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Signal of $h \rightarrow \mu\tau, \tau\tau$ in $v2HDM\otimes S_3$

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ABSTRACT

Nowadays in particle physics, the exploration of the flavor physics through the Higgs boson phenomenology is one of the main goals in the field. In particular we are interested in the Lepton Flavour Violation (LFV) processes. In this work, we explore the processes $h \rightarrow \mu\tau, \tau\tau$ in the theoretical framework of a flavored extension of the Standard Model, which has two Higgs fields and the horizontal permutation symmetry S_3 imposed in the Yukawa sector, this extension is called $v2HDM\otimes S_3$.We obtain the couplings $\phi\mu\tau, \tau\tau$ as well as $Br(h \rightarrow \mu\tau)$ in function of the model parameters in function of the model parameters, which are constricted by means the experimental results of $\phi_{SM} \rightarrow \mu\tau$ reported in the literature.

1. Introduction

Since the discovery of Higgs particle reported in 2012 by the ATLAS [1] and CMS [2] experiments at LHC, and the subsequent efforts made by LHC to produce findings that confirm the understanding of the Higgs field and particle. To CERN confirmation in 2017 that all measurements still agree with the predictions of the Standard Model (SM). It is easy conclude that SM is highly successful in terms of its phenomenological predictions. However, from a theoretical point of view, the SM still an incomplete theory because in its original formulation it is unable to predict the masses of fermions (leptons and quarks), neither explain the need of the replication of fermion families. Now, from the experimental point of view, the biggest challenge that has been faced the SM is trying to explain the experimental data on neutrino oscillations, because to have this phenomenon it is necessary that the neutrinos are massive particles, but in theoretical framework of the SM the neutrinos are massless particles. In general, if neutrino masses are non-degenerate, it is practically unlikely that exist a basis in which the eigenstates of flavour and mass are the same. A consequence of above is that we have the phenomenon of flavour mixing in leptonic sector, which is completely analogous to the flavour mixing in the quark sector. In other words, the leptonic flavour mixing matrix emerge from the mismatch between diagonalization of the mass matrices of neutrinos and charged leptons. Also, if there are irremovable phase factors in the Yukawa interactions, the CP violation will naturally appear both in the quark and lepton sector.

Based on the above, the current work on model building, which are extensions of the SM, it has focused on neutrino physics [3]. Specifically, we are seeking answers to unsolved questions on neutrino mass scale, if neutrinos are Dirac or Majorana particles, and the existence of new sources of Charge-Parity (CP) violation in leptonic sector. Many of the models beyond the SM are inspired on the experimental results concerning to neutrino oscillation experiments such as KamLAND reactor neutrinos [4,5]. In short-baseline (SBL) reactor experiments RENO [6,7], Double CHOOZ [8] and Daya Bay [9]. The masses generation and flavour are two concepts strongly intertwined. In order to know the flavour dynamics in models beyond the SM, it is necessary to understand first the masses generation and flavour mechanism in the context of the standard theory. In the SM the Yukawa matrices are of great interest because the values of its elements define the values of fermionic masses, as well as its phase factors are related with the CP violation through the

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flavour mixing matrix. The simplest renormalizable extension of the SM, consistent with neutrino oscillation experiments, is building by the addition of three right-handed neutrinos with masses smaller than the electroweak scale [10]. However, the value of the neutrino magnetic moment obtained in this minimal extension of the SM, is several orders of magnitude smaller that the best upper limit for the neutrino magnetic moment $\mu_v < 2.9 \times 10^{-11} \mu_B$ obtained by the GEMMA experiment at 90% CL [11]. We can improve this value if we increase the number of Higgs particles in the model.

The next renormalizable extension of the SM, consistent with neutrino oscillation experiments and GEMMA experiment, it is builded by the addition of three right-handed neutrinos and one Higgs boson to the matter contain of the SM. The multi-Higgs models allow the presence of flavor-changing neutral current (FCNCs) at tree level if all Higgs are coupled to all fermions. In particular we will study the flavour dynamics through the Yukawa matrices in the framework of the 2HDM-III [12]. Other models like the 2HDM-III allow the FCNC [13,14]. The 2HDM-III predicts three neutral states and a pair of charged states: $H^0_{1,2,3}$ and $H^{\pm}_{1,2}$ [15]. In the theoretical framework of 2HDM-III, the FCNCs are kept under control by imposing some texture zeros in the Yukawa matrices, which reproduce the observed fermion masses and mixing angles [16]. Also, this shape with texture zeros allows us to obtain the so-called Cheng-Sher ansatz for flavour mixing couplings, where couplings are proportional to geometrical mean of the involved fermion masses [17,12]. In this work we propose an extension to the Standard Model in which we consider a type-III two-Higgs-doublet model (2HDM) plus massive neutrinos and the horizontal flavor symmetry S_3. We obtain the couplings $\phi_{SM} \to \mu\tau$ as well as $Br(h \to \mu\tau)$ in function of the model parameters in function of the model parameters, which are constricted by means the experimental results of $\phi_{SM} \to \mu\tau$ reported in the literature.

2. The Model

In order to describe the dynamics of the flavour mixings in the quark and lepton sectors, neutrino masses generation, as well as the Higgs phenomenology, we study an extension of Standard Model in which we have two Higgs bosons and massive left-handed neutrinos. These last are considered as Majorana particles and acquire its small masses through of type-I seesaw mechanism. Additionally, in this theoretical framework, we consider that Hermitian matrix with two texture zeros class I [18], which is considered as a universal shape for all Dirac fermions mass matrices, is obtained by means of explicit breaking of S_3 flavour symmetry, $S_{3L} \otimes S_{3R} \supset S_3^{diag} \supset S_2^{diag}$ according to following breaking chain [19]. The above extension is called as $v2HDM \otimes S_3$ and have the same gauge group that the Standard Model, which is $G_{SM} = SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$. In this context, the right-handed neutrinos, as well as the two Higgs bosons, transform as singlets under the action of S_3 flavour symmetry. For this model the Yukawa Lagrangian for quarks and charged lepton in the weak bases has the form [19]:

$$\mathcal{L}_Y^w = \sum_{k=1}^{2} \left(Y_k^{w,u} \bar{Q} \tilde{\Phi}_k u_R + Y_k^{w,d} \bar{Q} \Phi_k d_R + Y_k^{w,l} \bar{L} \Phi_k l_R \right) + H.c. \tag{1}$$

Here, the $Y_k^{w,f}$ are the Yukawa matrices, $L = (\nu_l, l)_L^T$ and $Q = (u,d)_L^T$ are the left-handed doublet of $SU(2)$, while u_R, d_R and l_R are right-handed singlets of the same group. The indices *u, d, l* and *v*, represent the up-quaks, down-quarks, charged leptons and neutrinos, respectively. The $\Phi_k = (\phi_k^+, \phi_k^0)^T$ denotes the Higgs doublets of SU(2), with $\tilde{\Phi}_k = i\sigma_2 \Phi_k^*$. The active neutrinos acquire their small mass through type-I seesaw mechanism. So, the hybrid mass term that involves both Dirac and Majorana neutrinos and from which we can obtain the type-I seesaw mechanism, $M_L = M_D M_R^{-1} M_D^T$, has the form:

$$\mathcal{L}^{D+M} = -\bar{\nu}_L M_D N_R - \frac{1}{2} \overline{(N_R)^c} M_R N_R + H.c. \tag{2}$$

In this expression, M_D is the Dirac neutrino mass matrix and M_R is the right-handed neutrinos mass matrix, while $\nu_L = (\nu_{eL}, \nu_{\mu L}, \nu_{\tau L})^T$ are the three left-handed neutrinos and $N_R = (N_{1R}, N_{2R}, N_{3R})$ are the three right-handed neutrinos. These last are singlets under the action of SU(2) group, therefore only the left-handed fields take part in the electroweak interactions. The scalar potential before the spontaneous symmetry breaking for this model $v2HDM \otimes S_3$ has the form:

$$\begin{aligned} V(\Phi) = {} & m_{11}^2 \Phi_1 \Phi_1 + m_{22}^2 \Phi_1 \Phi_2 - m_{12}^2 \left(\Phi_1 \Phi_2 + \Phi_1 \Phi_1 \right) \\ & + \frac{\lambda_1}{2} \left(\Phi_1 \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\Phi_1 \Phi_2 \right)^2 + \lambda_3 \Phi_1 \Phi_1 \Phi_2 \Phi_2 \\ & + \lambda_4 \Phi_1 \Phi_2 \Phi_1 \Phi_1 + \frac{\lambda_5}{2} \left[\left(\Phi_1 \Phi_2 \right)^2 + \left(\Phi_1 \Phi_1 \right)^2 \right], \end{aligned} \tag{3}$$

where m_2^{11}, m_2^{22}, m_2^{12}, and $\lambda_{1,2,3,4}$ are real parameters, while λ_5 is complex. This Higgs potential preserves CP symmetry, whereby the CP violation in comes from the Yukawa matrices.

3. The Fermion Mass Matrices

After the spontaneous symmetry breaking, and in the flavour adapted basis the Dirac fermion mass matrix can be written as [19]:

$$M_j^s = \frac{v\cos\beta}{\sqrt{2}}\left(Y_1^{s,j} + \tan\beta Y_2^{s,j}\right), \tag{4}$$

where $\tan\beta = v_2 / v_1$, $v^2 = v_1^2 + v_2^2 = (246.22 \text{ GeV})^2$, $v_{1,2}$ are the vacuum expectation values (vev) associated with each of the Higgs doublets, and the $Y^{s,j}{}_{1,2}$ are the Yukawa matrices. These last matrices as well as the left-handed neutrinos mass matrices, in the flavour adapted basis have a shape with two texture zeros class-I [18]. Therefore, we obtain that the elements of the Yukawa matrices in the mass basis obey the so-called Cheng and Sher relation [19]

$$\left(\tilde{Y}_k^j\right)_{rt} = \frac{\sqrt{m_{jr}m_{jt}}}{v}\left(\tilde{\chi}_k^j\right)_{rt} \tag{5}$$

where r, t = 1, 2, 3 and $(\tilde{\chi}_k^j)_{rt}$ are dimensionless complex functions of the Yukawa matrix parameters and the mass matrix parameter δ_j which is associated with the breaking of flavour symmetry.

4. The lepton-Higgs couplings

After the electroweak spontaneous symmetry breaking, the two Higgs field takes are

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{h_1 + v_1 + ig_1}{\sqrt{2}} \end{pmatrix} \text{ and } \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{h_2 + v_2 + ig_2}{\sqrt{2}} \end{pmatrix}. \tag{6}$$

The all parameters into the above expression are real. The Higgs mass eigenstates (physical states) are obtained by means the transformations:

$$\begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix}\begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix} = \begin{pmatrix} G^+ \\ H^+ \end{pmatrix}, \tag{7}$$

$$\begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} H^0 \\ h^0 \end{pmatrix}, \tag{8}$$

$$\begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix}\begin{pmatrix} g_1 \\ g_2 \end{pmatrix} = \begin{pmatrix} G^0 \\ A^0 \end{pmatrix}, \tag{9}$$

where G^0 and $G+$ are Goldstone bosons, H^0 y h^0 are neutral Higgs fields, $H+$ is the charged Higgs field, while A^0 is the pseudoscalar Higgs Boson. In this work we only consider the decays of neutral Higgs bosons, thus with help of Equations (1) and (5) we can find that lepton-Higgs couplings in $v2HDM \otimes S_3$ have the form:

$$\begin{aligned} L_Y^1 = {} & \frac{g}{2}\bar{l}_i\left[\left(\frac{m_{l_i}}{m_w}\right)\frac{\cos\alpha}{\cos\beta}\delta_{ij} + \frac{\sin(\alpha-\beta)}{\sqrt{2}\cos\beta}\frac{\sqrt{m_{l_i}m_{l_j}}}{m_w}\tilde{\chi}_{ij}^l\right]l_j H^0 \\ & + \frac{g}{2}\bar{l}_i\left[-\left(\frac{m_{l_i}}{m_w}\right)\frac{\sin\alpha}{\cos\beta}\delta_{ij} + \frac{\cos(\alpha-\beta)}{\sqrt{2}\cos\beta}\frac{\sqrt{m_{l_i}m_{l_j}}}{m_w}\tilde{\chi}_{ij}^l\right]l_j h^0 \\ & + \frac{ig}{2}\bar{l}_i\left[-\left(\frac{m_{l_i}}{m_w}\right)\tan\beta\delta_{ij} + \frac{1}{\sqrt{2}\cos\beta}\frac{\sqrt{m_{l_i}m_{l_j}}}{m_w}\tilde{\chi}_{ij}^l\right]\gamma^5 l_j h^0. \end{aligned} \tag{10}$$

Now, form the results of a likelihood test reported in Ref. [19], we compute the other values of the coefficients $\tilde{\chi}_{ij}^l$ for charged leptons. If we consider an aliment between the phase factor of the Yukawa and mass matrices in Equation (4), we obtain that $\tilde{\chi}_{ij}^l$ in Equation (5) are real parameters. So, we have

$$\tilde{\chi}_2^l = \begin{pmatrix} 5.78 \leftrightarrow 18 & 0 & -0.1 \leftrightarrow 0.1 \\ 0 & 4.7 \leftrightarrow 15.72 & -0.06 \leftrightarrow 0.3 \\ -0.1 \leftrightarrow 0.1 & -0.5 \leftrightarrow 0.33 & 0.02 \leftrightarrow 1 \end{pmatrix}, \tag{11}$$

$$\tilde{\chi}_1^l = \begin{pmatrix} -17.81 \leftrightarrow -2.05 & 0 & -0.1 \leftrightarrow 0.1 \\ 0 & -15.87 \leftrightarrow 1.03 & -0.5 \leftrightarrow 0.33 \\ -0.1 \leftrightarrow 0.1 & -0.5 \leftrightarrow 0.33 & 0.34 \leftrightarrow 0.9 \end{pmatrix}. \tag{12}$$

Recent data on Higgs phenomenology reported by CMS and ATLAS experiments at the LHC can be employed to compute the Higgs couplings in $v2HDM \otimes S_3$. Here we present the predictions for the LFV Higgs decay as part of the test of $v2HDM \otimes S_3$ using the following exprimental data $Br(h \to \mu\tau) = (7.7 \mp 6.2) \times 10^{-3}$ $Br(h \to \mu\tau)$ [20]. The theoretical expression that we consider for is:

$$Br(h \to \tau\mu) \approx \frac{\Gamma(h \to \tau\mu)}{\Gamma(h \to \tau\tau)} Br_{SM}(h \to \tau\tau), \tag{13}$$

where $Br_{SM}(h \to \tau\tau) = 6.27 \times 10^{-2}$ is the branching ratio for in the SM context. So, in the theoretical framework of $v2HDM \otimes S_3$, $h \to \mu\tau$ with the values given in Equations. (11) and (12) and using the current experimental data for the Higgs boson, charged lepton and W boson masses, we obtain that

$$Br(h \to \mu\tau) \approx 1.6 \times 10^{-3}. \tag{14}$$

This value is in good agreement with the experimental data.

4. Conclusions

In the theoretical framework of Two Higgs Doublet Model type III plus massive neutrinos and a horizontal flavour symmetry S_3 ($\nu 2HDM \otimes S_3$), we can have a unified treatment for all fermion mass matrices in the model. The active neutrinos are considered as Majorana particles and acquire its small masses through of type-I seesaw mechanism. The parameter space exploration is done by means of likelihood test χ^2, where we have a good agreement with experimental data for the masses and flavour mixing for leptons. This allowed us to find the allowed values of the $\tilde{\chi}_{ij}^{l}$ parameters. Finally, it is observed that the mixing angle as function of $\delta\nu$ and δ_l are in very good agreement with experimental data. Here we present a prediction for the LFV Higgs decay $Br(h \rightarrow \mu\tau) \approx 1.6 \times 10^{-3}$, which is in good agreement with the experimental data.

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