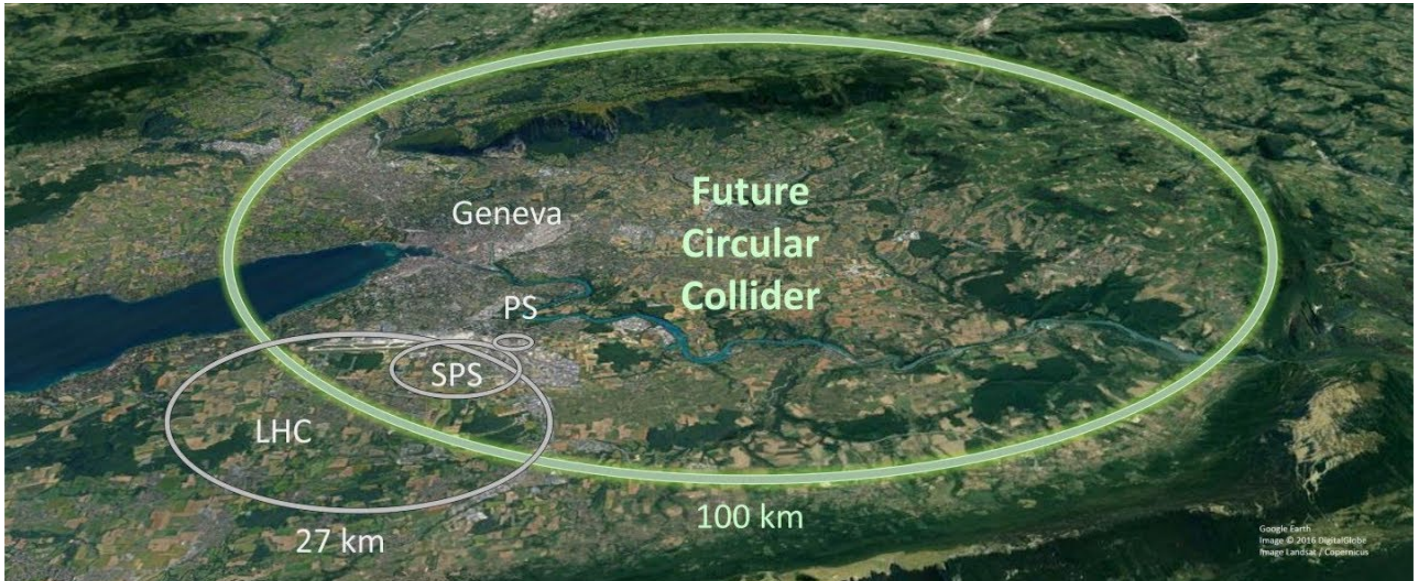
Higgs, EW, and top quark coupling projections at the FCC-hh: what do we need?

Juan Rojo, VU Amsterdam & Nikhef



FCC-hh Physics and Performance Meeting, CERN, 14/11/2024

What do we have now?

Table 25. Left) Inputs used for FCC-hh. All uncertainties are given as fractional 68% CL intervals and are taken to be symmetric. Right) Extra inputs used in the κ fit studies.

Inclusive Higgs signal strengths and branching fractions

FCC-hh	
$\delta\mu_{ggF,4\mu}$	0.019
$\delta\mu_{ggF,\gamma\gamma}$	0.015
$\delta\mu_{ggF,Z\gamma}$	0.016
$\delta\mu_{ggF,\mu\mu}$	0.012
$\delta(\mathrm{BR}_{\mu\mu}/\mathrm{BR}_{4\mu})$	0.013
$\delta(\mathrm{BR}_{\gamma\gamma}/\mathrm{BR}_{2e2\mu})$	0.008
$\delta(\mathrm{BR}_{\gamma\gamma}/\mathrm{BR}_{\mu\mu})$	0.014
$\delta(\mathrm{BR}_{\mu\mu\gamma}/\mathrm{BR}_{\gamma\gamma})$	0.018
$\delta(\sigma^{bb}_{ttH}/\sigma^{bb}_{ttZ})$	0.019
Invisible decays	
$\mathrm{BR}_{\mathrm{inv}}$	<0.00013
Direct constraint on Higgs self-interaction	
$\delta\kappa_3$	0.05

FCC-hh (Extra inputs used in κ fits)	
$\delta(\sigma^{H\to\gamma\gamma}_{WH}/\sigma^{Z\to e^+e^-}_{WZ})$	0.014
$\delta(\sigma^{H\to\tau\tau}_{WH}/\sigma^{Z\to\tau\tau}_{WZ})$	0.016
$\delta(\sigma^{H\to bb}_{WH}/\sigma^{Z\to bb}_{WZ})$	0.011
$\delta(\sigma^{H\to WW}_{WH}/\sigma^{H\to\gamma\gamma}_{WH})$	0.015

Table 26. Inputs used for a low-energy FCC-hh running at 37.5 TeV (LE-FCC). All uncertainties are given as fractional 68% CL intervals and are taken to be symmetric.

LE-FCC	
$\delta(\mathrm{BR}_{\mu\mu}/\mathrm{BR}_{4\mu})$	0.029
$\delta(\mathrm{BR}_{\gamma\gamma}/\mathrm{BR}_{2e2\mu})$	0.015
$\delta(\mathrm{BR}_{\gamma\gamma}/\mathrm{BR}_{\mu\mu})$	0.028
$\delta(\mathrm{BR}_{\mu\mu\gamma}/\mathrm{BR}_{\gamma\gamma})$	0.06
$\delta(\sigma^{bb}_{ttH}/\sigma^{bb}_{ttZ})$	0.04-0.06
Direct constraint on Higgs self-interaction	
$\delta\kappa_3$	0.15

From the "Granada" 2019 Higgs couplings paper

What do we have now?

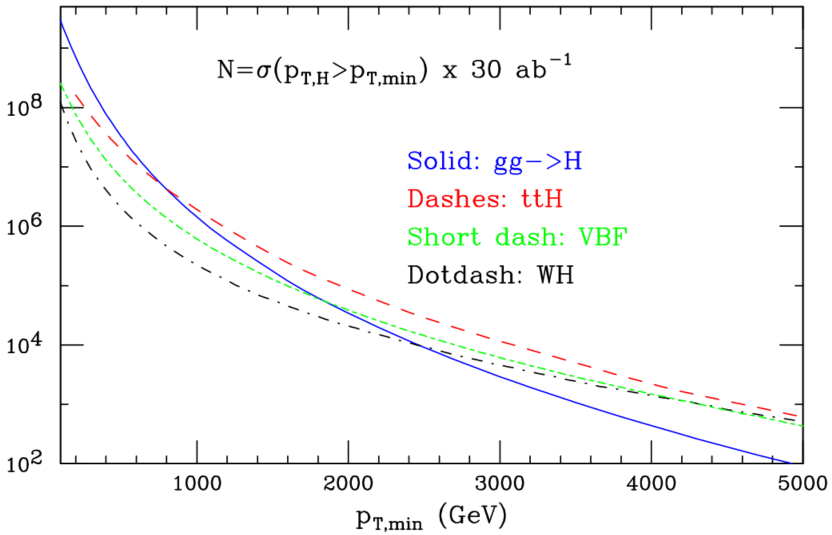


Figure 4.3: Production rates of Higgs bosons at high p_T, for various production channels at 100 TeV and 30 ab^{-1}.

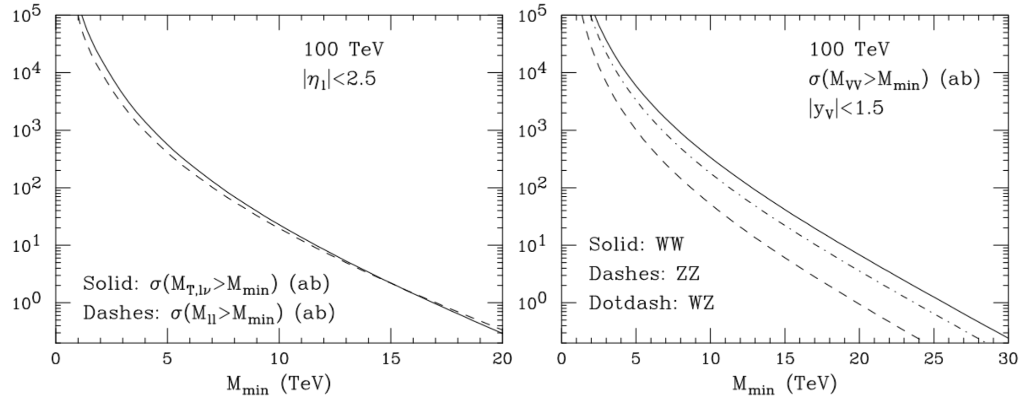


Figure S.2: Left: integrated lepton transverse (dilepton) mass distribution in $pp \to W^* \to \ell\nu$ ($pp \to Z^*/\gamma^* \to \ell^+\ell^-$). One lepton family is included, with $|\eta_\ell| < 2.5$. Right: integrated invariant mass spectrum for the production of gauge boson pairs in the central kinematic range $|y| < 1.5$. No branching ratios included

Differential distributions for Higgs, Drell-Yan, diboson production

(Binning & BRs & systematics to be added?)

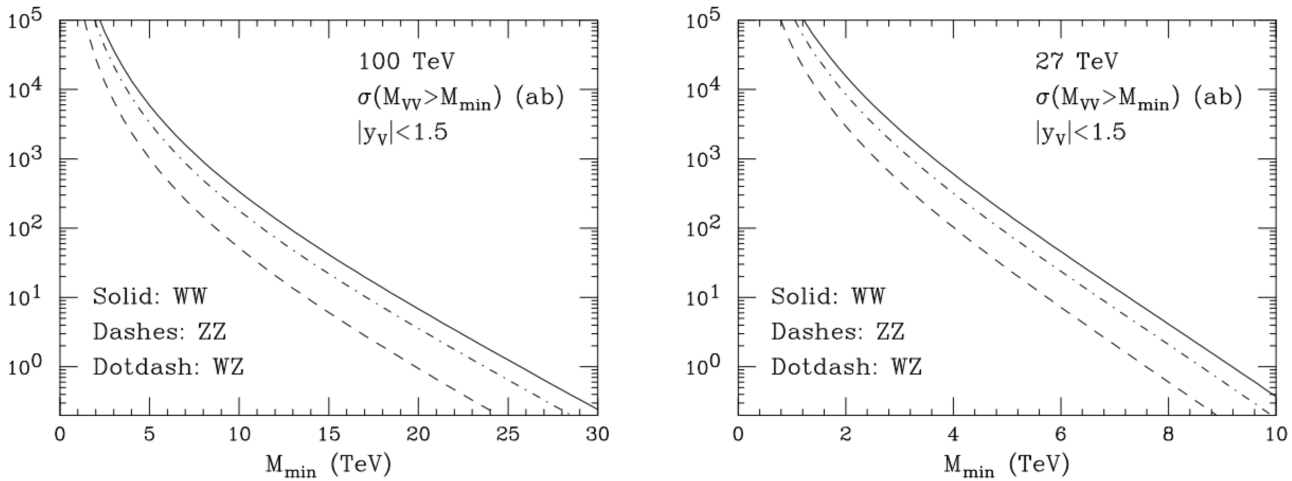


Figure 3.4: Integrated invariant mass spectrum for the production of gauge boson pairs in the central kinematic range $|y| < 1.5$, at 100 and 27 TeV. No branching ratios included.

From the FCC-hh 2018 Yellow Reports

What do we need?

It depends on how ambitious we want to be with FCC-hh studies in the coming months

Leading Order effort: repeat Granada kappa projections with different FCC-hh running scenarios

Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
c.m. energy	TeV	72	72	72	84	102	120	14
dipole field	T	12	12	12	14	17	20	8.33
beam current	A	0.5	1.12	1.12	0.5	0.5	0.2	(1.12) 0.58
bunch popul.	10^{11}	1.0	2.2	2.2	1.0	1.0	0.4	(2.2) 1.15
bunches/beam		9500	9500	9500	9500	9500	9500	(2760) 2808
rf voltage	MV	30	30	30	35	43	50	(16) 16
longit. emit.	eVs	6.9	6.9	6.9	8.1	9.7	11.4	2.5
norm. tr. emit.	μm	2.5	2.5	2.5	2.5	2.5	2.5	(2.5) 3.75
IP beta*	m	0.22	0.22	0.65	0.26	0.31	0.37	(0.15) 0.55
initial σ*	μm	3.8	3.8	6.5	3.8	3.8	3.8	(7.1 min) 16.7
initial L	$nb^{-1}s^{-1}$	175	845	286	172	209	39	(50, lev'd) 10
initial pile up		580	2820	955	590	732	141	(135) 27

kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2′	250	500	1000	380	15000	3000		240	365	
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

Need projections for the same observables as in the 2019 paper for the different running scenarios (and maybe others)

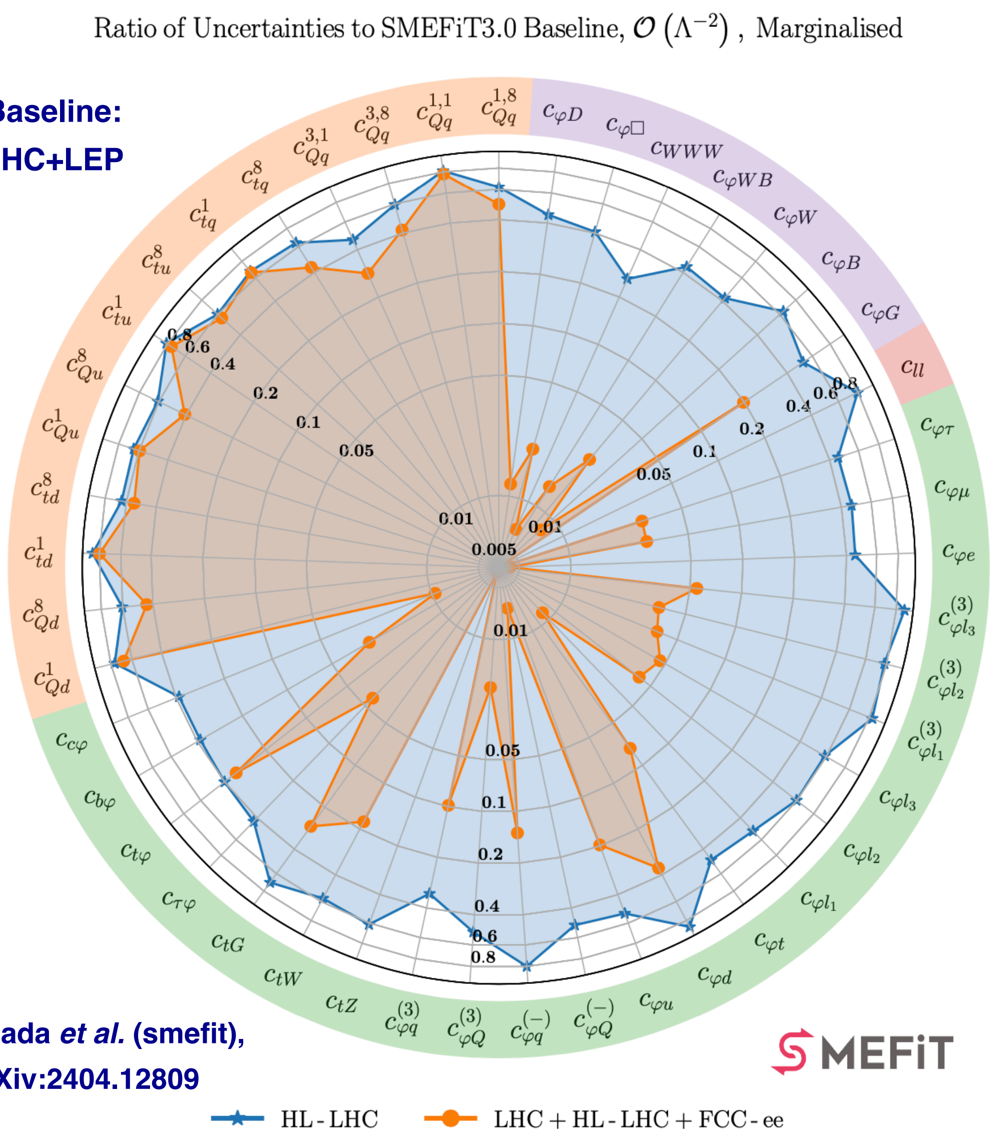
One can also study different collider combinations e.g. **HL-LHC + FCC-hh**

What do we need?

It depends on how ambitious we want to be with FCC-hh studies in the coming months

Next-to-Leading Order effort: FCC-hh interpretations in the SMEFT with inclusive signal strengths

Baseline: LHC+LEP



E. Celada *et al.* (smefit), arXiv:2404.12809

Perform global fit to LEP+(HL-)LHC data + future colliders (including FCC-hh) in different combinations

From experimental side: no extra effort as compared to LO

From theory side: need dedicated EFT calculations, which we can adapt from LHC studies

What do we need?

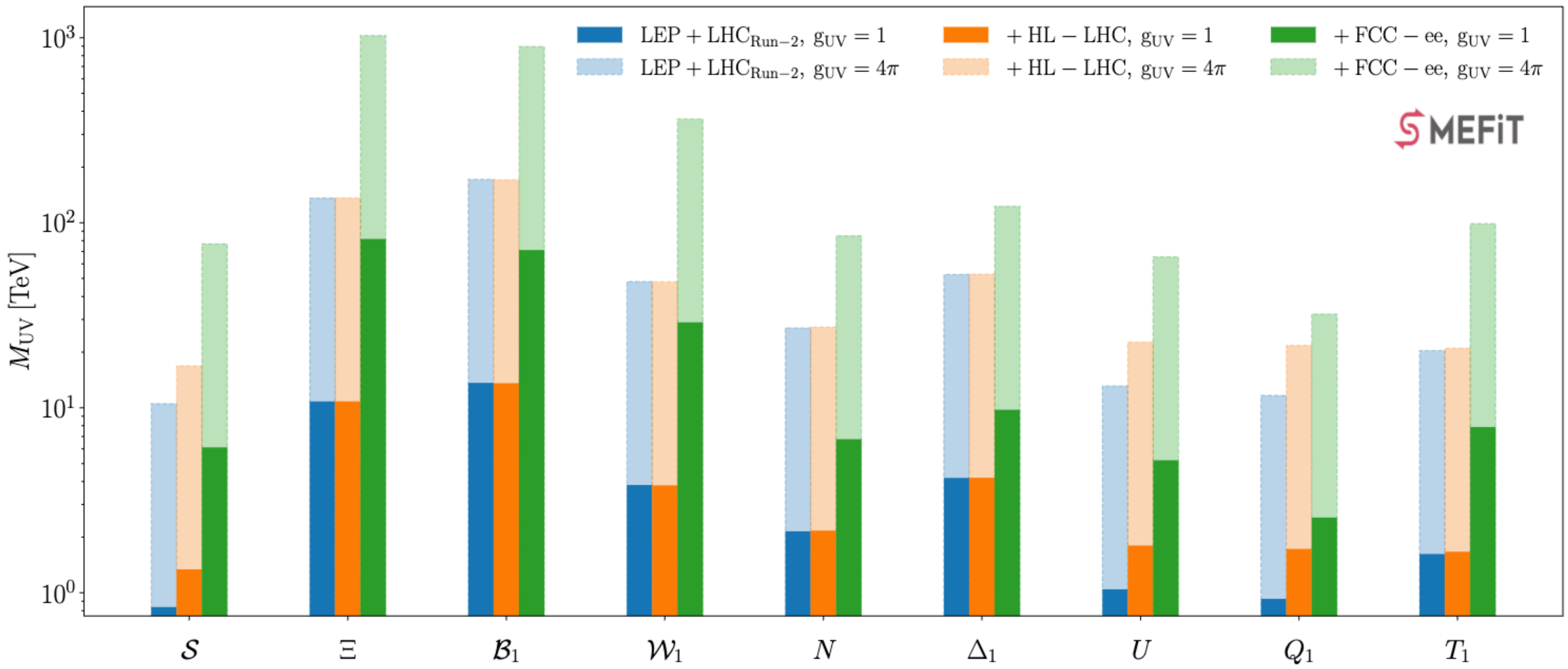
It depends on how ambitious we want to be with FCC-hh studies in the coming months

Next-to-Next-to-Leading Order effort: FCC-hh interpretations in the SMEFT with differential distributions for Higgs, top, diboson, Drell-Yan etc observables, and matching to UV models

From experimental side: determine binning from event rates, **(guess)timate systematics**

From theory side: need **(more) dedicated EFT calculations**, which we can adapt from LHC studies

Perform global fit to LEP+(HL-)LHC data + future colliders (including FCC-hh) in different combinations



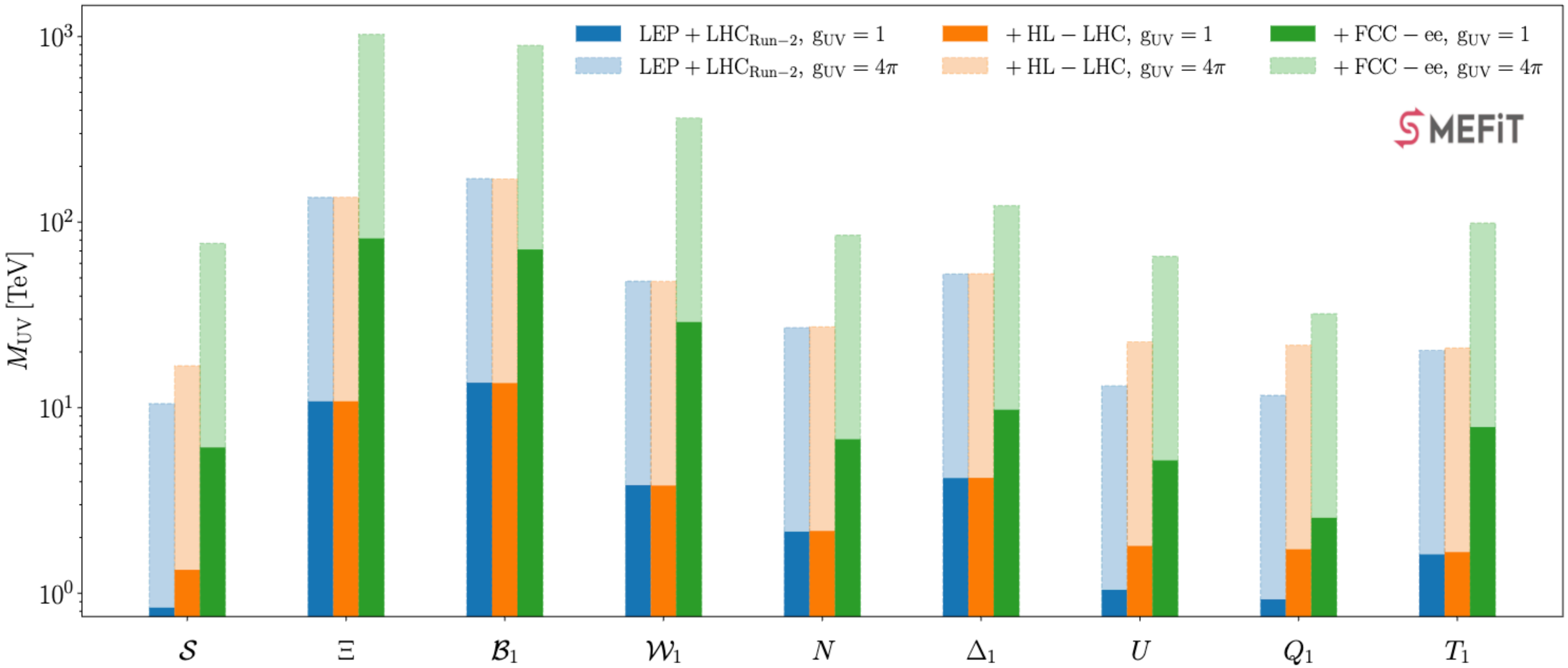
Interpretation frameworks for future colliders

Framework	Pros	Cons
Kappa	• Intuitive physical interpretation • Calculational simplicity	• **Only Higgs couplings** • No QFT, no matching with UV models • Neglects correlations with other processes e.g. EWPOs
Effective Couplings	• Intuitive physical interpretation • QFT, matched to (restricted) UV models	• **Only Higgs & EW couplings** • Limited operator basis • Neglects correlations with other processes e.g. ttbar
SMEFT	• Generality • QFT, matched to UV models, higher order corrections, RGEs, … • Correlations fully taken into account	• Less intuitive interpretation, unless matched to UV models • Large dimensionality of parameter space requires **global fit**

Priorities (imho)

- Update kappa framework fits for **different FCC-hh running scenarios**, with and without assuming an FCC-ee previously operating
- First EFT interpretation of **inclusive cross-sections** for Higgs, top, and diboson production at 100 TeV (and other energies), determine **indirect reach** in mass of some UV models
- Repeat for differential distributions, break degeneracies, determine **indirect reach** in mass of a broad range UV models

Ultimate (too ambitious?) goal: assess reach in heavy particle masses at the FCC-hh (with and without assuming FCC-ee) for various running options, and compare with other future colliders



Extra Material

Interpretation frameworks for future colliders

- Restricted to the **Higgs sector**, projections for future colliders can be interpreted in the **kappa framework** (coupling rescaling) without or with resolving the loops

$$\mu_i^{(f)} \equiv \frac{\sigma(i \to h)\mathrm{BR}(h \to f)}{\sigma_{\mathrm{SM}}(i \to h)\mathrm{BR}_{\mathrm{SM}}(h \to f)} = \frac{\kappa_i^2 \kappa_f^2}{\kappa_h^2}$$

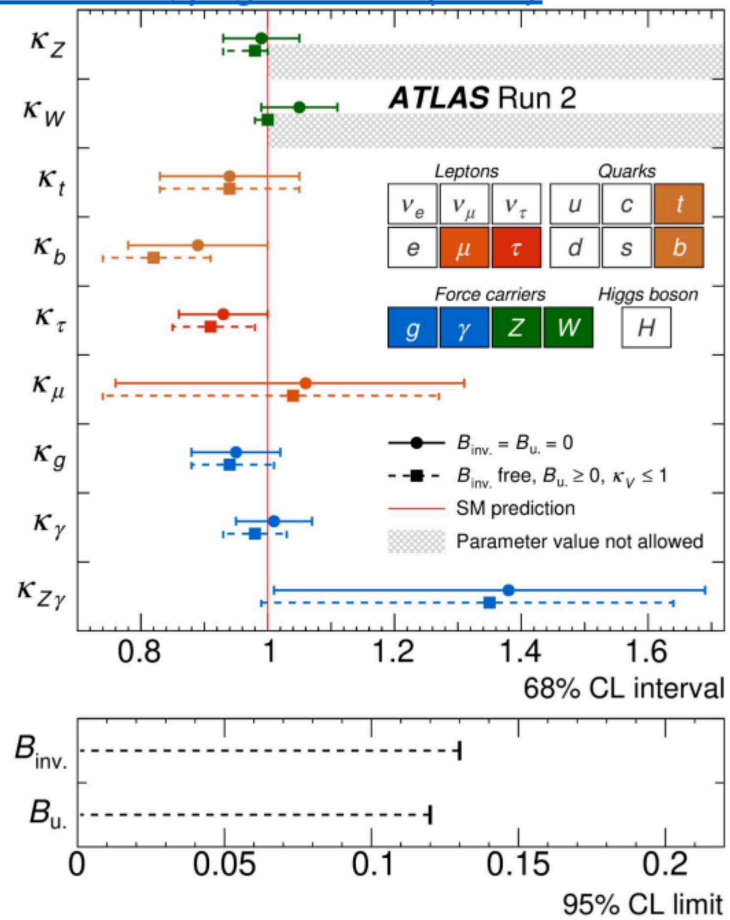
Higgs signal strengths in the kappa framework

$$\kappa_h^2 = \sum_j \frac{\kappa_j^2 \Gamma_j^{(\mathrm{SM})}}{\Gamma_h^{(\mathrm{SM})}}$$

Modifier of Higgs total decay width

Can be extended also to invisible decays

Nature 607, pages 52-59 (2022)



- **Intuitive** physical interpretation

- Main limitations: model rather than QFT, cannot be matched to UV theories, **neglects correlations with other sectors,** …

Several variants: with or without resolving loops, with or without invisible decays, etc

Interpretation frameworks for future colliders

- Restricted to the **Higgs sector**, projections for future colliders can be interpreted in the **kappa framework** (coupling rescaling) without or with resolving the loops

$$\mu_i^{(f)} \equiv \frac{\sigma(i \to h)\mathrm{BR}(h \to f)}{\sigma_{\mathrm{SM}}(i \to h)\mathrm{BR}_{\mathrm{SM}}(h \to f)} = \frac{\kappa_i^2 \kappa_f^2}{\kappa_h^2}$$

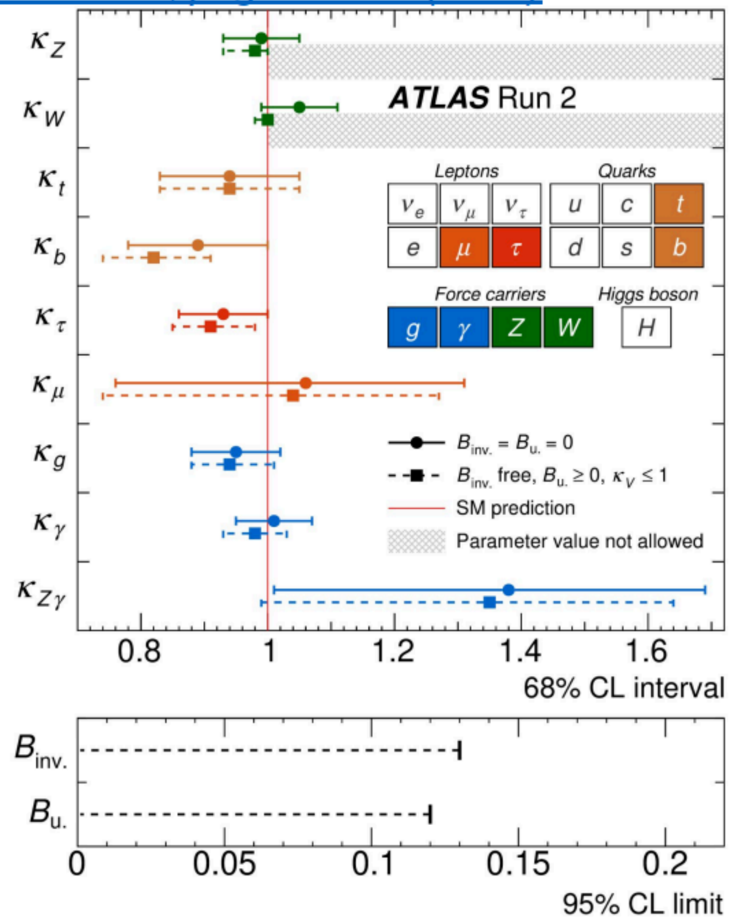
Higgs signal strengths in the kappa framework

$$\kappa_h^2 = \sum_j \frac{\kappa_j^2 \Gamma_j^{(\mathrm{SM})}}{\Gamma_h^{(\mathrm{SM})}}$$

Modifier of Higgs total decay width

Can be extended also to invisible decays

Nature 607, pages 52-59 (2022)



- **Intuitive** physical interpretation

- Main limitations: model rather than QFT, cannot be matched to UV theories, **neglects correlations with other sectors,** …

Several variants: with or without resolving loops, with or without invisible decays, etc

Interpretation frameworks for future colliders

- Restricted to the **Higgs and electroweak sectors**, projections for future colliders can be interpreted in the **effective coupling framework**

$$\delta g_{hX}^{(\mathrm{eff})} \equiv \left(\frac{\Gamma_{h\to X}}{\Gamma_{h\to X}^{(\mathrm{SM})}} \right)^{1/2}$$

decouples production from decay

- Expressed in terms of **SMEFT dimension-6 operators** (here Warsaw basis)

e.g.

$$\delta g_{h\gamma\gamma}^{(\mathrm{eff})} = \frac{2v^2}{g_{h\gamma\gamma}^2} \left(c_w^2 c_{\varphi B} + s_W^2 c_{\varphi W} - s_W c_W c_{\varphi WB} \right)$$

includes top mass dependence

- Also for anomalous **triple gauge couplings** and for $Z \to f\bar{f}$ couplings

e.g.

$$\delta g_{1,Z} = \frac{1}{4} \left(v^2 c_{\varphi D} - 2\Delta G_F + 4v^2 \frac{s_W^2}{c_W^2} c_{\varphi WB} \right)$$

- **Intuitive** physical interpretation combined within a QFT (matching, higher order corrections …)

- Main limitations: restricted operator basis **neglects correlations with other sectors** (top, flavour, …)

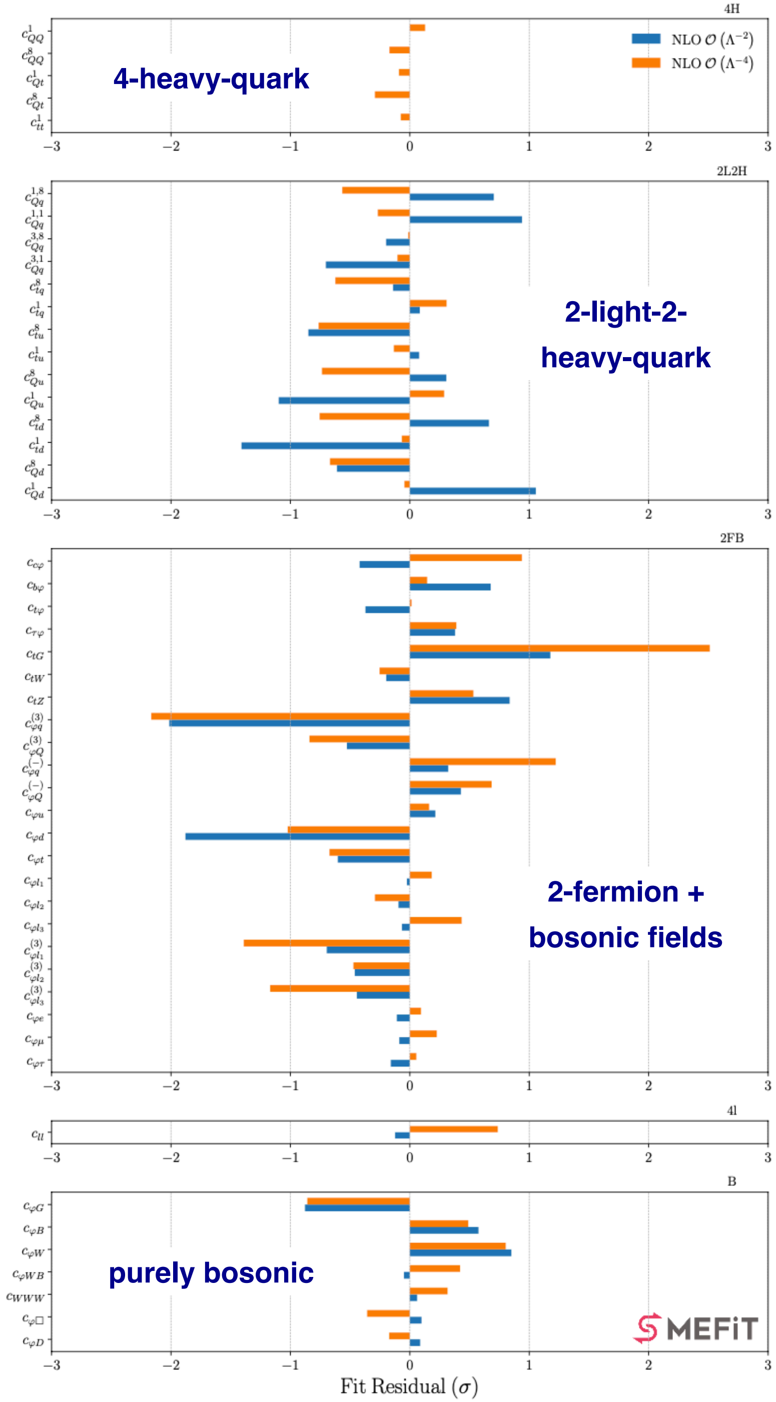
Interpretation frameworks for future colliders

- A more general interpretation can be carried out in the **full-fledged SMEFT**, connecting Higgs, electroweak, and top quark measurements within a consistent theory framework

- SMEFiT3.0 constraints **50 (45) Wilson coefficients** in quadratic (linear) EFT fits from **445 cross-sections** and flavour assumptions $U(2)_q \otimes U(3)_d \otimes U(2)_u \otimes \left(U(1)_\ell \otimes U(1)_e\right)^3$

E. Celada *et al.* (smefit), arXiv:2404.12809

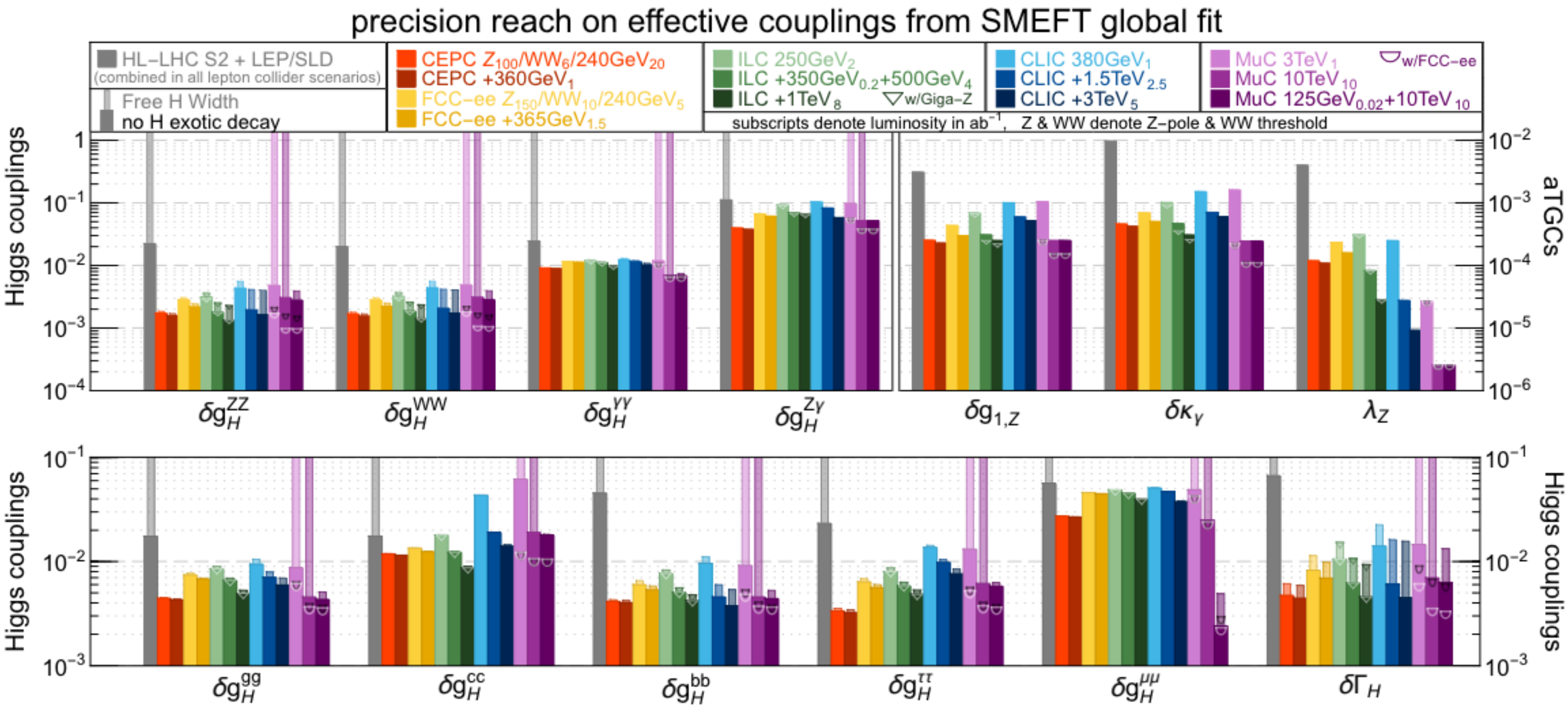
Category	Processes	n_{dat} SMEFiT2.0	n_{dat} SMEFiT3.0
Top quark production	$t\bar{t}+X$	94	115
	$t\bar{t}Z$, $t\bar{t}W$	14	21
	$t\bar{t}\gamma$	-	2
	single top (inclusive)	27	28
	tZ, tW	9	13
	$t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$	6	12
	Total	**150**	**189**
Higgs production and decay	Run I signal 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**



Higgs and EW couplings at future colliders

- The SMEFT framework (combined with UV-matching) is well suited to consistently **compare the reach of future particle colliders** on the parameter space of heavy BSM physics

- Several studies carried out for Snowmass and the FCC Feasibility Report, more ongoing for **ESPPU**



J. de Blas at al., arXiv:2206.08326 (Snowmass)

***nb*: interpretation done in terms of effective couplings**

The kappa framework at the FCC-hh

- Most studies of **Higgs couplings at the FCC-hh** presented in terms of the kappa framework:

kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2′	250	500	1000	380	15000	3000		240	365	
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

J. de Blas at al., arXiv:1905.03764 (ESPPU19)

$$\mu_i^{(f)} \equiv \frac{\sigma(i \to h)\mathrm{BR}(h \to f)}{\sigma_{\mathrm{SM}}(i \to h)\mathrm{BR}_{\mathrm{SM}}(h \to f)} = \frac{\kappa_i^2 \kappa_f^2}{\kappa_h^2}$$

$$\kappa_h^2 = \sum_j \frac{\kappa_j^2 \Gamma_j^{(\mathrm{SM})}}{\Gamma_h^{(\mathrm{SM})}}$$

Transparent relation between measurements and couplings, but may be **overoptimistic:** how robust Higgs coupling projections are in **other interpretation frameworks?**

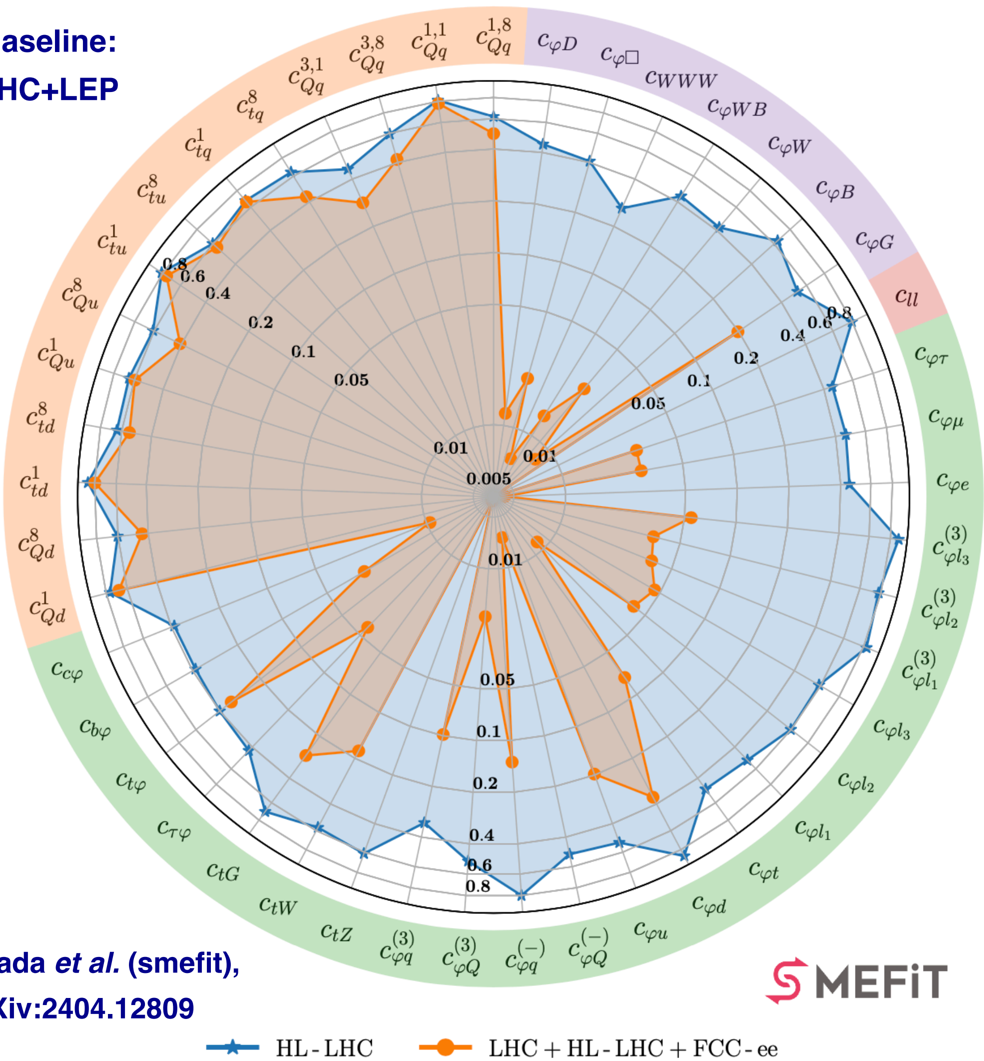
The SMEFT at the FCC-ee

- Start from **state-of-the-art global SMEFT fit** of Higgs, top, diboson, and EWPO data (SMEFiT3.0)
- Account for the projected **HL-LHC** and **FCC-ee** constraints (pseudo-data, assume SM)
- Match to a broad range of **UV complete models**

(HL-LHC: projected from Run-II)

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

Baseline: LHC+LEP

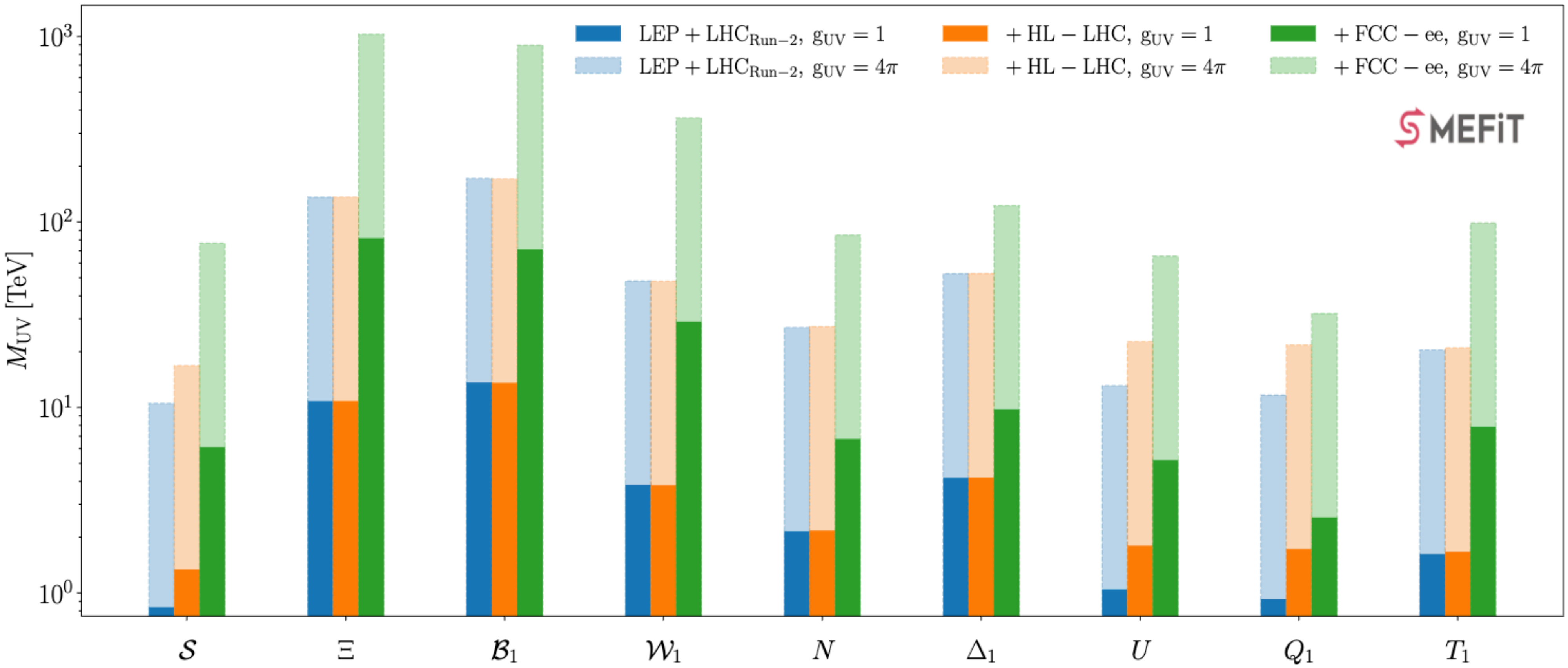


E. Celada *et al.* (smefit), arXiv:2404.12809

- FCC-ee: **huge improvements** (up to factor 100) for most EFT coefficients
- Most impact on **two-fermion**, **purely bosonic**, and **four-lepton operators**
- Four-fermion operators **involving top quarks** are unaffected by FCC-ee
- Shown are **global marginalised bounds**. If one performs **individual (one-parameter) fits**, impact of FCC-ee is even stronger (but not realistic)

The SMEFT at FCC-ee

- Start from **state-of-the-art global SMEFT fit** of Higgs, top, diboson, and EWPO data (SMEFiT3.0)
- Account for the projected **HL-LHC** and **FCC-ee** constraints (pseudo-data, assume SM)
- Match to a broad range of **UV complete models**



Matching both at tree-level and one-loop level available in SMEFiT

Impact of RGEs

- **One-loop QCD and electroweak corrections** induce running and mixing between RGE operators

$$\frac{dc_i(\mu)}{d\ln\mu} = \sum_{j=1}^{n_{\rm op}} \gamma_{ij} c_j(\mu) \qquad c_i(\mu) = \sum_{j=1}^{n_{\rm op}} \Gamma_{ij}(\mu,\mu_0) c_j(\mu_0)$$

Aebischer, Kumar, Straub

- Implemented in SMEFiT through an interface to the **wilson package**
- Cross-checked with multiple **stand-alone calculations** of RGE effects
- RGE modify the dependence of **physical observables** on the Wilson coefficients

$$\sigma_{\rm EFT} = \sigma_{\rm SM} + \sum_{i=1}^{n_{\rm op}} \kappa_i \frac{c_i}{\Lambda^2} + \sum_{i,j=1}^{n_{\rm op}} \widetilde{\kappa}_{ij} \frac{c_i c_j}{\Lambda^4}$$

Without RGEs

sums run over all non-zero contributions

$$\sigma_{\rm EFT} = \sigma_{\rm SM} + \sum_{i=1}^{n_{\rm op}} \kappa_i \frac{c_i(\mu)}{\Lambda^2} + \sum_{i,j=1}^{n_{\rm op}} \widetilde{\kappa}_{ij} \frac{c_i(\mu) c_j(\mu)}{\Lambda^4}$$

With RGEs

$$= \sigma_{\rm SM} + \sum_{i=1}^{n_{\rm op}} \kappa_i \frac{\Gamma_{ij}(\mu,\mu_0) c_j(\mu_0)}{\Lambda^2} + \sum_{i,j=1}^{n_{\rm op}} \widetilde{\kappa}_{ij} \frac{\Gamma_{ik}(\mu,\mu_0) c_k(\mu_0) \Gamma_{j\ell}(\mu,\mu_0) c_\ell(\mu_0)}{\Lambda^4}$$

with μ being the data scale and μ_0 the reference (high) scale

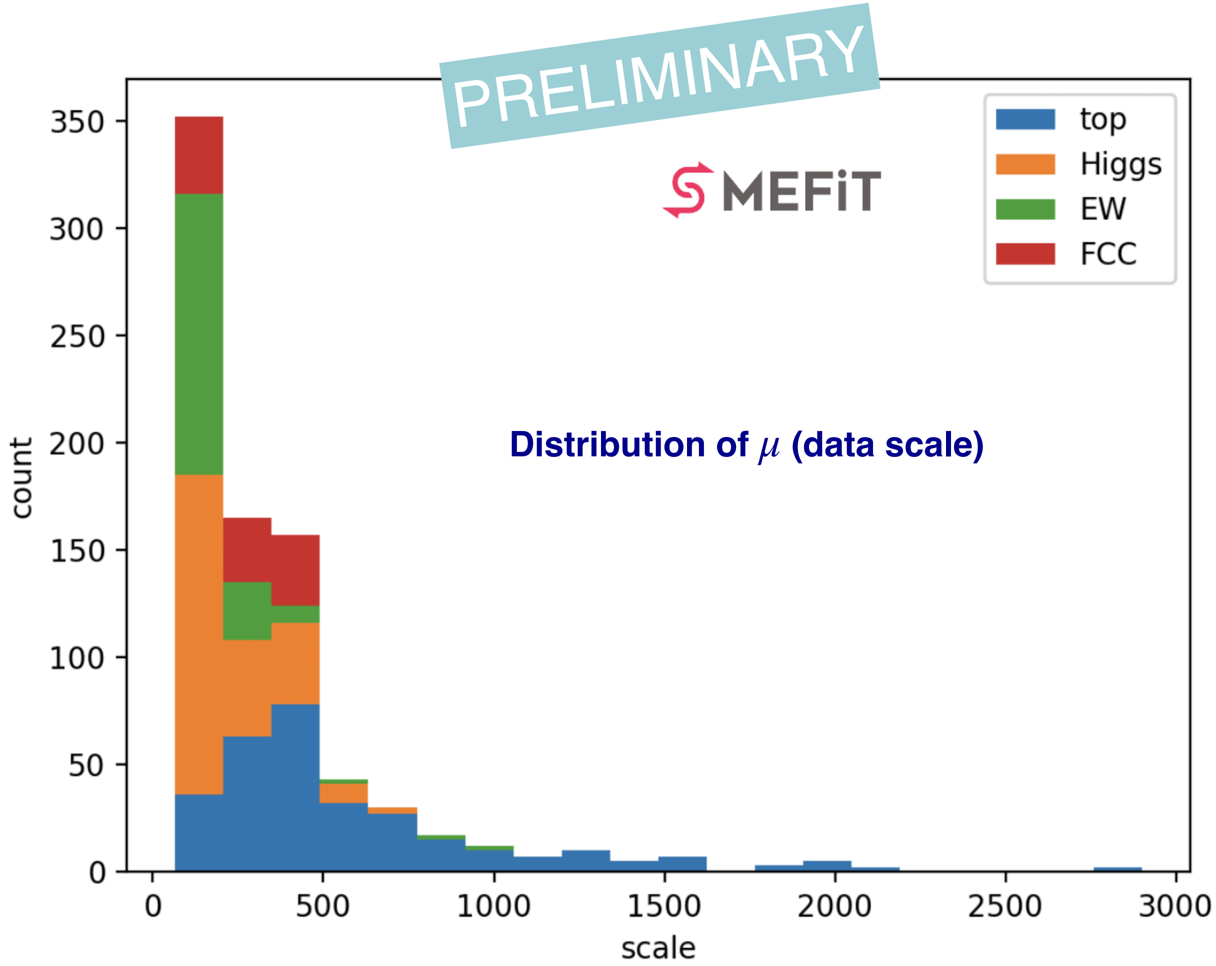
EFT basis must close under RGE

Impact of RGEs

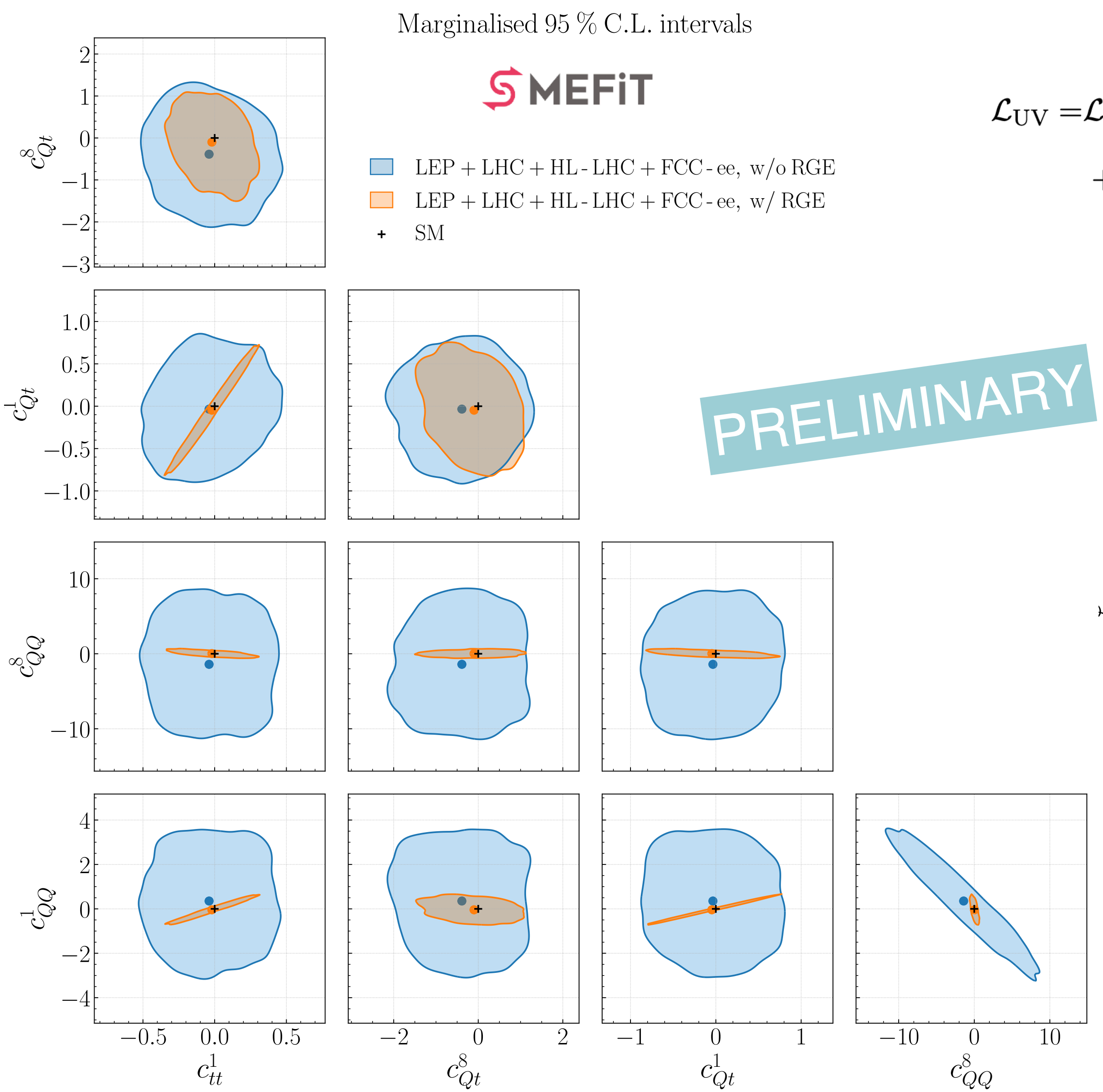
- One-loop QCD and electroweak corrections induce **running and mixing** between RGE operators

$$\frac{dc_i(\mu)}{d\ln\mu} = \sum_{j=1}^{n_{\rm op}} \gamma_{ij} c_j(\mu) \qquad c_i(\mu) = \sum_{j=1}^{n_{\rm op}} \Gamma_{ij}(\mu,\mu_0) c_j(\mu_0)$$

- Implemented in SMEFiT through an interface to the **wilson package**

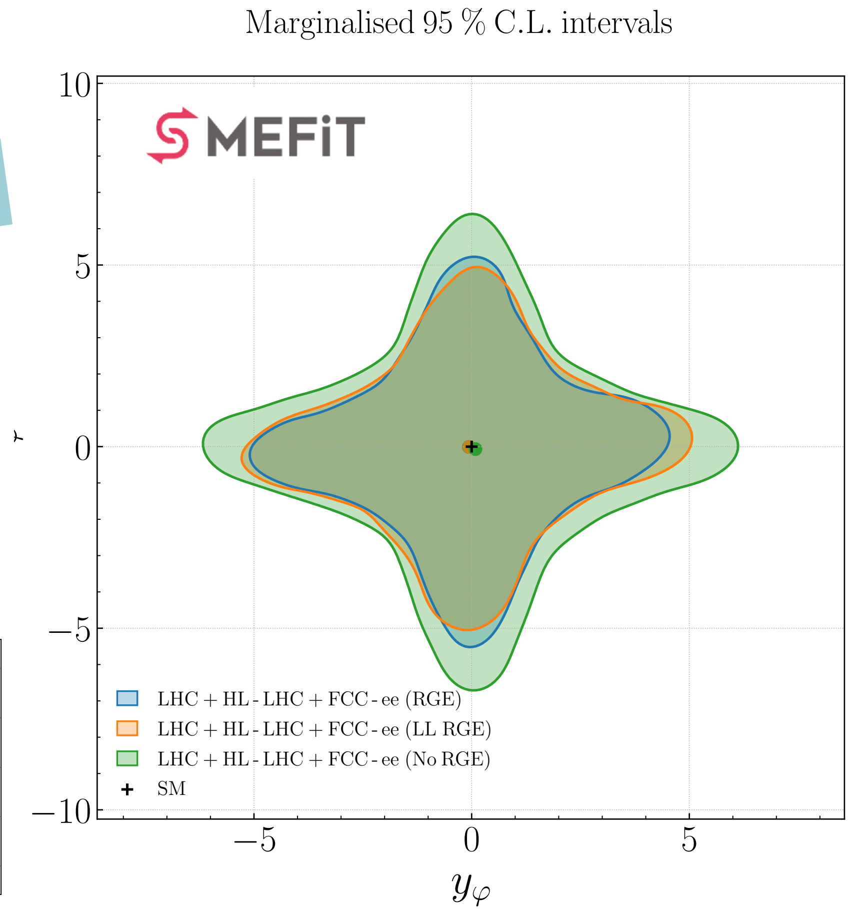


Impact of RGEs



2HDM model

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



nb RGE effects may also dilute the sensitivity by adding new directions to the parameter space

Ter Hoeve, Mantani, Rossia, Rojo, Vryodinou (WIP)

Towards Higgs coupling projections at FCC-hh

- As first approximation, and to compare with previous results, we have extended SMEFiT to carry out **fits in the kappa framework**

PRELIMINARY

	LHC	HL-LHC	FCC-ee 240		FCC-ee		FCC-hh	FCC-eh	muC 3	muC 10
			$\kappa_{Z\gamma}$=1	$\kappa_{Z\gamma}$ free	$\kappa_{Z\gamma}$=1	$\kappa_{Z\gamma}$ free				
$\kappa_W[\%]$	7.1	0.7	1.3	2.2	0.47	1.54	0.46	0.28	1.0	0.2
$\kappa_Z[\%]$	7.6	0.9	0.34	1.8	0.28	1.51	0.28	0.26	2.0	0.4
$\kappa_g[\%]$	5.9	0.5	1.5	2.3	0.9	1.7	0.73	0.50	1.7	0.5
$\kappa_\gamma[\%]$	7.3	0.9	4.6	4.8	3.8	4.1	0.64	0.51	3.3	0.8
$\kappa_{Z\gamma}[\%]$	–	10.6	–	61.0	–	59.6	1.04	0.94	29.3	6.3
$\kappa_c[\%]$	–	–	1.6	2.4	1.11	1.9	1.1	0.73	6.3	1.8
$\kappa_t[\%]$	9.9	2.2	–	–	–	–	1.0	0.97	–	–
$\kappa_b[\%]$	10.9	1.5	1.2	2.1	0.41	1.6	0.39	0.17	2.9	0.2
$\kappa_\mu[\%]$	–	3.7	9.5	9.1	8.5	8.6	0.65	0.53	16.4	2.8
$\kappa_\tau[\%]$	12.6	0.9	1.2	2.2	0.57	1.6	0.56	0.39	2.1	0.6

Very WIP, cross-checks and addition of other future colliders ongoing

- Many variations possible, such as fitting FCC-hh pseudo-data without assuming an FCC-ee first
- Here inputs are **inclusive signal strengths**: in the kappa framework, no information from kinematics
- In this framework **correlations between Higgs and other sectors** (e.g. electroweak) neglected

FCC-hh running scenarios

F. Zimmerman, FCC-hh ESPPU kick-off workshop

Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
c.m. energy	TeV	72	72	72	84	102	120	14
dipole field	T	12	12	12	14	17	20	8.33
beam current	A	0.5	1.12	1.12	0.5	0.5	0.2	(1.12) 0.58
bunch popul.	10^{11}	1.0	2.2	2.2	1.0	1.0	0.4	(2.2) 1.15
bunches/beam		9500	9500	9500	9500	9500	9500	(2760) 2808
rf voltage	MV	30	30	30	35	43	50	(16) 16
longit. emit.	eVs	6.9	6.9	6.9	8.1	9.7	11.4	2.5
norm. tr. emit.	μm	2.5	2.5	2.5	2.5	2.5	2.5	(2.5) 3.75
IP beta*	m	0.22	0.22	0.65	0.26	0.31	0.37	(0.15) 0.55
initial σ*	μm	3.8	3.8	6.5	3.8	3.8	3.8	(7.1 min) 16.7
initial *L*	$nb^{-1}s^{-1}$	175	845	286	172	209	39	(50, lev'd) 10
initial pile up		580	2820	955	590	732	141	(135) 27

F12LL: HL-LHC magnets
Lower energy
Low lumi

F12HL: HL-LHC magnets
Lower energy
High lumi

F12PU: HL-LHC magnets
Lower energy
Moderate lumi

F20: High field, HTS magnets
Higher energy
Lower luminosity

Impact of these choices for physics potential?

FCC-hh running scenarios

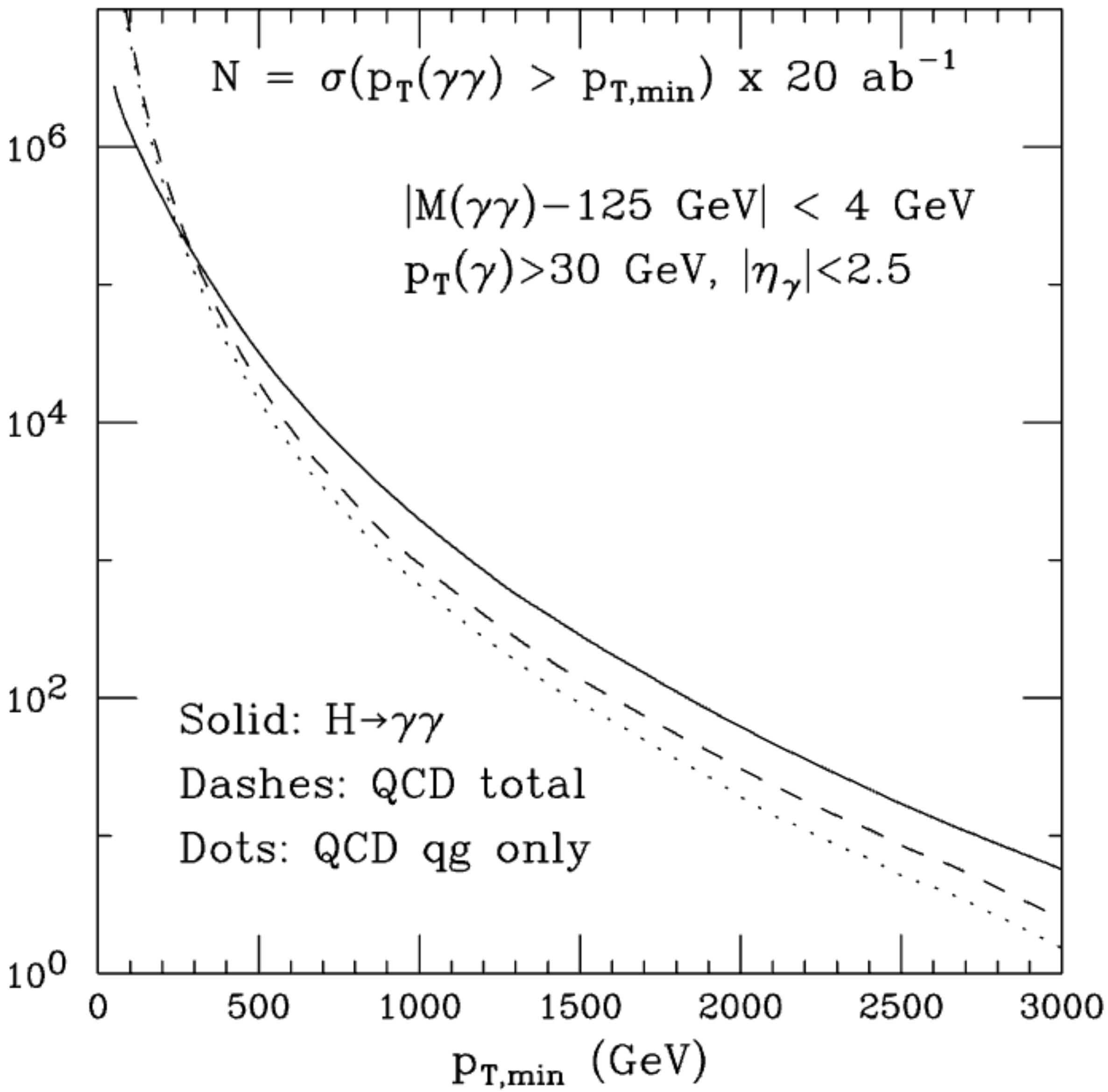
F. Zimmerman, FCC-hh ESPPU kick-off workshop

Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
c.m. energy	TeV	72	72	72	84	102	120	14
dipole field	T	12	12	12	14	17	20	8.33
beam current	A	0.5	1.12	1.12	0.5	0.5	0.2	(1.12) 0.58
bunch popul.	10^{11}	1.0	2.2	2.2	1.0	1.0	0.4	(2.2) 1.15
bunches/beam		9500	9500	9500	9500	9500	9500	(2760) 2808
rf voltage	MV	30	30	30	35	43	50	(16) 16
longit. emit.	eVs	6.9	6.9	6.9	8.1	9.7	11.4	2.5
norm. tr. emit.	μm	2.5	2.5	2.5	2.5	2.5	2.5	(2.5) 3.75
IP beta*	m	0.22	0.22	0.65	0.26	0.31	0.37	(0.15) 0.55
initial σ^*	μm	3.8	3.8	6.5	3.8	3.8	3.8	(7.1 min) 16.7
initial L	$nb^{-1}s^{-1}$	175	845	286	172	209	39	(50, lev'd) 10
initial pile up		580	2820	955	590	732	141	(135) 27

Possible Study #1: revisit Higgs Couling projections in the kappa framework with SMEFiT for the different running scenarios?

Towards Higgs coupling projections at FCC-hh

Beyond ``kappa framework” analyses of inclusive FCC-hh Higgs signal strengths, which other studies could be relevant in the framework of the ESPPU?

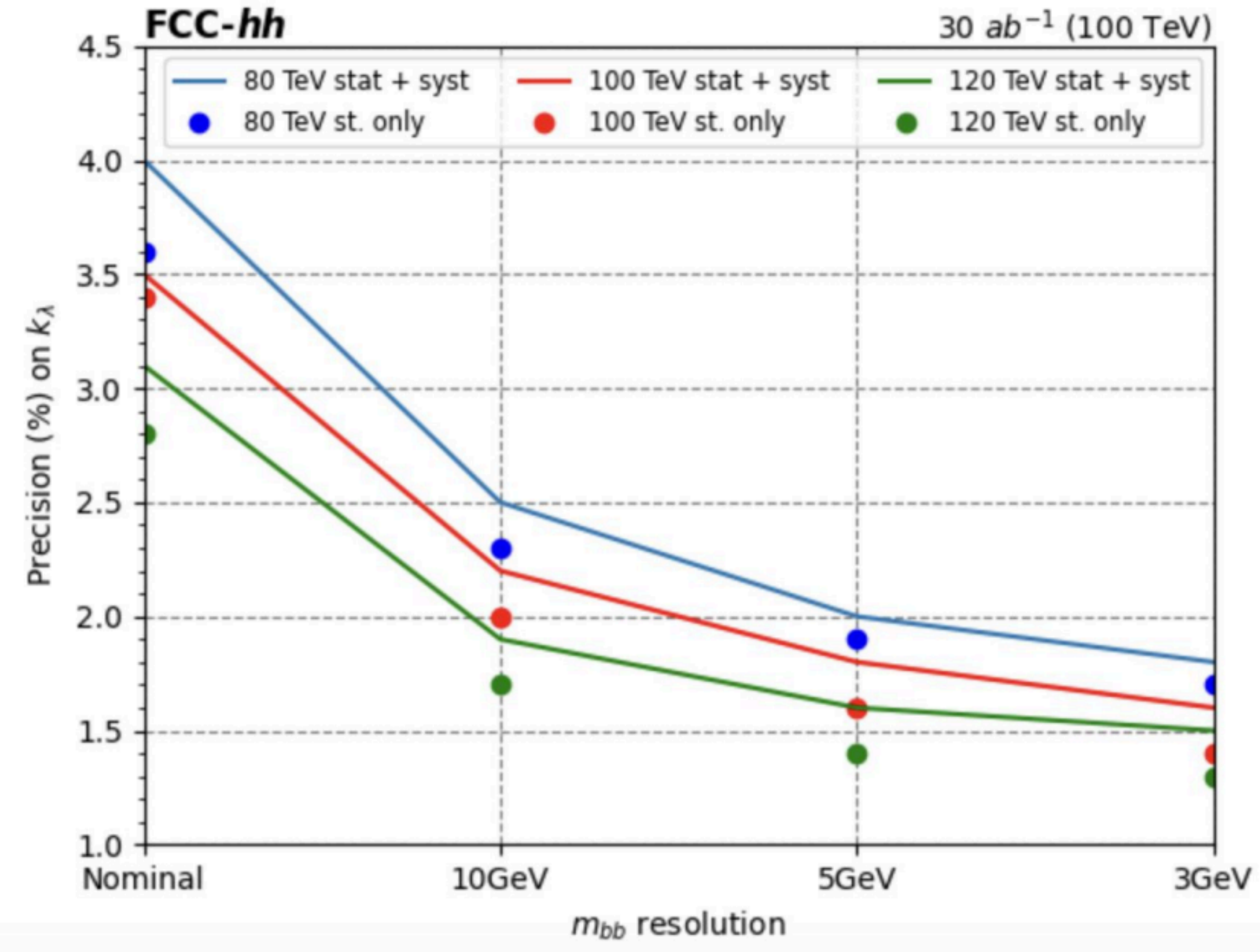


Possible Study #2: Higgs coupling interpretations of high-pT distributions using the SMEFT?

Towards Higgs coupling projections at FCC-hh

Beyond ``kappa framework" analyses of inclusive FCC-hh Higgs signal strengths, which other studies could be relevant in the framework of the ESPPU?

De Filippis, Mastrapasqua, Taliercio, Stapf



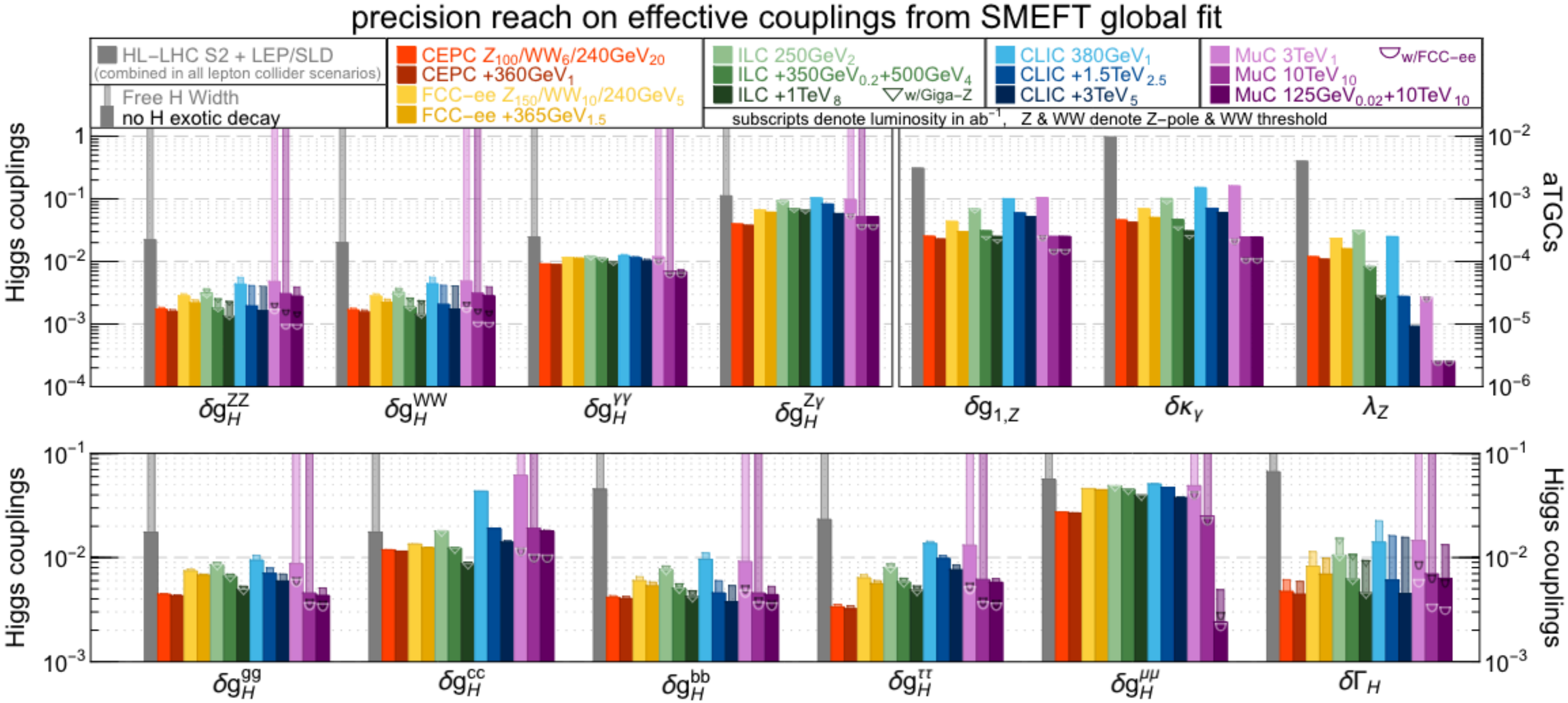
- Measurement of Higgs self-coupling is core goal of FCC-hh program
- Does sensitivity degrade if we also f**loat other Higgs couplings?**
- What is the impact of **FCC-ee constraints** here?

Possible Study #3: Higgs self-coupling beyond the kappa framework?

M. Selvaggi, kick-off meeting

Towards Higgs coupling projections at FCC-hh

Beyond ``kappa framework” analyses of inclusive FCC-hh Higgs signal strengths, which other studies could be relevant in the framework of the ESPPU?



- Most studies assume FCC-ee runs before FCC-hh
- How does the picture change **without FCC-ee**?
- How crucial is FCC-ee for program of the FCC-hh?

Kappa framework insufficient, requires global SMEFT fit

Possible Study #4:
Updated Higgs coupling studies **without assuming a prior FCC-ee run?**

Towards Higgs coupling projections at FCC-hh

PRELIMINARY

SMEFiT

	FCC-ee ($\sqrt{s} = 240$ GeV)	FCC-ee (full dataset)	FCC-hh	
			+ (FCC-ee 240 GeV)	+ FCC-ee (full)
$\kappa_W [\%]$	1.3	0.42	0.54	0.34
$\kappa_Z [\%]$	0.19	0.16	0.15	0.13
$\kappa_g [\%]$	1.6	1.0	0.89	0.74
$\kappa_\gamma [\%]$	4.7	3.9	0.71	0.66
$\kappa_{Z\gamma} [\%]$	69	69	1.4	1.3
$\kappa_c [\%]$	1.7	1.2	1.4	1.2
$\kappa_t [\%]$	–	–	1.3	1.0
$\kappa_b [\%]$	1.3	0.60	0.63	0.47
$\kappa_\mu [\%]$	9.7	8.8	0.98	0.94
$\kappa_\tau [\%]$	1.4	0.72	0.70	0.57

- Compare different combinations of the **FCC integrated running program**
- At FCC-ee, the **91, 165 & 365 GeV runs** improve mostly $\kappa_\tau, \kappa_b, \kappa_W$ (factor 2 or 3)
- As compared to FCC-ee, **FCC-hh** improves $\kappa_\gamma, \kappa_{Z\gamma}, \kappa_\mu$ (factor 10) and make possible accessing κ_t

Just one example of possible studies e.g. one could compare with FCC-hh stand-alone

Summary (I)

- Extensive machinery for **future collider studies** is (being) implemented in SMEFiT, including kappa framework and effective coupling fits

- SMEFT-based interpretations of FCC-ee mature, most FCC-hh projections based on **kappa framework**

- Extensive progress in the **SMEFiT framework** along several directions

    - **Dataset**: LHC Run-2 and Run-3 data, dedicated HL-LHC projections, future collider variants …

    - **Theory**: RGEs (QCD & electroweak), NLO QCD corrections for EFT at (HL-)LHC, NLO EW corrections for FCC-ee, state-of-the-art SM and their (projected) uncertainties …

    - **Methodology:** complementary interpretation frameworks, visualisation and data reduction techniques, user-friendly interface, performance speedups

    - **UV matching:** tree-level and one-loop matching essentially automated (with some exceptions)

    - **Flavour assumptions**: working on inclusion of **flavour** and related processes e.g. Drell-Yan

SMEFiT

Fully open source & reproducible results

For discussion

- Extensive machinery for **future collider studies** is (being) implemented in SMEFiT, including kappa framework and effective coupling fits
- SMEFT-based interpretations of FCC-ee mature, most FCC-hh projections based on **kappa framework**
- We should discuss which are the **most interesting studies** that we need to carry out for ESPPU

Some possible ideas

Possible Study #1: revisit Higgs Couling projections in the kappa framework with SMEFiT for the different running scenarios?

Possible Study #2: Higgs coupling interpretations of high-pT distributions using the SMEFT?

Possible Study #3: Higgs self-coupling beyond the kappa framework?

Possible Study #4: Updated Higgs coupling studies without assuming a prior FCC-ee run?

Possible Study #5: Global SMEFT with FCC-hh projections?