

Majorana neutrinos production at LHeC in an effective approachLucía Duarte^{*}*Instituto de Física, Facultad de Ingeniería, Universidad de la República,
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We investigate the possibility of detecting Majorana neutrinos at the Large Hadron-electron Collider, an electron-proton collision mode at CERN. We study the $l_j^+ + 3\text{jets}$ ($l_j \equiv e, \mu, \tau$) final states that are, due to leptonic number violation, a clear signature for intermediate Majorana neutrino contributions. Such signals are not possible if the heavy neutrinos have Dirac nature. The interactions between Majorana neutrinos and the Standard Model particles are obtained from an effective Lagrangian approach. We present our results for the total cross section as a function of the neutrino mass, the effective couplings, and the new physics scale. We also show the discovery region as a function of the Majorana neutrino mass and the effective couplings. Our results show that the Large Hadron-electron Collider may be able to discover Majorana neutrinos with masses lower than 700 and 1300 GeV for electron beams settings of $E_e = 50$ GeV and $E_e = 150$ GeV, respectively.

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I. INTRODUCTION

The discovery at the LHC of a new neutral boson has been a great scientific achievement for particle physics, and up to now, no new physics has been found involving the electroweak scalar sector [1,2]. Yet, it is well known that the Standard Model (SM)—based on the gauge group $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ undergoing a spontaneous symmetry breaking in its electroweak sector, up to the universal $U(1)_{EM}$ —leaves important questions unexplained. In recent years, the first discovery of physics beyond minimum SM has taken place through the observation of flavor neutrino oscillations. This also has led to nonzero neutrino masses below or of the order of an electron volt [3]. Considering this scenario, physics at new colliders should probe not only the mechanism behind electroweak symmetry breaking and the stabilization of the electroweak scale but also trace the existence and nature of neutrino masses. The recent Large Hadron-electron Collider (LHeC) proposal [4], an electron-proton collider at CERN, could serve both purposes.

Neutrino masses are difficult to generate in a natural way in the SM Yukawa interactions framework, and a very attractive and well-known scheme to obtain them is the

seesaw mechanism, which requires the presence of heavy right-handed neutrino species of the Majorana type that allow for lepton number violation (LNV) [5–8]. The discovery of Majorana neutrinos would have profound theoretical implications in the formulation of a new model framework, while yielding insights into the origin of mass itself. Observation of any LNV process would be of great impact on particle physics and cosmology as, if neutrinos are Majorana particles, they may fit into the leptogenesis scenario for creating the baryon asymmetry, and hence the ordinary matter of the Universe [9]. However, the minimal seesaw framework generally leads to the decoupling of the Majorana neutrinos, and the observation of any LNV signal would indeed point toward new physics beyond the minimal seesaw models [10]. In this work, we will investigate the possibility of discovering Majorana neutrinos at the LHeC, considering its interactions in a general and model-independent effective Lagrangian approach.

The seesaw mechanism, among other SM extensions, requires one or more extra right-handed neutrinos ν_R with a mass term

$$L^{\text{mass}} = -\frac{1}{2}\bar{\nu}_R^c M \nu_R - \bar{L} \tilde{\phi} Y \nu_R + \text{H.c.}, \quad (1)$$

where L denotes the left-handed lepton doublet, Y denotes the Yukawa coupling matrix, ϕ denotes the Higgs doublet, and M denotes the Majorana neutrino mass.

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The diagonalization of the mass term gives

$$m_\nu = m_{\mathcal{D}} M^{-1} m_{\mathcal{D}}^T, \quad \text{with} \quad m_{\mathcal{D}} = Y \frac{v}{\sqrt{2}} \quad (2)$$

and a mixing angle $U_{lN} \sim m_{\mathcal{D}}/M$ between the light and the heavy Majorana neutrinos N [11,12].

The mixing angle, U_{lN} weighs the coupling of N with the SM particles and in particular with the charged leptons through the $V - A$ interaction:

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} U_{lN} \bar{N}^c \gamma^\mu P_L l W_\mu^+ + \text{H.c.} \quad (3)$$

In typical seesaw scenarios, the Dirac mass terms are expected to be around the electroweak scale ($m_{\mathcal{D}} \sim m_W$) in order to have Yukawa couplings $Y \sim O(1)$ in Eq. (2), whereas the Majorana mass M —being a singlet under the SM gauge group—may be very large, close to the grand unification scale. Thereby, the seesaw mechanism can explain the smallness of the observed light neutrino masses ($m_\nu \sim 0.01$ eV) while leading to the decoupling of N . Even a different choice in which $M \sim 100$ GeV and $m_{\mathcal{D}} \sim 0.1 m_e$, keeping $m_\nu \sim 0.01$ eV, implies a vanishing mixing angle $U_{lN} \sim 10^{-7}$ [10]. This effect is so weak that the observation of LNV must indicate new physics beyond the minimal seesaw mechanism, as was indicated in Ref. [10].

In view of the above discussion, in this work, we consider—in a model-independent way—the effective interactions of the Majorana neutrino N with a mass value lower than the new physics scale Λ and a negligible mixing to ν_L . In the case that heavy neutrinos do exist, present and future experiments will be capable of determining their nature. In particular, the production of Majorana neutrinos via e^+e^- , e^-p , $\gamma\gamma$, and hadronic collision have been extensively investigated in the past [10,13–24].

In this paper, we study the possibility for an e^-p collider at CERN (LHeC) in order to produce clear signatures of Majorana neutrinos in the context of interactions coming from an effective Lagrangian approach. We study the lepton number violating reaction $e^-p \rightarrow l_j^+ + 3\text{jets}$ ($l_j \equiv e, \mu, \tau$), which receives contributions from the diagrams from the processes depicted in Fig. 1. We have not considered the pure lepton decay channels because they involve light neutrinos that escape detection, in which case the Majorana nature of the heavy neutrinos would have no effect on the signal, since we should be able to know whether the final state contains neutrinos or antineutrinos.

The lepton number violating process studied here was previously investigated in Refs. [25,26], for the type-I seesaw mechanism, focusing on the DESY experiment and extended to the LEP and LHC. Recent studies of the seesaw model at lepton-proton colliders like the LHeC were performed in Refs. [27,28].

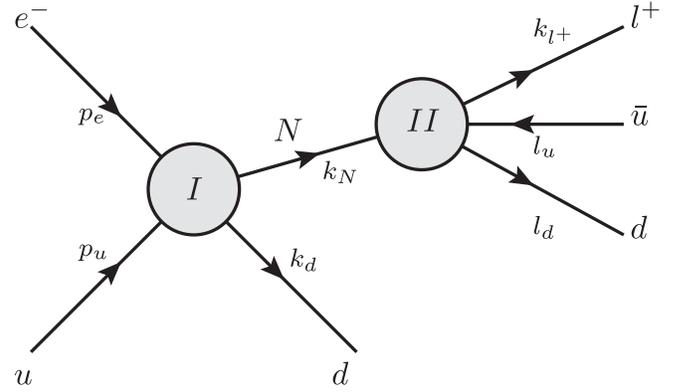


FIG. 1. Diagrams contributing to the production of Majorana neutrinos in ep colliders.

The principal advantage of electron-proton collisions with respect to hadron colliders is the cleanness of the signal. In the case of the LHeC, the leptonic number violation by 2 units is ensured by the presence of a final antilepton. Conversely, lepton number violation detection in hadron colliders implies tagging two leptons of the same sign in the final state, together with a higher number of jets, making the signal more challenging to search for. In Ref. [10], the process $pp \rightarrow l^+l^+jjjj$ is studied with the same effective formalism we apply here, and the authors claim that is possible to expect a 5σ same-sign lepton signal for $m_N \leq 600$ GeV. As will be shown, we expect a significant signal for larger masses; in particular, for $E_e \leq 50$ GeV, we expect $m_N \lesssim 700$ GeV, and for $E_e \leq 150$ GeV, we expect $m_N \lesssim 1300$ GeV. The ATLAS collaboration has published new physics searches in the same-sign dilepton signal for this model [29,30], finding limits for the Majorana neutrino mass and certain effective couplings.

In Sec. II, we review the effective Lagrangian approach and present our results for the scattering amplitudes. The numerical results are presented in Sec. III, including the SM backgrounds, the neutrinoless double- β decay bounds considered, and the obtained cross sections and discovery regions for the Majorana neutrino. Our conclusions are presented in Sec. IV.

II. EFFECTIVE LAGRANGIAN AND SCATTERING AMPLITUDES

The effects of new physics beyond the SM can be parametrized by a series of effective operators \mathcal{O} constructed with the SM and the Majorana neutrino fields and preserving the $SU(2)_L \otimes U(1)_Y$ gauge symmetry [31,32]. These effective operators represent the low-energy limit of an unknown theory, and their effects are suppressed by inverse powers of the new physics scale Λ . We consider the lowest-order new physics terms, taking into account only dimension-6 operators and nonviolating baryon number

interactions and discarding the operators generated at one-loop level in the underlying full theory, as they are naturally suppressed by a $\mathcal{O} \sim 1/16\pi^2$ factor [10,33].

The total Lagrangian is organized as

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{\mathcal{J},i} \frac{\alpha_{\mathcal{J}}^{(i)}}{\Lambda^2} \mathcal{O}_{\mathcal{J}}^i, \quad (4)$$

where the indices \mathcal{J} and i label the operators and families, respectively. For the considered operators, we follow Ref. [10], starting with a rather general effective Lagrangian density for the interaction of a Majorana neutrino N with leptons and quarks. All the operators listed here are generated at tree level in the unknown fundamental high-energy theory. The operators involving scalars and vectors are

$$\begin{aligned} \mathcal{O}_{LN\phi}^i &= (\phi^\dagger \phi)(\bar{L}_i N \tilde{\phi}), \\ \mathcal{O}_{NN\phi}^i &= i(\phi^\dagger D_\mu \phi)(\bar{N} \gamma^\mu N), \\ \mathcal{O}_{Ne\phi}^i &= i(\phi^T \epsilon D_\mu \phi)(\bar{N} \gamma^\mu e_i), \end{aligned} \quad (5)$$

and for the baryon-number conserving 4-fermion contact terms, we have

$$\mathcal{O}_{duNe}^i = (\bar{d}_i \gamma^\mu u_i)(\bar{N} \gamma_\mu e_i), \quad \mathcal{O}_{fNN}^i = (\bar{f}_i \gamma^\mu f_i)(\bar{N} \gamma_\mu N), \quad (6)$$

$$\mathcal{O}_{LNLe}^i = (\bar{L}_i N) \epsilon (\bar{L}_i e_i), \quad \mathcal{O}_{LNQd}^i = (\bar{L}_i N) \epsilon (\bar{Q}_i d_i), \quad (7)$$

$$\mathcal{O}_{QuNL}^i = (\bar{Q}_i u_i)(\bar{N} L_i), \quad \mathcal{O}_{QNld}^i = (\bar{Q}_i N) \epsilon (\bar{L}_i d_i), \quad (8)$$

$$\mathcal{O}_{LN}^i = |\bar{L}_i N|^2, \quad (9)$$

where e_i , u_i , d_i , and L_i , Q_i denote the $SU(2)$ right-handed singlets and left-handed doublets, respectively. These are the contributing operators to the Majorana neutrino N production and decay processes.

The relevant effective Lagrangian terms contributing to the production process considered are

$$\begin{aligned} \mathcal{L}_{\text{eff}}^N &= \frac{1}{\Lambda^2} \left\{ -\frac{m_W v}{\sqrt{2}} \alpha_W^{(i)} W^{\dagger\mu} \bar{N} \gamma_\mu e_{R,i} + \alpha_{V_0}^{(i)} \bar{d}_{R,i} \gamma^\mu u_{R,i} \bar{N} \gamma_\mu e_{R,i} \right. \\ &\quad + \alpha_{S_1}^{(i)} (\bar{u}_{L,i} u_{R,i} \bar{N} \nu_{L,i} + \bar{d}_{L,i} u_{R,i} \bar{N} e_{L,i}) \\ &\quad + \alpha_{S_2}^{(i)} (\bar{\nu}_{L,i} N_R \bar{d}_{L,i} d_{R,i} - \bar{e}_{L,i} N_R \bar{u}_{L,i} d_{R,i}) \\ &\quad \left. + \alpha_{S_3}^{(i)} (\bar{u}_{L,i} N_R \bar{e}_{L,i} d_{R,i} - \bar{d}_{L,i} N_R \bar{\nu}_{L,i} d_{R,i}) + \text{H.c.} \right\}, \end{aligned} \quad (10)$$

where the sum over i is understood and the constants $\alpha_{\mathcal{J}}^{(i)}$ are associated to specific operators

$$\begin{aligned} \alpha_W^{(i)} &= \alpha_{Ne\Phi}^{(i)}, & \alpha_{V_0}^{(i)} &= \alpha_{duNe}^{(i)}, & \alpha_{S_1}^{(i)} &= \alpha_{QuNL}^{(i)}, \\ \alpha_{S_2}^{(i)} &= \alpha_{LNQd}^{(i)}, & \alpha_{S_3}^{(i)} &= \alpha_{QNld}^{(i)}. \end{aligned} \quad (11)$$

Using the effective Lagrangian in Eq. (10), we calculate the cross section for the production of the Majorana neutrino according to the processes shown in Fig. 1. Taking the center of mass energy $\sqrt{s} = \sqrt{4E_e E_p}$, $\hat{\sigma}$ to be the parton level scattering cross section, and with x the usual deep inelastic scaling variable, we obtain

$$\sigma(ep \rightarrow l^+ + 3\text{jets}) = \sum_i \int_{m_N^2/s}^1 dx f_i(x) \hat{\sigma}_i(xs), \quad (12)$$

where $i = 1$ corresponds to the channel $eu \rightarrow Nd$ and $i = 2$ corresponds to the crossed channel $e\bar{d} \rightarrow N\bar{u}$ obtained by the crossing symmetry. The function $f_1(x)$ represents the $u(x)$ parton distribution function (PDF), and $f_2(x)$ represents the one for $\bar{d}(x)$ and

$$\hat{\sigma}_i(xs) = \int (2\pi)^4 \delta^{(4)} \left(p_e + p_u - \sum_{j=1,4} k_j \right) \overline{|M_{(i)}|^2} \prod_{j=1,4} \frac{d^4 k_j}{(2\pi)^3}, \quad (13)$$

The squared scattering amplitudes in the *narrow width approximation* are

$$\overline{|M_{(i)}|^2} = \left(\frac{\pi}{4m_N \Gamma_N} \right) \delta(k_N^2 - m_N^2) |\Lambda_{(I),i}|^2 (|\Lambda_{(II)}^{(+)}|^2 + |\Lambda_{(II)}^{(-)}|^2), \quad (14)$$

where

$$\begin{aligned} |\Lambda_{(I),1}|^2 &= \frac{4}{\Lambda^2} [4(\alpha_{S_2}(\alpha_{S_2} - \alpha_{S_3}) + \alpha_{S_1}^2)(k_d \cdot p_u)(k_N \cdot p_e) \\ &\quad + (4\alpha_W^2 |\Pi_W^{(2)}|^2 + \alpha_{S_3}(\alpha_{S_3} - \alpha_{S_2}))(k_d \cdot p_e)(k_N \cdot p_u) + (\alpha_{S_3} \alpha_{S_2} + 4\alpha_{V_0}^2)(k_d \cdot k_N)(p_e \cdot p_u)] \\ |\Lambda_{(II)}^{(-)}|^2 &= \frac{16}{\Lambda^4} [|\Pi_W^{(2)}|^2 \alpha_W^2 (k_N \cdot l_u)(k_{l^+} \cdot l_d) + \alpha_{V_0}^2 (k_N \cdot l_d)(k_{l^+} \cdot l_u)] \\ |\Lambda_{(II)}^{(+)}|^2 &= \frac{4}{\Lambda^4} [(\alpha_{S_1}^2 + \alpha_{S_2}^2 - \alpha_{S_2} \alpha_{S_3})(l_u \cdot l_d)(k_{l^+} \cdot k_N) \\ &\quad + (\alpha_{S_3}^2 - \alpha_{S_2} \alpha_{S_3})(k_{l^+} \cdot l_d)(l_u \cdot k_N) + \alpha_{S_2} \alpha_{S_3} (l_u \cdot k_{l^+})(l_d \cdot k_N)], \end{aligned} \quad (15)$$

with $\Pi_W^{(1)} = m_W^2 / (-2(p_u \cdot k_d) - m_W^2)$, $\Pi_W^{(2)} = m_W^2 / (2(l_u \cdot l_d) - m_W^2)$. The final leptons can be either of e^+ , μ^+ , or τ^+ since this is allowed by the interaction Lagrangian [Eq. (10)]. All these possible final states are clear signals for intermediary Majorana neutrinos, and thus we sum the cross section over the flavors of the final leptons. The total width (Γ_N) for the Majorana neutrino decay is the calculated in Ref. [21].

III. NUMERICAL RESULTS

For the numerical study, we assume an LHC-like beam of protons with an energy of 7 TeV, while examining two choices for the electron beam. We consider a low-energy scenario with an electron beam of $E_e = 50$ GeV (Scenario 1) and another high-energy scenario with $E_e = 150$ GeV (Scenario 2). For each experimental setup, we assume a baseline integrated luminosity of $L = 100 \text{ fb}^{-1}$ that is close to the values discussed for the LHeC proposal [4].

The total width, cross sections, and discovery regions for the Majorana neutrino in the effective Lagrangian approach considered in this paper depend on the quotient of the coupling constant $\alpha_{\mathcal{J}}^{(i)}$, associated with the operators in Eq. (10), and the new physics scale Λ squared, i.e., $\kappa_{\mathcal{J}}^{(i)} = \alpha_{\mathcal{J}}^{(i)} / \Lambda^2$, in addition to the Majorana neutrino mass m_N . The considered operators are bounded by LEP and low-energy data, and we have also taken into account the bounds on the operators that come from the neutrinoless double- β decay ($0\nu_{\beta\beta}$ -decay).

We start this section discussing the SM backgrounds, the LEP, low-energy data, and $0\nu_{\beta\beta}$ -decay bounds, before showing our results for the scattering cross section for the process $e^- p \rightarrow l_j^+ + 3\text{jets}$, the different distributions and cuts implemented, and the Majorana neutrino discovery regions for both considered scenarios.

A. Standard Model background

The considered signal, being a lepton number violating process, is strictly forbidden in the Standard Model. The SM background will always involve additional light neutrinos that escape the detectors and generate missing energy. This fact makes the signal very clean and difficult to mimic by SM processes.

As was pointed out in Ref. [27], the dominant background comes from W production, with its subsequent decay into l^+ (e^+ , μ^+ , τ^+). In particular, the process $e^- p \rightarrow e^- l^+ jj\nu$ is not distinguished from the signal if the outgoing electron is lost in the beam line. This process is dominated by the exchange of an almost real photon with a very collinear outgoing electron ($p\gamma \rightarrow l^+ jj\nu$). This last process, convoluted with the PDF representing the probability of finding a photon inside an electron, is found to be the major contribution to W production. The simulation of the background processes was done using the program CalcHep [34]. In Sec. III D, we discuss different cuts to

increase the sensitivity and improve the signal-to-background relation.

B. LEP, low-energy, and neutrinoless double- β decay bounds

The heavy Majorana neutrino couples to the three flavor families with couplings $\kappa_{\mathcal{J}}^{(i)} = \alpha_{\mathcal{J}}^{(i)} / \Lambda^2$. These couplings can be related with the mixing angle between light and heavy neutrinos U_{iN} , comparing the operator $\mathcal{O}_{Ne\phi}^i$ with the strength of the vector-axial vector interaction in Eq. (3).

The relation is $U_{iN} = \frac{v^2 \alpha_W^{(i)}}{2 \Lambda^2}$ [10]. The mixing angles U_{iN} are bounded by LEP and low-energy data [35–40]. In our case, with only one heavy neutrino N , and following the treatment made in Refs. [21,35], we translate these model-independent bounds to the couplings $\kappa^{(i)}$, considering that all the operators satisfy the same and most stringent constraint given on Ref. [40] for $\Omega_{e\mu} = U_{eN} U_{\mu N} = \frac{v^2}{2} \kappa^2 < 1.0 \times 10^{-4}$ with $v = 250$ GeV. This leads to $\kappa < 3.2 \times 10^{-7} \text{ GeV}^{-2}$, which, as we will show, is less restrictive than the constraints imposed by the $0\nu_{\beta\beta}$ -decay experiments.

To take into account the constraints imposed by the $0\nu_{\beta\beta}$ -decay experiments on some of the coupling constants $\alpha_{\mathcal{J}}^{(i)}$, we follow the developments presented in Refs. [41,42] and take the most stringent limits on the lifetime for neutrinoless double- β decay ($\tau_{0\nu_{\beta\beta}} \geq 2.1 \times 10^{25} \text{ yr}$) obtained by the GERDA collaboration [43].

The lowest-order contribution to $0\nu_{\beta\beta}$ decay from the considered effective operators comes from those that involve the W field and the 4-fermion operators with quarks u , d , the lepton e , and the Majorana neutrino N :

$$O_{Ne\phi}^1, \quad O_{duNe}^1, \quad O_{QuNL}^1, \quad O_{LNQd}^1, \quad O_{QNLd}^1. \quad (16)$$

The contribution of these operators to $0\nu_{\beta\beta}$ decay is shown in Fig. 2.

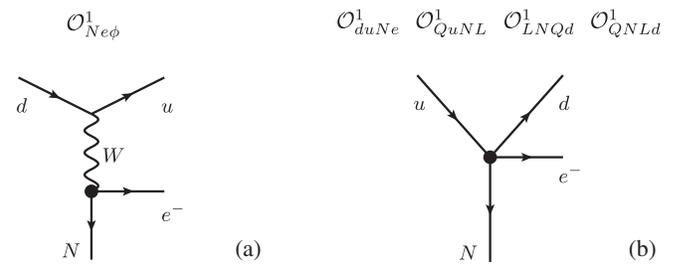


FIG. 2. Contribution to $0\nu_{\beta\beta}$ -decay. In the diagram (a) the solid dot represents the operator $\mathcal{O}_{Ne\phi}^1$ and in the diagram (b), the dot represents the 4-fermion operators \mathcal{O}_{duNe}^1 , \mathcal{O}_{QuNL}^1 , \mathcal{O}_{LNQd}^1 and \mathcal{O}_{QNLd}^1 .

For the coupling constant associated with each operator, we use the generic name $\alpha_{0\nu\beta\beta}$; that is to say

$$\alpha_{0\nu\beta\beta} = \alpha_{Ne\phi}^{(1)} = \alpha_{duNe}^{(1)} = \alpha_{QuNL}^{(1)} = \alpha_{LNQd}^{(1)} = \alpha_{QNLd}^{(1)}. \quad (17)$$

To estimate the bounds on the different $\alpha_{\mathcal{J}}^{(i)}$, we consider the case in which all coupling constants α are nonzero with equal values, and the individual contributions of each operator are considered to act alone. The maximum value for the α 's is limited by the $0\nu\beta\beta$ bound.

Following the treatment made in Ref. [21], we obtain the bound value for the quotient $\kappa_{0\nu\beta\beta} = \alpha_{0\nu\beta\beta}/\Lambda^2$:

$$\kappa_{0\nu\beta\beta} = \frac{\alpha_{0\nu\beta\beta}}{\Lambda^2} \leq 7.8 \times 10^{-8} \left(\frac{m_N}{100 \text{ GeV}} \right)^{1/2}. \quad (18)$$

C. Signal cross section

We have already discussed in the previous section that some of the operators that contribute to the neutrinoless double beta decay ($0\nu\beta\beta$ decay) may be strongly constrained. Therefore, for studying the Majorana neutrino production cross section in ep colliders and the following decay $N \rightarrow l^+ + 2\text{jets}$, we analyze two situations: in Set I, we consider the case in which the effective couplings for the operators that do not contribute to neutrinoless decay take all the same value $\alpha = 1$, and in Set II, we consider all those effective couplings to be equal and limited by the neutrinoless double beta decay bound [Eq. (18)].

The Majorana neutrino width was studied in detail in Ref. [21], in which all possible effective operators of dimension 6 involving quarks were taken into account.

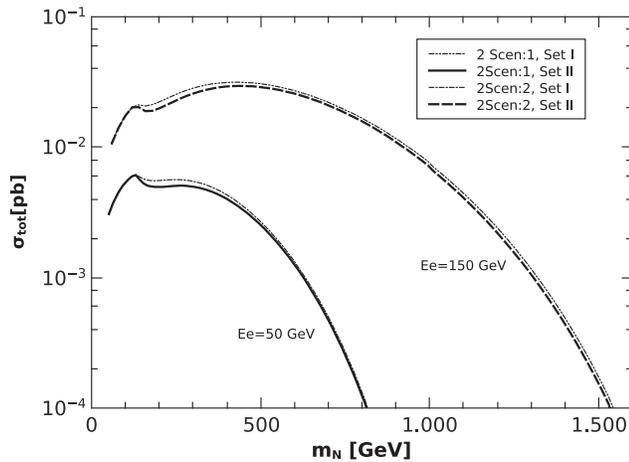
In Fig. 3(a), we show the results for the cross section, as a function of the Majorana neutrino mass m_N , for the considered electron beam energies: $E_e = 50 \text{ GeV}$

(Scenario 1) and $E_e = 150 \text{ GeV}$ (Scenario 2) for both Sets I and II. The results are very similar for both sets. We have considered $\sqrt{s} < \Lambda$ in order to ensure the validity of the effective Lagrangian approach. We display here the results for $\Lambda = 2500 \text{ GeV}$.

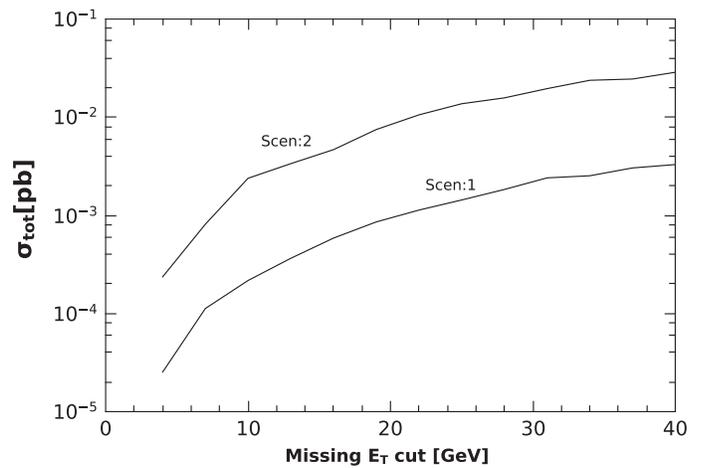
The phase-space integration of the squared amplitude is made generating the final momenta with the Monte Carlo routine RAMBO [44]. This allows us to make the distributions and necessary cuts in the phase space to study the possibility of discovering Majorana neutrino effects.

D. Distributions and kinematical cuts

The dominant backgrounds for the studied process have been studied in Ref. [27]. In particular, the authors conclude that a cut that could be effective to separate the signal and background is to reject events in which the outgoing l^+ does not have a minimum transverse momentum. On the other hand, as the signal only includes visible particles and the background includes at least one neutrino, another possible cut is imposing an upper bound on the missing transverse energy. We follow this approach and implement the mentioned cuts. In Fig. 3(b), we show the behavior of the background with the maximum missing energy E_T for the scenarios in which $E_e = 50 \text{ GeV}$ (Scenario 1) and $E_e = 150 \text{ GeV}$ (Scenario 2). A cut of $E_{T,\text{max}} \leq 10 \text{ GeV}$, which is a reasonable value for the detector resolution, does not have appreciable effects on the signal but reduces the background significantly. In Fig. 4, we show the differential cross section for the background and the signal for different values of the Majorana masses as a function of the transverse momentum p_{T,l^+} of the antilepton. In these figures, the cut on the missing energy E_T has already been included. As it can be appreciated, the background is mostly concentrated at low values of p_{T,l^+} , and a cut imposed on p_{T,l^+}^{min} could be



(a) Signal cross section.



(b) Background E_T dependence.

FIG. 3. Cross section for the process $ep \rightarrow NX$ with N decaying according to Ref. [21] (a) and background dependence with missing E_T (b).

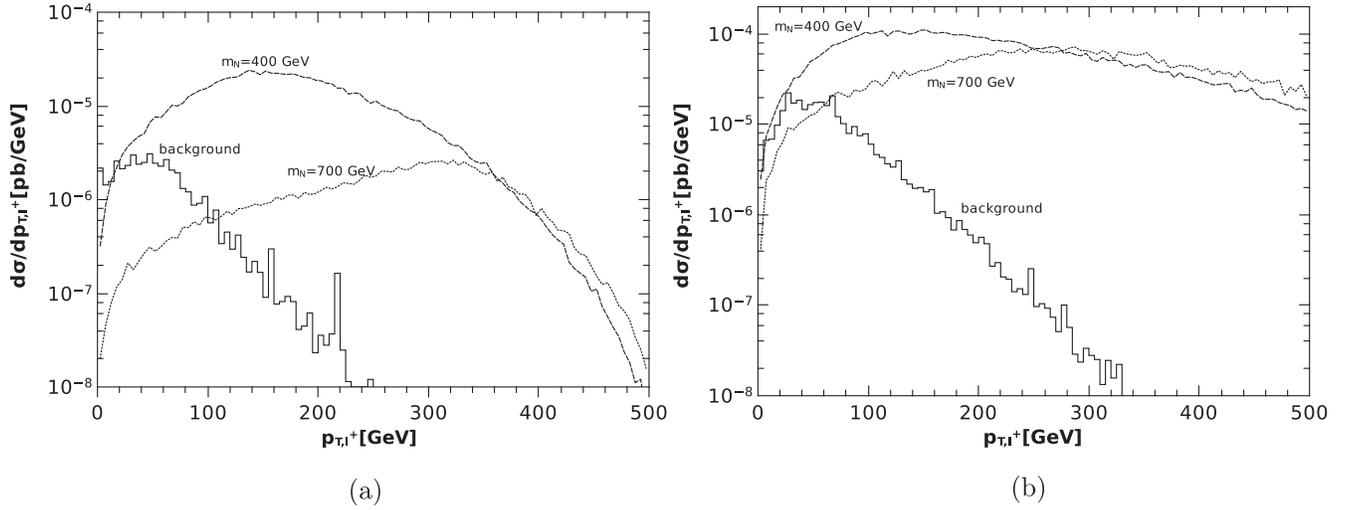


FIG. 4. Differential cross section of the signal and background in function of transverse momentum p_{T,l^+} . The cut in missing E_T is included. (a) Scenario 1 and (b) Scenario 2.

effective to improve the signal/background relation. Finally, in Fig. 5, we show a plot comparing the magnitude of the signal for different values of the Majorana neutrino mass (solid lines) and the background for different $E_{T,\max}$ cuts (dashed lines), depending on the p_{T,l^+}^{\min} cut imposed. In both figures, the arrows indicate the value of the cuts used in the analysis: we impose $p_{T,l^+} \geq 90$ GeV and $E_{T,\text{miss}} \leq 10$ GeV in order to reduce the background without appreciably decreasing the signal.

E. Discovery regions

To investigate the possibility of the detection of Majorana neutrinos in the process under consideration, we study the region (discovery region) where the signal can be separated from the background with a statistical significance higher than 5σ . We use the method of the *effective*

significance described in Refs. [45,46]. There, they show that the effective significance is well approximated by

$$S = 2(\sqrt{n_s + n_b} - \sqrt{n_b}) - k(\alpha), \quad (19)$$

with $k(\alpha) = 1.28$ for $\alpha = 0.1$, where $1 - \alpha$ is the probability of measuring a number of events bigger than a value n_0 , such that the probability (β) that the Standard Model reproduces such a number is rather small, $\beta < 3 \times 10^{-7}$ for $S > 5$ (5σ test). In Eq. (19), $n_s = L\sigma_s$ and $n_b = L\sigma_b$ are the numbers of events for the signal and backgrounds, with L being the luminosity.

In Fig. 6, we show the discovery regions for different values of the Majorana neutrino mass m_N , and the quotient $\kappa_{\mathcal{J}}^{(i)} = \alpha_{\mathcal{J}}^{(i)}/\Lambda^2$. As we explained in Sec. III B, we consider the case in which all the $0\nu\beta\beta$ contributing coupling

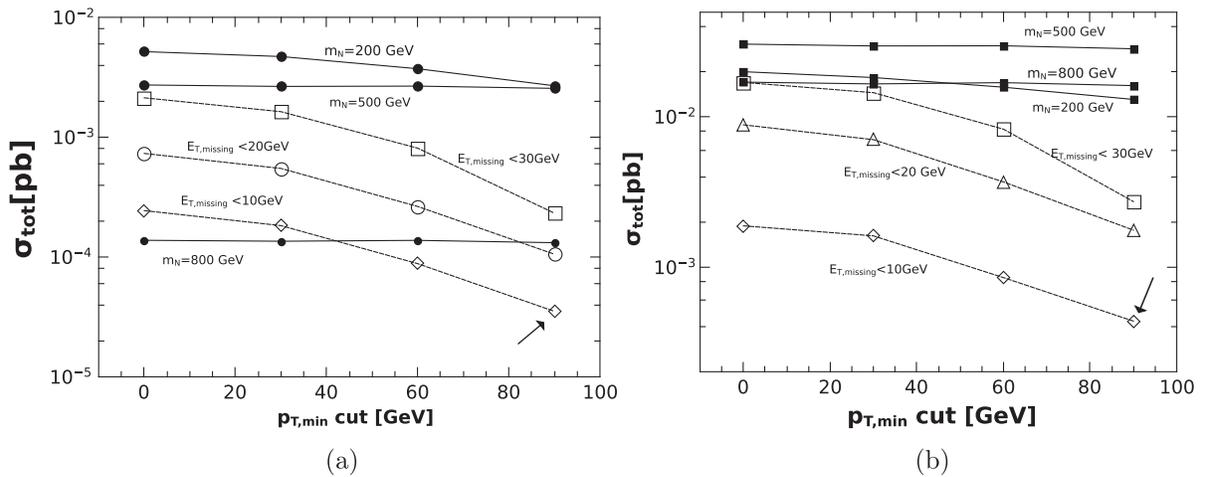


FIG. 5. Comparison between the signal and background for different Majorana neutrino masses, cut in missing E_T , and the transversal momentum of the final lepton p_{T,l^+} . The solid lines show the cross section for the signal, and the dotted lines show the cross section for the background. The arrows indicate the cuts and backgrounds used in the analysis. (a) Scenario 1 and (b) Scenario 2.

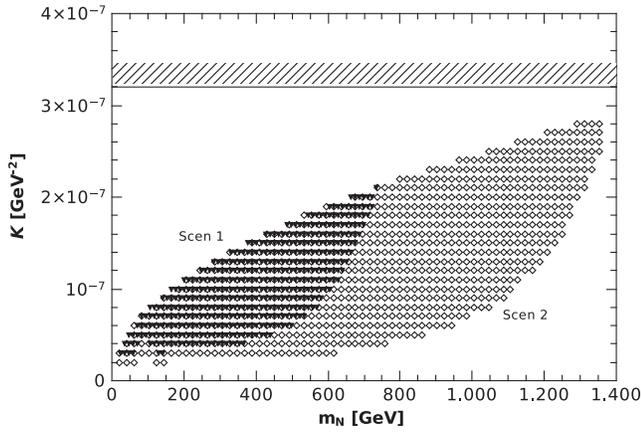


FIG. 6. Majorana neutrino discovery regions at 5σ . The horizontal line represents the low-energy and LEP limits discussed in Sec. III B.

constants $\alpha_{\mathcal{J}}^{(i)}$ (generically α) are nonzero and equal, so that $\kappa \leq \kappa_{0\nu\beta\beta}$ in Eq. (18). The figure shows that Majorana neutrinos of masses up to near 700 GeV for Scenario 1 and 1300 GeV for Scenario 2 may be detected.

The maximum allowed value for the Majorana neutrino mass corresponds to the intersection between the $0\nu\beta\beta$ bound [Eq. (18)] and the contour of level 5 for the surface \mathcal{S} [Eq. (19)]; this is $\mathcal{S}(m_N, \Lambda) = 5$. The last equation can be written as $\alpha_{0\nu\beta\beta}/\Lambda^2 \approx f(m_N)$, where f is a function of m_N and the collider energy but independent of Λ . Thus, the intersection and then the maximum value for m_N is almost independent of the new physics scale Λ .

Systematic uncertainties are hard to estimate without a detailed reconstruction of the detector, but they are expected to be around a few percent [47]. However, the influence of the background systematic uncertainties in the result is small because the background itself is small. In the case of the signal, we have calculated the modifications for the discovery region if the number of events for the

signal is changed by $\pm 30\%$. The results are shown in Fig. 7, showing no appreciable change in the region.

IV. SUMMARY AND CONCLUSIONS

To investigate the possibilities for discovering Majorana neutrinos in an e^-p collider at CERN (LHeC), we have calculated the cross section for the lepton number violating process $e^-p \rightarrow l_j^+ + 3\text{jets}$ in an effective Lagrangian approach, complementing previous analyses for this facility involving typical seesaw scenarios.

The effective Lagrangian framework parametrizes new physics effects in a model-independent way, allowing for sizable lepton number violating effects for effective couplings $\alpha_{\mathcal{J}}^{(i)}$ of order 1, in contrast to the minimal seesaw mechanism, that leads to the decoupling of the Majorana neutrinos.

While models like the minimal seesaw mechanism lead to the decoupling of the heavy Majorana neutrinos, predicting unobservable LNV, the effective Lagrangian framework considered in this work parametrizes the new physics effects in a model-independent way, enabling the occurrence of sizable LNV signals for effective couplings $\alpha_{\mathcal{J}}^{(i)}$ of order 1.

We have calculated the total unpolarized cross section $\sigma(e^-p \rightarrow l_j^+ + 3\text{jets})$ for different values of m_N , the effective couplings $\alpha_{\mathcal{J}}^{(i)}$ and the new physics scale Λ , and implemented cuts in the phase space that can help to enhance the signal-to-background relation. We obtained the Majorana neutrino discovery regions at 5σ statistical significance, combining the effect of the SM backgrounds with the most restrictive $0\nu\beta\beta$ -decay bounds for the effective couplings.

Our analysis shows that the LHeC facility could discover Majorana neutrinos with masses lower than 700 and 1300 GeV with a 7 TeV proton beam and electron beams of $E_e = 50$ and $E_e = 150$ GeV, respectively. Thus, we find lepton-proton colliders could provide a new probe of the Majorana nature of neutrinos, shedding light on this fundamental unsolved issue in particle physics.

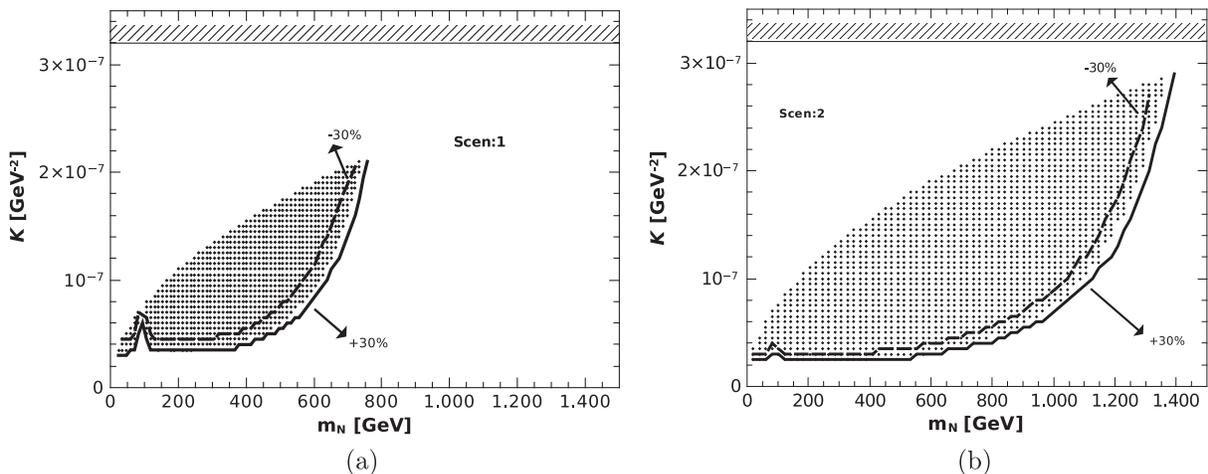


FIG. 7. Majorana neutrino discovery regions at 5σ , including systematic uncertainties in the signal. (a) Scenario 1 and (b) Scenario 2.

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