Alignment of Yukawa couplings in two Higgs doublet models

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Abstract

We study the alignment of Yukawa couplings in the framework of general two Higgs doublet models (2HDMs) considering a scenario in which the lightest neutral Higgs boson is purely CP even while the two heavier neutral Higgs bosons are allowed to mix in the presence of nontrivial CP-violating phases in the Higgs potential. Identifying the lightest neutral Higgs boson as the 125 GeV one discovered at the LHC, we find that the alignment of Yukawa couplings without decoupling could be easily achieved in the type-I 2HDM with no much conflict with the current LHC Higgs precision data. Otherwise, we observe that the Yukawa couplings of the lightest Higgs boson could decouple much slowly compared to the Higgs coupling to a pair of massive vector bosons and they significantly deviate from the corresponding SM values even when the deviation of the Higgs to vector boson coupling is below the percent level. On the other hand, independently of 2HDM type and regardless of decoupling, we find a wrong-sign alignment limit of the Yukawa couplings in which the Yukawa couplings to the down-type quarks and/or those to the charged leptons are equal in strength but opposite in sign to the corresponding SM ones. The magnitude and sign of the up-type quark Yukawa couplings remain the same as in the SM. Accordingly, in this limit, all four types of 2HDMs are viable against the LHC Higgs precision data.
I. INTRODUCTION

Since the discovery of the 125 GeV Higgs boson in 2012 at the LHC [1, 2], it has been scrutinized very closely and extensively. At the early stage, several model-independent studies [3–25] show that there were some rooms for it to be unlike the one predicted in the Standard Model (SM) but, after combining all the LHC Higgs data at 7 and 8 TeV [26] and especially those at 13 TeV [27–45], it turns out that it is best described by the SM Higgs boson. Specifically, the third-generation Yukawa couplings have been established. And the most recent model-independent study [46] shows that the 1σ error of the top-quark Yukawa coupling is about 6% while those of the bottom-quark and tau-lepton ones are about 10%. In addition, the possibility of negative top-quark Yukawa coupling has been completely ruled out and the bottom-quark Yukawa coupling shows a preference of the positive sign [1] at about 1.5σ level. For the tau-Yukawa coupling, the current data still do not show any preference for its sign yet. On the other hand, the coupling to a pair of massive vector bosons is constrained to be consistent with the SM value within about 5% at 1σ level.

Even though we have not seen any direct hint or evidence of new physics beyond the SM (BSM), we are eagerly anticipating it motivated by the tiny but non-vanishing neutrino masses, matter dominance of our Universe and its evolution driven by dark energy and dark matters, etc. In many BSM models, the Higgs sector is extended and it results in existence of several neutral and charged Higgs bosons. In this case, one of the neutral Higgs bosons should be identified as the observed one at the LHC which weighs 125.5 GeV and its couplings are strongly constrained to be very SM-like by the current LHC data as outlined above. One of the popular ways to achieve this is to identify the lightest neutral Higgs boson as the 125.5 GeV one and assume that all the other Higgs bosons are heavier or much heavier than the lightest one [47, 48]. But this decoupling scenario is not phenomenologically interesting and another scenario is suggested in which all the couplings of the SM-like Higgs candidate are (almost) aligned with those of the SM Higgs while the other Higgs bosons are not so heavy [49, 50].

The measure usually taken for decoupling and/or alignment is the Higgs coupling to a pair of W and Z bosons. In contrast, much attention has not been paid to the Yukawa couplings. In this work, we study the decoupling and alignment of Yukawa couplings in the

1 Precisely speaking, here the sign of the bottom-quark Yukawa coupling is relative to the top-quark Yukawa coupling configured through the b- and t-quark loop contributions to the Hgg vertex.
framework of the two Higgs doublet models (2HDMs) where the SM is extended by adding one more SU(2)$_L$ doublet [51]. Particularly, we consider a scenario in which the lightest neutral Higgs boson is purely CP even while the two heavier ones might mix in the presence of nontrivial CP-violating (CPV) phases in the Higgs potential.

In the type-I 2HDM, we find the Yukawa couplings are well aligned even without decoupling as long as $\tan \beta \gtrsim 2$ and the 125 GeV Higgs boson discovered at the LHC can be easily accommodated with no conflict with the current LHC Higgs precision data. Otherwise, we find that the Yukawa couplings decouple slowly compared to the Higgs coupling to a pair of massive vector bosons and the alignment with decoupling occurs much slower when $\tan \beta$ is large. Interestingly, we find a wrong-sign alignment limit of the Yukawa couplings regardless of decoupling where the Yukawa couplings to the down-type quarks in type-II and -IV 2HDMs and those to the charged leptons in type-II and -III 2HDMs take the opposite signs to the corresponding SM ones while their magnitudes remain the same as in the SM. Note that both magnitude and sign of the up-type quark Yukawa couplings are the same as those of the SM in this limit. In this limit, all four types of 2HDMs are viable against the LHC Higgs precision data.

This paper is organized as follows. Section 2 is devoted to a brief review of the 2HDM Higgs potential, the mixing among neutral Higgs bosons and their couplings to the SM particles. In Section 3, we build up a scenario in which the lightest Higgs boson is purely CP even while the two heavier Higgs bosons exhibit CPV mixing. And we take the scenario to study the alignment of Yukawa couplings in Section 4. Conclusions are made in Section 5.

II. TWO HIGGS DOUBLET MODELS

In this work, we consider the general 2HDMs in which the potential might be parameterized with three (two real and one complex) massive parameters and four real and three
complex dimensionless quartic couplings as [52]:

\[
V_{2\text{HDM}} = +\mu_1^2(\Phi_1^\dagger \Phi_1) + \mu_2^2(\Phi_1^\dagger \Phi_2) + m_{12}^2(\Phi_1^\dagger \Phi_2) + m_{12}^2(\Phi_2^\dagger \Phi_1) \\
+ \lambda_1(\Phi_1^\dagger \Phi_1)^2 + \lambda_2(\Phi_2^\dagger \Phi_2)^2 + \lambda_3(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
+ \lambda_5(\Phi_1^\dagger \Phi_2)^2 + \lambda_6(\Phi_1^\dagger \Phi_1)^2 + \lambda_7(\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_8(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_1) \\
+ \lambda_9(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_2) + \lambda_{10}(\Phi_1^\dagger \Phi_2)(\Phi_1^\dagger \Phi_1) .
\]

Note that the \( \mathbb{Z}_2 \) symmetry under \( \Phi_1 \rightarrow \pm \Phi_1 \) and \( \Phi_2 \rightarrow \mp \Phi_2 \) is hardly broken by the non-vanishing quartic couplings \( \lambda_6 \) and \( \lambda_7 \) and, in this case, we have three rephasing-invariant CPV phases in the potential as we will see. With the parameterization

\[
\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \phi_1 + ia_1) \end{pmatrix} ; \quad \Phi_2 = e^{i\xi} \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \phi_2 + ia_2) \end{pmatrix}
\]

and denoting \( v_1 = v \cos \beta = v c_\beta \) and \( v_2 = v \sin \beta = v s_\beta \), one may remove \( \mu_1^2, \mu_2^2, \) and \( \Im(m_{12}^2 e^{i\xi}) \) from the 2HDM potential using three tadpole conditions:

\[
\mu_1^2 = -v^2 \left[ \lambda_1 c_\beta^2 + \frac{1}{2}\lambda_3 s_\beta^2 + c_\beta s_\beta \Re(\lambda_6 e^{i\xi}) \right] + s_\beta^2 M_{H^\pm}^2 ,
\]

\[
\mu_2^2 = -v^2 \left[ \lambda_2 s_\beta^2 + \frac{1}{2}\lambda_3 c_\beta^2 + c_\beta s_\beta \Re(\lambda_7 e^{i\xi}) \right] + c_\beta^2 M_{H^\pm}^2 ,
\]

\[
\Im(m_{12}^2 e^{i\xi}) = -\frac{v^2}{2} \left[ 2c_\beta s_\beta \Im(\lambda_5 e^{2i\xi}) + c_\beta^2 \Im(\lambda_6 e^{i\xi}) + s_\beta^2 \Im(\lambda_7 e^{i\xi}) \right] ,
\]

with the charged Higgs-boson mass given by

\[
M_{H^\pm}^2 = -\frac{\Re(m_{12}^2 e^{i\xi})}{c_\beta s_\beta} - \frac{v^2}{2c_\beta s_\beta} \left[ 4c_\beta s_\beta \Re(\lambda_5 e^{2i\xi}) + c_\beta^2 \Re(\lambda_6 e^{i\xi}) + s_\beta^2 \Re(\lambda_7 e^{i\xi}) \right] .
\]

Then, to fully specify the general 2HDM potential, one may need the following 13 parameters plus one sign:

\[
v, t_\beta, |m_{12}| ;
\]

\[
\lambda_1, \lambda_2 , \lambda_3 , \lambda_4 , |\lambda_5| , |\lambda_6| , |\lambda_7| ;
\]

\[
\phi_5 + 2\xi , \phi_6 + \xi , \phi_7 + \xi , \text{sign}[\cos(\phi_{12} + \xi)] ,
\]
including the vacuum expectation value \( v \) and three rephasing-invariant CPV phases. Here \( m_{12}^2 = |m_{12}|^2 e^{i\phi_{12}} \) and \( \lambda_{5,6,7} = |\lambda_{5,6,7}| e^{i\phi_{5,6,7}} \). We observe that \( \sin(\phi_{12} + \xi) \) is fixed by the CP-odd tadpole condition for \( \Im(m_{12}^2 e^{i\xi}) \) when the three CPV phases \( \phi_5 + 2\xi, \phi_6 + \xi \) and \( \phi_7 + \xi \) are given and, accordingly, \( \cos(\phi_{12} + \xi) \) is determined up to the two-fold ambiguity. One may take the convention with \( \xi = 0 \) without loss of generality.

The Higgs potential includes the mass terms which can be cast into the form

\[
V_{2HDM,\text{mass}} = M_{H^\pm}^2 H^+ H^- + \frac{1}{2} (\phi_1 \phi_2 a) M_0^2 \begin{pmatrix} \phi_1 \\ \phi_2 \\ a \end{pmatrix}
\]

(6)

where \( H^\pm \) and \( a \) along with the Goldstone bosons of \( G^\pm \) and \( G^0 \) are defined through the following rotations:

\[
\begin{pmatrix} \phi_1^- \\ \phi_2^- \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} G^- \\ H^- \end{pmatrix}; \quad \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} G^0 \\ a \end{pmatrix}.
\]

(7)

And the \( 3 \times 3 \) mass matrix of the neutral Higgs bosons \( M_0^2 \) is given by

\[
M_0^2 = M_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta & 0 \\ -s_\beta c_\beta & c_\beta^2 & 0 \\ 0 & 0 & 1 \end{pmatrix} + M_A^2 \]

(8)

with

\[
M_A^2 = M_{H^\pm}^2 + \frac{1}{2} \lambda_A v^2 - \Re(\lambda_5 e^{2i\xi}) v^2,
\]

(9)
and

\[
\frac{M^2_\lambda}{v^2} = \begin{pmatrix}
2\lambda_1 c_\beta^2 + 2\text{Re}(\lambda_5 e^{2i\xi}) s_\beta^2 & \lambda_{34} c_\beta s_\beta + \text{Re}(\lambda_6 e^{i\xi}) c_\beta^2 & -3\text{m}(\lambda_5 e^{2i\xi}) s_\beta \\
+2\text{Re}(\lambda_6 e^{i\xi}) s_\beta c_\beta & +2\text{Re}(\lambda_7 e^{i\xi}) s_\beta^2 & -3\text{m}(\lambda_6 e^{i\xi}) c_\beta \\
\lambda_{34} c_\beta s_\beta + \text{Re}(\lambda_6 e^{i\xi}) c_\beta^2 & 2\lambda_2 s_\beta^2 + 2\text{Re}(\lambda_5 e^{2i\xi}) c_\beta^2 & -3\text{m}(\lambda_5 e^{2i\xi}) c_\beta \\
+\text{Re}(\lambda_7 e^{i\xi}) s_\beta^2 & +2\text{Re}(\lambda_7 e^{i\xi}) s_\beta c_\beta & -3\text{m}(\lambda_7 e^{i\xi}) s_\beta \\
-3\text{m}(\lambda_5 e^{2i\xi}) s_\beta & -3\text{m}(\lambda_5 e^{2i\xi}) c_\beta & 0 \\
-3\text{m}(\lambda_6 e^{i\xi}) c_\beta & -3\text{m}(\lambda_7 e^{i\xi}) s_\beta & 0
\end{pmatrix} \quad (10)
\]

where \(\lambda_{34} = \lambda_3 + \lambda_4\).

Once the mass matrix is given, the \(3 \times 3\) mixing matrix \(O\) is defined through

\[
(\phi_1, \phi_2, a)^T = O_{\alpha i}(H_1, H_2, H_3)^T \quad (11)
\]

such that \(O^T M^2_\lambda O = \text{diag}(M^2_{H_1}, M^2_{H_2}, M^2_{H_3})\) with the ordering of \(M_{H_1} \leq M_{H_2} \leq M_{H_3}\).

The trilinear interactions of the neutral and charged Higgs bosons with the gauge bosons \(Z\) and \(W^\pm\) are described by the three interaction Lagrangians:

\[
\mathcal{L}_{HVV} = g M_W \left( W_\mu^+ W^{-\mu} + \frac{1}{2c_W^2} Z_\mu Z^\mu \right) \sum_i g_{hiVV} H_i, \quad (12)
\]

\[
\mathcal{L}_{HHZ} = \frac{g}{2c_W} \sum_{i>j} g_{hiHz} Z_\mu (H_i \leftrightarrow \partial_\mu H_j), \quad (13)
\]

\[
\mathcal{L}_{HH\pm W^-} = -\frac{g}{2} \sum_i g_{hiH+w^-} W^{-\mu} (H_i \leftrightarrow \partial_\mu H^+) + \text{h.c.}, \quad (14)
\]

where \(i, j = 1, 2, 3\) and the couplings \(g_{hiVV}, g_{hiHz}\) and \(g_{hiH+w^-}\) are given in terms of the neutral Higgs-boson mixing matrix \(O\) by (note that \(\det(O) = \pm 1\) for any orthogonal matrix \(O\)):

\[
\begin{align*}
g_{hiVV} &= c_\beta O_{\phi_1 i} + s_\beta O_{\phi_2 i}, \\
g_{hiHz} &= \text{sign}[\det(O)] \varepsilon_{ijk} g_{hkVV}, \\
g_{hiH+w^-} &= c_\beta O_{\phi_2 i} - s_\beta O_{\phi_1 i} - iO_{\alpha i},
\end{align*} \quad (15)
\]
TABLE I. Classification of 2HDMs satisfying the Glashow-Weinberg condition [55] which guarantees the absence of tree-level FCNC.

|   | 2HDM I | 2HDM II | 2HDM III | 2HDM IV |
|---|--------|---------|----------|---------|
| $\eta^d_1$ | 0 | 1 | 0 | 1 |
| $\eta^d_2$ | 1 | 0 | 1 | 0 |
| $\eta^l_1$ | 0 | 1 | 1 | 0 |
| $\eta^l_2$ | 1 | 0 | 0 | 1 |

leading to the following sum rules:

$$\sum_{i=1}^{3} g_{h,iVV}^2 = 1 \quad \text{and} \quad g_{h,iVV}^2 + |g_{h,iH+iW-}|^2 = 1 \quad \text{for each } i . \quad (16)$$

On the other hand, the Yukawa couplings in 2HDMs could be written as [53]:

$$-L_Y = h_u \bar{u}_R Q_L^T (i\tau_2) \Phi_2 - h_d \bar{d}_R Q_L^T (i\tau_2) \left( \eta^d_1 \Phi_1 + \eta^d_2 \Phi_2 \right)$$

$$- h_l \bar{l}_R L_L^T (i\tau_2) \left( \eta^l_1 \Phi_1 + \eta^l_2 \Phi_2 \right) + \text{h.c.} \quad (17)$$

where $Q_L^T = (u_L, d_L)$, $L_L^T = (\nu_L, l_L)$, and $\Phi_i = i\tau_2 \Phi_i^\ast$. Note that, in our convention, we make the up-type quarks coupled to only $\Phi_2$ exploiting a freedom to redefine the two linear combinations of $\Phi_1$ and $\Phi_2$ [54]. And, the down-type quarks and the charged leptons are coupled to either $\Phi_1$ or $\Phi_2$ in $Z_2$ symmetric way leading to the 4 types of 2HDMs without tree-level flavor-changing neutral currents (FCNCs) as classified in Table [1]. By identifying the couplings [3]

$$h_u = \frac{\sqrt{2} m_u}{v} \frac{1}{s_\beta} ; \quad h_d = \frac{\sqrt{2} m_d}{v} \frac{1}{\eta^d_1 c_\beta + \eta^d_2 s_\beta} ; \quad h_l = \frac{\sqrt{2} m_l}{v} \frac{1}{\eta^l_1 c_\beta + \eta^l_2 s_\beta} . \quad (18)$$

the couplings of three neutral Higgs bosons to a pair of fermions could be cast into the form collectively:

$$\mathcal{L}_{H,ff} = - \sum_{f=u,d,\ell} \frac{m_f}{v} \sum_{i=1}^{3} \left[ \bar{f} \left( g_{H,ff}^S + i \gamma_5 g_{H,ff}^P \right) f \right] H_i . \quad (19)$$

2 Here we take the convention with $\xi = 0$ and the couplings $h_{u,d,l}$ are supposed to be real.
For the SM Higgs, the normalized Yukawa couplings are given by $g_{H_{SM}ff} = 1$ and $g_{H_{SM}ff}^P = 0$.

We note all the neutral Higgs-boson couplings to fermions and massive vector bosons are fully determined once the mixing matrix $O$ and $t_\beta$ are given, see Table II and Eq. (12).

### III. A SCENARIO

In this section, we study the mixing in the neutral Higgs boson sector of 2HDMs in the presence of nontrivial CPV phases in the quartic couplings of $\lambda_{5,6,7}$. To be specific, we consider a scenario in which the lightest neutral Higgs boson is purely CP even while a CPV mixing might occur between the two heavy neutral Higgs bosons which are mixtures of CP-even and CP-odd states. When a CPV mixing in the neutral heavy Higgs sector occurs, the couplings of the two neutral heavy Higgs bosons to a pair of massive gauge bosons exist simultaneously. Note that, in the CP-conserving (CPC) case, one of the neutral heavy Higgs bosons is purely CP odd and its coupling to a pair of massive gauges bosons is identically vanishing.

For general CPV scenarios in 2HDMs, all of the three neutral Higgs bosons do not carry definite CP parities and they become mixtures of CP-even and CP-odd states. In this case,
without loss of generality, the orthogonal $3 \times 3$ mixing matrix $O$ might be parameterized as

$$O = \begin{pmatrix} -s_\alpha & c_\alpha & 0 \\ c_\alpha & s_\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_\eta & 0 & s_\eta \\ 0 & 1 & 0 \\ -s_\eta & 0 & c_\eta \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_\omega & s_\omega \\ 0 & -s_\omega & c_\omega \end{pmatrix},$$

introducing a CP-conserving (CPC) mixing angle $\alpha$ and two CPV angles $\omega$ and $\eta$ which should be fixed to study Higgs decays in the 2HDM framework. Note that, in our parameterization of the mixing matrix $O$, we have $\det(O) = -1$ to follow the CPC convention usually taken in the literature:

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix},$$

in terms of the two CP-even states of $H$ (heavier) and $h$ (lighter).

We take $s_\eta = 0$ and $c_\eta = +1$ assuming that the lightest Higgs boson $H_1$ is purely CP even and, in this case, the mixing matrix $O$ takes the form of

$$O = \begin{pmatrix} -s_\alpha & c_\alpha c_\omega & c_\alpha s_\omega \\ c_\alpha & s_\alpha c_\omega & s_\alpha s_\omega \\ 0 & -s_\omega & c_\omega \end{pmatrix}.$$

We observe $H_3$ is CP odd when $|c_\omega| = 1$ while $H_2$ is CP odd when $|s_\omega| = 1$. With the above $O$, the couplings of three neutral Higgs bosons to a pair of massive vector bosons are given by

$$g_{H_1VV} = s_{\beta-\alpha} \equiv +\sqrt{1-\epsilon}, \quad g_{H_2VV} = c_{\beta-\alpha} c_\omega \equiv \delta_2, \quad g_{H_3VV} = c_{\beta-\alpha} s_\omega \equiv \delta_3,$$

with $\delta_2^2 + \delta_3^2 = \epsilon$. Note that we are taking $g_{H_1VV} > 0$ and the two mixing angles $\alpha$ and $\omega$ are
determined by giving \( \delta_{2,3} \) and \( t_\beta \):

\[
\begin{align*}
    s_\alpha &= -\sqrt{1 - \epsilon} c_\beta + \frac{\delta_2}{c_\omega} s_\beta = -\sqrt{1 - \epsilon} c_\beta + \text{sign} \left[ \frac{\delta_2}{c_\omega} \right] \sqrt{\epsilon} s_\beta, \\
    c_\alpha &= +\sqrt{1 - \epsilon} s_\beta + \frac{\delta_2}{c_\omega} c_\beta = \sqrt{1 - \epsilon} s_\beta + \text{sign} \left[ \frac{\delta_2}{c_\omega} \right] \sqrt{\epsilon} c_\beta, \\
    c_\omega &= -\frac{\delta_2^2}{\delta_2^2 + \delta_3^2} = -\frac{\delta_2^2}{\delta_2^2 + \delta_3^2} = -\frac{\delta_3^2}{\epsilon}. 
\end{align*}
\]

With our choice of \( s_\eta = 0 \), the relation \( O^T M_0^2 O = \text{diag}(M_{H_1}^2, M_{H_2}^2, M_{H_3}^2) \) gives

\[
\begin{align*}
    (M_0^2)_{11} &= s_\alpha^2 M_{H_1}^2 + c_\alpha^2 c_\omega^2 M_{H_2}^2 + c_\alpha^2 s_\omega^2 M_{H_3}^2, \\
    (M_0^2)_{22} &= c_\alpha^2 M_{H_1}^2 + s_\alpha^2 c_\omega^2 M_{H_2}^2 + s_\alpha^2 s_\omega^2 M_{H_3}^2, \\
    (M_0^2)_{33} &= s_\omega^2 M_{H_2}^2 + c_\omega^2 M_{H_3}^2 = M_A^2; \\
    (M_0^2)_{12} &= c_\alpha s_\alpha ( -M_{H_1}^2 + c_\omega^2 M_{H_2}^2 + s_\omega^2 M_{H_3}^2 ) , \\
    (M_0^2)_{13} &= c_\alpha c_\omega s_\omega ( M_{H_3}^2 - M_{H_2}^2 ) , \\
    (M_0^2)_{23} &= s_\alpha c_\omega s_\omega ( M_{H_2}^2 - M_{H_3}^2 ) . 
\end{align*}
\]

Using the third and fourth relations in the above and Eq. (8), we have

\[
\begin{align*}
    s_\alpha c_\alpha &= \frac{(M_0^2)_{12}}{M_{H_1}^2 + c_\omega^2 M_{H_2}^2 + s_\omega^2 M_{H_3}^2} = -s_\beta c_\beta (s_\omega M_{H_2}^2 + c_\omega^2 M_{H_3}^2) + (M_\lambda^2)_{12} \\
    \epsilon s_{2\beta} - \sqrt{1 - \epsilon} c_{2\beta} &= \frac{-c_\beta s_\beta \left[ M_{H_1}^2 + c_\omega^2 (M_{H_3}^2 - M_{H_2}^2) \right] + (M_\lambda^2)_{12}}{M_{H_1}^2 + c_\omega^2 M_{H_2}^2 + s_\omega^2 M_{H_3}^2} \equiv \chi. 
\end{align*}
\]

By solving it for \( \epsilon \), we have

\[
\epsilon = \left( \chi s_{2\beta} + \frac{c_{2\beta}^2}{2} \right) - \frac{|c_{2\beta}|}{2} \left[ 1 - (2\chi - s_{2\beta})^2 \right]^{1/2} = \frac{1}{c_{2\beta}^2} \chi^2 - \frac{2s_{2\beta}}{c_{2\beta}^4} \chi^3 + \cdots. 
\]

Note that \( 2\chi - s_{2\beta} = s_{2\alpha} \). We further note that \( \epsilon \) is suppressed by the quartic powers of the heavy Higgs-boson masses in the leading order.

In the decoupling limit of \( M_{H_{2,3}}^2 \gg M_{H_1}^2 \sim (M_\lambda^2)_{12} \sim (M_{H_3}^2 - M_{H_2}^2) \), \( \epsilon \) approaches 0 and,
accordingly, one has
\[ \delta_{2,3} \to 0; \quad s_\alpha \to -c_\beta, \quad c_\alpha \to +s_\beta. \] (29)

We also observe that, the fifth and sixth relations in Eq. (25) lead to
\[ t_\alpha = \frac{(M_0^2)^{23}}{(M_0^2)_{13}} = \frac{3m(\lambda_5) + 3m(\lambda_7)t_\beta}{3m(\lambda_5)t_\beta + 3m(\lambda_6)} \to -\frac{1}{t_\beta} \] (30)
which gives
\[ 3m(\lambda_5) \to -\frac{1}{2} \left[ \frac{3m(\lambda_6)}{t_\beta} + \frac{3m(\lambda_7) t_\beta}{t_\beta} \right]. \] (31)

To summarize, among the 13 free parameters of 2HDMs counted as in Eq. (5), we have addressed 8 parameters of
\[ v, \ t_\beta; \ s_\eta, \ \delta_2, \ \delta_3; \ M_{H_1}, \ M_{H_2}, \ M_{H_3}. \] (32)

The choice of \( s_\eta = 0 \) makes the lightest Higgs boson purely CP even and \( \delta_2 \) and \( \delta_3 \) (\( \epsilon = \delta_2^2 + \delta_3^2 \)) fix the two remaining mixing angles of \( \alpha \) and \( \omega \) up to signs with the given value of \( t_\beta \), see Eq. (24). Note that the masses of three neutral Higgs bosons are independent from each other when \( \lambda_6 \) and/or \( \lambda_7 \) are non-vanishing which is consistent with results presented in Refs. [56–58].

IV. ALIGNMENT OF YUKAWA COUPLINGS

In this section, we closely examine the couplings of the lightest Higgs boson \( H_1 \) in the scenario represented by Eq. (24) interpreting the CP-even \( H_1 \) is the Higgs boson discovered at the LHC with \( M_{H_1} = M_{H_{SM}} = 125.5 \) GeV. In this case, \( g_{H_1 ff}^S \) and \( g_{H_1 VV} \) should be close to the SM values of 1 for the decay pattern of \( H_1 \) to be consistent with the current LHC Higgs precision data.

From Table [11] irrelevant of the type of 2HDMs, we observe that any \( H_1 \) coupling to a pair of SM fermions is given by one of the following two quantities [7]
\[ \frac{O_{\phi_21}}{s_\beta} = \frac{c_\alpha}{s_\beta} = \sqrt{1 - \epsilon} + \text{sign} \left[ \frac{\delta_2}{c_\omega} \right] \sqrt{\epsilon}, \quad \frac{O_{\phi_11}}{c_\beta} = \frac{-s_\alpha}{c_\beta} = \sqrt{1 - \epsilon} - \text{sign} \left[ \frac{\delta_2}{c_\omega} \right] \sqrt{\epsilon} t_\beta, \] (33)

\[ ^3 \text{Note that, in our convention, both the lightest neutral Higgs boson couplings to a pair of vector bosons } \ V = W, Z \text{ and its Yukawa couplings to the up-type quarks are positive definite when sign} \left[ \frac{\delta_2}{c_\omega} \right] = +1 \text{ independently of 2HDM type and } t_\beta. \]
FIG. 1. The normalized Yukawa couplings of $H_1$ to a pair of SM fermions $g^S_{H_1ff}$ for sign $[\delta_2/\cos\omega] = +1$ (upper) and sign $[\delta_2/\cos\omega] = -1$ (lower) as functions of $\log_{10}(1/\epsilon)$ taking four values of $t_\beta = 0.5$ (dash-dotted), 1 (dotted), 2 (dashed), and 10 (solid).

with $g^P_{H_1ff} = 0$ taking $O_{n1} = -s_\eta = 0$. In Fig. 1 we show $O_{\phi_21}/s_\beta$ (left) and $O_{\phi_11}/c_\beta$ (right) as functions of $\log_{10}(1/\epsilon)$ for positive and negative $\delta_2/c_w$ in the upper and lower panels, respectively, taking four values of $t_\beta$. First of all, we see that both of the normalized Yukawa couplings approach to or align with the SM value of 1 in the decoupling limit where $\epsilon \rightarrow 0$. Otherwise, the couplings are not always positive and their magnitudes could be significantly larger than 1. Moreover, compared to the $g_{\mu_1VV} = \sqrt{1 - \epsilon}$ coupling, they decouple slowly or much slowly depending on $t_\beta$. If $\epsilon = 0.01$ and $t_\beta = 10$, for example, the $g_{\mu_1VV}$ coupling deviates from its SM value by only 0.5% but the Yukawa coupling $O_{\phi_11}/c_\beta$ could be as large

$\tan\beta = 0.5$

$\log_{10}(1/\epsilon)$

$O_{\phi_21}/s_\beta [+] = \sqrt{(1-\epsilon)} + \sqrt{\epsilon} / t_\beta$

$O_{\phi_11}/c_\beta [+] = \sqrt{(1-\epsilon)} - \sqrt{\epsilon} t_\beta$

$O_{\phi_21}/s_\beta [-] = \sqrt{(1-\epsilon)} - \sqrt{\epsilon} / t_\beta$

$O_{\phi_11}/c_\beta [-] = \sqrt{(1-\epsilon)} + \sqrt{\epsilon} t_\beta$
as 2 or even could vanish depending on the sign of $\delta_2/c_\omega$ resulting in 100% deviation from its SM value: see the black lines in the upper- and lower-right panels of Fig. 1. The similar observation could be made for $O_{\phi_2}/s_\beta$ for small $t_\beta < 1$.

In Fig. 2, we show the couplings of $H_1$ to a pair of the SM fermions $g_{H_1 ff}^S$ as functions of $t_\beta$ when $\delta_2/c_\omega > 0$ (black solid) and $\delta_2/c_\omega < 0$ (red dashed) taking $\epsilon = 0.1$. The coupling $|O_{\phi_1}/c_\beta|$ linearly grows as $t_\beta$ increases implying that the $H_1$ couplings to bottom quarks in type-II and -IV 2HDMs and those to tau leptons in type-II and -III 2HDMs could significantly deviate from the SM value of 1 for intermediate and/or large values of $t_\beta$ depending on the size of $\epsilon$. In contrast, in the type-I 2HDM, all the Yukawa couplings are given by $O_{\phi_2}/s_\beta$ and it remains more or less aligned with the SM value as long as $t_\beta \gtrsim 1$.

When $\delta_2/c_\omega > 0$, we note there is another possibility in which $O_{\phi_1}/c_\beta$ takes the opposite sign to the SM coupling but its absolute value is 1 [48]. This occurs at $t_\beta = (1+\sqrt{1-\epsilon})/\sqrt{\epsilon}$.
TABLE III. The normalized Yukawa couplings of the lightest neutral Higgs boson $H_1$ in the four types of 2HDMs in the wrong-sign alignment limit where $t_\beta = (1 + \sqrt{1 - \epsilon})/\sqrt{\epsilon}$.

| Couplings | I | II | III | IV |
|-----------|---|----|-----|----|
| $g_{H_1 tt, H_1 \bar{t} t, H_1 \bar{u} u}$ | 1 | 1 | 1 | 1 |
| $g_{H_1 bb, H_1 \bar{b} b, H_1 d d}$ | 1 | -1 | 1 | -1 |
| $g_{H_1 \tau \tau, H_1 \mu \mu, H_1 e e}$ | 1 | -1 | -1 | 1 |

FIG. 3. The ratio of the total decay width of the lightest Higgs boson $H_1$ to that of the SM, $\Gamma_{\text{tot}}(H_1)/\Gamma_{\text{tot}}(H_{\text{SM}})$, as functions of $t_\beta$ in the four types of 2HDMs: type I (black solid), type II (red dashed), type III (blue dotted), and type IV (magenta dash-dotted). We have taken $\epsilon = 0.1$ and sign[$\delta_2/c_\omega$] = +1. The SM decay width $\Gamma_{\text{tot}}(H_{\text{SM}}) = 4.122$ MeV with $M_{H_1} = M_{H_{\text{SM}}} = 125.5$ GeV.

and, surprisingly, this also makes $O_{\phi_{21}}/s_\beta = +1$, see the black solid lines in Fig. 2 around $t_\beta = 6$ and Table III. Therefore, every 2HDM could be made consistent with the LHC Higgs precision data independently of its type by making this specific choice of $t_\beta$ at the expense of wrong signs of the $H_1$ couplings to down-type quarks in type-IV 2HDM, those to charged leptons in type-III 2HDM, and those to both down-type quarks and charged leptons in type-II 2HDM. Note that this wrong-sign alignment of the Yukawa couplings happens for any value of $\epsilon$, whether in the decoupling limit or not.

In Fig. 3 we show the total decay width of the lightest Higgs boson $\Gamma_{\text{tot}}(H_1)$ normalized
FIG. 4. The ratios of branching ratios $B(H_1 \to D)/B(H_{SM} \to D)$ as functions of $t_\beta$ in the four types of 2HDMs: $D = bb$ (upper left), $c\bar{c}$ (upper middle), $gg$ (upper right), $\tau\tau$ (middle left), $\mu\mu$ (middle middle), $WW$ (middle right), $ZZ$ (lower left), $\gamma\gamma$ (lower middle), and $Z\gamma$ (lower right). The lines and the input parameters are the same as in Fig. 3.

to the SM one $\Gamma_{tot}(H_{SM}) = 4.122$ MeV. We consider all four types of 2HDMs taking $M_{H_1} = M_{H_{SM}} = 125.5$ GeV and $\text{sign}[\delta_2/c_\omega] = +1$ with $t_\beta$ varied. For $\epsilon$, we take $\epsilon/2 = 0.05$ adopting the 1\sigma error of 5\% for the $g_{H_1VV} = \sqrt{1-\epsilon}$ coupling obtained by the 4-parameter fit to the current LHC Higgs data [46]. Taking into account that the error of the total decay width of the 125.5 GeV Higgs boson is about 10\% at 95\% confidence level [46, 52], we find that the type-I 2HDM is reasonably viable for $t_\beta \gtrsim 2$ against the LHC Higgs precision data. The type-III 2HDM also seems viable unless $t_\beta$ is too large. But we note this is only true when sizeable deviation of the branching ratios of the decay modes into charged leptons from their SM values is tolerated, see the blue dotted lines in the middle-left and middle-middle panels.

The varied 4 parameters are the three third-generation Yukawa couplings and the coupling to a pair of massive vector bosons: $g_{H_1ti}^S$, $g_{H_1tb}^S$, $g_{H_1\tau\tau}^S$, and $g_{H_1VV}$. 

\[^4\] The varied 4 parameters are the three third-generation Yukawa couplings and the coupling to a pair of massive vector bosons: $g_{H_1ti}^S$, $g_{H_1tb}^S$, $g_{H_1\tau\tau}^S$, and $g_{H_1VV}$. 

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In Fig. 4, in the type-II and type-IV 2HDMs, the total decay width is consistent with the current LHC Higgs precision data only around \( t_\beta = 1/2 \) and 6. But, around \( t_\beta = 1/2 \), we observe discrepancies in the decay modes into fermions and gluons, see the dashed and dash-dotted lines in Fig. 4. Specifically, we find the reduction of the branching ratio into \( b\bar{b} \), which is mainly compensated by the increment in \( H_1 \rightarrow gg \), and conclude that the first case with \( t_\beta \sim 1/2 \) should be valid only for the smaller values of \( \epsilon \), see the horizontal lines locating the positions of \( \sqrt{1-\epsilon} \pm \sqrt{\epsilon} \) in Fig. 2. On the other hand, around \( t_\beta = 6 \) where the absolute values of the Yukawa couplings are exactly aligned with the SM ones for the given value of \( \epsilon = 0.1 \), the type-I and type-III 2HDMs are consistent with the current LHC Higgs precision data. In the wrong-sign alignment limit of the Yukawa couplings, the type-II and -IV 2HDMs are also made feasible if the preference of the positive sign of the bottom-quark Yukawa coupling, which is currently observed at \( \sim 1.5\sigma \) level, has not been taken seriously.

V. CONCLUSIONS

We study the alignment of Yukawa couplings in the framework of general 2HDMs identifying the lightest neutral Higgs boson as the 125 GeV one discovered at the LHC while the two heavier neutral Higgs bosons are allowed to mix in the presence of nontrivial CP-violating phases in the Higgs potential. We summarize our major findings as follows:

1. In the type-I 2HDM, the alignment of Yukawa couplings without decoupling could be easily achieved as long as \( \tan \beta \gtrsim 2 \) even for the largest possible value of \( \epsilon = 0.1 \) allowed by the current LHC Higgs precision data on the total decay width.

2. Otherwise, we find that the Yukawa couplings decouple much slowly compared to the \( g_{H_1VV} \) coupling. For \( \epsilon = 0.01 \), the \( g_{H_1VV} \) coupling deviates from its SM value by only 0.5% but the bottom-quark Yukawa coupling in type-II and -IV 2HDMs and the tau-lepton Yukawa coupling in type-II and -III 2HDMs could deviate from their SM values by more than 100% when \( t_\beta > 10 \).

3. In the wrong-sign alignment limit of the Yukawa couplings where \( t_\beta = (1+\sqrt{1-\epsilon})/\sqrt{\epsilon} \), all four types of 2HDMs are viable against the LHC Higgs precision data with the Yukawa couplings to the down-type quarks and/or those to the charged leptons being equal in strength but opposite in sign to the corresponding SM ones. In contrast, the
magnitude and sign of the up-type quark Yukawa couplings remain the same as in the SM.

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