Dark Matter Searches as New Physics at the Future Circular Collider (FCC)

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Abstract. We highlight the importance of the Future Circular Collider (FCC) in the search for possible Dark Matter (DM) signatures. The focus will be on well motivated Beyond the Standard Model (BSM) extensions. We consider a class of radiative neutrino mass models which extend the SM by adding heavy right handed neutrinos (RHNs), where the neutrino masses are generated at loop level. Within this class of models, the lightest RHN is considered to be stable and serves as DM candidate. We perform preliminary studies of final states which involve missing energy contributions from DM candidates to learn about the feasibility of observing these final states at the expected FCC-hh, FCC-eh and FCC-ee beam colliders. Some of our results are discussed where the topology of the the final states are analysed depending on the obtained sensitivity of the signal. The study also yields the most common promising discovery channels in exploring potential indirect DM signatures at future lepton and hadron colliders.

1. Introduction

The Standard Model (SM) was believed to be a complete theory in explaining the fundamental description of nature. In the SM framework, the neutrinos are considered to be massless. However, various astrophysical observations confirmed that neutrinos have non-zero masses based on neutrino oscillations and their mixing, which were first observed at the Super-Kamiokande [1] and later at the Sudbury Neutrino Observatory [2, 3]. Since then, neutrino physics has acquired great importance due to neutrino mass and mixing which have not been incorporated in the current SM of elementary particles. This puzzle of the unknown origin of neutrino masses in addition to the Dark Matter evidence in the universe provides robust indication of new physics beyond the SM. Therefore, the demand of new theories with the purpose of explaining neutrino
masses and provide possible explanations of DM through the neutrino sector have grown. Moreover, one has to consider the experimental challenge due to the fact that DM does not interact with any particles defined by the SM which makes it very difficult to detect at colliders.

Possible DM candidates in several BSM models are proposed and include new types of particles such as Weakly Interacting Massive Particles (WIMPs), Axions, supersymmetric particles in the hidden sector, etc. Another postulate to explore the nature of DM is Sterile neutrinos which is usually related to neutrinos with right-handed chirality (SM neutrinos are left-handed) preventing any interactions with the SM fermions. An overview of the known SM particles with the three heavy right-handed neutrinos are illustrated in Figure 1. In addition, one of the striking questions in the neutrino sector is the tagging of the neutrino as Dirac or Majorana type. Here comes the interplay between the DM and the neutrino masses generated at the loop level described by well motivated neutrino mass models (discussed in the next section) where the lightest right-handed neutrino is considered to be a DM candidate.

2. Majorana neutrino signatures with the FCC setup

Since the discovery of the Higgs boson at the CERN-LHC [5, 6], there has been more interest in looking for any evidence of new physics. Therefore, providing more precise SM measurements at future colliders will shed more light on any window of new physics that can manifest within the geometric acceptance of the expected detectors. Nowadays, particle accelerators are advancing towards higher energies and luminosity values; it will be now possible to look for rare massive particles (within the MeV-TeV scale) that interact very weakly with the SM particles.

Recent design studies of a proposed new collider, the Future Circular Collider (FCC), have shown great promise with three different beam settings: proton-proton (pp), electron-electron(ee) and electron-proton (ep) colliders, with center of mass energies reaching up to 100 TeV [7, 8]. Table 1 outlines the important parameters of the FCC design (LHC parameters given as comparison). Thus, the FCC with its high luminosity would be an ideal program towards probing the nature of DM as one of the big unexplained puzzles of the well confirmed physics beyond the SM.

Moreover, the FCC-ee offers a convenient environment for observations of new physics at lower $E_{CM}$, envisaged with clean signals (unlike in hadronic colliders), and reaching luminosity
values which are the highest for any collider in the $\sqrt{s} = [90, 360]$ GeV range. The expected luminosity dependence on the centre of mass energies for the two linear leptonic colliders, ILC and CLIC, as well as the Circular electron-Proton Collider (CePC) are shown in Figure 2 in comparison with the FCC-ee performance. As a consequence of the configuration comparison, it is clearly visible that the FCC-ee’s discovery potential is further augmented by the presence of the four heaviest SM particles (Z, W, H, and top) within its energy range, in addition to the accumulated statistics.

At the FCC, we propose the study of signals consisting of charged leptons and missing energy final states, where the $E_{\text{miss}}$ contributions come from the SM neutrinos as well as the Majorana neutrinos ($N_1$, $N_2$ and $N_3$), i.e. $e^-e^+ \rightarrow l^+l^- + E_{\text{miss}}$, $e^-e^- \rightarrow l^+l^- + E_{\text{miss}}$ or $pp \rightarrow l^+l^- + E_{\text{miss}}$ where $l = e, \mu$ and the missing energy contributions $E_{\text{miss}}$ can be any combination in $(\nu_e \bar{\nu}_e, \nu_\mu \bar{\nu}_e, \nu_\mu \bar{\nu}_\mu, \nu_\tau \bar{\nu}_\tau, \nu_\mu \bar{\nu}_\tau, N_i N_k)$ and $i, k = 1, 2, 3$. Table 2 represents the list of the charged dilepton final states of the considered neutrino mass models and the SM at different beam configurations ($pp$ and $e^-e^+$). A general mass hierarchy is observed as $M_{N_1} < M_{N_2} < M_{N_3} < M_{S_j}$ where $M_{S_j}$ are the charged scalars that have been introduced by the BSM model in question. We consider instances of radiative neutrino mass models that provide potential signatures (mentioned above) that can be studied at both hadronic and leptonic colliders. Among these models, one can list:

- **Inert Higgs Doublet Model (IHDM)**
  The version being discussed here extends the SM with an inert Higgs doublet in addition to three heavy RHNs. Here, we consider $N_1$ to be the DM candidate which is odd under a discrete $Z_2$ symmetry and making it stable. In this model, the SM neutrino masses are generated at one-loop.

- **Krauss - Nasri - Trodden (KNT) model**
  Detailed in [10], the model introduces two charged singlet scalars $S_{1,2}$ and three heavy RHNs ($N_1$, $N_2$ and $N_3$). The neutrino masses are generated radiatively at three-loop ensuring that the generated masses are very small. Here, the lightest RHN ($N_1$) is considered to be stable under $Z_2$ symmetry which makes it favourite to be the DM candidate.

- **Left Right Supersymmetric Model (LRSM)**
  Described in [12, 13], the model introduces two RH gauge bosons $W_R^\pm$ and $Z_R$, that can

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**Table 1.** Preliminary baseline parameters for the FCC-hh, FCC-eh and FCC-ee compared with the parameters of the LHC as of Run 2.

| Collider     | LHC       | FCC-hh    | FCC-eh    | FCC-ee    |
|--------------|-----------|-----------|-----------|-----------|
| Circumference| 26.7 km   | 97.8 km   | 97.8 km   | 97.8 km   |
| Beam energy  | 14 TeV    | 100 TeV   | 3.5 TeV   | 90 - 360 GeV |
| ($E_{CM}$)   |           |           |           |           |
| Luminosity   | 2.0 (end of Run 2) | 5.0 - 30.0 | 1.5       | 100.0 (Z pole) |
|              | $[10^{34} \text{cm}^{-2}\text{s}^{-1}]$ |           |           | 25.0 (W threshold) |
|              |           |           |           | 7.0 (H production) |
|              |           |           |           | 1.4 ($t\bar{t}$ threshold) |
| Bunch Population | 1.15 protons | 1.0 protons | 1.0 protons | 0.5 - 1.8 electrons |
|              | $[10^{11} / \text{bunch}]$ | 0.03 electrons |           |           |
Table 2. The list of the charged dilepton final states of the considered neutrino mass models and the SM at different beam configurations ($pp$ and $e^-e^+$).

| Models   | Final state | Collider | $e^-e^+ E_{miss}$ | $e^\pm\mu^\mp E_{miss}$ | $e^-\mu^+ E_{miss}$ | $\mu^-\mu^+ E_{miss}$ | $e^\pm\tau^\mp E_{miss}$ | $\mu^\pm\tau^\mp E_{miss}$ | $\tau^-\tau^+ E_{miss}$ |
|----------|-------------|----------|-------------------|--------------------------|----------------------|-----------------------|---------------------------|---------------------------|------------------------|
| SM       | $pp$        | 15 3     | 10 2              | 15 3                     | 10 2                 | 15 3                  |                           |                           |                        |
| IHDM3N   | $pp$        | 45 9     | 70 14             | 45 9                     | 70 14                | 45 9                  |                           |                           |                        |
| KNT      | $pp$        | 55 11    | 100 24            | 55 15                    | 100 24               | 55 15                 |                           |                           |                        |
| LRSM     | $pp$        | 32 6     | 32 4              | 32 6                     | 32 4                 | 32 6                  |                           |                           |                        |

decay into three RH Majorana neutrinos and leptons. Majorana mass terms are generated by Seesaw Type I mechanism.

By imposing the $Z_2$ symmetry the generation of the Dirac neutrino mass terms is prevented in the considered models mentioned above. In the radiative neutrino mass models, the used values of the fermion masses and couplings for the relic density calculation should be in agreement with the measured value of $\Omega_{DM} h^2 = 0.1199 \pm 0.0027$ [11]. Furthermore, the benchmark selection should not be in conflict with the bounds on Lepton Flavor Violating (LFV) processes, the muon anomalous magnetic moment and neutrinoless double beta decay.

Figure 2. The expected luminosity performance of FCC-ee with the future lepton colliders as a function of the centre-of-mass energies [9].
3. Results and Discussion

Previously, radiative neutrino mass models have been studied with oppositely charged dilepton final states at $pp$ colliders in [15], as well as at the linear $e^- e^+$ colliders in [16]. Here, preliminary results of the KNT model for different channels at the FCC collider are provided in terms of the signal and background cross sections across the beam energies ($E_{CM}$) at the FCC-hh and FCC-ee (see table 1). The search strategy of any possible signature is based on the benchmark selection where the afforded sensitivity in terms of the difference between the signal and background contributions is significant. This study will determine the parameter phase space and whether they are kinematically accessible by the collider experiment.

![Figure 3.](image1.png)  
**Figure 3.** The cross section distributions of $pp \rightarrow e^+ e^- + E_{miss}$ as functions of the centre of mass energies at the FCC-hh with the KNT model.

![Figure 4.](image2.png)  
**Figure 4.** The cross section distributions of $pp \rightarrow e^- \mu^+ + E_{miss}$ as functions of the centre of mass energies at the FCC-hh with the KNT model.
Figure 5. The cross section distributions of $pp \rightarrow \mu^+ \mu^+ + E_{\text{miss}}$ as functions of the centre of mass energies at the FCC-hh with the KNT model.

The numerical simulations of the presented physics processes were obtained using CalcHEP [14]. As a first step, the cross sections are given as a function of the centre of mass energies to investigate the most notable KNT and SM contributions. The focus here is to explore opposite charged dilepton signatures from the KNT radiative neutrino mass model at the FCC-hh, i.e.: $pp \rightarrow l_\alpha^- l_\beta^+ E_{\text{miss}}$ where $l_\alpha l_\beta = ee$ (Figure 3), $e\mu$ (Figure 4), and $\mu\mu$ (Figure 5).

In addition to the aforementioned investigation, we sum-up all possible contributions from KNT and SM considered in $pp \rightarrow \mu^- \mu^+ E_{\text{miss}}$ to visualise the yields of the signal production. The results are illustrated in Figure 6 where the signal contributions have slightly higher cumulative cross sections.

Moreover, these processes can be better probed at the higher luminosity FCC-hh collider where the signal over the background ratio is anticipated to be more clear. Figure 7 compares the detectability of one of the final states topologies discussed above at different collider luminosities. From the comparison, it can be seen that the expected number of events for the process is predicted to increase by more than an order of magnitude at the FCC-hh.

One has to mention, for the correct treatment of the kinematic regime in this busy hadronic environment, more statistics are needed to better identify the cut sets that should be applied at higher energy scales.
Figure 6. The comparison of the signal and background cross section values for the process \( pp \rightarrow l^+l^- + E_{\text{miss}} \).

4. Conclusions and Outlook

One of the promising complementary analysis of available radiative neutrino mass models is ongoing. The aim is to provide a complete comparison study which evolve the Majorana neutrinos in the final states that are kinematically and topologically accessible in collider environment.

Figure 7. Comparison of cross section values for signal (KNT) at LHC and FCC-hh luminosities.

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