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Search for heavy neutrinos in prompt decays at future lepton colliders

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Neutrinos are among the most mysterious particles of the Standard Model. The mass hierarchy and oscillations, as well as the nature of their antiparticles, are currently being studied in experiments around the world. In many models of New Physics, baryon asymmetry or dark matter density in the universe are explained by introducing new species of neutrinos whose masses might significantly surpass the electroweak scale. In this contribution, we study the possibility of observing heavy neutral leptons of either the Dirac or Majorana nature at future lepton colliders and constraining their properties.

This work was carried out in the framework of the ILD Concept Group

Contents

1 Introduction

Several cosmological observations, including the dark matter density in the Universe, as well as the baryon-antibaryon asymmetry, suggest that the Standard Model of particle physics needs to be extended. As the neutrino oscillations and their mass hierarchy are also not explained within this theory, certain models link the existence of New Physics with the neutrino sector; among others, Dirac and Majorana neutrinos with masses well above the electroweak scale have been proposed to simultaneously solve certain issues of the Standard Model. In the following, we consider the possibility of searching for heavy neutral leptons (HNL) at future linear e^+e^- colliders.

2 Analysis setup

In our study [1–3], we considered 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 assumed that heavy neutral leptons mixing with the SM partners are the only relevant trace of New Physics, no other new phenomena occur and for simplicity, we studied the case where only one heavy neutrino with a mass ranging from 100 GeV to 10 TeV couples to the SM particles.

The light-heavy neutrino pair production with the subsequent decay of the latter to two quarks and a lepton, $\mathrm{ll} \to N\nu \to \mathrm{qql}\nu$, was considered. This channel offers the possibility of the full reconstruction of the heavy neutrino from two jets and a lepton measured in the detector. We generated signal and background events in WHIZARD 2.8.5 [4, 5] (ver. 3.0.0 was used for the Majorana signal generation). Parton shower and hadronization were modelled with PYTHIA 6 [6]. We generated reference samples with the mixing parameter V_{lN} set to the same value for all the leptons, and all the quark, electron and muon masses set to zero.

To account for detector effects, the framework for fast detector simulation DELPHES 3.5.0 [7] was employed. The default cards for each collider project were used for detector parameterization. Based on the expected signal topology consisting of one lepton and two reconstructed jets, we used the exclusive two-jet clustering mode.

In the next step, we trained a Boosted Decision Trees (BDT) classifier, as implemented in the *TMVA* package [8]. Eight input variables characterising the kinematics of the process were used. The BDT response distribution was then used to build a model describing the measurement within the *RooStats* package[9]. 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.

The difference between Dirac and Majorana particles lies in their CP properties. This means that for Majorana particles for any specific decay channel also its CP-conjugated one exists, leading to lepton-number violation, while for Dirac neutrinos only one of them (lepton-number conserving). The chiral nature of weak decays together with the averaging over the decay process and its CP-conjugate for Majorana neutrinos leads to an experimental sensitivity, in particular, to the emission direction of a given final state particle (or anti-particle) in the rest frame of the decaying heavy neutrino. Hence, for the Dirac vs. Majorana discrimination, we considered 2 additional variables: the cosine of the lepton and dijet emission angle multiplied by the lepton charge.

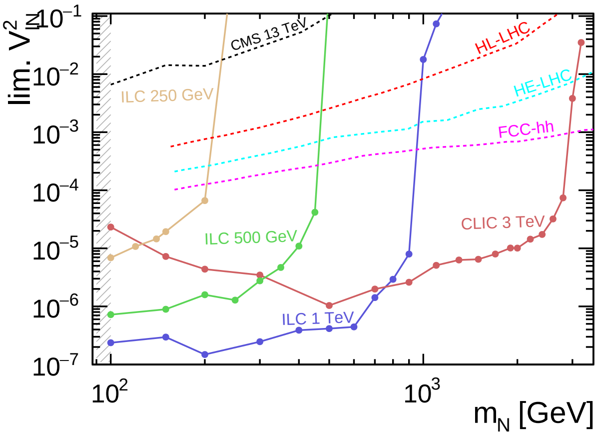

Figure 1: Expected limits on the mixing parameter V_{lN}^2 for e$^+$e$^-$ colliders as a function of the heavy neutrino mass, m_N.

In this extended framework, the BDT algorithm was trained to distinguish between a signal sample of lepton-number-violating (LNV) heavy neutrino decays and a background sample contaminated with a lepton-number conserving (LNC) signal sample with some arbitrary weight. For the second training, the LNC decay sample was used as a signal and the LNV decay sample was used to contaminate the background. Then, 2-dimensional distributions of the sum and the difference of the two BDT responses were used for statistical analysis. To find the minimal coupling allowing for model discrimination at 95% C.L., which we will refer to as the discrimination limit, the signal normalisation was varied for each mass to obtain the value of the χ^2-test statistic corresponding to the critical value of the χ^2 distribution for probability $p = 0.95$ and the considered number of degrees of freedom.

3 Results

In Fig. 1, the coupling limits obtained for Dirac neutrinos at future lepton colliders are compared with limits estimated for hadron machines. The CMS limits for the LHC running at 13 TeV (Fig. 2 in [10]) were obtained assuming the Majorana nature of the neutrinos. The projections for HL-LHC and future possible successors of the LHC were adapted from [11].

The final results of our study for the Dirac vs. Majorana discrimination are shown in Figure 2. The 95% C.L. discrimination limits are compared to the 5σ discovery limits for the six collider scenarios considered in our work. The analysis confirms that once the heavy neutrinos are discovered at lepton colliders, it will be possible to determine their nature (real or complex Lorentz representation).

4 Conclusions

Many theories suggest that new particles exist beyond the Standard Model. We analysed the possibility of discovering heavy neutrinos at future linear colliders. The proposed analysis strategy resulted in estimating limits on the V_{lN}^2 coupling which are much more stringent than any results for high-energy hadron colliders. The analysis framework was extended to discriminate between the Dirac and Majorana natures of the heavy states. Our analysis shows that, by employing such variables encoding the chiral character of the particles, one may efficiently discriminate between complex and real Lorentz representations (i.e. Dirac or Majorana nature) of the heavy neutrinos simultaneously with their discovery at future lepton colliders.

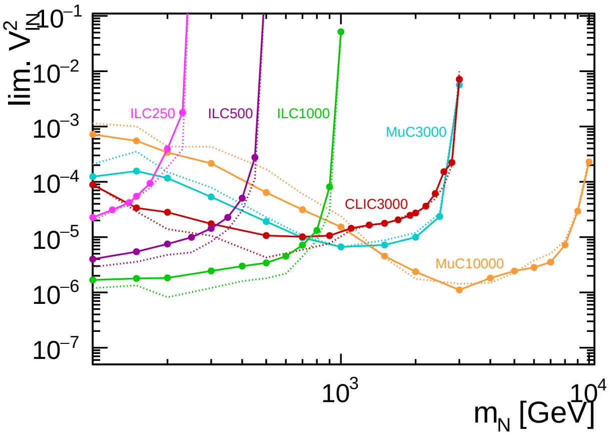

Figure 2: Comparison of the expected 95% C.L. discrimination limits between Majorana and Dirac neutrinos (solid lines), as a function of the heavy neutrino mass, m_N, and the 5σ discovery limits (dotted lines) for different collider scenarios considered in the study.

5 References

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