Combined Higgs/top/EW fit at the FCC-ee

Based on SMEFiT3.0 [*JHEP* 09 (2024) 091, arXiv:2404.12809]
with T. Giani, J. ter Hoeve, L. Mantani, J. Rojo, A. N. Rossia, M. Thomas, E. Vryonidou

2025 CEPC International Workshop,

Barcelona, Spain

18/06/25

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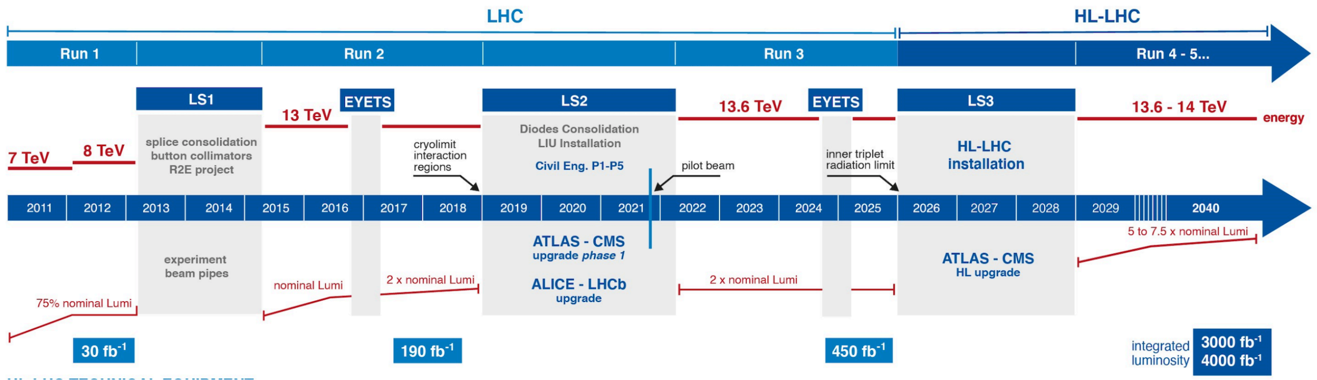
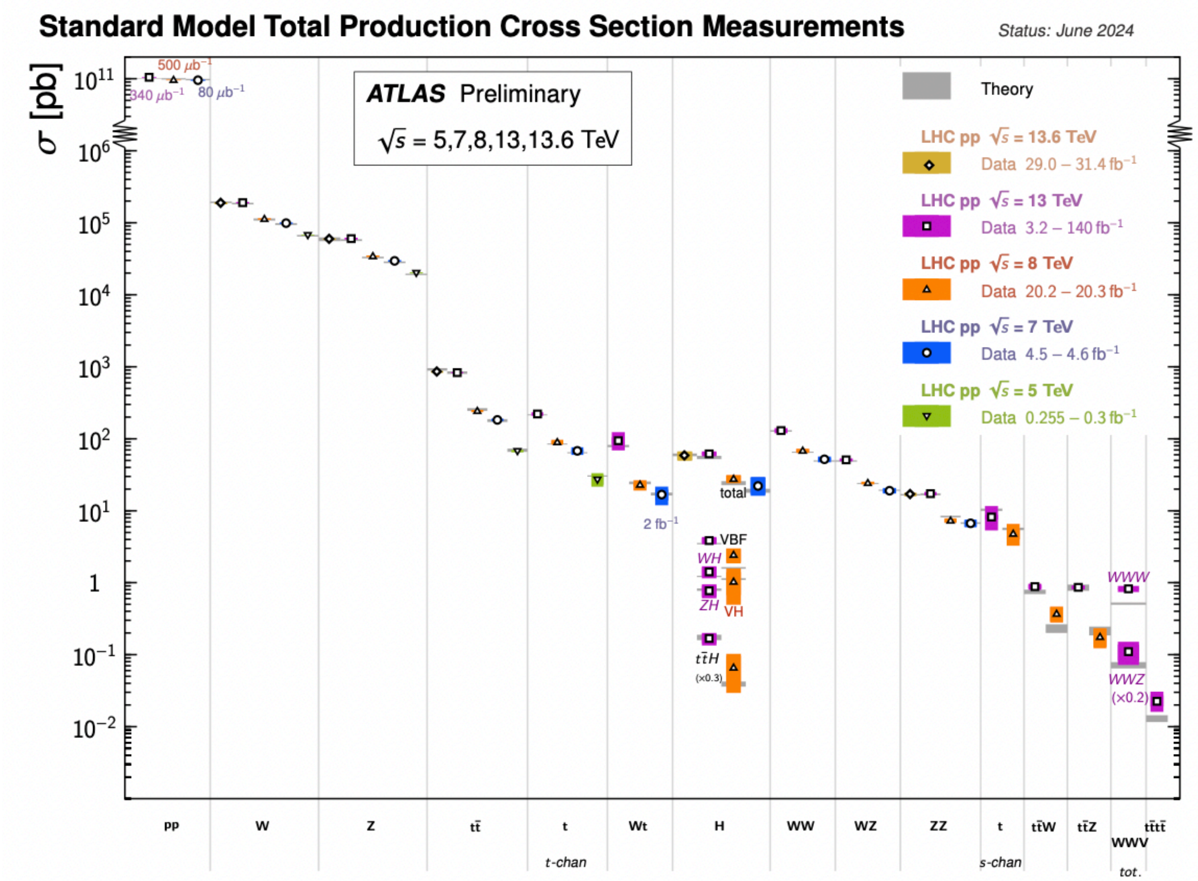
The high energy picture

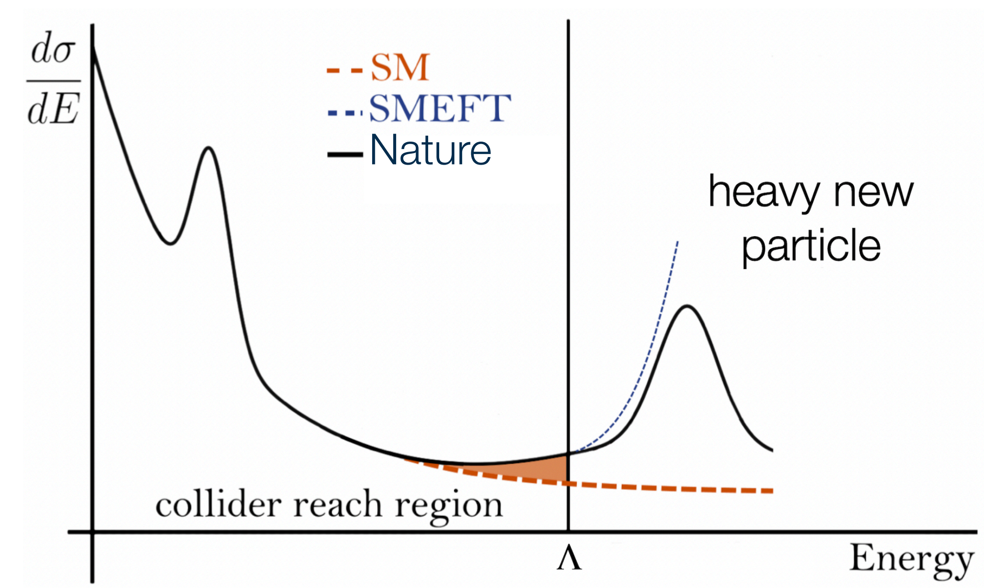




- Lots of measurements, mostly in agreement with the SM
- Searches for new physics at high energy require a **general approach**
- The **SMEFT** reveals high energy physics effects through precise measurements at low energy

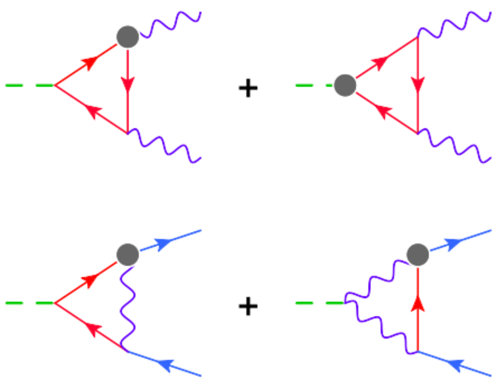
$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \mathcal{O}(\Lambda^{-3})$$

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



A way forward: global fits

- Cross-talk between different sectors (Higgs, top, EW)
- The interplay requires a **global analysis**



[arXiv: 1804.09766]

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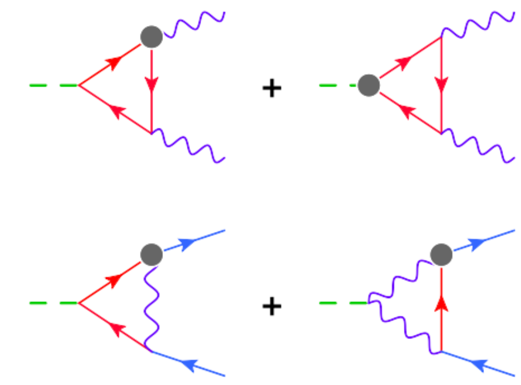

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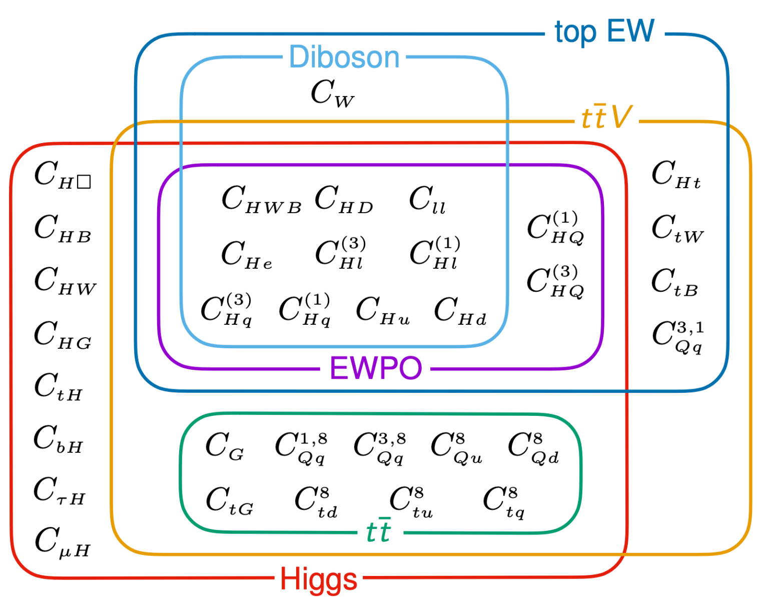
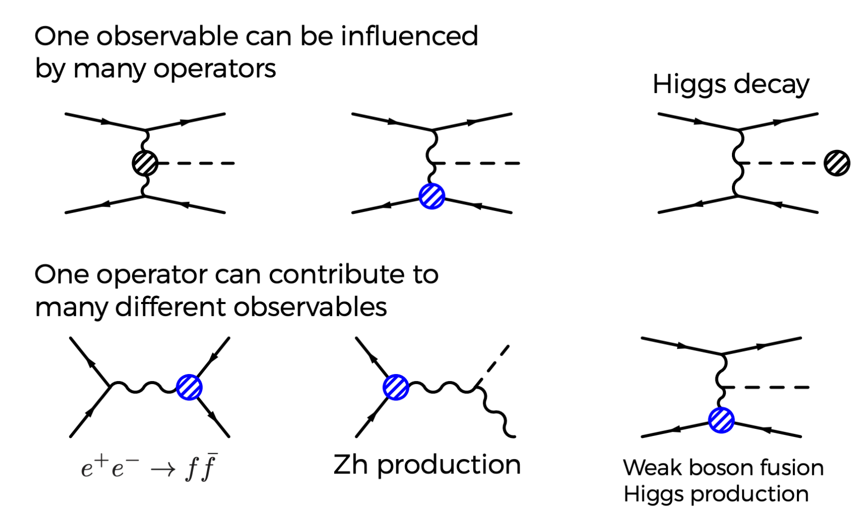
SMEFT is general 😃

- Ideal framework to look for overall pattern in global fits



Fitmaker Collaboration [arXiv:2012.02779]



Anke Biekötter - HET seminar Brookhaven

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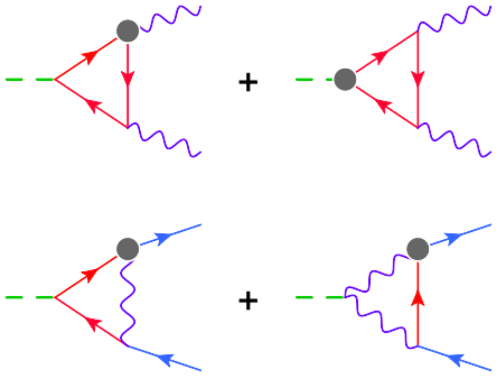

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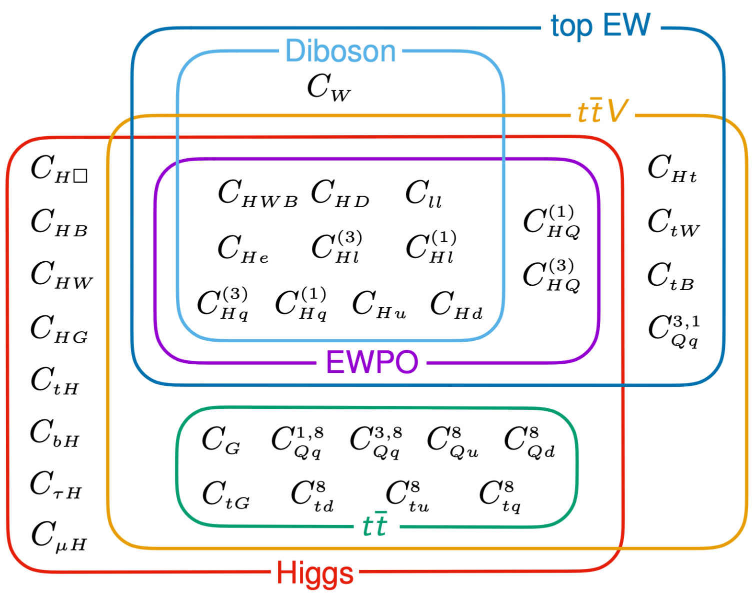
SMEFT is general 😃

- Ideal framework to look for overall pattern in global fits

SMEFT is general 😵‍💫

- Large number of operator coefficients, many datasets needed to break degeneracies



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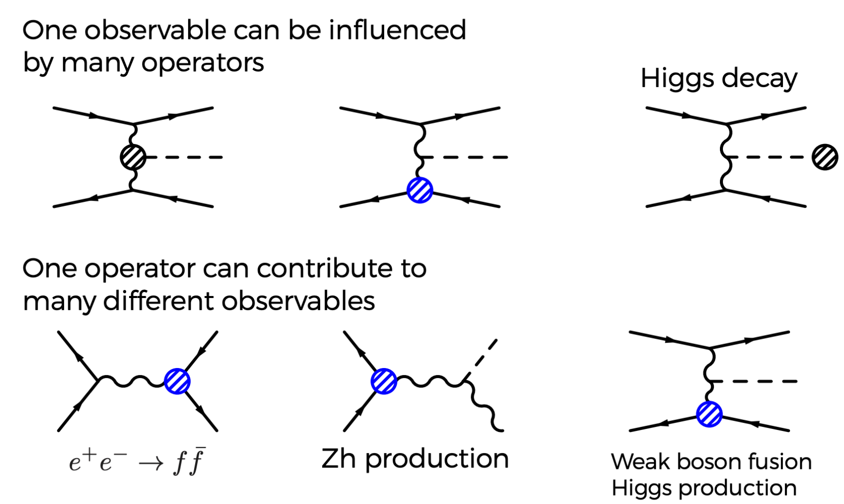

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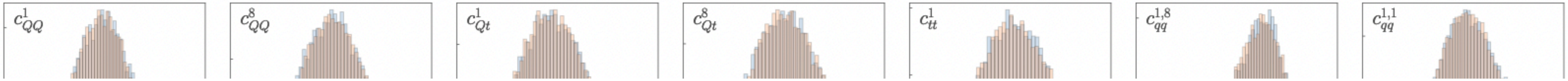
SMEFiT3.0: a summary



- Extension of SMEFiT2.0 with up-to-date **LHC Run-II datasets** on **top, diboson and Higgs production**

[arXiv:2105.00006]

- Exact treatment of LEP and SLD Electroweak Precision Observables (EWPOs)

- **Projections for HL-LHC pseudodata** extrapolated from Run-II data, **FCC-ee and CEPC pseudodata** from Snowmass predictions updated with FCC midterm Feasibility Report

[arXiv:2206.08326]
[CERN/3789/RA]

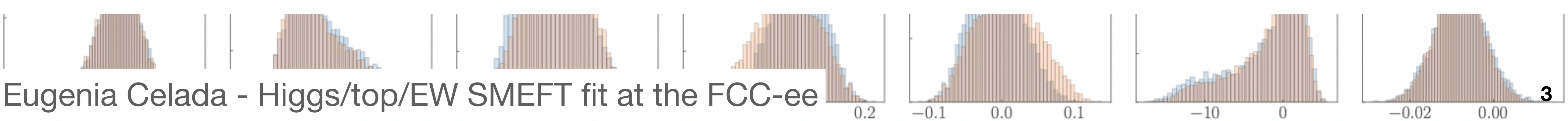
- Results for LHC Run-II and future colliders in terms of Wilson coefficients and **UV-complete models**

[arXiv:2309.04523]

- Impact of **RGE effects** in global fits and the prospects on **Higgs trilinear coupling** are now available: *see yesterday A. Rossia's talk for more*

[arXiv:2502.20453]
[arXiv:2504.05974]

- **Public code, data and theory**: results are fully reproducible [lhcfitnikhef.github.io/smefit_release/]



The SMEFiT setup

Experimental data

445 data points from Higgs, top, diboson (LHC) & EWPOs (LEP)

Experimental **uncertainties + correlations** as provided by experiments

SMEFiT

Giani, Magni, Rojo, arXiv:2302.06660

The SMEFiT setup

Theory

SM: **(N)NLO QCD + NLO EW**

EFT: **NLO QCD**, linear and quadratics, with **SMEFT@NLO** in madgraph

NNPDF4.0 no top

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Quadratic fit: **Nested sampling** (Bayesian inference)

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Output

Automatised fit report with **bounds** on coefficients, **posterior** distributions, **correlations**, **Fisher information**...

Experimental input

Extension of SMEFiT2.0 with recent **LHC Run-II datasets** on **top, diboson and Higgs production**

SMEFiT3.0: EC, Giani, ter Hoeve, Mantani, Rojo, Rossia, Thomas, Vryonidou [arXiv:2404.12809]
SMEFiT2.0: Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, Vryonidou, Zhang [arXiv:2105.00006]

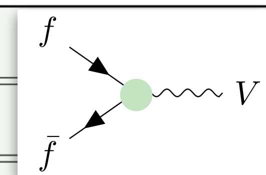
Category	Processes	$n_{\rm dat}$ SMEFiT2.0	$n_{\rm dat}$ SMEFiT3.0
Top quark production	$t\bar{t}+X$	94	115
	$t\bar{t}Z$, $t\bar{t}W$	14	21
	$t\bar{t}\gamma$	-	2
	single top (inclusive)	27	28
	tZ, tW	9	13
	$t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$	6	12
	Total	**150**	**191**
Higgs production and decay	Run I signal strengths	22	22
	Run II signal strengths	40	36 (*)
	Run II, differential distributions & STXS	35	71
	Total	**97**	**129**
Diboson production	LEP-2	40	40
	LHC	30	41
	Total	**70**	**81**
EWPOs	LEP-2	-	44
Baseline dataset	**Total**	**317**	**445**

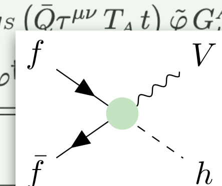
+118 data points

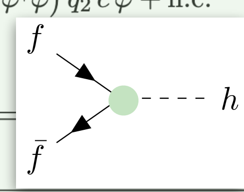
Theory input: operators

- Warsaw basis of dim-6 SMEFT operators
- Flavour symmetry:
  $U(2)_q \times U(3)_d \times U(2)_u \times (U(1)_l \times U(1)_e)^3$
  + Yukawa of bottom, charm and tau

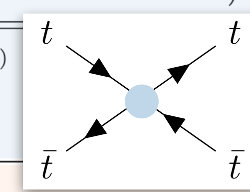
Operator	Coefficient	Definition	Operator	Coefficient	
		3rd generation quarks			
$\mathcal{O}_{\varphi Q}^{(1)}$	$c_{\varphi Q}^{(1)}$ (*)	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{Q}\gamma^\mu Q)$	$\mathcal{O}_{tW}$	c_{tW}	$i(\bar{Q}\tau^{\mu\nu}\tau_I t)\tilde{\varphi} W^I_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{\varphi Q}^{(3)}$	$c_{\varphi Q}^{(3)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{Q}\gamma^\mu \tau^I Q)$	$\mathcal{O}_{tB}$	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}	$ig_S(\bar{Q}\tau^{\mu\nu} T_A t)\tilde{\varphi} G^A_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{t\varphi}$	$c_{t\varphi}$	$(\varphi^\dagger\varphi)\bar{Q} t \tilde{\varphi} + \text{h.c.}$	$\mathcal{O}_{b\varphi}$	$c_{b\varphi}$	$(\varphi^\dagger$
		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			
$\mathcal{O}_{\ell\ell}$	$c_{\ell\ell}$	$(\bar{\ell}_1\gamma_\mu\ell_2)(\bar{\ell}_2\gamma^\mu\ell_1)$			

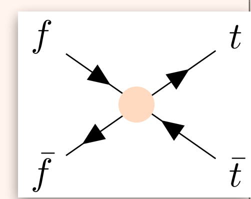




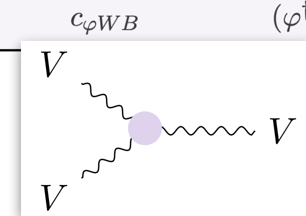


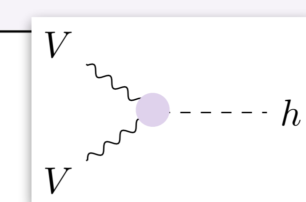
DoF	Definition (in Warsaw basis notation)	DoF	Definition (in Warsaw basis notation)
c^1_{QQ}	$2c_{qq}^{1(3333)} - \frac{2}{3}c_{qq}^{3(3333)}$	c^8_{QQ}	$8c_{qq}^{3(3333)}$
c^1_{Qt}	$c_{qu}^{1(3333)}$	c^8_{Qt}	$c_{qu}^{8(3333)}$
$c^{1,8}_{Qq}$	$c_{qq}^{1(i33i)} + 3c_{qq}^{3(i33i)}$	$c^{1,1}_{Qq}$	$c_{qq}^{1(ii33)}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





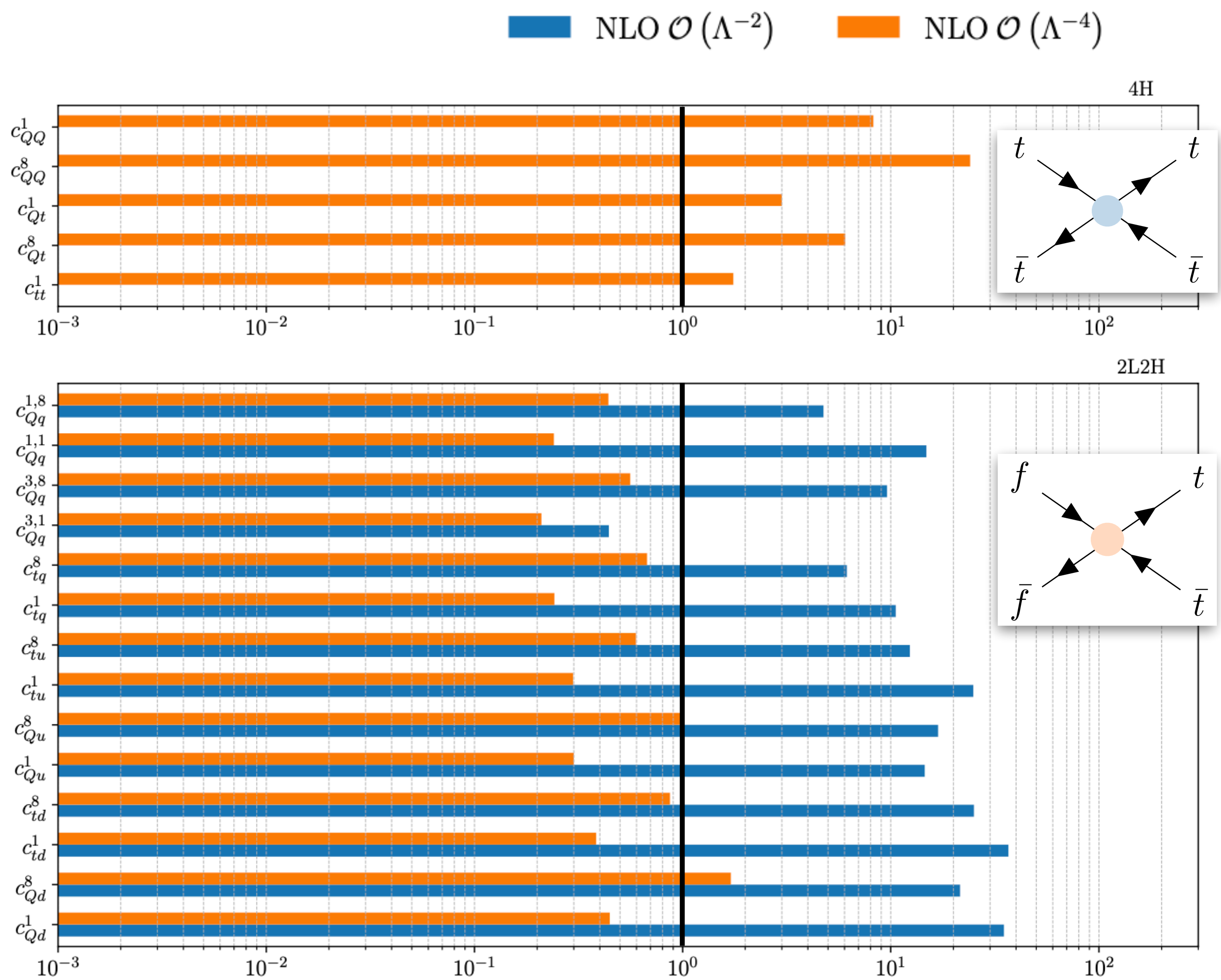
Operator	Coefficient	Definition	Operator	Coefficient	Definition
$\mathcal{O}_{\varphi G}$	$c_{\varphi G}$	$(\varphi^\dagger\varphi) G_A^{\mu\nu} G^A_{\mu\nu}$	$\mathcal{O}_{\varphi\Box}$	$c_{\varphi\Box}$	$\partial_\mu(\varphi^\dagger\varphi)\partial^\mu(\varphi^\dagger\varphi)$
$\mathcal{O}_{\varphi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

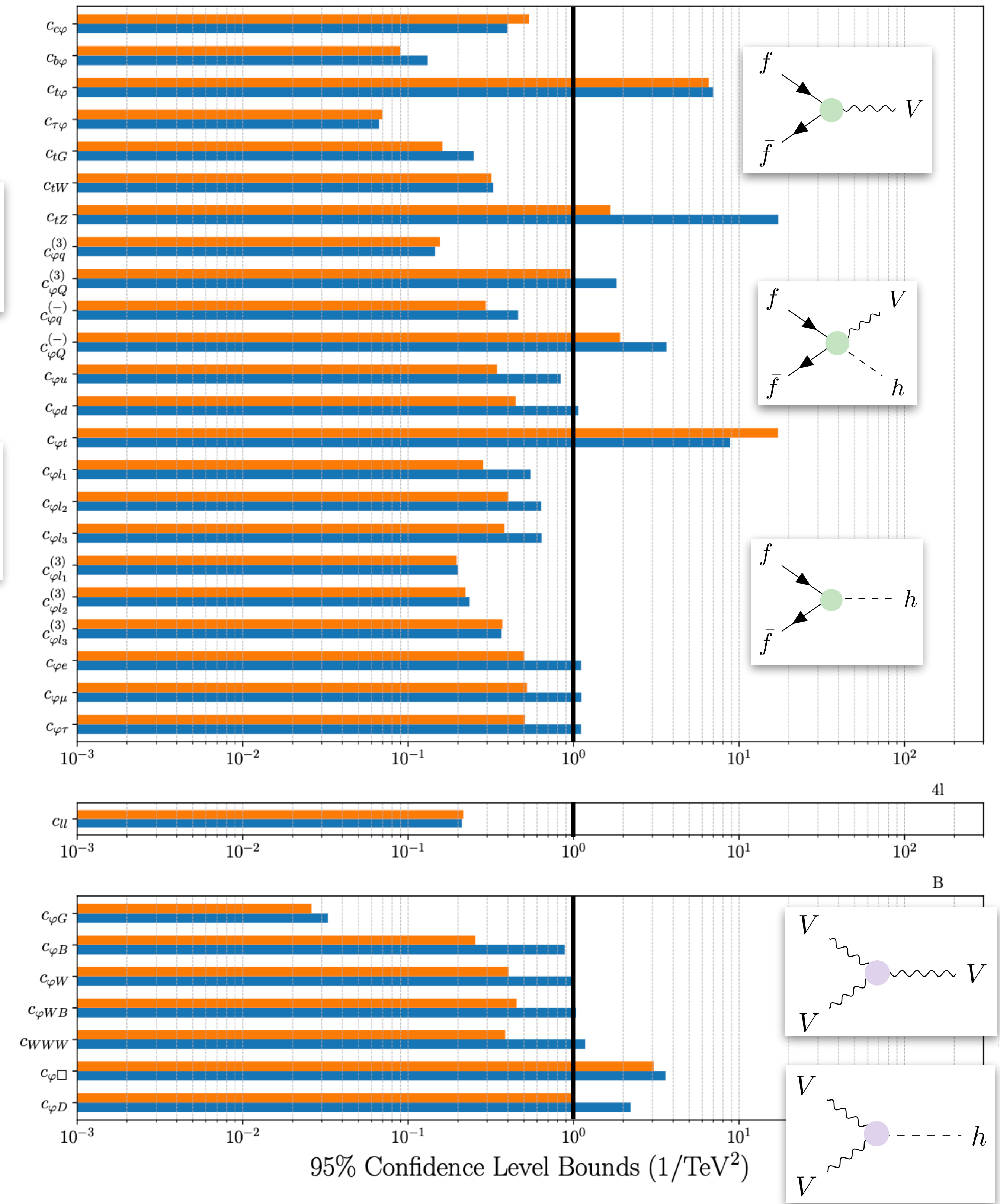




Current global fit results

Marginalised linear and quadratic





- Most bounds below 1 for $\Lambda = 1$ TeV

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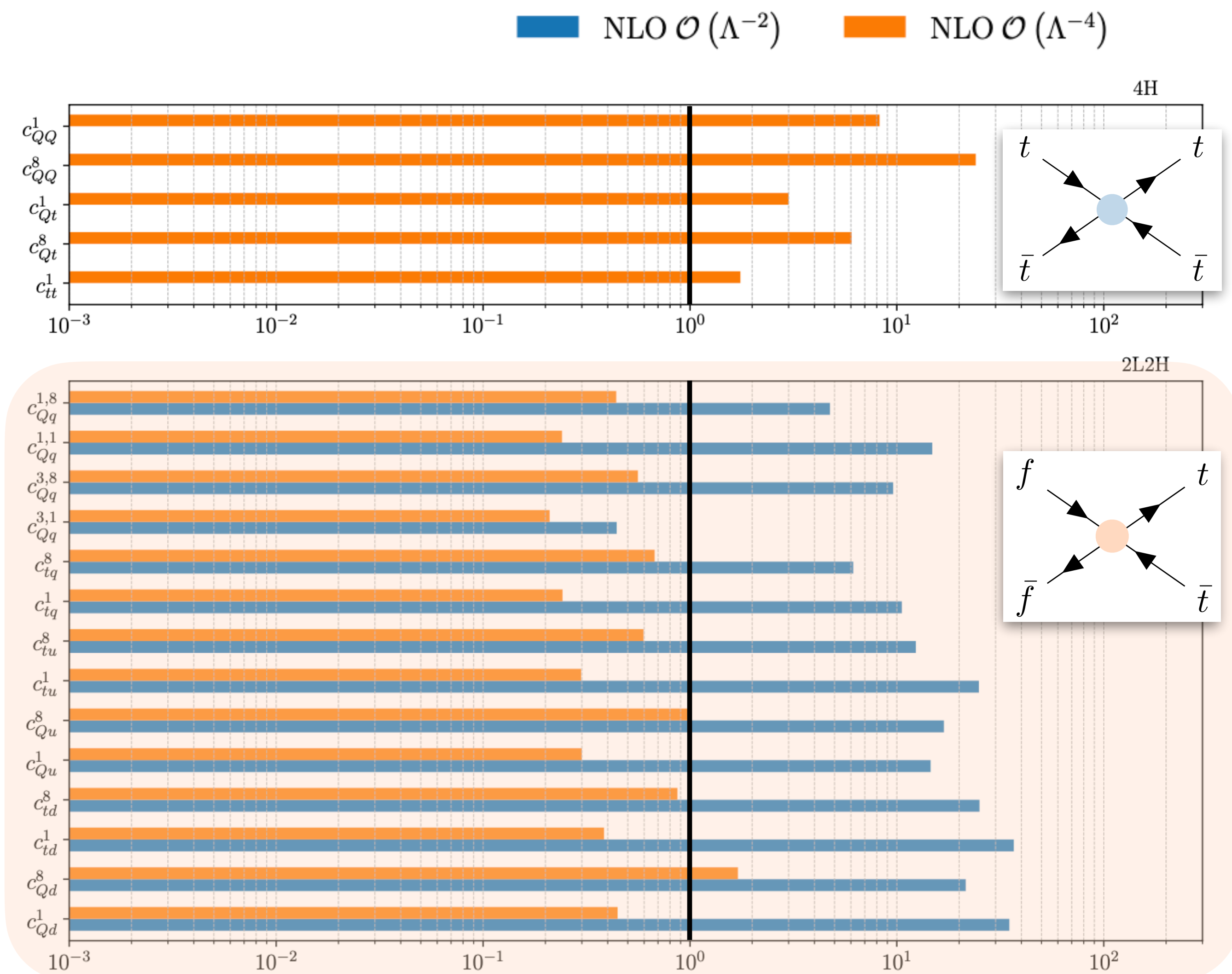

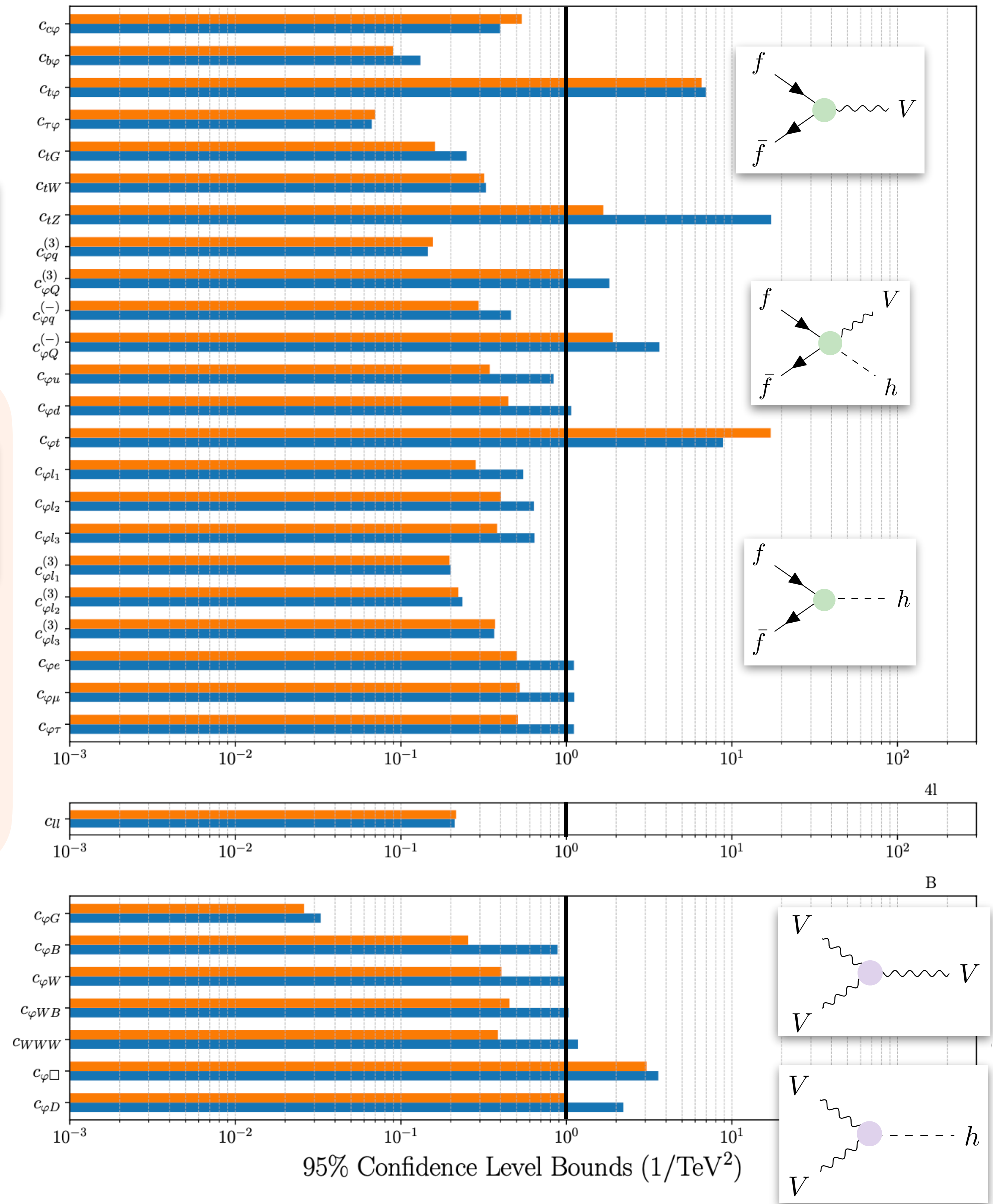

- Most bounds below 1 for $\Lambda = 1$ TeV
- Quadratic terms important (mostly 2-light-2-heavy)

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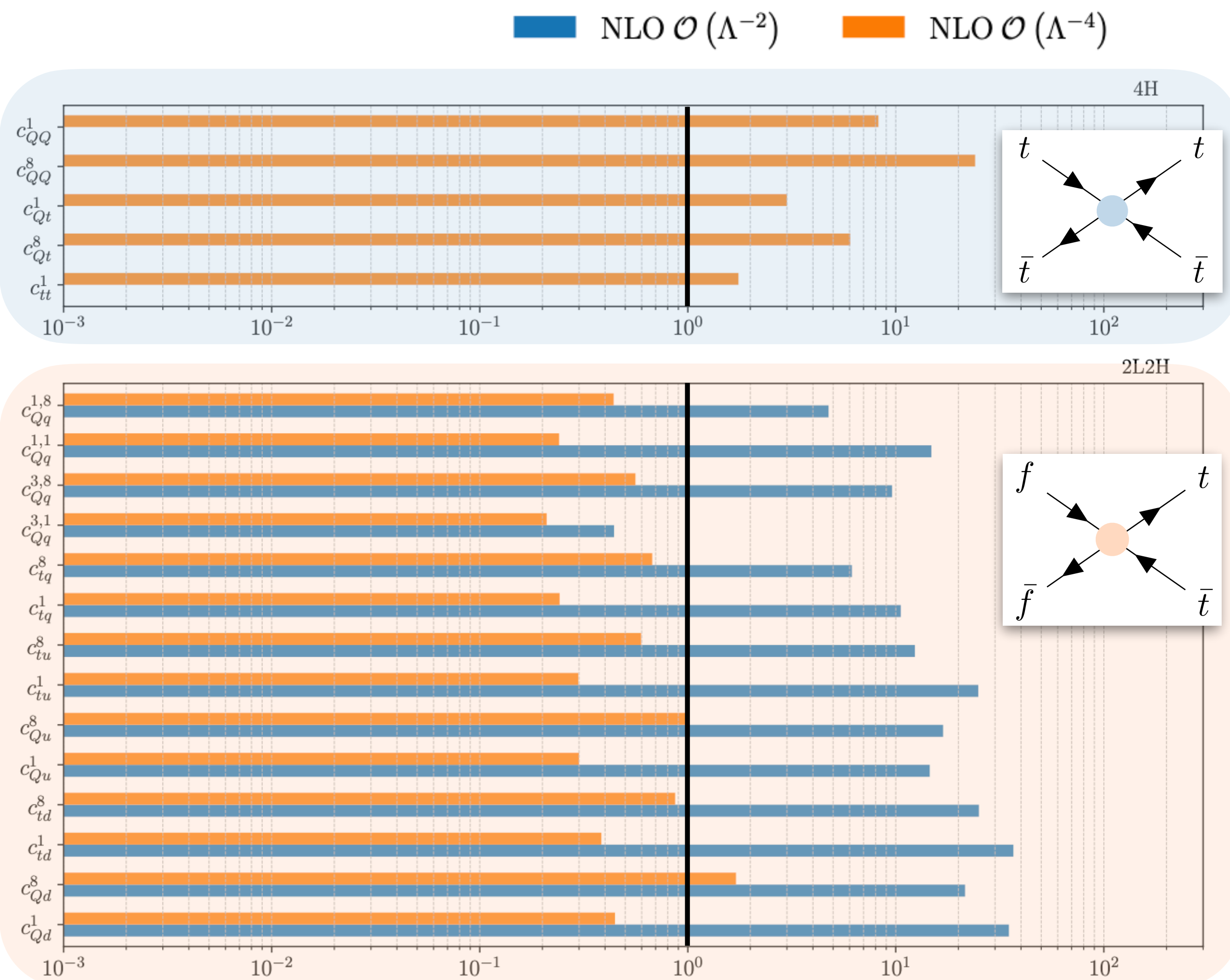
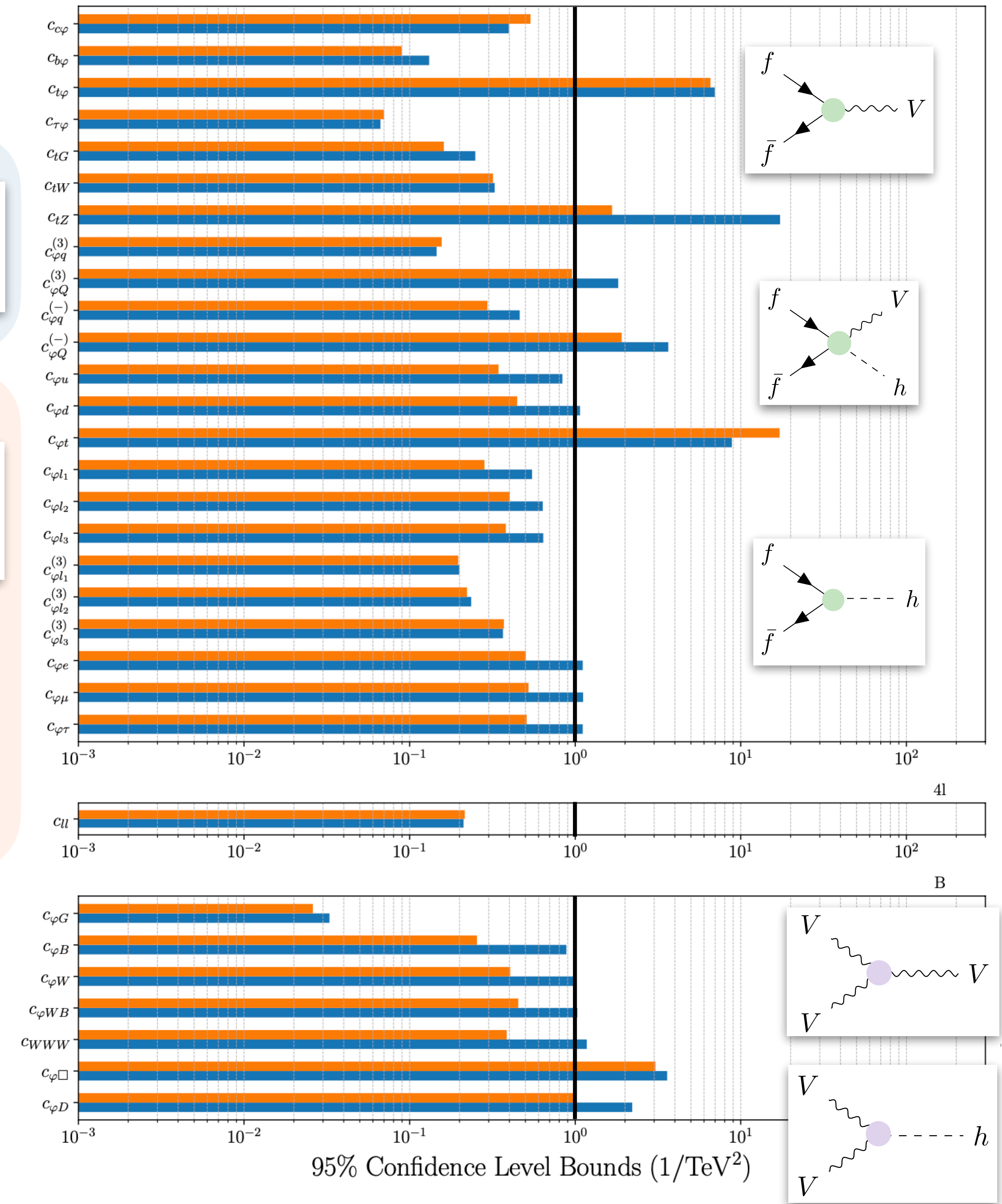




- Most bounds below 1 for $\Lambda = 1$ TeV
- Quadratic terms important (mostly 2-light-2-heavy)
- Least constrained are 4-heavy operators

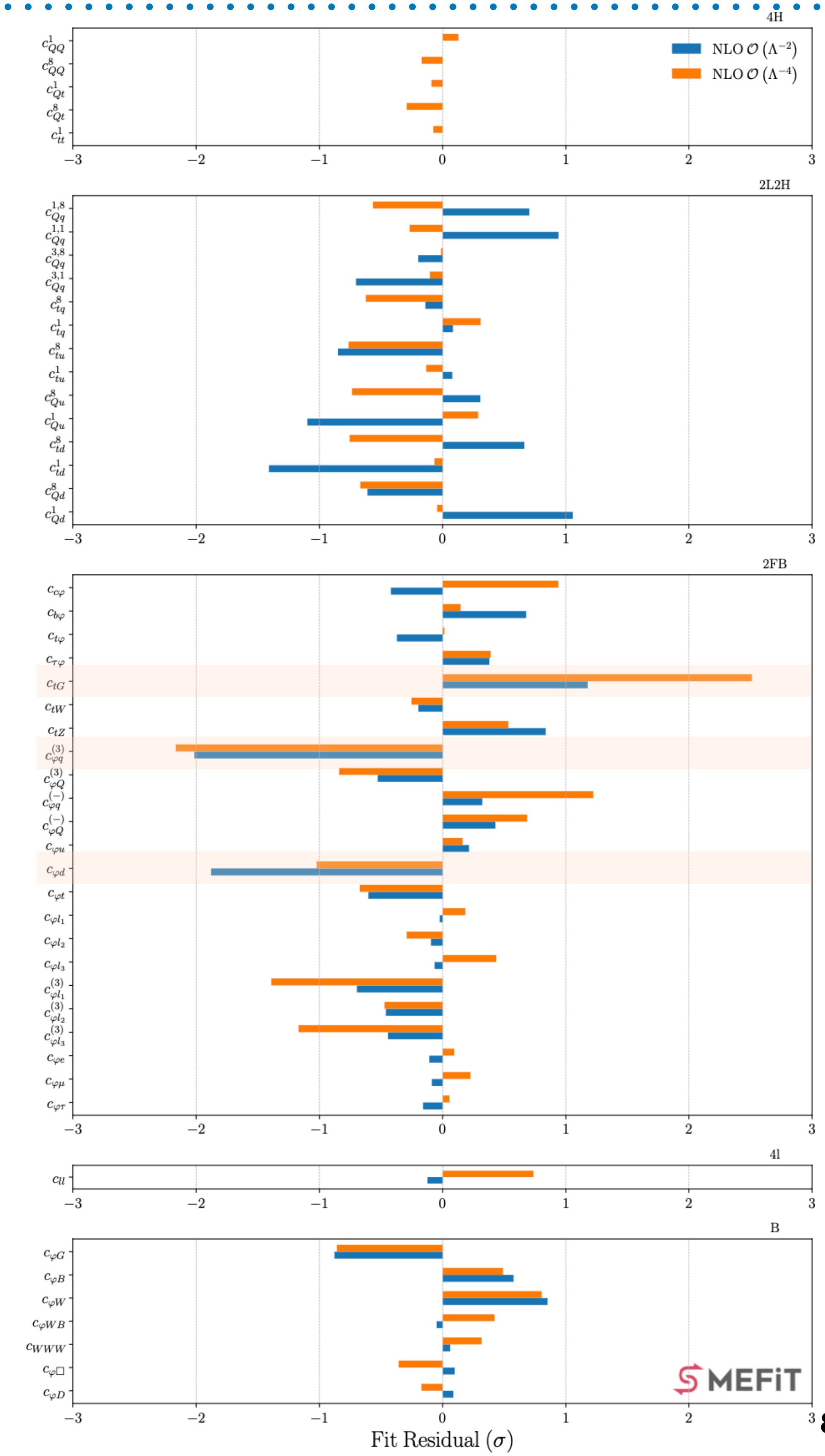
Current global fit results

Fit residuals (**pulls**) largely consistent with the SM

$$P_i \equiv 2\left(\frac{\langle c_i\rangle - c_i^{(\mathrm{SM})}}{\left[c_i^{\min}, c_i^{\max}\right]^{68\%\ \mathrm{CI}}}\right)$$

Exceptions

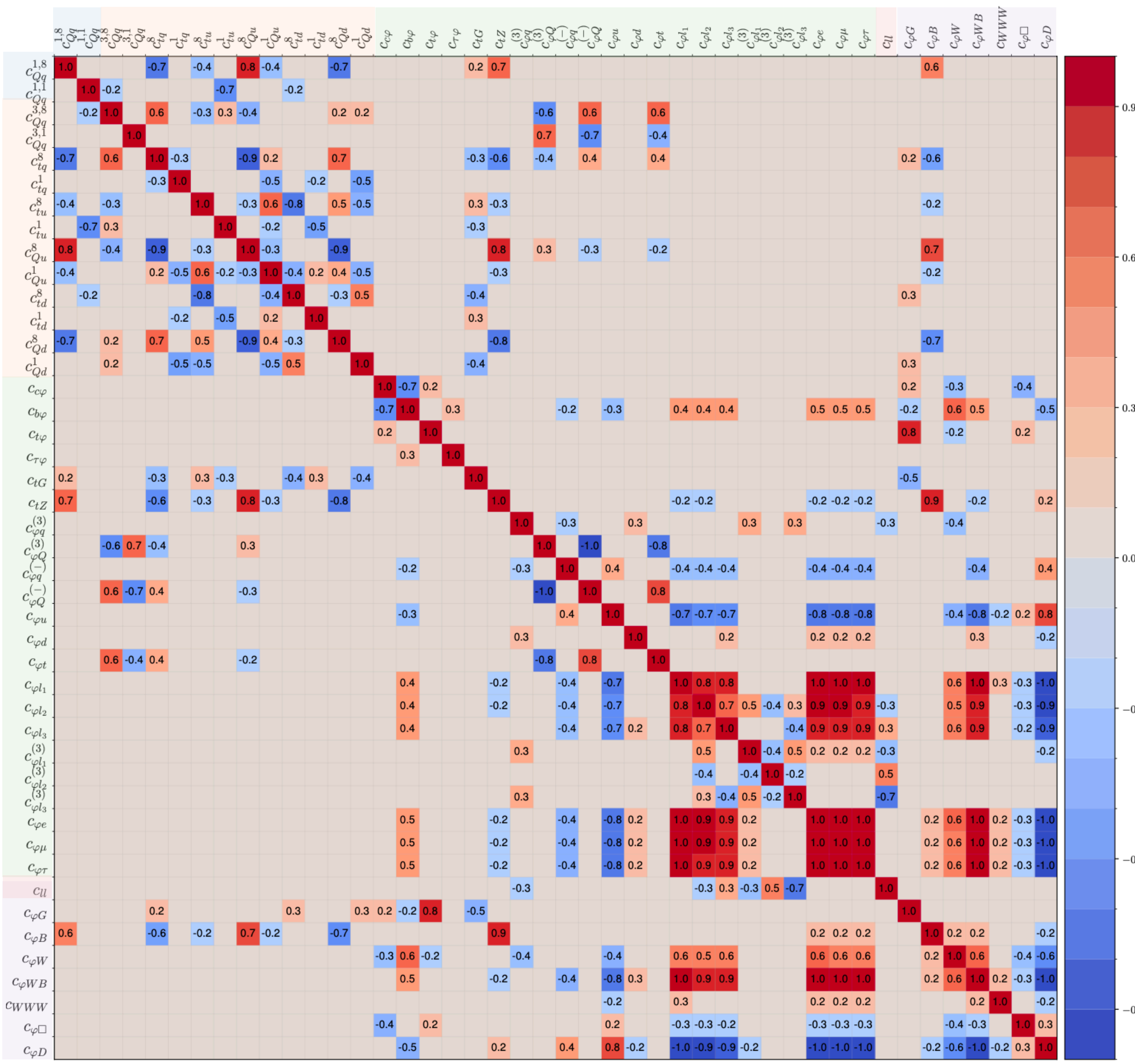
- c_{tG}: tension in one of the $t\bar{t}$ and the others included in the fit
- $c_{\phi d}$, $c_{\phi q}^{(3)}$: P>2 appear as a consequence of correlations (absent in one parameter fits)



Current global fit results

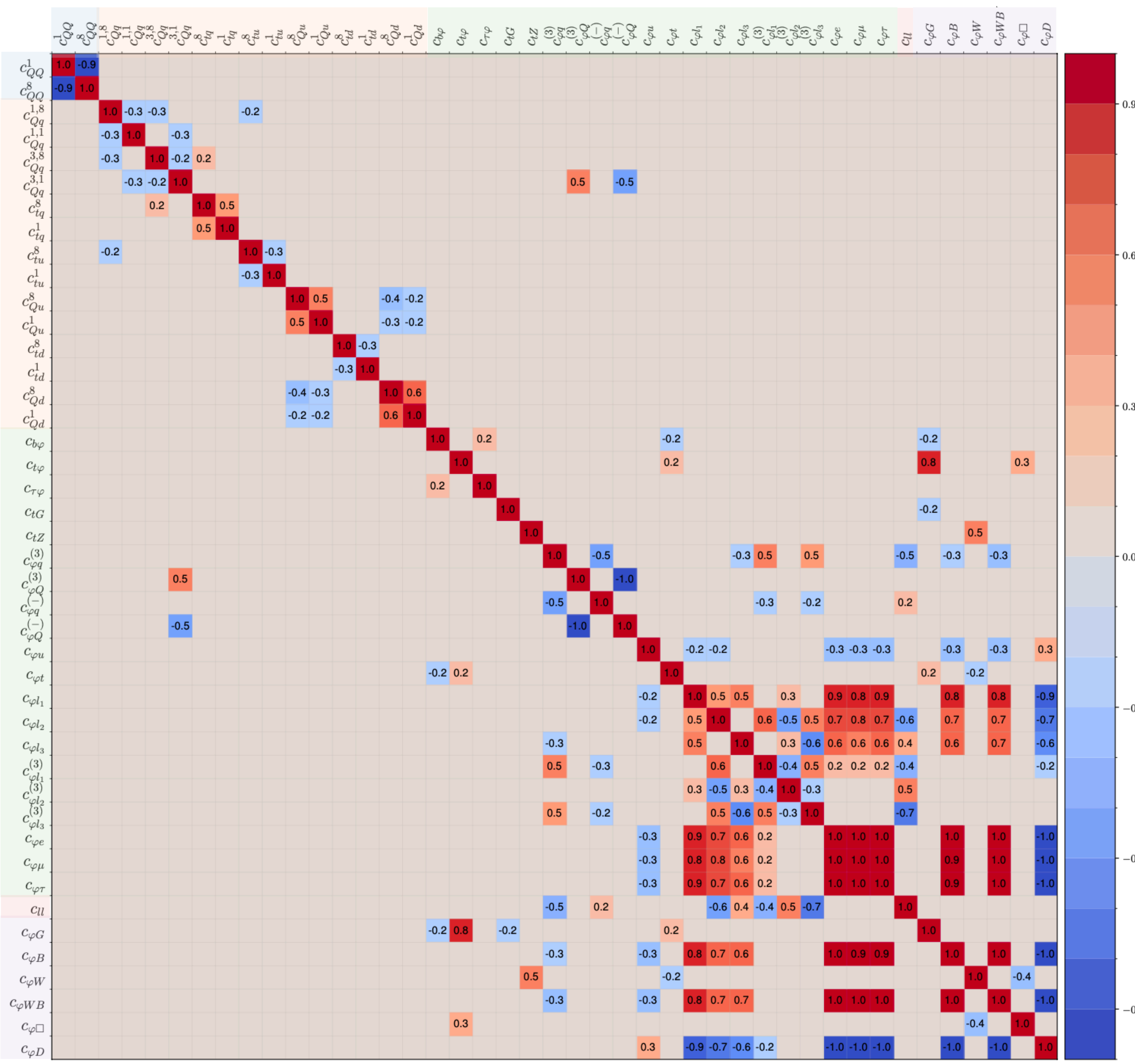
Quadratic contributions are relevant in removing correlations

Large correlations in the linear fit …



Correlation: NLO $\mathcal{O}\left(\Lambda^{-2}\right)$

… are lifted in the quadratic fit



Correlation: NLO $\mathcal{O}\left(\Lambda^{-4}\right)$

Prospects at future colliders

HiLumi
HL-LHC PROJECT

FCC
hh ee he

CEPC

clic

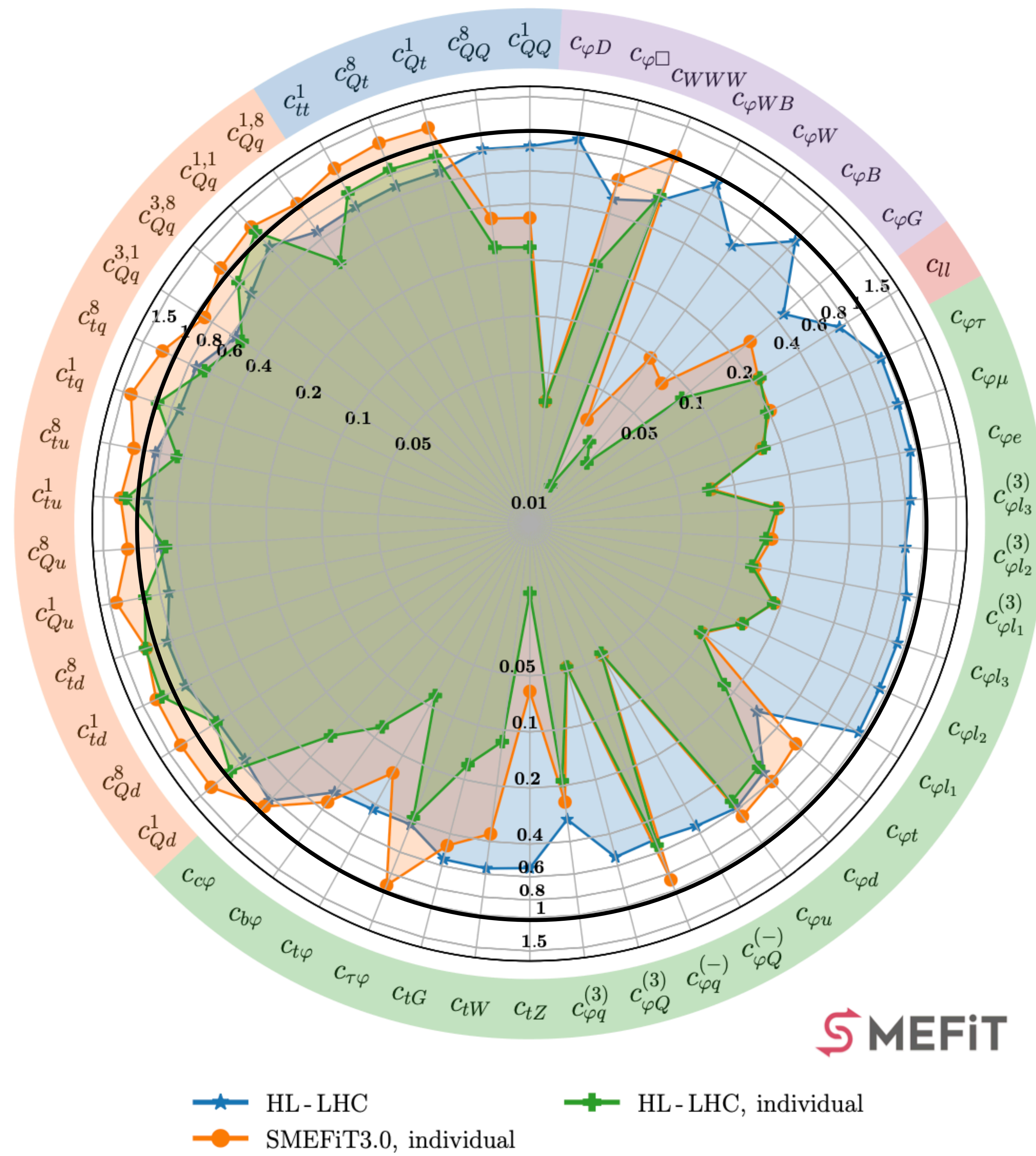
ilc
international linear collider

International
MUON Collider
Collaboration

HL-LHC results

$$R_{\delta c_i} = \frac{[c_i^{\min}, c_i^{\max}]^{95\%\ \mathrm{CI}}\ (\text{baseline} + \text{HL-LHC})}{[c_i^{\min}, c_i^{\max}]^{95\%\ \mathrm{CI}}\ (\text{baseline})}$$

Ratio of Uncertainties to SMEFiT3.0 Baseline, $\mathcal{O}\left(\Lambda^{-4}\right)$, Marginalised



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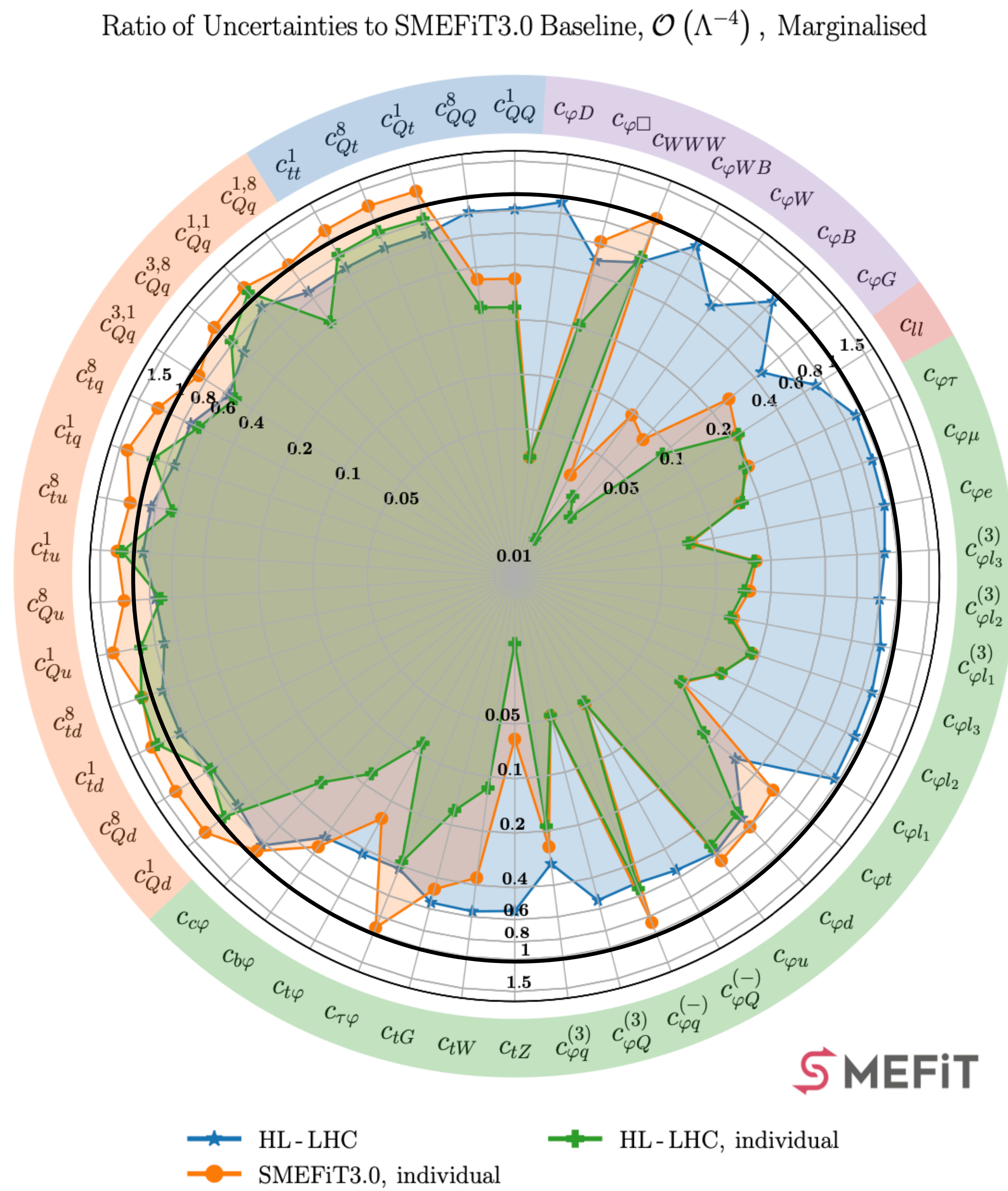
- L1 projections of **Run II datasets**
  - pseudodata fluctuated around SM theory
  - statistics rescaled by luminosity
  - systematics reduced by a factor 2



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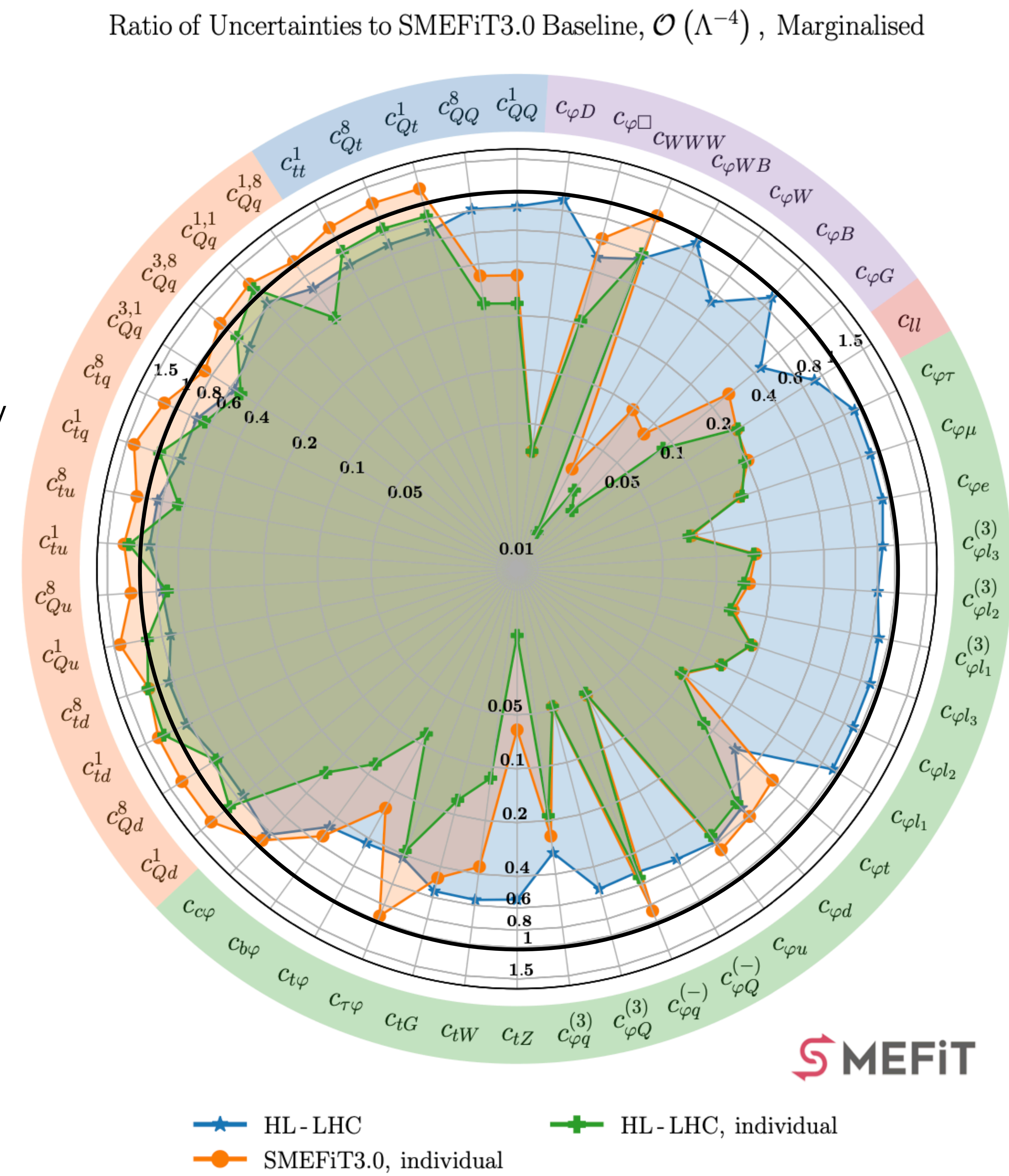
- **marginalised bounds improve by a factor 1.2-3**
- individual bounds are overly optimistic



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- L1 projections of **Run II datasets**
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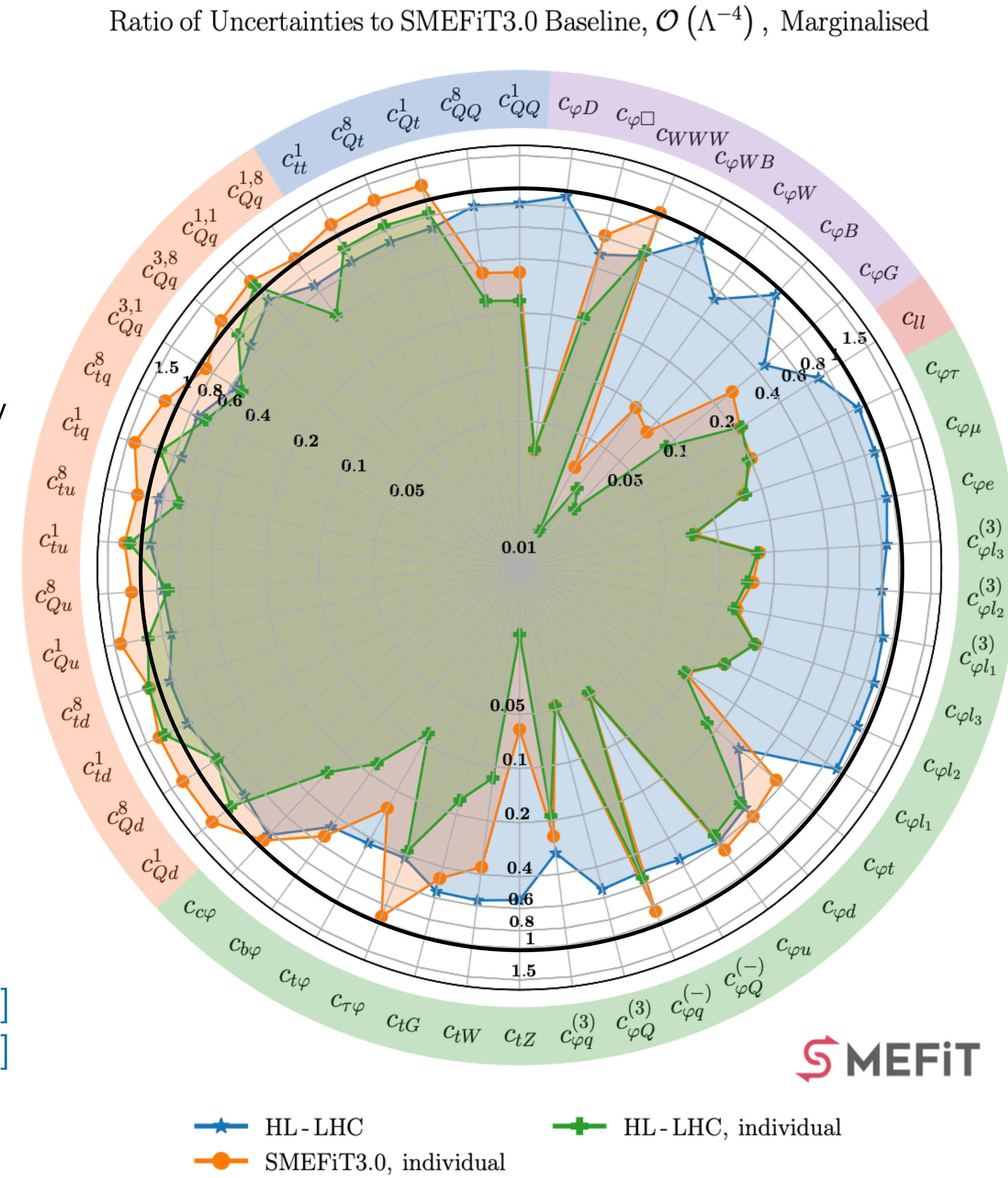
  - statistics rescaled by luminosity
  - systematics reduced by a factor 2
- **marginalised bounds improve by a factor 1.2-3**
- individual bounds are overly optimistic
- 2-light-2-heavy improved by 30% (further improvement of a factor 2 expected with a dedicated binning)

[arXiv:2206.08326]
[arXiv:2205.02140]



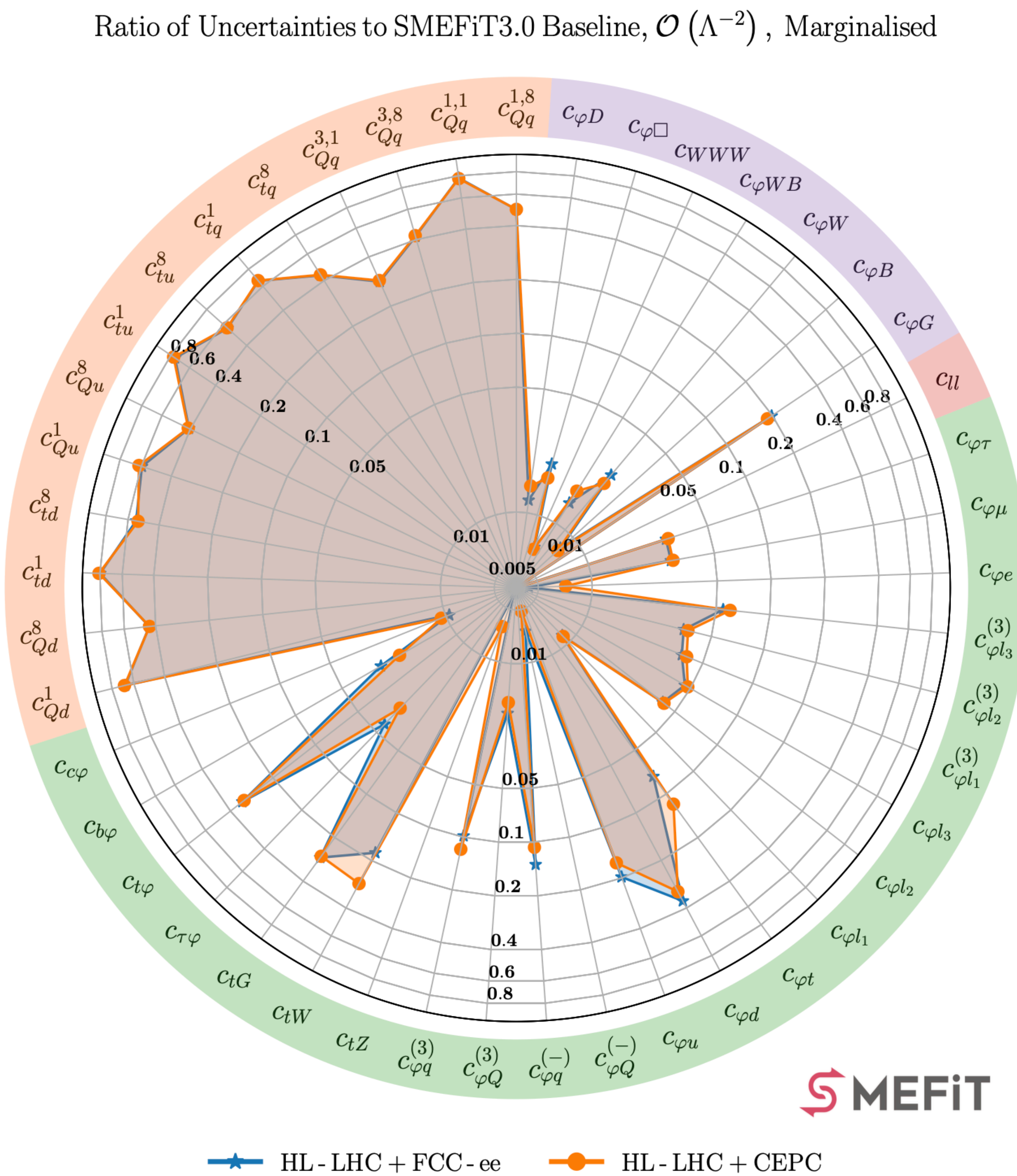
Future circular lepton colliders

- Dataset input
  - EWPOs at the Z pole
  - light fermion pair production
  - Higgs production (Higgstrahlung and VBF)
  - diboson (WW) production
  - top pair production
- Uncertainty projections from Snowmass study updated with FCC midterm Feasibility Report

[arXiv:2206.08326]
[CERN/3789/RA]

Energy ($\sqrt{s}$)	$\mathcal{L}_{\rm int}$ (Run time) FCC-ee (4 IPs)	$\mathcal{L}_{\rm int}$ (Run time) CEPC (2 IPs)	$\mathcal{L}_{\rm FCC-ee}/\mathcal{L}_{\rm CEPC}$
91 GeV (Z-pole)	300 ab^{-1} (4 years)	100 ab^{-1} (2 years)	3
161 GeV ($2\,m_W$)	20 ab^{-1} (2 years)	6 ab^{-1} (1 year)	3.3
240 GeV	10 ab^{-1} (3 years)	20 ab^{-1} (10 years)	0.5
350 GeV	0.4 ab^{-1} (1 year)	0.2 ab^{-1}	2
365 GeV ($2\,m_t$)	3 ab^{-1} (4 years)	1 ab^{-1} (5 years)	3

FCC-ee and CEPC



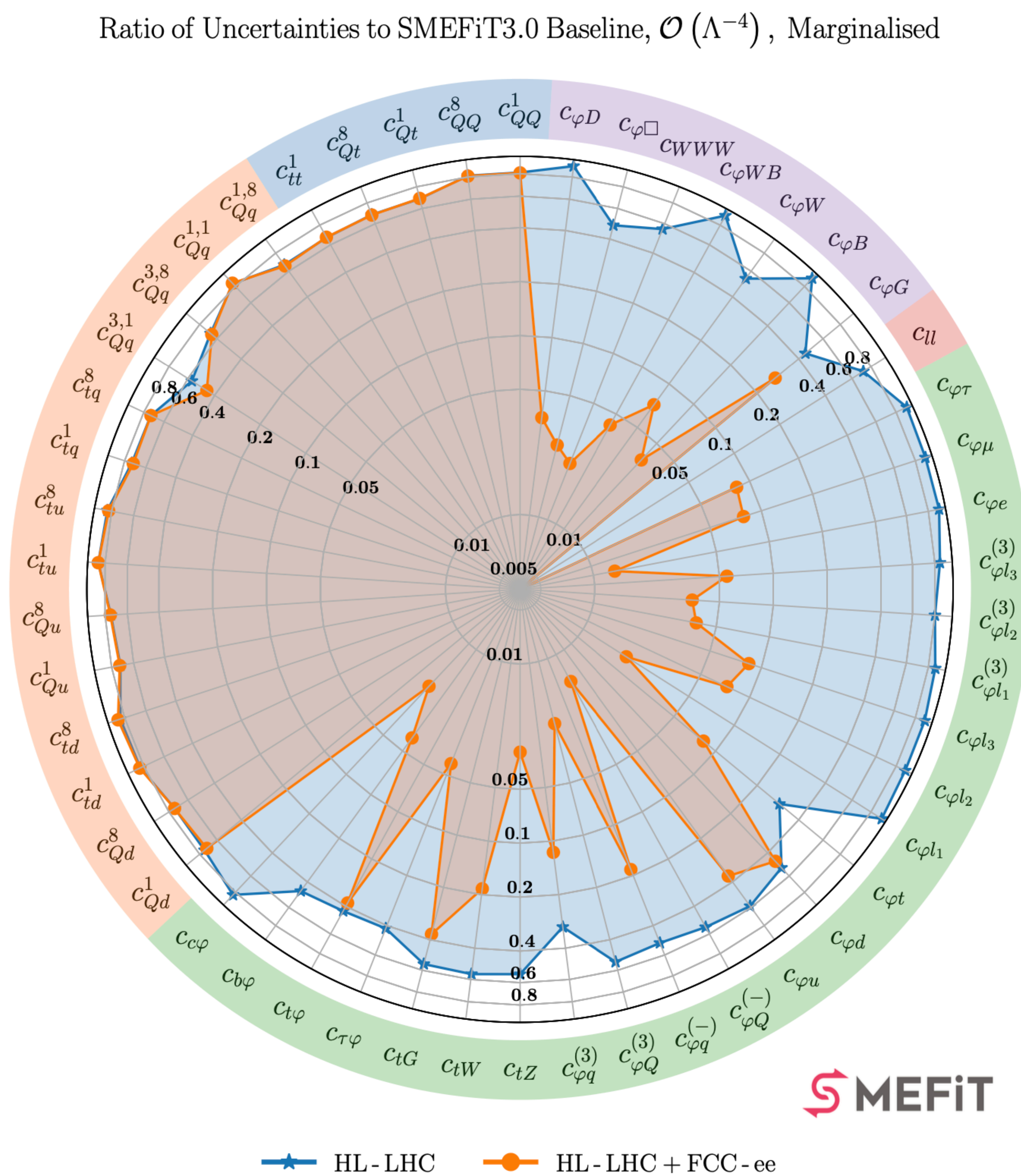
FCC-ee results

$$R_{\delta c_i} = \frac{\left[c_i^{\min}, c_i^{\max}\right]^{95\%\ \mathrm{CL}}\ (\mathrm{baseline} + \mathrm{HL\text{-}LHC})}{\left[c_i^{\min}, c_i^{\max}\right]^{95\%\ \mathrm{CL}}\ (\mathrm{baseline})}$$

- gauge operators improve of up to a factor 30
- 2-fermion operators improve of up to a factor 50
- no sensitivity to 4-quark operators: improvement only from marginalisation

Further improvement expected from NLO corrections

[see for instance arXiv: 1809.03520, arXiv: 2409.11466]



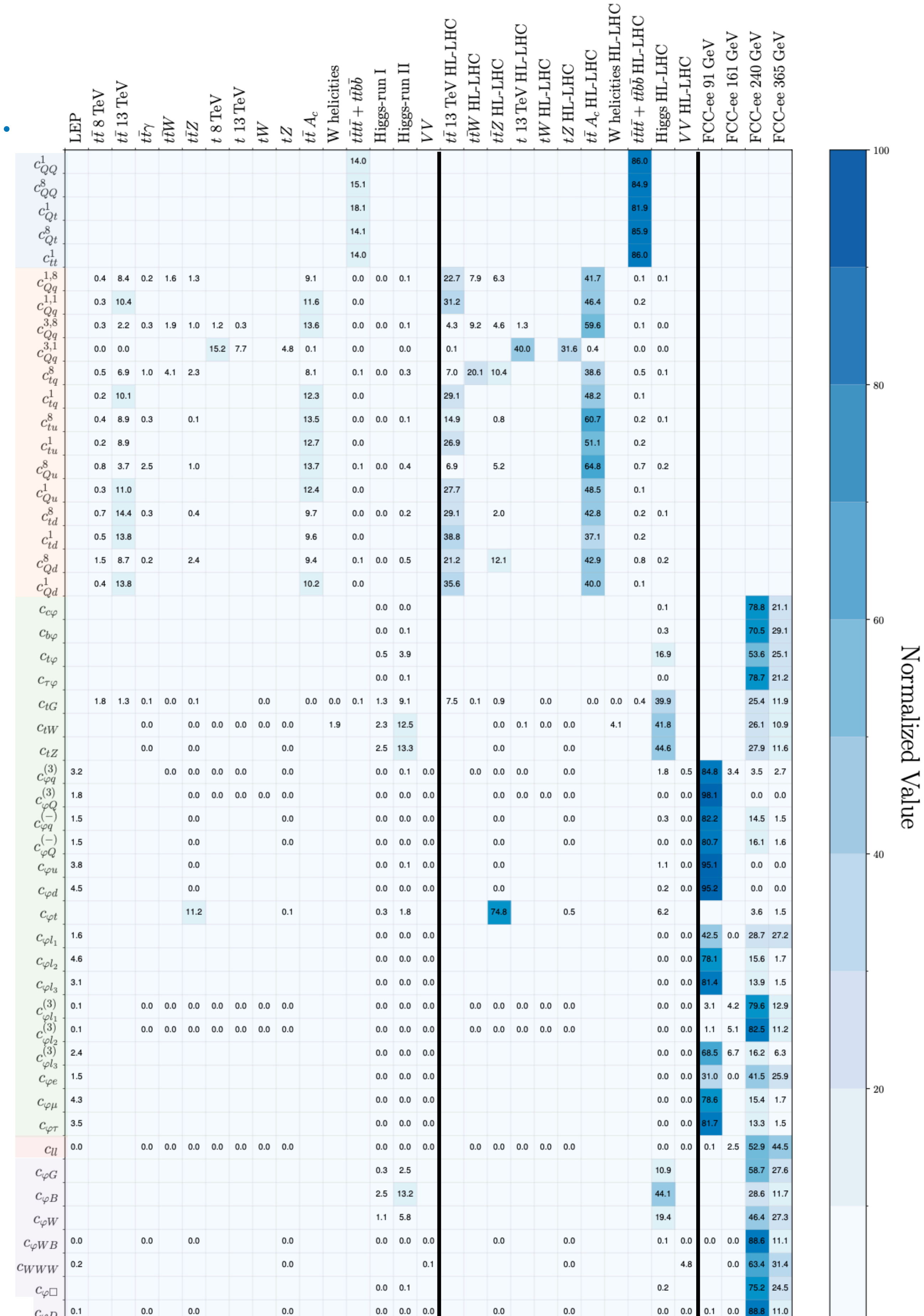
Fisher information

- The Fisher information matrix quantifies **which dataset is most sensitive** to a EFT parameter (each row is normalised by 100)

$$I_{ij} = \sum_{m=1}^{n_{\rm dat}} \frac{\sigma^{(\rm eft)}_{m,i}\,\sigma^{(\rm eft)}_{m,j}}{\delta^2_{\exp,m}}\,, \qquad i,j = 1,\ldots,n_{\rm eft}$$

- neglects correlations and quadratic effects

- HL-LHC dominates in the 2-light-2-heavy and 4-heavy sectors
- FCC-ee dominates in the bosonic and 2-fermion sector
- FCC-ee run at 161 GeV is the less useful for SMEFT



Conclusions & outlook

- SMEFT is a consistent way to look for new interactions
- Global fits need to combine all the processes available
- **SMEFiT3.0 in the biggest global SMEFT analysis to date**: 50 Wilson coefficients and 445 datapoints
- **Significant and complementary improvement** in New Physics reach expected at the **HL-LHC** and at **future circular lepton colliders**
- **Extension to other future colliders** (FCC-hh, ILC, CLIC, muon collider) in progress
- **Code, data and theory are public** and available at lhcfitnikhef.github.io/smefit_release/

Backup

EWPOs exact implementation

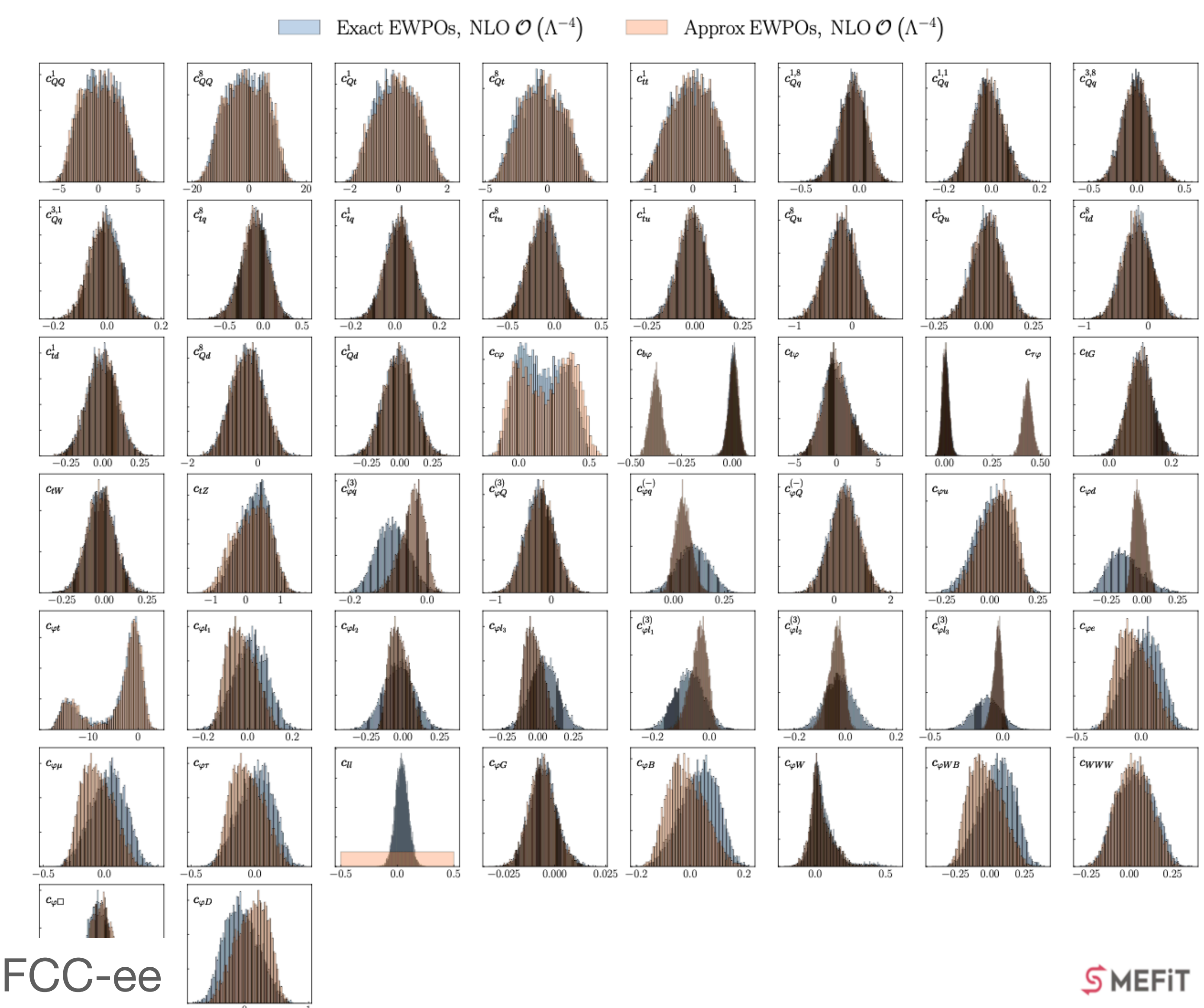
- In the SMEFT, Z and W fermionic coupling receive contributions from dim-6 operators

- **SMEFiT2.0**: assume LEP/SLD measurements precise enough to set coupling shift to 0
  ➡ **only 2 independent Wilson coefficients**

$$\begin{pmatrix} c_{\varphi\ell_i}^{(3)} \\ c_{\varphi\ell_i}^{(1)} \\ c_{\varphi e/\mu/\tau} \\ c_{\varphi q}^{(-)} \\ c_{\varphi q}^{(3)} \\ c_{\varphi u} \\ c_{\varphi d} \\ c_{\ell\ell} \end{pmatrix} = \begin{pmatrix} -\frac{1}{t_W} & -\frac{1}{4t_W^2} \\ 0 & -\frac{1}{4} \\ 0 & -\frac{1}{2} \\ \frac{1}{t_W} & \frac{1}{4s_W^2} - \frac{1}{6} \\ -\frac{1}{t_W} & -\frac{1}{4t_W^2} \\ 0 & \frac{1}{3} \\ 0 & -\frac{1}{6} \\ 0 & 0 \end{pmatrix} \begin{pmatrix} c_{\varphi WB} \\ c_{\varphi D} \end{pmatrix}$$

- **SMEFiT3.0**: EWPOs implemented like the rest of LHC data
  ➡ **16 independent Wilson coefficients**

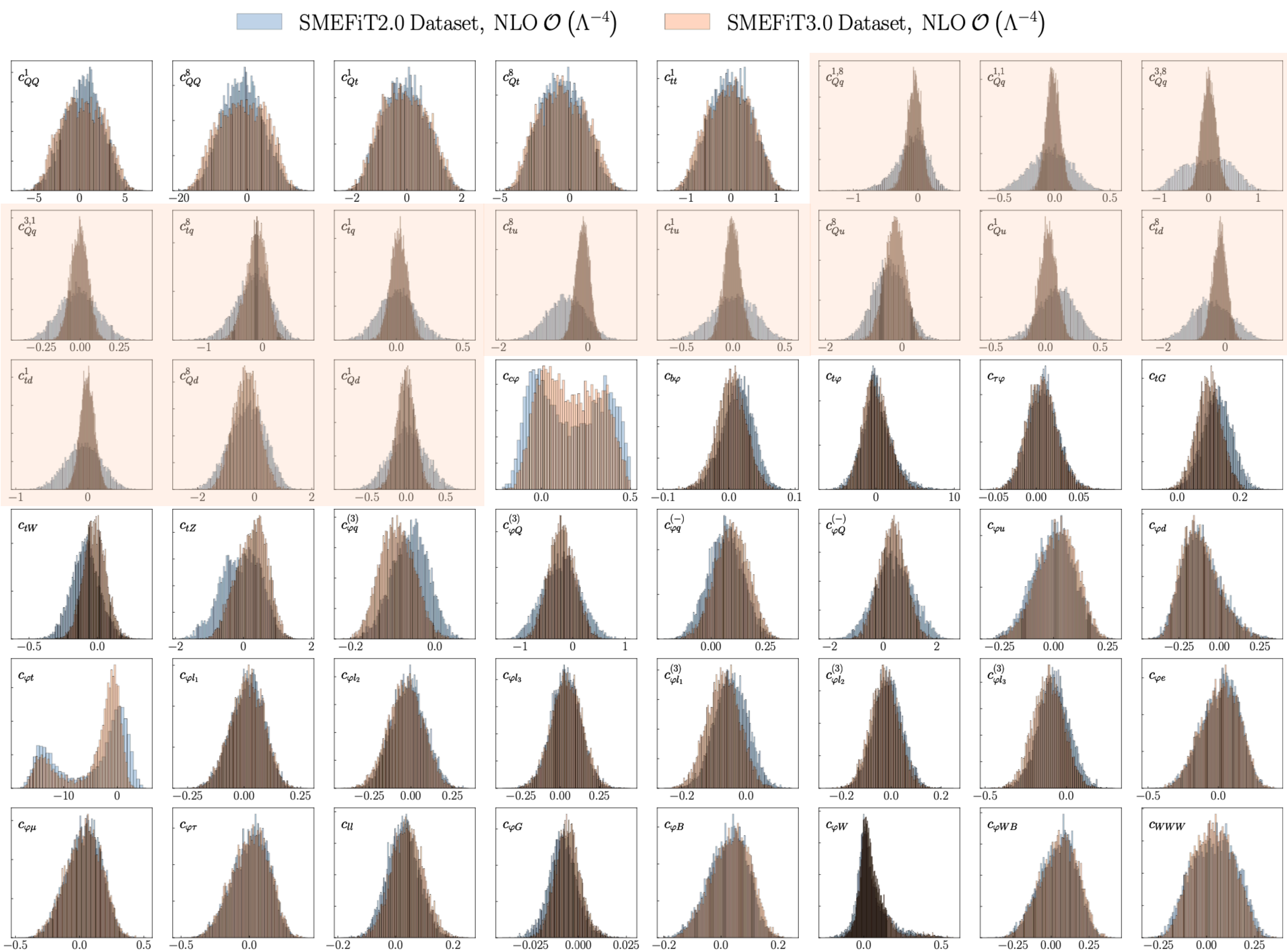
no major difference, but the approximate implementation resulted in too stringent constraints on some EW operators

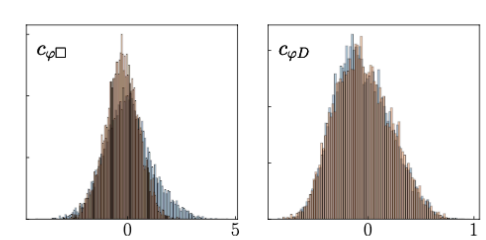


New LHC datasets

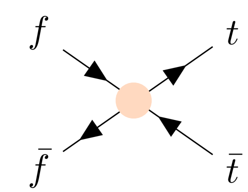
Dataset	$\sqrt{s}$ (TeV)	$\mathcal{L}$ (fb^{-1})	Info	Observables	$n_{\rm dat}$	ref.
ATLAS_STXS_RunII_13TeV_2022	13	139	ggF, VBF, Vh, $t\bar{t}h$, th	$d\sigma/dp_T^h$ $d\sigma/dm_{jj}$ $d\sigma/dp_T^V$	36	[82]
CMS_WZ_pTZ_13TeV_2022	13	137	WZ, fully leptonic	$1/\sigma d\sigma/dp_T^Z$	10	[83]
CMS_tt_13TeV_ljets_inc	13	137	$\ell+$jets	$\sigma(t\bar{t})$	1	[84]
CMS_tt_13TeV_Mtt	13	137	$\ell+$jets	$1/\sigma d\sigma/dm_{t\bar{t}}$	14	[84]
CMS_tt_13TeV_asy	13	138	$\ell+$jets	A_C	3	[85]
ATLAS_tt_13TeV_asy_2022	13	139	$\ell+$jets	A_C	5	[86]
ATLAS_Whel_13TeV	13	139	W-helicity fraction	F_0, F_L	2	[87]
ATLAS_ttZ_13TeV_pTZ	13	139	$t\bar{t}Z$	$d\sigma/dp_T^Z$	7	[88]
ATLAS_tta_8TeV	8	20.2	Inclusive	$\sigma(t\bar{t}\gamma)$	1	[89]
CMS_tta_8TeV	8	19.7	Inclusive	$\sigma(t\bar{t}\gamma)$	1	[90]
ATLAS_tttt_13TeV_slep_inc	13	139	single-lepton	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[91]
CMS_tttt_13TeV_slep_inc	13	35.8	single-lepton	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[92]
ATLAS_tttt_13TeV_2023	13	139	multi-lepton	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[93]
CMS_tttt_13TeV_2023	13	139	same-sign or multi-lepton	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[94]
CMS_ttbb_13TeV_dilepton_inc	13	35.9	dilepton	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[95]
CMS_ttbb_13TeV_ljets_inc	13	35.9	$\ell+$jets	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[95]
ATLAS_t_sch_13TeV_inc	13	139	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[96]
CMS_tZ_13TeV_pTt	13	138	dilepton	$d\sigma_{\rm fid}(tZj)/dp_T^t$	3	[97]
CMS_tW_13TeV_slep_inc	13	36	single-lepton	$\sigma_{\rm tot}(tW)$	1	[98]

Impact of new datasets





strongest improvement on the 2-light-2-heavy operator coefficients (factor 2-3)



from:

- $t\bar{t}$ production
- A_C in $t\bar{t}$

L0 vs L1 projections

- **Level-0**: no fluctuation of the pseudo-data

$$\mathcal{O}_i^{(\mathrm{exp})} = \mathcal{O}_i^{(\mathrm{th})}\,, \qquad i = 1, \ldots, n_{\mathrm{bin}}$$

- **Level-1**:
  - pseudodata fluctuated around SM

$$\mathcal{O}_i^{(\mathrm{exp})} = \mathcal{O}_i^{(\mathrm{th})}\left(1 + r_i \delta_i^{(\mathrm{stat})} + \sum_{k=1}^{n_{\mathrm{sys}}} r_{k,i}\delta_{k,i}^{(\mathrm{sys})}\right)\,, \qquad i = 1, \ldots, n_{\mathrm{bin}}$$

  - statistics rescaled by luminosity

$$\delta_i^{(\mathrm{stat})} = \tilde{\delta}_i^{(\mathrm{stat})}\sqrt{\frac{\mathcal{L}_{\mathrm{Run2}}}{\mathcal{L}_{\mathrm{HLLHC}}}}$$

  - systematics reduced by a factor $f_{\mathrm{red}}^{(k)} = 1/2$

$$\delta_{k,i}^{(\mathrm{sys})} = \tilde{\delta}_{k,i}^{(\mathrm{sys})} \times f_{\mathrm{red}}^{(k)}\,, \qquad i = 1, \ldots, n_{\mathrm{bin}}\,, \quad k = 1, \ldots, n_{\mathrm{sys}}$$

Good agreement found between the two approaches.

FCC-ee energy breakdown

Study the impact of sequentially adding different runs

- largest impact from 91 + 240 GeV combination
- 365 GeV also relevant