A global SMEFT analysis extended with HL-LHC and FCC-ee projections

Juan Rojo

VU Amsterdam & Theory group, Nikhef

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SMEFiT projections for future colliders

SMEFiT2.0

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

The SMEFiT Collaboration:
Jacob J. Ethier,[1,2] Giacomo Magni,[1,2] Fabio Maltoni,[3,4] Luca Mantani,[3] Emanuele R. Nocera,[2,5] Juan Rojo,[1,2], Emma Slade,[6] Eleni Vryonidou,[7] and Cen Zhang[8,9]

[1] *Department of Physics and Astronomy, Vrije Universiteit Amsterdam, NL-1081 HV Amsterdam, The Netherlands*
[2] *Nikhef Theory Group, Science Park 105, 1098 XG Amsterdam, The Netherlands*
[3] *Centre for Cosmology, Particle Physics and Phenomenology (CP3), Université Catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*
[4] *Dipartimento di Fisica e Astronomia, Università di Bologna and INFN, Sezione di Bologna, via Irnerio 46, 40126 Bologna, Italy*
[5] *The Higgs Centre for Theoretical Physics, The University of Edinburgh, JCMB, KB, Mayfield Rd, Edinburgh EH9 3JZ, Scotland*
[6] *Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, United Kingdom*
[7] *Department of Physics and Astronomy, University of Manchester, Oxford Road, Manchester M13 9PL, United Kingdom*
[8] *Institute of High Energy Physics, and School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China*
[9] *Center for High Energy Physics, Peking University, Beijing 100871, China*

Abstract

We present a global interpretation of Higgs, diboson, and top quark production and decay measurements from the LHC in the framework of the Standard Model Effective Field Theory (SMEFT) at dimension six. We constrain simultaneously 36 independent directions in its parameter space, and compare the outcome of the global analysis with that from individual and

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Public code paper

SMEFiT: a flexible toolbox for global interpretations of particle physics data with effective field theories

Tommaso Giani, Giacomo Magni, and Juan Rojo

Department of Physics and Astronomy, Vrije Universiteit Amsterdam, NL-1081 HV Amsterdam, The Netherlands
Nikhef Theory Group, Science Park 105, 1098 XG Amsterdam, The Netherlands

Abstract

The Standard Model Effective Field Theory (SMEFT) provides a robust framework to interpret experimental measurements in the context of new physics scenarios while minimising assumptions on the nature of the underlying UV-complete theory. We present the Python open source SMEFiT framework, designed to carry out parameter inference in the SMEFT within a global analysis of particle physics data. SMEFiT is suitable for inference problems involving a large number of EFT degrees of freedom, without restrictions on their functional dependence in the fitted observables, can include UV-inspired restrictions in the parameter space, and implements arbitrary rotations between operator bases. Posterior distributions are determined from two complementary approaches, Nested Sampling and Monte Carlo optimisation. SMEFiT is released together with documentation, tutorials, and post-analysis reporting tools, and can be used to carry out state-of-the-art EFT fits of Higgs, top quark, and electroweak production data. To illustrate its functionalities, we reproduce the results of the recent ATLAS EFT interpretation of Higgs and electroweak data from Run II and demonstrate how equivalent results are obtained in two different operator bases.

The automation of SMEFT-Assisted Constraints on UV-Complete Models

Automation UV matching

Jaco ter Hoeve,[a,b] Giacomo Magni,[a,b] Juan Rojo,[a,b] Alejo N. Rossia,[c] and Eleni Vryonidou[c]

[a] *Nikhef Theory Group, Science Park 105, 1098 XG Amsterdam, The Netherlands*
[b] *Physics and Astronomy, Vrije Universiteit Amsterdam, NL-1081 HV Amsterdam, The Netherlands*
[c] *Department of Physics and Astronomy, University of Manchester, Oxford Road, Manchester M13 9PL, United Kingdom*

E-mail: j.j.ter.hoeve@vu.nl, gmagni@nikhef.nl, j.rojo@vu.nl, alejo.rossia@manchester.ac.uk, eleni.vryonidou@manchester.ac.uk

Abstract: The ongoing Effective Field Theory (EFT) program at the LHC and elsewhere is motivated by streamlining the connection between experimental data and UV-complete scenarios of heavy new physics beyond the Standard Model (BSM). This connection is provided by matching relations mapping the Wilson coefficients of the EFT to the couplings and masses of UV-complete models. Building upon recent work on the automation of tree-level and one-loop matching in the SMEFT, we present a novel strategy automating the constraint-setting procedure on the parameter space of general heavy UV-models matched to dimension-six SMEFT operators. A new Mathematica package, match2fit, interfaces MatchMakerEFT, which derives the matching relations for a given UV model, and SMEFiT, which provides bounds on the Wilson coefficients by comparing with data. By means of this pipeline and using both tree-level and one-loop matching, we derive bounds on a wide range of single- and multi-particle extensions of the SM from a global dataset composed by LHC and LEP measurements. Whenever possible, we benchmark our results with existing studies. Our framework realises one of the main objectives of the EFT program in particle physics: deploying the SMEFT to bypass the need of directly comparing the predictions of heavy UV models with experimental data.

Keywords: SMEFT, Beyond the Standard Model, LHC Phenomenology, EFT Matching

SMEFiT projections for future colliders

- Extend SMEFiT2.0 with **recent LHC Run-2 datasets on top, diboson, and Higgs production**
- New, dedicated implementation of the constraints from **LEP's EWPOs**
- Include tailored projections for **HL-LHC pseudo-data** based on extrapolating Run-2 data
- Include ``Snowmass" projections for **FCC-ee & CEPC** pseudo-data, updated with FCC midterm Feasibility Report
- Results both Wilson coefficient and matched to **UV-complete models** that have SMEFT as low-energy limit
- **Public code, data, and theory**: user-friendly and straightforward to apply to any other future collider

extensive documentation and **example runcards,**
fully reproducible results

SMEFiT3.0 & Projections for HL-LHC & FCC-ee

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

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]

[a] *Department of Physics and Astronomy, University of Manchester, Oxford Road, Manchester M13 9PL, United Kingdom*
[b] *Nikhef Theory Group, Science Park 105, 1098 XG Amsterdam, The Netherlands*
[c] *Department of Physics and Astronomy, Vrije Universiteit Amsterdam, NL-1081 HV Amsterdam, The Netherlands*
[d] *DAMTP, University of Cambridge, Wilberforce Road, Cambridge, CB3 0WA, United Kingdom*

E-mail: eugenia.celada@manchester.ac.uk, tgiani@nikhef.nl, j.j.ter.hoeve@vu.nl, luca.mantani@maths.cam.ac.uk, j.rojo@vu.nl, alejo.rossia@manchester.ac.uk, marion.thomas@manchester.ac.uk, eleni.vryonidou@manchester.ac.uk

Abstract: We present SMEFiT3.0, an updated global SMEFT analysis of Higgs, top quark, and diboson data from the LHC complemented by electroweak precision observables (EWPOs) from LEP and SLD. We consider the most 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, by means of dedicated projections extrapolating from Run II data. We quantify the significant constraints that measurements from future high-energy circular electron-positron colliders 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 including 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 his work may be extended to other proposed colliders and running scenarios, providing a timely input to ongoing studies towards future high-energy particle colliders.

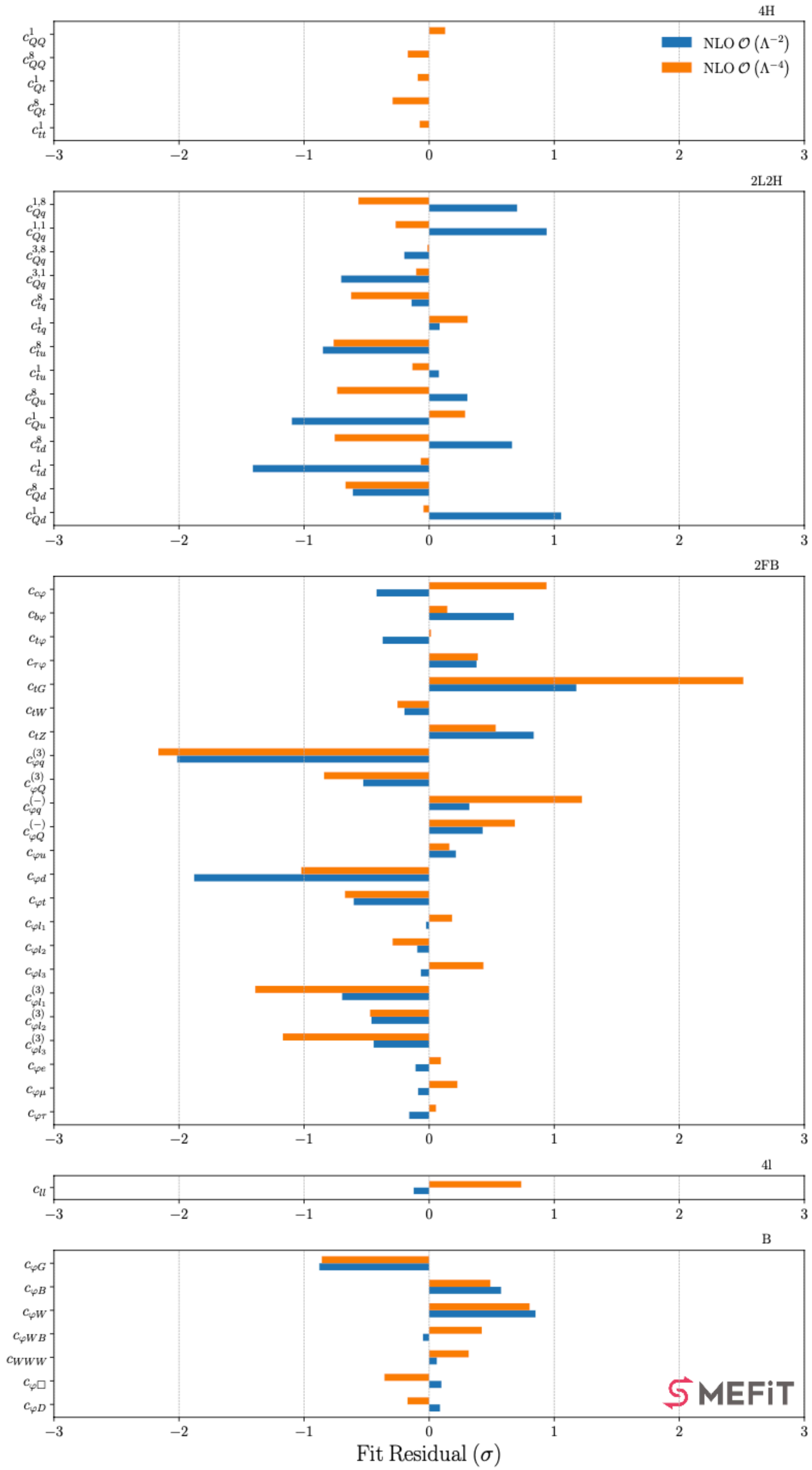
to appear Friday on the arXiv

Baseline SMEFT analysis

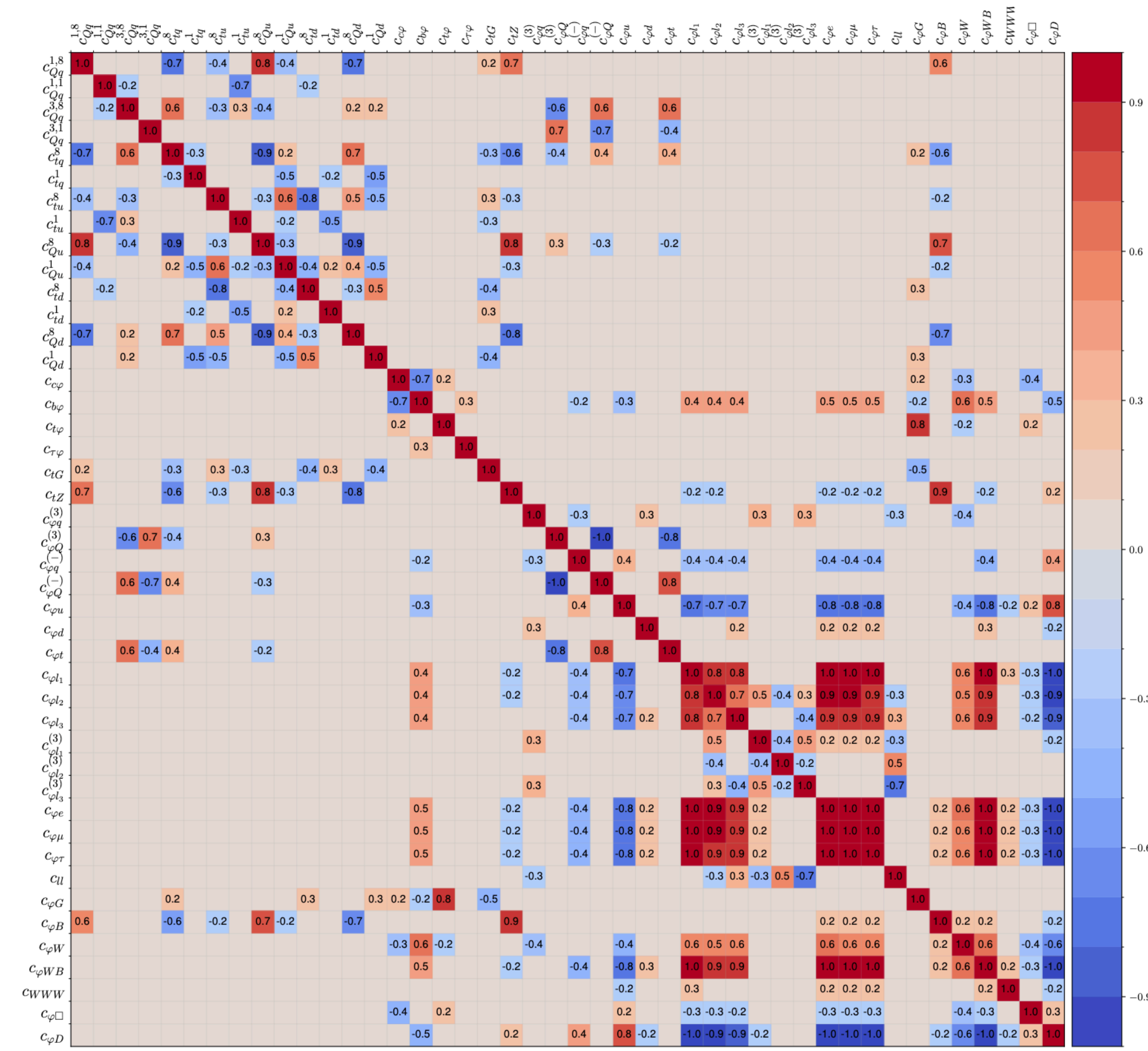
- **445 fitted cross-sections** from top (189), Higgs (129), and diboson production (81), complemented with LEP's EWPOs (44 data points)
- **50 (45) Wilson coefficients** in the quadratic (linear) EFT fits
- Posterior distributions provided by Nested Sampling (**Bayesian inference**). Linear fits cross-checked with analytic solution.
- Flavour assumptions: $U(2)_q \otimes U(3)_q \otimes U(2)_u \otimes \left(U(1)_\ell \otimes U(1)_e\right)^3$

Category	Processes	$n_{\rm dat}$	
		SMEFiT2.0	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	36 (*)
	Run II, differential distributions & STXS	35	71
	Total	**97**	**129**
Diboson production	LEP-2	40	40
	LHC	30	41
	Total	**70**	**81**
Z-pole EWPOs	LEP-2	-	44
Baseline dataset	**Total**	**317**	**445**

Baseline SMEFT analysis



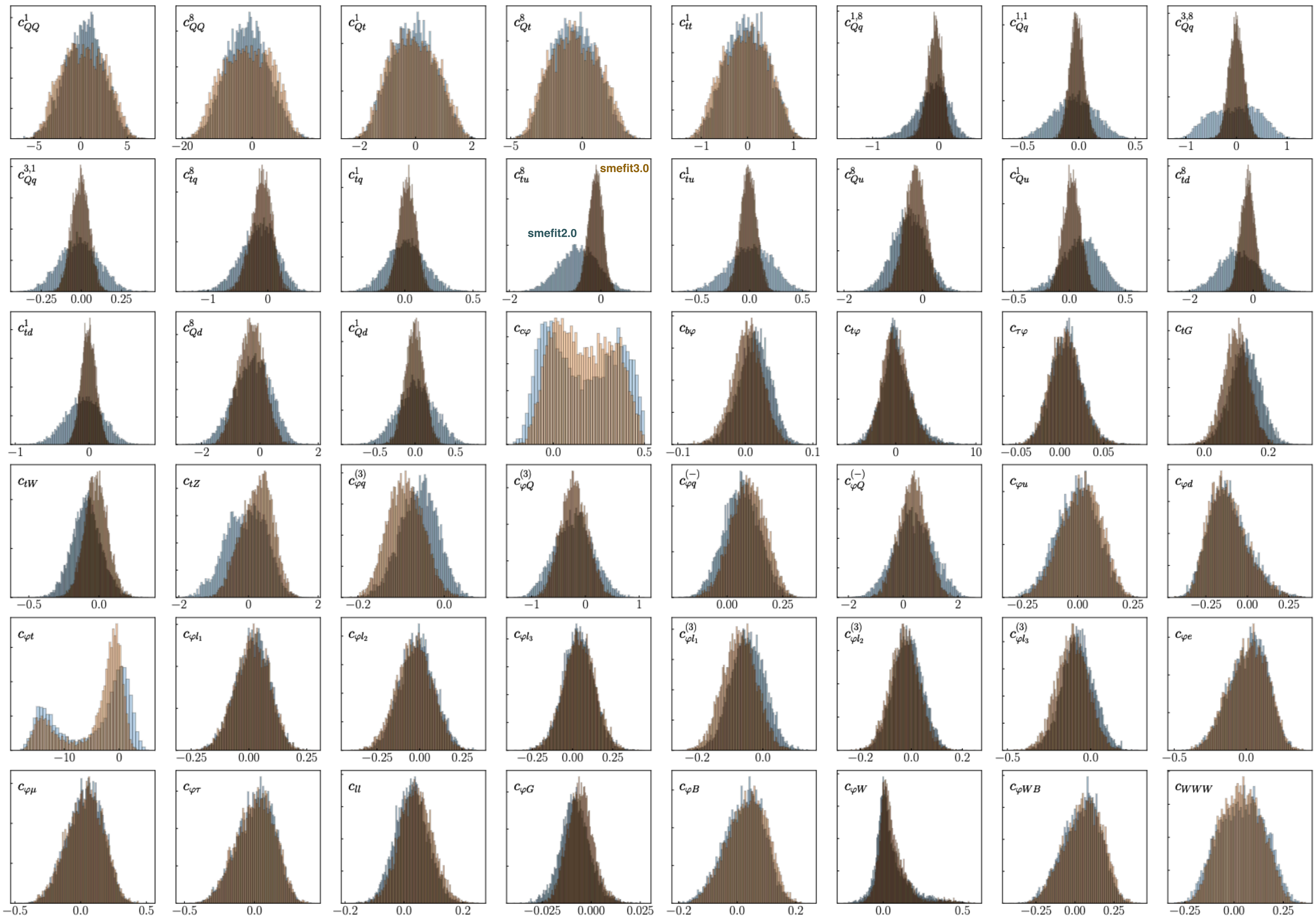
- **Good agreement with the SM expectations**, with a few (well understood) exceptions
- **Large correlations** between fitted coefficients, partially washed out in the quadratic EFT fits
- Full posterior distribution available, can be **marginalised** to the 1-coeff, 2-coeff, 3-coeff …. level



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

Baseline SMEFT analysis

Impact of **recent LHC data** in the quadratic global fit



HL-LHC projections

- Extrapolate available Run-2 data to the HL-LHC assuming the SM as underlying theory
- Rescale statistical and systematic errors, keep same binning

SM

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

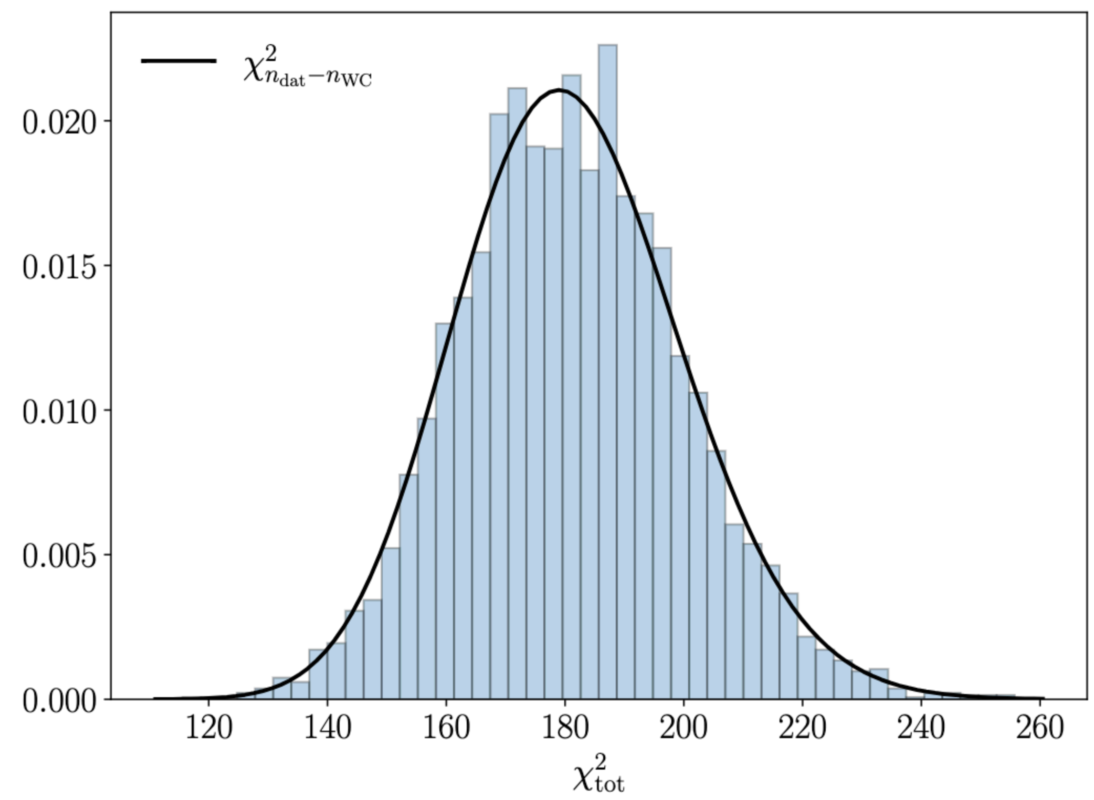
Run-2 stat error

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

Run-2 syst error

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

results for fits over different pseudo-data sets

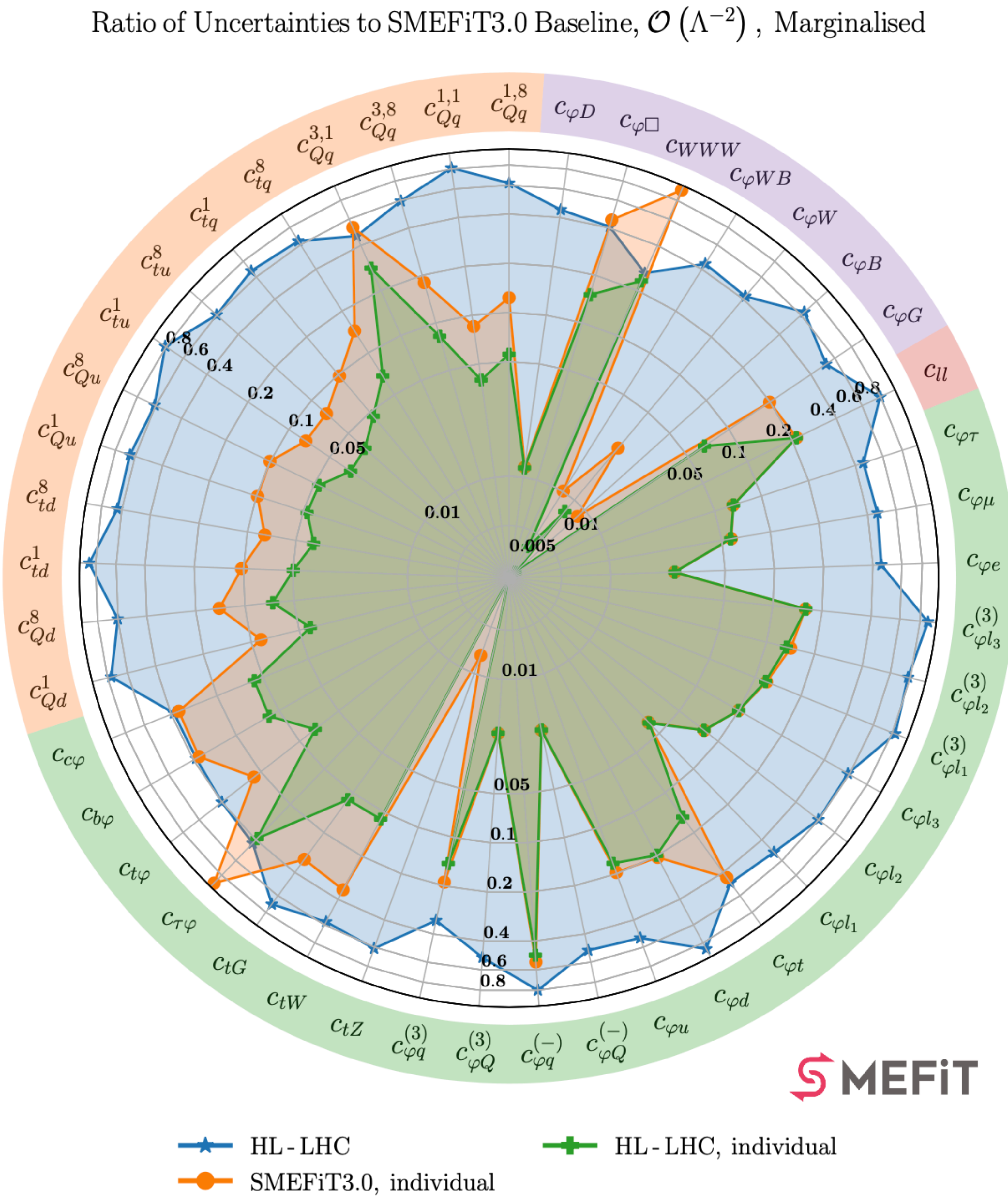


- pro: **keep in sync** global fit to actual data and HL-LHC projections
- con: does **not exploit HL-LHC optimisation** *e.g.* more bins in high-p_T region, multi-differential measurements

todo list: include the available tailored projections for HL-LHC observables

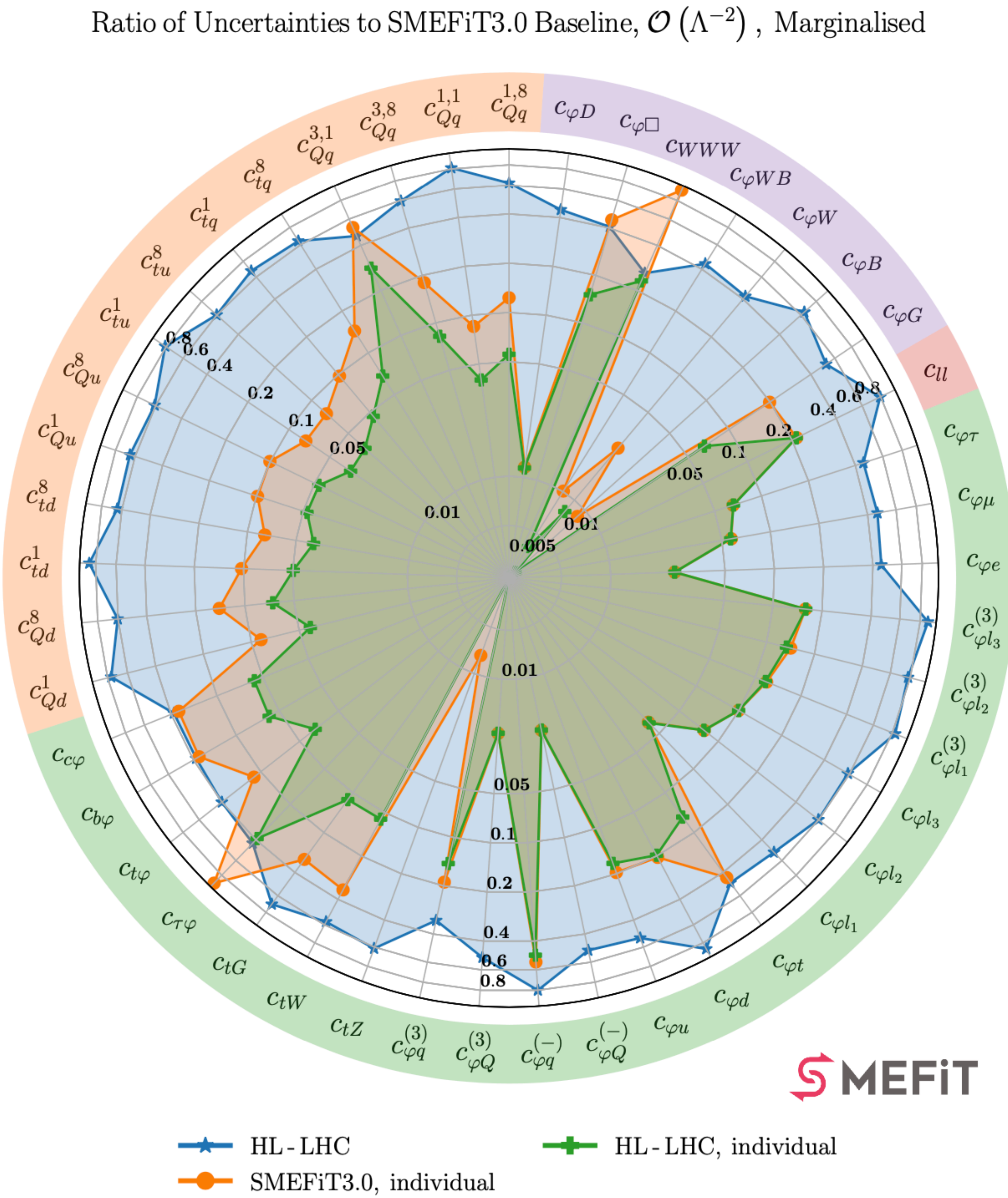
Goal: provide a **realistic baseline**, in preparation of the subsequent inclusion of the FCC-ee and CEPC projections, in terms of constraints in the SMEFT parameter space

HL-LHC projections



- HL-LHC: bounds on the EFT coefficients **improved by up to a factor 3** as compared to current dataset
- Large differences between marginalised bounds from global fit and individual (one-parameter fits) bounds: the latter are overly optimistic
- HL-LHC reach can be improved with inclusion of **optimised observables**
- Qualitatively similar picture in the quadratic fits

HL-LHC projections



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FCC-ee projections

FCC-ee and CEPC projections follow the **Snowmass study** (except for 4 IPs for FCC-ee, following feasibility study)

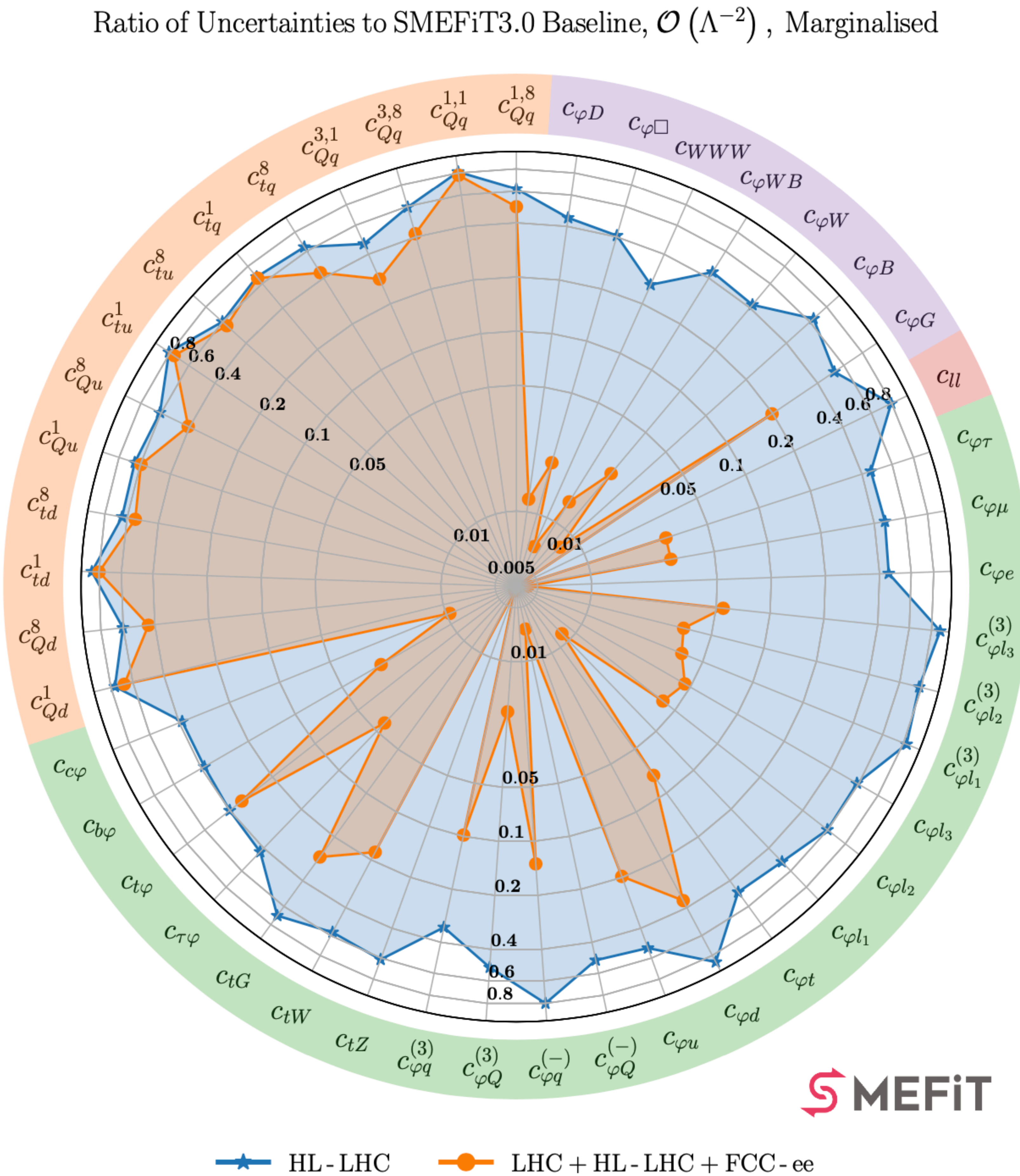
Energy ($\sqrt{s}$)	$\mathcal{L}_{\text{int}}$ (Run time)		$\mathcal{L}_{\text{FCC-ee}}/\mathcal{L}_{\text{CEPC}}$
	FCC-ee (4 IPs)	CEPC (2 IPs)	
91 GeV (Z-pole)	300 ab^{-1} (4 years)	100 ab^{-1} (2 years)	3
161 GeV ($2\,m_W$)	20 ab^{-1} (2 years)	6 ab^{-1} (1 year)	3.3
240 GeV	10 ab^{-1} (3 years)	20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

Variations upon this configuration would be easy to implement

In our analysis, we consider five different classes of observables that are accessible at high-energy circular electron-positron colliders such as the FCC-ee and the CEPC. These are the EWPOs at the Z-pole; light fermion (up to b quarks and τ leptons) pair production; Higgs boson production in both the hZ and $h\nu\nu$ channels; gauge boson pair production; and top quark pair production. Diboson (W^+W^-) production becomes available at $\sqrt{s} = 161$ GeV (WW threshold), Higgs production opens up at $\sqrt{s} = 240$ GeV, and top quark pair production is accessible starting from $\sqrt{s} = 350$ GeV, above the $t\bar{t}$ threshold.

Among these processes, the Z-pole EWPOs, light fermion-pair, W^+W^-, and Higgs production data are included at the level of inclusive cross-sections, accounting also for the corresponding branching fractions. The complete list of observables considered, together with the projected experimental uncertainties entering the fit, are collected in App. E. For diboson and top quark pair production, we consider also unbinned normalised measurements within the optimal observables approach, described in App. F. We briefly review below these groups of processes.

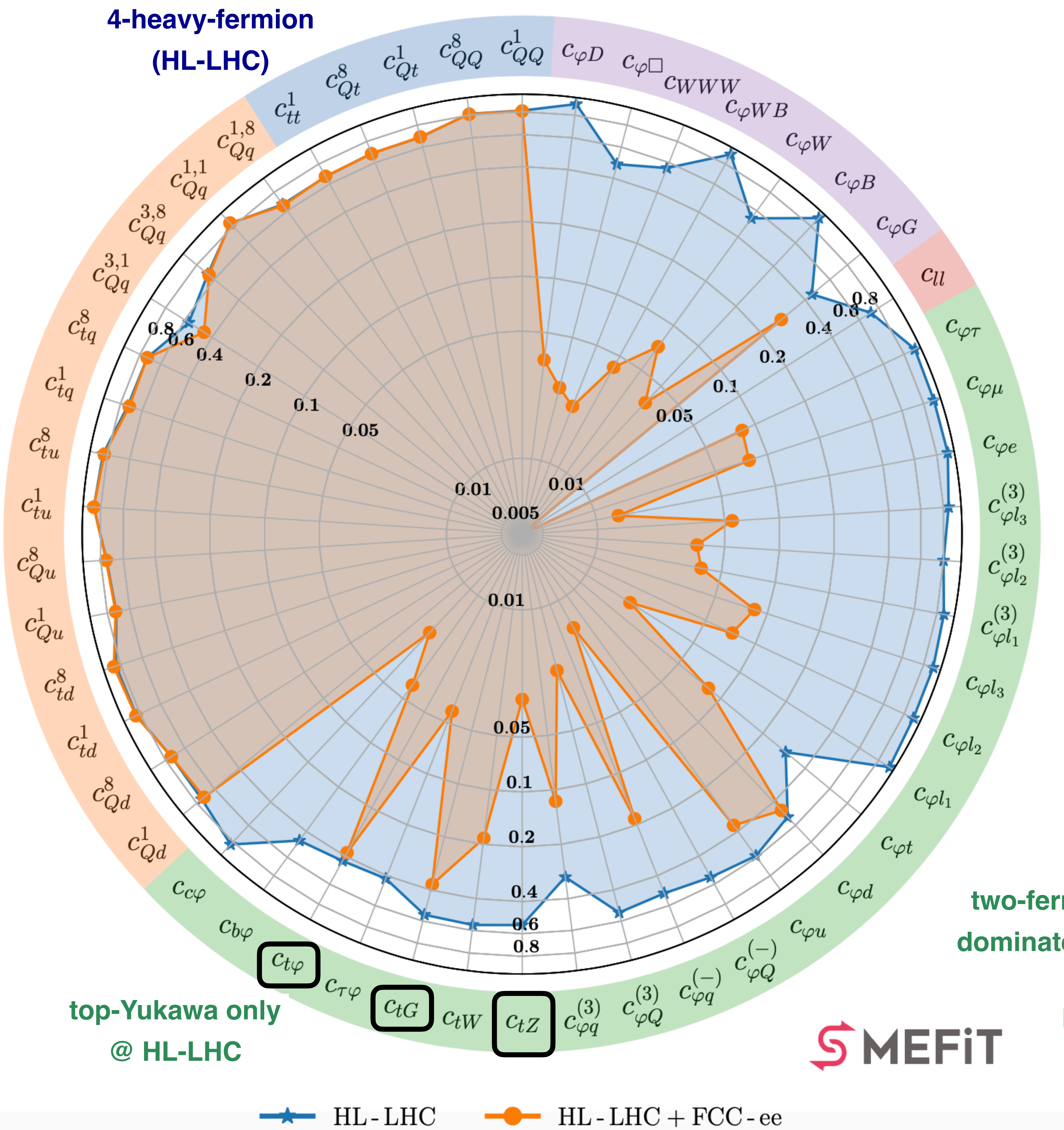
FCC-ee projections



- FCC-ee: **huge improvements** (up to factor 100) for most coefficients
- Clear impact on **two-fermion**, **purely bosonic**, and **four-lepton operators**
- Four-fermion operators **involving top quarks** are unaffected by FCC-ee
- Note: these are **global marginalised bounds**. If one performs individual (one-parameter) fits, impact of FCC-ee is even stronger.

Top couplings

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

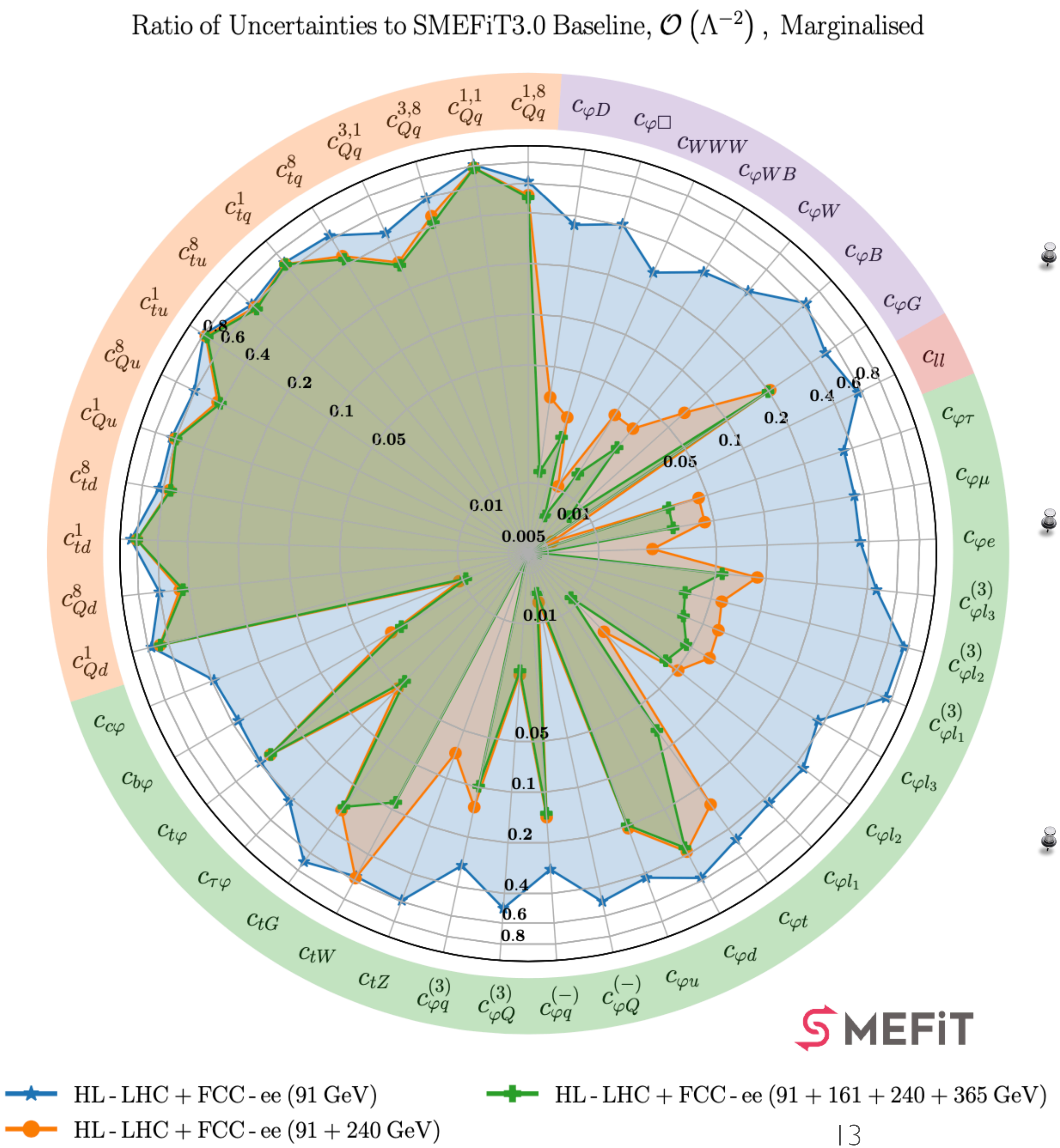


2-light-2-heavy 4-fermion (HL-LHC)

two-fermion (mostly dominated by FCC-ee)

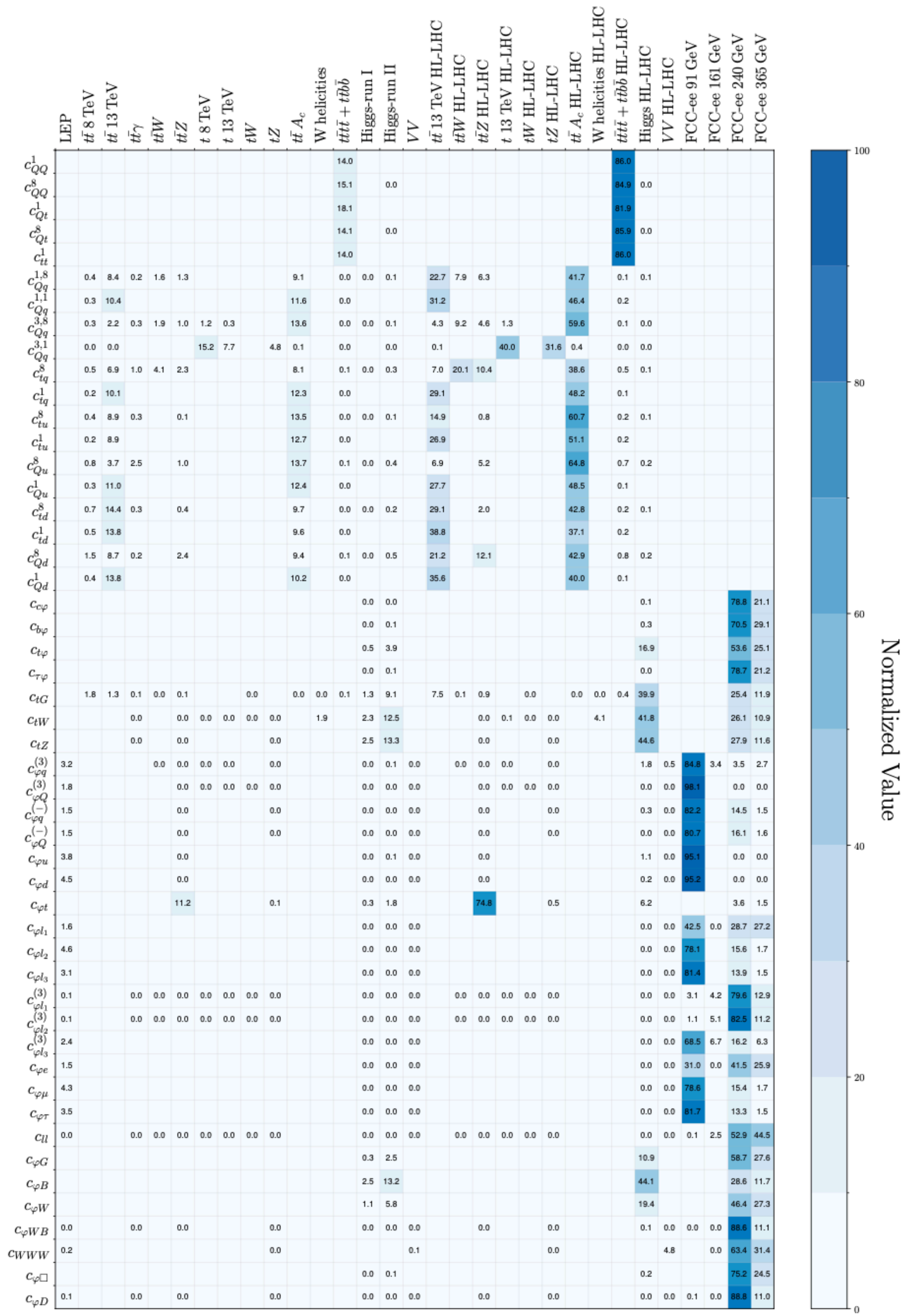
HL-LHC still best for c_{tG}, $c_{t\varphi}$

FCC-ee projections



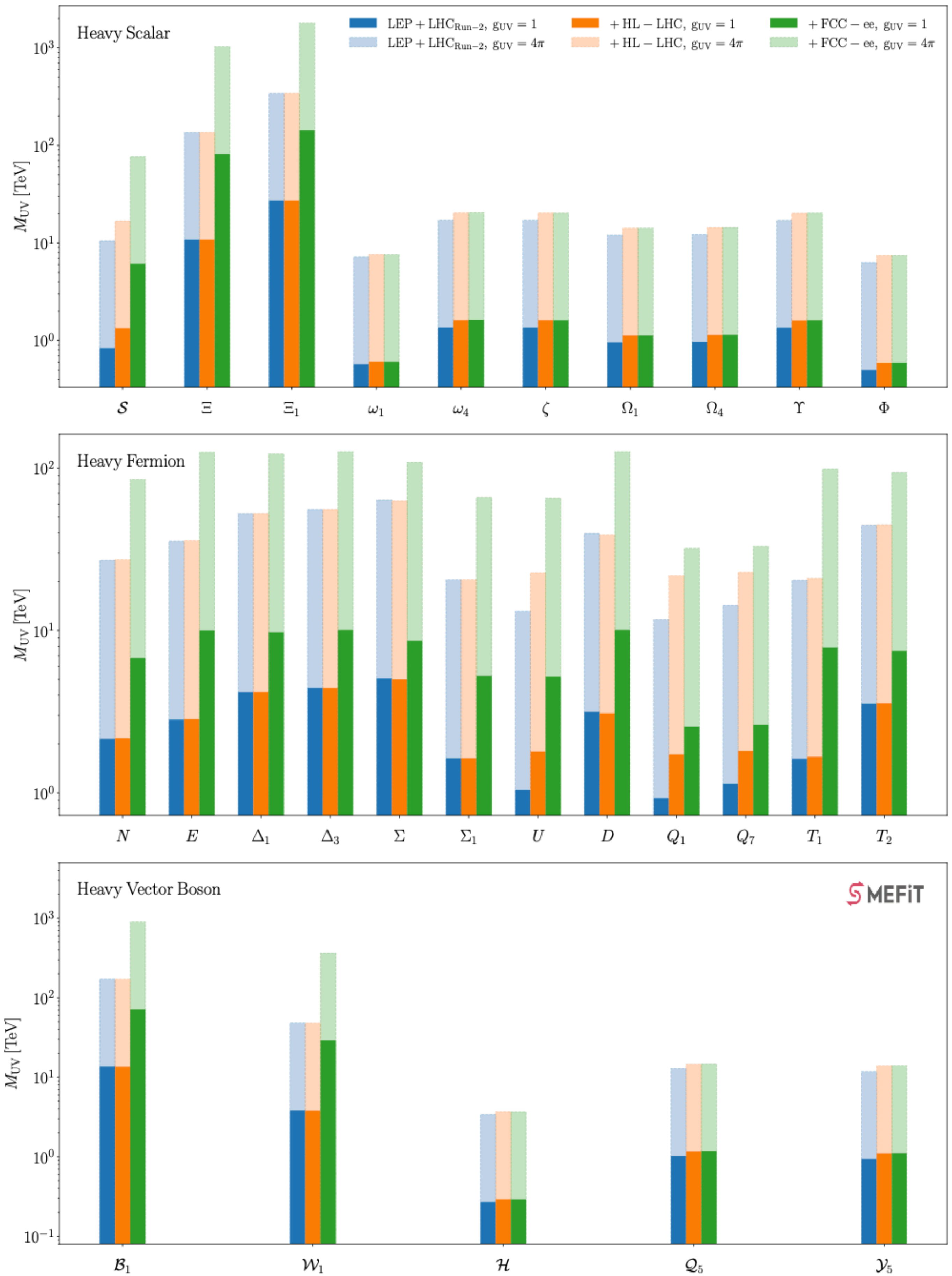
- Study impact of **sequentially adding FCC-ee datasets** for different energies
- Combining the **Z-pole run** with the **Higgs factory run at 240 GeV** dominates the final reach
- Can try **any other combination**, also to help determining which run order is most effective at least in terms of the SMEFT

Fisher Information analysis



- Various **statistical measures** available to determine which datasets dominate the reach for specific EFT directions
- FCC-ee fully **dominates the constraints on all operators** except the two-light-two-heavy ones
- In terms of the SMEFT, the run at **161 GeV** is the one providing less information

Matching to UV models

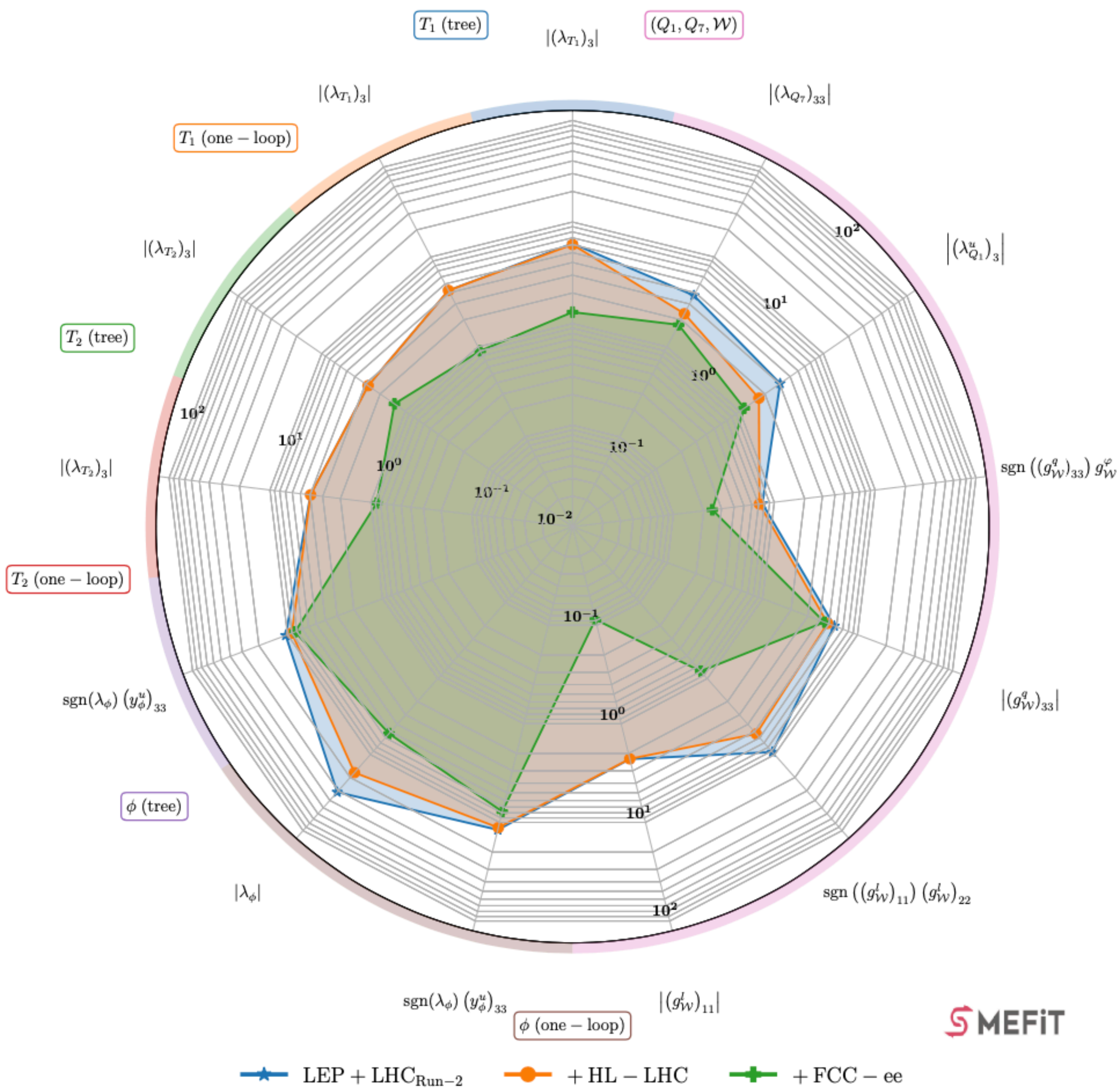


- Lower bounds (95% CL) on different **one-particle extensions** of the SM matched to the SMEFT at tree level

- FCC-ee has an (indirect) reach on **heavy particles with masses between a few TeV and up to around 100 TeV**, for O(1) UV couplings

- Strongest impact for UV models that induce the purely bosonic and two-fermion operators, which are tightly constrained by FCC-ee measurements

Matching to UV models



- Analysis can be extended to **multi-particle models** as well as to **one-loop matching** to the SMEFT

- Fully automated pipeline, determining constraints from FCC-ee data on **general UV models** matched to the SMEFT is now streamlined

Summary and outlook

- The SMEFiT framework enables detailed projection studies quantifying the **impact of future colliders** in the parameter space of the SMEFT and of UV-complete models matched upon it

- Starting point is a **state-of-the-art global EFT fit**, extended first with HL-LHC and then FCC-ee projections

- All results shown are fully reproducible by means of our **open-source, user-friendly code**

- Results for **CEPC** are in general similar to those of the FCC, with some noteworthy differences

- Projections for HL-LHC can be refined with the used of **optimised observables** (better coverage of high-mass region, multi-differential observables, benefitting from increased statistics)

- In the pipeline is incorporating projections for **other proposed future colliders** (ILC, CLIC, C3, muon collider), more extensive investigations of the impact on **UV complete models**, and making more general the operator basis (flavour assumptions) defining our baseline analysis

Interested in projections for future colliders? **Try SMEFiT**, and let us know if any required functionality is missing!