Mapping the SMEFT at High-Energy Colliders

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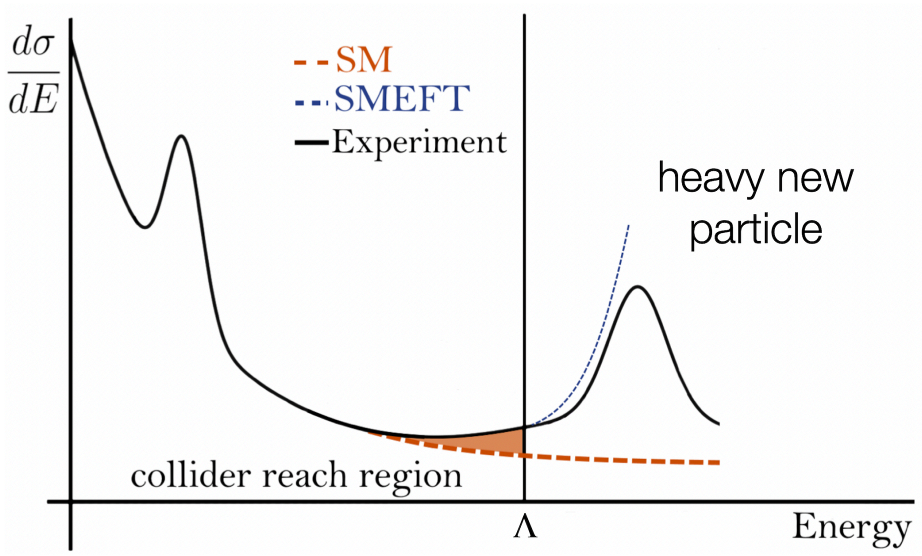
LFC24- Fundamental Interactions at Future Colliders

17/09/24

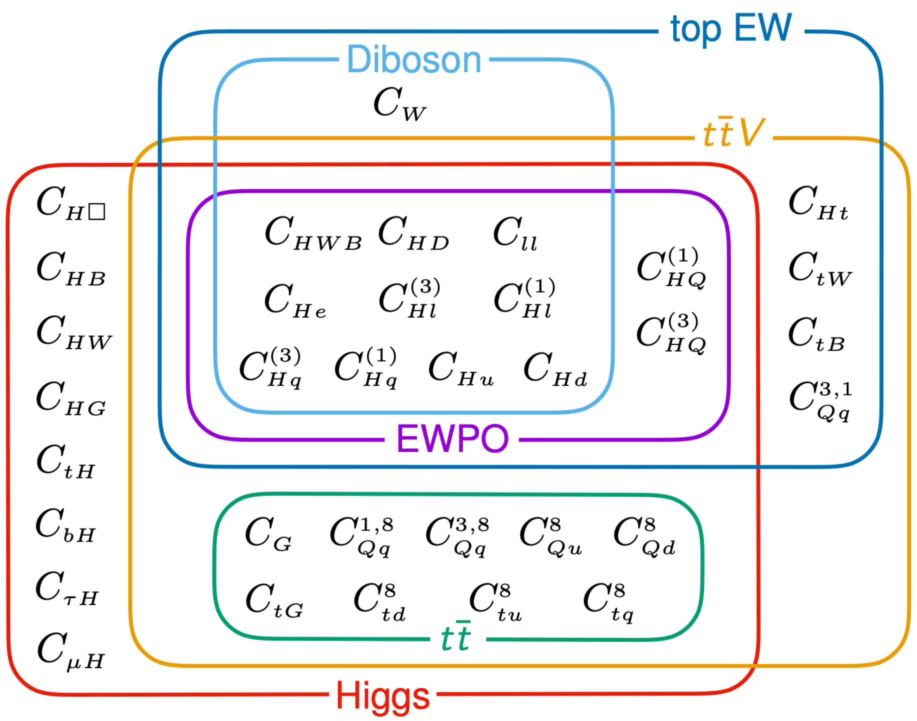
Based on SMEFiT3.0 [arXiv:2404.12809]

with E. Celada, T. Giani, J. ter Hoeve, L. Mantani, J. Rojo, A. N. Rossia and E. Vryonidou

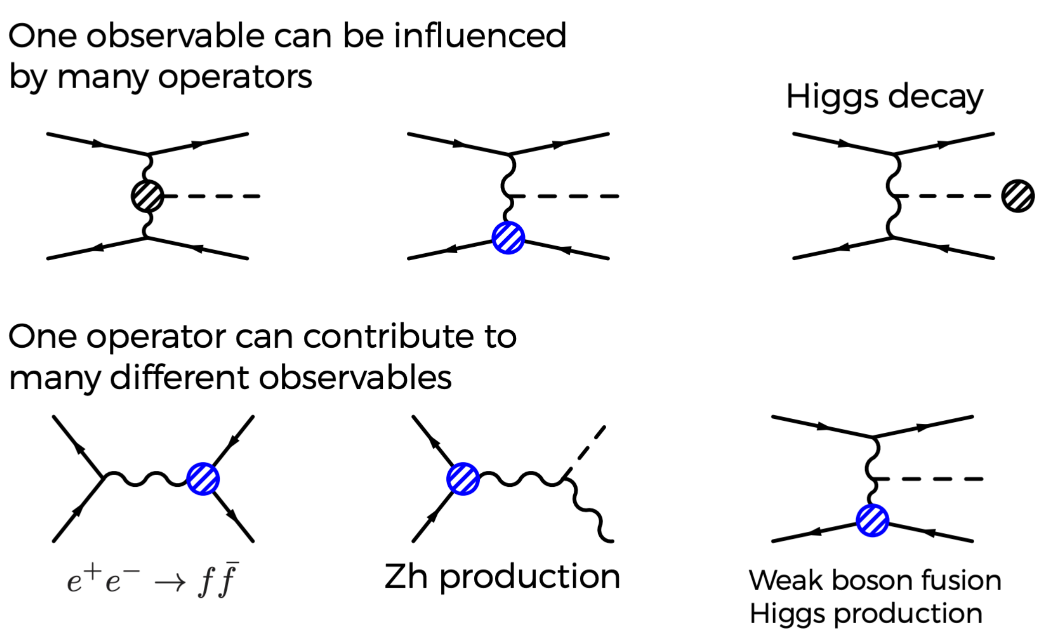
What can global EFT fits tell us?



- EFTs reveal **high energy physics** through **precise measurements at low energy.**
- Cross-talk between Higgs, top, diboson and EWPO (and eventually flavour) sectors
- Important to combine as many processes as possible to extract maximal information



Fitmaker Collaboration [arXiv:2012.02779]



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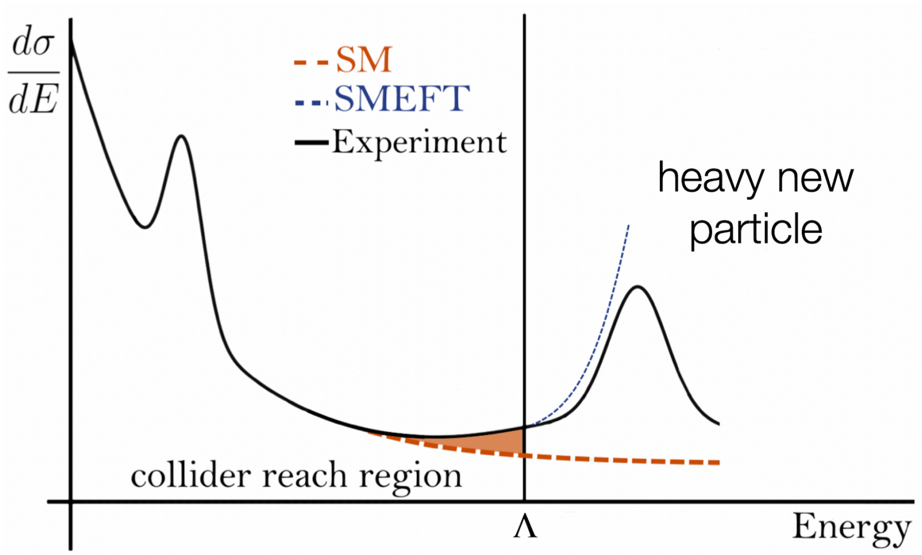
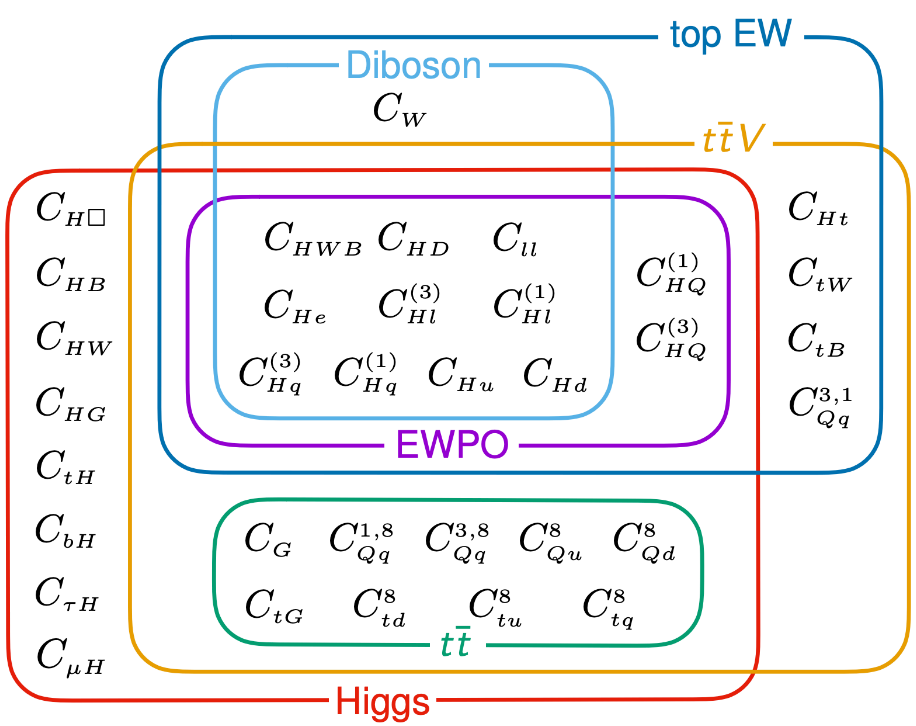


- EFTs reveal **high energy physics** through **precise measurements at low energy.**
- Cross-talk between Higgs, top, diboson and EWPO (and eventually flavour) sectors
- Important to combine as many processes as possible to extract maximal information

→ A simultaneous fit is a useful way forward

Challenge: a large number of operators, with many datasets needed to break degeneracies



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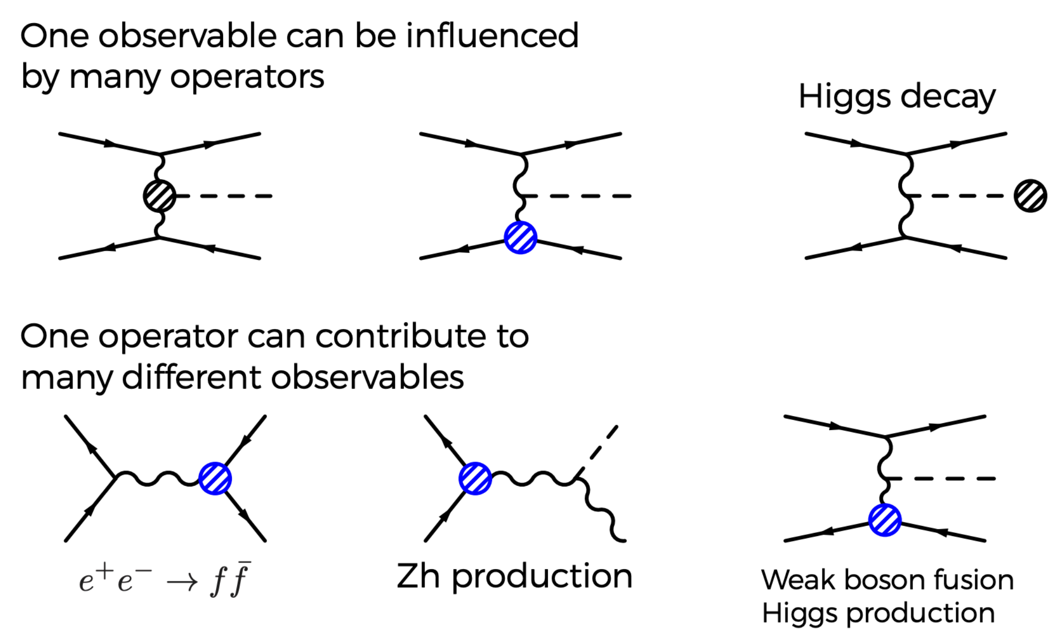

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The SMEFiT framework

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

SMEFiT

Giani, Magni, Rojo, arXiv:2302.06660

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

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Methodology

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

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

Output

Fit report with **bounds** on coefficients, **posterior** distributions, **PCA**, **Fisher information**...

Overview of SMEFiT3.0

- Extension of SMEFiT2.0 [arXiv:2105.00006] with recent **LHC Run-II datasets** on **top, diboson and Higgs production**
- Exact treatment of **LEP and SLD EWPOs**
- Projections for **HL-LHC pseudodata** extrapolated from Run-II data
- Projections for **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]
- **Public code, data and theory**: results are fully reproducible lhcfitnikhef.github.io/smefit_release/

Mapping the SMEFT at High-Energy Colliders: from LEP and the (HL-)LHC to the FCC-ee

arXiv:2404.12809v1 [hep-ph] 19 Apr 2024

Eugenia Celada,[a] Tommaso Giani,[b,c] Jaco ter Hoeve,[b,c] Luca Mantani,[d] Juan Rojo,[b,c] Alejo N. Rossia,[a] Marion O. A. Thomas,[a] and Eleni Vryonidou[a]

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[b] *Nikhef Theory Group, Science Park 105, 1098 XG Amsterdam, The Netherlands*
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Abstract: We present SMEFiT3.0, an updated global SMEFT analysis of Higgs, top quark, and diboson production data from the LHC complemented by electroweak precision observables (EWPOs) from LEP and SLD. We consider recent inclusive and differential measurements from the LHC Run II, alongside with a novel implementation of the EWPOs based on independent calculations of the relevant EFT contributions. We estimate the impact of HL-LHC measurements on the SMEFT parameter space when added on top of SMEFiT3.0, through dedicated projections extrapolating from Run II data. We quantify the significant constraints that measurements from two proposed high-energy circular e^+e^- colliders, the FCC-ee and the CEPC, would impose on both the SMEFT parameter space and on representative UV-complete models. Our analysis considers projections for the FCC-ee and the CEPC based on the latest running scenarios and includes Z-pole EWPOs, fermion-pair, Higgs, diboson, and top quark production, using optimal observables for both the W^+W^- and the $t\bar{t}$ channels. The framework presented in this work may be extended to other future colliders and running scenarios, providing timely input to ongoing studies towards future high-energy particle physics facilities.

The experimental input

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

Category	Processes	n_{dat} SMEFiT2.0	n_{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**

+128 data points

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

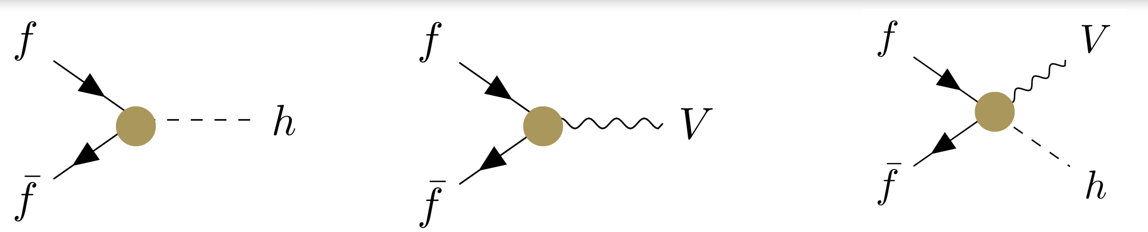
Which operators?

- 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	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			
$\mathcal{O}_{\ell\ell}$	$c_{\ell\ell}$	$(\bar{\ell}_1\gamma_\mu \ell_2)(\bar{\ell}_2\gamma^\mu \ell_1)$			

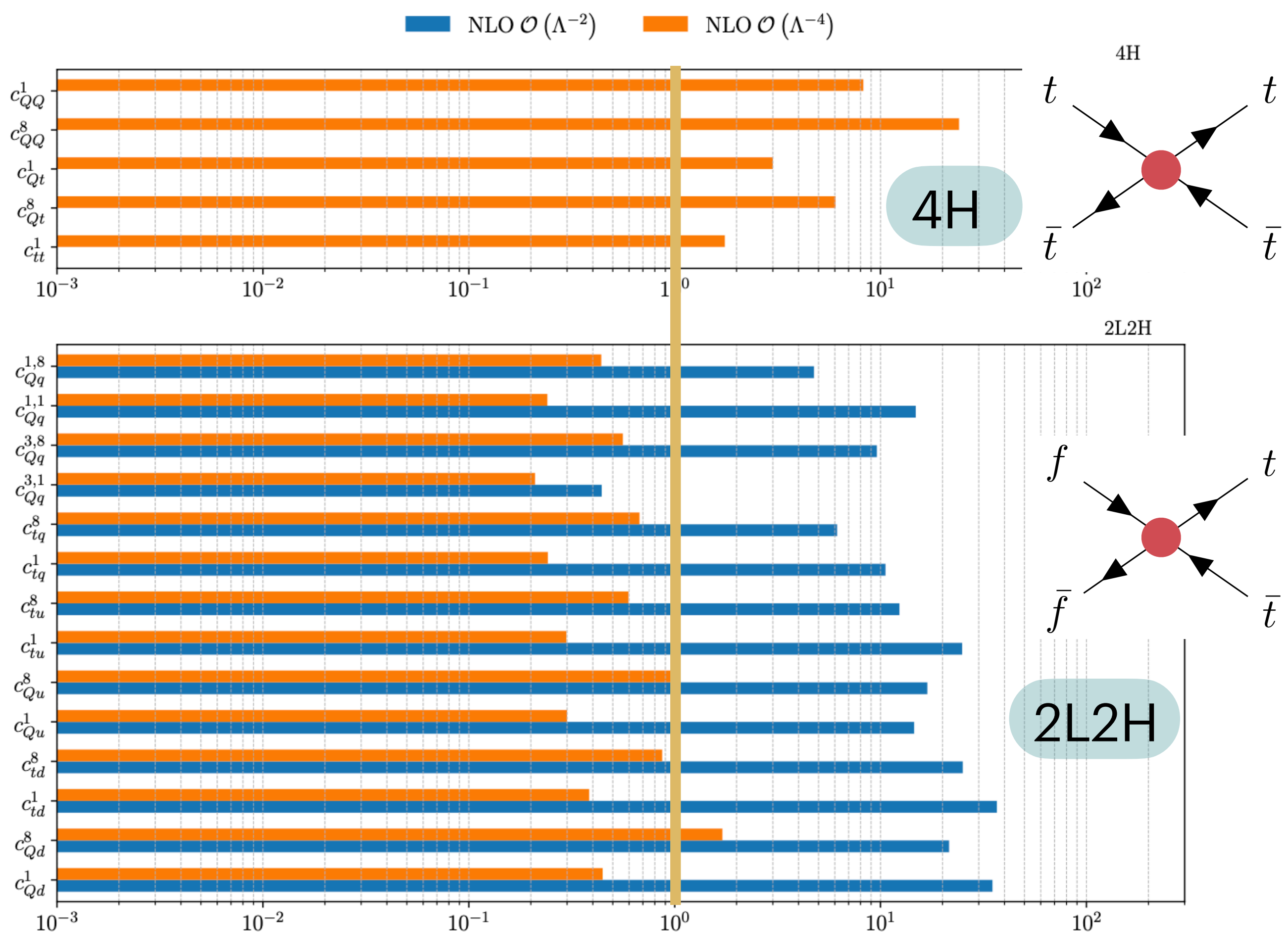


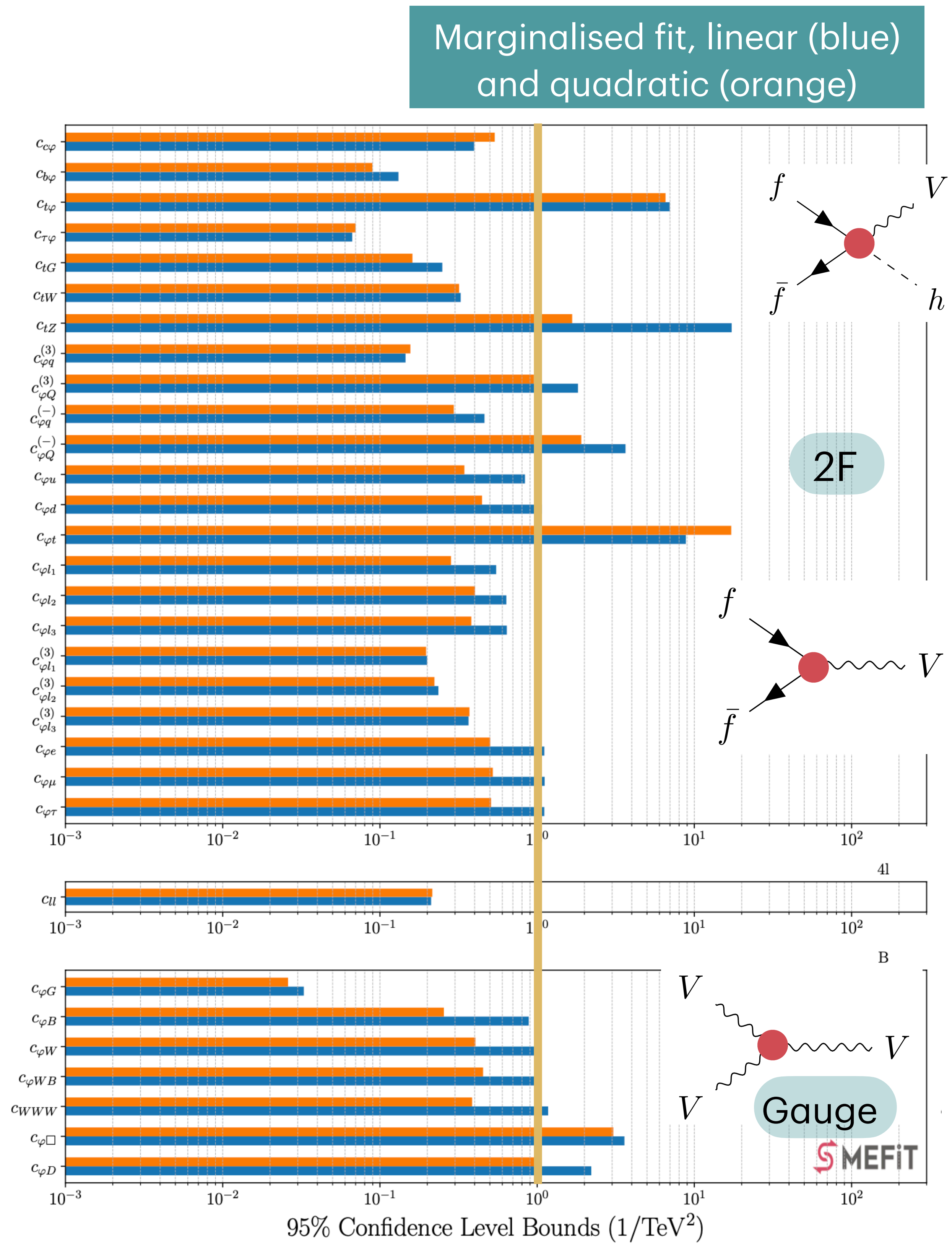
Operator	Coefficient	Definition	Operator	Coefficient	Definition
$\mathcal{O}_{\varphi G}$	$c_{\varphi G}$	$(\varphi^\dagger\varphi) G_A^{\mu\nu} G^A_{\mu\nu}$	$\mathcal{O}_{\varphi\Box}$	$c_{\varphi\Box}$	$\partial_\mu(\varphi^\dagger\varphi)\partial^\mu(\varphi^\dagger\varphi)$
$\mathcal{O}_{\varphi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

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}	$c_{qd}^{1(33jj)}$

Simultaneous fit of **45 (50) Wilson coefficients** at the linear (quadratic) level

SMEFiT3.0 global fit

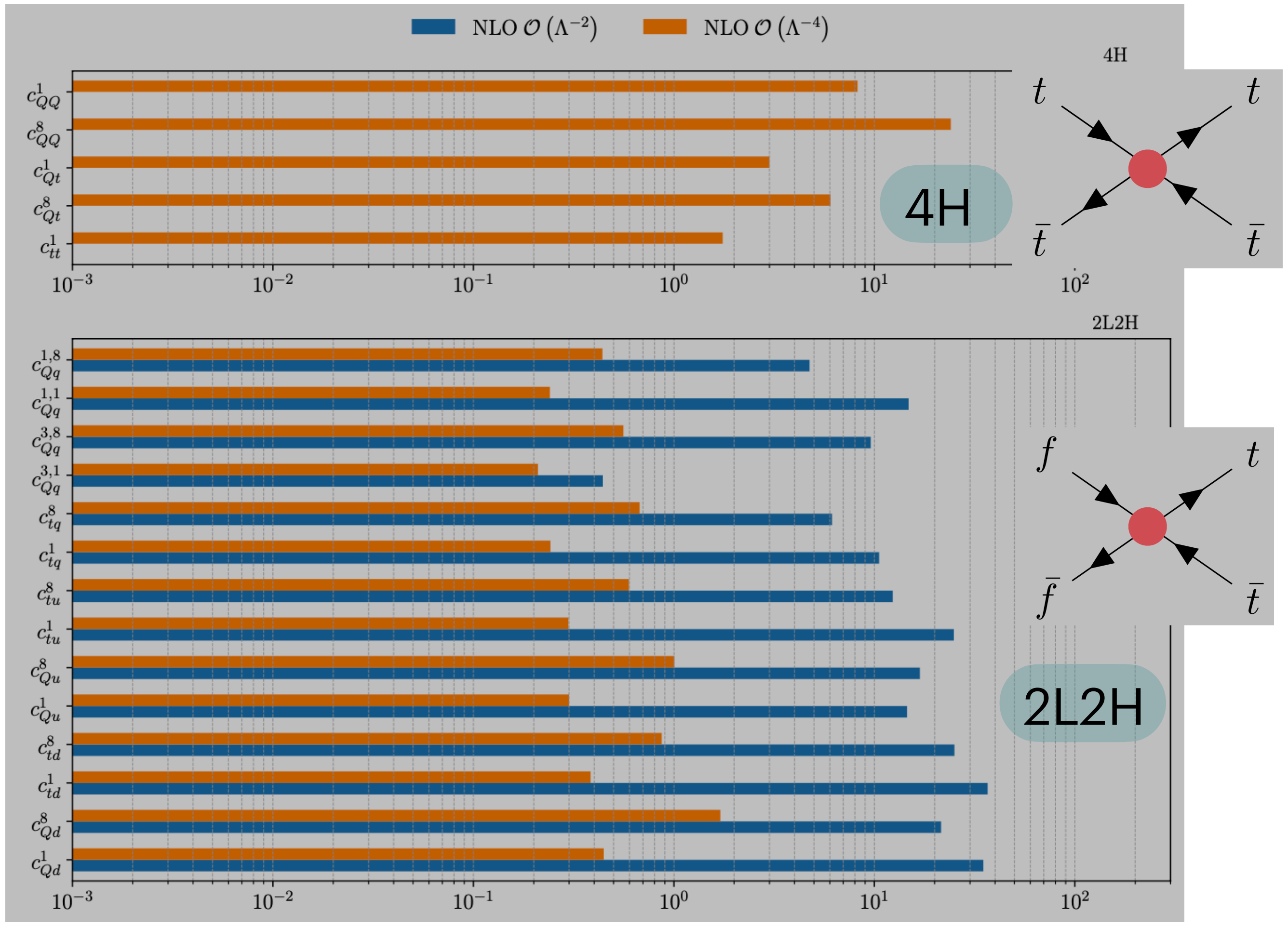


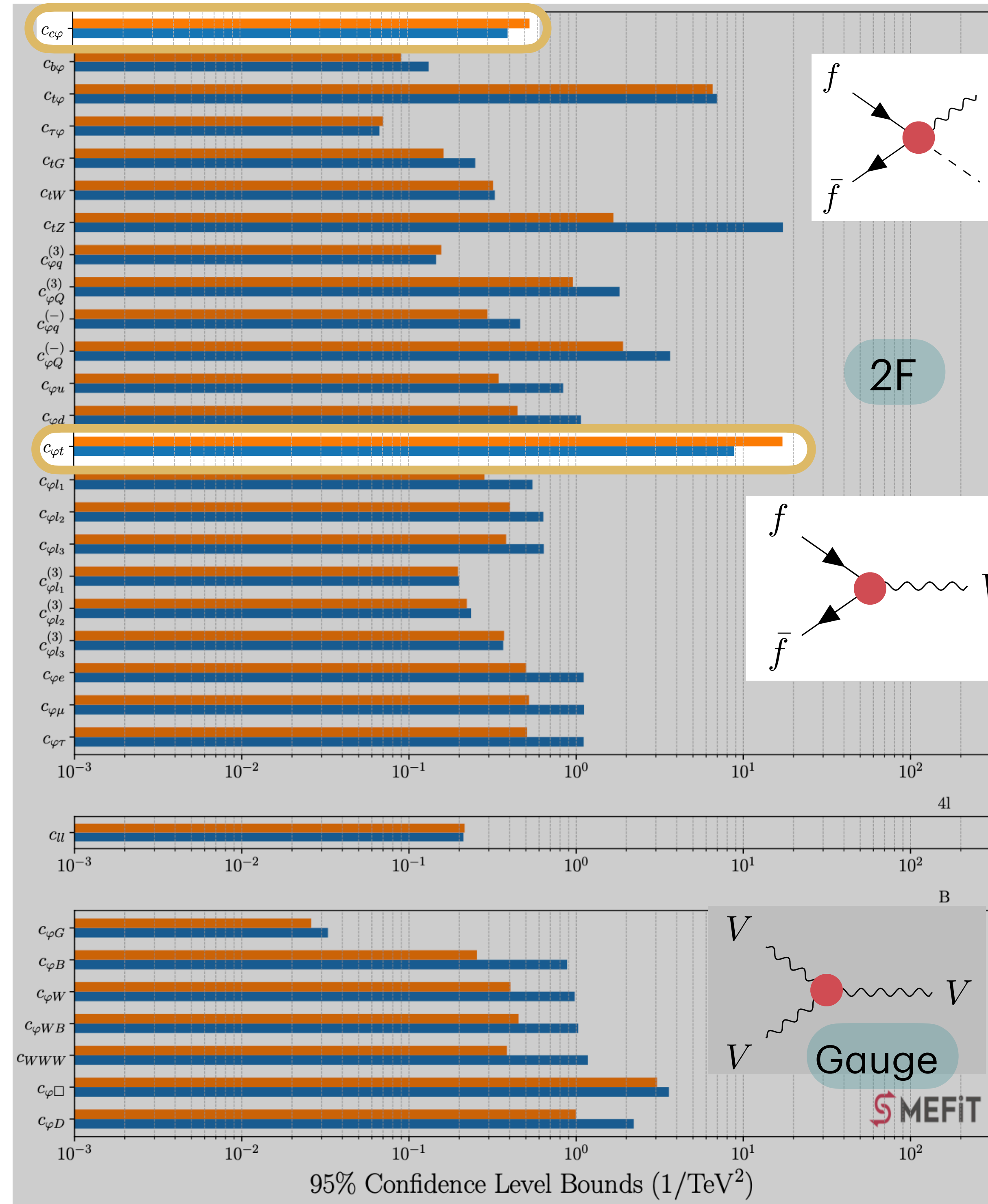


- Most Wilson coefficients have bounds below 1 for $\Lambda = 1$ TeV
- Quadratic terms important for most operators

SMEFiT3.0 global fit

Marginalised fit, linear (blue) and quadratic (orange)





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- Quadratic terms important for most operators
- Some exceptions like $c_{c\varphi}$ and $c_{\varphi t}$ due to degenerate solutions

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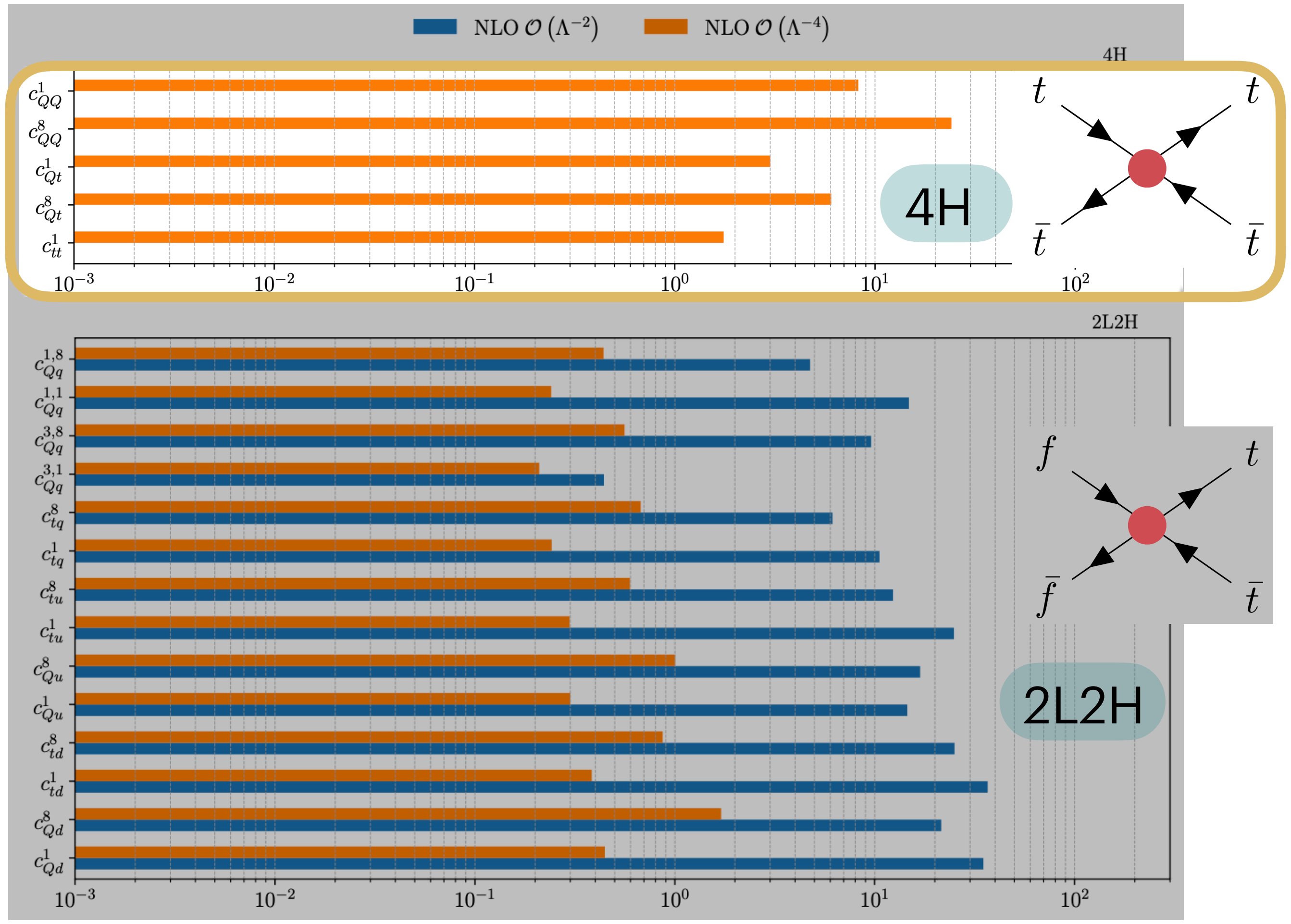
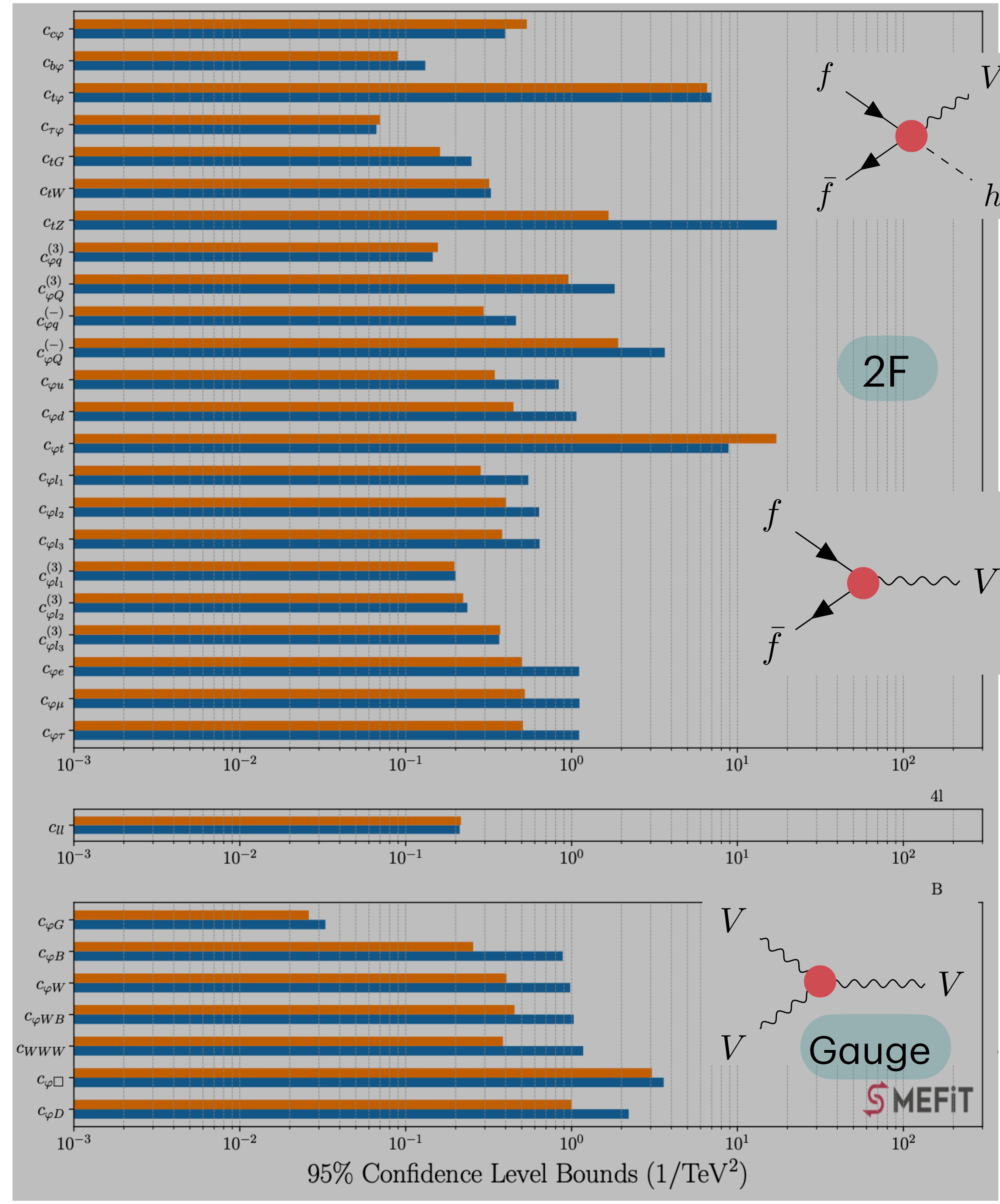
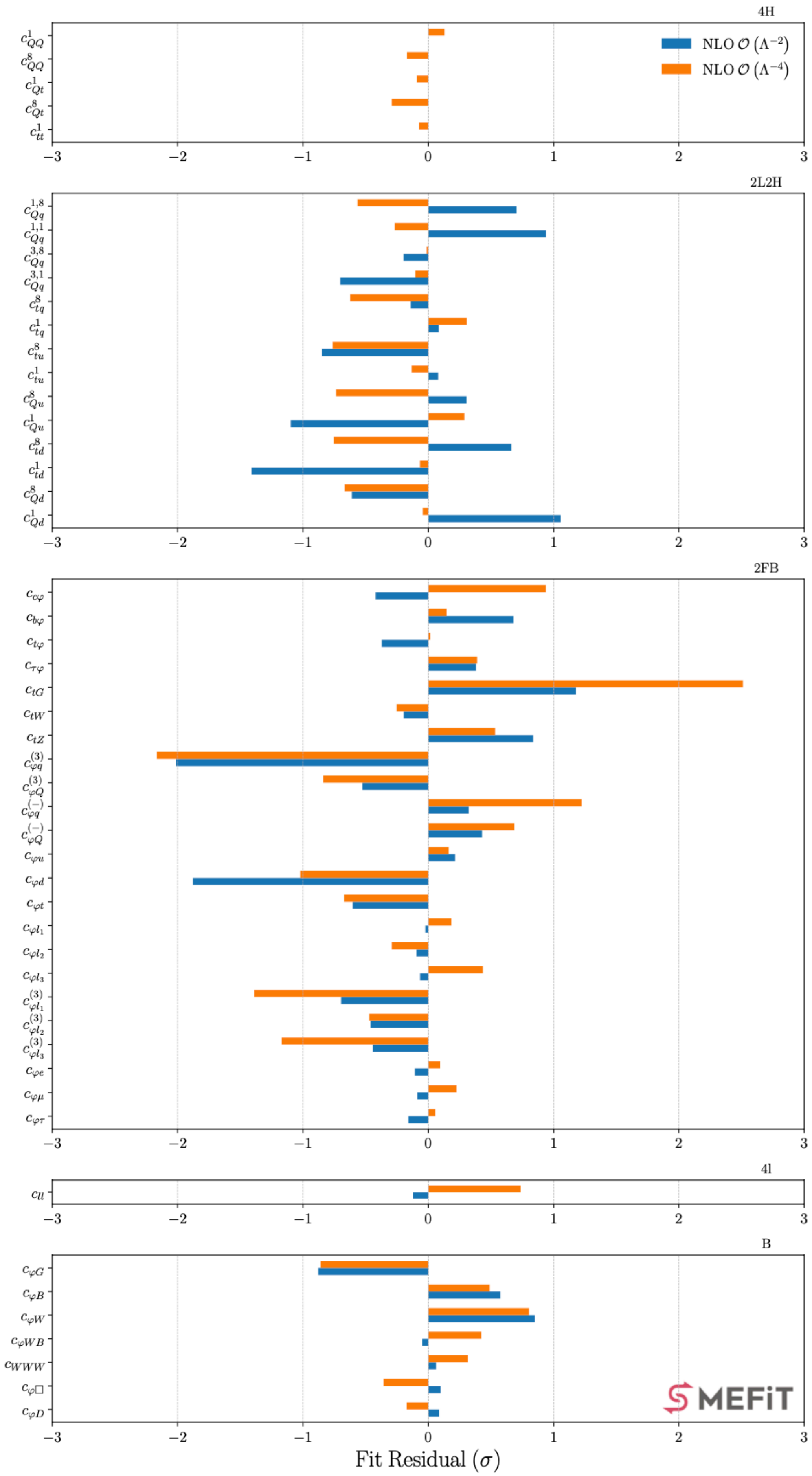




- Most Wilson coefficients have bounds below 1 for $\Lambda = 1$ TeV
- Quadratic terms important for most operators
- Some exceptions like $c_{c\varphi}$ and $c_{\varphi t}$ due to degenerate solutions
- Least constrained coefficients are 4-top operators

SMEFiT3.0 global fit

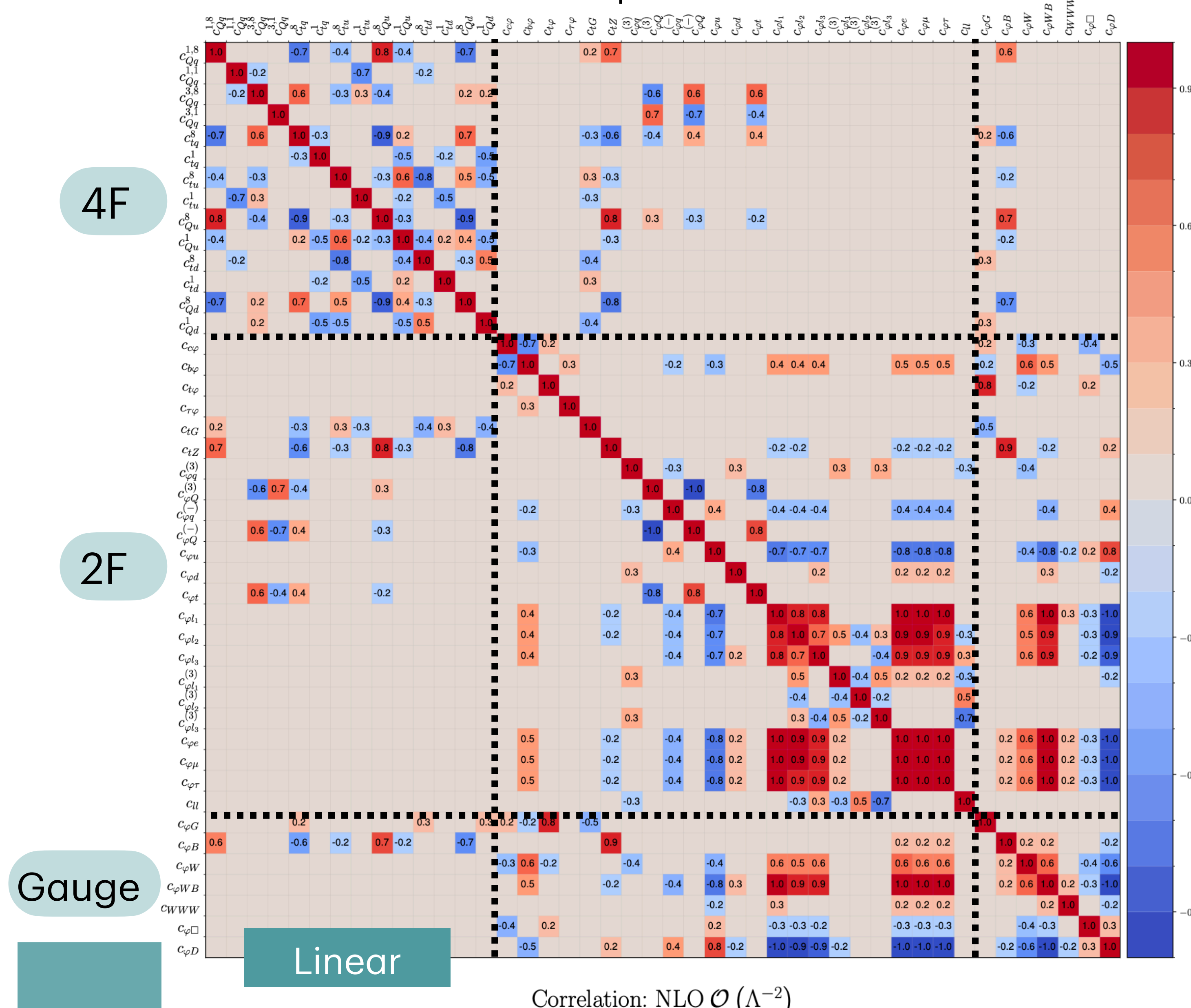
Marginalised fit



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

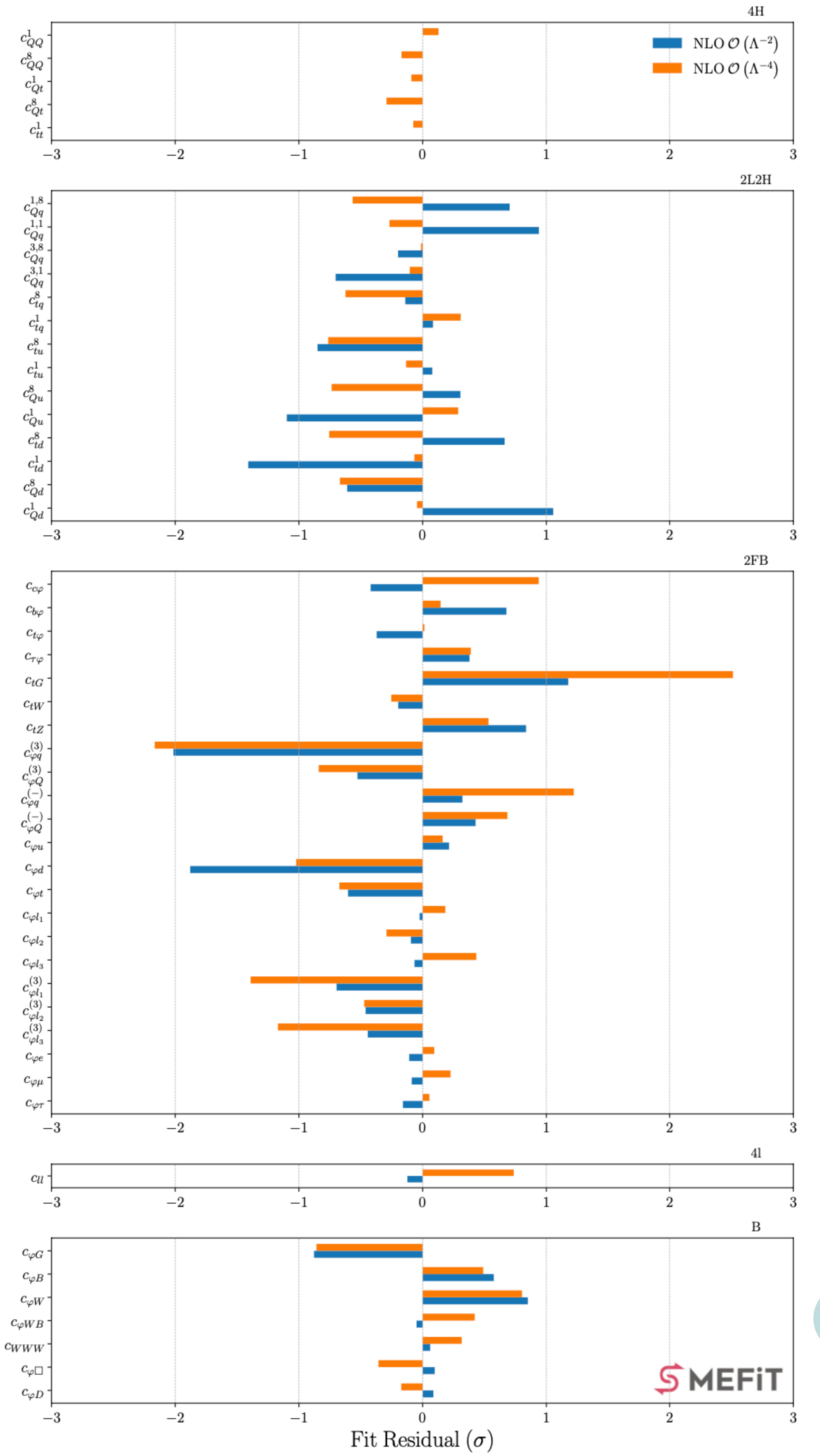
$$P_i \equiv 2\left(\frac{\langle c_i\rangle - c_i^{(\mathrm{SM})}}{\left[c_i^{\min}, c_i^{\max}\right]^{68\%\ \mathrm{CI}}}\right)$$

Large correlations in linear fit get lifted in the quadratic fit



SMEFiT3.0 global fit

Marginalised fit



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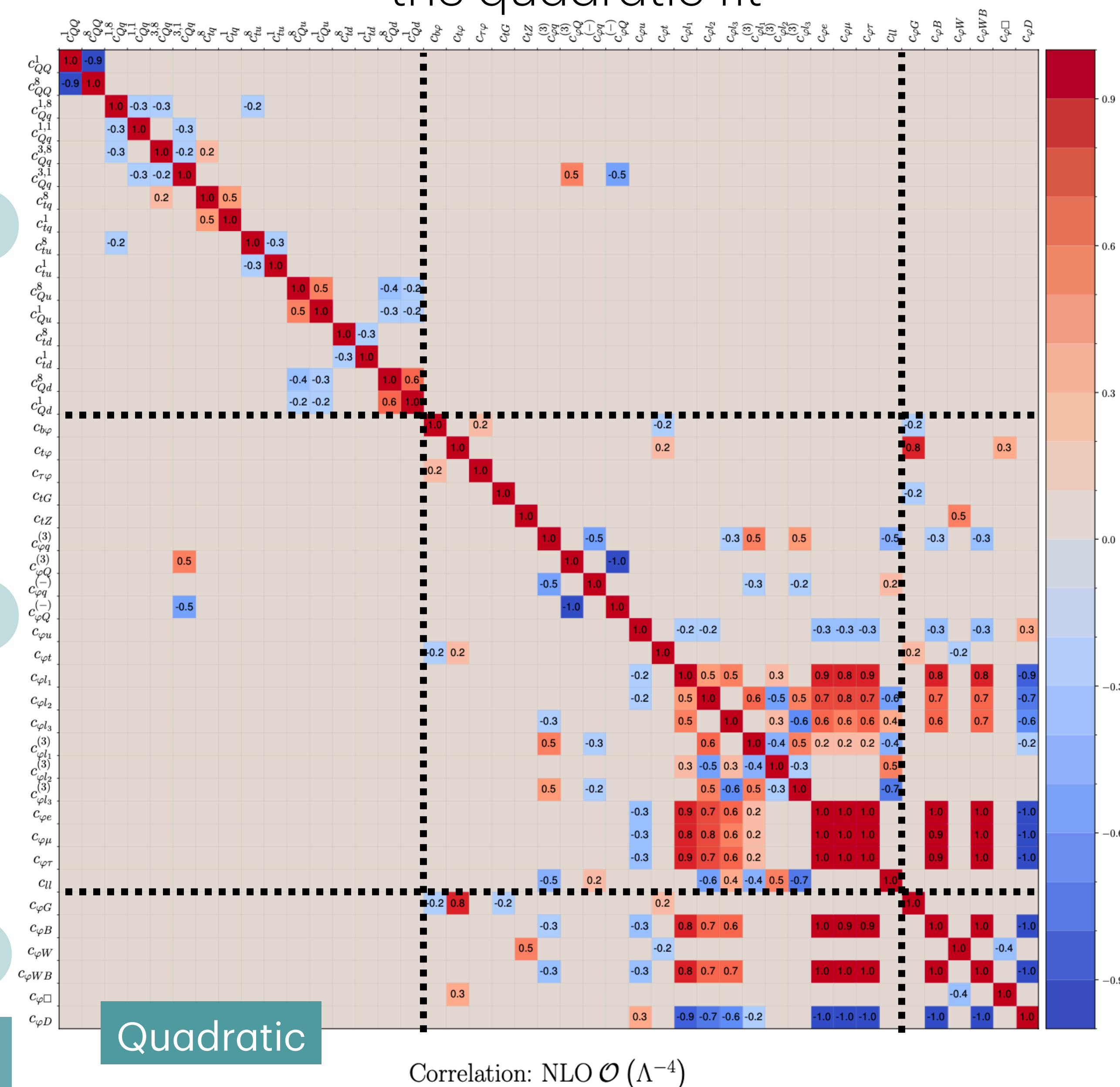
4F

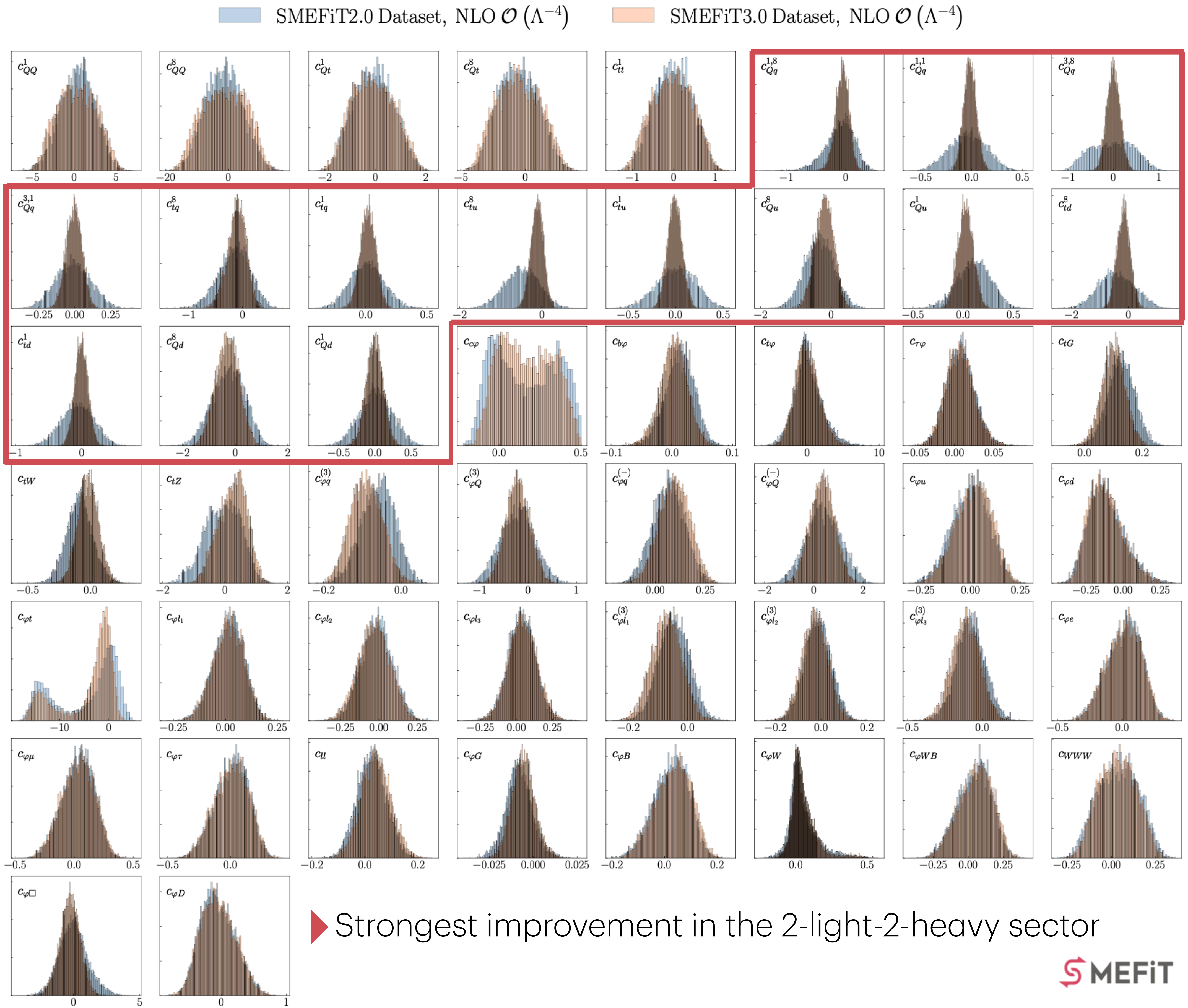
2F

Gauge



Impact of new datasets

Marginalised quadratic fit



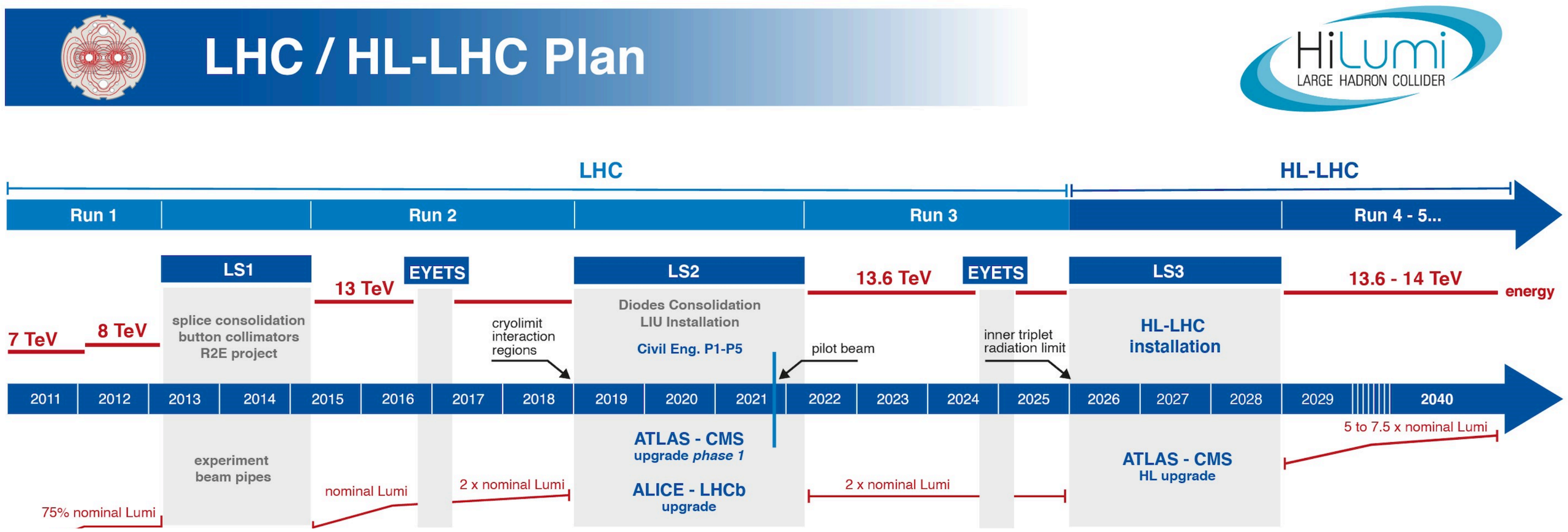
- Strongest improvement in the 2-light-2-heavy sector

SMEFiT

How will this change at future experiments?

Implemented in SMEFiT

HL-LHC projections



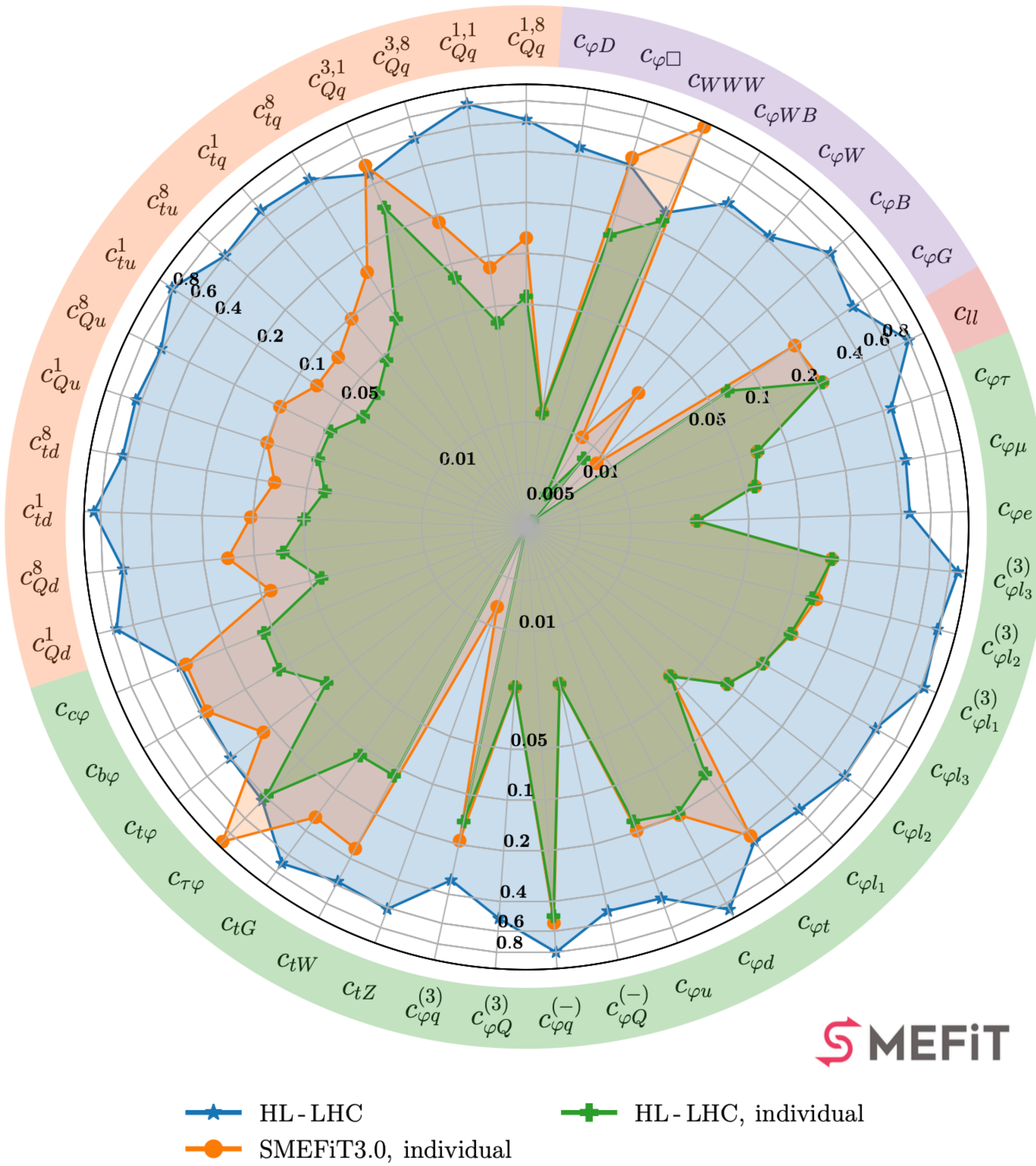
- Select SMEFiT3.0 datasets with highest integrated luminosity for each process type
- **Central values** of pseudodata **fluctuated around SM**
- Rescale **statistical uncertainties** with **luminosity**
  Rescale **systematic uncertainties** by **1/2**

+ Flexible framework that can project any Run-II dataset
- No HL-LHC optimisation (eg. bins in tail)

HL-LHC projections

- HL-LHC marginalised: **Improvement ranging from 20% to factor of 3**
- Individual bounds are overly optimistic
- **Further improvement expected** at HL-LHC with dedicated analyses

Ratio of Uncertainties to SMEFiT3.0 Baseline, $\mathcal{O}\left(\Lambda^{-2}\right)$, Marginalised



SMEFiT

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

Future circular lepton colliders

Observables considered:

- EWPOs at the Z-pole
- Light fermion pair production
- Higgs production in hZ and $h\nu\nu$ channels + all Higgs decays
- Diboson (W^+W^-) production
- Top quark pair production

Energy ($\sqrt{s}$)	$\mathcal{L}_{\text{int}}$ (Run time)		$\mathcal{L}_{\text{FCC-ee}}/\mathcal{L}_{\text{CEPC}}$
	FCC-ee (4 IPs)	CEPC (2 IPs)	
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

Uncertainty projections from Snowmass study updated with FCC midterm Feasibility Report

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

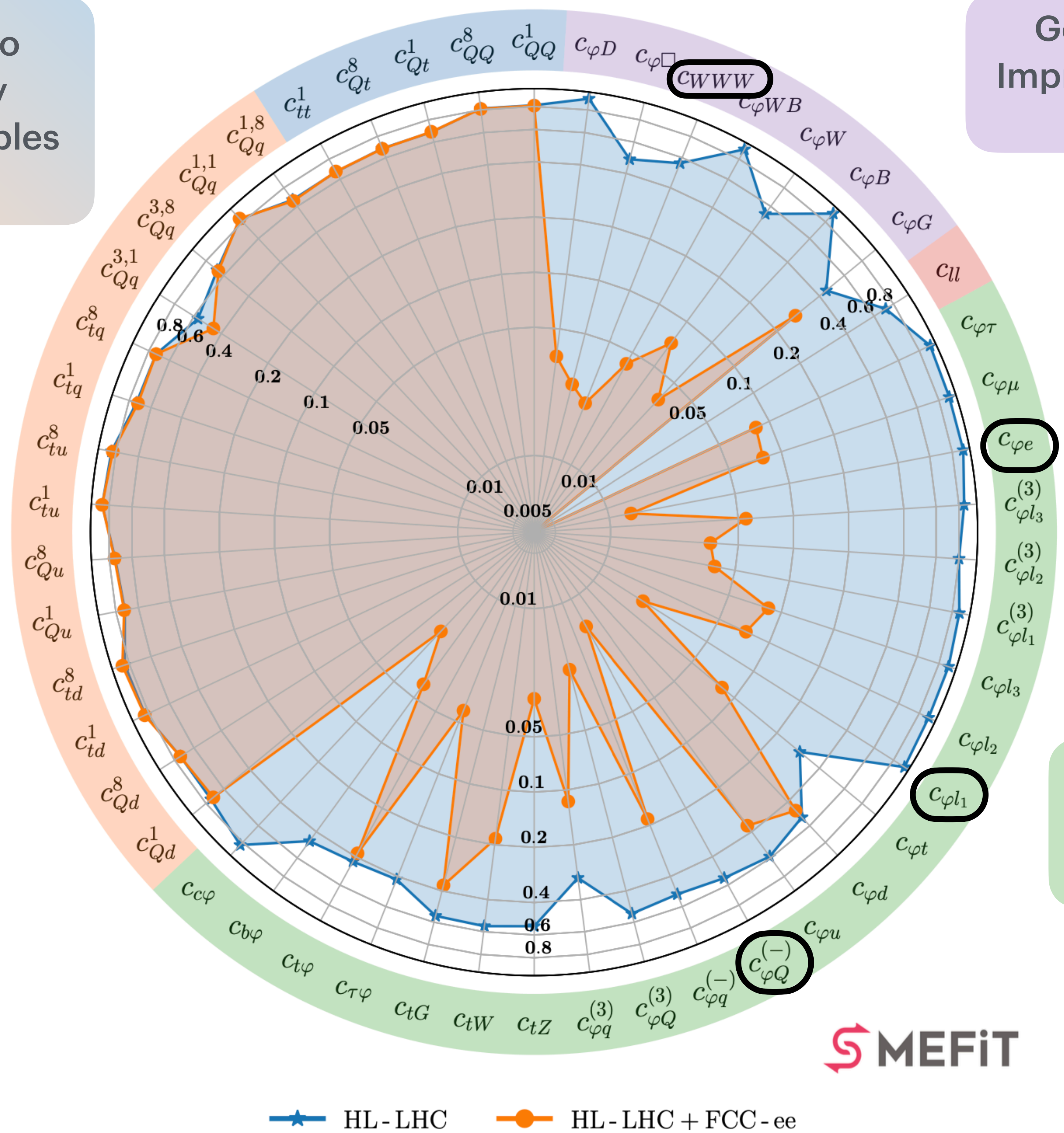
Constraints at the FCC-ee

- Overall **huge improvements** on many coefficients

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

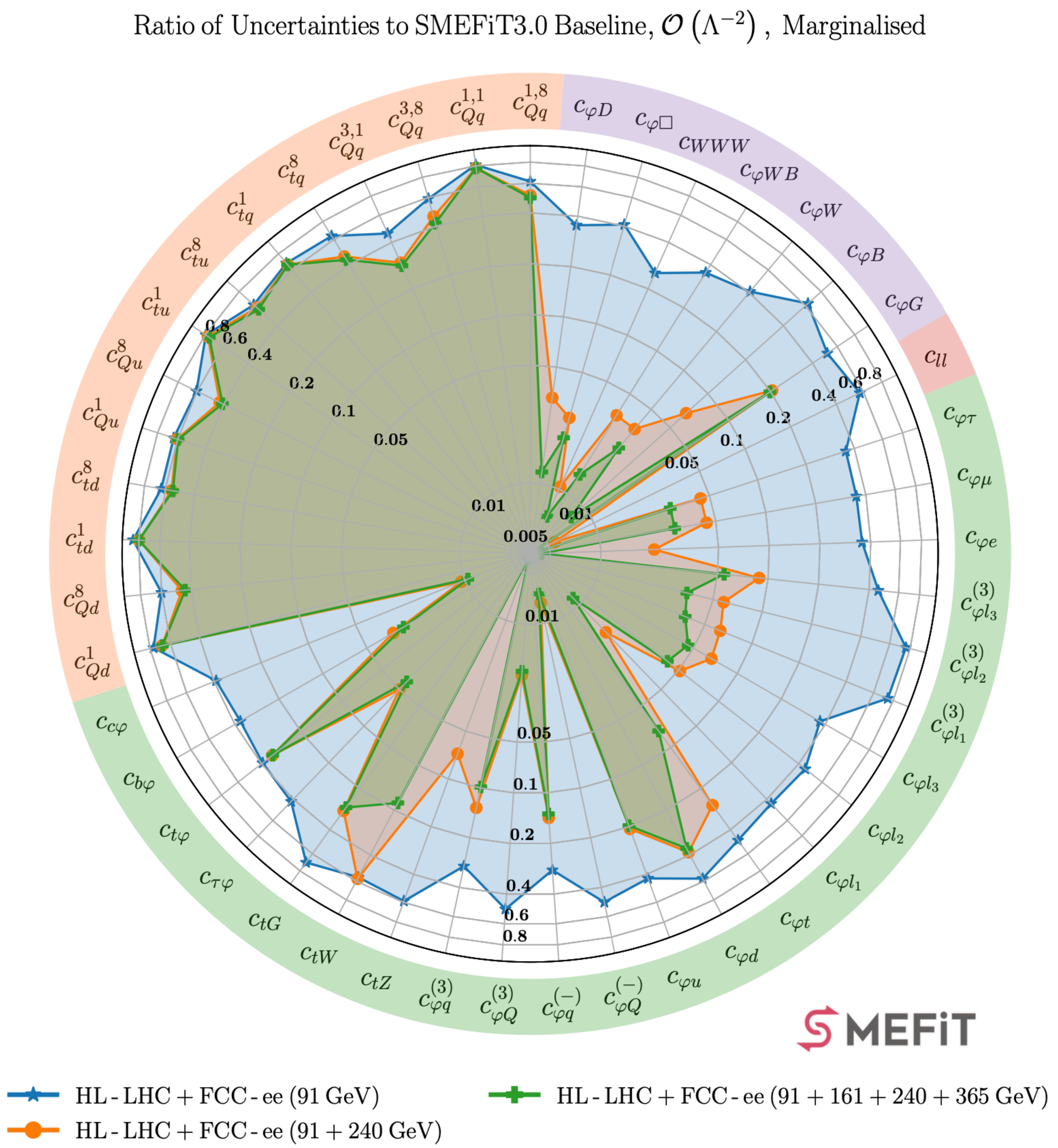
4-quark: no sensitivity (No observables in fit)

Gauge operators Improvement of up to factor 30



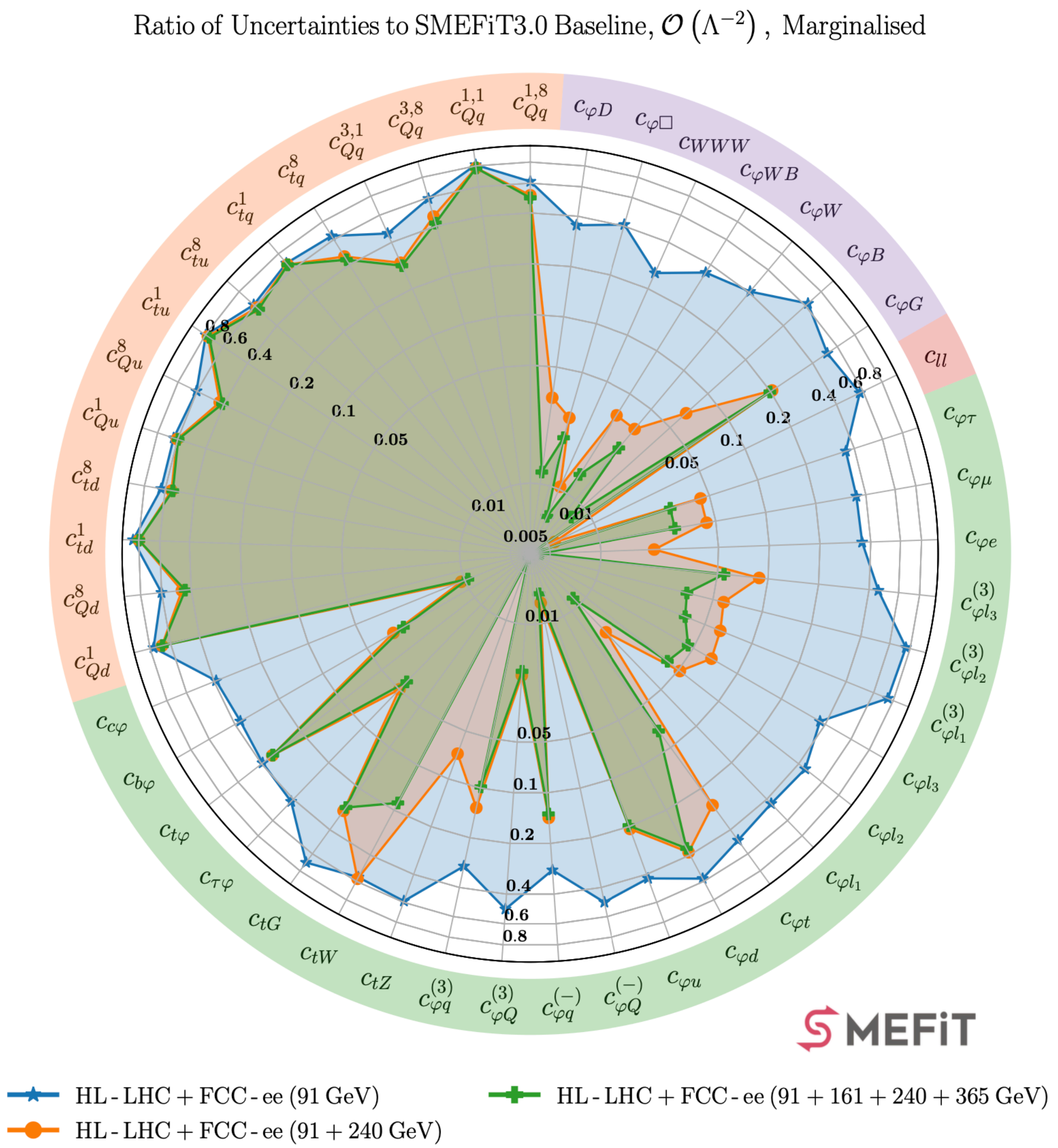
2-fermion Improvement of up to factor 50

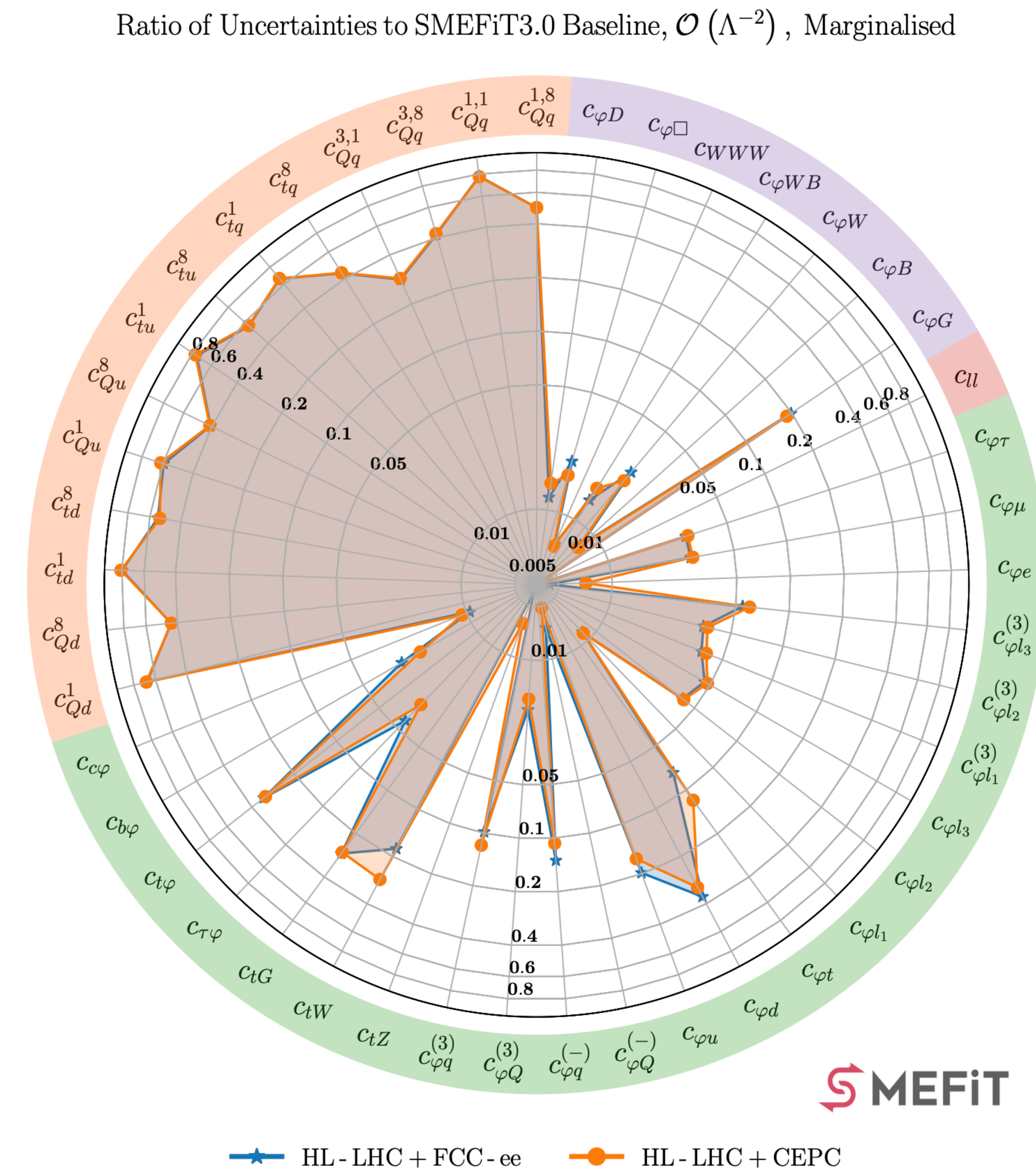
FCC-ee energy runs and CEPC



- Study impact of sequentially adding FCC-ee datasets for different energies
- Significant impact from **combined Z-pole run (91 GeV) + Higgs factory (240 GeV)**

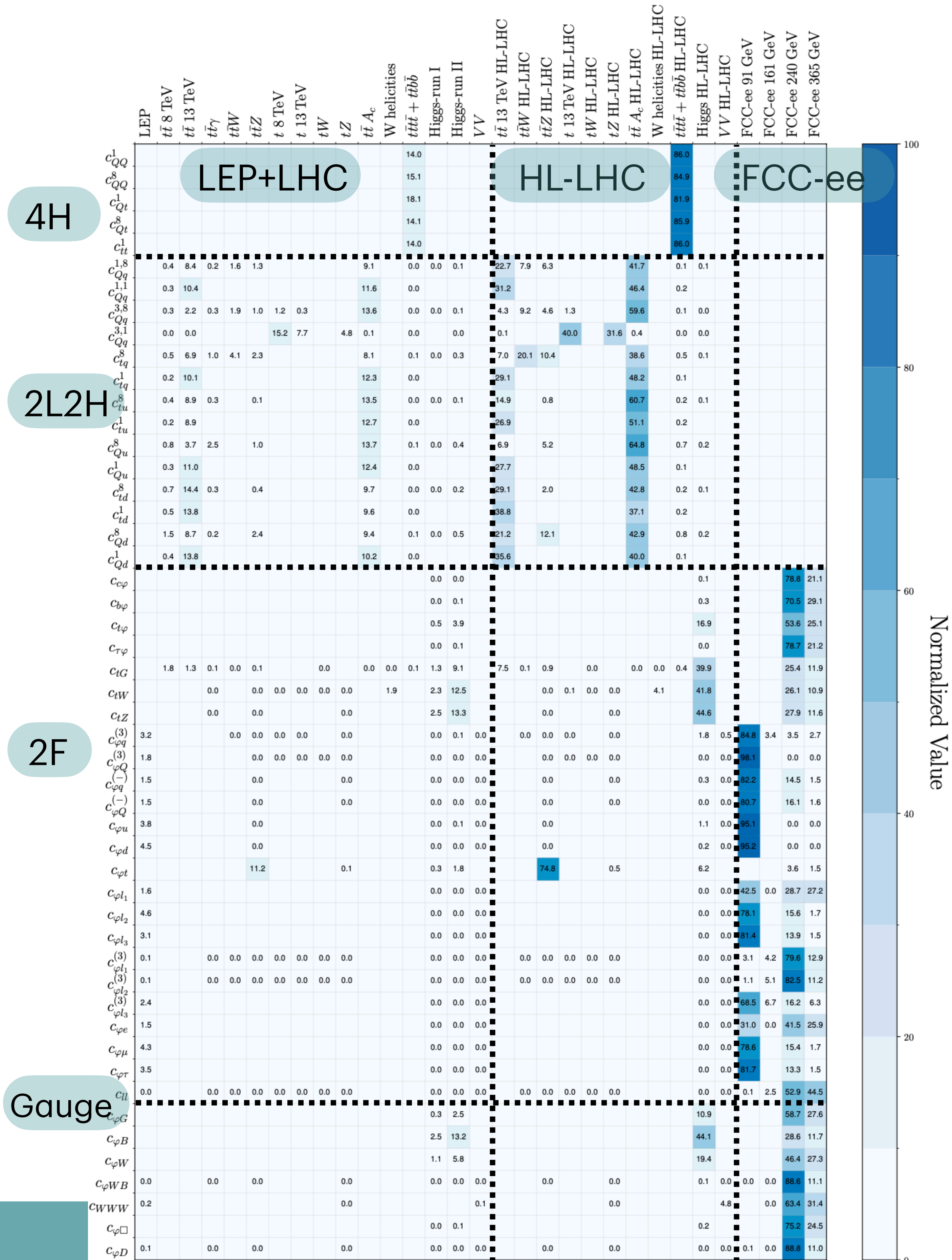
FCC-ee energy runs and CEPC





- Study impact of sequentially adding FCC-ee datasets for different energies
- Significant impact from **combined Z-pole run (91 GeV) + Higgs factory (240 GeV)**
- Very similar results for CEPC

Fisher information study



- Quantifies **which datasets have more sensitivity to given operator**
- Proxy for linear individual fit
- **FCC-ee dominates nearly all operators** except 4-quark operators, only accessible in pp collisions (tree level)
- **Combination of 91 GeV and 240 GeV** runs important to pin down 2-fermion and gauge operators
- FCC-ee run at 161 GeV is the least useful for the SMEFT

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

The future

HiLumi HL-LHC PROJECT

FCC hh ee he

CEPC

Implementation in progress

CLIC

ilc international linear collider

International MUON Collider Collaboration

Conclusions

- SMEFT is a consistent way to look for new interactions
- **Global fits** needed to **combine all the information available in LHC measurements**
- SMEFiT3.0: **biggest global SMEFT analysis to date** with **50 WC and 445 datapoints**
- Demonstrated the **impact of HL-LHC, FCC-ee and CEPC** on global SMEFT parameter space with **huge improvements** predicted
- Extension to other future colliders in progress
- **Public code**, data and theory lhcfitnikhef.github.io/smefit_release/

Conclusions

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Thank you !

Full treatment of EWPOs

- In the SMEFT, Z and W fermionic couplings receive corrections from dim-6 operators.

$$
\begin{aligned}
\delta g_V^{l_i} &= \delta \bar{g}_Z \bar{g}_V^{l_i} + Q^{l_i}\delta s_\theta^2 + \Delta_V^{l_i} = 0\,, \quad i=1,2,3\,,\\
\delta g_A^{l_i} &= \delta \bar{g}_Z \bar{g}_A^{l_i} + \Delta_A^{l_i} = 0\,, \quad i=1,2,3\,,\\
\delta g_V^{u} &= \delta \bar{g}_Z \bar{g}_V^{u} + Q^{u}\delta s_\theta^2 + \Delta_V^{u} = 0\,,\\
\delta g_A^{u} &= \delta \bar{g}_Z \bar{g}_A^{u} + \Delta_A^{u} = 0\,,\\
\delta g_V^{d} &= \delta \bar{g}_Z \bar{g}_V^{d} + Q^{d}\delta s_\theta^2 + \Delta_V^{d} = 0\,,\\
\delta g_A^{d} &= \delta \bar{g}_Z \bar{g}_A^{d} + \Delta_A^{d} = 0\,,\\
\delta g_V^{W,l_i} &= \frac{c_{ll} + 2c_{\varphi\ell_i}^{(3)} - c_{\varphi\ell_1}^{(3)} - c_{\varphi\ell_2}^{(3)}}{4\sqrt{2}G_F} = 0\,, \quad i=1,2,3\,,\\
\delta g_V^{W,q} &= \frac{c_{ll} + c_{\varphi q}^{(3)} - c_{\varphi\ell_1}^{(3)} - c_{\varphi\ell_2}^{(3)}}{4\sqrt{2}G_F} = 0\,,
\end{aligned}
$$

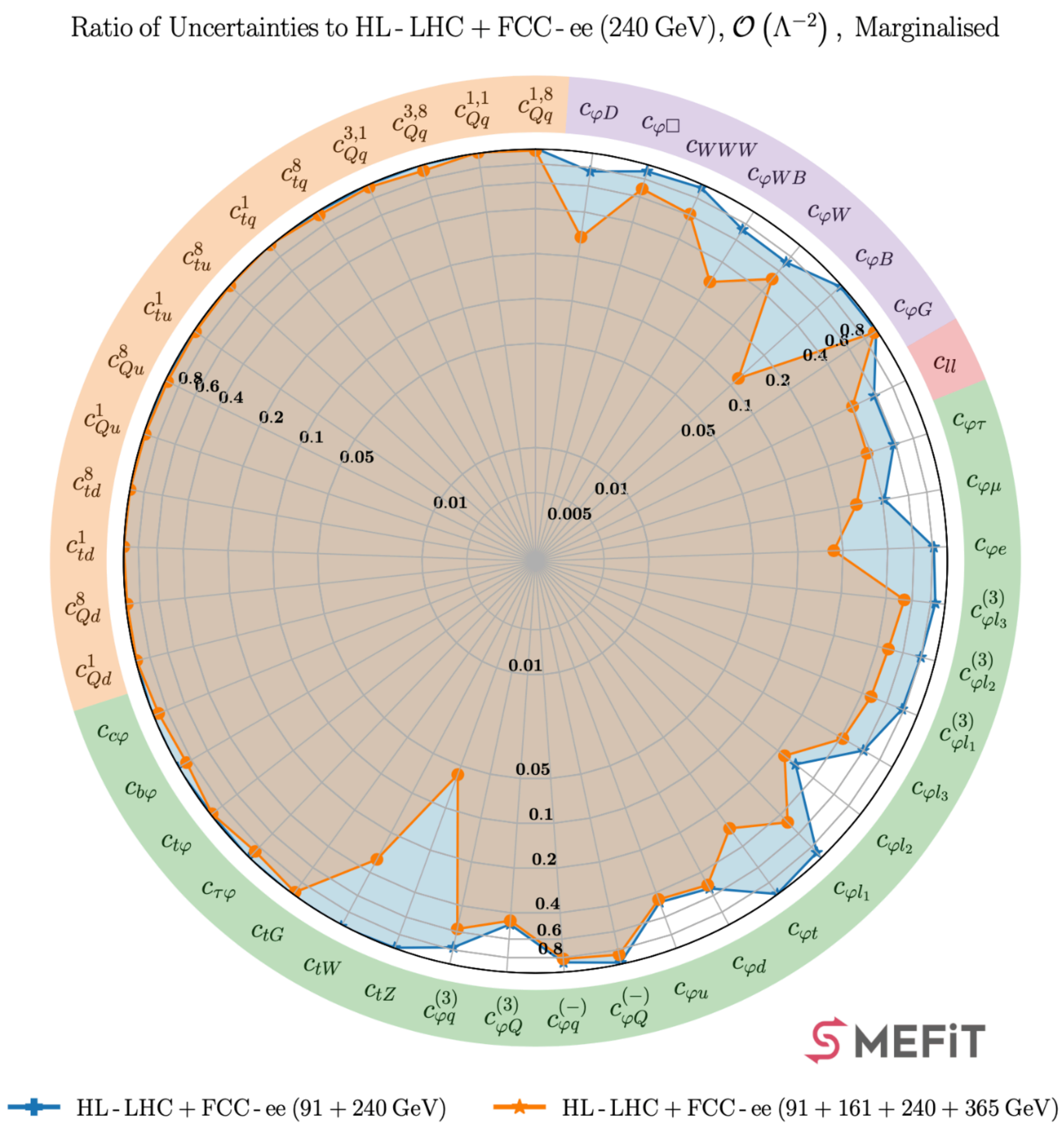
$$
\begin{pmatrix} c_{\varphi\ell_i}^{(3)} \\ c_{\varphi\ell_i}^{(1)} \\ c_{\varphi e/\mu/\tau} \\ c_{\varphi q}^{(-)} \\ c_{\varphi q}^{(3)} \\ c_{\varphi u} \\ c_{\varphi d} \\ c_{\ell\ell} \end{pmatrix}
=
\begin{pmatrix} -\frac{1}{t_W} & -\frac{1}{4t_W^2} \\ 0 & -\frac{1}{4} \\ 0 & -\frac{1}{2} \\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

- **SMEFiT2.0**: assumed LEP/SLD measurements were precise enough to set coupling shifts to zero → **only 2 independent WCs**

- **SMEFiT3.0**: EWPOs implemented like the rest of LHC data → **16 independent WCs**

Input	Observables
Z-pole EWPOs	Γ_Z, $\sigma^0_{\rm had}$, R^0_e, R^0_μ, R^0_τ, $A^{0,e}_{FB}$, $A^{0,\mu}_{FB}$, $A^{0,\tau}_{FB}$ R^0_b, R^0_c, $A^{0,b}_{FB}$, $A^{0,c}_{FB}$, A_b, A_c A_τ $(\mathcal{P}_\tau)$, A_e $(\mathcal{P}_\tau)$ A_e (SLD), A_μ (SLD), A_τ (SLD)
Bhabha scattering	$d\sigma/d\cos\theta$ $(n_{\rm dat}=21)$ $\sqrt{s} = 189, 192, 196, 200, 202, 205, 207$ GeV
$\alpha_{\rm EW}$	$\alpha^{-1}_{\rm EW}(m_Z)$
W branching ratios	${\rm Br}(W\to e\nu_e)$ ${\rm Br}(W\to \mu\nu_\mu)$ ${\rm Br}(W\to \tau\nu_\tau)$

FCC-ee energy runs



FCC-ee and CEPC observables

Z-pole EWPOs ($\sqrt{s} = 91.2$ GeV)		
$\mathcal{O}_i$	$\delta/\Delta\ \mathcal{O}_i$ FCC-ee	CEPC
$\alpha(m_Z)^{-1}\ (\times 10^3)$	$\Delta = 2.7\ (1.2)$	$\Delta = 17.8$
Γ_W (MeV)	$\Delta = 0.85\ (0.3)$	$\Delta = 1.8\ (0.9)$
Γ_Z (MeV)	$\Delta = 0.0028\ (0.025)$	$\Delta = 0.005\ (0.025)$
$A_e\ (\times 10^5)$	$\Delta = 0.5\ (2)$	$\Delta = 1.5$
$A_\mu\ (\times 10^5)$	$\Delta = 1.6\ (2.2)$	$\Delta = 3.0\ (1.8)$
$A_\tau\ (\times 10^5)$	$\Delta = 0.35\ (20)$	$\Delta = 1.2\ (6.9)$
$A_b\ (\times 10^5)$	$\Delta = 1.7\ (21)$	$\Delta = 3\ (21)$
$A_c\ (\times 10^5)$	$\Delta = 14\ (15)$	$\Delta = 6\ (30)$
σ^0_{had} (pb)	$\Delta = 0.025\ (4)$	$\Delta = 0.05\ (2)$
$R_e\ (\times 10^3)$	$\delta = 0.0028\ (0.3)$	$\delta = 0.003\ (0.2)$
$R_\mu\ (\times 10^3)$	$\delta = 0.0021\ (0.05)$	$\delta = 0.003\ (0.1)$
$R_\tau\ (\times 10^3)$	$\delta = 0.0021\ (0.1)$	$\delta = 0.003\ (0.1)$
$R_b\ (\times 10^3)$	$\delta = 0.001\ (0.3)$	$\delta = 0.005\ (0.2)$
$R_c\ (\times 10^3)$	$\delta = 0.011\ (1.5)$	$\delta = 0.02\ (1)$

$e^+e^- \to f\bar{f}$				
	$\sqrt{s} = 240$ GeV		$\sqrt{s} = 365$ GeV	
$\mathcal{O}_i$	$\Delta_{\text{exp}}\mathcal{O}_i$ (FCC-ee)	$\Delta_{\text{exp}}\mathcal{O}_i$ (CEPC)	$\Delta_{\text{exp}}\mathcal{O}_i$ (FCC-ee)	$\Delta_{\text{exp}}\mathcal{O}_i$ (CEPC)
$\sigma_{\text{tot}}(e^+e^-)$ [fb]	2.29	1.62	2.74	4.68
$A_{\text{FB}}(e^+e^-)$	$9.79 \cdot 10^{-6}$	$6.92 \cdot 10^{-6}$	$2.83 \cdot 10^{-5}$	$4.83 \cdot 10^{-5}$
$\sigma_{\text{tot}}(\mu^+\mu^-)$ [fb]	0.405	0.287	0.48	0.82
$A_{\text{FB}}(\mu^+\mu^-)$	$1.98 \cdot 10^{-4}$	$1.397 \cdot 10^{-4}$	$5.69 \cdot 10^{-4}$	$9.7 \cdot 10^{-4}$
$\sigma_{\text{tot}}(\tau^+\tau^-)$ [fb]	0.374	0.264	0.443	0.756
$A_{\text{FB}}(\tau^+\tau^-)$	$2.17 \cdot 10^{-4}$	$1.53 \cdot 10^{-4}$	$6.24 \cdot 10^{-4}$	0.00106
$\sigma_{\text{tot}}(c\bar{c})$ [fb]	0.088	0.062	0.102	0.175
$A_{\text{FB}}(c\bar{c})$	0.000813	$5.74 \cdot 10^{-4}$	0.00238	0.00405
$\sigma_{\text{tot}}(b\bar{b})$ [fb]	0.151	0.107	0.171	0.29
$A_{\text{FB}}(b\bar{b})$	$4.86 \cdot 10^{-4}$	$3.44 \cdot 10^{-4}$	0.00142	0.00243

$e^+e^- \to W^+W^-$						
$\mathcal{O}_i$	$\sqrt{s} = 161$ GeV		$\sqrt{s} = 240$ GeV		$\sqrt{s} = 365$ GeV	
	δ_{exp} (FCC-ee)	δ_{exp} (CEPC)	δ_{exp} (FCC-ee)	δ_{exp} (CEPC)	δ_{exp} (FCC-ee)	δ_{exp} (CEPC)
σ_{WW}	$1.36 \cdot 10^{-4}$	$2.48 \cdot 10^{-4}$	$1.22 \cdot 10^{-4}$	$8.63 \cdot 10^{-5}$	$2.81 \cdot 10^{-4}$	$4.87 \cdot 10^{-4}$
$\text{BR}_{W\to\ell_i\nu_i}$	$2.72 \cdot 10^{-4}$	$4.95 \cdot 10^{-4}$	$2.44 \cdot 10^{-4}$	$1.73 \cdot 10^{-4}$	$5.63 \cdot 10^{-4}$	$9.75 \cdot 10^{-4}$

Satistical (systematic) uncertainty in absolute unit (Δ) or relative to the central value (δ)

FCC-ee and CEPC observables

$e^+e^- \to Zh$				
	$\sqrt{s} = 240$ GeV		$\sqrt{s} = 365$ GeV	
$\mathcal{O}_i$	$\delta_{\rm exp}\mathcal{O}_i$ (FCC-ee)	$\delta_{\rm exp}\mathcal{O}_i$ (CEPC)	$\delta_{\rm exp}\mathcal{O}_i$ (FCC-ee)	$\delta_{\rm exp}\mathcal{O}_i$ (CEPC)
σ_{Zh}	0.0035	0.0026	0.0064	0.014
$\sigma_{Zh} \times {\rm BR}_{b\bar{b}}$	0.0021	0.0014	0.0035	0.009
$\sigma_{Zh} \times {\rm BR}_{c\bar{c}}$	0.0156	0.0202	0.046	0.088
$\sigma_{Zh} \times {\rm BR}_{gg}$	0.0134	0.0081	0.0247	0.034
$\sigma_{Zh} \times {\rm BR}_{ZZ}$	0.0311	0.0417	0.0849	0.2
$\sigma_{Zh} \times {\rm BR}_{WW}$	0.0085	0.0053	0.0184	0.028
$\sigma_{Zh} \times {\rm BR}_{\tau^+\tau^-}$	0.0064	0.0042	0.0127	0.021
$\sigma_{Zh} \times {\rm BR}_{\gamma\gamma}$	0.0636	0.0302	0.127	0.11
$\sigma_{Zh} \times {\rm BR}_{\gamma Z}$	0.12	0.085	-	-

$e^+e^- \to h\nu\nu$				
	$\sqrt{s} = 240$ GeV		$\sqrt{s} = 365$ GeV	
$\mathcal{O}_i$	$\delta_{\rm exp}\mathcal{O}_i$ (FCC-ee)	$\delta_{\rm exp}\mathcal{O}_i$ (CEPC)	$\delta_{\rm exp}\mathcal{O}_i$ (FCC-ee)	$\delta_{\rm exp}\mathcal{O}_i$ (CEPC)
$\sigma_{h\nu\nu} \times {\rm BR}_{b\bar{b}}$	0.0219	0.0159	0.0064	0.011
$\sigma_{h\nu\nu} \times {\rm BR}_{c\bar{c}}$	-	-	0.0707	0.16
$\sigma_{h\nu\nu} \times {\rm BR}_{gg}$	-	-	0.0318	0.045
$\sigma_{h\nu\nu} \times {\rm BR}_{ZZ}$	-	-	0.0707	0.21
$\sigma_{h\nu\nu} \times {\rm BR}_{WW}$	-	-	0.0255	0.044
$\sigma_{h\nu\nu} \times {\rm BR}_{\tau^+\tau^-}$	-	-	0.0566	0.042
$\sigma_{h\nu\nu} \times {\rm BR}_{\gamma\gamma}$	-	-	0.156	0.16

Satistical (systematic) uncertainty in absolute unit (Δ) or relative to the central value (δ)