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Sensitivity of low energy neutrino experiments to physics beyond the standard model

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We study the sensitivity of future low energy neutrino experiments to extra neutral gauge bosons, leptoquarks, and R-parity breaking interactions. We focus on future proposals to measure coherent neutrino-nuclei scattering and neutrino-electron elastic scattering. We introduce a new comparative analysis between these experiments and show that in different types of new physics it is possible to obtain competitive bounds to those of present and future collider experiments. For the cases of leptoquarks and R-parity breaking interactions we found that the expected sensitivity for most of the future low energy experimental setups is better than the current constraints.

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I. INTRODUCTION

The standard model (SM) is one of the most successful models in physics and it is in very good agreement with almost every measurement in high energy physics [1]. Despite this fact, there are many motivations to believe that the SM is not the last step in the description of the physics of elementary particles.

There are many theoretical motivations to believe that there is physics beyond the standard model, and recently the neutrino oscillation experiments have also given an experimental input on these thoughts. Among the most popular extensions of the SM we find grand unified theories (GUT), supersymmetry (SUSY), and extra dimensions. None of these theories have been observed in the laboratory, but there are extensive searches for signatures of them in collider physics. The main aim of this paper is to analyze the potential of low energy neutrino experiments either to confirm the presence of new physics if it would be discovered by the Large Hadron Collider (LHC), or put stronger or complementary constraints on their parameters.

We center our attention in signatures that could appear in two different reactions: coherent neutrino-nuclei scattering and neutrino-electron elastic scattering. As concrete examples of coherent neutrino-nuclei scattering we will consider the TEXONO proposal [2], a stopped pion source (SPS) with a noble gas detector [3] and the recently discussed proposal of low energy beta beams [4]. For the neutrino-electron-scattering case, we concentrate on the Double Chooz proposal [5].

For some of these experimental proposals there have already been discussions about their perspectives for constraining nonstandard neutrino interactions [3,6] or a nonzero neutrino magnetic moment [3,7–9]. In this work we introduce a new comparative analysis between different low energy experiments, focusing on three different types of new physics phenomenology, namely, extra neutral gauge bosons, leptoquarks, and R-parity breaking supersymmetry. As far as we know, this is the first time that the sensitivity of low energy neutrino proposals to leptoquarks is studied. On the other hand, extra neutral gauge boson sensitivity had been studied only for the TEXONO and neutrino-electron-scattering proposals [6,8,10]. For the case of R-parity breaking supersymmetry the existing studies have tested either long-baseline neutrino experiments [11] that introduce an extra dependence on θ_{13} or new physics effects in the source due to charged currents [12], while here we will focus on neutral currents effects, visible in the detector, specifically in a short baseline detector based on coherent neutrino-nuclei scattering. Moreover, the study of different future proposals at one time gives to the reader an extra usefulness of telling which future experiments will give better chances in the different types of new physics under study. We will see that, despite the fact that we are dealing with very low energy experiments, there are good chances to obtain a very good sensitivity to these types of new physics and to either compete or to give complementary constraints to those that could be obtained from collider experiments.

The structure of the article is the following: In Sec. II we describe the experimental proposals that we study. In Sec. III we introduce the different types of new physics under consideration and the expected sensitivity in the different experimental setups. Finally, in Sec. IV we present our conclusions.

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II. EXPERIMENTAL PROPOSALS

Before introducing the phenomenology to study new physics signatures we would like to discuss the low energy neutrino experimental proposals. In particular, we will discuss the case of future experiments aiming to measure the coherent neutrino scattering off nuclei as well as the case of low energy neutrino-electron-scattering experiments. For the first reaction we study three different recent proposals while for neutrino-electron scattering we concentrate on the Double Chooz case.

A. TEXONO

The TEXONO Collaboration has recently started a research program towards the measurement of neutrino-nuclei coherent scattering by using reactor neutrinos and an "ultralow-energy" germanium detector (ULEGe) [2].

The proposed detector would consist of 1 kg of an ultralow-energy germanium detector with a threshold as low as 100 eV and a background level below 1 keV in the range of 1 count per day that implies a signal-to-noise ratio bigger than 22. Although an estimate for the systematic uncertainties is not available, we can consider that they will be dominated by the reactor power, its fuel composition, and the antineutrino spectrum. We assume that these uncertainties will give an approximate error of 2% [13].

Besides the 100 eV threshold, we will also consider the more conservative case of a 400 eV threshold. The typical time scale of data taking is assumed to be from one to several years.

The electron antineutrino flux is coming from the Kuo-Sheng Nuclear Power Station. The detector will be located at a distance of 28 m from the reactor core. In our computation we will assume a typical reactor neutrino flux of $10^{13}\ \mathrm{s}^{-1}\,\mathrm{cm}^{-2}$. There are several parametrizations that consider in detail the neutrino spectrum coming from a reactor [13–15]. In this work we will use the most recent parametrization [13] for the neutrino spectrum. Since the proposed experiments are not running yet, we will assume that the relative contribution of the fissile isotopes (^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu) is given by the typical average values of the reactor operating period [16] which is given by 0.58:0.30:0.07:0.05. We have checked numerically that the result does not change significantly with other ratios. For energies below 2 MeV there are only theoretical calculations for the antineutrino spectrum that we take from Ref. [16].

Since we are not able to account for the detector efficiency and resolution, we will estimate the total number of expected events in a detector as

$$N_{\mathrm{events}}^{\mathrm{TEXONO}} = t\phi_0 \frac{M_{\mathrm{detector}}}{M} \int_0^{E_{\max}} dE_\nu \int_{T_{\mathrm{th}}}^{T_{\max}(E_\nu)} dT \lambda(E_\nu) \frac{d\sigma}{dT} \times (E_\nu, T), \tag{1}$$

with t the data taking time period, ϕ_0 the total neutrino flux, M_{detector} the total mass of the detector, $\lambda(E_\nu)$ the normalized neutrino spectrum, $E_{\max}$ the maximum neutrino energy, T_{th} the detector energy threshold. The maximal recoil energy is $T_{\max}(E_\nu) = 2E_\nu^2/(M + 2E_\nu)$. The same expression relates the minimum required incoming neutrino energy with the detector threshold T_{th}. For instance, for the detector's threshold 400 eV and ^{76}Ge nucleus, the minimum required incoming neutrino energy is about 3.8 MeV which is well satisfied for reactor neutrinos.

B. Stopped pion neutrino source

A different proposal for detecting the coherent neutrino-nucleus scattering considers the use of another source of neutrinos, a SPS, such as the Spallation Neutron Source at Oak Ridge National Laboratory. Recently, this type of source was proposed to measure coherent neutrino scattering off nuclei as well as nonstandard neutrino properties [3].

The total beam flux consists of the following well-known neutrino fluxes.

(i) The monoenergetic 29.9 MeV ν_μ's produced from pion decay at rest, $\pi^+ \to \mu^+\nu_\mu$, and
(ii) $\bar{\nu}_\mu$ and ν_e coming from muon decay, $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$, with a time delay of about 2.2 μs, muon decay time scale.

The neutrino spectra are well known. Here we will consider only the total delayed flux ($\nu_e + \bar{\nu}_\mu$) as was done in Ref. [3]. We assume a total flux of $\sim 10^7 \nu\ \mathrm{s}^{-1}\,\mathrm{cm}^{-2}$. Among different possible detector materials such as Ar, Ge, or Xe, we will concentrate on the noble gas detector, ^{20}Ne, of typical mass about 100 kg with a data taking time scale from one to several years and a threshold of 10 keV.

C. Low energy beta beams

The usage of accelerated radioactive nuclei to produce a well-known flux of neutrinos—beta beam—was proposed in [17]. It was shown soon afterwards that low energy beta beams open new possibilities to study neutrino properties [18] and, recently, a neutrino-nuclei coherent scattering experiment using neutrinos from low energy beta beams was discussed [4]. On the other hand, tests for R-parity violating supersymmetry have been discussed both by the direct detection of τ leptons in a nearby detector [12] and in long-baseline beta-beam experiments [11].

In particular we base our analysis on the beta-beam experiment discussed in [4,19]. We consider a storage ring of total length $L = 1885$ m with a straight section of length $D = 678$ m. In the stationary regime the mean number of ions in the storage ring is $\gamma\tau g$, where $\tau = t_{1/2}/\ln 2$ is the lifetime of the parent nuclei, $g = 2.7 \times 10^{12}$ is the number of injected ions per second, and $\gamma = 1/\sqrt{1-\beta^2}$ is the time delay factor with β the ion velocity in the laboratory frame. As previous authors, we will consider a cylindrical detector of radius $R = 52$ cm and depth $h = 40$ cm, aligned with one of the storage ring's straight sections, and located at a distance $d = 10$ m from it. Integration over the decay path and over the volume of the detector gives the total number of events per unit time

$$N_{\text{events}}^{\beta\text{ beam}} = tg\tau nh \int_0^{\infty} dE_\nu \Phi_{\text{tot}}(E_\nu)\sigma(E_\nu), \qquad (2)$$

where $t = 1$ yr is the data taking time, n is the number of target nuclei per unit volume, $\sigma(E_\nu)$ is the relevant neutrino-nucleus cross section. For definiteness we consider the case of a ton of Xe as a target and a factor $\gamma = 14$ for ^{6}He ions as described in Ref. [4]. As for the threshold energy, we consider both the realistic threshold of 15 keV where background events are negligible as well as the very optimistic 5 keV threshold that, according to the same reference, will give a bigger number of events if background could be subtracted, though at present there is no technology capable of dealing with such a background. The total neutrino flux through detector is given by

$$\Phi_{\text{tot}}(E_\nu) = \int_0^D \frac{d\ell}{L} \int_0^h \frac{dz}{h} \int_0^{\bar{\theta}(\ell,z)} \frac{\sin\theta d\theta}{2} \Phi_{\text{lab}}(E_\nu, \theta), \qquad (3)$$

where

$$\tan\bar{\theta}(\ell, z) = \frac{R}{d + \ell + z}. \qquad (4)$$

The boosted flux in the laboratory frame is

$$\Phi_{\text{lab}}(E_\nu, \theta) = \frac{\Phi_{cm}(E_\nu \gamma[1 - \beta\cos\theta])}{\gamma[1 - \beta\cos\theta]}, \qquad (5)$$

where E_ν and $\Omega \equiv (\theta, \varphi)$ denote the energy and solid angle of the emitted (anti-)neutrino in the laboratory (lab) frame and θ denotes the angle of emission with respect to the beam axis.

The neutrino flux in the rest frame, $\Phi_{cm}(E'_\nu)$, is given by the well-known formula [20]

$$\Phi_{cm}(E'_\nu) = \frac{\ln 2}{m_e^5 f t_{1/2}} (E'_\nu)^2 E_e \sqrt{E_e^2 - m_e^2} F(\pm Z, E_e) \times \Theta(E_e - m_e), \qquad (6)$$

where m_e is the electron mass and $ft_{1/2}$ the ft value. The energy of emitted lepton (electron or positron) is $E_e = Q - E'_\nu$, where Q is the Q value of the reaction, and the Fermi function $F(\pm Z, E_e)$ accounts for the Coulomb modification of the spectrum [21].

D. Reactor experiments

A different type of experiment that we will also consider in this article is based on low energy neutrino-electron scattering. This process has already been considered as a possible place to search for an extra gauge boson [10,22]. The case of a reactor source to constrain new physics has recently been discussed both for present [23] and future proposals [8]. In this work we will concentrate on the perspectives for the Double Chooz experiment [5]. As in [8], we assume that the Double Chooz will collect 10^4 neutrino-electron-scattering events considering a 3 GW reactor and a 26.5 ton detector with an electron visible energy window $3 < T < 5$ MeV. As in the case of the TEXONO proposal, we will use the most recent parametrization [13] for the neutrino spectrum and the same fuel composition.

E. Discussion on experiments

We summarize the main characteristics of the detectors in Table I. One can notice that in some cases it could be possible to run the experiment for a period longer than one year, or to upgrade the detector mass, obtaining a smaller statistical error without being dominated by systematic uncertainties. This is the case, for example, for a beta beam with a 15 keV threshold. On the other hand the stopped pion source seems to be suitable only for one year of data taking. Finally, we also consider the very optimistic cases in which experimentalists can reduce the uncertainties in a low threshold regime (like a beta beam with a 5 keV threshold). In this case we assume that the systematic uncertainties remain the same.

In the next sections we will take into account all these experimental setups. We will also show results for possible upgrades to these experiments; i.e., we will consider that the experimental setup can be running for a longer time (or that an upgrade in mass is possible). Among the difficulties for the upgrade we must take special care of the systematic error expectations. In order to make a reasonable compromise with future experimental capabilities, we will consider the systematic errors quoted in Table I. Since we are dealing with experiments that are not running yet, we

TABLE I. Expected events for different experimental setups.

Experiment	M_0	Expected events per year	Systematic error estimate
TEXONO, $E_{\text{th}} = 400$ eV	1 kg, Ge	3790	2%
TEXONO, $E_{\text{th}} = 100$ eV	1 kg, Ge	25 196	2%
Beta beam, $E_{\text{th}} = 15$ keV	1 ton, Xe	1390	2%
Beta beam, $E_{\text{th}} = 5$ keV	1 ton, Xe	5309	2%
Stopped pion, $E_{\text{th}} = 10$ keV	100 kg, Ne	627	5%
Double Chooz	26.5 ton, scintillator	10 000	1%

believe that this approach will be helpful to take notice of what would be the expected limits for each experiment.

III. MODELS AND SENSITIVITY

Once the experimental setups have been discussed, we turn our attention to different types of new physics that could be constrained in these future proposals. We will consider three different scenarios that will be discussed in detail in the following subsections.

A. Z' models

In this section we introduce the description of the extra gauge bosons to be considered. New massive gauge bosons are a common feature of physics beyond the standard model. Heavy neutral vector bosons Z' are predicted in string inspired extensions of the SM, in left-right symmetric models, in models with dynamical symmetry breaking, in "little Higgs" models, and in certain classes of theories with extra dimensions. In many of these models it is expected that the Z' mass can be around the TeV scale.

The present experimental lower limits to the neutral gauge boson mass come from the Tevatron and LEP experiments [1]. Forthcoming measurements at LHC will provide sensitivity to the Z' mass up to 5 TeV [24,25].

The new Z' boson affects the neutral current couplings of the SM, and its contribution at low energies can be tested from atomic parity violation and by electron-nucleon scattering experiments (see references in [1]). Since low energy experiments are not sensitive to the mixing angle between the SM gauge boson and the extra gauge boson, and this angle is very well constrained [1], we will neglect it.

We consider first the particular case of an additional neutral gauge boson Z' that arises from a primordial E_6 gauge symmetry [26]. These extensions usually involve an extra $U(1)$ hypercharge symmetry at low energies that may be given as the mixture of those associated with the symmetries $U(1)_\chi$ and $U(1)_\psi$. We show the quantum numbers for the SM particles in Table II.

The corresponding hypercharge is then specified by

$$Y_\beta = Y_\chi \cos\beta + Y_\psi \sin\beta, \tag{7}$$

while the charge operator is given as $Q = T^3 + Y$. Any value of β is allowed, giving us a continuum spectrum of possible models of the weak interaction. At tree level it is possible to write an expression for the effective 4-fermion Lagrangian describing low energy neutral current phenomena. We neglect nonstandard radiative correction because its contribution is of order $(\alpha/\pi)(M_Z^2/M_{Z'}^2)$ [27]. Another class of Z' models is coming from left-right symmetric models that have the premise that the fundamental weak interaction Lagrangian is invariant under parity symmetry at energies about 100 GeV. The gauge group of this type of model is given by $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$, which gives an additional neutral gauge boson plus a charge gauge boson [28,29]. We will concentrate in this work on the neutral currents.

TABLE II. Quantum numbers for the light particles in the **27** of E_6.

	T_3	$\sqrt{40}Y_\chi$	$\sqrt{24}Y_\psi$
Q	$\binom{1/2}{-1/2}$	-1	1
u^c	0	-1	1
e^c	0	-1	1
d^c	0	3	1
l	$\binom{1/2}{-1/2}$	3	1

In the following subsections we will introduce the modifications to the coupling constants, and therefore to the cross section, due to this type of new physics. With this information we will study the different experimental proposals and their sensitivity to both E_6 and left-right symmetric neutral gauge bosons.

1. Coherent neutrino-nuclei scattering coupling constants

Before introducing this description it is useful to recall the general description of the nonstandard neutrino-quark and neutrino-electron interactions and then we will specify the interactions for commonly used Z' models.

Generically the neutrino-quark interaction at low energies (energies $\ll M_Z$) can be described at the 4-fermion approximation by the effective Lagrangian

$$\mathcal{L}_{\nu\,\text{hadron}}^{NC} = -\frac{G_F}{\sqrt{2}} \sum_{q=u,d} [\bar{\nu}_e \gamma^\mu (1-\gamma^5)\nu_e] \times (f^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + f^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q]), \tag{8}$$

where

$$\begin{aligned} f^{uL} &= \rho_{\nu N}^{NC}(\tfrac{1}{2} - \tfrac{2}{3}\hat{\kappa}_{\nu N}\hat{s}_Z^2) + \lambda^{uL} + \varepsilon^{uL}, \\ f^{dL} &= \rho_{\nu N}^{NC}(-\tfrac{1}{2} + \tfrac{1}{3}\hat{\kappa}_{\nu N}\hat{s}_Z^2) + \lambda^{dL} + \varepsilon^{dL}, \\ f^{uR} &= \rho_{\nu N}^{NC}(-\tfrac{2}{3}\hat{\kappa}_{\nu N}\hat{s}_Z^2) + \lambda^{uR} + \varepsilon^{uR}, \\ f^{dR} &= \rho_{\nu N}^{NC}(\tfrac{1}{3}\hat{\kappa}_{\nu N}\hat{s}_Z^2) + \lambda^{dR} + \varepsilon^{dR}. \end{aligned} \tag{9}$$

Here $\hat{s}_Z^2 = \sin^2\theta_W = 0.231\,20$—the Weinberg weak mixing angle taken in the $\overline{\text{MS}}$ model. The radiative corrections [1] $\rho_{\nu N}^{NC} = 1.0081$, $\hat{\kappa}_{\nu N} = 0.9978$, $\lambda^{uL} = -0.0031$, $\lambda^{dL} = -0.0025$, and $\lambda^{dR} = 2\lambda^{uR} = 7.5 \times 10^{-5}$ are included into our analysis. In general, the parameters ε^{qP} ($q = u, d$ and $P = L, R$) describe a generic nonstandard neutrino interaction. For the specific case of E_6 string inspired models this is translated into

$$\varepsilon^{uL} = -4\gamma\sin^2\theta_W\rho^{NC}_{\nu N}\left(\frac{c_\beta}{\sqrt{24}} - \frac{s_\beta}{3}\sqrt{\frac{5}{8}}\right)\left(\frac{3c_\beta}{2\sqrt{24}} + \frac{s_\beta}{6}\sqrt{\frac{5}{8}}\right),$$
$$\varepsilon^{dR} = -8\gamma\sin^2\theta_W\rho^{NC}_{\nu N}\left(\frac{3c_\beta}{2\sqrt{24}} + \frac{s_\beta}{6}\sqrt{\frac{5}{8}}\right)^2, \tag{10}$$
$$\varepsilon^{dL} = \varepsilon^{uL} = -\varepsilon^{uR},$$

where $c_\beta = \cos\beta$, $s_\beta = \sin\beta$, and $\gamma = (M_Z/M_{Z'})^2$. Three main models have been extensively studied, namely, the χ model ($\cos\beta = 1$), the ψ model ($\cos\beta = 0$), and the η model ($\cos\beta = \sqrt{3/8}$). In previous articles [22] it has been stressed that low energy neutrino experiments are more sensitive to the χ model than to other E_6 models. However, for comparison with the expected sensitivity to Z' mass in different models at LHC we will consider a continuum spectrum of possible models over parameter β.

From the Lagrangian in Eq. (8) we can obtain the coherent neutrino-nucleus differential cross section which is given by

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi}\left\{(G_V + G_A)^2 + (G_V - G_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2}\right\}, \tag{11}$$

where M is the mass of the nucleus, T is the recoil nucleus energy, which varies from 0 to $T_{\max} = 2E_\nu^2/(M + 2E_\nu)$, E_ν is the incident neutrino energy, and

$$G_V = [(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV})Z + (g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV})N] \times F_{\text{nucl}}^V(Q^2), \tag{12}$$

$$G_A = [(g_A^p + 2\varepsilon_{ee}^{uA} + \varepsilon_{ee}^{dA})(Z_+ - Z_-) + (g_A^n + \varepsilon_{ee}^{uA} + 2\varepsilon_{ee}^{dA})(N_+ - N_-)]F_{\text{nucl}}^A(Q^2). \tag{13}$$

Z and N represent the number of protons and neutrons in the nucleus, while $Z_\pm$ ($N_\pm$) stands for the number of protons (neutrons) with spin-up and spin-down, respectively. From Eq. (13) it is possible to see that the axial couplings will vanish for even-even nuclei considered below.

The vector and axial nuclear form factors, $F_{\text{nucl}}^V(Q^2)$ and $F_{\text{nucl}}^A(Q^2)$, are usually assumed to be equal and of order of unity in the limit of small energies, $Q^2 \ll M^2$. In our computations, for the sake of completeness we take into account the vector form factor given in Ref. [30]. We have also made our computations taking into account previous calculations of this form factor [31–33], and we found that there is no difference in our results for both of them, which gives us confidence to consider that this theoretical estimation will not have an impact on the systematic errors. The SM neutral current vector couplings of neutrinos with protons, g_V^p, and with neutrons, g_V^n, are defined as

$$g_V^p = \rho^{NC}_{\nu N}(\tfrac{1}{2} - 2\hat{\kappa}_{\nu N}\hat{s}_Z^2) + 2\lambda^{uL} + 2\lambda^{uR} + \lambda^{dL} + \lambda^{dR},$$
$$g_V^n = -\tfrac{1}{2}\rho^{NC}_{\nu N} + \lambda^{uL} + \lambda^{uR} + 2\lambda^{dL} + 2\lambda^{dR}. \tag{14}$$

Besides string inspired models, we also consider left-right symmetric models. In this case the coupling constants in Eq. (9) can be expressed as [34]

$$f^{uL} = \rho^{NC}_{\nu N}A(\tfrac{1}{2} - \tfrac{2}{3}\hat{\kappa}_{\nu N}\hat{s}_Z^2) - B\tfrac{2}{3}\hat{s}_Z^2 + \lambda^{uL},$$
$$f^{dL} = \rho^{NC}_{\nu N}A(-\tfrac{1}{2} + \tfrac{1}{3}\hat{\kappa}_{\nu N}\hat{s}_Z^2) + B\tfrac{1}{3}\hat{s}_Z^2 + \lambda^{dL},$$
$$f^{uR} = \rho^{NC}_{\nu N}A(-\tfrac{2}{3}\hat{\kappa}_{\nu N}\hat{s}_Z^2) + B(\tfrac{1}{2} - \tfrac{2}{3}\hat{s}_Z^2) + \lambda^{uR}, \tag{15}$$
$$f^{dR} = \rho^{NC}_{\nu N}A(\tfrac{1}{3}\hat{\kappa}_{\nu N}\hat{s}_Z^2) + B(-\tfrac{1}{2} + \tfrac{1}{3}\hat{s}_Z^2) + \lambda^{dR},$$

where

$$A = 1 + \frac{\hat{s}_Z^4}{1 - 2\hat{s}_Z^2}\gamma, \qquad B = \frac{\hat{s}_Z^2(1 - \hat{s}_Z^2)}{1 - 2\hat{s}_Z^2}. \tag{16}$$

2. Neutrino-electron scattering coupling constants

For the case of neutrino-electron scattering the total Lagrangian has the form

$$\mathcal{L}^{NC}_{\nu e} = -\frac{G_F}{\sqrt{2}}\sum_{\alpha,\beta=e,\mu,\tau}[\bar{\nu}_\alpha\gamma^\mu(1 - \gamma^5)\nu_\beta] \times (f^{eL}[\bar{e}\gamma_\mu(1 - \gamma^5)e] + f^{eR}[\bar{e}\gamma_\mu(1 + \gamma^5)e]), \tag{17}$$

with $f^{eL,R} = g_{L,R} \pm \varepsilon^{L,R}$, and

$$\varepsilon^L = 2\gamma\sin^2\theta_W\rho^{NC}_{\nu e}\left(\frac{3c_\beta}{2\sqrt{6}} + \frac{s_\beta}{3}\sqrt{\frac{5}{8}}\right)^2,$$
$$\varepsilon^R = 2\gamma\sin^2\theta_W\rho^{NC}_{\nu e}\left(\frac{c_\beta}{2\sqrt{6}} - \frac{s_\beta}{3}\sqrt{\frac{5}{8}}\right)\left(\frac{3c_\beta}{\sqrt{24}} + \frac{s_\beta}{3}\sqrt{\frac{5}{8}}\right). \tag{18}$$

As in the previous subsection, here $\gamma = (M_Z/M_{Z'})^2$. With this Lagrangian, the neutrino-electron scattering will keep the same form,

$$\frac{d\sigma}{dT} = \frac{2G_F m_e}{\pi}\left[g_L^2 + g_R^2\left(1 - \frac{T}{E_\nu}\right)^2 - g_L g_R\frac{m_e T}{E_\nu^2}\right], \tag{19}$$

with the only difference that now the coupling constants $g_{L,R}$ will be defined as

$$g_L = \frac{1}{2} + \sin^2\theta_W + \varepsilon^L, \tag{20}$$

$$g_R = \sin^2\theta_W + \varepsilon^R. \tag{21}$$

For the left-right symmetric case, we can express the coupling constants as

$$g_L^{LR} = Ag_L + Bg_R, \tag{22}$$

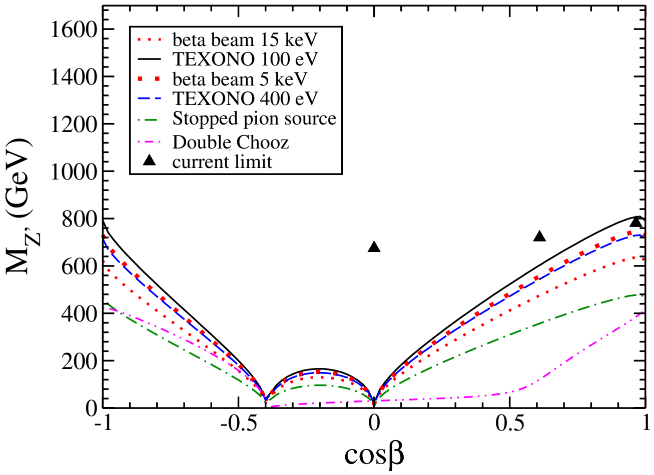

FIG. 1 (color online). Sensitivity, at 95% C.L., to different extra neutral gauge boson coming from E_6 models. We consider the case of the TEXONO proposal for an energy threshold of 100 eV (solid line) and 400 eV (dashed line), the case of a future stopped-pion source (dash-dotted line), and a beta-beam source with energy threshold of 15 keV (bold dotted line) and 5 keV (dotted line). Finally, the Double Chooz sensitivity is also shown (dashed-double-dotted line). The current limits (triangles) are also shown for comparison.

$$g_R^{LR} = Ag_R + Bg_L, \qquad (23)$$

where A and B were defined in Eq. (16).

3. *Future sensitivity*

In order to compute the expected Z' mass limit that these experiments could get, we consider that the future experiment will measure exactly the standard model prediction, and we add the systematic error in quadratures to the statistical one. With these hypotheses we can compute the 95% C.L. bound reachable at these future experiments after one year of data taking.

We make this computation for the string inspired models for all possible values of $\cos\beta$ considering the detector characteristics explained in the previous section. The results are shown in Fig. 1, where we also show, for comparison, the current constraints at 95% C.L. [1]. Note that the expectations for the Double Chooz experiment are in a qualitative agreement with similar analysis done before the MUNU experiment in Ref. [10]. For the left-right symmetric case the expected sensitivity is shown in Table III.

From Fig. 1 it is possible to see different phenomenological aspects. First, the χ model ($\cos\beta = 1$) is the most sensitive for low energy neutrino experiments. Second, for the coherent neutrino-nucleus scattering case, the ψ model ($\cos\beta = 0$) is in the opposite situation. This behavior is clear from Eq. (10), that for this specific value the corrections to the standard model Lagrangian cancel. A similar property arises both in the case of coherent neutrino-nucleus scattering as well as in anti-neutrino-electron scattering for $\cos\beta = -\sqrt{5/32}$. These features of different specific models seem to discourage the search for this type of new physics in low energy neutrino experiments, since only a few models can give a significant signature. However, in the case of a positive signature in LHC we can expect its confirmation in this kind of experiment, or their nonobservation in the case of other specific models, providing in any case indirect complementary information.

In order to test how the sensitivity to an extra Z signal could change with an upgraded version of these proposals, we show in Fig. 2 the improved sensitivity for each proposal in the case of an increase in mass or time exposure, which reduces the statistical error.

We can see that in the case of extra gauge boson Z' the neutrino experimental proposals could only give complementary information to the current Tevatron constraints [1].

B. Leptoquark models

A leptoquark is a scalar or vector boson that couples to a lepton and a quark. There are no such interactions in the SM, but they are expected to exist in various extensions of the SM [1], such as the Pati-Salam model [36], grand unification theories based on $SU(5)$ [37,38] and $SO(10)$ [39] gauge groups, and extended technicolor models [40].

The leptoquark contribution effectively (in 4-fermion approximation) can be written as [41]

$$\varepsilon^{uV} = \frac{\lambda_u^2}{m_{lq}^2}\frac{\sqrt{2}}{4G_F},$$

$$\varepsilon^{dV} = \frac{\lambda_d^2}{m_{lq}^2}\frac{\sqrt{2}}{4G_F},$$

where λ_u, λ_d are couplings, m_{lq} is leptoquark mass. This parametrization is given for vector leptoquarks. In the case of scalar leptoquarks, our results should be multiplied by a factor $1/2$ [41].

TABLE III. Expected sensitivity at 95% C.L., in GeV, for the mass of a left-right symmetric model extra gauge boson. We consider five different experimental proposals. The current limit is also shown for comparison.

Experiment	TEXONO (100 eV)	Beta beam (5 keV)	Beta beam (15 keV)	TEXONO (400 eV)	Stopped pion source	Double Chooz	Current limit
Sensitivity	450	419	358	406	251	565	860 [35]

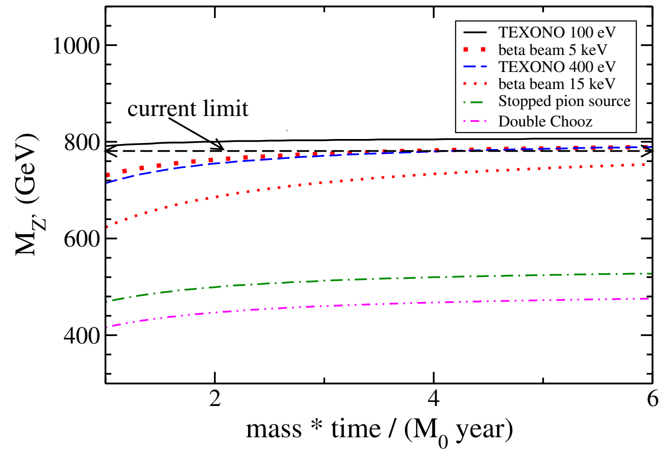

FIG. 2 (color online). Sensitivity, at 95% C.L., to an extra χ neutral gauge boson coming from E_6 models for different experimental setups. The dependence on the size of the detector and time of running is shown.

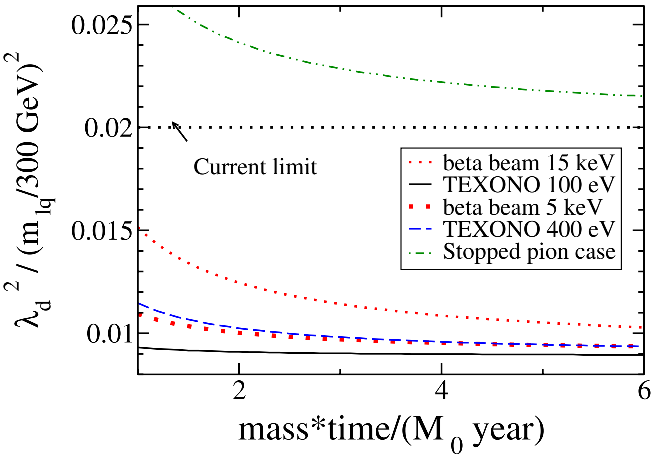

FIG. 3 (color online). Sensitivity, at 95% C.L., to a vector leptoquark coupling for different experimental setups. The limit on the coupling λ_d will depend on the leptoquark mass m_{lq} that here is chosen to be 300 GeV in agreement with current literature. The dependence on the size of the detector and time of running is also shown.

In the case of an observation at colliders like LHC and LEP, one can constrain directly the leptoquark mass. The expected sensitivity for LHC could be as high as 1.6 TeV [42]. However, for indirect observations, like our low energy 4-fermion case, one can constrain only the combination λ_q^2/m_{lq}^2. An extensive list of constraints on the leptoquark couplings and masses is given in Refs. [1,41]. The current limit for a leptoquark which couples to the first generation of leptons and first generation of quarks is given by

$$\lambda_q^2/(m_{lq}/300 \text{ GeV})^2 < 0.02.$$

We have calculated the sensitivity to the vector first generation leptoquark couplings and masses which is expected at different low energy neutrino experiments already discussed in this work. The results are shown in Fig. 3 where we show the expected sensitivity at 95% C. L. for each experiment and the possible improvements if the experimental setup could run with a bigger mass or for a longer time.

One can see that the low energy neutrino experiments are very promising for improving the present bounds.

The sensitivities for the case of scalar leptoquark masses for different low energy neutrino experiments are collected in Table IV. For easy comparison with the bounds given in [1] we have fixed the leptoquark effective coupling at the electroweak value, $\lambda_q^2/4\pi = 1/137$, and we compute the sensitivity of the scalar leptoquark mass at 95% C.L. These results also show a big potential for low energy neutrino experiments to give complementary information about leptoquark masses and couplings.

C. SUSY with broken *R* parity

In supersymmetric theories, gauge invariance does not imply baryon number (B) and lepton number (L) conservation and, in general, the so-called R parity [defined as $R = (-1)^{3B+L+2S}$ where S is the spin] is violated. However, one has to keep the consistency with the nonobservation of fast proton decay. One may consider, for instance, the R-parity violating minimal supersymmetric standard model (MSSM) (imposing baryon number conservation) with a superpotential that contains the following L-violating terms [44]:

$$\lambda_{ijk} L_L^i L_L^j \bar{E}_R^k \qquad \lambda'_{ijk} L_L^i Q_L^j \bar{D}_R^k, \tag{24}$$

where we use the standard notation, L_L, Q_L, $\bar{E}_R$, and $\bar{D}_R$ to denote the chiral superfields containing the left-handed lepton and quark doublets and the right-handed charged-lepton and d-quark singlets respectively; i, j, k are generation indices. A lepton-Higgs term (LH) can also be included in the superpotential, but it can be rotated away through an appropriate redefinition of the superfields.

TABLE IV. Expected 95% C.L. leptoquark mass sensitivity, in GeV, for future low energy neutrino experiments. The leptoquark effective coupling has been fixed to be $\lambda_q^2/4\pi = 1/137$.

Experiment	TEXONO (100 eV)	Beta beam (5 keV)	TEXONO (400 eV)	Beta beam (15 keV)	Stopped pion source	Current constraint
Sensitivity	894	805	805	684	546	298 [43]

At low energies, the heavy supersymmetry particles can be integrated out and the net effect of the R-breaking interactions is to generate effective 4-fermion operators involving the lepton and quark fields.

By considering the case where a single Yukawa coupling (with one flavor structure) is much larger than the others, the effective 4-fermion operator generated by $L_L^i Q_L^j \bar{D}_R^k$ takes the same form as in Eq. (8) with the new couplings [44,45]:

$$\begin{aligned} f^{uL} &= \rho_{\nu N}^{NC}(\tfrac{1}{2} - \tfrac{2}{3}\hat{\kappa}_{\nu N}\hat{s}_Z^2)(1 - r_{12k}(\tilde{e}_{kR})) + \lambda^{uL}, \\ f^{dL} &= \rho_{\nu N}^{NC}(-\tfrac{1}{2} + \tfrac{1}{3}\hat{\kappa}_{\nu N}\hat{s}_Z^2)(1 - r_{12k}(\tilde{e}_{kR})) + \lambda^{dL} \\ &\quad - r'_{11k}(\tilde{d}_{kR}), \\ f^{uR} &= \rho_{\nu N}^{NC}(-\tfrac{2}{3}\hat{\kappa}_{\nu N}\hat{s}_Z^2)(1 - r_{12k}(\tilde{e}_{kR})) + \lambda^{uR}, \\ f^{dR} &= \rho_{\nu N}^{NC}(\tfrac{1}{3}\hat{\kappa}_{\nu N}\hat{s}_Z^2)(1 - r_{12k}(\tilde{e}_{kR})) + \lambda^{dR} + r'_{1j1}(\tilde{d}_{jL}), \end{aligned} \tag{25}$$

where

$$r_{ijk}(\tilde{l}) = \left(\frac{M_W^2}{g^2}\right)\left(\frac{|\lambda_{ijk}|^2}{m_{\tilde{l}}^2}\right). \tag{26}$$

The factors $(1 - r_{12k}(\tilde{e}_{kR}))$ account for the Fermi coupling constant redefinition $G_F = G_F^{\rm SM}(1 + r_{12k}(\tilde{e}_{kR}))$ that arise from the modification to the μ decay due to R-breaking interaction. Since the value of the Fermi constant comes from muon decay experiments, we can not get any information on the charged current SUSY parameters and we should concentrate only on the neutral current corrections. As already mentioned in a previous section, a different approach has also been considered, that is the direct detection of τ leptons in a nearby detector [12].

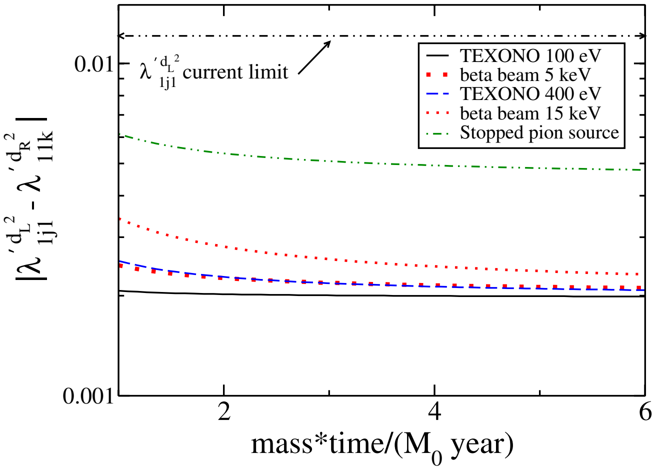

FIG. 4 (color online). Sensitivity, at 95% C.L., to neutral current R-parity breaking terms for different experimental setups. The dependence on the size of the detector and time of running is also shown as well as the current limits. See the text for a detailed explanation of these couplings.

From Eq. (25) we can see that the R-breaking terms appear both in the f^{dL} and f^{dR} couplings. We take into account this correlation and we show in Fig. 4 the possible future sensitivity at 95% C.L. of the neutrino-nucleus coherent experiments to the parameter

$$\lambda_{1j1}^{\prime d_L^2} - \lambda_{11k}^{\prime d_R^2} = \frac{|\lambda'_{1j1}|^2}{(m_{\tilde{d}_{jL}}^2/100\ \text{GeV})} - \frac{|\lambda'_{11k}|^2}{(m_{\tilde{d}_{kR}}^2/100\ \text{GeV})}. \tag{27}$$

As in previous sections, the possible improvements if the experimental setup could run with a bigger mass or for a larger time is shown in Fig. 4. The current constraints for these parameters are given by $\lambda_{1j1}^{\prime d_L^2} \leq 0.0121$ and $\lambda_{11k}^{\prime d_R^2} \leq 0.0001$ [45]. Stringent constraints exist for specific values of k and j, for instance, from neutrinoless double beta decay [46] in the particular case $k = j = 1$ ($\lambda_{111}^{\prime d_{L,R}^2} \leq 1.5 \times 10^{-7}$). We can neglect the $\lambda_{11k}^{\prime d_R^2}$ parameter and conclude that the perspectives to improve the sensitivity to $\lambda_{1j1}^{\prime d_L^2}$ are quite promising for this type of experiment.

IV. CONCLUSIONS

We have shown that low energy neutrino experiments could provide independent and complementary information on Z', leptoquark masses and couplings, and R-parity violating SUSY interactions. We have calculated the potential of various future low energy neutrino experiments to either confirm the discovery of extra heavy gauge bosons at LHC or to constrain their masses.

As concrete coherent neutrino-nuclei interaction proposals, we have discussed the TEXONO case, the stopped pion source with a noble gas detector, and the beta beams. In the neutrino-electron-scattering case we have concentrated on the Double Chooz experiment. We have found that a coherent neutrino-nuclei scattering using reactor neutrinos, such as the TEXONO proposal, or a beta-beam neutrino source, could have a high sensitivity to new interactions coming from leptoquarks or R-parity breaking SUSY, and we showed that the case of a stopped-pion source experiment could also improve the current R-parity breaking SUSY constraints. On the other hand, for this kind of experiments an improved constraint to extra heavy neutral gauge bosons seems to be difficult.

For the particular case of leptoquarks, we have found that all the discussed low energy neutrino experiments have the potential to improve the present bound on leptoquark masses and couplings. In particular, the sensitivity to the vector leptoquark mass is of the order of 800 GeV, assuming an electroweak value of the coupling, $\lambda_q^2/4\pi = 1/137$. For the case of supersymmetry with broken R parity, the perspectives to improve the constraint on the λ'_{1j1} and the corresponding mass for the $\tilde{d}_L$ are also very promising for all the experimental setups.

Finally, we would like to remark that low energy neutrino experiments have great potential to provide us with indirect information about high energy physics and therefore strongly complement accelerator experiments.

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