Implications of Yukawa textures in the neutral Higgs decays within the 2HDM-III

J E Barradas-Guevara$^1$, H Bello-Martínez$^1$, O Félix-Beltrán$^2$ and J Hernández-Sánchez$^{2,3}$

$^1$ Facultad de Ciencias Físico-Matemáticas, Benemérita Universidad Autónoma de Puebla, Apdo. Postal 1364, C.P. 72000 Puebla, Pue., México.
$^2$ Facultad de Ciencias de la Electrónica, Benemérita Universidad Autónoma de Puebla, Apdo. Postal 542, C. P. 72570 Puebla, Pue., México.
$^3$ Dual C-P Institute of High Energy Physics, Puebla, Pue., México.

E-mail: clever_884@hotmail.com, barradas@fcfm.buap.mx, olga_felix@ece.buap.mx, jaimeh@ece.buap.mx

Abstract. We discuss the implications of assuming a four-zero Yukawa ansatz for the neutral Higgs decays, within the context of the general 2-Higgs Doublet Model of type III. We begin by presenting a detailed analysis of the neutral Higgs boson couplings with fermions and gauge bosons and the resulting effects on its decays. In particular, we are interested on the possibility of the neutral Higgs boson production in current colliders.

1. Introduction

Two open problems in particle physics are the Higgs mechanism [1] which generates fermion masses, and the flavour problem [2]. Thus, the search for the Higgs boson is one of the major goals for the experiments at the Large Hadron Collider (LHC). Moreover, in the Standard Model (SM), the structure of Yukawa couplings is not well understood and neither are their origin nor the underlying principles [2, 3, 4]. Phenomenologically, the SM parameterizes the values of the Yukawa couplings, however, theoretically, we are in the darkness. This is one of the reasons why many physicists agree that the SM should be considered as an effective theory that remains valid up to an energy scale of $O$(TeV). One way to extend the SM is including an additional isodoublet SU(2) Higgs field. This model is known as the Two Higgs Doublet Model (2HDM) [5, 6, 7, 8], with a scalar spectrum extended (three neutral Higgs bosons and two charged Higgs bosons) and including the unwanted FCNC at tree level.

In the so called version III of the model [9, 10, 11], FCNC are kept under control by imposing a certain shape for the Yukawa matrices that reproduce the observed fermion masses and mixing angles [12]. The use of texture forms [13] permits to establish a direct relation from the elements of the matrix with the mixing parameter used in calculating the branching ratios, without dropping in advance terms proportional to the lighter fermion masses [14].

What we know so far about the Yukawa terms is that they should reproduce the fermion masses, the mixing angles of the CKM matrix and keep the FCNC under control, as they are restricted by experimental data. From the Lagrangian form, it is natural to consider that the flavor violation or the mixtures between families, could arise directly from the Yukawa terms,
which, in general, are not diagonal. In this work we are interested in the study of the Higgs boson decays \( H \rightarrow f_i f_j \), as a possible signal of fermion flavor violation for the complete spectrum of neutral Higgs bosons \( h^0, H^0, A^0 \) of the 2HDM-III.

A four texture zero ansatz for the Yukawa matrices in the context of 2HDM-III to evaluate the branching ratios of the neutral Higgs bosons decaying into fermion pairs is considered. Moreover, the model predictions and its test at future Large Hadron Collider (LHC) data are explored. Hence, our starting point is an Hermitian four texture ansatz in order to construct the mass matrices, which have been found to be in agreement with the observed data \([15, 16]\). The relation from the matrix elements to the mixing parameter used to calculate FCNC processes in the Higgs sector is developed in \([17]\). Some Higgs phenomenology has been addressed in the literature, mainly aimed to describe the light Higgs boson \([18, 19]\).

2. Structure of the Yukawa sector in 2HM-III

In general, the Higgs boson couplings to fermions are given as

\[
\mathcal{L}_Y = Y^i_a \bar{\phi}^i_L \Phi_a \phi^i_R + \text{h.c.},
\]

where \( \phi^i_L \) denotes the left fermion doublet, \( \phi^i_R \) is right-handed fermion field, \( \Phi_a \) are the two Higgs doublets \((a = 1, 2)\), and the coefficient \( Y^i_a \) \((i = l, u, d)\) can be expressed as a \( 3 \times 3 \) matrix (three generations), Yukawa matrix. Here we consider massless neutrinos. Then, in the Yukawa sector of the 2HDM-III, both Higgs doublets may couple with the two types of fermions, i.e., \( \text{up} \) and \( \text{down} \), so that we have two different Yukawa terms for each doublet \([9, 10, 11]\).

After spontaneous symmetry breaking, one can derive the fermion mass matrices, namely

\[
M_f = \frac{1}{\sqrt{2}}(v_1 Y_1^f + v_2 Y_2^f), \quad f = u, d, l.
\]

Here, we are taking into account the fact that working with a hierarchical ansatz for the mass matrix and by means of equation (2), the simplest case is to consider that both Yukawa couplings \( Y_{1,2}^f \) possess the same structure (without anomalous cancellation of any of the elements of the matrices). Particularly, we use a Hermitian four texture zero ansatz, and because of eq. (2) the complete mass matrix inherits this structure. The mass matrix is diagonalized through the bi-unitary matrices \( V_{L,R} \), though each Yukawa matrices are not diagonalized by this transformation. The diagonalization is performed in the following way \( \tilde{M}_f = V_{fL}^† M_f V_{fR} \).

The fact that \( M_f \) is Hermitian, under the considerations given above (Hermitian Yukawa matrices), directly implies that \( V_{fL} = V_{fR} \), and the mass eigenstates for the fermions are given by

\[
u = V_u^† u', \quad d = V_d^† d', \quad l = V_l^† l'.
\]

Then eq. (2) in this basis is given as

\[
\tilde{M}_f = \frac{1}{\sqrt{2}}(v_1 \tilde{Y}_1^f + v_2 \tilde{Y}_2^f),
\]

where \( \tilde{Y}_i^f = V_{fL}^† Y_i^f V_{fR} \) and for the quark case we may write

\[
\tilde{Y}_1^d = \frac{\sqrt{2}}{v \cos \beta} M_d - \tan \beta \tilde{Y}_2^d, \quad \tilde{Y}_2^u = \frac{\sqrt{2}}{v \sin \beta} M_u - \cot \beta \tilde{Y}_1^u.
\]

In the lepton case we perform the usual substitution \( d \rightarrow l \).

By using the redefined fields as the physical states, and considering the Yukawa couplings in this basis, the Lagrangian is obtained to carry out the phenomenology analysis. As we said
earlier, it is assumed that each of the Yukawa matrices has the same shape, Hermitian four

texture zero ansatz [12], and we see that the three matrices have the same hierarchy and can be

parameterized in the same manner.

Accordingly, the $V_{L,R}$ matrices are constructed as the product of two matrices, one of which
contains the complex phases$^1$. Furthermore, as is given in [17], we impose the condition

$m_{f_1} < m_{f_2}, m_{f_3}$, $A^f$ $| (f = u, d, l)$, with $A^f = m_{f_3} - \beta^f m_{f_2}$ and $\beta^f$ a number within the

interval $[0, 1]$. Therefore, the couplings $\tilde{Y}^{d,l}_2$ and $\tilde{Y}^u_1$, that appear in eq. (5) acquire a simple

structure given by $(\tilde{Y}^{d,l}_2)_{ij} = \sqrt{m_{l_i}m_{l_j}} e^{i\chi_{lj}} \tilde{x}^{d,l}_i$. Then we keep most of the FCNC processes under

control provided that $| \tilde{x}^{d,l}_i | \leq O(10^{-1})$. In order to carry out the phenomenological study, we

rewrite the Lagrangian in terms of the parameter of the model ($\tilde{x}^{d,l}_i$). We display here only the

leptonic part of the Lagrangian of Yukawa interactions

$$
\mathcal{L}_y^f = \frac{g_f}{2} \left[ \left( \frac{m_{l_i}}{m_{l_j}} \right) \cos \alpha_{ij} + \sin(\alpha - \beta) \left( \frac{\sqrt{m_{l_i}m_{l_j}}}{m_W} \right) \tilde{x}^{l}_{ij} \right] l_j H^0
$$

$$
- \frac{g_f}{2} \left[ \left( \frac{m_{l_i}}{m_{l_j}} \right) \sin \alpha_{ij} + \cos(\alpha - \beta) \left( \frac{\sqrt{m_{l_i}m_{l_j}}}{m_W} \right) \tilde{x}^{l}_{ij} \right] l_j h^0
$$

$$
+ \frac{g_f}{2} \left[ \left( \frac{m_{l_i}}{m_{l_j}} \right) \tan \beta_{ij} + \frac{1}{2} \left( \frac{\sqrt{m_{l_i}m_{l_j}}}{m_W} \right) \tilde{x}^{l}_{ij} \right] \tilde{x}^{l}_{ij} \gamma^5 l_j A^0.
$$

We consider that the model parameter is complex in general, $\tilde{x}^{l}_{ij} = \chi^{l}_{ij} \exp(i\vartheta_{ij})$; with the real

part $\chi^{l}_{ij} = |\tilde{x}^{l}_{ij}|$ and the effect of the phase $\vartheta_{ij}$ would be included as a variation of $-1$ to 1 on $\chi^{l}_{ij}$.

Having obtained the couplings in terms of the model parameter $\chi^{l}_{ij}$, we are ready to calculate the

Higgs branching ratios.

3. Branching ratios of the neutral Higgs bosons

Within the SM, we do not have flavor violation decays at tree level, the SM decay width of the

Higgs boson to fermions at tree level is given by [8, 20, 21]. In order to evaluate the

Higgs branching ratios, we need to include the dominant decay modes, in addition to the

fermionic ones. Although we are working within an extension of the SM, we may get some

hints for its possible application or connection to a more fundamental theory, by performing

phenomenological analysis of Higgs decays. More specifically, we use this model to evaluate the

branching ratios for the three neutral Higgs bosons in the 2HDM-III.

In this model, the angles $\alpha$ (the mixing angle in the $CP$ – even Higgs sector), and $\beta$ (which is the

ratio of the vacuum expectation value of the two doublets), are free parameters. Unlike the

case of the MSSM, where one can fix $\alpha$ in terms of $\tan \beta$ and $m_{A^0}$. However, we consider three
different scenarios that depend on how these angles are related to each other: (A) $\beta - \alpha = \pi/2$,

which it obtain for $h^0$ the SM-like decays; (B) $\beta - \alpha = 0$, by obtaining for $h^0$ no flavor violation;

and (C) $\beta - \alpha = \pi/3$, which take an angle in between these extreme cases.

Because for $h^0$ the flavor violation couplings vanish for $\alpha - \beta = 0$, we only show results for

scenarios A and C, $\tan \beta = 5, 15, 30$ with $\chi_{ij} = -1.0, 0, 1.0$. In the latter case: large $\tan \beta$, the

value is chosen where the behavior of the branching ratios becomes, in general, quite independent

of $\tan \beta$ for different channels of the light Higgs boson.

In Figs. 1 and 2 the dependence of the BR on the light Higgs mass $h^0$ is displayed, which

correspond to scenario A and C, respectively. In these cases, the vector boson decay channel is

open for almost the entire mass range, in fact it is the main decay mode, leaving $bb$ fermionic

$^1$ The complete process can be found in Ref. [13] and the explicit expression of these matrices is given in Refs. [15] 

and [17].
mode as dominant contribution of the decay rate when $50 \text{ GeV} \leq m_{h^0} \leq 100 \text{ GeV}$ with $\tan \beta = 5$, however, this channel is given dominant within $50 \text{ GeV} \leq m_{h^0} \leq 500 \text{ GeV}$ for $\tan \beta = 50$. However, there is a region where the fermion decay becomes important, when the top-threshold is reached. In this case, there is a strong dependence, mostly on large values of $\tan \beta$ and a model parameter close to 1: $\tan \beta > 15$ and $\chi_{ij} \to 1$. On the other hand, the flavor violating decays are reduced in the region of parameter space where $\tan \beta$ is small and $\chi_{ij}$ is close to zero as can be seen in the Fig. 1. Here we have fixed the heavy Higgs mass at 300GeV and taken the more favored scenario for the enhancement of these decays, $\beta - \alpha = \pi/2$.

Figure 1. Branching ratios of the fermionic and bosonic processes $h^0 \to XY$ in scenario A, within the Higgs mass range $50 \text{ GeV} < m_{h^0} < 500 \text{ GeV}$, for $\tan \beta = 5, 15, 50$, and $\chi_{ij} = -1.0, 0, 1.0$. 

| $\chi_{ij}$ | $\tan \beta = 5$ | $\tan \beta = 15$ | $\tan \beta = 50$ |
|------------|-----------------|-----------------|-----------------|
| $1$        |                 |                 |                 |
| $0$        |                 |                 |                 |
| $-1$       |                 |                 |                 |

| $m_{h^0}$ (GeV) | $10^0$ | $10^{-1}$ | $10^{-2}$ | $10^{-3}$ | $10^{-4}$ | $10^{-5}$ | $10^{-6}$ | $10^{-7}$ |
|----------------|--------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| $100$          |        |           |           |           |           |           |           |           |
| $200$          |        |           |           |           |           |           |           |           |
| $300$          |        |           |           |           |           |           |           |           |
| $400$          |        |           |           |           |           |           |           |           |
| $500$          |        |           |           |           |           |           |           |           |

| $m_{H^+}$ (GeV) | $10^0$ | $10^{-1}$ | $10^{-2}$ | $10^{-3}$ | $10^{-4}$ | $10^{-5}$ | $10^{-6}$ | $10^{-7}$ |
|----------------|--------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| $100$          |        |           |           |           |           |           |           |           |
| $200$          |        |           |           |           |           |           |           |           |
| $300$          |        |           |           |           |           |           |           |           |
| $400$          |        |           |           |           |           |           |           |           |
| $500$          |        |           |           |           |           |           |           |           |
Figure 2. Branching ratios of the fermionic and bosonic processes $h^0 \to XY$ in scenario C, within the Higgs mass range $50 \text{ GeV} < m_{h^0} < 500 \text{ GeV}$, for $\tan \beta = 5, 15, 50$, and $\chi_{ij} = -1.0, 0, 1.0$.

4. Conclusions

We studied the 2HDM type III and calculated the corresponding Lagrangian of Yukawa interactions with four texture zero matrices like a form of the Yukawa matrices, and using the Cheng-Sher anzats. Also, we obtained the Feynman rules to tree level for the neutral Higgs bosons and calculated the width of decay as well as the corresponding branching ratios for the main decay modes. The parameter space was scanned by defining three scenarios, in which we were considered that $\tan \beta = 5, 15, 50$, $\chi_{ij} = -1.0, 0, 1.0$, and $50 \text{ GeV} < m_{h^0} < 500 \text{ GeV}$. Thus, we have explored the parameter space of this model in order to determinate the areas where $h^0$ reaches maximal branching ratios. Studying these modes at current and future colliders could be important to find new Higgs signals.
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