_V)^2 + (p_T^t)^2}$ |
| $t\bar{t}H$ | $\sqrt{(2m_t + m_H)^2 + (p_T^H)^2}$ | $W$-helicities | $m_t$ |
| $tH$ | $m_t + m_H$ | $WZ$ | $m_T^{WZ}$ or $\sqrt{(m_Z + m_W)^2 + (p_T^Z)^2}$ |
| $t\bar{t}$ | $m_{tt}$ | $WW$ | $m_{e\mu}$ |
| Single-$t$ | $m_t$ | $V$ pole (incl. EWPOs) | $m_V$ |
| $t\bar{t}\gamma$ | $2m_t$ | Bhabha scattering | $\sqrt{s}$ |
| $t\bar{t}t\bar{t}$ | $4m_t$ | $e^+e^- \to WW\,/\,t\bar{t}\,/\,f\bar{f}$ | $\sqrt{s}$ |
| $HH$ | $2m_H$ | $e^+e^- \to ZH$ | $\sqrt{s}$ |

LHC (left column processes, all rows)

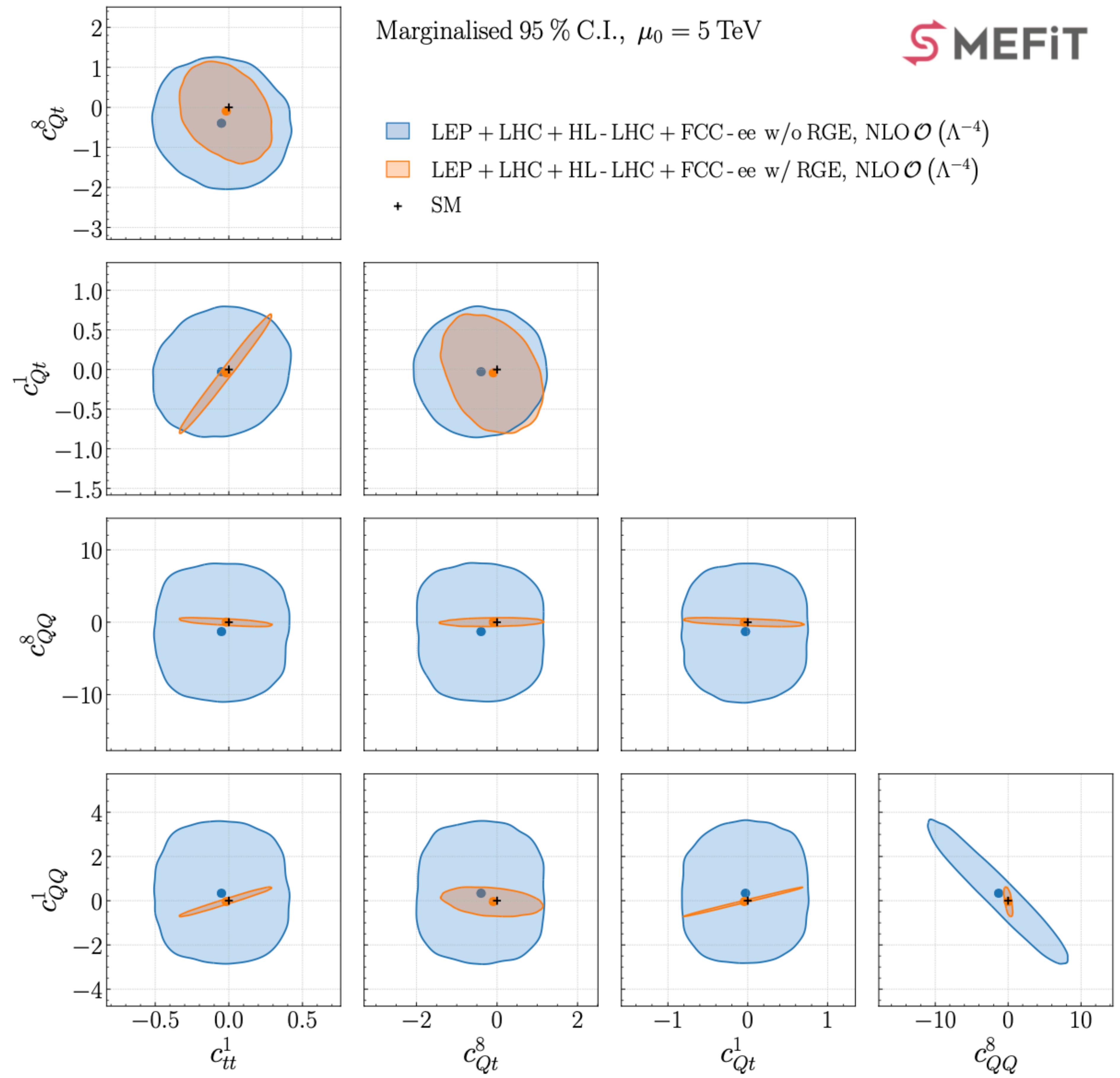
LHC (right column: $t\bar{t}b\bar{b}$ through $WW$)

LEP & FCC-ee (right column: $V$ pole through $e^+e^- \to ZH$)

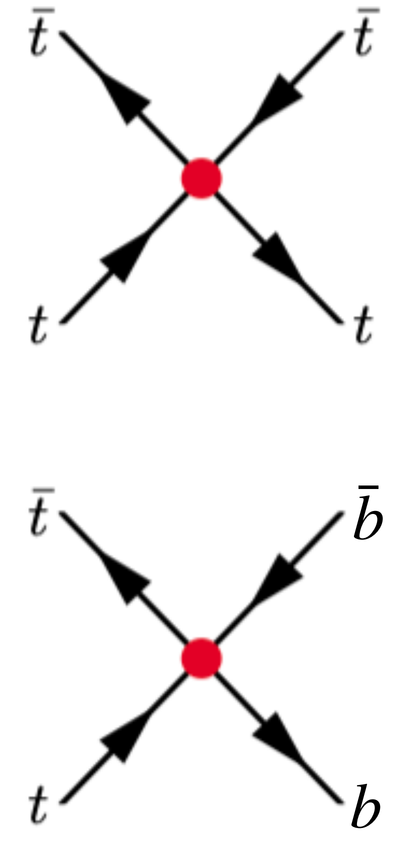
ter Hoeve, Mantani, Rojo, Rossia EV arXiv: 2502.20453

# RGE effects in global fits

## Example: 4-heavy operators




| | |
|---|---|
| $c_{QQ}^1$ | $2c_{qq}^{1(3333)} - \frac{2}{3}c_{qq}^{3(3333)}$ |
| $c_{QQ}^8$ | $8c_{qq}^{3(3333)}$ |
| $c_{Qt}^1$ | $c_{qu}^{1(3333)}$ |
| $c_{Qt}^8$ | $c_{qu}^{8(3333)}$ |
| $c_{tt}^1$ | $c_{uu}^{(3333)}$ |



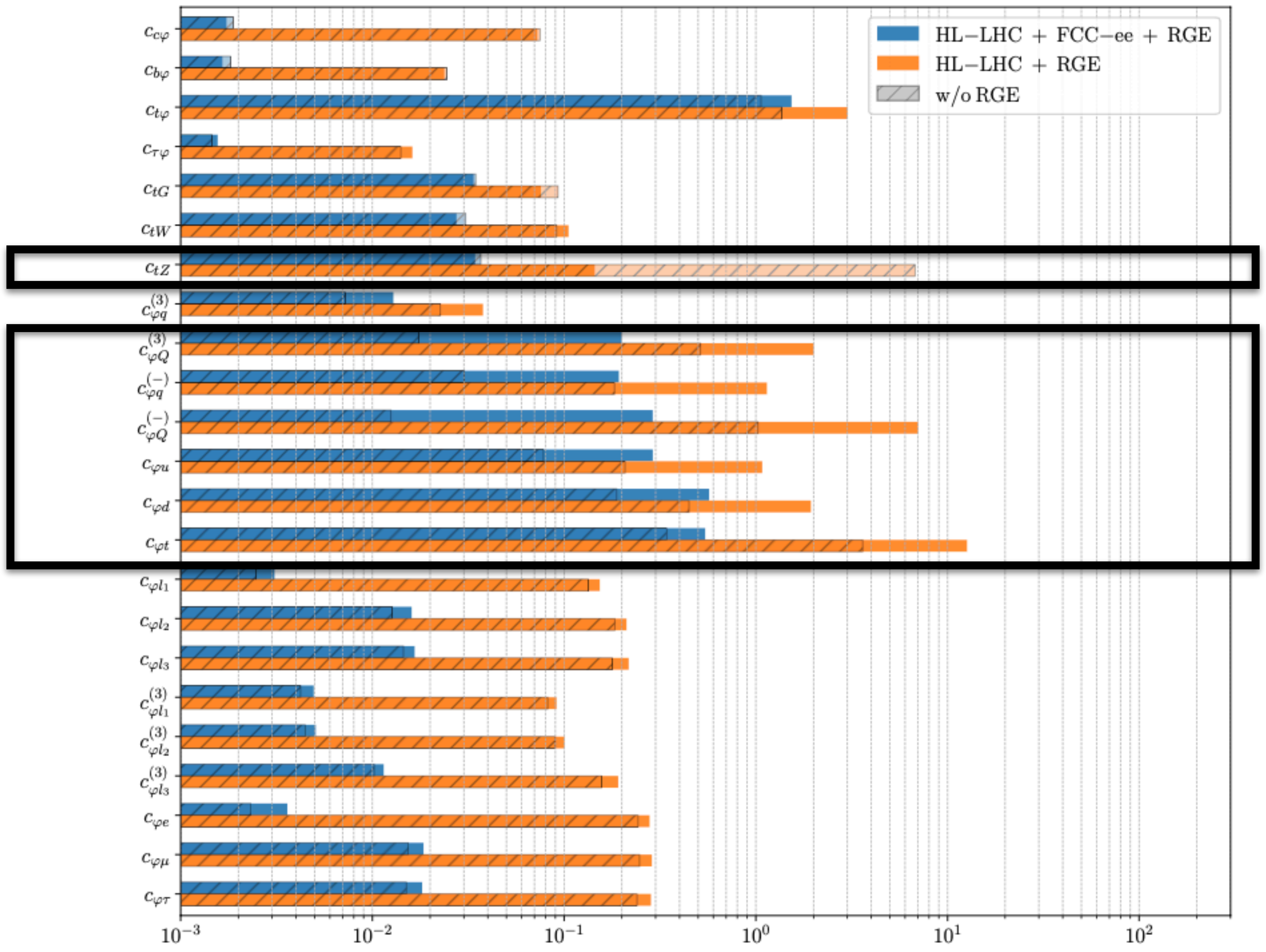

Probed at the LHC by 4-tops and ttbb production: worst constrained operators

RGE allows them to be probed by EWPOs

Significant improvement of the bounds in a restricted fit

ter Hoeve, Mantani, Rojo, Rossia EV arXiv: 2502.20453

# Impact of RGE on the global fit

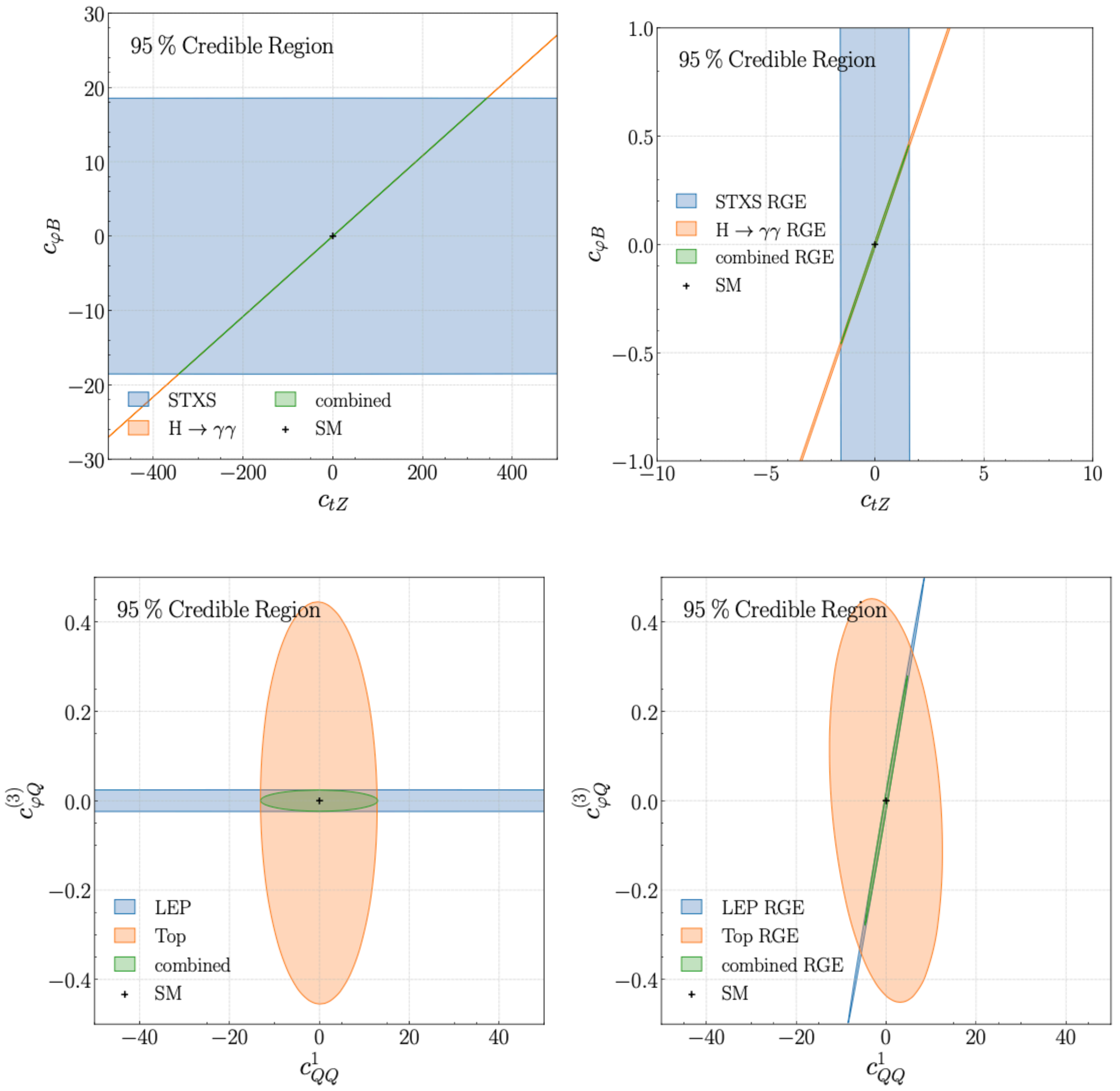




ter Hoeve, Mantani, Rojo, Rossia EV arXiv: 2502.20453

4-heavy operators unconstrained at linear level without RGE

Several other operators significantly impacted: why?

# Impact of RGE on the constraints




## What does RGE do?

- Change of linear combinations of coefficients probed (rotation of directions)
- Introduction of new dependences and hence correlations between coefficients
- RGE-improved constraints can be either more or less stringent depending on the operator

ter Hoeve, Mantani, Rojo, Rossia EV arXiv: 2502.20453

# Conclusions

- SMEFT is a consistent way to look for new interactions
- Global fits results already available: important to combine as many processes as possible to extract maximal information
- Eventually global fit results give us a clear indication of the scale of potential new physics and the reach of future colliders
- Significant improvements in New Physics reach at the HL-LHC and especially at future circular lepton colliders, including the precision on the Higgs self-coupling
- EFT probes translated to bounds on UV models

Thank you for your attention