Probing flavor changing neutral currents and CP violation through the decay $h \rightarrow c\bar{b}W^-$ in the two Higgs doublet model

L. Díaz-Cruz$^1$, A. Díaz-Furlong$^1$, R. Gaitán-Lozano$^2$ and J.H. Montes de Oca Y.$^2$

$^1$Cuerpo Académico de Partículas, Campos y Relatividad Facultad de Ciencias Físico-Matemáticas, BUAP. Apdo. Postal 1364, C.P. 72000 Puebla, Pue., México
$^2$Departamento de Física, Facultad de Estudios Superiores Cuautitlán, UNAM, C.P. 54770, Estado de México, México

E-mail: jldiaz@fcfm.buap.mx
E-mail: rgaitan@servidor.unam.mx
E-mail: josehalim@comunidad.unam.mx

Abstract. We discuss the formulation of the general two-Higgs doublet model type III, which incorporates flavor changing neutral scalar interactions (FCNSI) and CP violation from several sources. CP violation can arise either from Yukawa terms or from the Higgs potential, and it can explicit or spontaneous. We discuss the case that includes CP violation with Yukawa textures to control FCNSI and evaluate the CP asymmetry for the decay $h \rightarrow b\bar{c}W$, which may allow to test the patterns of FCNSI and CP violation, that arises in these models.

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‡ Corresponding author: josehalim@comunidad.unam.mx
1. Introduction

After many years of expectations, LHC is currently probing the mechanism of electroweak symmetry breaking (EWSB)\cite{1}. In fact, LHC has provided great results and we know now that only an small mass window remain open for the SM Higgs mass, namely $116 < m_{\text{higgs}} < 130$ GeV \cite{2}. This results are consistent with the analysis of electroweak precision of a Higgs mass around 125 GeV \cite{3}. If this result is confirmed by future analysis, we will have one of the greatest discoveries of mankind. On the other hand, the SM is often considered as an effective theory, valid up to an energy scale of $O(\text{TeV})$, that eventually will be replaced by a more fundamental theory \cite{4}, which will explain, among other things, the physics behind EWSB and perhaps even the origin of flavor. Many examples of candidate theories, which range from supersymmetry \cite{5} to strongly interacting models \cite{6} as well as some extra dimensional scenarios \cite{7}, include a multi-scalar Higgs sector. In particular, models with two scalar doublets have been studied extensively \cite{8}, as they include a rich structure with interesting phenomenology \cite{9}.

Several versions of the 2HDM have been studied in the literature \cite{10}. Some models (known as 2HDM-I and 2HDM-II) involve natural flavor conservation \cite{11}, while other models (known as 2HDM-III) \cite{10}, allow for the presence of flavor changing scalar interactions (FCNSI) at a level consistent with low-energy constraints \cite{12}. There are also some variants (known as top, lepton, neutrino), where one Higgs doublet couples predominantly to one type of fermion \cite{13}, while in other models it is even possible to identify a candidate for dark matter \cite{14}. The definition of all these models, depends on the Yukawa structure and symmetries of the Higgs sector \cite{15, 16, 17, 18, 19}, whose origin is still not known. The possible appearance of new sources of CP violation is another characteristic of these models \cite{20}.

In this paper we aim to discuss FCNC within general version of the Two-Higgs doublet model (2HDM-III), which incorporates flavor and CP violation from all possible sources \cite{21, 22, 23}. Within model I (2HDM-I) where only one Higgs doublet generates all gauge and fermion masses, while the second doublet only knows about this through mixing, and thus the Higgs phenomenology will share some similarities with the SM, although the SM Higgs couplings will now be shared among the neutral scalar spectrum. The presence of a charged Higgs boson is clearly the signal beyond the SM. Within 2DHM-II one also has natural flavor conservation \cite{11}, and its phenomenology will be similar to the 2HDM-I, although in this case the SM couplings are shared not only because of mixing, but also because of the Yukawa structure. The distinctive characteristic of 2HDM-III is the presence of FCNSI, which require a certain mechanism in order to suppress them, for instance one can imposes a certain texture for the Yukawa couplings \cite{24}, which will then predict a pattern of FCNSI Higgs couplings \cite{25}. Within all those models (2HDM I,II,III) \cite{26, 27, 28}, the Higgs doublets couple, in principle, with all fermion families, with a strength proportional to the fermion masses, modulo other parameters.
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There are also other models where the Higgs doublets couple non-universally to the fermion families, which have also been discussed in the literature \cite{13, 20, 30}. In principle, the general model includes CPV, which could arise from the same CPV phase that appears in the CKM matrix, as in the SM, from some other extra phase coming from the Yukawa sector or from the Higgs potential \cite{31}. However, in order to discuss which type of CP violation can appear in each case besides containing a generic pattern of FCNSI, modulated by certain texture, will include new sources of CPV as well.

In this paper we are interested in finding a signal of both FCNC and CPV. In particular, we identify the decay $h \rightarrow c\bar{b}W^-$ as a possible reaction where such test can be done. This decay process though the flavor current vertex $tch$, which is not severely constrained by data, and is also sensitive to the presence of CPV phases. We define a decay asymmetry to probe the CPV. The organization of the paper goes as follows: section 2 includes the model formalism, which is based on the results of ref. \cite{32}, and two considered scenarios. Section 3 contains the estimation of the width decay, branching ratio and CP asymmetry coefficient. Finally, the conclusions.

2. General two Higgs doublet model with textures in Yukawa matrices

The scalar field content of the model is two doublets under $SU(2)_L$ with hypercharges $Y_1 = Y_2 = 1/2$. The model is classified by choice of the Higgs potential and the scalar-fermion couplings. The simpler versions are considered when the potential is invariant under $Z_2$ discrete symmetry and none of the doublets couples simultaneously to the up-type and down-type fermions. These are known as 2HDM type I and II. In type I, only one of the doublets couples to fermions [gordon fest]. In type II, one doublet couples to up-type fermions, the other to down-type fermions to prevent tree-level FCNCs [gordon fest]. Type III is more general and realistic model which allows all possible Higgs-fermion couplings [gordon-sher]. This work is based on 2HDM type III with a general potential which contains explicit and spontaneous CP violation.

2.1. General Higgs potential and Higgs mass-eigenstates

We follow closely the formalism developed and notation introduced by \cite{32}. The most general gauge invariant renormalizable Higgs scalar potential in a covariant form with respect to global $U(2)$ transformation is given by

$$V = Y_{a,b} \Phi^\dagger_a \Phi_b + \frac{1}{2} Z_{a,b,c,d} \left( \Phi^\dagger_a \Phi_b \right) \left( \Phi^\dagger_c \Phi_d \right),$$

where $\Phi_a = (\phi^+_a, \phi^0_a)^T$ and $a, b, c, d$ are labels with respect to two dimensional Higgs flavor space. The index conventions means that replacing an unbarred index with a barred index is equivalent to complex conjugation and barred.unbarred index pair denotes a sum. The most general $U(1)_{EM}$-conserving vacuum expectation values are

$$\langle \Phi_a \rangle = \frac{v}{\sqrt{2}} \begin{pmatrix} 0 \\ \hat{v}_a \end{pmatrix},$$
where \( \left( \hat{v}_1, \hat{v}_2 \right) = e^{i\eta} \left( \cos \beta, \sin \beta e^{i\xi} \right) \) and \( v = 246 \) GeV. The covariant form for the scalar potential minimum conditions is

\[
v\hat{v}_a^* \left[ Y_{ab} + \frac{1}{2} v^2 Z_{abcd} \hat{v}_c^* \hat{v}_d \right] = 0.
\] (3)

The Higgs mass-eigenstates of the neutral Higgs bosons are explicitly derived in Ref. [32]. The expressions for Higgs bosons in terms of the generic basis is

\[
h_k = \frac{1}{\sqrt{2}} \tilde{\Phi}_a^0 (q_{k1} \hat{v}_a + q_{k2} \hat{w}_a e^{-i\theta_{23}})
\]

\[
\frac{1}{\sqrt{2}} (q_k^* \hat{v}_a^* + q_{k2}^* \hat{w}_a^* e^{i\theta_{23}}) \tilde{\Phi}_a^0
\] (4)

for \( k = 1, ..., 4 \), where \( h_{1,2,3} \) are the neutral physical Higgs bosons and \( h_4 = G^0 \) is the goldstone boson. The parameters \( q_{k1,2} \) are functions of the neutral Higgs mixing angles and the explicit values are shown in table 1. It is possible to invert the expression (4) and the result is given by

\[
\Phi_a = \left( \frac{v}{\sqrt{2}} \hat{v}_a + \frac{1}{\sqrt{2}} \sum_{k=1}^4 (q_{k1} \hat{v}_a + q_{k2} e^{-i\theta_{23}} \hat{w}_a) h_k \right).
\] (5)

where \( \hat{w}_a^T = e^{-i\eta} \left( -\sin \beta e^{-i\xi}, \cos \beta \right) \).

### 2.2. Higgs-fermions couplings

We focus on quarks fields with analogous treatment for leptons. The most general structure of the Yukawa lagrangian for the quark fields can be written as follows:

\[
\mathcal{L}_{Y^{quarks}} = \overline{q}_L^0 Y_1^U \Phi_1 d_R^0 + \overline{q}_L^0 Y_2^D \Phi_2 d_R^0 + \overline{q}_L^0 Y_1^U \Phi_1 u_R^0 + \overline{q}_L^0 Y_2^U \Phi_2 u_R^0 + h.c.,
\] (6)

where \( Y_{1,2}^{U,D} \) are the \( 3 \times 3 \) Yukawa matrices, \( q_L \) denotes the left handed quarks doublets and \( u_R, d_R \) correspond to the right handed singlets. The superscript zero means that the quarks are weak eigenstates. Here \( \tilde{\phi}_{1,2} = i\sigma_2 \phi_{1,2}^* \). After getting a correct SSB [48, 49, 50, 51], the Higgs doublets are decomposed as shown in (5) and the neutral scalar and pseudoscalar couplings within up-type quarks in mass eigenstate basis are

\[
\mathcal{L}_{up}^{neutral} = \overline{u}_i \left( S_{ijr}^u + \gamma^5 P_{ijr}^u \right) u_j H_r + \overline{u}_i M_{ij}^U u_j,
\] (7)

where we have denoted the scalar and pseudoscalar couplings as

\[
S_{ijr}^u = \frac{1}{v} M_{ij}^U \left( q_{r1} + \cot \beta \text{Re} \left[ q_{r2} e^{-i(\theta_{23} + \xi)} \right] \right)
\]

\[
+ \frac{1}{2 \sqrt{2} \sin \beta} \left( q_{r2} e^{i(\theta_{23} + \xi)} \overline{Y}_{2ij}^U + q_{r2} e^{-i(\theta_{23} + \xi)} \overline{Y}_{2ij}^U \right)
\] (8)

| \( r \) | \( q_{r1} \) | \( q_{r2} \) |
|---|---|---|
| 1 | \( \cos \theta_{12} \cos \theta_{13} \) | \( -\sin \theta_{12} - i \cos \theta_{12} \sin \theta_{13} \) |
| 2 | \( \sin \theta_{12} \cos \theta_{13} \) | \( \cos \theta_{12} - i \sin \theta_{12} \sin \theta_{13} \) |
| 3 | \( \sin \theta_{13} \) | \( i \cos \theta_{13} \) |

Table 1. Mixing angles for Higgs bosons which consider spontaneous and explicit CPV [32].
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and

\[ P_{ijr}^u = \frac{1}{v} M_{ij}^\mu \cot \beta \Im \left[ q_{\tau 2} e^{-i(\theta_{23} + \xi)} \right] \]

\[ + \frac{1}{2\sqrt{2} \sin \beta} \left( q_{\tau 2} e^{i\theta_{23}} \tilde{Y}_{2ij}^U - q_{\tau 2} e^{-i\theta_{23}} \tilde{Y}_{2ij}^{U\dagger} \right), \]

respectively. The mass matrices are given as follows:

\[ M^U = \frac{v_1}{\sqrt{2}} \tilde{Y}^U_1 + e^{-i\xi} \frac{v_2}{\sqrt{2}} \tilde{Y}^U_2, \]  

\[ M^D = \frac{v_1}{\sqrt{2}} \tilde{Y}^D_1 + e^i\xi \frac{v_2}{\sqrt{2}} \tilde{Y}^D_2, \]

where \( \tilde{Y}^U_{1,2} = U_L Y^U_{1,2} U_R^\dagger \) and \( \tilde{Y}^D_{1,2} = D_L Y^D_{1,2} D_R^\dagger \) with \( u_{L,R} = U_{L,R} u^0_{L,R} \) and \( d_{L,R} = D_{L,R} d^0_{L,R} \). The vacuum expectation values \( v_1 \) and \( v_2 \) are real and positive, while the phase \( \xi \) introduces spontaneous CP violation. Analogously, the down-type quarks are

\[ L^{neutral}_{down} = \tilde{d}_i \left( S^d_{ijr} + \gamma^5 P^d_{ijr} \right) d_j H_r + \tilde{d}_i M^D_{ij} d_j, \]

with

\[ S^d_{ijr} = \frac{1}{v} M^D_{ij} \left( q_{\tau 1} - \tan \beta \Re \left[ q_{\tau 2} e^{-i(\theta_{23} + \xi)} \right] \right) \]

\[ + \frac{1}{2\sqrt{2} \cos \beta} \left( q_{\tau 2} e^{-i\theta_{23}} Y^D_2 \right) + q_{\tau 2} e^{i\theta_{23}} \tilde{Y}^D_2 \]

and

\[ P^d_{ijr} = -\frac{1}{v} M^D_{ij} \tan \beta \Im \left[ q_{\tau 2} e^{-i(\theta_{23} + \xi)} \right] \]

\[ + \frac{1}{2\sqrt{2} \cos \beta} \left( q_{\tau 2} e^{-i\theta_{23}} \tilde{Y}^D_2 - q_{\tau 2} e^{i\theta_{23}} \tilde{Y}^D_2 \right). \]

For completeness, the Yukawa couplings for charged Higgs bosons is written as

\[ L^H_Y = \pi \left[ H^+ e^{-i\xi} M^U V I - \gamma^5 \sqrt{2} - H^+ e^{-i\xi} V M^D I - \gamma^5 \sqrt{2} \right] \]

\[ + \frac{1}{\cos \beta} \left( V \tilde{Y}_2^D I + \gamma^5 \right) d + h.c., \]

where \( V \) denotes the CKM matrix and physical eigenstates for the charged Higgs boson \( (H^\pm) \) can be obtained through \( (4) \).

### 2.3. Universal Yukawa textures

Suppression for FCNC can be achieved when a certain form of the Yukawa matrices that reproduce the observed fermion masses and mixing angles is implemented in the model. This could be done either by implementing the Frogart-Nielsen mechanism to generate the fermion mass hierarchies \( [39] \), or by studying a certain ansatz for the fermion mass
matrices \[24\]. The first proposal for the Higgs boson couplings \[25\], the so-called Cheng-Sher ansatz, was based on the Fritzsch six-texture form of the mass matrices, namely:

\[
M_l = \begin{pmatrix}
0 & C_q & 0 \\
C_q^* & 0 & B_q \\
0 & B_q^* & A_q \\
\end{pmatrix}.
\] (16)

Then, by assuming that each Yukawa matrix \(Y_{1,2}^q\) has the same hierarchy, one finds:

\[
A_q \simeq m_{q_3}, \quad B_q \simeq \sqrt{m_{q_2}m_{q_3}} \quad \text{and} \quad C_q \simeq \sqrt{m_{q_1}m_{q_2}}.
\]

Then, the fermion-fermion'Higgs boson \((ff'0)\) couplings obey the following pattern: \(Hf_if_j \sim \sqrt{m_{f_i}m_{f_j}}/m_W\), which is also known as the Cheng-Sher ansatz. This brings under control the FCNC problem, and it has been extensively studied in the literature to search for flavor-violating signals in the Higgs sector.

In our previous work we considered in detail the case of universal four-texture Yukawa matrices \[12\], and derived the scalar-fermion interactions, showing that it was possible to satisfy current constraints from LFV and FCNC \[40, 41\]. Predictions for Higgs phenomenology at the LHC was also studied in ref. \[42, 43\]. We can consider this a universal model, in the sense that it was assumed that each Yukawa matrix \(Y_{1,2}^q\) has the same hierarchy.

### 2.4. FCNC and CPV Feynman rules

The Higgs-fermions interactions and the scalar potential of the general 2HDM contain several sources of CPV and FCNC. In order to explore these sources we consider some limiting cases. As it is discussed in previous sections, the assumption of universal 4-textures for the Yukawa matrices, allows to express one Yukawa matrix in terms of the quark masses, and parametrization of the FCNSI in terms of the unknown coefficients \(\chi_{ij}\), namely \(Y_{2i}^U = \chi_{ij} \sqrt{m_{i}m_{j}} \). These parameters can be constrained by considering all types of low energy FCNC transitions. Although these constraints are quite strong for transitions involving the first and second families, as well as for the b-quark, it turns out that they are rather mild for the top quark. In this paper we shall consider two scenarios:

**A) Explicit CPV in the Higgs sector.** In this case we assume the hermiticity condition for the Yukawa matrices, but the Higgs sector admits explicit CP violating. Then, from \[8\] and \[9\], one obtains the following expressions for the couplings of the neutral Higgs bosons with up-type quarks, namely:

\[
S_{ijr}^u = \frac{1}{v} M_{ij}^U (q_{r1} + \cot \beta \text{Re}[q_{r2}]) + \frac{\sqrt{m_{i}m_{j}}}{\sqrt{2}v \sin \beta} \chi_{ij} (\text{Re}[q_{r2}])
\] (17)

and

\[
P_{ijr}^u = \frac{i}{v} M_{ij}^U \cot \beta \text{Im}[q_{r2}],
\] (18)

similar expressions can be obtained for the down-type quarks and leptons.

**B) CP conserving Higgs sector.** In this case we shall consider that the Higgs sector is CP conserving and the Yukawa matrices could be also hermitian. Then, without loss
of generality, we can assume that $h_3$ is CP odd, while $h_1$ and $h_2$ are CP even. Then:

$$\cos \theta_{12} = \sin (\beta - \alpha), \quad \sin \theta_{12} = \cos (\beta - \alpha), \quad \sin \theta_{13} = 0,$$

and $e^{-i\theta_{13}} = 1$. The mixing angles $\alpha$ and $\beta$ that appear in the neutral Higgs mixing, corresponds to the standard notation. Additionally, when one assumes a 4-texture for the Yukawa matrices, the Higgs-fermion couplings further simplify as $\tilde{Y}^u_{2ij} = \chi_{ij} \frac{m_i m_j}{v}$. Then, the corresponding coefficients for up sector and $h^0 \ (r = 1)$ are

$$S^u_{ij1} = \frac{1}{v} M^U_{ij} \left[ \sin (\beta - \alpha) + \cot \beta \cos (\beta - \alpha) \right] + \frac{\sqrt{m_i m_j} \chi_{ij} \cos (\beta - \alpha)}{\sqrt{2} v} \sin \beta \quad \text{(19)}$$

For $H^0 \ (r = 2)$ one finds:

$$S^u_{ij2} = \frac{1}{v} M^U_{ij} \left[ \cos (\beta - \alpha) + \cot \beta \sin (\beta - \alpha) \right] + \frac{\sqrt{m_i m_j} \chi_{ij} \sin (\beta - \alpha)}{\sqrt{2} v} \sin \beta \quad \text{(20)}$$

Finally, for $A^0 \ (r = 3)$ one obtains:

$$P^u_{ij3} = \frac{i}{2 v} M^U_{ij} \cot \beta - \frac{i \sqrt{m_i m_j} \chi_{ij}}{2 \sqrt{2} v \sin \beta} \quad \text{(21)}$$

Note that under hermiticity of the Yukawa matrices the $P^u_{ijr}$ couplings for the $h^0$ and $H^0$ and the coupling $S^u_{ij3}$ for the $A^0$ are vanished.

3. The Higgs decay $h \to c\bar{b}W^-$

In this section we shall evaluate the width of the decay $h \to c\bar{b}W^-$ and its respective branching ratio. Besides the decay width and branching ratio, we are also interested in defining a decay asymmetry coefficient for the decay $h \to c\bar{b}W^-$ in order to analyze presence of both FCNSI and CPV within the 2HDM. We consider the neutral Higgs boson decay $h \to W\bar{c}c$ at tree level. Two diagrams contribute to this decay, the first one is through the FCNC coupling $h \to \bar{t}c \to W^-\bar{c}c$, its Feynman diagram is shown on figure [1]. The other one goes through $h \to W^{++}W^- \to W^-\bar{t}c$, see figure [2]. The amplitude for these diagrams is thus

$$|\mathcal{M}|^2 = |\mathcal{M}_1|^2 + |\mathcal{M}_2|^2 + \mathcal{M}_1 \mathcal{M}_2 + \mathcal{M}_2 \mathcal{M}_1 \quad \text{(22)}$$

We can obtain an approximation when the terms proportional to the charm and bottom masses are neglected. Then, the explicit expressions are

$$|\mathcal{M}_1|^2 = \frac{g^4}{4 M_W^2} |P_1|^2 \left\{ \left| S^u_{231} + P^u_{231} \right|^2 \left[ 4 \left( p_1 \cdot p_2 \right) \left( p_1 \cdot q \right) \left( p_3 \cdot q \right) \right. \right.$$

$$+ 2 M_W^2 \left( p_2 \cdot q \right) \left( p_3 \cdot q \right) - M_W^2 q^2 \left( p_2 \cdot p_3 \right) - 2 q^2 \left( p_1 \cdot p_2 \right) \left( p_1 \cdot p_3 \right) \right.$$  

$$\left. + m_t^2 \left| S^u_{231} - P^u_{231} \right|^2 \left[ 2 \left( p_2 \cdot p_3 \right) + 2 \left( p_1 \cdot p_2 \right) \left( p_1 \cdot p_3 \right) \right] \right\}, \quad \text{(23)}$$

$$|\mathcal{M}_2|^2 = g^4 (q_{11})^2 |V_{cb}|^2 |P_W(k)|^2 \left( M_W^2 p_2 \cdot p_3 + 2 p_1 \cdot p_2 p_1 \cdot p_3 \right), \quad \text{(24)}$$

$$|\mathcal{M}_1 \mathcal{M}_2 + \mathcal{M}_2 \mathcal{M}_1| = \frac{g^4 m_t}{M_W} q_{11} V_{cb} P_W(k) \left( M_W^2 p_2 \cdot p_3 + 2 p_1 \cdot p_2 p_1 \cdot p_3 \right)$$

$$\left[ \text{Re} \left( S^u_{231} + P^u_{231} \right) \text{Re} P_1 - \text{Im} \left( S^u_{231} + P^u_{231} \right) \text{Im} P_1 \right], \quad \text{(25)}$$
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where \( P_W(k) = (k^2 - M_W^2 + iM_W\Gamma_W)^{-1} \) and \( P_t(q) = (q^2 - m_t^2 + i m_t\Gamma_t)^{-1} \). Then, the decay width is

\[
\Gamma_{h \rightarrow W^- b^c} = \frac{g^4 m_h}{256\pi^3} \left[ |S_{231}^u - P_{231}^u|^2 I_1 + |S_{231}^u + P_{231}^u|^2 I_2 + q_{11}^2 |V_{cb}|^2 I_3 
+ \Re(S_{231}^u + P_{231}^u)q_{11}V_{cb}I_4 - \Im(S_{231}^u + P_{231}^u)q_{11}V_{cb}I_5 \right] \quad (26)
\]

The analytical expressions and numerical values for the integrals \( I_1, \ldots, I_5 \) are shown in appendix. For scenario \( A \)

\[
\Gamma_{h \rightarrow W^- b^c}^A = \frac{g^4 m_h}{256\pi^3} \left[ |\chi_{23}|^2 m_c m_t v^{-2} \sin^2 \theta_{12} \frac{2}{2 \sin^2 \beta} (I_1 + I_2) 
+ |V_{cb}|^2 \cos^2 \theta_{12} \cos^2 \theta_{13} I_3 
+ V_{cb}\sqrt{m_c m_t} v^{-1} \sin \theta_{12} \cos \theta_{12} \cos \theta_{13} \frac{2}{2 \sin \beta} 
[I_5 \Im(\chi_{23}) - I_4 \Re(\chi_{23})] \right], \quad (27)
\]

while for scenario \( B \) we have:

\[
\Gamma_{h \rightarrow W^- b^c}^B = \frac{g^4 m_h}{256\pi^3} \left[ m_c m_t v^{-2} \cos^2 (\beta - \alpha) \frac{2}{2 \sin^2 \beta} |\chi_{23}|^2 (I_1 + I_2) 
+ |V_{cb}|^2 \sin^2 (\beta - \alpha) I_3 
- V_{cb}\sqrt{m_c m_t} v^{-1} \sin (\beta - \alpha) \cos (\beta - \alpha) \frac{2}{2 \sin \beta} 
(I_4 \Re(\chi_{23}) - I_5 \Im(\chi_{23})) \right], \quad (28)
\]

3.1. Branching ratio for \( h \rightarrow c\bar{b}W^- \)

Since the analysis of electroweak precision test favors a Higgs mass in the range \( 115 < m_h < 160 \text{ GeV} \), we should consider Higgs decay modes that could complete
with the dominant decay in this window, which in most models is $h \to b\bar{b}$, although $h \to WW^*$ $h \to ZZ^*$ could also significant contribution. Furthermore, given the recent LHC data, one could assume that the light Higgs boson will have SM like couplings, but current LHC precision admits some moderate deviations from SM. Thus, we shall include the 3-body decay $h \to c\bar{b}W^-$, which could receive an enhancement coming from the vertex $ht^*c$. The total width for the littlest neutral Higgs boson can be approximated by

$$
\Gamma_{Total} \approx \Gamma(h \to b\bar{b}) + \Gamma(h \to c\bar{c}) + \Gamma(h \to ZZ^*) \\
+ \Gamma(h \to WW^*) + \Gamma(h \to c\bar{b}W^-),
$$

(29)

The decay width for the decay of the Higgs boson to fermion and anti-fermion pair at tree level is given by

$$
\Gamma (h \to f_i f_j) = \frac{g^2 m_h}{8\pi} \left( 1 - 4 \frac{m_f^2}{m_h^2} \right) \\
\left[ \left( S_{ij1}^f + P_{ij1}^f \right)^2 + \left| S_{ij1}^f - P_{ij1}^f \right|^2 \right] \left( 1 - 2 \frac{m_f^2}{m_h^2} \right) \\
- \text{Re} \left[ \left( S_{ij1}^f + P_{ij1}^f \right) \left( S_{ij1}^{f*} - P_{ij1}^{f*} \right) \right]
$$

(30)

In general, the couplings $S_{ij1}^f$ and $P_{ij1}^f$ are given by the equations (8) and (9) for any of the proposed scenarios. Now, the decay width into a real $W$ and virtual $W^*$ is given by

$$
\Gamma (h \to WW^*) = \frac{g^4 m_h}{128\pi^3} \cos^2 (\theta_{12}) F \left( \frac{m_W}{m_h} \right).
$$

(31)

While the decay width $h \to ZZ^*$ is given by

$$
\Gamma (h \to ZZ^*) = \frac{g^4 m_h}{2048\pi^3} F \left( \frac{m_Z}{m_h} \right) \cos^2 (\theta_{12}) \\
\frac{7 - \frac{40}{3} \sin^2 \theta_W + \frac{160}{9} \sin^4 \theta_W}{\cos^4 \theta_W}
$$

(32)

where

$$
F (x) = - \left( 1 - x^2 \right) \left( \frac{47}{2} x^2 - \frac{13}{2} + \frac{1}{x^2} \right) - 3 \left( 1 - 6x^2 + 4x^4 \right) \ln (x) \\
+ 3 \frac{1 - 8x^2 + 20x^4}{\sqrt{4x^2 - 1}} \cos^{-1} \left( \frac{3x^2 - 1}{2x^3} \right).
$$

(33)

It is possible to write the explicit expressions of the total decay width for each scenario. However, the section 3.3 shows the behavior for the branching ratio and the CP asymmetry coefficient.

### 3.2. CPV decay asymmetry

In order to find the CP asymmetry coefficient we also need to calculate the conjugate decay. We denote the average amplitude of the conjugate decay as

$$
|\tilde{M}|^2 = |\tilde{M}_1|^2 + |\tilde{M}_2|^2 + \tilde{M}_1^\dagger \tilde{M}_2 + \tilde{M}_2^\dagger \tilde{M}_1.
$$

(34)
The square terms are the same as the above, $|\mathcal{M}_{1,2}|^2 = |\mathcal{M}_{1,2}|^2$, while for the interference terms we have

\[
|\mathcal{M}_1^* \mathcal{M}_2 + \mathcal{M}_2^* \mathcal{M}_1| = \frac{g^2 m_t}{M_W} q_{11} V_{cb} P_W(k) \left( M_W^2 p_2 \cdot p_3 \right) + 2 p_1 \cdot p_2 p_1 \cdot p_3 \left[ \text{Re} \left( S_{231}^u + P_{231}^u \right) \text{Re} (P) \right] + \text{Im} \left( S_{231}^u + P_{231}^u \right) \text{Im} (P),
\]

(35)

The CP asymmetry coefficient is defined as

\[
A_{CP} = \frac{\Gamma_{h \rightarrow W^+ \nu_e} - \Gamma_{h \rightarrow W^- \bar{\nu}_e}}{\Gamma_{h \rightarrow W^+ \nu_e} + \Gamma_{h \rightarrow W^- \bar{\nu}_e}}.
\]

(36)

Therefore, the CP asymmetry coefficient of the decay in general 2HDM is given by:

\[
A_{CP} = V_{cb} q_{11} I_5 \text{Im} \left( S_{231}^u + P_{231}^u \right) \left[ |S_{231}^u - P_{231}^u|^2 I_1 + |S_{231}^u + P_{231}^u|^2 I_2 \right.
\]

\[
+ |V_{cb}|^2 q_{11} I_3 + q_{11} V_{cb} \text{Re} \left( S_{231}^u + P_{231}^u \right) I_4 \left]^{-1},
\]

(37)

In case of CP explicit violation or CP conserving the asymmetry coefficient is written as

\[
A_{CP}^A = \frac{\text{Im} (\chi_{23}) I_5 \text{Re} (\chi_{23}) - \sqrt{2} I_3 V_{cb} \frac{\cos \theta_{13} \sin \beta}{\sqrt{m_c m_t}} \tan \theta_{12} - (I_1 + I_2) \frac{|\chi_{23}|^2 \sqrt{m_c m_t}}{\sqrt{2} v} \tan \theta_{12} \sin \beta \cos \theta_{13}}{\frac{\sqrt{m_c m_t}}{\sqrt{2} v} \sin \beta \cos \theta_{13}}
\]

(40)

and

\[
A_{CP}^B = \frac{\text{Im} (\chi_{23}) I_5 \text{Re} (\chi_{23}) - \sqrt{2} I_3 V_{cb} \frac{\sin \beta \tan (\beta - \alpha)}{\sqrt{m_c m_t}} - (I_1 + I_2) \frac{|\chi_{23}|^2 \sqrt{m_c m_t}}{\sqrt{2} v} \sin \beta \tan (\beta - \alpha)}{\frac{\sqrt{m_c m_t}}{\sqrt{2} v} \sin \beta \tan (\beta - \alpha)}
\]

(41)

### 3.3. Numerical results

The central numerical values for the SM parameters are the reported by [52]. Nevertheless, the mixing angles, texture parameters and neutral scalar mass are free parameters of the 2HDM. However, If the neutral scalar is considered like the Higgs boson scalar in the SM, the current experimental results and data analysis allow to take a central value equal to 125 GeV for the neutral scalar mass [2]. Additionally, the ratio of the vacuum expectation values, $\beta$ parameter, is bounded by the region $1 \leq \tan \beta \leq 50$ [52].
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Figure 3. Branching ratio of the decay $h \rightarrow c\bar{b}W^-$ for $(\theta_{12}, \theta_{13})$ bellows to region $[0,1] \times [0,1]$ taking $|\chi| = 0.1$, $\delta = 0.01$ and $\tan \beta = 1$ in scenario A.

Figure 4. Branching ratio of the decay $h \rightarrow c\bar{b}W^-$ for $(\alpha, \beta)$ bellows to region $[0,\pi/2] \times [\arctan 1, \arctan 50]$ taking $|\chi| = 0.1$ and $\delta = 0.01$ in scenario B.

Figure 5. CP asymmetry of the decay $h \rightarrow c\bar{b}W^-$ for $(\theta_{12}, \theta_{13})$ bellows to region $[0,1] \times [0,1]$ taking $|\chi| = 0.1$, $\delta = 0.01$ and $\tan \beta = 1$ in scenario A.

Figure 6. CP asymmetry of the decay $h \rightarrow c\bar{b}W^-$ for $(\alpha, \beta)$ bellows to region $[0,\pi/2] \times [\arctan 1, \arctan 50]$ taking $|\chi| = 0.1$ and $\delta = 0.01$ in scenario B.
We have noted that the texture parameters, \( \chi_{ij} \), have a small contribution in the branching ratio for both considered scenarios. Then, \( \chi_{23} = \chi e^{i\delta} \) are taken as same magnitude order as the CKM parameter, that is, \( \chi \approx 0.1 \) and \( \delta \approx 0.01 \). In figures and the dependence of the branching ratio on the mixing angles is shown. The textures parameters controls the magnitude order of the CP asymmetry coefficient defined previously, see \((5), (6)\). The CP asymmetry coefficient behavior is shown in figures and for the same numerical values of \( \chi_{23} \).

4. Conclusion

In summary, we have considered a general scalar potential written in \( U(2) \) covariant form and the Yukawa couplings of the type III with 4-texture ansatz. Under these assumptions the CP violation such as spontaneous or explicit from scalar sector are not the only source but Yukawa couplings contribute. For sake of simplicity, the spontaneous CP violation phase was assumed to be zero and the CP asymmetry coefficient has been obtained. The CP asymmetry coefficient not only depends of mixing angles but texture parameters of the Yukawa couplings. The explicit CP violation and CP conserving possibilities have been considered for scalar sector, which were named as scenario A and B respectively. The CP asymmetry coefficient has the order of magnitude from 0 to \( 10^{-2} \) for both scenarios.

The total width decay in the considered model was approximated by the \((29)\). Then an approximated expressions for the branching ratio of the decay \( h \to c\bar{b}W^- \) were obtained for the proposed scenarios. The order of magnitude bellows to range \([0, 4 \times 10^{-5}]\) for \( 0 \leq \theta_{12,13} \leq \pi/2 \) taking scenario A, meanwhile the order of magnitude bellows to range \([0, 6 \times 10^{-5}]\) for \( 0 \leq \alpha \leq \pi/2 \) and \( 1 \leq \tan \beta \leq 50 \) taking scenario B.

The decay \( h \to c\bar{b}W^- \) is an important signal for this type of model, 2HDM-III, which could be discriminated from others types of models.

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Appendix A. The integrals \( I_i \)

Defining the dimensionless variables as \((x, y) = \left( \frac{2E_1}{m_h}, \frac{2E_2}{m_h} \right)\), \( \mu_1 = \frac{m_W^2}{m_h}, \mu = \frac{m_t^2}{m_h}, \) and \( \Gamma^2 = \frac{\Gamma^2}{m_h} \), the integrals are

\[
I_1 = \int \int_{R_{xy}} \left( (x + y - 1 - \mu)^2 + \mu \Gamma^2 \right)^{-1} \\
[4\mu_1 (x + y - \mu_1 - 1) (x + y + \mu_1 - 1) (2 - x - y) \\
2 (x + y - \mu_1 - 1) (2 - x - y)]
\]
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\[ - (x + y - 1) (1 - x + \mu_1) \]
\[ - 2\mu_1 (x + y - 1) (x + y - \mu_1 - 1) (1 - y - \mu_1)] dxdy, \]

\[ I_2 = \int \int_{R_{xy}} (\frac{(x + y - 1 - \mu)^2 + \mu \Gamma^2}{\mu_1}) \]
\[ [2\mu_1 (x + y - \mu_1 - 1) (1 - y - \mu_1) \]
\[ \mu (1 - x + \mu_1)] dxdy, \]

\[ I_3 = \int \int_{R_{xy}} \frac{(x - 1)^2}{\mu_1 (1 - x + \mu_1)} \]
\[ + 2(x + y - \mu_1 - 1) (1 - y - \mu_1)] dxdy, \]

\[ I_4 = \int \int_{R_{xy}} \frac{(x + y - 1 - \mu)^2 + \mu \Gamma^2}{(1 - x)^2} \]
\[ - 2\mu (x + y + \mu_1 - 1) (1 - y - \mu_1) \]
\[ + \mu_1 (1 - x + \mu_1)] (x + y - \mu) dxdy, \]

\[ I_5 = \int \int_{R_{xy}} \frac{(x + y - 1 - \mu)^2 + \mu \Gamma^2}{(1 - x)^2} \]
\[ + 2\mu (x + y + \mu_1 - 1) (1 - y - \mu_1) \]
\[ + \mu_1 (1 - x + \mu_1)] \sqrt{\mu \Gamma} dxdy, \]

where the \( R_{xy} \) region is defined by

\[ \frac{1}{2} \left( 2 - x - \sqrt{x^2 - 4\mu_1} \right) \leq y \leq \frac{1}{2} \left( 2 - x + \sqrt{x^2 - 4\mu_1} \right) \]

and

\[ 2\sqrt{\mu_1} \leq x \leq 1 + \mu_1. \]

In figures \[ A1 \] and \[ A2 \] the dependence of the integrals \( I_{1,...,5} \) on the scalar mass \( h \) is shown.
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