CP–violating Chargino Contributions to the Higgs Coupling to Photon Pairs in the Decoupling Regime of Higgs Sector

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Abstract

In most supersymmetric theories, charginos $\tilde{\chi}^{\pm}_{1,2}$ belong to the class of the lightest supersymmetric particles and the couplings of Higgs bosons to charginos are in general complex so that the CP–violating chargino contributions to the loop–induced coupling of the lightest Higgs boson to photon pairs can be sizable even in the decoupling limit of large pseudoscalar mass $m_A$ with only the lightest Higgs boson kinematically accessible at future high energy colliders. We introduce a specific benchmark scenario of CP violation consistent with the electric dipole moment constraints and with a commonly accepted baryogenesis mechanism in the minimal supersymmetric Standard Model. Based on the benchmark scenario of CP violation, we demonstrate that the fusion of the lightest Higgs boson in linearly polarized photon–photon collisions can allow us to confirm the existence of the CP–violating chargino contributions even in the decoupling regime of the Higgs sector for nearly degenerate SU(2) gaugino and higgsino mass parameters of about the electroweak scale.

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1 Introduction

In the minimal supersymmetric extension of the Standard Model (MSSM) [1], the electroweak gauge symmetry is broken with two Higgs doublets, leading to the five physical states: a lighter CP–even Higgs boson $h$, a heavier CP–even Higgs boson $H$, a CP–odd Higgs boson $A$ and two charged Higgs bosons $H^\pm$ [2]. In some regions of MSSM parameter space, more than one Higgs boson can be discovered at the LHC. However, there exists a sizable region of the parameter space at moderate values of the ratio of two Higgs vacuum expectation values, $\tan \beta = v_2/v_1$, opening up from about $m_A = 200$ GeV to higher values in which the heavier Higgs bosons cannot be discovered at the LHC [3]. In this so–called decoupling regime of large $m_A$, only the lightest Higgs boson can be discovered not only at the LHC but also at the first stage of $e^+e^-$ linear colliders (LC) [4] and the properties of the lightest Higgs boson are nearly indistinguishable from those of the Standard Model (SM) Higgs boson. Therefore, high precision measurements of branching ratios and other properties of the lightest Higgs boson [3, 6, 7] are required in order to detect any deviations from SM Higgs predictions.

Deviations from SM properties in the decoupling limit can occur if the Higgs decay into supersymmetric particles are kinematically allowed [3], or if light supersymmetric particles contribute significantly to Higgs loop amplitudes [7]. In this light, the colliding $\gamma$ beam reaction

$$\gamma\gamma \rightarrow h,$$  \hspace{1cm} (1)

has been regarded as an important mechanism [8, 9, 10, 11, 12] for probing the properties of the Higgs boson $h$ precisely. Since the coupling of $h$ to photon pairs is mediated by loops of all charged particles with non–zero mass, the measurements of the coupling through the process (1) can virtually reveal the action of new particle species and help discriminate the lightest SUSY Higgs boson from the SM Higgs boson even in the decoupling regime of large $m_A$. In the decoupling regime, the chargino contributions to the $h\gamma\gamma$ coupling are responsible for most of the deviation from the SM for low $\tan \beta$ and nearly degenerate SU(2) gaugino and higgsino mass parameters $M_2$ and $\mu$ of the electroweak scale, and the top squark contributions to the $h\gamma\gamma$ coupling can be in general sizable for light top squark masses, in particular, in the maximal mixing scenario with large top squark mixing parameter [7].

In CP–noninvariant SUSY theories, the spin–1/2 charginos unlike any spin–zero charged particles have a distinct feature; while spin–zero top squarks contribute only to the CP–even part of the $h\gamma\gamma$ coupling, charginos can contribute to the CP–odd as well as the CP–even parts [12], leading to CP violation. This possible CP–violating coupling of the Higgs boson $h$ to photon pairs can be directly probed through the process $\gamma\gamma \rightarrow h$ by using high energy colliding beams of linearly polarized photons [8, 9, 10, 11, 12], generated by Compton back–scattering of linearly polarized laser light on electron/positron bunches at a LC [13].

The prime goal of the present note is to probe the possibility of measuring the CP–violating chargino contributions to the loop–induced $h\gamma\gamma$ coupling in the decoupling regime of large $m_A$ in detail through the process $\gamma\gamma \rightarrow h$ with linearly polarized photon–photon collisions, based on a specific benchmark scenario of CP violation consistent with all the present indirect constraints and direct searches.
The paper is organized as follows. In the next section, the chargino mixing and the couplings of the lightest Higgs boson to diagonal chargino pairs are described; the sum rules relating two couplings also are presented. Based on the recent works \cite{14} for electroweak baryogenesis in the framework of MSSM and the present experimental constraints on the lightest Higgs boson mass and the lighter chargino mass \cite{15} as well as the electric dipole moment (EDM) constraints \cite{16, 17, 18}, we introduce a feasible benchmark scenario with maximal CP–violating phase in the chargino mass matrix. Section 3 is devoted to a brief review of the production of the lightest Higgs boson through collisions of two back–scattered photons and of the polarization asymmetries for probing CP violation. After discussing the CP–violating chargino contributions to the $h\gamma\gamma$ coupling in Sect. 4, we present a detailed numerical study of the CP–violating chargino as well as right–handed top squark contributions to the coupling of the lightest Higgs bosons to photon pairs in Sect. 5, based on the benchmark scenario of CP violation. Conclusions are finally given in Section 6.

2 The lightest Higgs boson couplings to chargino pairs

The chargino masses and their couplings to Higgs particles are determined by the SU(2) gaugino mass parameter $M_2$ and the higgsino mass parameter $\mu$. In standard definition \cite{19}, the diagonalization $U_R \mathcal{M}_C U_L^\dagger = \text{diag}\{m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^\pm}\}$ of the chargino matrix $\mathcal{M}_C$ by two unitary matrices $U_L$ and $U_R$ in the MSSM

$$\mathcal{M}_C = \begin{pmatrix} M_2 & \sqrt{2m_W c_\beta} \\ \sqrt{2m_W s_\beta} & \mu \end{pmatrix},$$

(2)

generates the light and heavy chargino states $\tilde{\chi}_i^\pm$ ($i = 1, 2$), ordered with rising mass. The coefficients $s_\beta = \sin \beta$, $c_\beta = \cos \beta$ are given by $\tan \beta$, and $s_W = \sin \theta_W$, $c_W = \cos \theta_W$ are the sine and cosine of the electroweak mixing angle. In CP–noninvariant theories, the mass parameters are complex.

By reparametrization of the field basis, the SU(2) mass parameter $M_2$ in Eq.(2) can always be set real and positive, while the higgsino mass parameter $\mu$ is assigned the phase $\Phi_\mu$. The chargino masses are then given in terms of the real and positive parameters $\tan \beta$, $M_2$ and $|\mu|$ and the phase $\Phi_\mu$ by

$$m_{\tilde{\chi}_{i\pm}}^2 = \frac{1}{2} \left[ M_2^2 + |\mu|^2 + 2m_W^2 \mp \sqrt{(M_2^2 + |\mu|^2 + 2m_W^2)^2 - 4|m_W^2 s_{2\beta} - M_2|\mu|e^{i\Phi_\mu}|^2} \right],$$

(3)

which is symmetric with respect to the parameters $M_2$ and $\mu$. Here, $s_{2\beta} = \sin 2\beta$. The coupling of the lightest Higgs boson to diagonal chargino pairs in the decoupling regime is given in terms of the parameter $\tan \beta$ and the matrices $U_{L,R}$ by

$$\langle \tilde{\chi}_{iR}^\pm | h | \tilde{\chi}_{iL} \rangle \equiv \kappa_i = -\frac{g}{\sqrt{2}} (U_{Ri1} U_{Lj2}^* c_\beta + U_{Ri2} U_{Lj1}^* s_\beta),$$

(4)

and $\langle \tilde{\chi}_{iL}^\pm | h | \tilde{\chi}_{iR} \rangle = \langle \tilde{\chi}_{iR}^\pm | h | \tilde{\chi}_{iL} \rangle^* = \kappa_i^*$. We note that the diagonal couplings $\kappa_i$ depend symmetrically on $M_2$ and $\mu$ because the interchange of $M_2$ and $\mu$ in the chargino mass matrix
$\mathcal{M}_C$ is compensated simply by the interchanges, $U_{Ri1} \leftrightarrow U_{Li2}^*$ and $U_{Ri2} \leftrightarrow U_{Li1}^*$, giving the same chargino mass eigenvalues and leaving $\kappa_i$ invariant. Moreover, with the off–diagonal entries, $\sqrt{2}m_Wc_\beta$ and $\sqrt{2}m_Ws_\beta$, of the chargino mass matrix $\mathcal{M}_C$, the couplings of the lightest Higgs boson to chargino pairs, $\kappa_i$, and the chargino masses $m_{\tilde{\chi}^\pm_{1,2}}$ satisfy the sum rules:

$$m_{\tilde{\chi}^+_1} \Re(\kappa_1) + m_{\tilde{\chi}^+_2} \Re(\kappa_2) = -gm_W,$$

$$m_{\tilde{\chi}^+_1} \Im(\kappa_1) + m_{\tilde{\chi}^+_2} \Im(\kappa_2) = 0.$$

As a result, it is easy to see that in case of degenerate chargino masses, perfect cancellation occurs, causing no CP violation. In addition, the condition for the vanishing scalar coupling of the neutral Goldstone boson $G^0$ to chargino pairs leads to an interesting relation, $s_\beta \Im(U_{Ri2}U_{Li1}^*) = c_\beta \Im(U_{Ri1}U_{Li2}^*)$, forcing $\Im(\kappa_i)$ to be proportional to $s_{2\beta} \sin \Phi_\mu$. [18]

The couplings (4) clearly show that the Higgs boson $h$ couples to mixtures of gaugino and higgsino components of charginos. In particular, if the light chargino $\tilde{\chi}^+_1$ were either a pure gaugino ($|\mu| \gg |M_2|$) or a pure higgsino state ($|M_2| \gg |\mu|$), the $h\tilde{\chi}^+_1\tilde{\chi}^-_2$ couplings vanish. Only when the higgsino parameter $\mu$ is comparable to the gaugino mass parameters $M_2$ in size and the value of $\tan \beta$ is moderate, the coupling of the Higgs boson to diagonal chargino pairs could be significant. Consequently, the chargino contributions to the $h\gamma\gamma$ coupling can be significant (only) for moderate $\tan \beta$ and almost degenerate $M_2$ and $|\mu|$ of the electroweak scale.

It is also worthwhile to note that the most likely scenario for generating enough baryon asymmetry of the universe through electroweak baryogenesis in the framework of MSSM is to make use of the phase $\Phi_\mu$. [13]. In this scenario the phase $\Phi_\mu$ should be close to maximal, and the left–handed top squark must be very heavy to give sufficiently large radiative corrections to the lightest Higgs boson mass, given the need for a light right–handed top squark to get a strongly first order electroweak phase transition with small $\tan \beta$ and large pseudoscalar mass $m_A$. Moreover, the MSSM chargino baryogenesis requires nearly degenerate SU(2) gaugino and higgsino mass parameters $M_2$ and $|\mu|$ of the electroweak scale.

Motivated by the above observations for MSSM chargino baryogenesis and by the present experimental constraints on the lightest Higgs boson mass and lighter chargino mass [15] as well as the experimental EDM constraints [16], we consider the following CP–violating benchmark scenario of the lightest Higgs boson mass $m_h$ and the SUSY parameters:

$$m_h = 115 \text{ GeV}; \quad \tan \beta = 5; \quad M_2 = 150 \text{ GeV}, \quad |\mu| = 150 \text{ GeV}; \quad \Phi_\mu = \frac{\pi}{2},$$

and two values of the right–handed top squark mass, $m_{\tilde{t}_R} = 100$ and 250 GeV. For the parameter set (6) the lighter chargino mass turns out to be 105 GeV, slightly larger than the experimental lower bound of about 104 GeV set for the electron sneutrino mass exceeding 300 GeV and the difference of the lighter chargino and lightest neutralino masses larger than 4 GeV [15], which is supported by supergravity and gauge–mediation models with the gaugino mass unification $|M_1| \simeq 0.5M_2$. (In the anomaly–mediation models with inverse gaugino mass hierarchy [20], the experimental chargino mass bound could be much weaker, because of the almost degenerate lighter chargino and lightest neutralino states.) The lighter
Chargino mass $m_{\tilde{\chi}^\pm}$ is larger for negative $\cos \Phi_\mu$ and for nearly degenerate $M_2$ and $|\mu|$ as can be checked in Eq. (3) and from Fig. 1. If $M_2$ and/or $|\mu|$ are much larger than $m_W$, the lighter chargino mass is then nearly equal to $\min\{M_2, |\mu|\}$ and almost independent of $\tan \beta$ and $\Phi_\mu$.

**Figure 1:** The chargino masses, $m_{\tilde{\chi}^\pm}$, as a function of the CP-violating phase $\Phi_\mu$; the other SUSY parameters are given as in Eq. (6). The lower (upper) line is for the lighter (heavier) chargino mass; the dot-dashed line indicates the present experimental lower bound of about 104 GeV on the lighter chargino mass [15].

There may exist important constraints [16] on the CP phase $\Phi_\mu$ in the MSSM from experimental limits on the EDMs of the electron, neutron and $^{199}$Hg. However, the one-loop level contributions to the EDMs from sfermions, charginos and neutralinos in the MSSM are strongly suppressed if at least first and second generation sfermions are much heavier than sfermions of the third generation [16]. Moreover, we find that the two-loop level contributions from top squarks and/or charginos [17, 18], present even in case of very heavy first- and second-generation sfermions, are significantly suppressed in the decoupling limit of large $m_A$. Consequently, we emphasize that the entire range between 0 and $2\pi$ for the phase $\Phi_\mu$ can still be allowed in the decoupling limit of large pseudoscalar mass $m_A$ and for heavy sfermions of the first and second generations.

For the parameter set [16] some chargino and neutralino states as well as the light right-handed top squark state are accessible experimentally at the first phase of the LC. Then, the measurement of the masses and production cross sections with polarized $e^+e^-$ beams will allow us to determine the parameters, $\{\tan \beta, M_2, |\mu|\}$ and the U(1) gaugino mass parameter $M_1$ [5, 6] as well as the top squark mass $m_{\tilde{t}_R}$ with good precision [5]. Therefore, we can check whether the indirect measurements of the chargino and top squark systems through the process $\gamma\gamma \rightarrow h$ are consistent with their direct measurements through pair production.
in $e^+e^-$ collisions or not.

## 3 The lightest Higgs boson production at $\gamma\gamma$ colliders

The helicity amplitude of the reaction $\gamma\gamma \to h$ in the two–photon center–of-mass frame can be in general written as

$$M_{\lambda_1\lambda_2} = -m_h \frac{\alpha}{4\pi} [S(m_h) + i\lambda_1 P(m_h)] \delta_{\lambda_1\lambda_2},$$

with the photon helicities $\lambda_1,2 = \pm 1$. Here, the form factor $S(m_h)$ ($P(m_h)$) represents the CP–even (–odd) coupling strength of the Higgs boson to two photons; the simultaneous existence of both the CP–even and CP–odd form factors signals CP violation. In addition to the unpolarized cross section $\sigma_0(s) \equiv \hat{\sigma}_0 \delta(1 - m_h^2/s)$ with

$$\hat{\sigma}_0 \equiv \frac{\pi}{4m_h^2} \left[ |M_{++}|^2 + |M_{--}|^2 \right] = \frac{\alpha^2}{32\pi m_h^2} \left[ |S|^2 + |P|^2 \right],$$

we can define three polarization asymmetries in terms of the helicity amplitude (7) as

$$A_1 \equiv \frac{|M_{++}|^2 - |M_{--}|^2}{|M_{++}|^2 + |M_{--}|^2} = \frac{2\Im(S P^*)}{|S|^2 + |P|^2}.$$

$$A_2 \equiv \frac{2\Im(M_{--}^* M_{++})}{|M_{++}|^2 + |M_{--}|^2} = \frac{2\Re(S P^*)}{|S|^2 + |P|^2},$$

$$A_3 \equiv \frac{2\Re(M_{--}^* M_{++})}{|M_{++}|^2 + |M_{--}|^2} = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}.$$

In CP–invariant theories, the form factors $S$ and $P$ cannot be simultaneously non–vanishing, leading to the relations, $A_1 = A_2 = 0$ and $A_3 = \pm 1$ such that $A_1 \neq 0$, $A_2 \neq 0$ or $|A_3| < 1$ signals CP violation. Note that the asymmetry $A_1$ is non–zero only when $S$ and $P$ have a non–zero relative phase, which can be developed when the lightest Higgs boson mass is larger than twice the mass of any charged particles in the loop. Neglecting the tiny contributions from light quarks to the $h\gamma\gamma$ coupling, one can safely assume that both $S$ and $P$ are real, because the lightest Higgs boson mass $m_h$ is less than twice the $W$ boson mass as well as twice the experimental lower bound of about 104 GeV on the lighter chargino mass.

After folding the luminosity spectra of two linearly polarized photon beams, the event rate of the Higgs boson production via two–photon fusion is given by

$$N_h(P_T, \bar{P}_T, \eta) = N_h^0 \left[ 1 + P_T \bar{P}_T \left( A_2 \sin 2\eta + A_3 \cos 2\eta \right) \frac{\langle f_3 \ast f_3 \rangle_\tau}{\langle f_0 \ast f_0 \rangle_\tau} \right],$$

with $\tau = m_h^2/s$ taken, with $\{P_T, \bar{P}_T\}$ the degrees of linear polarization of the initial laser photon beams, respectively, and with $\eta$ the azimuthal angle between the directions of maximal
linear polarization of two initial laser beams. Here, the averaged number of Higgs bosons \( N_h^0 \) is given by
\[
N_h^0 \equiv \sigma_0 \frac{dL_{\gamma\gamma}}{ds_{\gamma\gamma}} \bigg|_{\gamma\gamma = m_h^2} = \frac{8\pi^2 \Gamma(h \to \gamma\gamma)}{m_h^3} \cdot \frac{dL_{\gamma\gamma}}{ds_{\gamma\gamma}} \bigg|_{\gamma\gamma = m_h^2} \approx 1.54 \times 10^2 \left( \frac{L_{ee}}{100 \text{ fb}^{-1}} \right) \left( \frac{\text{TeV}}{\sqrt{s}} \right) \left( \frac{\Gamma(h \to \gamma\gamma)}{\text{keV}} \left( \frac{100 \text{ GeV}}{m_h} \right) \right)^2 F(m_h),
\]
where \( \Gamma(h \to \gamma\gamma) \) is the two–photon decay width of the Higgs boson \( h \), and \( F(\sqrt{s}_{\gamma\gamma}) = (\sqrt{s}/L_{ee}) dL_{\gamma\gamma}/d\sqrt{s}_{\gamma\gamma} \) is a slowly varying function dependent upon the details of the machine design, but it could be of the order of unity. In Eq.(11), \( s(s_{\gamma\gamma}) \) and \( L_{ee}(L_{\gamma\gamma}) \) are the \( e^+e^- \) \((\gamma\gamma)\) c.m. energy squared and integrated luminosity, respectively. The integrated luminosity \( L_{ee} \) of about 1 ab\(^{-1}\) is expected to be accumulated within a few years in the first phase of a LC with a clean experimental environment. Numerically, \( \Gamma(h \to \gamma\gamma) \approx 4.4 \text{ keV} \) for the parameter set \( \bar{\eta} = 100 \text{ GeV} \) so that for \( \sqrt{s} = 500 \text{ GeV} \) or less the number of Higgs boson events \( N_h^0 \) is expected to be as large as 10000 with such a high integrated luminosity.

The ratio of the luminosity correlations, \( \langle f_3^* f_3 \rangle_{\tau}/\langle f_0^* f_0 \rangle_{\tau} \) in Eq. (10), whose definition can be found in Ref.[10][11], depends on the beam energy \( \sqrt{s} \) and the laser frequency \( \omega_0 \). As studied in detail in Ref.[10][11][12], the ratio reaches its maximal value for small values of \( x = 2\sqrt{s}\omega_0/m_e^2 \) and near the upper bound of \( \tau \lesssim \tau_{\max} = x^2/(1 + x)^2 \), i.e. if the energy is just sufficient to produce the lightest Higgs boson in the \( \gamma\gamma \) collisions; since the luminosity vanishes at \( \tau = \tau_{\max} \), the operating condition should be adjusted properly such that \( \tau \lesssim \tau_{\max} \) allows for a sufficiently large luminosity \( \langle f_0^* f_0 \rangle \). The coefficient of \( A_2(A_3) \) in Eq.(11) is proportional to \( P_T P_T \sin 2\eta (P_T P_T \cos 2\eta) \) so that setting \( P_T = 1 \) and \( P_T = 1 \), the CP–odd asymmetry \( A_2 \) is separated by taking the difference of cross sections for the azimuthal angle \( \eta = \pi/4 \) and \( -\pi/4 \), while the CP–even asymmetry \( A_3 \) would be determined by the difference of cross sections for \( \eta = 0 \) and \( \pi/2 \).

4 Chargino contributions to the \( h\gamma\gamma \) coupling

Neglecting the contributions of the left–handed top squarks and other squarks, (assumed to be very heavy in favor of electroweak baryogenesis and the EDM constraints), as well as those from the light charged fermions, the CP–even form factor \( S \) in the decoupling regime can be decomposed into the top quark, \( W^\pm \) boson, right–handed top squark and chargino parts but the CP–odd form factor \( P \) consists only of the chargino contributions:
\[
S = S_t + S_{W^\pm} + S_{t_R} + S_{\tilde{\chi}_1^\pm} + S_{\tilde{\chi}_2^\pm},
\]
\[
P = P_{\tilde{\chi}_1^\pm} + P_{\tilde{\chi}_2^\pm}.
\]}

The explicit form of the CP–even functions, \( S_t, S_{W^\pm} \) and \( S_{t_R} \), can be found in Ref.[11]. The SM contributions, \( S_t \) and \( S_{W^\pm} \), depend only on the Higgs boson mass \( m_h \), while the right–handed top squark contribution on its mass \( m_{t_R} \) as well as the lightest Higgs boson
mass and it decreases very quickly $\propto 1/m_{\tilde{t}_R}^2$ with increasing right-handed top squark mass. The CP–even and CP–odd amplitudes $S_{\tilde{\chi}_i^\pm}$ and $P_{\tilde{\chi}_i^\pm}$ $(i = 1, 2)$ for the chargino contributions are given in terms of the diagonalization matrices $U_{L,R}$ and the chargino masses $m_{\tilde{\chi}_{1,2}^\pm}$ by \cite{12}

$$S_{\tilde{\chi}_i^\pm} = +2\Re(\kappa_i) \frac{m_h}{m_{\tilde{\chi}_i^\pm}} F_{sf}(\tau_i),$$

$$P_{\tilde{\chi}_i^\pm} = -2\Im(\kappa_i) \frac{m_h}{m_{\tilde{\chi}_i^\pm}} F_{pf}(\tau_i),$$

with $\tau_i = m_R^2/4m_{\tilde{\chi}_i^\pm}^2$ $(i = 1, 2)$ and $\kappa_i = \langle \tilde{\chi}_{iR}^- | h | \tilde{\chi}_{iL}^- \rangle$ in Eq.\cite{13}. With the help of the so–called scaling function $f(\tau_i)$, which is $\arcsin^2(\sqrt{\tau_i})$ for $\tau_i \leq 1$, the functions $F_{sf}(\tau_i)$ and $F_{pf}(\tau_i)$ are given by

$$F_{sf}(\tau_i) = \tau_i^{-1} \left[ 1 + (1 - \tau_i^{-1}) f(\tau_i) \right],$$

$$F_{pf}(\tau_i) = \tau_i^{-1} f(\tau_i).$$

In the limit of heavy loop masses ($\tau_i \to 0$), these amplitudes reach the asymptotic values, $F_{sf} \to 2/3$ and $F_{pf} \to 1$, the minimum values in the range of $\tau_i \leq 1$. Note that the contributions of the charginos vanish in the large chargino mass limit since the amplitudes $S_{\tilde{\chi}_i^\pm}$ and $P_{\tilde{\chi}_i^\pm}$ are damped by the heavy chargino masses $\propto 1/m_{\tilde{\chi}_i^\pm}$.

5 Numerical results

First of all, let us investigate the dependence of the amplitudes $S_{\tilde{\chi}_i^\pm}$ and $P_{\tilde{\chi}_i^\pm}$ on the relevant SUSY parameters $\{\tan\beta, M_2, |\mu|, \Phi_\mu\}$ from the standpoint of the benchmark scenario \cite{0}. With the lighter chargino contribution larger than the heavier chargino contribution to the $h\gamma\gamma$ coupling and with the sum rules \cite{14} relating the two chargino contributions, it is sufficient to present the amplitudes $S_{\tilde{\chi}_1^\pm}$ and $P_{\tilde{\chi}_1^\pm}$.

Figure\cite{2} shows the dependence of the CP–even and CP–odd amplitudes, $S_{\tilde{\chi}_1^\pm}$ (solid lines) and $P_{\tilde{\chi}_1^\pm}$ (dashed lines) for the lighter chargino loop contribution on (a) $\tan\beta$, (b) $|\mu|$, (c) $M_2$ and (d) the phase $\Phi_\mu$, respectively. For the sake of comparison, we note that the sum of the SM contributions, $S_t + S_{W\pm} \simeq 2.9$ in size for $m_h = 115$ GeV, $m_W = 80$ GeV and $m_t = 165$ GeV at the electroweak scale. In each figure the other parameters except for each varied parameter are assumed to be given as in Eq.\cite{0} and $m_{\tilde{t}_R}$ is taken to be 100 GeV. Only the region with $|\mu| \geq 150$ GeV and $M_2 \geq 150$ GeV in the frames (b) and (c), respectively, and that with $90^\circ \leq \Phi_\mu \leq 270^\circ$ in the frame (d) satisfy the constraint $m_{\tilde{\chi}_1^\pm} \simeq 104$ GeV. Nevertheless, we show the amplitudes for all the ranges because the experimental chargino mass bound is model–dependent \cite{20}.

Firstly, we note that as $\tan\beta$ increases the CP–odd amplitude $P_{\tilde{\chi}_1^\pm}$ decreases, but the CP–even amplitude $S_{\tilde{\chi}_1^\pm}$ increases (see the upper–left frame of Fig\cite{1}). This different behavior is due to the fact that with increasing $\tan\beta$ the lighter chargino mass $m_{\tilde{\chi}_1^\pm}$ decreases for $\Phi_\mu =$
\[ \frac{\pi}{2}, \Im(\kappa_1) \text{ decreases in proportion to } s_{2\beta} = 2 \tan \beta/(1 + \tan^2 \beta), \text{ and } \Re(\kappa_1) \text{ approaches to a constant value. Secondly, as shown in the upper–right and lower–left frames the dependence of both the CP–even and CP–odd amplitudes on } M_2 \text{ and } |\mu| \text{ is identical as expected from the identical dependence of } \kappa_1 \text{ and the chargino masses on the parameters, and both amplitudes eventually decrease as either } M_2 \text{ and } |\mu| \text{ increases. This reflects that if either } M_2 \text{ or } |\mu| \text{ is very large the lighter chargino state is almost higgsino–like or gaugino–like, respectively, and the gaugino–higgsino mixing is significantly suppressed. The approximate plateau of } S_{\tilde{\chi}^\pm_1} \text{ in each frame for } M_2 \text{ (|}\mu|\text{) approaching to 150 GeV from below is due to the enhanced gaugino–chargino mixing for degenerate } M_2 \text{ and } |\mu| \text{ while with the slowly varying scalar function } F_{sf}(\tau_{\tilde{\chi}^\pm_1}). \text{ In contrast, the pseudoscalar function } F_{pf}(\tau_{\tilde{\chi}^\pm_1}) \text{ sharply decreases as the lighter chargino mass increases, i.e. } \tau_{\tilde{\chi}^\pm_1} \text{ decreases. Finally, the lower–right frame in Fig.2 shows the dependence of the CP–even and CP–odd amplitudes on the phase } \Phi_\mu \text{ for the parameter set } \text{(6). The CP–odd amplitude } P_{\tilde{\chi}^\pm_1} \text{ is proportional to } \sin \Phi_\mu \text{ apart from a function of } \cos \Phi_\mu \text{ and it reaches its maximal value of about 0.3 around } \Phi_\mu = 80^\circ. \text{ But, the CP–even amplitude}}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{The CP–even and CP–odd amplitudes, } S_{\tilde{\chi}^\pm_1} \text{ (solid lines) and } P_{\tilde{\chi}^\pm_1} \text{ (dashed lines), for the light chargino loop contribution as a function of (a) } \tan \beta, \text{ (b) } |\mu|, \text{ (c) } M_2 \text{ and (d) the phase } \Phi_\mu; \text{ in each figure, the other parameters except for each varied parameter are given as in Eq. (6)}. \text{ Here, } m_{\tilde{t}_R} = 100 \text{ GeV is assumed. For comparison, we note that the sum of the SM contributions, } S_t + S_{W^\pm} \simeq 2.9.\end{figure}
$S_{\tilde{\chi}^\pm_2}$ is an increasing function of $\cos \Phi_{\mu}$, but not of $\sin \Phi_{\mu}$. Again, we note that the amplitudes $S_{\tilde{\chi}^\pm_2}$ and $P_{\tilde{\chi}^\pm_2}$ from the heavier chargino contribution can be read off from the amplitudes $S_{\tilde{\chi}^\pm_1}$ and $P_{\tilde{\chi}^\pm_1}$ by exploiting the sum rules (5) and the chargino masses.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3}
\caption{(a) the ratio $R$ of the cross section $\hat{\sigma}_0$ to the SM prediction 150 fb and (b) the CP–odd asymmetry $A_2$ as a function of the phase $\Phi_{\mu}$ for $m_{\tilde{t}_R} = 100$ GeV (solid lines) and $m_{\tilde{t}_R} = 250$ GeV (dashed lines), respectively. The other relevant SUSY parameters except the varied parameter in each figure are given as in Eq. (6).}
\end{figure}

The chargino and right–handed stop contributions to the $h\gamma\gamma$ coupling affect both the Higgs production cross section and all the asymmetries. Nevertheless, we find that the deviation of the CP–even asymmetry $A_3$ from the unity is very tiny, maximally $\sim 2\%$ for the parameter set (6). So, we focus simply on the production cross section $\hat{\sigma}_0$ in Eq. (8) and the CP–odd asymmetry $A_2$ for our numerical demonstration. Then, for convenience we introduce the ratio $R$ of the cross section $\hat{\sigma}_0$ to the SM prediction of 150 fb for $m_h = 115$ GeV. Figure 3 shows the dependence of the ratio $R$ and the CP–odd asymmetry $A_2$ on the CP phase $\Phi_{\mu}$ for the parameter set (6); the solid (dashed) line in each frame is for $m_{\tilde{t}_R} = 100$ (250) GeV. The right–handed top squark contribution destructively interferes with the SM contributions, reducing the production cross section significantly for small $m_{\tilde{t}_R}$; about 40\% for $m_{\tilde{t}_R} = 100$ GeV but 5\% for $m_{\tilde{t}_R} = 250$ GeV. On the other hand, the chargino contributions to the cross section are maximal in the CP–invariant case, about 10\%, but they are significantly suppressed, i.e. almost vanishing for the maximal CP–violating case. (There may exist a perfect cancellation between the chargino and right–handed top squark contributions even for the CP–invariant case $\Phi_{\mu} = 0^\circ$ for $m_{\tilde{t}_R} \simeq 170$ GeV, leading to $R \simeq 1$.) In contrast, the CP–odd asymmetry $A_2$ is vanishing for the CP–invariant case, but it is maximal for nearly maximal values of the CP phase; $|A_2| \simeq 0.25$ for $\Phi_{\mu} \simeq 80^\circ$ or $280^\circ$, while as $m_{\tilde{t}_R}$ increases, the CP–odd asymmetry decreases slightly in magnitude. It is, therefore,
clear that the cross section ratio $R$ and the asymmetry $A_2$ play a complementary role in determining the chargino as well as right–handed top squark contributions in the decoupling limit.

As the lightest Higgs boson decays mainly into $b \bar{b}$ and $c \bar{c}$ pairs as well as $\tau^+ \tau^-$ pairs, it is necessary to understand the structure of possible backgrounds from the process $\gamma\gamma \rightarrow b \bar{b}$ and $c \bar{c}$ and the heavy quark production through the resolved $\gamma$ mechanisms to our Higgs boson signal and to suppress them as much as possible [10]. However, the resolved $\gamma$ mechanisms do not pose severe background problems in the kinematical configurations relevant to asymmetry measurements, because for the laser energy only slightly higher than the Higgs threshold the resolved $\gamma g \rightarrow b \bar{b}$ and $gg \rightarrow b \bar{b}$ are strongly suppressed due to the steeply falling gluon spectrum. Moreover, the background events from $\gamma\gamma \rightarrow b \bar{b}$ can be rejected by demanding small values of the rapidities of the $b$ and $\bar{b}$ quarks as the background events are strongly peaked at zero polar angles, but the signal events $\gamma\gamma \rightarrow h \rightarrow b \bar{b}$ are distributed isotropically in the center–of–mass frame. On the other hand, the background events from the process $\gamma\gamma \rightarrow c \bar{c}$ are expected to be effectively suppressed by almost perfect $\mu$–vertexing.

The continuum background processes do not affect the numerator of the asymmetry $A_2$ so that the background events reduce the asymmetry simply by a suppression factor $1/[1 + N_h/N_B]$. Here, $N_h/N_B$ denote the number of surviving signal (background) events. Then, the statistical significance $S_{A_2}$ for the asymmetry $A_2$ extracted with $\eta = \pm \pi/4$ and $P_T = \bar{P}_T = 1$ are

$$S_{A_2} = \frac{N_h}{\sqrt{N_h + N_B}} \left( \frac{\langle f_3 \ast f_3 \rangle_\tau}{\langle f_0 \ast f_0 \rangle_\tau} \right) |A_2|.$$  

(15)

The polarization factor $\langle f_3 \ast f_3 \rangle_\tau/\langle f_0 \ast f_0 \rangle_\tau$ can be as large as 0.8 if the laser is operated in the red/infrared regime [10] and the number of background events could be reduced to be comparable to or less than that of signal events [3]. In this case ($N_h \simeq N_B$), the significance $S_{A_2} \simeq 0.12 \sqrt{N_h}$ for $\Phi_\mu \simeq 80^\circ$ or $280^\circ$ giving $|A_2| \simeq 0.21$ for $m_{\tilde{t}}R = 100$ GeV so that the maximal CP violation can be detected with about 1600 signal events at the 5–\(\sigma\) level. On the other hand, the statistical significance $S_R$ for the deviation of the cross section due to the (mainly) right–handed top squark as well as chargino loops from the SM prediction reads

$$S_R = \frac{N_{hSM}}{\sqrt{N_{hSM} + N_B}} |R - 1|.$$  

(16)

If $N_B \simeq N_{hSM}$, the significance $S_R \simeq 0.36 (0.11)\sqrt{N_{hSM}}$ for $\Phi_\mu = 180^\circ$ and $m_{\tilde{t}}R = 100 (250)$ GeV so that the maximal deviation from the SM prediction can be detected with about 200 and 2000, respectively, at the 5–\(\sigma\) level. Certainly, a more detailed numerical analysis would be required to determine the statistical significances for the CP–odd asymmetry $A_2$ and the ratio $R$ more accurately, and to check their complementarity more reliably, which is beyond the scope of the present work.
6 Conclusions

Charginos as well as right–handed top squark belong to the class of the lightest supersymmetric particles in most SUSY theories and the couplings of the lightest Higgs boson to charginos are in general complex so that the chargino as well as right–handed top squark contributions to the loop–induced coupling of the lightest Higgs boson to two photons may be sizable and cause CP violation even in the decoupling limit of large pseudoscalar mass \( m_A \). We have introduced a specific benchmark scenario of CP violation consistent with both the EDM constraints and a commonly accepted mechanism for MSSM electroweak baryogenesis; small \( \tan \beta \), almost degenerate \( M_2 \) and \( |\mu| \) of about the electroweak scale, the phase \( \Phi_\mu \) close to maximal and the light right–handed top squark. All other SUSY particles are assumed to be very heavy mainly for avoiding the strong EDM constraints, and so they are essentially decoupled from the theory.

Based on the benchmark scenario of CP violation, we have analyzed the CP–violating chargino and CP–preserving right–handed top squark contributions to the \( h\gamma\gamma \) coupling through the fusion of the lightest Higgs boson in linearly polarized photon–photon collisions in the decoupling regime of Higgs sector in the MSSM and its related extensions. Our detailed analysis has clearly shown that the fusion of the lightest Higgs boson in two linearly polarized photon collisions can provide a significant opportunity for detecting the deviation of the production rate mainly due to the right–handed top squark contribution as well as due to the chargino contributions and for probing CP violation solely due to the CP–violating chargino contributions even in the decoupling limit of large pseudoscalar mass \( m_A \). We emphasize once more that the CP–violating phenomenon due to chargino contributions in the decoupling limit is a unique feature of CP–noninvariant SUSY theories.

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