

THE TEXTURIZED 2HDM (2HDM-TX) AND HIGGS SIGNATURE AT COLLIDERS

J. Lorenzo Diaz-Cruz¹, Enrique Díaz² and Javier A. Orduz-Ducura³

Facultad de Ciencias Físico Matematicas, Benemérita Universidad Autónoma de Puebla, 18 sur y Av. San Claudio, C.P. 72570 Puebla, Pue., Mexico

E-mail: ¹jldiaz@fcfm.buap.mx, ²alcmaeon@gmail.com, ³jaorduz@alumnos.fcfm.buap.mx

Abstract. We explore the phenomena of flavor violation, using combinations of Yukawa matrices in order to reproduce a hermitian mass matrix. We work within the Two-Higgs doublet model with a specific four-zero texture type (2HDM-Tx). Current experimental bounds from $K-\bar{K}$ mixing, $B_s \rightarrow \mu^+\mu^-$ and $\tau \rightarrow 3\mu$ are used in order to restrict the values for the parameters model: $\tan\beta(= \frac{v_2}{v_1})$ and γ ($0 < \gamma < 1$). We predict the rates for the Flavor Violating decays ($h \rightarrow \tau\mu$) and $t \rightarrow c + h$, which reach Branching ratios that could be tested at the LHC.

1. Introduction

Recently the Large Hadron Collider (LHC) has confirmed the existence of a Higgs-like particle with mass $m_H \approx 125$ GeV [1, 2]. This seems to confirm the linear realization of the mechanism of Electroweak symmetry breaking, which it needs to generate the masses of gauge bosons and fermions within the SM [3]. Additionally, the current experimental searches are testing the Higgs couplings, an information that can be used to discriminate between the minimal SM Higgs doublet case and other extensions of the SM, with more complicated Higgs sector [4].

For a time, a possible solution a the hierarchy problem, suffered by the SM Higgs boson, motivated many interesting proposals for extending the SM. It is expected that current and future data coming from LHC will give us the opportunity to test these scenarios. Two-Higgs Doublet Model (2HDM) is one the simplest proposals for physics Beyond the Standard Model (BSM). 2HDM was initially studied in connection with the search for the origin of CP violation [5], later on it was found that the model could be connected with the realization of new theoretical ideas, such as supersymmetry [6], extra dimensions [7] and strongly interacting models [8],[9].

Possible realizations of the general 2HDM that have been considered in the literature are known as Type I, II and III, for a review see [10]. There are also other models called X, Y, Z, but in some sense they can be considered variations of the above models. Model I has a discrete symmetry Z_2 , which permits a possible dark matter candidate coming from the Z_2 -odd scalar doublet [11]. Within Type- I models, a single Higgs doublet gives mass to the up, down quarks and leptons. The type II model [12] assigns one doublet to each fermion type (this type also arises in the minimal SUSY extension of the SM [13]), which suffices to avoid Flavor Changing Neutral Currents (FCNC) mediated by the Higgs bosons[14]. Within the most general 2HDM, the mass matrix for each fermion type $f(= u, d, l)$ receives contributions from both Higgs doublets, which have vevs v_1 and v_2 after SSB, i.e.



$$M^f = \frac{1}{\sqrt{2}} \left(v_1 Y_1^f + v_2 Y_2^f \right), \quad (1)$$

where $Y_{1,2}^f$ denote the Yukawa matrices associated with each Higgs doublet. Inside this general model, the Yukawa matrices must have a structure that should reproduce the observed fermion masses and mixing angles and, simultaneously, the level of FCNC must satisfy current bounds [5, 15, 16]. One possibility to have FCNC at acceptable levels, is the assumption that the Yukawa matrices have a certain texture form, i.e. with zeroes in different elements.

In the past this general model was called as 2HDM of type III. However, this naming scheme has become confusing, in part because it has been used to denote a different type of model [17], but also because some specific cases have acquired a relevance of their own. One can include the so-called Minimal Flavor violating 2HDM (MFV) in the relevant sub-cases of the general 2HDM [18], which provides precisely the minimal level of FCNC consistent with data; MFV could be studied from a pure phenomenological point of view [19] or as arising from flavor symmetries [20]. Although the so-called 2HDM with Alignment does not contain flavor violation, it is another possibility one can use to obtain realistic models [21]. Thus, in order to clarify the notation and to single out the use of textures within the 2HDM, from now on we shall call the two-higgs doublet model with textures as 2HDM-Tx.

Early studies of the 2HDM [22] considered the specific texture with six-zeroes, but also the so-called cyclic model. There, it was identified a specific pattern of FCNC Higgs-fermion couplings, known nowadays as the Cheng-Sher ansatz, which can be written as $\frac{\sqrt{m_i m_j}}{v}$. The extension of the 2HDM-Tx with four-zero texture was presented in [23, 24]. The phenomenological consequences of these matrix textures (Hermitian 4-textures or non-hermitian 6-textures) were considered in [25], whilst further phenomenological studies were presented in [26, 27, 28]. In all these cases, it happens that FCNC bounds are satisfied with Higgs masses lighter than O(TeV).

Nevertheless, most of the above studies assumed that both Y_1^f and Y_2^f have the same texture form, a pattern that can be called “Paralell textures” namely:

$$Y_1 = \begin{pmatrix} 0 & a_1 & 0 \\ a_1^* & c_1 & b_1 \\ 0 & b_1^* & a_1 \end{pmatrix}, \quad Y_2 = \begin{pmatrix} 0 & a_2 & 0 \\ a_2^* & c_2 & b_2 \\ 0 & b_2^* & a_2 \end{pmatrix}. \quad (2)$$

However, Y_1^f and Y_2^f could have different forms, but in such a way that the resulting mass matrix has a specific type of texture [3]. In this paper we shall discuss different combinations of Yukawa matrices that result in a mass matrix of the four-zero texture form. We shall discuss first the different types of Yukawa matrices that result in a mass matrix with four-zero textures. Section 2 contains the Lagrangian for the 2HDM-III, written in terms of mass eigenstates. Low energy constraints are discussed in section 4, including $K - \bar{K}$ mixing, $B_s \rightarrow \mu^+ \mu^-$ and $\tau \rightarrow 3\mu$. We explored one particular case in section 5, while other cases can be found in [42]. Section 6 contains results and conclusions.

2. Classification of the Textures

Here, we shall assume that at most one element from each of the Yukawa matrices $Y_{1,2}^f$ contributes to each entry of the full mass matrix; namely:

Case 1:

$$Y_1 = \begin{pmatrix} 0 & d & 0 \\ d & c & b \\ 0 & b & 0 \end{pmatrix}, Y_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a \end{pmatrix};$$

Case 3:

$$Y_1 = \begin{pmatrix} 0 & d & 0 \\ d & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, Y_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & c & b \\ 0 & b & a \end{pmatrix};$$

Case 5:

$$Y_1 = \begin{pmatrix} 0 & d & 0 \\ d & c & 0 \\ 0 & 0 & 0 \end{pmatrix}, Y_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & b \\ 0 & b & a \end{pmatrix};$$

Case 7:

$$Y_1 = \begin{pmatrix} 0 & d & 0 \\ d & c & b \\ 0 & b & a \end{pmatrix}, Y_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a' \end{pmatrix}$$

Case 2:

$$Y_1 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & c & 0 \\ 0 & 0 & 0 \end{pmatrix}, Y_2 = \begin{pmatrix} 0 & d & 0 \\ d & 0 & b \\ 0 & b & a \end{pmatrix}$$

Case 4:

$$Y_1 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & b \\ 0 & b & 0 \end{pmatrix}, Y_2 = \begin{pmatrix} 0 & d & 0 \\ d & c & 0 \\ 0 & 0 & a \end{pmatrix}$$

Case 6:

$$Y_1 = \begin{pmatrix} 0 & d & 0 \\ d & 0 & b \\ 0 & b & 0 \end{pmatrix}, Y_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & c & 0 \\ 0 & 0 & a \end{pmatrix}$$

Then, the above combinations of Yukawa matrices produce a mass matrix with a 4-zero texture:

$$M = \begin{pmatrix} 0 & D & 0 \\ D^* & C & B \\ 0 & B^* & A \end{pmatrix}.$$

3. The Lagrangian for the model

The Yukawa Lagrangian in the 2HDM-III is given by,

$$\mathcal{L} = Y_1^u \bar{Q}_L^0 \tilde{\Phi}_1 u_R^0 + Y_2^u \bar{Q}_L^0 \tilde{\Phi}_2 u_R^0 + Y_1^d \bar{Q}_L^0 \Phi_1 d_R^0 + Y_2^d \bar{Q}_L^0 \Phi_2 d_R^0 + h.c.$$

where,

$$Q_L^0 = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad \bar{Q}_L^0 = (\bar{u}_L, \bar{d}_L), \quad \Phi_1 = \begin{pmatrix} \phi_1^\pm \\ \phi_1 \end{pmatrix}. \quad (3)$$

and

$$\Phi_2 = \begin{pmatrix} \phi_2^\pm \\ \phi_2 \end{pmatrix}, \quad \tilde{\Phi}_j = i\sigma_2 \Phi_j^* = \begin{pmatrix} \phi_j^* \\ -\phi_j^\mp \end{pmatrix}. \quad (4)$$

After introducing the mass eigenstates and diagonalizing the spinor fields ($d = Vd'$), the rotated Yukawa are $\tilde{Y}_i^d = V^\dagger Y_i^d V$ and $Y_1^d = Y_1^{d^\dagger}$, $Y_2^d = Y_2^{d^\dagger}$. A more compact notation to write the Higgs-fermion interactions, is given by:

$$\mathcal{L}_N^d = \left(g \frac{\sqrt{m_i m_j}}{\sqrt{2} M_W} \right) \bar{d}_i' \left[\left(\eta^{(1)} \right)_{ij} h^0 + \left(\eta^{(2)} \right)_{ij} H^0 + i \left(\eta^{(3)} \right)_{ij} A^0 \gamma^5 \right] d_j'$$

where the η factors are defined as follows $\eta_{ij}^{(n)} = \chi_{ij}^{(1)} f_n(\alpha, \beta) + \chi_{ij}^{(2)} g_n(\alpha, \beta)$ and we defined: $f_1(\alpha, \beta) = -\frac{\sin \alpha}{\cos \beta}$, $g_1(\alpha, \beta) = \frac{\cos \alpha}{\sin \beta}$, $f_2(\alpha, \beta) = \frac{\cos \alpha}{\cos \beta}$, $g_2(\alpha, \beta) = \frac{\sin \alpha}{\sin \beta}$, $f_3(\alpha, \beta) = -\tan \beta$, $g_3(\alpha, \beta) = \cot \beta$.

4. Constraints from Low Energy

In order to find the allowed regions of parameter space we need to consider all relevant low energy and collider constraints. For the low energy constraints, this includes:

4.1. K - K Mixing

The Feynman diagram is,



the effective Hamiltonian is given by,

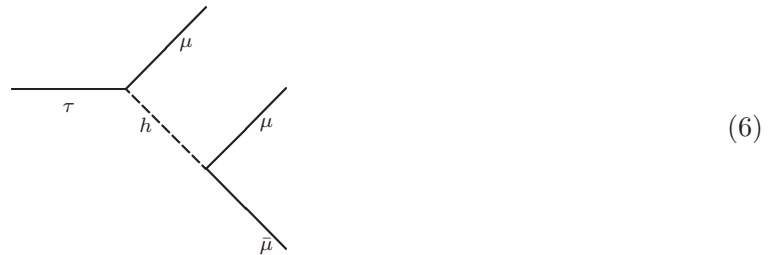
$$H_{eff}^{\Delta S=2} = \frac{G_F^2 M_W^2}{16\pi^2} \sum_i C_i Q_i.$$

with,

$$M_{12}^K = \frac{4}{3} F_K^2 \eta_2 \bar{B}_K(m_d m_s) \frac{1}{v_1^2} \sum_{a=1}^3 \left[\bar{P}_2^{LR} \frac{U_{2a} U_{1a}}{m_{\phi_a}^2} + \bar{P}_1^{SLL} \left(\frac{U_{2a}^2}{m_{\phi_a}^2} + \frac{U_{1a}^2}{m_{\phi_a}^2} \right) \right]$$

4.2. Decay $\tau \rightarrow \mu\mu\mu$

The Feynman diagram is



where,

$$\Gamma(\tau^- \rightarrow \mu^- \mu^+ \mu^-) = \frac{m_\tau V_{22}^2 V_{ij}^2}{192\pi^3 r_\phi^2 (R_\phi^2 + r_\phi^2)} \left(1 - 12r_\mu^3 - 36r_\mu^{1/2} + 4r_\mu \right) \quad (7)$$

with,

$$V_{ij}^2 = \left(\frac{1}{2v} \right)^2 \left(-\frac{(y_1)_{ij} \sin(n - \beta)}{\cos \beta} + \frac{(y_2)_{ij} \cos(n - \beta)}{\sin \beta} \right)^2$$

4.3. Decay $B_s \rightarrow \mu^+ \mu^-$

The Feynman diagram representing is,



where,

$$\text{Br}(B_s \rightarrow \mu^+ \mu^-) = \frac{G_F^2 \alpha_{em}^2}{16\pi^3} M_B \tau_B |V_{ts} V_{tb}^*|^2 \sqrt{1 - \frac{4m_l^2}{M_B^2}} \times \left[|F_s^d|^2 \left(1 - \frac{4m_l^2}{M_B^2}\right) + |F_p^d + 2m_l F_A^d|^2 \right]$$

the Wilson coefficients are,

$$C_p = \frac{2\pi \sqrt{m_2^q m_3^q} m_2^l}{G_F V_{tb}^* V_{ts} \alpha_{em} M_b v^2} \left[\frac{1}{4M_{A^0}^2} \prod_{r=q,l} \left((\chi_r^{(2)})_{23} g_3(\alpha, \beta) + (\chi_r^{(1)})_{23} f_3(\alpha, \beta) \right) \right] \quad (9)$$

and

$$C_s = \frac{2\pi \sqrt{m_2^q m_3^q} m_2^l}{G_F V_{tb}^* V_{ts} \alpha_{em} M_b v^2} \left[\frac{1}{4M_{H^0}^2} \prod_{r=q,l} \left((\chi_r^{(2)})_{23} g_2(\alpha, \beta) + (\chi_r^{(1)})_{23} f_2(\alpha, \beta) \right) + \frac{1}{4M_{h^0}^2} \prod_{r=q,l} \left((\chi_r^{(2)})_{23} g_1(\alpha, \beta) + (\chi_r^{(1)})_{23} f_1(\alpha, \beta) \right) \right]$$

5. A case Exploring

For illustration we shall display here some of the elements of the χ factors for case 5, the other cases can find in [42]. In general, each component has a complicated expression relating the masses of the particles and our parameter γ . For instance, the 12-Yukawa elements are given by,

$$\left(\chi_1 \right)_{12} = \sqrt{\frac{1}{1 - \frac{m_2 \gamma}{m_3}}} \left(1 - \frac{|m_1|}{m_2} \right) - \left(\frac{m_1}{m_2} + \gamma + 1 \right) \quad \left(\chi_2 \right)_{12} = 2\gamma + \left(\frac{m_2}{m_3} \gamma - 1 \right) \gamma$$

We obtain the figure 1

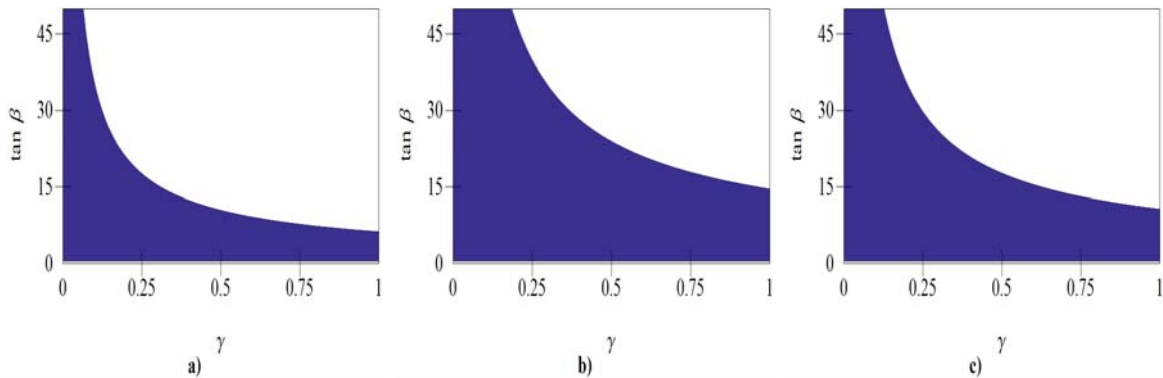


Figure 1. Allowed regions (blue) in the plane $\tan \beta - \gamma$ for case 6, where a) $\alpha - \beta = 0$, b) $\alpha - \beta = \pi/2$ and c) $\alpha - \beta = \pi/3$.

Figure 1 shows the allowed regions (blue) in the plane $\tan\beta - \gamma$ for case 5, where a) $\alpha - \beta = 0$, b) $\alpha - \beta = \pi/2$ and c) $\alpha - \beta = \pi/3$. Thus, we find that the Cheng-Sher ansatz still holds, up to corrections, for case 5 of complementary Yukawa matrices; and this remains valid for all the cases we are considering here.

6. Results and Conclusions

We predict that the LFV Higgs decays ($h \rightarrow \tau\mu$), as well as the rare top decay $t \rightarrow c + h$, could reach significant levels, which may be searched at the coming phases of LHC.

Branching ratios for Case 5 where: $\alpha - \beta = \frac{\pi}{3}$ and the first row corresponds to $\tan\beta = 10$, the second row $\tan\beta = 15$ and the third row $\tan\beta = 20$. The second part of the table has an analogous arrangement of $\tan\beta$.

	$\gamma = 0.1$	$\gamma = 0.2$	$\gamma = 0.3$
$\text{Br}(h \rightarrow \tau\mu) \times 10^5$	1.5	—	—
	—	4.0	—
	—	4.2	7.2
$\text{Br}(t \rightarrow ch) \times 10^5$	1.4	—	—
	—	8.1	—
	—	1.5	2.6

Acknowledgments

We also acknowledge support from CONACYT-SNI (Mexico).

References

- [1] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716**, 1 (2012) [arXiv:1207.7214 [hep-ex]].
- [2] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716**, 30 (2012) [arXiv:1207.7235 [hep-ex]].
- [3] J. F. Gunion, H. E. Haber, G. L. Kane and S. Dawson, Front. Phys. **80**, 1 (2000).
- [4] J. L. Diaz-Cruz and D. A. Lopez-Falcon, Phys. Lett. B **568**, 245 (2003) [hep-ph/0304212].
- [5] N. G. Deshpande and E. Ma, Phys. Rev. D **18**, 2574 (1978).
- [6] S. P. Martin, In *Kane, G.L. (ed.): Perspectives on supersymmetry II* 1-153 [hep-ph/9709356].
- [7] M. Quiros, hep-ph/0606153.
- [8] A. Pomarol, CERN Yellow Report CERN-2012-001, 115-151 [arXiv:1202.1391 [hep-ph]].
- [9] A. Aranda, J. L. Diaz-Cruz, J. Hernandez-Sanchez and R. Noriega-Papaqui, Phys. Lett. B **658**, 57 (2007) [arXiv:0708.3821 [hep-ph]].
- [10] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher and J. P. Silva, Phys. Rept. **516**, 1 (2012) [arXiv:1106.0034 [hep-ph]].
- [11] E. Ma, Mod. Phys. Lett. A **21**, 1777 (2006) [hep-ph/0605180];
R. Barbieri, L. J. Hall and V. S. Rychkov, Phys. Rev. D **74**, 015007 (2006) [hep-ph/0603188];
L. Lopez Honorez, E. Nezri, J. F. Oliver and M. H. G. Tytgat, JCAP **0702**, 028 (2007) [hep-ph/0612275];
I. F. Ginzburg, K. A. Kanishev, M. Krawczyk and D. Sokolowska, Phys. Rev. D **82**, 123533 (2010) [arXiv:1009.4593 [hep-ph]].
- [12] I. F. Ginzburg and M. Krawczyk, Phys. Rev. D **72**, 115013 (2005) [hep-ph/0408011].
- [13] J. F. Gunion and H. E. Haber, Nucl. Phys. B **307**, 445 (1988) [Erratum-ibid. B **402**, 569 (1993)].
- [14] S. L. Glashow and S. Weinberg, Phys. Rev. D **15**, 1958 (1977).
- [15] G. C. Branco, D. Emmanuel-Costa and R. Gonzalez Felipe, Phys. Lett. B **477**, 147 (2000) [hep-ph/9911418].
- [16] L. J. Hall and S. Weinberg, Phys. Rev. D **48**, 979 (1993) [hep-ph/9303241].
- [17] W. Altmannshofer, S. Gori and G. D. Kribs, Phys. Rev. D **86**, 115009 (2012) [arXiv:1210.2465 [hep-ph]].
- [18] A. J. Buras, M. V. Carlucci, S. Gori and G. Isidori, JHEP **1010**, 009 (2010) [arXiv:1005.5310 [hep-ph]].
- [19] G. D'Ambrosio, G. F. Giudice, G. Isidori and A. Strumia, Nucl. Phys. B **645**, 155 (2002) [hep-ph/0207036].
- [20] A. Aranda, C. Bonilla and J. L. Diaz-Cruz, Phys. Lett. B **717**, 248 (2012) [arXiv:1204.5558 [hep-ph]].
- [21] A. Pich and P. Tuzon, Phys. Rev. D **80**, 091702 (2009) [arXiv:0908.1554 [hep-ph]].
- [22] T. P. Cheng and M. Sher, Phys. Rev. D **35**, 3484 (1987).
- [23] Y. -F. Zhou, J. Phys. G **30**, 783 (2004) [hep-ph/0307240].

- [24] J. L. Diaz-Cruz, R. Noriega-Papaqui and A. Rosado, Phys. Rev. D **69**, 095002 (2004) [hep-ph/0401194].
- [25] J. L. Diaz-Cruz, R. Noriega-Papaqui and A. Rosado, Phys. Rev. D **71**, 015014 (2005) [hep-ph/0410391].
- [26] Y. -L. Wu and Y. -F. Zhou, Eur. Phys. J. C **36**, 89 (2004) [hep-ph/0403252].
- [27] W. -j. Li, Y. -d. Yang and X. -d. Zhang, Phys. Rev. D **73**, 073005 (2006) [hep-ph/0511273].
- [28] A. E. Carcamo Hernandez, R. Martinez and J. A. Rodriguez, Eur. Phys. J. C **50**, 935 (2007) [hep-ph/0606190].
- [29] M. Gomez-Bock and R. Noriega-Papaqui, J. Phys. G **32**, 761 (2006) [hep-ph/0509353].
- [30] A. Denner, S. Heinemeyer, I. Puljak, D. Rebuszi and M. Spira, Eur. Phys. J. C **71**, 1753 (2011) [arXiv:1107.5909 [hep-ph]].
- [31] A. Pilaftsis, Phys. Lett. B **285**, 68 (1992).
- [32] J. L. Diaz-Cruz and J. J. Toscano, Phys. Rev. D **62**, 116005 (2000) [hep-ph/9910233].
- [33] T. Han and D. Marfatia, Phys. Rev. Lett. **86**, 1442 (2001) [hep-ph/0008141];
K. A. Assamagan, A. Deandrea and P. -A. Delsart, Phys. Rev. D **67**, 035001 (2003) [hep-ph/0207302];
D. McKeen, M. Pospelov and A. Ritz, Phys. Rev. D **86**, 113004 (2012) [arXiv:1208.4597 [hep-ph]].
- [34] J. L. Diaz-Cruz, JHEP **0305**, 036 (2003) [hep-ph/0207030];
A. Brignole and A. Rossi, Nucl. Phys. B **701**, 3 (2004) [hep-ph/0404211].
E. Arganda, A. M. Curiel, M. J. Herrero and D. Temes, Phys. Rev. D **71**, 035011 (2005) [hep-ph/0407302].
S. Kanemura, T. Ota and K. Tsumura, Phys. Rev. D **73**, 016006 (2006) [hep-ph/0505191].
- [35] J. L. Diaz-Cruz, D. K. Ghosh and S. Moretti, Phys. Lett. B **679**, 376 (2009) [arXiv:0809.5158 [hep-ph]].
M. Arana-Catania, E. Arganda and M. J. Herrero, arXiv:1304.3371 [hep-ph];
A. Arhrib, Y. Cheng and O. C. W. Kong, Phys. Rev. D **87**, 015025 (2013) [arXiv:1210.8241 [hep-ph]];
R. Harnik, J. Kopp and J. Zupan, JHEP **1303**, 026 (2013) [arXiv:1209.1397 [hep-ph]].
A. Goudelis, O. Lebedev and J. -h. Park, Phys. Lett. B **707**, 369 (2012) [arXiv:1111.1715 [hep-ph]].
- [36] G. Eilam, J. L. Hewett and A. Soni, Phys. Rev. D **44**, 1473 (1991) [Erratum-ibid. D **59**, 039901 (1999)].
- [37] B. Mele, S. Petrarca and A. Soddu, Phys. Lett. B **435**, 401 (1998) [hep-ph/9805498].
- [38] S. Bejar, J. Guasch and J. Sola, hep-ph/0101294.
- [39] B. Mele, hep-ph/0003064.
- [40] J. L. Diaz-Cruz, H. -J. He and C. P. Yuan, Phys. Lett. B **530**, 179 (2002) [hep-ph/0103178].
- [41] J. A. Aguilar-Saavedra and G. C. Branco, Phys. Lett. B **495**, 347 (2000) [hep-ph/0004190].
- [42] M. Arroyo, J. L. Diaz-Cruz, E. Diaz and J. A. Orduz-Ducuara, arXiv:1306.2343 [hep-ph].