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Global SMEFT fits

from (HL)-LHC to future colliders

Jaco ter Hoeve

20/07

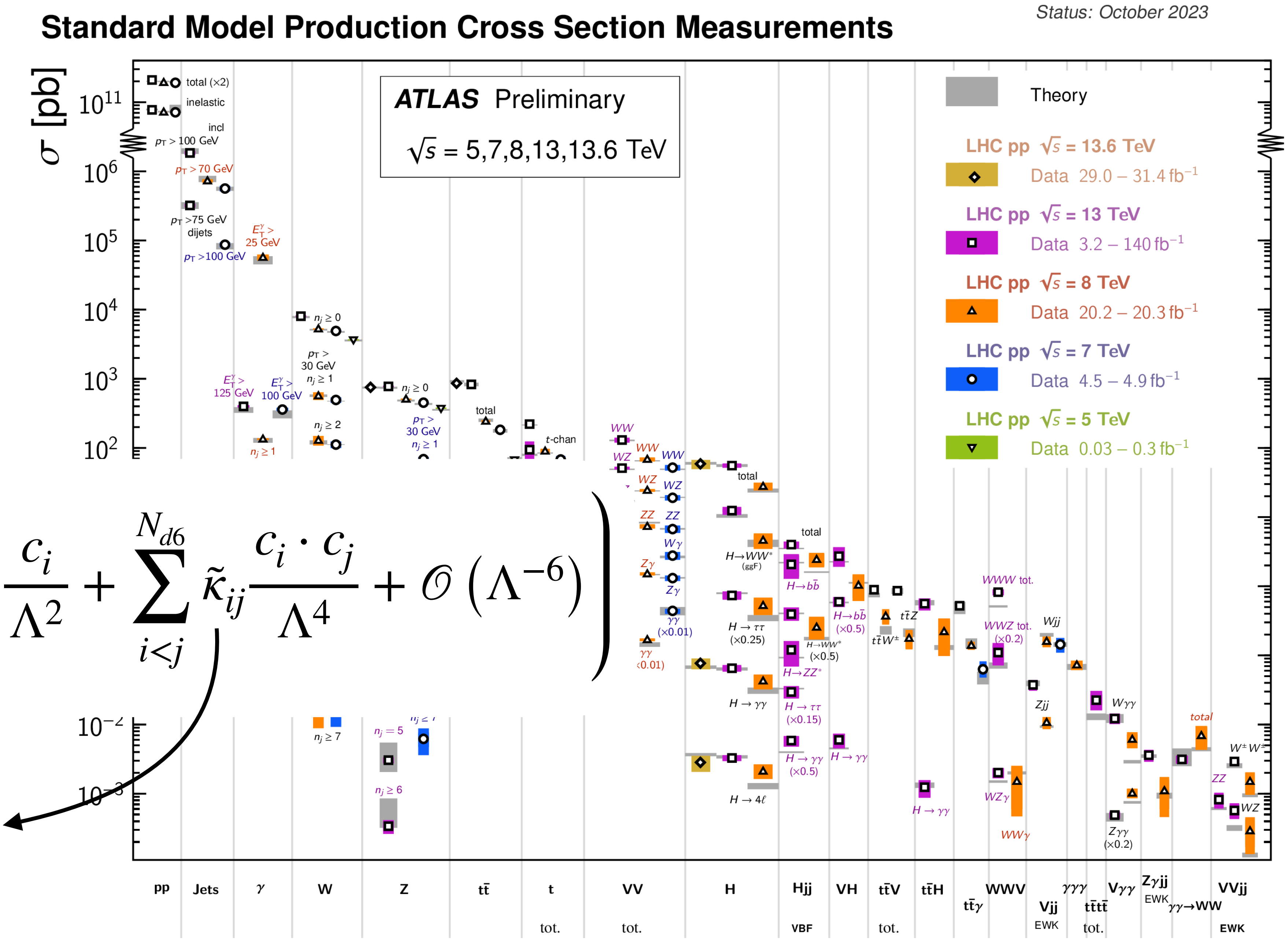
ICHEP 2024 | PRAGUE

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]



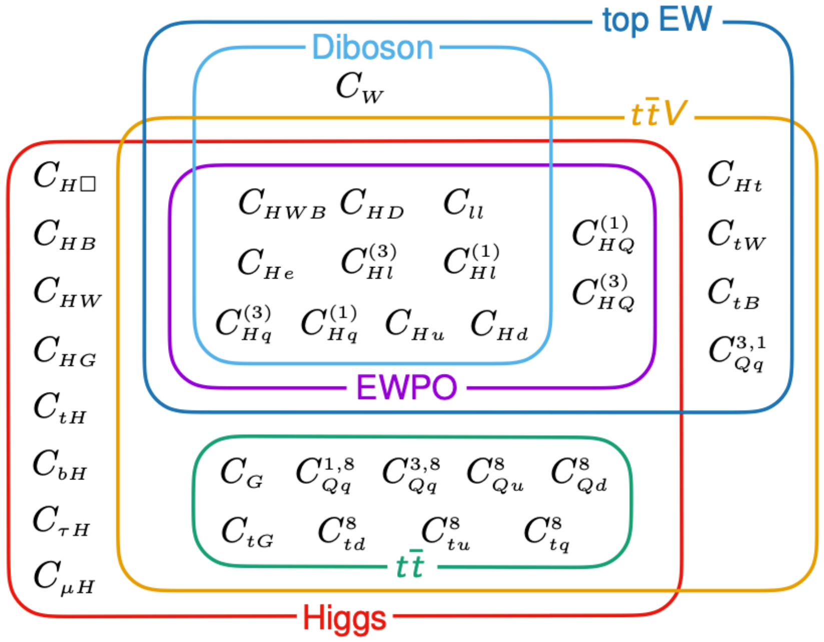
Linear EFT corrections:
interference SM-EFTd6
@NLO QCD

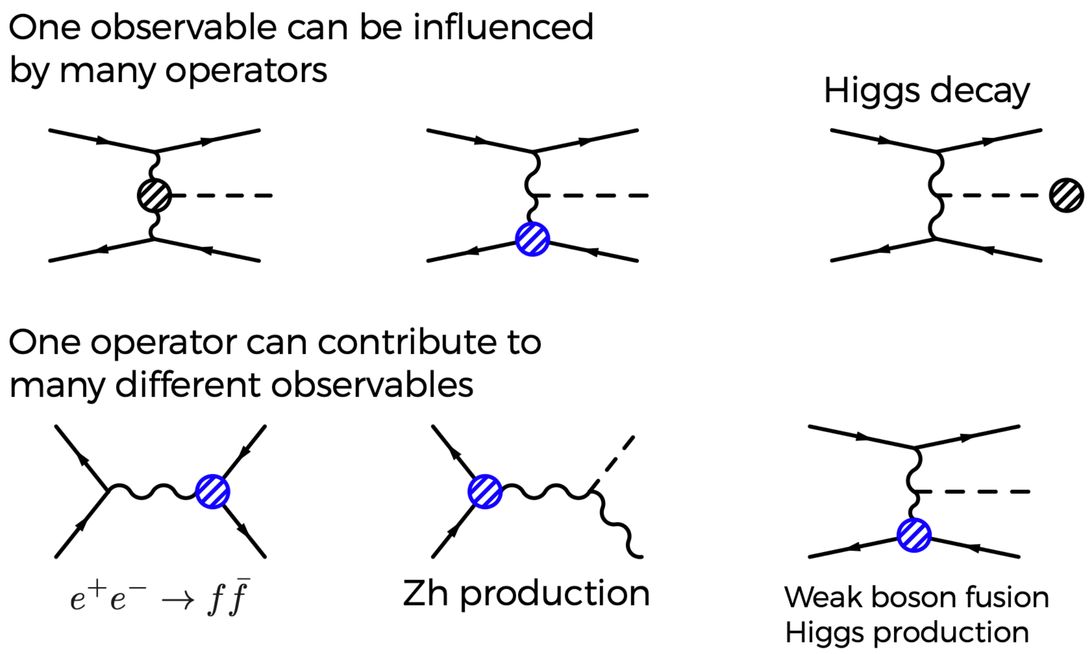
$$\sigma(c,\Lambda) = \sigma_{\rm SM} \times \left(1 + \sum_{i}^{N_{d6}} \kappa_i \frac{c_i}{\Lambda^2} + \sum_{i<j}^{N_{d6}} \tilde{\kappa}_{ij} \frac{c_i \cdot c_j}{\Lambda^4} + \mathcal{O}\left(\Lambda^{-6}\right) \right)$$

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

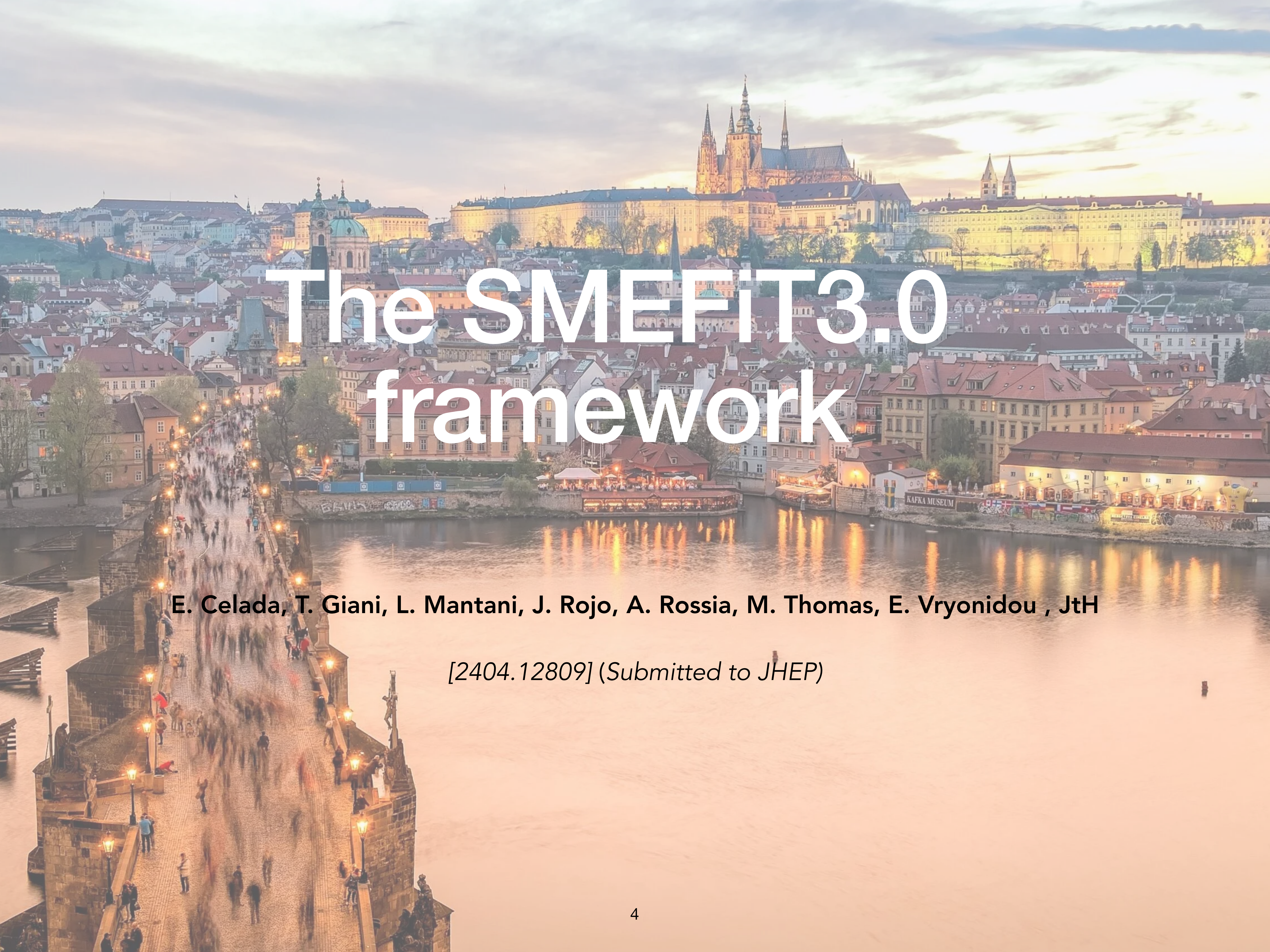



One observable can be influenced by many operators

One operator can contribute to many different observables

[2012.02779] Fitmaker collaboration

Anke Biekötter - HET seminar Brookhaven

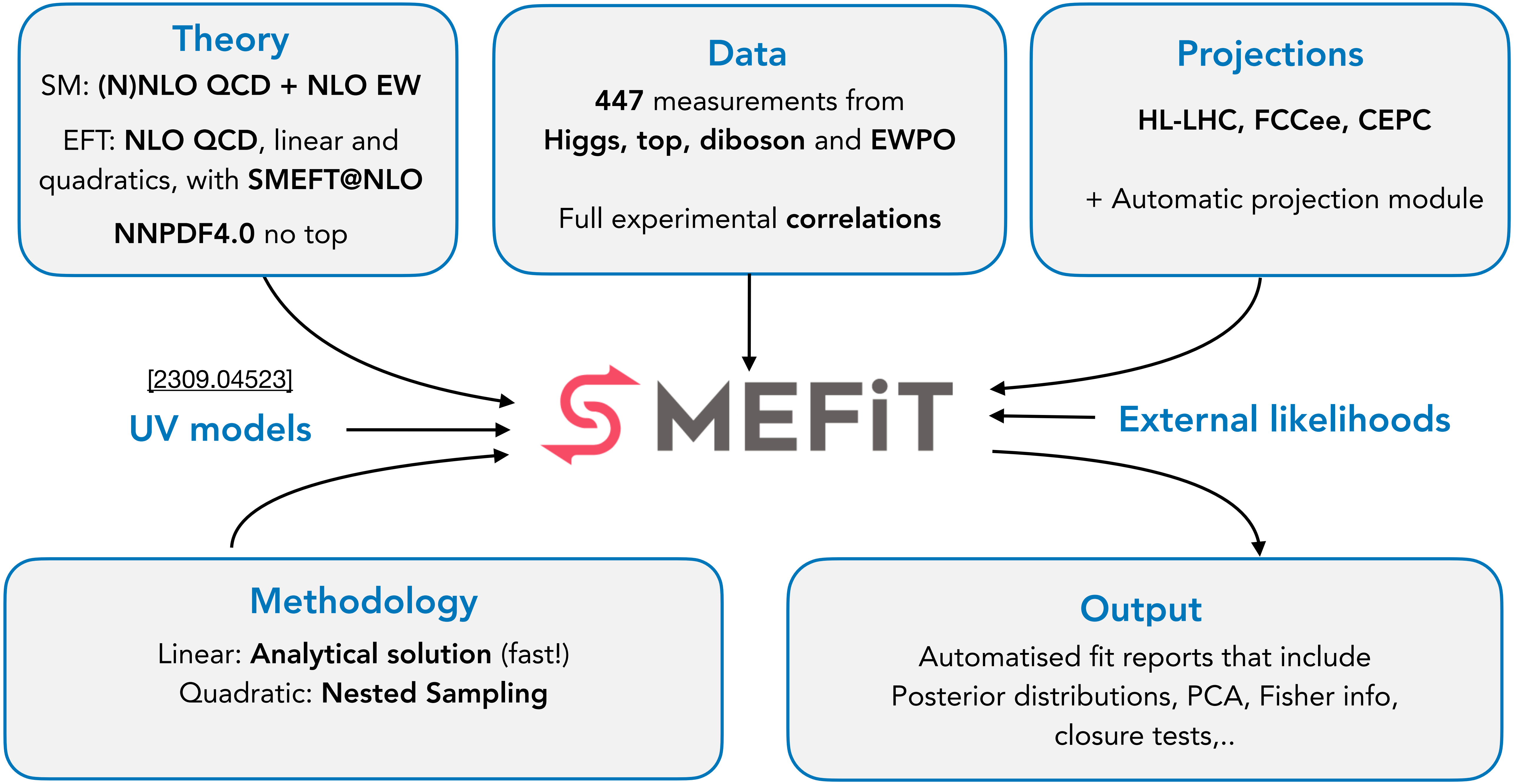


The SMEFiT3.0 framework

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

[2404.12809] (Submitted to JHEP)

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, FCCee, CEPC

+ Automatic projection module

[2309.04523]

UV models

SMEFiT

External likelihoods

Methodology

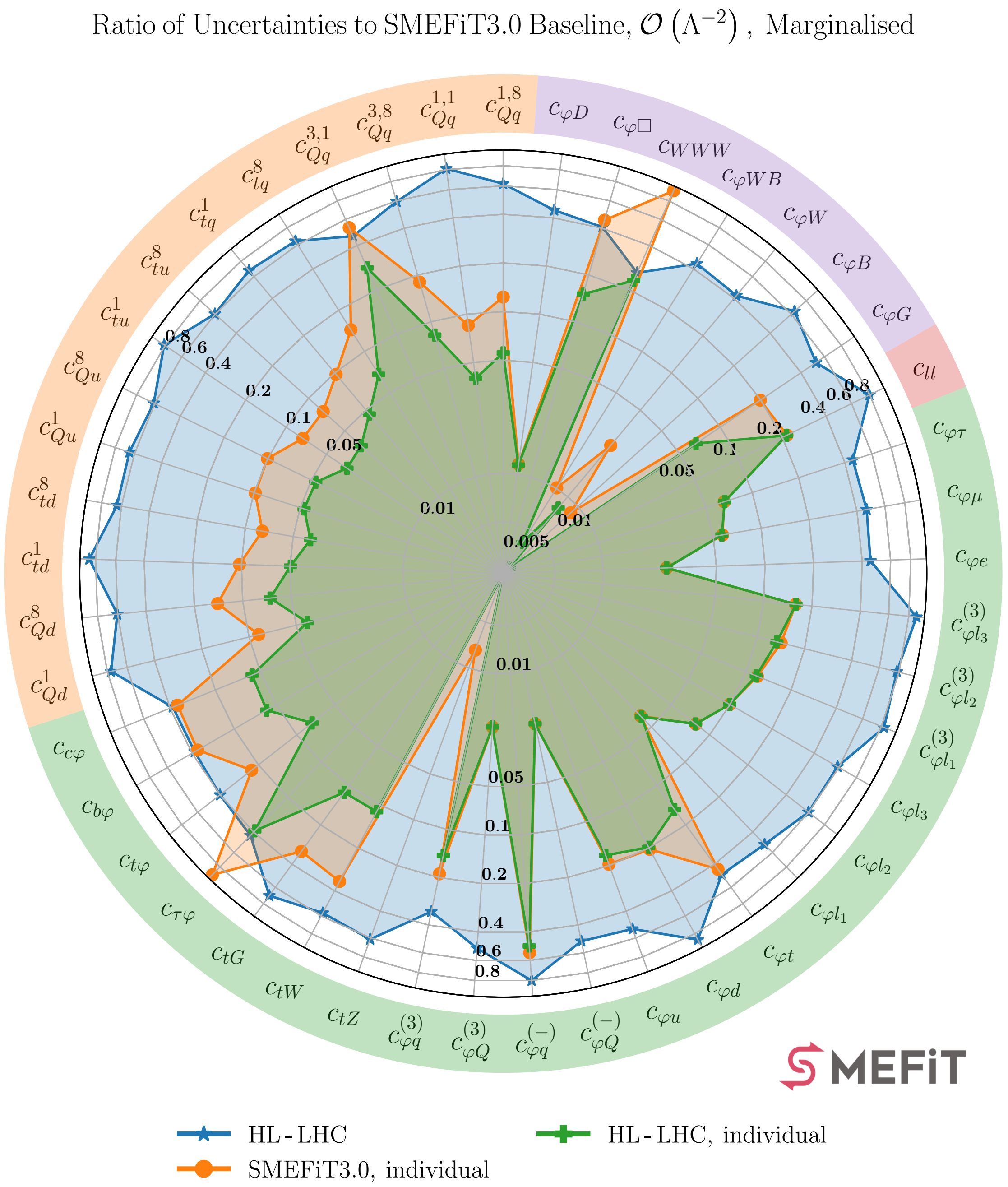
Linear: **Analytical solution** (fast!)
Quadratic: **Nested Sampling**

Output

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

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"

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

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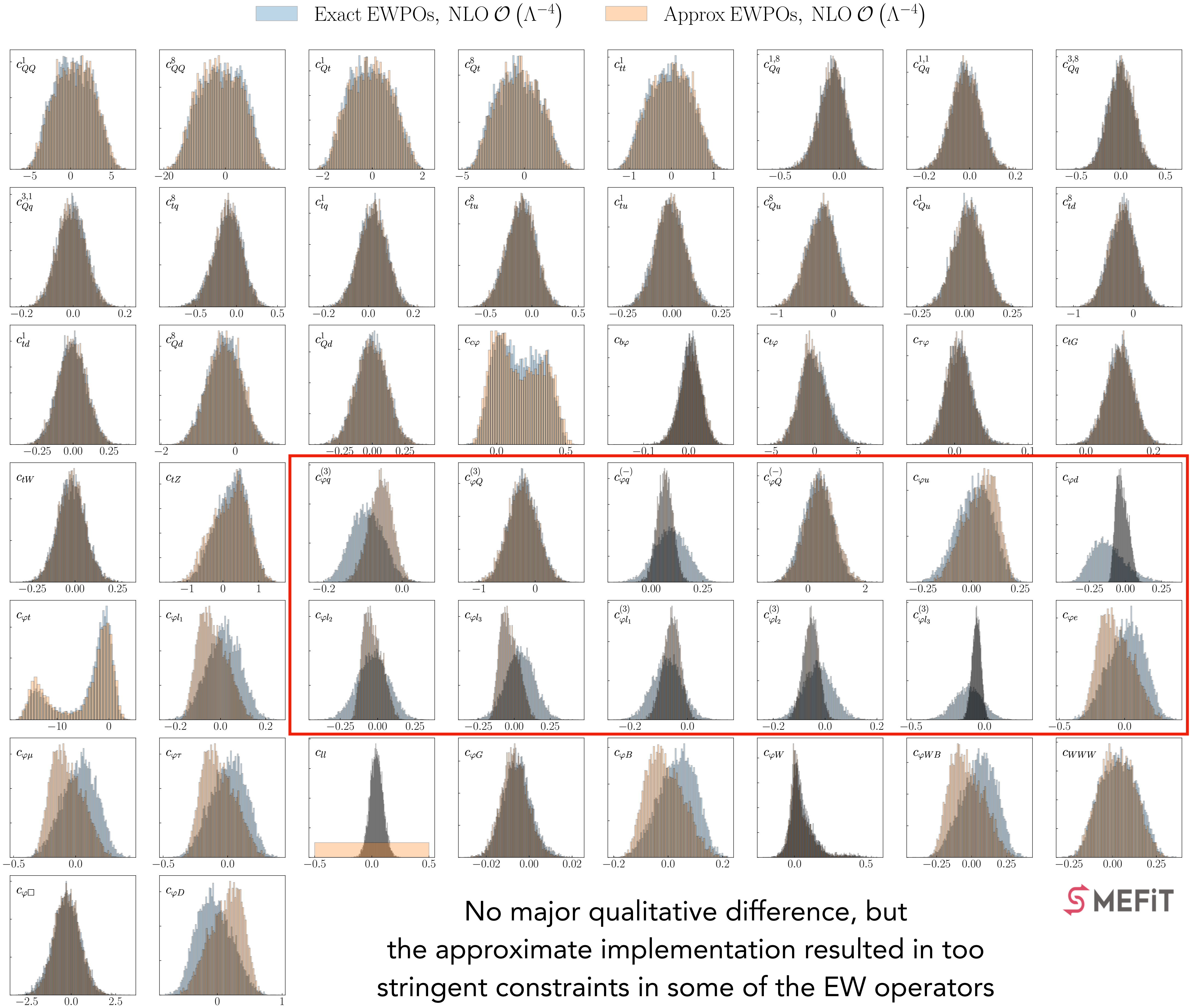
SMEFiT3.0 is simultaneously sensitive to **45 (50) Wilson coefficients** at the linear (quadratic) level!



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

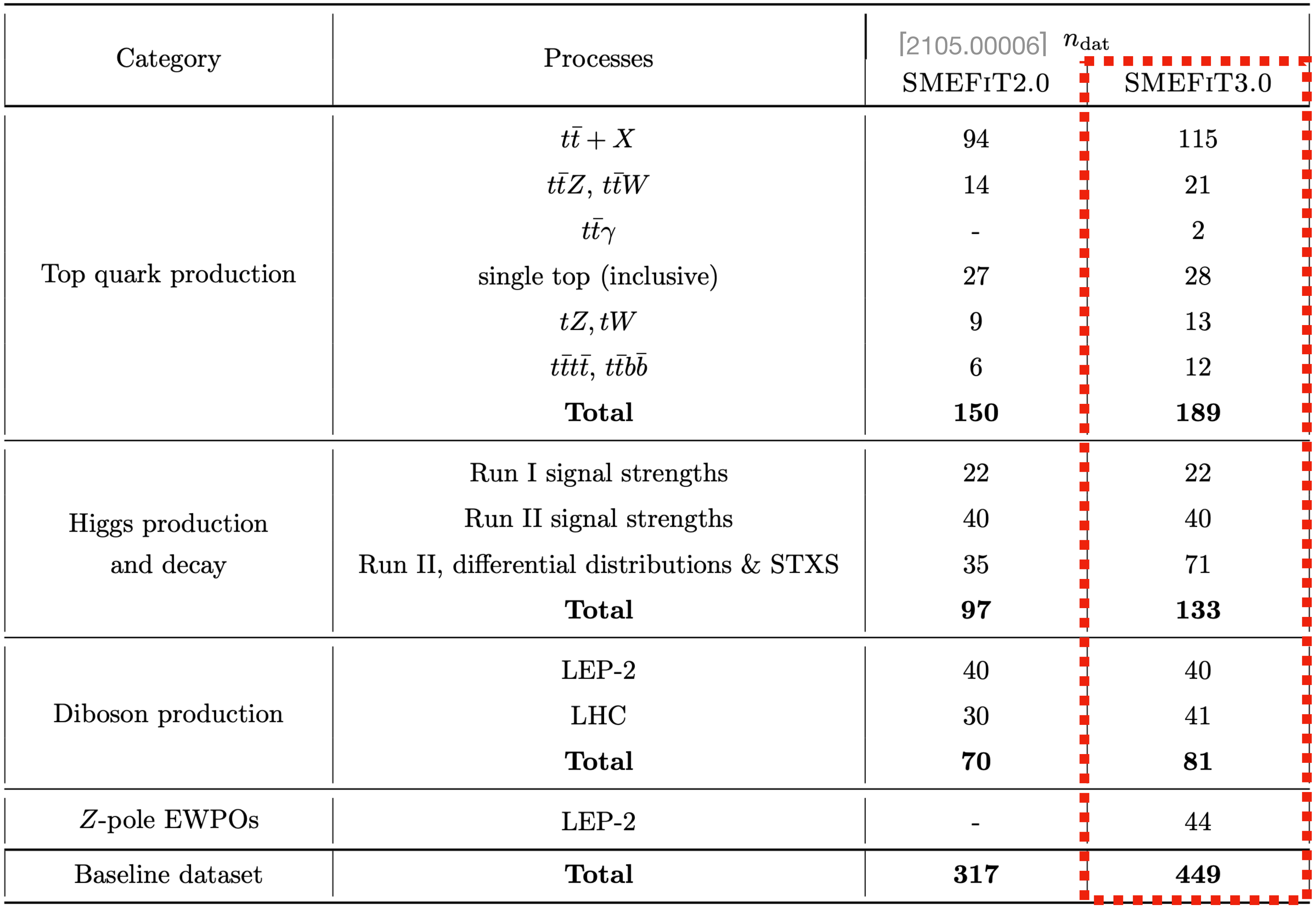
SMEFiT

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

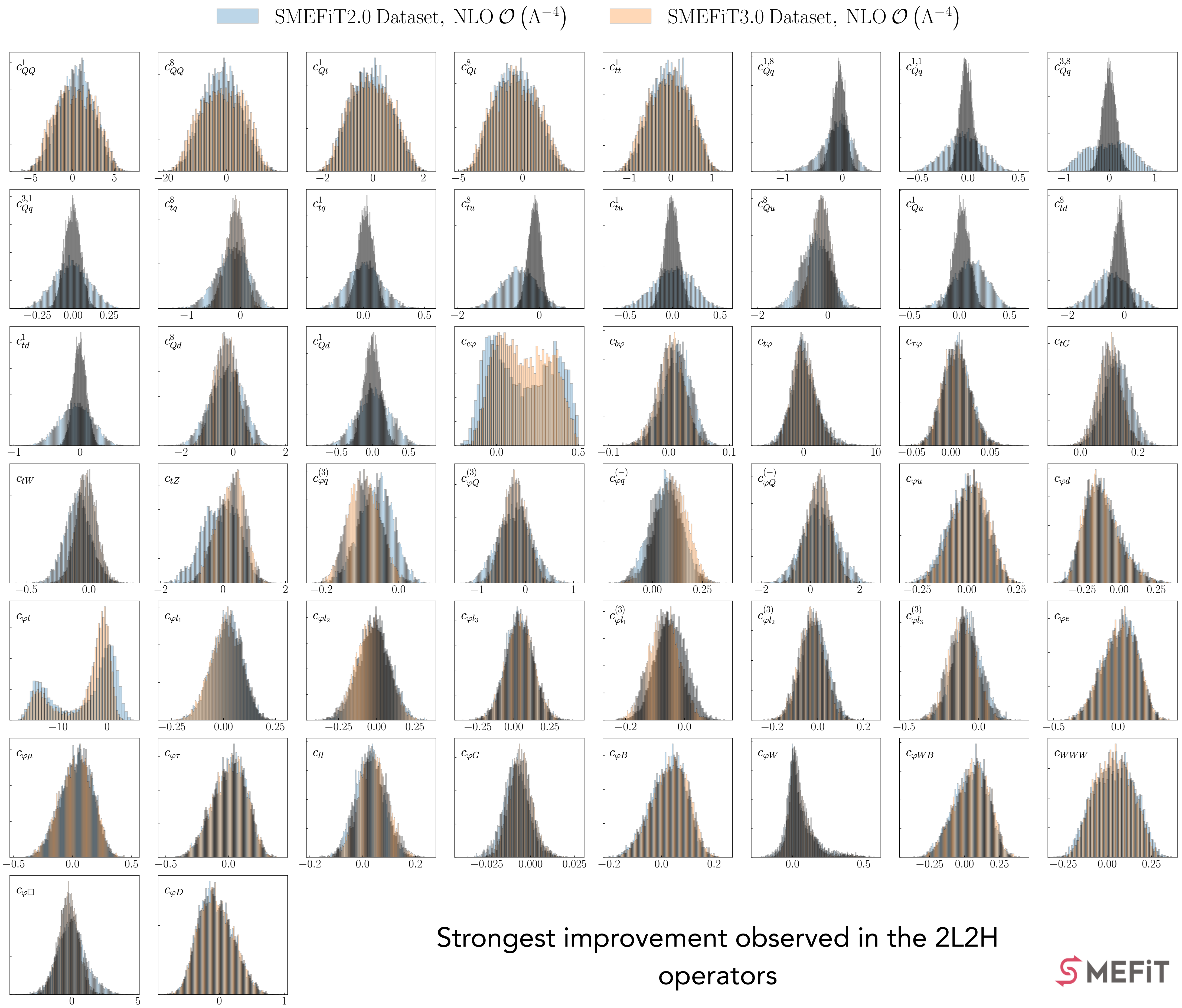
Dataset upgrade

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

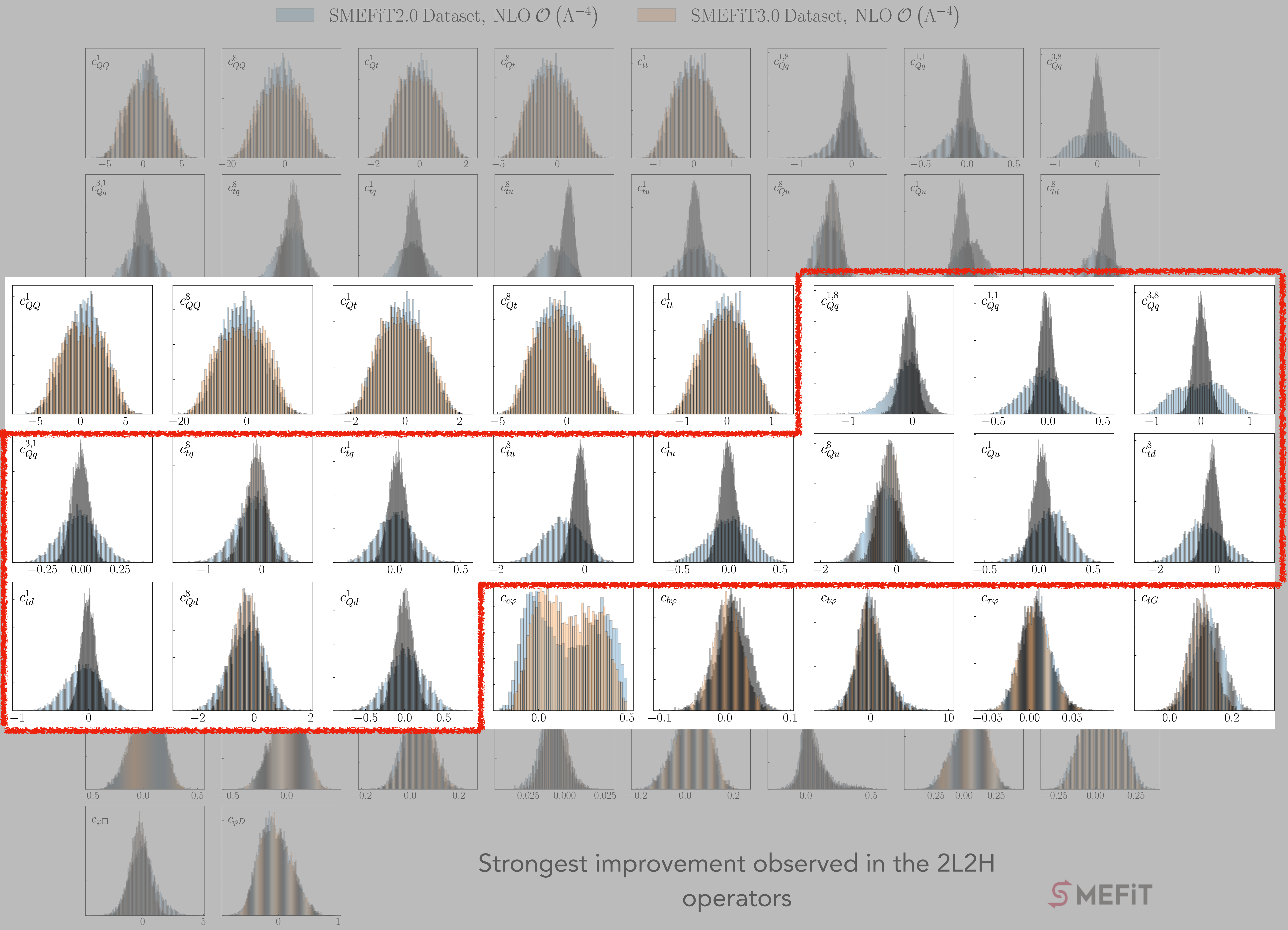


Category	Processes	n_{dat}	
		[2105.00006] SMEFiT2.0	SMEFiT3.0
Top quark production	$t\bar{t}+X$	94	115
	$t\bar{t}Z$, $t\bar{t}W$	14	21
	$t\bar{t}\gamma$	-	2
	single top (inclusive)	27	28
	tZ, tW	9	13
	$t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$	6	12
	Total	**150**	**189**
Higgs production and decay	Run I 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: $U(2)_q \times U(3)_d \times U(2)_u \times \left(U(1)_\ell \times U(1)_e\right)^3$



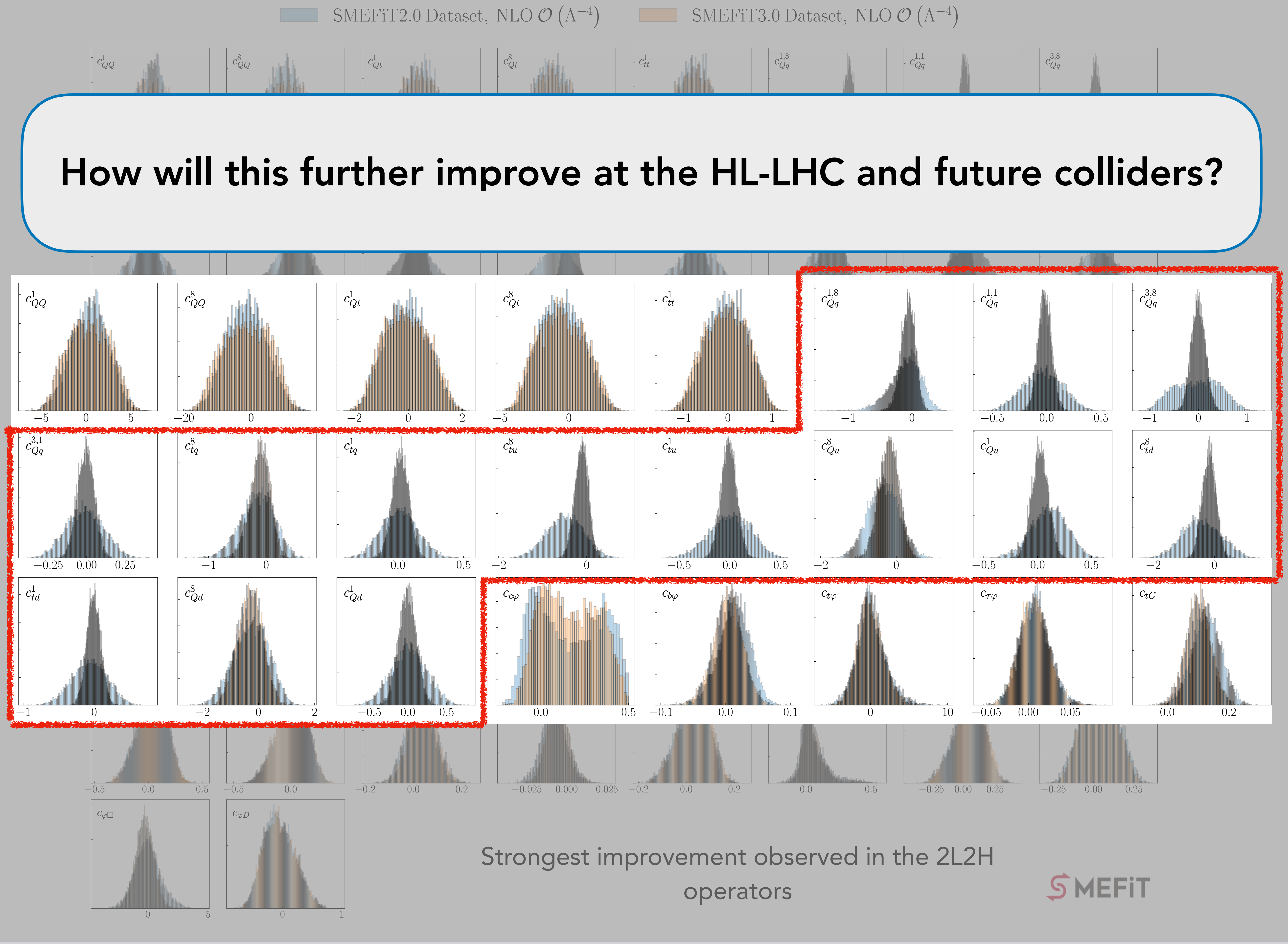
Strongest improvement observed in the 2L2H operators



Strongest improvement observed in the 2L2H operators

SMEFiT

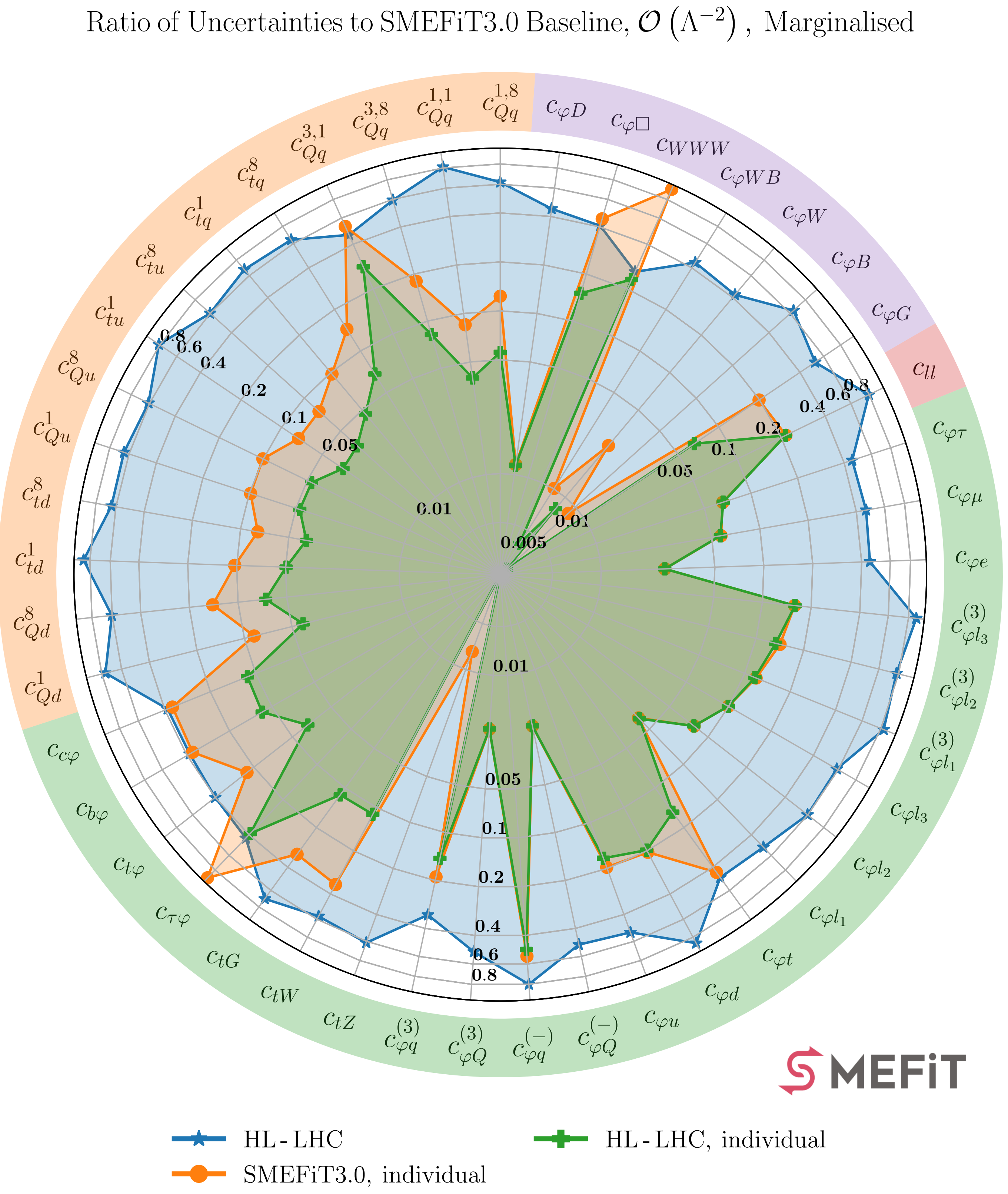
How will this further improve at the HL-LHC and future colliders?



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



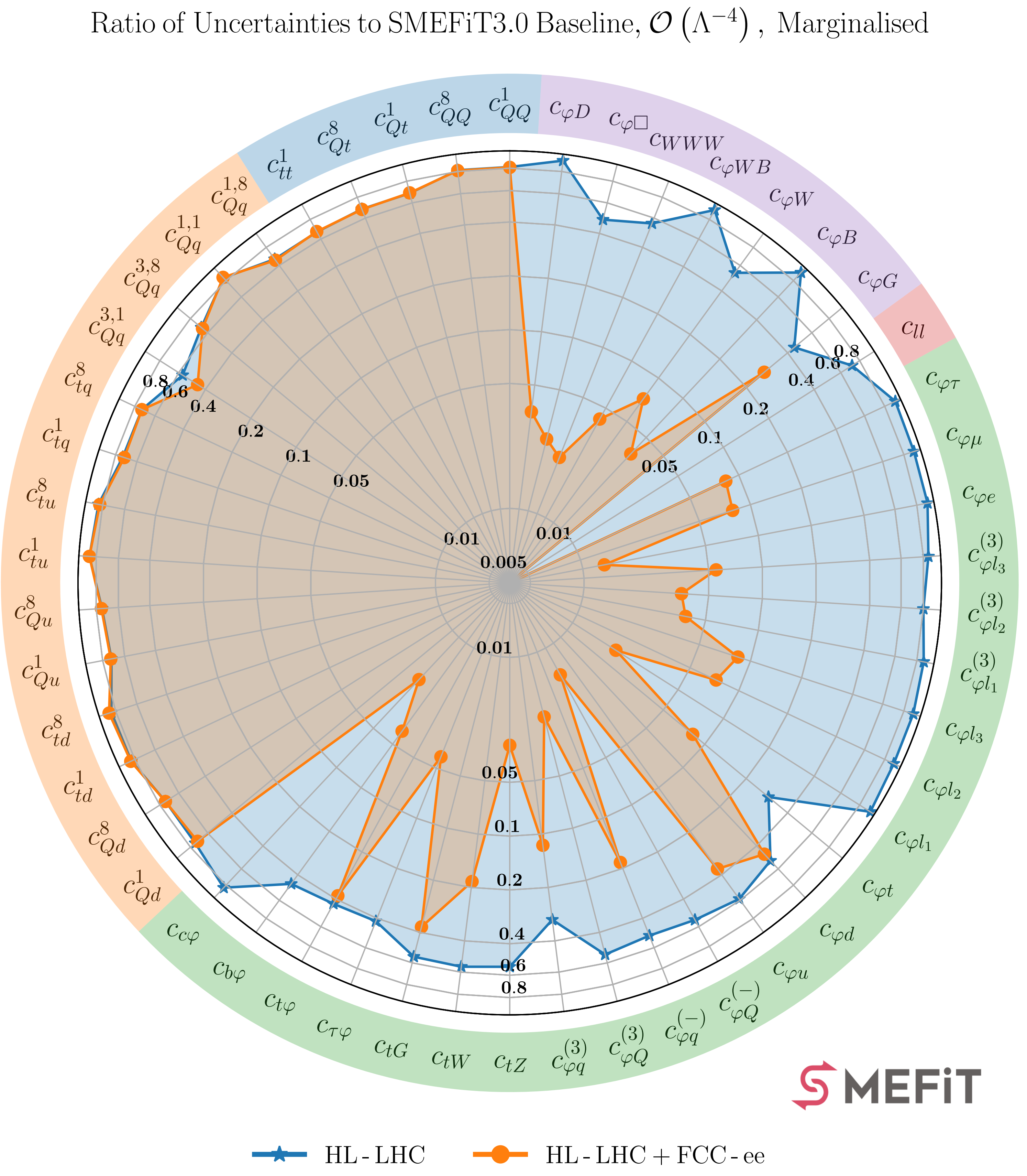
Ratio of Uncertainties to SMEFiT3.0 Baseline, $\mathcal{O}\left(\Lambda^{-2}\right)$, Marginalised

Result: FCC-ee

Dataset input

- EWPOs at the Z-pole
- Light fermion pair prediction
- Higgsstrahlung 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)

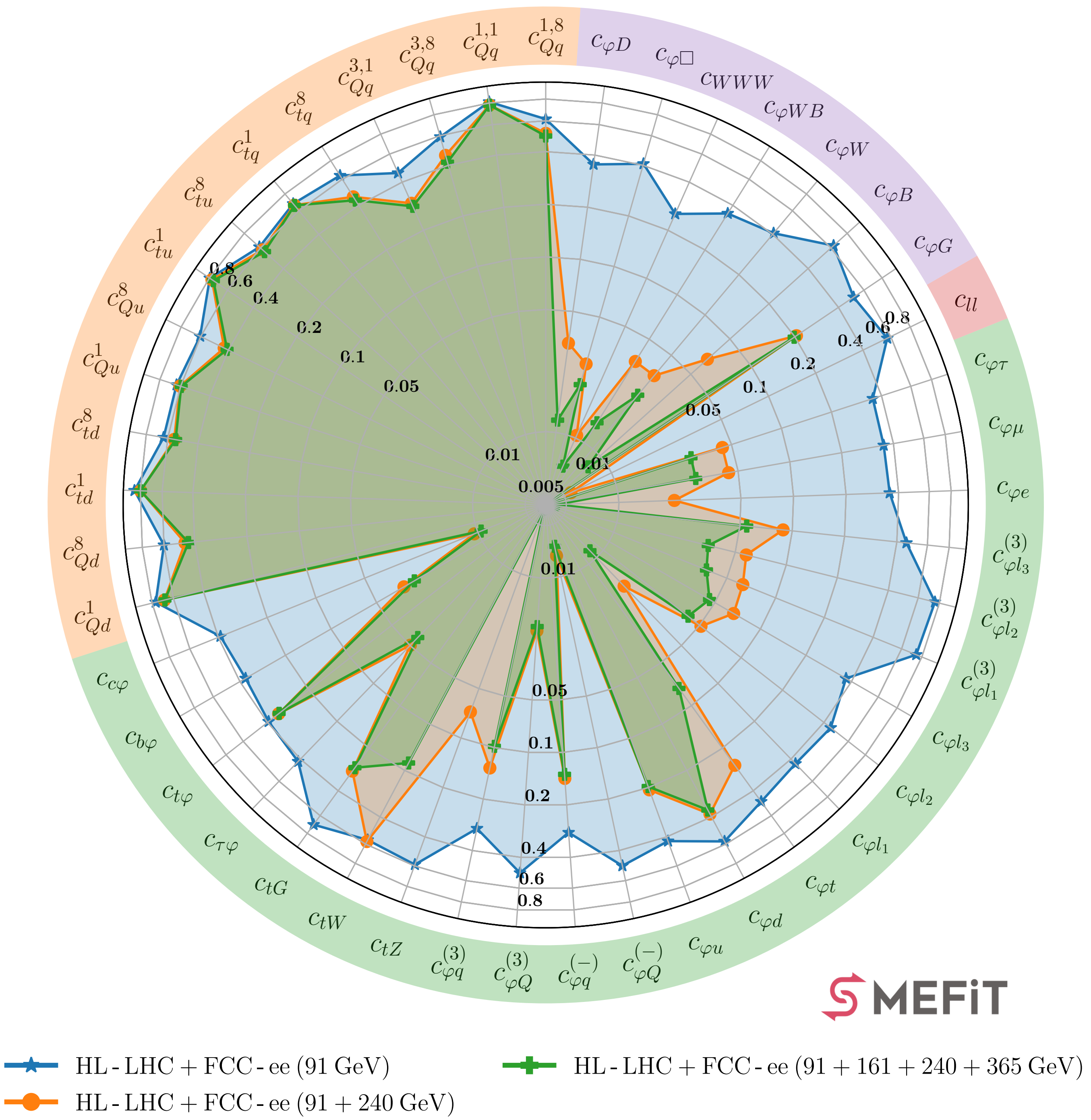


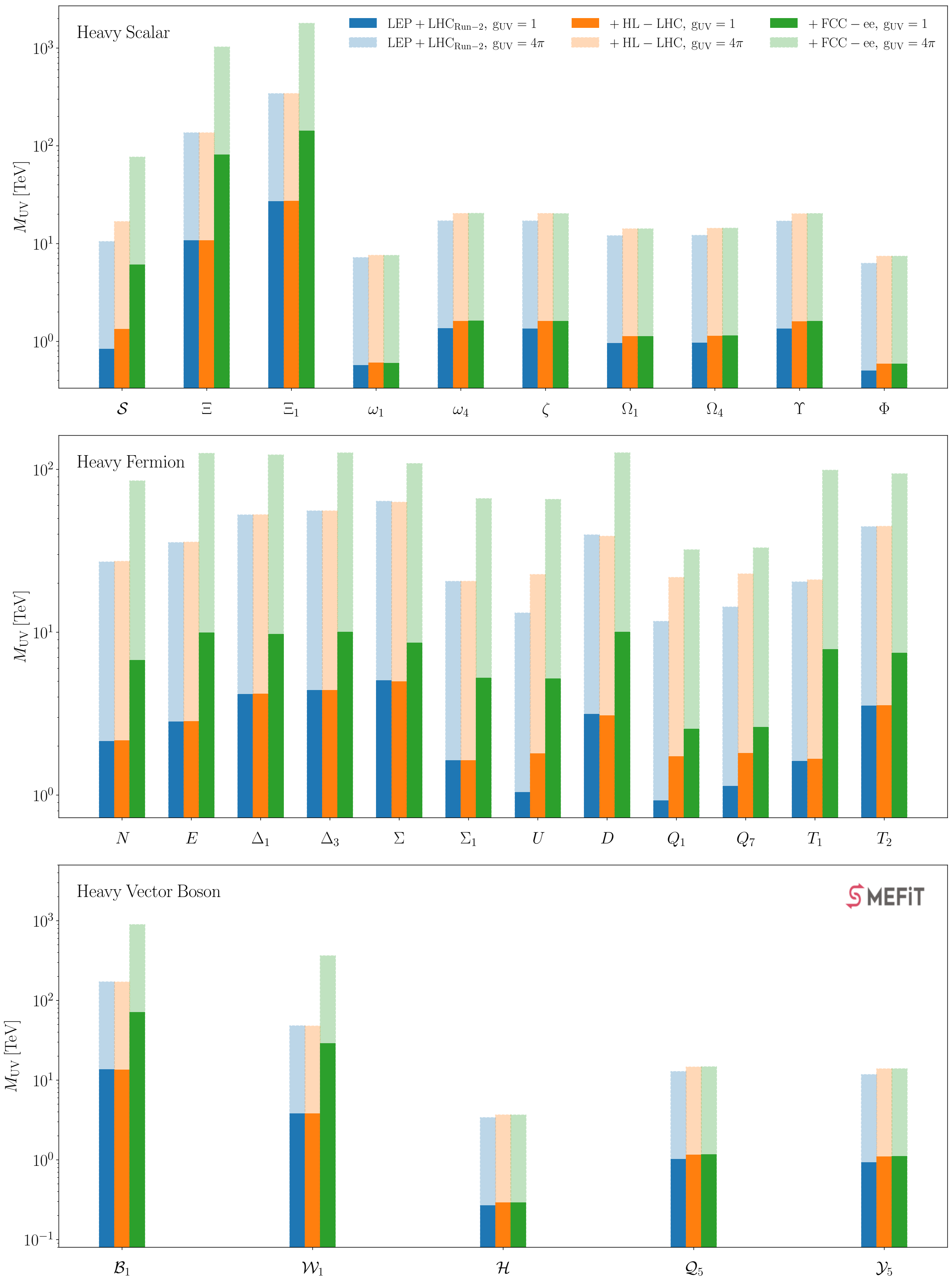
Ratio of Uncertainties to SMEFiT3.0 Baseline, $\mathcal{O}\left(\Lambda^{-4}\right)$, Marginalised

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





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	$(3,2)_{-5/6}$		

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
- 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

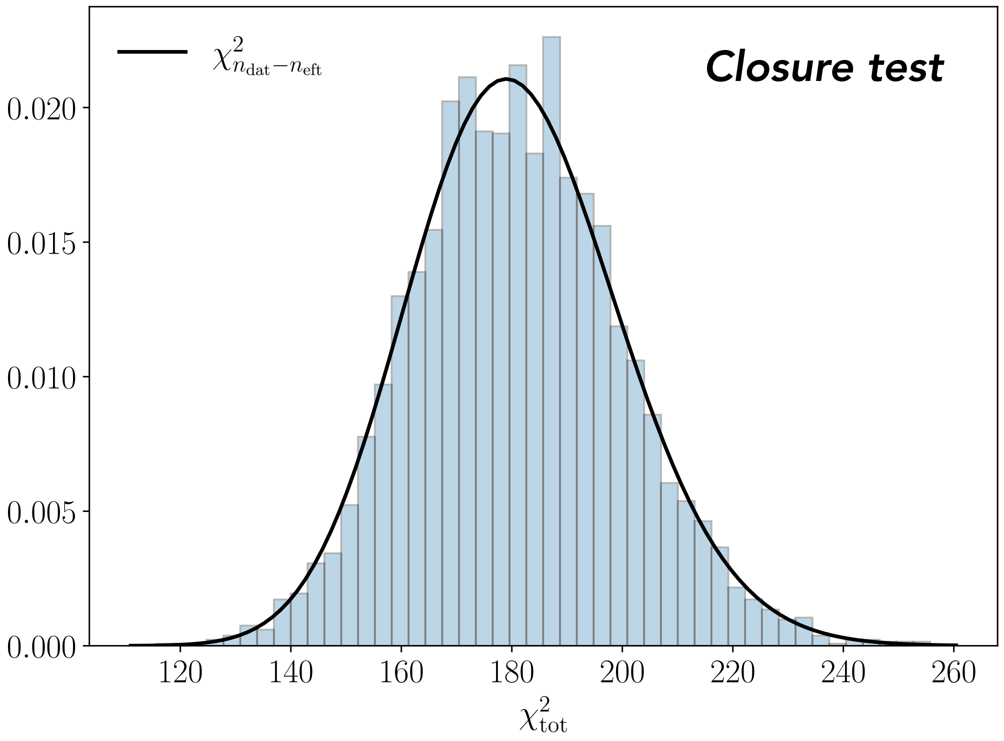
$$\mathcal{O}_i^{(\mathrm{exp})} = \mathcal{O}_i^{(\mathrm{th})}\left(1 + r_i\delta_i^{(\mathrm{stat})} + \sum_{k=1}^{n_{\mathrm{sys}}} r_{k,i}\delta_{k,i}^{(\mathrm{sys})}\right)$$

- 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

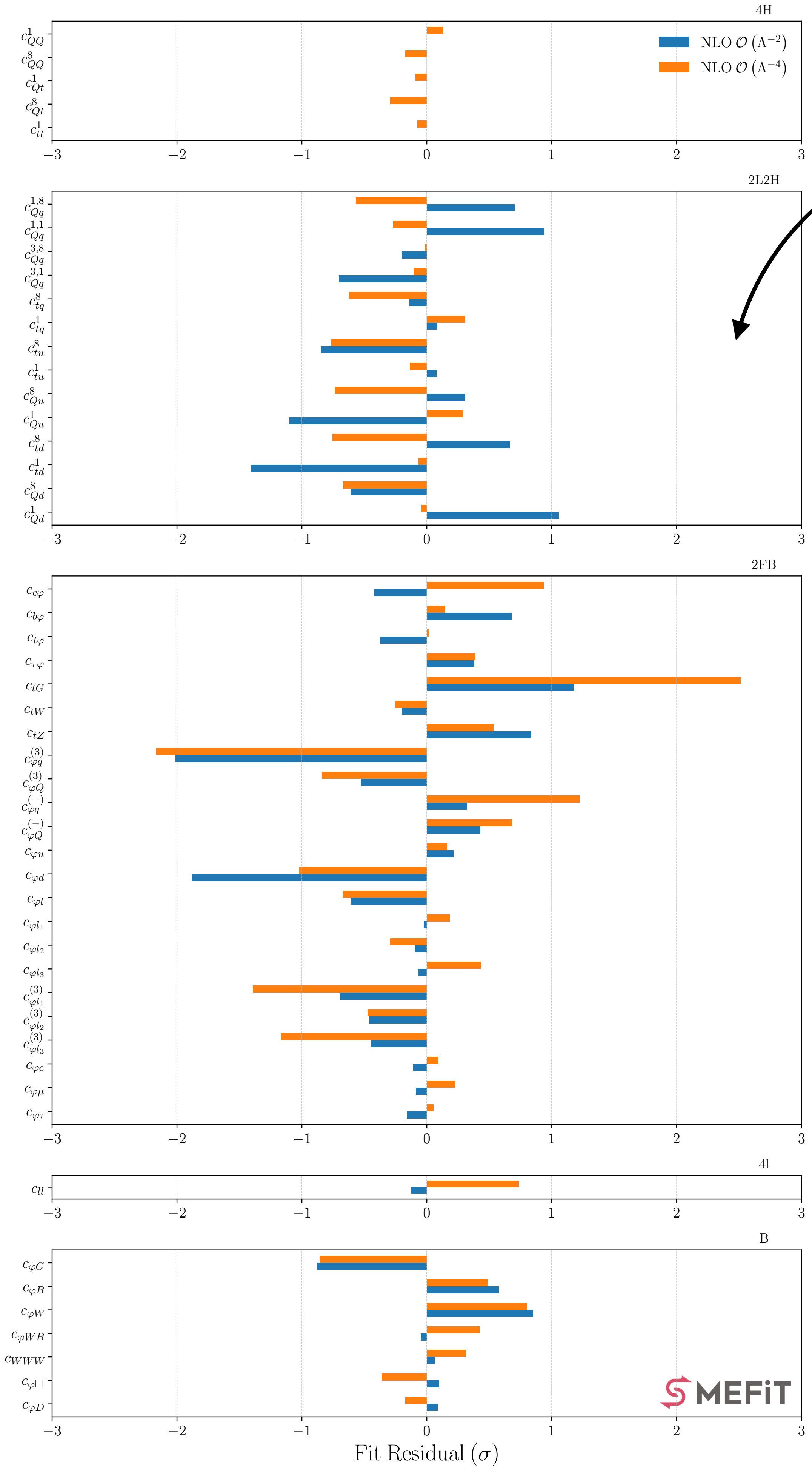
$$\delta_{k,i}^{(\mathrm{sys})} = \tilde{\delta}_{k,i}^{(\mathrm{sys})} \times f_{\mathrm{red}}^{(k)} \qquad k = 1, \ldots, n_{\mathrm{sys}}$$



\+ flexible framework that can project any Run II dataset

\+ SMEFT predictions can be recycled

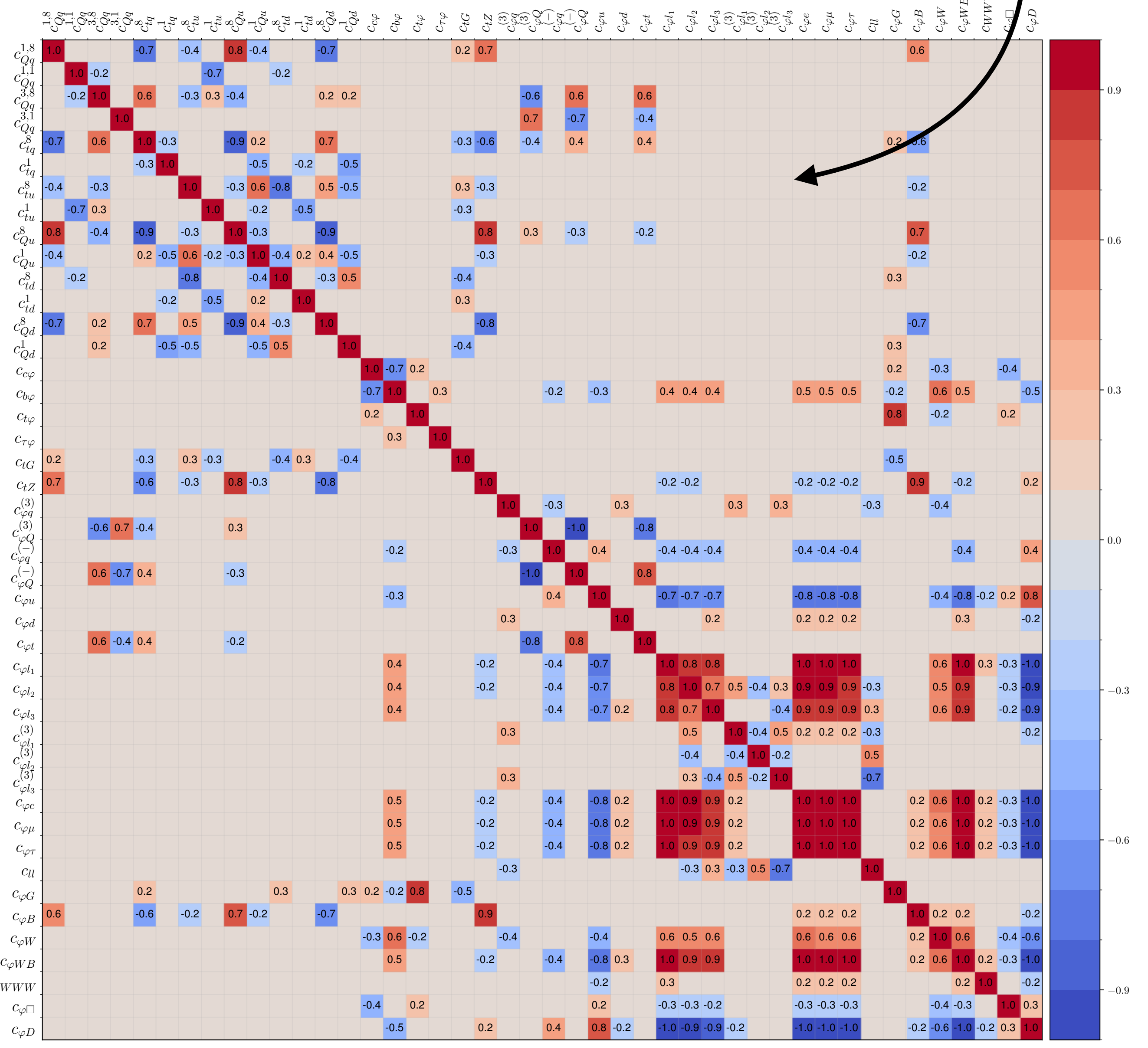
\- No additional bins in the tails



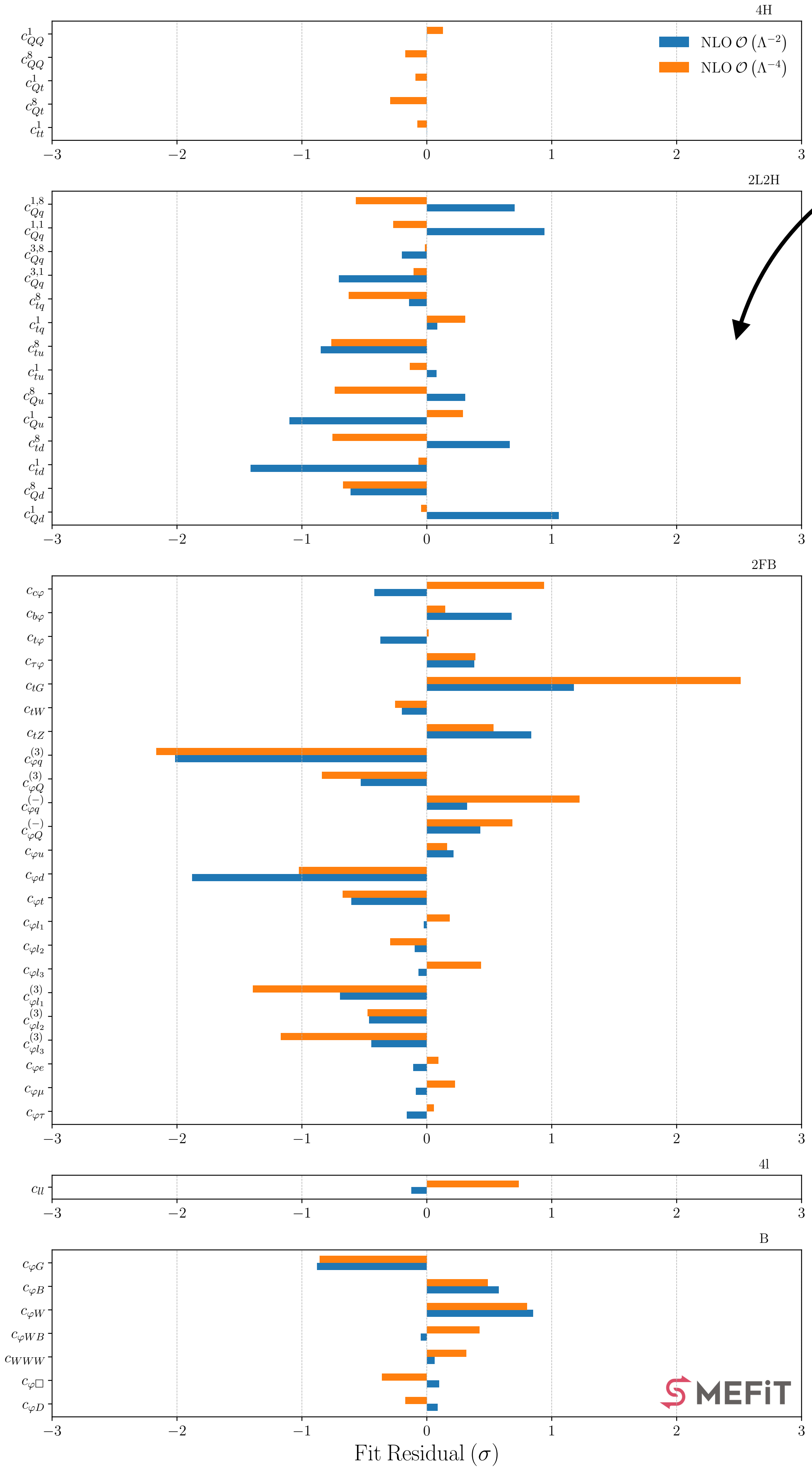
Fit residuals (pulls) are largely **consistent** with the SM

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

Large correlations in linear fit get lifted in the quadratic fit



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



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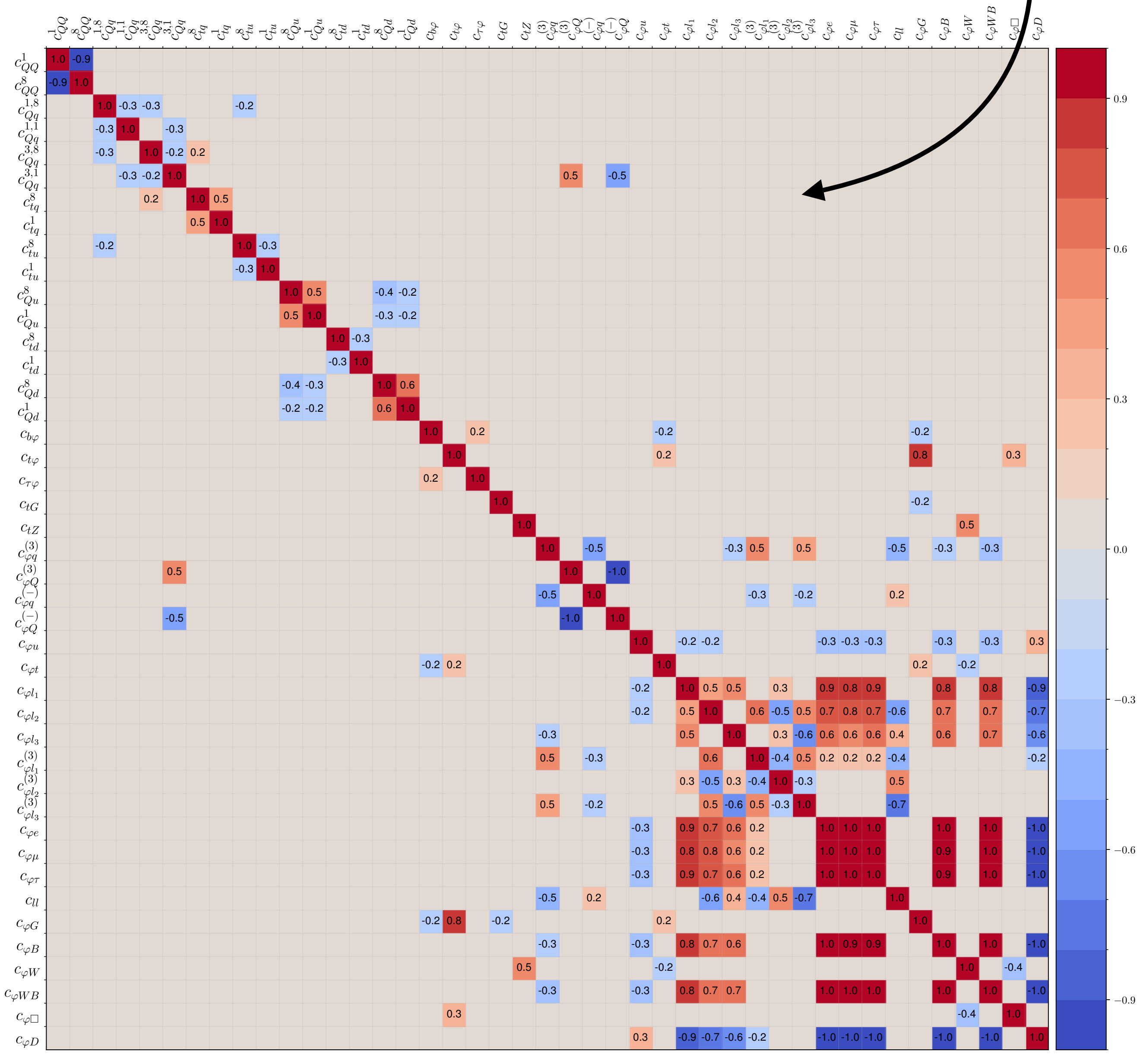
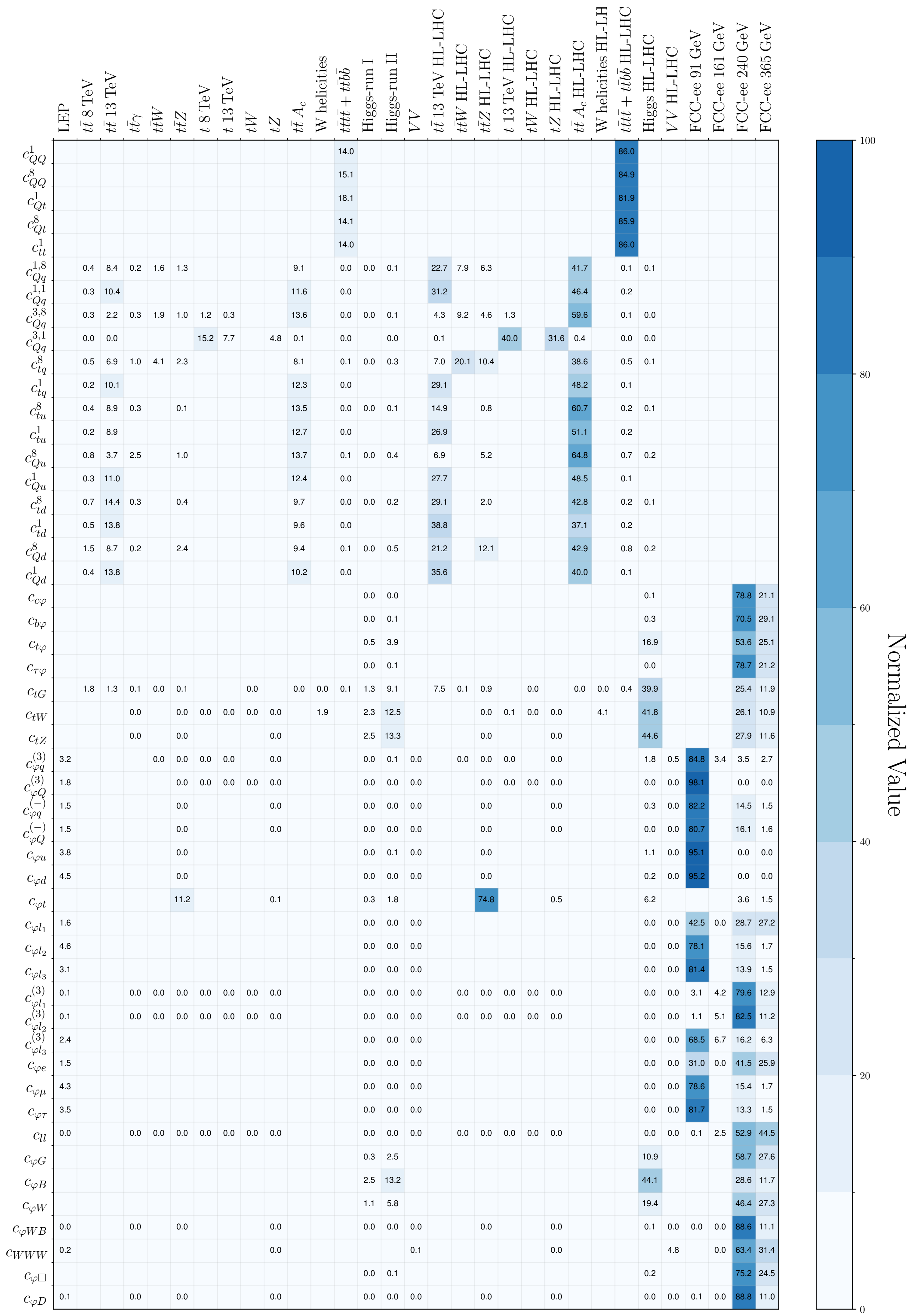


Correlation: NLO $\mathcal{O}(\Lambda^{-4})$



	LEP	$t\bar{t}$ 8 TeV	$t\bar{t}$ 13 TeV	$t\bar{t}\gamma$	$t\bar{t}W$	$t\bar{t}Z$	t 8 TeV	t 13 TeV	tW	tZ	$t\bar{t}$ A_c	W helicities	$t\bar{t}t\bar{t}+t\bar{t}b\bar{b}$	Higgs-run I	Higgs-run II	VV
c_{QQ}^{1}													14.0			
c_{QQ}^{8}													15.1			
c_{Qt}^{1}													18.1			
c_{Qt}^{8}													14.1			
c_{tt}^{1}													14.0			
$c_{Qq}^{1,8}$		0.4	8.4	0.2	1.6	1.3					9.1		0.0	0.0	0.1	
$c_{Qq}^{1,1}$		0.3	10.4								11.6		0.0			
$c_{Qq}^{3,8}$		0.3	2.2	0.3	1.9	1.0	1.2	0.3			13.6		0.0	0.0	0.1	
$c_{Qq}^{3,1}$		0.0	0.0				15.2	7.7		4.8	0.1		0.0		0.0	
c_{tq}^{8}		0.5	6.9	1.0	4.1	2.3					8.1		0.1	0.0	0.3	
c_{tq}^{1}		0.2	10.1								12.3		0.0			
c_{tu}^{8}		0.4	8.9	0.3		0.1					13.5		0.0	0.0	0.1	
c_{tu}^{1}		0.2	8.9								12.7		0.0			
c_{Qu}^{8}		0.8	3.7	2.5		1.0					13.7		0.1	0.0	0.4	
c_{Qu}^{1}		0.3	11.0								12.4		0.0			
c_{td}^{8}		0.7	14.4	0.3		0.4					9.7		0.0	0.0	0.2	
c_{td}^{1}		0.5	13.8								9.6		0.0			
c_{Qd}^{8}		1.5	8.7	0.2		2.4					9.4		0.1	0.0	0.5	
c_{Qd}^{1}		0.4	13.8								10.2		0.0			
$c_{c\varphi}$														0.0	0.0	
$c_{b\varphi}$														0.0	0.1	
$c_{t\varphi}$														0.5	3.9	
$c_{\tau\varphi}$														0.0	0.1	
c_{tG}		1.8	1.3	0.1	0.0	0.1			0.0		0.0	0.0	0.1	1.3	9.1	
c_{tW}				0.0		0.0	0.0	0.0	0.0	0.0		1.9		2.3	12.5	
c_{tZ}				0.0		0.0				0.0				2.5	13.3	
$c_{\varphi q}^{(3)}$	3.2				0.0	0.0	0.0	0.0		0.0				0.0	0.1	0.0
$c_{\varphi Q}^{(3)}$	1.8					0.0	0.0	0.0	0.0	0.0				0.0	0.0	0.0
$c_{\varphi q}^{(-)}$	1.5					0.0				0.0				0.0	0.0	0.0
$c_{\varphi Q}^{(-)}$	1.5					0.0				0.0				0.0	0.0	0.0
$c_{\varphi u}$	3.8					0.0								0.0	0.1	0.0
$c_{\varphi d}$	4.5					0.0								0.0	0.0	0.0
$c_{\varphi t}$						11.2				0.1				0.3	1.8	
$c_{\varphi l_1}$	1.6													0.0	0.0	0.0
$c_{\varphi l_2}$	4.6													0.0	0.0	0.0
$c_{\varphi l_3}$	3.1													0.0	0.0	0.0
$c_{\varphi l_1}^{(3)}$	0.1			0.0	0.0	0.0	0.0	0.0	0.0	0.0				0.0	0.0	0.0
$c_{\varphi l_2}^{(3)}$	0.1			0.0	0.0	0.0	0.0	0.0	0.0	0.0				0.0	0.0	0.0
$c_{\varphi l_3}^{(3)}$	2.4													0.0	0.0	0.0
$c_{\varphi e}$	1.5													0.0	0.0	0.0
$c_{\varphi \mu}$	4.3													0.0	0.0	0.0
$c_{\varphi \tau}$	3.5													0.0	0.0	0.0
c_{ll}	0.0			0.0	0.0	0.0	0.0	0.0	0.0	0.0				0.0	0.0	0.0
$c_{\varphi G}$														0.3	2.5	
$c_{\varphi B}$														2.5	13.2	
$c_{\varphi W}$														1.1	5.8	
$c_{\varphi WB}$	0.0			0.0		0.0				0.0				0.0	0.0	0.0
c_{WWW}	0.2									0.0						0.1
$c_{\varphi \Box}$														0.0	0.1	
$c_{\varphi D}$	0.1			0.0		0.0				0.0				0.0	0.0	0.0

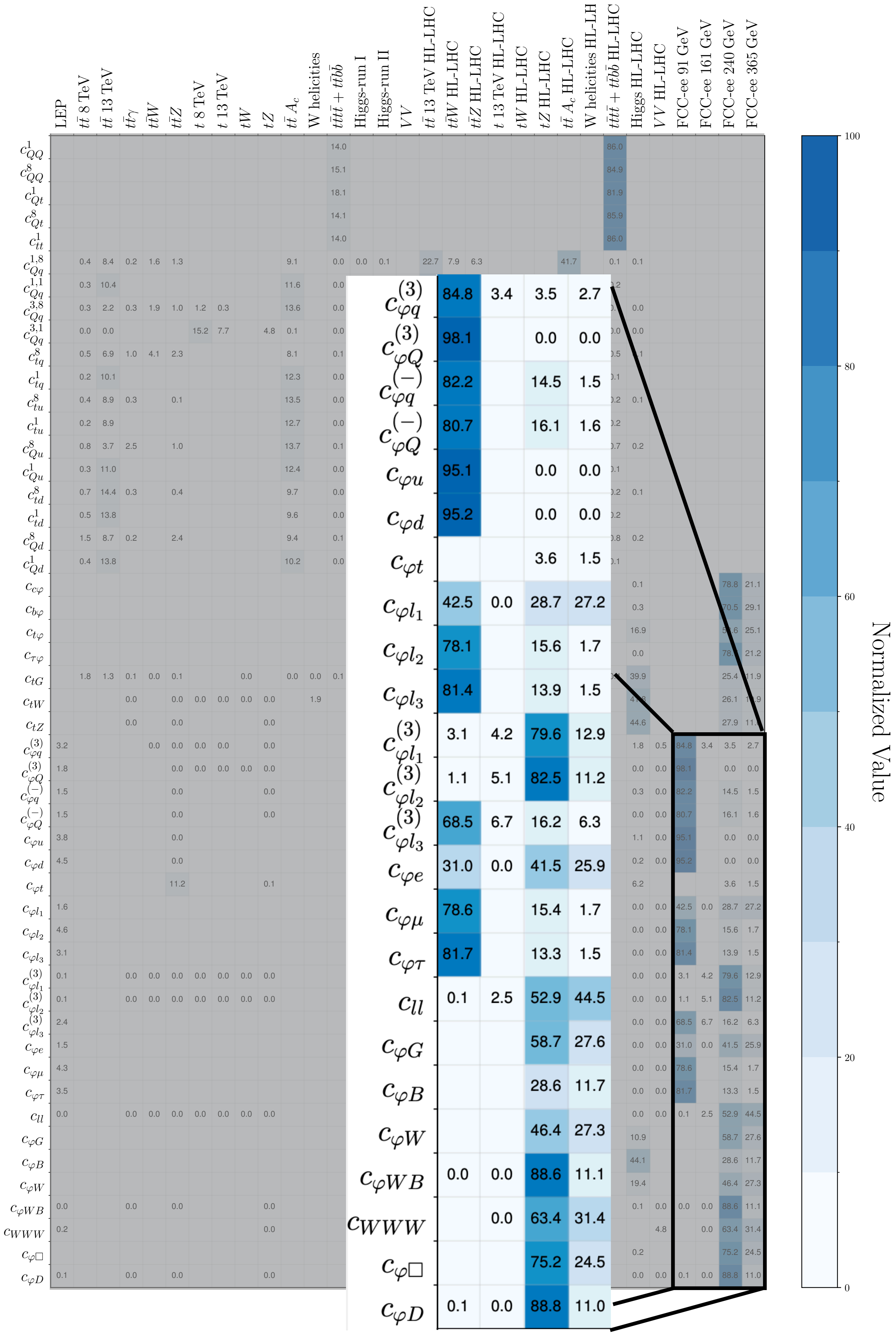
	$t\bar{t}$ 13 TeV HL-LHC	$t\bar{t}W$ HL-LHC	$t\bar{t}Z$ HL-LHC	t 13 TeV HL-LHC	tW HL-LHC	tZ HL-LHC	$t\bar{t}$ A_c HL-LHC	W helicities HL-LH	$t\bar{t}t\bar{t}+t\bar{t}b\bar{b}$ HL-LHC	Higgs HL-LHC	VV HL-LHC	FCC-ee 91 GeV	FCC-ee 161 GeV	FCC-ee 240 GeV	FCC-ee 365 GeV
c_{QQ}^{1}									86.0						
c_{QQ}^{8}									84.9						
c_{Qt}^{1}									81.9						
c_{Qt}^{8}									85.9						
c_{tt}^{1}									86.0						
$c_{Qq}^{1,8}$	22.7	7.9	6.3				41.7		0.1	0.1					
$c_{Qq}^{1,1}$	31.2						46.4		0.2						
$c_{Qq}^{3,8}$	4.3	9.2	4.6	1.3			59.6		0.1	0.0					
$c_{Qq}^{3,1}$	0.1			40.0		31.6	0.4		0.0	0.0					
c_{tq}^{8}	7.0	20.1	10.4				38.6		0.5	0.1					
c_{tq}^{1}	29.1						48.2		0.1						
c_{tu}^{8}	14.9		0.8				60.7		0.2	0.1					
c_{tu}^{1}	26.9						51.1		0.2						
c_{Qu}^{8}	6.9		5.2				64.8		0.7	0.2					
c_{Qu}^{1}	27.7						48.5		0.1						
c_{td}^{8}	29.1		2.0				42.8		0.2	0.1					
c_{td}^{1}	38.8						37.1		0.2						
c_{Qd}^{8}	21.2		12.1				42.9		0.8	0.2					
c_{Qd}^{1}	35.6						40.0		0.1						
$c_{c\varphi}$										0.1				78.8	21.1
$c_{b\varphi}$										0.3				70.5	29.1
$c_{t\varphi}$										16.9				53.6	25.1
$c_{\tau\varphi}$										0.0				78.7	21.2
c_{tG}	7.5	0.1	0.9		0.0		0.0	0.0	0.4	39.9				25.4	11.9
c_{tW}			0.0	0.1	0.0	0.0		4.1		41.8				26.1	10.9
c_{tZ}			0.0			0.0				44.6				27.9	11.6
$c_{\varphi q}^{(3)}$		0.0	0.0	0.0		0.0				1.8	0.5	84.8	3.4	3.5	2.7
$c_{\varphi Q}^{(3)}$			0.0	0.0	0.0	0.0				0.0	0.0	98.1		0.0	0.0
$c_{\varphi q}^{(-)}$			0.0			0.0				0.3	0.0	82.2		14.5	1.5
$c_{\varphi Q}^{(-)}$			0.0			0.0				0.0	0.0	80.7		16.1	1.6
$c_{\varphi u}$			0.0							1.1	0.0	95.1		0.0	0.0
$c_{\varphi d}$			0.0							0.2	0.0	95.2		0.0	0.0
$c_{\varphi t}$			74.8			0.5				6.2				3.6	1.5
$c_{\varphi l_1}$										0.0	0.0	42.5	0.0	28.7	27.2
$c_{\varphi l_2}$										0.0	0.0	78.1		15.6	1.7
$c_{\varphi l_3}$										0.0	0.0	81.4		13.9	1.5
$c_{\varphi l_1}^{(3)}$		0.0	0.0	0.0	0.0	0.0				0.0	0.0	3.1	4.2	79.6	12.9
$c_{\varphi l_2}^{(3)}$		0.0	0.0	0.0	0.0	0.0				0.0	0.0	1.1	5.1	82.5	11.2
$c_{\varphi l_3}^{(3)}$										0.0	0.0	68.5	6.7	16.2	6.3
$c_{\varphi e}$										0.0	0.0	31.0	0.0	41.5	25.9
$c_{\varphi \mu}$										0.0	0.0	78.6		15.4	1.7
$c_{\varphi \tau}$										0.0	0.0	81.7		13.3	1.5
c_{ll}		0.0	0.0	0.0	0.0	0.0				0.0	0.0	0.1	2.5	52.9	44.5
$c_{\varphi G}$										10.9				58.7	27.6
$c_{\varphi B}$										44.1				28.6	11.7
$c_{\varphi W}$										19.4				46.4	27.3
$c_{\varphi WB}$			0.0			0.0				0.1	0.0	0.0	0.0	88.6	11.1
c_{WWW}						0.0					4.8		0.0	63.4	31.4
$c_{\varphi \Box}$										0.2				75.2	24.5
$c_{\varphi D}$			0.0			0.0				0.0	0.0	0.1	0.0	88.8	11.0

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**

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

- 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



$c_{\varphi q}^{(3)}$	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

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**

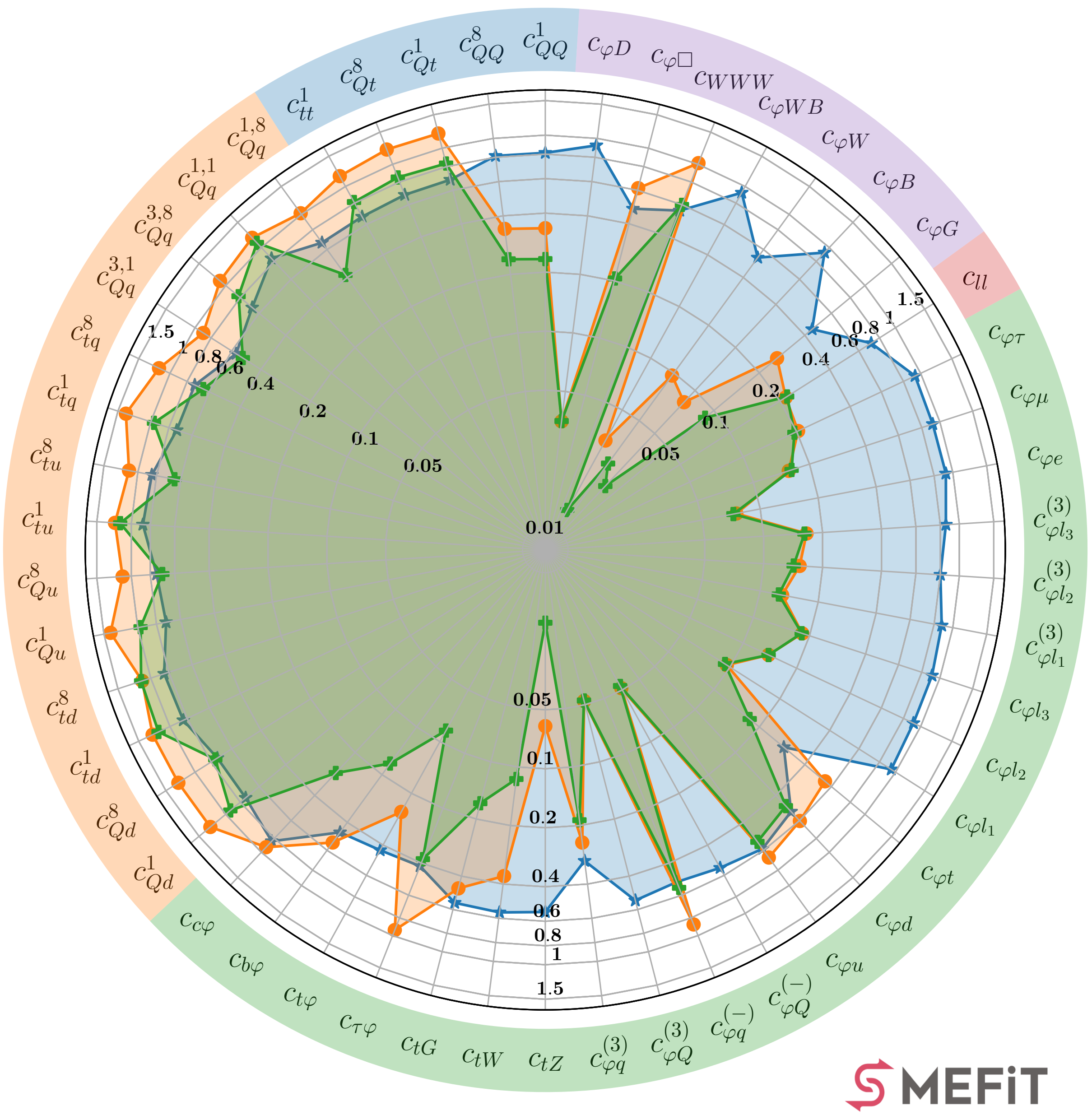
$$I_{ij} = \sum_{m=1}^{n_{\text{dat}}} \frac{\sigma_{m,i}^{(\text{eft})} \sigma_{m,j}^{(\text{eft})}}{\delta_{\text{exp},m}^2}$$

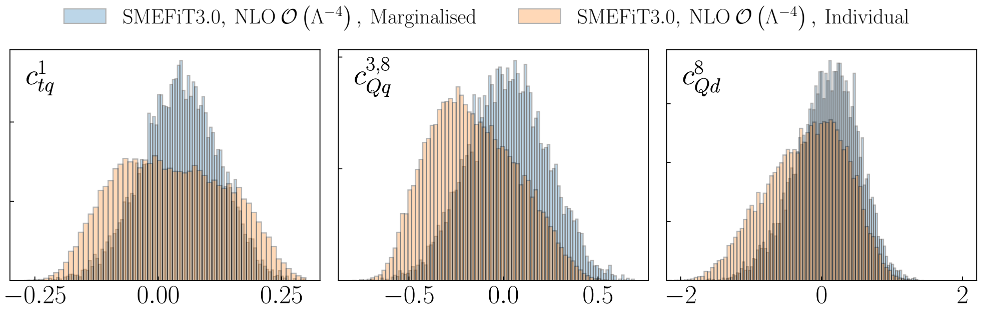
- The highest sensitivity in the 2FB sector comes in via the FCC-ee

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

With statistical noise = L1

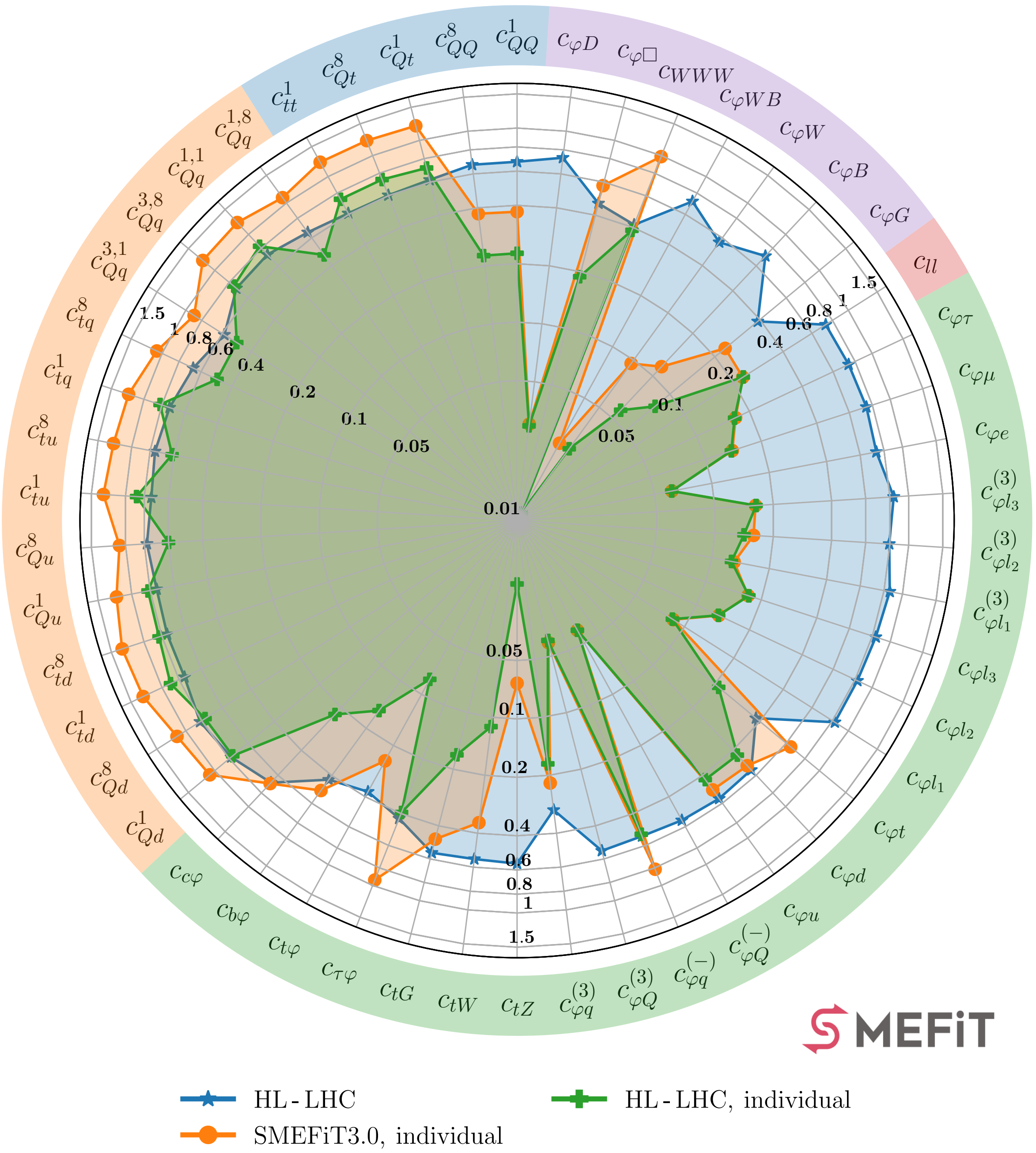
Ratio of Uncertainties to SMEFiT3.0 Baseline, $\mathcal{O}\left(\Lambda^{-4}\right)$, Marginalised



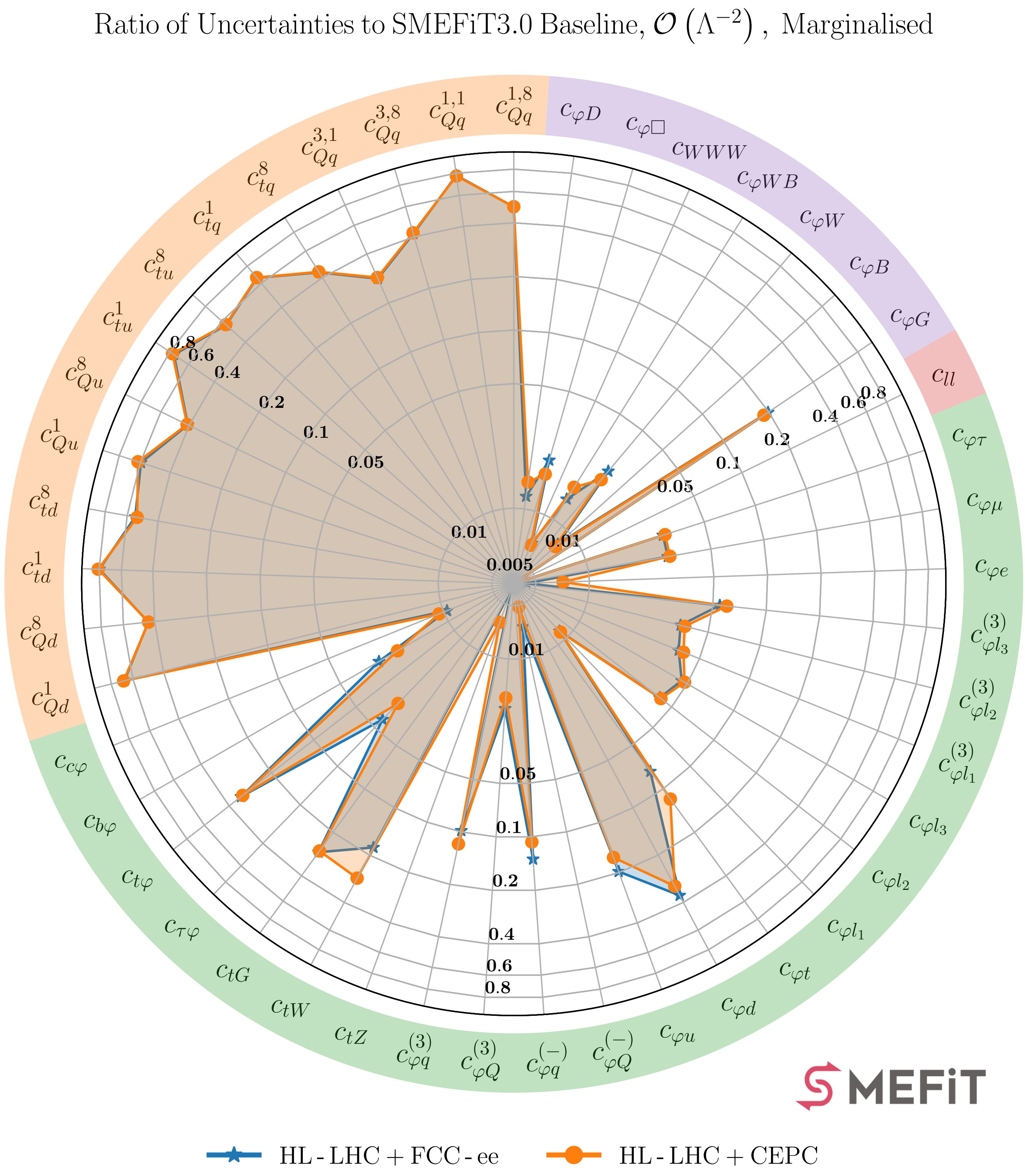


Without statistical noise = L0

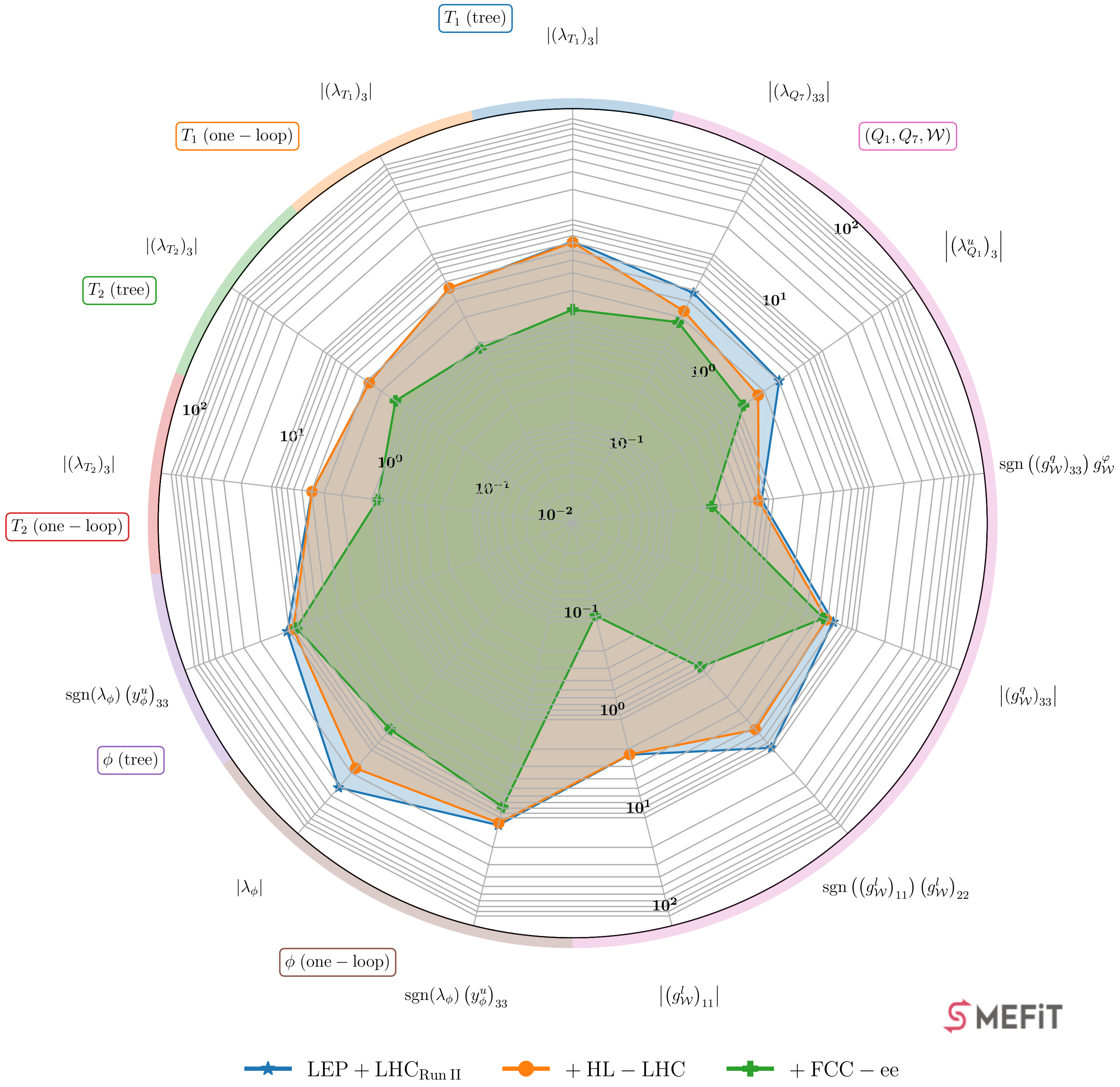
Ratio of Uncertainties to SMEFiT3.0 Baseline, $\mathcal{O}\left(\Lambda^{-4}\right)$, Marginalised



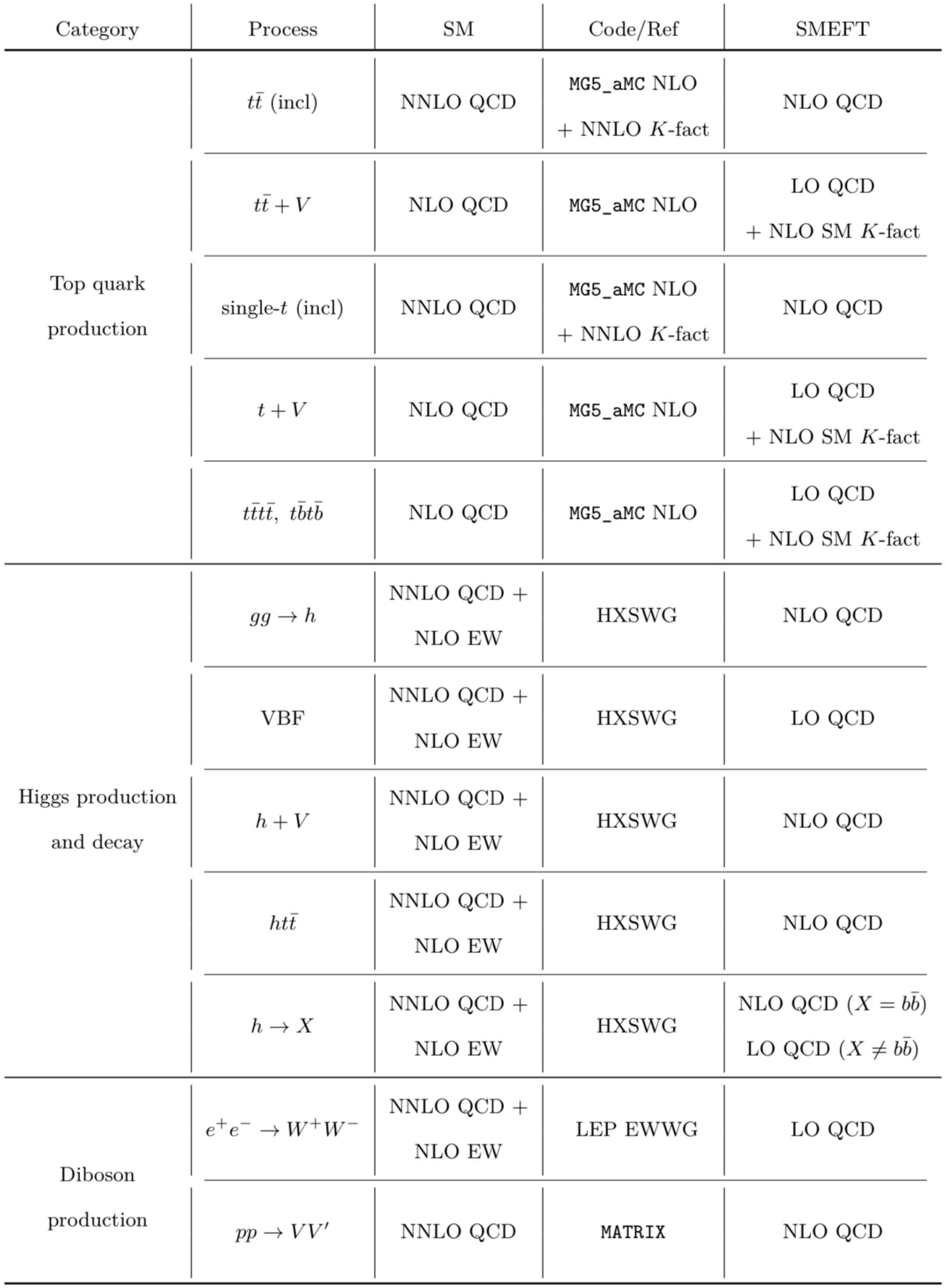
FCC-ee and CEPC



1-loop & multi-particle matching

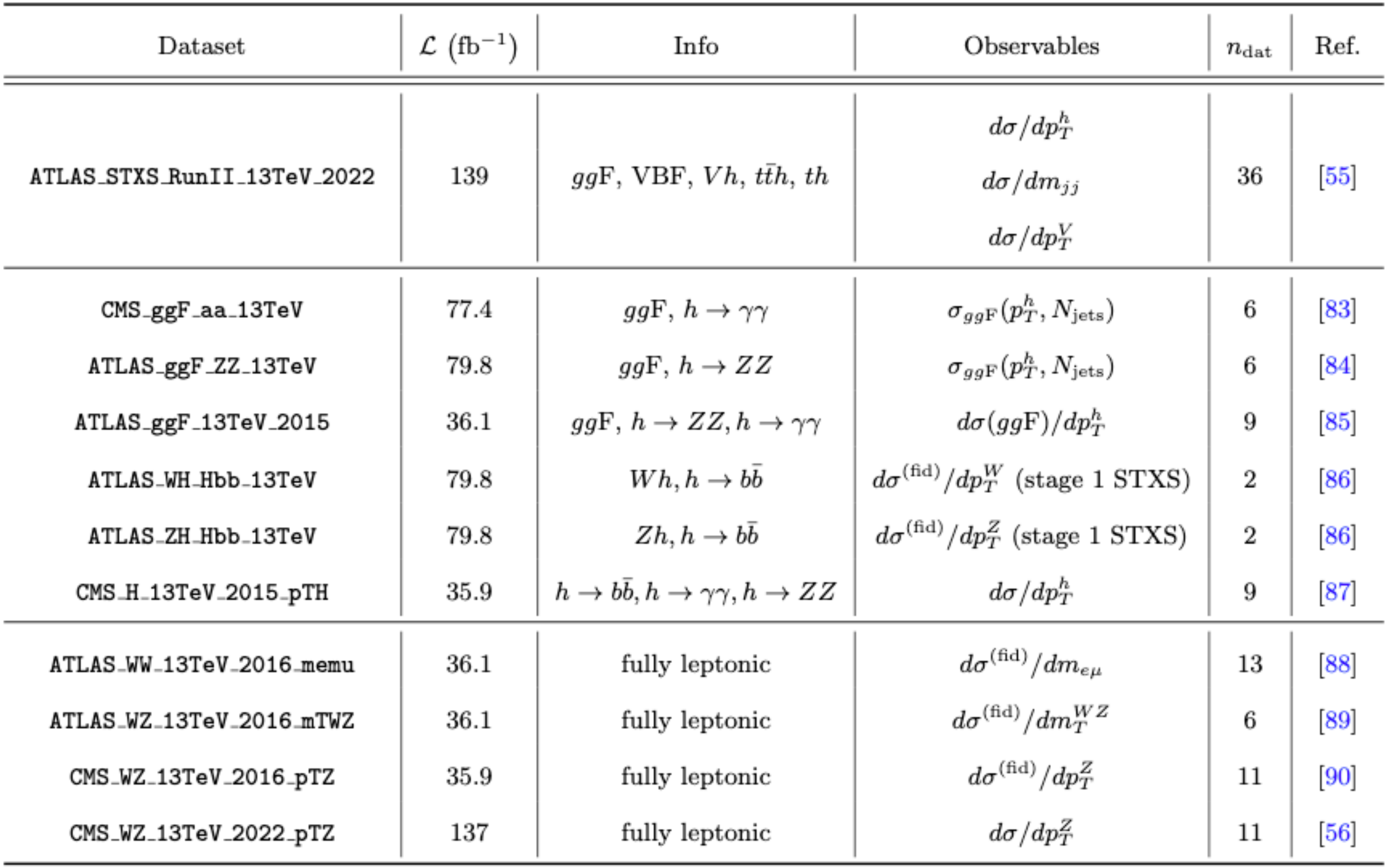


SM predictions

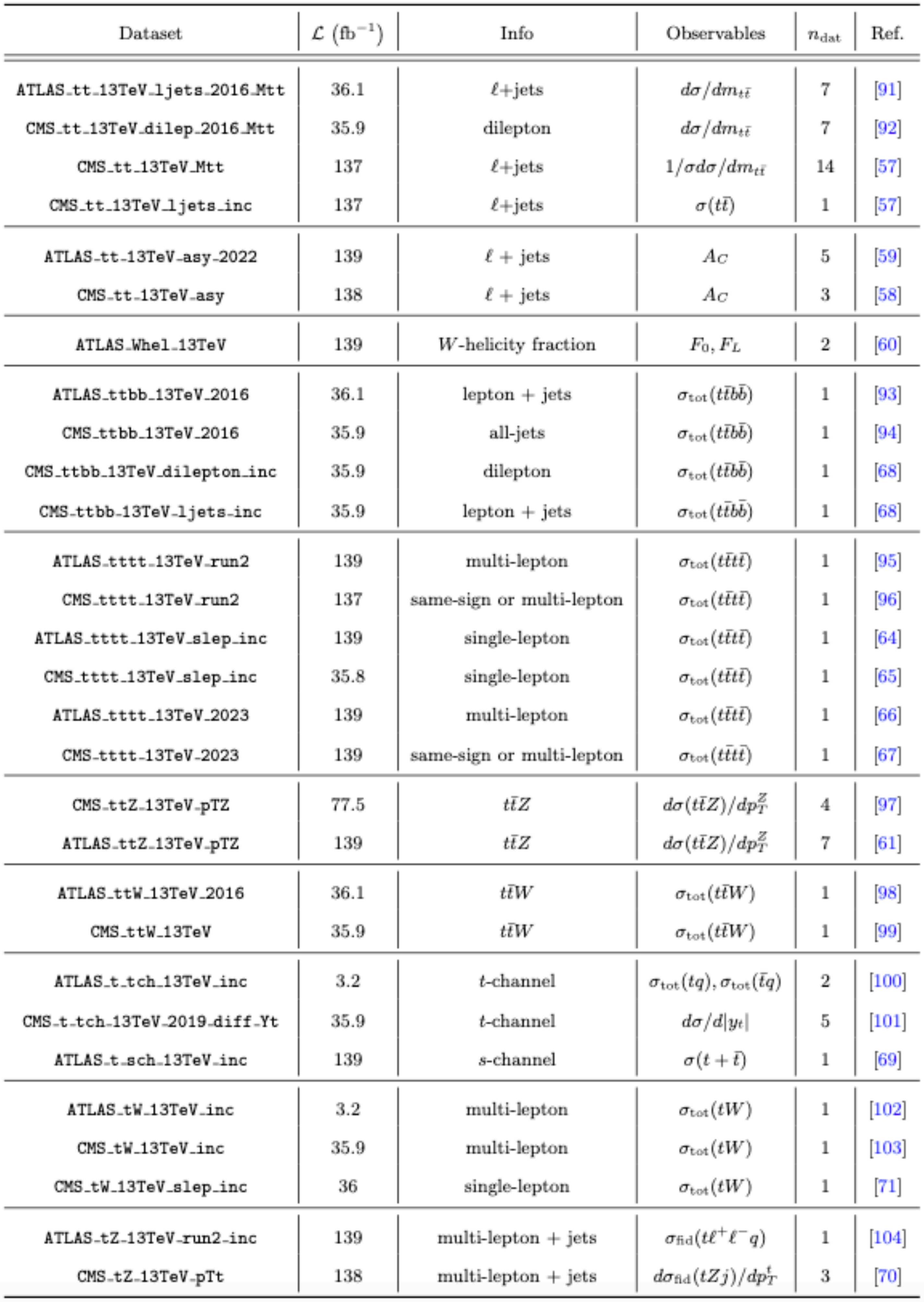


Category	Process	SM	Code/Ref	SMEFT
Top quark production	$t\bar{t}$ (incl)	NNLO QCD	`MG5_aMC` NLO + NNLO K-fact	NLO QCD
	$t\bar{t}+V$	NLO QCD	`MG5_aMC` NLO	LO QCD + NLO SM K-fact
	single-t (incl)	NNLO QCD	`MG5_aMC` NLO + NNLO K-fact	NLO QCD
	$t+V$	NLO QCD	`MG5_aMC` NLO	LO QCD + NLO SM K-fact
	$t\bar{t}t\bar{t},\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

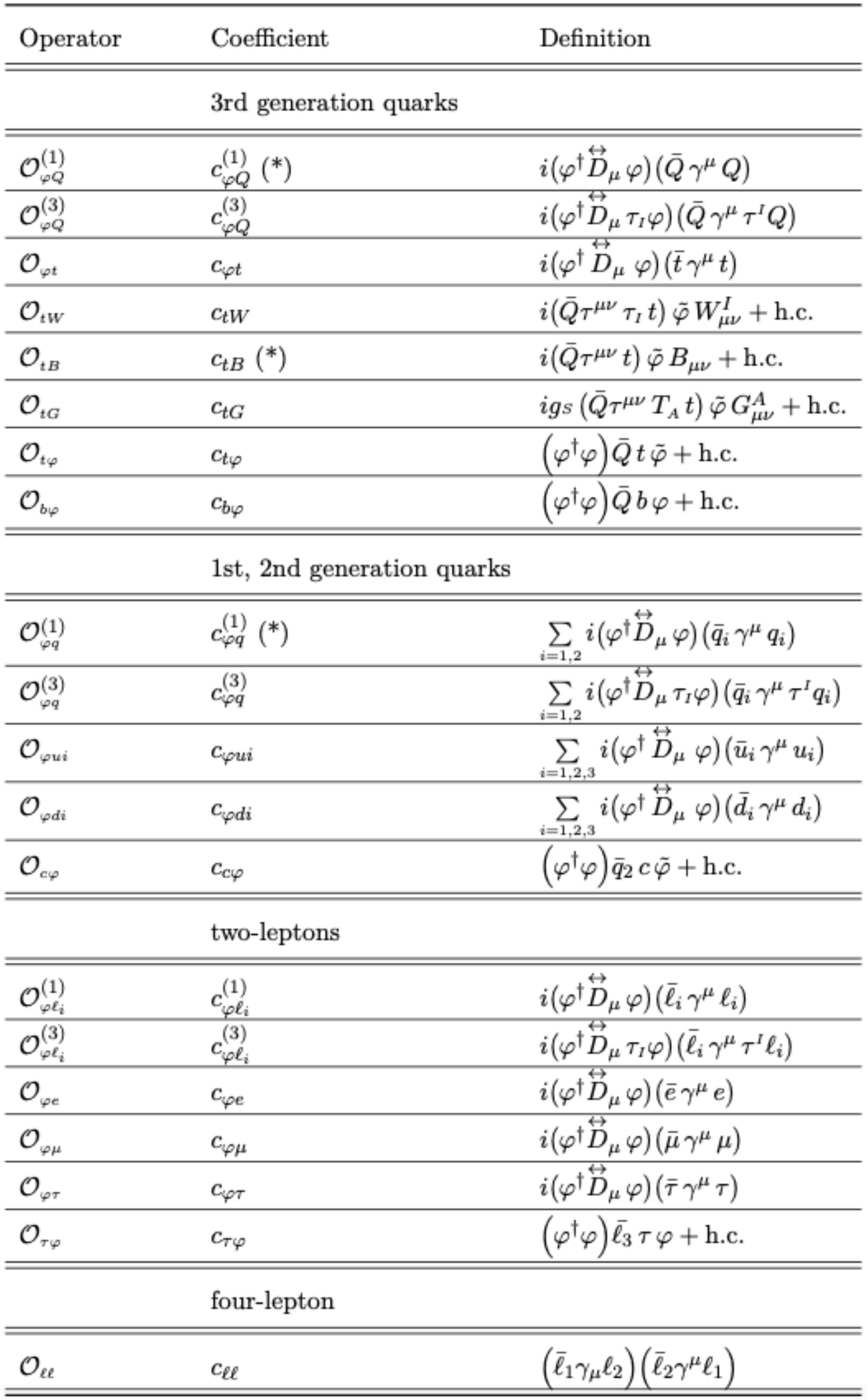


Dataset	$\mathcal{L}$ (fb^{-1})	Info	Observables	$n_{\rm dat}$	Ref.
ATLAS_STXS_RunII_13TeV_2022	139	ggF, VBF, Vh, $t\bar{t}h$, th	$d\sigma/dp_T^h$ $d\sigma/dm_{jj}$ $d\sigma/dp_T^V$	36	[55]
CMS_ggF_aa_13TeV	77.4	ggF, $h \to \gamma\gamma$	$\sigma_{gg\rm F}(p_T^h, N_{\rm jets})$	6	[83]
ATLAS_ggF_ZZ_13TeV	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	$d\sigma/d\|y_t\|$	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}	$i(\bar{Q}\tau^{\mu\nu}\,\tau_I\,t)\,\tilde{\varphi}\,W^I_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{tB}$	c_{tB} (*)	$i(\bar{Q}\tau^{\mu\nu}\,t)\,\tilde{\varphi}\,B_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{tG}$	c_{tG}	$ig_S\,(\bar{Q}\tau^{\mu\nu}\,T_A\,t)\,\tilde{\varphi}\,G^A_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{t\varphi}$	$c_{t\varphi}$	$\left(\varphi^\dagger\varphi\right)\bar{Q}\,t\,\tilde{\varphi} + \text{h.c.}$
$\mathcal{O}_{b\varphi}$	$c_{b\varphi}$	$\left(\varphi^\dagger\varphi\right)\bar{Q}\,b\,\varphi + \text{h.c.}$
	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	
$\mathcal{O}_{\ell\ell}$	$c_{\ell\ell}$	$\left(\bar{\ell}_1\gamma_\mu\ell_2\right)\left(\bar{\ell}_2\gamma^\mu\ell_1\right)$

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

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

FCC-ee and CEPC datasets

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

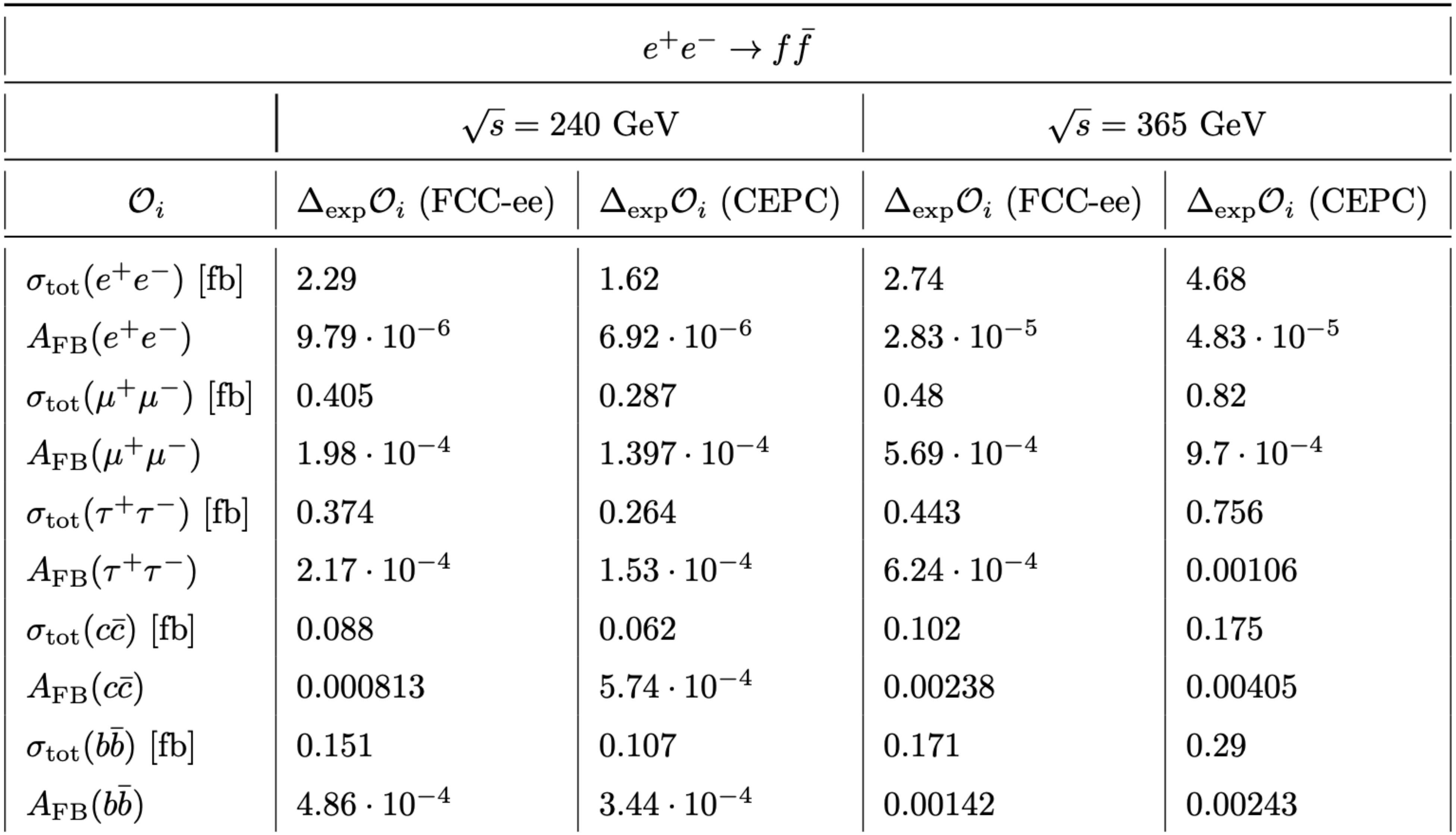
EWPOs

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

$e^+e^- \to Zh$				
	$\sqrt{s} = 240$ GeV		$\sqrt{s} = 365$ GeV	
$\mathcal{O}_i$	$\delta_{\exp}\mathcal{O}_i$ (FCC-ee)	$\delta_{\exp}\mathcal{O}_i$ (CEPC)	$\delta_{\exp}\mathcal{O}_i$ (FCC-ee)	$\delta_{\exp}\mathcal{O}_i$ (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	
$\mathcal{O}_i$	$\delta_{\exp}\mathcal{O}_i$ (FCC-ee)	$\delta_{\exp}\mathcal{O}_i$ (CEPC)	$\delta_{\exp}\mathcal{O}_i$ (FCC-ee)	$\delta_{\exp}\mathcal{O}_i$ (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

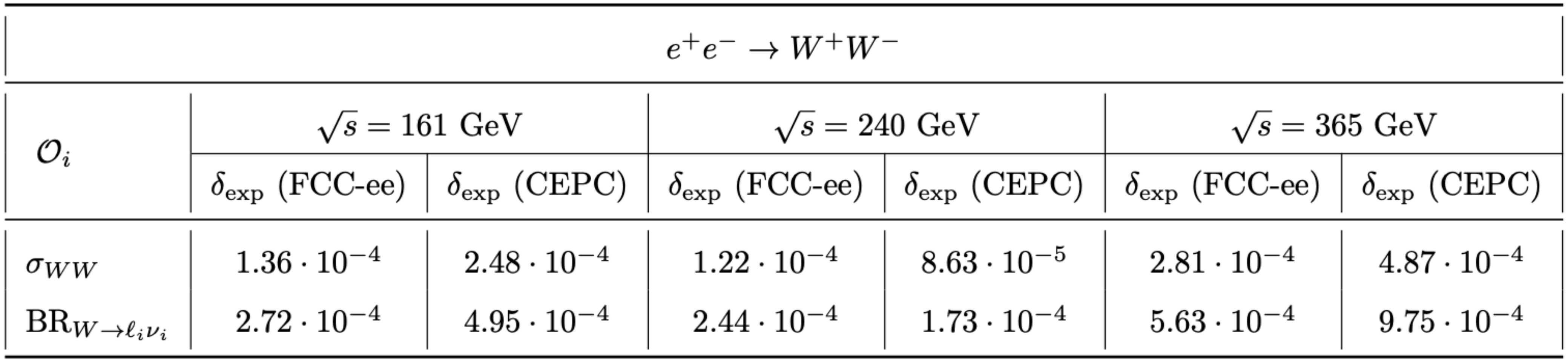
FCC-ee and CEPC datasets



Light fermion production

$e^+e^- \to f\bar{f}$

	$\sqrt{s} = 240$ GeV		$\sqrt{s} = 365$ GeV	
$\mathcal{O}_i$	$\Delta_{\rm exp}\mathcal{O}_i$ (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}	$1.36 \cdot 10^{-4}$	$2.48 \cdot 10^{-4}$	$1.22 \cdot 10^{-4}$	$8.63 \cdot 10^{-5}$	$2.81 \cdot 10^{-4}$	$4.87 \cdot 10^{-4}$
${\rm BR}_{W\to\ell_i\nu_i}$	$2.72 \cdot 10^{-4}$	$4.95 \cdot 10^{-4}$	$2.44 \cdot 10^{-4}$	$1.73 \cdot 10^{-4}$	$5.63 \cdot 10^{-4}$	$9.75 \cdot 10^{-4}$

EWPO benchmark