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The Higgs boson decays with the lepton flavor violation

O.M.Boyarkin*, G.G.Boyarkina, D.S.Vasileuskaya

Belorussian State University,

Dolgobrodskaya Street 23, Minsk, 220070, Belarus

Abstract

Within the left-right symmetric model (LRM) the decays

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

where S_1 is an analog of the standard model Higgs boson, are considered. The widths of this decays are found in the third order of the perturbation theory. Since the main contribution to the decay widths is caused by the diagram with the light and heavy neutrinos in the virtual state then investigation of this decays could shed light upon the neutrino sector structure.

The obtained decay widths critically depend on the charged gauge bosons mixing angle ξ and the heavy-light neutrinos mixing angle φ. The LRM predicts the values of these angles as functions of the vacuum expectation values v_L and v_R. Using the results of the existing experiments, on looking for the additional charged gauge boson W_2 and on measuring the electroweak ρ parameter, gives

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

However, even using the upper bounds on $\sin\xi$ and $\sin\varphi$ one does not manage to get the upper experimental bound on the branching ratio BR$(S_1 \to \tau\mu)_{exp}$ being equal to 0.25×10^{-2}. The theoretical expression proves to be on two orders of magnitude less than BR$(S_1 \to \tau\mu)_{exp}$.

Keywords: Higgs boson, lepton flavor violation, left-right symmetric model, heavy and light neutrinos, mixing in the neutrino sector, Large Hadron Collider.

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*E-mail:oboyarkin@tut.by

1 Introduction

Upon discovering 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 upgraded 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 lepton flavor violation (LFV). These decays do not take place even in the minimally extended SM (SM with massive neutrinos), since lepton flavor symmetry is an exact symmetry of the SM and therefore it predicts vanishing rates for all these LFV processes to all orders in perturbation theory. It should be noted that any experimental signal of LFV will indicate that some new physics, either new particles or new interactions must be responsible for it.

The ATLAS and CMS collaborations are actively searching for these LFV Higgs decays. For example, the CMS collaboration saw an excess on the $H \to \tau\mu$ channel after the run-I (this process includes both $H \to \mu^+\tau^-$ and $H \to \mu^-\tau^+$), with a significance of 2.4σ and a value [1, 2]

$$\mathrm{BR}(H \to \tau\mu) = (0.84^{+0.39}_{-0.37})\%. \tag{1}$$

However, neither this excess, nor other positive LFV Higgs decay signal, have been detected at the present run-II. As of now, ATLAS has released their results after analyzing 20.3 fb^{-1} of data at a center of mass energy of $\sqrt{s} = 8$ TeV, achieving sensitivities of the order of 10^{-2} for the $H \to \tau\mu$ and $H \to \tau e$ channels [3]. CMS has also searched for the $H \to \mu e$ channel after the run-I [4] and 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

$$\mathrm{BR}(H \to \mu e) < 3.5 \times 10^{-4} \tag{2}$$

$$\mathrm{BR}(H \to \tau e) < 0.61 \times 10^{-2} \tag{3}$$

$$\mathrm{BR}(H \to \tau\mu) < 0.25 \times 10^{-2} \tag{4}$$

There is no question that observation of the Higgs boson decay with the LFV is a smoking gun signal for physics beyond the SM. These decays have been studied for a long time in the literature within various SM extensions (for recent works see, [6, 7, 8, 9]).

The models predicting the Higgs boson 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. [10, 11]). 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 decays (2)-(4) 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 $H \to l_i\bar{l}_j$ at the one-loop level [12, 13]. Another example is the left-right symmetric model (LRM) [14, 15, 16], where the LFV processes are caused by the mixing in the neutrino sector. Within the LRM the LFV was investigated by the example of the processes [17]

$$e^- + \mu^+ \to W_k^- + W_n^+, \qquad e^- + \mu^- \to W_k^- + W_n^-,$$

which may be observed on the muon colliders and the decays [18]

$$\mu^- \to e^+ + e^- + e^-, \qquad \mu^- \to e^- + \gamma.$$

In so doing one was shown that within the LRM it could be possible to obtain the upper experimental bounds on the BR($\mu^- \to e^+e^-e^-$) and BR($\mu^- \to e^-\gamma$). In this work we also investigate the LFV processes from the point of view of the LRM. Our goal is to consider the Higgs decay $H \to \mu\tau$ and establish whether this decay is possible in the context of 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 4 includes our conclusion.

2 The left-right-symmetric model

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

$$\left.\begin{array}{ll} Q_L^a(\frac{1}{2},0,\frac{1}{3}) = \begin{pmatrix} u_L^a \\ d_L^a \end{pmatrix}, & Q_R^a(0,\frac{1}{2},\frac{1}{3}) = \begin{pmatrix} u_R^a \\ d_R^a \end{pmatrix}, \\ \Psi_L^a(\frac{1}{2},0,-1) = \begin{pmatrix} \nu_{aL} \\ l_{\alpha L} \end{pmatrix}, & \Psi_R^a(0,\frac{1}{2},-1) = \begin{pmatrix} N_{aR} \\ l_{aR} \end{pmatrix}, \end{array}\right\} \qquad (5)$$

where $a = 1, 2, 3$, in brackets the values of S_L^W, S_R^W and $B - L$ are given, S_L^W (S_R^W) is the weak left (right) isospin while B and L are the baryon and lepton numbers. Note that introducing the heavy neutrinos N_{aR} leads to the existence of the see-saw relation which, in its turn, gives explanation of the ν_l-neutrino mass smallness. The Higgs sector structure of the LRM determines the neutrino nature. The mandatory element of the

Higgs sector is the bi-doublet $\Phi(1/2, 1/2, 0)$

$$\Phi = \begin{pmatrix} \Phi_1^0 & \Phi_2^+ \\ \Phi_1^- & \Phi_2^0 \end{pmatrix}. \tag{6}$$

Its nonequal vacuum expectation values (VEV's) 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 $\Delta_L(1,0,2)$, $\Delta_R(0,1,2)$ [19]

$$(\boldsymbol{\tau}\cdot\boldsymbol{\Delta}_L) = \begin{pmatrix} \delta_L^+/\sqrt{2} & \delta_L^{++} \\ \delta_L^0 & -\delta_L^+/\sqrt{2} \end{pmatrix}, \qquad (\boldsymbol{\tau}\cdot\boldsymbol{\Delta}_R) = \begin{pmatrix} \delta_R^+/\sqrt{2} & \delta_R^{++} \\ \delta_R^0 & -\delta_R^+/\sqrt{2} \end{pmatrix}. \tag{7}$$

If the Higgs sector consists of two doublets $\chi_L(1/2,0,1)$, $\chi_R(0,1/2,1)$ and one bidoublet $\Phi(1/2,1/2,0)$ [20], 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

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

$$+if_{ab}[\Psi^T_{aL}C\tau_2(\boldsymbol{\tau}\cdot\boldsymbol{\Delta}_L)\Psi_{bL} + (L\to R)] + \text{h.c.}\}, \tag{8}$$

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 (YC's), 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 (VEV's):

$$<\delta^0_{L,R}>= \frac{v_{L,R}}{\sqrt{2}}, \qquad <\Phi_1^0>= k_1, \qquad <\Phi_2^0>= k_2. \tag{9}$$

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

$$v_L << \max(k_1, k_2) << v_R. \tag{10}$$

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 shape of V_H that was proposed in Ref. [21]. After the SSB we have 14 physical Higgs bosons. They are: four doubly-charged scalars $\Delta^{(\pm)}_{1,2}$, four singly-charged scalars $\tilde{\delta}^{(\pm)}$ and $h^{(\pm)}$, four neutral scalars $S_{1,2,3,4}$ (S_1 boson is an analog of the SM Higgs boson), and two neutral pseudoscalars $P_{1,2}$.

We now direct our attention to the sector of the neutral scalar Higgses. If one does not impose any conditions on the constants entering the Higgs potential V_H, then we have four scalars

$$\left.\begin{array}{c} S_1=(\Phi_-^{0r}\cos\theta_0+\Phi_+^{0r}\sin\theta_0)\cos\alpha-\delta_R^{0r}\sin\alpha,\ S_2=-\Phi_-^{0r}\sin\theta_0+\Phi_+^{0r}\cos\theta_0, \\ S_3=(\Phi_-^{0r}\cos\theta_0+\Phi_+^{0r}\sin\theta_0)\sin\alpha+\delta_R^{0r}\cos\alpha, \qquad S_4=\delta_L^{0r}, \end{array}\right\} \tag{11}$$

where

$$\Phi_-^{0r}=\frac{k_1\Phi_1^{0r}+k_2\Phi_2^{0r}}{k_+}, \qquad \Phi_+^{0r}=\frac{k_1\Phi_2^{0r}-k_2\Phi_1^{0r}}{k_+},$$

$k_\pm=\sqrt{k_1^2\pm k_2^2}$ and the superscript r means the real part of the corresponding quantity. The mixing angle θ_0 is defined by the expression [22]

$$\tan 2\theta_0=\frac{4k_1k_2k_-^2[2(2\lambda_2+\lambda_3)k_1k_2+\lambda_4k_+^2]}{k_1k_2[(4\lambda_2+2\lambda_3)(k_-^4-4k_1^2k_2^2)-k_+^2(2\lambda_1k_+^2+8\lambda_4k_1k_2)]-\alpha_2v_R^2k_+^4} \tag{12}$$

and, as a result, appears to be very small. In what follows we shall set it equal to zero. As far as the mixing angle α is concerned, it could be very sizeable. The theory predict that at $v_L=k_2=0$ the expression for the mixing angle α is as follows [23]

$$\tan 2\alpha=\frac{\alpha_Hk_1v_R}{\rho_Hv_R^2-\lambda_Hk_1^2}, \tag{13}$$

where λ_H,ρ_H and α_H are linear combinations of the constants entering the Higgs potential. Recent investigations [24, 25] allow for $\sin\alpha<0.44$ at 2σ CL, practically independently of the S_3 mass. Then the Lagrangian of interaction between the S_1 boson and leptons will look like

$$\mathcal{L}_l=-\frac{1}{\sqrt{2}k_+}\Big\{\sum_a m_a\bar{l}_{aR}l_{aL}S_1\cos\alpha+\sum_{a,b}\overline{N}_{aR}\nu_{bL}[h_{ab}k_1+h'_{ab}k_2]S_1\cos\alpha\Big\}+\text{h.c.}. \tag{14}$$

It is convenient to express the coupling constants of the S_1 boson with the neutrinos in terms of neutrino oscillation parameters [22, 17]. In the two flavor approximation the neutrino mass matrix in the basis $\Psi^T=\left(\nu_{aL}^T,N_{aR}^T,\nu_{bL}^T,N_{bR}^T\right)$ will look like

$$\mathcal{M}=\begin{pmatrix} f_{aa}v_L & m_D^a & f_{ab}v_L & M_D \\ m_D^a & f_{aa}v_R & M'_D & f_{ab}v_R \\ f_{ab}v_L & M'_D & f_{bb}v_L & m_D^b \\ M_D & f_{ab}v_R & m_D^b & f_{bb}v_R \end{pmatrix}. \tag{15}$$

where

$$m_D^a=h_{aa}k_1+h'_{aa}k_2, \tag{16}$$

$$M_D=h_{ab}k_1+h'_{ab}k_2, \qquad M'_D=h_{ba}k_1+h'_{ba}k_2. \tag{17}$$

The transition to the eigenstate neutrino mass basis m_i $(i = 1, 2, 3, 4)$ is carried out by the matrix

$$U = \begin{pmatrix} c_{\varphi_a}c_{\theta_\nu} & s_{\varphi_a}c_{\theta_N} & c_{\varphi_a}s_{\theta_\nu} & s_{\varphi_a}s_{\theta_N} \\ -s_{\varphi_a}c_{\theta_\nu} & c_{\varphi_a}c_{\theta_N} & -s_{\varphi_a}s_{\theta_\nu} & c_{\varphi_a}s_{\theta_N} \\ -c_{\varphi_b}s_{\theta_\nu} & -s_{\varphi_b}s_{\theta_N} & c_{\varphi_b}c_{\theta_\nu} & s_{\varphi_b}c_{\theta_N} \\ s_{\varphi_b}s_{\theta_\nu} & -c_{\varphi_b}s_{\theta_N} & -s_{\varphi_b}c_{\theta_\nu} & c_{\varphi_b}c_{\theta_N} \end{pmatrix}, \qquad (18)$$

where φ_a and φ_b are the mixing angles inside a and b generations respectively, $\theta_\nu(\theta_N)$ is the mixing angle between the light (heavy) neutrinos belonging to the a- and b-generations, $c_{\varphi_a} = \cos\varphi_a,\ s_{\varphi_a} = \sin\varphi_a$ and so on. Using the eigenvalues equation for the mass matrix we could obtain the relations which connect the YC's with the masses and mixing angles of the neutrinos

$$m_D^a = c_{\varphi_a}s_{\varphi_a}(-m_1c^2_{\theta_\nu} - m_3s^2_{\theta_\nu} + m_2c^2_{\theta_N} + m_4s^2_{\theta_N}), \qquad (19)$$

$$M_D = c_{\varphi_a}s_{\varphi_b}c_{\theta_\nu}s_{\theta_\nu}(m_1 - m_3) + s_{\varphi_a}c_{\varphi_b}c_{\theta_N}s_{\theta_N}(m_4 - m_2), \qquad (20)$$

$$f_{ab}v_R = s_{\varphi_a}s_{\varphi_b}c_{\theta_\nu}s_{\theta_\nu}(m_3 - m_1) + c_{\varphi_a}c_{\varphi_b}c_{\theta_N}s_{\theta_N}(m_4 - m_2), \qquad (21)$$

$$f_{aa}v_R = (s_{\varphi_a}c_{\theta_\nu})^2m_1 + (c_{\varphi_a}c_{\theta_N})^2m_2 + (s_{\varphi_a}s_{\theta_\nu})^2m_3 + (c_{\varphi_a}s_{\theta_N})^2m_4, \qquad (22)$$

$$f_{bb}v_R = (s_{\varphi_b}s_{\theta_\nu})^2m_1 + (c_{\varphi_b}s_{\theta_b})^2m_2 + (s_{\varphi_b}c_{\theta_\nu})^2m_3 + (c_{\varphi_b}c_{\theta_N})^2m_4, \qquad (23)$$

$$m_D^b = m_D^a(\varphi_a \to \varphi_b, \theta_{\nu,N} \to \theta_{\nu,N} + \frac{\pi}{2}), \qquad M'_D = M_D(\varphi_a \leftrightarrow \varphi_b), \qquad (24)$$

The change $L \to R$ in the left-hand sides of Eqs. (21)-(23) results in the replacement $\varphi_{a,b} \to \varphi_{a,b} + \frac{\pi}{2}$ in their right-hand sides. From definition of $f_{aa}v_R$ and $f_{aa}v_L$ follows the exact formula for the heavy-light neutrino mixing angle $\varphi_{a,b}$ [18]

$$\sin 2\varphi_a = 2\frac{\sqrt{f^2_{aa}v_Rv_L - [f_{aa}(v_R + v_L) - m_{\nu_1}c^2_{\theta_\nu} - m_{\nu_2}s^2_{\theta_\nu}](m_{\nu_1}c^2_{\theta_\nu} + m_{\nu_2}s^2_{\theta_\nu})}}{f_{aa}(v_R + v_L) - 2(m_{\nu_1}c^2_{\theta_\nu} + m_{\nu_2}s^2_{\theta_\nu})}, \qquad (25)$$

$$\sin 2\varphi_b = \sin 2\varphi_a\left(f_{aa} \to f_{bb}, \theta_\nu \to \theta_\nu + \frac{\pi}{2}\right). \qquad (26)$$

It should be remarked that according the LRM the heavy-light mixing angles belonging to different generations are practically equal in value

$$\sin 2\varphi_a \simeq \sin 2\varphi_b \simeq 2\frac{\sqrt{v_Rv_L}}{v_R + v_L} \equiv \sin 2\varphi. \qquad (27)$$

In following calculations we also need the Lagrangians which describe interaction of the charged gauge bosons both with the S_1 Higgs boson

$$\sqrt{2}\mathcal{L}^n_W = g^2_L\Big\{k_+[W^*_{1\mu}(x)W^\mu_1(x) + W^*_{2\mu}(x)W^\mu_2(x)] - \frac{2k_1k_2}{k_+}[c_{2\xi}(W^*_{2\mu}(x)W^\mu_1(x) + W^*_{1\mu}(x)W^\mu_2(x)) +$$

$$+ s_{2\xi}(W^*_{2\mu}(x)W_{2\mu}(x) - W^*_{1\mu}(x)W_{1\mu}(x))]\Big\}S_1(x), \qquad (28)$$

and with leptons

$$\mathcal{L}_l^{CC} = \frac{g_L}{2\sqrt{2}}\sum_l \Big[\bar{l}(x)\gamma^\mu(1-\gamma_5)\nu_{lL}(x)W_{L\mu}(x) + \bar{l}(x)\gamma^\mu(1+\gamma_5)N_{lR}(x)W_{R\mu}(x)\Big], \qquad (29)$$

where

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

The theory predicts the following connection between the heavy charged gauge boson mass m_{W_2} ($m_{W_2} \simeq g_L v_R$) and the mixing angle ξ [19]

$$\tan 2\xi \simeq \frac{4g_L g_R k_1 k_2}{g_R^2(2v_R^2 + k_+^2) - g_L^2(2v_L^2 + k_+^2)}. \qquad (30)$$

In Ref. [26] 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 φ_a and φ_b 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 φ_a and φ_b are equal to zero (no mass degeneration case — NMD case); (iii) $\varphi_a = \varphi_b$ and the heavy-heavy neutrino mixing is maximal, $\theta_N = \pi/4$, 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.

3 Decay of the Higgs boson into $\mu\tau$ pair

In this chapter we shall investigate the Higgs decay into the channel

$$S_1 \to \mu^+ + \tau^- \qquad (31)$$

within the LRM. 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. For the sake od simplicity we shall consider the individual contributions of each diagram to the total width of the decay (31). Let us start with the kind of the diagrams one of them shown in Fig.1a. There are eight diagrams 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

$$M_1^{(a)} = \frac{g_L^2 m_D^\tau \cos\alpha\sin 2\theta_N\sin\xi}{32k_+\sqrt{2}}\sqrt{\frac{m_\tau m_\mu}{2m_{S_1}E_\tau E_\mu}}\,\overline{u}(p_1)\gamma_\lambda(1-\gamma_5)\Big\{\int_\Omega \frac{\hat{p}-\hat{k}+m_{\nu_i}}{(p-k)^2-m_{\nu_i}^2}\times$$

$$\times(1+\gamma_5)\left[\frac{\hat{k}+m_{N_2}}{k^2-m_{N_2}^2}-\frac{\hat{k}+m_{N_1}}{k^2-m_{N_1}^2}\right]\gamma_\sigma(1+\gamma_5)\frac{g^{\lambda\sigma}-(k-p_2)^\lambda(k-p_2)^\sigma/m_{W_1}^2}{(k-p_2)^2-m_{W_1}^2}d^4k\Big\}v(p_2), \qquad (32)$$

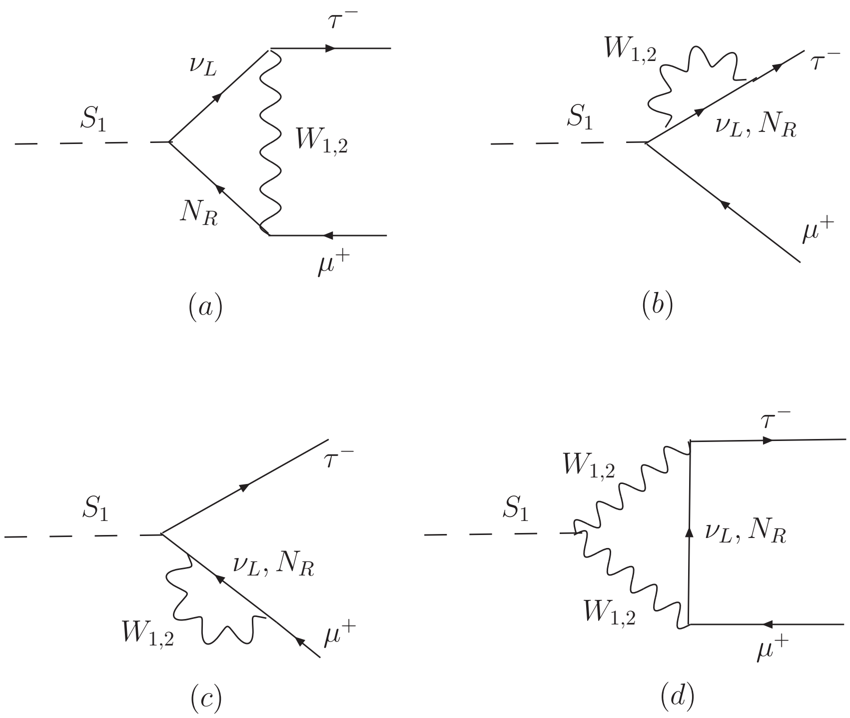

Figure 1: The Feynman diagrams contributing to the decay $S_1 \to \mu^+ + \tau^-$.

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 Eqs. (19), (20) and (24) we find that the matrix element corresponding to all eight diagrams is given by the expression

$$M^{(a)} = \sum_{i=1}^{8} M_i^{(a)} = \frac{g_L^2 \cos\alpha \sin 2\varphi \sin 2\theta_N \sin\xi}{16 k_+ \sqrt{2}} \sqrt{\frac{m_\tau m_\mu}{2 m_{S_1} E_\tau E_\mu}}\, \overline{u}(p_1)\gamma_\lambda(1-\gamma_5)\Big\{ \int_\Omega \frac{\hat{p} - \hat{k} + m_{\nu_i}}{(p-k)^2 - m_{\nu_i}^2} \times$$

$$\times(1+\gamma_5)\left[\frac{m_{N_2}(\hat{k} + m_{N_2})}{k^2 - m_{N_2}^2} - \frac{m_{N_1}(\hat{k} + m_{N_1})}{k^2 - m_{N_1}^2}\right]\gamma_\sigma(1+\gamma_5)\frac{g^{\lambda\sigma} - (k-p_2)^\lambda (k-p_2)^\sigma / m_{W_1}^2}{(k-p_2)^2 - m_{W_1}^2} d^4k \Big\} v(p_2). \tag{33}$$

Substituting (33) 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 and using the procedure of dimensional regularization, we get

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

$$+(m_{S_1}^2 - m_\tau^2 - m_\mu^2)[(\Delta L)^2 + (\Delta R)^2]\Big\}\sqrt{(m_{S_1}^2 - m_\mu^2 - m_\tau^2)^2 - 4m_\mu^2 m_\tau^2}, \qquad (34)$$

where

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

$$\Delta R = R(m_{N_2}) - R(m_{N_1}), \qquad R(m_{N_j}) = \frac{m_{N_j}}{k_+}\Big[R_g(m_{N_j}) + R_W^1(m_{N_j}) + R_W^2(m_{N_j}) +$$

$$+R_W^3(m_{N_j}) + R_W^4(m_{N_j})\Big],$$

$$R_g(m_{N_j}) = 2\int_0^1 xdx \int_0^1 \Big[\frac{(pp_x) - p_x^2}{l_{xy}^j - p_x^2} - 2\ln\left|\frac{l_{xy}^j}{l_{xy}^j - p_x^2}\right|\Big]dy, \qquad (35)$$

$$L_W^1(m_{N_j}) = \frac{2m_\mu m_\tau}{m_W^2}\int_0^1 xdx \int_0^1 \frac{(m_{S_1}^2 - m_\tau^2)(x - xy) - 2(p_2 p_x) + m_\mu^2 x}{l_{xy}^j - p_x^2}dy, \qquad (36)$$

$$R_W^1(m_{N_j}) = -\frac{2m_\mu^2}{m_W^2}\int_0^1 xdx \int_0^1 \frac{(m_{S_1}^2 - m_\tau^2)x + m_\tau^2(x - xy)}{l_{xy}^j - p_x^2}dy, \qquad (37)$$

$$L_W^2(m_{N_j}) = -\frac{2m_\mu m_\tau}{m_W^2}\int_0^1 xdx \int_0^1 \left[-3\ln\left|\frac{l_{xy}^j}{l_{xy}^j - p_x^2}\right| + \frac{(pp_x)(x - xy) - 2p_x^2}{l_{xy}^j - p_x^2}\right]dy, \qquad (38)$$

$$R_W^2(m_{N_j}) = \frac{2}{m_W^2}\int_0^1 xdx \int_0^1 \left[\ln\left|\frac{l_{xy}^j}{l_{xy}^j - p_x^2}\right|(2m_{S_1}^2 - 2m_\tau^2 + m_\mu^2) + \frac{(pp_x)xm_\mu^2 + (m_{S_1}^2 - m_\tau^2)p_x^2}{l_{xy}^j - p_x^2}\right]dy, \qquad (39)$$

$$L_W^3(m_{N_j}) = -\frac{m_\mu m_\tau}{m_W^2}\int_0^1 xdx \int_0^1 \left\{6xy\ln\left|\frac{l_{xy}^j}{l_{xy}^j - p_x^2}\right| + \frac{(2xy - 4x)p_x^2}{l_{xy}^j - p_x^2}\right\}dy, \qquad (40)$$

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

$$\left. + \frac{2p_x^2}{l_{xy}^j - p_x^2}\left[2(pp_x) + m_\mu^2 x - m_\tau^2(x - xy)\right]\right\}dy, \qquad (41)$$

$$R_W^4(m_{N_j}) = \frac{1}{m_W^2}\int_0^1 xdx \int_0^1 \left\{\ln\left|\frac{l_{xy}^j}{l_{xy}^j - p_x^2}\right|(24p_x^2 - 12l_{xy}^j) + p_x^2\left[12 + \frac{2p_x^2}{l_{xy}^j - p_x^2}\right]\right\}dy, \qquad (42)$$

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

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

$$(p_2 p_x) = m_\mu^2 x + \frac{1}{2}(m_{S_1}^2 - m_\mu^2 - m_\tau^2)(x - xy),$$

In the expression (33) we have neglected mixing in the light neutrino sector because of current experiments leads to the results [27]

$$\Delta(m_{21})^2 = \text{few}\times 10^{-5}\ \text{eV}^2, \qquad \Delta(m_{31})^2 = \text{few}\times 10^{-3}\ \text{eV}^2, \qquad \Delta(m_{32})^2 = \text{few}\times 10^{-3}\ \text{eV}^2. \tag{43}$$

Now we proceed to the diagrams of Fig.1b-1d. Calculations show that amongst them the greatest contributions are come from the following two diagrams pictured on Fig.1d. The first diagram contains the $W_2^- W_2^+ N_R$ particles in the virtual states. Its existence is caused by the heavy-heavy neutrino mixing (HHNM) and, as a result, contribution from this diagram turns into zero when $\theta_N = 0$. The second diagram holds the $W_1^- W_1^+ \nu_L$ particles in the virtual states and it leads to nonzero contribution in only case when both the HHNM and the heavy-light neutrino mixing are in existence. It is convenient to consider contributions of these diagrams to the decay width separately. In the case of the HHNM we obtain

$$\Gamma(S_1 \to W_2^{+*} W_2^{-*} N_R^* \to \mu^+\tau^-) = \frac{\pi^3 (g_L^4 k_+ \sin 2\theta_N)^2}{128 m_{S_1}^3}\Big\{4m_\tau m_\mu (\Delta L')(\Delta R') + (m_{S_1}^2 - m_\tau^2 -$$

$$-m_\mu^2)[(\Delta L')^2 + (\Delta R')^2]\Big\}\sqrt{(m_{S_1}^2 - m_\mu^2 - m_\tau^2)^2 - 4m_\mu^2 m_\tau^2}, \tag{44}$$

where the expressions for $\Delta L'$ and $\Delta R'$ are given in Appendix.

The expression for $\Gamma(S_1 \to W_1^{+*} W_1^{-*} \nu_L^* \to \mu^+\tau^-)$ follows from (44) under replacement

$$m_{W_2} \to m_{W_1}, \qquad (\sin 2\theta_N)^2 \to (\sin 2\theta_N \sin^2\varphi)^2. \tag{45}$$

In order to compare the obtained expressions it is necessary to have information concerning the values of such parameters as v_R, ξ, v_L and φ. Let us start with the v_R and ξ. The lower bound obtained by the ATLAS Collaboration on m_{W_2} from dijet searches at $\sqrt{s} = 13$ TeV is [28]

$$m_{W_2} \geq 3.7\ \text{TeV} \qquad \text{at } 95\%\text{C.L.} \qquad \text{with} \qquad L = 37\ \text{fb}^{-1}, \tag{46}$$

to give $v_R \simeq 5.7$ TeV. Since current experimental limits on the mixing angle ξ fall in the broad range between 0.12 and 0.0006 (see, for review [27]), then for definition of ξ one needs to use the relation (30) which is predicted by the LRM. Using $v_R = 5.7$ TeV we get $\xi \simeq 5 \times 10^{-4}$. In what follows we shall use this very value for the mixing angle ξ.

As far as the value of the heavy-light neutrino mixing angle φ is concerned, there are a lot of papers devoted to determination of experimental bounds on it (see, for example [29] and references therein). One way to find such bounds is connected with searches for the neutrinoless double beta decay ($0\nu\beta\beta$) and disentangle the heavy neutrino effect. In Ref. [30] considering the case of ^{76}Ge, the following expression was obtained

$$\Big|\sum_i \frac{U_{ei}^2}{m_{N_i}}\Big| < \frac{7.8\times 10^{-8}}{m_p}\left[\frac{104}{\mathcal{M}_{0\nu}(\text{Ge})}\right] \times \left[\frac{3\times 10^{25}\ \text{yr}}{\tau_{1/2}^{0\nu}}\right]^{1/2}, \tag{47}$$

where $\mathcal{M}_{0\nu}(\mathrm{Ge})$ is is the nuclear matrix element, m_p is the proton mass and $\tau^{0\nu}_{1/2}$ is the half-life for $0\nu\beta\beta$. However, there is the point of view that the $0\nu\beta\beta$ does not give the reliable answer on the value of the heavy-light mixing. Of course, the main uncertainties are connected with the determination of nuclear matrix element. In its calculation one should assume the definite values both for the axial coupling constants of the nucleon g_A and for the phase space factor. For example, when $g_A = g_{\mathrm{nucleon}} = 1.269$ and $g_A = g_{\mathrm{phen.}} = g_{\mathrm{nucleon}} \times A^{-0.18}$ (A is the atomic number) the $\mathcal{M}_{0\nu}(\mathrm{Ge})$ takes the values 104 ± 29 and 22 ± 6, respectively. Note, the $g_A = g_{\mathrm{phen.}}$ parametrization as a function of A comes directly from the comparison between the theoretical half-life for $2\nu\beta\beta$ and its observation in different nuclei [31]. Using $\tau^{0\nu}_{1/2}(^{76}\mathrm{Ge}) = 1.9 \times 10^{25}$ yr and setting $m_N = 100$ GeV, with the help of Eq. (47) we may get

$$(\sin\varphi)_{\max} \simeq \begin{cases} 3.2 \times 10^{-3} & \text{when} \quad g_A = g_{\mathrm{nucleon}}, \\ 7 \times 10^{-3} & \text{when} \quad g_A = g_{\mathrm{phen.}}. \end{cases}$$

The other way is to directly look for the presence of the heavy-light neutrino mixing, which can manifest in several ways, for example, (i) via departures from unitarity of the neutrino mixing matrix, which could be investigated in neutrino oscillation experiments as well as in lepton flavor violation searches, and (ii) via their signatures in collider experiments. To take an illustration, in Ref. [32] the final states with same-sign dileptons plus two jets without missing energy ($l^\pm l^\pm jj$), arising from pp collisions were considered. This signal depends crucially on the heavy-light neutrino mixing. Analysis of the channel

$$p + p \to N_l^* l^\pm \to l^\pm + l^\pm + 2j \tag{48}$$

led to the upper limit on $\sin\varphi$ equal to 3.32×10^{-2} for $m_{W_R} = 4$ TeV and $m_{N_l} = 100$ GeV. On the other hand to evaluate φ we could use the relation (27) as well. The precision measurements of the electroweak ρ parameter [33]

$$\rho = \frac{m^2_{Z_1}\cos^2\theta_W}{m^2_{W_1}} = \frac{1+4x}{1+2x} \tag{49}$$

($x = (v_L/k_+)^2$) set an upper bound on the VEV of $v_L \leq 3$ GeV. Taking into account this value we obtain

$$(\sin 2\varphi)_{\max} \simeq 4.6 \times 10^{-2}. \tag{50}$$

Setting

$$\left.\begin{array}{lll} \theta_N = \frac{\pi}{4}, & m_{N_1} = 140 \text{ GeV}, & m_{N_2} = 250 \text{ GeV}, \\ \sin\alpha = 0.44, & \sin\xi = 5 \times 10^{-4}, & \sin\varphi = 2.3 \times 10^{-2}, \end{array}\right\} \tag{51}$$

we get

$$\frac{\Gamma(S_1 \to \nu_L^* N_R^* W_1^* \to \mu^+\tau^-)}{\Gamma(S_1 \to W_1^* W_1^* \nu_L^* \to \mu^+\tau^-)} \simeq 10^5, \qquad \frac{\Gamma(S_1 \to \nu_L^* N_R^* W_1^* \to \mu^+\tau^-)}{\Gamma(S_1 \to W_2^* W_2^* N_R^* \to \mu^+\tau^-)} \simeq 10^4. \tag{52}$$

So, the main contribution to the decay $S_1 \to \mu^+ + \tau^-$ comes from the diagram of Fig.1a.

In order to obtain the width of the decay

$$S_1 \to \mu^- + \tau^+ \tag{53}$$

one should make in Eqs. (34) 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 (51) we get

$$\mathrm{BR}(S_1 \to \tau^-\mu^+) \simeq \begin{cases} 0.24 \times 10^{-4}, & \text{when} \quad \sin\varphi = 2.3 \times 10^{-2}, \\ 0.45 \times 10^{-6}, & \text{when} \quad \sin\varphi = 3.2 \times 10^{-3}. \end{cases} \tag{54}$$

So, we see that at most the obtained expression is two orders of magnitude less than the current experimental upper bound being equal to 0.25×10^{-2}.

4 Conclusion

Within the left-right symmetric model (LRM) the decays of the neutral Higgs boson S_1

$$S_1 \to \mu^+ + \tau^-, \qquad S_1 \to \mu^- + \tau^+ \tag{55}$$

where S_1 is an analog of the standard model (SM) Higgs boson, have been considered. These decays go with the lepton flavor violation (LFV) and, as result, are forbidden in the SM.

We have found the widths of the decays (55) in the third order of the perturbation theory. The width of this decay does not equal to zero only provided the heavy neutrino masses are hierarchical. It was shown that the main contribution to the decay width is caused by the diagram with the light and heavy neutrinos in the virtual state. Therefore, investigation of these decays could give information about the neutrino sector structure of the model under study.

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

$$\sin\xi \le 5 \times 10^{-4}, \qquad \sin\varphi \le 2.3 \times 10^{-2}. \tag{56}$$

However, even using the upper bounds on $\sin\xi$ and $\sin\varphi$ one does not manage to get for the branching ratio $\mathrm{BR}(S_1 \to \tau\mu)$ the value being equal to upper experimental bound 0.25×10^{-2}. The theoretical expression for the branching ratio of the decay $S_1 \to \tau\mu$ proves to be on two orders of magnitude less than the upper experimental bound. On the other hand, it should be remembered that in our case $\mathrm{BR}(S_1 \to \tau\mu)_{exp}$ 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 $S_1 \to \tau\mu$.

At future hadronic and leptonic colliders 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 [34, 35]. These large numbers provide an upgrading of sensitivities to $\mathrm{BR}(S_1 \to l_k\bar{l}_m)_{exp}$ of at least two orders of magnitude with respect to the present sensitivity. In much the same way, at the planned lepton colliders, similar to the international linear collider with $\sqrt{s} = 1$ TeV and $\sqrt{s} = 2.5$ TeV [36], and the future electron-positron circular collider, formerly known as TLEP, with $\sqrt{s} = 350$ GeV and 10 ab^{-1} [37], the expectations are of about 1 and 2 million Higgs boson events, respectively, with much lower backgrounds owing to the cleaner environment, which will also allow for a large improvement in LFV Higgs boson decay searches regarding to the current sensitivities.

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Appendix

The terms appearing in the width of the decay

$$S_1 \to W_2^{+*}W_2^{-*}N_R^* \to \mu^+\tau^-$$

are as follows:

$$\Delta L' = L'(m_{N_2}) - L'(m_{N_1}), \qquad L'(m_{N_j}) = L'_g(m_{N_j}) + \sum_{i=1}^{7} L'^i_W(m_{N_j}),$$

$$\Delta R' = R'(m_{N_2}) - R'(m_{N_1}), \qquad R'(m_{N_j}) = R'_g(m_{N_j}) + \sum_{i=1}^{7} R'^i_W(m_{N_j}),$$

$$L'_g(m_{N_j}) = 2m_\mu \int_0^1 x(x-1)dx \int_0^1 \frac{dy}{\beta^j_{xy} - q_x^2}, \qquad R'_g(m_{N_j}) = -2m_\tau \int_0^1 x^2 dx \int_0^1 \frac{ydy}{\beta^j_{xy} - q_x^2}, \tag{A.1}$$

$$R'^1_W(m_{N_j}) = -\frac{m_\tau}{m_W^2} \int_0^1 x^2 dx \int_0^1 ydy\Big\{6\ln\Big|\frac{l^j_{xy}}{l^j_{xy}-p_x^2}\Big| + 2[p_x^2 - 2(p_x p_2)]\frac{1}{l^j_{xy}-p_x^2}\Big\}, \tag{A.2}$$

$$L'^1_W(m_{N_j}) = \frac{2m_\mu}{m_W^2} \int_0^1 xdx \int_0^1 dy\Big\{(3x+1)\ln\Big|\frac{l^j_{xy}}{l^j_{xy}-p_x^2}\Big| + [p_x^2(x+1) - 2(p_x p_2)x]\frac{1}{l^j_{xy}-p_x^2}\Big\}, \tag{A.3}$$

$$R'^2_W(m_{N_j}) = \frac{m_\tau}{m_W^2} \int_0^1 xdx \int_0^1 dy\Big\{m_{S_1}^2 xy + [(m_\mu^2 - m_{S_1}^2 - m_\tau^2)xy + (m_\tau^2 - m_{S_1}^2 - m_\mu^2)(x-1)]\Big\}\frac{1}{l^j_{xy}-p_x^2}, \tag{A.4}$$

$$L'^2_W(m_{N_j}) = -\frac{m_\mu}{m_W^2} \int_0^1 xdx \int_0^1 dy\Big\{m_{S_1}^2 (x-1) + [(m_\mu^2 - m_{S_1}^2 - m_\tau^2)xy + (m_\tau^2 - m_{S_1}^2 - m_\mu^2)(x-1)\Big\}\frac{1}{l^j_{xy}-p_x^2}, \tag{A.5}$$

$$R'^3_W(m_{N_j}) = \frac{m_\tau}{m_W^2} \int_0^1 xdx \int_0^1 dy\Big[4\ln\Big|\frac{l^j_{xy}}{l^j_{xy}-p_x^2}\Big| + \frac{2p_x^2 - 2(p_x p_2) - 2(pp_2)xy}{l^j_{xy}-p_x^2}\Big], \tag{A.6}$$

$$L'^3_W(m_{N_j}) = -\frac{m_\mu}{m_W^2} \int_0^1 xdx \int_0^1 dy\Big[4\ln\Big|\frac{l^j_{xy}}{l^j_{xy}-p_x^2}\Big| + \frac{2p_x^2 - 2(p_x p_2) - 2(pp_2)x + 2(p_x p)}{l^j_{xy}-p_x^2}\Big], \tag{A.7}$$

$$R'^4_W(m_{N_j}) = \frac{m_\tau}{4m_W^4} \int_0^1 x^2 dx \int_0^1 ydy\{[80p_x^2 - 48l^j_{xy} - 32(p_x p_2)]\ln\Big|\frac{l^j_{xy}}{l^j_{xy}-p_x^2}\Big| +$$
$$+\frac{p_x^2}{l^j_{xy}-p_x^2}[4p_x^2 - 8(p_x p_2)]\Big\}, \tag{A.8}$$

$$L'^4_W(m_{N_j}) = -\frac{m_\mu}{4m_W^4} \int_0^1 xdx \int_0^1 dy\Big\{[(80p_x^2 - 48l^j_{xy})x + 32p_x^2 - 12l^j_{xy} - 32(p_x p_2)x]\ln\Big|\frac{l^j_{xy}}{l^j_{xy}-p_x^2}\Big| +$$
$$+12p_x^2 + \frac{4p_x^2}{l^j_{xy}-p_x^2}[p_x^2(x+1) - 2(p_x p_2)x]\Big\}, \tag{A.9}$$

$$R'^5_W(m_{N_j}) = \frac{m_\tau}{2m_W^4} \int_0^1 xdx \int_0^1 dy\{[12l^j_{xy} - 24p_x^2 + 6(m_{S_1}^2 - m_\tau^2)xy + 6m_\mu^2 x]\ln\Big|\frac{l^j_{xy}}{l^j_{xy}-p_x^2}\Big| +$$
$$+\frac{2p_x^2}{l^j_{xy}-p_x^2}[(m_{S_1}^2 - m_\tau^2)xy + m_\mu^2 x - p_x^2] - 12p_x^2\Big\}, \tag{A.10}$$

$$L'^5_W(m_{N_j}) = \frac{m_\mu}{2m_W^4} \int_0^1 xdx \int_0^1 dy\Big\{[24p_x^2 - 12l^j_{xy} + 6m_\tau^2 xy - 6m_\mu^2 x]\ln\Big|\frac{l^j_{xy}}{l^j_{xy}-p_x^2}\Big| +$$
$$+12p_x^2 + \frac{2p_x^2}{l^j_{xy}-p_x^2}[p_x^2 + m_\tau^2 xy - m_\mu^2 x]\Big\}. \tag{A.11}$$

$$R'^6_W(m_{N_j}) = \frac{m_\tau}{2m_W^4} \int_0^1 xdx \int_0^1 dy\Big\{[3l^j_{xy} - 4p_x^2 - 8(p_x p)xy + 2(p_x p_2) + 2(pp_2)xy]\ln\Big|\frac{l^j_{xy}}{l^j_{xy}-p_x^2}\Big| +$$

$$+\frac{2(p_xp)}{l^j_{xy}-p^2_x}[2(p_xp_2)-p^2_x]xy-3p^2_x\Big\}, \quad (A.12)$$

$$L'^6_W(m_{N_j})=\frac{m_\mu}{2m^4_W}\int_0^1 xdx\int_0^1 dy\Big\{[4p^2_x-3l^j_{xy}+8(p_xp)x-2(p_xp_2)-2(pp_2)x+4(p_xp)]\ln\Big|\frac{l^j_{xy}}{l^j_{xy}-p^2_x}\Big|+$$

$$+3p^2_x+\frac{2(p_xp)}{l^j_{xy}-p^2_x}[p^2_xx+p^2_x-2(p_xp_2)x]\Big\}, \quad (A.13)$$

$$R'^7_W(m_{N_j})=\frac{m_\tau}{2m^4_W}\int_0^1 xdx\int_0^1 dy\Big\{[6(p_xp)-m^2_{S_1}-m^2_\mu+m^2_\tau]\ln\Big|\frac{l^j_{xy}}{l^j_{xy}-p^2_x}\Big|-$$

$$-\frac{2(p_xp)}{l^j_{xy}-p^2_x}[(m^2_{S_1}-m^2_\tau)xy+m^2_\mu x]\Big\}, \quad (A.14)$$

$$L'^7_W(m_{N_j})=-\frac{m_\mu}{2m^4_W}\int_0^1 xdx\int_0^1 dy\Big\{[6(p_xp)+m^2_\tau-m^2_\mu]\ln\Big|\frac{l^j_{xy}}{l^j_{xy}-p^2_x}\Big|+$$

$$+\frac{2(p_xp)}{l^j_{xy}-p^2_x}[m^2_\tau xy-m^2_\mu x]\Big\}, \quad (A.15)$$

$$\beta^j_{xy}=yx(m^2_{S_1}-m^2_{W_2}-m^2_\mu+m^2_{N_j})+x(m^2_{W_2}+m^2_\mu-m^2_{N_j})-m^2_{W_2}, \quad (A.16)$$

$$q^2_x=x^2[m^2_\tau y^2+y(m^2_{S_1}-m^2_\mu-m^2_\tau)+m^2_\mu]. \quad (A.17)$$

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