

## Learning from Higgs Physics at Future Higgs Factories postprint

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### Abstract

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### Full Text

## Preamble

### Learning from Higgs Physics at Future Higgs Factories

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**Abstract:** Future Higgs factories can achieve impressive precision on Higgs property measurements. In this paper, instead of the conventional focus on Higgs precision in certain interaction bases, we explore its sensitivity to new physics models at electron-positron colliders. In particular, we study two categories of new physics models: Standard Model (SM) with a real scalar singlet extension, and Two Higgs Doublet Model (2HDM) as examples of weakly-interacting models; Minimal Composite Higgs Model (MCHM) and three typical patterns of the more general operator counting for strong interacting models as examples of strong dynamics. We perform a global fit to various Higgs search channels to obtain the 95% C.L. constraints on the model parameter space. In the SM with a singlet extension, we obtain limits on the singlet-doublet mixing angle  $\sin \theta$ , as well as the more general Wilson coefficients of the induced higher dimensional operators. In the 2HDM, we analyze tree-level effects in the  $\tan \beta$  vs.  $\cos(\beta - \alpha)$  plane, as well as the one-loop contributions from the heavy Higgs bosons in the alignment limit to obtain constraints on heavy Higgs masses for different types of 2HDM. In strong dynamics models, we obtain lower limits on the strong dynamics scale. In addition, once deviations of Higgs couplings are observed, they can be used to distinguish different models. We also compare the sensitivity of various future Higgs factories, namely Circular Electron Positron Collider (CEPC), Future Circular Collider (FCC)-ee, and International Linear Collider (ILC).

**Keywords:** Higgs Precision Measurements, 2HDM, Composite Higgs Models.

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## ## 1 Introduction

The discovery of a Standard Model (SM)-like Higgs boson at the Large Hadron Collider (LHC) strongly motivates studies of its properties. Lepton colliders running at center-of-mass energies of around 240 GeV or above are ideal Higgs factory machines for precision studies of the Higgs boson. Several plans for future lepton colliders, in particular Higgs factories, have been proposed, including the

Circular Electron Positron Collider (CEPC) in China [1], the electron-positron stage of the Future Circular Collider (FCC-ee) at CERN (previously known as TLEP [2]), and the International Linear Collider (ILC) in Japan [3].

Through the Higgsstrahlung process,  $e^+e^- \rightarrow hZ$ , Higgs cross sections can be measured to astonishing precision: about 0.2%–0.5% for the “inclusive”  $e^+e^- \rightarrow hZ$  cross section and  $e^+e^- \rightarrow hZ$ ,  $h \rightarrow b\bar{b}$  exclusive cross section, and about a few percent for many other exclusive cross sections, under typical running scenarios. The Compact Linear Collider (CLIC), while only planning to run at energies of 350 GeV and above, could also probe Higgs couplings very well by measuring the WW fusion process at high energies [4, 5], as well as measuring the top Yukawa and triple Higgs couplings. These colliders provide exciting opportunities in Higgs studies and will greatly improve our understanding of physics at the TeV scale.

Any deviation of Higgs couplings from their SM predictions is a strong indication of new physics beyond the SM. Even if no deviation is observed, it will provide tight constraints on new physics models. In studies of Higgs boson properties and the sensitivity of Higgs precision measurements to new physics, two “model-independent” approaches are usually taken. One is the so-called “kappa” framework, in which  $\kappa$  is defined as the Higgs coupling to SM particles, normalized to its SM value. The kappa framework features a simple and direct connection to measurable cross sections and straightforward inclusion of new light degrees of freedom beyond the SM, such as exotic Higgs decays [6–8]. Deviation of  $\kappa$  from their SM expectation indicates contributions from new physics [9–20]. Another approach using the language of the Standard Model Effective Field Theory (SMEFT) for Higgs couplings has also been extensively studied, both at the LHC and at future colliders [21–36]. The fitting parameters are the coefficients of various higher-dimensional operators. For both approaches, global fits to the SM observed values of  $\sigma \times \text{BR}$  for various Higgs search channels are usually performed to obtain robust constraints and correlations on couplings in the kappa framework, or Wilson coefficients in the EFT framework. These fitting results are then further used to impose constraints on parameter spaces of specific models when model parameters are mapped to either those couplings or Wilson coefficients.

Such model-independent approaches are very useful for evaluating measurement performance and providing general constraints on new physics models. However, they have certain disadvantages. The precision reaches of global fits in such approaches usually suffer from large degeneracy among fitting parameters. For specific models, the parameter space is usually much smaller, with various Higgs couplings determined by a small set of parameters. Furthermore, while coupling fit results are provided in official documents for each collider, the corresponding correlation matrix is often not provided. For poorly determined quantities, linear approximation might not be sufficient. Directly applying these coupling fitting results alone to specific models without including the correlation matrix may result in overly conservative estimations. A specific example of this is shown

later in Section 5. Moreover, in most model-independent approaches, certain model assumptions and simplifications are usually made, which may not be valid for particular new physics models. Typical examples are the omission of Higgs couplings with Lorentz structures different from SM ones (e.g.,  $hZ Z$  vs. the SM  $hZ Z$ ) in the kappa framework, or the absence of possible light beyond-the-SM (BSM) states in SMEFT. The latter may also lead to Higgs exotic decays, which are hard to study in a model-independent way, while many appealing BSM scenarios with light states can be sufficiently probed at  $e^-e^+$  colliders [7]. These disadvantages severely limit the usefulness of model-independent methods when applied to specific BSM models.

To demonstrate the sensitivity of Higgs factories to BSM new physics models and assess the capability of various machine options, it is thus important to directly study the implications of Higgs precision measurements on model parameter space. We focus on a few generic types of new physics models in our study. For weakly coupled models, we use the SM plus a real scalar singlet and Two Higgs Doublet Model (2HDM) as two prototypes, which are incorporated as the Higgs sector for many BSM scenarios such as supersymmetric models and left-right symmetric models. In particular, we study tree-level effects in the general case, as well as one-loop contributions from heavy Higgs bosons. For models with strong dynamics, we study the Minimal Composite Higgs Model (MCHM), including all ten different fermion embeddings, as well as three typical patterns of more generic operator counting for strong interacting models with a light Higgs. With these two classes of Higgs extension models covering both weakly interacting theories and strong dynamics, we can develop a better understanding of the physics potential of future Higgs factories.

We perform a global fit to various Higgs search channels in these two classes of specific models. In the case of no deviations observed in future Higgs factories, a 95% C.L. constrained parameter space is obtained. For the SM with a singlet extension, we obtain limits on the singlet-doublet mixing angle  $\sin \alpha$ , as well as the more general Wilson coefficients of the induced higher-dimensional operators. For 2HDM tree-level effects, the analysis shows how much deviation from the alignment limit can be tolerated. For loop effects under the alignment limit, a constrained range of heavy Higgs masses can be obtained. In the MCHM, we translate Higgs precision measurements into constraints on the vacuum misalignment parameter  $\beta$ , which further constrains the composite scale  $f$ . In the three cases of strong interacting models with a light Higgs, we obtain lower limits on the strong dynamics scale  $m^*$  as a function of the strong interaction coupling  $g^*$ . In cases of observed deviation of SM Higgs couplings, our studies also demonstrate how to distinguish different models.

While our analyses mostly use CEPC results, comparison with the reach of FCC-ee and ILC is also performed. Run-I, Run-II, and high-luminosity LHC Higgs precision measurements are included as well. We also compare the sensitivity of fitting using  $\Delta(\sigma \times \text{BR})/(\sigma \times \text{BR})_{\text{SM}}$  of various Higgs search channels directly with fitting results using constraints on effective couplings from existing

studies.

The rest of this paper is organized as follows. In Section 2 we summarize the run scenarios and estimated precisions of Higgs measurements for various future lepton collider Higgs factories, gathered from corresponding official documents. These inputs are used to obtain constraints in model parameter spaces. In Section 3, we present the global fitting method used in our analyses. In Section 4, we start with the simple case of the SM plus a singlet as a warm-up. The results for Two Higgs Doublet Models are presented in Section 5 and the results for Composite Higgs Models are presented in Section 6. We conclude in Section 7. The LHC Run-I Higgs measurement results and projected precisions for future LHC runs are collected in Appendix A. We also list the formulae of loop corrections to various Higgs couplings in the 2HDM along the alignment limit in Appendix B.

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## ## 2 The Higgs Precision Measurements at Future Lepton Colliders

At future lepton colliders, the dominant channel to measure Higgs boson properties is the Higgsstrahlung process,  $e^+e^- \rightarrow hZ$ , at center-of-mass energies of around 240–250 GeV. Due to the nature of lepton colliders, both the inclusive cross section  $\sigma(hZ)$  and exclusive ones for different Higgs decays in terms of  $\sigma(hZ) \times \text{BR}$  can be measured to remarkable precisions. The invisible decay width of the Higgs can also be very well constrained. In addition, the cross section of the WW fusion process for Higgs production grows with energy. While it cannot be measured very well at 240–250 GeV, at higher center-of-mass energies (particularly at linear colliders), such fusion processes become significantly more important and can provide crucial complementary information. For  $\sqrt{s} > 500$  GeV,  $t\bar{t}h$  production can also be used.

**Table 1.** Estimated statistical precisions for Higgs measurements obtained at the proposed CEPC program with  $5 \text{ ab}^{-1}$  integrated luminosity [1], FCC-ee program with  $10 \text{ ab}^{-1}$  integrated luminosity [2], and ILC with various center-of-mass energies [37].

To establish the baseline of our study, we list the run scenarios of various machines in terms of center-of-mass energy and corresponding integrated luminosity, as well as the estimated precisions of relevant Higgs measurements used in our global analyses:

- **CEPC:** According to the preCDR [1], CEPC plans to collect  $5 \text{ ab}^{-1}$  data at 240 GeV. The estimations for measurements of the Higgsstrahlung process  $e^+e^- \rightarrow hZ$  with various final states, as well as the WW fusion process with Higgs decaying to bottom pairs ( $e^+e^- \rightarrow \bar{\nu}h, h \rightarrow b\bar{b}$ ), are summarized in Table 1.
- **FCC-ee:** The FCC-ee CDR is expected to be finished by 2018 [38]. At present, the TLEP whitepaper [2] still provides the most updated estimations, which assume total luminosities of  $10 \text{ ab}^{-1}$  at 240 GeV and  $2.6 \text{ ab}^{-1}$

at 350 GeV. The estimations for  $e^+e^- \rightarrow hZ$  measurements at 240 GeV, as well as the  $h \rightarrow b\bar{b}$  channel in WW fusion, are listed in Table 1. Assuming statistical uncertainties only, Ref. [2] also estimated that the WW fusion process with  $h \rightarrow b\bar{b}$  can be measured to a precision of 0.6% at 350 GeV. We did not include the 350 GeV WW fusion process in our global fit since it has little impact on the constrained model parameter spaces considered in our study.

- **ILC:** The proposed run scenarios in the ILC TDR [3] have been updated in recent documents [37, 39], which suggest that the ILC could collect  $2 \text{ ab}^{-1}$  data at 250 GeV,  $200 \text{ fb}^{-1}$  at 350 GeV, and  $4 \text{ ab}^{-1}$  at 500 GeV. However, the estimations of signal strengths, summarized in Ref. [37], are only available for smaller benchmark luminosities for which full detector studies were performed. We took these estimations and scaled them up to the current run scenarios, assuming statistical uncertainties dominate [40]. The scaled estimations are summarized in Table 1. Such scaling provides a reasonable approximation as long as the luminosities are not excessively large and systematic uncertainties are under control.

With large center-of-mass energies up to 3 TeV, CLIC can also measure Higgs properties very well through the WW fusion process [4, 5]. On the other hand, with its extensive coverage of energy scales, the primary goal of CLIC is to directly search for new particles, particularly those coupled to SM particles only through electroweak interactions. CLIC is advantageous in its possibility of directly producing new particles that modify Higgs properties at low energy, and its large span of observables at different scales. Consequently, a study of CLIC physics potential for various models would require additional considerations beyond Higgs precision physics. A comprehensive study of CLIC physics potential including both direct and indirect searches of new physics is beyond the scope of this paper.

In our global fit to Higgs measurements, we only included rate information for the Higgsstrahlung and WW fusion processes. Measurements of angular distributions in the Higgsstrahlung process can provide important information in addition to rate measurements alone [29, 30]. The diboson process  $e^+e^- \rightarrow WW$  can be measured to great precision, imposing very strong constraints on anomalous triple gauge couplings (TGCs) [41–44]. These measurements are very helpful in probing new physics. In particular, Ref. [34] shows that inclusion of these measurements is crucial for constraining new physics in a global EFT framework, which exhibits large flat directions with Higgs rate measurements alone. However, their impacts are significantly smaller for specific models like the SM plus a singlet, 2HDM, and MCHM, due to a much smaller model parameter space (compared with SMEFT). Therefore, they were included in our global fit of operator approach for strong dynamics models only.

Electroweak (EW) precision measurements at the Z-pole also impose strong constraints on new physics [45, 46]. Current constraints from the Large Electron Positron Collider (LEP) could be significantly improved by a Z-pole run at any

future lepton collider. While these constraints were not explicitly considered in our study, we restricted ourselves to models with suppressed EW precision corrections (e.g., by imposing custodial symmetries) such that these constraints are automatically satisfied.

It is also important to compare the reaches of future Higgs factories to that of the LHC. For LHC Run-I Higgs measurements with  $5 \text{ fb}^{-1}$  integrated luminosity at  $\sqrt{s} = 7 \text{ TeV}$  and  $20 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$ , we used results from Ref. [47]. For the LHC with  $300 \text{ fb}^{-1}$  and  $3000 \text{ fb}^{-1}$  luminosities, we used ATLAS projections in Ref. [48], which collects information from several other studies. Detailed inputs are listed in Appendix A, with LHC Run-I results in Table 8 and ATLAS projections for LHC  $300 \text{ fb}^{-1}$  and  $3000 \text{ fb}^{-1}$  summarized in Table 9.

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### ### 3 Global Fit Framework

To translate estimated experimental measurement errors into constraints on model parameters, we performed a global fit by constructing  $\chi^2$  with the profile likelihood method:

$$\chi^2 = \sum_i \frac{(\mu_i^{\text{BSM}} - \mu_i^{\text{obs}})^2}{\sigma_{\mu_i}^2}, \quad \text{where} \quad \mu_i \equiv \frac{(\sigma \times \text{Br})^{\text{BSM}}}{(\sigma \times \text{Br})^{\text{SM}}}$$

Here  $\hat{\mu}_i^{\text{BSM}}$  for various Higgs search channels and  $\sigma_{\mu_i}$  is the experimental precision on a particular channel. We note that correlations among different  $\sigma \times \text{BR}$  are usually not provided and are thus assumed to be zero in the fits.  $\hat{\mu}_i^{\text{BSM}}$  is predicted in each specific model, depending on model parameters. For LHC Run-I, the measured  $\hat{\mu}_i^{\text{obs}}$  and corresponding  $\sigma_{\mu_i}$  are given in Table 8. In our analyses for future colliders,  $\hat{\mu}_i^{\text{obs}}$  are set to the SM value:  $\hat{\mu}_i^{\text{obs}} = 1$ , assuming no deviation from SM observables. The corresponding  $\sigma_{\mu_i}$  are the estimated errors for each process, as shown in Table 1 for CEPC, FCC-ee, ILC and Table 9 for the LHC. For ILC with three different center-of-mass energies, we summed contributions from each individual channel. For one- or two-parameter fits, the corresponding  $\Delta\chi^2 = \chi^2 - \chi^2_{\text{min}}$  for 95% C.L. is 3.84 or 5.99, respectively.

We fitted directly to signal strength  $\mu$ , rather than effective couplings  $\kappa$ . The latter are usually presented in most experimental papers. While using the  $\mu$ -framework is easy to map to specific models, unlike  $\kappa$ , various  $\mu$  are not independent experimental observables. Ultimately, fitting to either  $\mu$  or  $\kappa$  should give the same results if correlations between  $\mu$  are properly included. Those correlation matrices, however, are typically not provided. Therefore, fitting to  $\mu$  only, assuming they are uncorrelated, usually leads to more relaxed constraints. Comparison of  $\mu$ -fit versus  $\kappa$ -fit results is given later in the example of the 2HDM.

In the last example of our study for future collider constraints on generic strong dynamics, we adopted the fitting results in EFT coefficients given in Ref. [34]

since various scenarios can only be meaningfully discussed in power counting of the structure of induced EFT operators. EFT provides more complex and rich structure for Higgs couplings, which requires inclusion of additional measurements to ensure parameters are reasonably well-constrained. In particular, diboson process ( $e^+e^- \rightarrow WW$ ) and angular observables in  $e^+e^- \rightarrow hZ$  were included in the global fit in addition to Higgs rate measurements. In the EFT framework, <sup>2</sup> from Higgs rate measurements and other measurements can be constructed similarly as Eq. (3.1), with  $\hat{\{BSM\}}$  being a function of EFT parameters (i.e., Wilson coefficients).

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#### ## 4 SM with a Real Singlet Extension

We first applied this global fit to the simplest extension of the SM with a real scalar singlet. The general Lagrangian for this model is:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \Lambda_{SH} S(H^\dagger H) - \frac{1}{2}\lambda_{SH} S^2(H^\dagger H) - \Lambda_S S^3 - \lambda_S S^4,$$

where  $H$  is the SM Higgs doublet and  $S$  is the new real singlet field.

This simplest extension of the SM can already induce many test scenarios. Such a model is of particular interest as it can generally help enhance the electroweak phase transition to be a strong first-order one [49], which is needed for electroweak baryogenesis. With certain constraints on model parameters, it is also a good description of the scalar sector for the next-to-minimal supersymmetric Standard Model [50, 51] in the decoupling regime.

The Lagrangian given in Eq. (4.1) can be categorized into two scenarios:  $Z_2$ -preserving and  $Z_2$ -breaking. In the  $Z_2$ -preserving scenario, the Lagrangian is further simplified:  $\Lambda_{SH} = \Lambda_S = 0$ , reducing the number of free parameters in this model to three. Note that in the  $Z_2$  limit, it is still possible to have spontaneous  $Z_2$  breaking once  $S$  acquires a vacuum expectation value (VEV), leaving the same number of terms for the interaction Lagrangian compared to the  $Z_2$ -breaking case, but still with only three free parameters. Since the purpose of this study is to focus on Higgs physics implications rather than extraction of singlet model parameters, we did not single out spontaneous  $Z_2$  breaking as a separate scenario.

The biggest difference between  $Z_2$ -preserving and  $Z_2$ -breaking is that the latter enables singlet-Higgs mixing. The 125 GeV Higgs is one of the mass eigenstates, which is a mixture of the real component of the SM doublet  $h_{\text{SM}}$  and the singlet  $S$ :

$$h_{125} = \cos\theta h_{\text{SM}} + \sin\theta S,$$

where  $\theta$  is the mixing angle. All SM-like Higgs couplings to other SM particles are scaled down by  $\cos\theta$  at tree level:  $g_{i\{SM+singlet\}} = g_{i\{SM\}} \cos\theta$ . Since  $\cos\theta$  does not exceed unity, modifications of Higgs couplings through mixing with the singlet always lead to a reduction of Higgs couplings to SM particles. This mixing angle description remains the same for both a light and heavy singlet-like scalar and is widely used due to its simplicity.

As the first and simplest application of the global fit, we applied it to the SM plus singlet model with the only fitting parameter being  $\sin\theta$ . The  $\Delta^2$  distribution is shown in the left panel of Fig. 1 [Figure 1: see original paper] for CEPC, ILC, and FCC-ee precisions. The mixing angle  $|\sin\theta|$  is constrained to be 0.062, 0.058, and 0.052 for CEPC, ILC, and FCC-ee, respectively, at 95% C.L.

While the mixing angle  $\sin\theta$  captures the most important tree-level effect for Higgs properties, it does not characterize changes to the Higgs trilinear coupling or loop corrections to Higgs physics from the singlet field [52]. To fully explore changes of SM Higgs properties in models with an extra real scalar singlet, we adopted the EFT language to examine all possible effects.

After integrating out the singlet field, the general EFT with dimension-six operators can be written as:

$$\mathcal{L}_{\text{EFT}} = \frac{c_H}{\Lambda^2} \mathcal{O}_H + \frac{c_6}{\Lambda^2} \mathcal{O}_6, \quad \text{with} \quad \mathcal{O}_H \equiv \frac{1}{2} (\partial_\mu |H^\dagger H|)^2, \quad \mathcal{O}_6 \equiv |H^\dagger H|^3.$$

The operator  $\mathcal{O}_H$  induces a universal shift in Higgs couplings through Higgs wave-function renormalization. The mixing angle  $\theta$  can be mapped with  $c_H$  as  $1 - \cos\theta = \sqrt{2} \sqrt{1/2 \times c_H v^2 / \Lambda^2}$ , for  $v = 246$  GeV.

The Wilson coefficients for  $\mathcal{O}_H$  and  $\mathcal{O}_6$  can be mapped through tree-level processes in the  $Z_2$ -breaking scenario as [53, 54]:

$$\frac{c_H}{\Lambda^2} = \frac{1}{2} \left( \frac{\lambda_{SH} v}{\Lambda_{SH}} \right)^2, \quad \frac{c_6}{\Lambda^2} = \frac{\lambda_{SH}^2}{\Lambda_{SH}^2},$$

and through loop-level processes in both  $Z_2$ -preserving and  $Z_2$ -breaking scenarios as [54]:

$$\frac{c_H}{\Lambda^2} = \frac{1}{16\pi^2} \frac{\lambda_{SH}^2}{m_S^2}, \quad \frac{c_6}{\Lambda^2} = -\frac{1}{16\pi^2} \frac{\lambda_{SH}^3}{m_S^2}.$$

The sign of the  $\mathcal{O}_H$  operator is positive semi-definite for both  $Z_2$ -breaking and  $Z_2$ -preserving scenarios, consistent with the mixing angle description that  $\cos\theta \leq 1$  and Higgs couplings are always reduced compared to the SM. The  $\mathcal{O}_6$  operator modifies mostly Higgs couplings to electroweak gauge bosons and top quarks at loop level. In our analysis we took into account loop corrections

to Higgs to weak gauge boson couplings via  $O_6$  operators using calculations detailed in Ref. [55].

We performed our global fit to this singlet scenario with CEPC, ILC, and FCC-ee Higgs precision measurements, with 95% C.L. limits in the  $c_6 v^2/\Lambda^2$  vs.  $c_H v^2/\Lambda^2$  plane shown in the right panel of Fig. 1 [Figure 1: see original paper]. The corresponding values of mixing angle  $\sin\theta$  are shown on the upper axis, and the corresponding relative change to the SM trilinear Higgs coupling  $\Delta\lambda_3/\lambda_{\text{SM}}$  is shown on the right axis. One-parameter fit results with  $c_H v^2/\Lambda^2$  (or equivalently,  $\sin\theta$ ) are also shown as vertical dashed lines.

From Fig. 1, the allowed range in  $c_6 v^2/\Lambda^2$  is almost one order of magnitude larger than that of  $c_H v^2/\Lambda^2$ . In the general case, at 95% C.L., the maximum allowed Wilson coefficient  $c_H v^2/\Lambda^2$  is 0.032, 0.021, and 0.005, corresponding to maximum singlet-doublet mixing parameter  $\sin\theta$  values of 0.18, 0.15, and 0.07, for CEPC, FCC-ee, and ILC, respectively. Loop modifications to Higgs-gauge boson couplings through modifications of the trilinear Higgs coupling have sizable energy dependence. Hence, ILC achieves much better precision in this two-parameter fit via measuring Higgs processes through different production modes well at separated center-of-mass energies of 250 GeV and 500 GeV. On the other hand, in the restricted one-parameter fit case with  $c_6$  set to zero, the limit on  $c_H v^2/\Lambda^2$  improves to 0.0038, 0.0034, and 0.0028 for CEPC, ILC, and FCC-ee, respectively. These limits correspond to the maximum singlet-doublet mixing parameter  $\sin\theta$  derived from the left panel of this figure.

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## ## 5 Two Higgs Doublet Model

Two Higgs Doublet Models (2HDMs) are very generic BSM Higgs extensions of the SM, including MSSM, gauge extensions (such as left-right symmetric models), and flavor models [58, 59]. Understanding the Higgs physics potential of 2HDM at future lepton colliders provides unique information covering a broad class of BSM scenarios.

Two  $SU(2)_L$  scalar doublets  $\Phi_i$ ,  $i = 1, 2$  are introduced in 2HDM:

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i^0 + iG_i)/\sqrt{2} \end{pmatrix}.$$

Each obtains a VEV  $v_1$  or  $v_2$  after electroweak symmetry breaking (EWSB) with  $v_1^2 + v_2^2 = (246 \text{ GeV})^2$ , and  $v_1/v_2 = \tan\beta$ . The 2HDM Lagrangian for the Higgs sector can be written as:

$$\mathcal{L}_{\text{2HDM}} = \sum_{i=1,2} |D_\mu \Phi_i|^2 - V(\Phi_1, \Phi_2) + \mathcal{L}_{\text{Yuk}},$$

with the Higgs potential:

$$V(\Phi_1, \Phi_2) = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{h.c.}) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1)$$

assuming CP-conserving and a soft  $Z_2$  symmetry breaking term  $m_{12}^2$ . After EWSB, one of the four neutral components and two of the four charged components are eaten by the SM  $Z, W^\pm$ , providing their masses. The remaining physical mass eigenstates are the two CP-even Higgses  $h$  and  $H$ , with  $m_h < m_H$ , one CP-odd Higgs  $A$ , and a pair of charged ones  $H^\pm$ .

Instead of the eight parameters appearing in the Higgs potential ( $m_{11}^2, m_{22}^2, m_{12}^2, \lambda_{1,2,3,4,5}$ ), a more convenient parameter choice is: ( $v, \tan \beta, \alpha, m_h, m_H, m_A, m_{H^\pm}, m_{12}^2$ ), where  $\alpha$  is the rotation angle diagonalizing the CP-even Higgs mass matrix. The CP-even Higgs couplings to SM gauge bosons are:  $g_{hVV} = \sin(\beta - \alpha)$  and  $g_{HVV} = \cos(\beta - \alpha)$ . For  $\cos(\beta - \alpha) = 0$ , the light CP-even Higgs  $h$  couples to gauge bosons with full SM coupling strength while  $H$  decouples. This is usually referred to as the ‘‘alignment limit’’ [60] with  $h$  identified as the SM Higgs. For  $\sin(\beta - \alpha) = 0$ , the opposite occurs with heavy  $H$  being identified as the SM Higgs. While it is still a viable option for the heavy Higgs being the observed 125 GeV SM-like Higgs [61], parameter spaces are squeezed by tight direct and indirect experimental constraints. Therefore, in our analyses below, we identify the light CP-even Higgs  $h$  as the SM-like Higgs with  $m_h$  fixed to 125 GeV.

The most general Yukawa interactions of  $\Phi_{1,2}$  with SM fermions under  $Z_2$  symmetry is:

$$-\mathcal{L}_{\text{Yuk}} = Y_u \bar{Q}_L i \sigma_2 \Phi_u^* u_R + Y_d \bar{Q}_L \Phi_d d_R + Y_e \bar{L}_L \Phi_e e_R + \text{h.c.},$$

where  $\Phi_{\{u,d,e\}}$  are either  $\Phi_1$  or  $\Phi_2$ . Depending on interactions of  $\Phi$  coupling to the fermion sector, there are typically four types of 2HDM:

- **Type-I:**  $\Phi_1$  couples to all fermions while  $\Phi_2$  does not couple to fermions at all.
- **Type-II:**  $\Phi_1$  couples to up-type quarks, and  $\Phi_2$  couples to down-type quarks and leptons.
- **Type-L:**  $\Phi_1$  couples to quarks and  $\Phi_2$  couples to leptons.
- **Type-F:**  $\Phi_1$  couples to up-type quarks and leptons while  $\Phi_2$  couples to down-type quarks.

For a review of different types of 2HDM and their phenomenology, see Ref. [62].

After EWSB, the effective Lagrangian for light CP-even Higgs couplings to SM particles can be parameterized as:

$$\mathcal{L} = \kappa_Z \frac{2m_Z^2}{v} Z_\mu Z^\mu h + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} h - \sum_{f=u,c,t} \kappa_f \frac{m_f}{v} \bar{f} f h - \sum_{f=d,s,b} \kappa_f \frac{m_f}{v} \bar{f} f h - \sum_{f=e,\mu,\tau} \kappa_f \frac{m_f}{v} \bar{f} f h + \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{\mu\nu a}$$

where  $\kappa_h$  is the SM-like Higgs coupling normalized to the corresponding SM value (same as  $\kappa_h$  in Table 2). Table 2 summarizes all tree-level non-zero  $\kappa$  of the light CP-even Higgs  $h$  for the four different types of 2HDM, as well as normalized couplings of non-SM Higgses  $H$  and  $A$ . Note that while  $\kappa_g$  and  $\kappa_\gamma$  are zero at tree level for both SM and 2HDM, they are generated at loop level. In the SM, both  $\kappa_g$  and  $\kappa_\gamma$  receive contributions from fermions (mostly top quark) running in the loop, while  $\kappa_\gamma$  receives additional contribution from  $W$ -loop [54]. In 2HDM, the corresponding  $hff$  and  $hWW$  couplings that enter loop corrections need to be modified to 2HDM values. Expressions for dependence of  $\kappa_g$ ,  $\kappa_\gamma$ , and  $\kappa_{Z\gamma}$  on  $\kappa_V$  and  $\kappa_f$  can be found in Ref. [63]. There are also loop corrections to  $\kappa_g$ ,  $\kappa_\gamma$  from extra Higgses.

In the alignment limit  $\cos(\beta - \alpha) = 0$ , light CP-even Higgs couplings are exactly identical to SM ones. However, deviations of Higgs couplings from the alignment limit are still allowed given current LHC Higgs measurements [14, 64, 65]. Note that all tree-level deviations to SM couplings in Table 2 are parameterized by only two parameters:  $\beta$  and  $\alpha$ , or more conveniently,  $\tan \beta$  and  $\cos(\beta - \alpha)$ . In Section 5.1, we study constraints on 2HDM tree-level effects, namely in the parameter space of  $\tan \beta$  vs.  $\cos(\beta - \alpha)$  with Higgs precision measurements.

There are also loop corrections to all  $\kappa$  above with non-SM heavy Higgses running in the loop. While their contributions are typically small compared to tree deviations, in the alignment limit their contributions could be manifest given the high-precision Higgs coupling measurements achievable at future Higgs factories. The masses of heavy Higgses enter loop corrections, as well as the soft  $Z_2$  symmetry breaking parameter  $m_{12}^2$ . We study constraints on 2HDM loop effects in Section 5.2 under the alignment limit.

### ### 5.1 2HDM Tree-Level Results

Performing a global fit to Higgs rate measurements at the LHC and CEPC, we obtained the 95% C.L. region in the  $\tan \beta$  vs.  $\cos(\beta - \alpha)$  plane for various 2HDM types, as shown in Fig. 2 [Figure 2: see original paper]. For Type-I 2HDM with  $\tan \beta \geq 2$ ,  $|\cos(\beta - \alpha)|$  is constrained to be less than about 0.5 with current LHC Run-I data. With full LHC luminosity of  $300 \text{ fb}^{-1}$ , the range in  $|\cos(\beta - \alpha)|$  can be shrunk by about a factor of 2. At HL-LHC with 10 times the luminosity, the range can be further constrained to less than 0.2. At CEPC with  $5 \text{ ab}^{-1}$ ,  $|\cos(\beta - \alpha)|$  is constrained to be less than about 0.08. The preferred range in  $\cos(\beta - \alpha)$  shrinks quickly at small  $\tan \beta$ , given that:

$$\Delta\kappa_{u,d,e} = \frac{\cos \alpha}{\sin \beta} - 1 = -\frac{\cos^2(\beta - \alpha)}{2} + \cos(\beta - \alpha) \cot \beta.$$

The deviation of Yukawa couplings from the experimental central value is proportional to  $1/\tan \beta$ , resulting in reduced survival parameter space at small  $\tan \beta$ . The up-type Yukawa couplings are the same for all four 2HDM types, so the small  $\tan \beta$  behavior is similar.

For Type-II, Type-L, and Type-F 2HDM, corrections to down quark and/or lepton Yukawa couplings receive  $\tan \beta$  enhancement at large values:

$$\Delta \kappa_x = -\frac{\sin \beta}{\cos \alpha} - 1 = -\frac{\cos^2(\beta - \alpha)}{2} - \cos(\beta - \alpha) \times \tan \beta,$$

where x is d, e in Type-II, e in Type-L, and d in Type-F. Therefore, the survival parameter space at large  $\tan \beta$  is reduced significantly in all three types.

For Type-II (upper right panel of Fig. 2), as a result of larger  $\tan \beta$  enhancement from  $\Delta_{\{d,e\}}$  and small  $\tan \beta$  enhancement from  $\Delta_{\{u\}}$ , the region around  $\tan \beta = 1$  accommodates the largest deviation from alignment. Current LHC Run-I constrains  $|\cos(\beta - \alpha)|$  to be less than 0.1 around  $\tan \beta = 1$  (except for wrong-sign Yukawa couplings region [66, 67]), and LHC Run-II with 300 (3000)  $\text{fb}^{-1}$  can reduce this to less than 0.03 (0.015). CEPC precision measurements further reduce it to less than 0.006. Similar behavior appears in Type-L and Type-F, with small differences mostly coming from  $\Delta_{\{b\}}$  and  $\Delta_{\{\tau\}}$  parameter dependence. A summary of the 95% C.L. allowed maximum  $|\cos(\beta - \alpha)|$  range is given in Table 3.

Because of these large or small  $\tan \beta$ -enhanced Higgs coupling deviations, we can examine which Higgs decay channel provides the best constraints in certain regions. A conservative 7-parameter fit with CEPC Higgs measurements shows that  $\sigma_{\{V\}} \leq 0.16\%$ ,  $\sigma_{\{b\}} \leq 1.2\%$ ,  $\sigma_{\{c\}} \leq 1.6\%$ ,  $\sigma_{\{\tau\}} \leq 1.3\%$  [1].  $\Delta_{\{V\}}$  and  $\Delta_{\{b\}}$  typically provide the strongest constraints. For Type-I, hbb coupling provides the strongest constraints at  $\tan \beta \leq 1$ , while hZZ coupling constraints dominate for  $\tan \beta \geq 5$ . For Type-II, hbb coupling dominates at large  $\tan \beta$  and hgg coupling dominates at small  $\tan \beta$ . For Type-L, while the small  $\tan \beta$  case is similar to Type-I,  $h\tau\tau$  dominates at large  $\tan \beta$ . Type-F is very similar to Type-II, only that  $h\tau\tau$  enters at small  $\tan \beta$  instead.

The special “arm” region surviving for Type-II, L, and F in Fig. 2 is the so-called wrong-sign Yukawa couplings region [66], coming from fermion couplings with  $\Phi_1$ :  $\cos \alpha / \sin \beta$ , as shown in Eq. (5.6). For  $\tan \beta = 2 / \cos(\beta - \alpha)$ , there is no deviation of the corresponding couplings, which corresponds exactly to the “arm” central lines. For regions near this line,  $\Delta$  flips sign while its absolute value is small. The  $\Delta$  for other fermions that couple to  $\Phi_2$  is near -1, therefore “wrong-sign” while still surviving Higgs measurements at the LHC. There would be another “arm” making zero deviation for Eq. (5.7):  $\tan \beta = -1/2 \cos(\beta - \alpha)$ . For Type-I, there is no such coupling, and for other types, such region does not appear in our plot since we consider  $\tan \beta > 0.1$ . Smaller  $\tan \beta$  regions are tightly constrained by perturbativity of top Yukawa couplings.

To compare potential reaches for different Higgs factories, we show the 95% C.L. reach in the  $\tan \beta$  vs.  $\cos(\beta - \alpha)$  plane based on estimated Higgs measurement precision at CEPC (red), ILC (blue), and FCC-ee (green) in Fig. 3 [Figure 3: see original paper], for four different 2HDM types. The red CEPC region is a zoom-in of the red region in Fig. 2. The 95% C.L. green and blue regions are

almost identical, showing that ILC and FCC-ee have about the same constraining power, both slightly better than CEPC results, covering about 70%–90% of the maximum  $|\cos(\beta - \alpha)|$  range.

In Fig. 3, we also studied CEPC results with different luminosity to understand various running scenarios. With dashed red lines from outer to inner, we present CEPC reaches for 2.5, 10, and 25  $\text{ab}^{-1}$  luminosity. In particular, results with CEPC 10  $\text{ab}^{-1}$  are almost identical to FCC-ee 10  $\text{ab}^{-1}$ .

We also show comparison between results using signal strength  $\mu$ -fit (red region) or effective coupling  $\kappa$ -fit (red line) for CEPC precision. We adopted precision for  $\mu$  using CEPC 7-parameter fit [1]. Results with  $\kappa$ -fit are less constrained than  $\mu$ -fit since no correlations between  $\kappa$  were taken into account. Numerically, except for Type-I, the range of  $|\cos(\beta - \alpha)|$  at  $\tan \beta = 1$  with  $\mu$ -fit is about 3 times that of  $\kappa$ -fit for all three 2HDM types. For Type-II and Type-F, CEPC  $\mu$ -fit results are similar to HL-LHC, while for Type-I and Type-L, CEPC  $\mu$ -fit results are still better than HL-LHC. This demonstrates underestimation of Higgs physics potential when using  $\kappa$  results without full correlation information.

Once a deviation of Higgs couplings from SM is observed, simultaneous measurements of various couplings can distinguish different 2HDM types. In Fig. 4 [Figure 4: see original paper], we plot  $\Delta_{\kappa_e}$  vs.  $\Delta(\kappa_V/\kappa_d)$  for four 2HDM types, for  $|\cos(\beta - \alpha)| = 0.01$  (green), 0.02 (blue), and 0.03 (red). Left and right panels are for negative and positive  $\cos(\beta - \alpha)$ , respectively. Dashed lines show different  $\tan \beta$  values, as labeled. Experimental precision of those couplings is indicated by the black cross, with a random central point, for comparison.

Type-I, II, L, and F are well separated, occupying the second, fourth, first, and third quadrants, respectively, for  $\cos(\beta - \alpha) < 0$ . For  $\cos(\beta - \alpha) > 0$ , behavior is similar, except for exchange of quadrants: Type-I  $\leftrightarrow$  Type-II and Type-L  $\leftrightarrow$  Type-F. For Type-I and II,  $\Delta_{\kappa_e} = \Delta_{\kappa_d}$ . Therefore, variations of coupling deviation with  $\cos(\beta - \alpha)$  are small, given the small allowed  $\cos(\beta - \alpha)$  range we picked. Smaller  $\tan \beta$  values lead to larger deviation from SM for Type-I, while the opposite occurs for Type-II. For Type-L and Type-F,  $\Delta_{\kappa_e}$  and  $\Delta(\kappa_V/\kappa_d)$  spread over the whole region, depending on  $\tan \beta$  and  $\cos(\beta - \alpha)$  values.

### ### 5.2 2HDM Loop-Level Results in the Alignment Limit

Beyond tree-level deviations of light Higgs couplings (and loop-generated  $hgg$  and  $h\gamma\gamma$  couplings with SM particles) in 2HDM away from alignment, heavy Higgses in 2HDM also provide loop corrections to those couplings [68–70]. While these contributions are typically small given loop suppression and heavy Higgs mass suppression, they become the dominant correction to Higgs physics in or close to the alignment limit,  $\cos(\beta - \alpha) \rightarrow 0$ . Heavy Higgs contributions to  $hgg$  and  $h\gamma\gamma$  could also be important, given the loop-suppressed SM values at leading order.

In this section, we analyze implications of Higgs precision measurements on heavy Higgs loops and explore sensitivity to heavy Higgs masses, as well as

Higgs self-couplings that enter loop corrections. For simplicity, we set  $m_H = m_{\{H^\pm\}} = m_A$  in the following discussion, which satisfies EW precision  $\beta$ -parameter constraints automatically. We also work under the most challenging scenario of 2HDM with tree-level alignment limit  $\cos(\beta - \alpha) = 0$  to show relevance and importance of these loop corrections.

### 5.2.1 Theoretical and Experimental Constraints

Heavy Higgs loop corrections involve Higgs self-couplings, which are constrained by various theoretical considerations and experimental measurements, such as vacuum stability, perturbativity and unitarity, as well as heavy flavor, electroweak precision measurements, and LHC direct searches. We briefly summarize constraints adopted in our analyses:

- **Vacuum stability:** To have a stable vacuum, the following conditions on quartic couplings must be satisfied [71]:

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1 \lambda_2}, \quad \lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1 \lambda_2}.$$

- **Perturbativity and unitarity:** We adopted a general perturbativity condition  $|\lambda| \leq 4\pi$  and tree-level unitarity of the scattering matrix in the 2HDM scalar sector [72].
- **Electroweak precision measurements:** LEP constraints on the  $\beta$ -parameter constrain charged Higgs mass to be close to either neutral Higgs mass (H or A) [73, 74]. In our analyses, we adopted the simplification  $m_{\{H^\pm\}} = m_H = m_A = m_\phi$  so that  $\beta$ -parameter constraints are automatically satisfied. The results show characteristic features of Higgs factory sensitivities to heavy Higgs mass, even though numerical values might differ if heavy Higgs masses deviate from this simplified relation.

Under alignment limit and equal mass for all heavy Higgses, all Higgs quartic couplings are related to a particular linear combination of  $m_\phi^2$  and  $m_{12}^2/(\sin \beta \cos \beta)$ . The above theoretical considerations can be translated to constraints on  $\lambda v^2 = m_\phi^2 - m_{12}^2/(\sin \beta \cos \beta)$ , we have:

$$\lambda v^2 = \lambda_3 v^2 - m_{12}^2/(\sin \beta \cos \beta) \quad \text{and} \quad m_\phi^2 - m_h^2 + \lambda v^2 \tan^2 \beta > 0, \quad m_\phi^2 - m_h^2 + \lambda v^2 \cot^2 \beta > 0,$$

for  $\lambda v^2 < 0$ , and:

$$\tan^2 \beta + \cot^2 \beta < \frac{64\pi^2 v^4 + 5m_h^4 - 48\pi v^2 m_h^2}{3\lambda v^2 (8\pi v^2 - 3m_h^2) + 8\lambda^2 v^4 - 4m_h^2 \lambda v^2},$$

for  $\lambda v^2 > 0$ .

In Fig. 5 [Figure 5: see original paper], we show the allowed shaded region in  $\tan \beta$  vs.  $\lambda v^2$  plane given theoretical considerations. Region in  $\tan \beta$  and  $1/\tan \beta$  is symmetric, obvious from Eqs. (5.9) and (5.10). A few representative  $\lambda v^2$  values used in later analyses and corresponding acceptable  $\tan \beta$  ranges are shown in Table 4. Note that for  $\lambda = 0$  (i.e.,  $m_{12}^2/(\sin \beta \cos \beta) = 0$ ),  $\tan \beta$  is unconstrained, consistent with Ref. [73]. Given symmetry between  $\tan \beta$  and  $1/\tan \beta$ , the largest region in  $\lambda v^2$  occurs at  $\tan \beta = 1$ :

$$m_h^2 < \lambda v^2 < (600 \text{ GeV})^2,$$

which gives  $-0.258 < \lambda = -\lambda_4 = -\lambda_5 < 5.949$  and  $0 < \lambda_3 < 6.207$ .

There are direct searches for non-SM heavy Higgses at the LHC [75], with dominant channel  $A/H \rightarrow \tau\tau$ . In MSSM framework,  $m_{A/H}$  is excluded to about 250 GeV for  $\tan \beta \geq 1.0$ , and about 1.5 TeV for  $\tan \beta \geq 45$ . Since branching ratio of dominant search channel  $A/H \rightarrow \tau\tau$  could be highly suppressed once other exotic decay channels of non-SM Higgs open up [76–78], current exclusion limits could depend highly on non-SM Higgs spectrum. Direct search limits on heavy charged Higgs  $H^\pm$  above  $m_t$  are relatively weak given large SM backgrounds for dominant  $H^\pm \rightarrow tb$  channel and relatively small branching fraction of  $H^\pm \rightarrow \tau$  [79].

Flavor physics considerations usually constrain charged Higgs mass to be larger than about 600 GeV for Type-II 2HDM [79]. However, charged Higgs contributions to various flavor observables can be cancelled by other new particles in specific models [80] and relaxed consequently. In our analyses, we focused on indirect search potential of Higgs factories on heavy Higgs masses. Therefore, we did not impose flavor constraints on 2HDM parameter space, nor LHC direct search limits.

### ### 5.2.2 2HDM Loop Effects

We defined the normalized Higgs coupling including loop effects as:

$$\kappa_{2\text{HDM}}^{\text{loop}} \equiv \frac{g_{2\text{HDM}}^{\text{tree}} + g_{2\text{HDM}}^{\text{1-loop}}}{g_{\text{SM}}^{\text{tree}} + g_{\text{SM}}^{\text{1-loop}}},$$

where  $g_{2\text{HDM}}^{\text{1-loop}}$  is the 2HDM loop correction involving both SM loop corrections and non-SM parts. To leading order of 1-loop correction, this simplifies to:

$$\kappa_{2\text{HDM}}^{\text{1-loop}} = \kappa_{\text{tree}} + \Delta \kappa_{2\text{HDM}}^{\text{1-loop}},$$

with  $g_{2\text{HDM}}^{\text{tree}}/g_{\text{SM}}^{\text{tree}}$  and  $\Delta g_{2\text{HDM}}^{\text{1-loop}}/g_{\text{SM}}^{\text{tree}} - g_{\text{SM}}^{\text{1-loop}}/g_{\text{SM}}^{\text{tree}}$ . In

the alignment limit  $\cos(\beta - \alpha) = 0$ ,  $\kappa_{\text{tree}} = 1$ , and the expression simplifies to:

$$\kappa_{2\text{HDM}}^{\text{1-loop}}|_{\text{alignment}} = 1 + \Delta\kappa_{2\text{HDM}}^{\text{1-loop}}.$$

Expressions for non-SM Higgs loop corrections to Higgs couplings are summarized in Appendix B [68–70] under alignment limit  $\cos(\beta - \alpha) = 0$  and mass simplification  $m_{\{H^\pm\}} = m_A = m_H = m_\phi$ . Note that tree-level relations  $\kappa_W = \kappa_Z$  and  $\kappa_\tau = \kappa_\tau$  remain approximately valid at 1-loop level.

Following the same global fitting techniques as in the tree-level case, we obtained 95% C.L. constraints on the  $\tan \beta$  vs.  $m_\phi$  plane for four 2HDM types given CEPC precision, as shown in Fig. 6 [Figure 6: see original paper]. Four benchmark values of  $\lambda v^2$  are chosen: 0, 100, 300, and 500 GeV, corresponding to red, blue, green, and orange curves. Regions to the right of curves for large  $m_\phi$  or to the left for small  $m_\phi$  (enclosed region for blue curves) are allowed.

For Type-I, small  $\tan \beta$  values ( $< 0.5$ ) are excluded since all non-SM Higgs Yukawa couplings are proportional to  $1/\tan \beta$ . Dependence on  $\tan \beta$  is weak once  $\tan \beta \geq 2$ . While smaller  $\lambda v^2$  values allow  $m_\phi$  as low as 125 GeV,  $m_\phi$  is constrained to be larger than 500 GeV for  $\lambda v^2 = 500$  GeV, given that heavy Higgs loop corrections enhance as  $\lambda v^2$  increases. The small kink around  $m_\phi \approx 350$  GeV is due to top quark threshold effects in Yukawa couplings. Relaxed constraints on  $\tan \beta$  around  $m_\phi \approx 500$  GeV are caused by smallness of  $\Delta\kappa_{\{b,c,\tau\}}$ , which flips sign near that region.

For Type-II, while generic features of excluded regions are similar to Type-I, there are three major differences. First, constraints at large  $\tan \beta$  get tighter since both down-type Yukawa and lepton Yukawa (particularly bottom and tau) are proportional to  $\tan \beta$ , making loop contributions more tightly constrained. Second, top quark threshold effects are stronger since relevant terms lack  $1/\tan^2 \beta$  suppression as in Type-I. Third, constraints at small  $\tan \beta$  get weaker because only up-type Yukawa couplings are proportional to  $1/\tan \beta$ , while precision on that is worse than  $bb$  and  $\tau\tau$  channels.

Results for Type-L are similar to Type-II, with small  $\tan \beta$  constraints getting stronger since down-type Yukawa couplings are now proportional to  $1/\tan \beta$  as well. Sensitivity at large  $\tan \beta$  becomes a bit weaker since lepton Yukawa coupling structure is the same as Type-II. Results for Type-F are almost identical to Type-II, since for the most precisely measured couplings  $hZZ$  and  $hbb$ , dominant loop contributions (from bottom quark and heavy Higgses) in these two types are identical.

To explore effects of different running scenarios with different integrated luminosities, we present 95% C.L. Higgs precision constraints on  $\tan \beta$  vs.  $m_\phi$  plane in Fig. 7 [Figure 7: see original paper], with rescaled error bars for integrated luminosities of 2.5, 5, 10, and 25  $\text{ab}^{-1}$ , based on CEPC 5  $\text{ab}^{-1}$  results. We assumed statistical error dominates [1, 39]. Both upper and lower limits on

$\tan \beta$ , as well as lower limits for  $m_\phi$  at large  $m_\phi$  region, get stronger with increasing luminosity. For both Type-I and II with  $\lambda v^2 = 300$  GeV, the lower limit on  $m_\phi$  increases from 400 GeV to 700 GeV when luminosity increases from 2.5 to 25  $\text{ab}^{-1}$ .

To compare sensitivity of different future Higgs factories with running scenarios listed in Table 1, as well as effects of  $\Delta$  / -fit vs. -fit, we show 95% C.L. constrained regions in  $\tan \beta$  vs.  $m_\phi$  plane for CEPC (red lines), ILC (blue lines), and FCC-ee (green lines) in Fig. 8 [Figure 8: see original paper]. For CEPC precision,  $\Delta$  / -fit results are shown as solid lines and -fit results as dashed lines. ILC and FCC-ee have similar sensitivities, both better than CEPC results. In addition, results with  $\Delta$  / fit are better than -fit results, confirming tree-level fitting results that including correlations between different couplings is important. Overlooking these correlation effects might lead to overly conservative results.

Results presented so far assume a fixed value of  $\lambda v^2 = m_\phi^2 - m_{12}^2 / (\sin \beta \cos \beta)$ . It is convenient to do so since  $\lambda v^2$  directly enters tri-Higgs couplings. Another common strategy is to fix the soft  $Z_2$  breaking parameter  $m_{12}^2$ . Global fitting results are shown in Fig. 9 [Figure 9: see original paper] for fixed  $m_{12}^2$  values of 0 (red), 150<sup>2</sup> (blue), 500<sup>2</sup> (green), and 1000<sup>2</sup> (orange) GeV<sup>2</sup>. As before, top quark threshold effects typically lead to large  $\lambda v^2$ , showing up in the blue region. Negative  $m_{12}^2$  values give much worse  $\lambda v^2$  and are disfavored. Survival regions now exhibit (almost) enclosed behavior, with both upper and lower limits on  $m_\phi$  for given  $\tan \beta$ . The location of allowed  $m_\phi$  region also shifts to larger mass for larger  $m_{12}^2$  values. For asymptotic large  $m_\phi$  and  $\tan \beta$  region, the allowed region centers around  $m_\phi^2 = m_{12}^2 / (\sin \beta \cos \beta)$  line, which minimizes corresponding  $\lambda v^2$ .

To study sensitivity of Higgs precision measurements on model parameters and demonstrate how well they can distinguish different model types once coupling deviations are measured, we show loop corrections of  $\Delta_{\tau}$  vs.  $\Delta_b$  for four 2HDM types, for  $m_\phi = 600$  GeV, with  $\lambda v^2 = 300$  GeV (left panels) and 500 GeV (right panels) in Fig. 10 [Figure 10: see original paper]. Different  $\tan \beta$  values are indicated with dots to show sensitivity of  $\Delta_{\{b,\tau\}}$  to  $\tan \beta$ .

For Type-I, loop corrections to both  $\Delta_b$  and  $\Delta_\tau$  are large for small  $\tan \beta$ , about 4.3% in  $\Delta_b$  and 2.3% in  $\Delta_\tau$  for  $\tan \beta = 0.7$  with  $\lambda v^2 = 500$  GeV, well within reach of precision measurements. Contributions quickly decrease once  $\tan \beta$  gets larger. For Type-II,  $\tan \beta$  dependence is flipped, with corrections to  $\Delta_\tau$  significantly larger than Type-I. For Type-L, correction to  $\Delta_b$  is large at small  $\tan \beta$ , while corrections to  $\Delta_\tau$  increase for larger  $\tan \beta$ . Opposite behavior occurs for Type-F. For larger  $\lambda v^2$  values, loop corrections get even larger.

Since each 2HDM type sweeps out a different region in  $\Delta_b$  vs.  $\Delta_\tau$  space, simultaneous measurements of  $\Delta_b$  and  $\Delta_\tau$  with estimated precision could help distinguish the four types. For CEPC with 5  $\text{ab}^{-1}$  7-parameter fit, estimated

precision is about 1.2% for  $\delta b$  and 1.3% for  $\delta \tau$ , as indicated by the cross in Fig. 10, providing enough precision to separate contributions from different models. Note that without knowing  $\tan \beta$  a priori, there is degeneracy between Type-L and Type-F, particularly if only  $\delta b$  deviation is observed while  $\delta \tau$  deviation is small. However, with theoretical constraints discussed in Section 5.2.1 imposing a constrained  $\tan \beta$  range as shown in Fig. 5 and Table 4, this degeneracy can be lifted. Since loop corrections typically get smaller for larger  $m_\phi$  and smaller  $\lambda$ , the potential of  $\delta b$  and  $\delta \tau$  measurements to determine  $\tan \beta$  becomes limited accordingly.

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## ## 6 Composite Higgs Models

The class of BSM physics featuring strong dynamics leads to testable predictions through precision measurements. Composite Higgs Models are a representative class that ties directly to the hierarchy problem. The Higgs boson, instead of being a fundamental particle as in SM, SUSY, or gauge extensions, would be a composite particle as a bound state of additional strong dynamics. The Higgs can be viewed as a pseudo-Nambu-Goldstone boson, with mass protected by global symmetry breaking scale parameter  $f$  generated by condensation of strongly interacting particles. The separation between electroweak scale and composite scale  $f$  is naturally a tuning parameter, representing fine-tuning of the underlying composite model.

There is a vast range of plausible composite Higgs models. To evaluate physics reach of Higgs precision measurements on this broad class, we adopted two approaches. The first interprets Higgs precision results in the Minimal Composite Higgs Model (MCHM) [81] with various embeddings of SM fermion partners. The second adopts EFT language and follows discussion of patterns of strong interactions [84], comparing implications of Higgs precisions on Accidentally Light Higgs (ALH), Strongly Interacting Light Higgs (SILH) [85], and general SILH (GSILH). Each pattern has different assumptions on symmetries of underlying strong dynamics.

### ### 6.1 Minimal Composite Higgs Models

MCHMs represent a minimal embedding of the Higgs as a pseudo-Nambu-Goldstone boson of global symmetry  $SO(5)/SO(4)$  that respects custodial symmetry. We investigated and found a way to best present limits on various fermion representations in MCHMs, following notation and calculations in Ref. [86].

In the minimal coset  $SO(5)/SO(4)$ , gauge invariance fixes the rescaled gauge coupling  $\kappa_V$  to be:

$$\kappa_V = \sqrt{1 - \xi},$$

where  $v^2/f^2$  parameterizes vacuum misalignment. To simplify notation, in

this section we refer to rescaled couplings of SM Higgs  $\hat{h}$  as  $\kappa$ . Modifications to Yukawa couplings depend on fermion representations. In many models, rescaled Higgs to fermion couplings  $\kappa_t$  or  $\kappa_b$  can be either:

$$F_1 \equiv \frac{1 - 2\xi}{\sqrt{1 - \xi}}, \quad \text{or} \quad F_2 \equiv \sqrt{1 - \xi},$$

if summed over all tower contributions. In these cases  $\xi$  is the only model parameter at leading order for a specific model. For more complex fermion embeddings, such as MCHM<sub>14</sub> [14, 10], MCHM<sub>14,5</sub> [10], and MCHM<sub>5,14</sub> [10], Higgs couplings are modified in more complex ways [86]. Corresponding Yukawa couplings are related to functions  $F_{3,4,5}$ , which depend on several microscopic Yukawa couplings, with explicit expressions in Ref. [86]. Resulting Higgs couplings vary in a certain range even for fixed  $\xi$ . In several limiting cases when one microscopic Yukawa coupling turns off, these additional coupling functions reduce to simpler  $F_1$  and  $F_2$  functions.

Note that these simple closed-form expressions are obtained by summing over infinite tower fermions. In reality, summation is truncated after a few tower fermions, generating more complicated and scattered relations between model parameters. For simplicity, and since modifications to Higgs couplings are dominated by the first few tower fermions in most cases, we adopted these simplified formulae to obtain qualitative physics reach of Higgs precision program in MCHMs.

Table 5 tabulates various MCHM fermion representations and corresponding leading modifications to  $\kappa_t$  (and thus  $\kappa_g$ ) and  $\kappa_b$ , while modifications to  $\kappa_Z$  always follow function  $F_2$ . All Higgs couplings depend on only one parameter  $\xi$  for the first four cases when  $\kappa_t$  and  $\kappa_b$  are either  $F_1$  or  $F_2$ . The remaining three embeddings have extra parameter dependence entering  $F_{3,4,5}$ .

Adopting the global fitting method described in Section 3, we obtained 95% C.L. ranges on  $\xi$ , listed in Table 5 for CEPC, ILC, and FCC-ee Higgs measurement precisions. We further translated corresponding limits on  $\xi$  into more intuitive limits on composite scale parameter  $f$ . Note that  $\kappa_t$  can be well constrained by  $h \rightarrow gg$  here as we assume  $h \rightarrow gg$  receives no additional new physics contribution. We made no assumption on model prediction of  $\kappa_c$ . If further assumptions are made (e.g.,  $\kappa_c = \kappa_t$ ), marginal improvement on  $\xi$  constraint is expected, as bounds on  $\kappa_V$  and  $\kappa_b$  are much more constraining. At 95% C.L.,  $\xi$  can be limited to less than a few  $\times 10^{-3}$ , assuming future measurements follow SM expectations. The composite scale is constrained to be larger than 4 TeV. For embeddings with  $\kappa_t$  related to functions  $F_{3,4,5}$ , 95% C.L. bounds on  $\xi$  and  $f$  vary in a certain range given extra parameter dependence.

Once deviations of Higgs couplings are observed at future colliders, different fermion tower embeddings might be distinguished through predicted correlations between Higgs couplings. In Fig. 11 [Figure 11: see original paper], we show

68% C.L. and 95% C.L. exclusion limits of Higgs precision measurements of CEPC, FCC-ee, and ILC in the  $\Delta_V$ - $\Delta_t$  plane, obtained from global fit in reduced parameter space of four parameters  $\Delta_V$ ,  $\Delta_t$ ,  $\Delta_c$ , and  $\Delta_b$ . Loop contributions of these parameters in  $hgg$ ,  $h\gamma\gamma$ ,  $hZ\gamma$  couplings are included. In the right panel, 95% C.L. from LHC  $300\text{ fb}^{-1}$  and  $3000\text{ fb}^{-1}$  runs are also shown for comparison with lepton colliders.

The four-parameter fit is very useful for capturing main characterization of MCHMs without making specific assumptions on fermion representations. Projection to  $\Delta_V$ - $\Delta_t$  plane allows focus on the two couplings most relevant for MCHMs. For specific fermion representations, parameter space is further constrained, implying certain correlations between  $\Delta_V$  and  $\Delta_t$ . For  $\Delta_t = F_1$  or  $F_2$  defined in Eq. (6.2), both  $\Delta_Z$  and  $\Delta_t$  are fixed by  $\Delta_V$  value, shown by magenta and cyan lines in Fig. 11. For  $\Delta_t = F_{3,4,5}$  with variation of additional model parameters, predicted range is covered by the gray region.

The right panel of Fig. 11 clearly shows that Higgs measurements at future lepton colliders can significantly improve constraints on MCHMs from LHC measurements by more than one order of magnitude. Once Higgs coupling deviations are measured, different fermion content embeddings could also be tested. This is due to much better determination of Higgs couplings at lepton colliders. In particular, Higgs coupling to Z boson is very well constrained by Higgsstrahlung processes, while at LHC it is probed by Higgs decay  $h \rightarrow 4\ell$  or VH production mode and suffers from systematic uncertainties.

### ### 6.2 General Patterns of Strongly Interacting Light Higgs

Given richness and depth of strong dynamics with a light Higgs, it is informative to understand Higgs factory potentials on strong dynamics models under generic arguments about patterns of corresponding EFTs. In our analyses, we considered three typical patterns of strong dynamics with a light Higgs [84]: ALH, SILH, and GSILH. These are categorizations of general patterns of strong interactions rather than explicit models.

To capture main features without loss of generality, we worked in EFT framework with dimension-6 (D6) operators, parameterized by:

$$\mathcal{L}_{\text{EFT}} = \sum_i \frac{c_i}{m_*^2} \mathcal{O}_i,$$

where  $m_*$  is the new physics scale and coefficients  $c_i$  are generally determined by new physics coupling, denoted  $g_*$ , as well as SM gauge couplings ( $g_s$ ,  $g$ ,  $g'$  for SU(3), SU(2), and U(1), respectively) and Yukawa couplings  $y_f$ . Relevant operators  $\mathcal{O}_i$  are listed in Table 6. Among these operators,  $\mathcal{O}_H$  requires renormalization of Higgs field and shifts Higgs couplings universally.  $\mathcal{O}_Y$  operators further modify Higgs Yukawa couplings. Operators  $\mathcal{O}_{\text{BB}}$ ,  $\mathcal{O}_{\text{HB}}$ ,  $\mathcal{O}_{\text{HW}}$ , and  $\mathcal{O}_{\text{GG}}$  directly modify Higgs-gauge boson couplings. Operators  $\mathcal{O}_W$ ,  $\mathcal{O}_B$ ,  $\mathcal{O}_{\text{HW}}$ ,  $\mathcal{O}_{\text{HB}}$ , and  $\mathcal{O}_{\text{3W}}$  also contribute to elec-

troweak precision observables and anomalous TGCs. Consequently, additional measurements beyond Higgs properties are crucial for developing global constraints on these operators.

For the three strong dynamics cases considered, estimated parametric counting and scaling of operators are listed in Table 2 of Ref. [84], reproduced here in Table 7. For each case, there are only two free parameters:  $g_*$  and  $m_*$ . However, Table 7 provides estimation of  $c_i$  magnitudes rather than predicted values, which are available only if the model is specified. We therefore assume no relations among operators in Table 7, but only use estimated coupling size to derive new physics scale  $m_*$ .

We derived reach of new physics scale  $m_*$  as function of  $g_*$  for three scenarios from 95% C.L. constraints on overall coefficient of EFT operators derived in Ref. [34], presented as  $m_*/\sqrt{c_i}$  in Fig. 12 [Figure 12: see original paper] for CEPC (red), ILC (blue), and FCC-ee (green) Higgs precisions. HL-LHC Higgs measurements are included in total <sup>2</sup> to optimize reach. HL-LHC improves limits through better diphoton statistics and ttH processes that complement Higgs factory measurements. This differs from global analyses on 2HDM and MCHM in previous sections, where inclusion of HL-LHC Higgs measurements does not affect results much.

In addition to Higgs measurement inputs listed in Section 2, angular observables in  $e^+e^- \rightarrow hZ$  and constraints on anomalous TGCs from  $e^+e^- \rightarrow WW$  measurements are included from Ref. [34] to help discriminate different EFT parameters and maximize overall precision reach. Ref. [34] also assumed CEPC can collect  $200 \text{ fb}^{-1}$  data at 350 GeV, assuming statistical uncertainties dominate. Differences between unpolarized and polarized beams are also taken into account.

Note that Ref. [34] focuses only on operators in Table 6 that can be probed by Higgs processes and diboson production ( $e^+e^- \rightarrow WW$ ). Furthermore, relation  $c_W + c_B = 0$  is imposed so there are no additional contributions to electroweak precision observables, resulting in only one combination of  $O_W$  and  $O_B$  surviving. Ignoring flavor-changing effects and considering only relevant diagonal Yukawa couplings  $y_t, y_c, y_b, y_\tau$ , and  $y_*$ , we end up with 12 coefficients to be constrained by global fit.

Fig. 12 shows results from individual constraints on operators obtained by switching on one at a time (light shade) and from 12-parameter global fit (solid shade). Single operator fit results are typically factors of a few better for operators involving electroweak gauge bosons, due to their correlation in Higgs physics. We also note typical scale from global fit on these operators is around 1–3 TeV with  $c_i = 1$ , except for  $m_*/\sqrt{c_{BB}}$  and  $m_*/\sqrt{c_{GG}}$ , which could reach around 10 TeV. This is because leading SM contribution to  $h \rightarrow \gamma\gamma$ , gg appears at one-loop level.

Using bounds on  $m_*/\sqrt{c_i}$  in Fig. 12, reach of new physics scale  $m_*$  can be derived as function of strong coupling  $g_*$ . Reaches are presented in Fig.

13 [Figure 13: see original paper] at 95% C.L. for three cases under future Higgs factories. We varied  $g_*$  from 1 to 10, covering typical strong interaction coupling range  $1 < g_* < 4\pi$ . Two sets of bounds are shown for each case (ALH, GSILH, SILH): one from individual fit (left panel) and one from global fit (right panel). Constraints from individual fit provide optimistic estimation as realistic models unlikely generate only one D6 operator. Global fit provides conservative bound, with all 12 coefficients treated as independent free parameters. For each case, the operator providing strongest constraints is labeled alongside curves.

For  $g_*$  varying between 1 to 10,  $m_*$  reach is about 5 to 50 TeV for individual fit, and about 2 to 30 TeV for global fit. For individual fit, CEPC and ILC reach is similar, except for small  $g_*$  region, while FCC-ee reach is slightly better. For global fit, ILC reach improves over CEPC and FCC-ee, due to additional measurements of Higgs and diboson processes at higher center-of-mass energy. While reaches in GSILH and SILH are almost identical, reach in ALH is quite different, particularly for  $O_{\{GG\}}$  operator where loop suppression from shift-symmetry argument is absent.

Dominating Higgs production process, Higgsstrahlung  $e^+e^- \rightarrow hZ$ , is ideal for probing  $O_H$ , which provides universal shift to all Higgs couplings. However, in global fit its bound suffers from large degeneracy with other parameters, particularly operators generating anomalous  $hZZ$  couplings with Lorentz structures different from SM. Therefore, in individual fits  $O_H$  provides best reach for GSILH and SILH, while for global fit best reach comes from  $O_{\{yb\}}$  instead at CEPC and FCC-ee. ILC with 500 GeV run is more powerful at discriminating these operators through WW-fusion Higgs production and ZH associated production [87], therefore with global fit  $O_H$  still has best reach. For smaller  $g_*$  values,  $O_W$  provides best reach since its coefficient is independent of  $g_*$ .

For ALH,  $O_{\{GG\}}$  provides best sensitivity to  $m_*$ , around 50 TeV in individual operator fit case and around 20 TeV in global fit case for  $g_* \approx 6$ . This is because  $O_{\{GG\}}$  can be generated at tree level in ALH, while at one-loop level in SM, GSILH, and SILH. In global fit, bound on  $O_{\{GG\}}$  usually suffers from flat directions associated with  $O_{\{yt\}}$  which also contributes to hgg coupling by modifying top Yukawa coupling in loop. Therefore, in ALH the most sensitive operator in global fitting at large  $g_*$  is  $O_{\{yb\}}$  at CEPC/FCC-ee and  $O_H$  at ILC, similar to GSILH and SILH.

With these results on typical patterns of strongly interacting light Higgs, we see how different components of Higgs precision programs complement each other in probing models of strong dynamics. In particular, running at different center-of-mass energies of Higgs factories can be sensitive to particular sets of operators.

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## ## 7 Conclusion and Outlook

In this work, we studied implications of Higgs precision measurements from var-

ious Higgs factories (CEPC, ILC, FCC-ee) on new physics models. We focused on two types of new physics scenarios: perturbative models and strong dynamics. For perturbative models, we studied SM plus singlet extension and 2HDM as explicit examples, exploring both tree-level effects and loop corrections. For strong dynamics, we studied MCHM as a concrete example and explored EFT language in three typical patterns of operators from strong interactions. We took estimated precision from Higgs factories and LHC results, performing global fits in relevant parameter spaces to derive reaches in different models. When no deviation from SM predictions is observed, 95% C.L. reaches in parameter ranges were derived. When deviations are observed, we explored how different models can be distinguished.

For SM with real scalar singlet extension, we obtained 95% C.L. limits on singlet-doublet mixing angle  $\sin \theta$  of 0.062, 0.058, and 0.052 for CEPC, ILC, and FCC-ee, respectively. We also studied the more general case with induced  $O_H$  and  $O_6$  operators, obtaining constraints on Wilson coefficients  $c_H/\Lambda^2$  and  $c_6/\Lambda^2$ . While  $c_H/\Lambda^2$  is tightly constrained to around  $10^{-2}/v^2$ , the limit on  $c_6/\Lambda^2$  is about an order of magnitude weaker.

For 2HDM, we analyzed four types: Type-I, II, L, and F. For tree-level effects, we found  $|\cos(\beta - \alpha)|$  is tightly constrained to about  $10^{-4}$  or smaller at small and/or large  $\tan \beta$  for Types II, L, F, reaching maximum range of about 0.005–0.007 for  $\tan \beta \leq 1$ . For Type-I, large  $\tan \beta$  region is much less constrained:  $|\cos(\beta - \alpha)| \leq 0.08$ . For 2HDM loop effects under alignment limit, lower bounds on heavy Higgs masses depend on  $\lambda v^2 = m_\phi^2 - m_{12}^2/(s_\beta c_\beta)$ : about 350, 450, and 1100 GeV for  $\lambda v^2 = 100, 300, 500$  GeV, respectively. For smaller  $\lambda v^2$  values, a small mass region of  $125 \text{ GeV} < m_\phi < 350 \text{ GeV}$  is also viable. We also explored constrained parameter space in  $\tan \beta$  vs.  $m_\phi$  plane when  $m_{12}^2$  is varied as independent parameter.

For MCHM, the main parameter is  $\lambda = v^2/f^2$ , linked to global symmetry breaking scale  $f$ . With different fermion content embeddings, we obtained 95% C.L. limits on  $\lambda$  of about a few  $\times 10^{-3}$ , corresponding to  $f \sim 4$  TeV. We also studied ALH, GSILH, and SILH as three representative EFT operator patterns in strong dynamics. The 95% C.L. constraints on strong dynamics scale  $m_*$  as function of strong coupling  $g_*$  were obtained, either with individual fit to single operator or through global fit of all twelve operators. For  $g_*$  varying between 1 to 10,  $m_*$  varies between 5 to 50 TeV for individual fit, and 2 to 30 TeV for global fit.

We also studied reach for three different Higgs factory machines: CEPC, ILC, and FCC-ee under typical running scenarios summarized in Table 1. FCC-ee and ILC reaches are slightly better than CEPC. With higher center-of-mass energy running, ILC has advantage in sensitivity to operators contributing to hWW couplings.

In our analyses, we used global fit to signal strength  $\mu$  for each search channel. This provides stronger constraints on parameter spaces than usual  $\kappa$ -scheme

when correlations between  $\mu$  are not treated properly.

To summarize, impressive precisions achievable in future Higgs measurements provide powerful tools to explore new physics models through indirect probes. These indirect searches complement direct searches at current and future colliders, sometimes superseding direct limits given hadronic environment at LHC and limited energy reach of lepton colliders. Our studies provide concrete examples of how sensitive Higgs precision measurements can be to particular model parameters, new particle masses, or symmetry breaking scales. While results are specific to SM singlet extension, 2HDM, MCHM, and three particular strong dynamics setups, the approaches are general and can be applied to any model as long as Higgs couplings and other relevant interactions are specified. Our study also provides guidelines for future Higgs factory design, including choices of center-of-mass energies and corresponding luminosities.

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#### ## Appendix A: LHC Higgs Measurements

In Table 8, we list LHC Run-I Higgs measurements for  $\gamma\gamma$ ,  $WW$ ,  $\tau\tau$ ,  $bb$ , and  $ZZ$  in various production channels. In Table 9, we list estimated precision on normalized Higgs signal strength for  $300 \text{ fb}^{-1}$  and  $3000 \text{ fb}^{-1}$  integrated luminosity, as well as corresponding production contamination information. These tables are used as input for our global fit using LHC data.

## ## Appendix B: 2HDM Loop Corrections

Formulas for one-loop corrections from 2HDM to Higgs couplings are summarized here, under alignment limit  $\cos(\beta - \alpha) = 0$  and universal mass assumption  $m_{\{H^\pm\}} = m_A = m_H = m_\phi$ .

The correction to  $h\gamma\gamma$  coupling is:

$$\Delta\kappa_{h\gamma\gamma}^{2\text{HDM},1\text{-loop}} = -\frac{v^2}{32\pi^2 m_\phi^2} [\lambda_{hH^+H^-}^2 (1 + 2m_{H^\pm}^2 C_0(0, 0, m_h^2, m_{H^\pm}^2, m_{H^\pm}^2, m_{H^\pm}^2)) + \dots],$$

with  $A_{\gamma\gamma}\{\text{SM}\} = 6.53$  representing one-loop induced  $h\gamma\gamma$  coupling in SM, including W boson, top quark, and bottom quark contributions.

The correction to  $hff$  coupling is:

$$\Delta\kappa_{hff}^{2\text{HDM},1\text{-loop}} = -\frac{v^2}{16\pi^2} \left[ \kappa_f^2 \left( \frac{2m_f^2}{v^2} \right) C_0(m_f^2, m_f^2, m_h^2, m_f, m_\phi, m_f) + \dots \right],$$

where  $f'$  is the fermion whose electromagnetic charge differs by one unit from  $f$ , and  $I_f = +1/2$  ( $-1/2$ ) for  $f = u$  ( $d, e$ ).

The correction to  $hVV$  coupling is:

$$\Delta\kappa_{hVV}^{2\text{HDM},1\text{-loop}} = -\frac{1}{16\pi^2 v^2} [\lambda_{hH^+H^-}^2 B_0(p^2; m_{H^\pm}, m_{H^\pm}) + \dots],$$

with scalar three-point couplings given by:

$$\lambda_{h\Phi\Phi} = \frac{m_\phi^2 - 2m_h^2 + 2m_{12}^2}{v \sin\beta \cos\beta}, \quad \lambda_{H\Phi\Phi} = \frac{m_{12}^2}{v \sin\beta \cos\beta} - \lambda v \cot 2\beta.$$

All B and C functions are Passarino-Veltman functions [95]. We emphasize that all above equations are in alignment limit  $\cos(\beta - \alpha) = 0$  and  $m_\phi = m_{\{H^\pm\}} = m_A = m_H$ . Following fitting techniques at tree level,  $\kappa_W = \kappa_Z$  and  $\kappa_\tau = \kappa_\mu$  still hold at 1-loop.

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