\[ H \to \gamma\gamma \text{ in the Complex Two Higgs Doublet Model} \]

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We explore the parameter regions in the complex Two Higgs Doublet Model (c2HDM) with explicit CP violation that can describe current LHC hints for one or more Higgs boson signals at 125 GeV. Such a simple extension of the Standard model has three neutral Higgs bosons and a pair charged Higgs and leads to rich CP-violating sources including the CP-even CP-odd mixing of the neutral Higgs bosons. Within this model we present the production of light Higgs boson at the LHC followed by its decay into two photons. Our numerical study takes into account theoretical and experimental constraints on the Higgs potential like positivity, unitarity and perturbativity as well as \( \rho \)-parameter, \( b \to s\gamma \) and \( R_b \). These requirement together with the minimum conditions could explain the di-photon excess observed at the LHC. We also discuss the effects of the CP violating phases on the CP violation observable which is the difference between left-circular and right-circular polarization.

I. INTRODUCTION

LHC experiments at 7 TeV after analyzing their 5/fb dataset restrict the Standard Model (SM) light Higgs boson mass to be in the following range \( 115.5 \text{ GeV} < m_h < 131 \text{ GeV} \) for ATLAS [1] and \( m_h < 127 \text{ GeV} \) for CMS [2] at 95\% confidence level (CL). Both ATLAS and CMS have reported some excess at low mass Higgs Boson with low statistical significance in the \( WW^* \), \( ZZ^* \) and di-photon channels. Moreover, from the di-photon channel, both detectors have excluded a SM Higgs in the narrow mass range of 114–115 GeV for ATLAS and of 127–131 GeV for CMS at the 95\%CL. Moreover, in the mass range \( 115 < m_h < 135 \text{ GeV} \), Tevatron also observes the excess events in \( h \to bb \) decay [3].

LHC is now running at 8 TeV, the hope is to reach more than 5/fb luminosity taken during 7 TeV run. This would allow the LHC experiments to take more and more data and then could elucidate the existing hint at 125 GeV. The effective cross-section of di-photon (\( \gamma\gamma \)) mode can be estimated by inclusive process \( \sigma^{\gamma\gamma} = \sigma(pp \to H) \times Br(H \to \gamma\gamma) \). This \( (\sigma^{\gamma\gamma} ) \) could provide possibly the best mode to search for light Higgs Boson in mass range 110-140 GeV.

There are several studies has been done for higgs decay into 2 photons in the framework of extended Higgs sector [4]. In the present work, we assume that the Higgs is produced dominantly by gluon fusion, the signal strength is defined by the ratio

\[
R_{XX}(h_1) = \frac{[\sigma(pp \to h_1) \times Br(h_1 \to XX)]}{[\sigma(pp \to h) \times Br(h \to XX)]}_{SM}
\]

where \( X \) can be either photons, \( W \) or \( b \). In this ratio, we have used the narrow width approximation.

In our calculations, we take into account positivity, unitarity and perturbativity of the Higgs potential as well as \( \rho \)-parameter, \( b \to s\gamma \) and \( R_b \). Since the complex Yukawa couplings are chosen in the calculations, in addition to...
the CKM-matrix elements, there is a new source for CP-violation. Using those new CP violating sources, we obtain $R_{\gamma\gamma} \sim 3$ and a rate difference between left-circular and right-circular polarization $A_{+\pi}$ of the order of 10%.

The paper is organized as follows: In section II we shortly review the general 2HDM, fix the parameterization for the scalar potential. In the third section we investigate how each phase can affect $R_{\gamma\gamma}$, $R_{WW}$ and $R_{BB}$, we then discuss the phenomenology implications of such phases on $A_{+\pi}$. Finally, we devote section IV to our summary and conclusions.

II. GENERAL C2HDM

The general 2HDM is obtained via extending the SM Higgs sector, consisting of one complex $Y = +1$, SU(2)$_L$ doublet scalar field $\Phi_1$, with an additional complex $Y = +1$, SU(2)$_L$ doublet scalar field $\Phi_2$. Using $\Phi_{1,2}$, one can build the most general renormalizable SU(2)$_L \times U(1)_Y$ gauge invariant Higgs potential [2,14,19]:

$$V_{\text{Higgs}}(\Phi_1, \Phi_2) = \frac{l_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{l_2}{2}(\Phi_2^\dagger \Phi_2)^2 + l_3(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + l_4(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)$$

$$+ \frac{1}{2} \left[l_5(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right] + \left\{l_5(\Phi_1^\dagger \Phi_1) + l_7(\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + \text{h.c.} \right\}$$

$$- \frac{1}{2} \left\{m_{12}^2 \Phi_1^\dagger \Phi_1 + \left(m_{12}^2 \Phi_2^\dagger \Phi_2 + \text{h.c.} \right) + m_{23}^2 \Phi_2^\dagger \Phi_2 \right\}.$$  (2)

By hermiticity of eq. (2), $l_{1,2,3,4}$, as well as $m_{11}$ and $m_{22}$ are real-valued; while the dimensionless parameters $l_5$, $l_6$, $l_7$ and $m_{12}^2$ are in general complex.

1. Mass eigenstates

After the SU(2)$_L \times U(1)_Y$ gauge symmetry is broken down to $U(1)_{em}$ via the Higgs mechanism, one can choose a basis where the vacuum expectation values (VEVs) of the two Higgs doublets, $v_1$ and $v_2$ are non-zero, real and positive, and fix the following parameterization [13]:

$$\Phi_1 = \left(\begin{array}{c} \varphi_1^+ \\ (v_1 + \eta_1 + i\chi_1)/\sqrt{2} \end{array}\right), \quad \Phi_2 = \left(\begin{array}{c} \varphi_2^+ \\ (v_2 + \eta_2 + i\chi_2)/\sqrt{2} \end{array}\right).$$  (3)

Here $\eta_{1,2}$ and $\chi_{1,2}$ are neutral scalar fields and $\varphi_{1,2}^\pm$ are charged scalar fields. The physical Higgs eigenstates are obtained as follows.

The charged Higgs fields $H^\pm$ and the charged would-be Goldstone boson fields $G^\pm$ are a mixture of the charged components of the Higgs doublets [2], $\varphi_{1,2}^\pm$:

$$H^\pm = -\sin \beta \varphi_1^\pm + \cos \beta \varphi_2^\pm,$$

$$G^\pm = \cos \beta \varphi_1^\pm + \sin \beta \varphi_2^\pm,$$  (4)

where the mixing angle $\beta$ is defined through the ratio of the VEVs of the two Higgs doublets $\Phi_2$ and $\Phi_1$, $\tan \beta = v_2/v_1$. $G^\pm$ give masses to the $W^\pm$ bosons.

Obtaining the neutral physical Higgs states is a few steps procedure. First, one rotates the imaginary parts of the neutral components of eq. (3) $(\chi_1, \chi_2)$ into the basis $(C^0, \eta_3)^t$:

$$G^0 = \cos \beta \chi_1 + \sin \beta \chi_2,$$

$$\eta_3 = -\sin \beta \chi_1 + \cos \beta \chi_2,$$  (5)

where $C^0$ is the would-be Goldstone boson which gives a mass to the $Z$ gauge boson. After elimination of the Goldstone mode, the remaining neutral CP-odd component $\eta_{1,2}$ mixes with the neutral CP-even components $\eta_{1,2}$. The relevant squared mass matrix $M_{ij}^2 = \partial^2 V_{\text{Higgs}}/(\partial \eta_i \partial \eta_j)$, $i, j = 1, 2, 3$, has to be rotated from the so called "weak basis" $(\eta_1, \eta_2, \eta_3)$ to the diagonal basis $(H_1^0, H_2^0, H_3^0)$ by an orthogonal 3 $\times$ 3 matrix $R$ as follows:

$$R M^2 R^T = M^2_{\text{diag}} = \text{diag}(M_{H_1^0}^2, M_{H_2^0}^2, M_{H_3^0}^2),$$  (6)

1 Note that in the case of $m_{12}^2 = l_6 = l_7 = 0$ and all other parameters of eq. (3) are real, the physical Higgs sector of the 2HDM is analogous to the one of the tree-level MSSM. In this case the scalar field $\eta_3$ is equivalent to the MSSM neutral CP-odd Higgs boson $A^0$. 


with
\[
\begin{pmatrix}
H_1^0 \\
H_2^0 \\
H_3^0
\end{pmatrix}
= \mathcal{R}
\begin{pmatrix}
\eta_1 \\
\eta_2 \\
\eta_3
\end{pmatrix},
\]
(7)
where we have defined the Higgs fields $H_i^0$ such that their masses satisfy the inequalities:
\[
M_{H_2} \leq M_{H_1} \leq M_{H_3}.
\]
(8)
Note that the mass eigenstates $H_i^0$ have a mixed CP structure.

Following [16], we parameterize the orthogonal $3 \times 3$ matrix $\mathcal{R}$ by three rotation angles $\alpha_i$, $i = 1, 2, 3$:
\[
\mathcal{R} = \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \alpha_3 & \sin \alpha_3 \\
0 & -\sin \alpha_3 & \cos \alpha_3
\end{pmatrix}
\begin{pmatrix}
\cos \alpha_2 & 0 & \sin \alpha_2 \\
0 & 1 & 0 \\
-\sin \alpha_2 & 0 & \cos \alpha_2
\end{pmatrix}
\begin{pmatrix}
\cos \alpha_1 & \sin \alpha_1 & 0 \\
-\sin \alpha_1 & \cos \alpha_1 & 0 \\
0 & 0 & 1
\end{pmatrix},
\]
(9)
with $s_i = \sin \alpha_i$ and $c_i = \cos \alpha_i$, which we vary in our numerical analysis in the following ranges:
\[
-\frac{\pi}{2} < \alpha_1 \leq \frac{\pi}{2}; \quad -\frac{\pi}{2} < \alpha_2 \leq \frac{\pi}{2}; \quad 0 \leq \alpha_3 \leq \frac{\pi}{2}.
\]
(10)
Note that in the limit of no CP violation $\alpha_{2,3} \to 0 (R_{13}, R_{23} \to 0)$ in this case the neutral Higgs sector is parameterized by the familiar mixing angle $\alpha_1$ of the CP-even sector. For consistency, this requires $\text{Im}(\lambda_5)$ and $\text{Im}(m_{12}^2)$ to be zero. For the next section we will study the general 2HDM where $\lambda_6 = \lambda_7 = 0$.

A. $Z_2$ symmetry and input parameter set

In the most general 2HDM, some types of Yukawa interactions can introduce flavor changing neutral currents (FCNC) already at tree level. It is well known that the latter effects are small in nature. This problem has been solved by imposing a discrete $Z_2$ symmetry on the Lagrangian. It forbids $\Phi_1 \leftrightarrow \Phi_2$ transitions and in its exact form it also leads to conservation of CP [17]. In order to allow some effects of CPV it is necessary to violate the $Z_2$ symmetry. Basically, there are two ways of $Z_2$ symmetry violation — “soft” and “hard”. A softly broken $Z_2$ symmetry suppresses FCNC at tree level, but still allows CPV.

In this paper we will work in a model of a softly broken $Z_2$ symmetry of the 2HDM Lagrangian. This forbids the quartic terms proportional to $l_6$ and $l_7$ in eq. (2), but the quadratic term with $m_{12}^2$ is still allowed [18] :
\[
V_{\text{Higgs}}^{\text{soft}}(\Phi_1, \Phi_2) = \frac{l_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{l_2}{2}(\Phi_2^\dagger \Phi_2)^2 + l_3(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + l_4(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)
\]
\[
+ \frac{1}{2} l_5(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right) - \frac{1}{2} \left[ m_{11}^2(\Phi_1^\dagger \Phi_1 + m_{12}^2(\Phi_2^\dagger \Phi_2 + \text{h.c.}) + m_{22}^2(\Phi_2^\dagger \Phi_2) \right].
\]
(11)
The Higgs potential [11] has 12 real parameters: 2 real masses: $m_{11,22}^2$, 2 VEVs: $v_1, v_2$, four real quartic couplings: $l_1, l_2, l_3, l_4$ and two complex parameters: $l_5$ and $m_{12}^2$. The conditions for having an extremum of eq. (11) reduce the number of parameters: $m_{11,22}^2$ are eliminated by the minimization conditions, and the combination $v_1^2 + v_2^2$ is fixed at the electroweak scale $v = (\sqrt{2} G_F)^{-1/2} = 246$ GeV. Moreover, in this case the minimization conditions also relates $\text{Im}(m_{12}^2)$ and $\text{Im}(l_5)$:
\[
\text{Im}(m_{12}^2) = v_1 v_2 \text{Im}(l_5).
\]
(12)
Thus, our Higgs potential [11] is a function of 8 real independent parameters:
\[
\{l_{1,2,3,4}, \text{Re}(l_5), \text{Re}(m_{12}^2), \tan \beta, \text{Im}(m_{12}^2)\}.
\]
(13)
It contains minimal CPV generated by $m_{12}^2 \neq 0$ and complex. In our further analysis we will use the following parameter set equivalent to eq. (13):
\[
\left\{ M_{H^0}, M_{H^0}, M_{H^+}, \alpha_1, \alpha_2, \alpha_3, \tan \beta, \text{Re}(m_{12}) \right\}.
\]
(14)
Note that the mass of the heaviest neutral Higgs boson $H_0^3$ is not an independent parameter. In the considered CP violating case, the matrix elements $(M^2)_{13}$ and $(M^2)_{23}$ of the squared mass matrix are non-zero and correlated:\n\begin{equation}
(M^2)_{13} = \tan(\beta) (M^2)_{23},
\end{equation}
Writing this relation in terms of the physical masses $M_{H_0^1}, M_{H_0^2}, M_{H_0^3}$ one obtains:\n\begin{equation}
M_{H_0^3}^2 = \frac{M_{H_0^1}^2 R_{13}(R_{12}\tan \beta - R_{11}) + M_{H_0^2}^2 R_{23}(R_{22}\tan \beta - R_{21})}{R_{33}(R_{31} - R_{32}\tan \beta)},
\end{equation}
where $R_{ij}, i, j = 1, 2, 3,$ are the elements of the rotation matrix.

The expressions for the parameters $l_{1,2,3,4}, \Re l_5, \Im l_5$ of the scalar potential as functions of the physical masses and mixing angles are given in \cite{16}. Note that several CP conserving limit exists depending on which Higgs $H_i$ is pure CP-odd we can set different limit. If we want $H_3$ to be the CP-odd then we take $\alpha_2 = \alpha_3 = 0,$ and $\alpha_1$ arbitrary.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Allowed parameter space in the $\alpha_1 - \alpha_2$ plane for $\tan \beta = 1.5$ (left), $\tan \beta = 2$ (middle) and $\tan \beta = 2.5$ (right). The coding color correspond to: $R_{\gamma\gamma} \leq 1$ (red), $1 \leq R_{\gamma\gamma} \leq 2$ (green), $2 \leq R_{\gamma\gamma} \leq 3$ (blue) and $3 \leq R_{\gamma\gamma}$ (mangeta). The other parameters are taken as follow: $m_{h_1} = 125$ GeV, $m_{h_2} = 220$ GeV, $m_{H^\pm} = 350$ GeV, $\Re (m_{12}^2) = 200$ GeV, $\alpha_3 = \frac{\pi}{3}$.}
\end{figure}

\section{III. RESULT}

In this section we present our numerical analysis for various Higgs decays. We consider only the type II c2HDM. In our analysis, we use the following 8 physical real parameters:\n\begin{equation}
\left\{M_{H_1}, M_{H_2}, \alpha_1, \alpha_2, \alpha_3, M_{H^\pm}, \tan \beta, \Re m_{12}^2\right\}.
\end{equation}

To satisfy $b \to s\gamma$ constraint in this model we assume that the charged Higgs mass is heavier than 295 GeV \cite{23} \cite{24} (eventually the unitarity constraint excludes high values of $M_{H^\pm}$). In our scans, we assume $\tan \beta > 1$ in order to satisfy $Z b \bar{b},$ B-B mixing constraints. We also impose perturbative unitarity and vacuum stability constraints on the parameters of the scalar potential \cite{25} as well as the constraint coming from electroweak physics, related to the precise determination of the $\rho$-parameter \cite{27}.

At collider one measures the total cross-section $\sigma_{h^\gamma} = \sigma(pp \to h \to \gamma\gamma)$ where the largest contribution to the production cross-section for this observable $\sigma_{h^\gamma}$ is through gluon fusion, $gg \to h \to \gamma\gamma$. For phenomenological
FIG. 2: $R_{\gamma\gamma}(h_1)$ as a function of $\alpha_1$ (left) and $\alpha_2$ (right), for different values of $\tan \beta = 1.5$, 2 and 2.5. The other parameters are taken as follow: $m_{h_1} = 125$ GeV, $m_{h_2} = 220$ GeV, $m_{H^\pm} = 350$ GeV, $Re(m_{12}^2) = 200$ GeV, $\alpha_3 = \frac{\pi}{3}$.

FIG. 3: Branching ratios of $h_1$ in the c2HDM as a function $\alpha_2$ with $\alpha_1 = 1.4$ rad, $\alpha_3 = 1.04$ rad, $\tan \beta = 1.5$ and $m_{h_1} = 125$ GeV. The other parameters are as in Fig.1.

purpose, we will use the ratio $R_{\gamma\gamma}$, $R_{WW}$ and $R_{bb}$ defined previously in equation 1. Several recent studies use LHC data to put bounds on those ratios $R_{\gamma\gamma}$, $R_{WW}$ and $R_{bb}$ in a model independent way [26]. We will not apply those bounds here but rather give the predictions of the c2HDM.

In Figure 4 we show for $m_{h_1} = 125$ GeV the allowed parameter space in the $\alpha_1 - \alpha_2$ plane, for $\tan \beta = 1.5$ (left), $\tan \beta = 2$ (middle) and $\tan \beta = 2.5$ (right). The other parameters are taken as follow: $m_{h_1} = 125$ GeV, $m_{h_2} = 220$ GeV, $m_{H^\pm} = 350$ GeV, $Re(m_{12}^2) = 200$ GeV, $\alpha_3 = \frac{\pi}{3}$. The white region is excluded by one of the above constraints. It is clear that for small $\tan \beta = 1.5$, the allowed region of $\alpha_1 - \alpha_2$ plane is larger and get reduced when taking $\tan \beta = 2.5$. The coding color correspond to: $R_{\gamma\gamma} \leq 1$ (red), $1 \leq R_{\gamma\gamma} \leq 2$ (green), $2 \leq R_{\gamma\gamma} \leq 3$ (blue) and $3 \leq R_{\gamma\gamma}$ (magenta). The dependence of the allowed regions on $R_{\gamma\gamma}(h_1)$ is illustrated in figure 1 while $\alpha_3$ kept fixed at $\pi/3$. The figure shows the deviation of the c2HDM from the SM predictions can occur due to the mixing effect appears at the tree-level. For
small $\tan \beta$ there are still regions where theoretical and experimental constraints are satisfied. However, when $\tan \beta$ approaches 2.5 (or even 3), the allowed regions tend to be restricted to small values of $\alpha_2$.

In figure 2 we illustrate the ratio $R_{\gamma\gamma}$ as a function of $\alpha_1$ (left) and $\alpha_2$ (right). It is clear from this plot that enhancing $R_{\gamma\gamma}$ requires $\alpha_1 \approx \pm \pi/2$ and $\alpha_2 \approx 0$. In fact taking $\alpha_1 \approx \pm \pi/2$ and $\alpha_2 \approx 0$ would suppress the partial width of the Higgs $\Gamma(h_1 \to b\bar{b})$ which contribute dominantly to the total width. Such a suppression of the total width will give an enhancement of $Br(h_1 \to \gamma\gamma)$. This is clearly illustrated in figure 3 where we plot $Br(h_1 \to xx)$ as a function of $\alpha_2$ for $\alpha_1 \approx \pi/2$ rad, $\alpha_2 = 1.04$ rad, $\tan \beta = 1.5$ and $m_{h_1} = 125$ GeV. It is clear from this plot that when $\alpha_2$ decrease from $\alpha_2 = -\pi$ down to $\alpha_2 \approx 0$ one can see from one side a reduction of $Br(h_1 \to b\bar{b}, \tau^+\tau^-)$ and from the other side we can see an enhancement of $Br(h_1 \to c\bar{c}, gg, W^+W^-, ZZ, \gamma\gamma)$. One can use CMS and ATLAS data to put some constraints on c2HDM parameter such as $\alpha_1$, $\alpha_2$ and $\tan \beta$. For $m_{h_1} = 125$ GeV it is known from CMS data that $R_{\gamma\gamma} \leq 3.6$. As one can see from figure 2 this constraint on $R_{\gamma\gamma}$ clearly disfavor $\alpha_1 \approx \pm \pi/2$, $\alpha_1 \approx 0$ and $\tan \beta > 2$.

As stated before, the Higgs in this model is a mixture of CP-even and CP-odd components. In Figure 4 we plot the
ratio $R_{\gamma\gamma}$ of the $h_1$ as a function of $|Z_{11}|^2 = |(h_1 WW)/h_{sm} WW|^2$ which is the coupling $h_1 WW$ normalized to SM coupling. It is clear that $R_{\gamma\gamma}(h_1)$ is enhanced only for $|Z_{11}|^2 \geq 0.5$ which means that $h_1$ has a substantial contribution from CP-even component.

Since the main contribution to $h_1 \to \gamma\gamma$ comes from the diagrams containing W-boson loops, a strong correlation between these two channel is expected. This correlation is confirmed by Figure 5(left). It is apparent from Figure 5(left) that we have an approximate linear correlation between $R_{\gamma\gamma}(h_1)$ and $R_{WW}(h_1)$. The simultaneous enhancement of those two modes can be understood as an effect of large suppression of the main coupling $h_1bb$ which favors both decays equally.

In this scenario, enhancing/suppressing $R_{\gamma\gamma}(h_1)$ would also enhance/suppress $R_{WW}(h_1)$. From Figure 5(right) one can see that large $R_{\gamma\gamma}(h_1)$ prefer rather suppressed $R_{bb}(h_1)$, but there is also substantial region of parameter space where we can have some excess in $R_{\gamma\gamma}(h_1)$ while $R_{bb}(h_1)$ is more or less consistent with SM.

### IV. CP-ASYMMETRY OF $h_1\gamma\gamma$ MODE

Now we discuss the effect of the CP violating phases on some CP violation observable related to di-photon events. To quantify the size of CP violation in $h_1\gamma\gamma$, we introduce the following observable $28$:

$$A_{+-} = \frac{\Gamma(h_1 \to \gamma\gamma(++) - \Gamma(h_1 \to \gamma\gamma(--))}{\Gamma(h_1 \to \gamma\gamma(++) + \Gamma(h_1 \to \gamma\gamma(--)))}$$

which is the rate difference between left-circular and right-circular polarization of the final photons.

In order to get CP violation using the above asymmetries, we need both weak CP violating phases in the Lagrangian and CP conserving phases (strong phases) in the absorptive parts of the one-loop amplitudes. The weak phase comes from Higgs fermion pairs coupling that contribute to $h_1\gamma\gamma$. The CP conserving phases originate from various on-shell intermediate states of the one-loop amplitudes. In this case, the strong phases coming from cuts of $h_1 \to bb, \tau^+\tau^-$.

In Figure 6 we provide a scan for the rate difference between left-circular and right-circular polarization of the final photons $A_{+-}$ as a function of $\alpha_1$ and $\alpha_2$. This asymmetry could reach up to more than 10% in some region of parameter space. Such asymmetry can be measured in the photon-photon option of the International linear collider (ILC).

### V. CONCLUSIONS

We have studied Higgs production and its decay to di-photon in c2HDM in which the couplings of non-self-hermitian terms in the Higgs potential are complex. Due to the complex couplings, CP-even and CP-odd scalars will mix and the mixture leads to CP violation. We find that a large region of the c2HDM parameter space will be excluded when the constrains from precision measurement of $\rho$ parameter and tree-level unitarity of Higgs-Higgs scattering are included. With the allowed values of CP mixing angles, we found that the excess in $h_1 \to \gamma\gamma$ process reported by ATLAS and CMS at $M_{h_1} = 125$ GeV could be explained. We have also shown that such excess in $h_1 \to \gamma\gamma$ could be easily obtained with suppressed $h_1 \to bb$ but we could also have an excess in $h_1 \to \gamma\gamma$ while $h_1 \to bb$ is still consistent with the SM predictions. Additionally, with polarized photon we also study the direct CPA in di-photon channel. We find that the CPA could be as large as 10%, which could be tested at linear collider.

**Note added:** While we were finishing this work, we received papers $29$ and $30$ which deals with similar subject and our results agree in type II c2HDM which was considered in this study. $30$ discuss production and detection of light charged Higgs in type I 2HDM and also the effect of such light charged Higgs in $h \to \gamma\gamma$, we are not interested in such a scenario.

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FIG. 6: The CP-Asymmetry $A_{CP}$ of $h_1 \rightarrow \gamma \gamma$ mode in the $(\alpha_1 - \alpha_2)$ plan with $m_{h_1} = 125$ GeV and $\tan \beta = 1.5$ in the c2HDM. The other parameters are the same as in Figure.1.

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