Probing Higgs couplings to diphoton and Z-photon from Higgs+photon production at a Higgs factory

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Abstract

In this paper, we revisit the associated production of the SM-like Higgs boson ($H$) with a hard photon in the MSSM at $e^+e^-$ Higgs factory. Considering the constraints from the flavor physics, precision electroweak measurements, Higgs data and dark matter detections, we scan over the parameter space of the MSSM and calculate the cross section of $e^+e^-\rightarrow H\gamma$ in the allowed parameter space. Since the loop-induced gauge couplings $H\gamma\gamma$ and $HZ\gamma$ can simultaneously contribute to the process $e^+e^-\rightarrow H\gamma$, we find the cross section can be sizably enhanced by the light stau, maximally 1.8 times larger than the SM prediction at $\sqrt{s} = 240$ GeV. So at a high luminosity Higgs factory, the precise measurement of $e^+e^-\rightarrow H\gamma$ may be used to diagnose the anomalous gauge couplings $H\gamma\gamma$ and $HZ\gamma$ in the MSSM.

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I. INTRODUCTION

The existence of a 125 GeV Higgs boson has been recently confirmed by the ATLAS and CMS collaborations at the LHC [1, 2]. The next main step of the LHC searches is to discover new particles beyond the SM. As one of the most theoretically well-motivated scenarios for new physics, the Minimal Supersymmetric Standard Model (MSSM) have been widely studied by the theorists and experimentalists. However, up to now, the LHC has not found any evidences of the SUSY particles (sparticles). The negative results of direct searches for sparticles have pushed up the mass limits of the first two generation squarks and gluino into TeV region [3]. The third generation squarks and non-colored sparticles have also been constrained in the simplified models [4–6]. But they are still allowed to be at hundred GeV and may live in some hidden corners, due to their complicated decay modes [7–10].

In contrast with the direct searches, an advantage of indirect searches lies in the fact that the results weakly depend on the kinematics configurations of sparticles. In this case, an alternative way is to find the indirect SUSY signals via loop corrections by the high precise measurements of the newly discovered Higgs boson at a Higgs factory. Among several proposals for the Higgs factories, the $e^+e^-$ collider has been widely investigated, such as ILC, TLEP and CHF [11, 12]. At $\sqrt{s} \sim 240 – 250$ GeV with an integrated luminosity of 500 fb$^{-1}$, about $O(10^5)$ Higgs bosons can be produced per year through Higgs bremsstrahlung process [13–16]. This allows to precisely measure the Higgs boson couplings at a percent level [17, 18]. So various Higgs boson productions and decays that can be induced by the new particles should be considered at a Higgs factory.

In this paper, we investigate the associated production of the SM-like Higgs boson ($H$) with a hard photon in the MSSM at a 240 GeV Higgs factory under the current experimental constraints. Since the process $e^+e^- \rightarrow H\gamma$ occurs at loop level, it will be sensitive to the contributions from the new particles. Such a process has been studied in Refs. [19–22], however, it will be worthy to reexamine it from the following considerations: (1) due to the recent constraints on the parameter space of the MSSM from the LHC experiments and the dark matter detections, it is necessary to reevaluate the size of the SUSY corrections to $e^+e^- \rightarrow H\gamma$ in the allowed parameter space; (2) The process $e^+e^- \rightarrow H\gamma$ can be used to probe the anomalous couplings of $H\gamma\gamma$ and $HZ\gamma$ [23–28]. At the LHC, most measurements
of the properties of the Higgs boson are consistent with the SM expectations \cite{29}. However, the signal strength of diphoton decay mode reported by ATLAS is considerably larger than the SM prediction \cite{30}, and this excess may persist in the future. In the MSSM, $H \rightarrow \gamma \gamma$ and $H \rightarrow Z\gamma$ can be simultaneously enhanced by a light stau with the large $\mu$ and $\tan \beta$ \cite{31}, which will also lead to a significant enhancement in the process $e^+e^- \rightarrow H\gamma$. So, with the help of the enough luminosity at a 240 GeV Higgs factory, the measurement of $e^+e^- \rightarrow H\gamma$ may shed light on the sparticles searches \cite{32}. The paper is organized as follows. In Sec. II, we briefly describe the scan of the parameter space of the MSSM and the calculations for the process $e^+e^- \rightarrow H\gamma$. In Sec.III we present the numerical results and discussions. Finally, we draw the conclusions in Sec. IV.

II. SCAN METHODOLOGY AND CALCULATION OF $e^+e^- \rightarrow H\gamma$

In the MSSM, after the electroweak symmetry breaking, there are two CP-even Higgs bosons($h, H$), one CP-odd Higgs boson($A$) and the charged Higgs bosons($H^\pm$). Although the mass of the lighter CP-even Higgs boson ($m_h$) is smaller than $M_Z$ at tree level, it can receive the large radiative corrections from the stop sector at one-loop level. The leading part of the corrections from the stop sector can be expressed as \cite{33}

$$
\Delta m_h^2(t) \simeq \frac{3m_t^4}{2\pi^2 v^2 \sin^2 \beta} \left[ \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} + \frac{X_t^2}{2m_{\tilde{t}_1} m_{\tilde{t}_2}} (1 - \frac{X_t^2}{6m_{\tilde{t}_1} m_{\tilde{t}_2}}) \right]
$$

where $X_t \equiv A_t - \mu \cot \beta$ is the mixing parameter of stop. To increase $m_h$ to 125 GeV, it needs the heavy stop masses or a sizable stop mixing parameter $X_t$. In our study, we calculate the Higgs mass by using the package \texttt{FeynHiggs2.10.0} \cite{34} and impose the collider constraints on the MSSM Higgs sector by using the package \texttt{HiggsBounds-4.1.0} \cite{35}. In order to get the parameter space of the MSSM allowed by the current experiments, we scan the following parameter space:

$$
1 \leq \tan \beta \leq 60, \quad 100 \text{ GeV} \leq M_A \leq 1 \text{ TeV}, \quad 100 \text{ GeV} \leq \mu \leq 2 \text{ TeV},
$$

$$
100 \text{ GeV} \leq (M_{Q_3}, M_{U_3}) \leq 2 \text{ TeV}, \quad 100 \text{ GeV} \leq (M_{L_3}, M_{E_3}) \leq 1 \text{ TeV},
$$

$$
-3 \text{ TeV} \leq A_t \leq 3 \text{ TeV}, \quad 50 \text{ GeV} \leq M_1 \leq 500 \text{ GeV}.
$$

We fix the first two generation squark soft masses($M_{\tilde{q}_{1,2}}$) and gluino mass($M_3$) at 2 TeV, and set $m_{U_3} = m_{D_3}$, $A_t = A_b$. We take the grand unification relation $3 M_1/5 \alpha_1 = M_2/\alpha_2$ for
electroweak gaugino masses. We also assume $A_{\tau} = A_{\mu} = A_{e} = 0$, $M_{L_{3}} = M_{L_{2}} = M_{L_{1}}$ and $M_{E_{3}} = M_{E_{2}} = M_{E_{1}}$ to reduce the number of free parameters.

In the scan, we consider the following experimental constraints: (i) We require that the mass of light CP-even Higgs is in the region of $123 \text{ GeV} < m_{h} < 127 \text{ GeV}$ and the bounds for Higgs bosons from LEP, Tevatron and LHC are satisfied; (ii) We require our samples to satisfy the B-physics bounds at $2\sigma$ level, including $B \rightarrow X_{s}\gamma$ and the latest measurements of $B_{s} \rightarrow \mu^{+}\mu^{-}$, $B_{d} \rightarrow X_{s}\mu^{+}\mu^{-}$ and $B^{+} \rightarrow \tau^{+}\nu$. We use the package of SuperIso v3.3 \[36\] to implement these constraints; (iii) By using the package of MicrOmega v2.4 \[37\], we impose the dark matter constraints of the neutralino relic density from PLANCK (in $2\sigma$ range) \[38\] and the direct detection results from LUX (at 90% confidence level) \[39\]; (iv) We also require our samples to explain the muon anomalous magnetic moment data $\Delta a_{\mu} = (26.1 \pm 8.0) \times 10^{-10}$ at $2\sigma$ level \[40\].

In the MSSM, the process $e^{+}e^{-} \rightarrow h\gamma$ includes the following subprocesses: (i) s–channel: $\gamma, Z$ vertex diagrams that are corrected by the charged Higgs boson, chargino, squark and slepton; (ii) t–channel: $Hee$ vertex diagrams that are corrected by chargino/sneutrino and neutralino/selectron; (iii) box diagrams that involve neutralino/selectron and chargino/sneutrino states. We denote the four-momenta of initial and final states in the process as

$$e^{+}(q_{1}) + e^{-}(q_{2}) \rightarrow h(p_{3}) + \gamma(p_{4}) \quad (3)$$

All the amplitudes of Eq. (3) are generated by FeynArts-3.9 \[41\], and are further reduced by FormCalc-8.3 \[42\]. The numerical calculations are performed by using LoopTools-2.8 \[43\].

In order to preserve supersymmetry, we adopt the constrained differential renormalization (CDR) \[44\] to regulate the ultraviolet divergence (UV) in the virtual corrections, which is equivalent to the dimensional reduction method at one-loop level \[45\]. We numerically checked the UV cancellation and notice that the $Z - \gamma$ self-energy mixing term is required to get the finite results. We also checked our results with those of Ref. \[21\] by setting the same SM parameters and found they are consistent well. In order to show the SUSY effects in the process $e^{+}e^{-} \rightarrow H\gamma$, we define the following ratio:

$$R_{H\gamma} \equiv \frac{\sigma_{\text{MSSM}}(e^{+}e^{-} \rightarrow h\gamma)}{\sigma_{\text{SM}}(e^{+}e^{-} \rightarrow h\gamma)} \quad (4)$$
III. NUMERICAL RESULT AND DISCUSSIONS

In our numerical calculations, we take the input parameters of the SM as [46]

\[ m_t = 171.2 \text{ GeV}, \quad m_e = 0.519991 \text{ MeV}, \quad m_Z = 91.19 \text{ GeV}, \]

\[ \sin^2 \theta_W = 0.2228, \quad \alpha(m_Z^2)^{-1} = 127.918. \quad (5) \]

For the calculation of \( e^+e^- \rightarrow H\gamma \) in the SM, the Higgs mass is taken as \( m_H = 125.66 \text{ GeV} \) [47], which is the combined result of the measurements of the ATLAS and CMS collaborations.

![Graph](image)

**FIG. 1:** The dependence of the ratio \( R_{H\gamma} \) on the lighter stop mass \( m_{\tilde{t}_1} \), the lighter stau mass \( m_{\tilde{\tau}_1} \) and \( \mu \tan \beta \) at \( \sqrt{s} = 240 \text{ GeV} \).

In Fig. 1 we present the dependence of the ratio \( R_{H\gamma} \) on the lighter stop mass \( m_{\tilde{t}_1} \), the lighter stau mass \( m_{\tilde{\tau}_1} \) and \( \mu \tan \beta \) at \( \sqrt{s} = 240 \text{ GeV} \). We can see that the large values of \( R_{H\gamma} \) are obtained when the masses of sparticles involving in the loop become small. The maximal value of \( R_{H\gamma} \) can be 1.8 times larger than the SM prediction \( (\sigma_{SM} = 0.10 \text{fb}) \). When the stop mass becomes heavy, the value of \( R_{H\gamma} \) will be small but can still be enhanced by a light stau with large \( \mu \tan \beta \). The reason is that the dominant contribution of sfermions to \( e^+e^- \rightarrow H\gamma \) comes from the stau loop, which can be understood from the followings: the leading part of the amplitudes of the sfermions loop is proportional to \( (g_A \tilde{f}_{\tilde{f}} + g_{\mu} \mu \tan \beta) \sin 2\theta_{\tilde{f}}/m_{\tilde{f}_1}^2 \) [21].

To satisfy the requirement of the Higgs mass, heavy stops or a large mixing parameter \( A_t \) is needed. The light \( \tilde{t}_1 \) can be obtained by the large \( A_t \) but accompanies with a heavy \( \tilde{t}_2 \). This will lead to a small stop mixing angle \( \theta_{\tilde{t}_1} \) and reduce the stop loop contribution. However, the light stau can be achieved without a large \( A_\tau \) by setting the relevant soft mass parameters...
$M_{E_3}$ and $M_{E_3}$. So only a light stau with a large value of $\mu \tan \beta$ can sizably contribute to the process $e^+e^- \to H\gamma$.

FIG. 2: The dependence of the ratio $R_{H\gamma}$ on the lightest chargino mass($\tilde{\chi}^+_{1}$) and the lighter stau mass($m_{\tilde{\tau}_1}$) at $\sqrt{s} = 240$ GeV.

In Fig. 2, we show the effects of $m_{\tilde{\chi}^+_{1}}$ and $m_{\tilde{\tau}_1}$ in the ratio $R_{H\gamma}$. We can see that when the mass of $\tilde{\chi}^+_{1}$ is below 400 GeV, the mass of $\tilde{\tau}_1$ is always smaller than about 200 GeV. This is because that such a light stau is needed to co-annihilate with the neutralino dark matter(\tilde{\chi}^0_{1}) to guarantee the correct dark matter relic density [48, 49]. We also find that the contribution of light $\tilde{\chi}^+_{1}$ loop is much smaller than the light stau loop. It is because that the coupling $C_{H\tilde{\chi}^+_{1}\tilde{\chi}^-_{1}}$ is determined by the component of $\tilde{\chi}^+_{1}$, which can be large only when $\tilde{\chi}^+_{1}$ is a mixture of higgsino and wino [50]. But in the mass range $m_{\tilde{\chi}^+_{1}} \lesssim 400$ GeV, we find that $\tilde{\chi}^+_{1}$ is dominated by wino, which will highly suppress the contribution of $\chi^+_{1}$ loop.

FIG. 3: The correlation of $R_{H\gamma}$ at 240 GeV Higgs factory with $R_{\gamma\gamma}$ and $R_{Z\gamma}$ at the LHC.
In Fig. 3, we study the correlation of $R_{H\gamma}$ at Higgs factory with the signal strengths $R_{\gamma\gamma}$ and $R_{Z\gamma}$ at the LHC, which are defined as followings:

$$R_{\gamma\gamma} \equiv \frac{\sigma_{\text{MSSM}}(pp \rightarrow h \rightarrow \gamma\gamma)}{\sigma_{\text{SM}}(pp \rightarrow h \rightarrow \gamma\gamma)}, \quad (6)$$

$$R_{Z\gamma} \equiv \frac{\sigma_{\text{MSSM}}(pp \rightarrow h \rightarrow Z\gamma)}{\sigma_{\text{SM}}(pp \rightarrow h \rightarrow Z\gamma)}. \quad (7)$$

It can be seen that the ratio $R_{H\gamma}$ is approximately proportional to $R_{\gamma\gamma}$ and $R_{Z\gamma}$. The reason is that the loop-induced couplings $H\gamma\gamma$ and $HZ\gamma$ can simultaneously contribute to the process $e^+e^- \rightarrow H\gamma$, when both of $R_{\gamma\gamma}$ and $R_{Z\gamma}$ get the enhancement from light stau, $R_{H\gamma}$ can be significantly enhanced and maximally reach about 1.8. Therefore, the measurement of $e^+e^- \rightarrow H\gamma$ at Higgs factory may be served as a sensitive probe for testing the anomalous gauge couplings $H\gamma\gamma$ and $HZ\gamma$ in the MSSM.

IV. SUMMARY AND CONCLUSION

In this work, we reexamined the process $e^+e^- \rightarrow H\gamma$ in the MSSM at a 240 GeV Higgs factory. Under the current experimental constraints, we found that the cross section of $e^+e^- \rightarrow H\gamma$ has a strong correlation with the loop couplings $H\gamma\gamma$ and $HZ\gamma$, and can be enhanced to 0.18 fb by a light stau with large $\mu\tan\beta$. Although the cross section is small but the signal is rather clean, we may expect that such a process will be observed the at a high luminosity Higgs factory.

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