PROCEEDINGS OF SCIENCE

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

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Since the Standard Model cannot describe the observed baryon asymmetry or dark matter density in the universe, many models of New Physics introduce heavy neutrinos as an explanation for these effects. Such heavy Dirac or Majorana neutrinos could be produced at future linear e^+e^- colliders, such as the Compact LInear Collider (CLIC) or the International Linear Collider (ILC). We analysed the possibility of observing the production and decay of the heavy neutrinos in the qql final state at ILC running at 500 GeV and 1 TeV and CLIC running at 3 TeV. In the analysis, the event generation was based on Whizard and fast simulation of the detector response was performed with DELPHES. Both Dirac and Majorana neutrinos with masses from 200 GeV to 3.2 TeV were considered. Estimated limits on the production cross sections and on the neutrino-lepton coupling were compared with the current CMS limits, as well as the projected limits coming from future hadron colliders. The obtained results are more stringent than any other limit estimate published so far.

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1. Introduction

Different models of extension of the Standard Model (SM) are proposed to address problems of this fundamental theory, such as baryon asymmetry or observed dark-matter density. One of the ways to address the issues is to introduce new species of neutrinos. Right-handed neutrinos with masses of hundreds of GeV could be produced and detected at future linear e^+e^- colliders, such as CLIC [1] or ILC [2]. In our paper [3], we considered the possibility of observing decays of heavy Dirac and Majorana neutrinos into the final state qql (experimentally measured as two observed jets and one lepton) at ILC running at 500 GeV (with a total integrated luminosity of 4000 fb^{-1}) and 1 TeV (with 8000 fb^{-1}) [4], and at 3 TeV CLIC (with 5000 fb^{-1}) [5]. The achieved limits exceed all other estimates published to date for pp machines by several orders of magnitude. The results presented in this contribution were previously presented in [6].

2. Model setup

For the generation of reference signal samples, we used the *HeavyN* model [7, 8] with Dirac or Majorana neutrinos. It is an effective extension of the Standard Model introducing three flavours of right-handed neutrinos (denoted as $N1$, $N2$ and $N3$). 12 free parameters in addition to the SM parameters are introduced in the model: three heavy neutrinos masses (m_{N1}, m_{N2} and m_{N3}) and nine real mixing parameters (V_{lk}, where $l = e, \mu, \tau$ and $k = N1, N2, N3$). The Lagrangian yields:

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_N + \mathcal{L}_{WN\ell} + \mathcal{L}_{ZN\nu} + \mathcal{L}_{HN\nu} \tag{1}$$

where $\mathcal{L}_N$ is a sum of kinetic and mass terms for heavy neutrinos:

$$\mathcal{L}_N = \xi_\nu \cdot \left(\bar{N}_k i\partial\!\!\!/ N_k - m_{N_k}\bar{N}_k N_k\right) \qquad \text{for } k = 1,\ 2,\ 3, \tag{2}$$

with an overall factor $\xi_\nu = 1$ for the Dirac neutrino and $\xi_\nu = \frac{1}{2}$ for the Majorana neutrino scenarios. $\mathcal{L}_{WN\ell}$ corresponds to neutrino interactions with a W boson:

$$\mathcal{L}_{WN\ell} = -\frac{g}{\sqrt{2}} W^+_\mu \sum_{k=1}^{3}\sum_{l=e}^{\tau} \bar{N}_k V^*_{lk} \gamma^\mu P_L \ell^- + \text{ h.c.}, \tag{3}$$

$\mathcal{L}_{ZN\nu}$ to interactions with a Z boson:

$$\mathcal{L}_{ZN\nu} = -\frac{g}{2\cos\theta_W} Z_\mu \sum_{k=1}^{3}\sum_{l=e}^{\tau} \bar{N}_k V^*_{lk} \gamma^\mu P_L \nu_l + \text{ h.c.}, \tag{4}$$

and $\mathcal{L}_{HN\nu}$ to interactions with a Higgs boson:

$$\mathcal{L}_{HN\nu} = -\frac{g m_N}{2M_W} h \sum_{k=1}^{3}\sum_{l=e}^{\tau} \bar{N}_k V^*_{lk} P_L \nu_l + \text{ h.c.} \tag{5}$$

The vertices that involve N introduced in the model are illustrated in Figure 1.

3. Simulation framework

In the presented analysis, we focus on the production of a light-heavy neutrino pair followed by the decay of the heavy neutrino into qql, which corresponds to a jjl signature, as shown in Figure 2. This signature allows for a complete reconstruction of the decaying neutrino and hence its mass.

Since the generation of the neutrino pair is very sensitive to the initial beam polarisation, we analysed the possibility of heavy neutrino detection only at preferred polarisation settings. We consider ILC running at 500 GeV (1 TeV), with beam polarisation of −80% for electrons and +30% (+20%) for positrons, and an integrated luminosity of 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).

Whizard 2.8.5 [9] (ver. 3.0.0 for the production of Majorana neutrino samples) was used to generate signal events. In order to simplify the analysis, it is assumed that only one heavy neutrino ($N1$) couples with SM particles. Therefore, the masses of $N2$ and $N3$ are fixed to 10 TeV and their couplings to zero. Masses of $N1$ in the range 200-3200 GeV were considered, and all the couplings to the SM leptons (denoted as V_{lN}^2) were set to the same reference value of 0.0003. As for the background, processes with at least one lepton in the final state were taken into account. We also included γ-induced background channels, both from real photons (from beamstrahlung) and virtual ones (generated within the Equivalent Photon Approximation). The fast detector simulation framework Delphes 3.4.2 [10] was then used to model detector response, with built-in cards for the parameterisation of the ILC and CLIC detectors. An exclusive two-jet clustering mode was applied due to the expected signal topology.

4. Analysis procedure and results

Only events with expected signal topology of two jets and one charged lepton (electron or muon) were accepted for further analysis. Events with any other activity in the detector (for instance, reconstructed photons) were rejected. Figure 3 shows the reconstructed distributions of the invariant mass of two jets and a lepton, separately for accepted events with an electron and a muon in the final state, for ILC running at 500 GeV. One can notice that peaks at a mass of 300 GeV (the reference scenario) for the signal distributions are visible in both plots.

The Boosted Decision Trees (BDT) method implemented in the *TMVA* package [11] was used to distinguish between signal and background events in the next step. The algorithm was trained using eight input variables that characterise the kinematics of the event. The BDT response distribution was then used to build a model describing the measurement within the *RooStats* package. By scaling

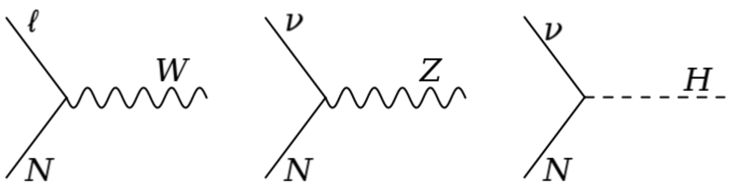


Figure 1: Extra vertices in the *HeavyN* model.

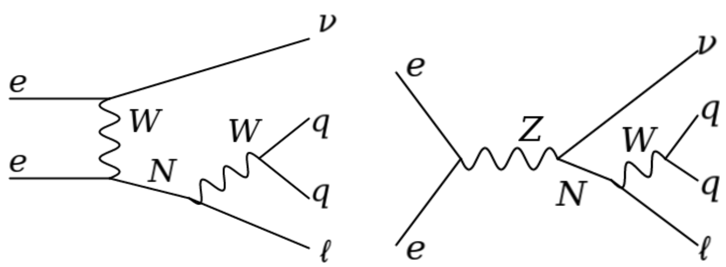
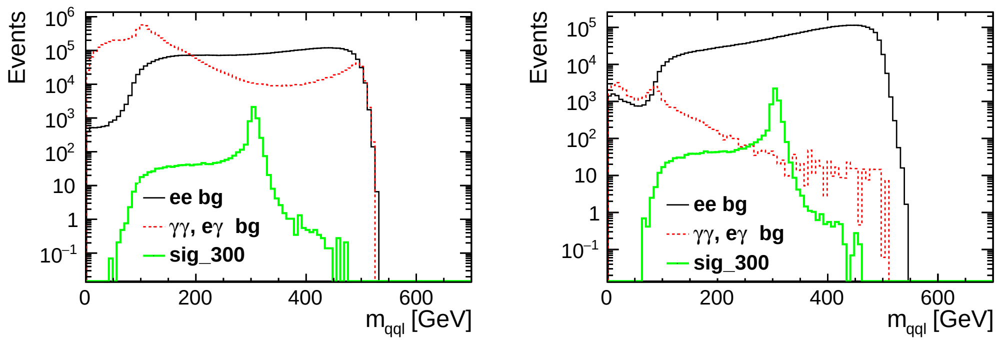


Figure 2: Light-heavy neutrino pair production signal considered in the study.



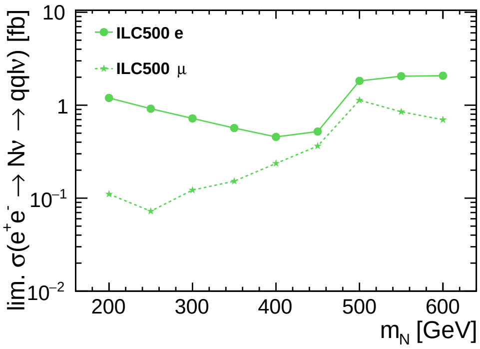
(a) electron channel

(b) muon channel

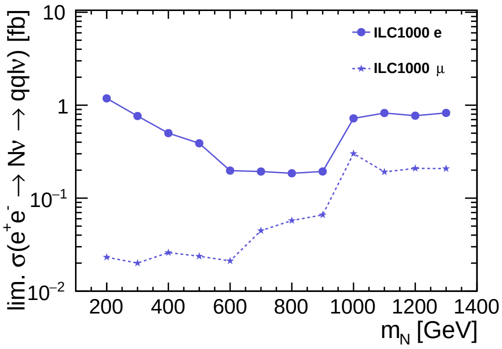
Figure 3: Expected *qql* mass distribution for ILC running at 500 GeV, for electrons (left) and muons (right) in the final state. Black solid lines stand for the e^+e^- background, red dashed lines for the γ-induced background and thick green lines for the signal with Dirac neutrinos with a mass of 300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

V_{lN}^2 with respect to the reference scenario, we extracted 95% C.L. limits on the heavy neutrino production cross section for the processes considered using the CL$_s$ approach. Due to much smaller background levels, combined limits on the cross sections are dominated by the measurements in the muon channel. Only for the highest neutrino masses probed at CLIC, above 2 TeV, the results for the electron channel are more stringent, as shown in Figure 4.

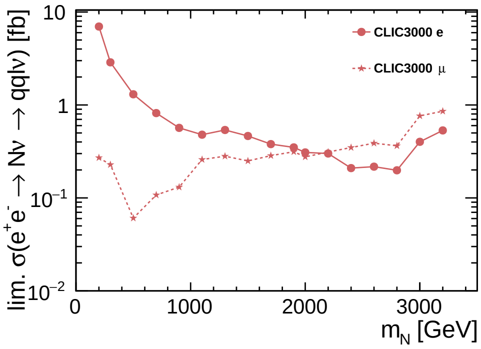
The cross-section limits were then translated into coupling limits V_{lN}^2. In Figure 5a, the projected limits for Majorana and Dirac neutrinos are presented. The comparison shows that they are similar up to the energy threshold, but they split for the off-shell heavy neutrino production, which is more sensitive to the neutrino width and thus to the neutrino nature. In Figure 5b, the coupling limits calculated for Dirac neutrinos at future lepton colliders are compared with the limits obtained for hadron machines. The CMS limits for the LHC running at 13 TeV (Fig. 2 in [12]) were obtained for the Majorana nature of the neutrinos. The projections for HL-LHC and future possible successors of the LHC were taken from [7] (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 have provided even stronger limits than those presented above.



(a) ILC500



(b) ILC1000



(c) CLIC3000

Figure 4: 95% C.L. limits on the cross section of the heavy Dirac neutrino production and decay (the $qql\nu$ final state) as a function of the neutrino mass for different collider setups.

5. Conclusions

Many theories suggest that new particles beyond the Standard Model exist. We analysed the possibility of discovering heavy neutrinos of Dirac and Majorana natures at future linear lepton colliders. Our analysis procedure allows setting limits on the V_{lN}^2 coupling which are much more stringent than any LHC results, as well as estimates for other higher-energy hadron machines published so far. Currently, an extended analysis procedure suited for model discrimination between the Dirac and Majorana natures is being developed.

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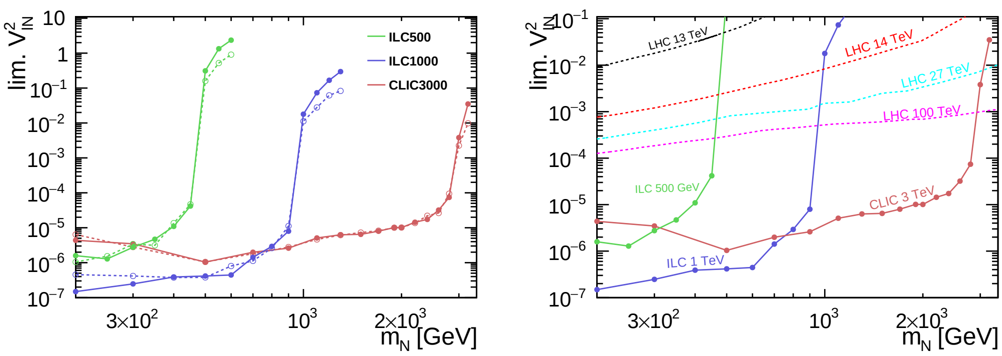

(a) Dirac vs Majorana neutrinos

(b) Final results

Figure 5: 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.

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