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Neutrino Mixings as a Source of Charged Lepton Flavor Violations

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Within the left-right symmetric model the Higgs boson and Z boson decays with the lepton flavor violation are investigated. In this model apart from the ordinary light neutrinos ν_{lL} $(l = e, \mu, \tau)$ three heavy neutrinos N_{lR} being partners of ν_{lL} on the see-saw mechanism are in existence. It is shown that the main contributions to these decays are caused by the diagrams with the heavy neutrinos in the virtual state. Then comparison of the theoretical and experimental results will allow to set bounds on the heavy neutrino sector parameters.

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1. Introduction

The standard model (SM) of particle physics has been very successfully predicting or explaining most experimental results and phenomena. However it still has a few outstanding problems with empirical observations. One of them is connected with neutrinos. In the SM the lepton flavors $L_{e,\mu,\tau}$ are conserved quantities. However, neutrino oscillation experiments demonstrated that the neutrinos have the masses and the neutral lepton flavors is not conserved. It should be stressed that this nonconservation is caused by the mixing in the neutrino sector. Of course, the minimally extended SM (SM with the massive neutrinos — MESM) may be invoked for description of neutrino oscillation experiments but processes involving violation of charged lepton flavors are extremely suppressed in it because of the small neutrino masses. Owing to a positive signal in any of the experimental looking for charged lepton flavors violation (CLFV) processes would automatically imply the existence of physics beyond the SM. Although no such processes have been detected to date, this is a very active field that is being explored by many experiments which have adjusted upper limits to this kind of CLFV processes.

The currently running LHC could throw light on CLFV processes. The LHC has been searching the Z boson decays into two leptons of different flavor $Z \to l_k \bar{l}_m$ [1, 2]. The experimental limits set by LHC are as follows [3]

$$\mathrm{BR}(Z \to e^{\pm}\mu^{\mp}) < 1.7 \times 10^{-6} \tag{1}$$

$$\mathrm{BR}(Z \to e^{\pm}\tau^{\mp}) < 9.8 \times 10^{-6} \tag{2}$$

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$$\mathrm{BR}(Z \to \mu^{\pm}\tau^{\mp}) < 1.2 \times 10^{-5} \tag{3}$$

Looking for the CLFV Z decays will certainly continued during the new runs, so hopefully new interesting data will come from ATLAS and CMS collaborations.

At LHC three new CLFV channels of the Higgs boson decays into two leptons of different flavor, $H \to l_k \bar{l}_m$ $(k \neq m)$, are also searched by the CMS [4, 5] and ATLAS [2] collaborations. Notwithstanding the fact that CMS observed a small but intriguing excess in the $H \to \tau\mu$ channel after run-I [4], it has not been confirmed yet with run-II data and, at present, it has further enhanced the sensitivities of the $H \to \tau\mu$ and $H \to \tau e$ channels with new run-II data [5] of $\sqrt{s} = 13$ TeV, setting the most stringent upper bounds for the LFV Higgs decays, that at the 95% CL are as follows

$$\mathrm{BR}(H \to \mu e) < 3.5 \times 10^{-4} \tag{4}$$

$$\mathrm{BR}(H \to \tau e) < 0.61 \times 10^{-2} \tag{5}$$

$$\mathrm{BR}(H \to \tau\mu) < 0.25 \times 10^{-2} \tag{6}$$

Looking for the CLFV Higgs boson decays will certainly continued during the new LHC runs and at future leptonic colliders where the more high statistics of Higgs boson events will be achieved. For example, the future LHC runs with $\sqrt{s} = 14$ TeV and total integrated luminosity of first 300 fb^{-1} and later 3000 fb^{-1} expect the production of about 25 and 250 millions of Higgs boson events, respectively, to be compared with 1 million Higgs boson events that the LHC produced after the first runs. These large numbers provide an upgrading of sensitivities to $\mathrm{BR}(H \to l_k \bar{l}_m)$ of at least two orders of magnitude with respect to the present sensitivity.

There are a lot of models predicting the CLFV in the decays of the Higgs [6–9] and Z bosons [10–12]. It is clear that amongst them the models having common mechanism both for NLFV and for CLFV are most attractive. The left-right model (LRM) [13] belongs among such models. The neutrino sector of the LRM, apart from light left-handed neutrinos ν_{lL}, also includes heavy right-handed neutrinos N_{lR} which are partners on the see-saw mechanism for ν_{lL}. As this takes place, heavy neutrinos mixing are a principal source of the CLFV.

In this work we shall examine the CLFV processes from the point of view of the LRM. Our goal is to investigate the CLFV decays of the Z and Higgs bosons and to establish what parameters of the LRM neutrino sector therewith could be determined. The organization of the paper goes as follows. In the next section we fulfill our calculations and analyze the results obtained. Section 3 includes our conclusion.

2. CLFV decays

Let us start with the investigation of the Z boson decay into the channel

$$Z_1 \to \mu^+ + \tau^- \tag{7}$$

within the LRM. Due to the mixing into the neutrino sector this decay could proceed in the third order of the perturbation theory. The corresponding diagrams are shown in Fig.1. The analysis show that the dominant contribution to the decay width comes from the diagram pictured on Fig.1.a. with the $W_1^+ W_1^- \nu_L$ in the virtual state. The matrix element corresponding to the diagram under consideration has the form

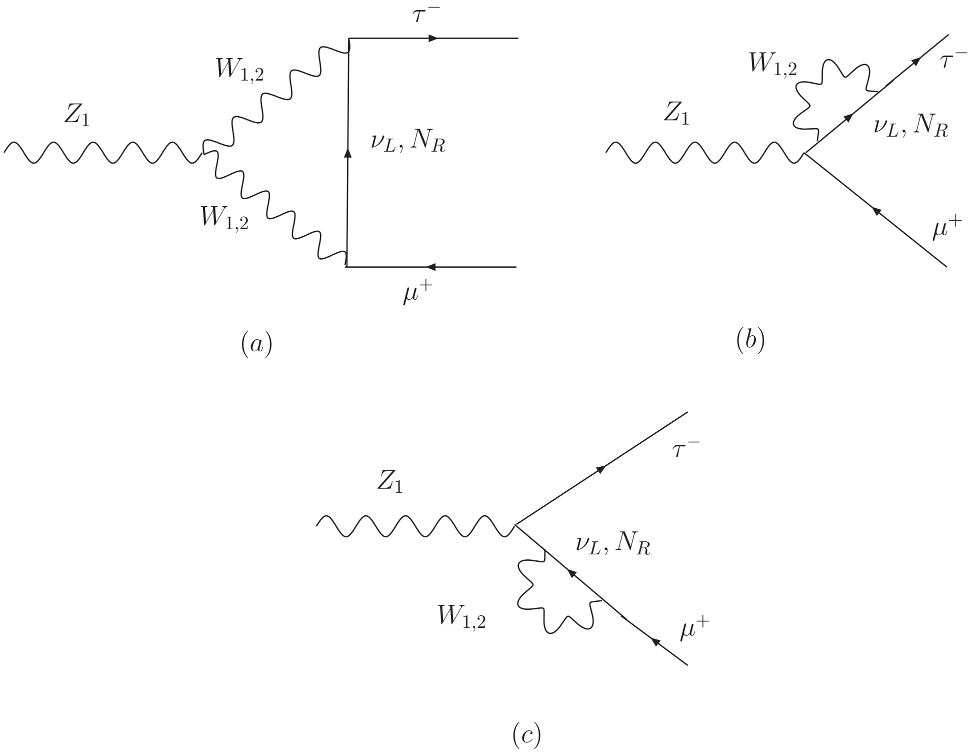

Figure 1: The Feynman diagrams contributing to the decay $Z_1 \to \mu^+ + \tau^-$.

$$M = \frac{g_L^3 c_W \sin 2\theta_N \sin^2\varphi}{8}\sqrt{\frac{m_\tau m_\mu}{2m_{Z_1}E_\tau E_\mu}}\,\overline{u}(p_1)\gamma^m(1-\gamma_5)\int_\Omega \Big\{\Big[\frac{\hat{k}-\hat{p}_2+m_{N_1}}{(k-p_2)^2-m_{N_1}^2}-$$

$$-\frac{\hat{k}-\hat{p}_2+m_{N_2}}{(k-p_2)^2-m_{N_2}^2}\Big]\gamma^n(1-\gamma_5)v(p_2)\Big[g_{\sigma\lambda}\Lambda_{m\nu}(k-p)\Lambda_{n\beta}(k)k_\mu-$$

$$-g_{\nu\lambda}\Lambda_{n\sigma}(k)\Lambda_{m\beta}(k-p)(k-p)_\mu - g_{\beta\lambda}\Lambda_{m\sigma}(k-p)\Lambda_{n\nu}(k)p_\mu\Big]B^{\mu\nu,\beta\sigma}Z^\lambda(p)\Big\}d^4k, \qquad (8)$$

where

$$\Lambda_{\mu\nu}(k) = \frac{g_{\mu\nu} - k_\mu k_\nu/m_W^2}{k^2 - m_W^2},$$

m_{N_j} $(j=1,2)$ is the mass of the heavy neutrino, φ is a heavy-light neutrino mixing angle, θ_N is a heavy-heavy neutrino mixing angle, while p_1 and p_2 are momentum of τ-lepton and μ-meson, respectively.

Using the procedure of dimensional regularization and considering the motion equations permits to write the expression (8) in the form

$$M = \frac{i\pi^2 g_L^3 c_W \sin 2\theta_N \sin^2\varphi}{4}\sqrt{\frac{m_\tau m_\mu}{2m_{Z_1}E_\tau E_\mu}}\,\overline{u}(p_1)\Big[(1+\gamma_5)(A\gamma_\lambda + Bp_{1\lambda})+$$

$$(1-\gamma_5)(C\gamma_\lambda + Dp_{1\lambda})\Big]v(p_2)Z^\lambda(p), \qquad (9)$$

where the quantities A, B, C and D represent the two-dimensional integrals. Substituting (9) into the partial decay width

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

integrating the obtained expression over p_1, p_2, we obtain

$$\Gamma(Z_1 \to \tau^-\mu^+) \simeq \frac{g_L^6 c_W^2 \pi^3 \sin\varphi^4 \sin^2 2\theta}{64 m_{Z_1}^3}\Big\{[(m_{Z_1}^2 - m_\mu^2 - m_\tau^2)[\Delta A(m_1,m_2)]^2\Big\}\times$$
$$\times\sqrt{(m_{Z_1}^2 - m_\mu^2 - m_\tau^2)^2 - 4m_\mu^2 m_\tau^2}, \qquad (10)$$

where in the curly bracket we have taken into account

$$m_{Z_1} \gg m_\tau, m_\mu$$

and

$$A = \int_0^1 dy \int_0^1 xdx \Bigg\{\Bigg[8 + m_{W_1}^{-2}\Bigg(\frac{21}{2} l_{xy}^j - 22p_x^2 + (p_1p_2)(23x - 17xy - 2)\Bigg)\Bigg]\ln\left|\frac{l_{xy}^j}{l_{xy}^j - p_x^2}\right| +$$
$$+\frac{1}{l_{xy}^j - p_x^2}\Bigg[3p_x^2 - (p_1p_2)(6x - 2xy - 4) + m_{W_1}^{-2}\Bigg(-2p_x^4 + p_x^2(p_1p_2)(8x - 6xy) -$$
$$-4(p_1p_2)^2(x - xy)(2x - xy)\Bigg)\Bigg]\Bigg\}, \qquad (11)$$

$$p_x = p_1(x - xy) + p_2 x, \quad p_x^2 = m_{Z_1}^2 x^2 + m_\tau^2 x^2 y^2 - (m_{Z_1}^2 + m_\tau^2 - m_\mu^2)x^2 y,$$
$$l_{xy}^j = (m_\mu^2 - m_j^2 - m_{Z_1}^2 + m_{W_1}^2)xy + m_{Z_1}^2 x - m_{W_1}^2, \quad (p_1p_2) = \frac{1}{2}(m_{Z_1}^2 - m_\mu^2 - m_\tau^2),$$

and

$$\Delta A(m_1, m_2) = A(m_1) - A(m_2). \qquad (12)$$

Let us estimate $\Gamma(Z_1 \to \tau^-\mu^+)$ using obtained expression. Setting

$$\theta = \frac{\pi}{4}, \qquad \varphi = 2.3\times 10^{-2},$$

we get

$$\mathrm{BR}(Z_1 \to \tau\mu) \simeq \begin{cases} 0.5\times 10^{-7}, & \text{when} \quad m_{N_1} = 100 \text{ GeV},\ m_{N_2} = 150 \text{ GeV},\\ 0.3\times 10^{-6}, & \text{when} \quad m_{N_1} = 100 \text{ GeV},\ m_{N_2} = 200 \text{ GeV},\\ 0.4\times 10^{-7}, & \text{when} \quad m_{N_1} = 150 \text{ GeV},\ m_{N_2} = 200 \text{ GeV}.\end{cases} \qquad (13)$$

As we see that, at its best, the theoretical expression for the branching ratio $\mathrm{BR}(Z_1 \to \tau\mu)$ proves to be on two orders of magnitude less than the existing upper experimental bound.

Now we proceed to the decay

$$S_1 \to \tau^- + \mu^+. \qquad (14)$$

The corresponding diagrams are shown in Fig.2. Analysis demonstrates that the main contribution comes from the diagrams one of them shown on Fig.2a. There are eight diagrams such a kind depending on what neutrinos are produced in the virtual state. For example, when in the virtual state the $\nu_\tau \overline{N}_\tau$ pair comes into being the corresponding matrix element take the form

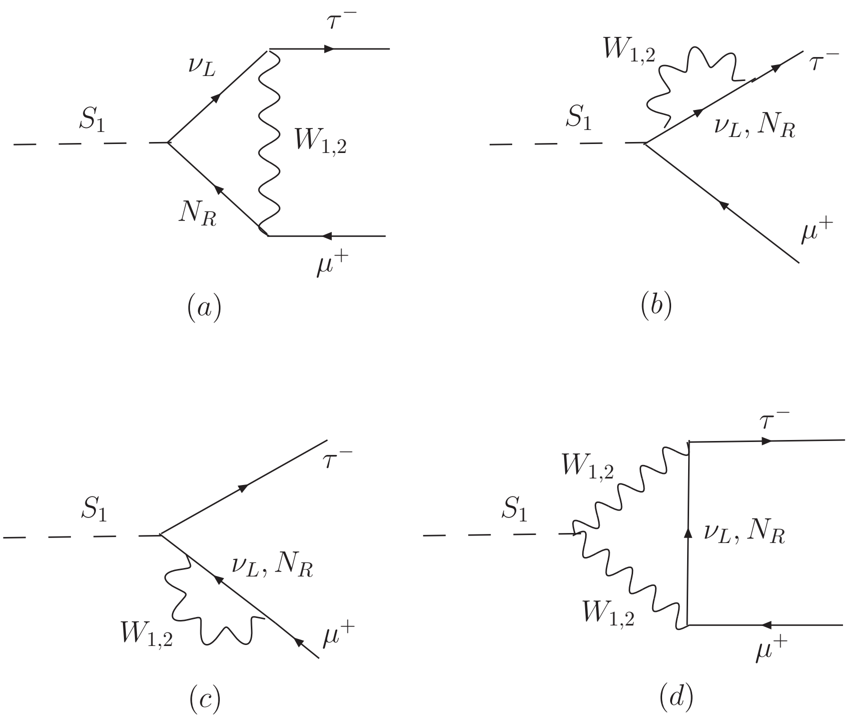

Figure 2: The Feynman diagrams contributing to the decay $S_1 \to \mu^+ + \tau^-$.

$$M_1^{(a)} = \frac{g_L^2 m_D^\tau \cos\alpha \sin 2\theta_N \sin\xi}{32k_+\sqrt{2}} \sqrt{\frac{m_\tau m_\mu}{2m_{S_1} E_\tau E_\mu}} \times$$
$$\times \overline{u}(p_1)\gamma_\lambda(1-\gamma_5)\Big\{ \int_\Omega \frac{\hat{p}-\hat{k}+m_{\nu_i}}{(p-k)^2-m_{\nu_i}^2}(1+\gamma_5)\left[\frac{\hat{k}+m_{N_2}}{k^2-m_{N_2}^2} - \frac{\hat{k}+m_{N_1}}{k^2-m_{N_1}^2}\right]\times$$
$$\times\gamma_\sigma(1+\gamma_5)\frac{g^{\lambda\sigma}-(k-p_2)^\lambda(k-p_2)^\sigma/m_{W_1}^2}{(k-p_2)^2-m_{W_1}^2} d^4k\Big\} v(p_2), \qquad (15)$$

where m_{N_j} $(j = 1, 2)$ is the mass of the heavy neutrino, p_1 and p_2 are momentum of τ-lepton and μ-meson, respectively. Taking into account the relations connecting the Higgs sector parameters with the neutrino sector ones we find that the matrix element corresponding to all eight diagrams is given by the expression

$$M^{(a)} = \sum_{i=1}^{8} M_i^{(a)} = \frac{g_L^2 \cos\alpha \sin 2\varphi \sin 2\theta_N \sin\xi}{16k_+\sqrt{2}} \sqrt{\frac{m_\tau m_\mu}{2m_{S_1} E_\tau E_\mu}}\times$$
$$\times \overline{u}(p_1)\gamma_\lambda(1-\gamma_5)\Big\{ \int_\Omega \frac{\hat{p}-\hat{k}+m_{\nu_i}}{(p-k)^2-m_{\nu_i}^2}(1+\gamma_5)\left[\frac{m_{N_2}(\hat{k}+m_{N_2})}{k^2-m_{N_2}^2} - \frac{m_{N_1}(\hat{k}+m_{N_1})}{k^2-m_{N_1}^2}\right]\times$$
$$\times\gamma_\sigma(1+\gamma_5)\frac{g^{\lambda\sigma}-(k-p_2)^\lambda(k-p_2)^\sigma/m_{W_1}^2}{(k-p_2)^2-m_{W_1}^2} d^4k\Big\} v(p_2). \qquad (16)$$

Calculations demonstrate that the set of diagrams pictured on Fig.2a leads to the result

$$\Gamma(S_1\to\overline{\nu}_L^*N_R^*W_1^*\to\mu^+\tau^-)=\frac{\pi^3(g_L^2\cos\alpha\sin 2\varphi\sin 2\theta_N\sin\xi)^2}{16m_{S_1}^3}\Big\{4m_\tau m_\mu(\Delta L)(\Delta R)+$$

$$+(m_{S_1}^2-m_\tau^2-m_\mu^2)[(\Delta L)^2+(\Delta R)^2]\Big\}\sqrt{(m_{S_1}^2-m_\mu^2-m_\tau^2)^2-4m_\mu^2m_\tau^2}, \qquad (17)$$

where

$$\Delta L=L(m_{N_2})-L(m_{N_1}),\quad L(m_{N_j})=\frac{m_{N_j}}{k_+}\Big[L_W^1(m_{N_j})+L_W^2(m_{N_j})+L_W^3(m_{N_j})\Big],$$

$$\Delta R=R(m_{N_2})-R(m_{N_1}),$$

$$R(m_{N_j})=\frac{m_{N_j}}{k_+}\Big[R_g(m_{N_j})+R_W^1(m_{N_j})+R_W^2(m_{N_j})+R_W^3(m_{N_j})+R_W^4(m_{N_j})\Big],$$

$$R_g(m_{N_j})=2\int_0^1xdx\int_0^1\Big[\frac{(pp_x)-p_x^2}{l_{xy}^j-p_x^2}-2\ln\left|\frac{l_{xy}^j}{l_{xy}^j-p_x^2}\right|\Big]dy, \qquad (18)$$

$$L_W^1(m_{N_j})=\frac{2m_\mu m_\tau}{m_W^2}\int_0^1xdx\int_0^1\frac{(m_{S_1}^2-m_\tau^2)(x-xy)-2(p_2p_x)+m_\mu^2x}{l_{xy}^j-p_x^2}dy, \qquad (19)$$

$$R_W^1(m_{N_j})=-\frac{2m_\mu^2}{m_W^2}\int_0^1xdx\int_0^1\frac{(m_{S_1}^2-m_\tau^2)x+m_\tau^2(x-xy)}{l_{xy}^j-p_x^2}dy, \qquad (20)$$

$$L_W^2(m_{N_j})=-\frac{2m_\mu m_\tau}{m_W^2}\int_0^1xdx\int_0^1\left[-3\ln\left|\frac{l_{xy}^j}{l_{xy}^j-p_x^2}\right|+\frac{(pp_x)(x-xy)-2p_x^2}{l_{xy}^j-p_x^2}\right]dy, \qquad (21)$$

$$R_W^2(m_{N_j})=\frac{2}{m_W^2}\int_0^1xdx\int_0^1\left[\ln\left|\frac{l_{xy}^j}{l_{xy}^j-p_x^2}\right|\times\right.$$

$$\left.\times(2m_{S_1}^2-2m_\tau^2+m_\mu^2)+\frac{(pp_x)xm_\mu^2+(m_{S_1}^2-m_\tau^2)p_x^2}{l_{xy}^j-p_x^2}\right]dy, \qquad (22)$$

$$L_W^3(m_{N_j})=-\frac{m_\mu m_\tau}{m_W^2}\int_0^1xdx\int_0^1\left\{6xy\ln\left|\frac{l_{xy}^j}{l_{xy}^j-p_x^2}\right|+\frac{(2xy-4x)p_x^2}{l_{xy}^j-p_x^2}\right\}dy, \qquad (23)$$

$$R_W^3(m_{N_j})=-\frac{1}{m_W^2}\int_0^1xdx\int_0^1\left\{\ln\left|\frac{l_{xy}^j}{l_{xy}^j-p_x^2}\right|\left[12(pp_x)+6m_\mu^2x-6m_\tau^2(x-xy)\right]+\right.$$

$$\left.+\frac{2p_x^2}{l_{xy}^j-p_x^2}\left[2(pp_x)+m_\mu^2x-m_\tau^2(x-xy)\right]\right\}dy, \qquad (24)$$

$$R_W^4(m_{N_j})=\frac{1}{m_W^2}\int_0^1xdx\int_0^1\left\{\ln\left|\frac{l_{xy}^j}{l_{xy}^j-p_x^2}\right|(24p_x^2-12l_{xy}^j)+p_x^2\left[12+\frac{2p_x^2}{l_{xy}^j-p_x^2}\right]\right\}dy, \qquad (25)$$

$$l_{xy}^j=yx(m_\mu^2-m_{W_1}^2-m_{S_1}^2)+x(m_{S_1}^2+m_{N_j}^2)-m_{N_j}^2,$$

$$p_x^2=m_\tau^2x^2y^2+m_{S_1}^2x^2-(m_{S_1}^2+m_\tau^2-m_\mu^2)x^2y,\qquad (pp_x)=m_{S_1}^2x-\frac{1}{2}(m_{S_1}^2-m_\mu^2+m_\tau^2)xy,$$

$$(p_2p_x)=m_\mu^2x+\frac{1}{2}(m_{S_1}^2-m_\mu^2-m_\tau^2)(x-xy),$$

In order to obtain the width of the decay

$$S_1 \to \mu^- + \tau^+ \tag{26}$$

one should make in Eqs. (17) the following replacement

$$m_\tau \leftrightarrow m_\mu.$$

Now we shall find out whether could the obtained expressions for $\mathrm{BR}(S_1 \to \mu^+\tau^-) + \mathrm{BR}(S_1 \to \mu^-\tau^+)$ reproduce the experimental bound on the branching ratio of the decay $S_1 \to \mu\tau$? First and foremost we note that the width of this decay does not equal to zero only provided the heavy neutrino masses are hierarchical while the heavy-heavy and heavy-light neutrino mixing angles do not equal to zero. Using (17) we get

$$\mathrm{BR}(S_1 \to \tau^-\mu^+) \simeq \begin{cases} 0.24 \times 10^{-4}, & \text{when} \quad \sin\varphi = 2.3 \times 10^{-2}, \\ 0.45 \times 10^{-6}, & \text{when} \quad \sin\varphi = 3.2 \times 10^{-3}. \end{cases} \tag{27}$$

So, we see that at most the obtained expression is two orders of magnitude less than the current experimental upper bound.

3. Conclusion

Within the LRM the decays

$$Z_1 \to \tau^- + \mu^-, \tag{28}$$

and

$$S_1 \to \tau^- + \mu^- \tag{29}$$

where Z_1 (S_1) is an analog of the standard model (SM) Z (Higgs) boson, have been considered. These decays go with the charged lepton flavor violation (CLFV) and, as result, are forbidden in the SM. We have found the widths of these decays in the third order of the perturbation theory. The widths of these decays do not equal to zero only provided the heavy neutrino masses are hierarchical and neutrino mixing angles do not equal to zero. Therefore, investigation of these decays could give information on the following parameters of the LRM neutrino sector: (i) heavy-heavy neutrino mixing; (ii) heavy-light neutrino mixing; (iii) heavy neutrino masses.

The obtained decay widths critically depend on the angle ξ which defines the mixing in the charged gauge boson sector and the heavy-light neutrino mixing angle φ. Within the LRM there exist the formulae connecting the values of these angles with the VEV's v_L and v_R. Using the results of the current experiments, on looking for the additional charged gauge boson W_2 and on measuring the electroweak ρ parameter, gives

$$\sin\xi \leq 5 \times 10^{-4}, \qquad \sin\varphi \leq 2.3 \times 10^{-2}. \tag{30}$$

However, even using the upper bounds on $\sin\xi$ and $\sin\varphi$ one does not manage to get for $\mathrm{BR}^{\mathrm{exp}}(S_1 \to \tau\mu)$ the value 0.25×10^{-2} which is predicted by the existing experiments. The theoretical values of these decays width prove to be on two order of magnitude less than the upper experimental bounds obtained at ATLAS and CMS. The same is true for $Z \to \tau^-\mu^+$ decay.

On the other hand, it should be remembered that in our case $\mathrm{BR}^{\mathrm{exp}}(S_1 \to \tau\mu)$ is nothing more than the experiment precision limit, rather than the measured value of the branching ratio. Therefore, the experimental programs with higher precision than at present are required to get more detail information about the decay $S_1 \to \tau\mu$.

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