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Higgs decays with the lepton flavor violation

O.M. Boyarkin,* G.G. Boyarkina, and V.V. Makhnatch
Belorussian State University
Dolgobrodskaya Street 23,
Minsk, 220070, Belarus

Within the left-right symmetric model the decays of the analog of the standard model Higgs boson

$$S_1 \to \mu^+ + \tau^-, \qquad S_1 \to \mu^- + \tau^+$$

have been investigated. Consideration has been constrained by the no mass degeneration (NMD) case (heavy neutrino masses are hierarchical while the light-heavy neutrino mixing angles are equal to zero). Calculations have shown that the theoretical value of the Higgs decays width obtained within the NMD case is three order of magnitude smaller than the experimental value. By this means, the NMD scenario should be eliminated from further viewing.

In the LRM the following scenarios are also possible: (i) the light-heavy neutrino mixing angles are arbitrary but equal each other whereas the heavy neutrino masses are quasi-degenerate; (ii) the light-heavy neutrino mixing angles are equal to each other and the heavy-heavy neutrino mixing is maximal while the heavy neutrino masses are hierarchical. Therefore, the Higgs decays with the lepton flavor violation should be examined from the point of view of these scenarios.

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1. Introduction

After the discovery of the Higgs boson, the obvious next step is to elucidate if it is an elemental or a composite particle and if there is physics beyond the Standard Model (SM) that could be hidden in the Higgs sector. Expectation for departure from SM behavior are based on the following facts. The SM has not found satisfactory explanation of baryon asymmetry of the Universe, neutrino mass smallness, the value of the muon anomalous magnetic moment, hierarchy problem and so on. Moreover, among the SM particles there are no candidates on the role of weakly interacting massive particles which enter into the non-baryonic cold dark matter.

It is clear that the future ambitious experimental program, both at the Large Hadron Collider (LHC) and future linear colliders, which will determine all the Higgs couplings with higher precision than at present, will play a central role. A particularly interesting possible departure from the Higgs standard properties will be Higgs decays going with leptonic flavor violation (LFV). These decays do not take place even in the minimally extended SM (SM with massive neutrinos), since they are unobservably small by virtue of

*E-mail: oboyarkin@tut.by

the fact that the amplitudes are controlled by the tiny neutrino masses. However, recently the CMS and ATLAS experiments have hinted at the existence of a flavor violating decay of the Higgs boson $H \to \mu\tau$ (this process includes both $H \to \mu^+\tau^-$ and $H \to \mu^-\tau^+$). The combined branching ratio for this decay is found to be [1]

$$BR(H \to \mu\tau) = 0.82^{+0.33}_{-0.32}\%. \tag{1}$$

It is clear that observation of this decay is a smoking gun signal for physics beyond the SM. The Higgs decays with the LFV have been studied for a long time in the literature within various SM extensions (for recent works see, for examples, [2],[3]).

The models predicting the Higgs decays with LFV could be classified into two categories. Among the first are the SM extensions in which existence of these decays is provided by introducing the Higgs boson LFV couplings by hand. This can be achieved by an extension of the scalar sector with some additional discrete symmetries (see, for example, Ref. [4]). It is clear that all these SM extensions necessarily introduce a number of new arbitrary parameters. Notice that in the models of this kind the Higgs decay (1) proves to be allowed even at the tree approximation.

However, the more elegant explanation of the Higgs decays with LFV gives models falling into the second category in which the flavor mixing among particles of different generations is embedded by the construction. Example is provided by the supersymmetric models in which the flavor mixing among the three generations of the charged sleptons and/or sneutrinos takes place. This mixing produces via their contributions the Higgs decay channel (1) at the one-loop level [5],[6]. Another example is the left-right symmetric model (LRM) (see, for review, the book [7]).

In this work we shall investigate the Higgs decay (1) within the LRM. The organization of the paper goes as follows: section 2 contains a summary of the LRM. In sections 3 we fulfill our calculations and analyze the results obtained. Section 5 includes our conclusion.

2. The left-right-symmetric model

In the LRM quarks and leptons enter into the left- and right-handed doublets

$$\left.\begin{array}{ll} Q^a_L(\frac{1}{2},0,\frac{1}{3}) = \begin{pmatrix} u^a_L \\ d^a_L \end{pmatrix}, & Q^a_R(0,\frac{1}{2},\frac{1}{3}) = \begin{pmatrix} u^a_R \\ d^a_R \end{pmatrix}, \\ \Psi^a_L(\frac{1}{2},0,-1) = \begin{pmatrix} \nu_{aL} \\ l_{\alpha L} \end{pmatrix}, & \Psi^a_R(0,\frac{1}{2},-1) = \begin{pmatrix} N_{aR} \\ l_{aR} \end{pmatrix}, \end{array}\right\} \tag{2}$$

where $a = 1,2,3$, in brackets the values of S^W_L, S^W_R and $B-L$ are given, S^W_L (S^W_R) is the weak left (right) isospin while B and L are the baryon and lepton numbers.

The Higgs sector structure of the LRM determines the neutrino nature. The mandatory element of the Higgs sector is the bi-doublet $\Phi(1/2,1/2,0)$

$$\Phi = \begin{pmatrix} \Phi^0_1 & \Phi^+_2 \\ \Phi^-_1 & \Phi^0_2 \end{pmatrix}. \tag{3}$$

Its nonequal VEVs of the electrically neutral components bring into existence the masses of quarks and leptons. For the neutrino to be a Majorana particle, the Higgs sector must include two triplets $\Delta_L(1,0,2)$, $\Delta_R(0,1,2)$

$$(\boldsymbol{\sigma}\cdot\boldsymbol{\Delta}_L)=\begin{pmatrix}\delta_L^+/\sqrt{2} & \delta_L^{++}\\ \delta_L^0 & -\delta_L^+/\sqrt{2}\end{pmatrix},\qquad (\boldsymbol{\sigma}\cdot\boldsymbol{\Delta}_R)=\begin{pmatrix}\delta_R^+/\sqrt{2} & \delta_R^{++}\\ \delta_R^0 & -\delta_R^+/\sqrt{2}\end{pmatrix}. \tag{4}$$

If the Higgs sector consists of two doublets $\chi_L(1/2,0,1)$, $\chi_R(0,1/2,1)$ and one bidoublet $\Phi(1/2,1/2,0)$, then the neutrino represents a Dirac particle. In what follows we shall consider the LRM version with Majorana neutrinos.

The masses of fermions and their interactions with the gauge boson are controlled by the Yukawa Lagrangian. Its expression for the lepton sector is as follows

$$\mathcal{L}_Y=-\sum_{a,b}\{h_{ab}\overline{\Psi}_{aL}\Phi\Psi_{bR}+h'_{ab}\overline{\Psi}_{aL}\tilde{\Phi}\Psi_{b,R}+$$

$$if_{ab}[\Psi_{aL}^T C\tau_2(\vec{\tau}\cdot\vec{\Delta}_L)\Psi_{bL}+(L\to R)]+\text{h.c.}\}, \tag{5}$$

where C is a charge conjugation matrix, $\tilde{\Phi}=\tau_2\Phi^*\tau_2$, $a,b=e,\mu,\tau$, h_{ab}, h'_{ab} and $f_{ab}=f_{ba}$ are bidoublet and triplet Yukawa couplings, respectively.

The spontaneous symmetry breaking (SSB) according to the chain

$$SU(2)_L\times SU(2)_R\times U(1)_{B-L}\to SU(2)_L\times U(1)_Y\to U(1)_Q$$

is realized for the following choice of the vacuum expectation values (VEVs):

$$<\delta_{L,R}^0>=\frac{v_{L,R}}{\sqrt{2}},\qquad <\Phi_1^0>=k_1,\qquad <\Phi_2^0>=k_2. \tag{6}$$

To achieve agreement with experimental data, it is necessary to ensure fulfillment of the conditions

$$v_L<<\max(k_1,k_2)<<v_R. \tag{7}$$

The structure of the Higgs potential V_H is the essential element of the theory because it defines the physical states basis of Higgs bosons, Higgs masses, and interactions between Higgses. We shall use the most general form of V_H proposed in Ref. [8]. After the SSB we are left with 14 physical Higgs bosons: four doubly-charged scalars $\Delta_{1,2}^{(\pm)}$, four singly-charged scalars $\tilde{\delta^{(\pm)}}$ and $h^{(\pm)}$, four neutral scalars $S_{1,2,3,4}$, and two neutral pseudoscalars $P_{1,2}$. The S_1 boson is an analog of the SM Higgs boson. In what follows we shall centre on this boson.

The Lagrangians describing interaction of the S_1 boson with leptons and gauge bosons are given by the expressions

$$\mathcal{L}_l=-\frac{1}{\sqrt{2}k_+}\Big\{\sum_a m_a\bar{l}_{aR}l_{aL}S_1c_{\theta_0}+\sum_{a,b}\bar{l}_{aR}l_{bL}[(h_{ab}k_1-h'_{ab}k_2)S_1s_{\theta_0}+$$

$$+\sum_{a,b}\overline{N}_{aR}\nu_{bL}[h_{ab}(k_1c_{\theta_0}-k_2s_{\theta_0})+h'_{ab}(k_2c_{\theta_0}+k_1s_{\theta_0})]S_1\Big\}+\text{h.c.}, \tag{8}$$

$$\sqrt{2}\mathcal{L}_W=k_+[W_{1\mu}^*W_{1\mu}(g_L^2c_\xi^2+g_R^2s_\xi^2)+W_{2\mu}^*W_{2\mu}(g_L^2s_\xi^2+g_R^2c_\xi^2)+$$

$$+\frac{1}{2}s_{2\xi}(g_L^2-g_R^2)(W_{1\mu}^*W_{2\mu}+W_{2\mu}^*W_{1\mu})]S_1c_{\theta_0}-\frac{g_Lg_R}{k_+}\{[c_{2\xi}(W_{2\mu}^*W_{1\mu}+W_{1\mu}^*W_{2\mu})+$$

$$+s_{2\xi}(W_{2\mu}^*W_{2\mu}-W_{1\mu}^*W_{1\mu})][(2k_1k_2c_{\theta_0}+k_-^2s_{\theta_0})S_1+\text{h.c.}, \tag{9}$$

where the symbols h.c. describe hermitian conjugate terms, $k_\pm = \sqrt{k_1^2 \pm k_2^2}$, θ_0 is the mixing angle in the sector of neutral Higgs bosons ($\tan 2\theta_0 \sim k_+^2/v_R^2$), m_a is a lepton mass being equal to $h_{aa}k_2 + h'_{aa}k_1$, and

$$W_1 = W_L \cos\xi + W_R \sin\xi, \qquad W_2 = -W_L \sin\xi + W_R \cos\xi.$$

In following calculations we also need the Lagrangians describing interaction of the gauge bosons with leptons

$$\mathcal{L}_l^{CC} = \frac{g_L}{2\sqrt{2}} \sum_l \bar{l}(x)\gamma^\mu(1-\gamma_5)\nu_l(x)W_{L\mu}(x) + \frac{g_R}{2\sqrt{2}} \sum_l \bar{l}(x)\gamma^\mu(1+\gamma_5)N_l(x)W_{R\mu}(x), \quad (10)$$

where for neutrinos the connection between the flavor and mass eigenstate bases, $\Psi^f(x)$ and $\Psi^m(x)$, will look like

$$\Psi^f(x) = \begin{pmatrix} \nu_{eL}(x) \\ \nu_{\mu L}(x) \\ \nu_{\tau L}(x) \\ N_{eR}(x) \\ N_{\mu R}(x) \\ N_{\tau R}(x) \end{pmatrix} = \mathcal{U}\Psi^m(x) = \mathcal{U} \begin{pmatrix} \nu_1(x) \\ \nu_2(x) \\ \nu_3(x) \\ N_1(x) \\ N_2(x) \\ N_3(x) \end{pmatrix} \quad (11)$$

with

$$\mathcal{U} = \mathcal{M}^{\nu N} \begin{pmatrix} \mathcal{D}^{\nu\nu} & 0 \\ 0 & \mathcal{D}^{NN} \end{pmatrix}, \quad (12)$$

$$\mathcal{M}^{\nu N} = \begin{pmatrix} c_{11} & 0 & 0 & s_{11} & 0 & 0 \\ 0 & c_{22} & 0 & 0 & s_{22} & 0 \\ 0 & 0 & c_{33} & 0 & 0 & s_{33} \\ -s_{11} & 0 & 0 & c_{11} & 0 & 0 \\ 0 & -s_{22} & 0 & 0 & c_{22} & 0 \\ 0 & 0 & -s_{33} & 0 & 0 & c_{33} \end{pmatrix},$$

$$\mathcal{D}^{\eta\eta} = \begin{pmatrix} c_{12}^\eta c_{13}^\eta & s_{12}^\eta c_{13}^\eta & s_{13}^\eta e^{-i\delta_\eta} \\ -s_{12}^\eta c_{23}^\eta - c_{12}^\eta s_{23}^\eta s_{13}^\eta e^{i\delta_\eta} & c_{12}^\eta c_{23}^\eta - s_{12}^\eta s_{23}^\eta s_{13}^\eta e^{i\delta_\eta} & s_{23}^\eta c_{13}^\eta \\ s_{12}^\eta s_{23}^\eta - c_{12}^\eta c_{23}^\eta s_{13}^\eta e^{i\delta_\eta} & -c_{12}^\eta s_{23}^\eta - s_{12}^\eta c_{23}^\eta s_{13}^\eta e^{i\delta_\eta} & c_{23}^\eta c_{13}^\eta \end{pmatrix},$$

where $c_{ii} = \cos\theta_{ii}$, $s_{ii} = \sin\theta_{ii}$, θ_{ii} is the mixing angle between the light and heavy neutrinos in the i generation, $c_{ik}^\eta = \cos\theta_{ik}^\eta$, $s_{ik}^\eta = \sin\theta_{ik}^\eta$, θ_{ik}^η is the mixing angle between the i and k generations in the sector of the light $\eta = \nu$ (heavy $\eta = N$) neutrinos, and δ_η is a CP-phase.

3. Higgs-boson decay

Let us consider the Higgs decay into the channel

$$H \to \mu^+ + \tau^- \quad (13)$$

within the LRM. From the Lagrangian (8) it follows that the decay (13) may proceed even in the first order of the perturbation theory. However, in this case it is greatly suppressed by the factor $\sim (m_l \sin\theta_0/k_+)^2$. On the other side, thanks to the mixing into the neutrino sector this decay could go in the third order of the perturbation theory. The corresponding diagrams are pictured in Fig.1 and Fig.2.

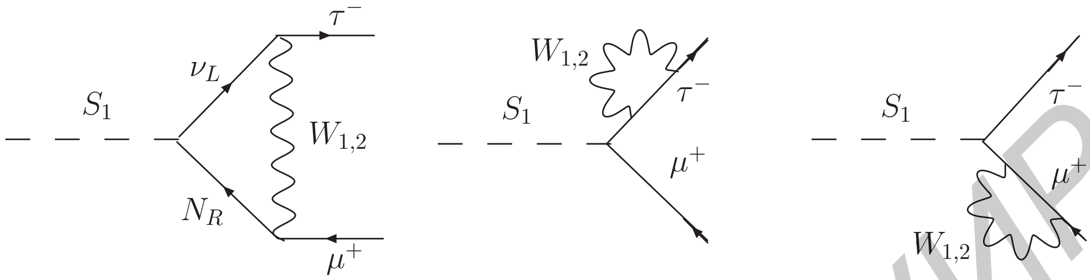

Figure 1: The Feynman diagrams contributing to the decay $S_1 \to \mu^+ + \tau^-$.

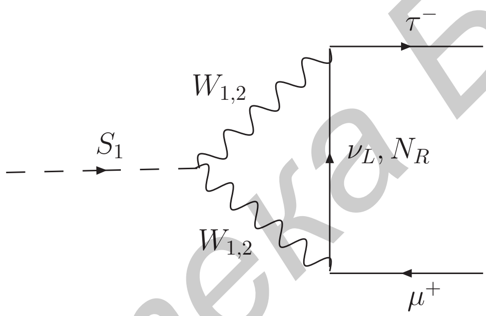

Figure 2: The Feynman diagrams contributing to the decay $S_1 \to \mu^+ + \tau^-$.

Further we shall be constrained by considering the diagrams shown in Fig.2 only. The reasons for that are as follows. The first diagram of Fig.1 is proportional to the mixing angle in the charged gauge boson sector ξ. The current limit on this angle is $\sim \xi < 10^{-2}$. So, in the early stage of investigation we may neglect contribution coming from this diagram. As far as the second and third diagrams of Fig.1 are concerned, their contributions being the self-energy type are proportional to m_l and will thus be neglected as well. Proceeding to the diagrams of Fig.2, we note that the diagram with the $W_1^+W_1^-$ pair in the virtual state gives the same contribution as the minimal extended SM and we could safely ignore it.

In Ref. [9] investigation of Mikheyev-Smirnov-Wolfenstein resonance with the solar and reactor neutrinos has be done. The sector of heavy neutrino in two flavor approximation has been considered. It was demonstrated that only three versions of the heavy neutrino sector structure are possible: (i) the light-heavy neutrino mixing angles θ_{11} and θ_{22} are arbitrary but equal each other whereas the heavy neutrino masses are quasi-degenerate (quasi-degenerate mass case — QDM case); (ii) the heavy neutrino masses are hierarchical ($m_{N_1} < m_{N_2}$) while the angles θ_{11} and θ_{22} are equal to zero (no mass degeneration case — NMD case); (iii) $\theta_{11} = \theta_{22}$ and the heavy-heavy neutrino mixing is maximal, $\theta_{12} = \pi/4$, and as a result the heavy neutrino masses are hierarchical (maximal heavy-heavy mixing case — MHHM case). It is logical to assume that the same pattern takes place in the three flavor approximation as well. Further, to be concrete we shall assume that the NMD scheme is realized. Then, the partial width of the decay (13) is given by the expression

$$d\Gamma = (2\pi)^4\delta^{(4)}(p - p_1 - p_2)|M^b|^2\frac{d^3p_1d^3p_2}{(2\pi)^8}, \qquad (14)$$

where

$$M^b = \frac{g_L^4 k_+ \cos\theta}{8\sqrt{2}}\sqrt{\frac{m_\tau m_\mu}{2m_H E_\tau E_\mu}}\,\overline{u}(p_1)\gamma^\lambda(1+\gamma_5)\Big\{U_{\tau j}U^\dagger_{j\mu}\int\frac{\hat{k} - \hat{p_2} + m_j}{(k-p_2)^2 - m_j^2}\times$$

$$\times\frac{g_{\lambda\beta} + (k-p)_\lambda(k-p)_\beta/m^2_{W_2}}{(k-p)^2 - m^2_{W_2}}\times\frac{g^{\beta\kappa} + k^\beta k^\kappa/m^2_{W_2}}{k^2 - m^2_{W_2}}d^4k\Big\}\gamma_\kappa(1+\gamma_5)v(p_2), \qquad (15)$$

m_j $(j = 1, 2, 3)$ is the mass of the heavy neutrino N_j, p_1 and p_2 are momentum of τ and μ, respectively.

Integrating over p_1, p_2 and using the procedure of dimensional regularization, we get

$$\Gamma(S_1 \to \mu^+\tau^-) = \frac{g_L^8 k_+^2}{64\pi m^3_{S_1}}(m^2_{S_1} - m^2_\mu - m^2_\tau)[(m^2_{S_1} + m^2_\mu - m^2_\tau)^2 - 4m^2_{S_1}m^2_\mu]^{1/2}J^{\mu\tau}, \qquad (16)$$

where

$$J^{\mu\tau} = (U_{\tau j}U^\dagger_{j\mu}J^\tau_j)^2 + (U_{\tau j}U^\dagger_{j\mu}J^\mu_j)^2,$$

$$J^\tau_j = -2i\pi^2 m_\tau\int_0^1\frac{x^2}{2a_j}\Big\{\ln\Big|\frac{a_j + b_j + c_j}{c_j}\Big| - \frac{b_j}{\sqrt{b_j^2 - 4a_jc_j}}\ln\Big|\frac{2c_j + b_j + \sqrt{b_j^2 - 4a_jc_j}}{2c_j + b_j - \sqrt{b_j^2 - 4a_jc_j}}\Big|\Big\},$$

$$J^\mu_j = -2i\pi^2 m_\mu\int_0^1\frac{x(1-x)2}{\sqrt{b_j^2 - 4a_jc_j}}\ln\Big|\frac{2c_j + b_j + \sqrt{b_j^2 - 4a_jc_j}}{2c_j + b_j - \sqrt{b_j^2 - 4a_jc_j}}\Big|,$$

$$a_j = -x^2m^2_\tau, \qquad b_j = -x^2(m^2_{S_1} - m^2_\mu - m^2_\tau) + x(m^2_{S_1} - m^2_{W_2} - m^2_\mu + m^2_j),$$

$$c_j = -x^2m^2_\mu + x(m^2_{W_2} + m^2_\mu - m^2_j) - m^2_{W_2}.$$

In order to obtain the partial width of the decay

$$S_1 \to \mu^- + \tau^+ \qquad (17)$$

one should make in Eq. (16) the following replacement

$$m_\tau \leftrightarrow m_\mu. \qquad (18)$$

Analysis shows that the obtained partial width displays a weak dependence both on m_{W_2} and on $\Delta m_N = m_{N_\tau} - m_{N_\mu}$. Typical value of the factor $J^{\mu\tau}$ that represents a function of m_{W_2} and Δm_N is few $\times 10^{-5}$. Using this value, we get

$$\Gamma(S_1 \to \mu^+\tau^-) + \Gamma(S_1 \to \mu^-\tau^+) \approx \text{few} \times 10^{-2}\ \text{KeV} \qquad (19)$$

which proves to be on three order of magnitude smaller than the experimental value (we remember that the total Higgs boson width is around 4 MeV).

4. Conclusion

Within the left-right symmetric model the decays of the SM Higgs boson analog

$$S_1 \to \mu^+ + \tau^-, \qquad S_1 \to \mu^- + \tau^+$$

have been investigated. These decays go with the lepton flavor violation and, as result, are forbidden in the SM. Previous analysis of the oscillation experiments has shown that there are only three patterns of building of the heavy neutrino sector. They are: (i) the case of quasi-degenerate masses (QDM); (ii) no masses degeneration case (NMD; (iii) the case of maximal heavy-heavy mixing (MHHM). We have constrained by examining the NMD case only. Calculations have shown that the theoretical value of the Higgs decays width obtained within the NMD case is three order of magnitude smaller than the experimental value. By this means, the NMD should be eliminated from further viewing. Therefore, in what follows, the Higgs decay with the lepton flavor violation should be examined from the point of view both the QDM and MHHM scenarios.

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