PROCEEDINGS OF SCIENCE

Hunting for heavy neutral leptons at future lepton colliders

PoS(EPS-HEP2023)460

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Neutrinos are the most elusive particles known. Heavier sterile neutrinos mixing with the Standard Model partners might solve the mystery of the baryon asymmetry of the universe and take part in the mass generation mechanism for the light neutrinos. Future lepton colliders, including e^+e^- Higgs factories, as well as multi-TeV electron and muon machines, will provide the farthest search reach for such neutrinos in the mass range from above the Z pole into the multi-TeV regime. In our contribution, we will discuss the future lepton collider search potential for such particles in their prompt decays. We will also present a new approach to constrain the nature of heavy neutrinos, probing their Majorana or Dirac nature, based on the kinematic variable distributions. Finally, we will discuss the complementarity in the flavour-mixing parameter space between the two types of lepton colliders.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

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1. Introduction

To address several problems of the Standard Model, different models of new physics have been proposed. One of the possible scenarios is to introduce new species of neutrinos which, having masses of hundreds of GeV, could be abundantly produced and detected at future lepton colliders, such as CLIC [1], ILC [2] or a muon collider (MuC) [3]. In our papers [4, 5], we studied the discovery reach for heavy Dirac and Majorana neutrinos decaying into two jets and a lepton at ILC running at 250 GeV, 500 GeV and 1 TeV (with a total integrated luminosity of 2 ab^{-1}, 4 ab^{-1} and 8 ab^{-1}, respectively), CLIC at 3 TeV (5 ab^{-1}) and MuC at 3 TeV and 10 TeV (1 ab^{-1} and 10 ab^{-1}, respectively). We also showed how to efficiently probe the nature of the new states. The expected limits exceed all estimates published to date for pp machines by several orders of magnitude.

2. Model setup and simulation framework

The *HeavyN* model [6, 7] has been employed for the generation of reference signal samples. It effectively extends the Standard Model by three right-handed neutrinos (denoted as $N1$, $N2$ and $N3$) which mix with the SM leptons. The model introduces 12 new parameters as compared to the SM: three heavy neutrinos masses and nine real mixing parameters (V_{lk}, where $l = e, \mu, \tau$ and $k = N1, N2, N3$). The heavy-neutrino vertices introduced in the model are illustrated in Fig. 1.

In the presented analysis, we focus on the production of a light-heavy neutrino pair followed by the decay of the heavy neutrino into two jets and a charged lepton, as shown in Fig. 2. This signature allows for a complete reconstruction of the mass of the heavy neutrino. With a dominant contribution coming from the t-channel W exchange, the cross section for the neutrino pair is very sensitive to the initial beam polarisation. Hence, we studied the prospects for heavy neutrino detection only for preferred polarisation settings. We considered ILC running at 250 GeV and 500 GeV (1 TeV), with beam polarisation of −80% for electrons and +30% (+20%) for positrons, and an integrated luminosity of 0.9 ab^{-1} and 1.6 ab^{-1} (3.2 ab^{-1}), and CLIC running at 3 TeV, with an integrated luminosity of 4 ab^{-1} and −80% electron beam polarisation only (no polarisation for positrons). As for the MuC, no beam polarisation was considered and a total integrated luminosity of 1 ab^{-1} and 10 ab^{-1} was assumed for 3-TeV and 10-TeV running, respectively. While Whizard 2.8.5 [8] was used to generate most of the event samples, version 3.0.0 was required to properly simulate Majorana neutrino production.

The analysis was simplified by setting the masses of $N2$ and $N3$ to 100 TeV and all their couplings to zero. A wide range of masses of $N1$ was probed, starting at 100 GeV, going up to the collision energy and even above. For the reference scenario, all the $N1$ couplings to the charged leptons (denoted as V_{lN}^2) were set to the same value of 0.0003. Processes with at

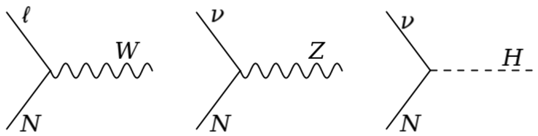

Figure 1: Heavy-neutrino interaction vertices introduced in the *HeavyN* model.

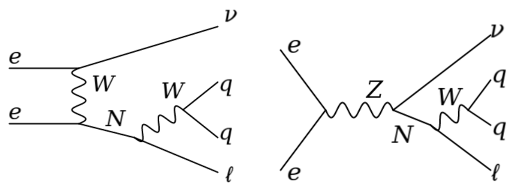

Figure 2: Light-heavy neutrino pair production signal considered in the study.

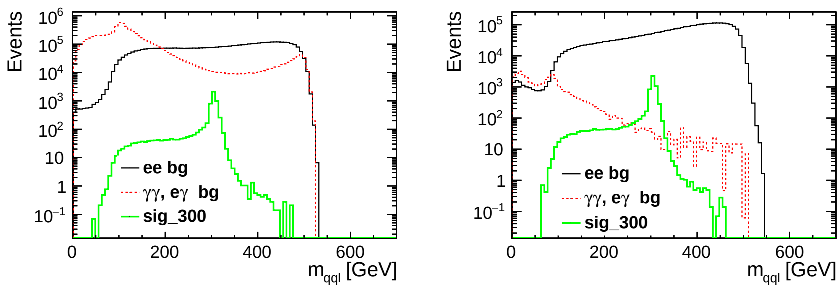

Figure 3: Expected distribution of the qql mass for ILC running at 500 GeV, for electrons (left) and muons (right) in the final state. Black solid lines stand for the e^+e^- background, red dashed lines for the γ-induced background and thick green lines for the signal of a 300-GeV Dirac neutrino.

least one charged lepton in the final state were generated as background. For the e^+e^- colliders, contributions from γ-induced background channels, both from real photons (beamstrahlung) and virtual ones (generated within the Equivalent Photon Approximation), were taken into account. The corresponding processes at the MuC were found to be negligible. The fast detector simulation framework Delphes 3.4.2 [9] was used to model detector response. Due to the expected signal topology, an exclusive two-jet clustering mode was applied.

3. Analysis procedure

For further analysis, we selected events with two jets, one charged lepton (electron or muon) and no other activity in the detector. Fig. 3 shows distributions of the reconstructed invariant mass of the jets and lepton, separately for accepted events with electrons and muons in the final state, for ILC running at 500 GeV. The visible peaks in both plots correspond to a heavy neutrino with a mass of 300 GeV. In the next step, we used a Boosted Decision Trees (BDT) classifier implemented in the *TMVA* package [10]. The algorithm was trained using eight input variables which characterised the kinematics of the process. The BDT response distribution was then used to build a model describing the measurement within the *RooStats* package. By scaling V_{lN}^2 with respect to the reference scenario, we extracted the expected 95% C.L. limits on the mixing parameter using the CL$_s$ approach. Combined limits are dominated by measurements in the channel in which the background is smaller: the muon channel for the e^+e^- colliders, the electron channel for the MuC.

In Fig. 4, the coupling limits calculated for Dirac neutrinos at future lepton colliders are compared with limits obtained for hadron machines. The CMS limits for the LHC running at 13 TeV (Fig. 2 in [11]) were obtained assuming the Majorana nature of the neutrinos. The projections for

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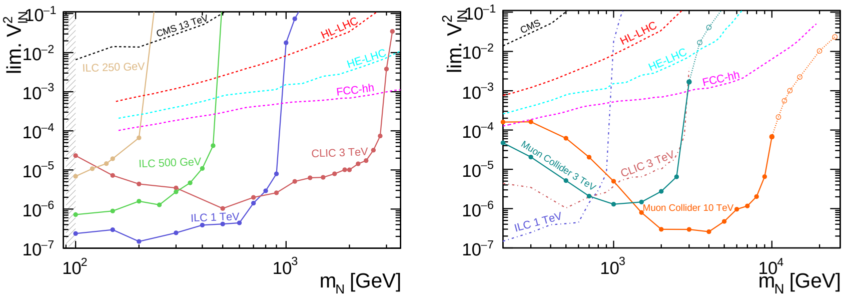

Figure 4: Expected limits on the coupling V_{lN}^2 for e^+e^- colliders (left) and the Muon Collider (right).

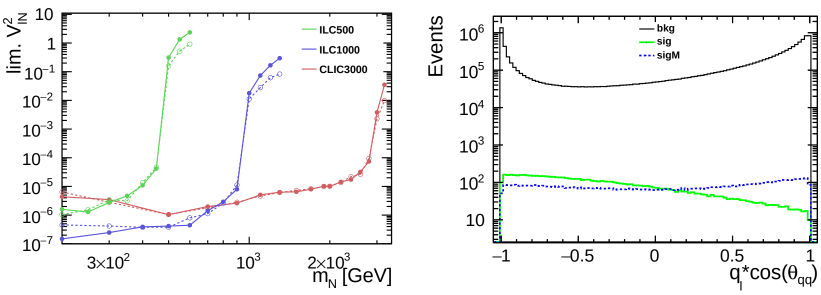

Figure 5: Left: Comparison between results for Majorana (dashed line) and Dirac (solid line) neutrinos for different collider scenarios. Right: distribution of the cosine of the dijet emission angle multiplied by the lepton charge for background (black solid line), Dirac signal (thick green line) and Majorana signal (dashed blue line).

HL-LHC and future possible successors of the LHC were taken from [6] (Fig. 25b). In this paper, Dirac neutrinos with only two nonzero flavour couplings were considered ($V_{eN}^2 = V_{\mu N}^2 \neq V_{\tau N}^2 = 0$). For such an assumption, our analysis would provide even stronger limits than those presented above.

4. Model-discrimination potential

The procedure described above has however little discriminant power between different possible natures of the heavy neutrino. It can be observed in Fig. 5 (left) where results for Majorana and Dirac neutrinos are compared. The comparison shows that they are very similar up to the energy thresholds and split for the off-shell heavy neutrino production, which is more sensitive to the neutrino width and thus to the neutrino nature.

To distinguish between the Dirac or Majorana natures of the heavy neutrino, we decided to consider variables sensitive to the CP properties of the produced particles. The 8-variable set used for BDT training was extended by 2 new variables, the cosines of the dijet and of the lepton emission angle multiplied by the lepton charge. As shown in Fig. 5 (right), the distribution differs significantly for Dirac and Majorana samples.

The BDT training was performed twice for each neutrino mass; first, the algorithm was trained to distinguish between the lepton-number-violating (LNV) signal sample and the background sample contaminated with the lepton-number-conserving (LNC) signal sample with some arbitrary weight α_{BDT} ($\alpha_{BDT} = 1$ means that the relative weight of the background channel and the signal sample is

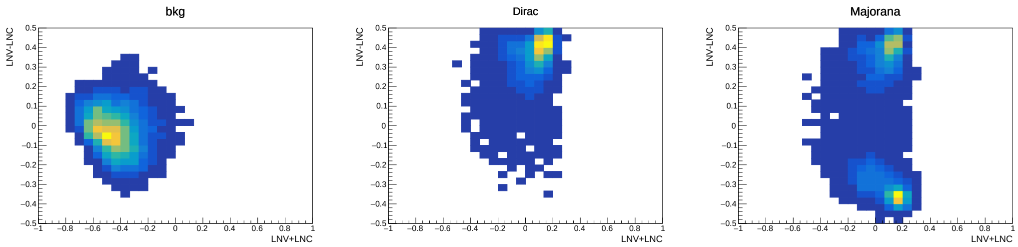

Figure 6: Two-dimensional distributions of the BDT classifier response for the background sample (left), Dirac neutrino production signal (middle) and Majorana neutrino production (right).

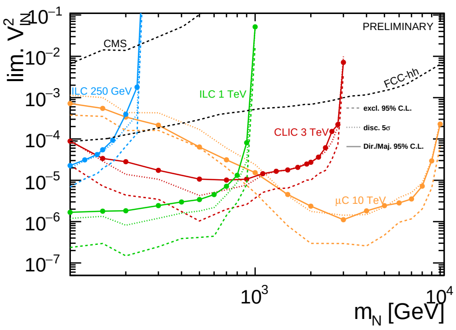

Figure 7: Comparison of the expected exclusion limits (dashed line), 5σ discovery limits (dotted line) and discrimination limits between Majorana and Dirac neutrinos (solid line) for different collider scenarios.

the same as for the reference value of the mixing parameter). For the second training, the LNV and LNC samples were swapped. Then, 2-dimensional distributions of the sum and the difference of the BDT responses (the rotation of the variables slightly improved the separation for the rectangular binning), as shown in Fig. 6, were used for statistical analysis based on a test statistic:

$$T(\alpha_{lim}) = \sum_{bins} \frac{\alpha_{lim}^2 (D - M)^2}{B + \alpha_{lim} \cdot \frac{D+M}{2}} + \#\text{DOF}, \tag{1}$$

where D, M and B stand for the numbers of Dirac, Majorana and background events in a given bin, α_{lim} is a parameter modifying the signal cross section and #DOF, the number of degrees of freedom, reflects the expected statistical fluctuations of event numbers in the 2-D histogram bins.

To find the minimum coupling limit allowing for model discrimination at 95% C.L., which we will refer to as the discrimination limit in the following, the parameter α_{lim} was varied for each mass to obtain the test statistics value T corresponding to the critical value of the χ^2 distribution for probability $p = 0.95$ and the considered number of degrees of freedom: $T(\alpha_{lim}) = \chi^2_{crit}(\#DOF)$. The procedure was iterated for different values of α_{BDT} producing a set of minimal values of α_{lim}; the smallest of them was used to scale the reference coupling parameter to obtain the final limit at each mass value. The results are shown in Fig. 7. The analysis confirms that once the heavy neutrinos are discovered at lepton colliders, their nature will be revealed as well.

5. Conclusions

Many theories suggest that new particles exist beyond the Standard Model. We analysed the possibility of discovering heavy neutrinos of Dirac and Majorana natures at future lepton colliders. The proposed analysis strategy results in the expected limits on the V_{lN}^2 coupling which are much more stringent than any LHC results, as well as other estimates for other higher-energy hadron machines published so far. The analysis framework was extended to discriminate between the Dirac and Majorana nature of the heavy particles.

Acknowledgements

The work was partially supported by the National Science Centre (Poland) under OPUS research project no. 2021/43/B/ST2/01778. KM and JRR acknowledge the support of the Deutsche Forschungsgemeinschaft (DFG, German Research Association) under Germany's Excellence Strategy-EXC 2121 "Quantum Universe"-3908333. This work has also been funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - 491245950.

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