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Signal of FCNC and CP violation through $h \to c\bar{b}W^-$ in two Higgs doublet model

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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, be it explicit or spontaneous. We discuss the limit that includes CP violation and Yukawa four textures to control FCNSI and evaluate the CP asymmetry for the decay $h \to bcW$, which may allow to test the patterns of FCNSI and CP violation, that arises in these models.

1. Introduction

Despite the success of the Standard Model (SM) in the gauge and fermion sectors, the Higgs sector remains the least tested aspect of the model [1], which leaves the puzzles associated with the mechanism of electroweak symmetry breaking (EWSB) still unsolved. On one hand, the analysis of radiative corrections within the SM [2, 3, 4, 5], points towards the existence of a Higgs boson, with a mass of the order of the EW scale, which in turn could be detected at the LHC [6, 7]. Nowdays, the Higgs boson mass has a experimental bound of the order of 125 GeV [CMS , ATLAS]. On the other hand, the SM is often considered as an effective theory, valid up to an energy scale of $O(TeV)$, that eventually will be replaced by a more fundamental theory [8], 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 [9, 10, 11] to strongly interacting models [12, 13] as well as some extra dimensional scenarios [14, 15, 16], include a multi-scalar Higgs sector. In particular, models with two scalar doublets have been

studied extensively [17, 18, 19], as they include a rich structure with interesting phenomenology [20, 21, 22].

Several versions of the 2HDM have been studied in the literature [23]. Some models (known as 2HDM-I and 2HDM-II) involve natural flavor conservation [24], while other models (known as 2HDM-III) [23], allow for the presence of flavor changing scalar interactions (FCNSI) at a level consistent with low-energy constraints [25]. There are also some variants (known as top, lepton, neutrino), where one Higgs doublet couples predominantly to one type of fermion [27], while in other models it is even possible to identify a candidate for dark matter [26]. The definition of all these models, depends on the Yukawa structure and symmetries of the Higgs sector [28, 29, 30, 31, 32], whose origin is still not known. The possible appearance of new sources of CP violation is another characteristic of these models [33].

In this paper we aim to discuss FCNC at general version of the Two-Higgs doublet model (2HDM-III), which incorporates flavor or CP violation from all possible sources [34, 35, 36].

Within model I (2HDM-I) where only one Higgs doublet generates all gauge and fermion masses [6], 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 [24], 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. On the other hand, 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 [37], which will then predict a pattern of FCNSI Higgs couplings [38]. Within all those models (2HDM I,II,III) [39, 40, 41], the Higgs doublets couple, in principle, with all fermion families, with a strength proportional to the fermion masses, modulo other parameters.

There are also other models where the Higgs doublets couple non-universally to the fermion families, which have also been discussed in the literature [27, 42, 43]. 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 [44]. However, in order to discuss which type of CP violation can appear in each case besides containing a generic pattern of FCNSI, moduled by certain texture, will include new sources of CPV as well.

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. In type II, one doublet couples to up-type fermions, the other to down-type fermions to prevent tree-level FCNCs. Type III is more general and realistic model which allows all possible Higgs-fermion couplings. 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 [45]. The most general gauge invariant renormalizable Higgs scalar potential in a covariant form with respect to global $U(2)$ transformation is given by

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

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 [45].

where $\Phi_a = (\phi_a^+, \phi_a^0)^T$ 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

$$\langle \Phi_a \rangle = \frac{v}{\sqrt{2}} \begin{pmatrix} 0 \\ \hat{v}_a \end{pmatrix}, \tag{2}$$

where $\begin{pmatrix} \hat{v}_1, & \hat{v}_2 \end{pmatrix} = e^{i\eta} \begin{pmatrix} \cos\beta, & \sin\beta e^{i\xi} \end{pmatrix}$ and $v = 246$ GeV. The covariant form for the scalar potential minimum conditions is

$$v\hat{v}_{\bar{a}}^* \left[Y_{a\bar{b}} + \frac{1}{2} v^2 Z_{a\bar{b}c\bar{d}} \hat{v}_{\bar{c}}^* \hat{v}_d \right] = 0. \tag{3}$$

The Higgs mass-eigenstates of the neutral Higgs bosons are explicitly derived in [45]. The expressions for Higgs bosons in terms of the generic basis is

$$\begin{aligned} h_k &= \frac{1}{\sqrt{2}} \overline{\Phi}_{\bar{a}}^{0\dagger} (q_{k1}\hat{v}_a + q_{k2}\hat{w}_a e^{-i\theta_{23}}) \\ & \quad \frac{1}{\sqrt{2}} (q_{k1}^* \hat{v}_{\bar{a}}^* + q_{k2} * \hat{w}_{\bar{a}}^* e^{i\theta_{23}}) \overline{\Phi}_{\bar{a}}^0 \end{aligned} \tag{4}$$

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

$$\Phi_a = \begin{pmatrix} G^+\hat{v}_a + H^+\hat{w}_a \\ \frac{v}{\sqrt{2}}\hat{v}_a + \frac{1}{\sqrt{2}} \sum_{k=1}^{4} \left(q_{k1}\hat{v}_a + q_{k2} e^{-\theta_{23}} \hat{w}_a \right) h_k \end{pmatrix}, \tag{5}$$

where $\hat{w}_a^T = e^{-i\eta} \begin{pmatrix} -\sin\beta e^{-i\xi}, & \cos\beta \end{pmatrix}$.

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:

$$\mathcal{L}_Y^{quarks} = \overline{q}_L^0 Y_1^D \phi_1 d_R^0 + \overline{q}_L^0 Y_2^D \phi_2 d_R^0 + \overline{q}_L^0 Y_1^U \widetilde{\phi}_1 u_R^0 + \overline{q}_L^0 Y_2^U \widetilde{\phi}_2 u_R^0 + h.c., \tag{6}$$

where $Y_{1,2}^{U,D}$ are the 3×3 Yukawa matrices, q_L denotes the left handed quarks doublets and u_R, d_R correspond to the right handed singlets. Here $\widetilde{\phi}_{1,2} = i\sigma_2 \phi_{1,2}^*$. The superscript zero means that the quarks are weak eigenstates. After getting a correct SSB [60, 61, 62, 63], 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

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

where we have denoted the scalar and pseudoscalar couplings as

$$\begin{aligned} S_{ijr}^u &= \frac{1}{v} M_{ij}^U \left(q_{r1} - \tan\beta \mathrm{Re}\left[q_{r2} e^{-i(\theta_{23}+\xi)} \right] \right) \\ &+ \frac{1}{2\sqrt{2}\cos\beta} \left(q_{r2}^* e^{i\theta_{23}} \widetilde{Y}_{2ij}^U + q_{r2} e^{-i\theta_{23}} \widetilde{Y}_{2ij}^{U\dagger} \right) \end{aligned} \tag{8}$$

and

$$\begin{aligned} P_{ijr}^u &= \frac{1}{v} M_{ij}^U \tan\beta \mathrm{Im}\left[q_{r2} e^{-i(\theta_{23}+\xi)} \right] \\ &+ \frac{1}{2\sqrt{2}\cos\beta} \left(q_{r2}^* e^{i\theta_{23}} \widetilde{Y}_{2ij}^U - q_{r2} e^{-i\theta_{23}} \widetilde{Y}_{2ij}^{U\dagger} \right), \end{aligned} \tag{9}$$

respectively. The mass matrices are given as follows:

$$M^U = \frac{v_1}{\sqrt{2}} \widetilde{Y}_1^U + e^{-i\xi} \frac{v_2}{\sqrt{2}} \widetilde{Y}_2^U \tag{10}$$

and

$$M^D = \frac{v_1}{\sqrt{2}} \widetilde{Y}_1^D + e^{i\xi} \frac{v_2}{\sqrt{2}} \widetilde{Y}_2^D, \tag{11}$$

where $\widetilde{Y}_{1,2}^U = U_L Y_{1,2}^U U_R^\dagger$ and $\widetilde{Y}_{1,2}^D = D_L Y_{1,2}^D D_R^\dagger$ with $u_{L,R} = U_{L,R} u_{L,R}^0$ and $d_{L,R} = D_{L,R} d_{L,R}^0$. The v.e.v. v_1 and v_2 are real and positive, while the phase ξ introduces spontaneous CP violation.

Analogously, the down-type quarks are

$$\mathcal{L}_{down}^{neutral} = \overline{d}_i \left(S_{ijr}^d + \gamma^5 P_{ijr}^d \right) d_j H_r + \overline{d}_i M_{ij}^D d_j, \tag{12}$$

with

$$\begin{aligned} S_{ijr}^d &= \frac{1}{v} M_{ij}^D \left(q_{r1} - \tan\beta \mathrm{Re}\left[q_{k2} e^{-i(\theta_{23}+\xi)} \right] \right) \\ &+ \frac{1}{2\sqrt{2}\cos\beta} \left(q_{r2} e^{-i\theta_{23}} Y_2^D + q_{r2}^* e^{i\theta_{23}} \widetilde{Y}_2^{D\dagger} \right) \end{aligned} \tag{13}$$

and

$$\begin{aligned} P_{ijr}^d &= -\frac{1}{v} M_{ij}^D \tan\beta \mathrm{Im}\left[q_{k2} e^{-i(\theta_{23}+\xi)} \right] \\ &+ \frac{1}{2\sqrt{2}\cos\beta} \left(q_{r2} e^{-i\theta_{23}} \widetilde{Y}_2^D - q_{r2}^* e^{i\theta_{23}} \widetilde{Y}_2^{D\dagger} \right). \end{aligned} \tag{14}$$

For completeness we write the Yukawa couplings for charged Higgs bosons,

$$\begin{aligned} \mathcal{L}_Y^{H^+} &= \overline{u} \left[H^+ e^{-i\xi} M^U V \frac{I-\gamma^5}{\sqrt{2}} - H^+ e^{-i\xi} V M^D \frac{I+\gamma^5}{\sqrt{2}} \right. \\ &+ \left. \frac{1}{\cos\beta} H^+ \left(V \widetilde{Y}_2^D \frac{I+\gamma^5}{2} - \widetilde{Y}_2^{U\dagger} V \frac{I-\gamma^5}{2} \right) \right] d \\ &+ h.c. \end{aligned} \tag{15}$$

where V denotes the CKM matrix and physical eigenstates for the charged Higgs boson ($H^\pm$) can be obtain through (5).

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 [52], or by studying a certain ansatz for the fermion mass matrices [37]. The first proposal for the Higgs boson couplings [38], the so called Cheng-Sher ansazt, was based on the Fritzsch six-texture form of the mass matrices, namely:

$$M_l = \begin{pmatrix} 0 & C_q & 0 \\ C_q^* & 0 & B_q \\ 0 & B_q^* & A_q \end{pmatrix}. \tag{16}$$

Then, by assuming that each Yukawa matrix $Y^q_{1,2}$ has the same hierarchy, one finds: $A_q \simeq m_{q_3}$, $B_q \simeq \sqrt{m_{q_2} m_{q_3}}$ and $C_q \simeq \sqrt{m_{q_1} m_{q_2}}$. 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 [25], and derived the scalar-fermion interactions, showing that it was possible to satisfy current constraints from LFV and FCNC [53, 54]. Predictions for Higgs phenomenology at the LHC was also studied in ref. [55, 56]. We can consider this a universal model, in the sense that it was assumed that each Yukawa matrix $Y^q_{1,2}$ has the same hierarchy.

3. FCNC and CP violation sources

The Higgs-fermions interactions and 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 parametrize the FCNSI in terms of the unknown coefficients χ_{ij}, namely $\widetilde{Y}^U_{2ij} = \chi_{ij} \frac{\sqrt{m_i m_j}}{v}$, where the hermiticity condition reads $\chi_{ij} = \chi^\dagger_{ij}$. 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.

3.1. FCNC and explicit CP violation

In this case we assume the hermiticity condition for the Yukawa matrices, but the Higgs sector could be only 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:

$$S^u_{ijr} = \frac{1}{v} M^U_{ij} \left(q_{r1} - \tan\beta \mathrm{Re}\left[q_{r2}\right]\right) + \frac{\sqrt{m_i m_j}}{\sqrt{2} v \cos\beta} \chi_{ij} \left(\mathrm{Re}\left[q_{r2}\right]\right) \tag{17}$$

and

$$P^u_{ijr} = \frac{1}{v} M^U_{ij} \left[\tan\beta \mathrm{Im}\left[q_{r2}\right]\right] - \frac{\sqrt{m_i m_j}}{\sqrt{2} v \cos\beta} \chi_{ij} \mathrm{Im}\left[q_{r2}\right], \tag{18}$$

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

3.2. FCNC and CP conserving

In this case we shall consider that the Higgs sector is CP conserving, while the Yukawa matrices could be non-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: $\cos\theta_{12} = \sin(\beta-\alpha)$, $\sin\theta_{12} = \cos(\beta-\alpha)$, $\sin\theta_{13} = 0$, and $e^{-i\theta_{13}} = 1$. The mixing angles α and β 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 $\widetilde{Y}^U_{2ij} = \chi_{ij}\frac{\sqrt{m_i m_j}}{v}$. Then, the corresponding coefficient expressions for up sector and h^0 $(r=1)$ are

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

$$P^u_{ij1} = \frac{\sqrt{m_i m_j}}{2\sqrt{2}v}\frac{\cos(\beta-\alpha)}{\cos\beta}\left(\chi_{ij} - \chi^\dagger_{ij}\right) \tag{20}$$

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

$$S^u_{ij2} = \frac{1}{v}M^U_{ij}\left[\cos(\beta-\alpha) - \tan\beta\sin(\beta-\alpha)\right] + \frac{\sqrt{m_i m_j}}{2\sqrt{2}v}\frac{\sin(\beta-\alpha)}{\cos\beta}\left(\chi_{ij} + \chi^\dagger_{ij}\right), \tag{21}$$

$$P^u_{ij2} = \frac{\sqrt{m_i m_j}}{2\sqrt{2}v}\frac{\sin(\beta-\alpha)}{\cos\beta}\left(\chi_{ij} - \chi^\dagger_{ij}\right) \tag{22}$$

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

$$S^u_{ij3} = i\frac{\sqrt{m_i m_j}}{2\sqrt{2}v\cos\beta}\left(\chi_{ij} - \chi^\dagger_{ij}\right), \tag{23}$$

$$P^u_{ij3} = \frac{i}{2v}M^U_{ij}\tan\beta - i\frac{\sqrt{m_i m_j}}{2\sqrt{2}v\cos\beta}\left(\chi_{ij} + \chi^\dagger_{ij}\right) \tag{24}$$

Note that under hermiticity on Yukawa matrices the P_{ijr} couplings for the h^0 and H^0 and S_{ijr} for the A^0 are vanished.

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

In this section we shall evaluate the asymmetry coefficient for the decay $h \to c\bar{b}W$ in order to analyze presence of both FCNSI and CPV within the 2HDM. In the SM the FCNC are suppressed, but in the 2HDM extensions these processes are found even at tree level. We consider the neutral Higgs boson decay $h \longrightarrow W\bar{b}c$ at tree level. Two diagrams contribute to this decay, the first one is through the FCNC coupling $h \longrightarrow \bar{t}^* c \longrightarrow W^-\bar{b}c$, its Feynman diagram is shown on left figure 1. The other one is through $h \longrightarrow W^{+*}W^- \longrightarrow W^-\bar{b}c$, also shown in figure 2.

The couplings of the neutral Higgs with the quarks and the charged boson W with the neutral Higgs are written as $i\left(S^u_{231} + \gamma^5 P^u_{231}\right)$ and $igM_W q_{11} g^{\mu\nu}$, respectively. The other vertices are the usual SM contribution. The average amplitude for these diagrams is thus

$$\overline{|\mathcal{M}|}^2 = \overline{|\mathcal{M}_1|}^2 + \overline{|\mathcal{M}_2|}^2 + \overline{\mathcal{M}^\dagger_1\mathcal{M}_2} + \overline{\mathcal{M}^\dagger_2\mathcal{M}_1} \tag{25}$$

We can obtain an approximation when the terms proportional to the charm and bottom masses

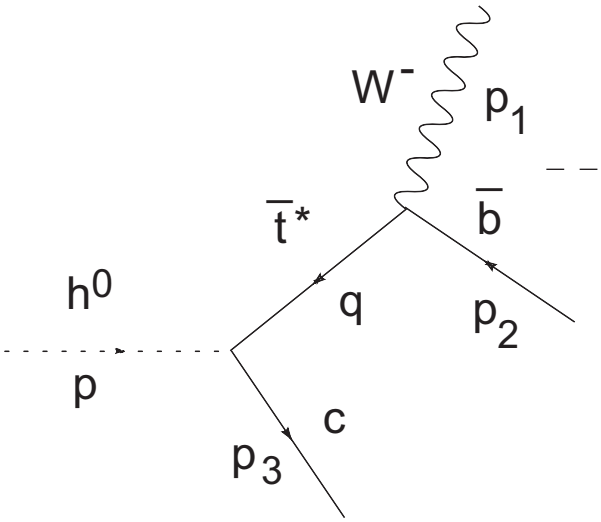

Figure 1. Tree level Feynman diagrams for $h \longrightarrow W^{-}\bar{b}c$.

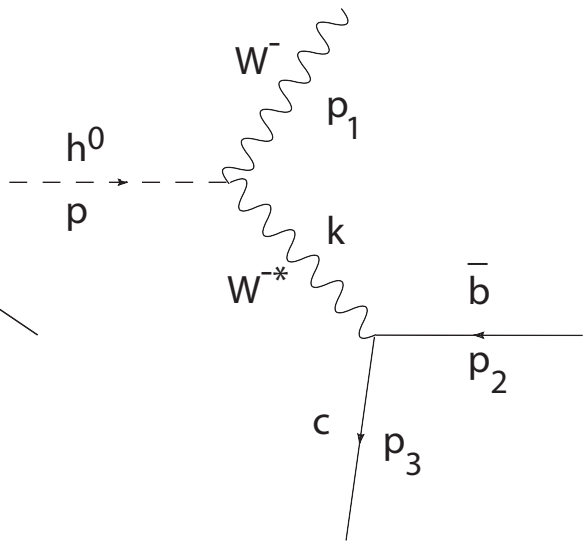

Figure 2. Tree level Feynman diagrams for $h \longrightarrow W^{-}\bar{b}c$.

are neglected. Then, the explicit expressions are

$$\begin{aligned}\overline{|M_1|}^2 &= \frac{g^4}{4M_W^2}|P_t|^2\Big\{|S^u_{231}+P^u_{231}|^2\left[4\left(p_1\cdot p_2\right)\left(p_1\cdot q\right)\left(p_3\cdot q\right)\right.\\ &\left.+2M_W^2\left(p_2\cdot q\right)\left(p_3\cdot q\right)-M_W^2q^2\left(p_2\cdot p_3\right)-2q^2\left(p_1\cdot p_2\right)\left(p_1\cdot p_3\right)\right]\\ &+m_t^2|S^u_{231}-P^u_{231}|^2\left[M_W^2\left(p_2\cdot p_3\right)+2\left(p_1\cdot p_2\right)\left(p_1\cdot p_3\right)\right]\Big\}, \end{aligned} \tag{26}$$

$$\overline{|\mathcal{M}_2|}^2 = g^4\left(q_{11}\right)^2|V_{cb}|^2|P_W(k)|^2\left(M_W^2p_2\cdot p_3+2p_1\cdot p_2p_1\cdot p_3\right), \tag{27}$$

$$\begin{aligned}\overline{\mathcal{M}_1^\dagger\mathcal{M}_2}+\overline{\mathcal{M}_2^\dagger\mathcal{M}_1} &= \frac{g^4m_t}{M_W}q_{11}V_{cb}P_W(k)\left(M_W^2p_2\cdot p_3+2p_1\cdot p_2p_1\cdot p_3\right)\\ &\left[\mathrm{Re}\left(S^u_{231}+P^u_{231}\right)\mathrm{Re}P_t-\mathrm{Im}\left(S^u_{231}+P^u_{231}\right)\mathrm{Im}P_t\right], \end{aligned} \tag{28}$$

where $P_W(k)=\left(k^2-M_W^2+iM_W\Gamma_W\right)^{-1}$ and $P_t\left(q\right)=\left(q^2-m_t^2+im_t\Gamma_t\right)^{-1}$. Then, the width for the decay is

$$\begin{aligned}\Gamma_{h\longrightarrow W\bar{b}c} &= \frac{g^4m_h}{256\pi^3}[|S^u_{231}-P^u_{231}|^2I_1+|S^u_{231}+P^u_{231}|^2I_2+q_{11}^2|V_{cb}|^2I_3\\ &+\mathrm{Re}(S^u_{231}+P^u_{231})q_{11}V_{cb}I_4-\mathrm{Im}(S^u_{231}+P^u_{231})q_{11}V_{cb}I_5] \end{aligned} \tag{29}$$

where the the analytical expressions for the dimensionless integrals $I_{1,\ldots,5}$ are given in appendix and numerical values as function of littlest neutral Higgs bosons are shown in table. In case of CP explicit violation or CP conserving the width decay is written as

$$\begin{aligned}\Gamma_{CPV} &= \frac{g^4m_h}{256\pi^3}\Big\{\left(I_1+I_2\right)|\chi_{23}|^2\frac{m_cm_t}{2v^2\cos^2\beta}\left(\sin^2\theta_{12}+\cos^2\theta_{12}\sin^2\theta_{13}\right)\\ &-\frac{\sqrt{m_cm_t}}{2\sqrt{v}\cos\beta}V_{cb}\cos\theta_{12}\cos\theta_{13}\left[\mathrm{Re}\left(\chi_{23}\right)\left(I_4\sin\theta_{12}+I_5\cos\theta_{12}\sin\theta_{13}\right)\right.\\ &\left.-\mathrm{Im}\left(\chi_{23}\right)\left(I_4\cos\theta_{12}\sin\theta_{13}+I_5\sin\theta_{12}\right)\right]+I_3|V_{cb}|^2\cos^2\theta_{12}\cos^2\theta_{13}\Big\} \end{aligned} \tag{30}$$

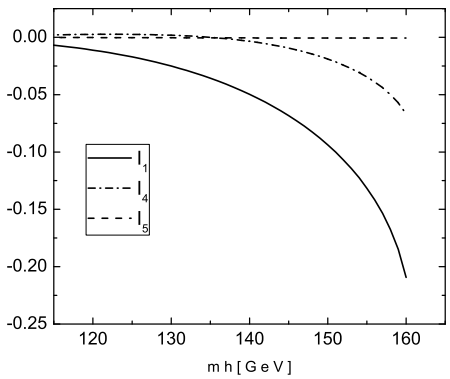

Figure 3. Numerical integrals $I_{1,4,5}$.

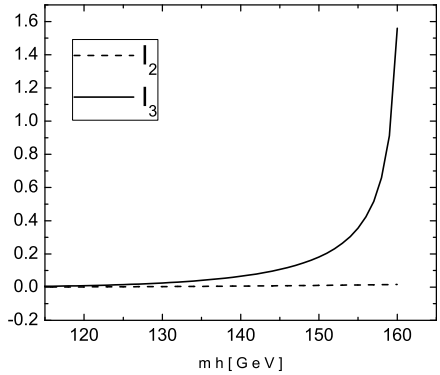

Figure 4. Numerical integrals $I_{2,3}$.

or

$$\Gamma_{CPC} = \frac{g^4 m_h}{256\pi^3}\left[(I_1+I_2)\left|\chi_{23}\right|^2 \frac{m_c m_t \cos^2(\beta-\alpha)}{2v^2\cos^2\beta} + I_3\left|V_{cb}\right|^2\sin^2(\beta-\alpha)\right.$$
$$\left. -\frac{\sqrt{m_c m_t}V_{cb}}{2\sqrt{v}}\frac{\sin(\beta-\alpha)\cos(\beta-\alpha)}{\cos\beta}\left(I_4\mathrm{Re}\left(\chi_{23}\right)-I_5\mathrm{Im}\left(\chi_{23}\right)\right)\right], \tag{31}$$

respectively.

4.1. CP asymmetry coefficient

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

$$\overline{\left|\widetilde{\mathcal{M}}\right|}^2 = \overline{\left|\widetilde{\mathcal{M}_1}\right|}^2 + \overline{\left|\widetilde{\mathcal{M}_2}\right|}^2 + \overline{\widetilde{\mathcal{M}_1}^\dagger\widetilde{\mathcal{M}_2}} + \overline{\widetilde{\mathcal{M}_2}^\dagger\widetilde{\mathcal{M}_1}}. \tag{32}$$

The square terms are the same as the above, $\overline{\left|\widetilde{\mathcal{M}}_{1,2}\right|}^2 = \overline{\left|\mathcal{M}_{1,2}\right|}^2$, while for the interference terms we have

$$\overline{\widetilde{\mathcal{M}}_1^\dagger\widetilde{\mathcal{M}}_2} + \overline{\widetilde{\mathcal{M}}_2^\dagger\widetilde{\mathcal{M}}_1} = \frac{g^4 m_t}{M_W} q_{11} V_{cb} P_W(k)\left(M_W^2 p_2\cdot p_3 + 2p_1\cdot p_2 p_1\cdot p_3\right)$$
$$\left[\mathrm{Re}\left(S_{231}^u + P_{231}^u\right)\mathrm{Re}P_t + \mathrm{Im}\left(S_{231}^u + P_{231}^u\right)\mathrm{Im}P_t\right]. \tag{33}$$

The definition for the CP asymmetry coefficient is

$$A_{CP} = \frac{\Gamma_{h\to W^+\bar{b}c} - \Gamma_{h\to W^-b\bar{c}}}{\Gamma_{h\to W^+\bar{b}c} + \Gamma_{h\to W^-b\bar{c}}}. \tag{34}$$

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

$$A_{CP} = \frac{V_{cb} q_{11} I_5 \mathrm{Im}\left(S_{231}^u + P_{231}^u\right)}{f\left(S_{231}^u, P_{231}^u, q_{11}, m_h\right)}, \tag{35}$$

where

$$f\left(S_{231}^{u},P_{231}^{u},q_{11},m_{h}\right) = \left|S_{231}^{u}-P_{231}^{u}\right|^{2}I_{1}+\left|S_{231}^{u}+P_{231}^{u}\right|^{2}I_{2} + \left|V_{cb}\right|^{2}q_{11}^{2}I_{3}+q_{11}V_{cb}\mathrm{Re}\left(S_{231}^{u}+P_{231}^{u}\right)I_{4}. \quad (36)$$

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

$$A_{CPV}=\frac{\sqrt{m_{c}m_{t}}I_{5}\cos\theta_{12}\cos\theta_{13}}{\sqrt{2}v\cos\beta}\frac{\mathrm{Re}\left(\chi_{23}\right)\cos\theta_{12}\sin\theta_{13}-\mathrm{Im}\left(\chi_{23}\right)\sin\theta_{12}}{f_{CPV}\left(\theta_{12},\theta_{13},\beta,\chi_{23}\right)} \quad (37)$$

or

$$A_{CPC}=\frac{\sqrt{m_{c}m_{t}}I_{5}\sin\left(\beta-\alpha\right)}{\sqrt{2}v\cos\beta}\frac{\cos\left(\beta-\alpha\right)\mathrm{Im}\left(\chi_{23}\right)}{f_{CPC}\left(\alpha,\beta,\chi_{23},m_{h}\right)}, \quad (38)$$

respectively. The f_{CPV} and f_{CPC} are defined as

$$\begin{aligned} f_{CPV} &= \left(I_{1}+I_{2}\right)\left|\chi_{23}\right|^{2}\frac{m_{c}m_{t}}{2v^{2}\cos^{2}\beta}\left(\sin^{2}\theta_{12}+\cos^{2}\theta_{12}\sin^{2}\theta_{13}\right) \\ &-\frac{\sqrt{m_{c}m_{t}}V_{cb}}{2\sqrt{v}\cos\beta}\cos\theta_{12}\cos\theta_{13}\mathrm{Re}\left(\chi_{23}\right)\left(I_{4}\sin\theta_{12}+I_{5}\cos\theta_{12}\sin\theta_{13}\right) \\ &+I_{3}\left|V_{cb}\right|^{2}\cos^{2}\theta_{12}\cos^{2}\theta_{13} \end{aligned} \quad (39)$$

and

$$\begin{aligned} f_{CPC} &= \left(I_{1}+I_{2}\right)\left|\chi_{23}\right|^{2}\frac{m_{c}m_{t}\cos^{2}\left(\beta-\alpha\right)}{2v^{2}\cos^{2}\beta}+I_{3}\left|V_{cb}\right|^{2}\sin^{2}\left(\beta-\alpha\right) \\ &-\frac{\sqrt{m_{c}m_{t}}V_{cb}}{2\sqrt{v}}\frac{\sin\left(\beta-\alpha\right)\cos\left(\beta-\alpha\right)}{\cos\beta}I_{4}\mathrm{Re}\left(\chi_{23}\right) \end{aligned} \quad (40)$$

4.2. Numerical results

We shall discuss in detail the result for FCNC and CP conserving case. The asymmetry depends of the five free parameters. One of them is the Higgs boson mass which appears in the J integrals, the other ones are the mixing angles α, β and the complex parameter χ_{23}. The mixing angle β is taken within the values $1<\tan\beta<50$ [64]. For the mixing angle α we study three scenarios, $\alpha<\beta$, $\alpha\approx\beta$ and $\alpha>\beta$. For each scenario we take two possible values for $|\chi_{23}|$. Therefore, the scenarios studied here are:

i) $\alpha<\beta$ for $|\chi_{23}|=0.9$ and $|\chi_{23}|=0.1$, figures 5 and 6.

ii) $\alpha\approx\beta$ for $|\chi_{23}|=0.9$ and $|\chi_{23}|=0.1$, figure 7 and 8.

iii) $\alpha>\beta$ for $|\chi_{23}|=0.9$ and $|\chi_{23}|=0.1$, figure 9 and 10.

We use the reported values $m_t=171.2$ GeV, $m_b=4.2$ GeV, $m_c=1.27$ GeV, $M_W=80.39$ GeV and $\sin\theta_W=0.231$ [64].

The figures 5, , 6, 7, 8, 9 and 10 show that the asymmetry has values of the order 10^{-3} to 10^{-2} (10^{-4} to 10^{-3} and 10^{-3}) for scenario i) (ii) and iii)).

5. Conclusion

The FCNC in Yukawa sector has been considered in a basis independent formalism and general mixing amount neutral scalar bosons has been used in such a way to introduce CP violation. The CP violation sources can then be related to scalar mixing or textures of Yukawa matrices. In the case of scalar mixing are the possibilities to have explicit and spontaneous CP violation, here we just considered the first one possibility.

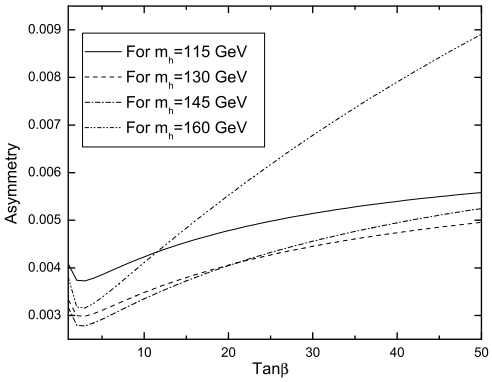

Figure 5. The asymmetry as function of $\tan\beta$ for scenario 1 for $|\chi_{23}| = 0.1$

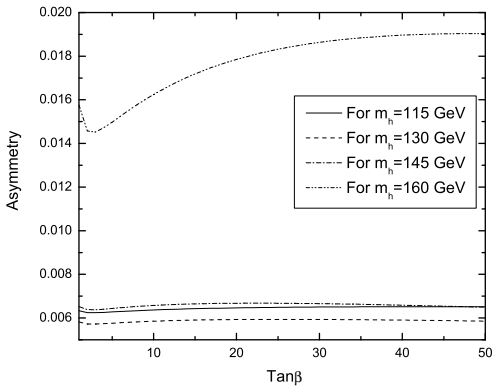

Figure 6. The asymmetry as function of $\tan\beta$ for scenario 1 for $|\chi_{23}| = 0.9$

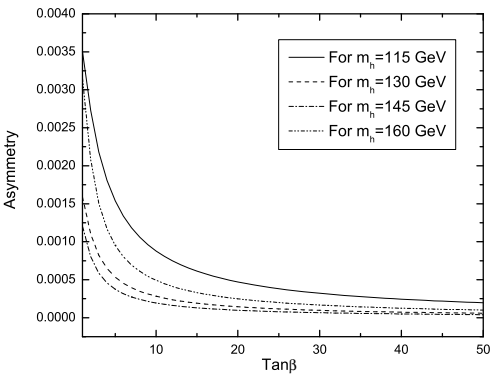

Figure 7. The asymmetry as function of $\tan\beta$ for scenario 2 for $|\chi_{23}| = 0.1$

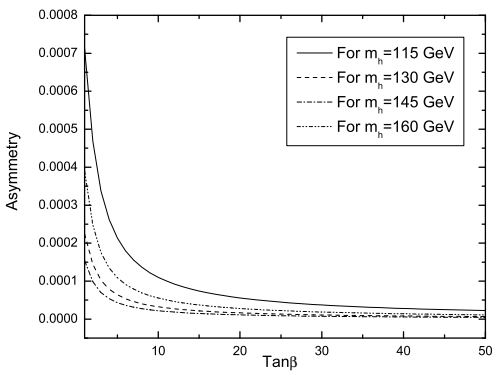

Figure 8. The asymmetry as function of $\tan\beta$ for scenario 2 for $|\chi_{23}| = 0.9$

We have also evaluated the CPV asymmetry for the decay $h \to c\bar{b}W$, which allows to test the presence of both FCNC and CPV. We found that for certain optimal range of parameters the decay asymmetry could be of $O(10^{-2})$ to $O(10^{-4})$ in the FCNC and CP conserving case. The asymmetry behavior has a dependency proportional to the mixing complex parameter χ_{23} too. The mixing angles α and β control the shape of the graphs. The asymmetry keeps same shape for the Higgs boson mass range between 115 GeV and 160 GeV.

In order to detect this asymmetry we could have to resort to a linear collider, since the final state seems difficult to reconstruct at a hadron collider. Although a final conclusion would require a detailed study, which we plan to address in a future publication.

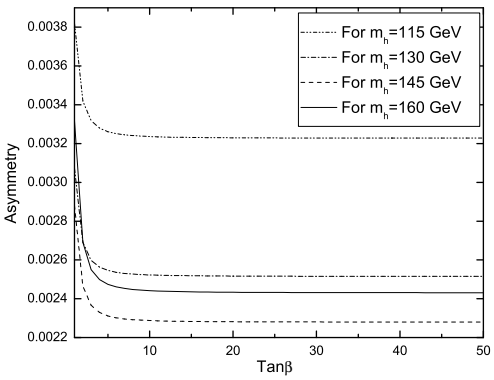

Figure 9. The asymmetry as function of $\tan\beta$ for scenario 3 for $|\chi_{23}| = 0.1$

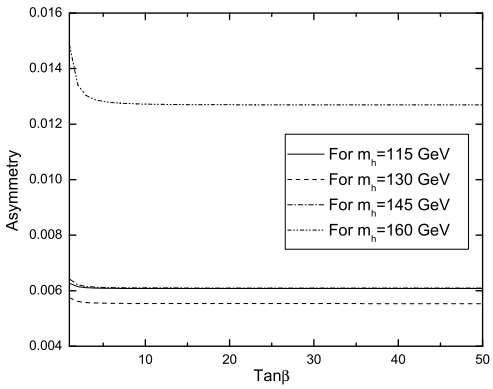

Figure 10. The asymmetry as function of $\tan\beta$ for scenario 3 for $|\chi_{23}| = 0.9$

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