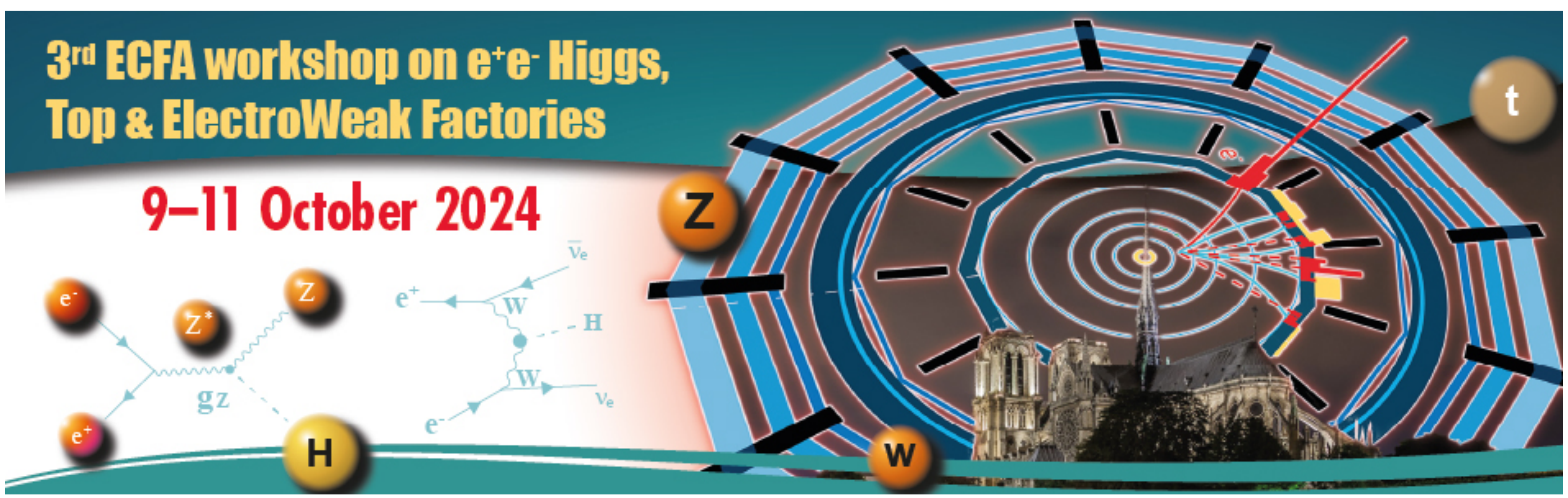
Updates from the SMEFiT collaboration

towards the next ESPPU

Based on JHEP 09 (2024) 091
with E. Celada, T. Giani, L. Mantani, J. Rojo, A. N. Rossia, M. Thomas, E. Vryonidou



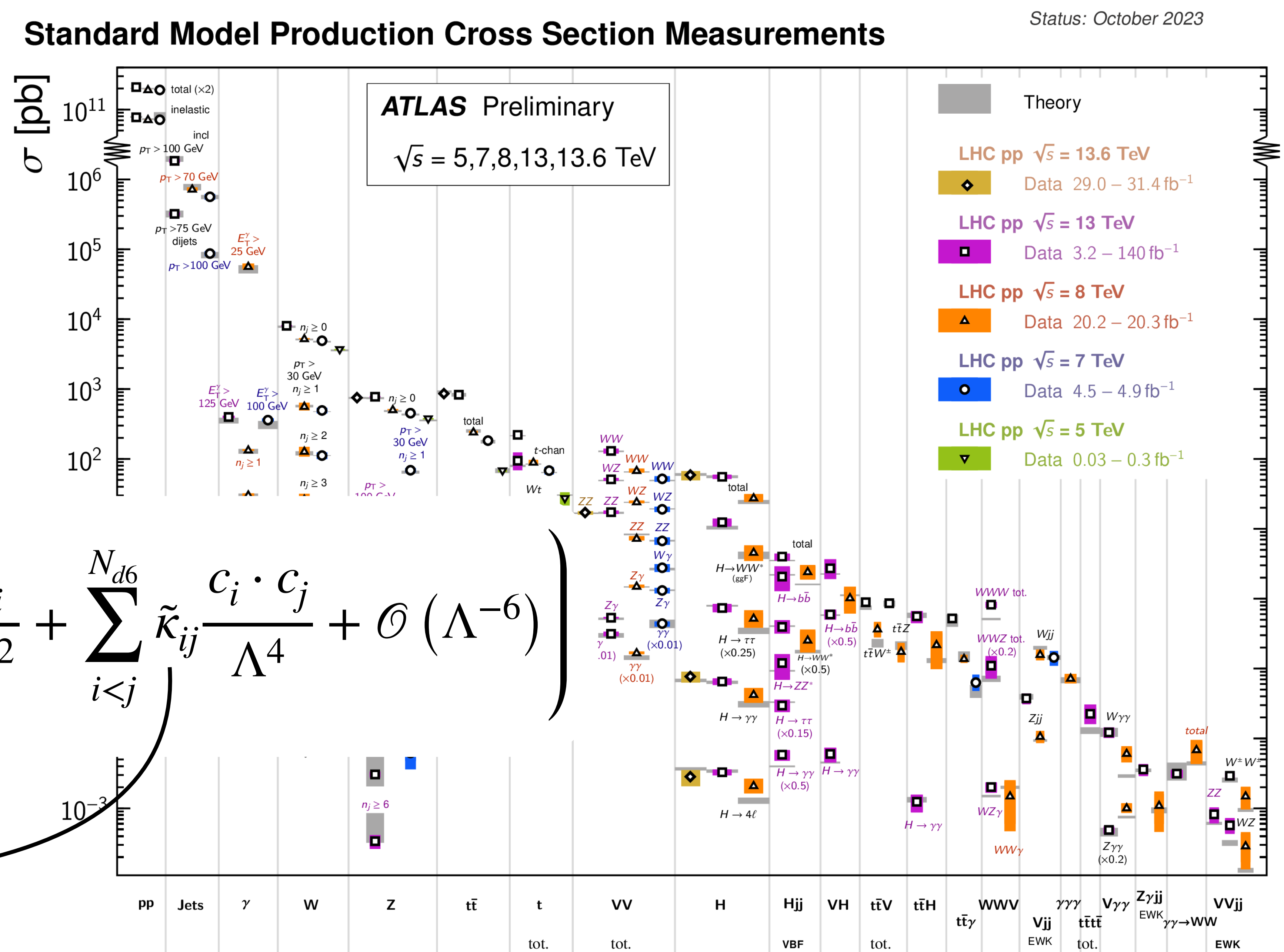
Jaco ter Hoeve
09/10/24

The high energy landscape

Lots of impressive cross-section measurements, but no clear deviation from the SM (yet) …

… so we study their overall pattern!

[ATL-PHYS-PUB-2023-039]



Linear EFT corrections:
interference SM-EFTd6
@NLO QCD

$$\sigma(c,\Lambda) = \sigma_{\rm SM} \times \left(1 + \sum_{i}^{N_{d6}} \kappa_i \frac{c_i}{\Lambda^2} + \sum_{i<j}^{N_{d6}} \tilde{\kappa}_{ij} \frac{c_i \cdot c_j}{\Lambda^4} + \mathcal{O}\left(\Lambda^{-6}\right) \right)$$

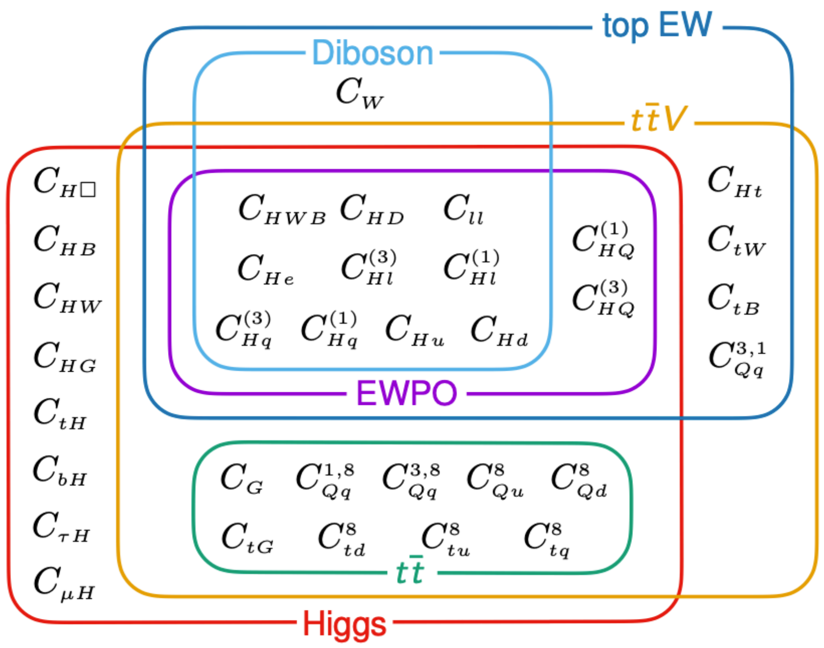
Quadratic EFT
corrections:
EFTd6-EFTd6
@NLO QCD

Why global SMEFT fits?

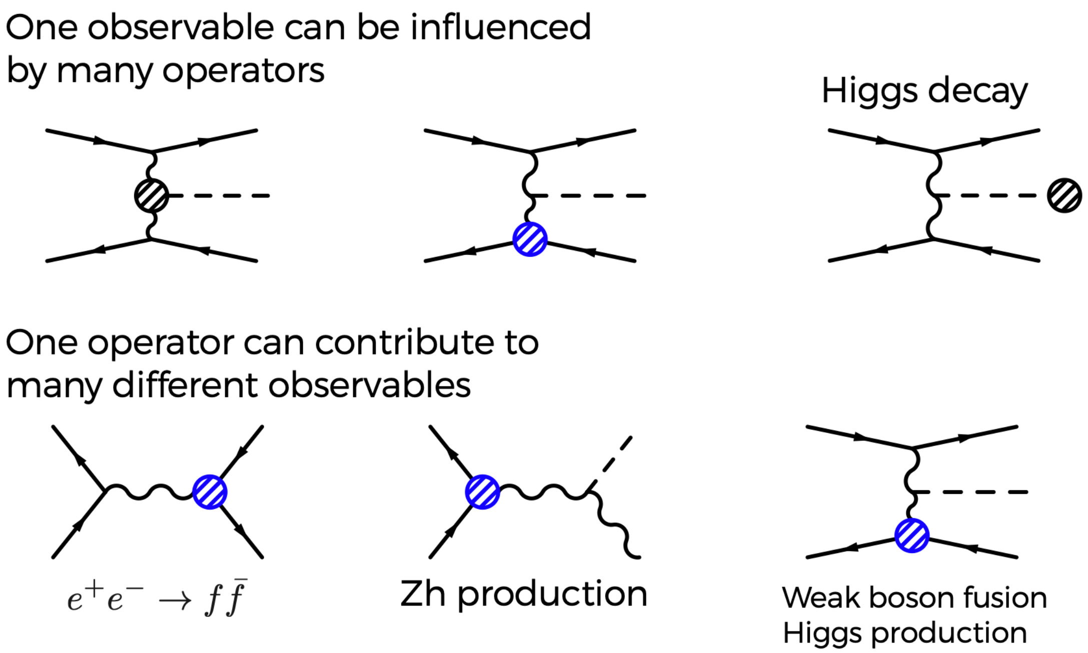
- The SMEFT is our **universal** tool to search for BSM physics above the EW scale, with **minimal assumptions** on what it may look like

- Given the **cross-talk** between Higgs, top, diboson and EWPO (and flavour and low energy observables), a simultaneous fit is our only way forward

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



[2012.02779] Fitmaker collaboration



Anke Biekötter - HET seminar Brookhaven

The SMEFiT3.0 framework

E. Celada, T. Giani, L. Mantani, J. Rojo, A. Rossia, M. Thomas, E. Vryonidou , JtH

JHEP 09 (2024) 091 [2404.12809]

The SMEFiT timeline

SMEFiT 1.0
1901.05965

SMEFiT VBS
2101.03180

SMEFiT 2.0
2105.00006

SMEFiT code paper
2302.06660

2023: SMEFiT UV
2309.04523

SMEFiT 3.0 + Future colliders
2404.12809

2019 2021 2023 2024


SMEFiT

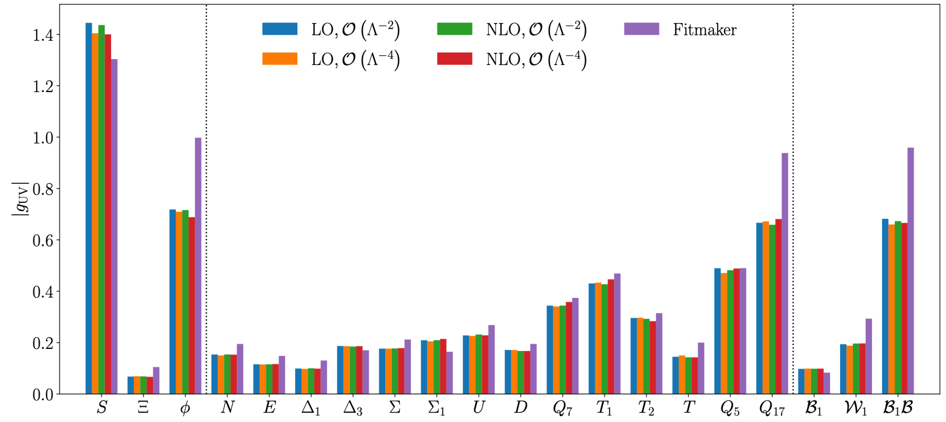
OUTP-20-05P
Nikhef-2020-020
CP3-21-12
MCNET-21-07
MAN/HEP/2021/004

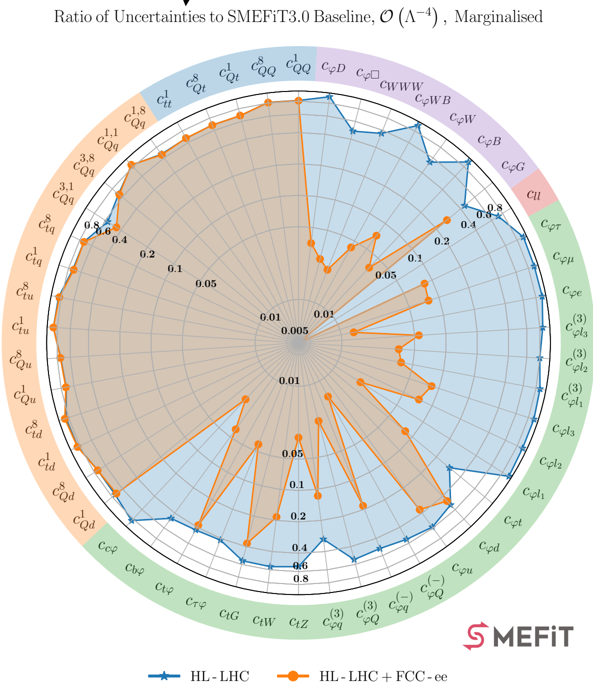
Combined SMEFT interpretation of Higgs, diboson, and top quark data from the LHC

The SMEFiT Collaboration:

arXiv:2105.00006v3 [hep-ph] 31 Oct 2021

Abstract





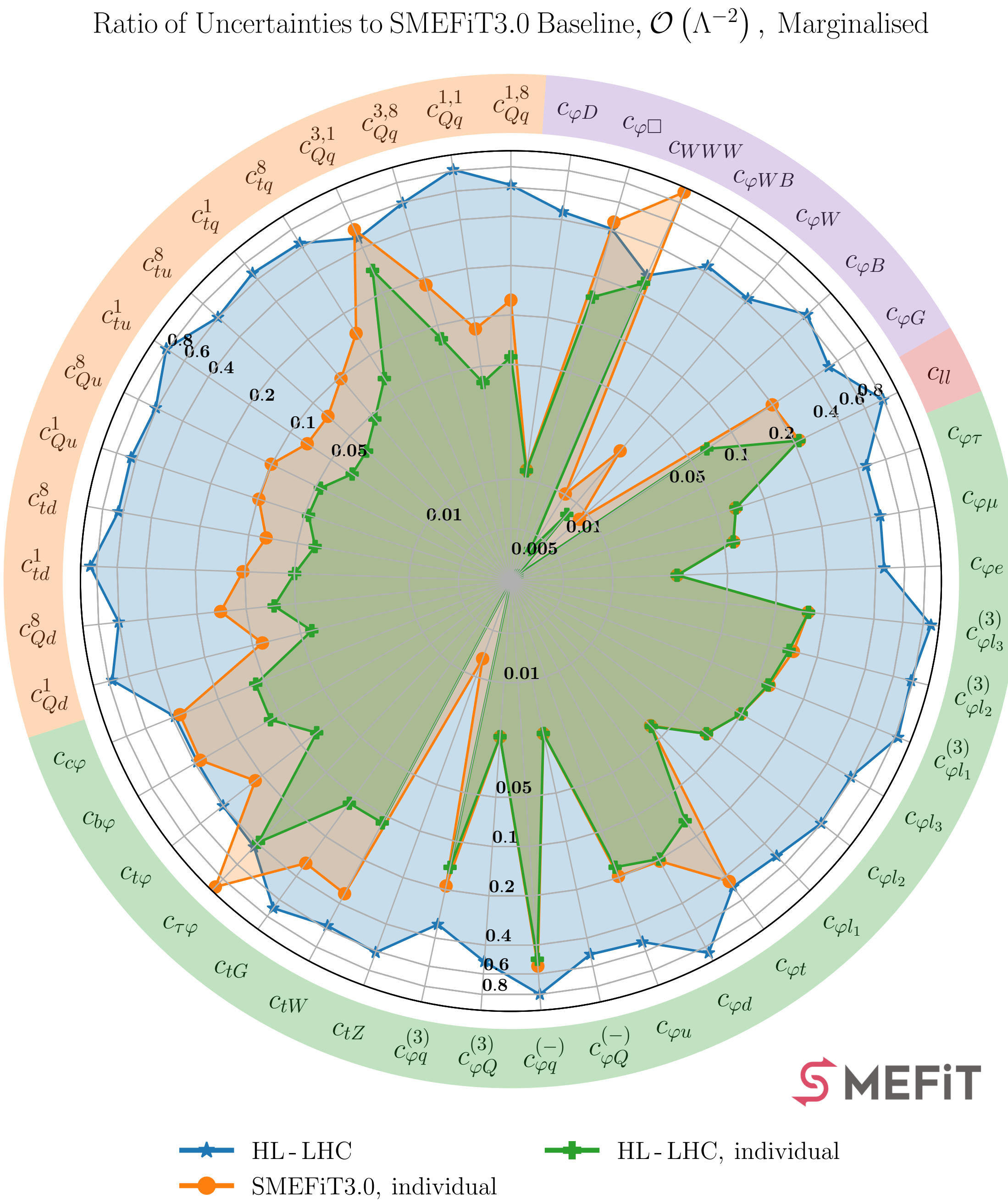
SMEFiT RGE at Future colliders
24xx.xxxx

SMEFiT NP injection 25xx.xxxx

SMEFiT3.0 in a nutshell

- ✔ SMEFiT2.0 extended with recent datasets in **top, diboson and Higgs production** based on the full Run II luminosity
- ✔ Full **independent treatment of the EWPOs** from LEP and SLD
- ✔ Dedicated **projection module** to extrapolate Run II data to HL-LHC
- ✔ **FCC-ee and CEPC pseudodata** from Snowmass predictions, updated to 4 IPs as per the FCC feasibility midterm report [2206.08326], CERN/3789/RA
- ✔ Both results in terms of Wilson coefficients and **UV-complete models**
- ✔ **Public code, data and theory**: results are fully reproducible

lhcfitnikhef.github.io/smefit_release



"Spider plots / Antarctica plots"

SMEFiT under the hood

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

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

NNPDF4.0 no top

Data
447 measurements from **Higgs, top, diboson** and **EWPO**

Full experimental **correlations**

Projections
HL-LHC, FCC-ee, CEPC, ...

+ Automatic projection module

[2309.04523]

UV models

SMEFiT

External likelihoods

Methodology
Linear: **Analytical solution** (fast!)
Quadratic: **Nested Sampling**

Output
Automatised fit reports that include
Posterior distributions, PCA, Fisher info, closure tests,..

Full treatment of EWPOs

- In the SMEFT, the SM 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 measurements at LEP were precise enough to set the coupling shifts to zero: 14 constraints, 16 d.o.f

- **SMEFiT3.0:** hardwired constraints get no longer imposed, EWPOs are treated on the same footing as (existing) LHC data: 14 **extra** d.o.f

Full treatment of EWPOs

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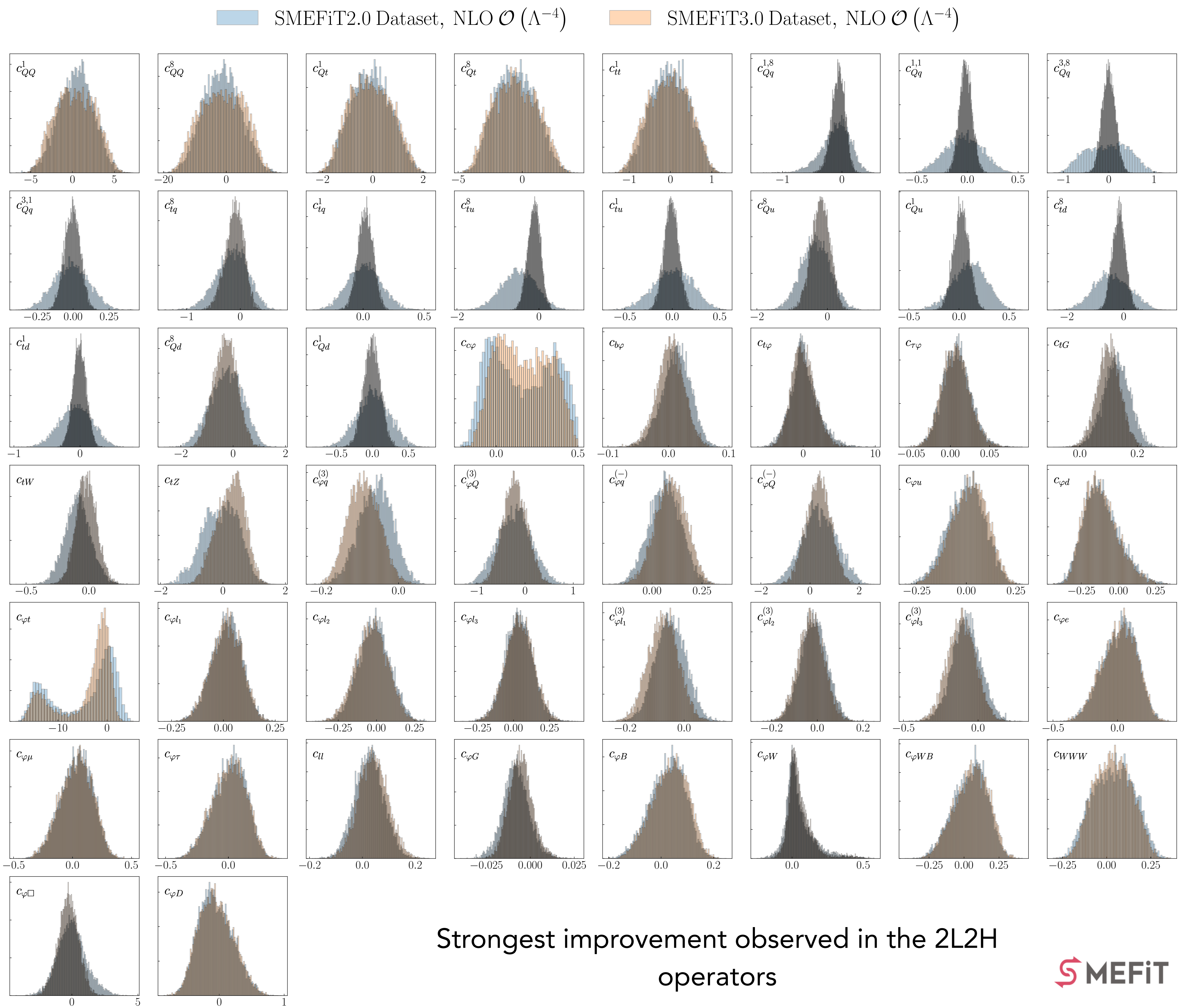
SMEFiT3.0 is simultaneously sensitive to **45 (50) Wilson coefficients** at the linear (quadratic) level!

Dataset upgrade

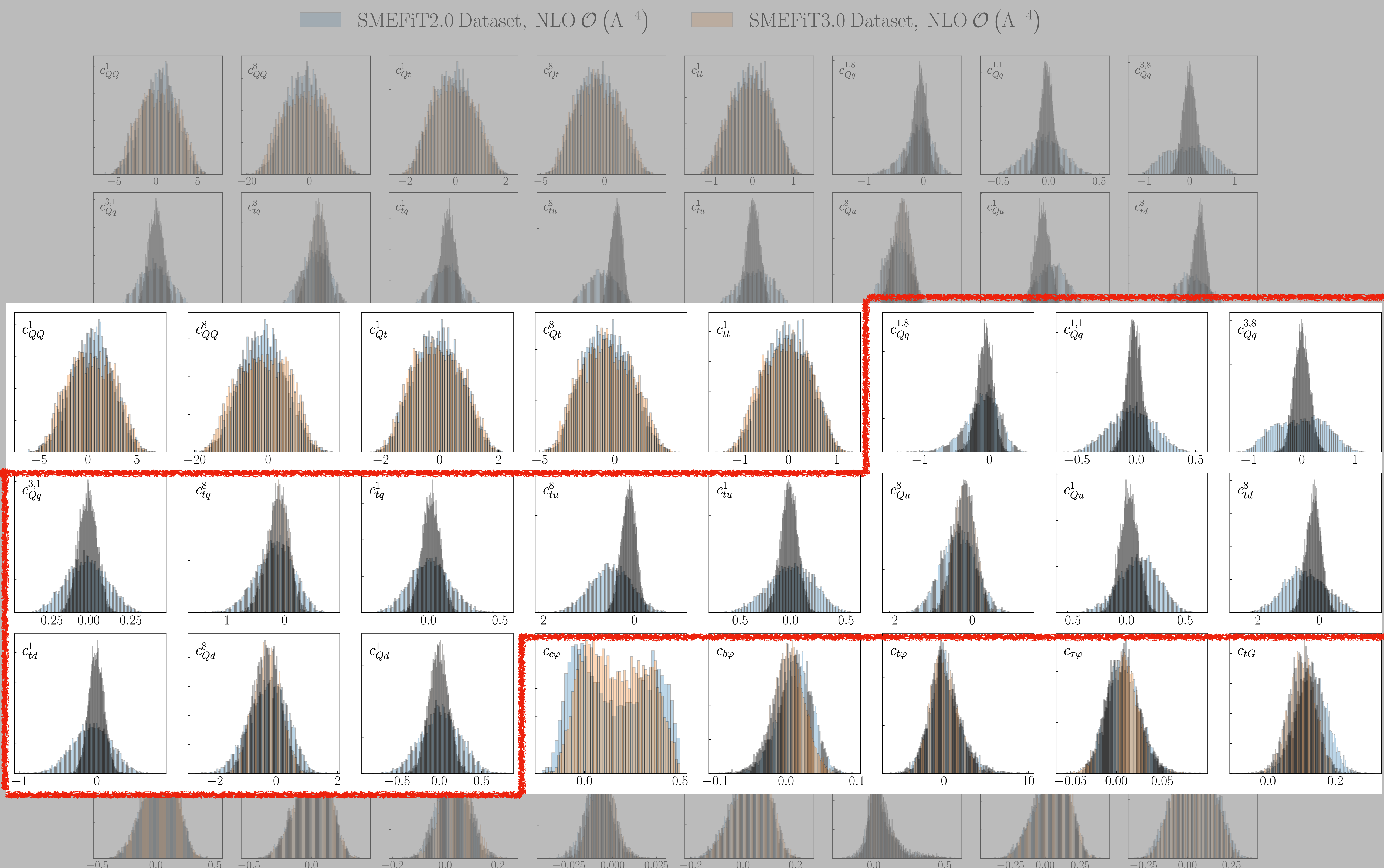
We extended SMEFiT2.0 with recent Run II datasets from top, diboson and Higgs production

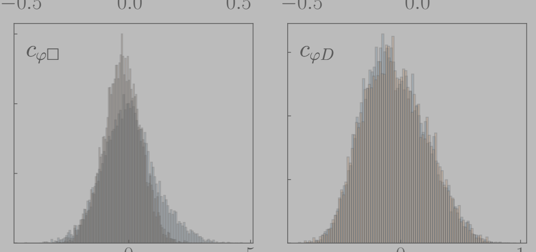
Category	Processes	$n_{\rm dat}$ SMEFiT2.0 [2105.00006]	$n_{\rm dat}$ SMEFiT3.0
Top quark production	$t\bar{t}+X$	94	115
	$t\bar{t}Z$, $t\bar{t}W$	14	21
	$t\bar{t}\gamma$	-	2
	single top (inclusive)	27	28
	tZ, tW	9	13
	$t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$	6	12
	Total	**150**	**189**
Higgs production and decay	Run I signal strengths	22	22
	Run II signal strengths	40	40
	Run II, differential distributions & STXS	35	71
	Total	**97**	**133**
Diboson production	LEP-2	40	40
	LHC	30	41
	Total	**70**	**81**
Z-pole EWPOs	LEP-2	-	44
Baseline dataset	**Total**	**317**	**449**

Flavour assumption: $U(2)_q \times U(3)_d \times U(2)_u \times \left(U(1)_\ell \times U(1)_e\right)^3$



Strongest improvement observed in the 2L2H operators





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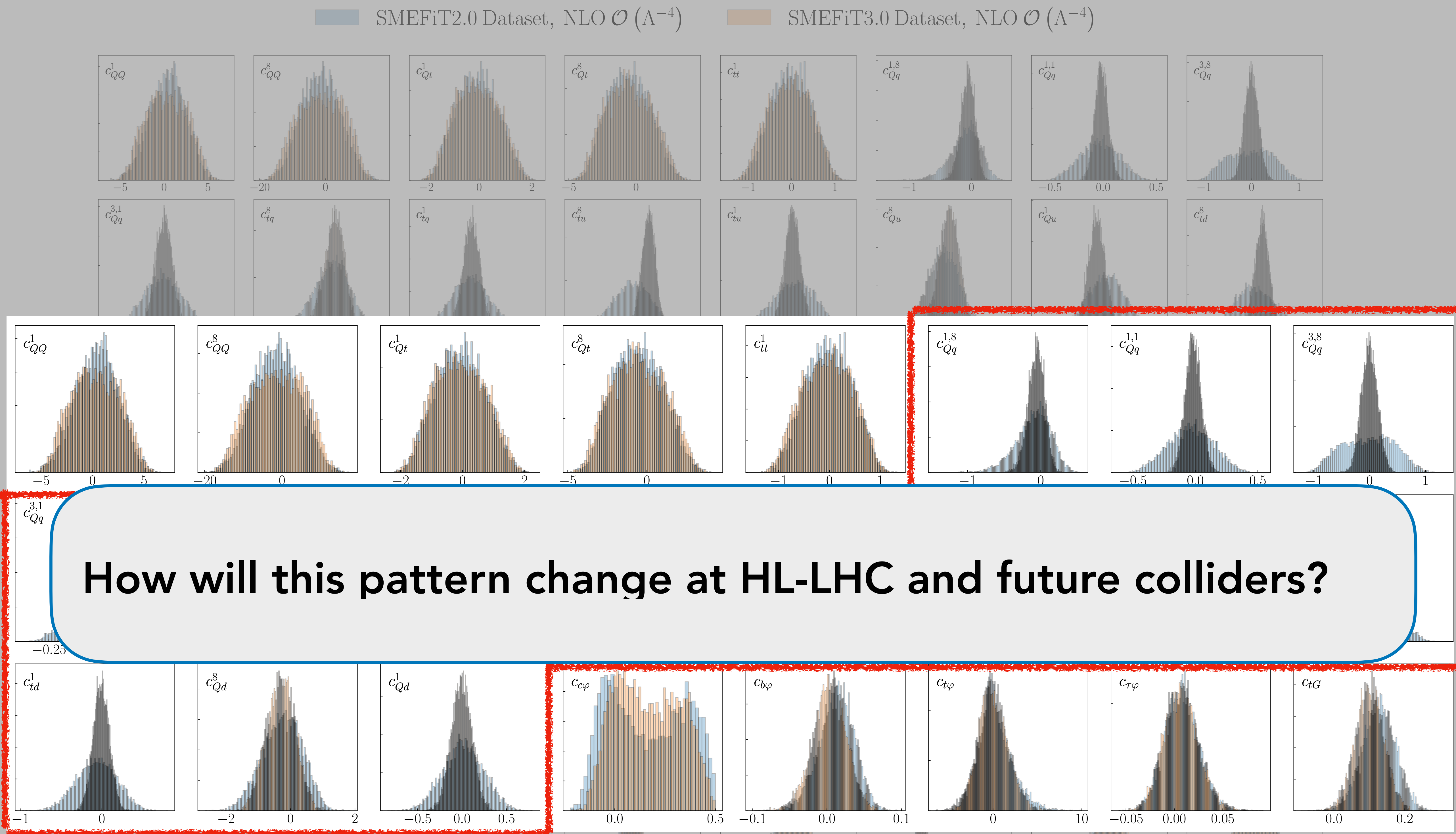
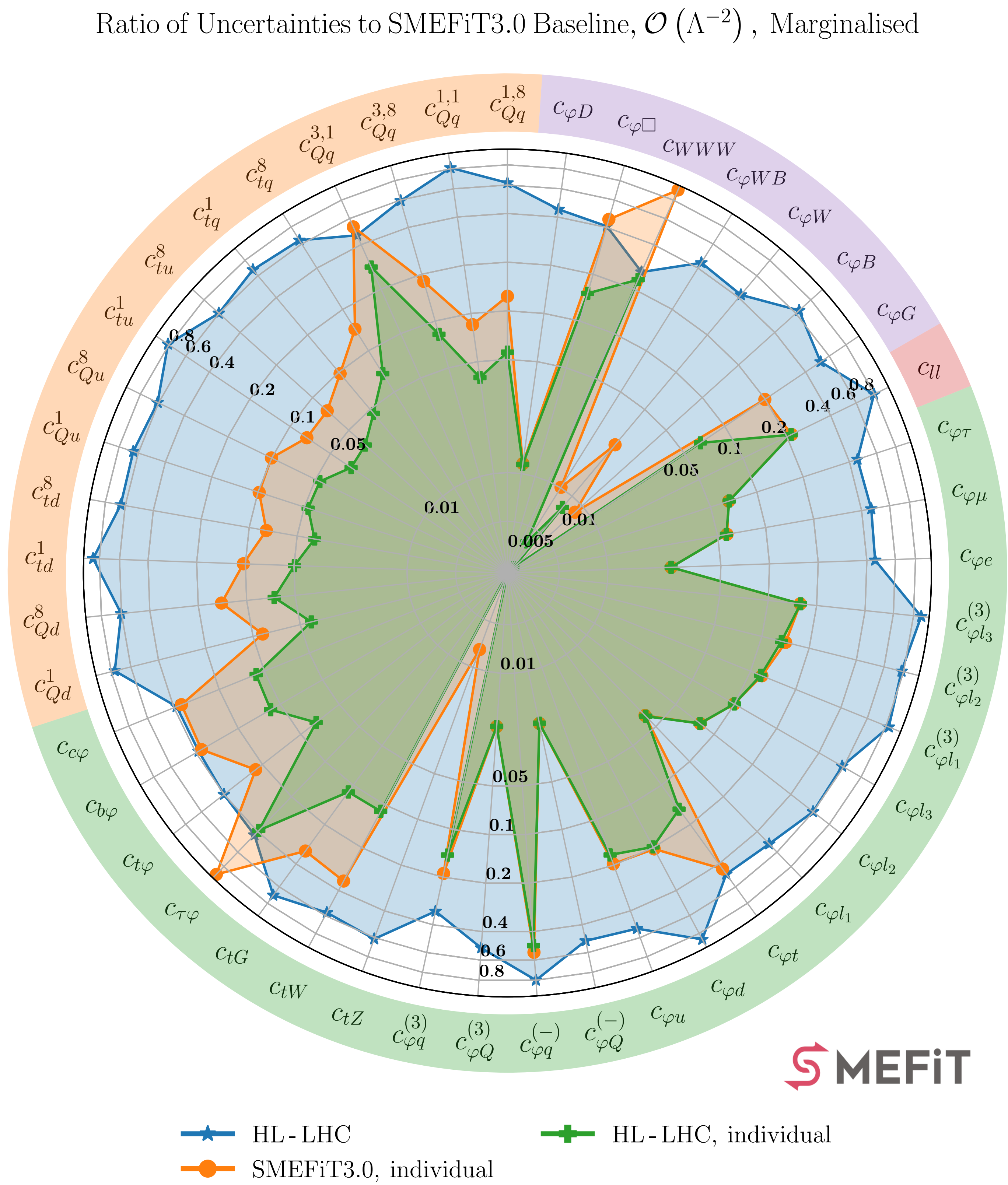


How will this pattern change at HL-LHC and future colliders?

Strongest improvement observed in the 2L2H operators

Result: HL-LHC

- We project all RunII datasets from the SMEFiT 3.0 baseline: one for each process and final state see backup for details
- We see an improvement ranging from 20 to 70 % in the marginalised fit
- The EW operators only improve in the marginalised fit because of correlations

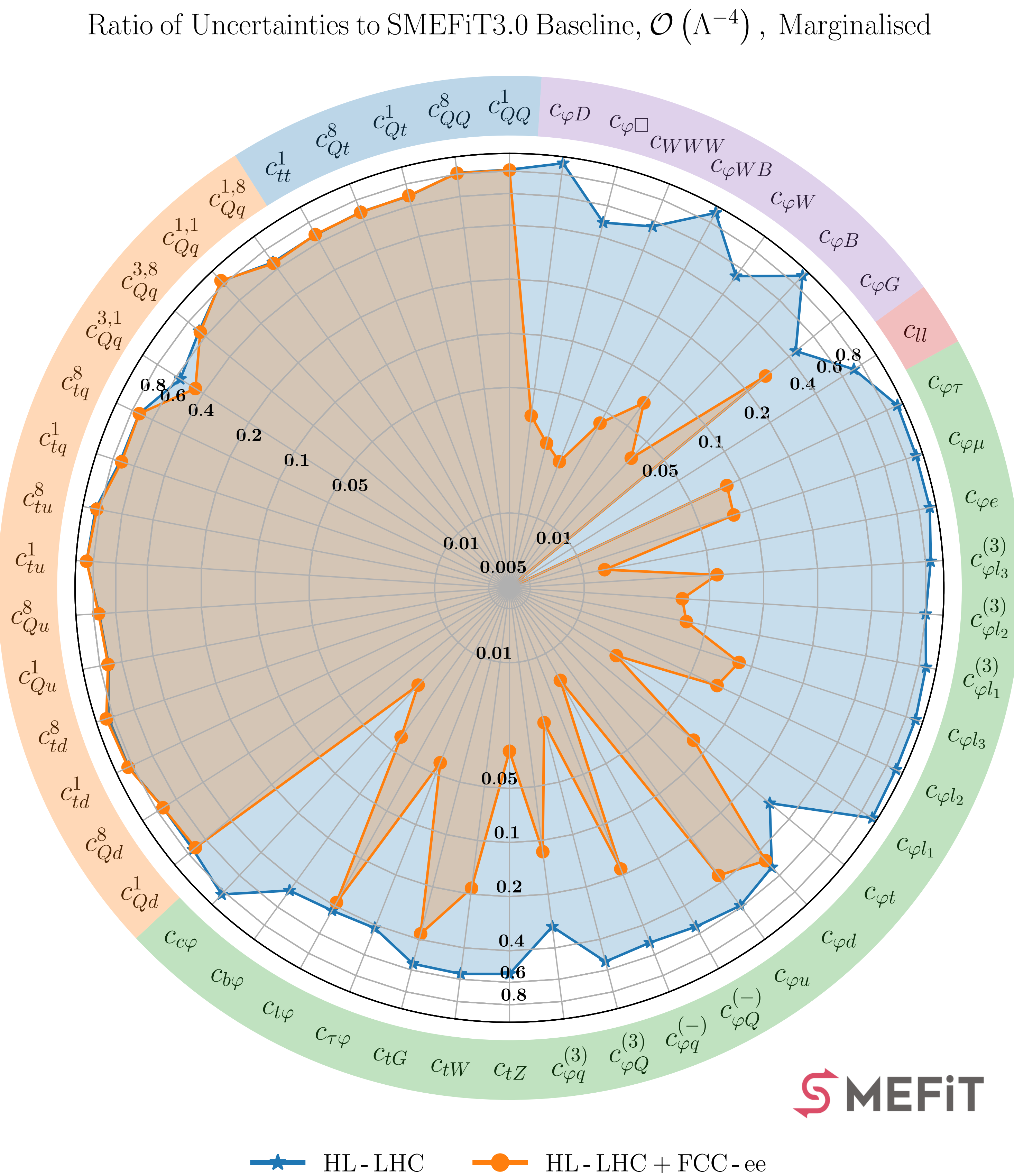


Result: FCC-ee

Dataset input

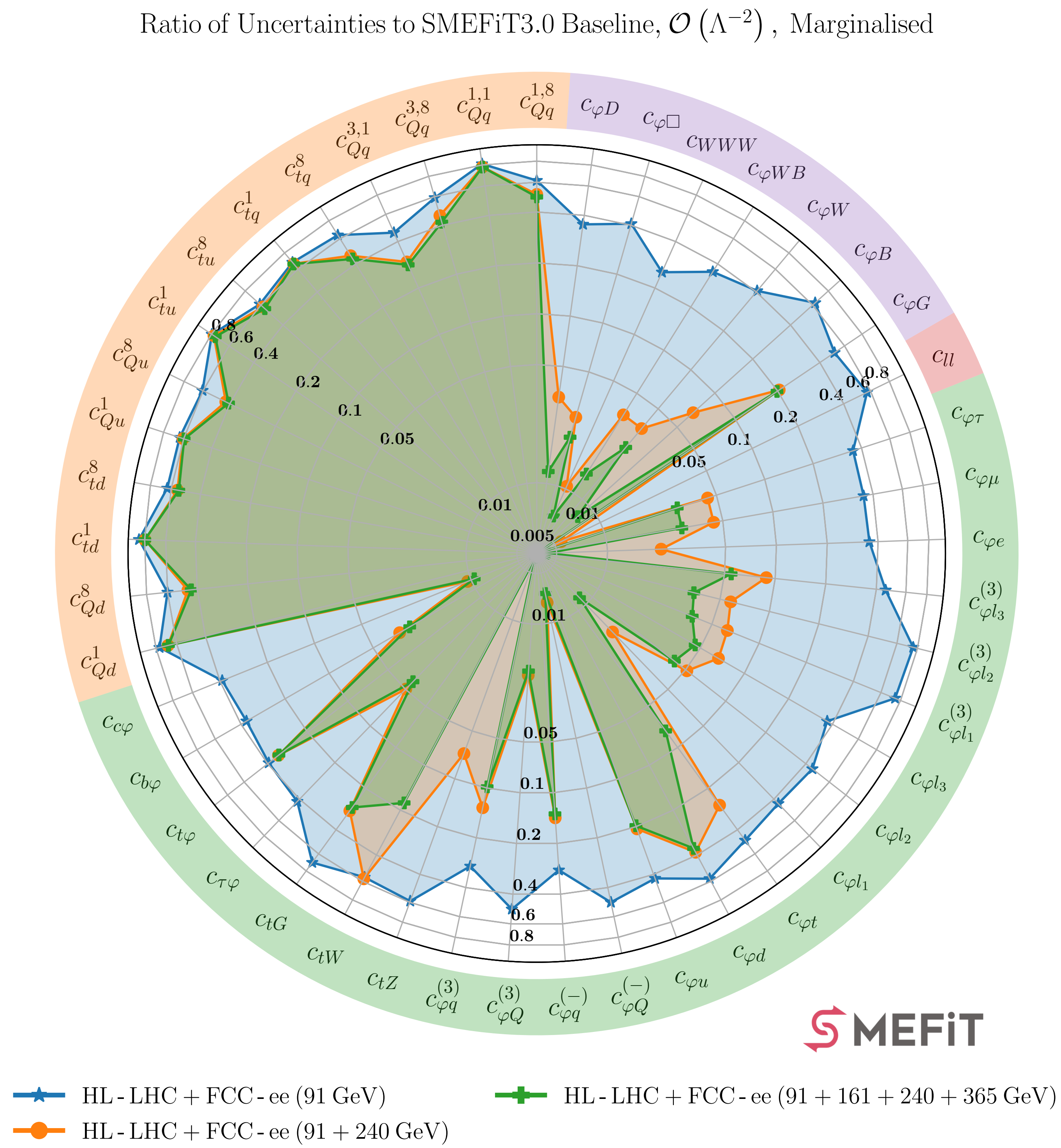
- EWPOs at the Z-pole
- Light fermion pair prediction
- Higgstrahlung and VBF
- Gauge boson pair production
- Top-quark pair production
- Optimal Observables

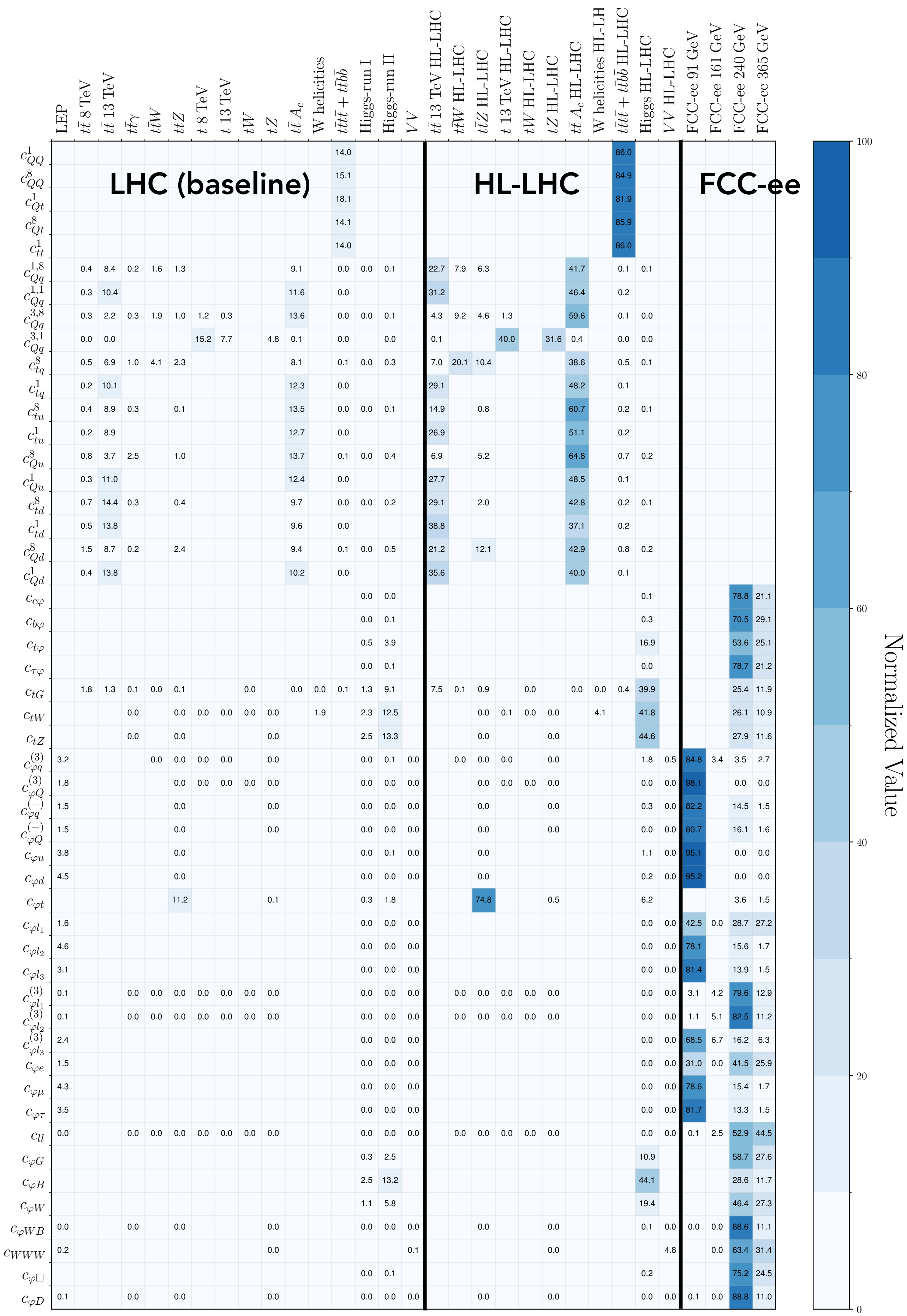
Energy ($\sqrt{s}$)	$\mathcal{L}_{\text{int}}$ (Run time)	
	FCC-ee	CEPC
91 GeV (Z-pole)	300 ab^{-1} (4 years)	100 ab^{-1} (2 years)
161 GeV ($2\,m_W$)	20 ab^{-1} (2 years)	6 ab^{-1} (1 year)
240 GeV	10 ab^{-1} (3 years)	20 ab^{-1} (10 years)
350 GeV	0.4 ab^{-1} (1 years)	-
365 GeV ($2\,m_t$)	3 ab^{-1}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



Result: FCC-ee energy breakdown

- The FCC-ee plans to operate **sequentially**, hence we need to study the impact at the various energies
- Largest impact for Z-pole at 91 GeV plus the Higgs factory run at 240 GeV
- We can try other combinations too in order to find the most optimal run order for the SMEFT.





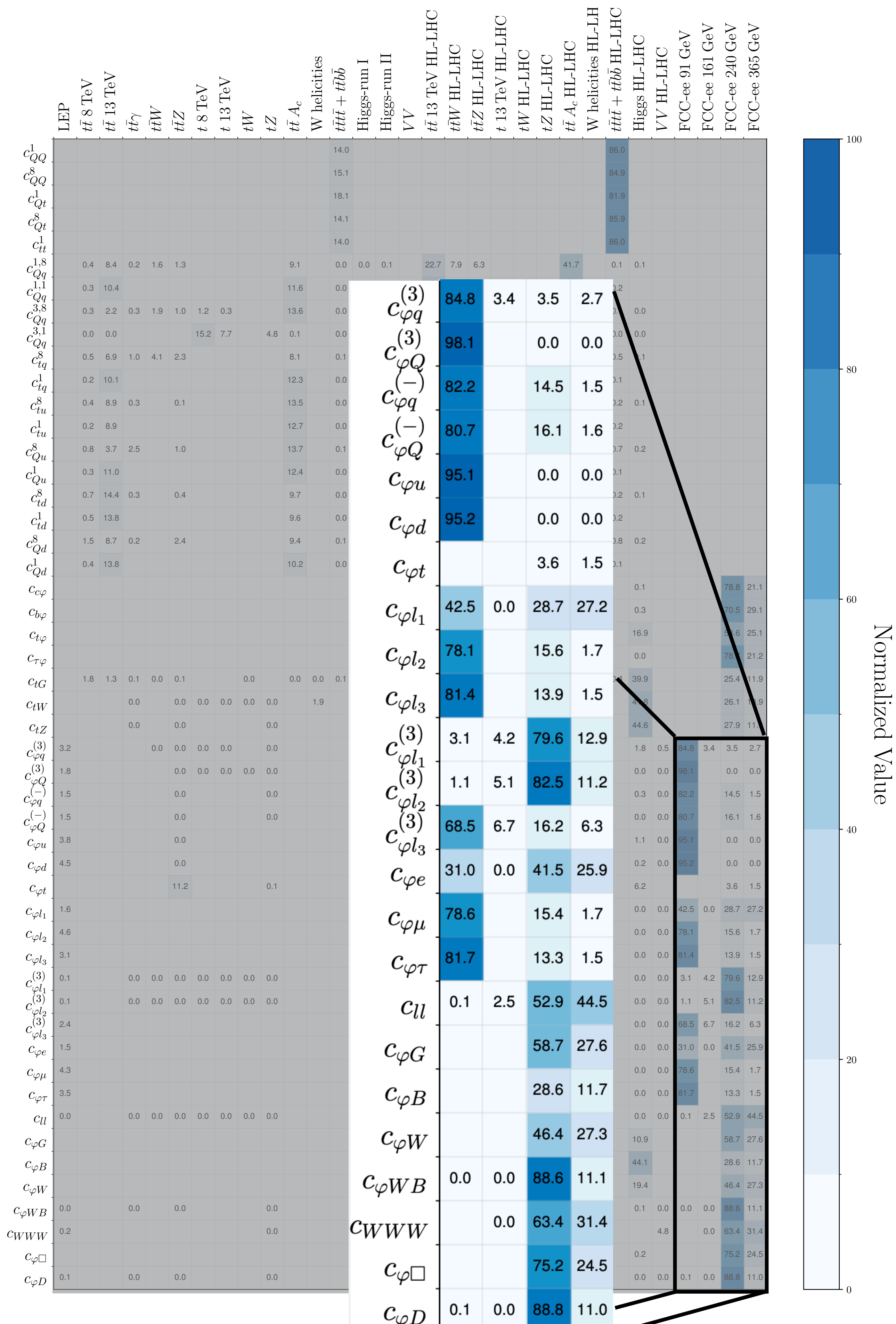
Fisher information matrix

- The sensitivity of the EFT parameters to the Run II, HL-LHC and FCC-ee datasets is quantified by the **fisher information**

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

- The highest sensitivity in the 2FB and bosonic sectors comes in via the FCC-ee

- The FCC-ee run at 161 GeV is the least sensitive for the SMEFT



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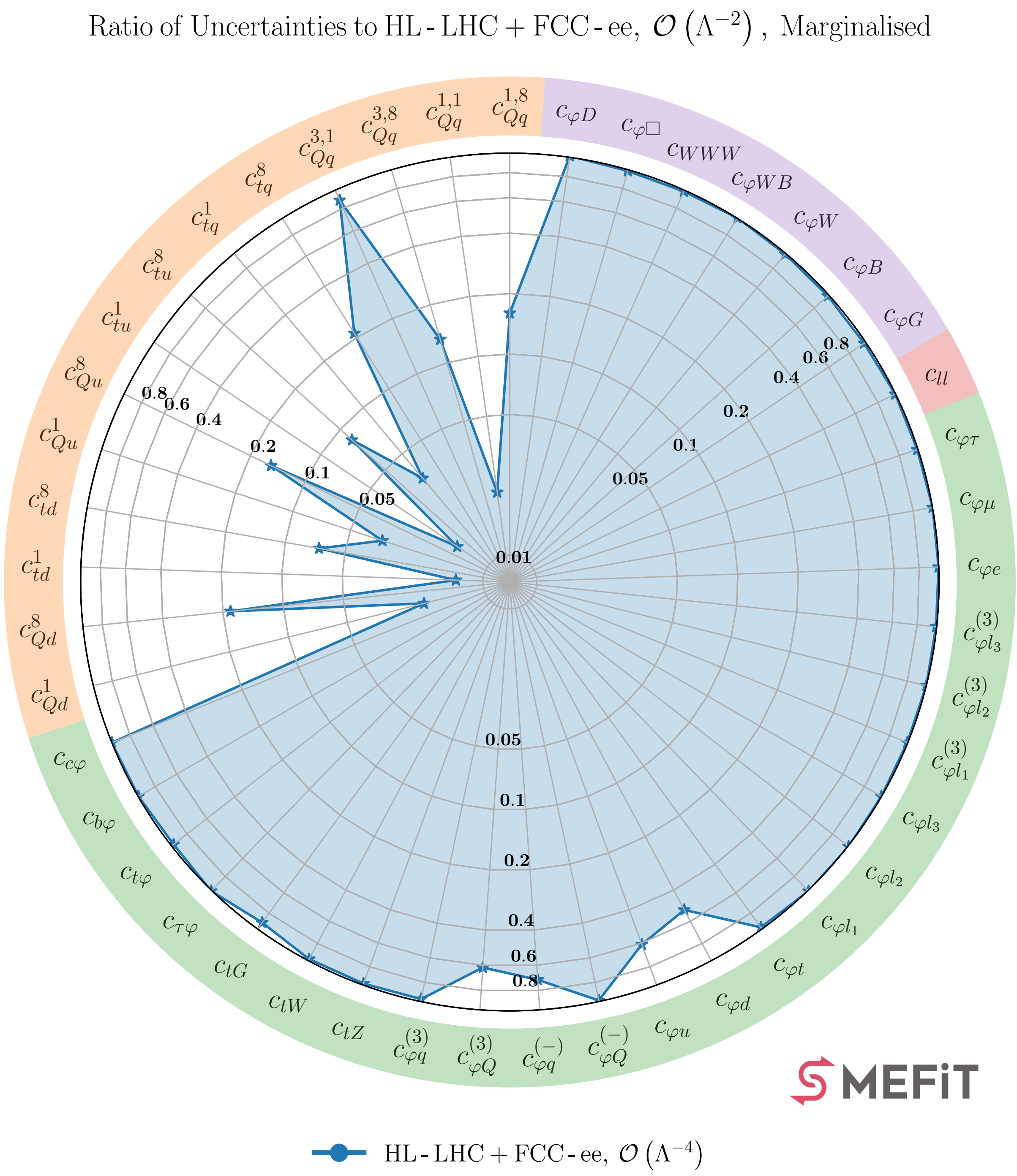
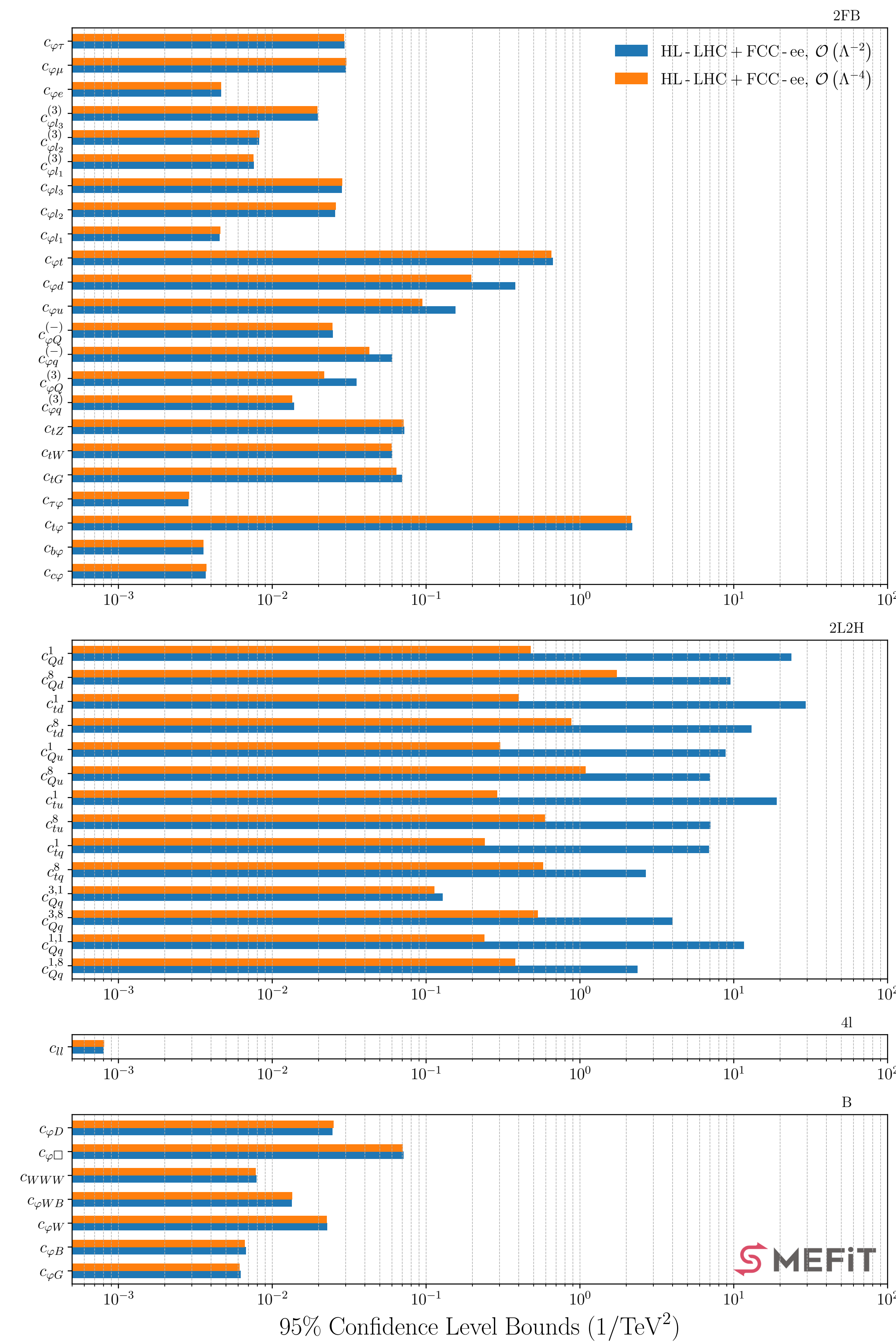
Impact of quadratics

The uncertainty due to the EFT truncation is small except for 4F



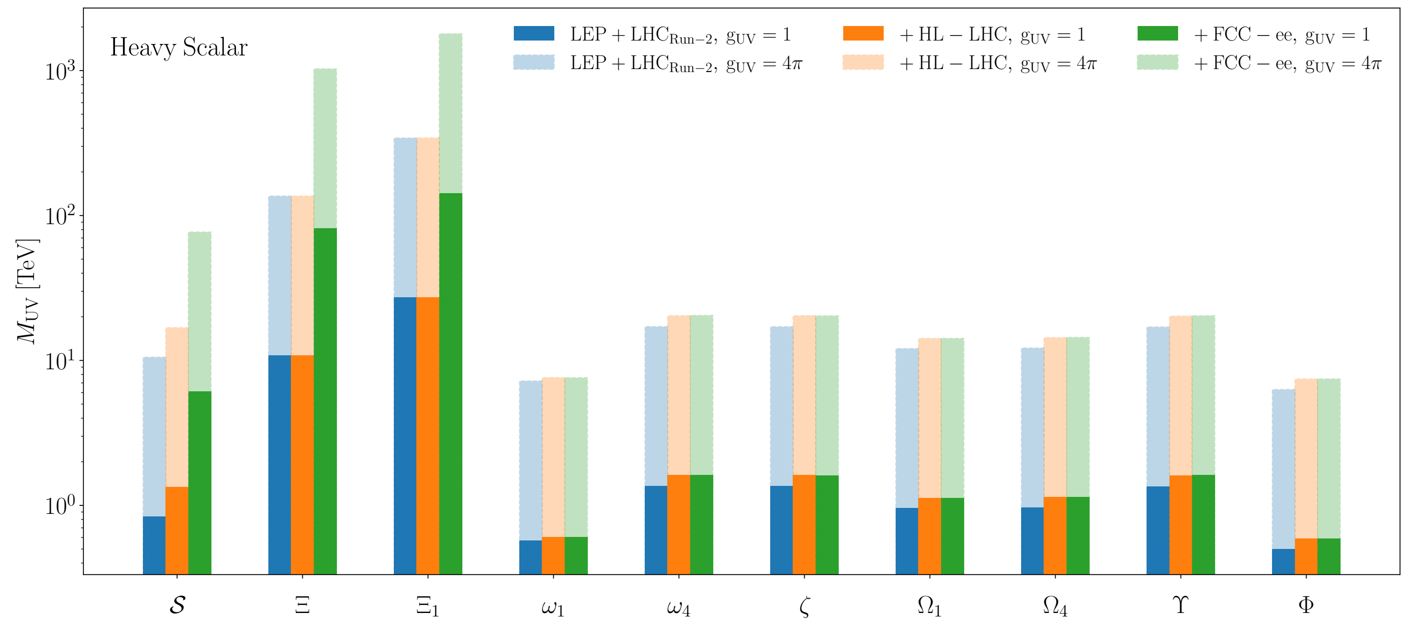


RGE effects

- Experimental input to global fits spans **a wide range of different energy scales,** from m_Z at LEP to $m_{t\bar{t}} \sim 3\,\mathrm{TeV}$ in tails at LHC
- At FCC-ee this gap becomes **even more sizeable** due to an unprecedented indirect mass reach up $\mathcal{O}(100)\,\mathrm{TeV}$
- A consistent treatment that connects measurements across different scales thus becomes necessary and is provided by the **Renormalisation Group Equations (RGEs)**

$$\frac{dc_i(\mu)}{d\ln\mu} = \sum_{j=1}^{n_{\mathrm{op}}} \gamma_{ij} c_j(\mu)$$

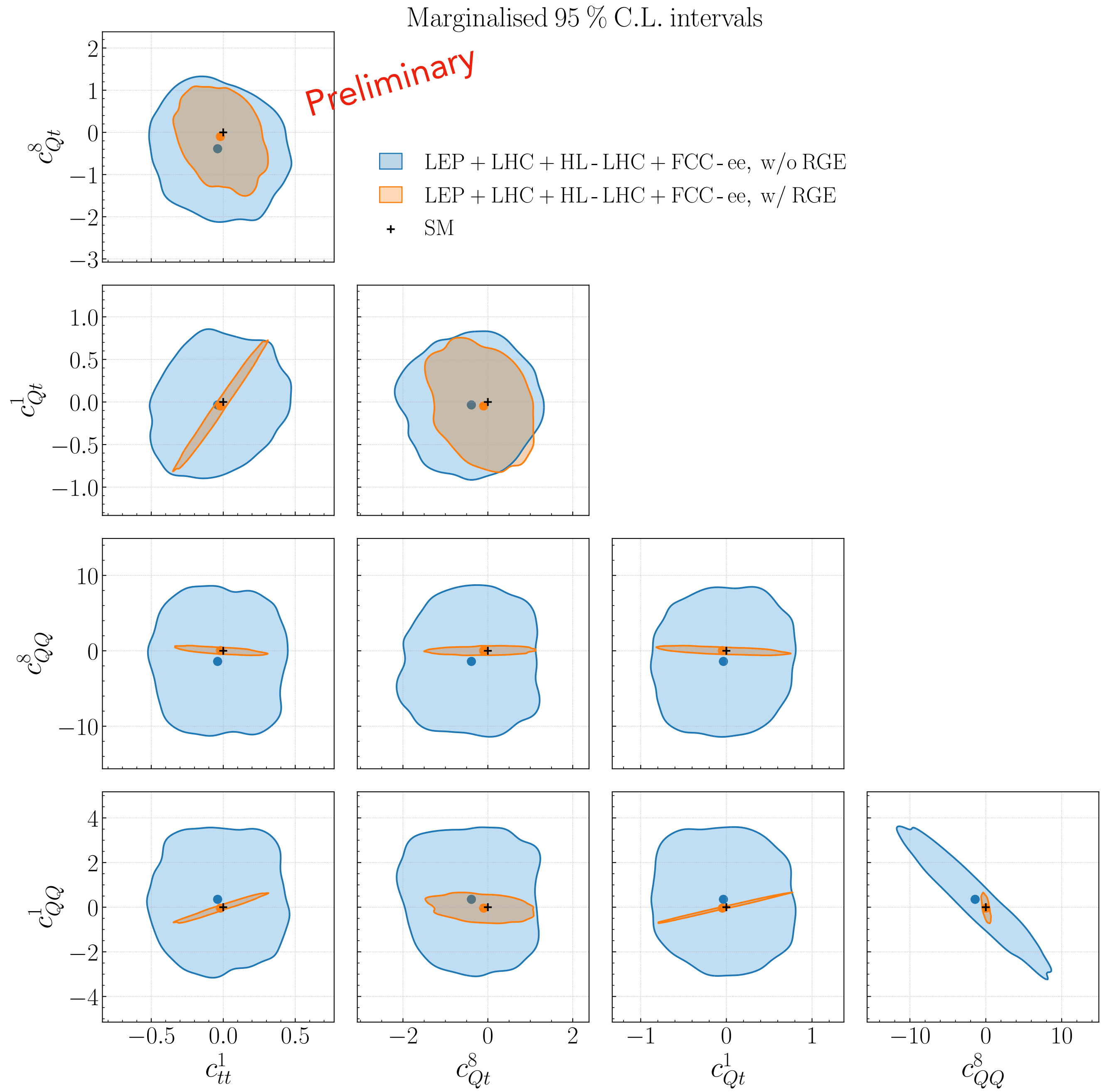
Anomalous dimension



ter Hoeve et al [2309.04523]

RGE effects

Wilson Coefficients run and mix with energy under the RGEs, possibly resulting in higher sensitivity



Two competing effects:

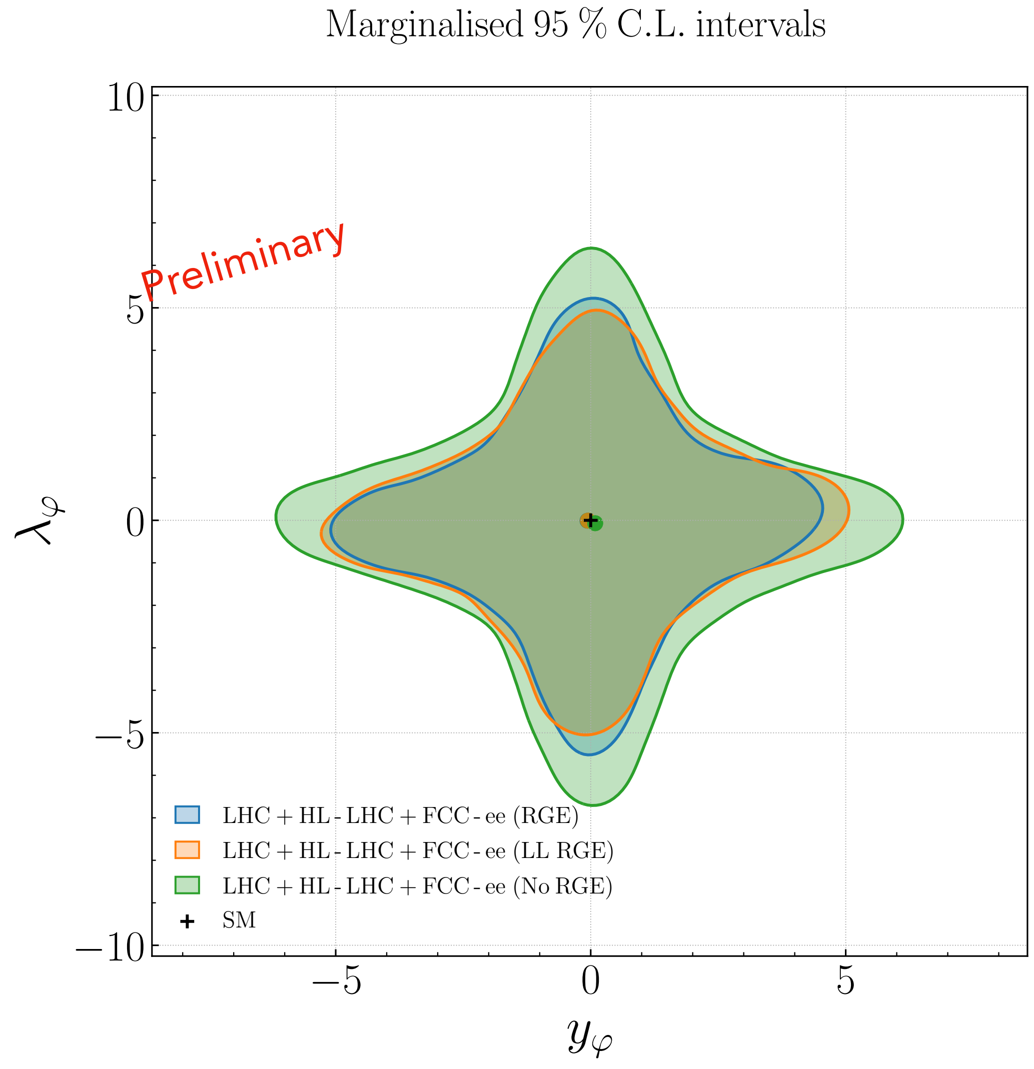
- More operators enter the same observable
- An ill constrained operator could flow into a precisely determined observable

[1804.05033] Aebischer, Kumar, Straub

RGE effects in the UV

The 2HDM* is seen to benefit from including RG effects, with bounds improving by around 20%

* In the decoupling limit



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

Two competing effects:

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- An ill constrained operator could flow into a precisely determined observable

SMEFiT

wilson

[1804.05033] Aebischer, Kumar, Straub

Conclusion and outlook

- Presented **SMEFiT3.0**, a global fit of 50 Wilson coefficients to Higgs, top, diboson and EWPOs, including **quadratic corrections**
- We are becoming **increasingly sensitive** to possible new physics effects, both through the still expanding LHC datasets, as well as through future colliders
- The FCC-ee offers an **unprecedented indirect mass reach** on new heavy particles
- RGE effects are relevant to include to connect experiments at widely separated scales
- The inclusion of other proposed future colliders are WIP for the ESPPU

Conclusion and outlook

- Presented **SMEFiT3.0**, a global fit of 50 Wilson coefficients to Higgs, top, diboson and EWPOs, including **quadratic corrections**
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Thanks for your attention!

Backup

Theory input

We fit a total of **50 Wilson coefficients** simultaneously at quadratic order in the EFT

2 fermion bosonic operators

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}	$i(\bar{Q}\tau^{\mu\nu}\tau_I t)\tilde{\varphi} W_{\mu\nu}^I + \text{h.c.}$
$\mathcal{O}_{\varphi Q}^{(3)}$	$c_{\varphi Q}^{(3)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{Q}\gamma^\mu \tau^I Q)$	$\mathcal{O}_{tB}$	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}	$ig_S(\bar{Q}\tau^{\mu\nu} T_A t)\tilde{\varphi} G_{\mu\nu}^A + \text{h.c.}$
$\mathcal{O}_{t\varphi}$	$c_{t\varphi}$	$(\varphi^\dagger\varphi)\bar{Q} t \tilde{\varphi} + \text{h.c.}$	$\mathcal{O}_{b\varphi}$	$c_{b\varphi}$	$(\varphi^\dagger\varphi)\bar{Q} b \varphi + \text{h.c.}$
		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 lepton operators

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

4 fermion operators

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

Purely bosonic

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

Flavour assumption:

$$U(2)_q \times U(3)_d \times U(2)_u \times \left(U(1)_\ell \times U(1)_e\right)^3$$

HL-LHC projections

- The central values of the pseudo data are fluctuated around the SM

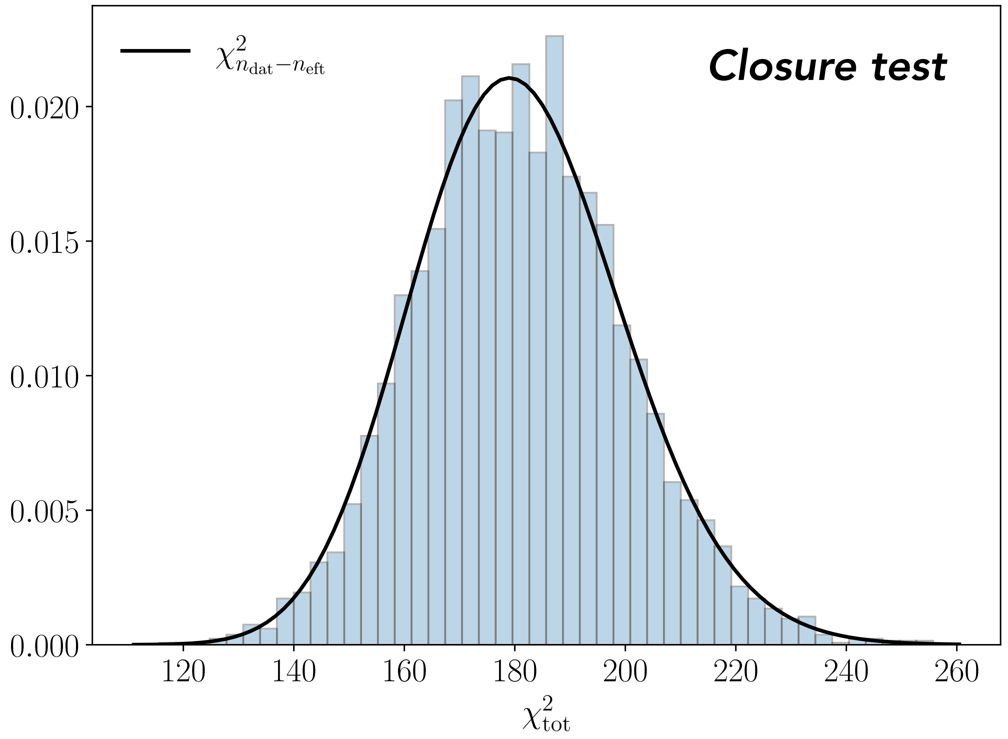
$$\mathcal{O}_i^{(\mathrm{exp})} = \mathcal{O}_i^{(\mathrm{th})}\left(1 + r_i\delta_i^{(\mathrm{stat})} + \sum_{k=1}^{n_{\mathrm{sys}}} r_{k,i}\delta_{k,i}^{(\mathrm{sys})}\right)$$

- Statistical uncertainties we rescale according to the improved luminosity

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

- While systematics are rescaled by an overall factor, namely 1/2 for all datasets

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

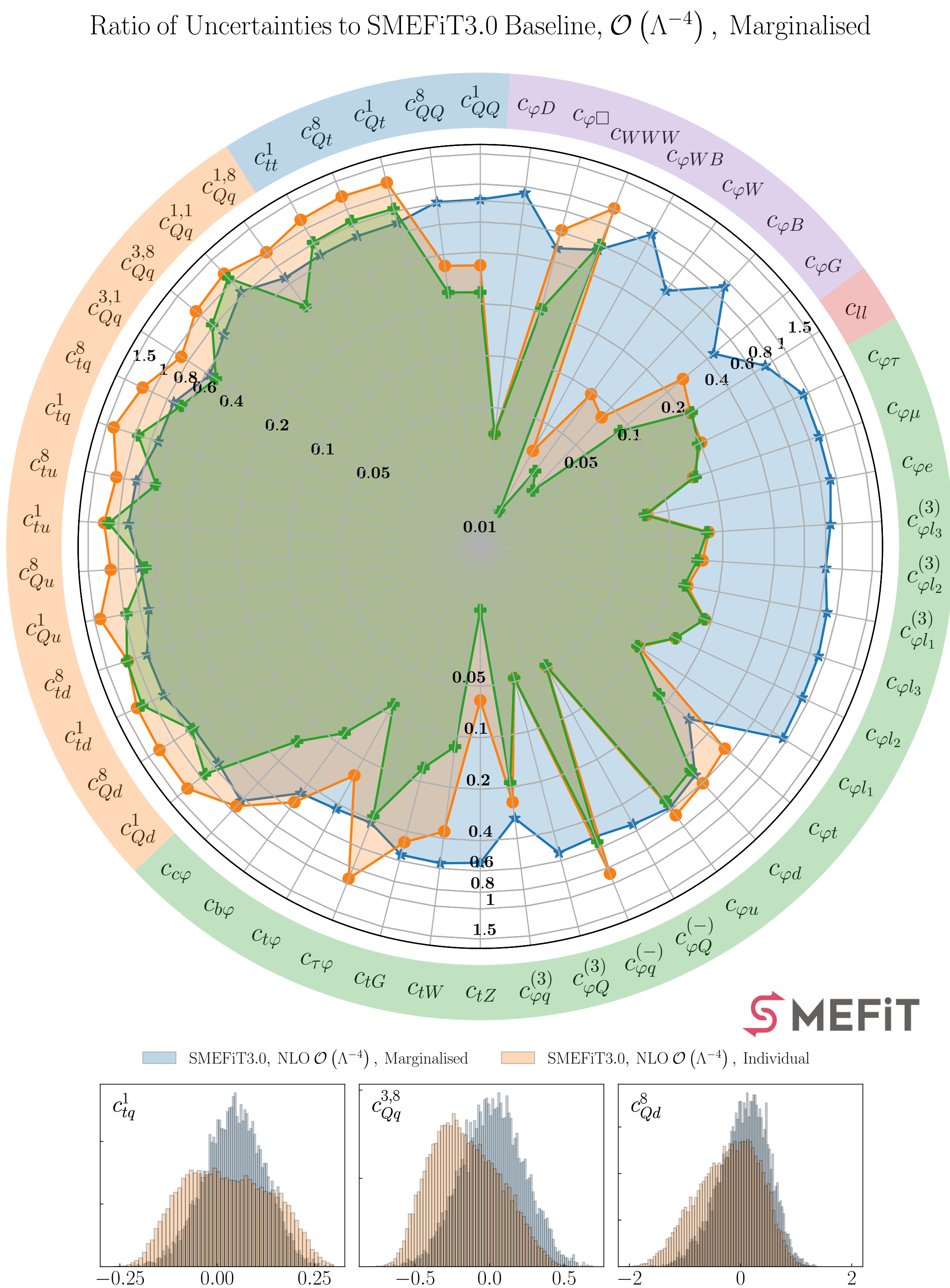


+ flexible framework that can project any Run II dataset

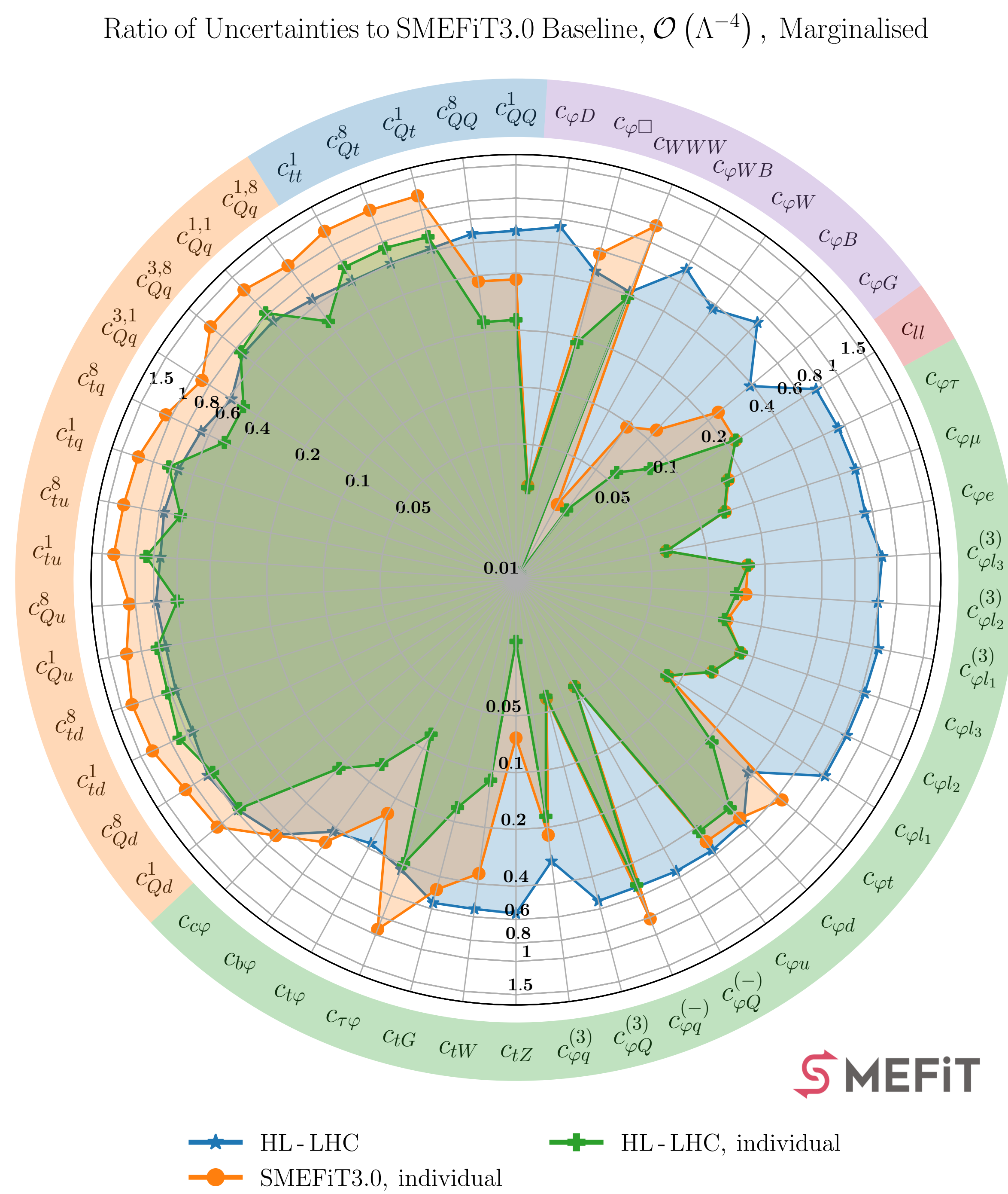
+ SMEFT predictions can be recycled

- No additional bins in the tails

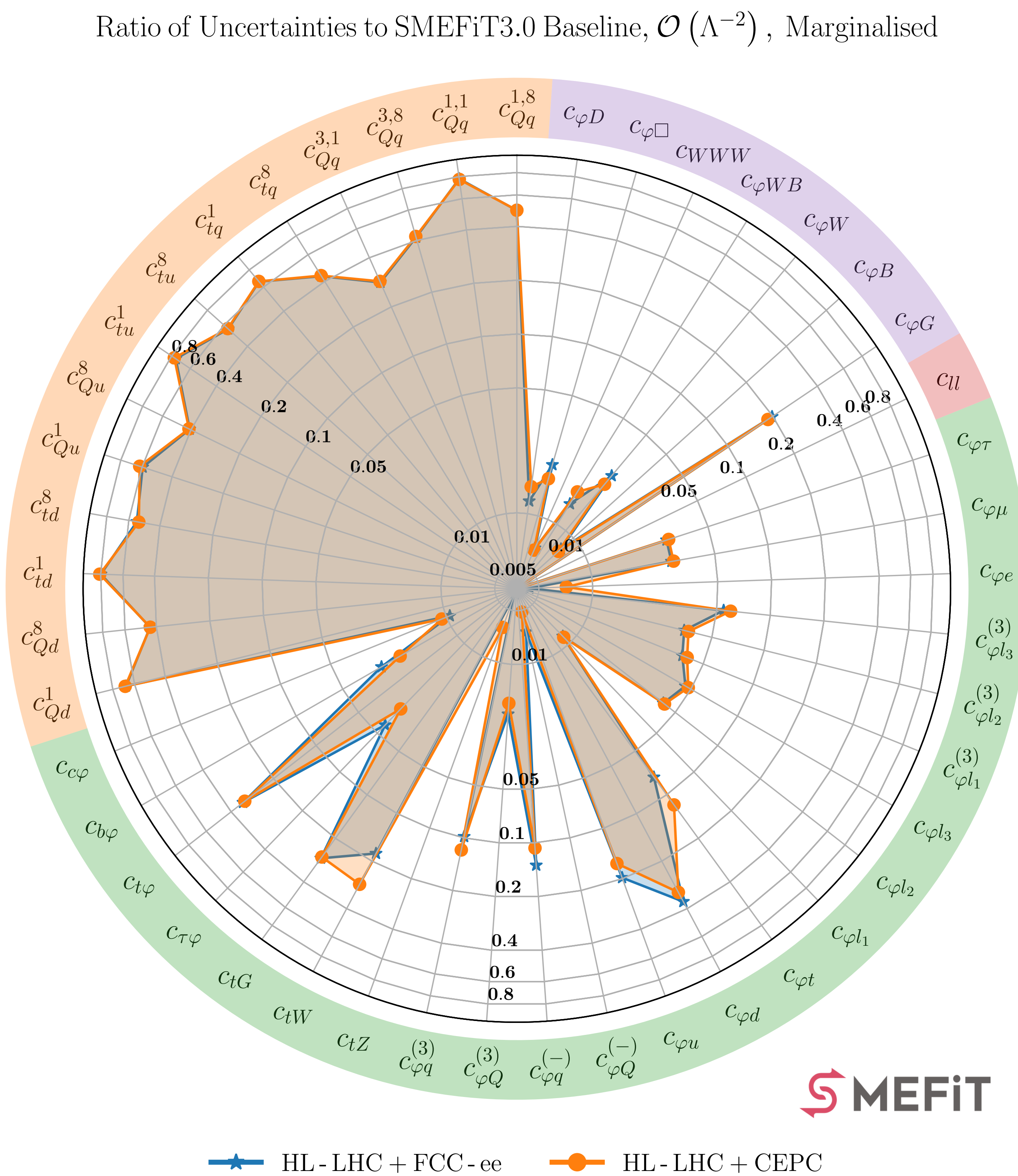
With statistical noise = L1

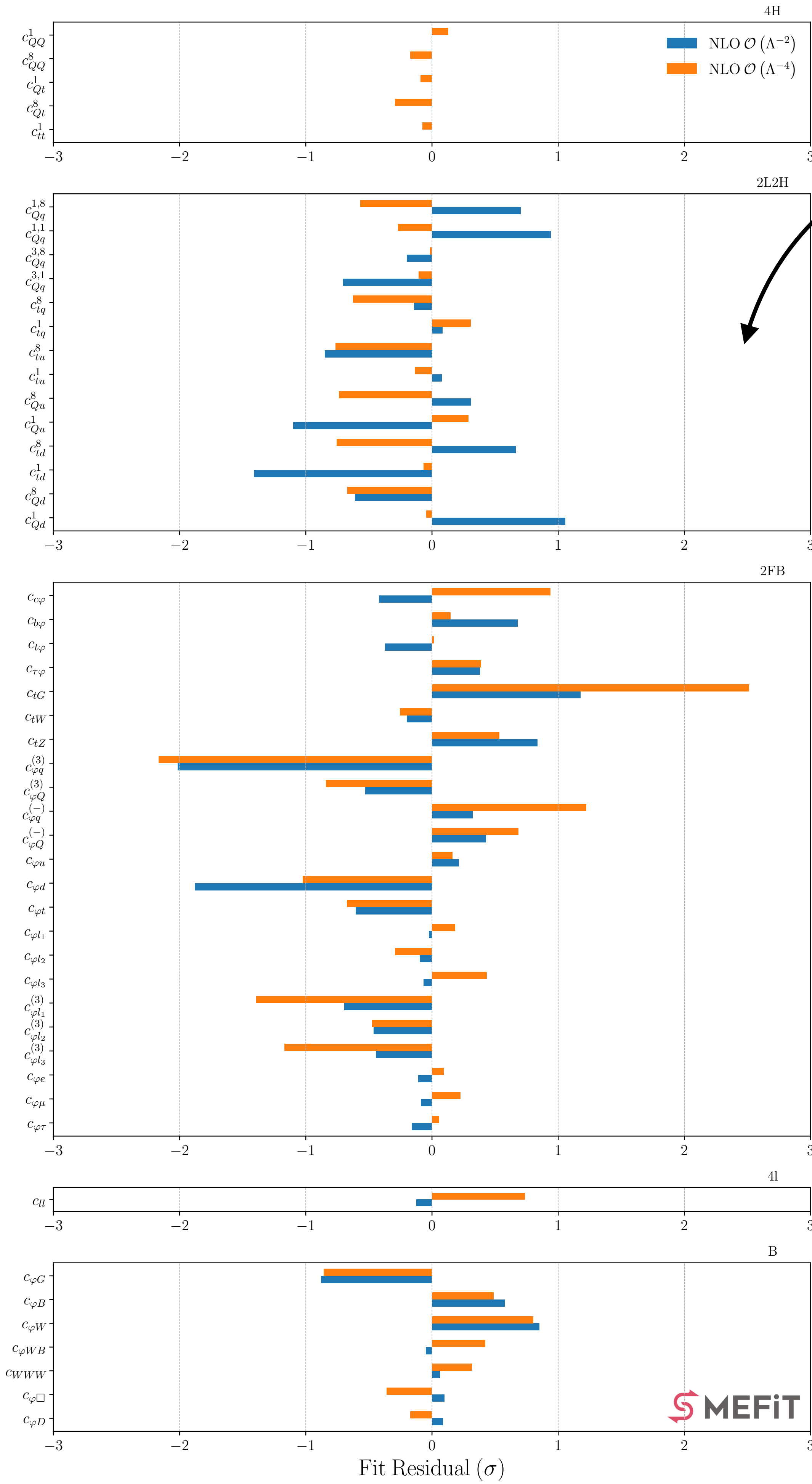


Without statistical noise = L0



FCC-ee and CEPC

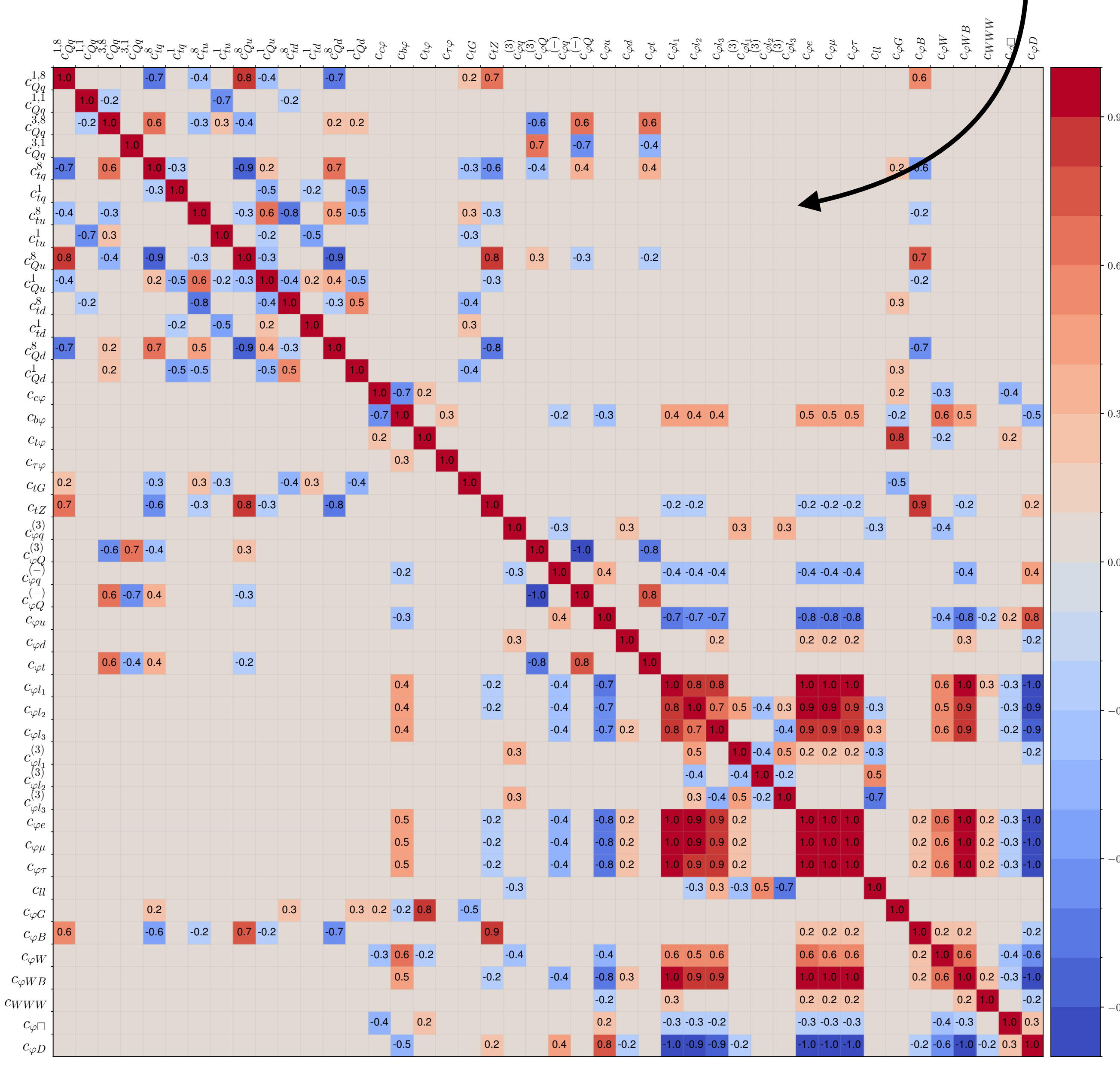




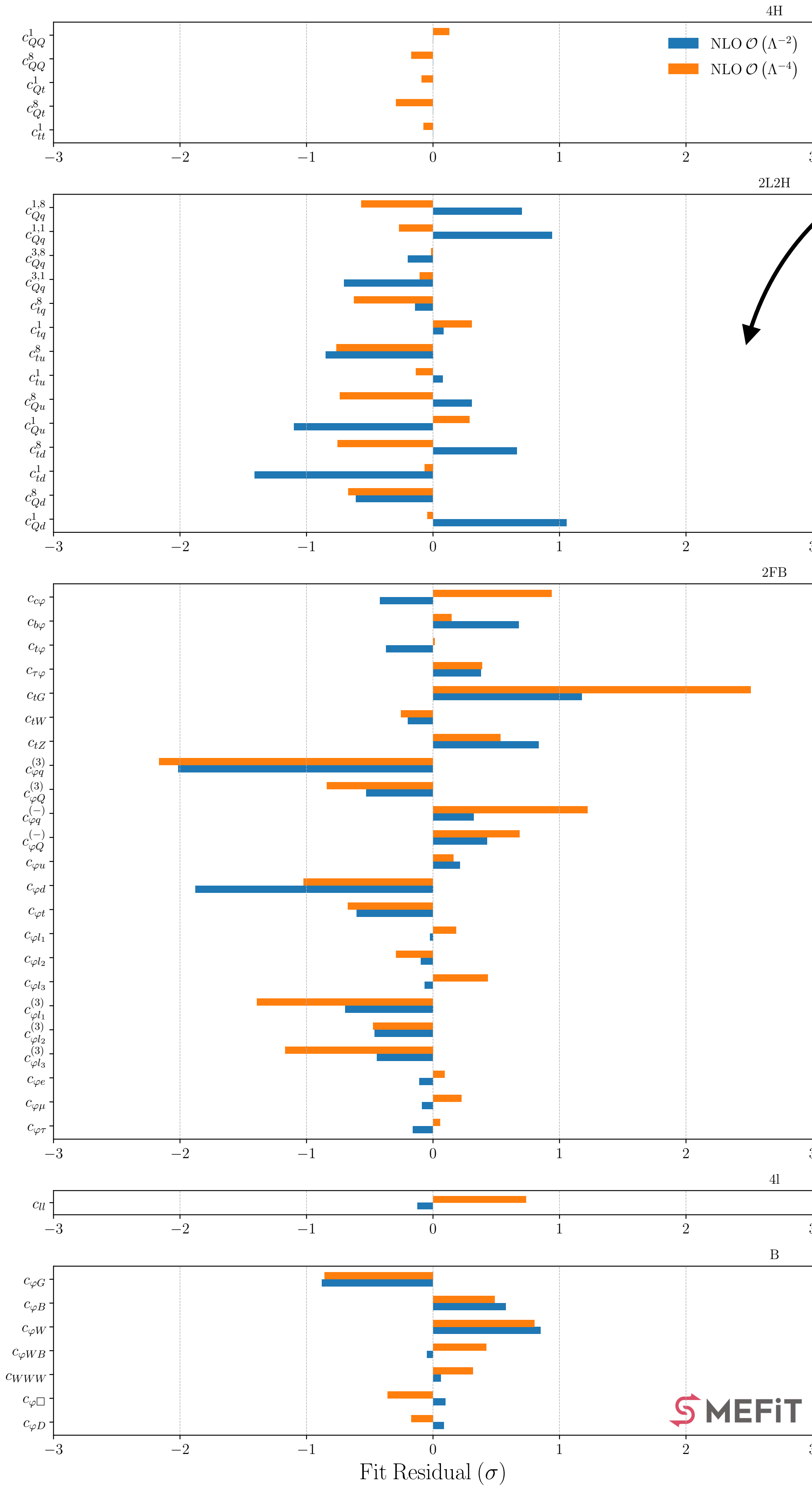
Fit residuals (pulls) are largely **consistent** with the SM

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

Large correlations in linear fit get lifted in the quadratic fit



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



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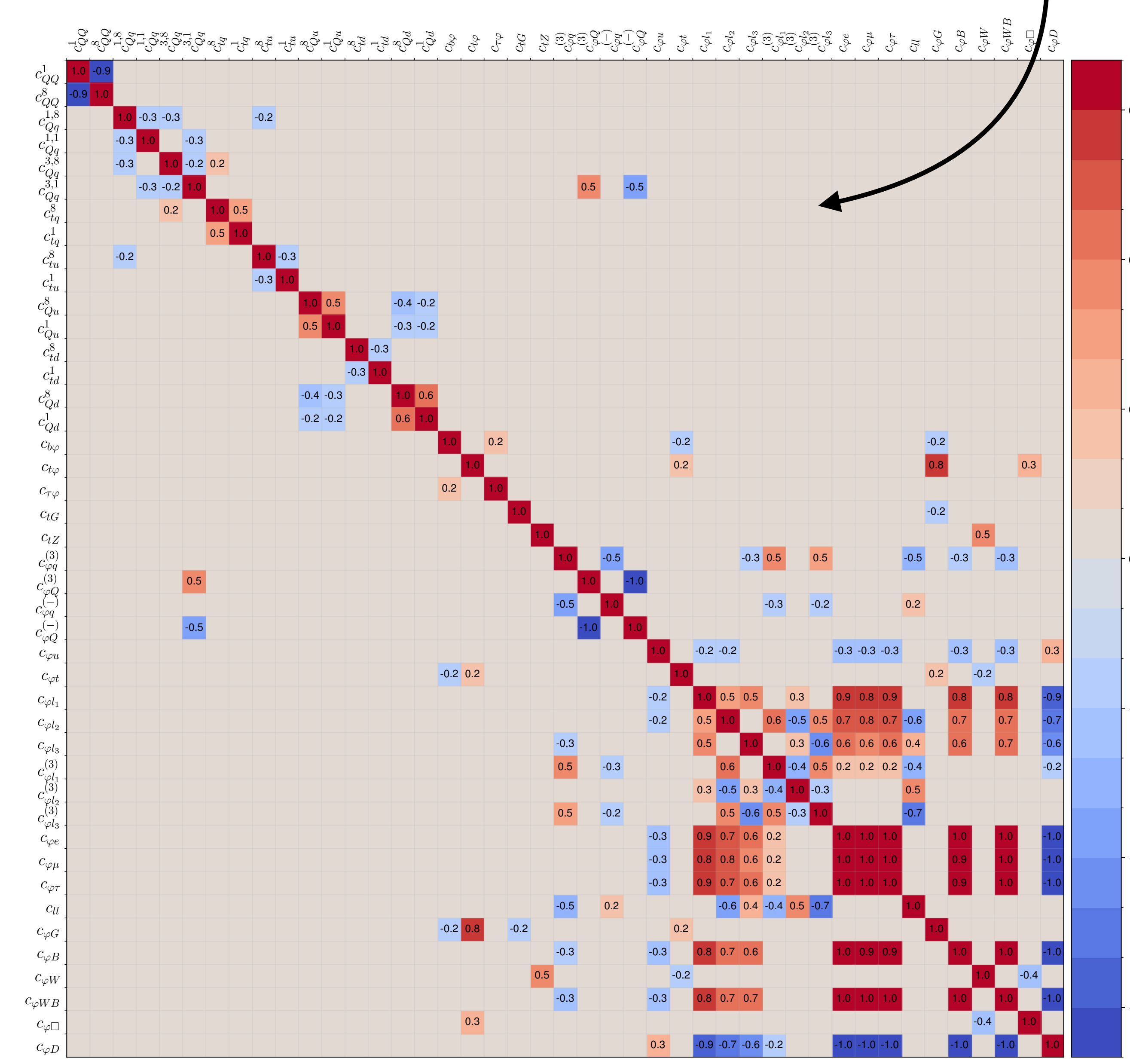


Correlation: NLO $\mathcal{O}(\Lambda^{-4})$

Building the likelihood

From (differential) cross sections …

$$\sigma_{\mathrm{SMEFT}}(c,\Lambda) = \sigma_{\mathrm{SM}} \times \left(1 + \sum_{i}^{N_{d6}} \kappa_i \frac{c_i}{\Lambda^2} + \sum_{i<j}^{N_{d6}} \tilde{\kappa}_{ij} \frac{c_i \cdot c_j}{\Lambda^4} + \mathcal{O}\left(\Lambda^{-6}\right)\right)$$

Linear EFT corrections: interference SM-EFTd6 @NLO QCD

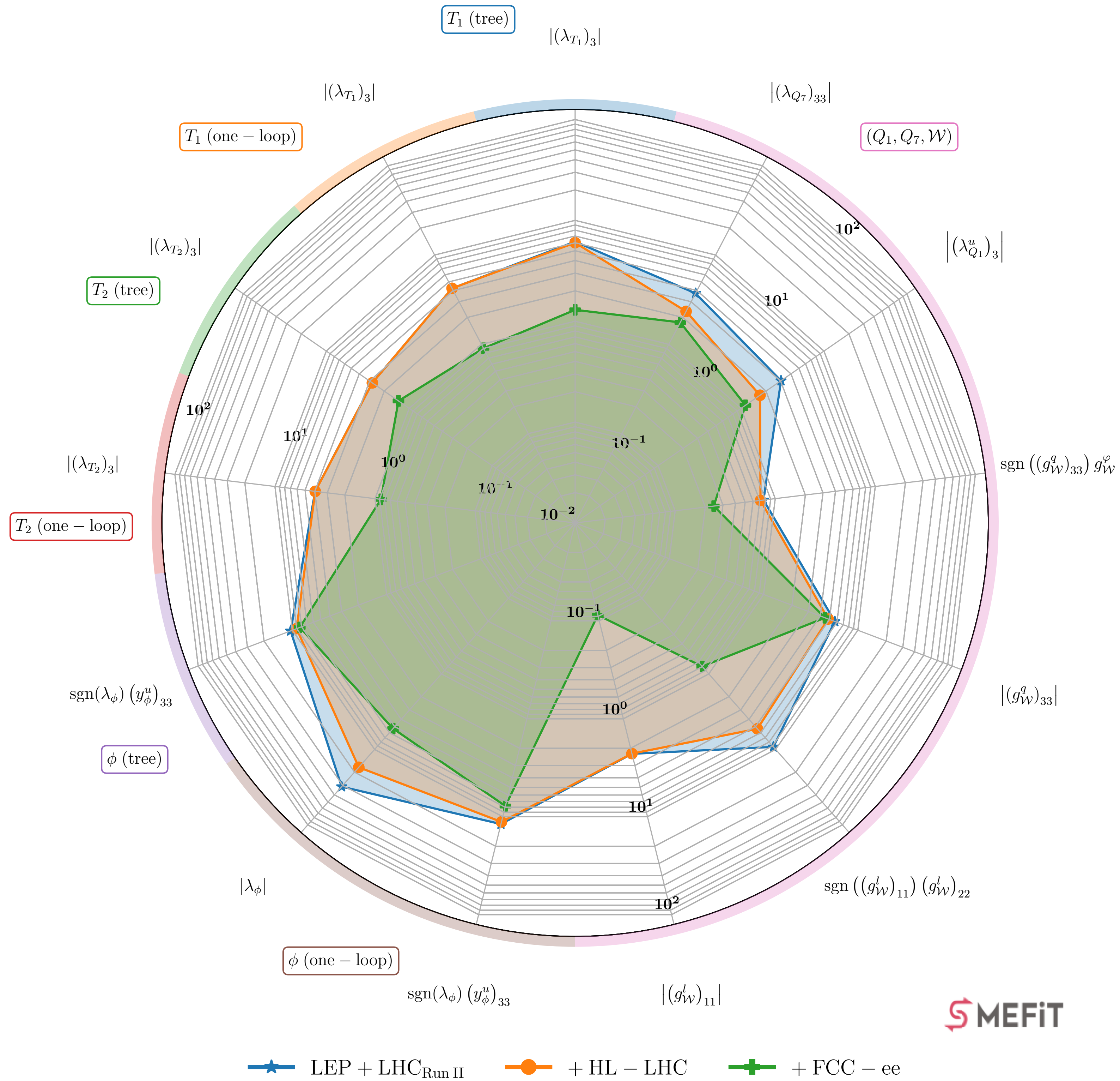
Quadratic EFT corrections: EFTd6-EFTd6 @NLO QCD

To a combined likelihood ready for optimisation …

$$-2\log\mathcal{L} = \frac{1}{n_{\mathrm{dat}}} \sum_{i,j=1}^{n_{\mathrm{dat}}} \left(\sigma_{i,\mathrm{SMEFT}}(c) - \sigma_{i,\mathrm{exp}}\right) \left(\mathrm{cov}^{-1}\right)_{ij} \left(\sigma_{j,\mathrm{SMEFT}}(c) - \sigma_{j,\mathrm{exp}}\right)$$

Theory (pdf + scale) and experimental uncertainties (stat + systematics): $\mathrm{cov}^{(\mathrm{tot})}{}_{ij} = \mathrm{cov}^{(\mathrm{th})}{}_{ij} + \mathrm{cov}^{(\mathrm{exp})}{}_{ij}$

1-loop & multi-particle matching



SM predictions

Category	Process	SM	Code/Ref	SMEFT
Top quark production	$t\bar{t}$ (incl)	NNLO QCD	MG5_aMC NLO + NNLO K-fact	NLO QCD
	$t\bar{t}+V$	NLO QCD	MG5_aMC NLO	LO QCD + NLO SM K-fact
	single-t (incl)	NNLO QCD	MG5_aMC NLO + NNLO K-fact	NLO QCD
	$t+V$	NLO QCD	MG5_aMC NLO	LO QCD + NLO SM K-fact
	$t\bar{t}t\bar{t}$, $t\bar{b}t\bar{b}$	NLO QCD	MG5_aMC NLO	LO QCD + NLO SM K-fact
Higgs production and decay	$gg \to h$	NNLO QCD + NLO EW	HXSWG	NLO QCD
	VBF	NNLO QCD + NLO EW	HXSWG	LO QCD
	$h+V$	NNLO QCD + NLO EW	HXSWG	NLO QCD
	$ht\bar{t}$	NNLO QCD + NLO EW	HXSWG	NLO QCD
	$h \to X$	NNLO QCD + NLO EW	HXSWG	NLO QCD ($X = b\bar{b}$) LO QCD ($X \neq b\bar{b}$)
Diboson production	$e^+e^- \to W^+W^-$	NNLO QCD + NLO EW	LEP EWWG	LO QCD
	$pp \to VV'$	NNLO QCD	MATRIX	NLO QCD

HL-LHC projected datasets

Dataset	$\mathcal{L}$ (fb^{-1})	Info	Observables	$n_{\rm dat}$	Ref.
ATLAS_STXS_RunII_13TeV_2022	139	ggF, VBF, Vh, $t\bar{t}h$, th	$d\sigma/dp_T^h$ $d\sigma/dm_{jj}$ $d\sigma/dp_T^V$	36	[55]
CMS_ggF_aa_13TeV	77.4	ggF, $h \to \gamma\gamma$	$\sigma_{gg\rm F}(p_T^h, N_{\rm jets})$	6	[83]
ATLAS_ggF_ZZ_13TeV	79.8	ggF, $h \to ZZ$	$\sigma_{gg\rm F}(p_T^h, N_{\rm jets})$	6	[84]
ATLAS_ggF_13TeV_2015	36.1	ggF, $h \to ZZ, h \to \gamma\gamma$	$d\sigma(gg\rm F)/dp_T^h$	9	[85]
ATLAS_WH_Hbb_13TeV	79.8	$Wh, h \to b\bar{b}$	$d\sigma^{(\rm fid)}/dp_T^W$ (stage 1 STXS)	2	[86]
ATLAS_ZH_Hbb_13TeV	79.8	$Zh, h \to b\bar{b}$	$d\sigma^{(\rm fid)}/dp_T^Z$ (stage 1 STXS)	2	[86]
CMS_H_13TeV_2015_pTH	35.9	$h \to b\bar{b}, h \to \gamma\gamma, h \to ZZ$	$d\sigma/dp_T^h$	9	[87]
ATLAS_WW_13TeV_2016_memu	36.1	fully leptonic	$d\sigma^{(\rm fid)}/dm_{e\mu}$	13	[88]
ATLAS_WZ_13TeV_2016_mTWZ	36.1	fully leptonic	$d\sigma^{(\rm fid)}/dm_T^{WZ}$	6	[89]
CMS_WZ_13TeV_2016_pTZ	35.9	fully leptonic	$d\sigma^{(\rm fid)}/dp_T^Z$	11	[90]
CMS_WZ_13TeV_2022_pTZ	137	fully leptonic	$d\sigma/dp_T^Z$	11	[56]

Dataset	$\mathcal{L}$ (fb^{-1})	Info	Observables	n_{dat}	Ref.
ATLAS_tt_13TeV_ljets_2016_Mtt	36.1	ℓ+jets	$d\sigma/dm_{t\bar{t}}$	7	[91]
CMS_tt_13TeV_dilep_2016_Mtt	35.9	dilepton	$d\sigma/dm_{t\bar{t}}$	7	[92]
CMS_tt_13TeV_Mtt	137	ℓ+jets	$1/\sigma d\sigma/dm_{t\bar{t}}$	14	[57]
CMS_tt_13TeV_ljets_inc	137	ℓ+jets	$\sigma(t\bar{t})$	1	[57]
ATLAS_tt_13TeV_asy_2022	139	ℓ + jets	A_C	5	[59]
CMS_tt_13TeV_asy	138	ℓ + jets	A_C	3	[58]
ATLAS_Whel_13TeV	139	W-helicity fraction	F_0, F_L	2	[60]
ATLAS_ttbb_13TeV_2016	36.1	lepton + jets	$\sigma_{\text{tot}}(t\bar{t}b\bar{b})$	1	[93]
CMS_ttbb_13TeV_2016	35.9	all-jets	$\sigma_{\text{tot}}(t\bar{t}b\bar{b})$	1	[94]
CMS_ttbb_13TeV_dilepton_inc	35.9	dilepton	$\sigma_{\text{tot}}(t\bar{t}b\bar{b})$	1	[68]
CMS_ttbb_13TeV_ljets_inc	35.9	lepton + jets	$\sigma_{\text{tot}}(t\bar{t}b\bar{b})$	1	[68]
ATLAS_tttt_13TeV_run2	139	multi-lepton	$\sigma_{\text{tot}}(t\bar{t}t\bar{t})$	1	[95]
CMS_tttt_13TeV_run2	137	same-sign or multi-lepton	$\sigma_{\text{tot}}(t\bar{t}t\bar{t})$	1	[96]
ATLAS_tttt_13TeV_slep_inc	139	single-lepton	$\sigma_{\text{tot}}(t\bar{t}t\bar{t})$	1	[64]
CMS_tttt_13TeV_slep_inc	35.8	single-lepton	$\sigma_{\text{tot}}(t\bar{t}t\bar{t})$	1	[65]
ATLAS_tttt_13TeV_2023	139	multi-lepton	$\sigma_{\text{tot}}(t\bar{t}t\bar{t})$	1	[66]
CMS_tttt_13TeV_2023	139	same-sign or multi-lepton	$\sigma_{\text{tot}}(t\bar{t}t\bar{t})$	1	[67]
CMS_ttZ_13TeV_pTZ	77.5	$t\bar{t}Z$	$d\sigma(t\bar{t}Z)/dp_T^Z$	4	[97]
ATLAS_ttZ_13TeV_pTZ	139	$t\bar{t}Z$	$d\sigma(t\bar{t}Z)/dp_T^Z$	7	[61]
ATLAS_ttW_13TeV_2016	36.1	$t\bar{t}W$	$\sigma_{\text{tot}}(t\bar{t}W)$	1	[98]
CMS_ttW_13TeV	35.9	$t\bar{t}W$	$\sigma_{\text{tot}}(t\bar{t}W)$	1	[99]
ATLAS_t_tch_13TeV_inc	3.2	t-channel	$\sigma_{\text{tot}}(tq), \sigma_{\text{tot}}(\bar{t}q)$	2	[100]
CMS_t_tch_13TeV_2019_diff_Yt	35.9	t-channel	$d\sigma/d\lvert y_t\rvert$	5	[101]
ATLAS_t_sch_13TeV_inc	139	s-channel	$\sigma(t+\bar{t})$	1	[69]
ATLAS_tW_13TeV_inc	3.2	multi-lepton	$\sigma_{\text{tot}}(tW)$	1	[102]
CMS_tW_13TeV_inc	35.9	multi-lepton	$\sigma_{\text{tot}}(tW)$	1	[103]
CMS_tW_13TeV_slep_inc	36	single-lepton	$\sigma_{\text{tot}}(tW)$	1	[71]
ATLAS_tZ_13TeV_run2_inc	139	multi-lepton + jets	$\sigma_{\text{fid}}(t\ell^+\ell^- q)$	1	[104]
CMS_tZ_13TeV_pTt	138	multi-lepton + jets	$d\sigma_{\text{fid}}(tZj)/dp_T^t$	3	[70]

FCC-ee and CEPC datasets

EWPOs

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

Zh and VBF ($h\nu\nu$)

$e^+e^- \to Zh$				
	$\sqrt{s} = 240$ 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

FCC-ee and CEPC datasets

Light fermion production

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

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