PROCEEDINGS OF SCIENCE

Heavy Neutrinos at Future Linear e^+e^- Colliders

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With the Standard Model being unable to describe the observed baryon asymmetry or dark matter density in the universe, many models of New Physics introduce heavy neutrino species as a possible explanation for these effects. Dirac or Majorana neutrinos with masses above the electroweak scale could be produced at future linear e^+e^- colliders, such as the Compact LInear Collider (CLIC) or the International Linear Collider (ILC). We studied the possibility of observing production and decays of the heavy neutrinos in the qql final state at ILC running at 500 GeV and 1 TeV and CLIC running at 3 TeV. The analysis is based on the WHIZARD event generation and fast simulation of the detector response with DELPHES. Dirac and Majorana neutrinos with masses from 200 GeV to 3.2 TeV are considered. Estimated limits on the production cross sections and on the neutrino-lepton coupling are compared with the current limits coming from the LHC running at 13 TeV, as well as the expected future limits from hadron colliders. The obtained results are stricter than any other limit estimates published so far.

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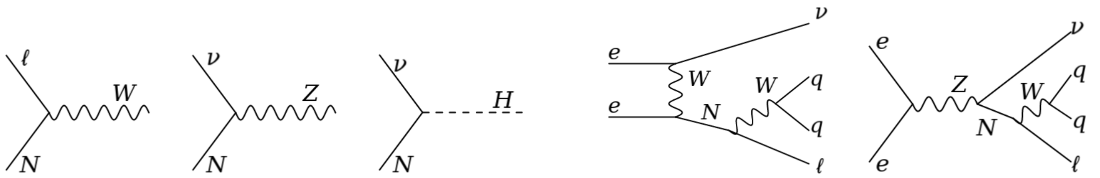
1. Introduction

In some models of New Physics, problems of the Standard Model, such as the baryon asymmetry or the observed dark matter density, are explained by introducing new species of neutrinos. Neutrinos with masses above the electroweak scale could be produced at future linear e^+e^- colliders, such as CLIC [1] or ILC [2]. In our analysis, we studied the possibility of observing decays of heavy Dirac and Majorana neutrinos into the qql final state (corresponding to two observed jets and one lepton) at the ILC running at 500 GeV and 1 TeV, and the CLIC at 3 TeV. Obtained limits exceed any other estimates published so far for pp machines by several orders of magnitude.

2. Simulation framework

We considered the *HeavyN* model [3, 4] with Dirac and Majorana neutrinos, an effective extension of the Standard Model introducing three flavours of right-handed neutrinos (denoted as $N1$, $N2$ and $N3$). Vertices introduced by the model are shown in Figure 1a. The model contains 12 free parameters in addition to the SM parameters: three masses of the heavy neutrinos (m_{N1}, m_{N2} and m_{N3}) and nine real mixing parameters (V_{lk}, where $l = e, \mu, \tau$ and $k = N1, N2, N3$). We focused on the light-heavy neutrino pair production with a subsequent decay of the heavy neutrino into qql, corresponding to the jjl signature, as presented in Figure 1b. This signature allows for the complete reconstruction of the heavy neutrino mass.

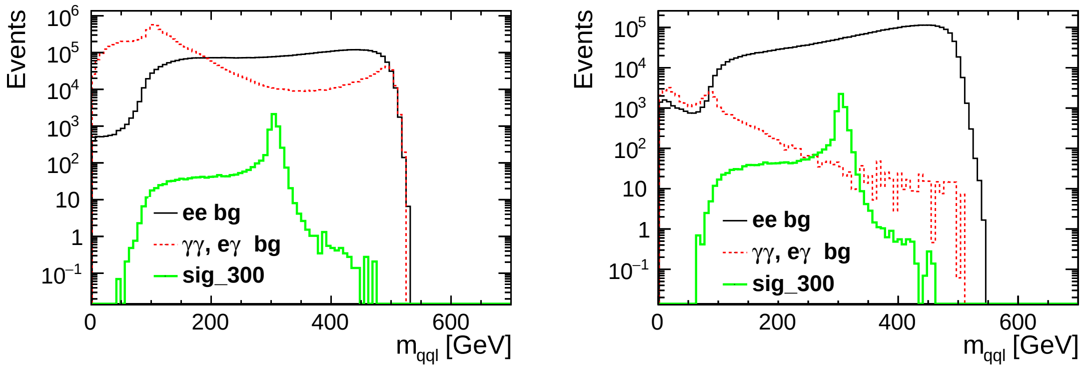


(a) Extra vertices **(b)** Signal diagrams

Figure 1: Left: extra vertices in the *HeavyN* model. Right: light-heavy neutrino pair production processes considered in the study.

We analysed prospects for heavy neutrino detection at ILC running at 500 GeV (1 TeV), with beam polarisation of −80% for electrons and +30%(+20%) for positrons, and integrated luminosity of 1.6 ab^{-1} (3.2 ab^{-1}), and CLIC running at 3 TeV, with integrated luminosity of 4 ab^{-1} and −80% electron beam polarisation (no polarisation for positrons).

Signal events were generated using Whizard 2.8.5 [5] (ver. 3.0.0 for the Majorana neutrino production). To simplify the analysis, only one heavy neutrino ($N1$) is assumed to couple to the Standard Model particles. Therefore, masses of $N2$ and $N3$ are set to 10 TeV and their couplings to zero. Masses of $N1$ in the range 200-3200 GeV were considered and all its couplings (denoted as V_{lN}^2) were set to the same reference value of 0.0003. For the background, processes with at least one lepton in the final state were considered. We also included γ-induced background channels, both from real photons (from beamstrahlung) and virtual ones (estimated with the Equivalent Photon Approximation). The fast detector simulation framework Delphes 3.4.2 [6] was used to simulate detector response, with built-in cards for parametrisation of the ILC and CLIC detectors. Due to the expected signal topology, the exclusive two-jet mode was applied.



(a) electron channel **(b)** muon channel

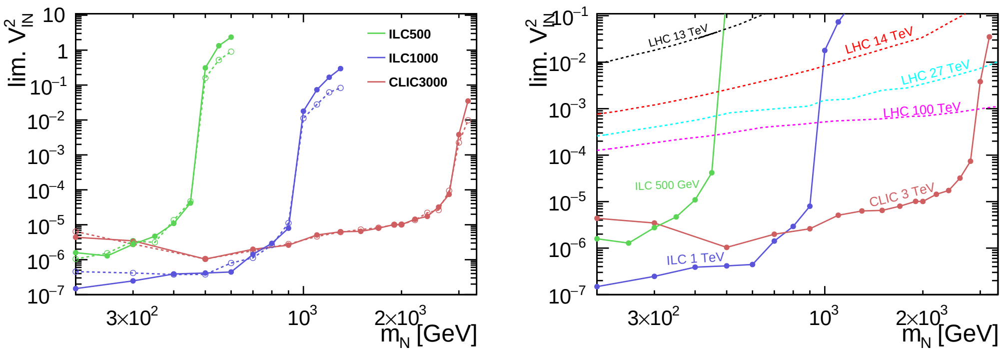
Figure 2: Expected *qql* mass distribution for ILC running at 500 GeV, for electrons (left) and muons (right) in the final state. Black solid lines stand for the e^+e^- background, red dashed lines for the γ-induced background and thick green lines for the signal with Dirac neutrinos with a mass of 300 GeV.

3. Analysis procedure and results

Only events matching the expected signal topology, those consisting of two jets and one lepton (electron or muon), were accepted for the analysis. Events with any other activity in the detector (for example reconstructed photons) were rejected. Shown in figure 2 are the reconstructed distributions after these selections of the invariant mass of two jets and a lepton for ILC running at 500 GeV.

In the next step, the Boosted Decision Trees (BDT) method implemented in the *TMVA* package [7] was used to discriminate between signal and background events. The algorithm was trained using 8 input variables. 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 95% C.L. limits on the heavy neutrino production cross section for the considered processes using the CL$_s$ approach. Due to much smaller background levels, combined limits on the heavy neutrino coupling are dominated by the measurements in the muon channel, except for the highest neutrino masses, above 2 TeV, probed at CLIC.

In Figure 3a, expected limits on the coupling V_{lN}^2 for Majorana and Dirac neutrinos are compared. Limits are very similar below the energy threshold but they split above the threshold, as the off-shell heavy neutrino production is more sensitive to the neutrino width. In Figure 3b, limits on V_{lN}^2 expected for Dirac heavy neutrino production at future e^+e^- colliders are compared with the limits obtained at hadron machines. The limits for the LHC at 13 TeV come from the CMS Collaboration (Fig. 2 in [8]) and were obtained for Majorana neutrinos. The limits expected for future possible successors of the LHC were taken from [3] (Fig. 25b) where Dirac neutrinos were considered and only two non-zero flavour couplings were taken into account ($V_{eN}^2 = V_{\mu N}^2 \neq V_{\tau N}^2 = 0$). For such an assumption, our analysis would give even stronger limits than those presented above.



(a) Dirac vs Majorana neutrinos

(b) Final results

Figure 3: Left: Comparison between results for Majorana (dashed line) and Dirac (solid line) neutrinos for different collider scenarios. Right: limits on the coupling V^2_{lN} for different colliders.

4. Conclusions

Many theories suggest that new particles beyond the Standard Model do exist. In this work, we studied the possibility of discovering heavy neutrinos of both Dirac and Majorana nature at future linear e^+e^- colliders. The described analysis procedure allows to set limits on the V^2_{lN} coupling which are much more stringent than any LHC results and estimates for the proposed higher-energy hadron machines published so far.

References

[1] L. Linssen, A. Miyamoto, M. Stanitzki, and H. Weerts, "Physics and Detectors at CLIC: CLIC Conceptual Design Report." arXiv:1202.5940, 2012.

[2] T. Behnke *et al.*, "The International Linear Collider Technical Design Report - Volume 1: Executive Summary." arXiv:1306.6327, 2013.

[3] S. Pascoli, R. Ruiz, and C. Weiland, "Heavy neutrinos with dynamic jet vetoes: multilepton searches at $\sqrt{s}$ = 14 , 27, and 100 TeV," *JHEP*, vol. 06, p. 049, 2019.

[4] A. Atre, T. Han, S. Pascoli, and B. Zhang, "The Search for Heavy Majorana Neutrinos," *JHEP*, vol. 05, p. 030, 2009.

[5] W. Kilian, T. Ohl, and J. Reuter, "WHIZARD: Simulating Multi-Particle Processes at LHC and ILC," *Eur. Phys. J.*, vol. C71, p. 1742, 2011.

[6] J. de Favereau *et al.*, "DELPHES 3, A modular framework for fast simulation of a generic collider experiment," *JHEP*, vol. 02, p. 057, 2014.

[7] A. Hocker *et al.*, "TMVA - Toolkit for Multivariate Data Analysis." arXiv:physics/0703039, 2007.

[8] A. Sirunyan *et al.*, "Search for heavy neutral leptons in events with three charged leptons in proton-proton collisions at $\sqrt{s}$ = 13 TeV," *Phys. Rev. Lett.*, vol. 120, no. 22, p. 221801, 2018.