

2HDM without FCNC: off the beaten tracks

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Abstract We propose an alternative method of constructing two Higgs-doublet models free from scalar mediated FCNC couplings at the tree-level. In a toy scenario, we have presented semi realistic textures for the Yukawa matrices, which can reproduce the approximate flavor structure in the quark sector. Presence of flavor diagonal but nonuniversal Yukawa couplings emerges as a distinguishing feature of such models.

1 Introduction

After the discovery of a Higgs-like particle at the Large Hadron Collider (LHC) [1,2], it is now time to settle whether this new particle is the Higgs scalar as predicted by the Standard Model (SM), or it is a Higgs-like particle stemming from a more elaborate construction beyond the SM (BSM). In view of this, recent years have seen a growing interest for BSM scenarios with an extended Higgs sector, where the scalar boson observed at the LHC is only the first to appear in a series of many others to follow. Two Higgs-doublet models (2HDMs) [3,4] constitute one of the simplest examples of this category and therefore have received a lot of attention in recent times.

2HDMs extend the scalar potential of the SM by adding an extra Higgs-doublet. Consequently, we will now have two Yukawa matrices for each type of fermions and diagonalization of the fermion mass matrix will not guarantee, in general, the simultaneous diagonalization of the Yukawa matrices. Thus, there will be flavor changing neutral currents (FCNC), at the tree level, mediated by the neutral scalars. However, it has been shown by Glashow and Weinberg [5] and independently by Paschos [6] that absence of tree-level FCNC can be ensured if suitable arrangements are made such that fermions of a particular charge receive their masses from a single scalar doublet (ϕ_1 or ϕ_2). Usually, a Z_2 symme-

try, under which $\phi_1 \rightarrow \phi_1$ and $\phi_2 \rightarrow -\phi_2$, is employed to accomplish this. Proper assignments of the Z_2 charges to different fermions then achieves the purpose.

To make things explicit, let us write down the Yukawa part of a 2HDM Lagrangian as follows:

$$\mathcal{L}_Y = -\sum_{k=1}^2 [\bar{\mathbf{Q}}_L \Gamma_k \phi_k \mathbf{d}_R + \bar{\mathbf{Q}}_L \Delta_k \tilde{\phi}_k \mathbf{u}_R + \bar{\mathbf{L}}_L \Sigma_k \phi_k \mathbf{e}_R] + \text{h.c.}, \quad (1)$$

where \mathbf{Q}_L and \mathbf{L}_L denote the quark and lepton doublets respectively and \mathbf{u}_R , \mathbf{d}_R and \mathbf{e}_R represent the up, down and charged lepton singlets respectively. We have also used the standard abbreviation $\tilde{\phi}_k = i\sigma_2 \phi_k^*$, where σ_2 is the second Pauli matrix. Note that we have suppressed the flavor indices in Eq. (1). Therefore, Δ_k , Γ_k and Σ_k stand for 3×3 Yukawa matrices in the up, down and charged lepton sectors respectively. We have also assumed that the neutrinos are massless.

From Eq. (1) one can write the mass matrix for the down type quarks, for example, as follows:

$$M_d = \Gamma_1 \langle \phi_1 \rangle + \Gamma_2 \langle \phi_2 \rangle, \quad (2)$$

where $\langle \phi_k \rangle = v_k / \sqrt{2}$ denotes the vacuum expectation value (VEV) of ϕ_k . Since Γ_1 and Γ_2 , in principle, can be arbitrary, there is no reason for them to be simultaneously diagonal once M_d is diagonalized using a biunitary transformation. Therefore, in general, there will be Higgs mediated FCNC at the tree level. Following the Glashow-Weinberg-Paschos (GWP) prescription, if either Γ_1 or Γ_2 vanishes, then the mass matrix becomes proportional to the Yukawa matrix, just as in the SM, and tree-level FCNC in the down quark sector can be avoided altogether. The same method can be applied to remove tree-level FCNC from the up quark and the charged lepton sectors too. The GWP prescription can be attributed to a Z_2 symmetry which prevails in the Yukawa Lagrangian. Consider, for example, the case with $\Gamma_2 = \Delta_2 = \Sigma_2 = 0$ which implies that a Z_2 transformation under which only ϕ_2 is odd, keeps the Yukawa Lagrangian invariant. This Z_2

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symmetry, when extended to the full Lagrangian, also prevents the corresponding Yukawa couplings from getting generated via quantum corrections. Thus the GWP prescription, by design, offers a natural solution to the FCNC problem.

On the other hand, Pich and Tuzon [7] suggested that an alternative way to avoid tree-level FCNC will be to make the mass matrix proportional to the Yukawa matrix by assuming the two Yukawa matrices for fermions of a particular charge to be proportional to each other. These types of 2HDMs are called aligned 2HDMs (A2HDMs). However, the Yukawa alignment imposed at a certain energy scale does not guarantee, in general, that the alignment will be maintained at a different scale too [8,9]. But it has been shown that the FCNCs generated due to such misalignments are expected to be small [10] because the Yukawa aligned 2HDMs belong to a general category of models with minimal flavor violation (MFV) [11].

2 An alternative lifestyle

However, for two Yukawa matrices to be simultaneously diagonalizable, it is not necessary to assume one of them to be zero or they are proportional to each other. It has been shown [12,13] that if M_1 and M_2 are two complex square matrices then there exist unitary matrices U_1 and U_2 such that both $U_1^\dagger M_1 U_2$ and $U_1^\dagger M_2 U_2$ are diagonal if and only if both $M_1 M_2^\dagger$ and $M_2^\dagger M_1$ are normal matrices.¹

Keeping in mind the near block diagonal structure of the CKM matrix in the Wolfenstein parametrization [15], we take, for instance²

$$\Gamma_1 = \begin{pmatrix} b_1 & 0 & 0 \\ 0 & b_1 & 0 \\ 0 & 0 & b_3 \end{pmatrix}, \quad \Gamma_2 = \begin{pmatrix} b'_2 & b_2 & 0 \\ b_2 & -b'_2 & 0 \\ 0 & 0 & 0 \end{pmatrix}. \tag{3}$$

These Yukawa matrices will lead to the following mass matrix in the down quark sector:

$$M_d = \frac{1}{\sqrt{2}} (\Gamma_1 v_1 + \Gamma_2 v_2) = \frac{1}{\sqrt{2}} \begin{pmatrix} b_1 v_1 + b'_2 v_2 & b_2 v_2 & 0 \\ b_2 v_2 & b_1 v_1 - b'_2 v_2 & 0 \\ 0 & 0 & b_3 v_1 \end{pmatrix}. \tag{4}$$

We will assume that the Yukawa couplings are real. Under this assumption, Γ_1 and Γ_2 become mutually commuting hermitian matrices and therefore they can be diagonalized

¹ Additionally, if we also impose the reality of the diagonal elements, then both $M_1 M_2^\dagger$ and $M_2^\dagger M_1$ need to be hermitian matrices[14].

² Notice that it is not necessary to assume $(\Gamma_2)_{33} = 0$ in Eq. (3). But as we will see later, this assumption makes it easier to motivate the mass matrix from symmetry.

simultaneously. As a consequence, there should be no FCNC at the tree-level mediated by the neutral scalars.

To verify this assertion explicitly, we note that M_d can be diagonalized as follows:

$$D_d = \mathcal{D}_L^\dagger M_d \mathcal{D}_R = \text{diag} \{m_d, m_s, m_b\}, \tag{5}$$

where,

$$\mathcal{D}_L = \mathcal{D}_R = \begin{pmatrix} \cos \theta_d & \sin \theta_d & 0 \\ -\sin \theta_d & \cos \theta_d & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{6}$$

Then we have the following relations:

$$m_d \cos^2 \theta_d + m_s \sin^2 \theta_d = (b_1 v_1 + b'_2 v_2) / \sqrt{2}, \tag{7a}$$

$$m_d \sin^2 \theta_d + m_s \cos^2 \theta_d = (b_1 v_1 - b'_2 v_2) / \sqrt{2}, \tag{7b}$$

$$(m_d - m_s) \sin \theta_d \cos \theta_d = b_2 v_2 / \sqrt{2}, \tag{7c}$$

$$\tan 2\theta_d = \frac{b_2}{b'_2}. \tag{7d}$$

Similarly we can define unitary matrices \mathcal{U}_L and \mathcal{U}_R which diagonalize the mass matrix in the up quark sector and are characterized by the angle θ_u . The CKM matrix will then be given by

$$V = \mathcal{U}_L^\dagger \mathcal{D}_L = \begin{pmatrix} \cos(\theta_d - \theta_u) & \sin(\theta_d - \theta_u) & 0 \\ -\sin(\theta_d - \theta_u) & \cos(\theta_d - \theta_u) & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{8}$$

Thus, we can identify $\sin(\theta_d - \theta_u)$ as the Cabibbo mixing parameter, λ . We also note that Γ_1 and Γ_2 can be diagonalized simultaneously and using Eq. (7a) we may write,

$$X_1 = \mathcal{D}_L^\dagger \Gamma_1 \mathcal{D}_R = \frac{\sqrt{2}}{v_1} \text{diag} \left\{ \frac{m_d + m_s}{2}, \frac{m_d + m_s}{2}, m_b \right\} \tag{9}$$

$$X_2 = \mathcal{D}_L^\dagger \Gamma_2 \mathcal{D}_R = \frac{\sqrt{2}}{v_2} \text{diag} \left\{ \frac{m_d - m_s}{2}, \frac{m_s - m_d}{2}, 0 \right\}. \tag{10}$$

Therefore, there will be no Higgs mediated FCNC at the tree level.

In passing, we note that although Eq. (8) gives only an approximate form of the CKM matrix, it is not very difficult, using a bottom-up approach, to reconstruct suitable Yukawa textures which are compatible with the full CKM structure. As an example, let us assume that the Yukawa matrices in the up quark sector, Δ_1 and Δ_2 are already diagonal, so that we may choose $\mathcal{U}_L = \mathcal{U}_R = 1$. Thus, in this case, the CKM matrix, V , becomes identical to \mathcal{D}_L which has been defined in Eq. (5). Now, let us also assume that Γ_1 and Γ_2 have been diagonalized simultaneously as

$$X_1 = V^\dagger \Gamma_1 \mathcal{D}_R, \quad X_2 = V^\dagger \Gamma_2 \mathcal{D}_R, \tag{11}$$

so that we may write

$$X_1 \frac{v_1}{\sqrt{2}} + X_2 \frac{v_2}{\sqrt{2}} = \text{diag} \{m_d, m_s, m_b\}. \tag{12}$$

We can easily find nontrivial solution sets for X_1 and X_2 , which satisfy the relation above. We can then choose any structure for the unitary matrix, \mathcal{D}_R and invert Eq. (11) to obtain a set of solutions for the Yukawa matrices, Γ_1 and Γ_2 , which are congenial to the full CKM structure, yet can ensure the absence of FCNC at the tree-level. However, one should keep in mind that such a bottom up approach contains too much arbitrariness in the resulting Yukawa matrices which might be difficult to motivate from an underlying symmetry.

3 Impact on flavor universality

If we express the scalar doublet, ϕ_k as

$$\phi_k = \begin{pmatrix} w_k^+ \\ \frac{h_k + iz_k}{\sqrt{2}} \end{pmatrix}, \tag{13}$$

then it is well known that the combination $h = (v_1 h_1 + v_2 h_2)/v$, where $v = \sqrt{v_1^2 + v_2^2} \approx 246$ GeV, has SM-like gauge and Yukawa couplings at the tree-level. The limit where h corresponds to a physical eigenstate is known as the *alignment limit* [16–19] which is being increasingly favored by the LHC Higgs data [20]. In the down quark sector, the Yukawa couplings for h and its orthogonal combination, $H = (v_2 h_1 - v_1 h_2)/v$, are given by

$$\begin{aligned} \mathcal{L}_Y^d &= -\frac{h}{v} \bar{\mathbf{d}} D_d \mathbf{d} - \frac{H}{v} \bar{\mathbf{d}} (N_d P_R + N_d^\dagger P_L) \mathbf{d} \\ &= -\frac{h}{v} \bar{\mathbf{d}} D_d \mathbf{d} - \frac{H}{v} \bar{\mathbf{d}} N_d \mathbf{d}, \end{aligned} \tag{14}$$

where, $\mathbf{d} = (d, s, b)^T$ and in writing the last step, it has been assumed that N_d is a real diagonal matrix. For our choice of Yukawa textures in Eq. (3), N_d has the following form:

$$N_d = \text{diag} \left\{ \frac{m_d + m_s}{2} \tan \beta - \frac{m_d - m_s}{2} \cot \beta, \frac{m_d + m_s}{2} \tan \beta - \frac{m_s - m_d}{2} \cot \beta, m_b \tan \beta \right\}, \tag{15}$$

where $\tan \beta = v_2/v_1$. Looking at this structure of N_d , we can see that the nonstandard scalar, H , couples to the fermions in a flavor diagonal but nonuniversal manner. This is in sharp contrast with other flavor conserving 2HDMs e.g., the Z_2 symmetric 2HDMs and the A2HDM. To be more precise, we define the following quantity:

$$\alpha_f = \frac{v Y_{Hff}}{m_f}, \tag{16}$$

where Y_{Hff} denotes the diagonal Yukawa coupling of H with the $f\bar{f}$ pair and m_f represents the mass of the fermion, f .

In Z_2 symmetric 2HDMs and in A2HDM, the quantity, α_f , for fermions of a particular charge, is a constant independent of the fermion masses. For instance, in the case of type II 2HDM, $\alpha_f = \tan \beta$ for the down type quarks. From the expression of N_d in Eq. (15), we see that this is clearly not satisfied for our choice of Yukawa matrices in Eq. (3). It is in this sense that we claim that the Yukawa couplings for the nonstandard Higgs bosons are flavor nonuniversal.

It is worth emphasizing that this nonuniversality is not a special outcome of our particular choice for the Yukawa matrices in Eq. (3). Whereas the precise nature of the flavor nonuniversal couplings depends on the details of the textures for the Yukawa matrices, the mere presence of nonuniversality is a general artefact of such constructions. To illustrate our point, we note that the matrix, N_d , introduced in Eq. (14) has the following general form:

$$N_d = \frac{1}{\sqrt{2}} \mathcal{D}_L^\dagger (v_2 \Gamma_1 - v_1 \Gamma_2) \mathcal{D}_R = \frac{1}{\sqrt{2}} (v_2 X_1 - v_1 X_2). \tag{17}$$

In writing Eq. (17) we have assumed that Γ_1 and Γ_2 have been diagonalized simultaneously to X_1 and X_2 respectively. Then following Eq. (16) we may write,

$$\alpha_q = \frac{(N_d)_{qq}}{m_q} = \frac{v_2 (X_1)_{qq} - v_1 (X_2)_{qq}}{v_1 (X_1)_{qq} + v_2 (X_2)_{qq}}, \tag{18}$$

where the subscript, q , stands for a generic down type quark and m_q has been obtained by diagonalizing Eq. (2). Now, if we demand $\alpha_q = \alpha$ to be a constant for the down type quarks, then we will have,

$$X_1 (\tan \beta - \alpha) = X_2 (1 + \alpha \tan \beta) \tag{19}$$

which implies that the Yukawa matrices, Γ_1 and Γ_2 , should be proportional to each other. Note that, conventional Z_2 symmetric 2HDMs constitute very special cases of the A2HDM scenario[8]. For instance, if we have either $\Gamma_1 = 0$ or $\Gamma_2 = 0$ then, using Eq. (19), we can recover $\alpha = -\cot \beta$ or $\alpha = \tan \beta$ as expected for type I and type II 2HDMs respectively [3].

Thus we have shown that for the nonstandard scalars to have flavor universal Yukawa couplings, the 2HDM must either correspond to a conventional 2HDM with Z_2 symmetry or to the A2HDM. Any other way of constructing 2HDM without FCNC will inevitably lead to flavor nonuniversal couplings which can serve as a distinguishing feature of such constructions.

4 A symmetry origin

At this stage, it is reasonable to ask whether the Yukawa structures presented in Eq. (3) will be stable under quantum corrections. Evidently, the answer will be affirmative if we

can find a symmetry that can give rise to such textures. As it happens, we can motivate the Yukawa structures of Eq. (3) within a 2HDM framework using an approximate $Z_3 \times Z_2$ flavor symmetry. First we assign the following transformation properties to the quark and scalar fields under Z_3 :³

$$Q_{L3} \rightarrow \omega Q_{L3}, \quad u_{R3} \rightarrow \omega^2 u_{R3}, \quad \phi_1 \rightarrow \omega \phi_1, \quad (20)$$

where, Q_{Lk} ($k = 1, 2, 3$) stands for the left handed $SU(2)$ doublet of quarks in the k -th generation and similarly for the right handed quark singlets in the up and down sectors, and ϕ_k ($k = 1, 2$) denotes the k -th scalar doublet of $SU(2)$. The scalar doublet, ϕ_2 , and the other quark fields remain unaffected under Z_3 . Under the Z_2 part of the symmetry only Q_{L3}, u_{R3} , and d_{R3} are assigned odd parities while the rest are assumed to be even. With these assignments, certain terms such as $\overline{Q}_{L3}(\Gamma_2)_{3k}\phi_2 d_{Rk}$ ($k = 1, 2, 3$) will be forbidden in the Yukawa Lagrangian of Eq. (1). One can easily verify that, because of the symmetry, the Yukawa matrices will take the following forms:⁴

$$\Gamma_1, \Delta_1 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \checkmark \end{pmatrix}, \quad \Gamma_2, \Delta_2 = \begin{pmatrix} \checkmark & \checkmark & 0 \\ \checkmark & \checkmark & 0 \\ 0 & 0 & 0 \end{pmatrix}. \quad (21)$$

Thus, as long as only the block configurations are concerned, the structures of Eq. (21) look very similar to those in Eq. (3) except for the fact that $b_1 = 0$ in Eq. (21), which is a consequence of the Z_3 part of the symmetry. But adding Eqs. (7a) and (7b) we can see that b_1 is of the order of the Yukawa couplings for the second generation of quarks, which for $\tan\beta \sim \mathcal{O}(1)$ is quite small. Therefore, even in the presence of b_1 (and its counterpart in the up quark sector) the Yukawa Lagrangian can be considered to possess an approximate $Z_3 \times Z_2$ symmetry which is expected to protect the zeros in Eq. (3) from large quantum corrections. Moreover, when N_d and N_u (analog of N_d in the up sector) are diagonal, the Yukawa Lagrangian possesses an approximate $U(1)_1 \times U(1)_2 \times U(1)_3$ symmetry⁵ which is broken only by the off-diagonal elements of the CKM matrix. Thus, in addition to the usual loop suppression factor, the FCNC couplings generated by quantum effects will be moderated further by the off-diagonal CKM elements.

³ This will lead to an accidental $U(1)$ symmetry in the scalar potential, under which $\phi_1 \rightarrow e^{i\theta}\phi_1; \phi_2 \rightarrow \phi_2$. Consequently, a massless pseudoscalar should appear after the SSB. This can be prevented by introducing a bilinear term of the form $\{m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\}$ to the scalar potential, which breaks the symmetry softly. Details of the scalar spectrum for such a model can be found in Ref. [21].

⁴ If the Yukawa textures of Eq. (21) were exact, then flavor universality would prevail separately in the first two generations and in the third generation of fermions.

⁵ If the CKM matrix were the unit matrix, then, under this symmetry, the individual generation numbers would have been conserved in the quark sector.

5 Summary

To summarize, we have proposed a novel way of constructing 2HDMs devoid of tree-level FCNCs mediated by neutral scalars. We have argued how, to have a FCNC free 2HDM, it is not necessary to assume the vanishing of one of the Yukawa matrices or the proportionality between the two Yukawa matrices for fermions of a particular charge. We have shown, with a semi-realistic example in the quark sector, that for judiciously chosen nontrivial structures for the Yukawa matrices one can still prevent FCNCs from appearing at the tree-level. Although the main idea of this paper is simple in its conception, yet, to our knowledge, this is the first time that such a possibility has been pointed out explicitly. Despite the simplicity, the unavoidable presence of flavor diagonal but nonuniversal Yukawa couplings for the nonstandard scalars is a unique and interesting outcome which should enable us to experimentally distinguish such constructions from the existing conventional 2HDMs. In view of the fact that recent anomalies in the B -physics data may call for flavor nonuniversal couplings[22–24], such a 2HDM can open up new possibilities along this direction.

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Appendix

For the sake of completeness and to give the reader an intuitive feel, we present here the requirement for simultaneous diagonalization of two complex matrices as a necessary condition. First we recall that a normal matrix commutes with its hermitian conjugate. Now, if we assume that N is diagonalizable via a unitary similarity transformation, i.e., $U^\dagger N U = D$ where D is a diagonal matrix, then we have

$$\begin{aligned} N N^\dagger &= (U D U^\dagger) (U D^\dagger U^\dagger) = U D D^\dagger U^\dagger = U D^\dagger D U^\dagger \\ &= (U D^\dagger U^\dagger) (U D U^\dagger) = N^\dagger N, \end{aligned} \quad (22)$$

which implies that N is a normal matrix. Note that in Eq. (22) we have used the fact that D , being diagonal, commutes with D^\dagger .

Conversely, we can also show that if N is a normal matrix then it can be diagonalized via a unitary similarity transformation. To prove this, we note that N can be decomposed as:

$$N = N_1 + i N_2, \quad (23)$$

where N_1 and N_2 are both hermitian matrices and are given by

$$N_1 = \frac{1}{2} (N + N^\dagger), \quad \text{and} \quad N_2 = -\frac{i}{2} (N - N^\dagger). \quad (24)$$

Now, one can check that, if N is a normal matrix, i.e., $[N, N^\dagger] = 0$, then we must have, $[N_1, N_2] = 0$. Thus, N_1 and N_2 , being hermitian matrices, can be diagonalized by the same unitary similarity transformation, which means, in view of Eq. (23), that N can be diagonalized via a unitary similarity transformation. Hence, we have proved that a matrix, N , can be diagonalized via a unitary similarity transformation if and only if N is a normal matrix.

Now, let us suppose that two complex Yukawa matrices, Y_1 and Y_2 , can be diagonalized simultaneously via the following biunitary transformation:

$$U_1^\dagger Y_1 U_2 = D_1, \quad \text{and} \quad U_1^\dagger Y_2 U_2 = D_2. \quad (25)$$

Then we can write,

$$\left(U_1^\dagger Y_1 U_2 \right) \left(U_2^\dagger Y_2^\dagger U_1 \right) \equiv U_1^\dagger \left(Y_1 Y_2^\dagger \right) U_1 = D_1 D_2^\dagger \quad (26)$$

$$\text{and} \quad \left(U_2^\dagger Y_1^\dagger U_1 \right) \left(U_1^\dagger Y_2 U_2 \right) \equiv U_2^\dagger \left(Y_1^\dagger Y_2 \right) U_2 = D_1^\dagger D_2. \quad (27)$$

Since the matrices on the right hand sides of Eqs. (26) and (27) are diagonal, we can conclude that $Y_1 Y_2^\dagger$ and $Y_1^\dagger Y_2$ must be normal matrices.

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