Has a Flavon with $M = 750$ GeV been detected at the LHC13?

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Abstract. Higgs-flavon fields appear as a part of the Froggatt-Nielsen (FN) mechanism, which attempts to explain the hierarchy of Yukawa couplings. We explore the possibility that the 750 GeV diphoton resonance recently reported at the LHC13, could be identified with a low-scale Higgs-flavon field $H_F$ and find the region of the parameter space consistent with CMS and ATLAS data. It is found that the extra vector-like fermions of the ultraviolet completion of the FN mechanism are necessary in order to reproduce the observed signal. We consider a standard model (SM) extension that contains two Higgs doublets (a standard one and an inert one) and one complex FN singlet. The inert doublet includes a stable neutral boson, which provides a viable dark matter candidate, while the mixing of the standard doublet and the FN singlet induces flavor violation in the Higgs sector at the tree-level. Constraints on the parameters of the model are derived from the LHC Higgs data, which include the search for the lepton flavor violating decay of the SM Higgs boson $h \rightarrow \bar{\mu}\tau$.

1. Introduction
Several ideas have been proposed to address the flavor problem [1]. For instance, textures and GUT-inspired relations, flavor symmetries and radiative generation, etc. The flavor symmetry approach can be supplemented with the Froggatt-Nielsen (FN) mechanism, which assumes that above some scale $M_F$ there is a symmetry that forbids the appearance of Yukawa couplings; SM fermions are charged under this symmetry [which could be of Abelian type $U(1)_F$]. However, the Yukawa matrices can arise through non-renormalizable operators. The Higgs spectrum of these models could include light Higgs-flavons, which could mix with the scalar bosons. In these models, the diagonal flavor conserving (FC) couplings of the SM-like Higgs boson could deviate from the SM, while FV couplings could be induced at small rates too, but still produce detectable signals. On the other hand, extending the Higgs sector of the SM opens up the possibility of including a scalar dark matter (DM) candidate, such as occurs with the well studied inert doublet model (IDM). There are important motivations to supplement this model with a complex singlet, for instance to have extra sources of CP violation, as in the IDM with a complex singlet (IDMS) recently studied [7].

2. The IDMS-FN model
We shall consider a model with a multi-Higgs model that includes one standard-like Higgs doublet, denoted as $\Phi_s$, as well as an inert-type doublet $\Phi_i$. Furthermore, we shall also include Froggatt-Nielsen scalar field (SM singlet $S$). The possibility of having light flavon fields was
studied in ref. [3], and more recently in [4, 5]. Thus, besides breaking the EW symmetry, and thereby generating the masses of the W and Z gauge bosons, the field $\Phi_s$ gives masses to up-type quarks, d-type quarks and leptons. We shall impose a discrete symmetry in such a way that the doublet $(\Phi_n)$ is of the inert-type, and therefore contains a Dark matter candidate [6]. The FN mechanism could be UV completed through the introduction of heavy mirror fermions, as we shall discuss later these fermions could play a role in order to help reproducing the 750 GeV signal hinted at LHC.

In our model only the $Z_2$-even fields $\Phi_s$ and $S_F$ acquire vacuum expectation values $v$ and $u$, respectively. We shall use the following field decomposition around the vacuum state:

$$\Phi_s = \left( \frac{1}{\sqrt{2}} (v + \phi^0 + ig_z) \right), \quad \Phi_n = \left( \frac{1}{\sqrt{2}} (H^+ + iA) \right),$$

$$S_F = \frac{1}{\sqrt{2}} (u + s_1 + ip_1).$$

2.1. The Higgs potential

The Higgs potential of our model resembles the one of the IDMS model, which was studied in [7]. The IDMS model includes a $U(1)$ symmetry to simplify the number of free parameters of the model. Here such symmetry has a physical motivation, namely it is identified as the flavor symmetry, whose breaking helps to address the hierarchy of the Yukawa couplings associated with the broad spectrum of quark and lepton masses. Furthermore, our scalar potential is invariant under CP symmetry, and it takes the following form:

$$V = -\frac{1}{2} \left[ m_{F_s}^2 \Phi_s \Phi_s^\dagger + m_{F_n}^2 \Phi_n \Phi_n^\dagger \right] + \frac{1}{2} \left[ \lambda_1 \left( \Phi_s^\dagger \Phi_s \right)^2 + \lambda_2 \left( \Phi_n^\dagger \Phi_n \right)^2 \right]$$

$$+ \lambda_3 \left( \Phi_s^\dagger \Phi_s \right) \left( \Phi_n^\dagger \Phi_n \right) + \lambda_4 \left( \Phi_s^\dagger \Phi_n \right) \left( \Phi_n^\dagger \Phi_s \right) + \frac{\lambda_5}{2} \left[ \left( \Phi_s^\dagger \Phi_s \right)^2 + \left( \Phi_n^\dagger \Phi_n \right)^2 \right]$$

$$- \frac{m_F^2}{2} S_F^\dagger S_F - \frac{m_F^2}{2} (S_F^F)^2 + S_F^F + \lambda_{s1}(S_F^F)S_F^F + \lambda_{s2}(S_F^F)S_F^\dagger S_F + \lambda_{s3}(S_F^F)(S_F^\dagger S_F)$$

2.2. The Yukawa Lagrangian

On the other hand, the FN lagrangian of the model includes the terms that would become the Yukawa Lagrangian for the Higgs-fermion couplings, we shall discuss later these fermions could play a role in order to help reproducing the 750 GeV signal hinted at LHC.

After substituting the Higgs-Flavon mass eigenstates, one gets finally the following interaction lagrangian for the Higgs-fermion couplings,

$$\mathcal{L}_Y = \frac{1}{v} \left[ \bar{U} M_u U + \bar{D} M_d D + \bar{L} M_L L \right] (c_a h + s_a H_F)$$

$$+ \frac{v}{\sqrt{2}u} \left[ \bar{U} \tilde{Z}^a U_j + \bar{D} \tilde{Z}^d D_j + \bar{L} \tilde{Z}^l L_j \right] (-s_a h + c_a H_F + iA_F)$$
Here, the information about the size of FV Higgs couplings is contained in the matrices Z. Thus, the (diagonal and non-diagonal) interactions of the scalars \( h, H_F, A_F \) with any fermion \( f \) are:

\[
\begin{align*}
(\bar{f}_i f_i h) &= \frac{c_\alpha}{v} M^f_{ii} - \frac{s_\alpha v}{\sqrt{2} u} Z^f_{ii} \\
(\bar{f}_i f_j h) &= -\frac{s_\alpha v}{\sqrt{2} u} Z^f_{ij} \\
(\bar{f}_i f_i H_F) &= \frac{s_\alpha}{v} M^f_{ii} + \frac{c_\alpha v}{\sqrt{2} u} Z^f_{ii} \\
(\bar{f}_i f_j H_F) &= \frac{c_\alpha v}{\sqrt{2} u} Z^f_{ij} \\
(\bar{f}_i f_j A_F) &= \frac{i v}{\sqrt{2} u} Z^f_{ij}
\end{align*}
\]  

(5)

Besides the Yukawa couplings, we also need to specify the Higgs couplings with vector bosons, which is written as \( g_{hVV} = \chi^h_V g_{hVV}^{sm} \), with the factor \( \chi^h_V \) given as: \( \chi^h_V = \cos \alpha \) and \( \chi^{H_F} = \sin \alpha \).

Moreover, since the Higgs couplings to first generation quarks and leptons is highly suppressed, in order to study the FV Higgs coupling, which depends on the matrices \( Z^f \), we shall consider the 2-3 family sub-system. Namely, for up quarks the Z-matrix (in mass eigenstate basis), is given by:

\[
Z^u = \begin{pmatrix} Y^u_{22} & Y^u_{23} \\ Y^u_{32} & 2s_\alpha Y^u_{33} \end{pmatrix}
\]  

(6)

and similarly for d-quarks and leptons. We find a relation among the parameters, such that we can express the \( r_{ij}^{u,d} \)'s in terms of the ratios of masses and the CKM angle \( V_{tb} \simeq s_{23} \). Namely, we define: \( r_u = m_c/m_t \), \( r_d = m_s/m_b \), and \( r_u^u = Y^u_{22}/Y^u_{32} \), \( r_u^d = Y^d_{22}/Y^d_{32} \). Similarly: \( r_1^u = Y^u_{22}/Y^u_{33} \), \( r_2^u = Y^u_{23}/Y^u_{33} \), \( r_1^d = Y^d_{22}/Y^d_{33} \), \( r_2^d = Y^d_{23}/Y^d_{33} \). Within this approximation we have: \( Y^u_{33} \simeq Y^u_{33} \) for \( f = u, d \). Then, \( r_1^f = r_1^f + r_2^f \), and the ratios of Yukawas must satisfy the following relation:

\[
r_2^u = r_2^d \frac{1 + r_d}{1 + r_u} - \frac{s_{23}}{1 + r_u}
\]  

(7)

3. Scenarios for Higgs couplings in the IDMS-FN model

Here we shall discuss the formulae needed to express all relevant Higgs couplings, which will permit us to define some benchmark points.

(i) **FC Higgs couplings.** First, we shall use LHC data to derive bounds on the Higgs couplings, following the analysis presented in ref. [8]; Here, the deviation from the SM Higgs couplings are assumed to be small and are expressed as: \( g_{h,XX} = g_{h,XX}^{sm} (1 + \epsilon_X) \), where \( \eta^X = 1 + \epsilon_X \). The results obtained in [8] give the following allowed ranges at 95 % C.L.: \( \epsilon_t = -0.21 \pm 0.23 \), \( \epsilon_b = -0.19 \pm 0.30 \), \( \epsilon_\tau = 0.00 \pm 0.18 \); while for W (Z) bosons they find: \( \epsilon_W = -0.15 \pm 0.14 \), \( \epsilon_Z = -0.01 \pm 0.13 \). We shall use the strongest constraints, which come from a combination of \( \epsilon_Z \) and \( \epsilon_t \), in such a way that the resulting constraints on the mixing angles is 0.86 < cos \( \alpha < 1.0 \).

(ii) **FV Higgs couplings with up-type quarks.** Then, regarding the couplings with up-type quarks, we consider the following sample values: \( r_2^u = 0.05, 0.1, 0.3 \), then table 1 shows the values of the entries for the \( Z^u \) matrix for the 2nd-3rd family case for up-type quarks. We choose to focus on the up-quark sector, because we want to get an estimate for the most relevant predictions of the model.
Table 1. Relevant elements of the matrix $\tilde{Z}_{ij}^u$ for up-type quarks

| Scenario | $Z_{33}^u$ | $Z_{23}^u$ | $Z_{22}^u$ |
|----------|-----------|-----------|-----------|
| X1       | $4 \times 10^{-4}$ | $2 \times 10^{-2}$ | $2 \times 10^{-4}$ |
| X2       | $1.4 \times 10^{-2}$ | $1.2 \times 10^{-1}$ | $7.2 \times 10^{-3}$ |
| X3       | 0.27      | 0.52      | 0.14      |

(iii) LFV Higgs couplings. These couplings are written in terms of the parameters $\rho_{ij}$, which appear in the charged lepton mass matrix, and are of $O(1)$. Namely,

$$\tilde{Z}_{33}^l = 2\sqrt{2} \frac{m_\tau}{v} \simeq 1.95 \times 10^{-2}$$

$$\tilde{Z}_{23}^l = 4\lambda^4 \rho_{l23}^l \simeq 10^{-2} \rho_{23}^l$$

$$\tilde{Z}_{22}^l = 4.1 \times 10^{-2} \rho_{23}^l + 2.41 \times 10^{-3} \quad (8)$$

We shall consider values of $\rho_{23}^l = 0.25, 0.75$.

An interesting probe of FV Higgs couplings is provided by the decay $h \rightarrow \tau\mu$, which was initially studied in refs. [9, 10]. Subsequent studies on detectability of the signal appeared soon after [11, 12, 13]. Precise loop calculations with massive neutrinos, SUSY and other models appeared in [14, 15, 16, 17]. The recent search for this decay at LHC [18], have resulted in a bound for the corresponding branching ratio of order $B.r.(h \rightarrow \tau\mu) < 1.51 \times 10^{-2}$ at 95% c.l.. Furthermore, given that the best fit to the data gives $B.r.(h \rightarrow \tau\mu) = 0.84^{+0.39}_{-0.37} \times 10^{-2}$, many more papers have appeared recently, trying to explain this result [19]. The search for this LFV Higgs decay could be one great opportunity to find new physics at the LHC RunII.

4. Branching ratios

Given the interactions of the model, we can evaluate the decays of the heavy flavon state $H_F$, with parameters satisfying the constraints from LHC Higgs searches. They are shown in figure 1.2. In figure 1, we show the branching ratios for the tree-level modes with the vev $u = 500$ Gev, including $H_F \rightarrow tt, bb, ZZ, WW, hh$. We notice that the modes ZZ, WW, are the dominant ones, with B.R. of order 0.7 and 0.35, respectively, even after the threshold for the $tt$ decay, which also reaches at most a B.R. $\simeq 0.2$. We also notice that the decay $H \rightarrow hh$ could reach a B.R. of order 0.1, which should be searched at LHC13.

![Figure 1. The BR for the tree-level decays of the heavy flavon state.](image-url)
To explore further the interesting mode $H_F \to hh$, we show in figure 3 the contour regions for the Branching Ratio in the plane $u - M_{H_F}$. We can notice that for the full range $500 < u < 3000$ GeV and $250 < M_{H_F} < 1500$ GeV, the corresponding B.R. is larger than about 0.01, which seems amenable to be searched at LHC13.

5. Conclusions and outlook
We have studied the Higgs couplings, within a model within the IDMS-FN model, where one Higgs doublet participates in SSB while the second one is of inert-type and contains a dark matter candidate. This model also includes mixing of the Higgs doublets with a Flavon field, which generates the Yukawa hierarchies and induces Flavor-violating Higgs couplings at acceptable rates.

Constraints on these couplings, derived from Higgs search at LHC, and their implications for Higgs anomalies observed at LHC. We find that within this model it is possible to explain both the decay $h \to \tau \mu$, as well as the new 750 GeV resonance observed at LHC13 in the two-photon final state.

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References
[1] G. Isidori, Y. Nir and G. Perez, Ann. Rev. Nucl. Part. Sci. 60, 355 (2010) [arXiv:1002.0900 [hep-ph]].
[2] C. Bonilla, D. Sokolowska, J. L. Diaz-Cruz, M. Krawczyk and N. Darvishi, arXiv:1412.8730 [hep-ph].
[3] I. Dorsner and S. M. Barr, Phys. Rev. D 65, 095004 (2002) [hep-ph/0210207].
[4] K. Tsumura and L. Velasco-Sevilla, Phys. Rev. D 81, 036012 (2010) [arXiv:0911.2149 [hep-ph]].
[5] E. L. Berger, S. B. Giddings, H. Wang and H. Zhang, Phys. Rev. D 90, no. 7, 076004 (2014) [arXiv:1406.6054 [hep-ph]].
[6] J. L. Diaz-Cruz, arXiv:1405.0990 [hep-ph].
[7] C. Bonilla, D. Sokolowska, J. L. Diaz-Cruz, M. Krawczyk and N. Darvishi, arXiv:1412.8730 [hep-ph].
[8] P. P. Giardino, K. Kannike, I. Masina, M. Raidal and A. Strumia, arXiv:1303.3570 [hep-ph].
[9] A. Pilaftsis, Phys. Lett. B 285, 68 (1992).
[10] J. L. Diaz-Cruz and J. J. Toscano, Phys. Rev. D 62, 116005 (2000) [hep-ph/9910233].
[11] T. Han and D. Marfatia, Phys. Rev. Lett. 86, 1442 (2001) [hep-ph/0008141].
[12] K. A. Assamagan, A. Deandrea and P. A. Delsart, Phys. Rev. D 67, 035001 (2003) [hep-ph/0207302].
[13] S. Kanemura, T. Ota and K. Tsumura, Phys. Rev. D 73, 016006 (2006) [hep-ph/0505191].
[14] E. Arganda, A. M. Curiel, M. J. Herrero and D. Temes, Phys. Rev. D 71, 035011 (2005) [hep-ph/0407302].
[15] J. L. Diaz-Cruz, JHEP 0305, 036 (2003) [hep-ph/0207030].
[16] A. Brignole and A. Rossi, Nucl. Phys. B 701, 3 (2004) [hep-ph/0404211].
[17] J. L. Diaz-Cruz, D. K. Ghosh and S. Moretti, Phys. Lett. B 679, 376 (2009) [arXiv:0809.5158 [hep-ph]].
[18] V. Khachatryan et al. [CMS Collaboration], arXiv:1502.07400 [hep-ex].
[19] For a recent review see: A. Vicente, arXiv:1503.08622 [hep-ph].