Higgs boson contributions to neutrino production in $e^-e^+$ collisions in a left-right symmetric model

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Abstract

In gauge models with bigger number of Higgs particles their couplings to fermions are more complicated than in the standard model (SM). The influence of the Higgs bosons exchange on the neutrino production cross section in $e^-e^+$ collision ($e^-e^+ \rightarrow \nu N$) is investigated. The study has been done in the framework of the left-right symmetric model with the rich Higgs sector containing bidoublet and two triplets. The couplings of the Higgs particles even to light leptons can be as large as the gauge bosons couplings. The total effect of the Higgs bosons is small as a result of the big Higgs mass in the propagators.

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1 Introduction

Despite the extraordinary phenomenological success of the SM it is not excluded that new gauge interactions will become visible already at TeV energies. Many such extended gauge theories have been suggested. One of the most popular is the model with right-handed currents based on the symmetry group $SU_L(2) \otimes SU_R(2) \otimes U_{B-L}(1)$ [1]. Left and right-handed weak neutrino states appear in the natural way in this model. In the most popular version of the model with one bidoublet and two triplets of the Higgs particles[2] neutrino mass matrix diagonalization gives three heavy and three light physical Majorana neutrinos. It is possible that the mass of some heavy neutrinos lie in the energy of the new symmetry breaking scale. These GeV-TeV mass neutrinos can be produced in the future colliders. Light neutrinos with the eV-keV-MeV range masses are generated by ‘see-saw’ mechanism [3]. In the previous paper [4] we investigated the production of two heavy and light-heavy neutrinos in the $e^+e^-$ future colliders (LEP II, Next Linear Colliders (NLC),...). Six Feynman diagrams with two charged gauge bosons $W_{1,2}^\pm$ in $t$ and $u$ channels and two neutral bosons $Z_{1,2}$ in $s$-channel were taken into account. We didn’t consider any diagram with Higgs particles exchange. In the models with one Higgs particle like in the SM the Higgs-fermions coupling is proportional to the fermion mass. In the energy range where heavy neutrinos are produced in $e^+e^-$ scattering the electron mass and thus Higgs exchange diagrams are negligible. In the models with greater number of Higgs particles, their coupling to fermions is more complicated. It is not so obvious then that the Higgs exchange diagrams in the considered process are also negligible. On the pure phenomenological ground this mechanism in $e^-e^+ \rightarrow \nu N$ process has been considered in the literature [5]. In this paper we consider the Higgs exchange mechanism in all details. First, in the next Chapter, the couplings of physical Higgs particles to the physical leptons are considered. Next (Chapter III) we discuss the parametrization of the neutrino mass matrix and the various mixing matrices between weak
and mass states. The problem of CP conservation and non conservation is considered. In Chapter IV the results of numerical calculations are presented and finally Chapter V contains our conclusions.

2 Higgs boson couplings with fermion pairs.

To find the influence of the Higgs bosons on the neutrino production process $e^-e^+ \rightarrow \nu N$ we need to know the Higgs boson couplings with fermions. All details of the $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ left-right symmetric models which we consider are described in Ref.[2] and [4]. Before the spontaneous symmetry breaking the Lagrangian has the left-right symmetry specified by the transformation

$$\Psi_L \leftrightarrow \Psi_R, \quad \Delta_L \leftrightarrow \Delta_R \quad \text{and} \quad \phi \leftrightarrow \phi^\dagger$$

where $\Psi_{L,R}$ are the column vectors containing the left-handed and right-handed leptons, $\phi$ and $\Delta_{L,R}$ are bidoublets and left (right)-handed Higgs triplets respectively

$$\phi = \begin{pmatrix} \phi_0^0 \\ \phi_2^0 \\ \phi_2^+ \end{pmatrix}, \quad \Delta_{L,R} = \begin{pmatrix} \delta_{L,R}/\sqrt{2} \\ \delta_{L,R}^0 \\ -\delta_{L,R}^+ \end{pmatrix}. \quad (2)$$

The neutral Higgs fields $\phi^0_{R,L}, \phi^0_{1,2}$ can acquire vacuum expectation values

$$\langle \phi \rangle = \begin{pmatrix} k_1/\sqrt{2} \\ 0 \\ k_2/\sqrt{2} \end{pmatrix}, \quad \langle \Delta_{L,R} \rangle = \begin{pmatrix} 0 \\ \Delta_{L,R}/\sqrt{2} \\ 0 \end{pmatrix}. \quad (3)$$

From the present experimentally obtained bounds the additional gauge bosons $W_2$ and $Z_2$ are much heavier than the standard one $W_1, Z_1$ [6], so

$$v_R \gg k_1, k_2 \gg v_L,$$

and we have

$$M_{W_1}^2 \approx \frac{g^2}{4} \left( k_1^2 + k_2^2 \right), \quad (4)$$

$$M_{W_2}^2 \approx \frac{g^2}{2} v_R^2. \quad (5)$$
The Yukawa interaction has the form

\[ L_{Yukawa} \equiv L_Y^R + L_Y^L + L_Y^L = - \tilde{\Psi}_L \left[ h \phi + \tilde{h} \tilde{\phi} \right] \Psi_R \]

\[ - \tilde{\Psi}_L C i \tau_2 h_L \Delta_L \Psi_L - \tilde{\Psi}_R C i \tau_2 h_R \Delta_R \Psi_R \]

(6)

where

\[ \tilde{\phi} = \tau_2 \phi^* \tau_2, \]

and from left-right symmetry (1) we get

\[ h = h^\dagger, \quad \tilde{h} = \tilde{h}^\dagger, \quad h_L = h_R. \]

(7)

To find the physical Higgs bosons their interaction potential must be specified. We consider the most general Higgs potential which was discussed in Ref. [2]. To avoid the fine tuning problem the \( \beta \) terms (Eq.(A2) in [2]) are made to vanish, \( \beta_i = 0 \) (i=1,2,3). Then also \( v_L \) has to vanish and \( v_L = 0 \). The \( \alpha_2 \) parameter is assumed to be real so there is no explicit CP violation (in the Higgs potential) and the spontaneous CP symmetry breaking also does not appear (vacuum expectation values are real). Then the most general Higgs potential has the form [2]

\[ V = - \mu_1^2 \left( Tr \left[ \phi^\dagger \phi \right] \right) - \mu_2^2 \left( Tr \left[ \tilde{\phi} \phi^\dagger \right] + Tr \left[ \tilde{\phi}^\dagger \phi \right] \right) \]

\[ - \mu_3^2 \left( Tr \left[ \Delta_L \Delta_L^\dagger \right] + Tr \left[ \Delta_R \Delta_R^\dagger \right] \right) \]

\[ + \lambda_1 \left( \left( Tr \left[ \phi \phi^\dagger \right] \right)^2 \right) + \lambda_2 \left( \left( Tr \left[ \tilde{\phi} \phi^\dagger \right] \right)^2 + \left( Tr \left[ \tilde{\phi}^\dagger \phi \right] \right)^2 \right) \]

\[ + \lambda_3 \left( Tr \left[ \phi \phi^\dagger \right] Tr \left[ \tilde{\phi} \phi^\dagger \right] \right) \]

\[ + \lambda_4 \left( Tr \left[ \phi \phi^\dagger \right] \right) \left( Tr \left[ \tilde{\phi} \phi^\dagger \right] + Tr \left[ \tilde{\phi}^\dagger \phi \right] \right) \]

\[ + \rho_1 \left( \left( Tr \left[ \Delta_L \Delta_L^\dagger \right] \right)^2 + \left( Tr \left[ \Delta_R \Delta_R^\dagger \right] \right)^2 \right) \]

\[ + \rho_2 \left( Tr \left[ \Delta_L \Delta_L \right] Tr \left[ \Delta_L^\dagger \Delta_L^\dagger \right] + Tr \left[ \Delta_R \Delta_R \right] Tr \left[ \Delta_R^\dagger \Delta_R^\dagger \right] \right) \]

\[ + \rho_3 \left( Tr \left[ \Delta_L \Delta_R \right] Tr \left[ \Delta_L^\dagger \Delta_R^\dagger \right] \right) \]

\[ + \rho_4 \left( Tr \left[ \Delta_L \Delta_L \right] Tr \left[ \Delta_R^\dagger \Delta_R^\dagger \right] + Tr \left[ \Delta_L^\dagger \Delta_R \right] Tr \left[ \Delta_R \Delta_L \right] \right) \]

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The precise form of the mass matrices are given in Ref. [2]. The 20 degrees of freedom in the Higgs sector give two charged \( G_{L,R}^\pm \), two neutral \( G_{1,2}^0 \) Goldstone bosons and 14 physical degrees of freedom. These physical degrees of freedom produce:

- four neutral scalars with \( J^{PC} = 0^{+ \pm} \) (\( H_i^0 \; i = 0, 1, 2, 3 \)).

Masses of three of them \( H_0^0, H_1^0 \) and \( H_2^0 \) are given from the diagonalization of the mass matrix which in the basis \( \left( \sqrt{2} y \; Re \left( k_1 \phi_1^0 + k_2 \phi_2^0 \right), \sqrt{2} y \; Re \delta_R^0, \sqrt{2} y \; Re \delta_L^0 \right) \) has elements

\[
M_{11} = 2y^2 \left[ \lambda_1 + \epsilon^2 (2\lambda_2 - \lambda_3 + 2\lambda_A) \right], \\
M_{12} = M_{21} = 2y^2 \sqrt{1 - \epsilon^2} (2\lambda_2 + \lambda_3 + \lambda_A), \\
M_{13} = M_{31} = \frac{1}{2} y v_R \left[ 2\alpha_1 + 2\alpha_2 \epsilon + \alpha_3 \left( 1 - \sqrt{1 - \epsilon^2} \right) \right], \\
M_{22} = 2(2\lambda_2 + \lambda_3) y^2 \left( 1 - \epsilon^2 \right) + \frac{1}{2} \alpha_3 v_R^2 \frac{1}{\sqrt{1 - \epsilon^2}}, \\
M_{23} = M_{32} = \frac{1}{2} y v_R \left[ 4\alpha_2 \sqrt{1 - \epsilon^2} + \alpha_3 \epsilon \right], \\
M_{33} = 2\rho_1 v_R^2,
\]

where

\[
y^2 = k_1^2 + k_2^2 \quad \text{and} \quad \epsilon = \frac{2k_1 k_2}{k_1^2 + k_2^2} ; 0 \leq \epsilon \leq 1.
\]

Then after diagonalization of the mass matrix we have

\[
\begin{pmatrix}
\phi_0^0 \\ \phi_+^0 \\ \delta_R^0
\end{pmatrix} =
\begin{pmatrix}
a_0 & a_1 & a_2 \\ b_0 & b_1 & b_2 \\ c_0 & c_1 & c_2
\end{pmatrix}
\begin{pmatrix}
H_0^0 \\ H_1^0 \\ H_2^0
\end{pmatrix},
\]

(10)
where the parameters $a_i, b_i, c_i$ depend on the mass matrix elements (9). If, however, $v_R \gg y$ we can find approximately that $H_0^0 \simeq \phi_-^R$, $H_1^0 \simeq \phi_+^R$, $H_2^0 \simeq \phi_R^0$ with the masses

\begin{align*}
H_0^0, & \quad M_{H_0^0} \simeq 2y^2 \left[ \lambda_1 + \epsilon^2 (2\lambda_2 + \lambda_3) + 2\lambda_4 \epsilon \right], \\
H_1^0, & \quad M_{H_1^0} \simeq \frac{1}{2} \alpha_3 v_R^2 \frac{1}{\sqrt{1 - \epsilon^2}}, \quad (11) \\
H_2^0, & \quad M_{H_2^0} \simeq 2\rho_1 v_R.
\end{align*}

The lightest Higgs $H_0^0$ does not couple in neutral standard current to the different flavour quarks (no FCNC). The other Higgs particles are heavy and the FCNC, in the energy range which we consider, are reduced by the propagator effect. The fourth scalar Higgs particle $H_3^0$ has the mass

\begin{equation}
H_3^0, \quad M_{H_3^0} = \frac{1}{2} v_R^2 (\rho_3 - 2\rho_1). \quad (12)
\end{equation}

- two neutral pseudoscalars with $J^{PC} = 0^{+-}$

\begin{align*}
A_1^0; & \quad M_{A_1^0} = \frac{1}{2} \alpha_3 v_R^2 \frac{1}{\sqrt{1 - \epsilon^2}} - 2y^2 (2\lambda_2 - \lambda_3), \\
A_2^0; & \quad M_{A_2^0} = \frac{1}{2} v_R^2 (\rho_3 - 2\rho_1). \quad (13)
\end{align*}

- two singly charged bosons

\begin{align*}
H_1^\pm; & \quad M_{H_1^\pm} = \frac{1}{2} v_R^2 (\rho_3 - 2\rho_1) + \frac{1}{4} \alpha_3 y^2 \sqrt{1 - \epsilon^2}, \\
H_2^\pm; & \quad M_{H_2^\pm} = \frac{1}{2} \alpha_3 \left[ v_R^2 \frac{1}{\sqrt{1 - \epsilon^2}} + \frac{1}{2} y^2 \sqrt{1 - \epsilon^2} \right], \quad (14)
\end{align*}

and finally

- two doubly charged Higgs particles
The parameters \( \rho, \lambda, \alpha \) are defined in the Higgs potential (Eq.8). The relations between the nonphysical Higgs particles specified in Yukawa Lagrangian (Eq.6) and the physical ones are given by \( (k_\pm = \sqrt{k_1^2 \pm k_2^2}) \)

\[
\begin{align*}
\delta_{R}^{\pm} ; \\
M_{R}^{\pm} &= \frac{1}{2} \left[ v_{R}^{2} (\rho_{3} - 2 \rho_{1}) + \alpha_{3} y^{2} \sqrt{1 - c^2} \right],
\end{align*}
\]

\[
\begin{align*}
\delta_{R}^{\pm} ; \\
M_{R}^{\pm} &= 2 \rho_{2} v_{R}^{2} + \frac{1}{2} \alpha_{3} y^{2} \sqrt{1 - c^2}. \quad \text{(15)}
\end{align*}
\]

If \( v_{R} \gg y \) then the relations for \( \phi_{1,2}^{0}, \phi_{1,2}^{\pm}, \phi_{R}^{0} \) and \( \delta_{R}^{\pm} \) are simpler

\[
\phi_{1}^{0} \simeq \frac{1}{y \sqrt{2}} \left[ k_{1} H_{0}^{0} - k_{2} H_{1}^{0} + i k_{1} G_{1}^{0} - i k_{2} A_{1}^{0} \right], \quad \text{(24)}
\]
where

\[ k_1 = y \left[ \frac{1 + \sqrt{1 - \epsilon^2}}{2} \right]^{1/2}; \quad k_2 = y \left[ \frac{1 - \sqrt{1 - \epsilon^2}}{2} \right]^{1/2}. \]

The doubly charged Higgs bosons are already physical. \( G_1^0 \) and \( G_{L,R}^\pm \) Goldstone bosons are ‘eaten’ by \( Z_{1,2} \) and \( W_{L,R}^\pm \) respectively.

Now we can express the Yukawa interaction Lagrangian in the terms of physical quantities. For the bidoublet interaction

\[-L_Y^B = \bar{\nu}_L (h \phi_1^0 + \tilde{h} \phi_2^0) \nu_R + \bar{\nu}_L (h \phi_1^+ - \tilde{h} \phi_2^+) \epsilon_R + \epsilon_L (h \phi_2^- - \tilde{h} \phi_1^-) \nu_R + \epsilon_L (h \phi_2^0 + \tilde{h} \phi_1^0) \epsilon_R + h.c., \]

one has

\[ \bar{\nu}_L (h \phi_1^0 + \tilde{h} \phi_2^0) \nu_R + h.c. = \]

\[ \sum_a \bar{N}_a \left\{ \left[ (\Omega_L)_{aa} m_a^N B_0 + \sum_l (K_{L})_{al} (K_{R}^*)_{al} m_l A_0^* \right] P_R + \left[ m_a^N (\Omega_L)_{aa} B_0 + \sum_l (K_{L}^*)_{al} (K_{R})_{al} m_l A_0 \right] P_L \right\} N_a \]

\[ + \sum_{a>b} \bar{N}_a \left\{ \left[ \left( (\Omega_L)_{ac} m_c^N (\Omega_R)_{cb} + (\Omega_L)_{bc} m_c^N (\Omega_R)_{ca} \right) B_0 \right] \right\} N_a \]

\[ + \sum_l m_l ((K_{L})_{al} (K_{R}^*)_{bl} + (K_{L})_{bl} (K_{R}^*)_{al}) A_0^* \right\} P_R \]

\[ + \sum_{a>b} \bar{N}_a \left\{ \left[ \left( (\Omega_L)_{ac} m_c^N (\Omega_R)_{cb} + (\Omega_L)_{bc} m_c^N (\Omega_R)_{ca} \right) B_0 \right] \right\} N_a \]

\[ + \sum_l m_l ((K_{L})_{al} (K_{R}^*)_{bl} + (K_{L})_{bl} (K_{R}^*)_{al}) A_0^* \right\} P_R \]
\[ + \left[ \left( \Omega_L \right)_{ac} m_c^N (\Omega_R)_{cb} + (\Omega_L)_{bc} m_c^N (\Omega_R)_{ca} \right] R_0^a \]

\[ + \sum_l m_l \left[ \left( K_L \right)_{bl} (K_R)_{al} + (K_L^+)_{al} (K_R^+)_{bl} \right] A_0 \right] \} N_b, \]

\[ \bar{e}_L \left( h \phi_1^+ - \tilde{h} \phi_2^+ \right) e_R + \bar{\nu}_L \left( h \phi_1^- - \tilde{h} \phi_2^- \right) \nu_R + h.c. = \]

\[ + \sum_a \bar{N}_a \left[ \left[ \sum_b (\Omega_L)_{ab} m_b^N (K_R)_{bl} A^+ - (K_L)_{al} m_l B^+ \right] P_R \]

\[ + \left[ m_a^N (K_L)_{al} B^+ - (K_R)_{al} m_l A^+ \right] P_L \]

\[ + \left[ 0 \right] N_a, \]

and

\[ \bar{e}_L \left( h \phi_1^0 + \tilde{h} \phi_1^{*0} \right) e_R + h.c. = \]

\[ \sum_l \bar{e}_l \left[ \left[ \delta_l m_l B_0 + \sum_a (K_L)_{al} (K_R)_{ak} m_a^N A_0 \right] P_R \]

\[ + \left[ \delta_l m_l B_0 + \sum_a (K_L)_{al} (K_R^+)_{ak} m_a^N A_0 \right] P_L \} e_l. \]

\[ m_b^N \] denote neutrino masses, three light (b=1,2,3) and three heavy (b=4,5,6). \( m_l \) are the charged lepton masses (l=e, μ, τ). For the definition of matrices \( K_{L,R} \) and \( \Omega_{L,R} \) see Ref. [4]. The parameters \( A_0, B_0, A^\pm \) and \( B^\pm \) denote the combination of the Higgs fields

\[ A_0 = \frac{\sqrt{2}}{k_2^2} \left( k_1 \phi_2^0 - k_2 \phi_1^{0*} \right), \]

\[ B_0 = \frac{\sqrt{2}}{k_2^2} \left( k_1 \phi_1^0 - k_2 \phi_2^{0*} \right), \]

\[ A^\pm = \frac{\sqrt{2}}{k_2^2} \left( k_1 \phi_1^\pm + k_2 \phi_2^{\pm} \right), \]

and

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\[ B^\pm = \frac{\sqrt{2}}{k_L^2} \left( k_2 \phi_1^\pm + k_1 \phi_2^\pm \right). \]  

The right-handed triplet interaction with leptons is

\[ -L_R^R = \delta_R^0 \bar{\nu}_L^R h_R \nu_R - \frac{\delta_R^+}{\sqrt{2}} (\bar{\nu}_L^R h_R e_R + \bar{e}_L^R h_R \nu_R) - \delta_R^+ \bar{e}_L^R h_R e_R + h.c., \]

where the first two parts are given by

\[ \delta_R^0 \bar{\nu}_L^R h_R \nu_R + h.c. = \]

\[- \frac{1}{2v_R} \left\{ \sum_a \bar{N}_a \left( \sum_c m_c^N \left[ (\Omega_R)_a^2 P_R + (\Omega_R')_a^2 P_L \right] \right) N_a \right\} \]

\[- \frac{1}{v_R} \sum_{a>b} \bar{N}_a \left( \sum_c m_c^N \left[ (\Omega_R)_a^2 (\Omega_R')_a^2 P_R + (\Omega_R')_a^2 (\Omega_R')_a^2 P_L \right] \right) N_b \left( \sqrt{2} Re \delta_R^0 \right) \]

+ Goldston boson interaction,

and

\[- \frac{\delta_R^+}{\sqrt{2}} (\bar{\nu}_L^R h_R e_R + \bar{e}_L^R h_R \nu_R) + h.c. = \]

\[- \frac{1}{v_R} \sum_{a,b} \bar{N}_a \left( \sum_c m_c^N \left[ (\Omega_R')_a^2 (K_R')_a^2 \right] P_R \epsilon_i \delta_R^+ \right) \]

\[ + \bar{e}_L \left( \sum_c m_c^N \left[ (\Omega_R')_a^2 (\Omega_R')_a^2 \right] P_L N_a \delta_R^+ \right). \]

To get the interaction of the left-handed triplet the indices L(R) in the formulae (35) and (36) should be replaced by R(L) (if \( v_L \neq 0 \)). If the left handed triplet does not condensate \( (v_L = 0) \) it will still interact with the leptons \( (h_L = h_R \neq 0) \). Then to get its interaction with physical leptons we have to use the formulae

\[ \delta_R^0 \bar{\nu}_L^R h_L \nu_L + h.c. = \]

\[- \frac{1}{\sqrt{2}v_R} \sum_a \bar{N}_a \left[ X_{aa} \delta_R^0 P_L + X_{aa}^* \delta_R^0 P_R \right] N_a \]

\[ + \frac{\sqrt{3}}{v_R} \sum_{a>b} \bar{N}_a \left[ X_{ab} \delta_R^0 P_L + X_{ab}^* \delta_R^0 P_R \right] N_b, \]
and
\[ -\frac{\delta_{L}^{+}}{\sqrt{2}}(\bar{e}_{R}h_{L}e_{L} + \bar{\nu}_{R}h_{L}\nu_{L}) + h.c. = \]
\[ -\frac{1}{v_{R}}\delta_{L}^{+} \sum_{a,l} \tilde{N}_{a} \sum_{b} X_{ab}(K_{L})_{ib} \nu_{L} + \frac{1}{v_{R}}\delta_{L}^{-} \sum_{a,l} \tilde{\nu}_{l} \sum_{b} (K_{L}^{t})_{ib} (X^{*})_{ha} P_{R} N_{a}, \]
where the matrix \( X \) is given by
\[ X_{ab} = \sum_{c} \left( U_{R}^{t}U_{L} \right)_{ac} m_{c}^{N} \left( U_{R}^{t}U_{L} \right)_{cb} = X_{ba}. \] (39)

3 Parametrization of mass and mixing matrices for leptons.

In the model which we consider the left-handed triplet does not acquire the vacuum expectation value \( (v_{L} = 0) \) so the neutrino mass matrix has the form
\[ M^{\nu} = \begin{pmatrix} 0 & M_{D} \\ M_{D}^{T} & M_{R} \end{pmatrix}, \]
(40)
where
\[ M_{D} = \frac{1}{\sqrt{2}}(hk_{1} + \tilde{h}k_{2}) \quad \text{and} \quad M_{R} = \sqrt{2}h_{R}v_{R} \]
are hermitian and symmetric \( 3 \times 3 \) matrices respectively. The charged leptons’ masses come from the same \( h \) and \( \tilde{h} \) terms
\[ M_{l} = \frac{1}{\sqrt{2}}(hk_{2} + \tilde{h}k_{1}). \] (42)
We can perform a unitary transformation, the same for the left and the right-handed lepton fields (L-R symmetry), without changing the physical interpretation of the theory. It means that the matrices
\[ M_{D} \leftrightarrow VM_{D}V^{t}, \]
\[ M_{R} \leftrightarrow V^{t}M_{R}V^{t}, \]
\[ M_{l} \leftrightarrow VM_{l}V^{t}. \] (43)
are totally equivalent from the physical point of view [7]. Using the equivalence relations (Eq.43) we can diagonalize the \( M_R \) matrix leaving the matrices \( M_D \) and \( M_l \) still hermitian. So we see that the lepton sector of our theory with the left-right symmetry (Eq.1) is described by \( 6+6+3=15 \) moduli (9 masses + 6 angles) and \( 3+3=6 \) CP violating phases.

\[
M_l = \begin{pmatrix}
a_l & b_l e^{i \beta_l} & c_l e^{i \eta_l} \\
b_l e^{-i \beta_l} & d_l & f_l e^{i \eta_l} \\
c_l e^{-i \eta_l} & f_l e^{-i \eta_l} & g_l
\end{pmatrix}, \quad M_D = \begin{pmatrix}
a_D & b_D e^{i \beta_D} & c_D e^{i \eta_D} \\
b_D e^{-i \beta_D} & d_D & f_D e^{i \beta_D} \\
c_D e^{-i \eta_D} & f_D e^{-i \eta_D} & g_D
\end{pmatrix},
\]

and

\[
M_R = \text{diag}(\tilde{M}_1, \tilde{M}_2, \tilde{M}_3).
\]

The neutrino mass matrix \( M^\nu \) and the charged lepton mass matrix \( M_l \) are diagonalized by the orthogonal and unitary transformations respectively

\[
U^T M^\nu U = \text{diag}(m_1, m_2, m_3, M_1, M_2, M_3) \equiv M^\nu_{\text{diag}}
\]

\[
U_l^T M_l U_l = \text{diag}(m_e, m_\mu, m_\tau) \equiv m^l_{\text{diag}}.
\]

We use the procedure (see e.g. Ref. [8]) that gives us means to find the matrix \( U \) in the approximate way. As \( v_R \gg [k_1^2 + k_2^2]^{1/2} \) we assume that

\[
\tilde{M}_i \gg a_D, b_D, \ldots, g_D \quad (i = 1, 2, 3)
\]

so the elements of the matrix

\[
\xi = M_D M_R^{-1}
\]

are small

\[
|\xi_{ij}| \ll 1.
\]

Then the form of matrix \( U \) to the third order in \( \xi \) can be estimated as

\[
U \equiv \begin{pmatrix}
U_L^* \\
U_R
\end{pmatrix} = \begin{pmatrix}
\left[ 1 - \frac{1}{2} \xi^* \xi^T \right] J_l & \left[ \xi^* \left( 1 - \frac{1}{2} \xi^T \xi^* \right) \right] J_l \\
-\xi^T \left( 1 - \frac{1}{2} \xi^* \xi^T \right) J_l & \left[ 1 - \frac{1}{2} \xi^T \xi^* \right] J_l
\end{pmatrix},
\]

(49)
where $J_l$ and $J_h$ are diagonal unitary matrices that guarantee that the mass eigenvalues are positive. The diagonal elements of matrices $J_l$ and $J_h$ are equal 1 or i and in case of CP conservation describe the CP parity $\eta_{CP}$ of the appropriate Majorana neutrino

$$\eta_{CP} = +i \quad \text{if the diagonal element equals } +1$$

$$\eta_{CP} = -i \quad \text{if the diagonal element equals } +i.$$ 

Now we can easily find the all necessary mixing matrices

$$K_L = U_L^\dagger U_i = \begin{pmatrix} J_l \left(1 - \frac{1}{2} \xi \xi^\dagger \right) U_i \\ J_h \left(1 - \frac{1}{2} \xi^\dagger \xi \right) \xi^\dagger U_i \end{pmatrix},$$

$$K_R = U_R^\dagger U_i = \begin{pmatrix} -J_l^* \left(1 - \frac{1}{2} \xi^* \xi^T \right) \xi^* U_i \\ J^*_h \left(1 - \frac{1}{2} \xi^T \xi^* \right) U_i \end{pmatrix},$$

$$\Omega_L = U_L^\dagger U_L = \begin{pmatrix} J_l \left(1 - \xi \xi^\dagger \right) J_l^* & J_l \xi \left(1 - \xi^\dagger \xi \right) J_h^* \\ J_h \xi^\dagger \left(1 - \xi^\dagger \xi \right) J_l^* & J_h \xi^\dagger \xi J_h^* \end{pmatrix},$$

$$\Omega_R = U_R^\dagger U_R = \begin{pmatrix} J_l^* \xi^T J_l & -J_l^* \xi \left(1 - \xi^T \xi^* \right) J_h \\ -J_h^* \xi^T \left(1 - \xi^* \xi^T \right) J_l & J_h^* \left(1 - \xi^T \xi^* \right) J_h \end{pmatrix},$$

and

$$\Omega_{RL} \equiv U_R^\dagger U_L =$$

$$\begin{pmatrix} -J_l^* \xi^\dagger \left(1 - \frac{1}{2} \xi^T \xi^* - \frac{1}{2} \xi \xi^T \right) J_l^* \\ J_h^* \left(1 - \frac{1}{2} \xi^T \xi^* - \frac{1}{2} \xi \xi^T \right) J_l^* \\ -J_l^* \xi \xi^\dagger \\ J_h^* \xi \xi^\dagger \left(1 - \frac{1}{2} \xi^T \xi^* - \frac{1}{2} \xi \xi^T \right) J_h^* \end{pmatrix}.$$ 

If the CP symmetry holds then the matrices $h, \tilde{h}$ and $h_L = h_R$ are real and the phases in matrices $M_D$ and $M_l$ disappear. If there are neutrinos with opposite CP parities then certain columns in the matrices $K$ and the relevant rows and columns in matrices $\Omega$ are pure imaginary.
4 Higgs particles influence on heavy Majorana neutrino production: numerical results.

The full cross section for the $e^-e^+ \rightarrow \nu N$ process is described in our model by six diagrams with $W_{1,2}$ (t and u channels) and $Z_{1,2}$ (s channel) exchange (Fig.1) and by the Higgs exchange diagrams in all three channels (Fig.2). The influence of the spin and boson exchange diagrams are discussed in details in Ref.[4]. Here we would like to ascertain about the role of Higgs exchange diagrams. In the t and u channels two charged Higgs particles can be exchanged (Fig.2a,b). In the approximation which we consider ($v_R \gg y$, $m_e \approx 0$) only two neutral Higgses couple in the s channel. All the calculations are done in the unitary gauge, so we do not take into account the Goldston particles exchange. The full helicity amplitude for the process $e^-e^+ \rightarrow \nu N$ and the precise values of all couplings are presented in the Appendix. We can see that like in the SM the lighter Higgs particle $H^0_0$ couple to the $e^-e^+$ proportionally to the electron mass and its effect is negligible in the energy range which we consider. The influence of two charged $H^+_{1,2}$ and two neutral ($A^0_1, A^0_0$) Higgs particles is not obvious. At first sight their coupling, even to the light leptons ($e^-e^+, e\nu$), can be large as there are terms in the vertex proportional to heavy neutrinos mass. They are, however, multiplied by the mixing matrices which can have small terms so the total effect needs numerical analysis. As an example let’s take the $M_D$ and $M_R$ mass matrices in the form

$$M_D = \begin{pmatrix} 1 & 1 & 0.9 \\ 1 & 1 & 0.9 \\ 0.9 & 0.9 & 0.95 \end{pmatrix}, \quad M_R = \begin{pmatrix} 10^2 & 0 & 0 \\ 0 & 10^3 & 0 \\ 0 & 0 & 10^9 \end{pmatrix}, \quad (55)$$

which produce the realistic spectrum of neutrino masses ($m_{\nu_e} = 0$, $m_{\nu\mu} \approx 1.7 eV$, $m_{\nu\tau} = 33 MeV$, $M_1 = 100 GeV$, $M_2 = 10^3 GeV$, $M_3 = 10^6 GeV$). The matrix $U$ which diagonalizes neutrino mass matrix $M^\nu$ and gives positive eigenvalues of masses can be calculated precisely and is equal
\[ U = \begin{pmatrix} .707 & -.408i & -.577i & -.010 & -.001 & .9 \cdot 10^{-6} \\ -.707 & -.408i & -.577i & -.010 & -.001 & .9 \cdot 10^{-6} \\ .6 \cdot 10^{-12} & .816i & -.577i & -.010 & -.001 & 1. \cdot 10^{-6} \\ -.1 \cdot 10^{-16} & .3 \cdot 10^{-7}i & .017i & -1 & -3 \cdot 10^{-5} & .3 \cdot 10^{-11} \\ -.1 \cdot 10^{-16} & .3 \cdot 10^{-8}i & .002i & .3 \cdot 10^{-4} & -1 & .3 \cdot 10^{-11} \\ -.3 \cdot 10^{-19} & -.4 \cdot 10^{-7}i & .2 \cdot 10^{-5}i & .3 \cdot 10^{-7} & .3 \cdot 10^{-8} & 1. \end{pmatrix} \]

from which all other necessary mixing matrices (50)-(54) can be calculated. To find the role of the Higgs sector in our case we calculate the cross section for three different processes \( e^{-} e^{+} \to \nu_{\mu} N(100) \), \( \nu_{\mu} N(100) \) and \( \nu_{\tau} N(100) \). The values of \( \nu_{R} \) and \( y \) are obtained from massses \( M_{H_{1}}^{2} \approx \frac{1}{4} y^{2} \) and \( M_{H_{2}}^{2} \approx \frac{1}{2} y^{2} \nu_{R}^{2} \). To calculate the Higgs boson masses we use the relations (11)-(15) with the Higgs potential parameters (or some their combinations) equal to 1, so we have

\[
\begin{align*}
M_{H_{1}}^{2} & = \frac{1}{2} \left[ \nu_{R}^{2} + \frac{1}{2} y^{2} \sqrt{1 - \epsilon^{2}} \right], \\
M_{H_{2}}^{2} & = \frac{1}{2} \left[ \nu_{R}^{2} + \frac{1}{2} y^{2} \sqrt{1 - \epsilon^{2}} \right], \\
M_{H_{0}}^{2} & \simeq \frac{1}{2} \nu_{R}^{2} \sqrt{1 - \epsilon^{2}}, \\
M_{A_{0}}^{2} & \simeq \frac{1}{2} \left[ \nu_{R}^{2} \sqrt{1 - \epsilon^{2}} - 4 y^{2} \right].
\end{align*}
\]  
(56)

For \( M_{H_{1}} \approx 80 \text{GeV} \) and \( M_{H_{2}} \approx 1600 \text{GeV} \) (the value accepted from experimental data Ref.[9]) we find the range for \( y \) and \( \nu_{R} \)

\[
y \approx 250 \text{GeV}, \\
\nu_{R} \approx 3500 \text{GeV}.
\]  
(57)

Then for \( \epsilon = 0 \) all Higgs boson masses from Eq.(56) are of 2.5 TeV order

\[
M_{H_{1}} \approx M_{H_{2}} \approx M_{H_{0}} \approx M_{A_{0}} \approx 2450 \text{GeV}.
\]  
(58)
For the neutral Higgs bosons $H^0_1$ and $A^0_1$ which cause the FCNC the masses of order 2.5 TeV are not large enough to reduce the $\bar{K}^0 - K^0$ transition. To generate proper mass splitting in $\bar{K}^0 - K^0$ system it was found that Ref.[10]

$$M_{H^0_1}, M_{A^0_1} > 10 \text{ TeV}.$$  \hfill (59)

There are two ways of obtaining these large mass values for the FCNC neutral Higgs bosons

- we can choose the parameter $\alpha_3$ in Eq.(11) and (13) to be greater then 1 e.g. $\alpha_3 \simeq 16$. Then $M_{H^0_1}, M_{A^0_1}$ satisfy the bound (59) and the charged bosons can be lighter $M_{H^\pm_1} \simeq M_{H^\pm_2} \simeq 2500 GeV$ (for $\epsilon$ not too close to 1),

or

- we avoid the fine tuning for the Higgs parameters ($\alpha_3 \simeq 1$) but we assume that the $\phi^0_1$ and $\phi^0_2$ acquire approximately the same VEV $k_1 \simeq k_2$, so then $\epsilon \simeq 1$ and the masses $M_{H^0_1}, M_{A^0_1}$ and $M_{H^\pm_2}$ are much greater then $\frac{1}{2} \nu^2_\nu$ and can also satisfy the bound (59).

In the first case the presence of large masses in the propagator causes that the total contribution of the $H^0_1$ and $A^0_1$ exchange in the s channel is very small. In the second case, when $\epsilon \to 1$, the couplings of neutral Higgses $H^0_1$ and $A^0_1$ to leptons become stronger (see (A.18)) and compensate the influence of the propagator. The total effect depends on the additional vertex contributions given in (A.19) and (A.20). We calculate numerically the factors of the type

$$(K^\dagger_L M^e_{\text{diag}} K^R)_{ee} \ , \ (K^\dagger_L m^e_{\text{diag}} K^R)_{ab} \ , \ \Omega_L M^e_{\text{diag}})_{ab}$$  \hfill (60)

which are present in the couplings (A.19) and (A.20) for different values of the heavy neutrino mass. The factors are of the same order independently of the neutrino masses. It is caused by the fact that for bigger neutrino masses the appropriate mixing matrix elements are smaller. We have calculated the influence of the scalar $H^0_1$ and pseudoscalar $A^0_1$ exchange diagrams on the
Table 1: The contribution of the gauge and Higgs bosons to the total cross section for LEP II energy.

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma_{gauge}/\sigma_{total}$</th>
<th>$\sigma_{Higgs}/\sigma_{total}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e N(100)$</td>
<td>$\simeq 100%$</td>
<td>$\simeq 0.0001%$</td>
</tr>
<tr>
<td>$\nu_\mu N(100)$</td>
<td>$\simeq 100%$</td>
<td>$\simeq 0.01%$</td>
</tr>
<tr>
<td>$\nu_\tau N(100)$</td>
<td>$\simeq 100%$</td>
<td>$\simeq 0.01%$</td>
</tr>
</tbody>
</table>

total cross section. For the energy range which we consider (200-500 GeV) this contribution is completely negligible. We have checked also the contribution of the charged Higgs bosons exchange in the t-u channel. In Table 1 we present the ratios of cross sections with only gauge bosons ($\sigma_{gauge}$) or Higgs particles ($\sigma_{Higgs}$) to $\sigma_{total}$ in which all Feynman diagrams are taken into account. We can see that Higgses have no meaning for heavy Majorana neutrino production. For $\nu_\mu N$ and $\nu_\tau N$ neutrino production the Higgs exchange mechanism gives only the contribution of order $10^{-4}$. Moreover, these results are not sensitive to the $\epsilon$ factor. The Feynman diagram with $H_1^+$ exchange (which is the most important) is not sensitive to this factor at all (A.15). The $H_1^+$ exchange diagram is sensitive to this factor and the contribution to the total cross section increases with increasing $\epsilon$, but as the propagator for this particle is sensitive to this factor too, the increase is rather small and even for $\epsilon = 1$ does not predominate the $H_1^+$ contribution. The result is shown in Fig.4. Finally, in Fig.5. we gather all processes that give a single heavy neutrino production with mass equal 100 GeV as the CM energy function. For LEP II it gives about 2 heavy neutrino productions per year ($L/yr = 500 pb^{-1}$) and about 100 events per year for NLC energy ($L/yr = 10 fb^{-1}$). It is worth to mention that for smaller $M_{W_2}$ also $H_{1,2}^\pm$ Higgs particles masses can be smaller and the total Higgs contribution will be larger.
5 Conclusions

We have investigated in details the importance of the Higgs boson exchange diagrams in the neutrino production in $e^- e^+$ collisions. For the general Higgs potential in the left-right symmetric model we have found the physical eigenmass states. The couplings of these physical Higgs particles with leptons are expressed in terms of physical quantities (masses, mixing angles, CP violating phases). If we neglect the electron’s mass, only four non-standard Higgs bosons couple with $e^- e^+$ and $\nu N$ systems: two charged $H_{1,2}^\pm$, two neutral ones, one scalar $H^0_1$, and one pseudoscalar $A^0_1$. As the result of lack of the FCNC, masses of the neutral Higgs bosons must be large ($> 10$ TeV). The influence of such Higgs particles on the $e^- e^+ \rightarrow \nu N$ cross section is very small even if their coupling with leptons is of the same order as the gauge bosons couplings. The couplings of the charged Higgs bosons are also comparable to the gauge bosons ones and their small contribution ($10^{-4}$) to the cross section is caused mainly by the bigger mass in the Higgs propagators. The contribution of all Higgs exchange diagrams to the full neutrino production $e^- e^+ \rightarrow \nu N$ cross section is small and almost independent of the masses of the heavier neutrinos.

Appendix

We present here the full helicity amplitudes for the process

$$e^-(p, E; \sigma) + e^+(p, E; \bar{\sigma}) \rightarrow \nu(q, E'; \lambda) + N(q, E''; \bar{\lambda}). \quad (A.1)$$

In brackets momentum, energy and helicities of particles are denoted. The other symbols we use are

$$\beta' = \frac{q}{E'} , \quad \beta'' = \frac{q}{E''} , \quad \Delta \sigma = \sigma - \bar{\sigma} \quad \text{and} \quad \Delta \lambda = \lambda - \bar{\lambda}.$$ 

The gauge bosons couplings are precisely defined in Ref. [4].

$$-i M \left( \sigma \bar{\sigma}; \lambda \bar{\lambda} \right) = \frac{s}{2} \sqrt{1 - \left( \frac{M^2}{s} \right)^2} \sum_{i=1}^2 \left\{ D^i_{\Delta \sigma, \Delta \lambda} (\phi, \Theta, 0) \right\}$$
\[
(\sqrt{2})^{\abs{\Delta t}+\abs{\Delta l}} \left[ \frac{A_i^u}{t-M_W^2} - \frac{A_i^\nu}{u-M_W^2} + \frac{A_i^\nu}{s-M_W^2 + i\Gamma_M} \right] + \\
(\sqrt{2})^{-2\abs{\Delta t}+\abs{\Delta l}} \left[ \frac{A^u_2}{t-M_W^2} - \frac{A^\nu_2}{u-M_W^2} + \frac{A^\nu_2}{t-M_W^2 - u-M_W^2} \right]
\]
\[
+ \delta_{\sigma,\hat{\sigma}} \delta_{\lambda,\hat{\lambda}} \left[ \frac{h^u_i + f^u_i}{t-M_W^2} - \frac{h^\nu_i + f^\nu_i}{u-M_W^2} + \frac{g^\nu_i}{s-M_W^2 + i\Gamma_M} \right],
\]
where the sum \(\sum_{i=1}^2\) is over \(W_{1,2}, Z_{1,2}, H_{1,2}^0\) and \(H_1^0\) or \(A_1^i\). All other symbols are explained in Ref. [4].

\[
A_i^l \left( \sigma; \lambda, \lambda \right) = (A_{L_N}^{(N)})^*_{\nu e} (A_{L_N}^{(N)})_{\nu e} \delta_{\sigma,\hat{\lambda}} \sqrt{(1-2\lambda\beta')(1+2\bar{\lambda}\beta')} \\
+ (A_{R_N}^{(N)})^*_{\nu e} (A_{R_N}^{(N)})_{\nu e} \delta_{\sigma,\hat{\lambda}} \sqrt{(1+2\lambda\beta')(1-2\bar{\lambda}\beta')},
\]

\[
A_i^\nu \left( \sigma; \lambda, \lambda \right) = A_i^\nu \left( \lambda \mapsto \bar{\lambda}, \beta' \mapsto \beta'' \right),
\]

\[
A_i^\nu \left( \sigma; \lambda, \lambda \right) = \left\{ A_{L_N}^{(N)} \delta_{\sigma,\hat{\lambda}} - 1 + A_{R_N}^{(N)} \delta_{\sigma,\hat{\lambda}} + 1 \right\} \\
\times \left\{ (A_{L_N}^{(N)})_{\nu e} \sqrt{(1-2\lambda\beta')(1+2\bar{\lambda}\beta')} + (A_{R_N}^{(N)})_{\nu e} \sqrt{(1+2\lambda\beta')(1-2\bar{\lambda}\beta')} \right\},
\]

where

\[
(A_{L_N}^{(N)})_{\nu e} = \frac{g}{2\cos\Theta_W} \xi_{L,R}^{(1)} \Omega_{N_{\nu e}} \quad (A_{R_N}^{(N)})_{\nu e} = - (A_{L_N}^{(N)})^*_{\nu e} \quad (A_{L_N}^{(N)})^*_{\nu e}
\]

with

\[
\xi_{L,R}^{(1)} = \cos\phi - \frac{\sin\phi}{\sqrt{\cos 2\Theta_W}} \quad \xi_{L,R}^{(2)} = \sin\phi + \frac{\cos\phi}{\sqrt{\cos 2\Theta_W}}
\]

\[
A_i^l = \frac{M_{W_N}^2}{M_W^2} \left\{ (A_{L_N}^{(N)})_{\nu e} \delta_{\sigma,\hat{\lambda}} \sqrt{(1+2\lambda\beta')} + (A_{R_N}^{(N)})_{\nu e} \delta_{\sigma,\hat{\lambda}} \sqrt{(1-2\lambda\beta')} \right\} \\
\times \left\{ (A_{L_N}^{(N)})^*_{\nu e} \delta_{\sigma,\hat{\lambda}} \sqrt{(1-2\bar{\lambda}\beta')} + (A_{R_N}^{(N)})^*_{\nu e} \delta_{\sigma,\hat{\lambda}} \sqrt{(1+2\bar{\lambda}\beta')} \right\},
\]

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\[
A^{\nu}_{\sigma} \left( \sigma \bar{\nu}; \lambda \bar{\lambda} \right) = A^{\nu}_{\sigma} \left( \lambda \leftarrow \bar{\lambda}, \beta' \leftarrow \beta'', \nu \leftarrow N \right) , \tag{A.7}
\]

\[
h^{\nu} = +2(-)^{\sigma - \lambda} \left\{ \left( A^{\nu N}_{R} \right)^{*} \left( A^{\nu N}_{L} \right)_{\nu e} \delta_{\sigma, -1/2} \sqrt{1 - 2 \lambda \beta'} \right\} \times \left\{ \left( A^{\nu N}_{R} \right)^{*} \left( A^{\nu N}_{L} \right)_{\nu e} \delta_{\sigma, +1/2} \sqrt{1 - 2 \lambda \beta''} \right\} , \tag{A.8}
\]

\[
h^{\nu} = -h^{\nu} \left( \nu \leftarrow N \right) \]

\[
A^{\nu}_{H} = \left( \left( B^{\nu N}_{L} \right)_{\nu e} \delta_{\sigma, -1/2} \sqrt{1 + 2 \lambda \beta'} + \left( B^{\nu N}_{R} \right)_{\nu e} \delta_{\sigma, +1/2} \sqrt{1 - 2 \lambda \beta'} \right) \times \left( \left( B^{\nu N}_{L} \right)_{\nu N} \delta_{\sigma, -1/2} \sqrt{1 + 2 \lambda \beta''} + \left( B^{\nu N}_{R} \right)_{\nu N} \delta_{\sigma, +1/2} \sqrt{1 - 2 \lambda \beta''} \right) , \tag{A.9}
\]

\[
A^{\nu}_{H} \left( \sigma \bar{\nu}; \lambda \bar{\lambda} \right) = A^{\nu}_{H} \left( \lambda \leftarrow \bar{\lambda}, \beta' \leftarrow \beta'', \nu \leftarrow N \right) , \tag{A.10}
\]

and finally

\[
f^{l, u} = \pm \frac{1}{2} A^{l, u}_{2} \left( \left( - \right)^{\sigma - \lambda} \mp \cos \Theta \right) , \tag{A.11}
\]

\[
g^{l, u}_{H} = \pm \frac{1}{2} A^{l, u}_{H} \left( \left( - \right)^{\sigma - \lambda} \mp \cos \Theta \right) , \tag{A.12}
\]

and

\[
g^{l, u}_{H} \left( \sigma \bar{\nu}; \lambda \bar{\lambda} \right) = \bar{\sigma} \left\{ \left( B^{l}_{L} \right)_{\nu e} \delta_{\sigma, -1/2} - \left( B^{l}_{R} \right)_{\nu e} \delta_{\sigma, +1/2} \right\} \] \times \left\{ \left( B^{l}_{R} \right)_{\nu N} \sqrt{1 - 2 \lambda \beta'} \left( 1 - 2 \bar{\lambda} \beta'' \right) - \left( B^{l}_{L} \right)_{\nu N} \sqrt{1 + 2 \lambda \beta'} \left( 1 + 2 \bar{\lambda} \beta'' \right) \right\} , \tag{A.13}
\]

We present also the vertices that describe the coupling between Higgs and fermion particles in the left-right symmetric model. In general the vertex is given by (Fig.3)

\[
i\Gamma^{(x)} \left( H \right) \equiv i \left( B^{l}_{L} \left( H \right) P_{L} + B^{l}_{R} \left( H \right) P_{R} \right) , \quad x = l, N, l N . \tag{A.14}
\]

Then, in the approximation we make \((v_R \gg y)\) when we neglect the electron mass, the left \(B^{l}_{L} \) and right \(B^{l}_{R} \) handed couplings for the diagrams from Fig.2 are given by

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$H_1^\pm$ exchange

$$\Gamma^{\text{IN}} (H_1^\pm)_{N_e^-} = \frac{1}{v_R} \sum_{c=4,5,6} X_{bc} (K_L)_{ce} P_L,$$

$$\Gamma^{\text{IN}} (H_1^\pm)_{e+N_a} = \frac{1}{v_R} \sum_{c=4,5,6} (K^t_L)_{ce} (X^*)_{ea} P_R. \quad (A.15)$$

$H_2^\pm$ exchange ($\alpha_2 = \frac{\sqrt{2}}{y\sqrt{1-c^2}}$).

$$\Gamma^{\text{IN}} (H_2^\pm)_{N_e^-} = - \left[ m_b^N (K_L)_{be} \epsilon \alpha_2 \right] P_L +$$

$$\left[ - \sum_{c=4,5,6} (\Omega_L)_{bc} m_e^N (K_R)_{ce} \alpha_2 + \frac{1}{\alpha_2 v_R^2} \sum_{c=4,5,6} (\Omega^*_R)_{bc} m_e^N (K_R)_{ce} \right] P_R, \quad (A.16)$$

$$\Gamma^{\text{IN}} (H_2^\pm)_{e+N_a} = - \left[ (K^t_L)_{ea} m_e^N \alpha_2 \right] P_R +$$

$$\left[ - \sum_{c=4,5,6} (K^t_R)_{ec} m_e^N (\Omega_L)_{ea} \alpha_2 + \frac{1}{\alpha_2 v_R^2} \sum_{c=4,5,6} (K^t_R)_{ec} m_e^N (\Omega^*_R)_{ea} \right] P_L. \quad (A.17)$$

$H_0^0, H_1^0$ and $A_1^0$ exchanges.

If we denote

$$A_0 \simeq \frac{1}{y \sqrt{1-c^2}} \left[ H_1^0 - i A_1^0 \right],$$

$$B_0 \simeq \frac{1}{y} H_0^0 - \frac{\epsilon}{y \sqrt{1-c^2}} \left[ H_1^0 + i A_1^0 \right], \quad (A.18)$$

then the couplings ($e^-e^+H$) and ($N_aN_bH$) can be find from

$$\Gamma^i (H_1^0, A_1^0)_{e^-e^+} = - \left[ \sum_{c=4,5,6} (K^*_L)_{cc} (K_R)_{ce} m_e^N A_0 \right] P_R$$

$$- \left[ \sum_{c=4,5,6} (K_L)_{cc} (K^*_R)_{ce} m_e^N A_0^* \right] P_L. \quad (A.19)$$
and we can see that the lightest Higgs $H^0_0$ does not couple to $e^-e^+$ (if we neglect the electron mass),

$$
\begin{align*}
\Gamma^N \left( H^0_0, H^1_0, A^0_1 \right)_{N_a N_b} &= - \left[ \left( (\Omega_L)_{ba} m^N_a + (\Omega_L)_{ab} m^N_b \right) B_0 \right. \\
&\quad + \left. \sum_{l=\mu,\tau} m_l \left( (K_R)_{bl} (K_R^*)_{al} + (K_L)_{al} (K_R^*)_{bl} \right) A^*_0 \right] P_R \\
&\quad - \left[ \left( (\Omega_L)_{ba} m^N_a + (\Omega_L)_{ab} m^N_b \right) B_0 \right. \\
&\quad + \left. \sum_{l=\mu,\tau} m_l \left( (K_L)_{bl} (K_R^*)_{al} + (K_L^*)_{al} (K_R)_{bl} \right) A^*_0 \right] P_L.
\end{align*}
$$

References


**Figure Captions**

**Fig.1** Diagrams with gauge boson exchange describing the process $e^-e^+ \rightarrow \nu N$ in the left-right symmetric model on the tree level.

**Fig.2** Diagrams with Higgs boson exchange describing the process $e^-e^+ \rightarrow \nu N$ in the left-right symmetric model on the tree level.

**Fig.3** Higgs-fermions vertex. $l$ and $N$ denote charged and neutral leptons respectively.

**Fig.4** The $\epsilon$-dependence for $\sigma(e^-e^+ \rightarrow \nu N(100))$ cross section given by all physical Higgs bosons exchange (solid line) and only for $H_2^+$ Higgs exchange (asterisks line) for LEPII energy.

**Fig.5** Total cross section for the single heavy Majorana and three different light neutrinos production, $\nu_e$ (cross-line), $\nu_\mu$ (dotted line) and $\nu_\tau$ (asterisks line) as the energy function. As the light neutrinos are not detected only the sum of these three processes can be observed (solid line).
Fig. 1.

(a) $e^- \rightarrow W_1^+ , W_2^+$

(b) $e^- \rightarrow W_1^+ , W_2^+$

(c) $e^- \rightarrow Z_1^0 , Z_2^0$
Fig. 2.

$$e^- \quad \text{\(N_b\)} \quad (a) \quad H_1^+, H_2^+ \quad e^+ \quad \text{\(N_a\)}$$

$$e^- \quad \text{\(N_b\)} \quad (b) \quad H_1^+, H_2^+ \quad e^+ \quad \text{\(N_a\)}$$

$$e^- \quad \text{\(H_1^0, A_1^0\)} \quad \text{\(N_b\)} \quad \text{\(e^+\)} \quad \text{\(N_a\)}$$

(c)
Fig. 3.

\[ H \rightarrow_{i \Gamma^{L,N,N}} (H) \rightarrow \Gamma, N_0, N \]

\[ 1, N_0, 1 \]