

Complete Next-to-Leading-Order Standard-Model-Effective-Field-Theory Electroweak Corrections to Higgs Decays

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(Received 2 September 2025; revised 25 November 2025; accepted 18 December 2025; published 4 February 2026)

Precise predictions for Higgs decays are a crucial ingredient of the search for beyond the standard model physics and the standard model effective field theory (SMEFT) is a valuable tool for quantifying deviations from the standard model. We present the complete set of predictions for the two- and three-body Higgs decays at next-to-leading order, considering QCD and electroweak corrections and including all contributions from the dimension-6 SMEFT operators and with an arbitrary flavor structure. Including the next-to-leading-order SMEFT results for Higgs decays greatly increases the sensitivity to beyond the standard model physics of the $e^+e^- \rightarrow Zh$ process at FCC-ee, as compared with that obtained using only the total cross section.

DOI: 10.1103/2wqp-5zfm

Introduction—The study of Higgs properties is central to current and future collider experiments and at the present time measurements of Higgs production and decay are in excellent agreement with theoretical predictions at the LHC. Deviations from the standard model (SM) can be parametrized in terms of the standard model effective field theory (SMEFT) [1], in which the Lagrangian is expanded in terms of higher dimension operators whose effects are suppressed by powers of a large new physics scale, Λ . The SMEFT provides a consistent and model-independent framework to combine results from diverse datasets within global fits and to obtain limits on physics beyond the SM at high scales. The global fits typically include LHC data, Z and W pole observables, and diboson production both at the LHC and LEP [2–5].

Global fits in the context of the SMEFT often are performed using next-to-leading order (NLO) QCD calculations that can be automated [6,7], while NLO electroweak (EW) corrections must be computed on a case by case

basis. The complete set of NLO EW SMEFT calculations needed for the global fits does not exist, and here we present an important step in this direction. We compute the NLO EW and QCD corrections for all two- and three-body Higgs decays. Using the narrow-width approximation and previously computed NLO EW SMEFT results for Z and W decays [8,9], the Higgs decay rates to four-fermion final states that are accurate to NLO in the dimension-6 SMEFT are obtained. The impact of these corrections is illustrated for the Higgstrahlung process, $e^+e^- \rightarrow Zh$, at the future FCC-ee collider [10,11]. (The sensitivity at the future Circular Electron Positron Collider will be similar, but we have not optimized for polarization, which could increase the sensitivity [12].) The sensitivity from a measurement of the total cross section has been previously presented [13,14] and here we demonstrate the impressive improvement in accuracy when the NLO SMEFT corrections for the Higgs decays are included using the narrow-width approximation.

SMEFT NLO calculation—The dimension-6 SMEFT Lagrangian is defined as an $SU(3) \times SU(2) \times U(1)$ gauge invariant expansion around the SM,

$$L = L_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} O_i + \dots, \quad (1)$$

where the operators O_i contain only SM fields, Λ is the scale of new physics, and all information about beyond the SM physics resides in the coefficient functions, C_i . We use the Warsaw basis [15] to define the dimension-6 operators

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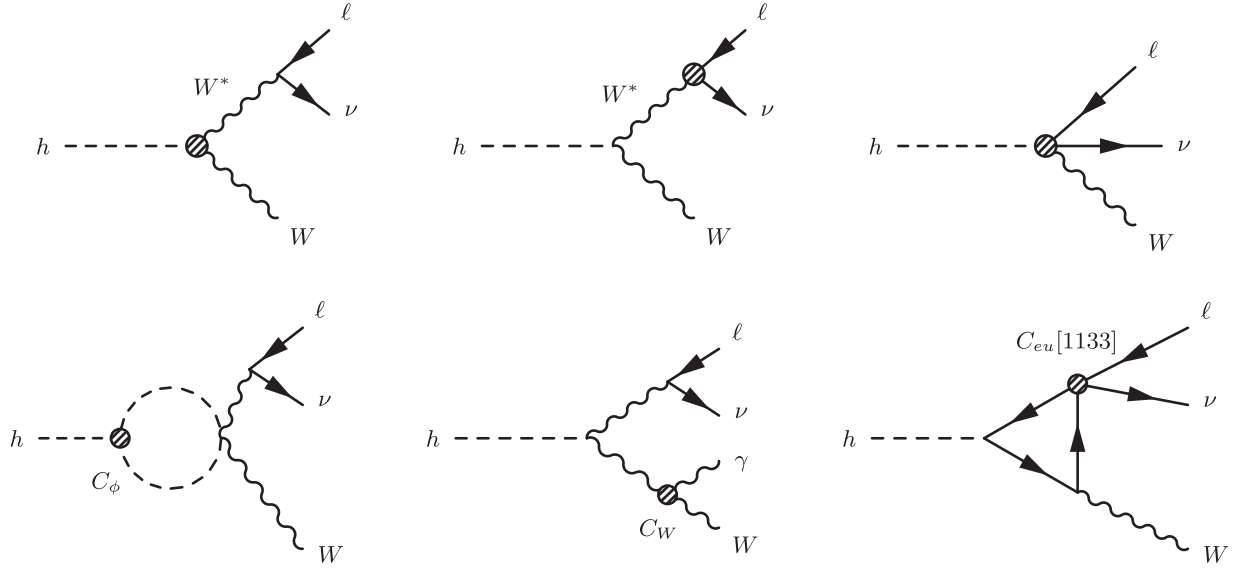


FIG. 1. Top: diagrams contributing to $h \rightarrow Wl\nu$ at leading order in the dimension-6 SMEFT. Bottom: representative virtual and real emission diagrams from SMEFT dimension-6 operators that first arise at one loop. The circles represent dimension-6 SMEFT insertions.

and make no flavor assumptions other than that the Cabibbo-Kobayashi-Maskawa matrix be diagonal.

We compute the complete set of two- and three-body processes that are relevant for Higgs decays at NLO EW and NLO QCD in the dimension-6 SMEFT and truncate the SMEFT expansion at $1/\Lambda^2$. The processes that we include are $h \rightarrow f\bar{f}$; $h \rightarrow Zf\bar{f}$; $h \rightarrow Wf\bar{f}'$; $h \rightarrow gg$, $h \rightarrow \gamma\gamma$, $h \rightarrow \gamma Z$; and $h \rightarrow Zgg$, where $f = e, \mu, \tau, u, d, s, c, b$. The NLO SMEFT corrections to $h \rightarrow f\bar{f}$ can be found in [16–18], and those for $h \rightarrow Ze^+e^-$ and $h \rightarrow Z\mu^+\mu^-$ in [19]. The Higgs decays to two gauge bosons, $\gamma\gamma$ [20–22], γZ [23,24], and gg [25,26] are known to one-loop accuracy. The result for $h \rightarrow Zgg$ can be found from [27].

The NLO dimension-6 SMEFT calculations of $h \rightarrow Wf\bar{f}'$ and of the quark contribution to $h \rightarrow Zf\bar{f}$ are new results of this Letter. As an example, we show in the first row of Fig. 1 the relevant leading-order diagrams for the calculation of the $h \rightarrow Wl\nu$ process, while we present some sample NLO diagrams in the second row. In particular, at NLO we have many additional operators that contribute, such as the Higgs trilinear vertex and four-fermion top quark operators, entering the virtual corrections (first and third diagram), as well as new contributions to the real photon emission, e.g., the triple gauge boson vertex (in the middle).

We take as input parameters G_μ , M_W , and M_Z and use a hybrid scheme where the coefficient functions C_i are renormalized in the $\overline{\text{MS}}$ scheme [28–30] while SM parameters are defined on-shell. The SMEFT relation between G_μ and the Higgs vacuum expectation value can be found in the appendix of Ref. [23]. We use dimensional regularization to treat infrared divergences in the virtual diagrams and dipole subtraction for the corrections from real photon and gluon emission [31].

The complete set of NLO EW and QCD results for the dimension-6 Higgs decays have been implemented in a flexible Monte Carlo code, which gives as outputs the complete NLO SMEFT decay width for the Higgs boson, Γ_{tot} , and all branching ratios for the two- and three-body decays, along with differential distributions for the three-body decays. The code will be documented in a forthcoming paper. A result that is consistent to LO can be found by computing the widths for Higgs decays, $h \rightarrow (f_1\bar{f}_2)(f_3\bar{f}_4)$, exactly without using the narrow-width approximation and employing the complex-mass scheme to treat the off-shell W/Z bosons in a gauge-invariant way. An NLO accurate result for Higgs decays to the experimentally measured four-fermion final states can be found consistently by using the narrow-width approximation,

$$\Gamma_{\text{NLO}}(h \rightarrow (f_1\bar{f}_2)(f_3\bar{f}_4)) = \Gamma(h \rightarrow Vf_1\bar{f}_2) \frac{\Gamma(V \rightarrow f_3\bar{f}_4)}{\Gamma(V \rightarrow \text{all})}, \quad (2)$$

where $V = W, Z$. The NLO EW and QCD results for Z and W decays are in [8,32] and the result of Eq. (2) must be expanded consistently to $\mathcal{O}(1/\Lambda^2)$ [19].

We present our results by combining Higgs production and decay in the narrow-width approximation,

$$\sigma(e^+e^- \rightarrow ZXX) = \sigma(e^+e^- \rightarrow Zh) \frac{\Gamma(h \rightarrow XX)}{\Gamma(h \rightarrow \text{all})}, \quad (3)$$

where XX stands for any of the channels listed above, either two- or three-body decays.

Results—As inputs, we take $m_H = 125.1$ GeV, $m_t = 172.5$ GeV, $m_b = 4.92$ GeV, $M_W^{\text{exp}} = 80.379$ GeV, and

$M_Z^{\text{exp}} = 91.1876$ GeV. The vector boson masses, M_W and M_Z , are defined following [33,34], as we adopt the complex-mass scheme for the treatment of finite width effects in the $h \rightarrow \bar{f}f$ decays [35],

$$M_Z = \frac{M_Z^{\text{exp}}}{\sqrt{1 + (\Gamma_Z^{\text{exp}}/M_Z^{\text{exp}})^2}} = 91.1535 \text{ GeV},$$

$$M_W = \frac{M_W^{\text{exp}}}{\sqrt{1 + (\Gamma_W^{\text{exp}}/M_W^{\text{exp}})^2}} = 80.352 \text{ GeV}. \quad (4)$$

$$\frac{\Gamma_{\text{tot}}(h \rightarrow \text{all})}{\Gamma_{\text{tot}}(h \rightarrow \text{all})_{\text{SM}}} = 1 - 0.0352C_{\phi B} + 0.126C_{\phi \square} - 0.0303C_{\phi D} + 1.62C_{\phi G} - 0.0353C_{\phi W} + 0.0287C_{\phi WB}$$

$$- 0.0223C_{dG}[33] - 4.46C_{d\phi}[33] + 0.19C_{dW}[33] - 0.588C_{e\phi}[33] - 0.0103C_{lequ}^{(1)}[3333] + 0.071C_{ll}[1111]$$

$$- 0.149C_{\phi l}^{(3)}[11] - 0.0118C_{\phi ud}[33] - 0.0333C_{qu}^{(1)}[1331] - 0.0444C_{qu}^{(8)}[1331] + 0.0988C_{quqd}^{(1)}[3333]$$

$$+ 0.0188C_{quqd}^{(8)}[3333] - 0.0355C_{uG}[33] + 0.00148C_{\phi}, \quad (5)$$

where we have adopted the $U(2)^5$ symmetric limit and neglected coefficients smaller than 10^{-2} , with the exception of C_{ϕ} , which is phenomenologically relevant, for the sake of compactness. The operators with the small coefficients are predominantly the two- and four-fermion operators not involving the top quark. The indices in square brackets are flavor indices, and we have taken $\Lambda = 1$ TeV. Numerical values for the coefficients of all dimension-6 operators that contribute, without the $U(2)^5$ flavor assumption, are given in Supplemental Material [37].

At an e^+e^- collider, we can perform a consistent study including NLO SMEFT effects in both production and decay. The dependence of precise measurements of the Higgstrahlung cross section on variations of the SMEFT coefficients at NLO was found in [13,14]. The sensitivity to SMEFT operators can be improved significantly by tagging the Higgs decays and incorporating the NLO results also for the decays. The projected FCC-ee sensitivities for the various Higgs decay channels are given in Table I [38].

We present the correlations between constraints on different coefficient functions, obtained by combining production and decay, in Figs. 2–4. For each plot, we set all but the displayed coefficients to 0. The left panel of Fig. 2 shows the sensitivity to $C_{u\phi}[3,3]$ and C_{ϕ} . We consider the $e^+e^- \rightarrow Zh$ production channel at 240 GeV, assuming a 0.5% accuracy on the FCC-ee cross section measurement for this process, and compare the sensitivity curve for production only (in gray) with the one obtained by taking into account also the Higgs decays (in red). The main contribution comes from the $b\bar{b}$ and gg channels, which allow us to significantly constrain C_{ϕ} and $C_{u\phi}[3,3]$, respectively. In the right panel one can see the limits on C_W and $C_{\phi D}$. Adding the information on SMEFT effects from

Corrections to (4) in the SMEFT are suppressed by terms of $\mathcal{O}(CM_Z\Gamma_Z/\Lambda^2)$, which we consistently neglect. With these inputs, we compute the total Higgs width at NLO (our tree level widths agree with those of [36]) and all Higgs branching ratios for the processes listed above to NLO electroweak and QCD order in the dimension-6 SMEFT. In this Letter we have fixed the renormalization scale at $\mu = m_H$.

We report here the expression for the Higgs total width,

the Higgs decays, in particular the $h \rightarrow WW^*$ contribution calculated here for the first time offers a sensitive tool to constrain new physics [39].

Figure 3 shows the sensitivity curves obtained by combining Higgstrahlung production, followed by the Higgs decay, at two center-of-mass energies, $\sqrt{s} = 240$ GeV and $\sqrt{s} = 365$ GeV. We assume uncertainties of 0.5% and 1% on the FCC-ee measurement of the $e^+e^- \rightarrow Zh$ cross section at $\sqrt{s} = 240$ GeV and $\sqrt{s} = 365$ GeV, respectively. The reason for considering two energy runs to gain constraining power on $C_{eu}[1,1,3,3]$ and $C_{\phi u}[3,3]$ has been demonstrated in [13,14]. On the left-hand side, we present the correlation between limits on $C_{eu}[1,1,3,3]$ and C_{ϕ} . A key role is played by $h \rightarrow b\bar{b}$. The run at $\sqrt{s} = 240$ GeV is crucial to constrain C_{ϕ} , as also shown in Fig. 2, while the

TABLE I. Uncertainty in % on Higgstrahlung measurements that include Higgs decays at FCC-ee with 10.8 ab^{-1} (3.12 ab^{-1}) at $\sqrt{s} = 240$ GeV ($\sqrt{s} = 365$ GeV) [38].

	$\sqrt{s} = 240$ GeV	$\sqrt{s} = 365$ GeV
$b\bar{b}$	0.21	0.38
$c\bar{c}$	1.6	2.9
$s\bar{s}$	120	350
gg	0.8	2.1
$\tau^+\tau^-$	0.58	1.2
$\mu^+\mu^-$	11	25
WW^*	0.8	1.8
ZZ^*	2.5	8.3
$\gamma\gamma$	3.6	13
$Z\gamma$	11.8	22

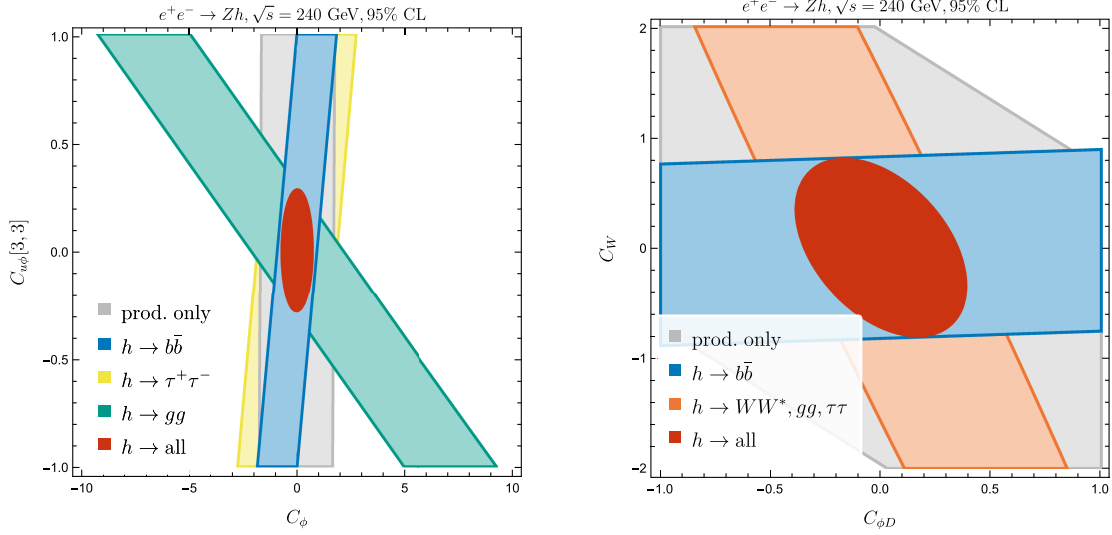


FIG. 2. Left: 95% confidence level sensitivity to $C_{u\phi}[3,3]$ and C_ϕ assuming $\Lambda = 1 \text{ TeV}$. The gray band assumes a 0.5% measurement of the total Higgstrahlung cross section, while the other bands assume the precision on the Higgs decays given in Table I. The red circle includes all measured Higgs decays. Right: bounds on C_W and $C_{\phi D}$.

result at $\sqrt{s} = 365 \text{ GeV}$ allows us to put significant limits on $C_{eu}[1, 1, 3, 3]$.

The right panel shows the bounds for the coefficients $C_{u\phi}[3,3]$ and $C_{\phi u}[3,3]$. The $h \rightarrow gg$ channel at $\sqrt{s} = 240 \text{ GeV}$ constrains $C_{u\phi}[3,3]$, as pointed out also in Fig. 2, while $h \rightarrow b\bar{b}$ at $\sqrt{s} = 365 \text{ GeV}$ offers complementary information to derive the bounds on $C_{\phi u}$. The limits on both sets of coefficients are greatly improved as compared to Fig. 3 of Ref. [13], which considers SMEFT NLO effects in the total rate for $e^+e^- \rightarrow Zh$ only.

Finally, in Fig. 4 we see the sensitivity to $C_{\phi D}$ and C_ϕ on the left-hand side and to δ_Z and κ_λ on the right-hand side. We can reinterpret our linear dimension-6 SMEFT

calculation in terms of the parameters δ_Z and κ_λ , which are widely used [27,38,40–42] to describe new physics effects in the hZZ/hWW couplings and the Higgs self-interaction, via the relations [14]

$$\begin{aligned} \delta_Z &= \frac{1}{4} \frac{v^2}{\Lambda^2} (C_{\phi D} + 4C_{\phi\Box}) \\ \delta\kappa_\lambda &= \frac{v^2}{\Lambda^2} \left(3 \left[\frac{C_{\phi D}}{4} - C_{\phi\Box} \right] - 2 \frac{v^2}{m_H^2} C_\phi \right). \end{aligned} \quad (6)$$

Including the Higgs decays at NLO, especially in the $h \rightarrow b\bar{b}$ and $h \rightarrow WW^*$ channels, is crucial for constraining the Higgs coupling to vector bosons and the Higgs trilinear

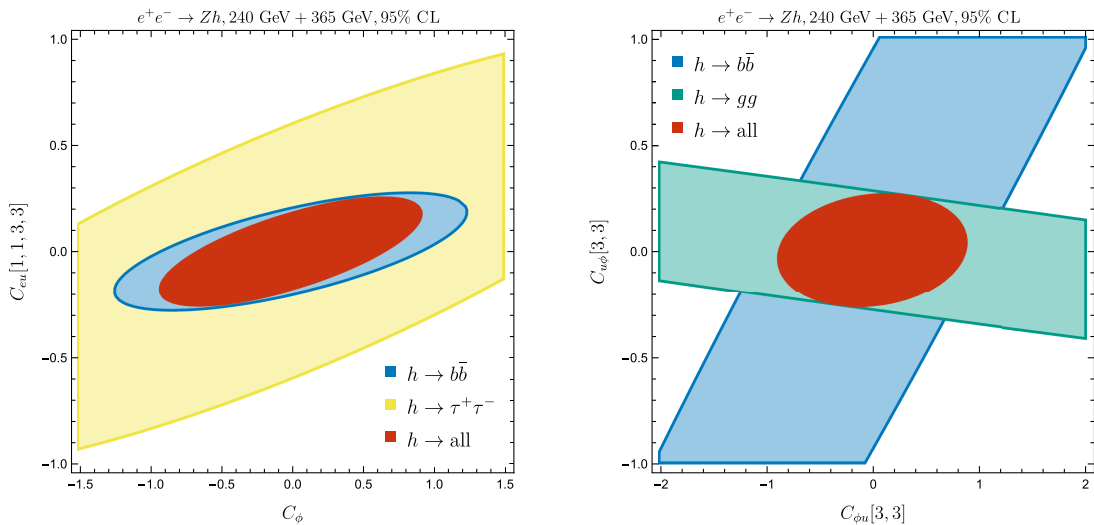


FIG. 3. Left: 95% confidence level limits on $C_{eu}[1, 1, 3, 3]$ and C_ϕ . Right: sensitivity to $C_{u\phi}[3,3]$ and $C_{\phi u}[3,3]$. We combine Higgstrahlung production at two energies, $\sqrt{s} = 240 \text{ GeV}$ and $\sqrt{s} = 365 \text{ GeV}$.

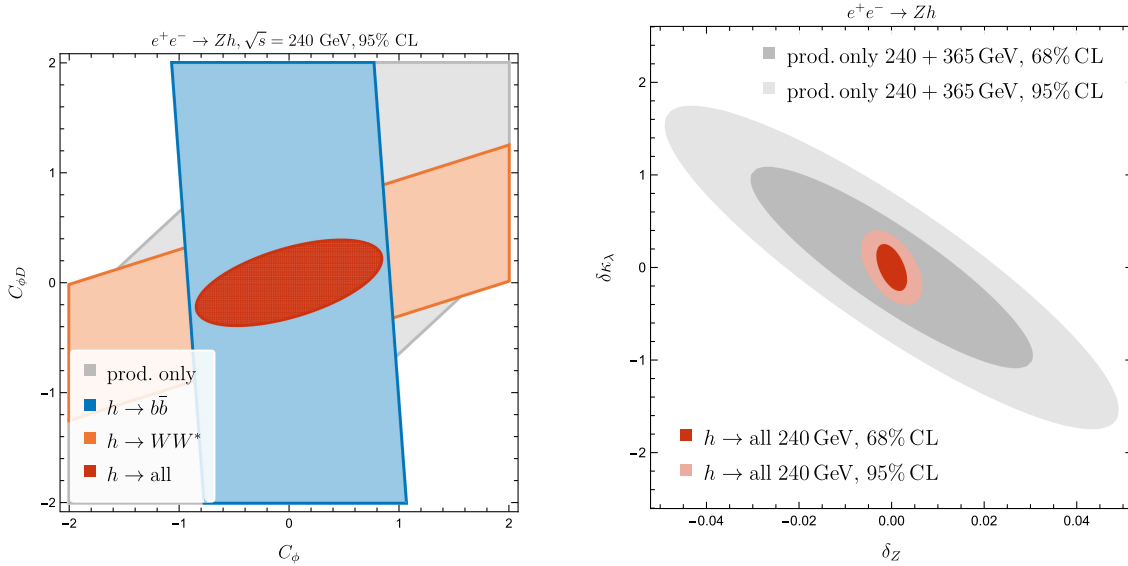


FIG. 4. Bounds on coefficients contributing to hZZ/hWW and trilinear couplings. Left: SMEFT calculation in terms of $C_{\phi D}$ and C_{ϕ} . Right: interpretation in the framework that makes use of the parameters δ_Z and $\delta\kappa_{\lambda}$ computed to linear order, with $C_{\phi\Box}$ set to 0.

interaction and significantly improves the limits with respect to those from production alone, already in the 240 GeV run, as seen on the left-hand side of Fig. 4. On the right-hand side, we combine the information from $\sqrt{s} = 240$ GeV and $\sqrt{s} = 365$ GeV obtained by considering only the production process (gray ellipses). Lighter colors correspond to 95% CL and darker ones to 68% CL. Without the data from the Higgs decays, it is necessary to run at two energies in order to obtain a constraint. The red circles in the right-hand panel of Fig. 4 correspond to the information from $\sqrt{s} = 240$ GeV, including the decays, and we see a significant improvement over the gray ellipses with just the run at a single energy.

Conclusions—The understanding of Higgs interactions at a precise level is central to the goals of future colliders. We have accomplished an important milestone in this program with the complete NLO EW plus QCD SMEFT dimension-6 calculation for all two- and three-body Higgs decays, computing for the first time the complete NLO EW results for $h \rightarrow WW^*$ and $h \rightarrow ZZ^*$, including all decay channels. At the LHC, not all relevant Higgs production processes are known at NLO EW order for the SMEFT. At future circular colliders, however, we have studied the process $e^+e^- \rightarrow Zh, h \rightarrow \text{all}$. Our results allow for a consistent NLO fit to production and decay and we find that including both production and decay significantly improves the limits on the SMEFT coefficients from those obtained using only the total rate for $e^+e^- \rightarrow Zh$. In particular, the extraction at FCC-ee of C_{ϕ} , which impacts the Higgs trilinear coupling, is strengthened by including our results for the NLO SMEFT Higgs decays. The impact of the Higgs decay information on the extraction of the Higgs trilinear coupling was anticipated in the single parameter fit

of [43]. Without the information from the Higgs decay, separating the effects of C_{ϕ} from other coefficients requires measurements at two different energies, while here we have explicitly shown how including the Higgs decays allows to significantly improve the sensitivity to C_{ϕ} in a single energy run.

Both analytic and numerical results for the Higgs decays at NLO discussed here will be presented in a forthcoming paper, along with the flexible Monte Carlo code used to generate the plots in this Letter.

Acknowledgments—S. D. and C. D. P. are supported by the U.S. Department of Energy under Contract No. DE-SC0012704. P. P. G. is supported by the Ramón y Cajal grant RYC2022-038517-I funded by MCIN/AEI/10.13039/501100011033 and by FSE+, and by the Spanish Research Agency (Agencia Estatal de Investigación) through the grant IFT Centro de Excelencia Severo Ochoa No. CEX2020-001007-S. The work of L. B. is supported in part by the U.S. Department of Energy under Grant No. DE-SC0010102 and by the College of Arts and Sciences of Florida State University. L. B. thanks the Technische Universität München (TUM) for the hospitality and the Excellence Cluster ORIGINS, which is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany’s Excellence Strategy—EXC-2094—390783311 for partial support during the completion of this work. The work of M. F. is supported by the U.S. National Science Foundation Grant No. PHY-2210533.

Data availability—The data that support the findings of this article are openly available [44].

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