

Update of the 2HDM-III with a four-zero texture in the Yukawa matrices and phenomenology of the charged Higgs Boson

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We update the flavor-violating constraints on the charged Higgs sector of the 2-Higgs Doublet Model Type-III (2HDM-III), using a four-zero texture in the Yukawa matrices. We give a generic Lagrangian of the 2HDM-III. In order to show the relevance of the off-diagonal terms of such a texture, we utilize the main constraints from B -physics, $\mu - e$ universality in τ decays and the radiative decay $Z \rightarrow b\bar{b}$ presented recently in arXiv:1212.6818 [hep-ph]. In particular, we show that the $H^- c\bar{b}$ coupling can be very large and very different with respect to 2HDMs with a flavor discrete symmetry (i.e., \mathcal{Z}_2). We also discuss the possible enhancements of the vertices $H^\pm W^\mp V$ ($V = Z, \gamma$) that arise at one-loop level.

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1. Introduction

Once discovered the new particle at LHC [1], which is very compatible with the neural Higgs Boson of the Standard Model (SM) [2]. The LHC aims to search for physics beyond SM. In particular the flavor physics could be a scope of interesting, where the main problem is to control the presence of Flavor Changing Neutral Currents (FCNCs). In the most general version of a 2HDM, the fermionic couplings of the neutral scalars are non-diagonal in flavor and, therefore, generate unwanted FCNC phenomena [3]. The simplest and most common approach is to impose a \mathcal{L}_2 symmetry forbidding all non-diagonal terms in flavor space in the Lagrangian [4].

In particular, we focus here on the version where the Yukawa couplings depend on the hierarchy of masses. This version is the one where the mass matrix has a four-zero texture form [7] forcing the non-diagonal Yukawa couplings to be proportional to the geometric mean of the two fermion masses, $g_{ij} \propto \sqrt{m_i m_j} \chi_{ij}$ [5, 6]. This matrix is based on the phenomenological observation that the off-diagonal elements must be small in order to dim the interactions that violate flavor, as experimental results show. In this work, we will discuss the increase in sensitivity to the Branching Ratio (BR) for $H^\pm \rightarrow cb, W^\pm \gamma, W^\pm Z$ and to the fermionic couplings of a H^\pm in the 2HDM-III scenario.

2. The Higgs-Yukawa sector of the 2HDM-III

The 2HDM includes two Higgs scalar doublets of hypercharge +1: $\Phi_1^\dagger = (\phi_1^-, \phi_1^{0*})$ and $\Phi_2^\dagger = (\phi_2^-, \phi_2^{0*})$. The most general $SU(2)_L \times U(1)_Y$ invariant scalar potential can be written as [9]

$$\begin{aligned} V(\Phi_1, \Phi_2) = & \mu_1^2(\Phi_1^\dagger \Phi_1) + \mu_2^2(\Phi_2^\dagger \Phi_2) - \left(\mu_{12}^2(\Phi_1^\dagger \Phi_2) + \text{H.c.} \right) + \frac{1}{2} \lambda_1(\Phi_1^\dagger \Phi_1)^2 \\ & + \frac{1}{2} \lambda_2(\Phi_2^\dagger \Phi_2)^2 + \lambda_3(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ & + \left(\frac{1}{2} \lambda_5(\Phi_1^\dagger \Phi_2)^2 + \left(\lambda_6(\Phi_1^\dagger \Phi_1) + \lambda_7(\Phi_2^\dagger \Phi_2) \right) (\Phi_1^\dagger \Phi_2) + \text{H.c.} \right), \end{aligned} \quad (2.1)$$

where all parameters are assumed to be real¹. When a specific four-zero texture is implemented as a flavor symmetry in the Yukawa sector, discrete symmetries in the Higgs potential are not needed. Thence, one must keep the terms proportional to λ_6 and λ_7 . These parameters play an important role in one-loop processes, where self-interactions of Higgs bosons could be relevant [8].

Otherwise, in order to derive the interactions of the type Higgs-fermion-fermion, the Yukawa Lagrangian is written as follows:

$$\mathcal{L}_Y = - \left(Y_1^u \bar{Q}_L \tilde{\Phi}_1 u_R + Y_2^u \bar{Q}_L \tilde{\Phi}_2 u_R + Y_1^d \bar{Q}_L \Phi_1 d_R + Y_2^d \bar{Q}_L \Phi_2 d_R + Y_1^l \bar{L} \Phi_1 l_R + Y_2^l \bar{L} \Phi_2 l_R \right), \quad (2.2)$$

where $\Phi_{1,2} = (\phi_{1,2}^+, \phi_{1,2}^0)^T$ refer to the two Higgs doublets, $\tilde{\Phi}_{1,2} = i\sigma_2 \Phi_{1,2}^*$. After spontaneous EW Symmetry Breaking (EWSB), one can derive the fermion mass matrices from eq. (2.2), namely: $M_f = \frac{1}{\sqrt{2}}(v_1 Y_1^f + v_2 Y_2^f)$, $f = u, d, l$. Assuming that both Yukawa matrices Y_1^f and Y_2^f have the four-zero texture form and are Hermitian [6]. The diagonalization is performed in the following way:

¹The μ_{12}^2 , λ_5 , λ_6 and λ_7 parameters are complex in general, but we will assume that they are real for simplicity.

2HDM-III	X	Y	Z	ξ_h^u	ξ_h^d	ξ_h^l	ξ_H^u	ξ_H^d	ξ_H^l
2HDM-I-like	$-\cot\beta$	$\cot\beta$	$-\cot\beta$	c_α/s_β	c_α/s_β	c_α/s_β	s_α/s_β	s_α/s_β	s_α/s_β
2HDM-II-like	$\tan\beta$	$\cot\beta$	$\tan\beta$	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	s_α/s_β	c_α/c_β	c_α/c_β
2HDM-X-like	$-\cot\beta$	$\cot\beta$	$\tan\beta$	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$	s_α/s_β	s_α/s_β	c_α/c_β
2HDM-Y-like	$\tan\beta$	$\cot\beta$	$-\cot\beta$	c_α/s_β	$-s_\alpha/c_\beta$	c_α/s_β	s_α/s_β	c_α/c_β	s_α/s_β

Table 1: Parameters ξ_ϕ^f , X , Y and Z defined in the Yukawa interactions of eq. (3.4) for four versions of the 2HDM-III with a four-zero texture. Here $s_\alpha = \sin\alpha$, $c_\alpha = \cos\alpha$, $s_\beta = \sin\beta$ and $c_\beta = \cos\beta$.

$\bar{M}_f = V_{fL}^\dagger M_f V_{fR}$. Then, $\bar{M}_f = \frac{1}{\sqrt{2}}(v_1 \tilde{Y}_1^f + v_2 \tilde{Y}_2^f)$, where $\tilde{Y}_i^f = V_{fL}^\dagger Y_i^f V_{fR}$. One can derive a better approximation for the product $V_q Y_n^q V_q^\dagger$, expressing the rotated matrix \tilde{Y}_n^q as:

$$[\tilde{Y}_n^q]_{ij} = \frac{\sqrt{m_i^q m_j^q}}{v} [\tilde{\chi}_n^q]_{ij} = \frac{\sqrt{m_i^q m_j^q}}{v} [\chi_n^q]_{ij} e^{i\theta_{ij}^q}, \quad (2.3)$$

where the χ 's are unknown dimensionless parameters of the model. Following the recent analysis of [10], we can obtain the generic expression for the interactions of Higgs bosons with the fermions:

$$\begin{aligned} \mathcal{L}^{\bar{f}_i f_j \phi} = & - \left\{ \frac{\sqrt{2}}{v} \bar{u}_i (m_{d_j} X_{ij} P_R + m_{u_i} Y_{ij} P_L) d_j H^+ + \frac{\sqrt{2} m_{l_j}}{v} Z_{ij} \bar{\nu}_L l_R H^+ + H.c. \right\} \\ & - \frac{1}{v} \left\{ \bar{f}_i m_{f_i} h_{ij}^f f_j h^0 + \bar{f}_i m_{f_i} H_{ij}^f f_j H^0 - i \bar{f}_i m_{f_i} A_{ij}^f f_j \gamma_5 A^0 \right\}, \end{aligned} \quad (2.4)$$

where ϕ_{ij}^f ($\phi = h, H, A$), X_{ij} , Y_{ij} and Z_{ij} are defined as:

$$\begin{aligned} \phi_{ij}^f &= \xi_\phi^f \delta_{ij} + G(\xi_\phi^f, X), \quad \phi = h, H, A, \\ X_{ij} &= \sum_{l=1}^3 (V_{CKM})_{il} \left[X \frac{m_{d_l}}{m_{d_j}} \delta_{lj} - \frac{f(X)}{\sqrt{2}} \sqrt{\frac{m_{d_l}}{m_{d_j}}} \tilde{\chi}_{lj}^d \right], \\ Y_{ij} &= \sum_{l=1}^3 \left[Y \delta_{il} - \frac{f(Y)}{\sqrt{2}} \sqrt{\frac{m_{u_l}}{m_{u_i}}} \tilde{\chi}_{il}^u \right] (V_{CKM})_{lj}, \\ Z_{ij} &= \left[Z \frac{m_{l_i}}{m_{l_j}} \delta_{ij} - \frac{f(Z)}{\sqrt{2}} \sqrt{\frac{m_{l_i}}{m_{l_j}}} \tilde{\chi}_{ij}^l \right]. \end{aligned} \quad (2.5)$$

where $G(\xi_\phi^f, X)$ can be obtained from [10] and the parameters ξ_ϕ^f , X , Y and Z are given in the Table 1. When the parameters $\chi_{ij}^f = 0$, one recovers the Yukawa interactions given in Refs. [11, 12, 13]. As was pointed in [10], we suggest that this Lagrangian could represent a Multi-Higgs Doublet Model (MHDM) or an Aligned 2HDM (A2HDM) with additional flavor physics in the Yukawa matrices as well as the possibility of FCNCs at tree level.

3. Flavor constraints on the 2HDM-III with a four-zero Yukawa texture

According to the recent analysis of flavor constraints on the 2HDM-III with a four-zero texture reported in [10], we now enumerate those for the new physics parameters χ_{ij}^f that come from a four-zero Yukawa texture.

2HDM-III's	$\chi_{23}^d(B \rightarrow \tau\nu)$	$\chi_{23}^u(D_s \rightarrow l\nu)$	$\chi_{23}^u(B \rightarrow D\tau\nu)$	χ_{23}^u (combination)
2HDM-I-like	(-0.35,-0.15) or (0,0.15)	(-1.5,0.9)	(-0.05,0.45)	(-0.05,0.45)
2HDM-II-like	(-0.35,-0.2) or (0,0.2)	(-2,27)	(-9.6,1.2)	(-2,1.2)
2HDM-X-like	(-7,2)	(-4,14)	(-3.8,0.47)	(-4,0.47)
2HDM-Y-like	(-1.8,-1.2) or (-0.2,0.6)	(-40,50)	(-16,50)	(-16,50)

Table 2: Constraints from $B \rightarrow D\tau\nu$, $D_s \rightarrow \tau\nu$, $\mu\nu$ and $B \rightarrow \tau\nu$ decays. We show the allowed intervals for off-diagonal terms $\chi_{23}^{u,d}$.

- $\mu - e$ universality in τ decays

The τ decays into $\mu\bar{\nu}_\mu\nu_\tau$ and $e\bar{\nu}_e\nu_\tau$ produce important constraints onto charged Higgs boson states coupling to leptons, through the requirement of $\mu - e$ universality. We can get the constraint: $\frac{|Z_{22}Z_{33}|}{m_{H^\pm}^2} \leq 0.16 \text{ GeV}^{-1}$ (95% CL). We obtain that the parameter space more favored is when $0.8 \leq |\chi_{ij}| \leq 2$, for $0.5 \leq Z \leq 100$, $X \leq 80$ and $m_{H^\pm} \geq 100 \text{ GeV}$.

- Leptonic meson decays $B \rightarrow \tau\nu$, $D \rightarrow \mu\nu$, $D_s \rightarrow \mu\nu$, $\tau\nu$ and semileptonic decays $B \rightarrow D\tau\nu$

Given the leptonic decays $B \rightarrow \tau\nu$, $D \rightarrow \mu\nu$, $D_s \rightarrow \mu\nu$, $\tau\nu$ and the semileptonic ones $B \rightarrow D\tau\nu$, we show in the Table 2 the constraints for the off-diagonal terms $\chi_{23}^{u,d}$ of the Yukawa texture. We assume $0.1 \leq \chi_{22}^l = \chi_{33}^l \leq 1.5$ as well as $\chi_{22}^d = \chi_{22}^u = 1$ and take $80 \text{ GeV} \leq m_{H^\pm} \leq 160 \text{ GeV}$.

- $B \rightarrow X_s\gamma$ decays

Using values for the charged Higgs boson mass in the interval $80 \text{ GeV} \leq m_{H^\pm} \leq 300 \text{ GeV}$, we can establish the following constraints: $\left| \frac{Y_{33}Y_{32}^*}{V_{tb}V_{ts}} \right| < 0.25$, $-1.7 < \text{Re} \left[\frac{X_{33}Y_{32}^*}{V_{tb}V_{ts}} \right] < 0.7$. One can then extract the bounds $-0.75 \leq \chi_{23}^u \leq -0.15$ for $\chi_{33}^u = 1$ and $0.4 \leq \chi_{23}^u \leq 0.9$ for $\chi_{33}^u = -1$, both when $Y \ll 1$. Assuming the allowed interval for χ_{23}^d from $B \rightarrow \tau\nu$ and $\chi_{33}^u = 1 = \chi_{33}^d = 1$. We can, e.g., obtain $\chi_{23}^u \in (-0.55, -0.48)$ for the case $X = 20$ and $Y = 0.1$. Another interesting scenario for the 2HDM-III is the 2HDM-X-like one, where the allowed region is larger than in other scenarios, with $\chi_{23}^u \in (-2.2, 0.45)$ and $\chi_{23}^d \in (-7, -2)$.

- $B^0 - \bar{B}^0$ mixing

Considering the areas allowed by the measured ΔM_{B_d} value within a 2σ error, when we have a light charged Higgs ($80 \text{ GeV} \leq m_{H^\pm} \leq 200 \text{ GeV}$) one can extract the limit $\left| \frac{Y_{33}^*Y_{31}}{V_{tb}V_{td}} \right| \leq 0.25$, which is consistent with the bounds obtained from $B \rightarrow X_s\gamma$.

In summary, the diagonal terms are such that $\chi_{kk}^f \sim 1$ and the off-diagonal terms such that $|\chi_{ij}^f| \leq 0.5$, which establish a parameter space region allowed by these constraints.

4. The dominance of the BR($H^\pm \rightarrow cb$)

A distinctive signal of a H^\pm state from the 2HDM-III for $m_{H^\pm} < m_t - m_b$ would be a sizable BR for $H^\pm \rightarrow cb$. For $m_{H^\pm} < m_t - m_b$, the scenario of $|X| \gg |Y|, |Z|$ in a 2HDM-III gives rise to a ‘‘leptophobic’’ H^\pm with $\text{BR}(H^\pm \rightarrow cs) + \text{BR}(H^\pm \rightarrow cb) \sim 100\%$, as the $\text{BR}(H^\pm \rightarrow \tau\nu)$ is negligible ($\ll 1\%$). Conversely, one can see that the configuration $Y \gg X, Z$ (this imply that $Y_{ij} \gg X_{ij}, Z_{ij}$, see eqs. (2.5) is very interesting, because the decay $H^+ \rightarrow c\bar{b}$ is now dominant. In order to show this situation, we calculate the dominant terms $m_c Y_{23}, m_c Y_{22}$ of the width $\Gamma(H^+ \rightarrow c\bar{b}, c\bar{s})$, respectively, which are given by: $m_c Y_{cb} = m_c Y_{23} = V_{cb} m_c \left(Y - \frac{f(Y)}{\sqrt{2}} \chi_{22}^u \right) - V_{tb} \frac{f(Y)}{\sqrt{2}} \sqrt{m_t m_c} \chi_{23}^u$ and $m_c Y_{cs} = m_c Y_{22} = V_{cs} m_c \left(Y - \frac{f(Y)}{\sqrt{2}} \chi_{22}^u \right) - V_{ts} \frac{f(Y)}{\sqrt{2}} \sqrt{m_t m_c} \chi_{23}^u$. As Y is large and $f(Y) = \sqrt{1+Y^2} \sim Y$, then the term $\left(Y - \frac{f(Y)}{\sqrt{2}} \chi_{22}^u \right)$ could be absent or small, when $\chi_{ij} = O(1)$. Besides, the last term is very large because $\propto \sqrt{m_t m_c}$, given that $m_t = 173$ GeV, so that in the end this is the dominant contribution. Therefore, we can compute the ratio of two dominant decays, namely, $\text{BR}(H^\pm \rightarrow cb)$ and $\text{BR}(H^\pm \rightarrow cs)$, which is given as follows:

$$R_{sb} = \frac{\text{BR}(H^\pm \rightarrow cb)}{\text{BR}(H^\pm \rightarrow cs)} \sim \frac{|V_{tb}|^2}{|V_{ts}|^2}. \quad (4.1)$$

In this case $\text{BR}(H^\pm \rightarrow cb) \sim 100\%$ (for $m_{H^\pm} < m_t - m_b$, of course) so that to verify this prediction would really be the hallmark signal of the 2HDM-III. Therefore, we can see that the non-diagonal term χ_{23}^u cannot be omitted and this is an important result signalling new physics even beyond the standards 2HDMs. Another case is when $X \gg Y, Z$, here, we get that the dominants terms are $\propto m_b X_{23}, m_s X_{22}, m_b X_{cb} = m_b X_{23} = V_{cb} m_b \left(X - \frac{f(X)}{\sqrt{2}} \chi_{33}^d \right) - V_{cs} \frac{f(X)}{\sqrt{2}} \sqrt{m_b m_s} \chi_{23}^d$ and $m_s X_{cs} = m_s X_{22} = V_{cs} m_s \left(X - \frac{f(X)}{\sqrt{2}} \chi_{22}^d \right) - V_{ts} \frac{f(X)}{\sqrt{2}} \sqrt{m_b m_s} \chi_{23}^d$. In this case there are two possibilities. If $\chi = O(1)$ and positive then $\left(X - \frac{f(X)}{\sqrt{2}} \chi_{33}^d \right)$ is small and

$$R_{sb} \sim \frac{|V_{cs}|^2}{|V_{cb}|^2}. \quad (4.2)$$

Here, the $\text{BR}(H^\pm \rightarrow cb)$ becomes large, again, this case too could be another exotic scenario of the 2HDM-III. The other possibility is when $\chi = O(1)$ and negative, then

$$R_{sb} \sim \frac{m_b^2 |V_{cb}|^2}{m_s^2 |V_{cs}|^2}, \quad (4.3)$$

which is very similar to the cases studied recently in [12]. In summary, one can see two possibilities to study the $\text{BR}(H^\pm \rightarrow cb)$: firstly, the scenarios given in eqs. (4.1) and (4.2), which are peculiar to the 2HDM-III; secondly, the scenario very close to the MHD/A2HDM expressed in eq. (4.3).

In a similar spirit, one can study other interesting channels, both in decay and production and both at tree and one-loop level [6, 8]. For instance, in processes at one-loop level is possible to combine two effects in the model: firstly, the term $\left(Y - \frac{f(Y)}{\sqrt{2}} \chi_{22}^u \right)$ (or X for d) could be absent

or small, when $\chi_{ij} \sim 1$; secondly, the self-interaction $H^+H^-\phi^0$ can be large because the Higgs potential parameters $\lambda_{6,7}$ are sizable. Then, one can typically get a $\text{BR}(H^+ \rightarrow W^+\gamma) \sim 10^{-4}, 10^{-3}$ and a $\text{BR}(H^+ \rightarrow W^+Z) \sim 10^{-3}, 10^{-2}$.

5. Conclusions

In our model (2HDM-III), $\text{BR}(H^\pm \rightarrow cb)$ could be as large as 90%. Along the lines indicated by previous literature, in the context of the 2HDM-III with a four-zero Yukawa texture, we would conclude by suggesting that a dedicated search for $t \rightarrow H^\pm b$ and $H^\pm \rightarrow cb$ or $cb \rightarrow H^\pm$ would probe values of the fermionic couplings of H^\pm that are compliant with current searches. The outlook is therefore clear. Depending on the search channel, both the Tevatron (possibly) and the LHC (certainly) have the potential to constrain or else discover the 2HDM-III supplemented by a four-zero Yukawa texture including non-vanishing off-diagonal terms in the Yukawa matrices.

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