The Yukawa couplings in the Two Higgs Doublet Model and the Froggart-Nielsen mechanism

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Abstract. Mixing of the TeV-scale flavon fields with the electroweak Higgs bosons of the Two Higgs Doublet Model, could induce large Flavor Changing Neutral Curretns (FCNC), interactions which can be tested both at low and high energy experiments. We construct a model of this kind, that involves the Froggart-Nielsen mechanism that TeV-scale flavon field, which mixes with a Two Higgs doublet model and explore its phonomenology.

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INTRODUCTION

Probing the origin of mass is one of the main goals of the Large Hadron Collider (LHC). Whithin the Standard Model (SM), this means studying the properties of the Higgs boson, including its decays and production mechanisms. The Higgs sector of many well motivated extensions of the SM, often include several Higgs multiplets, in particular, the Two Higgs Doublet Model (THDM), in boht its SUSY and non-SUSY versions, can be considered a prototype of a Higgs sector that includes neutral (h^0, H^0, A^0) and charge Higgs bosons $(H^{\pm})$ [1]. Hopefully the LHC will allow to determine whether the Higgs sector belongs to the SM or some extension [2, 3]. However, a definitive test of the mechanism of electroweak symmetry breaking will require further studies. In particular, probing the fermionic couplings of the Higgs bosons could help to find some posible connection with the flavor problem.

In this regard, one of the most attractive proposal to derive the mass hierarchy and the mixing angles, is the Froggart-Nielsen mechanism [4], which is based on the assumtion that a flavor symmetry (FS) is broken by the v.e.v of a singlet field (S). The quarks and leptons are charge under this symmetry, in such a way that it is not possible to write dimension four Yukawa terms. However, higher dimensional operators, invariant under the flavor symmetry can be write down, in such a way that the Yukawa couplings appear after spontaneous breaking of the flavor symmetry [5].

Here we are interested in presenting a correct set of flavor charges, which automatically lead to the realistic mass hierarchy for leptons. Also, we study the scalar potential and compute the mixing terms among the flavon field and the Higgs bosons. For this, we work within the context of the version II of the THDM, with an $U(1)$ abelian flavor symmetry being responsable for the generation of the Yukawa matrices.

TABLE 1.

leptons	L_{L1}	L_{L2}	L_{L3}	l_{R1}	l_{R2}	l_{R3}	Φ_i	S
$U(1)_F$ charge	h_1	h_2	h_3	α_1	α_2	α_3	0	1

THDM YUKAWAS FROM THE FN MECHANISM

The model we shall study involves one TeV-scale flavon field S that is a singlet under the $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge group, plus two scalar fields Φ_1 and Φ_2, doublets under $SU(2)_L$; We also consider a $U(1)_F$ flavor symmetry with the charge assignment given in the table 1.

We have presented a detailed study of the THDM-III Yukawa lagrangian, assuming certain texture pattern [6]. Phenomenological implications of this model for the neutral Higgs sector including lepton flavor violation and FCNC has been presented [7]:

The effective Yukawa coupling of leptons to S and Φ_1 field is given by:

$$\mathscr{L}_Y = \alpha_{mn} \left(\frac{S}{\Lambda}\right)^{h_m+\alpha_n} \bar{L}'_{Lm} \Phi_1 \, l'_{Rn} + h.c. \tag{1}$$

where L_L denotes the left-handed lepton doublet, l_R is the right-handed lepton singlet, m, n are the generation indices and h_m, α_n are respectively the $U(1)_F$ charges of the leptons. The parameter Λ is the heavy scale that communicate the $U(1)_F$ symmetry for the leptons. Upon breaking the $U(1)_F$ symmetry the Yukawa couplings can be written as [8, 9]:

$$Y_{mn} = \alpha_{mn} \, \varepsilon^{h_m+\alpha_n}, \tag{2}$$

where $\varepsilon = \frac{\langle S \rangle}{\Lambda}$. We take this parameter of the same order as the Cabibbo angle $\varepsilon \sim 0.22$. The mass matrix is given by:

$$M_{mn} = \frac{v_1}{\sqrt{2}} Y_{mn} = \frac{v_1}{\sqrt{2}} \alpha_{mn} \, \varepsilon^{h_m+\alpha_n}. \tag{3}$$

Without lost of generality, we consider a hermitian mass matrix that can be parameterized as follows:

$$M_{mn} = \alpha \, \frac{v_1}{\sqrt{2}} \begin{pmatrix} a\,\varepsilon^{h_1+\alpha_1} & c\,\varepsilon^{h_1+\alpha_2} & e\,\varepsilon^{h_1+\alpha_3} \\ c\,\varepsilon^{h_2+\alpha_1} & b\,\varepsilon^{h_2+\alpha_2} & d\,\varepsilon^{h_2+\alpha_3} \\ e\,\varepsilon^{h_3+\alpha_1} & d\,\varepsilon^{h_3+\alpha_2} & \varepsilon^{h_3+\alpha_3} \end{pmatrix}, \tag{4}$$

with the relations:

$$h_2 + \alpha_1 = h_1 + \alpha_2, \qquad h_1 + \alpha_3 = h_3 + \alpha_1, \qquad h_2 + \alpha_3 = h_3 + \alpha_2, \tag{5}$$

and a, b, c, d, e are coefficients of order one.

The mass matrix (4) is diagonalized through of unitary transformation in the following way:

$$O^\dagger M O = \frac{v_1}{\sqrt{2}} \alpha \, O^\dagger Y O = m_\tau \begin{pmatrix} \tilde{a}\,\varepsilon^6 & 0 & 0 \\ 0 & \tilde{b}\,\varepsilon^2 & 0 \\ 0 & 0 & 1 \end{pmatrix} = \bar{M}. \tag{6}$$

Then, as a first aproximation we can choose $\alpha = \sqrt{2}\frac{m_\tau}{v_1}$ and

$$h_1 + \alpha_1 = 6, \qquad h_2 + \alpha_2 = 2, \qquad h_3 + \alpha_3 = 0. \tag{7}$$

Solving the set of equations given in (5) and (7), we get a parametric solution of the exponents α_1, α_2, α_2, h_1 and h_2, given by:

$$\alpha_1 = 3 - h_3, \qquad \alpha_2 = 1 - h_3, \qquad \alpha_3 = -h_3, \qquad h_1 = 3 + h_3, \qquad h_2 = 1 + h_3, \tag{8}$$

and we get the following Yukawa matrix:

$$Y = \alpha \begin{pmatrix} a\varepsilon^6 & c\varepsilon^4 & e\varepsilon^3 \\ c\varepsilon^4 & b\varepsilon^2 & d\varepsilon \\ e\varepsilon^3 & d\varepsilon & 1 \end{pmatrix}. \tag{9}$$

The rotation matrix O has the form:

$$O = \begin{pmatrix} 1-(b-d^2)\varepsilon^2 & 0 & e\varepsilon^3 \\ 0 & 1-(b-d^2)\varepsilon^2 & d\varepsilon \\ -e\varepsilon^3 & -d\varepsilon & 1-(b-d^2)\varepsilon^2 \end{pmatrix}, \tag{10}$$

The physical states of the leptons are defined as:

$$l_L = l'_L\, O, \qquad l_R = O^\dagger\, l'_R. \tag{11}$$

Scalar Potential

The Higgs potential is assumed to have the form:

$$\begin{aligned} V(\Phi_1,\Phi_2,S) &= \mu_1^2\Phi_1^\dagger\Phi_1 + \mu_2^2\Phi_2^\dagger\Phi_2 + \lambda_1(\Phi_1^\dagger\Phi_1)^2 \\ &+ \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\ &+ \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.] \\ &+ \mu_s^2 S^*S + \lambda_s(S^*S)^2 + \lambda_{1s}(S^*S)\Phi_1^\dagger\Phi_1 \\ &+ \lambda_{2s}(S^*S)\Phi_2^\dagger\Phi_2, \end{aligned} \tag{12}$$

where $\Phi_i = (\phi_i^+, \phi_i^0)^T$. The first three lines refer to the THDM-II potential. The analisys of this potential is underway. However we can guess the result; namely we shall express the weak eigenstates $\phi_i^0 = \Re\phi_i^0 + i\Im\phi_i^0$, $S = \Re S + i\Im S$ in terms of the mass eigenstates [10]:

$$\begin{pmatrix} \Im\phi_1^0 \\ \Im\phi_2^0 \\ \Im S \end{pmatrix} = V_{ij} \begin{pmatrix} G_z^0 \\ A_2^0 \\ A_1^0 \end{pmatrix}, \qquad \begin{pmatrix} \Re\phi_1^0 \\ \Re\phi_2^0 \\ \Re S \end{pmatrix} = U_{ij} \begin{pmatrix} h_1^0 \\ h_2^0 \\ h_3^0 \end{pmatrix}. \tag{13}$$

NEUTRAL HIGGS BOSONS-LEPTONS INTERACTIONS

Having defined the physical spectrum of the leptons and scalar fields, we can compute the interaction Lagrangian, which comes from:

$$\mathscr{L}_Y^0 = \alpha_{mn} \left(\frac{S}{\Lambda}\right)^{h_m+\alpha_n} \left(\bar{l}'_{Lm}\, \phi_1^0\, l'_{Rn}\right) + h.c. \tag{14}$$

Then, considering the values of h_i, α_i given in (8) and after some algebra we get:

$$\begin{aligned}
\mathscr{L}_Y^0 &= \bar{l}'_L M \bar{l}'_R + \frac{\alpha v_1}{\sqrt{2}} \bar{l}'_L A \bar{l}'_R \left(\frac{S}{\Lambda}\right) \\
&+ \frac{\sqrt{2}}{v_1} \bar{l}'_L M \bar{l}'_R\, \phi_1^0 + \alpha \bar{l}'_L A \bar{l}'_R \left(\frac{S}{\Lambda}\right) \phi_1^0 + h.c.
\end{aligned} \tag{15}$$

where we have ignored terms higher than linear in the field S, the matrices M and A are:

$$M = \alpha \frac{v_1}{\sqrt{2}} \begin{pmatrix} a\varepsilon^6 & c\varepsilon^4 & e\varepsilon^3 \\ c\varepsilon^4 & b\varepsilon^2 & d\varepsilon \\ e\varepsilon^3 & d\varepsilon & 1 \end{pmatrix}, \qquad A = \begin{pmatrix} 6a\varepsilon^5 & 4c\varepsilon^3 & 3e\varepsilon^2 \\ 4c\varepsilon^3 & 2b\varepsilon & d \\ 3e\varepsilon^2 & d & 0 \end{pmatrix}. \tag{16}$$

By using the redefined fields (11) and considering the Lagrangian (15) in this basis, the interactions of the neutral Higgs bosons S and ϕ_1^0 with lepton pairs acquire the form:

$$\begin{aligned}
\mathscr{L}_Y^0 &= \bar{l}_L \bar{M} \bar{l}_R + \frac{\alpha v_1}{\sqrt{2}} \bar{l}_L \tilde{A} \bar{l}_R \left(\frac{S}{\Lambda}\right) \\
&+ \frac{\sqrt{2}}{v_1} \bar{l}_L \bar{M} \bar{l}_R\, \phi_1^0 + \alpha \bar{l}_L \tilde{A} \bar{l}_R \left(\frac{S}{\Lambda}\right) \phi_1^0 + h.c.
\end{aligned} \tag{17}$$

where $\tilde{A} = O^\dagger A\, O$. We can see from this lagrangian that the field ϕ_1^0 does not present flavor changing couplings with leptons, but the field S does, in particular the $\mu - \tau$ transition can induce interesting phenomenology.

CONCLUSIONS

We present a simple flavon model with an $U(1)$ flavor symmetry, and we find a set of charges of this symmetry that can accommodate the observed hierarchy of the charge leptons masses. We present the lagrangian that describes this system, and re-write it in terms of mass eigenstates. Flavor conserving and flavor changing coupling of neutral Higgs boson with leptons are described through of this lagrangian.

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