Probing heavy Majorana neutrino pair production at ILC in a $U(1)_{B-L}$ extension of the Standard Model

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We consider a gauged B–L (Baryon number minus Lepton number) extension of the Standard Model (SM), which is anomaly free in the presence of three SM singlet Right Handed Neutrinos (RHNs). Associated with the $U(1)_{B-L}$ gauge symmetry breaking, the RHNs acquire Majorana masses and then with the electroweak symmetry breaking, tiny Majorana masses for the SM(-like) neutrinos are naturally generated by the seesaw mechanism. As a result of the seesaw mechanism, the heavy mass eigenstates which are mainly composed of the SM-singlet RHNs obtain suppressed electroweak interactions through small mixings with the SM neutrinos. To investigate the seesaw mechanism, we study the pair production of heavy Majorana neutrinos through the $U(1)_{B-L}$ gauge boson Z' at the 250 GeV and 500 GeV International Linear Collider (ILC). Considering the current and prospective future bounds on the B–L model parameters from the search for a resonant Z' boson production at the Large Hadron Collider (LHC), we focus on a "smoking-gun" signature of the Majorana nature of the heavy neutrinos: a final state with a pair of same-sign, same-flavor leptons, small missing momentum, and four hadronic jets. We estimate the projected significance of the signature at the ILC.

This is a preliminary study performed in the framework of the ILD concept group, submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

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I. INTRODUCTION

Although the SM postulated the neutrinos to be massless, experimental evidence of neutrino oscillations indicates that SM(-like) neutrinos have tiny masses and flavor mixings [1]. The type-I seesaw mechanism [2–7] is probably the simplest idea to explain the origin of light neutrino mass generation, where the SM is extended with three SM gauge singlet Right Handed Neutrinos(RHNs). It has been known that the RHNs are naturally introduced in the minimal B–L (Baryon minus Lepton) model where the accidental global $U(1)_{B-L}$ symmetry in the SM is gauged. In addition to the SM particles, this model incorporates three SM singlet RHNs with $U(1)_{B-L}$ charge -1 to cancel the gauge and the mixed gauge-gravitational anomalies, an electric-charge neutral B–L gauge boson (Z'), and an SM singlet scalar with $U(1)_{B-L}$ charge +2 called $U(1)_{B-L}$ Higgs field. The $U(1)_{B-L}$ gauge symmetry is broken by a non-zero vacuum expectation value (VEV) of the B–L Higgs field, through which a mass for the Z' boson and Majorana masses for the RHNs are generated. With the Majorana RHNs, light neutrino masses are generated by the seesaw mechanism after electroweak symmetry breaking. As a result of the seesaw mechanism, the heavy mass eigenstates which are mainly composed of the SM-singlet RHNs obtain suppressed electroweak interactions through small mixings with the SM neutrinos.

If the heavy Majorana neutrino mass eigenstates lie at the TeV scale or lower, they can be pairproduced in a process mediated by the Z' boson in the s-channel at high energy colliders such as the LHC and ILC. Once pair-produced, each heavy Majorana neutrino decays to SM particles through its (suppressed) electroweak interactions acquired through the seesaw mechanism. A leading decay mode of interest is to a W boson accompanied by a charged (anti-)lepton, followed by two jets from hadronic W decay. Due to the Majorana nature of the heavy neutrino, each heavy neutrino can produce either a charged lepton or anti-lepton. Therefore, heavy neutrino pair production can provide a very distinctive "smoking-gun" signature of its Majorana nature with a same-sign lepton pair, small missing energy, and four hadronic jets.

The gauge boson Z' has been sought at the LHC Run-2 and its production cross section is already severely constrained. The prospects for discovering the heavy Majorana neutrino in future LHC runs can be found in [8–16]. A theoretical investigation for this ILC study can be found in [17], in which the authors point out the possibility that even after a null Z' boson search result at the High-Luminosity LHC, the 250 GeV ILC can search for heavy Majorana neutrino pair production to explore the origin of neutrino mass generation through the seesaw mechanism.

II. THE B-L MODEL

Here we present a brief summary of the theoretical framework of the B-L model. New Yukawa couplings involving the RHNs are given by

$$-\mathcal{L}_{\text{int}} \supset \sum_{i,j=1}^{3} Y_D^{ij} \overline{\ell_L^i} H N_R^j + \frac{1}{2} \sum_{i=1}^{3} Y_N^j \overline{(N_R^i)^C} \Phi N_R^i + \text{h.c.}, \qquad (1)$$

where ℓ_L^i and N_R^i are the SM lepton doublet and RHN of the *i*-th generation (i = 1, 2, 3), respectively, H is the SM Higgs doublet, and Φ is the B–L Higgs field. Without loss of generality, we work in the flavor diagonal basis for the Majorana-type Yukawa couplings (Y_N^j) for RHNs. We assume a suitable Higgs potential to yield VEVs for $\langle H \rangle = (\frac{v}{\sqrt{2}} \ 0)^T$ and $\langle \Phi \rangle = \frac{v_{\Phi}}{\sqrt{2}}$ to break the electroweak and $U(1)_{\rm B-L}$ symmetries, respectively. Hence, the Z' boson mass, the neutrino Dirac mass term and the Majorana mass term for the RHNs are, respectively, generated as

$$M_{Z'} = 2g_{\rm B-L}v_{\Phi}, \ M_D^{ij} = \frac{y_D^{ij}}{\sqrt{2}}v, \ M_N^i = \frac{Y_N^i}{\sqrt{2}}v_{\Phi},$$
(2)

where $g_{\rm B-L}$ is the B–L gauge coupling. The mass matrix for the light SM(-like) neutrinos is generated to be $m_{\nu} \simeq m_D M^{-1} m_D^T$ by the seesaw mechanism. The heavy Majorana neutrino of the *j*-th generation acquire the gauge coupling with the *i*-th generation charged lepton/anti-lepton and W^+/W^- suppressed by a factor of $m_D^{ij}/(M^j)$. A pair of (*i*-th generation) heavy Majorana neutrinos can be produced at the ILC with a center of mass energy \sqrt{s} , whose production cross section is approximately given by

$$\sigma(e^-e^+ \to Z'^* \to N^i N^i) = \frac{s}{24\pi} \left(\frac{g_{\rm B-L}}{M_{Z'}}\right)^4 \left(1 - 4\frac{M_{N^i}^2}{M_{Z'}^2}\right)^{\frac{3}{2}},\tag{3}$$

where we assume $\sqrt{s} \ll M_{Z'}$.

The upper bound on the gauge coupling g_{B-L} as a function of $M_{Z'}$ can be obtained from the LHC Run-2 results of the search for a narrow resonance with the dilepton final states by the ATLAS [18] and the CMS [19] collaborations. The High-Luminosity LHC prospective reach is from ATLAS-TDR [20]. The results of the search for a narrow resonance with the dijet final states by the ATLAS [21] and the CMS [22] collaborations are also used to derive the upper bound on g_{B-L} . Considering the case when $M'_Z > \sqrt{s}$ and using the limits on the effective scale for the left and right handed fermions from LEP-II [23] and ILC [24] following [25–27] we show the limits on the $g' - M_{Z'}$ plane from LEP-II and prospective ILC in Fig. 1. The LEP-II results [28] also constrain g_{B-L} as a function of $M_{Z'}$. These constraints are summarized in Fig. 1. For details on how to extract the upper bounds on g_{B-L} from various experimental results, see Ref. [27], where



FIG. 1. A summary of the upper bounds and prospective search reach on g' as a function of $M_{Z'}$.

the limits have been estimated using the generic $U(1)_X$ model file from FeynRules. implementing the UFO model file in MadGraph [29, 30]. In Fig. 1, we also show the prospective search reach by the ILC with $\sqrt{s} = 250$ GeV, 500 GeV and 1 TeV.

III. EXPERIMENTAL STUDY

High energy electron-positron colliders such as the International Linear Collider ILC [31] have as their principal aim the study of the Higgs boson and electro-weak symmetry breaking. Such a machine also provides a clean experimental environment and collision energies never before seen in lepton collisions, which opens many opportunities to search for new physics beyond the SM, either though precision measurements of known processes, or the direct production of new particles.

The ILC is a proposed electron-positron collider which can provide several ab^{-1} of data at centre-of-mass energies from 250 to 1000 GeV. The beams can be longitudinally polarized to 80% and 30% for the electron and positron beams. We refer to the case in which the electron (positron) beam is predominantly left(right)-handed as $e_L^{80}p_R^{30}$, and the opposite configuration as $e_R^{80}p_L^{30}$. In this study we consider the 500 GeV stage, ILC-500, and assume a run scenario in which the total integrated luminosity at 500 GeV is $4ab^{-1}$.

The International Large Detector ILD is a proposed detector concept for use at ILC [32]. It consists of a high precision vertex detector, a hybrid tracking system based on a TPC with silicon

layers, and highly granular calorimeters to enable optimal particle flow reconstruction. In this experimental study, we simulate RHN and SM background events in a detailed Geant-4 model of ILD.

A. Signal and Background process

We focus on the pair production of massive right-handed neutrinos, $e^+e^- \rightarrow NN$, at ILC-500. In the case of a RHN with mass greater than m_H , RHN can decay to $N \rightarrow l^{\pm}W^{\mp}, \nu Z$ and νH . In this study we assume that the lightest RHN decays to the first lepton generation, and consider the decay $N \rightarrow e^{\pm}W^{\mp}$.



FIG. 2. RHN pair production at tree level, with subsequent decay $N \to eW, W \to jj$.

Feynman diagrams for $e^+e^- \to NN \to e^\pm e^\pm + 4j$ are shown in Fig. 2: the process can occur either via s-channel Z' exchange or t-channel W exchange. Since the RHN is a Majorana particle, in half of such decays, the electrons have the same sign. The cross-section for the s-channel process depends on the Z' mass $M_{Z'}$, the coupling constant g_{B-L} and the branching ratio $BR(N \to eW)$ that in turn depends on the mixing parameter V_{eN}

$$\sigma(ee \to NN) \times (BR(N \to e^{\pm}W^{\mp}))^2 \propto \left(\frac{g_{\rm B-L}}{M_{Z'}}\right)^4 \times BR(N \to e^{\pm}W^{\mp})^2,\tag{4}$$

while the t-channel process depends only on the M_N and V_{eN} .

The cross-section as a function of RHN mass is shown in Fig. 3 in the case of $g_{B-L} = 1$, $M_{Z'} = 7 \ TeV$ and mixing parameter $V_{eN} = 0.03$, for the 100% polarized beam combinations $e_L^{100} p_R^{100}$ and $e_R^{100} p_L^{100}$. In the case of $e_R^{100} p_L^{100}$ only the s-channel diagram contributes, since the right-handed electron does not couple to W. In the opposite polarization scenario both diagrams contribute, and the resulting cross-section is significantly suppressed due to destructive interference. For this reason, in this study the results are mainly presented for the $e_R^{80} p_L^{30}$ polarization.



FIG. 3. The cross-section $\sigma(ee \rightarrow NN)$ as a function of the RHN mass at the model point $g_{B-L} = 1, M_{Z'} = 7$ TeV and $V_{eN} = 0.03$.

Table I shows the parameters of the four considered benchmark points. We study RHN masses M_N in the range $M_N = 100 \sim 225 \ GeV$, allowing the RHNs to be pair-produced at ILC-500. We assume $M_{Z'} = 7$ TeV, which can be seen from Fig. 1 is unconstrained by current measurements, and study various values of the V_{eN} and g_{B-L} model parameters.

| | A. | Mai | <i>a</i> ′ | $ V _{\rm NI}$ | $BR(N \rightarrow eW)$ | σ. p | (T.D.I. |
|----|------|-------|------------|----------------|------------------------|----------|----------|
| 1 | VI N | MZ' | g_{B-L} | veN | DIC(IV / CVV) | O_{LR} | 0_{RL} |
| [G | eV] | [GeV] | | | | [| fb] |
| 1 | 00 | 7 | 1 | 0.03 | 0.44 | 0.55 | 0.71 |
| 1 | 50 | 7 | 1 | 0.03 | 0.33 | 0.36 | 0.45 |
| 2 | 200 | 7 | 1 | 0.03 | 0.30 | 0.14 | 0.16 |
| 2 | 225 | 7 | 1 | 0.03 | 0.29 | 0.046 | 0.0052 |

TABLE I. Benchmark points considered in this analysis. Cross-sections assume 100% beam polarization and take account of ISR and beamstrahlung.

The final state in which we search for the signal has no irreducible backgrounds from Standard Model processes. Possible sources of background occur when a lepton originating in hadron decay (particularly from heavy flavor hadrons) is identified as an isolated lepton, and paired with a charged lepton from e.g. W decay. The potential for charge misidentification of the considered electrons was found to be completely negligible in the full simulation of the ILD. To estimate the SM backgrounds, 4– and 6–fermion final states with at least one electron and two quarks are considered.

- 4–fermion: $e^+e^- \rightarrow e\nu q\bar{q}$ and $e^+e^- \rightarrow e^+e^-q\bar{q}$
- 6-fermion: $e^+e^- \rightarrow e^+e^-q\bar{q}q\bar{q}$
- $e^+e^- \rightarrow t\bar{t}$

Feynman diagrams corresponding to some of these processes are shown in Fig. 4. We expect these processes to provide the majority of backgrounds in this analysis, however in a later update of this note additional processes which could potentially provide additional background contributions will be added.



FIG. 4. Examples of Feynman diagrams contributing to the main backgrounds

Table II shows the cross-sections for backgrounds. The cross-section of 4–fermion processes are significantly enhanced in the $e_L^{100} p_R^{100}$ polarisation.

B. Simulation Setup

Signal events were generated using the WHIZARD event generator 2.8.5 [33]. The general model file is written in FeynRules and the UFO model of a general U(1) extension of the SM is written

| Beam pol. | 4-fer | mion | 6-fermion | | | |
|-----------|-----------|------|-----------|----------------|----------------|----------------|
| (100%) | $e\nu qq$ | eeqq | eeqqqq | $t\bar{t}(2e)$ | $t\bar{t}(1e)$ | $t\bar{t}(0e)$ |
| $e_L p_R$ | 7810 | 1960 | 16.63 | 20.1 | 313.2 | 1200 |
| $e_R p_L$ | 22.8 | 1730 | 3.74 | 7.56 | 119 | 461 |
| $e_L p_L$ | 753 | 1780 | 6.69 | 0.11 | 0.74 | 0 |
| $e_R p_R$ | 750 | 1780 | 6.66 | 0.11 | 0.73 | 0 |

TABLE II. The cross-sections [in fb] for the SM backgrounds considered in this analysis. Beam polarization of 100% is assumed. The $t\bar{t}$ process is split into events with 0, 1, and 2 electrons.

in [34]. The B-L scenario can be obtained using $x_H = 0$ and $x_{\Phi} = 1$. The UFO file of the general U(1) model file can be found from the FeynRules database.

We set very large masses for two of the RHNs and set the RHN mixing parameter to μ and τ leptons to zero. Samples of background events, prepared by the ILD software group, using the WHIZARD 1.9.5. Signal and background events include the effect of Initial State Radiation (ISR), as well as of beamstrahlung simulated by GuineaPig [35] based on ILC accelerator parameters [36]. WHIZARD generates the hard event, and the subsequent parton shower and hadronisation was simulated by Pythia v6.24 [37].

DDsim [38], a software toolkit based on Geant4 [39], was used to simulate the interaction of final state particles in a detailed model of ILD. Reconstruction and analysis was performed in the Marlin analysis framework [40], including track finding and fitting, and particle flow analysis using PandoraPFA [41]. The IsolatedLeptonTagging processor was used to identify isolated electrons and muons, and particles other than isolated leptons and photons are clustered into jets using the Durham algorithm [42].

C. Cut Based Analysis

In this section, we present the event selection cuts designed to isolate the signal from SM backgrounds. The most useful signature of the signal process is the presence, in half of the events, of a pair of same-sign isolated electrons, most usually together with 4 hadronic jets from W decay. We impose the following selection cuts:

- 1. Exactly two same-sign isolated electrons, and no isolated muons or photons.
- 2. The energy of both isolated electrons should be < 200 GeV

- 3. Both isolated electron polar angles $|\cos \theta_{isoe}| < 0.95$. The dominant backgrounds involve t-channel processes, which tend to have forward-going electrons.
- 4. IsolatedLeptonTagging parameter of both electrons > 0.9. The IsolatedLeptonTagging parameter is the output of a Multivariate Data Analysis trained to identify isolated electrons. Same sign background events almost always have one true and one mis-identified isolated electron. This cut reduces events with mis-identified electrons.
- 5. Jet clustering parameter with Durham $\log_{10}(y_{12}) > -1$. To reduce events with less than 4 jets.
- 6. Magnitude of the missing momentum $P_{miss} < 100$ [GeV], and $(P_{miss} < 40$ [GeV] or $|\cos \theta_{P_{miss}}| > 0.95$)

Missing momentum in the signal is either small, or due to unseen ISR in the very forward region. This cut removes events with leptonic W boson decays.

Distributions of the some of the observables are shown in Fig. 5, scaled to the integrated luminosity expected at ILC500 (1600 fb^{-1} for each of $e_L^{80} p_R^{30} e_R^{80} p_L^{30}$).

Table III shows the effect of the cuts in the $e_L^{80} p_R^{30}$ and $e_R^{80} p_L^{30}$ polarization data. Many backgrounds involve the W boson, so more background events remain in the case of $e_L^{80} p_R^{30}$ than in $e_R^{80} p_L^{30}$: in the case of $e_L^{80} p_R^{30}$ 158 SM background events remain, while only 24 remain for $e_R^{80} p_L^{30}$.

In this study, RHN pair production has 4 jets in the final state. After removing isolated e, μ , γ , particles are forced into 4 jets. To reconstruct the RHN mass, we search for the best jet pairing combination. We assume that the jet pair masses M_{jj} should be consistent with the W mass, and choose the jet pairing which minimizes

$$F_1 = (M_{jj1} - M_w)^2 + (M_{jj2} - M_w)^2.$$
(5)

We also assume that the two reconstructed RHN masses M_{jje1} , M_{jje2} should be equal, so we then choose the electron-jet-pair combination which minimizes

$$F_2 = (M_{jje1} - M_{jje2})^2. (6)$$

Figure 6 shows the average of the two reconstructed RHN masses in signal and background, in the two polarisations. The background is consistent with a flat distribution in the relevant range of this mass observable, while the signals are strongly peaked around the RHN mass for each benchmark point.



FIG. 5. Distributions of some cut observables after full simulation and reconstruction. Product of electron charges; electron energy; electron polar angle; IsolatedTaggingProcesser output; missing momentum. The signal processes are shown in red/purple/pink. Normalized to 1600 fb⁻¹ with $e_R^{80} p_L^{30}$.

D. Results

In addition to the previous cuts, a mass window from -10 GeV to +15 GeV around each true RHN mass was applied. The background distribution was assumed to be flat. Table IV shows the number of signal and background events remaining after applying the mass window cut. We

| | | Sig | nal | | | Ba | ckgrour | nds | | |
|--------------------------------------|---|-------|---------------|---------------|-------------------|-------|---------|----------------|----------------|----------------|
| | 1 | M_N | [GeV |] | 4–fer | mion | | 6–fer | mion | |
| | 100 | 150 | 200 | 225 | $e\nu qq$ | eeqq | eeqqqq | $t\bar{t}(2e)$ | $t\bar{t}(1e)$ | $t\bar{t}(0e)$ |
| | | | $e_{L}^{80}p$ | $p_R^{30}, 1$ | 1600 fb | -1 | | | | |
| No cut | 559 | 364 | 141 | 46 | 7.77M | 3.01M | 20k | 19k | 0.30M | 1.15M |
| $\#e_{iso}, \mu_{iso}, \gamma_{iso}$ | 275 | 190 | 70 | 22 | 90.8k | 163k | 4.7k | 9.4k | 2.2k | 201 |
| same sign e | 136 | 94 | 34 | 11 | 46.0k | 3.6k | 36 | 8 | 430 | 25 |
| electron E | 136 | 94 | 34 | 11 | 41.2k | 3.3k | 36 | 8 | 430 | 15 |
| $\cos \theta_{isoe}$ | 126 | 87 | 31 | 10 | 17.5k | 606 | 12 | 4 | 261 | 15 |
| electron MVA | 79 | 77 | 28 | 9 | 2.6k | 128 | 2 | 1 | 50 | 0 |
| y_{12} | 79 | 77 | 27 | 8 | 501 | 70 | 2 | 0 | 50 | 0 |
| $P_{miss}, \cos \theta_{P_{miss}}$ | 72 | 72 | 26 | 8 | 118 | 30 | 1 | 0 | 9 | 0 |
| | $e_R^{80} p_L^{30}, 1600 \text{ fb}^{-1}$ | | | | | | | | | |
| No cut | 695 | 438 | 161 | 51 | $0.92 \mathrm{M}$ | 2.81M | 8.48k | 8.27k | 0.13M | 0.50M |
| $\#e_{iso}, \mu_{iso}, \gamma_{iso}$ | 420 | 343 | 126 | 40 | 7.2k | 140k | 1.2k | 3.9k | 870 | 94 |
| same sign e | 164 | 114 | 40 | 12 | 3.7k | 3.1k | 14 | 2 | 173 | 12 |
| electron E | 164 | 113 | 40 | 12 | 3.4k | 2.9k | 14 | 2 | 173 | 12 |
| $\cos \theta_{isoe}$ | 149 | 104 | 36 | 11 | 1.3k | 450 | 3 | 1 | 111 | 9 |
| electron MVA | 96 | 93 | 32 | 10 | 198 | 101 | 0 | 0 | 15 | 1 |
| y_{12} | 95 | 93 | 32 | 9 | 62 | 32 | 0 | 0 | 15 | 1 |
| $P_{miss}, \cos \theta_{P_{miss}}$ | 86 | 87 | 30 | 9 | 7 | 15 | 0 | 0 | 2 | 0 |

TABLE III. Expected number of events remaining for the 4 benchmark points and SM background, after sequentially applying the cuts described in the text.

use the above results on the number of selected signal and background events N_S , N_B to calculate the signal significance $(N_S/\sqrt{N_B + N_S})$ and expected 95% confidence upper limits on the partial cross-section. The table also shows the calculated limits, which are presented graphically in Fig. 7. The cross-section limits are significantly stronger for the $e_R^{80}p_L^{30}$ polarization, as expected due to the larger signal cross-section and smaller background.

The cross-section limits in two different beam polarization setups will allow the constraining of the various parameters of the $U(1)_{B-L}$ extension considered in this paper, thanks to the different dependencies of the *s*- and *t*-channel diagrams on the model parameters M_N , $M_{Z'}$, g'_{B-L} , $|V_{eN}|$. We plan to investigate this further during the Snowmass study.



FIG. 6. The reconstructed average RHN mass, in signal and background. The combined background distribution has been rebinned to reduce the visual effect of fluctuations due to limited MC statistics.) Left: $e_L^{80} p_R^{30}$, Right: $e_R^{80} p_L^{30}$

| $M_N \; [{ m GeV}]$ | N_S | N_B | $N_S/\sqrt{N_B + N_S}$ | σ^{95}/σ_0 | | | | | |
|---------------------|-------|-------|------------------------|------------------------|--|--|--|--|--|
| $e_L^{80} p_R^{30}$ | | | | | | | | | |
| 100 | 53 | 20.12 | 6.25 | 0.21 | | | | | |
| 150 | 52 | 20.12 | 6.18 | 0.21 | | | | | |
| 225 | 18 | 20.12 | 2.95 | 0.61 | | | | | |
| 250 | 5 | 20.12 | 1.18 | 1.8 | | | | | |
| $e_R^{80} p_L^{30}$ | | | | | | | | | |
| 100 | 66 | 3.24 | 7.98 | 0.092 | | | | | |
| 150 | 63 | 3.24 | 7.77 | 0.097 | | | | | |
| 225 | 21 | 3.24 | 4.29 | 0.29 | | | | | |
| 250 | 6 | 3.24 | 1.99 | 1.0 | | | | | |

TABLE IV. Remaining events after the mass window cuts, signal significance, and 95% confidence limit exclusion on cross-section σ^{95} . Results assume 1600 fb⁻¹ in the $e_L^{80} p_R^{30}$ and $e_R^{80} p_L^{30}$ polarizations at ILC-500.

IV. SUMMARY

An experimental study of Majorana RHN pair production in the context of a $U(1)_{B-L}$ extension of the SM was performed using full simulation of ILD at the 500 GeV stage of ILC. This process proceeds via two diagrams at tree level: *s*-channel Z' exchange or *t*-channel W exchange. The relative size contributions depend both on the parameters of the underlying model and on the ILC's beam polarization. For the benchmarks studied in this paper, the signal cross-section is larger with predominantly right-handed electrons / left-handed positrons, in which case the *s*-



FIG. 7. The obtained 95% upper limits on the partial cross-section $\sigma = \sigma(ee \to NN) \times (BR(N \to e^{\pm}W^{\mp}))^2$ normalised to the benchmark points' cross-sections σ_0 , as a function of M_N . We assume 1600 fb⁻¹ of data at ILC-500 in beam polarizations $e_L^{80} p_R^{30}$ (black) and $e_R^{80} p_L^{30}$ (red).

channel dominates. The signal cross-section in the other polarization is suppressed by strong negative interference between the diagrams. The SM backgrounds, which often involve a W boson, are suppressed when right-handed electrons / left-handed positrons are used.

The decay of both RHNs to electron+W provides a unique and almost background-free signature when the two electrons have the same electric charge. Standard Model backgrounds in the samesign electron, low missing momentum, and 4–jet final state are extremely small. RHN masses in the range 100–225 GeV were studied in the context of a minimal B-L model. We considered the dominant 2- and 4-fermion backgrounds, and find that after the event selection only 3 (20) background events remain in $1600 f b^{-1}$ of integrated luminosity in the $e_R^{80} p_L^{30}$ ($e_L^{80} p_R^{30}$) polarization, allowing the setting of cross-section upper limits up to 10 times smaller than those of the chosen benchmarks.

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