Global SMEFT fits

from (HL)-LHC to future colliders

Jaco ter Hoeve

10/05

STANDARD MODEL AT THE LHC

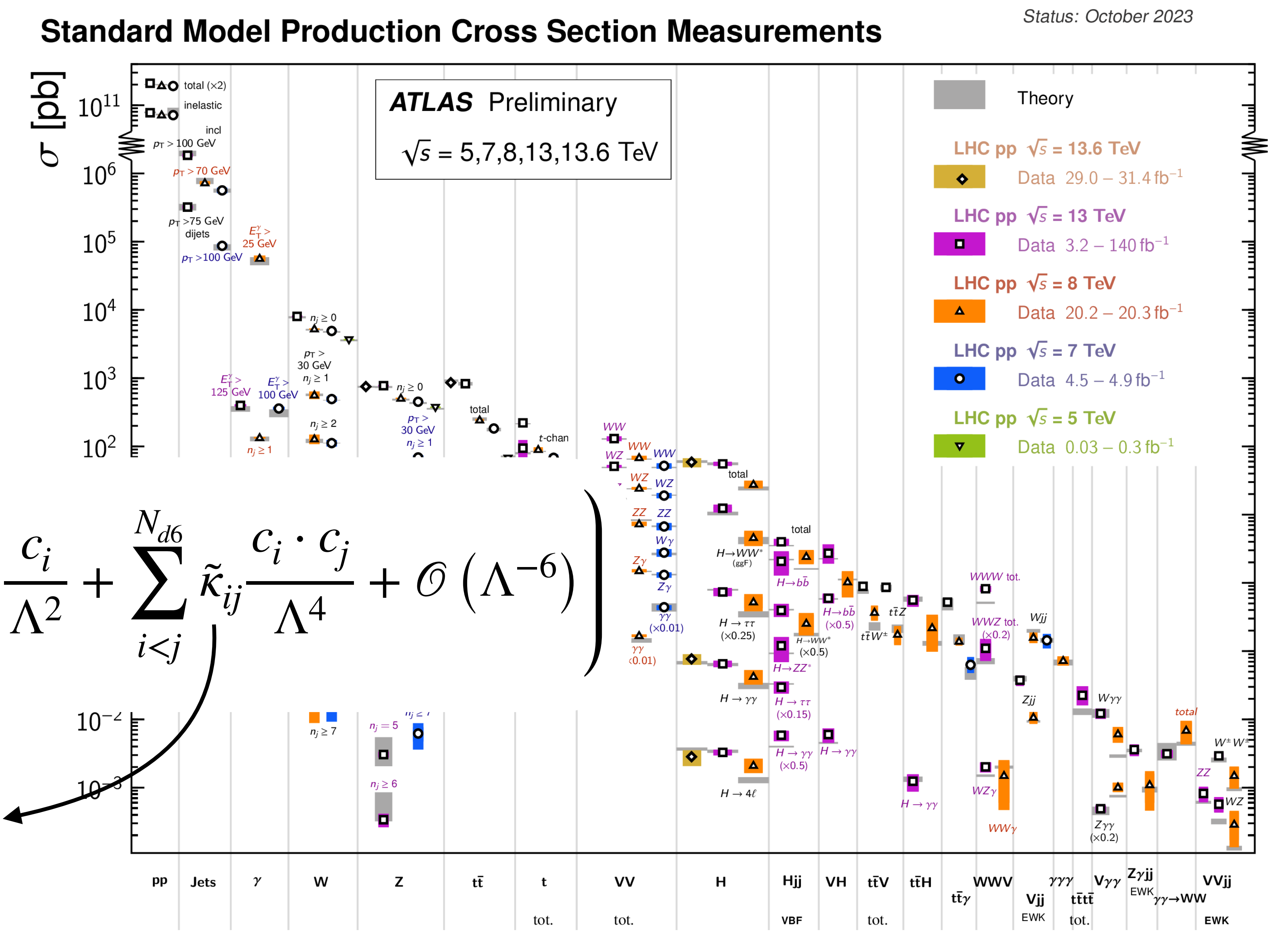
Rome, May 7-10, 2024

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]



Standard Model Production Cross Section Measurements

Status: October 2023

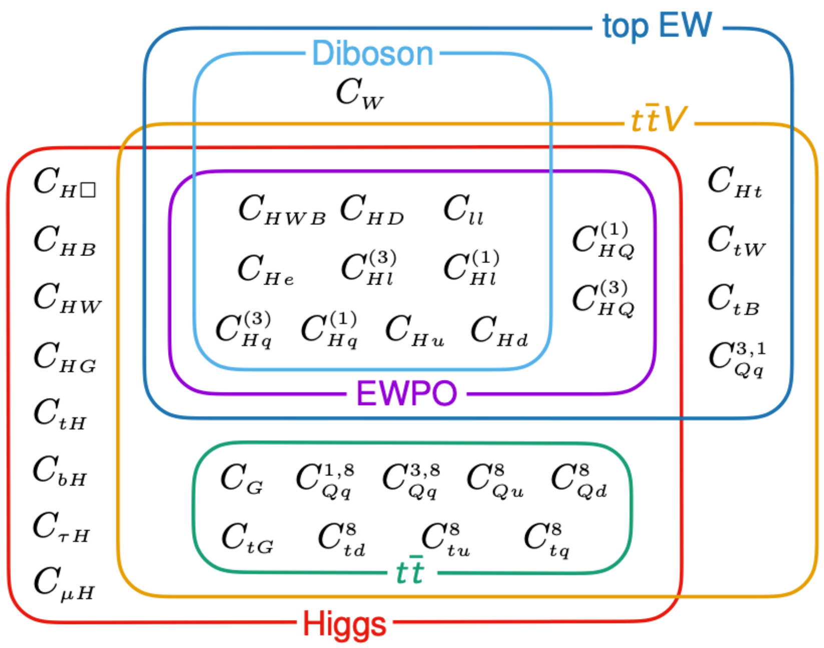
Linear EFT corrections:
interference SM-EFTd6
@NLO QCD

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

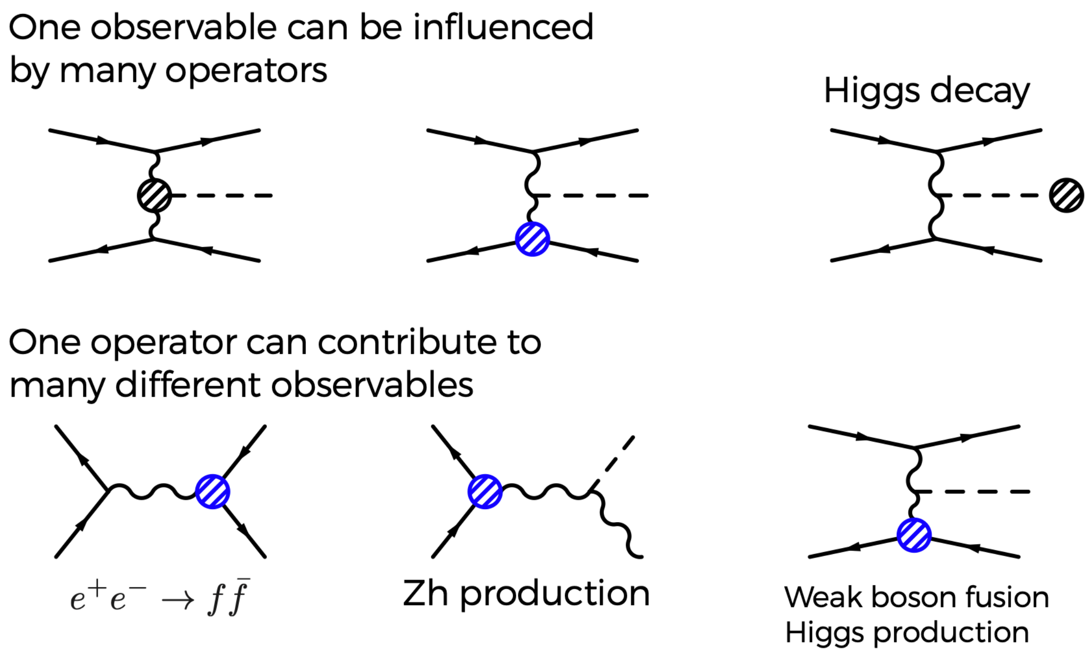
Quadratic EFT
corrections:
EFTd6-EFTd6
@NLO QCD

Why global 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

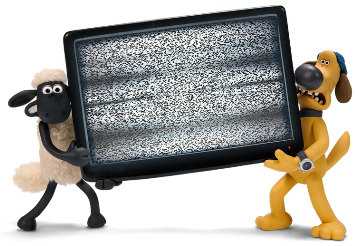


[2012.02779] Fitmaker collaboration

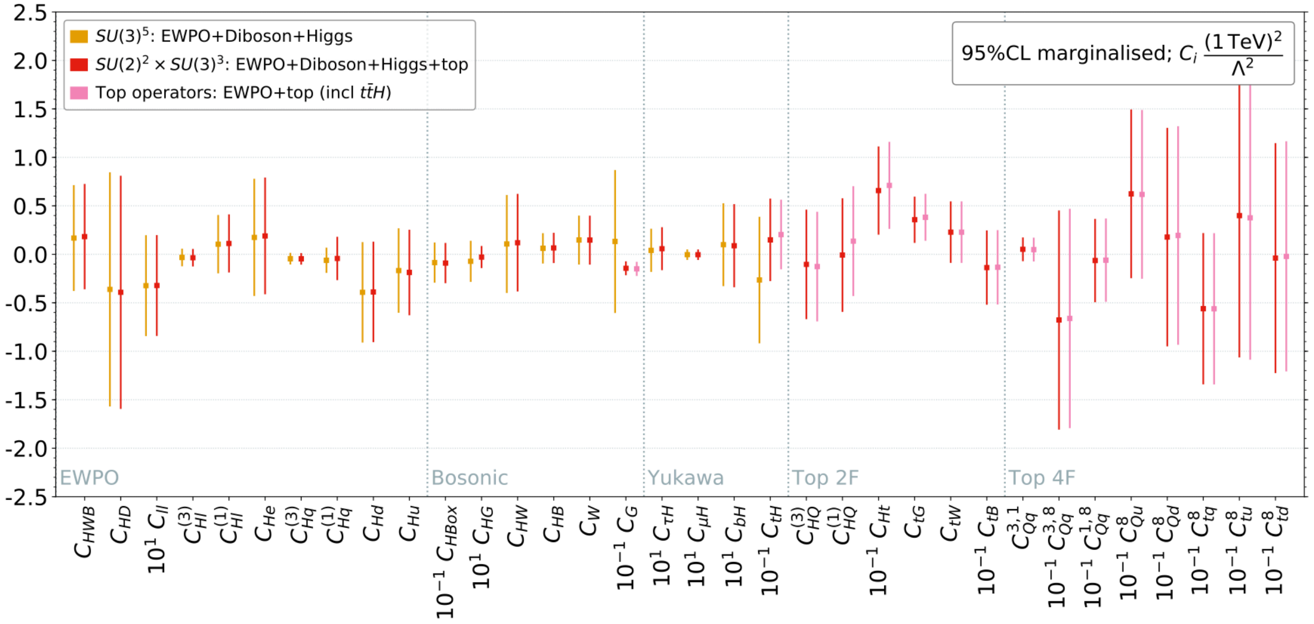


Anke Biekötter - HET seminar Brookhaven

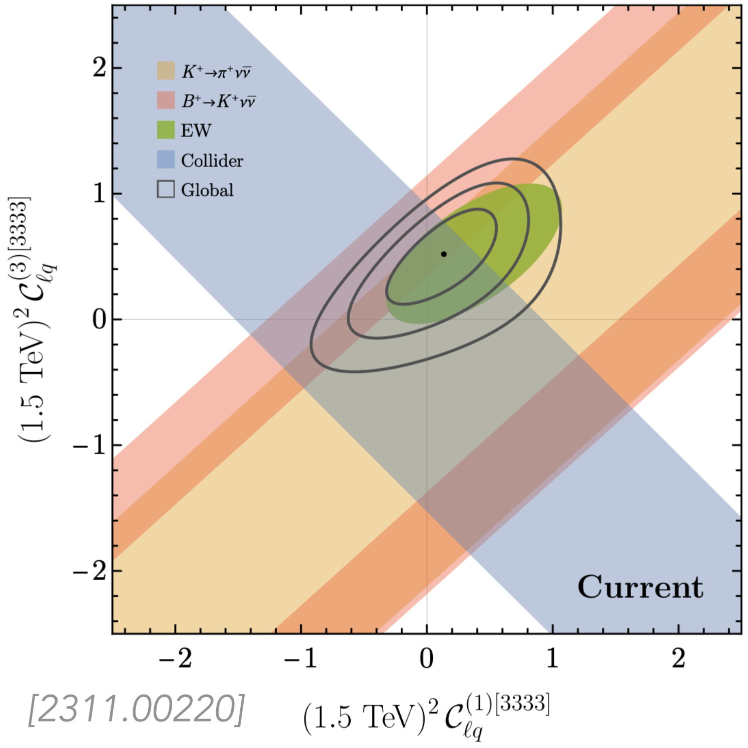
Previously on global fits…



- **SMEFiT**: EW + Higgs + diboson + top + projections, NLO, quadratic - *[2105.00006, 2309.04523 , 2404.12809]*
- **ATLAS**: EW + Higgs, LO, quadratic - *[ATL-PHYS-PUB-2022-037]* → See Andrea Visibile's talk!
- **simuNET:** simultaneous EFT + PDF fit in EW + Higgs + diboson + top, NLO, linear - *[2402.03308]*
- **Fitmaker**: EW + Higgs + top + diboson, linear - *[2012.02779, 2204.05260]*
- **SFitter**: EW + Higgs, top, NLO, quadratic - *[1812.07587, 1910.03606]*
- **HEPfit:** EW, flavour, projections, LO, linear - *[1910.14012]*
- **TopFitter:** top, linear, LO - *[1901.03164]*
- **EFTfitter:** top + DY + flavour, LO, quadratic, RG effects - *[1605.05585, 2304.12837]* → Lara Nollen's talk from Wednesday
- **Mainz group:** EW + Higgs + top + flavour + dijet + PV + lepton scattering, NLO, linear - *[2311.04963]*
- **Zurich group:** EW + flavour + (DY, LEPII, Jet observables), individual, RG effects - *[2311.00020]* → Lukas Allwicher's talk from Wednesday



Fitmaker collaboration [2012.02779]

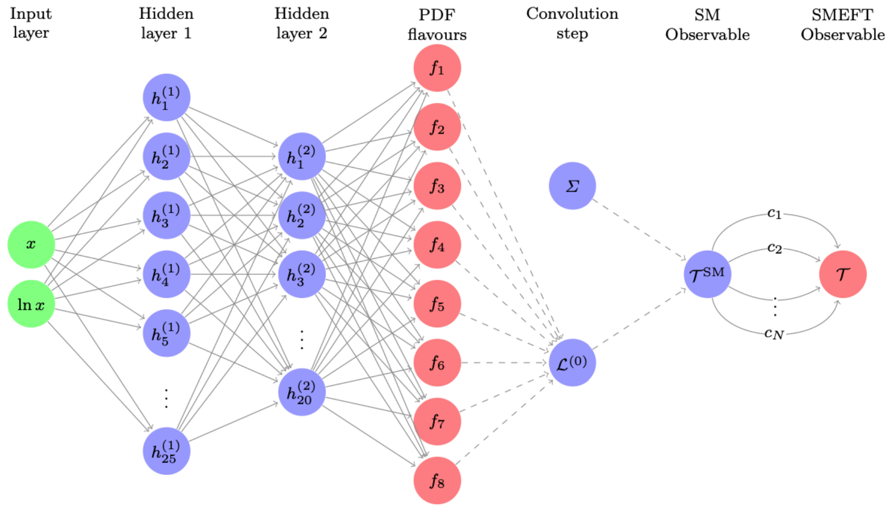


[2311.00220]

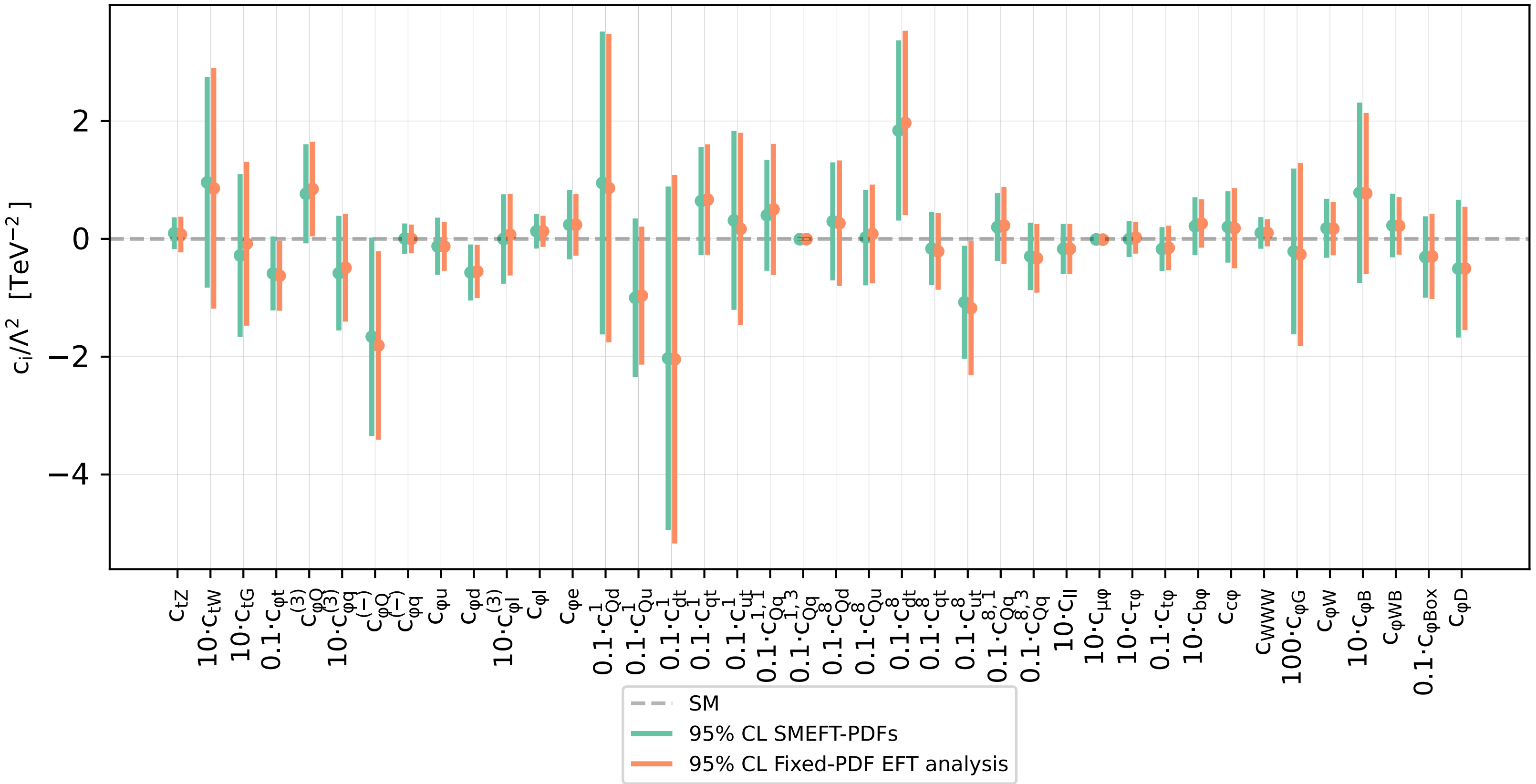
simuNET: a simultaneous PDF + EFT fit

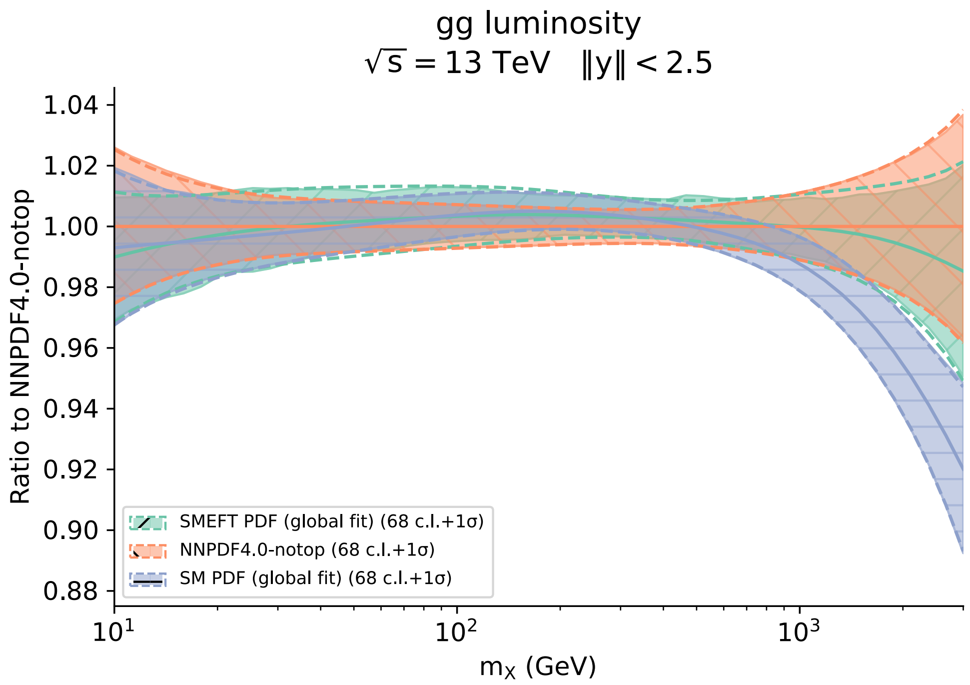
- Most EFT global fits assume a fixed PDF set. A full treatment should fit the EFT and PDF parameters **simultaneously**, as done by simuNET

- EFT parameters are stable, while the PDF fits undergo **shifts** at high invariant mass in e.g. the gluon-gluon luminosity



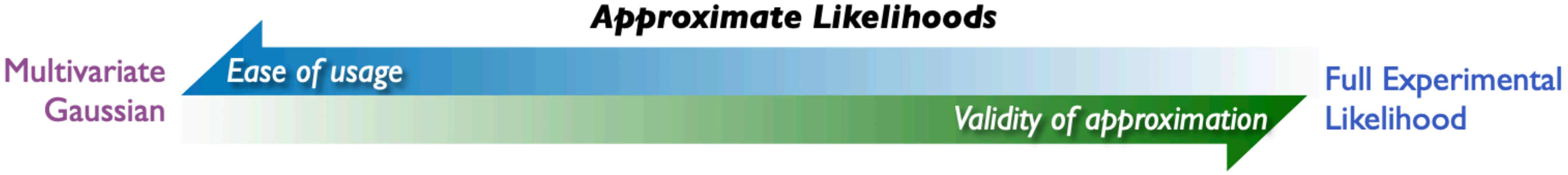
Costantini, Hammou, Madigan, Mantani, Moore, Morales, Ubiali [2402.03308]





SMEFT and public likelihoods

- Publishing the full statistical model in **HistFactory** format is getting more and more common (30 public ATLAS likelihoods so far) → Nicholas Wardle's talk from Thursday



Approximate Likelihoods

Multivariate Gaussian

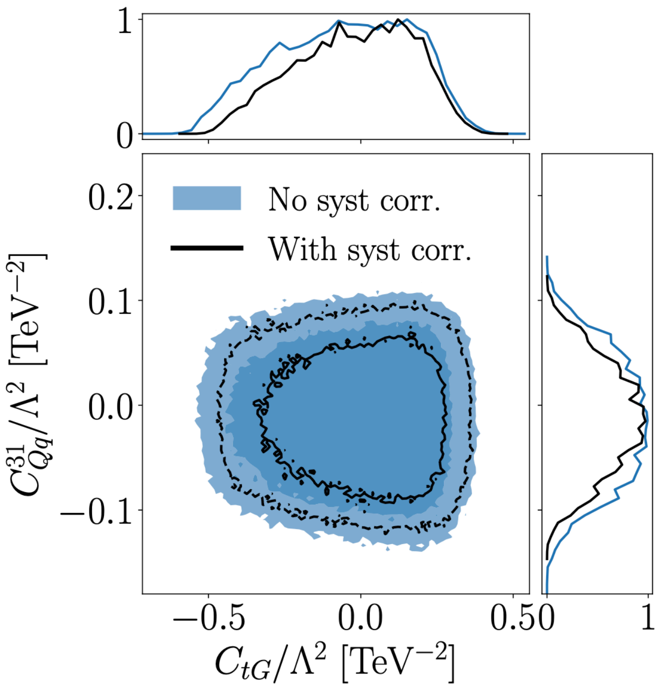
Ease of usage

Validity of approximation

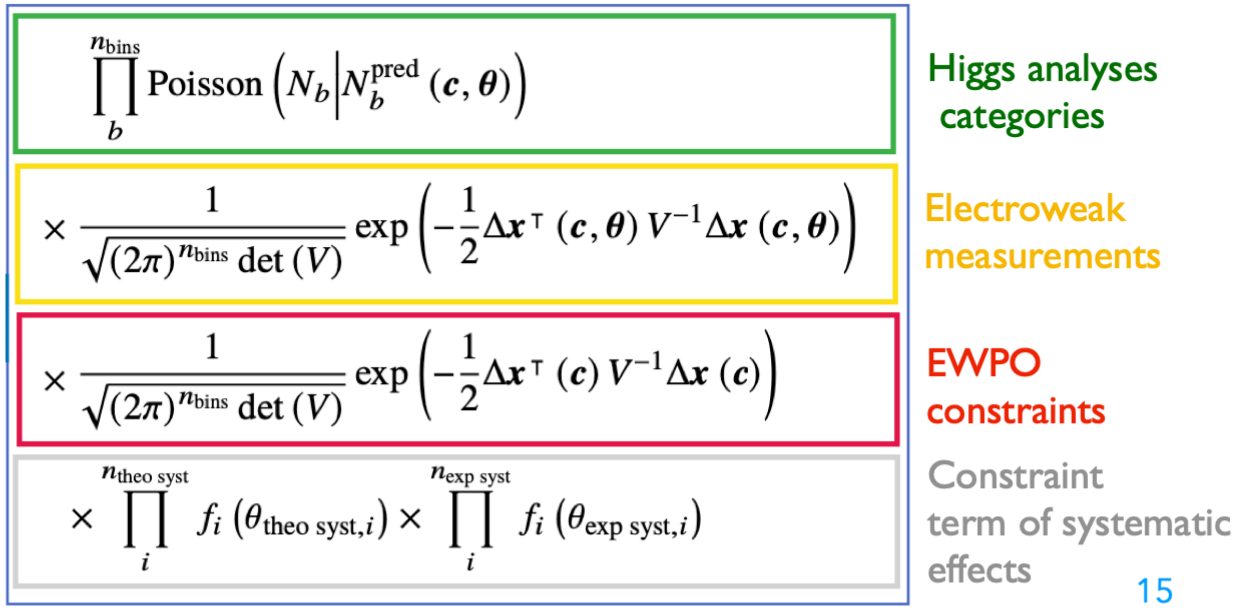
Full Experimental Likelihood

Reinterpretation forum, R. Balasubramanian

- Extremely valuable and a promising tool **outside** experimental collaborations



Elmer, Madigan, Plehn, Schmal - [2312.12502]



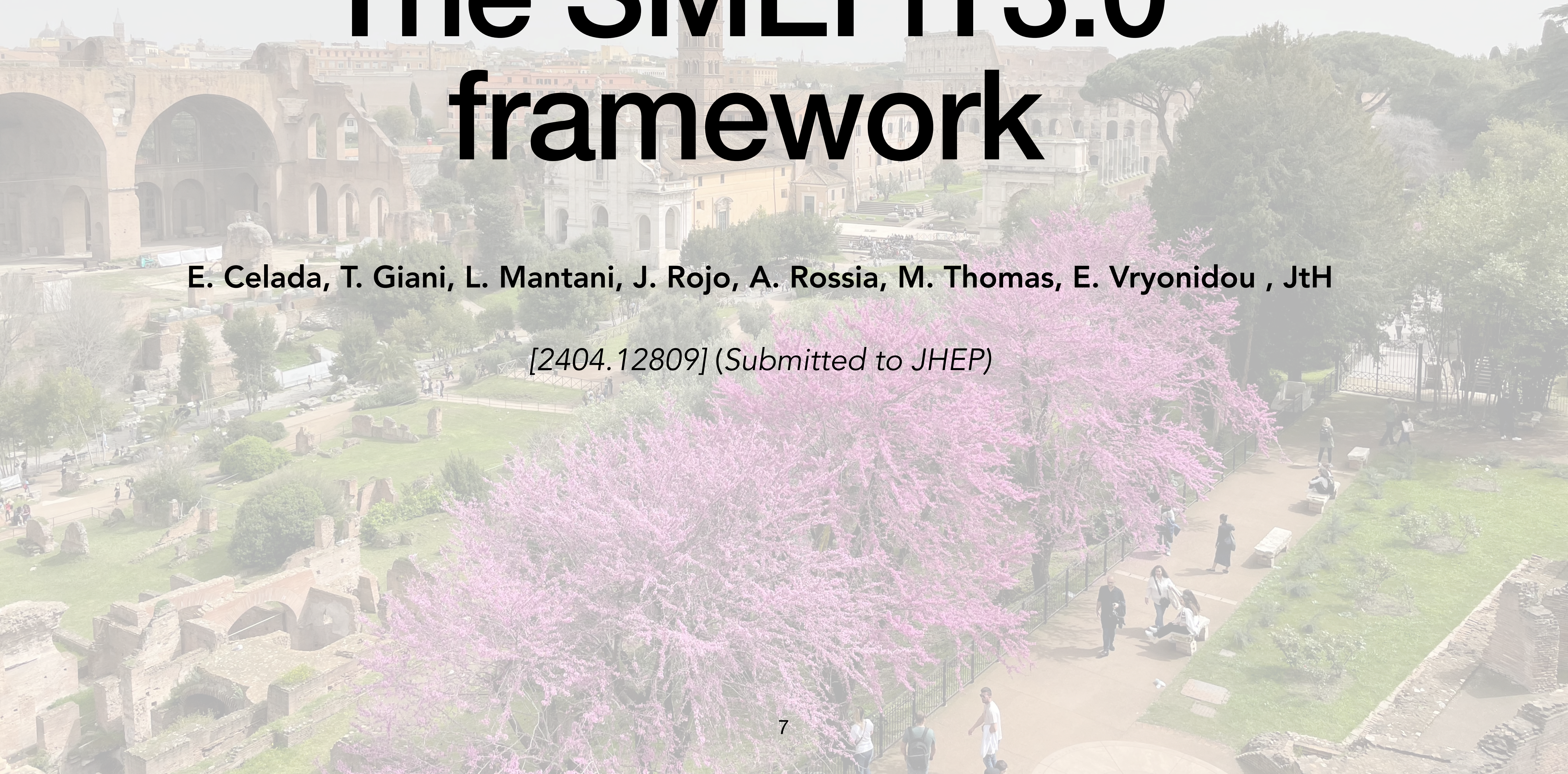
$$\prod_{b}^{n_{\text{bins}}} \text{Poisson}\left(N_b \middle| N_b^{\text{pred}}(\boldsymbol{c},\boldsymbol{\theta})\right)$$

$$\times \frac{1}{\sqrt{(2\pi)^{n_{\text{bins}}}\det(V)}} \exp\left(-\frac{1}{2}\Delta\boldsymbol{x}^{\intercal}(\boldsymbol{c},\boldsymbol{\theta})\, V^{-1}\Delta\boldsymbol{x}(\boldsymbol{c},\boldsymbol{\theta})\right)$$

$$\times \frac{1}{\sqrt{(2\pi)^{n_{\text{bins}}}\det(V)}} \exp\left(-\frac{1}{2}\Delta\boldsymbol{x}^{\intercal}(\boldsymbol{c})\, V^{-1}\Delta\boldsymbol{x}(\boldsymbol{c})\right)$$

$$\times \prod_{i}^{n_{\text{theo syst}}} f_i\left(\theta_{\text{theo syst},i}\right) \times \prod_{i}^{n_{\text{exp syst}}} f_i\left(\theta_{\text{exp syst},i}\right)$$

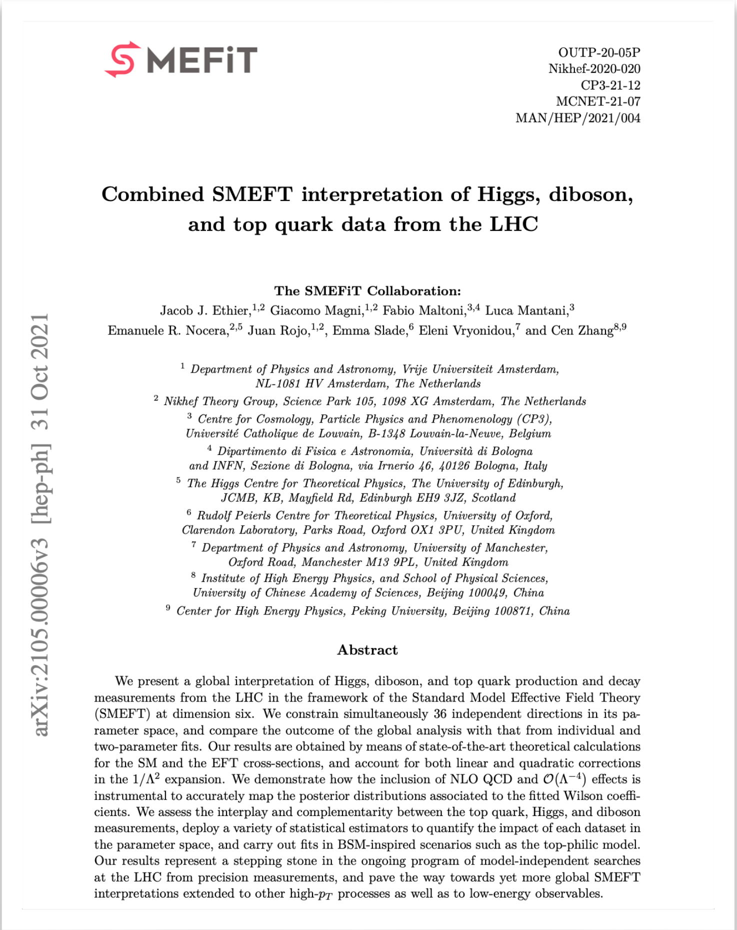
The SMEFiT3.0 framework



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

[2404.12809] (*Submitted to JHEP)*

The SMEFiT timeline



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

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:
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]

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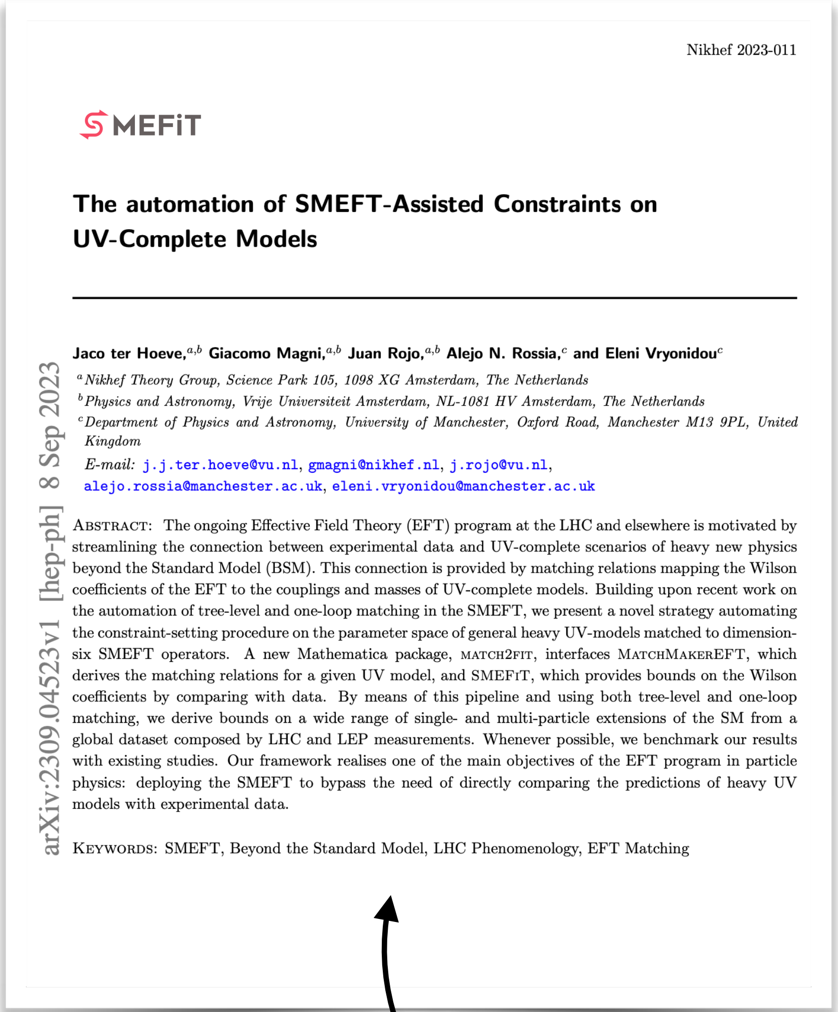
[2] *Nikhef Theory Group, Science Park 105, 1098 XG Amsterdam, The Netherlands*
[3] *Centre for Cosmology, Particle Physics and Phenomenology (CP3), Université Catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*
[4] *Dipartimento di Fisica e Astronomia, Università di Bologna and INFN, Sezione di 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 two-parameter fits. Our results are obtained by means of state-of-the-art theoretical calculations for the SM and the EFT cross-sections, and account for both linear and quadratic corrections in the $1/\Lambda^2$ expansion. We demonstrate how the inclusion of NLO QCD and $\mathcal{O}(\Lambda^{-4})$ effects is instrumental to accurately map the posterior distributions associated to the fitted Wilson coefficients. We assess the interplay and complementarity between the top quark, Higgs, and diboson measurements, deploy a variety of statistical estimators to quantify the impact of each dataset in the parameter space, and carry out fits in BSM-inspired scenarios such as the top-philic model. Our results represent a stepping stone in the ongoing program of model-independent searches at the LHC from precision measurements, and pave the way towards yet more global SMEFT interpretations extended to other high-p_T processes as well as to low-energy observables.



Nikhef 2023-011

SMEFiT

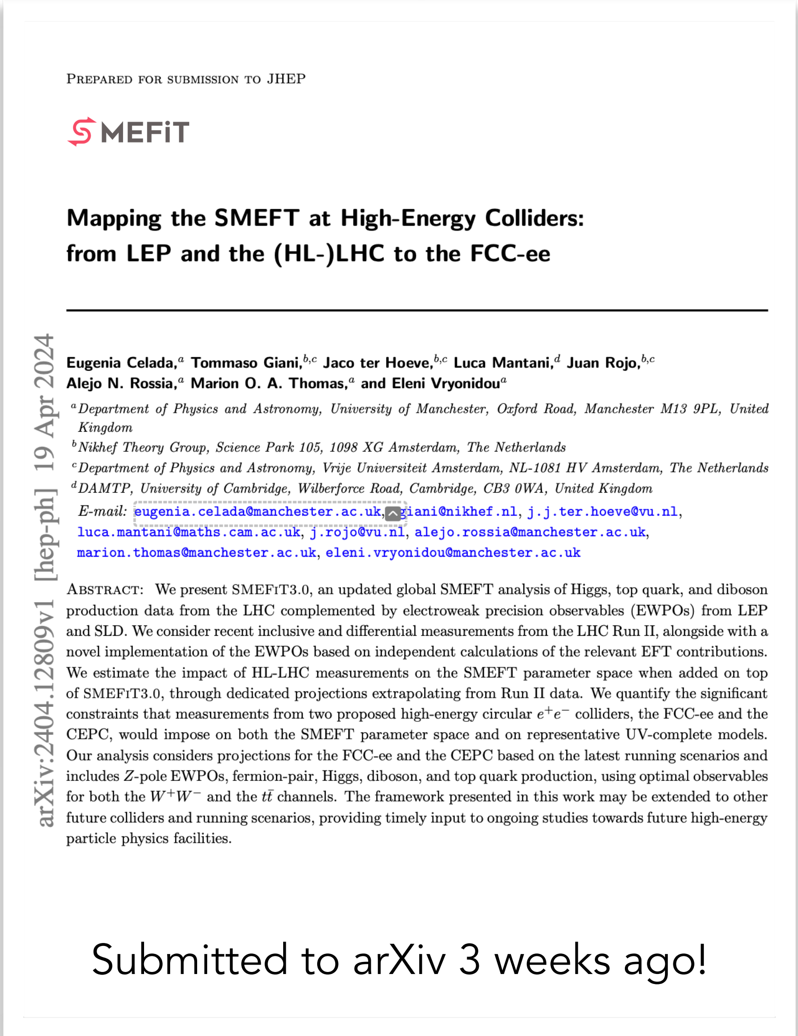
The automation of SMEFT-Assisted Constraints on UV-Complete Models

arXiv:2309.04523v1 [hep-ph] 8 Sep 2023

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



PREPARED FOR SUBMISSION TO JHEP

SMEFiT

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]
[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, giani@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 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.

Submitted to arXiv 3 weeks ago!

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 under the hood

Theory

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

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

NNPDF4.0 no top

SMEFiT

SMEFiT under the hood

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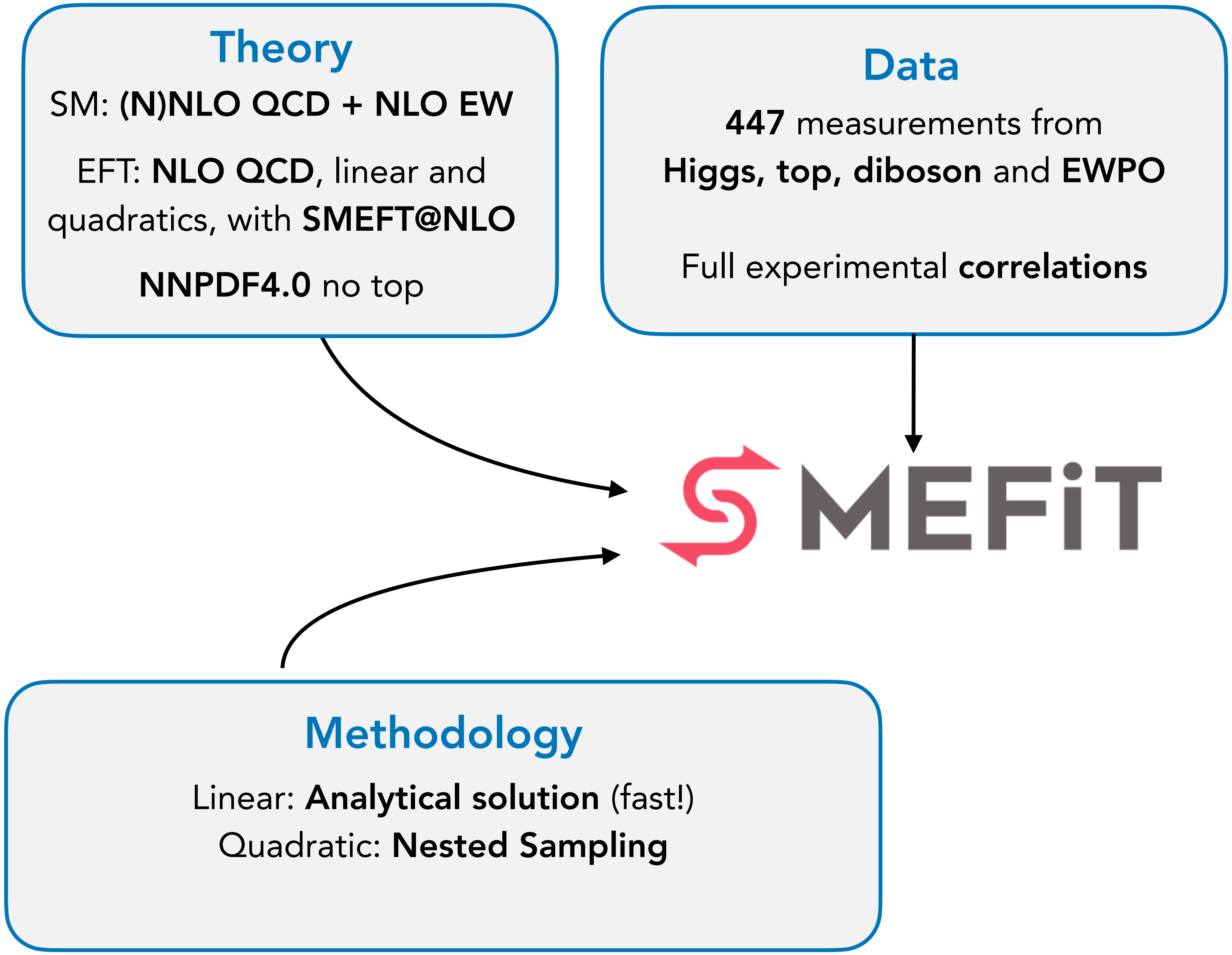
Data

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

Full experimental **correlations**

SMEFiT

SMEFiT under the hood



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SMEFiT

Methodology

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

SMEFiT under the hood

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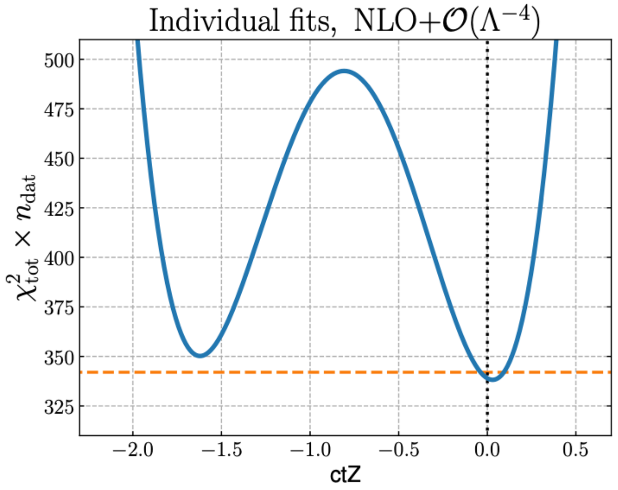
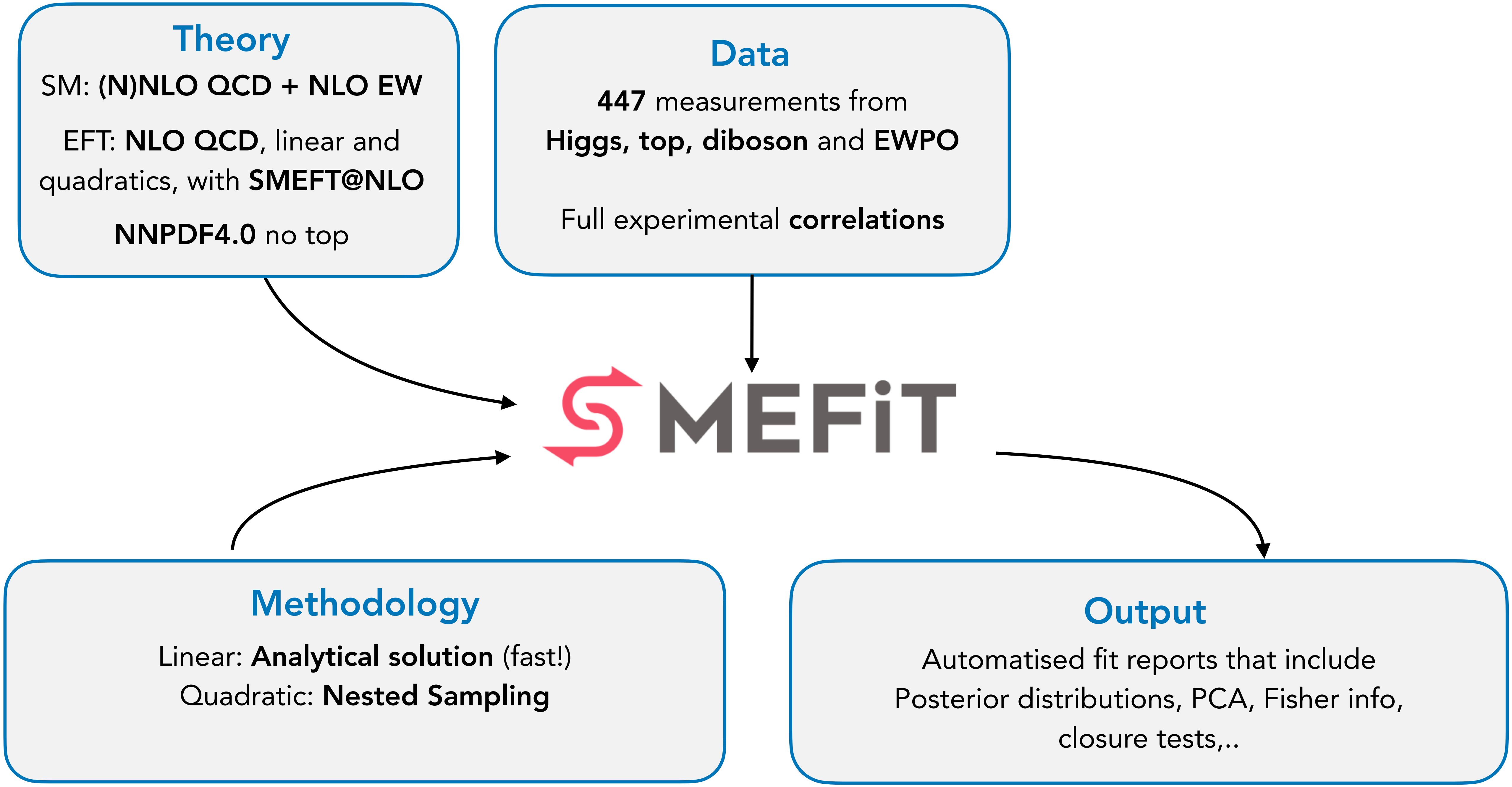


SMEFiT under the hood



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SMEFiT

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Linear: **Analytical solution** (fast!)
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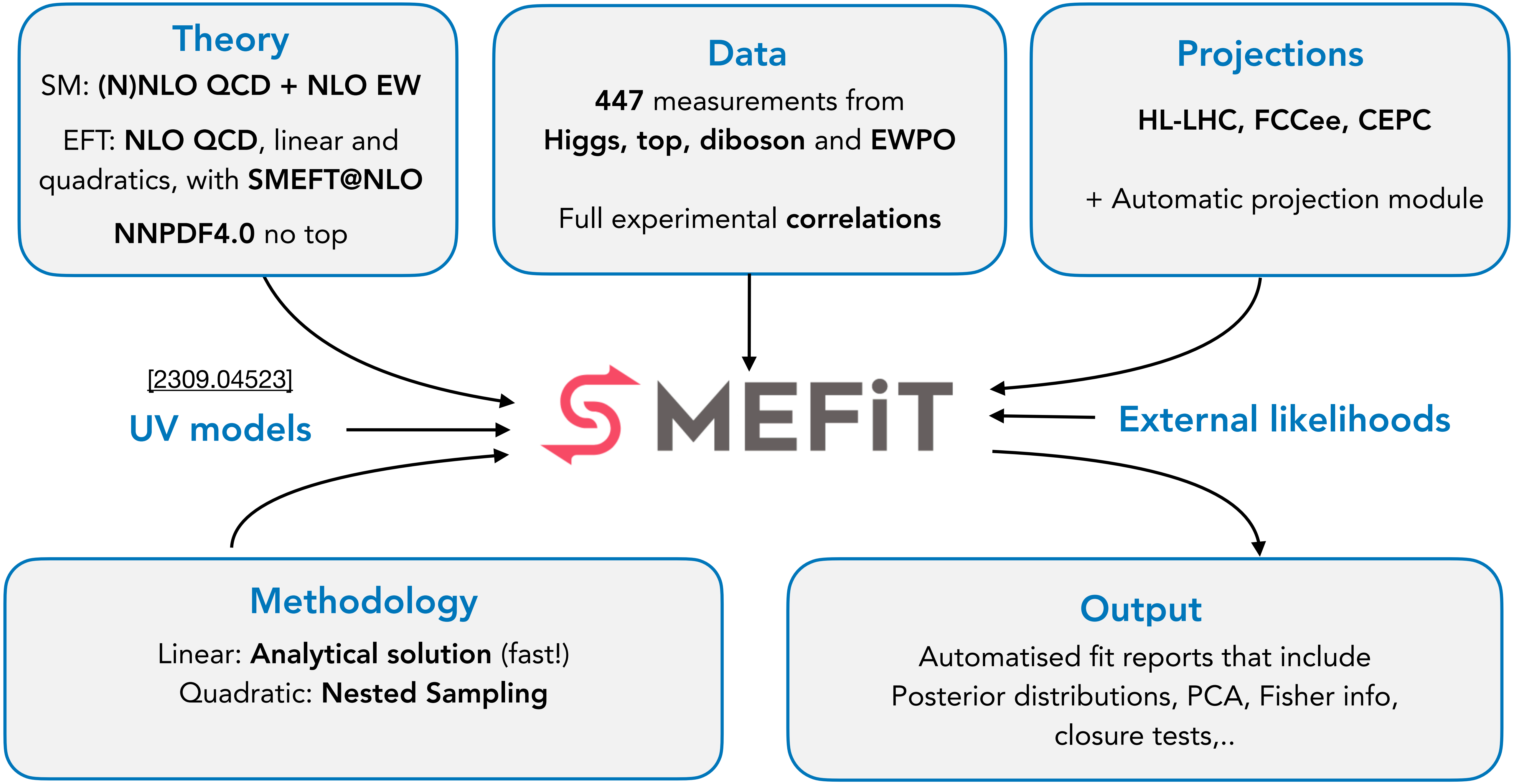
Output

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

SMEFiT under the hood



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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, FCCee, 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,..

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-EFT$_{d6}$
@NLO QCD

Quadratic EFT
corrections:
EFT$_{d6}$-EFT$_{d6}$
@NLO QCD

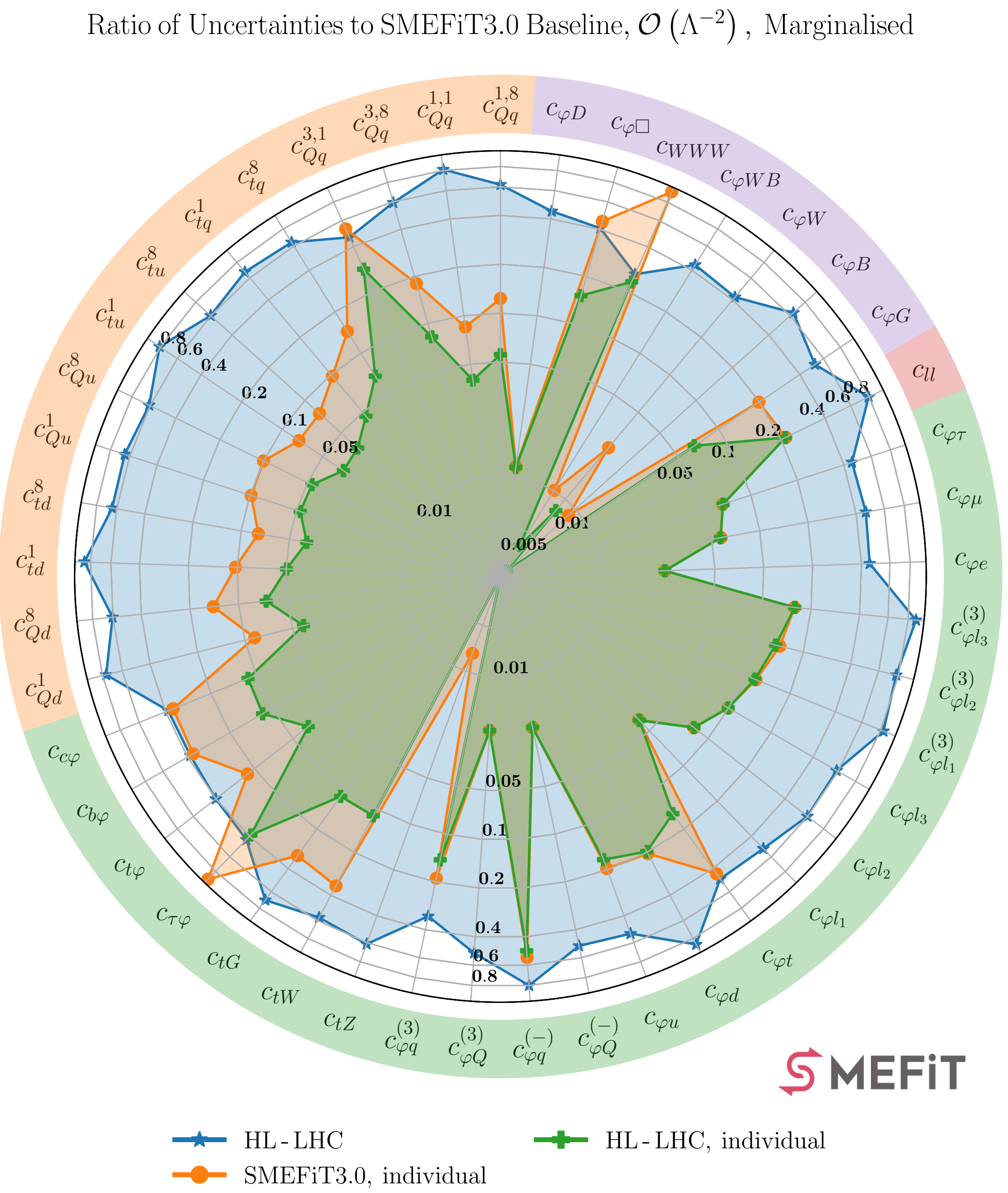
To a combined likelihood ready for optimisation …

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

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

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 [2206.08326], updated to 4 IPs as per the FCC feasibility midterm report
- Both results in terms of Wilson coefficients and **UV-complete models**
- **Public code, data and theory**: results are fully reproducible



"Spider plots / Antarctica plots"

Dataset upgrade

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

Category	Processes	[2105.00006] $n_{\rm dat}$ 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	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: $U(2)_q \times U(3)_d \times U(2)_u \times \left(U(1)_\ell \times U(1)_e\right)^3$

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

- In the SMEFT, the SM couplings receive corrections from dim-6 operators

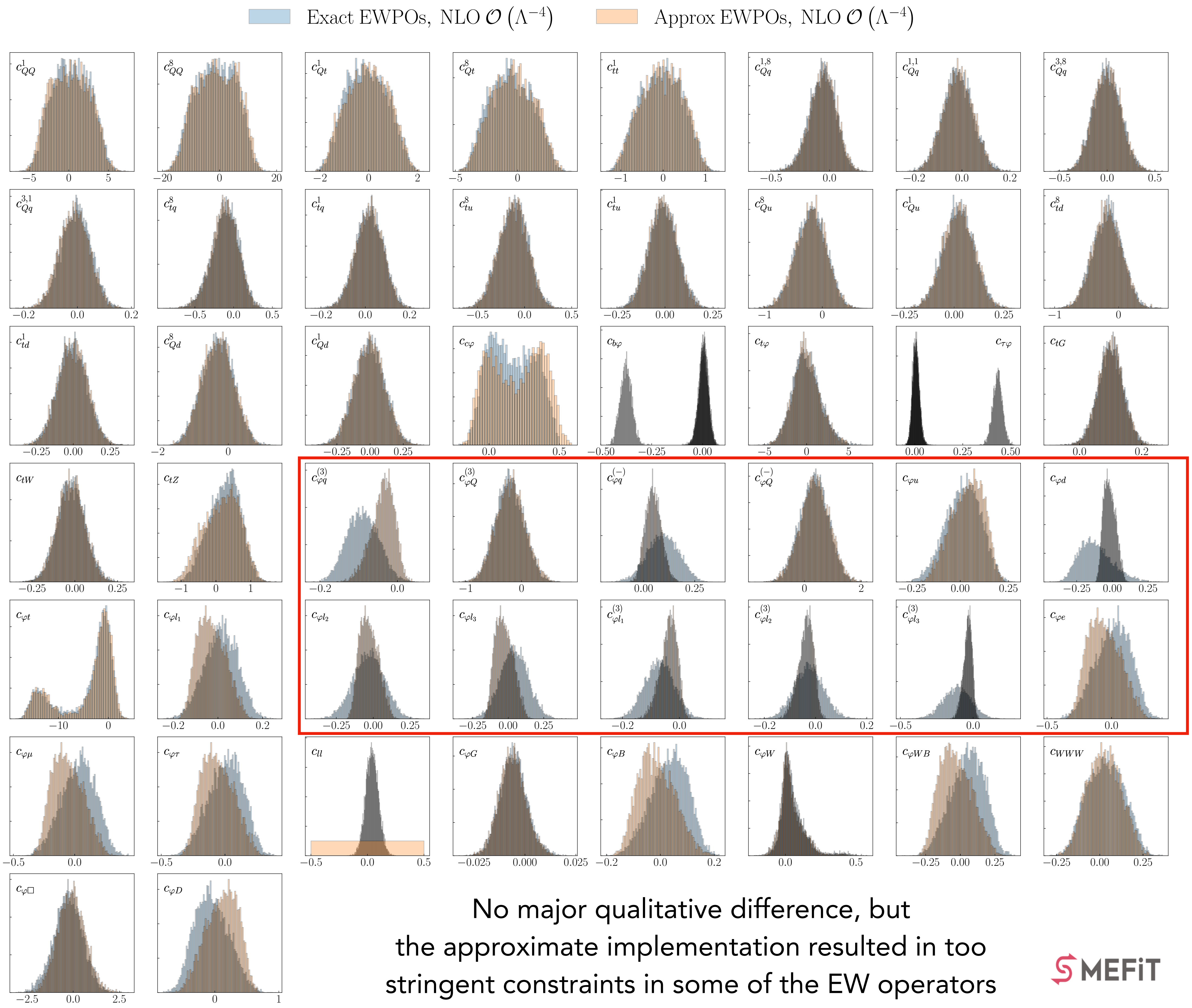
$$\begin{aligned}
\delta g_V^{l_i} &= \delta \bar{g}_Z \bar{g}_V^{l_i} + Q^{l_i} \delta s_\theta^2 + \Delta_V^{l_i} = 0\,, \quad i = 1,2,3\,,\\
\delta g_A^{l_i} &= \delta \bar{g}_Z \bar{g}_A^{l_i} + \Delta_A^{l_i} = 0\,, \quad i = 1,2,3\,,\\
\delta g_V^{u} &= \delta \bar{g}_Z \bar{g}_V^{u} + Q^{u} \delta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

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

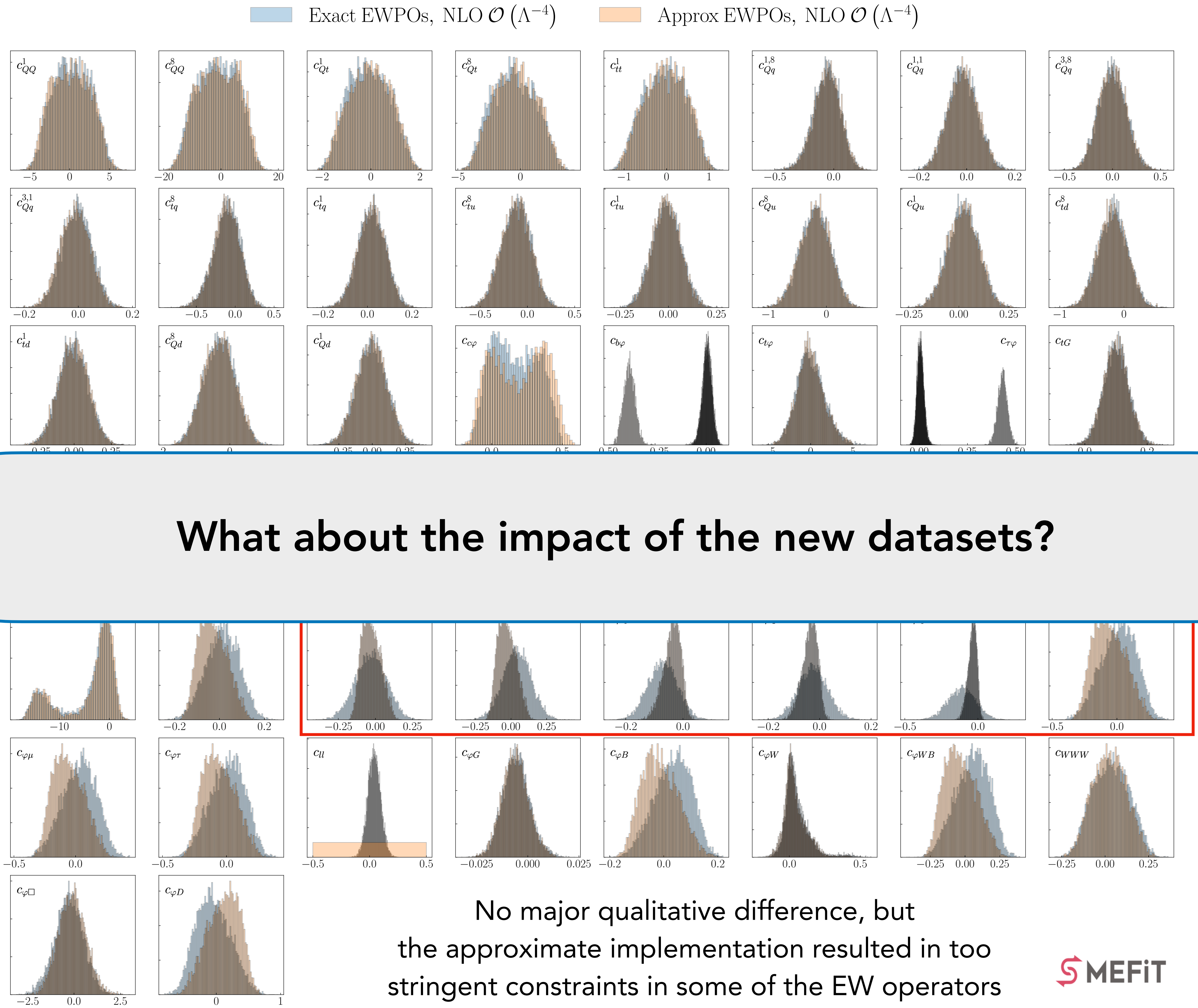
- **SMEFiT2.0:** assumed measurements at LEP were precise enough to set the coupling shifts to zero: 14 constraints, 16 d.o.f

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

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

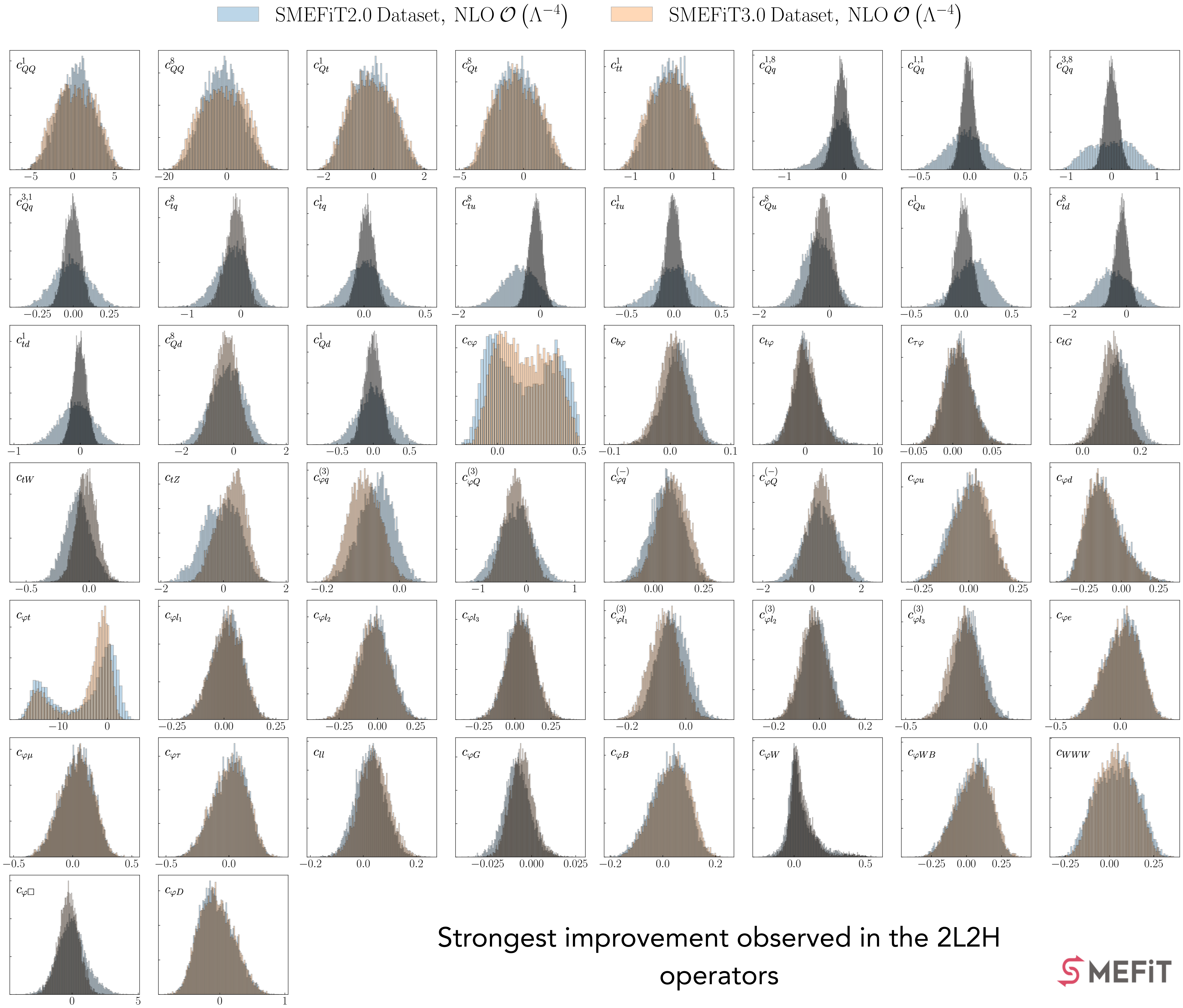


No major qualitative difference, but
the approximate implementation resulted in too
stringent constraints in some of the EW operators



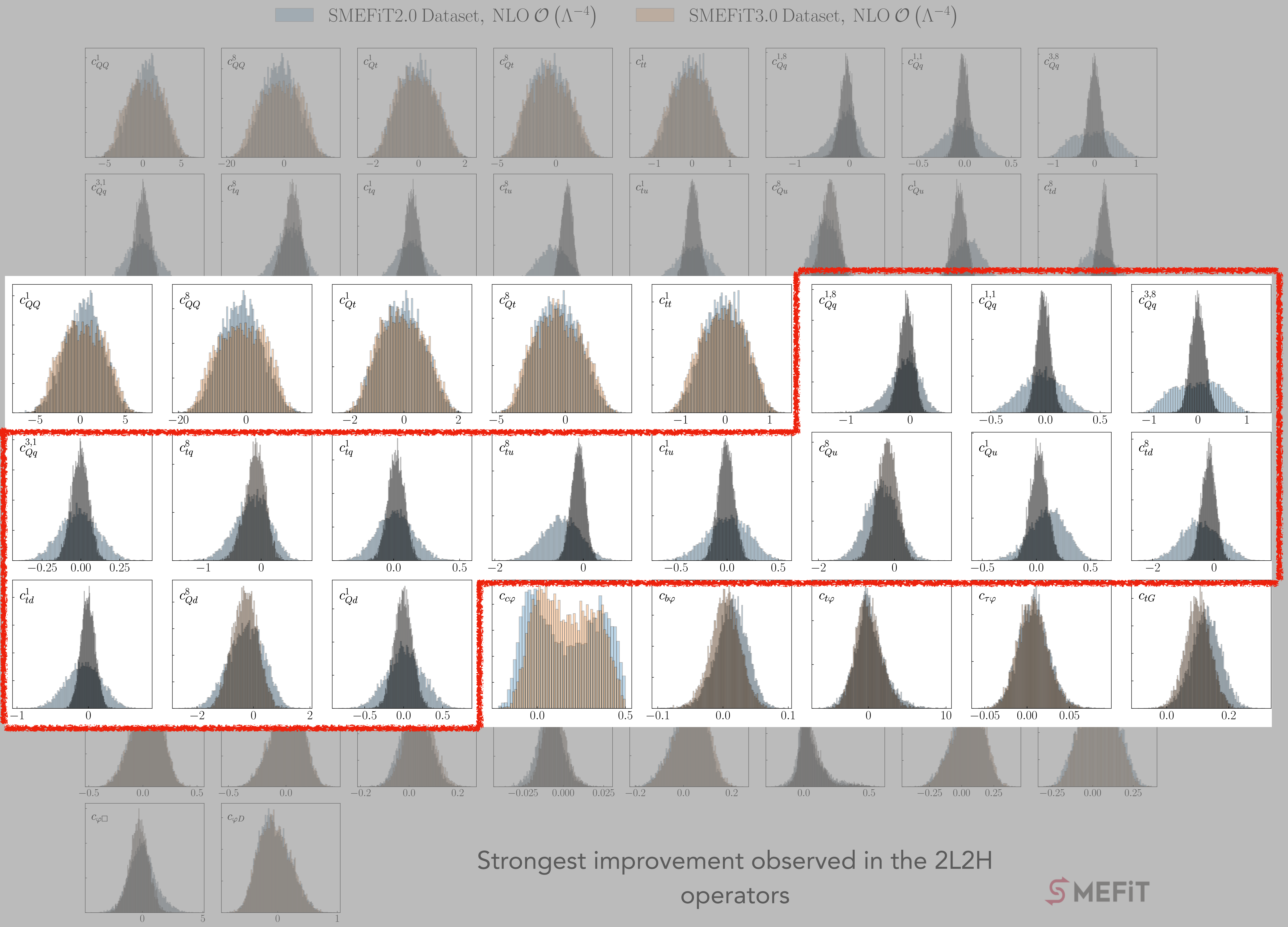
What about the impact of the new datasets?

No major qualitative difference, but
the approximate implementation resulted in too
stringent constraints in some of the EW operators

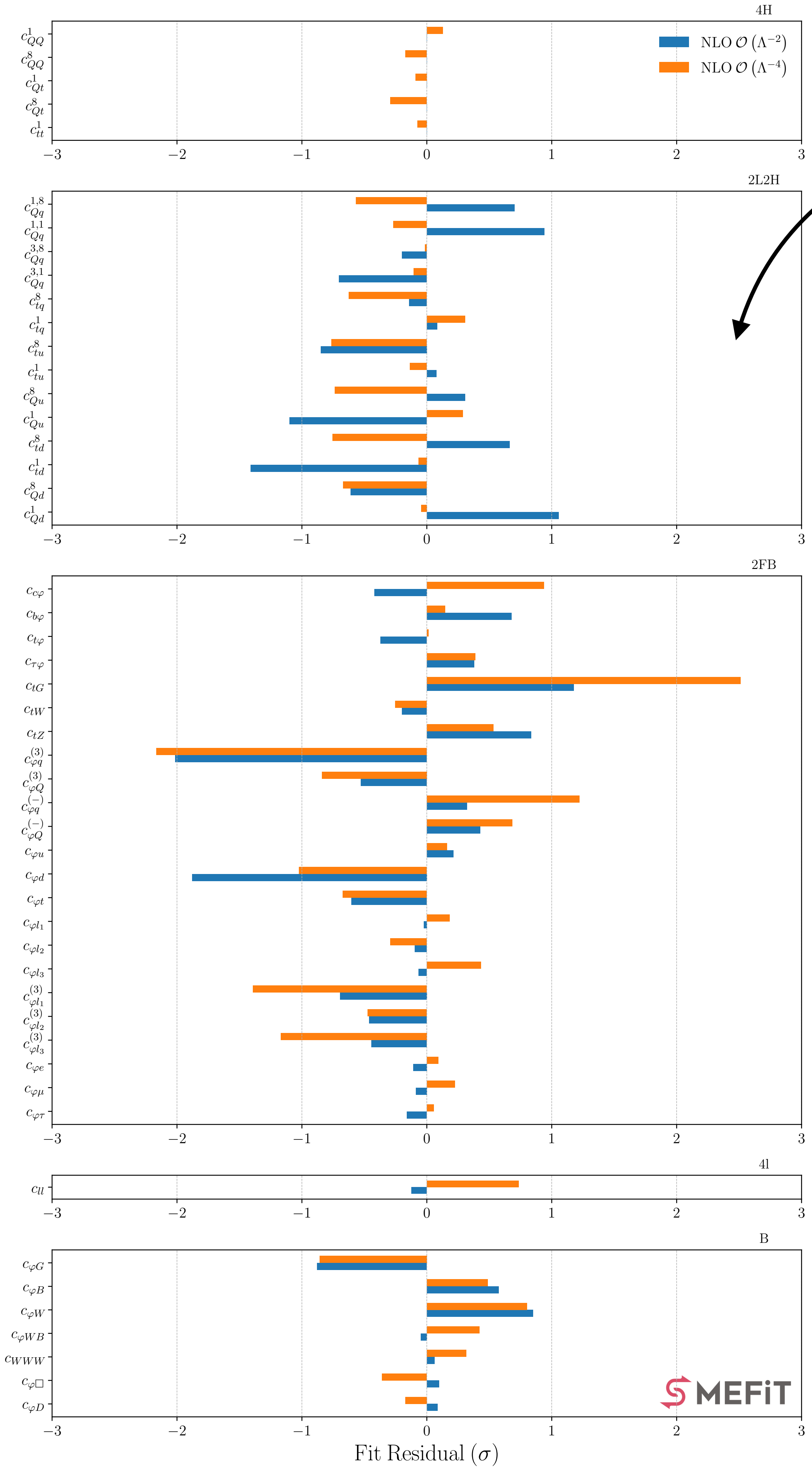


Strongest improvement observed in the 2L2H operators

SMEFiT



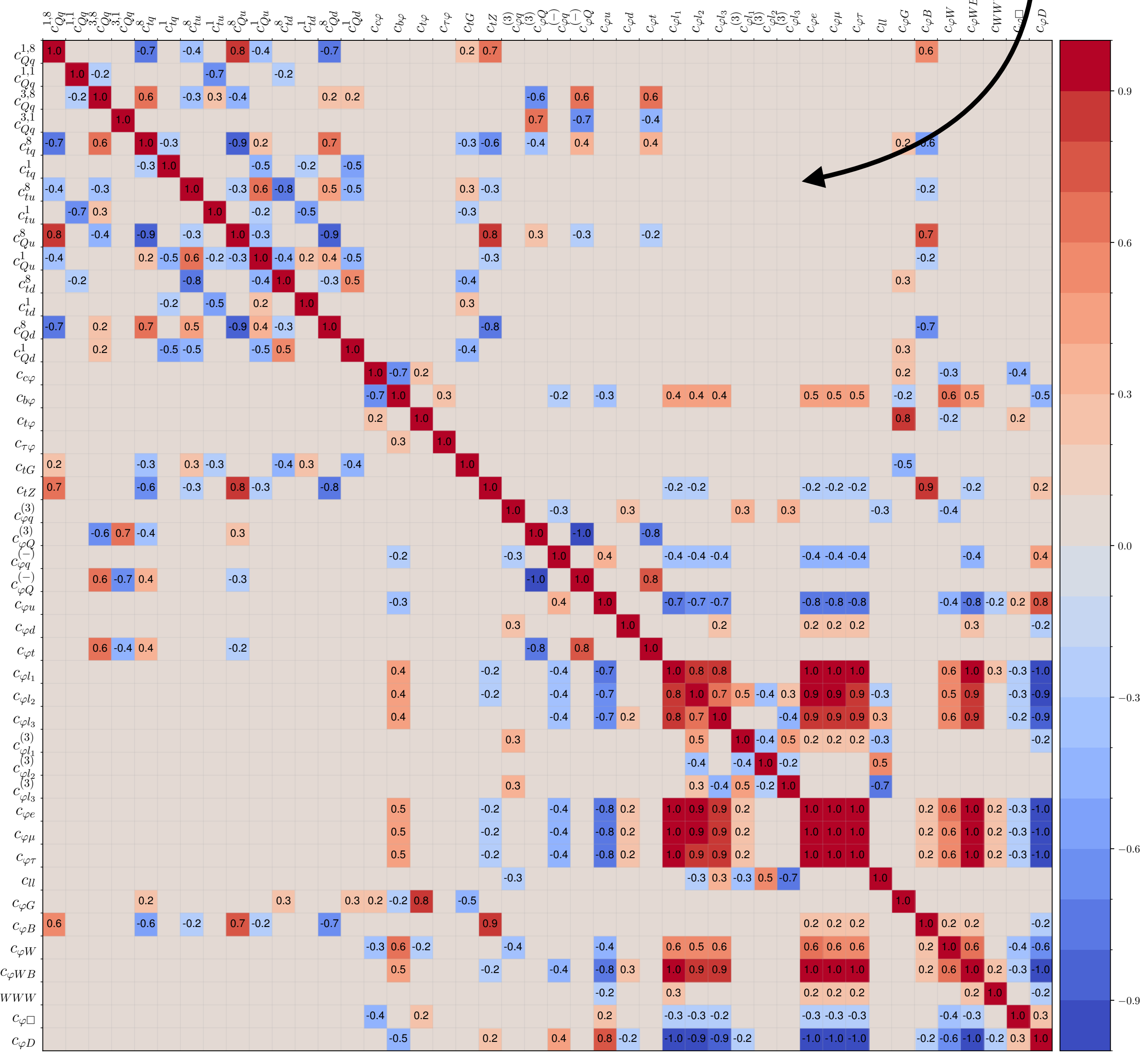
Strongest improvement observed in the 2L2H operators



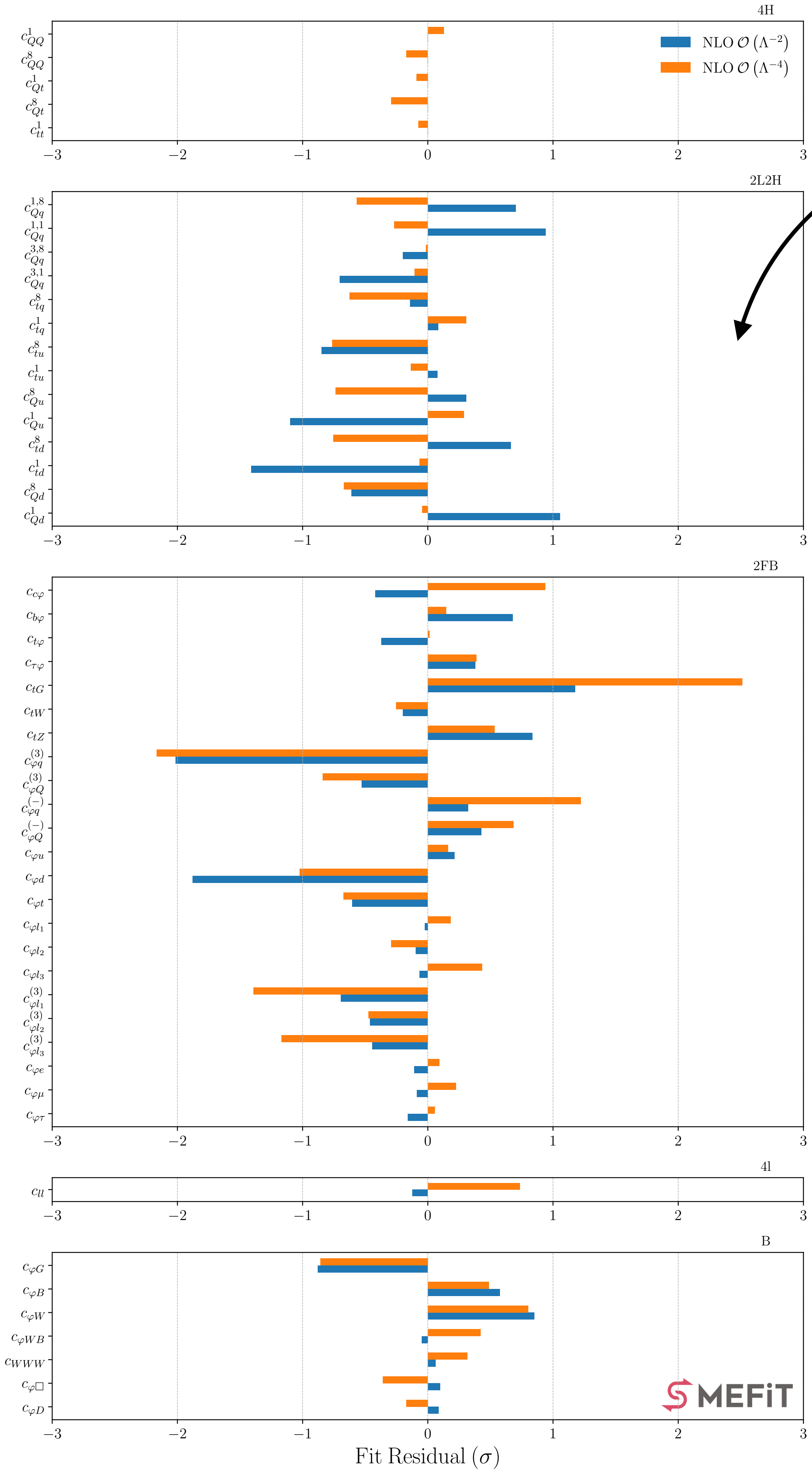
Fit residuals (pulls) are largely **consistent** with the SM

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

Large correlations in linear fit get lifted in the quadratic fit



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



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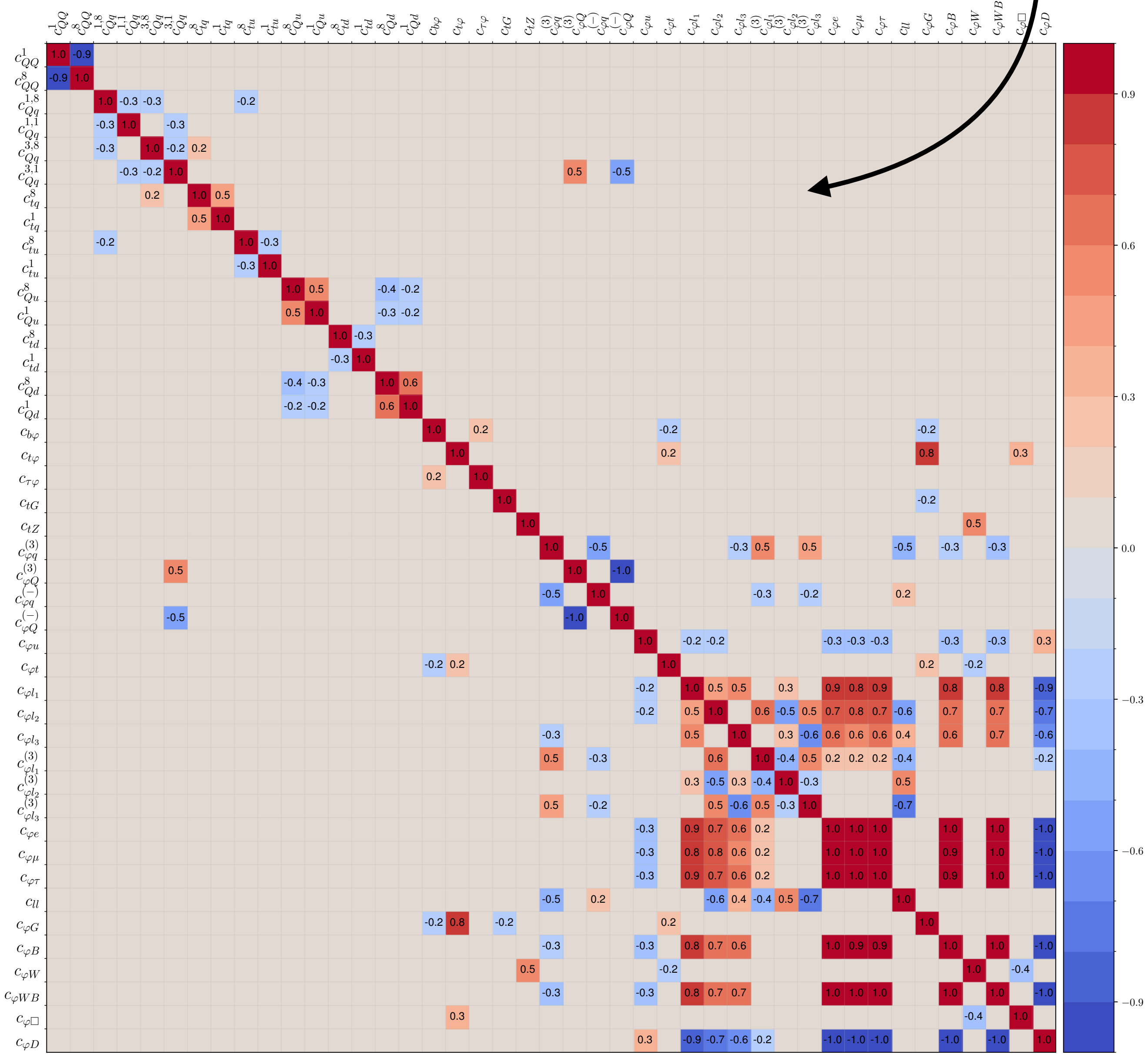
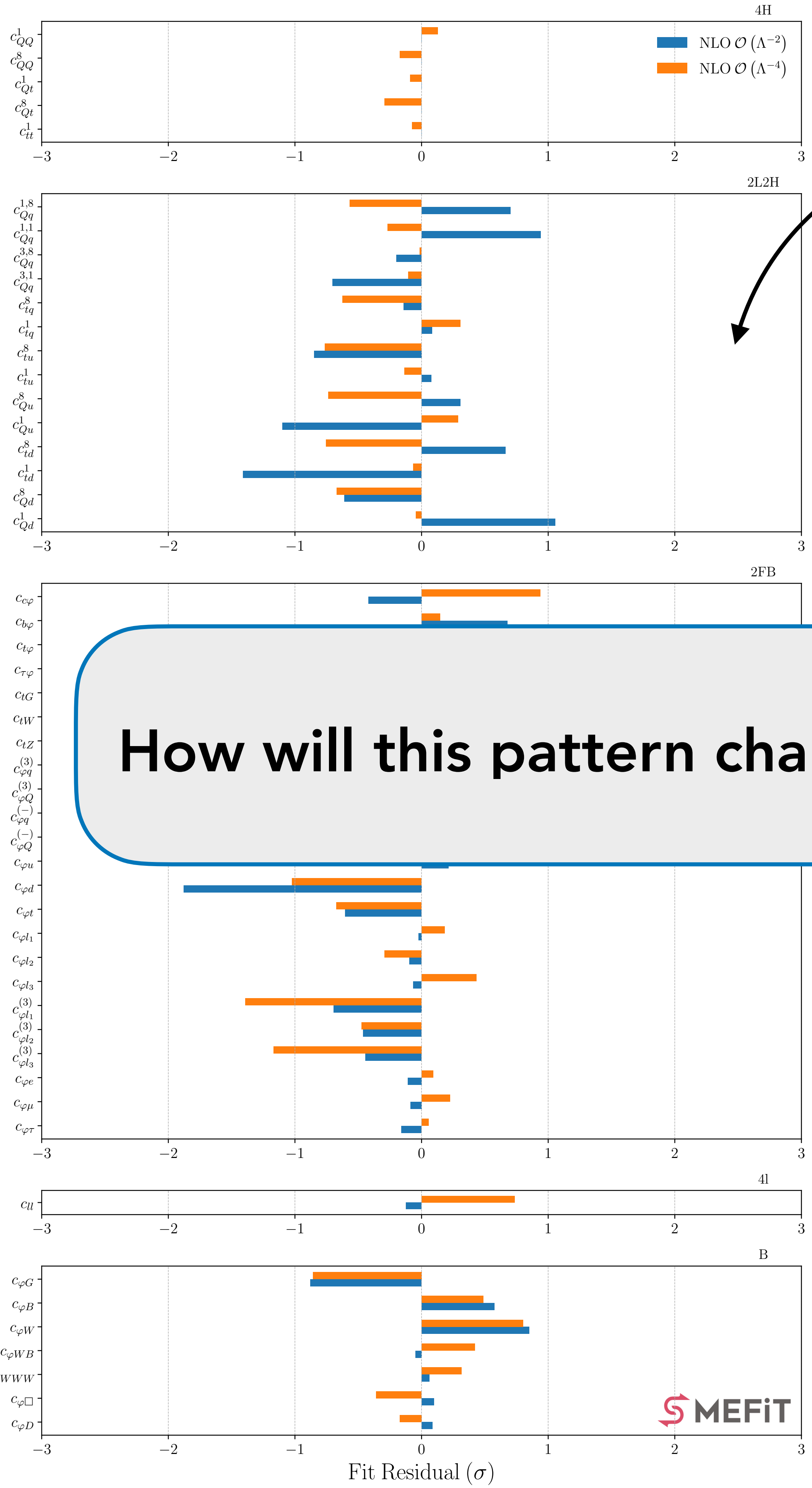


Correlation: NLO $\mathcal{O}(\Lambda^{-4})$



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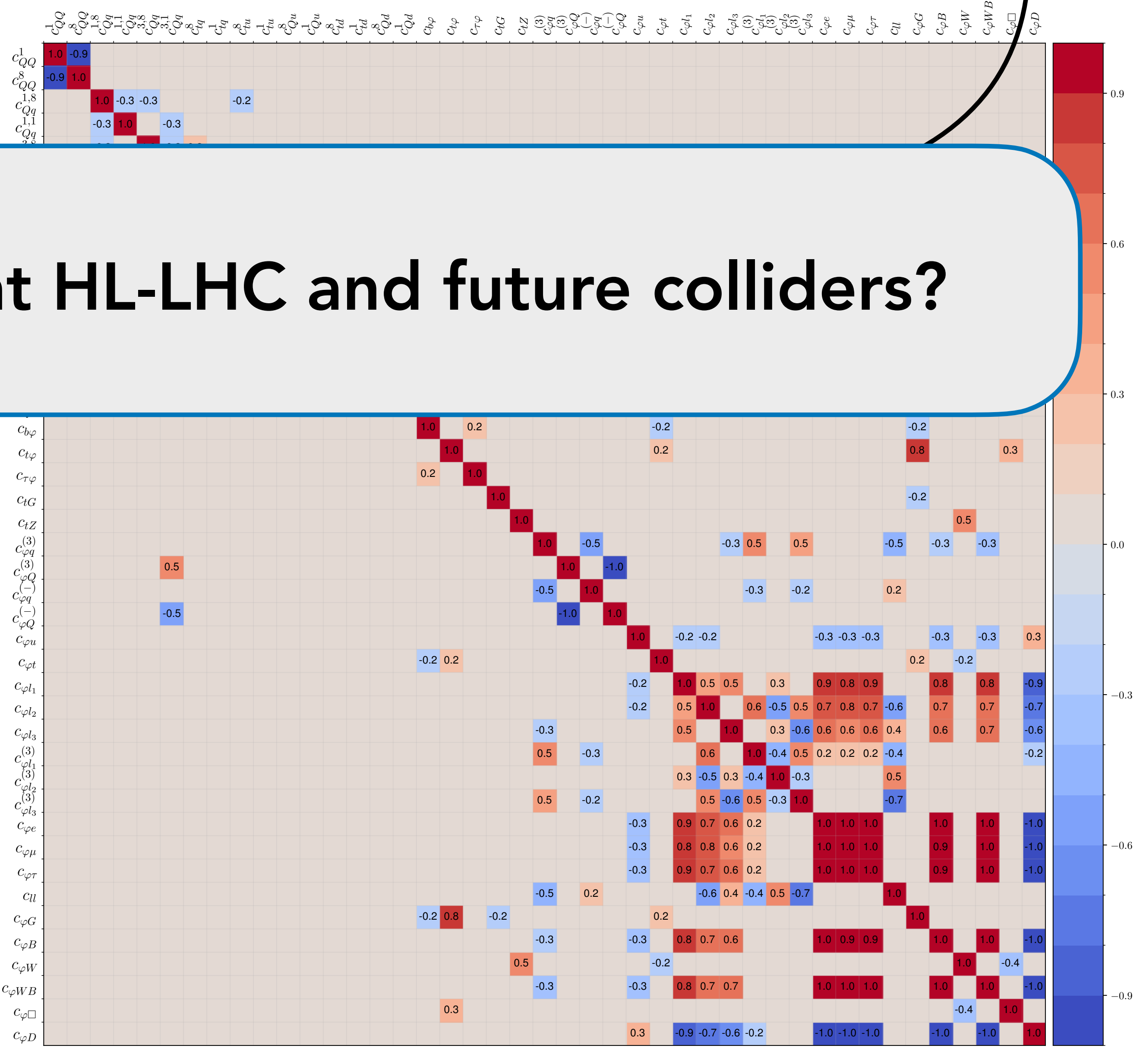
Large correlations in linear fit get lifted in the quadratic fit

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

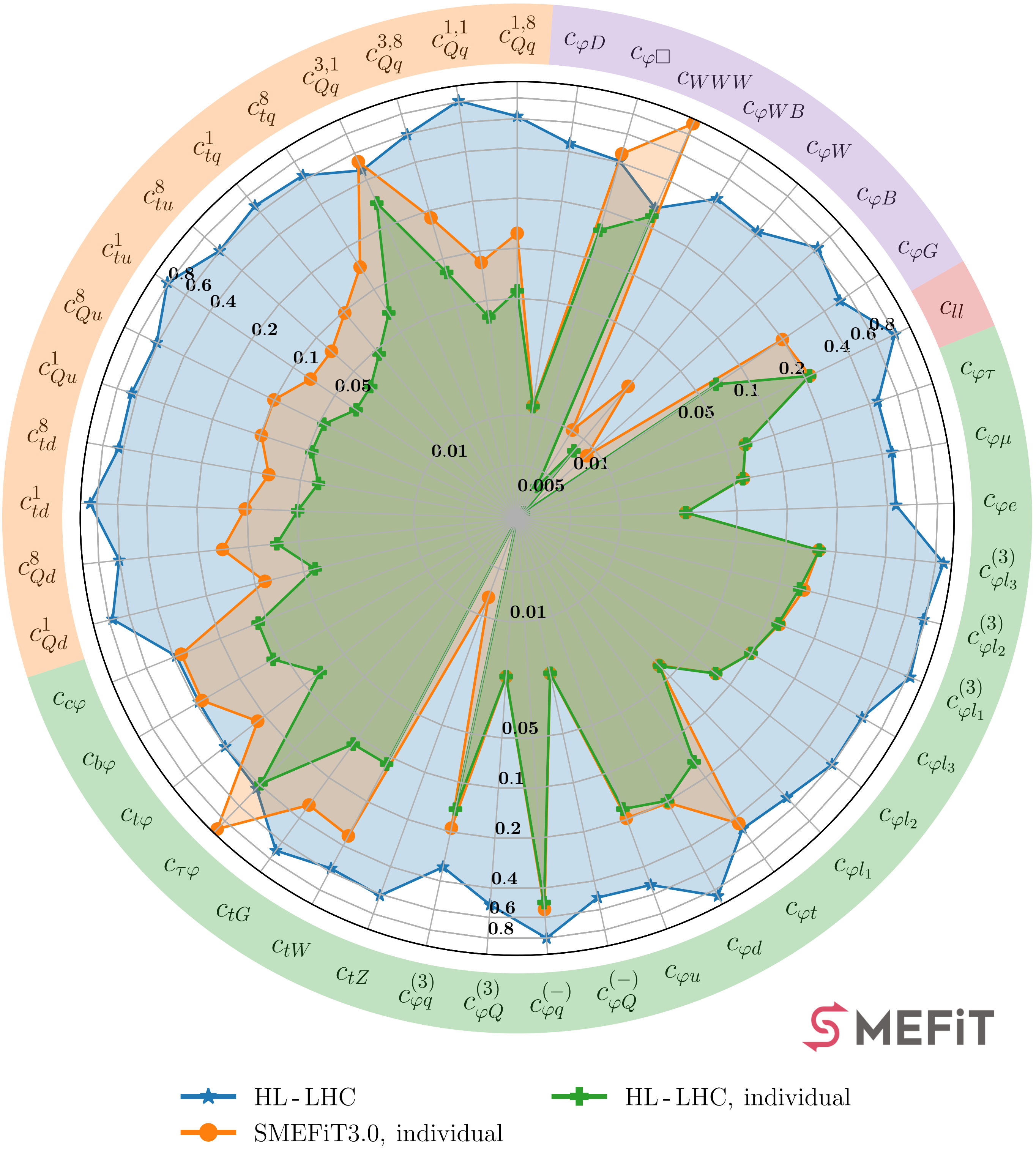


Correlation: NLO $\mathcal{O}(\Lambda^{-4})$

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

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



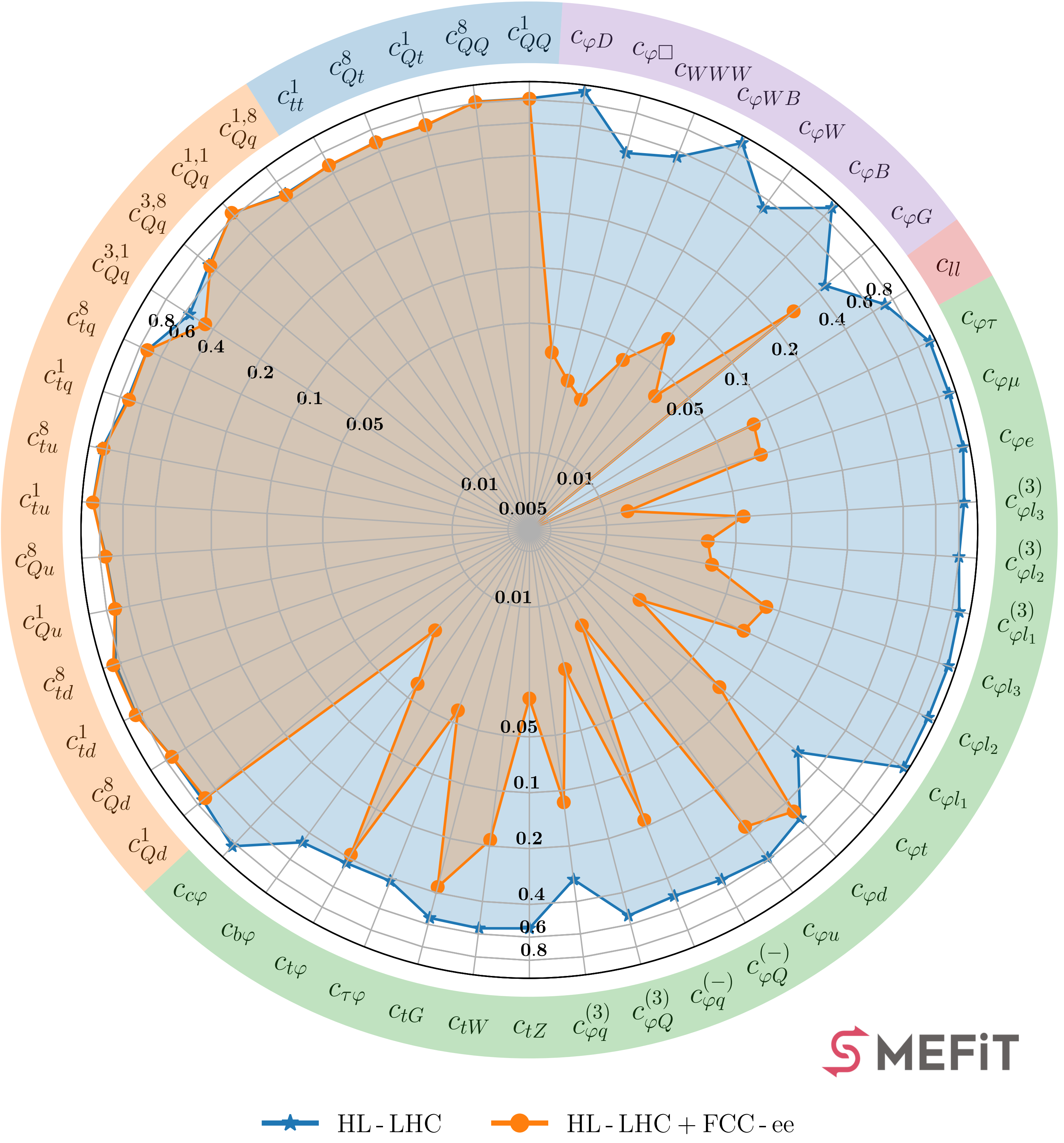
Result: FCC-ee

Dataset input

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

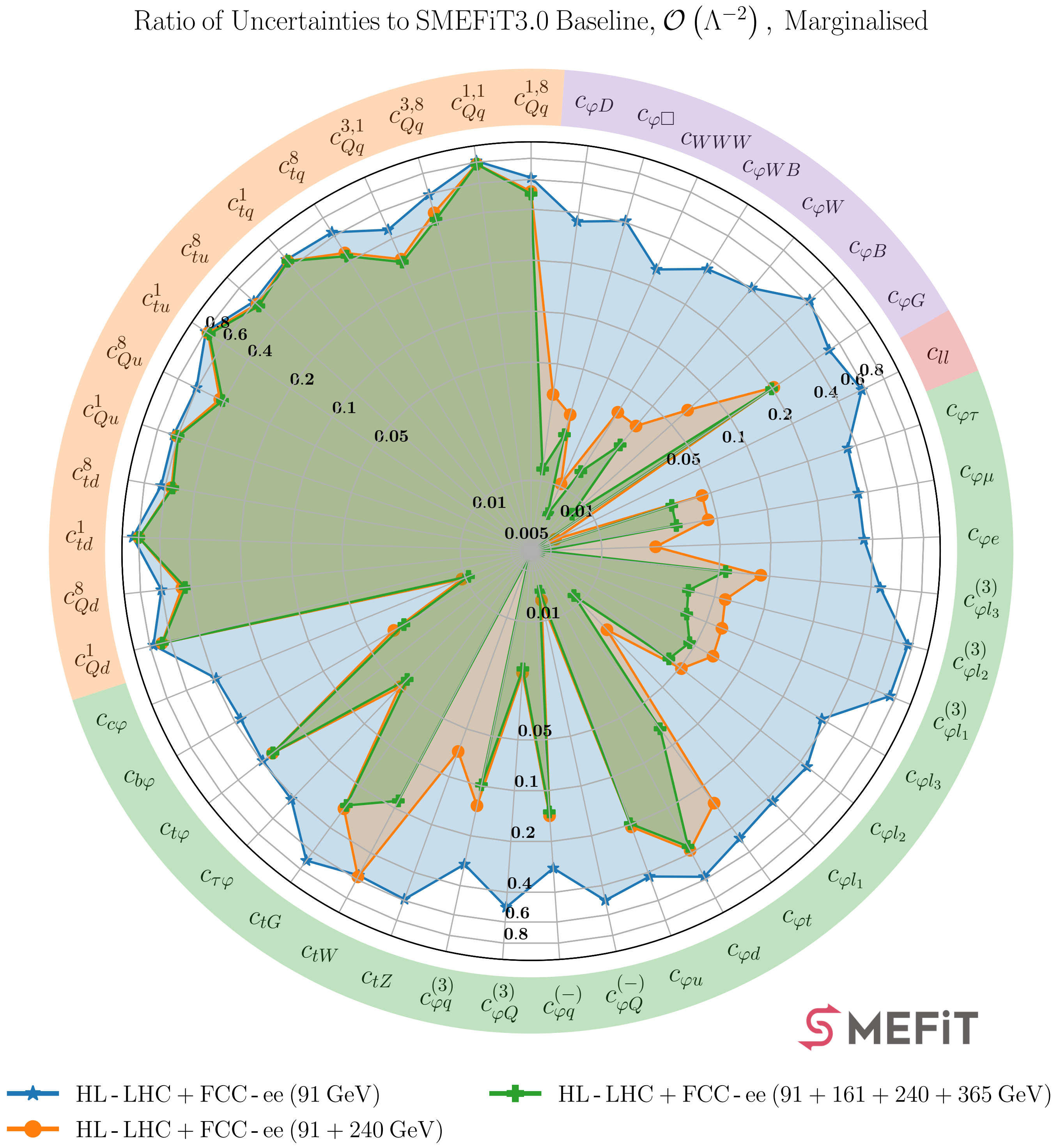
Energy ($\sqrt{s}$)	$\mathcal{L}_{\text{int}}$ (Run time)	
	FCC-ee	CEPC
91 GeV (Z-pole)	300 ab^{-1} (4 years)	100 ab^{-1} (2 years)
161 GeV ($2\,m_W$)	20 ab^{-1} (2 years)	6 ab^{-1} (1 year)
240 GeV	10 ab^{-1} (3 years)	20 ab^{-1} (10 years)
350 GeV	0.4 ab^{-1} (1 years)	-
365 GeV ($2\,m_t$)	3 ab^{-1}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

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

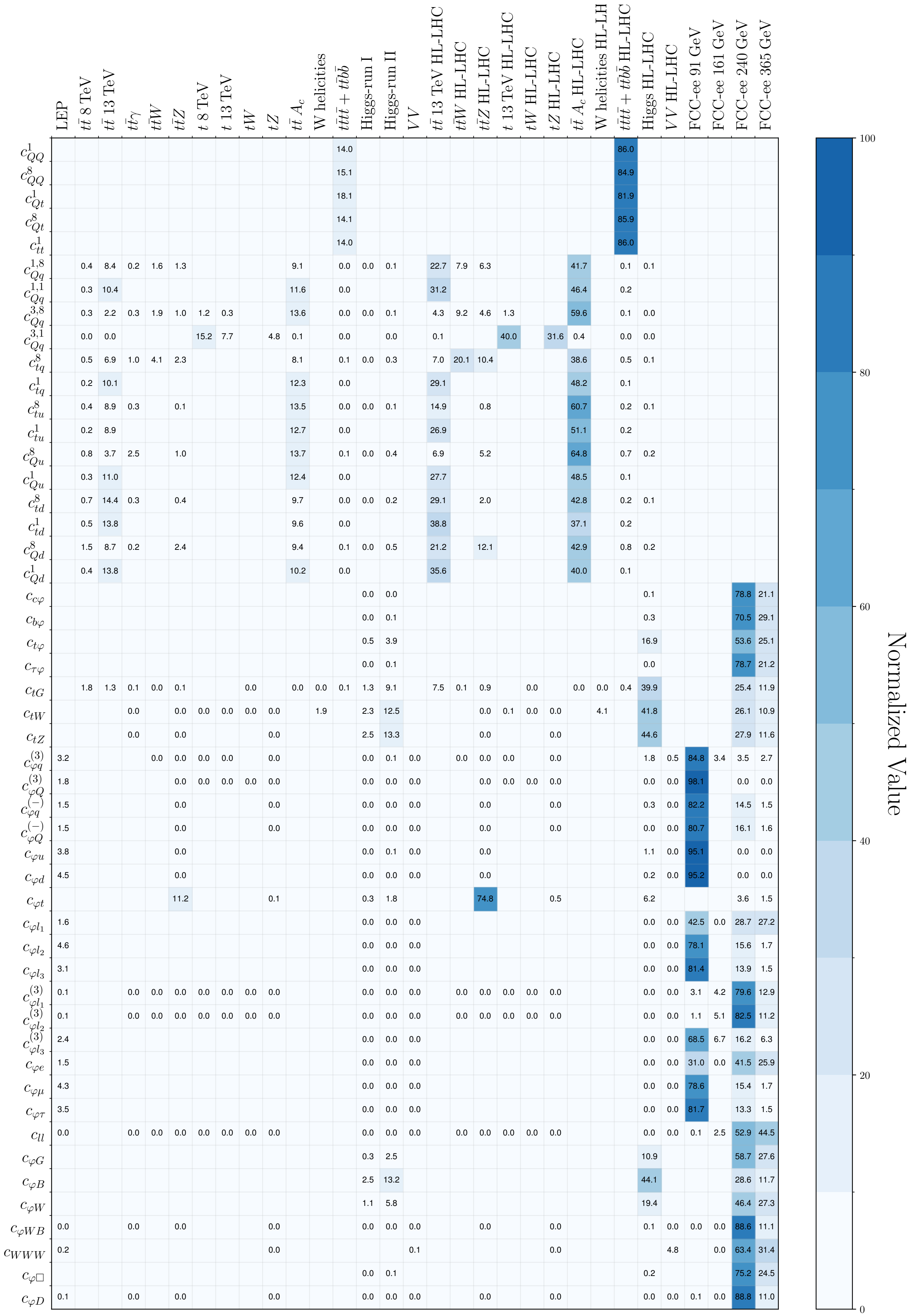


Result: FCC-ee energy breakdown

- 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



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



Fisher information study

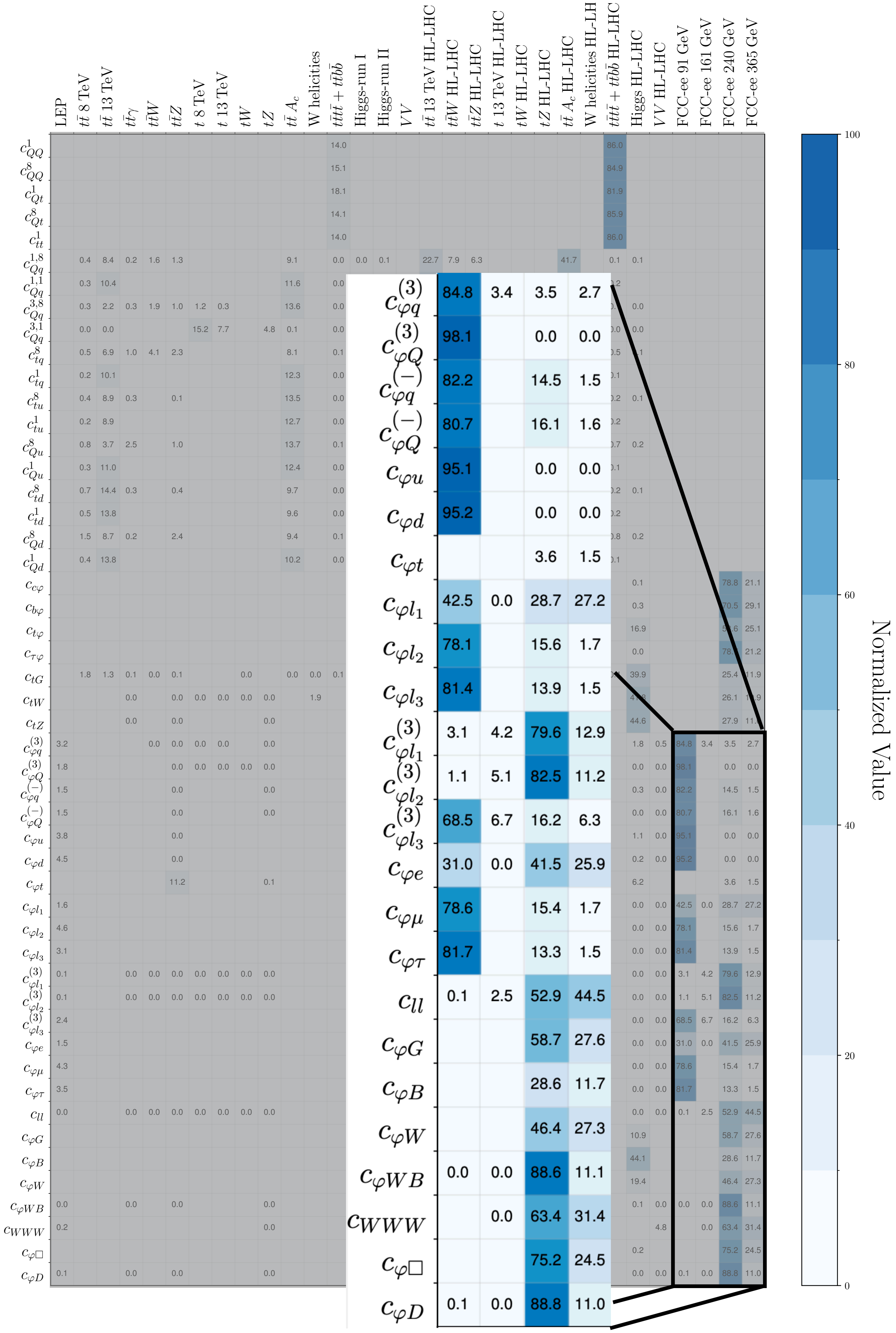
- The sensitivity of the EFT parameters to the Run II, HL-LHC and FCC-ee datasets is quantified by the **fisher information**

$$I_{ij} = \sum_{m=1}^{n_{\text{dat}}} \frac{\sigma_{m,i}^{(\text{eft})}\sigma_{m,j}^{(\text{eft})}}{\delta_{\text{exp},m}^2}$$

- The highest sensitivity in the 2FB sector comes in via the FCC-ee

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

Fisher information study



$c_{\varphi q}^{(3)}$	84.8	3.4	3.5	2.7
$c_{\varphi Q}^{(3)}$	98.1		0.0	0.0
$c_{\varphi q}^{(-)}$	82.2		14.5	1.5
$c_{\varphi Q}^{(-)}$	80.7		16.1	1.6
$c_{\varphi u}$	95.1		0.0	0.0
$c_{\varphi d}$	95.2		0.0	0.0
$c_{\varphi t}$			3.6	1.5
$c_{\varphi l_1}$	42.5	0.0	28.7	27.2
$c_{\varphi l_2}$	78.1		15.6	1.7
$c_{\varphi l_3}$	81.4		13.9	1.5
$c_{\varphi l_1}^{(3)}$	3.1	4.2	79.6	12.9
$c_{\varphi l_2}^{(3)}$	1.1	5.1	82.5	11.2
$c_{\varphi l_3}^{(3)}$	68.5	6.7	16.2	6.3
$c_{\varphi e}$	31.0	0.0	41.5	25.9
$c_{\varphi \mu}$	78.6		15.4	1.7
$c_{\varphi \tau}$	81.7		13.3	1.5
c_{ll}	0.1	2.5	52.9	44.5
$c_{\varphi G}$			58.7	27.6
$c_{\varphi B}$			28.6	11.7
$c_{\varphi W}$			46.4	27.3
$c_{\varphi WB}$	0.0	0.0	88.6	11.1
c_{WWW}		0.0	63.4	31.4
$c_{\varphi \Box}$			75.2	24.5
$c_{\varphi D}$	0.1	0.0	88.8	11.0

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

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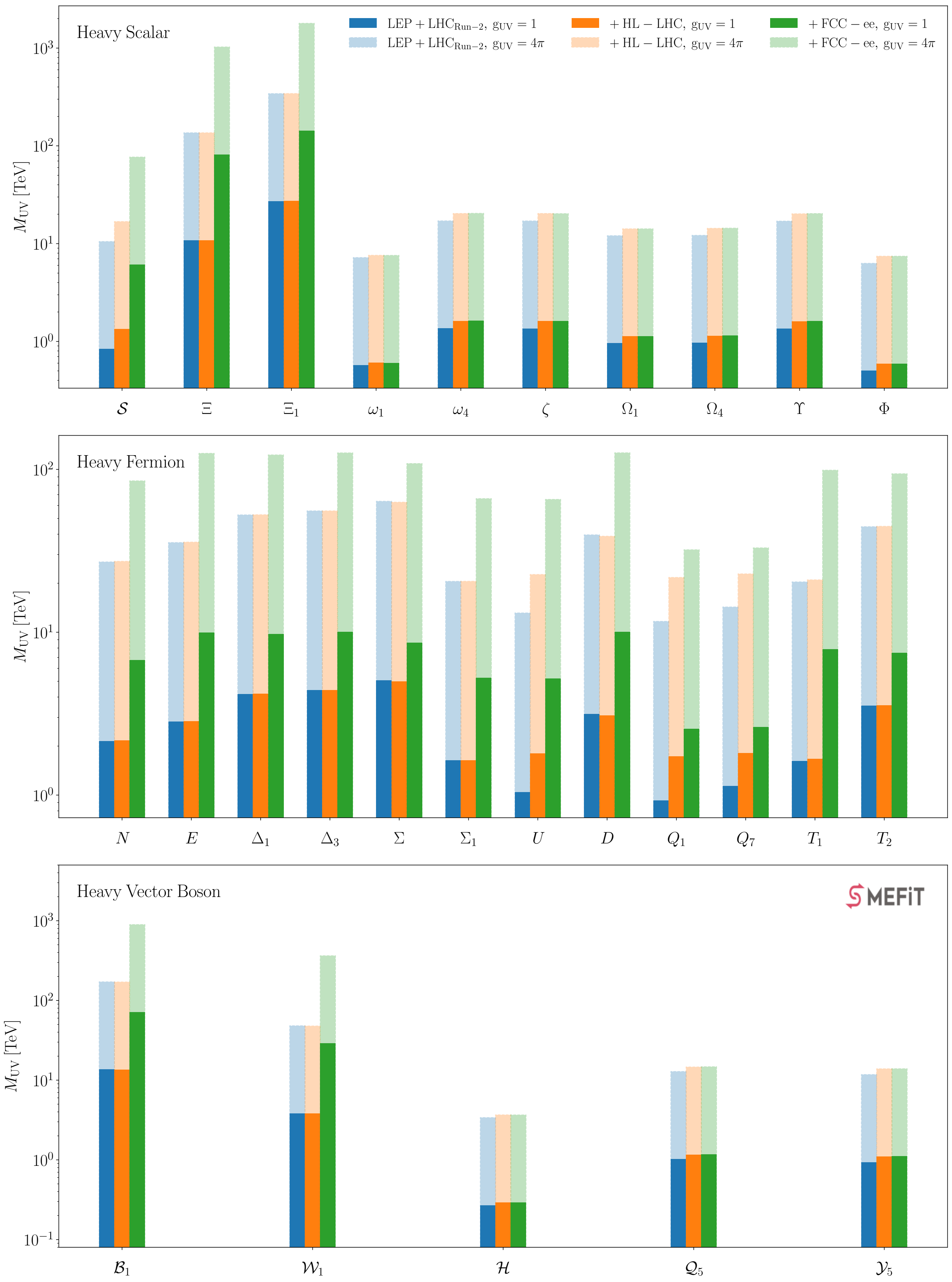


UV-complete models

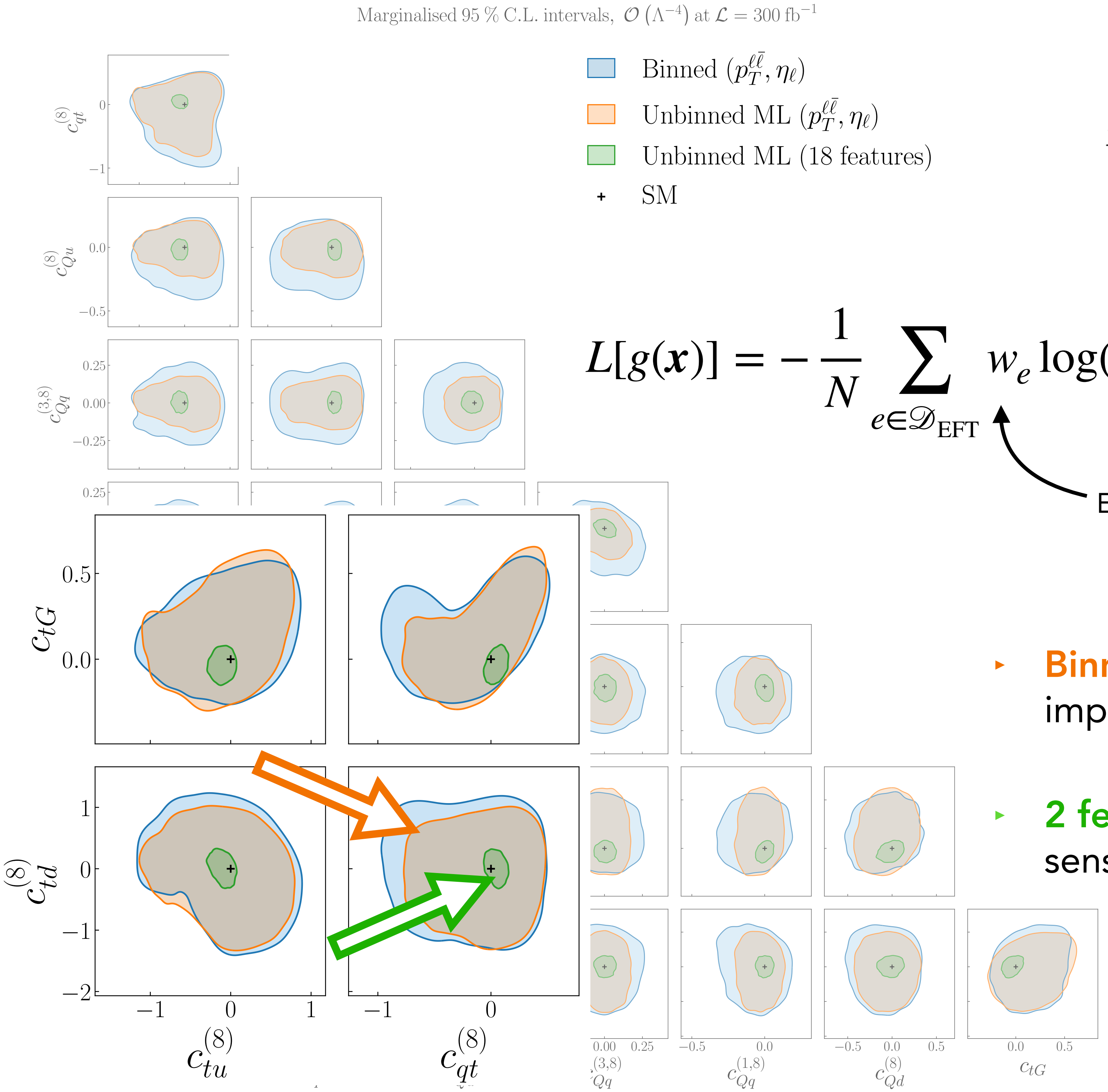
- We quantify the mass reach of one-particle extensions of the SM matched at tree level
- Future colliders will give an unprecedented indirect mass reach: 100 TeV, 10 TeV and 70 TeV for some of the heavy scalars, fermion, vector bosons (assuming $g_{\mathrm{UV}} = 1$)
- Models sensitive to EW operators are dominantly constrained at the FCC-ee

Scalars		Fermions		Vectors	
Particle	Irrep	Particle	Irrep	Particle	Irrep
$\mathcal{S}$	$(1,1)_0$	N	$(1,1)_0$	$\mathcal{B}$	$(1,1)_0$
$\mathcal{S}_1$	$(1,1)_1$	E	$(1,1)_{-1}$	$\mathcal{B}_1$	$(1,1)_1$
ϕ	$(1,2)_{1/2}$	Δ_1	$(1,2)_{-1/2}$	$\mathcal{W}$	$(1,3)_0$
Ξ	$(1,3)_0$	Δ_3	$(1,2)_{-3/2}$	$\mathcal{W}_1$	$(1,3)_1$
Ξ_1	$(1,3)_1$	Σ	$(1,3)_0$	$\mathcal{G}$	$(8,1)_0$
ω_1	$(3,1)_{-1/3}$	Σ_1	$(1,3)_{-1}$	$\mathcal{H}$	$(8,3)_0$
ω_4	$(3,1)_{-4/3}$	U	$(3,1)_{2/3}$	$\mathcal{Q}_5$	$(8,3)_0$
ζ	$(3,3)_{-1/3}$	D	$(3,1)_{-1/3}$	$\mathcal{Y}_5$	$(\bar{6},2)_{-5/6}$
Ω_1	$(6,1)_{1/3}$	Q_1	$(3,2)_{1/6}$		
Ω_4	$(6,1)_{4/3}$	Q_7	$(3,2)_{7/6}$		
Υ	$(6,3)_{1/3}$	T_1	$(3,3)_{-1/3}$		
Φ	$(8,2)_{1/2}$	T_2	$(3,3)_{2/3}$		
		Q_5	$(3,2)_{-5/6}$		

ML observables at HL-LHC

[1907.10621,
2007.10356,
2107.10859,
2205.12976,
2211.02058,
2401.10323,
....]

$pp \to t\bar{t} \to b\bar{b}\ell^+\ell^-\nu_\ell\bar{\nu}_\ell$



$$p_T^{\ell\bar{\ell}} \in [0, 10, 20, 40, 60, 100, 150, 400, \infty)\ \mathrm{GeV},$$
$$\eta^\ell \in [0, 0.3, 0.6, 0.9, 1.2, 1.5, 1.8, 2.1, 2.5]\ .$$

$$L[g(\boldsymbol{x})] = -\frac{1}{N}\sum_{e\in\mathscr{D}_{\mathrm{EFT}}} w_e \log(1-g(\boldsymbol{x}_e)) - \frac{1}{N}\sum_{\mathscr{D}_{\mathrm{SM}}} w_e \log g(\boldsymbol{x}_e)$$

Event weights

$\{m_{t\bar{t}}, \eta_l, \Delta\phi, \ldots\}$

- **Binned vs unbinned** in $(p_T^{\ell\bar{\ell}}, \eta_\ell)$ small improvement relative to binned setup
- **2 features vs 18 features:** big increase in sensitivity

[2211.02058]

Conclusion and outlook

- New physics might be just **around the corner**, and the SMEFT provides the ideal framework to capture its effects with a minimal set of model assumptions

- **A community effort**: many global fitting efforts, including combined PDF + EFT studies

- SMEFiT3.0: the biggest global SMEFT analysis to date with 50 WC to 449 datapoints

- Demonstrated the impact of HL-LHC and FCC-ee on the global SMEFT parameter space

- The FCC-ee offers an **unprecedented indirect mass reach** on new heavy particles

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Contact: jthoeve@nikhef.nl

Thanks for your attention!

Backup

HL-LHC projections

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

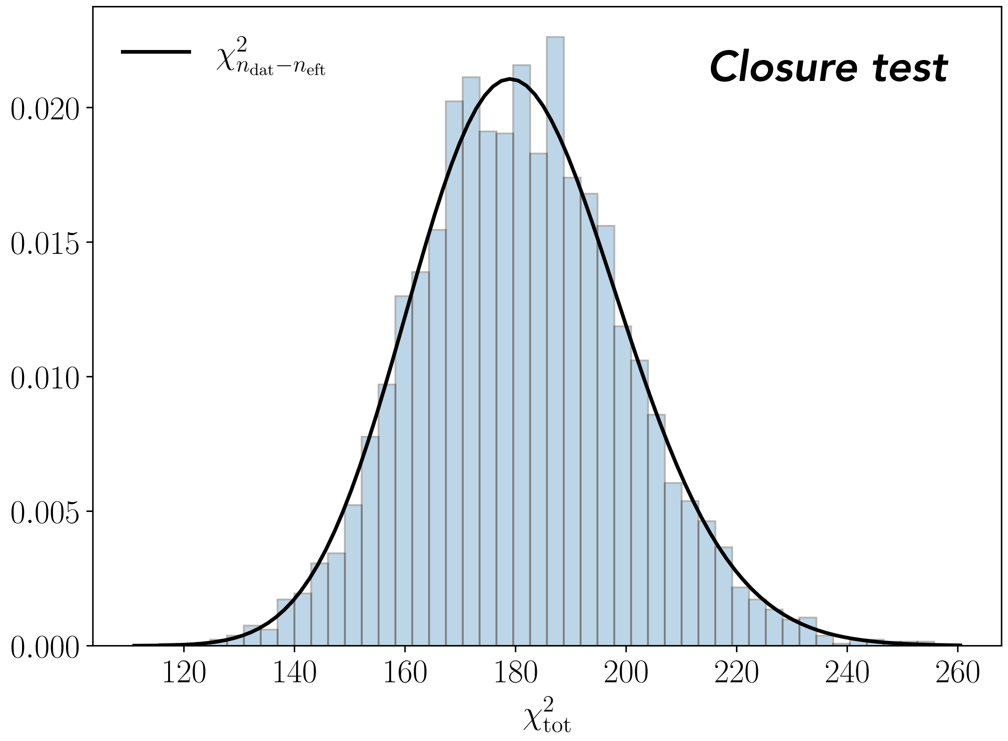
$$\mathcal{O}_i^{(\mathrm{exp})} = \mathcal{O}_i^{(\mathrm{th})}\left(1 + r_i\delta_i^{(\mathrm{stat})} + \sum_{k=1}^{n_{\mathrm{sys}}} r_{k,i}\delta_{k,i}^{(\mathrm{sys})}\right)$$

- 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

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



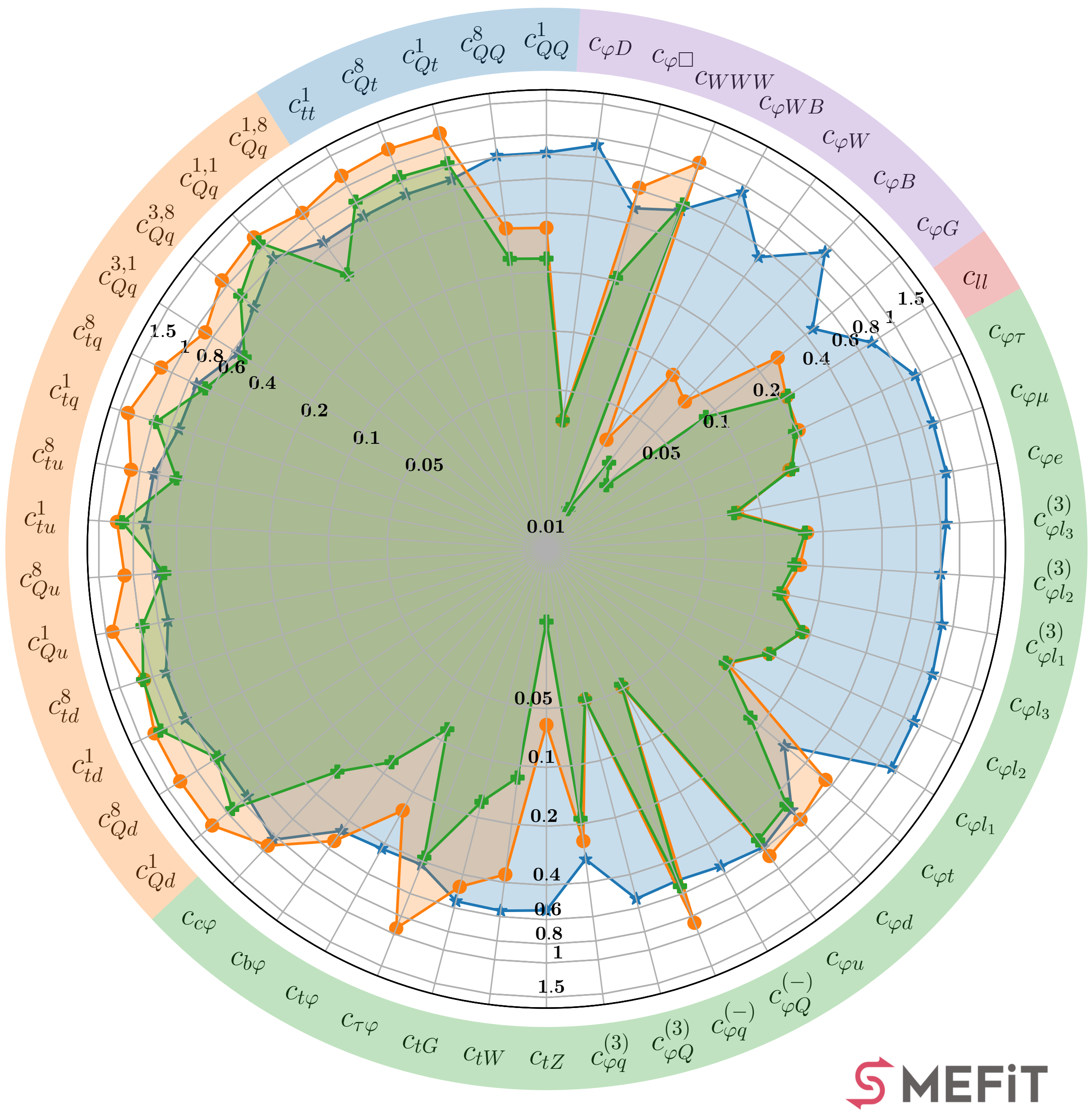
+ flexible framework that can project any Run II dataset

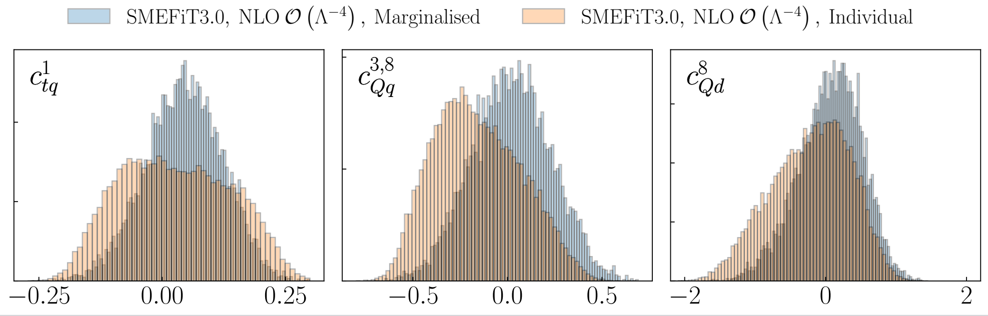
+ SMEFT predictions can be recycled

- No additional bins in the tails

With statistical noise = L1

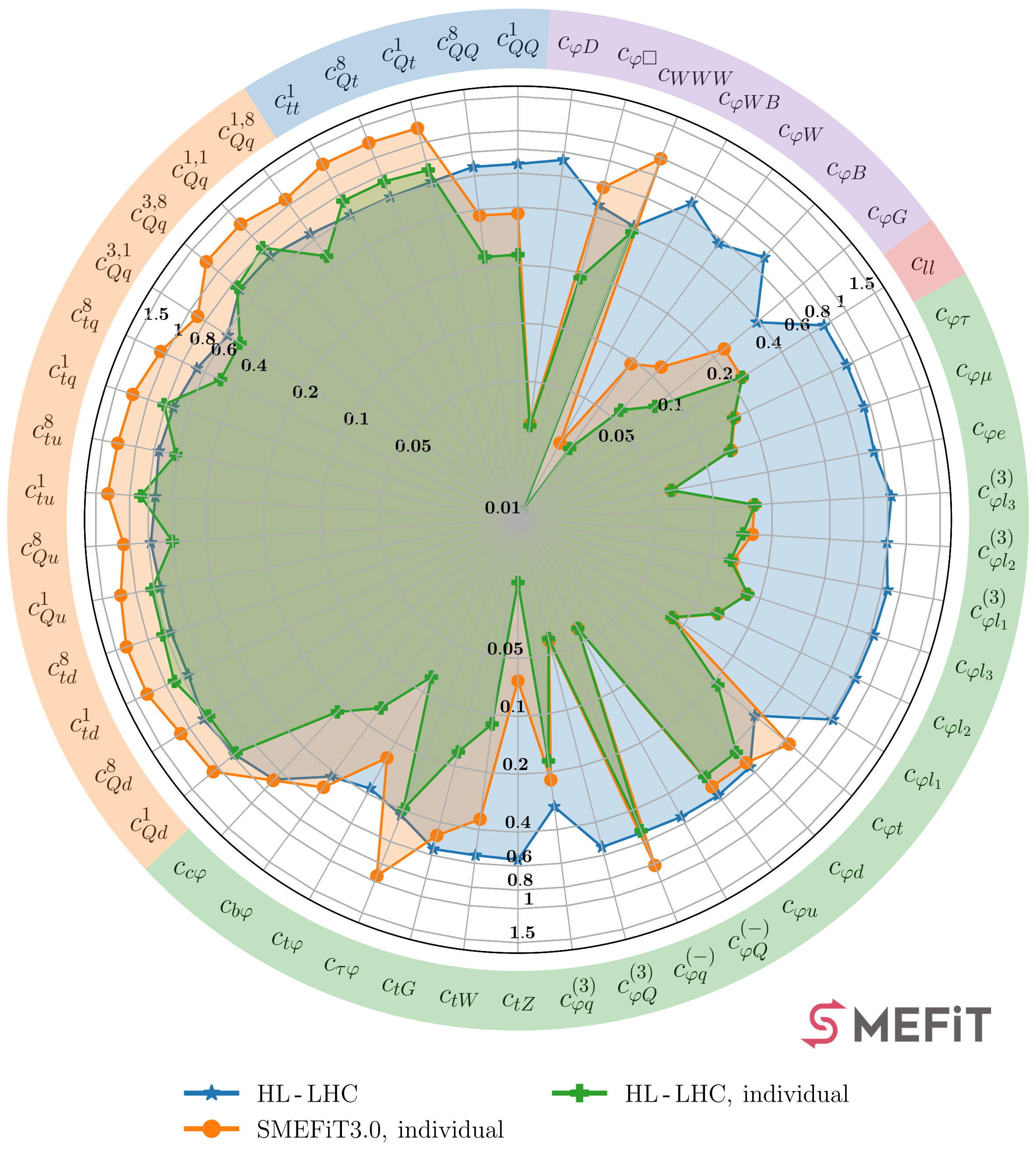
Ratio of Uncertainties to SMEFiT3.0 Baseline, $\mathcal{O}\left(\Lambda^{-4}\right)$, Marginalised



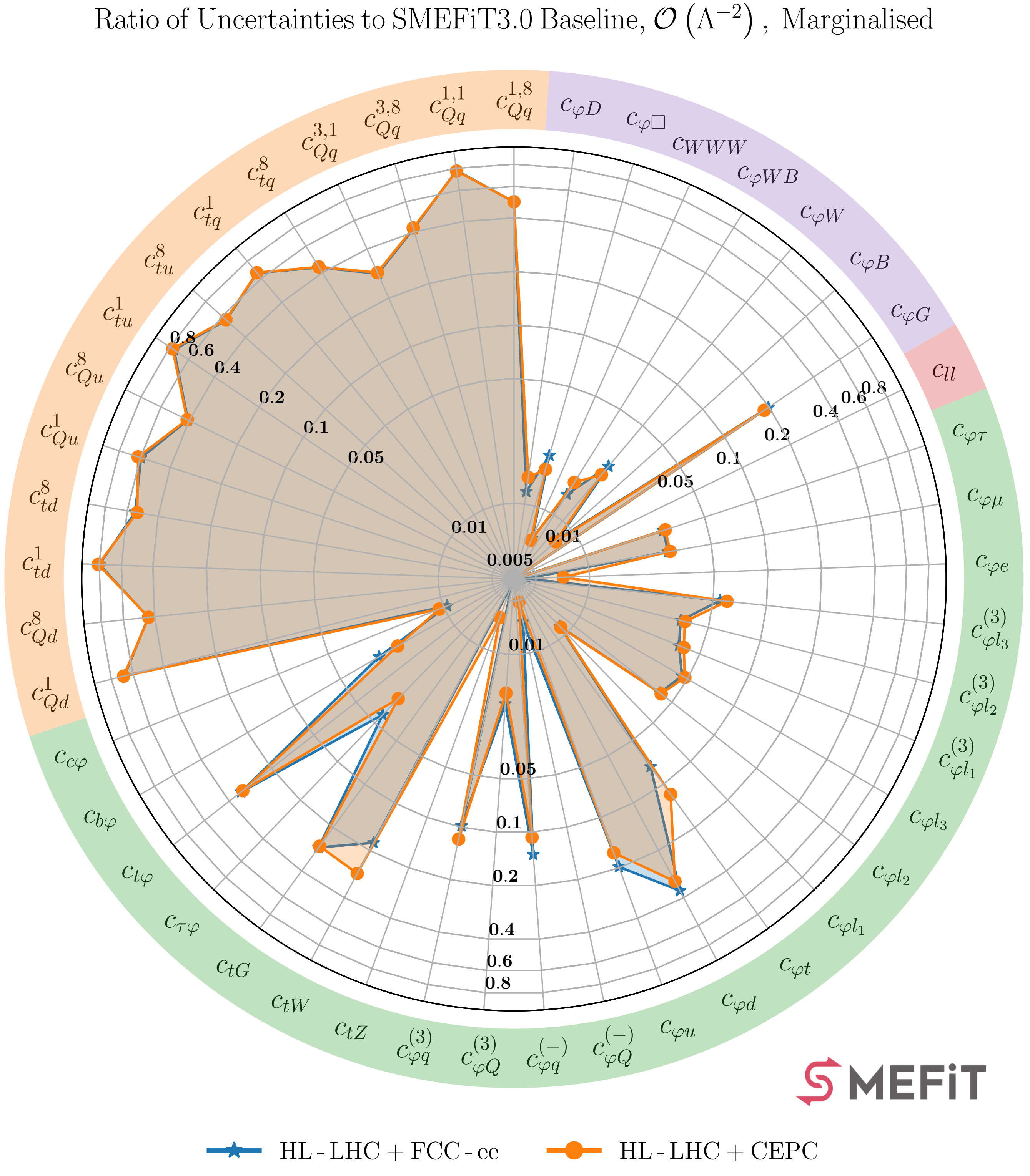


Without statistical noise = L0

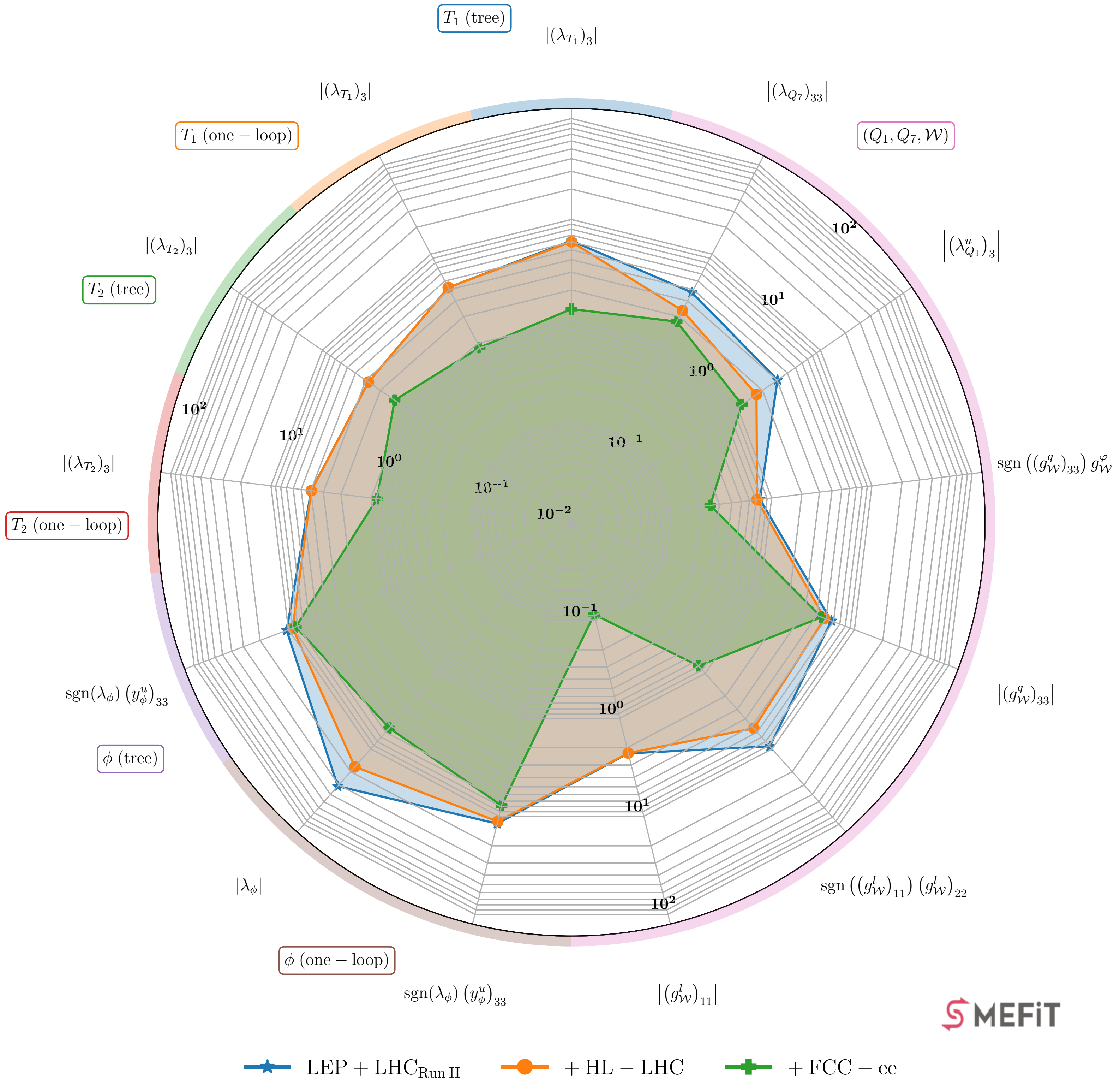
Ratio of Uncertainties to SMEFiT3.0 Baseline, $\mathcal{O}\left(\Lambda^{-4}\right)$, Marginalised



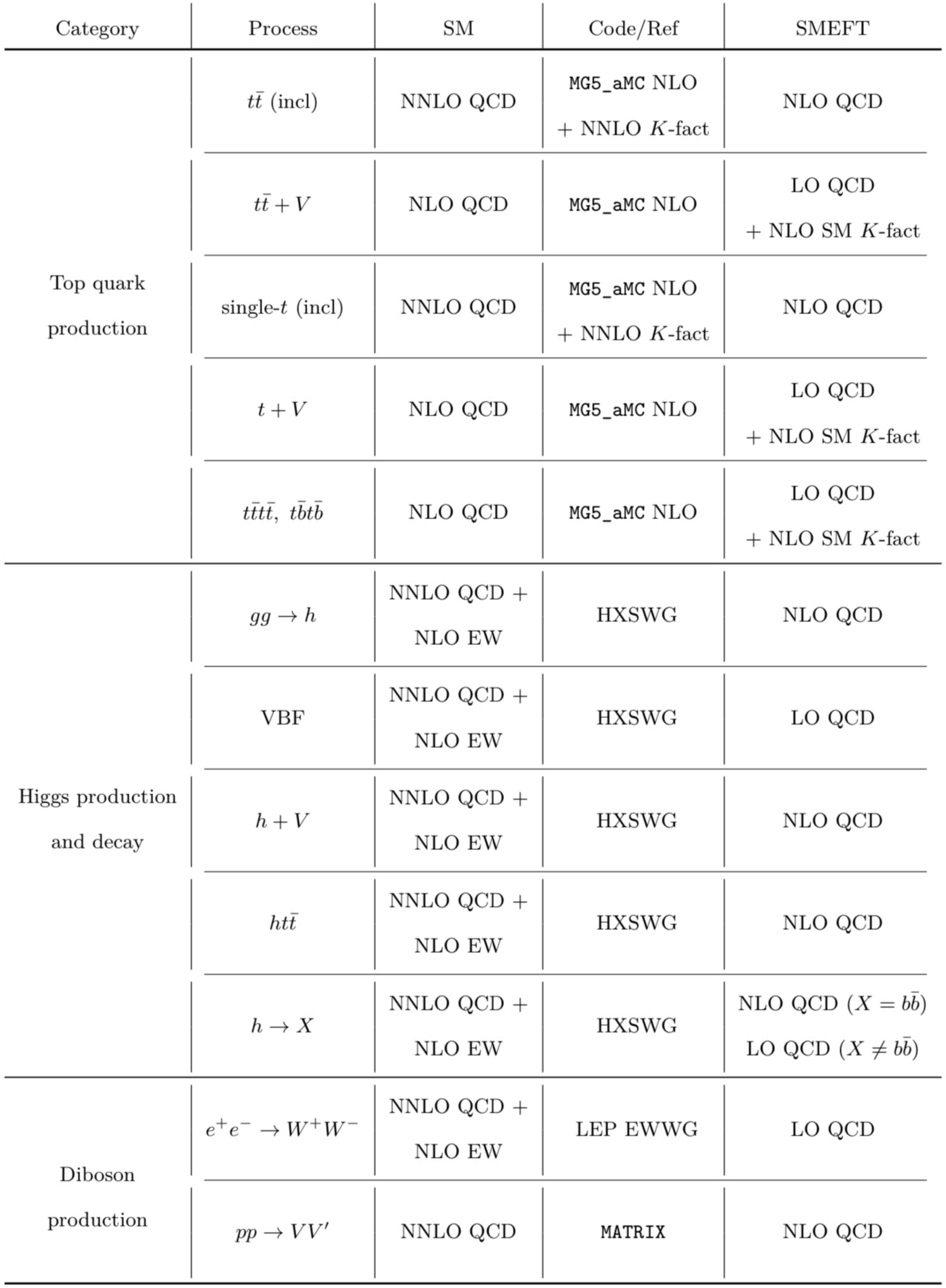
FCC-ee and CEPC



1-loop & multi-particle matching

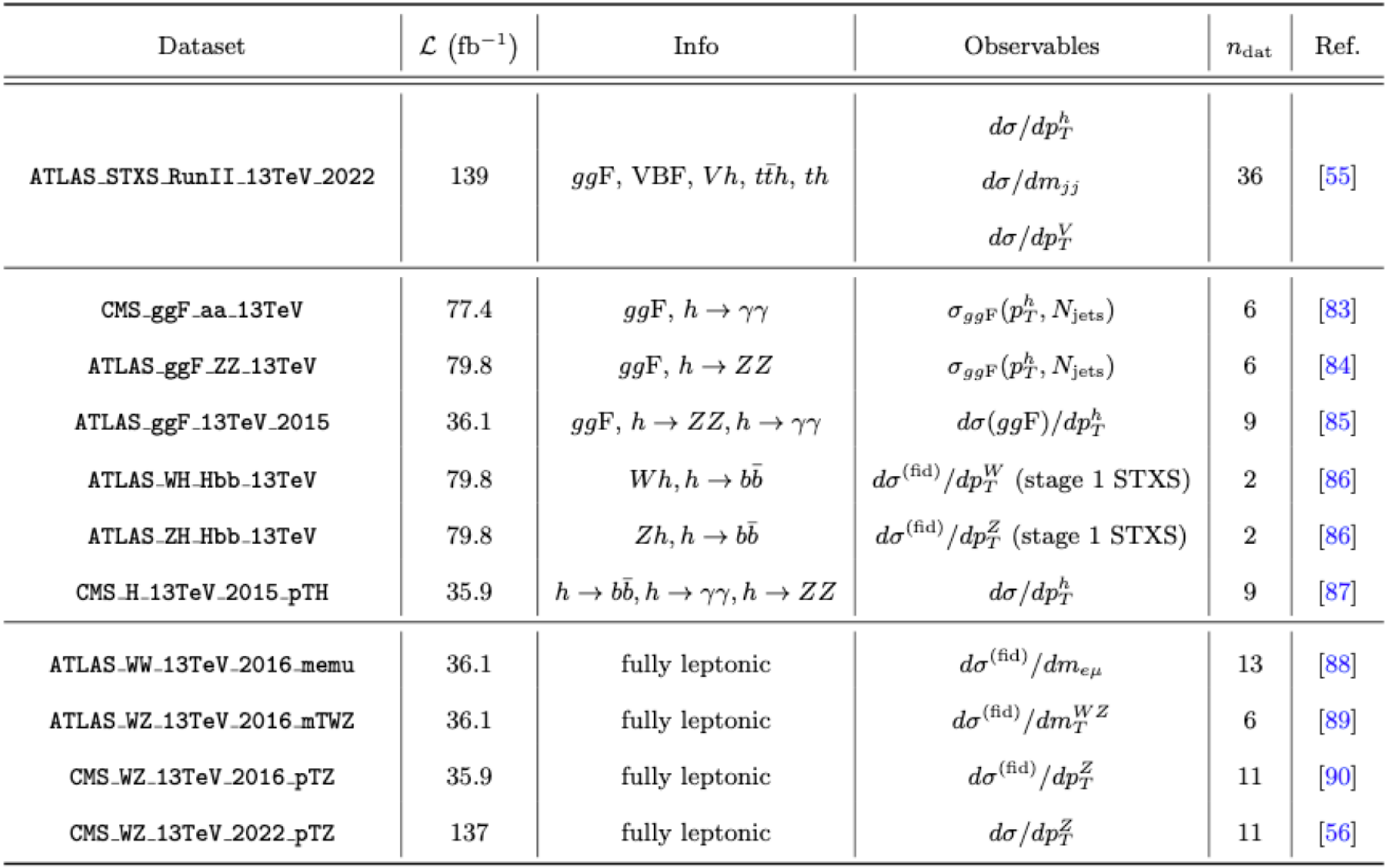


SM predictions

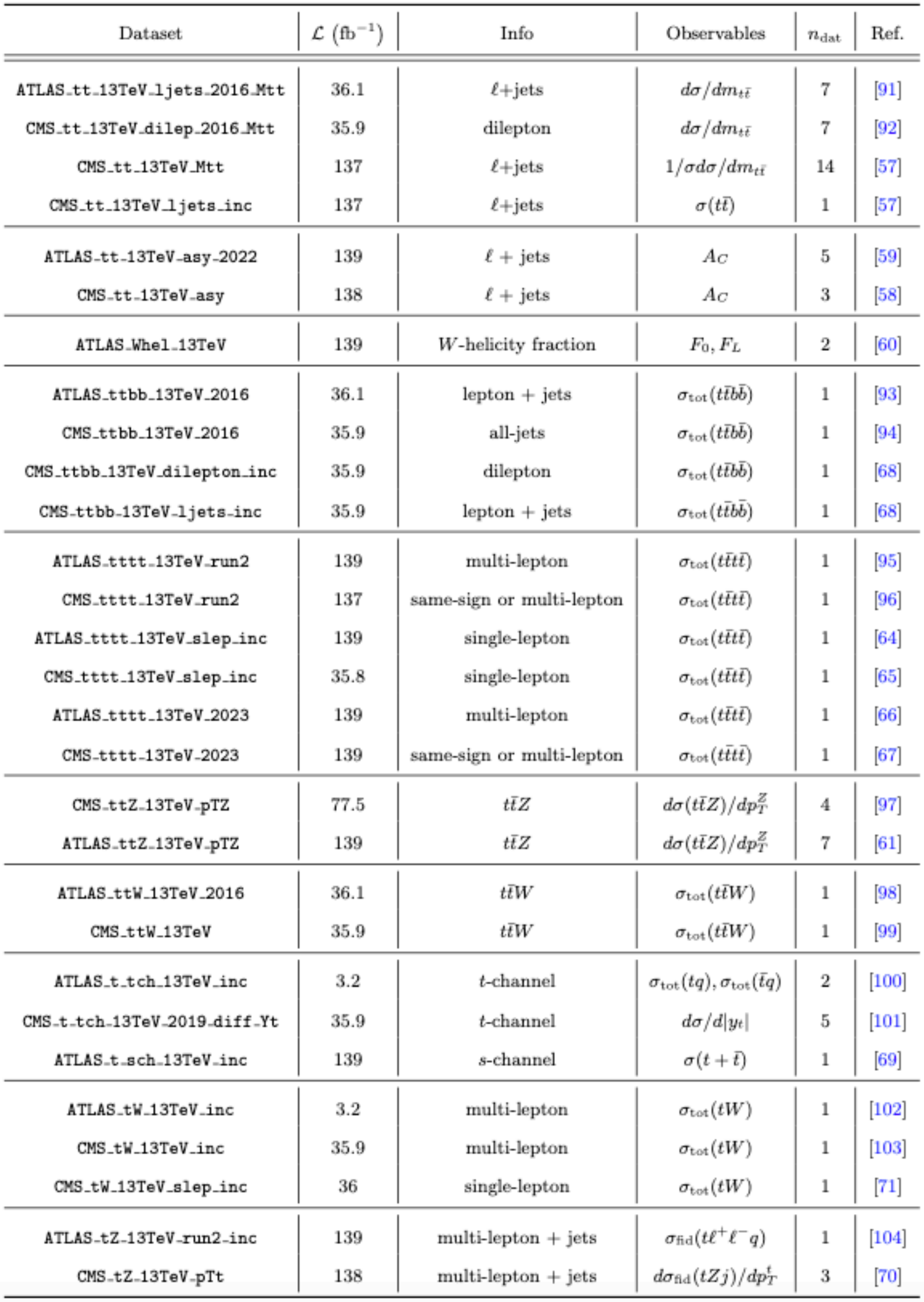


Category	Process	SM	Code/Ref	SMEFT
Top quark production	$t\bar{t}$ (incl)	NNLO QCD	`MG5_aMC` NLO + NNLO K-fact	NLO QCD
	$t\bar{t}+V$	NLO QCD	`MG5_aMC` NLO	LO QCD + NLO SM K-fact
	single-t (incl)	NNLO QCD	`MG5_aMC` NLO + NNLO K-fact	NLO QCD
	$t+V$	NLO QCD	`MG5_aMC` NLO	LO QCD + NLO SM K-fact
	$t\bar{t}t\bar{t},\ t\bar{b}t\bar{b}$	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

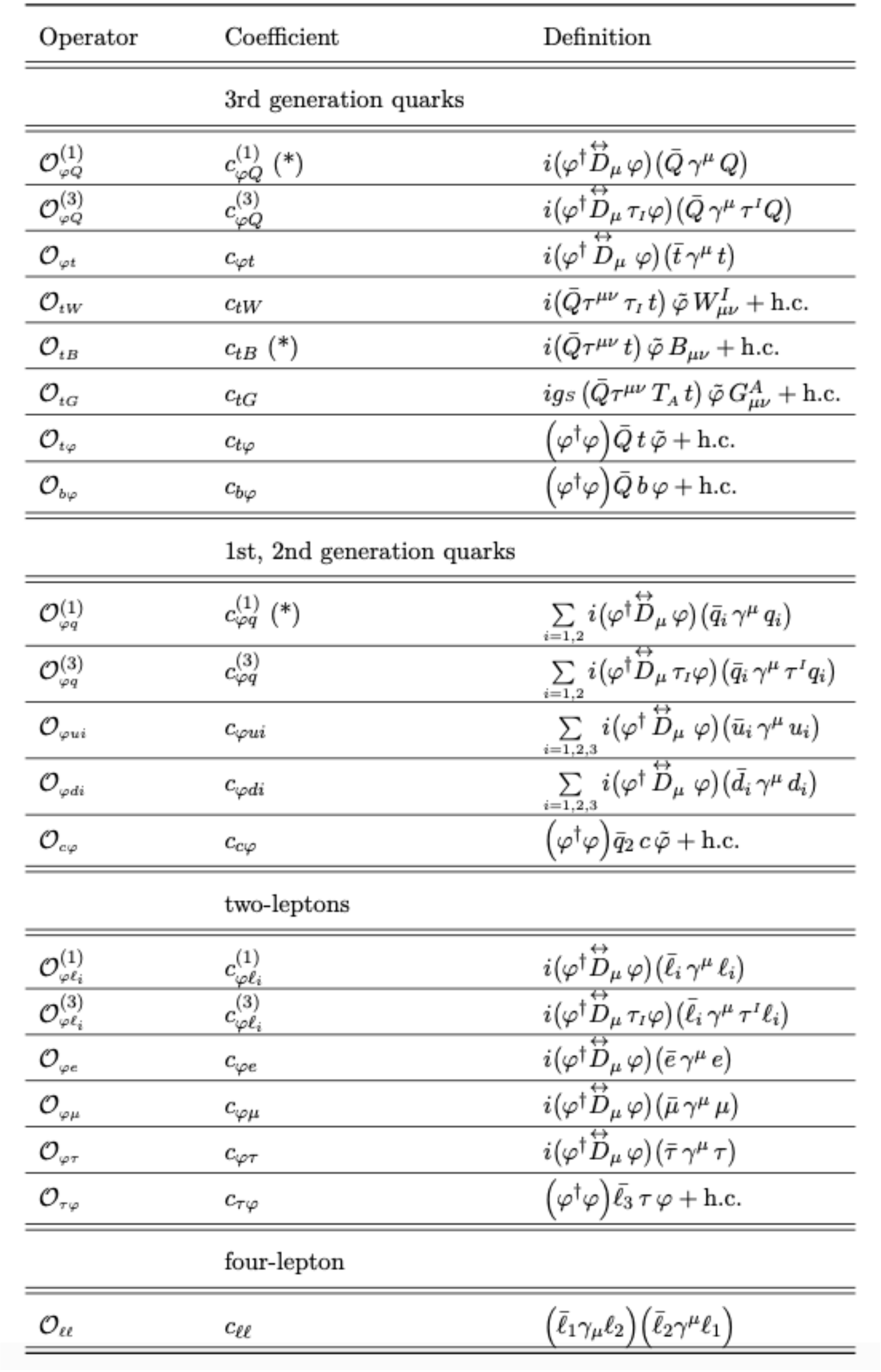


Dataset	$\mathcal{L}$ (fb^{-1})	Info	Observables	$n_{\rm dat}$	Ref.
ATLAS_STXS_RunII_13TeV_2022	139	ggF, VBF, Vh, $t\bar{t}h$, th	$d\sigma/dp_T^h$ $d\sigma/dm_{jj}$ $d\sigma/dp_T^V$	36	[55]
CMS_ggF_aa_13TeV	77.4	ggF, $h\to\gamma\gamma$	$\sigma_{gg{\rm F}}(p_T^h, N_{\rm jets})$	6	[83]
ATLAS_ggF_ZZ_13TeV	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	$n_{\rm dat}$	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	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[93]
CMS_ttbb_13TeV_2016	35.9	all-jets	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[94]
CMS_ttbb_13TeV_dilepton_inc	35.9	dilepton	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[68]
CMS_ttbb_13TeV_ljets_inc	35.9	lepton + jets	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[68]
ATLAS_tttt_13TeV_run2	139	multi-lepton	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[95]
CMS_tttt_13TeV_run2	137	same-sign or multi-lepton	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[96]
ATLAS_tttt_13TeV_slep_inc	139	single-lepton	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[64]
CMS_tttt_13TeV_slep_inc	35.8	single-lepton	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[65]
ATLAS_tttt_13TeV_2023	139	multi-lepton	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[66]
CMS_tttt_13TeV_2023	139	same-sign or multi-lepton	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	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	$t\bar{t}W$	$\sigma_{\rm tot}(t\bar{t}W)$	1	[98]
CMS_ttW_13TeV	35.9	$t\bar{t}W$	$\sigma_{\rm tot}(t\bar{t}W)$	1	[99]
ATLAS_t_tch_13TeV_inc	3.2	t-channel	$\sigma_{\rm tot}(tq), \sigma_{\rm tot}(\bar{t}q)$	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	$\sigma_{\rm tot}(tW)$	1	[102]
CMS_tW_13TeV_inc	35.9	multi-lepton	$\sigma_{\rm tot}(tW)$	1	[103]
CMS_tW_13TeV_slep_inc	36	single-lepton	$\sigma_{\rm tot}(tW)$	1	[71]
ATLAS_tZ_13TeV_run2_inc	139	multi-lepton + jets	$\sigma_{\rm fid}(t\ell^+\ell^-q)$	1	[104]
CMS_tZ_13TeV_pTt	138	multi-lepton + jets	$d\sigma_{\rm fid}(tZj)/dp_T^t$	3	[70]

Operator basis



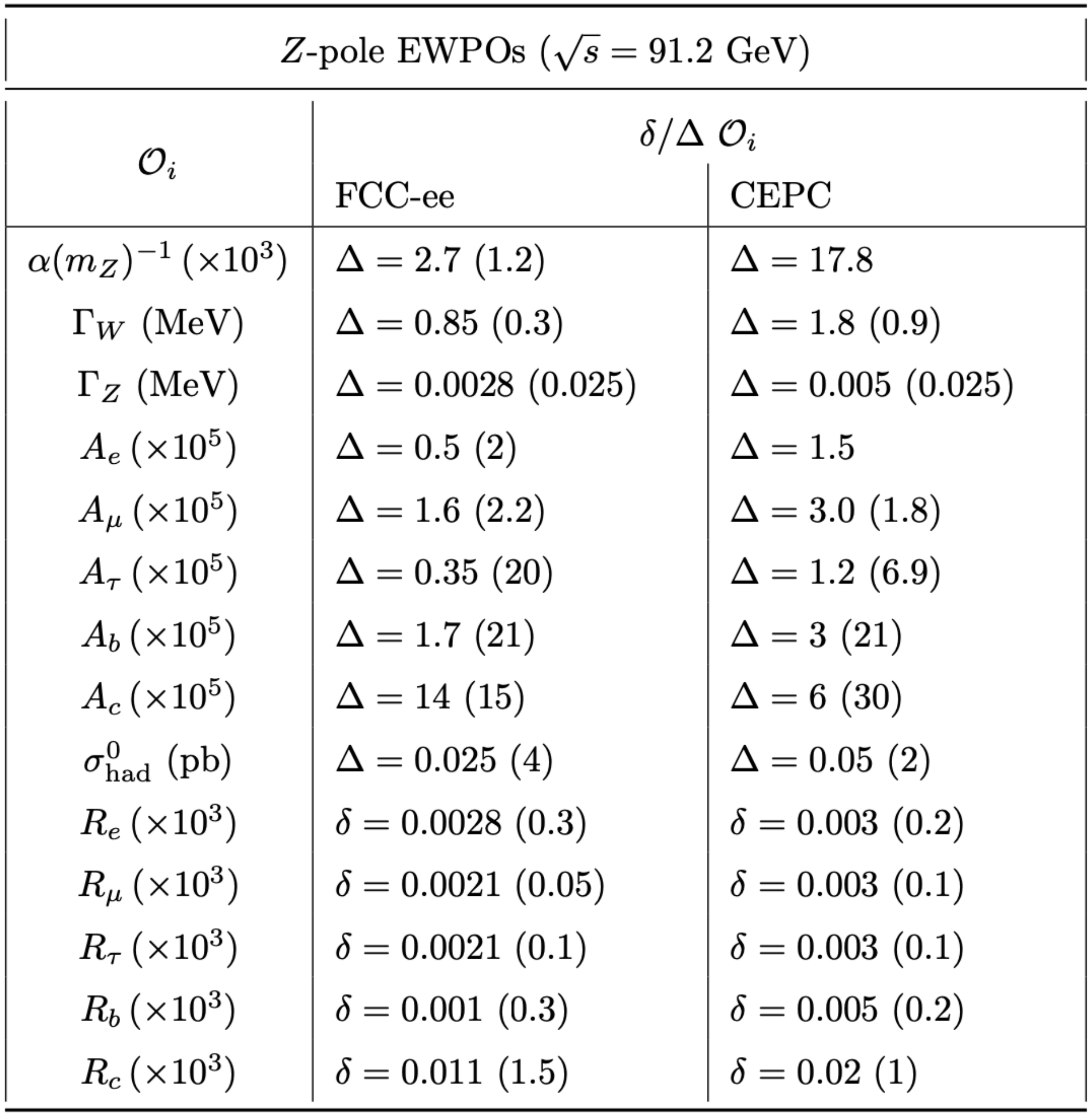
Operator	Coefficient	Definition
	3rd generation quarks	
$\mathcal{O}_{\varphi Q}^{(1)}$	$c_{\varphi Q}^{(1)}$ (*)	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{Q}\,\gamma^\mu\, Q)$
$\mathcal{O}_{\varphi Q}^{(3)}$	$c_{\varphi Q}^{(3)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu\, \tau_I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

$$\begin{aligned}
\mathcal{O}_{qq}^{1(ijkl)} &= (\bar{q}_i\gamma^\mu q_j)(\bar{q}_k\gamma_\mu q_l),\\
\mathcal{O}_{qq}^{3(ijkl)} &= (\bar{q}_i\gamma^\mu\tau^I q_j)(\bar{q}_k\gamma_\mu\tau^I q_l),\\
\mathcal{O}_{qu}^{1(ijkl)} &= (\bar{q}_i\gamma^\mu q_j)(\bar{u}_k\gamma_\mu u_l),\\
\mathcal{O}_{qu}^{8(ijkl)} &= (\bar{q}_i\gamma^\mu T^A q_j)(\bar{u}_k\gamma_\mu T^A u_l),\\
\mathcal{O}_{qd}^{1(ijkl)} &= (\bar{q}_i\gamma^\mu q_j)(\bar{d}_k\gamma_\mu d_l),\\
\mathcal{O}_{qd}^{8(ijkl)} &= (\bar{q}_i\gamma^\mu T^A q_j)(\bar{d}_k\gamma_\mu T^A d_l),\\
\mathcal{O}_{uu}^{(ijkl)} &= (\bar{u}_i\gamma^\mu u_j)(\bar{u}_k\gamma_\mu u_l),\\
\mathcal{O}_{ud}^{1(ijkl)} &= (\bar{u}_i\gamma^\mu u_j)(\bar{d}_k\gamma_\mu d_l),\\
\mathcal{O}_{ud}^{8(ijkl)} &= (\bar{u}_i\gamma^\mu T^A u_j)(\bar{d}_k\gamma_\mu T^A d_l)\,,
\end{aligned}$$

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

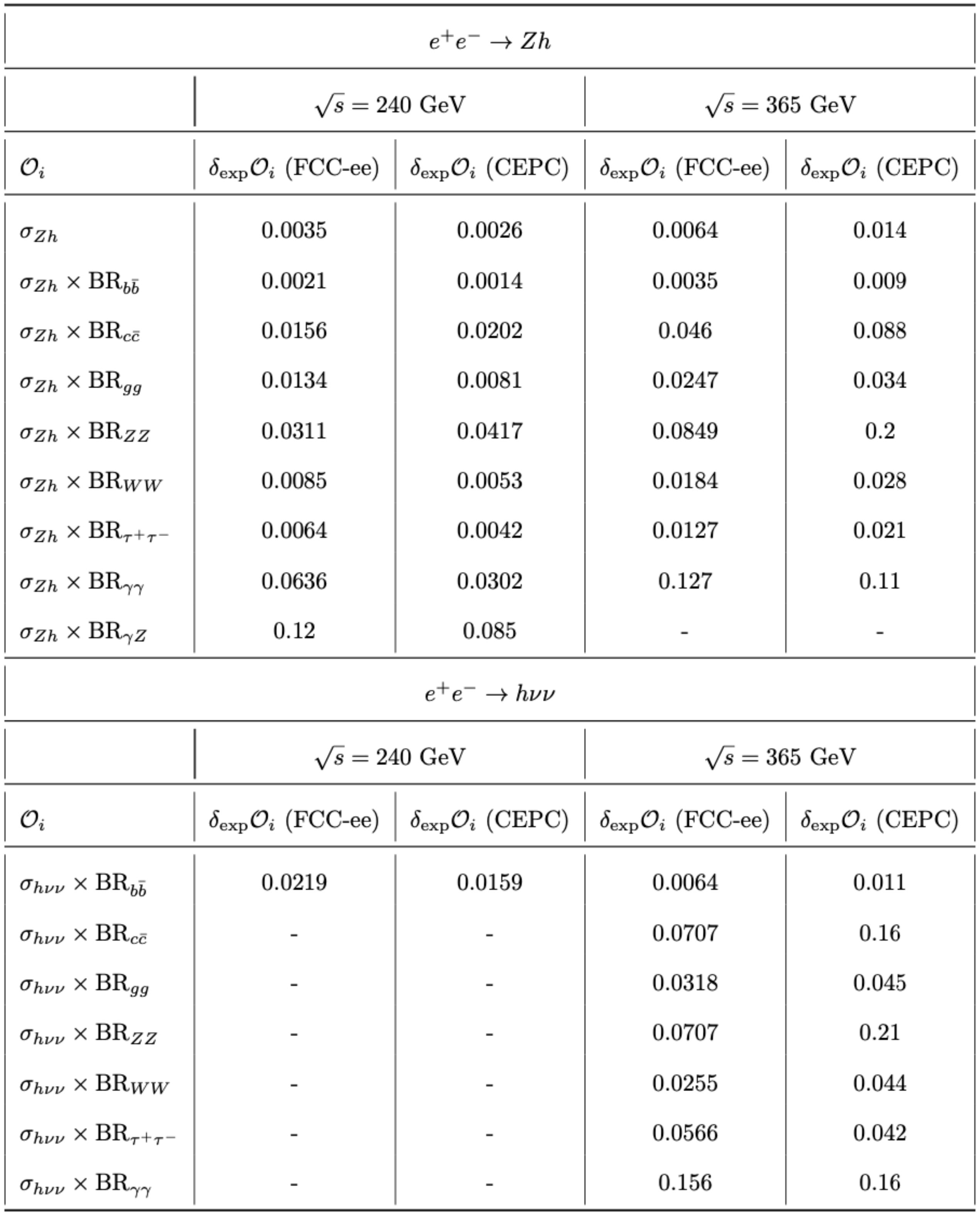
FCC-ee and CEPC datasets

EWPOs



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)	$\Delta = 0.025\ (4)$	$\Delta = 0.05\ (2)$
$R_e\,(\times 10^3)$	$\delta = 0.0028\ (0.3)$	$\delta = 0.003\ (0.2)$
$R_\mu\,(\times 10^3)$	$\delta = 0.0021\ (0.05)$	$\delta = 0.003\ (0.1)$
$R_\tau\,(\times 10^3)$	$\delta = 0.0021\ (0.1)$	$\delta = 0.003\ (0.1)$
$R_b\,(\times 10^3)$	$\delta = 0.001\ (0.3)$	$\delta = 0.005\ (0.2)$
$R_c\,(\times 10^3)$	$\delta = 0.011\ (1.5)$	$\delta = 0.02\ (1)$

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



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

$e^+e^- \to h\nu\nu$				
	$\sqrt{s} = 240$ GeV		$\sqrt{s} = 365$ GeV	
$\mathcal{O}_i$	$\delta_{\text{exp}}\mathcal{O}_i$ (FCC-ee)	$\delta_{\text{exp}}\mathcal{O}_i$ (CEPC)	$\delta_{\text{exp}}\mathcal{O}_i$ (FCC-ee)	$\delta_{\text{exp}}\mathcal{O}_i$ (CEPC)
$\sigma_{h\nu\nu} \times \text{BR}_{b\bar{b}}$	0.0219	0.0159	0.0064	0.011
$\sigma_{h\nu\nu} \times \text{BR}_{c\bar{c}}$	-	-	0.0707	0.16
$\sigma_{h\nu\nu} \times \text{BR}_{gg}$	-	-	0.0318	0.045
$\sigma_{h\nu\nu} \times \text{BR}_{ZZ}$	-	-	0.0707	0.21
$\sigma_{h\nu\nu} \times \text{BR}_{WW}$	-	-	0.0255	0.044
$\sigma_{h\nu\nu} \times \text{BR}_{\tau^+\tau^-}$	-	-	0.0566	0.042
$\sigma_{h\nu\nu} \times \text{BR}_{\gamma\gamma}$	-	-	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	
$\mathcal{O}_i$	$\Delta_{\text{exp}}\mathcal{O}_i$ (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}	$1.36 \cdot 10^{-4}$	$2.48 \cdot 10^{-4}$	$1.22 \cdot 10^{-4}$	$8.63 \cdot 10^{-5}$	$2.81 \cdot 10^{-4}$	$4.87 \cdot 10^{-4}$
$\text{BR}_{W \to \ell_i \nu_i}$	$2.72 \cdot 10^{-4}$	$4.95 \cdot 10^{-4}$	$2.44 \cdot 10^{-4}$	$1.73 \cdot 10^{-4}$	$5.63 \cdot 10^{-4}$	$9.75 \cdot 10^{-4}$

EWPO benchmark