Heavy Neutrinos at Large Colliders

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Abstract. In this work we discuss the state of the art of the heavy neutrinos at colliders. The neutrinos in the Standard Model (SM) are considered to be massless which is in contradiction with the evidence from the neutrino oscillations experiments. These cosmological observations established that at least two SM neutrinos have non-zero masses and that individual lepton number is violated. Therefore a strong conclusive first evidence of new physics caused by the neutrino mass mechanism is emerged. In this work we discuss the collider phenomenology of neutrino mass models at the existing (LHC) and next generation large colliders (FCC: ee, hh, eh, ILC and CePC) at different high synergies. It is naturally known that colliders are not sensitive to the SM light neutrinos; however the production of heavy neutrinos is very possible to be detected; giving rise to several signal processes which are categorised by different final state topologies according to theirs physics interests. We will present the state of the art of the heavy neutrinos generated with radiative neutrino mass models and their experimental searches; mainly for Majorana neutrino signals allowing for probing the nature of the Dark Matter candidates at high energy colliders. The focus will be on the well-motivated neutrino mass models which provide an elegant framework to explore new directions in Dark Matter phenomenology at the TeV scale and the future experimental prospects.

1. Introduction

Established 40 years ago, the Standard Model (SM) of elementary particle physics has been enormously successful theory in explaining physics around the electroweak scale. However, several fundamental questions are currently unanswered, making it mandatory to explore possible extensions into which the SM model can be embedded in a natural way. Among these unexplained puzzles: the neutrino masses and mixing [1], the nature of the dark matter (DM) [2], and the origin of the baryon asymmetry of the Universe. None of these issues is
successfully explained within the SM framework. Yet on the other hand, we have discovered through the neutrino oscillations that zero neutrino masses is not an accurate model which has been confirmed by the T2K Collaboration [3]. The later provides a breakthrough measurement which confirms the non-zero neutrino mass and a clear evidence of the only established physics beyond the SM so far.

Indeed, many generic models, which are available in the market, are trying to investigate this issue among them: Seesaw mechanism (Type I, II or III), Radiative Models: one loop (A. Zee [5], Ma [6]), two loops (Zee-Babu), or three loops models (Krauss,Nasri, Troden (KNT)). The focus in this work, will be on the latter model (KNT) in [7] which proposed the extension of the SM with two electrically charged $SU(2)_L$ singlet scalars and one right handed (RH) neutrino field $N_1$, where a $Z_2$ symmetry was imposed at the Lagrangian level in order to forbid the Dirac neutrino mass terms. After the breaking of the electroweak symmetry, neutrino masses are generated at three-loop, which makes their masses naturally small due to the high loop suppression. Moreover, the field $N_1$ is odd under $Z_2$ symmetry, and thus it is guaranteed to be stable, which makes it a good candidate for DM. It was shown also that in order to fit the neutrino oscillation data and be consistent with different recent experimental constraints such as lepton flavor violation (LFV), one needs to have three RH neutrinos.

The aim of this paper is to elaborate an overview as well as systematic assessment on the possible signatures for heavy neutrino searches that can be tackled mainly at future hadron and leptons colliders. Furthermore, for the time being and driven by the overwhelming experimental data available at the ATLAS and CMS experiments at the CERN-Large Hadron Collider (LHC), one could explore in details any possible signature at new energy frontiers with its high rate of beam energies are provided. In section IV, we conclude and discuss prospects for future work.

2. Phenomenology of the model and its setup

The considered model in [7] is an extension of the SM. It has two charged scalar singlets $S_{1,2}$ under $SU(2)_L$ gauge group and three right handed neutrinos. In order to forbid Dirac neutrino mass terms, a $Z_2$ symmetry was imposed at the Lagrangian level.

The main form for the model Lagrangian is given by:

$$
\mathcal{L} = \mathcal{L}_{SM} + \{ f_{\alpha \beta} L_\alpha^T C \tau_2 L_\beta S_1^+ + g_{\alpha R} N_1^C \ell_\alpha R S_2^+ + \frac{1}{2} M_{N_1} N_1^C N_1 + h.c \} - V(\Phi, S_{1,2}) \tag{1}
$$

where $f_{\alpha \beta}$ denotes the Yukawa couplings, $\alpha$ and $\beta$ represents the lepton family indices, and $L_\alpha$ is the LH lepton doublet. The Majorana RH neutrino masses are $M_{N_1}$. $V(\Phi, S_{1,2})$ is the tree-level scalar potential whose exact form is given by:

$$
V(\Phi, S_{1,2}) = \lambda \left( |\Phi|^2 \right)^2 - \mu^2 |\Phi|^2 + M_1^2 S_1^+ S_1 + M_2^2 S_2^+ S_2 + \lambda_1 S_1^+ S_1 |\Phi|^2 + \lambda_2 S_2^+ S_2 |\Phi|^2 + \frac{\eta_1}{2} (S_1^+ S_1)^2 + \frac{\eta_2}{2} (S_2^+ S_2)^2 + \eta_2 S_1^+ S_1 S_2^+ S_2 + \{ \lambda_3 S_1 S_2 S_2^+ S_1^+ + h.c \} \tag{2}
$$

where $\Phi$ represents the SM Higgs filed doublet. One of the features of this model is that by imposing $Z_2$ symmetry, Dirac neutrino mass term at all levels of perturbation theory is forbidden. After the electroweak symmetry breaking, the neutrino masses are produced at three-loop. $N_1$ is considered to be the lightest RH neutrino in the model and hence the most
stable and designated candidate for DM. The three-loop diagram that generates the small non-zero neutrino mass matrix elements is illustrated at Fig. 1.

In addition, one has to mention that the model has the main following features:

- The generated small neutrino masses at three-loop fit the neutrino oscillation data.
- Furthermore, no conflict with the bounds on Lepton Flavor Violating (LFV) processes, the muon anomalous magnetic moment and $0\nu\beta\beta$ decay.
- $N_1$ is the considered DM candidate with a relic density that is in agreement with the observation for masses around the EW scale.
- Yields a strong first order electroweak phase transition that ensures any baryogenesis scenario and its testability with the Higgs mass measurement currently provided by the CERN-LHC experiments.

Neutrino mass matrix and mixing:

Analogously to other heavy neutrino mass models, the masses of the light neutrinos are generated after breaking the protective electroweak symmetry. In this framework, the three loop Feynman diagram that contributes to neutrino mass matrix is illustrated in Fig.1. Furthermore, from Eq.(1), one can obtain the mass matrix element of the neutral fermions that can be simplified as:

$$(M_{\nu})_{\alpha\beta} = \frac{\lambda_{\alpha} M_{\ell_{\alpha}} M_{\ell_{\beta}}}{(2\pi)^6 M_{S_2}} f_{\alpha j} f_{\beta k} g_{ij} g_{kj} F_{\alpha\beta} \left( \frac{M_{N_1}^2}{M_{S_1}^2} \right) \left( \frac{M_{S_2}^2}{M_{S_2}^2} \right)$$ (3)

where $\alpha$ and $\beta$ denote the charged lepton flavors.

To describe the neutrino flavor mixing in the light of the oscillation data, the neutrino mass matrix is diagonalised using the mixing matrix and the usual Pontecorvo-Maki-Nakagawa-Sakata $U_{PMNS}$ matrix, relevant for the neutrino oscillation experiments. Thus, this can be expressed as:

$$M_\nu = U_{PMNS} \cdot \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} \cdot U_{PMNS}^T$$ (4)

where we have the corresponding $U_{PMNS}$ parametrisation which can be found in the literature as:

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - c_{23}s_{12}s_{13}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{pmatrix}$$ (5)
Here, \( c_{ij} = \cos(\theta_{ij}) \), \( s_{ij} = \sin(\theta_{ij}) \) where the three mixing angles \( \theta_{12} \), \( \theta_{23} \), and \( \theta_{13} \) are used and with \( \delta \) being the Dirac CP phase whereas \( \alpha_1 \) and \( \alpha_2 \) are the two Majorana phases associated with the Majorana nature. In addition, as matter of fact for an accurate model benchmarking we consider in our calculations the last experimentally measured parameter values from the current best-fit values [8].

Imposing the most stringent experimental constraints on the main sources of Lepton Flavor Violation (LFV) contribution which arises from \( l_\alpha \to l_\beta \gamma \), the branching ratio is then calculated and simplified as:

\[
B(\mu \to e\gamma) = \frac{\alpha v^4}{384\pi} \left[ \frac{|f_{\mu e}|^2 + |f_{ee}|^2}{M_{S_1}} + \frac{36|g_{1e}g_{1\mu}|^2}{M_{S_2}^4} F_2^2(M_{S_1}/M_{S_2}) + \frac{6|g_{2e}g_{2\mu}|^2}{M_{S_2}^4} F_2^2(M_{S_1}/M_{S_2}) \right] \tag{6}
\]

where \( v \) is the vacuum expectation value of H, \( \alpha \) denotes the the electromagnetic fine structure constant and \( F_2 \) is the loop function given by \( F_2(x) = (1/6(x - 1)^4)(1 - 6x + 3x^2 + 2x^3 - 6x^2 - 6x^2 \log x) \). In this case, the considered value shall be \( B(\mu \to e\gamma) < 5.7 \times 10^{-13} \) in accordance with the MEG collaboration upper bound [9]. On the other hand if \( l_\alpha = l_\beta = \mu \), new contribution is added to the muon anomalous magnetic moment \( \Delta a_\mu \) described as:

\[
\Delta a_\mu = \frac{m_\mu^2}{96\pi^2} \left( \frac{|f_{\mu e}|^2 + |f_{ee}|^2}{M_{S_1}} + \frac{6|g_{1e}g_{1\mu}|^2}{M_{S_2}^4} F_2(M_{S_1}/M_{S_2}) + \frac{6|g_{2e}g_{2\mu}|^2}{M_{S_2}^4} F_2(M_{S_1}/M_{S_2}) \right) \tag{7}
\]

with the upper limit \( \Delta a_\mu < 2.89 \times 10^{-9} \) [10].

**Relic Density:**

In this scenario, the Dark Matter emerges as the lightest RH neutrino. The total thermal average annihilation cross-section (for the the nonrelativistic expansion) is given by:

\[
\sigma_{N_1N_1} v_r \simeq \sum_{\alpha,\beta} |g_{1\alpha}g_{1\beta}^*|^2 \frac{m_{N_1}^4 (m_{N_1}^2 + m_{N_1}^2)}{48\pi (m_{N_2}^2 + m_{N_1}^2)} v_r^2 \tag{8}
\]

where \( v_r \) is the relative velocity between the two \( N_1 \)s. The abundance of the DM candidate is given by the relic density equation:

\[
\Omega_{N_1} h^2 \simeq \frac{1.28 \times 10^{-2}}{\sum_{\alpha,\beta} |g_{1\alpha}g_{1\beta}^*|^2 (m_{N_1}/135 \text{ GeV})^2} \left( \frac{m_{N_1}}{1 + m_{N_2}^2/m_{N_1}^2} \right)^4 \left( 1 + m_{N_2}^2/m_{N_1}^2 \right)^4 \tag{9}
\]

### 3. Numerical Simulation for possible signatures

Neutrinos manifest inside the detector as missing energy. The production mechanism of RH heavy neutrinos proceeds via the new lepton flavor violating interactions given by the \( f \) and \( g \) terms in (1). Phenomenologically, the radiative neutrino mass model is simulated and reported for various of possible collider signatures such as \( e^-e^+ \to e^-\mu^+ + E_{miss} \) at the International Linear Collider (ILC) [11] and \( pp \to \tau^+\tau^- + E_{miss} \) (with \( \ell_\alpha\ell_\beta = ee, e\mu, \mu\mu \)) at the existing CERN Large Hadron Collider at both energies 8 TeV and 14 TeV [12]. Within this study it was found out that an accurate cut on the \( M_T^2 \) event variable is vital for an effective suppression of the large Standard Model background and it eventually enhances the significance of the signal over the background. The full LHC results were summarised in our previous work. Moreover, to provide the sensitivity estimates for future colliders in which the focus will
be on the ILC and FCC-ee colliders. Along this direction, several production channels of possible final states where the heavy neutrino constitute different signatures for Majorana neutrino searches were explored. These signatures where the missing energy in the process $e^- e^+ \rightarrow e^- \mu^+ + E_{\text{miss}}$ corresponds to any state involving $E_{\text{miss}} \subset \{\nu_\mu \bar{\nu}_e, \nu_e \bar{\nu}_\tau, \nu_\tau \bar{\nu}_e, \nu_\mu \bar{\nu}_\mu, \nu_\tau \bar{\nu}_\mu, \nu_\tau \bar{\nu}_\tau, N_i N_k; i, k = 1, 2, 3\}$. The signal and background distributions were studied using benchmarks that are in agreement with the experimental constraints such as the bounds on lepton flavor violating processes, the muon anomalous magnetic moment and the neutrino-less double beta decay. In addition, the physics analyses were extended provided with the powerful characteristics of future $e^+ e^-$ linear colliders, such as the ILC, where the possibility of having polarized beams of electron and/or positron. This feature can be used to reduce the background contribution which can result in a significant improvement of the signal to background ratio.

At the ILC, both electron and positron polarizations are chosen to lie in the range:

$$|P(e^-)| \leq 0.8; \quad |P(e^+)| \leq 0.3,$$

with $P(f) = (N_{R} - N_{L})/(N_{R} + N_{L})$; and $N_{R}$ ($N_{L}$) is the number of right (left) handed fermions. For CLIC, the positron polarization could reach up to $|P(e^+)| = 0.6$; therefore one expects the background to be more suppressed. Hence, by considering the electron (positron) polarization $P(e^-) < 0$ ($P(e^+) > 0$), the excess in the number of LH (RH) neutrino events gets enhanced. The simulation is based on the selected benchmark, and use the ILC run at different

| $E_{\text{CM}}$ (GeV) | $L$ ($fb^{-1}$) | $P(e^-, e^+)$ | $N_B$ | $N_{EX}$ | $N_S$ |
|----------------------|----------------|----------------|------|--------|------|
| 250                  | 250            | 0, 0           | 16480| 16851  | 371  |
|                      |                | $-0.8, +03$    | 38498| 39775  | 1277 |
| 350                  | 350            | 0, 0           | 20609| 21055  | 446  |
|                      |                | $-0.8, +03$    | 47740| 48990  | 1250 |
| 500                  | 500            | 0, 0           | 28280| 28815  | 535  |
|                      |                | $-0.8, +03$    | 65500| 67250  | 1750 |
| 1000                 | 1000           | 0, 0           | 19.217| 469.76 | 450.54|
|                      |                | $+0.8, -03$    | 2.07 | 727.10 | 725.03|

Table 1: The expected ($N_{EX}$) and background ($N_B$) number of events for different CM energy values with/without polarized beams within the considered cuts.

Figure 2: The significance versus luminosity at different CM energies within the cuts defined in Table-1; with (left) and without (right) polarized beams. The two horizontal dashed lines represent $S = 3$ and $S = 5$, respectively.
CM energy: $E_{CM} =$250, 350, 500 GeV and 1 TeV, with unpolarized beams at first; then we consider the polarized beams with $P(e^-, e^+) = [-0.8, +0.3]$ and/or $P(e^-, e^+) = [+0.8, -0.3]$. In Figure 2, we show the dependence of the significance on the accumulated luminosity with and without polarized beams for the considered CM energies. In addition Table-1 illustrates the expected events number excess for each CM energy with and without polarized beams. The full details of the analysis is described in [11].

Furthermore, in addition to the previous analyses, we have investigated our work with the physics program of the two presently ongoing FCC-ee and CePC colliders. Several possible signatures have been extensively studied at the kinematic reach of these two planned circular colliders at their corresponding specific center of mass energies and envisaged luminosity values [13].

Starting by tackling the mono-photon plus missing energy final state ($e^- e^+ \rightarrow \gamma + E_{\text{miss}}$), Figure 3 shows the individual angular distributions of the different missing energy contributions (left) and the photon energy produced at 1 TeV energies (right). The resulting signal and background distributions of the total of all individual angular distributions as well as the energy of the photon are shown in Figure 4. Although this work is still ongoing but a clear discriminant variables from Figure 4 can used in the event selection to provide a good separation of the signal from the background processes.

Another promising final state that can give rise to missing transverse energy (MET) signals at the the kinematical reach of ILC as well as FCC-ee would be $e^- e^+ \rightarrow \ell_\alpha^+ \ell_\beta^- + E$ (with $\ell_\alpha \ell_\beta = ee, e\mu$). The cross section of different same-sign final state contributions $\sigma(E_{\text{miss}})$ versus the center of mass energy is illustrated in Figure-5. The same-sign leptons final states provides a unique event topology to test the radiative neutrino mass models at different center of mass energies.
Figure 4: Left, the combined cross section distributions of the different same-sign final state contributions $\sigma(E_{\text{miss}})$ versus the energy of the photon arising from the KNT processes in addition to the SM processes. The combined cross section distributions of the different same-sign final state contributions versus the photon angular distribution is shown on the right.

Figure 5: The cross section of different same-sign final state contributions $\sigma(E_{\text{miss}})$ versus the center of mass energy. The $e^-e^- + E_{\text{miss}}$ final state is on the left side whereas the $e^-\mu^+ + E_{\text{miss}}$ final state is displayed on the right.
4. Conclusions and Outlook

In this talk, we presented an overview of the production mechanisms and the decay modes of RH heavy neutrinos in the radiative neutrino mass models framework with $e^+e^-$, $e^-e^-$ and $pp$ collisions. We have studied the detectability at the future colliders and actual colliders with different CM energies. It was found that for the ILC CM energies 250, 350 and 500 GeV, the missing energy is mainly light LH neutrinos, while at $E_{CM} = 1\, TeV$, the RH neutrinos contribution is dominant. Furthermore, the signal gets enhanced and can be observed for all the considered CM energies by using polarized beams. We determined in our previous works that the LHC Run I data ($L = 20\, fb^{-1}$) can be used to exclude the charged scalars with masses below 400 GeV. However at the LHC@14 TeV ($L=100 \, fb^{-1}$), the signal is mostly likely to be seen when more luminosity is recorded.

Many possible signature studies are ongoing and will provide more sensitivity estimates to the radiative neutrino mass models like the same-sign leptons plus missing energy final states at FCC-ee, ILC and CePC which are currently undergoing their conceptual phases.

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