Abstract

We assume that a massive Dirac neutrino is characterized by two phenomenological parameters, a magnetic moment, and a charge radius, and we calculate the cross-section of the scattering $e^+e^- \rightarrow \nu\bar{\nu}$ in a left-right symmetric model. We also analyze the angular distribution of the neutrino (antineutrino) with respect to the original direction of the electron (positron) to different state of helicity of the neutrino. We find that the favored directions for the neutrino (antineutrino) with respect to the electron (positron) is forward ($\theta = 0$) and backward ($\theta = \pi$), and is not very probable in the perpendicular direction ($\theta = \pi/2$). The calculation is for $\phi = -0.005$ and $M_{Z_2} = 500 \text{ GeV}$, parameters of the Left-Right symmetric model.

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I. INTRODUCTION

Of all the particles of the Standard Model (SM) [1], neutrinos are the least known. Because they are treated as massless particles, the physical phenomena associated with them are rather limited. On the other hand, in case of massive neutrinos, which are predicted by some Grand Unified Theories [2], several new effects can occur. Massive neutrinos open up the possibility of a variety of new physical phenomena.

Neutrinos seem to be likely candidates for carrying features of physics beyond the standard model. Not only masses and mixings, but also charge radius, magnetic moment and electric dipole moment [3,4] are signs of new physics, and are of relevance in terrestrial experiments, the solar neutrino problem [5,6], astrophysics and cosmology [7,8].

When the explosion of the Supernova 1987 A (SN 1987 A) occurred, the astrophysics of neutrinos was born. The observation of neutrinos from SN 1987 A [9,10], in fair agreement with predictions from supernova models, has been used by several authors to bound the properties and interactions of various exotic and non-exotic particles [11]. The experimental observation of SN 1987 A launched several new searches for supernova neutrinos. Besides specially developed detectors, basically all new real-time solar neutrino detectors like Super-Kamiokande, ICARUS and SNO will be able to see such neutrinos.

Thus we can conclude that, the study of the neutrino continues to be the subject of current research, both theoretical and experimental.

At the present time, all the available experimental data for electroweak processes can be well understood in the context of the Standard Model of the electroweak interactions (SM) [1], except the results of the Super-Kamiokande experiment on the neutrino mass [12]. Hence, the SM is the starting point of all the extended gauge models. In other words, any gauge group with physical sense must have as a subgroup the $SU(2)_L \times U(1)$ group of the standard model, in such a way that their predictions agree with those of the SM at low energies. The purpose of the extended theories is to explain some fundamental aspects which are not clarified in the framework of the SM. One of these aspects is the origin of the
parity violation at the current energies. The Left-Right Symmetric Model (LRSM) based on the $SU(2)_R \times SU(2)_L \times U(1)$ gauge group [13] gives an answer to that problem, since it restores the parity symmetry at high energies and gives its violations at low energies as a result of the breaking of gauge symmetry. Detailed discussions on LRSM can be found in the literature [13–16].

Although in the framework of the SM, neutrinos are assumed to be electrically neutral. Electromagnetic properties of the neutrino are discussed in many gauge theories beyond the SM. Electromagnetic properties of the neutrino may manifest themselves in a magnetic moment of the neutrino as well as in a non-vanishing charge radius, both making the neutrino subject to the electromagnetic interaction.

In this paper, we start from a Left-Right Symmetric Model (LRSM) with massive Dirac neutrinos left and right-handed, with an electromagnetic structure that consists of a charge radius $\langle r^2 \rangle$ and of an anomalous magnetic moment $\mu_\nu$, and we calculated the total cross-section of the scattering $e^+e^- \rightarrow \nu\bar{\nu}$. We emphasize here the simultaneous contribution of the charge radius, of the anomalous magnetic moment as well as of the additional $Z_2$ heavy gauge boson, and of the mixing angle $\phi$ parameters of the LRSM to the cross-section. The Feynman diagrams which contribute to the process $e^+e^- \rightarrow \nu\bar{\nu}$ are shown in Fig. 1. We also analyzed the angular distribution of the neutrino (antineutrino) with respect to the original direction of the electron (positron) to different state of helicity of the neutrino. We find that the directions of the neutrino (antineutrino) with respect to the electron (positron) is forward ($\theta = 0$) and backward ($\theta = \pi$), and is not very probable in the perpendicular direction ($\theta = \frac{\pi}{2}$).

This paper is organized as follows. In Sec. II we carry out the calculations of the process $e^+e^- \rightarrow \nu\bar{\nu}$. In Sec. III we present the expressions for the helicities. In Sec. IV we achieve the numerical computations. Finally, we summarize our results in Sec. V.
II. THE ELECTRON POSITRON-NEUTRINO ANTINEUTRINO SCATTERING

In this section we obtain in the context of the LRSM the cross-section of the process

\[ e^- (p_1) + e^+ (p_2) \rightarrow \bar{\nu}(k_1, \lambda_1) + \nu(k_2, \lambda_2), \]  

(1)

here \( p_1, p_2, k_1, \) and \( k_2 \) are the particle momenta and \( \lambda_1 (\lambda_2) \) is the neutrino (antineutrino) helicity.

We will assume that a massive Dirac neutrino is characterized by two phenomenological parameters, a magnetic moment \( \mu_\nu \), expressed in units of the electron Bohr magnetons, and a charge radius \( \langle r^2 \rangle \). Therefore, the expression for the amplitude \( \mathcal{M} \) of the process \( e^- e^+ \rightarrow \nu \bar{\nu} \) Eq. (1) due only to \( \gamma \) and \( Z^0 \) exchange, according to the diagrams depicted in Fig. 1 is given by

\[ \mathcal{M}_\gamma = -i e^2 \bar{\nu}(k_2, \lambda_2) \frac{\Gamma^{\mu}}{q^2} \nu(k_1, \lambda_1) \bar{e}(p_2) \gamma^{\mu} e(p_1), \]  

(2)

with

\[ \Gamma^{\mu} = e F_1(q^2) \gamma^{\mu} - \frac{i e}{2 m_\nu} F_2(q^2) \sigma^{\mu \nu} q_\nu, \]  

(3)

the neutrino electromagnetic vertex, where \( q \) is the momentum transfer and \( F_{1,2}(q^2) \) are the electromagnetic form factors of the neutrino. Explicitly [6]

\[ F_1(q^2) = \frac{1}{6} q^2 \langle r^2 \rangle, \]

\[ F_2(q^2) = -\mu_\nu \frac{m_\nu}{m_e}, \]

where, as already mentioned, \( \langle r^2 \rangle \) is the neutrino mean-square charge radius and \( \mu_\nu \) the anomalous magnetic moment. Therefore

\[ \mathcal{M}_\gamma = -i e^2 \frac{q^2}{q^2} [F \bar{\nu}(k_2, \lambda_2) \gamma^{\mu} \nu(k_1, \lambda_1) \bar{e}(p_2) \gamma^{\mu} e(p_1) + G K^{\mu} \bar{\nu}(k_2, \lambda_2) \nu(k_1, \lambda_1) \bar{e}(p_2) \gamma^{\mu} e(p_1)], \]  

(4)

with
\[ F = F_1 + iF_2, \quad G = -i \frac{F_2}{2m_\nu}, \quad \text{and} \quad K^\mu = (k_2 - k_1)^\mu. \]

Furthermore

\[ M_{Z^0} = -i \frac{g^2}{8c_W^2 (q^2 - M_{Z^0}^2)} [P \bar{\nu}(k_2, \lambda_2) \gamma^\mu \nu(k_1, \lambda_1) \bar{e}(p_2) \gamma_\mu e(p_1) + Q \bar{\nu}(k_2, \lambda_2) \gamma^\mu \gamma_5 \nu(k_1, \lambda_1) \bar{e}(p_2) \gamma_\mu e(p_1) + R \bar{\nu}(k_2, \lambda_2) \gamma^\mu \nu(k_1, \lambda_1) \bar{e}(p_2) \gamma_\mu \gamma_5 e(p_1)] \tag{5} \]

where

\[ P = (A + 2B + C)g_V, \]
\[ Q = (-A + C)g_A, \tag{6} \]
\[ R = (-A + C)g_V, \]
\[ S = (A - 2B + C)g_A, \]

the constants \( A, B \) and \( C \) depend only on the LRSM, and are given by [17]

\[ A = a^2 + \Gamma c^2 = (c_\phi - \frac{s_W^2}{r_W} s_\phi)^2 + \Gamma (\frac{s_W^2}{r_W} c_\phi + s_\phi)^2, \]
\[ B = ab + \Gamma cd = (c_\phi - \frac{s_W^2}{r_W} s_\phi)(-\frac{c_W^2}{r_W} s_\phi) + \Gamma (\frac{s_W^2}{r_W} c_\phi + s_\phi)(\frac{c_W^2}{r_W} c_\phi), \]
\[ C = b^2 + \Gamma d^2 = (\frac{c_W^2}{r_W} s_\phi)^2 + \Gamma (\frac{c_W^2}{r_W} c_\phi)^2, \]

with

\[ \Gamma = \frac{q^2 - M_{Z^0}^2}{q^2 - M_{Z^0}^2}. \]

While \( g_V = -\frac{1}{2} + 2 \sin^2 \theta_W \) and \( g_A = -\frac{1}{2} \), according to the experimental data [18].

The square of the amplitude is obtained by sum over spin states of the final fermions, so

\[ \sum_{s_p} |M_T|^2 = \sum_{s_p} |M_\gamma + M_{Z^0}|^2 = \sum_{s_p} (|M_\gamma|^2 + |M_{Z^0}|^2 + M_{Z^0} M_\gamma^\dagger + M_{Z^0}^\dagger M_\gamma), \tag{7} \]

where:
\[
\sum_{sp}|M_{\gamma}|^2 = 4H_1E^4\{(F_1^2 + F_2^2)(1 + x^2)(1 - \lambda_\nu\lambda_\nu) \\
- 2F_2^2(x^2 - 1 - \lambda_\nu\lambda_\nu) + \frac{E^2}{m_\nu}F_2^2(1 - x^2)(1 + \lambda_\nu\lambda_\nu)\}, \quad (8)
\]

\[
\sum_{sp}|M_{Z^0}|^2 = 4H_2E^4\{(P^2 + Q^2 + R^2 + S^2)(1 + x^2)(1 - \lambda_\nu\lambda_\nu) \\
+ 4x(PS + QR)(1 - \lambda_\nu\lambda_\nu) + 2(PR + QS)(1 + x^2)(\lambda_\nu - \lambda_\nu) \\
+ 4x(PR + QS)(\lambda_\nu - \lambda_\nu)\}, \quad (9)
\]

\[
\sum_{sp}(M_{Z^0}\mathcal{M}_\gamma + \mathcal{M}_{Z^0}\mathcal{M}_\gamma) = 8H_3E^4\{F_1[P(1 + x^2)(1 - \lambda_\nu\lambda_\nu) + Q(1 + x^2)(\lambda_\nu - \lambda_\nu) \\
+ 2xR(\lambda_\nu - \lambda_\nu) + 2xS(1 - \lambda_\nu\lambda_\nu)] \\
+ F_2[P(2 - \lambda_\nu\lambda_\nu) - \frac{1}{2}x^2 + Q(\lambda_\nu - \lambda_\nu)(1 - \frac{1}{2}x^2) \\
+ \frac{3}{2}xR(\lambda_\nu - \lambda_\nu) + xS(2 - \lambda_\nu\lambda_\nu)]\}, \quad (10)
\]

with

\[
H_1 = \frac{e^4}{q^4}, \quad H_2 = \frac{g^4}{64e^4W(s - M_{Z^0}^2)^2}, \quad H_3 = \frac{e^2g^2}{8e^4W^2(q^2 - M_{Z^0}^2)},
\]

and \(x = \cos \theta\), where \(\theta\) is the scattering angle.

In the expressions (8), (9), and (10) the simultaneous contribution of the anomalous magnetic moment, of the charge radius electroweak, of the heavy gauge boson \(Z^0_R\) and of the mixing angle \(\phi\) are observed.

The scattering cross-section in the center of mass system (where \(s\) is the square of the center-of-mass energy) is given by

\[
\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2s} \sum_{sp} |\mathcal{M}_T|^2, \quad (11)
\]

where the square of the total amplitude of transition \(\sum_{sp}|\mathcal{T}||^2\) is given in the Eq. (7).

The differential cross-section to each contribution is

\[
\left(\frac{d\sigma}{d\Omega}\right)_\gamma = \frac{\alpha^2}{16s}\mathcal{F}_1(F_1, F_2, E, m_\nu, \lambda_\rho, \lambda_\nu, x), \quad (12)
\]
\[
\left(\frac{d\sigma}{d\Omega}\right)_{Z^0} = \frac{\alpha^2}{64s}\mathcal{R}_2^2(s)\mathcal{F}_2(P, Q, R, S, \lambda_\rho, \lambda_\nu, x), \quad (13)
\]
\[
\left(\frac{d\sigma}{d\Omega}\right)_{Z^0} = \frac{\alpha^2}{16s}\mathcal{R}_1(s)\mathcal{F}_3(F_1, F_2, P, Q, R, S, \lambda_\rho, \lambda_\nu, x), \quad (14)
\]
so that the total cross-section is

\[
\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{16s} \mathcal{F}_1(F_1, F_2, E, m_\nu, \lambda_\nu, \bar{\lambda}_\nu, x) \\
+ \frac{\alpha^2}{64s} R_1^2(s) \mathcal{F}_2(P, Q, R, S, \lambda_\nu, \bar{\lambda}_\nu, x) \\
+ \frac{\alpha^2}{16s} R_1(s) \mathcal{F}_3(F_1, F_2, P, Q, R, S, \lambda_\nu, \bar{\lambda}_\nu, x),
\]

(15)

where

\[
R_1(s) = \frac{s}{\sin^2 2\theta_W(s - M_{Z_1}^2)},
\]

(16)
is the factor of resonance.

The kinematics to each contribution to be contained in the functions

\[
\gamma : \mathcal{F}_1 = (F_1^2 + F_2^2)(1 + x^2)(1 - \lambda_\nu \lambda_\nu) - 2F_2^2(x^2 - 1 - \lambda_\nu \lambda_\nu) \\
+ \frac{E^2}{m_{\phi}^2} F_2^2(1 - x^2)(1 + \lambda_\nu \lambda_\nu),
\]

(17)

\[
Z^0 : \mathcal{F}_2 = (P^2 + Q^2 + R^2 + S^2)(1 + x^2)(1 - \lambda_\nu \lambda_\nu) \\
+ 4x(PS + QR)(1 - \lambda_\nu \lambda_\nu) + 2(PQ + RS)(1 + x^2)(\lambda_\nu - \bar{\lambda}_\nu) \\
+ 4x(PR + QS)(\lambda_\nu - \bar{\lambda}_\nu),
\]

(18)

\[
\gamma Z^0 : \mathcal{F}_3 = F_1[P(1 + x^2)(1 - \lambda_\nu \lambda_\nu) + Q(1 + x^2)(\lambda_\nu - \lambda_\phi) \\
+ 2xR(\lambda_\nu - \lambda_\phi) + 2xS(1 - \lambda_\nu \lambda_\phi)] \\
+ F_2[P(2 - \lambda_\nu \lambda_\nu x^2) + Q(\lambda_\nu - \lambda_\phi)(1 - \frac{1}{2} x^2) \\
+ \frac{3}{2} xR(\lambda_\nu - \lambda_\phi) + xS(2 - \lambda_\nu \lambda_\nu)],
\]

(19)

where explicitly P, Q, R, and S are

\[
P = [(c_\phi - \frac{s_\phi}{r_W})^2 + \Gamma(s_\phi + \frac{c_\phi}{r_W})^2]g_V, \\
Q = (c_{2\phi} - \frac{s_{2\phi}^2}{r_W})(\Gamma - 1)g_A, \\
R = (c_{2\phi} - \frac{s_{2\phi}^2}{r_W})(\Gamma - 1)g_V, \\
S = [(c_\phi + r_W s_\phi)^2 + \Gamma(s_\phi - r_W c_\phi)^2]g_A.
\]

(20)
III. FORMULAS FOR THE HELICITIES

A. Formulas with right currents

We only take the part of interference Eq. (14) for the analysis. To simplify, we define the functions $H_1$ and $H_2$ from the following manner

\[ F = F_1 H_1(\phi, M_{Z^0}, x, \lambda_\nu, \lambda_\nu)_{LRSM} + F_2 H_2(\phi, M_{Z^0}, x, \lambda_\nu, \lambda_\nu)_{LRSM}, \]  

(21)

where

\[ H_1(\phi, M_{Z^0}, x, \lambda_\nu, \lambda_\nu)_{LRSM} = R_1(s)\left[ P(1 + x^2)(1 - \lambda_\nu \lambda_\nu) + Q(1 + x^2)(\lambda_\nu - \lambda_\nu) \right. \]
\[ \left. + 2xR(\lambda_\nu - \lambda_\nu) + 2xS(1 - \lambda_\nu \lambda_\nu) \right], \]  

(22)

\[ H_2(\phi, M_{Z^0}, x, \lambda_\nu, \lambda_\nu)_{LRSM} = R_1(s)\left[ P(2 - \lambda_\nu \lambda_\nu x^2) + Q(1 - \frac{x^2}{2})(\lambda_\nu - \lambda_\nu) \right. \]
\[ \left. + \frac{3}{2}xR(\lambda_\nu - \lambda_\nu) + xS(2 - \lambda_\nu \lambda_\nu) \right], \]  

(23)

these functions depend on the parameters of the LRSM, on the helicities of the neutrino and on the scattering angle.

From Eqs. (22) and (23) we consider four combinations of helicities for the neutrino (antineutrino), obtaining the following:

**Case 1**

Neutrino and antineutrino with positive helicity

\[ H_1(\phi, M_{Z^0}, x, \lambda_\nu = \lambda_\nu = 1)_{LRSM} = 0, \]
\[ H_2(\phi, M_{Z^0}, x, \lambda_\nu = \lambda_\nu = 1)_{LRSM} = R_1(s)[P(2 - x^2) + Sx]. \]  

(24)

**Case 2**

Neutrino and antineutrino with negative helicity

\[ H_1(\phi, M_{Z^0}, x, \lambda_\nu = \lambda_\nu = -1)_{LRSM} = 0, \]
\[ H_2(\phi, M_{Z^0}, x, \lambda_\nu = \lambda_\nu = -1)_{LRSM} = R_1(s)[P(2 - x^2) + Sx]. \]  

(25)
Case 3
Neutrino with positive helicity and antineutrino with negative helicity

\( \mathcal{H}_1(\phi, M_{Z^0}, x, \lambda_\nu = -1, \lambda_\bar{\nu} = 1)_{LRSM} = R_1(s)[2(P + Q)(1 + x^2) + 4x(R + S)], \)

\( \mathcal{H}_2(\phi, M_{Z^0}, x, \lambda_\nu = -1, \lambda_\bar{\nu} = 1)_{LRSM} = R_1(s)[P(2 + x^2) + Q(2 - x^2) + 3x(R + S)]. \)  

(26)

Case 4
Neutrino with negative helicity and antineutrino with positive helicity

\( \mathcal{H}_1(\phi, M_{Z^0}, x, \lambda_\nu = 1, \lambda_\bar{\nu} = -1)_{LRSM} = R_1(s)[2(P - Q)(1 + x^2) - 4x(R - S)], \)

\( \mathcal{H}_2(\phi, M_{Z^0}, x, \lambda_\nu = 1, \lambda_\bar{\nu} = -1)_{LRSM} = R_1(s)[P(2 + x^2) - Q(2 - x^2) - 3x(R - S)]. \)  

(27)

B. Formulas without right currents

In this case we calculate the functions \( \mathcal{H}_1 \) and \( \mathcal{H}_2 \) in the absence of right currents. This is obtained taking the limit when the mixing angle \( \phi = 0 \) and \( M_{Z^0} \to \infty \) so that \( \Gamma \to 0 \). In this limit \( P = g_V, Q = -g_A, R = -g_V, S = g_A \) and the functions \( \mathcal{H}_1 \) and \( \mathcal{H}_2 \) Eqs. (22) and (23) take the form

\[
\mathcal{H}_1(x, \lambda_\nu, \lambda_\bar{\nu}) = R_1(s)[\{g_V(1 + x^2) + 2xg_A\}(1 - \lambda_\nu\lambda_\bar{\nu}) \\
-\{g_A(1 + x^2) + 2xg_V\}(\lambda_\nu - \lambda_\bar{\nu})],
\]

(28)

\[
\mathcal{H}_2(x, \lambda_\nu, \lambda_\bar{\nu}) = R_1(s)[g_V(2 - \lambda_\nu\lambda_\bar{\nu}x^2) - g_A(1 - \frac{x^2}{2})(\lambda_\nu - \lambda_\bar{\nu}) \\
-\frac{3}{2}g_Vx(\lambda_\nu - \lambda_\bar{\nu}) + g_Ax(2 - \lambda_\nu\lambda_\bar{\nu})].
\]

(29)

In a similar manner as in the previous section, we consider the following states of helicity of the neutrino (antineutrino):

Case 1

Neutrino and antineutrino with positive helicity

\( \mathcal{H}_1(x, \lambda_\nu = \lambda_\bar{\nu} = 1) = 0, \)

\( \mathcal{H}_2(x, \lambda_\nu = \lambda_\bar{\nu} = 1) = R_1(s)[g_V(2 - x^2) + g_Ax]. \)  

(30)
Case 2
Neutrino and antineutrino with negative helicity

\[ \mathcal{H}_1(x, \lambda_\nu = \lambda_\bar{\nu} = -1) = 0, \]
\[ \mathcal{H}_2(x, \lambda_\nu = \lambda_\bar{\nu} = -1) = R_1(s)[g_V(2 - x^2) + g_A x]. \]  

(31)

Case 3

Neutrino with positive helicity and antineutrino with negative helicity

\[ \mathcal{H}_1(x, \lambda_\nu = -1, \lambda_\bar{\nu} = 1) = 2R_1(s)(g_V - g_A)(1 - x)^2, \]
\[ \mathcal{H}_2(x, \lambda_\nu = -1, \lambda_\bar{\nu} = 1) = R_1(s)[g_V(2 + x^2) - g_A(2 - x^2) + 3x(-g_V + g_A)]. \]  

(32)

Case 4

Neutrino with negative helicity and antineutrino with positive helicity

\[ \mathcal{H}_1(x, \lambda_\nu = 1, \lambda_\bar{\nu} = -1) = 2R_1(s)(g_V + g_A)(1 + x)^2, \]
\[ \mathcal{H}_2(x, \lambda_\nu = 1, \lambda_\bar{\nu} = -1) = R_1(s)[g_V(2 + x^2) + g_A(2 - x^2) + 3x(g_V + g_A)]. \]  

(33)

In the following section we analyze the angular distribution of the neutrino (antineutrino), and interpret the cases obtained for the four combinations of helicity.

IV. RESULTS

The experiments of collision in the accelerators give results that depend on the collision energy \( E \) between the electron and the positron. We consider energies available in the actual accelerators, that is, \( \sqrt{s} = 100 \text{ GeV} \) [18]. This energy is distributed between the particles that collide; then the center-of-mass energy varies by a few GeV and up to \( E = 50 \text{ GeV} \). The mass of the \( Z_0^1 \) is \( M_{Z_0^1} = 91.2 \text{ GeV} \) [18], therefore resonance exists when \( E = 45.6 \text{ GeV} \), that is, when \( \sqrt{s} = 2E = 91.2 \text{ GeV} \). This is manifest in the factor of resonance \( R_1(s) \), Eq. (16).

We first analyze the different states of helicity of the neutrino (antineutrino) and subsequently the angular distribution of the pair production of neutrinos.
In the standard model, the neutrino has negative helicity ($\lambda_\nu = -1$), and the antineutrino has positive helicity ($\lambda_{\bar{\nu}} = 1$). Immediately we interpret the cases obtained for the four combinations of helicity, with and without right currents, Eqs. (24)-(27) and (30)-(33).

From the Eqs. (24) and (30), we observe that the antineutrino appears with normal helicity while the neutrino is created with the opposite helicity. It is clear from these equations that the magnetic moment induces change of helicity to have right currents or not.

In this case, Eqs. (25) and (31) the antineutrino has helicity opposite to normal, while the neutrino has normal helicity. The magnetic moment induces a change in the helicity, independently of the right-handed currents.

Now, both the neutrino and the antineutrino are created with the helicities opposite to normal, Eqs. (26) and (32). In this case, both functions $H_1$ and $H_2$ contribute.

The neutrino and the antineutrino appear with the normal helicities, Eqs. (27) and (33). This corresponds to the standard model extended to the case of neutrinos with electromagnetic interaction. This situation has already been calculated in the collision $\nu e \rightarrow \nu e$ without right currents [6] and measurement experimentally [19].

The numerical computation of the functions $H_1$, and $H_2$ with and without right currents is present in the Figs. 2-7. According to the experimental data, the allowed range for the mixing angle between $Z_1^0$ and $Z_2^0$ is $-0.009 \leq \phi \leq 0.004$ with a 90% C.L. [20–22]. We chose $M_{Z_2^0} = 500 \text{ GeV}$ [18]. This figure does not take into account the values of the charge radius $\langle r^2 \rangle$, and the magnetic moment $\mu_\nu$; therefore the analysis is independent from the manner in which we derive these quantities.

Fig. 2, shows $H_1(\phi, M_{Z_2^0}, \lambda_{\bar{\nu}}, \lambda_\nu, x)_{LRSM}$ for the four states of helicities of the neutrino, and as function of the scattering angle $x = \cos \theta$, with $\phi = -0.005$, and $M_{Z_2^0} = 500 \text{ GeV}$. We consider the energy $E = 40 \text{ GeV}$, that is to say, $\sqrt{s} = 80 \text{ GeV}$ before the resonance of the $Z_1^0$. The unities in the vertical scale are arbitrary. We observed that $H_1(-1, 1)_{LRSM}$ have an increasing behavior, while $H_1(1, -1)_{LRSM}$ have a decreasing behavior. In this case $H_1(\pm 1, \pm 1)_{LRSM} = 0$. 

11
In Fig. 3, again graphic the functions $\mathcal{H}_1(1, -1)_{LRSM}$ and $\mathcal{H}_1(-1, 1)_{LRSM}$ with the same data, except that now the energy of collision is $E = 50 \text{ GeV}$, that is to say, for resonance above $Z_1^0$. Again the functions have an increasing and decreasing behavior, only that now these change sign.

Fig. 4 shows $\mathcal{H}_2(\phi, M_{Z_2^0}, \lambda_\nu, \lambda_{\bar{\nu}}, x)_{LRSM}$, with $\phi = -0.005$, $M_{Z_2^0} = 500 \text{ GeV}$ and $E = 40 \text{ GeV}$. The functions have an increasing and decreasing behavior however, $\mathcal{H}_2(-1, 1)_{LRSM}$ is increasing, while $\mathcal{H}_2(1, -1)_{LRSM}$ is decreasing, and $\mathcal{H}_2(1, 1)_{LRSM} = \mathcal{H}_2(-1, -1)_{LRSM}$.

Fig. 5 shows again $\mathcal{H}_2(\phi, M_{Z_2^0}, \lambda_\nu, \lambda_{\bar{\nu}}, x)_{LRSM}$ with the same data as $\phi$ and $M_{Z_2^0}$ in Fig. 4, only now with $E = 50 \text{ GeV}$. The behavior is similar except for a change of sign proceeding of the sign relative to $s$ and $M_{Z_2^0}^2$ in $R_1(s)$ Eq. (16).

Finally, in Figs. 6, 7 we show the functions $\mathcal{H}_1$ and $\mathcal{H}_2$ for $\phi = -0.005$, $M_{Z_2^0} = 500 \text{ GeV}$, and $E = 40 \text{ GeV}$, with and without the contribution of the parameters of the LRSM. We observe than the contribution of the right-handed currents is small.

V. CONCLUSIONS

In this paper, we have calculated the total cross-section of the pair production of neutrinos and we also analyze the different states of helicity of the neutrino (antineutrino), as well as the angular distribution of the neutrino (antineutrino) with respect to the original direction of the electron (positron) to different states of helicity of the neutrino.

We find than the favored directions of the neutrino (antineutrino) with respect to the electron (positron) direction are forward ($\theta = 0$) and backward ($\theta = \pi$) and is not very probable in the perpendicular direction ($\theta = \frac{\pi}{2}$).

The angular distributions that before the resonance are constructive or destructive, after resonance inverted their character. The angular distributions are more sensitive to the changes of helicity than to the contributions of the right-handed currents.

The existence of the magnetic moment favors the creation of pairs with one of the two neutrinos with the helicity opposite to the normal.
Only the right-handed currents favors the creation of neutrinos and antineutrinos both with helicities opposite to normal.

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Fig. 1 The Feynman diagrams contributing to the process $e^- e^+ \to \nu \bar{\nu}$, in a left-right symmetric model.

Fig. 2 Plot of $\mathcal{H}_1(\phi, M_{Z^2}, \lambda_\nu, \lambda_\bar{\nu}, x)$ as a function of the scattering angle $x = \cos \theta$ with $\phi = -0.005$, $M_{Z^2} = 500$ GeV, and $\sqrt{s} = 80$ GeV.

Fig. 3 Same as in Fig. 2, but with $\sqrt{s} = 100$ GeV.

Fig. 4 Plot of $\mathcal{H}_2(\phi, M_{Z^2}, \lambda_\nu, \lambda_\bar{\nu}, x)$ as a function of the scattering angle $x = \cos \theta$ with $\phi = -0.005$, $M_{Z^2} = 500$ GeV, and $\sqrt{s} = 80$ GeV.

Fig. 5 Same as in Fig. 4, but with $\sqrt{s} = 100$ GeV.

Fig. 6 Plot of $\mathcal{H}_1$ for $\sqrt{s} = 80$ GeV with and without the contributions of the parameters of the LRSM.

Fig. 7 Same as in Fig. 6, but for $\mathcal{H}_2$. 
REFERENCES


