Chinese Physics C Vol. 39, No. 11 (2015) 113101

New physics searches with Higgs-photon associated production at the Higgs factory *

REN Hong-Yu(任泓雨)[1,2;1)]

[1] Department of Physics, Tsinghua University, Beijing 100084, China
[2] Laboratory for Elementary Particle Physics, Cornell University, Ithaca, NY 14853, USA

Abstract: A future Higgs factory is being designed for precise measurement of Higgs characteristics and to search for new physics. In this paper we propose that the Higgs-photon associated production process, $e^+e^-\to\gamma h$ could be a useful channel for new physics. We express new physics model-independently in the effective Lagrangian approach, and find that the new physics effects of γh have only two degrees of freedom, much fewer than the Higgsstrahlung process. This point could be used to reduce the degeneracies of Wilson coefficients. We also calculate for the first time the 95% confidence level(CL) bounds of γh at the Higgs factory, and prove that γh is more sensitive to some dimension-6 operators than the current experimental data. In the optimistic scenario new physics effects may be observed at the CEPC or FCC-ee after the first couple of years of their run.

Key words: Higgs-photon associated production, Higgs factory, new physics, effective Lagrangian

PACS: 12.15.-y, 12.60.Fr **DOI:** 10.1088/1674-1137/39/11/113101

1 Introduction

Following the discovery of the Higgs boson, precise understanding of the nature of this particle is a top priority for particle physics. All measurements of rates involving the Higgs production and decay in Run 1 of the LHC agree with the predictions of the Standard Model (SM), but statistical uncertainties limit their precision to 10%–20% level at best. The LHC is expected to ultimately reach a precision of order of a few percent, at which point systematic and theoretical issues, such as parton distribution function uncertainties, become a limiting factor. Further improvements in precision are possible at an electron–positron collider with sufficient center-of-mass energy to produce a large sample of Higgs bosons, the so-called "Higgs factory" [1]. Currently, proposals for Higgs factories are being discussed by the physics community, including the CEPC [2, 3], as well as circular collider designs such as FCC-ee (formerly known as TLEP) [3, 4] and the International Linear Collider [5]. The physics case for all these machines rests on their ability to test the SM, and search for new physics beyond the SM (BSM), via precision measurements of the Higgs properties.

The dominant Higgs production process in electron–positron collisions in the energy range relevant for Higgs factories, $\sqrt{s}\sim 225\cdots 350$ GeV, is the Higgsstrahlung process, $e^+e^-\to Zh$. The cross section of this process is expected to be measured with exquisite precision, well below 1% level, at the Higgs factory. The sensitivity of this measurement to new physics involving the Higgs has been explored by many authors [6–9, 11–20]. In this paper, we propose that the Higgs production in association with a photon, $e^+e^-\to\gamma h$, could be a new way to study new physics. In the SM, the leading contribution to the scattering amplitude for this process appears at the one-loop order, as a result of which, its cross section is strongly suppressed compared to Higgsstrahlung, which occurs at tree-level. For this reason, the γh production channel has not received as much attention so far in the studies of a Higgs factory physics potential. However, small SM cross section may offer an advantage in searches for BSM physics, since the BSM effects in the γh channel are expected to produce much larger relative change of cross section than in the case of Zh. This may compensate for larger statistical uncertainties in the γh rate measurement, resulting in competitive sensitivity to new physics. The goal of this paper is to study this issue quantitatively, in the framework for new physics: the effective Lagrangian approach.

Received 17 March 2015

∗ Supported by National Natural Science Foundation of China (11275102) and Tsinghua Scholarship for Overseas Graduate Studies

1) E-mail: renhy10@mails.tsinghua.edu.cn

The effective Lagrangian method is widely used in studies of new physics [10, 21–24], especially after Run I of the LHC [25–27], since none of the new physics models, including supersymmetry (SUSY), the 2-Higgs-doublets model (2HDM), etc., have had any evidence for them found at the LHC. As a consequence, compared to searching for new physics model by model, it is much more efficient to do it in a model-independent way. The effective Lagrangian, which is in the framework of effective field theory (EFT), has the advantage that it is not a specific model, but corresponds to a large number of models. Since it is quite likely that new physics will appear at a rather high (compared to electroweak scale E_{EW}) energy level, say Λ, the degrees of freedom with energy above Λ can be integrated out and the Lagrangian is then a function of Λ and other parameters of the new physics model. Expanding the Lagrangian by E_{EW}/Λ, we can get the effective Lagrangian

$$\mathcal{L}_{\mathrm{EFT}}=\mathcal{L}_{\mathrm{SM}}+\sum_{n=1}^{\infty}\sum_{i}\frac{f_i^{(n)}}{\Lambda^n}\mathcal{O}_i^{(n)}, \tag{1}$$

where the n is the order of the expansion and $f_i^{(n)}$ is the Wilson coefficient. The operator $\mathcal{O}_i^{(n)}$ is of dimension-$(n+4)$ and describes a kind of anomalous coupling beyond the SM. From Eq. (1) it is clear that the effective Lagrangian is just the SM if all the Wilson coefficients are 0. Models with new physics scales $\Lambda \gg E_{\mathrm{EW}}$ can all be described in the language of effective Lagrangian in Eq. (1). For example, it has been proved that a specific supersymmetry model, with only the super partners of the top quark undecoupled, has almost the same phenomenology as the EFT, if the Wilson coefficients are expressed by the SUSY parameters [20, 28]. In general, each of the new physics models corresponds to a group of Wilson coefficients in the EFT. In other words, once a deviation from the SM background is observed through the γh process, we can then measure the related Wilson coefficients, which reflect a property of nature. If the related Wilson coefficients predicted by a new physics model are consistent with the measured values, the model can survive. Otherwise the model is ruled out. So the effective Lagrangian method enables us to study new physics in a model-independent way: we need only detect the anomalous couplings (or the effective operators $\mathcal{O}_i$) through some observables. Information of new physics models could be collected easily after we measure these couplings, or Wilson coefficients, precisely.

In this paper, we prove that the γh process could be very useful to help measure Wilson coefficients, and this, as mentioned above, is very important to new physics studies.

2 $e^+e^-\to\gamma h$ in the Standard Model

The SM cross section for $e^+e^-\to\gamma h$ has been computed by several groups [29–31]. We calculate the amplitudes of all the Feynman diagrams in this process, as shown in Fig. 1. The loop integrals are expressed in terms of Passarino-Veltman integrals, which can be calculated numerically with the help of LoopTools [32]. We make the calculation in Feynman gauge and the results are proved to be gauge-invariant[1].

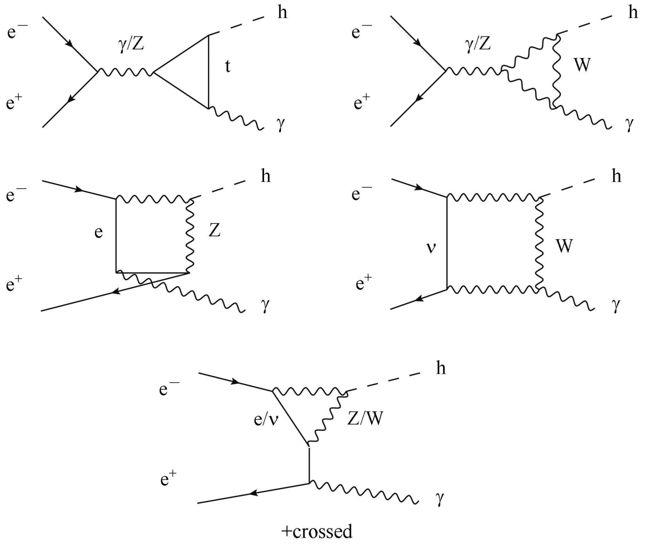

Fig. 1. The main Feynman diagrams of $e^+e^-\to\gamma h$ in the SM. The crossed diagrams are not displayed here.

The SM cross section with unpolarized beams as a function of the center-of-mass energy is shown in Fig. 2. The cross section at $\sqrt{s}=250$ GeV, a benchmark energy for Higgs factories, is close to the maximum, about 0.08 fb. This is about 2500 times smaller than the Zh cross section at the same energy, since the γh process is loop-suppressed. Still, with projected luminosities of Higgs factories, a significant number of γh events can be expected. For example, data samples in the 1–10 ab^{-1} range, envisioned in proposals for circular Higgs factories, would contain hundreds of such events.

The separation of the signal from the backgrounds is straightforward. At an e^+e^- collider, the photons produced in association with the Higgs are monoenergetic:

$$E_{\gamma}=\frac{s-m_{\mathrm{h}}^2}{2\sqrt{s}}. \tag{2}$$

At $\sqrt{s}=250$ GeV, this gives a "spectral line" at 93.75 GeV. The natural Higgs width being very small,

---

[1] All the results agree with these papers numerically.

the width of the line is dominated by the detector resolution, which is expected to be $\delta E_\gamma/E_\gamma \approx 1\%$ [33]. This allows for clear separation between the γh line and the much larger γγ and Zγ lines, at 125.0 and 108.4 GeV, respectively. To increase S/B further, one can demand that the Higgs boson be reconstructed, for example as a pair of jets consistent with an invariant mass of 125 GeV. This requirement will virtually completely eliminate most of the backgrounds, with the remainder mainly coming from a γ and an off-shell Z boson associated production, while the Z boson decays to two jets. The clean environment of the e^+e^- collisions allows for reconstruction of the Higgs with high efficiency in all relevant decay channels. We generate the background with MadGraph [34], requiring that the $\delta E_\gamma/E_\gamma \approx 1$ (as mentioned above) and the reconstructed Higgs mass $M_h \approx 125\pm5$ GeV [1]. In this study, we will assume that the dominant error in the $e^+e^-\to\gamma h$ cross section measurement is statistical, while the significance can be calculated by the relation $S/\sqrt{B}$.

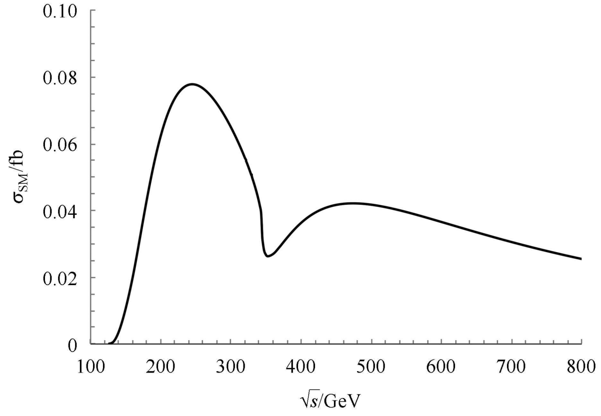

Fig. 2. The cross section of $e^+e^-\to\gamma h$ in the SM.

3 New physics in $e^+e^- \to \gamma h$: effective Lagrangian

If new physics appears at a scale $\Lambda \gg \sqrt{s}$, its effects can be described model-independently in the language of the effective Lagrangian, by adding all possible non-renormalizable operators consistent with gauge and global symmetries of the SM. The leading term in the $\sqrt{s}/\Lambda$ expansion of the Lagrangian contains dimension-6 operators [10]:

$$\mathcal{L}_{\mathrm{dim6}}=\sum_i \frac{f_i}{\Lambda^2}\mathcal{O}_i, \tag{3}$$

where the f_i are dimensionless Wilson coefficients.

The following dim.-6 operators contribute to the process $e^+e^-\to\gamma h$:

$$\begin{aligned}\mathcal{O}_{\mathrm{HW}} &= \mathrm{i}g(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu},\\ \mathcal{O}_{\mathrm{HB}} &= \mathrm{i}g'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu},\\ \mathcal{O}_{\mathrm{BB}} &= g'^2|H|^2B_{\mu\nu}B^{\mu\nu},\\ \mathcal{O}_{\mathrm{eW}} &= gy_l\bar{L}_L\sigma^a\gamma^{\mu\nu}He_RW^a_{\mu\nu}+\mathrm{h.c.},\\ \mathcal{O}_{\mathrm{eB}} &= g'y_l\bar{L}_L\gamma^{\mu\nu}He_RB_{\mu\nu}+\mathrm{h.c.}\end{aligned} \tag{4}$$

The last two operators are expected to be Yukawa-suppressed due to chirality flip, and we will not consider them further in this paper. The first three operators are related to the anomalous Higgs-vector boson couplings, which can be generated in most new physics models, such as the simple SUSY model in Ref. [28]. After electroweak symmetry breaking, the first three operators induce $Z\gamma h$ and $\gamma\gamma h$ vertices, leading to a tree-level contribution to the $e^+e^-\to\gamma h$ amplitude, as shown in Fig. 3, although they are s/Λ^2-suppressed.

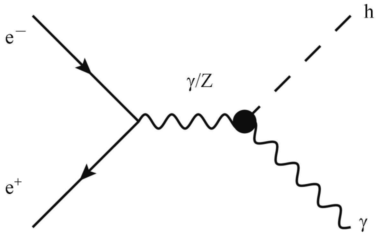

Fig. 3. The Feynman diagram of $e^+e^-\to\gamma h$ in the EFT. The big black dot represents the anomalous Hγγ or HZγ coupling.

The new physics contribution to the scattering amplitude is given by

$$\mathcal{A}_{\mathrm{EFT}}=\sum_{a=+,-}\Lambda^aC^a_{\mathrm{EFT}}, \tag{5}$$

where

$$\Lambda^\pm=\bar{v}(p_+)(1\pm\gamma_5)[\not\epsilon_\gamma p_\gamma\cdot(p_++p_-)-\not p_\gamma\epsilon_\gamma\cdot(p_++p_-)]u(p_-) \tag{6}$$

and

$$\begin{aligned}C^\pm_{\mathrm{EFT}} = &-\frac{2e^2s_\theta m_{\mathrm{W}}^3}{\Lambda^2}\times\Bigg[\frac{2}{s}f_{\mathrm{BB}}\\ &+\frac{\lambda^\pm}{8s_\theta^2(1-s_\theta^2)(s-m_{\mathrm{Z}}^2)}(f_{\mathrm{HW}}-f_{\mathrm{HB}}+8s_\theta^2f_{\mathrm{BB}})\Bigg].\end{aligned} \tag{7}$$

Here s_θ is the sine of the Weinberg angle; p_- and p_+ are the electron and positron momenta; $s=(p_-+p_+)^2$; and

$$\lambda^+=-1+2s_\theta^2,\quad \lambda^-=2s_\theta^2. \tag{8}$$

The leading correction to the cross section is due to interference between the SM one-loop amplitude and $\mathcal{A}_{\mathrm{EFT}}$. Numerically, the relative change in the total cross section at $\sqrt{s}$=250 GeV is given by

$$\begin{aligned}\frac{\Delta\sigma(\gamma \mathrm{h})}{\sigma(\gamma \mathrm{h})} \approx\ & [0.76(f_{\mathrm{HW}}-f_{\mathrm{HB}})-1.47f_{\mathrm{BB}} \\ & +0.23(f_{\mathrm{HW}}-f_{\mathrm{HB}})^2+5.63f_{\mathrm{BB}}^2 \\ & +0.59(f_{\mathrm{HW}}-f_{\mathrm{HB}})f_{\mathrm{BB}}]\Lambda_{\mathrm{TeV}}^{-2}, \end{aligned} \tag{9}$$

where $\Lambda_{\mathrm{TeV}}\equiv\Lambda/(1\ \mathrm{TeV})$. For comparison, the relative change of the $\mathrm{e^+e^-}\rightarrow\mathrm{hZ}$ cross section at the same energy is [20]

$$\frac{\Delta\sigma(\mathrm{hZ})}{\sigma(\mathrm{hZ})}\approx(0.05f_{\mathrm{HW}}-0.005f_{\mathrm{HB}}+0.01f_{\mathrm{BB}}+\cdots)\Lambda_{\mathrm{TeV}}^{-2}, \tag{10}$$

where we omit the contributions from operators that do not contribute to γh. These formulas illustrate the advantage of the γh process mentioned in the Introduction: the SM amplitude is tree-level in hZ and loop-suppressed in γh, resulting in a much larger relative change of the cross section in the latter case.

The numerator in Eq. (9), $\Delta\sigma(\gamma\mathrm{h})$, which means the difference in the cross section of the $\mathrm{e^+e^-}\rightarrow\gamma\mathrm{h}$ caused by new physics effects, is the signal. The background is $\sigma(\gamma\mathrm{h})+\sigma_{\mathrm{BKG}}$, where the σ_{BKG} is the background cross section of the γh process,

$$\sigma_{\mathrm{BKG}}=\sigma(\mathrm{e^+e^-}\rightarrow\gamma\mathrm{b\bar{b}})+\cdots. \tag{11}$$

In this case, if

$$\frac{\Delta\sigma(\gamma\mathrm{h})L_{\mathrm{int}}}{\sqrt{(\sigma(\gamma\mathrm{h})+\sigma_{\mathrm{BKG}})L_{\mathrm{int}}}}\geqslant 2, \tag{12}$$

it can be claimed that the new physics effects could be observed at least at 95%CL. Otherwise we get a 95% exclusion limit of the new physics parameters. In this paper, the $\Delta\sigma(\gamma\mathrm{h})$ and $\sigma(\gamma\mathrm{h})$ are calculated directly from their expressions in terms of the numerical results of Passarino-Veltman integrals (as shown in Fig. 2 and Eq. (9)), and the σ_{BKG} are generated by MadGraph [34], using a Monte Carlo method. The restriction of the background events are stated at the end of Section 2.

Using Eq. (9) and Eq. (12), we can get the 95% exclusion limit of the effective parameters at the Higgs factory for some integrated luminosity. The results are listed in Table 1. The estimates assume integrated luminosity of $L_{\mathrm{int}}=10\ \mathrm{ab}^{-1}$ at $\sqrt{s}$=250 GeV, corresponding to the FCC-ee projection in Ref. [3]; the sensitivities scale as $L_{\mathrm{int}}^{-1/2}$. For these parameters, a sample of about 800 γh events would be collected. The difference of the cross sections $\Delta\sigma$ caused by the effective operators should be about 20% of σ_{SM} at 95%CL, considering both the γh process in SM and the background cross sections (assuming statistical error dominance and 100% event reconstruction efficiency). For clarity and ease of comparison among various measurements, the reach for each operator is estimated assuming that all other operators are set to zero. Table 1 also list bounds from a global fit to currently available data [26], such as precision electroweak observables and the Higgs rate measurements at the LHC. For two of the three relevant operators, $\mathcal{O}_{\mathrm{HB}}$ and $\mathcal{O}_{\mathrm{HW}}$, the $\sigma(\gamma\mathrm{h})$ measurement at the Higgs factory will probe scales exceeding the current bounds. The third operator, $\mathcal{O}_{\mathrm{BB}}$, is already very well constrained by the measurement of $Br(\mathrm{h}\rightarrow\gamma\gamma)$ at the LHC, where the competing SM amplitude only appears at the one-loop order. In this case, neither the γh nor the Zh channel could perform better than current data. However, it should be emphasized that this is so only as long as the operators are turned on one-by-one; the LHC bound on $\hat{c}_{\mathrm{BB}}$ can be significantly relaxed if other operators, for example $\mathcal{O}_{\mathrm{GG}}=|H|^2G^a_{\mu\nu}G^{a\mu\nu}$, are present. The measurement of the γh cross section at the Higgs factory will allow us to resolve such ambiguities.

The operators that contribute to $\mathrm{e^+e^-}\rightarrow\gamma\mathrm{h}$ will also modify the Zh cross section. For comparison, the sensitivities of this measurement are also listed in Table 1. In all cases, we assume that statistical errors dominate, and use the same benchmark value of 10 ab^{-1} for integrated luminosity. (As long as the precision is statistics-limited, all estimates scale as $L_{\mathrm{int}}^{-1/2}$, so that statements concerning the relative power of various measurements remain valid.) For all three operators, $\sigma(\mathrm{Zh})$ measurements have somewhat higher reach compared to the $\sigma(\gamma\mathrm{h})$ measurement. Still, including $\sigma(\gamma\mathrm{h})$ in a global fit should give a meaningful improvement in sensitivity to new physics.

In general, angular distributions of final-state particles may contain additional information allowing for better discrimination between SM and new physics, and also, should a new physics effect be observed, between various possible combinations of dim.-6 operators. Unfortunately, in the case of $\mathrm{e^+e^-}\rightarrow\gamma\mathrm{h}$, no significant information is contained in the photon angular distribution,

Table 1. Current 95%CL bounds (2nd column) and future Higgs factory 95%CL exclusion sensitivities (3rd-4th columns) on the coefficients of the dim.-6 operators that contribute to $\mathrm{e^+e^-}\rightarrow\gamma\mathrm{h}$. Here $\hat{f}_i=m_{\mathrm{W}}^2f_i/\Lambda^2$. The current bounds are taken from Ref. [26]. Higgs factory estimates assume that statistical uncertainties dominate. The main background of γh is included while that of Zh is not, because the huge cross section of Zh can surpasses the effects of background.

coefficients	current bound	γh bound	Zh bound
$\hat{f}_{\mathrm{HW}}$	$(-0.042,\ 0.008)$	$(-0.0050,\ 0.0033)$	$(-1.8,\ 1.8)\times10^{-4}$
$\hat{f}_{\mathrm{HB}}$	$(-0.053,\ 0.044)$	$(-0.0033,\ 0.0050)$	$(-1.8,\ 1.8)\times10^{-3}$
$\hat{f}_{\mathrm{BB}}$	$(-4.0,\ 2.3)\times10^{-4}$	$(-0.0012,\ 0.0028)$	$(-9,\ 9)\times10^{-4}$

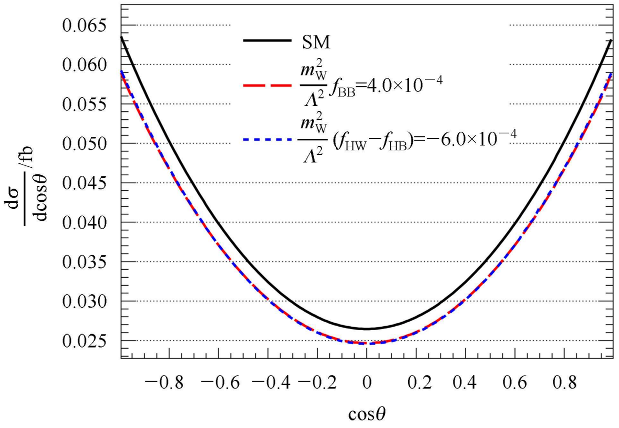

Fig. 4. (color online) Photon angular distributions at $\sqrt{s}=250$ GeV, in the SM (black/solid) and in the EFT with two different choices of the dimension-6 new physics operators (red/long-dashed and blue/short-dashed).

as is clear from Fig. 4. The angular distribution can be calculated from the scattering amplitude given by Eq. (5). There may be additional information in angular correlations between γ and the Higgs decay products; we defer a study of such correlations for future work.

So far, we have considered bounds in the situation where a single dimension-6 operator is assumed to be dominant. However, the more general situation is that each observable constrains a particular linear combination of operators, leaving a subspace in the operator coefficient space unconstrained. For example, if described by an effective Lagrangian, the new physics in Zh has about 10 degrees of freedom [20] but only one observable. We therefore need more observables to reduce, or even eliminate such degeneracies. γh could be one such observable. From Eq. (9) we can see that the cross section of γh has only two degrees of freedom, $f_{HW}-f_{HB}$ and f_{BB}, and the latter has been constrained strictly by the current data. This means if a new physics effect is observed through γh in future, we can almost be certain that it comes from the $\mathcal{O}_{HW}$ or $\mathcal{O}_{HB}$. This is the advantage of γh compared to Zh, and is why we claim that γh is still valuable although it is less sensitive than Zh.

We can also implement a full(two)-parameter analysis on the 95% CL bounds of γh, as shown in Fig. 5. The shaded (green) area is the range of the coefficients where the anomalous couplings cannot be detected by the Higgs factory at $L_{int}=10$ ab^{-1}($L_{int}=1$ ab^{-1}). From this figure it is clear that γh can be helpful to measure or give new bounds to the Wilson coefficients $f_{HW}-f_{HB}$ especially, without any assumption about other new physics factors. If there are new physics effects within the sensitivity of γh, it is hopeful that we can see them in the first few years of running of CEPC or FCC-ee. If not, we could give limits on $f_{HW}-f_{HB}$, and these limits can be applied to Zh or other processes to extract more information about new physics effects.

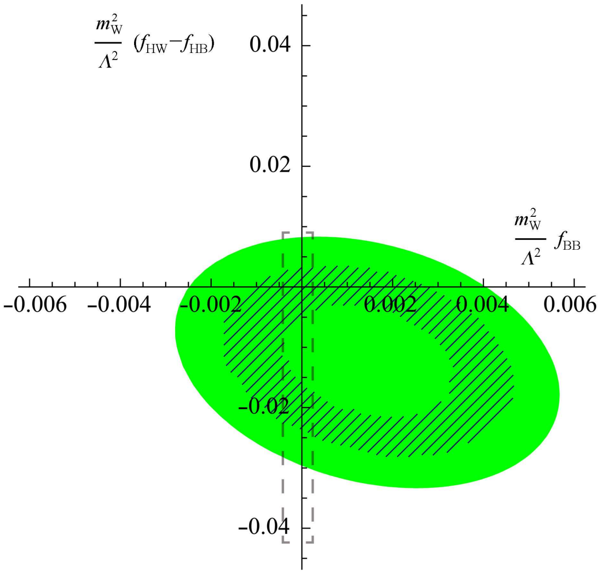

Fig. 5. (color online) The 95%CL bounds of γh at the Higgs factory with different integrated luminosities. The bounds are obtained through a two-parameter analysis. The shaded region is where the effective operators are beyond the sensitivity of γh at the integrated luminosity of 10 ab^{-1}, which could be provided by FCC-ee in about 5 y. The green region corresponds to 1 ab^{-1}, which could be provided by CEPC in about 2 y [3]. The dashed grey lines are the current 95%CL bounds obtained with single-parameter analysis.

We close this section with a comment of a technical nature. Numerical SM predictions of cross sections such as $\sigma(\gamma h)$ depend on the values of the electroweak gauge couplings and the Higgs vacuum expectation value, which are inferred from the three most precisely measured electroweak observables, currently M_Z, α, and G_F (from muon lifetime). New physics can contribute to these observables, producing a shift between the inferred and the true values of these parameters. In general, such shifts contribute to the deviation of cross sections from their SM values. For example, in the case of σ(hZ), the contribution of such anomalous coupling constants is of the same order as the direct contribution of the dim.-6 operators, and both need to be taken into account for consistency [20]. However, in the case of $\sigma(\gamma h)$, where the leading SM amplitude is one-loop, the correction of the scattering amplitude due to the anomalous couplings is of the order $\frac{1}{16\pi^2}\frac{s}{\Lambda}$, whereas the direct contribution of dim.-6 operators is of the order $\frac{s}{\Lambda^2}$. The additional loop factor in the anomalous couplings correction renders it negligible, and we do not include this effect in our analysis.

4 Conclusion

The proposed Higgs factories, CPEC, FCC-ee and ILC, are being designed to study the Higgs couplings with other particles precisely, by producing a large number of Higgs bosons mainly through the Higgsstrahlung process, $e^+e^- \rightarrow Zh$. Higgsstrahlung is commonly believed to be one of the most precise processes for measuring the Higgs couplings, and it can be very sensitive to new physics. In order to do an exhaustive scan of new physics effects, we use the effective Lagrangian, which is currently very popular in new physics searches, to describe anomalous couplings model-independently. The Wilson coefficients of the effective operators are degrees of freedom beyond the SM in this framework. Higgsstrahlung then has too many degrees of freedom, but not enough observables. This may cause degeneracies and "blind spots" where new physics effects escape the reach of the detectors. In this paper, we propose a new idea, the $e^+e^- \rightarrow \gamma h$ channel, as another valuable channel to detect new physics effects. The advantage of γh is that it has only two degrees of freedom and also a good sensitivity, compared to the current data. We also calculate for the first time the amplitude and cross section of γh in terms of Wilson coefficients. With the help of γh, we can extract the information on $f_{HW}-f_{HB}$ and this will tell if a new physics model could be ruled out by the experiment. Only those new physics models that are consistent with the measurement can survive. Otherwise they should be ruled out. In our future work, we will also study the Higgs decay processes $h\rightarrow\gamma\gamma$ and $h\rightarrow Z\gamma$. These two decay modes have the same degrees of freedom as γh and are believed to be sensitive to BSM effects too [35]. The $h\rightarrow\gamma\gamma$ decay has been studied in Refs. [1, 3] but $h \rightarrow Z\gamma$ has not. These two channels may be valuable in reducing the degeneracies of Wilson coefficients, acting as a cross check of the Zh and γh results, and is worth an exhaustive analysis.

The author is very grateful for the guidance of Prof. Maxim Perelstein, and the conversations with Prof. Yu-Ping Kuang and Ling-Hao Xia.

References

1 Dawson S, Gritsan A, Logan H, QIAN J M, Tully C et al. arXiv: 1310.8361, 2013

2 CEPC webpage. http://cepc.ihep.ac.cn/intro.html

3 RUAN M. arXiv: 1411.5606, 2014

4 Bicer M et al. JHEP, **1401**: 164

5 Baer H, Barklow T, Fujii K, GAO Y, Hoang A et al. arXiv: 1306.6352, 2013

6 Hagiwara K, Stong M L. Z. Phys. C, 1994, **62**: 99-108

7 Gounaris G J, Renard F M, Vlachos N D. Nucl. Phys. B, 1996, **459**: 51–74

8 Kilian W, Kramer M, Zerwas P M. Phys. Lett. B, 1996, **381**: 243–247

9 Gonzalez-Garcia M C. Int. J. Mod. Phys. A, 1999, **14**: 3121–3156

10 Buchmller W, Wyler D. Nuclear Physics B, 1986, **268**: 621–653

11 Hagiwara K, Ishihara S, Kamoshita J, Kniehl B A. Eur. Phys. J. C, 2000, **14**: 457–468

12 Biswal S S, Godbole R M, Singh R K, Choudhury D. Phys. Rev. D, 2006, **73**: 035001

13 Barger V, HAN T, Langacker P, McElrath B, Zerwas P. Phys. Rev. D, 2003, **67**: 115001

14 Kile J, Ramsey-Musolf M J. Phys. Rev. D, 2007, **76**: 054009

15 Dutta S, Hagiwara K, Matsumoto Y. Phys. Rev. D. 2008, **78**: 115016

16 Rindani S D, Sharma P. Phys. Rev. D, 2009, **79**: 075007

17 Contino R, Grojean C, Pappadopulo D, Rattazzi R, Thamm A. JHEP, **1402**: 006

18 Amar G, Banerjee S, von Buddenbrock S, Cornell A S, Mandal T et al. arXiv:1405.3957

19 Beneke M, Boito D, WANG Y M. arXiv: 1406.1361

20 Craig N, Farina M, McCullough M, Perelstein M. arXiv:1411.0676, 2014

21 Hagiwara K, Ishihara S, Szalapski R, Zeppenfeld D. Phys. Rev. D. 1993, **48**: 2182–2203

22 Gonzalez-Garcia M C. International Journal of Modern Physics A, 1999, **14**: 3121–3156

23 ZHANG B, KUANG Y P, HE H J, YUAN C P. Phys. Rev. D, 2003, **67**: 114024

24 QI Y H, KUANG Y P, LIU B J, ZHANG B. Phys. Rev. D, 2009, **79**: 055010

25 KUANG Y P, REN H Y, XIA L H. Phys. Rev. D, 2014, **90**: 115002

26 Ellis J, Sanz V, You T. arXiv: 1410.7703, 2014

27 CAO Q H, WANG H R, ZHANG Y. arXiv: 1503.05060, 2015

28 Henning B, LU X, Murayama H. arXiv: 1404.1058, 2014

29 Barroso A, Pulido J, Romao J C. Nucl. Phys. B, 1986, **267**: 509–530

30 Abbasabadi A, Bowser-Chao D, Dicus D A, Repko W W. Phys. Rev. D, 1995, **52**: 3919–3928

31 Djouadi A, Driesen V, Hollik W, Rosiek J. Nucl. Phys. B, 1997, **491**: 68–102

32 Hahn T. Nucl. Phys. B - Proceedings Supplements, 2000, **89(13)**: 231236

33 Behnke T, Brau J E, Burrows P N, Fuster J, Peskin M et al. arXiv: 1306.6329, 2013

34 Alwall J, Herquet M, Maltoni F, Mattelaer O, Stelzer T. JHEP, 2011, **06**: 128

35 HU S L, LIU N, REN J, WU L. Journal of Physics G: Nuclear and Particle Physics, 2014, **41**: 125004