

Higgs Self-Coupling at the Future Circular e^+e^- Collider

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Single Higgs production at FCC-ee probes the Higgs self-coupling at next-to-leading order (NLO). Extracting a bound requires a global analysis accounting for other possible new physics contributions up to NLO. We determine the FCC-ee sensitivity to Higgs self-coupling modifications $\delta\kappa_\lambda$ within the standard model effective field theory framework, including for the first time flavor, LEP, LHC, and FCC-ee observables in a global analysis with all leading NLO effects via one-loop renormalization group evolution, as well as incorporating finite NLO contributions to electroweak precision and ZH observables. The global sensitivity to $\delta\kappa_\lambda$ is estimated by marginalizing over the effects of all other operators, bringing flavor considerations to the fore. We find that, under reasonable assumptions, FCC-ee sensitivity to $\delta\kappa_\lambda$ can exceed that of the HL-LHC.

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Introduction—The Higgs self-coupling is one of the last remaining parameters of the standard model (SM) to be determined precisely. Tied to the cosmological history and fate of our Universe, it is of fundamental importance for a deeper understanding of the Higgs sector. While Higgs couplings measurements have reached the $\mathcal{O}(10)\%$ level [1–3], the sensitivity to the Higgs self-coupling from di-Higgs production at the LHC currently stands at $\mathcal{O}(100)\%$ [4,5]. Projections for HL-LHC have been refined to an estimated 30% [6–8], from a combination of channels and improved analyses, using 3000 fb^{-1} of data. A percent-level determination is anticipated at future high-energy hadron colliders such as FCC-hh [9].

On the other hand, future circular e^+e^- colliders at the precision frontier, such as FCC-ee [10–12] or CEPC [13], would operate below the energy threshold necessary to have significant leading order (LO) access to the Higgs self-coupling in di-Higgs production. However, as pointed out in Ref. [14], it can still be indirectly constrained through its next-to-leading order (NLO) contribution to ZH single-Higgs production [15]. The extraction of a meaningful bound must then account for other possible contributions within some theoretical framework. A well-motivated

possibility is the parametrization of heavy new physics effects using the standard model effective field theory (SMEFT) [28–30].

An estimate of the indirect sensitivity to the Higgs self-coupling at FCC-ee marginalizing over the effects of other dimension-6 operators in the SMEFT was performed in Ref. [31]. This analysis did not vary the full set of LO operators entering the inclusive ZH cross section $\sigma(ZH)$, assuming those affecting electroweak (EW) precision observables could be neglected due to strong constraints from Z - and W -pole observables. However, as recently demonstrated in Ref. [32], the sensitivity of operators entering $\sigma(ZH)$ at LO is comparable to that of their effect at NLO at the Z/W pole; the variation of those operators must therefore be taken into account simultaneously for a more complete, self-consistent global analysis.

Since the analysis of Ref. [31], a full NLO computation of SMEFT contributions to $\sigma(ZH)$ inclusive has become available [33]. This brings sensitivity to a plethora of new operators, predominantly four-fermion operators of the type $(\bar{e}\gamma^\mu e)(\bar{f}_p\gamma_\mu f_p)$, where f_p is any SM fermion with flavor index p . As these operators enter at the same order as the Higgs self-coupling, a consistent global analysis must include their variation. Sensitivity to Higgs self-coupling modifications in single-Higgs production is therefore inextricably tied to flavor symmetries that control the structure of the SMEFT [34–36].

Higgs self-coupling modifications of $\mathcal{O}(50)\%$ correspond to a naïve new physics scale of about 1 TeV. However, a very specific flavor structure is required for new physics to reside at nearby energy scales [37]. Flavor data and the lack of new physics beyond the SM (BSM) at the LHC have given us two important clues about this

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TABLE I. Datasets used in our global analysis, publicly available on [47]. For all FCC-ee projections, we exclude di-Higgs data and use the latest luminosity figures in Ref. [12].

	Name	Description	Refs.
FCCee	Z/W-pole	Electroweak Precision Observables	[32,48]
	Single H	Inclusive $e^+e^- \rightarrow ZH, \nu\bar{\nu}H$ cross sections	[42,48]
	Diboson	Total cross sections at 163, 240, 365 GeV	[48]
	Di-fermion	Cross sections and A_{fb} at 163, 240, 365 GeV	[39,49]
LEP	Diboson	Diboson total and differential cross sections	[38]
	Di-lepton	Di-lepton production for $\sqrt{s} > m_Z$	[50]
HL-LHC	Top	$t, \bar{t}, t\bar{t}V, t\bar{t}t\bar{t}$ and $b\bar{b}t\bar{t}$ (diff.) cross section	[38,51]
	Higgs	Higgs signal strengths and STXS data	[38,40,52]
	Diboson	Fiducial differential dist. for VV and Zjj	[38]
	Drell-Yan	Di- and mono-lepton high- p_T tails	[43,53]
	Flavor	$\Delta F = 2, b \rightarrow c\tau\nu, b \rightarrow s\ell\ell$, and $b \rightarrow s\nu\nu$	[37]
	Di-Higgs	Combined Di-Higgs signal strength	[6,7]

structure: (i) in order to evade stringent bounds on flavor-changing neutral currents, new physics should couple universally at least to the light families, and (ii) new physics does not couple strongly to valence quarks at nearby energy scales. A possibility that satisfies (i) is flavor-universal new physics, described by $U(3)^5$ symmetry. However, compatibility with both (i) and (ii) hints at new physics coupled universally to the light families, while it may have a larger coupling to the third generation, a scenario described by $U(2)^n$ flavor symmetries.

In this Letter, we perform the first global analysis (i.e., including hundreds of measurements across multiple channels and experiments and simultaneously varying all operators contributing to them) going beyond leading order to determine the projected sensitivity of FCC-ee to the Higgs self-coupling. We vary all operators entering inclusive single-Higgs production up to NLO accuracy, as well as any new operators introduced by the constraining datasets, which include flavor, EW, and collider observables. As these observables are measured at different energy scales, we consistently account for renormalization group evolution to build our global likelihood at a common high scale $\Lambda = 1$ TeV. We assume only the validity of the SMEFT framework and four possibilities for flavor symmetries, namely $U(3)^5$ and various $U(2)^n$ scenarios.

Details of the global analysis—We define the SMEFT Lagrangian as

$$\mathcal{L}_{\text{SMEFT}} = \sum_i C_i(\mu) Q_i, \quad (1)$$

where $C_i(\mu)$ are dimensionful Wilson coefficients evaluated at the renormalization scale μ and Q_i are operators in the Warsaw basis [30]. Throughout this work, all Wilson coefficients will be evaluated at the high scale $C_i(\Lambda)$, with $\Lambda = 1$ TeV. Because of stringent constraints on CP

violation, we assume that only CP -even operators are present at the high scale Λ .

Our global analysis incorporates the observables listed in Table I, with experimental and theoretical uncertainties implemented as in Refs. [32,38]. All observables are computed at leading order in the SMEFT [38–43] except for $\sigma(ZH)$ inclusive and electroweak precision observables (EWPO), which we include at NLO accuracy [33,44,45]. Nevertheless, the leading-logarithmic NLO contributions are automatically included for all observables via the renormalization group (RG) evolution. We solve the one-loop RG equations using the evolution matrix approximation implemented in DsixTools 2.0 [46], which resums higher loop contributions in the leading-logarithmic series while allowing us to keep the likelihood analytic in the Wilson coefficients. We will work to $\mathcal{O}(1/\Lambda^2)$ in the SMEFT, keeping only linear contributions to our observables.

The inclusive ZH cross section at NLO as computed in Ref. [33] depends on the bosonic operators $Q_H, Q_{H\Box}, Q_{HD}, Q_{HB/W}, Q_{HWB}, Q_W$, EW vertex corrections $\psi^2 H^2 D$, four-fermion operators of the type $(\bar{e}\gamma^\mu e)(\bar{f}_p\gamma_\mu f_p)$, and top Yukawa and dipole corrections [54]. Without making any flavor assumptions there are 66 CP -even operators, the bulk of which (35 of 66) are four-fermion operators, bringing sensitivity to the flavor structure of the SMEFT. Our approach is to analyze sensitivity to Higgs self-coupling modifications assuming four flavor symmetries that allow for new physics at nearby energy scales, shown in Table II. Motivated by tight LHC bounds on new physics coupling to valence quarks, the scenario denoted “ $U(2)^5$ (3rd-gen. dominance)” corresponds to the $U(2)^5$ scenario with the additional dynamical assumption that couplings to the light generations are suppressed. This is implemented by keeping only $U(2)^5$ invariants with fully third-generation fields.

TABLE II. Flavor symmetries considered in this work. We have defined $U(3)^3 \equiv U(3)_d \times U(3)_l \times U(3)_e$.

Flavor symmetry	CP -even parameters
$U(3)^5$	41
$U(2)_q \times U(2)_u \times U(3)^3$	72
$U(2)^5$	124
$U(2)_{q,u,d}^3 \times U(1)_{e,\mu,\tau}^3$	168
$U(2)^5$ (3rd-gen. dominance)	53

All symmetries including flavor and CP are imposed only at the high scale Λ —we consistently allow them to be broken by rotations to the SM fermion mass basis as well as RG effects. Even our $U(3)^5$ scenario thus includes minimal flavor violating effects [55] at one loop. The rotation matrices are fixed assuming the most conservative “down-aligned” scenario discussed in Ref. [37], where flavor-violating effects in the more sensitive down-quark observables come only from RG contributions.

The four-fermion operators entering $\sigma(ZH)$ at NLO may be constrained by $e^+e^- \rightarrow \bar{f}f$ observables above the Z pole at LEP and FCC-ee, such as total cross sections and forward-backward asymmetries A_{fb} [56]. In the case of FCC-ee, the 365 GeV run enables constraints on $eett$ operators. Semileptonic operators receive complementary constraints from high-energy Drell-Yan tails at the LHC. To constrain some of the bosonic operators, we include data from single-Higgs production and decay at the LHC, as well as diboson data from both LHC and FCC-ee. Wherever LHC data is concerned, we take projections for the HL-LHC from official publications if available [52,57], otherwise we rescale the Run 2 statistical uncertainties by the luminosity increase to 3 ab^{-1} and assume a factor of 2 reduction in systematic and theoretical uncertainties, following the S2 scenario described in Ref. [6]. While subleading, we also include the $e^+e^- \rightarrow \bar{\nu}\nu h$ single-Higgs production channel at FCC-ee. Concerning FCC-ee projections, we use the luminosity figures presented in the feasibility study report [12], which are roughly double for all runs above the Z pole compared with Ref. [11]. We keep and vary all additional operators entering the aforementioned observables at LO in our global analysis.

As previously mentioned, variations in EW vertices and the bosonic operators Q_{HD} and Q_{HWB} must be taken into account, as EWPO are sensitive to many ZH operators at NLO with a similar precision as $\sigma(ZH)$ at leading order. Indeed, EWPO at NLO are sensitive to almost all parameters in our fit.

Therefore, while we always include the full LO dependence, we make the following assumptions, *which apply only concerning EWPO at NLO*. (1) We keep the full NLO dependence for operators we already had in the observables discussed above. (2) New operator dependencies at NLO

proportional to weak couplings are neglected. We include new operators only if they are proportional to the large couplings y_i or g_s .

This assumption leads to the inclusion of $4t$, $2t2q$, and $2t2l$ operators, while it only excludes third-family $4l$ and light-quark $4q$ operators that do not enter any other observables added so far. To constrain the new four-quark and semileptonic operators involving q_L^3 and t_R , we add top data projections for the HL-LHC [38,51] and low-energy flavor data from B , K , D meson mixing as well as semileptonic $b \rightarrow c\tau\nu$, $b \rightarrow s\ell\ell$, and $b \rightarrow s\nu\nu$ transitions. We include all flavor observables of these types given in Ref. [37], which does not add any significant new operator dependence. On the other hand, we consistently include all new operators brought by the top dataset (including their full NLO contributions to EWPO).

In total, 150 operators are included in our analysis before imposing any flavor symmetry, which is roughly half of all flavor-conserving and CP -even operators in the SMEFT. In the limit of $U(2)_{q,u,d}^3 \times U(1)_{e,\mu,\tau}$ invariance, 116 independent Wilson coefficients remain, which is the largest parameter set we consider. Even in this case, the more than 400 observables we include is sufficient to close our global fit, though some linear combinations of Wilson coefficients that do not enter single-Higgs production remain poorly constrained in the least symmetric cases. To ensure the validity of our dimension-6 EFT, as well as to justify neglecting quadratic contributions to observables, we place an upper bound on the size of all Wilson coefficients except C_H in the fit. This is implemented by the inclusion of a “boundary condition (BC) likelihood,”

$$\chi_{BC}^2 = 4 \sum_{i \neq H} \left(\frac{C_i}{C_{BC}} \right)^2, \quad C_{BC} = \frac{1}{(250 \text{ GeV})^2}, \quad (2)$$

where the sum runs over all Wilson coefficients in the fit except for C_H . This likelihood has the effect of enforcing $C_i < C_{BC}$ at 95% CL, essentially acting as a theoretical prior on the size of the Wilson coefficients. We do not impose a boundary condition for C_H as our goal is to determine the FCC-ee sensitivity to this Wilson coefficient. Instead, $C_H < C_{BC}$ as determined from our global fit will serve as a consistency check on the analysis.

The choice of C_{BC} is motivated by considering new physics (NP) with a mass scale of $M_{NP} \gtrsim 1 \text{ TeV}$ to trust the EFT description, while assuming a perturbative NP coupling $g_{NP} < \sqrt{4\pi}$. Together, these conditions yield $C_{BC} = g_{NP}^2/M_{NP}^2 \lesssim 1/(250 \text{ GeV})^2$, corresponding to new physics effects smaller than SM electroweak processes.

We build our likelihood by performing renormalization group evolution to express all observables O_i as linear, analytic functions of the high-scale Wilson coefficients $C_i(\Lambda)$, which we use to compute the χ^2 function

TABLE III. Higgs self-coupling sensitivities at FCC-ee switching on C_H only, bosonic operators only, or imposing the flavor symmetries listed in Table II.

Scenario	σ_H [TeV $^{-2}$]	68% CL $\delta\kappa_\lambda$
C_H Only	0.39	18%
Bosonic Only	0.52	24%
$U(3)^5$	0.57	27%
$U(2)_q \times U(2)_u \times U(3)^3$	0.61	29%
$U(2)^5$	0.62	29%
$U(2)_{q,u,d}^3 \times U(1)_{e,\mu,\tau}^3$	0.68	32%
$U(2)^5$ (3rd-gen. dominance)	0.54	25%

$$\chi_{\text{data}}^2 = \sum_{ij} [O_{i,\text{exp}} - O_{i,\text{th}}](\sigma_{\text{exp}}^{-2})_{ij} [O_{j,\text{exp}} - O_{j,\text{th}}]. \quad (3)$$

We then add the boundary condition likelihood such that the total likelihood is given by $\chi^2 = \chi_{\text{data}}^2 + \chi_{\text{BC}}^2$.

Higgs self-coupling sensitivity at FCC-ee: We are interested in modifications of the Higgs self-coupling, which we parametrize by $\kappa_\lambda \equiv \lambda_3/\lambda_3^{\text{SM}}$, where $2\lambda_3^{\text{SM}}v^2 = m_h^2$. The shift $\delta\kappa_\lambda$ at the dimension-6 level from the operator $(H^\dagger H)^3$ with Wilson coefficient C_H is

$$\delta\kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\text{SM}}} - 1 = \frac{v^2 C_H}{\lambda_3^{\text{SM}}}. \quad (4)$$

We will always determine $\delta\kappa_\lambda$ using Eq. (4) with C_H evaluated at $\Lambda = 1$ TeV. Since our likelihood is Gaussian and fully analytic in the Wilson coefficients, we extract the allowed range for C_H marginalized over the contributions of all other Wilson coefficients by analytically computing and inverting the Hessian matrix $\mathbf{H}$,

$$\mathbf{H}_{ij} \equiv \frac{1}{2} \frac{\partial^2 \chi^2}{\partial C_i \partial C_j}, \quad \sigma_i^2 = \text{diag}(\mathbf{H}^{-1}), \quad (5)$$

where σ_i is the marginalized 68% CL interval for each Wilson coefficient C_i . The results of our analysis are shown in Table III, where we report σ_H as well as the corresponding 68% CL interval on $\delta\kappa_\lambda$, for several different flavor assumptions. We also plot the marginalized likelihood for C_H (or $\delta\kappa_\lambda$) under the various flavor scenarios in Fig. 1. For comparison, the vertical grid lines give the 68% CL marginalized sensitivity at the HL-LHC, which we find to be $\delta\kappa_\lambda = 0.38$ from a global fit combining di-Higgs production with all other HL-LHC observables in Table I [58]. For the projected di-Higgs sensitivity at the HL-LHC, we use the S2 scenario of Ref. [8] with 3 ab $^{-1}$, which yields $\delta\kappa_\lambda = 0.36$ for a C_H -only fit. The apparent discrepancy with the quoted $\delta\kappa_\lambda = 0.3$ is due to the running of C_H up to $\Lambda = 1$ TeV. We emphasise that di-Higgs data is not included in our global fit for FCC-ee; direct determination of the Higgs self-coupling at the HL-LHC is

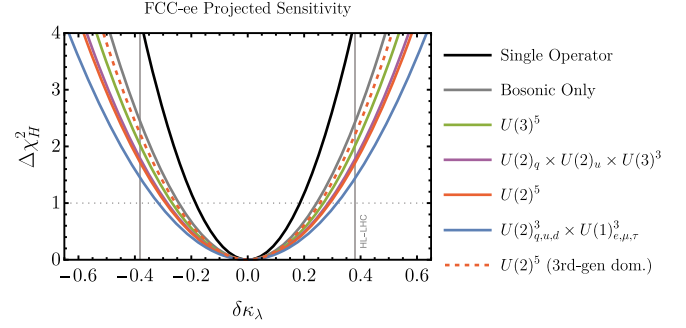


FIG. 1. Marginalized SMEFT likelihood for the Higgs self-coupling, $\delta\kappa_\lambda$, under various assumptions for flavor symmetries. The single-operator and bosonic-only scenarios are also shown for reference. For comparison, vertical solid gray grid lines denote the fully marginalized HL-LHC sensitivity at 68% CL.

complementary to our indirect approach and could be straightforwardly included in the fit, but our goal here is to compare the sensitivity of the two. Our key result, shown in Fig. 1, is that FCC-ee is able to achieve better sensitivity on $\delta\kappa_\lambda$ than the HL-LHC for all flavor symmetries considered in our analysis, namely $\delta\kappa_\lambda \lesssim 30\%$.

To examine the dependence of our results on the choice of the theoretical prior imposing an upper limit on all Wilson coefficients, we vary C_{BC} in the range $(350 \text{ GeV})^{-2} < C_{\text{BC}} < (150 \text{ GeV})^{-2}$. Under this variation, σ_H changes by about 5% in the $U(2)_{q,u,d} \times U(1)_{e,\mu,\tau}^3$ scenario, while it is $\lesssim 2\%$ in all others. If the boundary condition is removed entirely, we find $\delta\kappa_\lambda \lesssim 37\%$ at 68% CL in the least symmetric case, demonstrating the stability of our fit.

Restoring the boundary condition and examining the two least symmetric cases $U(2)^5$ and $U(2)_{q,u,d}^3 \times U(1)_{e,\mu,\tau}^3$, we find the most poorly constrained directions involve four-fermion operators with all third-generation fields that do not enter single-Higgs production at NLO, namely $Q_{qd}^{(1)}, Q_{ud}^{(1)}, Q_{qu}^{(1)}, Q_{qu}^{(8)}, Q_{ld}, Q_{ed}, Q_{eu}, Q_{lu}$, which have poorly lifted flat directions in our datasets. Of the operators entering in single-Higgs production, the weakest constraints are on the top Yukawa and EW vertex correction $[C_{uH}]_{33}, [C_{Hu}]_{33} \lesssim 1/(900 \text{ GeV})^2$ at 95% CL. While $eett$ operators are allowed the most variation of the semi-leptonics, they are overall well constrained in our fit—the weakest bounds are $[C_{leu}]_{1133} \lesssim 1/(1.4 \text{ TeV})^2$ at 95% CL. This is because a flat direction in $\sigma(e^+e^- \rightarrow t\bar{t})$ at 365 GeV is broken by the A_{fb}^t as well as the large NLO contribution of these operators to EWPO proportional to $y_t^2 N_c$.

Implications for BSM models—We now discuss the implications of our results in the context of explicit BSM scenarios. Interestingly, Table III shows that the sensitivity in the $U(2)^5$ scenario can become better than $U(3)^5$, $\delta\kappa_\lambda \lesssim 25\%$, if new physics is dominantly coupled to the third generation. This is the case for a large swathe of well-motivated new physics scenarios addressing the flavor

and/or EW hierarchy problems, such as flavor deconstructions [59–67], composite Higgs, and split-supersymmetric models. For example, the class of composite Higgs models where the top quark has a significant degree of compositeness as studied in Ref. [68] is well described by $U(2)^5$ with third-generation dominance.

In general, it seems difficult to construct explicit models naturally yielding sizeable Higgs self-coupling modifications without introducing correlated effects in other better constrained operators [69,70]. Roughly speaking, a one-loop hierarchy is allowed without fine-tuning, which is best exemplified by the custodial quadruplet model generating only Q_H at tree level [69]. The full one-loop SMEFT matching was given in Ref. [32], which generates $Q_{H\Box}$, operators corresponding to the EW $\hat{W}$ and $\hat{Y}$ parameters, and Q_{uH}, Q_{dH}, Q_{eH} proportional to their respective SM Yukawa couplings. The model thus inherits the same flavor structure as the SM Yukawas, making it well described by all our flavor symmetries except $U(3)^5$; one may therefore expect a sensitivity of at least $\delta\kappa_\lambda \lesssim 25\%$ at FCC-ee.

Even in this model designed to only generate Q_H at tree level, the loop-generated operators lead indirectly to comparable or better constraints on $\delta\kappa_\lambda$ than those coming from Q_H , both at HL-LHC and FCC-ee. In the HL-LHC case, there is comparable sensitivity in $H \rightarrow b\bar{b}$ decays modified at one loop by Q_{dH} , while in the case of FCC-ee the best constraint comes from the large RG mixing of $Q_{H\Box}$ into the custodial-violating operator Q_{HD} corresponding to the $\hat{T}$ parameter [32]. As these operators are fully correlated with Q_H within this model, measurements of these observables would constrain the model parameters to corresponding limits of $\delta\kappa_\lambda \lesssim 40\%$ (HL-LHC) and $\delta\kappa_\lambda \lesssim 14\%$ (FCC-ee), which are similar or better than their respective single-operator sensitivity on Q_H in both cases. This example does not provide a no-go theorem—large Higgs self-coupling modifications with suppressed effects elsewhere may still be possible in certain BSM models.

Outlook and conclusions—The LHC has opened a new frontier to the Higgs sector and TeV scale that we have barely begun to explore. Many open questions surround the Higgs. Is it elementary or composite? What generates its potential and Yukawa couplings? What stabilizes the electroweak scale against quantum corrections? Was the electroweak phase transition first order? Are there any other particles that get most of their mass from the Higgs? Is the electroweak vacuum metastable? At what scale is it destabilized?

All these fundamental questions and many more can be explored at a next-generation Higgs factory. In particular, the Higgs self-coupling is a major target for future colliders. At FCC-ee, the NLO contribution of the Higgs self-coupling means that the marginalized sensitivity greatly benefits from the plethora of complementary measurements across FCC-ee, together with the HL-LHC and flavor sectors. In this Letter, we provided the first self-consistent

assessment of the indirect sensitivity to Higgs self-coupling modifications $\delta\kappa_\lambda$ at FCC-ee via a global SMEFT analysis, including all the leading NLO effects.

The large number of flavored operators at NLO are controlled by imposing various flavor symmetries that may be exhibited by new physics lying within reach of future colliders. These symmetries are realized in a wide class of well-motivated BSM models, including those deeply connected to the nature of the electroweak scale such as composite Higgs or supersymmetric models. In all cases, we found that FCC-ee can achieve a global sensitivity that is better than di-Higgs production at HL-LHC. It may considerably outperform the HL-LHC in constraining explicit models and for BSM physics exhibiting a Yukawa-like flavor structure dominantly coupled to the third generation, where we find a marginalized global sensitivity of $\delta\kappa_\lambda \lesssim 25\%$. FCC-ee can therefore reach an impactful level of sensitivity on the Higgs self-coupling [70]. This conclusion does not depend strongly on the particular flavor symmetry, as overall we find $\delta\kappa_\lambda \lesssim 30\%$. Moreover, the sensitivity can likely be improved further including observables such as $\sigma(ZH) \times \text{Br}(H \rightarrow b\bar{b})$ when the necessary NLO SMEFT contributions are calculated, as the self-coupling constraint could benefit from the improved precision in this channel (reaching the 10% level for a C_H -only fit) if the additional NLO operators can be controlled.

There is a clear consensus on a Higgs factory as the next step for particle physics [71,72]. The importance of complementary and interdependent measurements across all sectors of the standard model not directly related to the Higgs must also not be overlooked; in particular, the crucial role of a Tera-Z factory for exploring BSM physics at the tens of TeV scale has recently been emphasized, e.g., in Refs. [32,37,41,68,73–77]. As a Tera-Z, Higgs, and flavor factory, FCC-ee provides the most complete coverage of a broad range of particle physics phenomena, ranging from precision measurements at the Z/W pole, WW , ZH , and $t\bar{t}$ thresholds, followed by direct exploration of the high-energy frontier at FCC-hh that will ultimately probe the Higgs self-coupling at the percent level.

Note added—We recently became aware of Ref. [78], which also studies the sensitivity to the Higgs self-coupling at FCC-ee. The main differences seem to be (1) their analysis omits the majority of relevant semileptonic and four-lepton operators that are included in our global fit and cannot be neglected by the assumed symmetries; (2) while we use the inclusive ZH cross section, their limits are dominated by $\sigma(ZH) \times \text{Br}(H \rightarrow b\bar{b})$, which is expected to be measured with a higher precision of 0.21% vs 0.3% for the inclusive cross section. We conservatively chose the latter as the NLO SMEFT contributions to the inclusive cross section have been calculated and can be included for a fully self-consistent global analysis at NLO, whereas the

$\sigma(ZH) \times \text{Br}(H \rightarrow \bar{b}b)$ observable requires NLO SMEFT contributions to $\Gamma(H \rightarrow \bar{b}b)$ as well as to the total Higgs width, which are not included in Ref. [78].

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Data availability—The data are not publicly available. The data are available from the authors upon reasonable request.

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