Sensitivity study of anomalous $HZZ$ couplings at future Higgs factory

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Abstract

We study the sensitivity of constraining the model independent Higgs-Z-Z coupling under effective theory up to dimension-6 operators at the future Higgs factory. Utilizing the current conceptual design parameters of the Circular Electron Positron Collider, we give the experimental limits for the model independent operators by the total Higgsstrahlung cross section and angular distribution of Z boson decay in the Higgs factory. Especially, we give very small sensitivity limit for the CP violation parameter $\tilde{g}$, which will be a clear window to test the Standard Model and look for New Physics signal.

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I. INTRODUCTION

Since the large hadron collider (LHC) announced the discovery of a scalar-like resonance [1, 2], many subsequent measurements confirmed that it is just the Higgs particle as the last brick of Standard Model (SM) [3]. Among these measurements, the generic Higgs coupling to vector gauge bosons presented the largest ($\sim 7\%$) deviation from SM prediction, but its experimental error is so big ($\pm 56\%$) that the good agreements with SM still stand tenable. Both the non-explained phenomena like dark matter and the theoretical tension like hierarchy (naturalness) problem still keep the extensions to SM necessary. The interaction between Higgs scalar and vector gauge bosons is a key ingredient for the underlying nature of spontaneously breaking of electroweak gauge symmetry. In addition to the suggested experiments on kinematic distributions at LHC Run2 [4–6], future Higgs factories are under considerations, such as the Circular Electron Positron Collider (CEPC) in China, the International Linear Collider (ILC) in Japan, the Compact Linear Collider (CLIC) and Future Circular Collider (FCC-ee) in Europe [7, 8]. Along this line, many pre-analysis have been put forward [9, 10], to unveil the nature of gauge boson and Higgs couplings. These lepton colliders will accumulate events with full kinematics and less backgrounds at high luminosity, which will support precision tests in the Higgs sector. Such it become indispensable to unfold and utilize the events shapes as the details presented by data to explore the subtleties in Higgs properties.

Theoretically, an Effective Field Theory approach is adopted with the so called Strongly Interacting Light Higgs (SILH) scenario [11, 12] on the HZZ couplings. This model-independent description however consists of 12 independent operators for a single HZZ vertex, it is not practical to extract so many Wilson coefficients in experiments or even on the above mentioned lepton colliders with luminosity up to several thousands of femtobarn. So further compression are described in [12, 13] where only four phenomenological parameters are involved. Many works have been done on theoretical analysis [14–16], and on the running experiment of LHC to demonstrate how to constrain these 4 parameters with the distributions of polarization angle and azimuthal angle [17, 19]. Cross section sensitivity studies of anomalous Higgs couplings have been performed at the LHC and electron-positron colliders in [20]. In ref. [21], the authors discussed also the angular distribution sensitivity of Z boson and Higgs decays at the electron-position collider at the energy of 350GeV and
500 GeV. Since both of the current circular electron position collider and the international linear collider are designed at the center of mass energy around 240GeV, it is necessary to do the sensitivity study of the Higgs production in detail at the specific design of detector. The sensitivity study of cross sections has been done in ref. [22]. And in ref. [23], the authors did sensitivity study on some asymmetry parameters of the angular distributions of these effective operators.

In this work, we will investigate the polarization angle of Z decay associated in Higgsstrahlung [24, 25], also the azimuthal angle of the Z decay on future leptonic colliders. Our work pays more attention to the physics/parameters to be extracted from these angle distributions, by the sensitivity study relying on the characteristics of detector design at the future electron position collider. Differing from most of previous studies which came mainly in theoretical fashion, it is worthy to stress that, in this work the potential systematical errors from experiment have been quoted in the Pearson $\chi^2$, which are assumed to be at the same level of the statistical one.

The paper is organized as follows: In Sec. II, analytical formulas of angular distribution and CP-violation terms for $Z$ decays to 2 leptons affected by new coupling $HZZ$ are presented. Sec. III gives our numerical limit on the sensitivity of new physics parameters on CEPC. Sec. IV is the summary.

II. NEW PHYSICS EFFECTS ON HZZ COUPLING

The generic effective Hamiltonian of $HZZ$ sector is written as [12]

$$
L_{HZZ} = -\frac{1}{4}g_1 Z_{\mu \nu} Z^{\mu \nu} h - g_2 Z_{\nu} \partial_{\mu} Z^{\mu \nu} h +
 g_3 Z_{\mu} Z^{\mu \nu} h - \frac{1}{4}\bar{g} Z_{\mu \nu} \bar{Z}^{\mu \nu} h,
$$

(1)

from which, the effective Feynman rule can be derived as

$$
V_{\mu \nu} = ig_{\mu \nu} [g_0 + g_3 + g_2 (p_3^2 + p_2^2) + g_1 (p_2 \cdot p_3)] -
 i \left[ \frac{1}{2} g_1 (p_3^\mu p_2^\nu + p_2^\mu p_3^\nu) + g_2 (p_2^\mu p_2^\nu + p_3^\mu p_3^\nu) -
\bar{g}\epsilon_{\mu \nu \rho \sigma} p_3^\rho p_2^\sigma \right].
$$

(2)
In this parametrization, $g_0 = e M_Z / (c_w s_w)$ is the HZZ coupling in Standard model. Taking the convention of [13], $g_3$ is a small fraction defined with an implicit unit of $g_0$, while $g_1, g_2, \tilde{g}$ are also small fractions defined with an implicit unit $e^2 / (g_0 s_w^2 c_w^4)$ so that the interaction are consistent in dimensions of mass. The new type of coupling $g_1, g_2, \tilde{g}$ should also be smaller than the SM one, since most of the experimental data are consistent with the SM up to now. The number of free parameters in new physics is then reduced from 12 [13] to only 4 while keeping a sufficiently general structure in interaction between Higgs and vector bosons.

In the Higgs factory of lepton collider, the on-shell Z boson and Higgs boson are produced simultaneously through a virtual Z boson, after electron and positron annihilation. Both the Z and Higgs boson are going to decay promptly. We will focus only on the Z decay to a pair of leptons, since they are the kinds of particles with the highest detection efficiency and carrying on the polarization message of Z boson. The kinematics of this process is illustrated in Fig. [1]. Above-mentioned new physics coupling of $HZZ$ beyond SM will make the $e^+ e^- \rightarrow Z^* \rightarrow HZ$ cross section different from SM, which has been discussed before.

Obviously the complicated new physics structure in eq.(2) will also change the polarization fraction of the Z boson, making the angle distributions of the final lepton pairs different from the SM case.

The momenta and the helicities of incoming (anti)electron and outgoing bosons are defined through:

$$e^- (p_1, \sigma_1) + e^+ (p_2, \sigma_2) \rightarrow Z (k, \lambda) + H (q),$$

where $\sigma_{1,2} = +\frac{1}{2}, -\frac{1}{2}$ and $\lambda = -1, 0, +1$. The invariant amplitude for this Higgs production...
is
\[ \mathcal{M}^\lambda = \bar{v}(p_1)(v_e I + a_e \gamma_5)\gamma_\tau u(p_2)P^{\tau\mu}V_{\mu\nu}(k + q, k)\epsilon^{\lambda\nu}, \quad (4) \]
where \( P^{\tau\mu} \) is the propagator of virtual Z boson in unitary gauge and the polarization vector \( \epsilon^\lambda(k) \) of real Z is
\[
\begin{align*}
\epsilon^{\pm\mu} &= (0, \cos \hat{\theta}, \mp I, \pm \sin \hat{\theta})/\sqrt{2}, \\
\epsilon^{0\mu} &= (k, E_z \sin \hat{\theta}, 0, E_z \cos \hat{\theta})/M_z, \quad (5)
\end{align*}
\]
with \( E_Z \) the energy of Z boson.

In the rest frame of real Z, the decay (helicity) amplitude is written as \[14]\)
\[
D_{\lambda,\tau}(k^2, \vartheta, \phi) = \sqrt{k^2}(v_f + \tau a_f) d^\tau_{\lambda}(\vartheta, \phi), \quad (6)
\]
where \( \tau \) is the helicity of the spin analyzer in Z decay, and \( d^\tau_{\lambda}(\vartheta, \phi) \) is the usual \( \frac{1}{2} \)-representation of rotation group. There is also a Breit-Wigner form but left out as an overall factor. The scattering angle \( \hat{\vartheta} \), polarization angle \( \vartheta \) and azimuthal angle \( \phi \) is defined in Fig.1.

\section{A. Total cross section for Higgsstrahlung}

The differential cross section for Higgs production at Born approximation reads
\[
\frac{d\sigma}{d\cos \vartheta d\cos \vartheta d\varphi} = K \sum_{\tau} D^*_{\lambda',\tau}\rho^{\lambda\lambda'}D_{\lambda,\tau} \\
= K \sum_{\tau} \sum_{\sigma_1,\sigma_2} D^*_{\lambda',\tau}\mathcal{M}^{\chi}_{\sigma_1,\sigma_2}\mathcal{M}^\lambda D_{\lambda,\tau}. \quad (7)
\]
The kinetic factor \( K \) reads :
\[
K = \frac{\beta(m_Z^2/s, m_h^2/s)}{128s |s - m_Z^2|^2 32\pi^3 M_Z^2 \Gamma_Z}, \quad (8)
\]
where \( \beta(a, b) = (1 + a^2 + b^2 - 2a - 2b - 2ab)^{1/2} \), with \( s \) the center of mass energy square and \( |\mathbf{p}_l| \) the momentum of lepton as Z spin analyzer.
After integration of phase space, the total cross section is:

$$\sigma = K \frac{128\pi C_{ij}}{9} s Q,$$

where

$$Q = (g_0^2 + 2g'_3g_0)(E_Z^2 + 2m_Z^2) + \frac{1}{2} g_1g_0 s^2 E_Z s^{3/2}.$$  

(10)

Since the New Physics couplings are a small perturbation from the SM couplings, we keep only the leading order linear term contributions. It’s interesting that, the anomalous couplings appear as a combination:

$$g'_3 = 2g_2(s + m_Z^2) + g_3 + g_1 \sqrt{s} E_Z.$$  

(11)

This further reduces the number of free parameters to three, $g_1$, $g'_3$ and $\tilde{g}$. We’d also like to point out that, this combination take place at the level of amplitude of ZH associating production, so it is regarded as a new parameterization for the analyzing of Higgsstrahlung channel. To isolate the $g_2$ contribution one has to investigate the channel of Higgs’s decaying to Z pair whose yields seems smaller, as become an independent issue beyond the scope of this work.

### B. Polarization in Z boson decay

Although only three effective couplings left, one can not distinguish their contributions by only the total cross section measurement. Different kinds of new physics structure will give more information in the angular distributions of the decay products of Z boson, which characterize the polarization fractions of the Z boson. The polar angle distribution of the outgoing lepton is derived as

$$\frac{d\sigma}{d\sigma d\cos \theta} = \frac{3M_Z^2}{8(a_f^2 + v_f^2) Q} \times \left\{ \left[ (g_0^2 + 2g'_3g_0) \frac{E_Z^2}{M_Z^2} + g_1g_0 \frac{Q_1}{M_Z^2} \right] \Gamma^0(\theta) + \right.$$

$$\left. (g_0^2 + 2g'_3g_0) \left[ \Gamma^- (\theta) + \Gamma^+ (\theta) \right] \right\},$$

(12)
where $\Gamma^\lambda(\vartheta)$ is the normalized partial width of Z boson in $\lambda$ helicity state, defined as

$$
\Gamma^\pm(\vartheta) = \frac{1}{2}M_Z^2 \left[\left(a_f^2 + v_f^2\right)(\cos 2\vartheta + 3) + 8 \pm a_f v_f \cos \vartheta\right]
\tag{13}
$$

$$
\Gamma^0(\vartheta) = 2M_Z^2 (a_f^2 + v_f^2) \sin^2 \vartheta.
\tag{14}
$$

The fraction of each spin polarization characterized by the distribution of the polarization angle $\vartheta$, are obtained by integrating out the scattering angle $\hat{\vartheta}$. It is interesting to note that, the fraction of transverse polarization can be increased, if integration of the scattering angle not in the entire region, for example, a forward region can be defined by $|\cos \hat{\vartheta}| > \cos \frac{\pi}{4}$,

$$
\frac{d\sigma}{\sigma d\cos \vartheta}\bigg|_{\text{fwd}} = \frac{3M_Z^2}{128(a_f^2 + v_f^2) Q} \times \left\{2(8 - 5\sqrt{2}) \cdot \left[\left(g_0^2 + 2g_3g_0\right) \frac{E_Z^2}{M_Z^2} + g_1g_0 \frac{Q_1}{M_Z^2}\right] \Gamma^0(\vartheta) + (16 - 7\sqrt{2})(g_0^2 + 2g_3g_0) \times \left[\Gamma^-(\vartheta) + \Gamma^+(\vartheta)\right] \right\}.
\tag{15}
$$

It’s obvious that the contribution from $\Gamma^\pm(\vartheta)$ is enhance by a factor of 3.3 in the forward region. In experiments, this polarization distribution, together with the total cross section, will be used to fit the parameters $g_1$ and $g'_3$.

C. Azimuthal angle distribution for CP violation

Up to now, all the analyses are independent of the CP violation term $\tilde{g}$ in the effective Hamiltonian of eq.[1]. This term in the effective Hamiltonian characterizes the CP violating effects in the new physics beyond the standard model. We have to study the azimuthal angle $\varphi$ dependence in the Z boson decay in order to study this CP violation effects:

$$
\frac{d\sigma}{\sigma d\varphi} = \frac{1}{2\pi} - \frac{M_Z^2}{4\pi Q} \times \left\{(g_0^2 + 2g_3g_0) \cos 2\varphi + g_0\tilde{g}s\beta \sin 2\varphi\right\}.
\tag{16}
$$

Here the first two terms came as a background from Standard Model, CP-violation shows up in the third term, whose $\sin 2\varphi$ dependence signal itself against the background in the shape of $\cos 2\varphi$.

There is no $\sin \varphi$ term in the above equation. However it can be recovered by breaking
FIG. 2: Differential cross section of Higgs production as function of azimuthal angle $\varphi$ by Eq. (17), black for SM while blue for possible new physics beyond SM

the symmetry in decay angle $\vartheta$ integration only $0 \rightarrow \pi/2$ or $\pi/2 \rightarrow \pi$, at a price of $\cos \varphi$ background in the SM

$$\frac{d\sigma}{d\varphi}|_{\vartheta \geq \pi/2} = \frac{M_Z^2}{16\pi Q} \times \left\{ \frac{8Q}{M_Z^2} - 4(g_0^2 + 2g_3'g_0) \cos 2\varphi - 4g_0\tilde{g}s\beta \sin 2\varphi + 3g_0\tilde{g}s - \frac{2a_e^2}{v_e^2 + a_e^2} M_Z \sin \varphi \pm 6\frac{\pi a_e v_e}{(v_e^2 + a_e^2)} \left[ (g_0^2 - 2g_3'g_0) \frac{E_Z}{M_Z} + g_0g_3' \frac{Q_1}{E_Z M_Z} \right] \cos \varphi \right\}. \quad (17)$$

One can see from Fig. 2 that this distribution with $\sin \varphi$ will signature CP violation by breaking the height-equality of two peaks in the background; while the $\sin 2\varphi$ term makes a phase shift against CP conserving backgrounds of the standard model.

III. ESTIMATIONS OF CONSTRAIN LIMITS AT FUTURE HIGGS FACTORIES

At future Higgs factories, millions of Higgs production events are expected, which will give signal of new physics or provide at least constrains to the new physics presented in the form of Eq. (2). For example, the circular electron position collider may deliver a luminosity of $5000 fb^{-1}$ at center of mass energy $E = 240 GeV$. In the conceptual design report [26], the exclusive channel of $e^-e^+ \rightarrow ZH \rightarrow l^+l^-b\bar{b}$ is investigated with phase space cuts:

- $p_l \geq 18 GeV, p_b \geq 20 GeV$,

- $|cos\theta_l| \leq 0.98, |cos\theta_b| < 0.98$,
• $|M_{l^+ l^-} - M_Z| < 15\text{GeV}, |M_{b\bar{b}} - M_H| < 12\text{GeV}$.

Furthermore the CEPC simulations provided the expected performance to use:

• lepton identification efficiency : 85%

• bottom jet tagging efficiency : 75%.

We have adopted relatively tighter cuts on phase space and on particle tagging (identification) so that the background (mainly $ZZ$ production) can be suppressed to ignorable level, at least their contamination can be well estimated and subtracted in future experiment.

Before the real Higgs factory data and the details of possible systematical studies become available, we simply do the simulations with Monte Carlo comparing the new physics contribution with that from standard model. Based on the histograms for the angle distributions in SM, a Pearson $\chi^2$ is defined simply with the events numbers by hypothesis of new physics from each bin of angle histogram. When the parameters $g_1, g_3'$ and $\tilde{g}$ reach to sufficiently small magnitudes, the effect of new physics will be concealed beneath the coverage of (mainly statistical) SM errors (reflected by $\chi^2$) in the future experiment, so their limits of sensitivity can be estimated accordingly.

Instead of inviting additional assumptions or more complicated procedures, anywhere we quoted as well a systematical error at the same level as the statistical one, then the sensitivities limits estimated in following subsections are very conservative. Any optimized and reliable limit-setting should be left to the actual data analysis in future upon more reasonable experimental inputs.

A. Limit from total cross section

Using the above mentioned cuts in the Higgs factory, we scanned the new physics parameters $(g_1, g_3')$ simultaneously. Their sensitivity limits will arrive when $\Delta \sigma/\sigma \geq \sqrt{2}/\sqrt{N_{\text{evt}}}$, where $N_{\text{evt}}$ is the observed (signal) event number in $ZH \rightarrow l^+ l^- b\bar{b}$, as shown in Fig.3. The new physics parameters of $(g_1, g_3')$ inside the parallelogram will be difficult to distinguish from the standard model within experimental errors. It can be understood that CEPC can set a limit down to $|g_3'| \leq 0.015$ and $|g_1| \leq 0.035$.

One may also set the limits lower to $|g_3'| \leq 0.005$ and $|g_1| \leq 0.015$ to pursue a higher sensitivity, by discarding the systematical errors and relaxing events selections.
FIG. 3: New physics sensitivity limits from total cross section measurements. The parameters inside the parallelogram region are difficult to distinguish from the standard model within experimental errors.

Just for the total cross section, on the other hand, the reconstruction of recoiled Z boson will lead to an inclusive analysis with Higgs decaying to anything rather than merely $b\bar{b}$ final states. In this case, a tighter limit can be set with about 3 times larger statistics. In such a reconstruction of recoiled Higgs, it’s possible to walk around the dependence on the invisible decays from Higgs, however its details go beyond the scope of this paper.

B. Limit from Z polarization

FIG. 4: Expected event number distributed along the polarization angle $\vartheta$, blue for Eq. (12) and black for Eq. (15)

When there is enough experimental data, we can also study the new physics effect sensi-
tivity through polarization angle distribution shown in Eq. (12) and (15). The expected event number distributed along the polarization angle \( \vartheta \), are shown in Fig. 4, with blue points for Eq. (12) and black points for Eq. (15). The polarization angle will distribute differently as the black plot in Fig. 4 if only the forward region of the decay angle is investigated as in Eq. (15). Since it will come with lower statistics (only half number of events), it will be skipped in the current numerical analysis, until there is better input for experimental systematics.

![FIG. 5: Limits from polarization angle, no sensitivity in the belt closed by the blue lines. The black belt is from Fig. 3. The overlap of two belts are in the meshed region](image)

After sensitivity study, we show the experimental limits from polarization angle distributions for the new physics parameters \( g_1 \) and \( g_3' \) in Fig. 5. Parameter regions inside the blue lines are not distinguishable from the standard model. We also copy the limits from cross section study in Fig. 3. It shows in Fig. 5 that, the two limit regions have some overlaps and also some differences. This means that the sensitivity limits are further narrowed into the meshed region. The polarization angle distribution will be anyway helpful since it will constrain new physics from a different direction rather than the cross section. It’s also worth to point out that, the distribution of polarization angle is normalized as in Eq. (12) by the cross section. It means less dependence or uncertainties from Higgs production or decay, because of the actual analysis by a fit solely on the shape. This indicates better determination of the HZZ couplings.
C. Limit for CP Violation parameter \( \tilde{g} \)

According to Eq.\((16)\), we show the expected event number distributed along azimuthal angle \( \phi \) in Fig.\(6\), where CP violation effect may show up. Without losing of generality, each time only one of new physics parameters \( g_1 \) or \( g'_3 \) will be scanned together with the CP violation parameter \( \tilde{g} \).

![Figure 6: Expected event number distributed along azimuthal angle \( \phi \)](image)

Again the forward region defined in Eq.\((17)\) will be skipped in the current study for its lower statistics. After careful study of the backgrounds, we derive the experimental limit of \( \tilde{g} \) with the correlation of \( g'_3 \) shown in Fig.\(7\). The correlation sensitivity of \( \tilde{g} \) and \( g_1 \) are shown in Fig.\(8\). These figures indicate that, the experimental sensitivity can reach the limit of \( \tilde{g} \) to \(-0.04 \sim 0.01\).

IV. SUMMARY

We have studied the new physics sensitivity in the \(e^+e^- \to HZ\) process of the future Higgs factory. By the cross section and angular distribution measurements, we set experimental limits for the Dimension-6 operators of Effective Field Theory in a model independent way. Especially by the study of azimuthal angle distribution of the Z boson decay, we found that the future Higgs factory can set a stringent limit to the CP-violation effective operators in the new physics, i.e. the \( \tilde{g} \) sensitivity limit up to \(-0.04 \sim 0.01\). Our study shows that the future electron positron collider will be an ideal machine for the search of New Physics signal.
FIG. 7: Experimental limits of $\tilde{g}$ from azimuthal angle distribution study, with $g'_3$ in correlation, with no sensitivity in the belt.

FIG. 8: Experimental limits of $\tilde{g}$ from azimuthal angle distribution study, with $g_1$ in correlation, no sensitivity in the belt.

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