

Probing new neutral gauge bosons with CE ν NS and neutrino-electron scattering

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The potential for probing extra neutral gauge boson mediators (Z') from low-energy measurements is comprehensively explored. Our study mainly focuses on Z' mediators present in string-inspired E_6 models and left-right symmetry. We estimate the sensitivities of coherent-elastic neutrino-nucleus scattering (CE ν NS) and neutrino-electron scattering experiments. Our results indicate that such low-energy high-intensity measurements can provide a valuable probe, complementary to high-energy collider searches and electroweak precision measurements.

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I. INTRODUCTION

Despite its amazing success [1], it is well-accepted that the Standard Model (SM) can not be the whole truth. Although the SM seems to capture the most essential features concerning the gauge description of fundamental interactions, it leaves many in the open. Indeed, many are the theoretical motivations for having an extended gauge structure. The latter include the desire of incorporating a dynamical seesaw mechanism that can naturally account for small neutrino masses [2,3] in such a way that these are linked to the origin of parity violation in the weak interaction [4]. Embedability into a simple unified structure at high energies [5] also motivates the existence of new gauge bosons.

Searches for heavy intermediate vector bosons have been extensively performed using high energy accelerators such as the LHC [6]. Their existence could also have important implications for electroweak precision tests [7–9] and induce charged lepton flavor violation [10,11]. Building on early work [12,13], here we will examine the sensitivity of a number of experimental low-energy setups to the existence of heavy electrically neutral intermediate vector bosons Z' . These are expected in theories

with gauged B-L [14,15], in extended electroweak models predicting the number of families [16,17], in models with dynamical symmetry breaking [18–20], in string-inspired extensions of the SM [21], as well as in ambitious “comprehensive unification” scenarios with extra dimensions [22]. It has been shown that a neutral Z' can have masses at the TeV scale in a way consistent with a neutrino mass generation as well as gauge coupling unification in $SO(10)$ [23]. In this work, we focus on scenarios where a Z' boson has mass around the few TeV scale.

The recent discovery of coherent elastic neutrino-nucleus scattering (CE ν NS) by the COHERENT experiment [24] at the Spallation Neutron Source (SNS) has inspired many phenomenological studies addressing the sensitivity of low-energy approaches to new physics (for a review, see Ref. [25]). New constraints have been placed on nonstandard and generalized interactions [26–29], nuclear physics parameters [30–32], neutrino electromagnetic properties [33,34], sterile neutrinos [35–37] as well as implications for dark matter [38]. It has been noted [39–48] that light mediators may be accessible to CE ν NS experiments, providing information that is complementary to what can be achieved from high-energy and/or precision measurements. Constraints on the Z' parameters from CE ν NS have been reported in Refs. [26,49].

In the present paper, we further explore the complementarity of the high-intensity, low-energy approach as a tool to search for new physics. In the same spirit as Refs. [12,13], here we consider the sensitivity of various low-energy experimental setups involving CE ν NS and neutrino-electron scattering to the existence of extra neutral gauge bosons arising from well-motivated left-right (LR) symmetric and E_6 -based theories. Regarding SNS

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neutrinos, in addition to the “first light” CE ν NS measurement with a CsI[Na] detector, we also explore the new physics potential at the future Ge, liquid argon (LAr) and NaI[Tl] detector subsystems of COHERENT [50]. In addition, we test the corresponding capabilities at various proposed reactor-based CE ν NS facilities such as CONUS [51], CONNIE [52], MINER [53], TEXONO [54], RED100 [55], RICOCHET [56], and NUCLEUS [57]. We also explore the potential for probing these vector mediators through $\nu_e - e^-$ scattering [58] using a liquid xenon (LXe) detector exposed to neutrinos from a $^{51}\text{Cr}^1$ source [61].

Our paper is organized as follows. In Sec. II, we introduce the formalism for CE ν NS and neutrino-electron scattering in left-right and E_6 theories. The various experimental setups using both SNS and reactor neutrinos for the case of CE ν NS, as well as ^{51}Cr neutrinos for the case of neutrino-electron scattering are described in Sec. III. Finally, in Sec. IV, we present our numerical results for the expected sensitivities to the mass of Z' gauge bosons in the context of the models discussed.

II. CE ν NS AND NEUTRINO-ELECTRON SCATTERING WITHIN Z' MODELS

In this section, we first introduce the notation relevant for the description of CE ν NS and $\nu_e - e^-$ cross sections in the SM. We provide the new couplings in the neutrino-quark and neutrino-charged lepton sectors present in extended electroweak models based on left-right or E_6 gauge symmetries. Next, we discuss their subleading effect on the dominant Standard Model cross sections.

We start from the neutral-current interaction cross section of a neutrino with an energy E_ν scattering off a nucleus with Z protons, $N = A - Z$ neutrons (A is the mass number), and mass m_A . In the framework of Standard Model interactions only and for a sufficiently low momentum transfer, the CE ν NS channel dominates the cross section, provided that the coherence condition $q \leq 1/R$ (R is the nuclear radius) is satisfied. Assuming a four-fermion contact interaction, the relevant CE ν NS cross section can be expressed in terms of the nuclear recoil energy T_A as [49,62]

$$\left(\frac{d\sigma}{dT_A}\right)_{\text{SM}} = \frac{G_F^2 m_A}{\pi} Q_V^2 \left(1 - \frac{m_A T_A}{2E_\nu^2}\right) F^2(Q^2), \quad (1)$$

where G_F denotes the Fermi constant and Q_V is the vector weak charge written in the form,

$$Q_V = [2(g_u^L + g_u^R) + (g_d^L + g_d^R)]Z + [(g_u^L + g_u^R) + 2(g_d^L + g_d^R)]N. \quad (2)$$

¹This follows the same spirit as the proposal in [59]. Note also that a proposal for measuring CE ν NS with a ^{51}Cr source also exists; see Ref. [60].

For later convenience, Q_V is expressed in terms of the left- and right-handed couplings of the quark $q = \{u, d\}$ to the Z -boson, as

$$\begin{aligned} g_u^L &= \rho_{\nu N}^{NC} \left(\frac{1}{2} - \frac{2}{3} \hat{\kappa}_{\nu N} \hat{s}_Z^2\right) + \lambda_u^L, \\ g_d^L &= \rho_{\nu N}^{NC} \left(-\frac{1}{2} + \frac{1}{3} \hat{\kappa}_{\nu N} \hat{s}_Z^2\right) + \lambda_d^L, \\ g_u^R &= \rho_{\nu N}^{NC} \left(-\frac{2}{3} \hat{\kappa}_{\nu N} \hat{s}_Z^2\right) + \lambda_u^R, \\ g_d^R &= \rho_{\nu N}^{NC} \left(\frac{1}{3} \hat{\kappa}_{\nu N} \hat{s}_Z^2\right) + \lambda_d^R, \end{aligned} \quad (3)$$

with the weak mixing angle taken in the $\overline{\text{MS}}$ scheme, i.e., $\hat{s}_Z^2 = 0.2312$. The radiative corrections from the Particle Data Group, $\rho_{\nu N}^{NC} = 1.0082$, $\hat{\kappa}_{\nu N} = 0.9972$, $\lambda_u^L = -0.0031$, $\lambda_d^L = -0.0025$, and $\lambda_d^R = 2\lambda_u^R = 3.7 \times 10^{-5}$, are also included.

In the present study, important corrections due to the finite nuclear size are incorporated through the momentum variation of the nuclear form factors $F(Q^2)$. These lead to a suppression of the expected CE ν NS event rate. A comprehensive analysis of the form factor effects has been recently conducted in Refs. [30,31] using the first COHERENT data. Here, we consider the symmetrized Fermi (SF) approximation [63],

$$\begin{aligned} F(Q^2) &= \frac{3}{Qc[(Qc)^2 + (\pi Qa)^2]} \left[\frac{\pi Qa}{\sinh(\pi Qa)} \right] \\ &\times \left[\frac{\pi Qa \sin(Qc)}{\tanh(\pi Qa)} - Qc \cos(Qc) \right], \end{aligned} \quad (4)$$

with

$$c = 1.23A^{1/3} - 0.60 \text{ (fm)}, \quad a = 0.52 \text{ (fm)}, \quad (5)$$

where c and a represent the half-density radius and diffuseness, respectively.

Within the SM, the differential cross section describing $\nu_e - e^-$ scattering arises from both neutral- and charged-current interactions and reads [13]

$$\begin{aligned} \frac{d\sigma}{dT_e}(E_\nu, T_e) &= \frac{2G_F m_e}{\pi} \left[(g_e^L)^2 + (g_e^R)^2 \left(1 - \frac{T_e}{E_\nu}\right)^2 \right. \\ &\quad \left. - g_e^L g_e^R \frac{m_e T_e}{E_\nu^2} \right], \end{aligned} \quad (6)$$

where the QED corrections have been neglected and the chiral couplings take the form,

$$\begin{aligned} g_e^L &= \rho_{\nu e} \left(-\frac{1}{2} + \hat{\kappa}_{\nu e} \hat{s}_Z^2\right) + 1, \\ g_e^R &= \rho_{\nu e} \hat{\kappa}_{\nu e} \hat{s}_Z^2, \end{aligned} \quad (7)$$

with the radiative corrections $\rho_{\nu e} = 1.0128$ and $\hat{\kappa}_{\nu e} = 0.9963$.

We now proceed with our discussion by expressing the new couplings $f_q^{L,R}$ and $f_e^{L,R}$ relevant to CE ν NS and $\nu_e - e^-$ scattering in a more convenient form. In the context of the E_6 and LR symmetric models discussed below, the corresponding beyond the Standard Model cross sections are obtained through the substitutions $g_q^{L,R} \rightarrow f_q^{L,R}$ and $g_e^{L,R} \rightarrow f_e^{L,R}$ in the cross sections expressions in Eqs. (1) and (6) for CE ν NS and $\nu_e - e^-$ scattering, respectively.

A. Left-right symmetry

There are various left-right-symmetric models using the gauge group $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$, restoring the parity symmetry at high energies [4]. These models give an interesting phenomenology, associated to the existence of additional charged and neutral gauge bosons [7–11]. Here we consider models where the Z' arises from left-right symmetrical extensions of the SM. In contrast to the charged intermediate vector bosons, it has been shown that the neutral one, Z' , can have masses at the TeV scale consistent with neutrino mass generation and gauge coupling unification in $SO(10)$ [23]. In what follows, we will focus on the phenomenology coming from such a Z' boson.

1. CE ν NS

In the framework of the left-right symmetric model, the relevant parameters describing CE ν NS are modified as follows [64]:

$$\begin{aligned} f_u^L &= \rho_{\nu N}^{NC} \mathcal{A} \left(\frac{1}{2} - \frac{2}{3} \hat{\kappa}_{\nu N} \hat{s}_Z^2 \right) - \mathcal{B} \frac{2}{3} \hat{s}_Z^2 + \lambda_u^L, \\ f_d^L &= \rho_{\nu N}^{NC} \mathcal{A} \left(-\frac{1}{2} + \frac{1}{3} \hat{\kappa}_{\nu N} \hat{s}_Z^2 \right) + \mathcal{B} \frac{1}{3} \hat{s}_Z^2 + \lambda_d^L, \\ f_u^R &= \rho_{\nu N}^{NC} \mathcal{A} \left(-\frac{2}{3} \hat{\kappa}_{\nu N} \hat{s}_Z^2 \right) + \mathcal{B} \left(\frac{1}{2} - \frac{2}{3} \hat{s}_Z^2 \right) + \lambda_u^R, \\ f_d^R &= \rho_{\nu N}^{NC} \mathcal{A} \left(\frac{1}{3} \hat{\kappa}_{\nu N} \hat{s}_Z^2 \right) + \mathcal{B} \left(-\frac{1}{2} + \frac{1}{3} \hat{s}_Z^2 \right) + \lambda_d^R, \end{aligned} \quad (8)$$

with the definitions,

$$\mathcal{A} = 1 + \frac{\hat{s}_Z^4}{1 - 2\hat{s}_Z^2} \gamma, \quad \mathcal{B} = \frac{\hat{s}_Z^2(1 - \hat{s}_Z^2)}{1 - 2\hat{s}_Z^2} \gamma, \quad (9)$$

and $\gamma = (M_Z/M_{Z'})^2$, where $M_{Z'}$ denotes the Z' mass.

2. Neutrino-electron scattering

Turning to the case of neutrino-electron scattering in the left-right symmetric model, the relevant couplings are trivially obtained as

$$\begin{aligned} f_e^L &= \mathcal{A} g_e^L + \mathcal{B} g_e^R, \\ f_e^R &= \mathcal{A} g_e^R + \mathcal{B} g_e^L, \end{aligned} \quad (10)$$

TABLE I. Hypercharge quantum numbers for the Standard Model fermions under E_6 .

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

where the dependence on the Z' mass is incorporated through the parameters \mathcal{A} and \mathcal{B} defined as in the case of CE ν NS in Eq. (9).

B. E_6 models

New neutral gauge bosons also appear in the primordial E_6 gauge symmetry [7–9]. Since it is a rank-six group, E_6 in general yields two neutral gauge bosons beyond those present in the SM. These gauge bosons couple to two new hypercharges, χ and ψ that correspond to the $U(1)$ symmetries present in $E_6/SO(10)$ and in $SO(10)/SU(5)$. The corresponding hypercharge quantum numbers are given in Table I. We assume that, at low energies, there is only one $U(1)$ symmetry, written as the combination of the symmetries $U(1)_\chi$ and $U(1)_\psi$. This defines a one-parameter family of models with hypercharge given as

$$Y_\beta = Y_\chi \cos \beta + Y_\psi \sin \beta, \quad (11)$$

whereas the charge operator takes the usual form $Q = T^3 + Y$. Within this framework, we can write the expressions for the low-energy effective Lagrangian and compute the corresponding corrections to the SM couplings.

1. Coherent elastic neutrino-nucleus scattering

In the context of the E_6 model, the new couplings read

$$\begin{aligned} f_u^L &= g_u^L + \epsilon_u^L, \\ f_d^L &= g_d^L + \epsilon_d^L, \\ f_u^R &= g_u^R + \epsilon_u^R, \\ f_d^R &= g_d^R + \epsilon_d^R, \end{aligned} \quad (12)$$

where the ϵ_q^p contributions are written as [65]

$$\begin{aligned} \epsilon_u^L &= -4\gamma \hat{s}_Z^2 \rho_{\nu N}^{NC} \left(\frac{c_\beta}{\sqrt{24}} - \frac{s_\beta}{3} \sqrt{\frac{5}{8}} \right) \left(\frac{3c_\beta}{2\sqrt{24}} + \frac{s_\beta}{6} \sqrt{\frac{5}{8}} \right), \\ \epsilon_d^R &= -8\gamma \hat{s}_Z^2 \rho_{\nu N}^{NC} \left(\frac{3c_\beta}{2\sqrt{24}} + \frac{s_\beta}{6} \sqrt{\frac{5}{8}} \right)^2, \\ \epsilon_d^L &= \epsilon_u^L = -\epsilon_u^R, \end{aligned} \quad (13)$$

with the abbreviations $c_\beta = \cos \beta$ and $s_\beta = \sin \beta$. Three different E_6 models are considered here, namely the

TABLE II. CE ν NS experiments and various setups considered in the present study.

Experiment	Detector	Mass	Threshold	Efficiency	Exposure	Baseline (m)
SNS						
COHERENT [24]	CsI[Na]	14.57 kg	5 keV	[66]	308.1 days	19.3
COHERENT [50]	HPGe	15 kg	5 keV	50%	1 yr	22
COHERENT [50]	LAr	1 ton	20 keV	[67]	1 yr	29
COHERENT [50]	NaI[Tl]	2 ton	13 keV	50%	1 yr	28
Reactor experiments						
CONUS [51]	Ge	3.85 kg	100 eV	50%	1 yr	17
CONNIE [52]	Si	1 kg	28 eV	50%	1 yr	30
MINER [53]	2Ge:1Si	1 kg	100 eV	50%	1 yr	2
TEXONO [54]	Ge	1 kg	100 eV	50%	1 yr	28
RED100 [55]	Xe	100 kg	500 eV	50%	1 yr	19
RICOCHEM [56]	(Zn, Ge)	(1 kg, 1 kg)	(50 eV, 50 eV)	50%	1 yr	100
NUCLEUS [57]	(CaWO ₄ , Al ₂ O ₃) (Ge, Si)	(4.41 gr, 6.84 gr) (0.5 kg, 0.5 kg)	20 eV 50 eV	50%	1 yr	100

(χ, ψ, η) models corresponding to $\cos\beta = (1, 0, \sqrt{3/8})$. Note that, for $\cos\beta = (-\sqrt{5/32}, 0)$, the new physics contributions vanish, and therefore, there is no sensitivity to Z' ; i.e., the ψ model can not be probed in CE ν NS studies.

2. Neutrino-electron scattering

For this case, the relevant couplings read

$$\begin{aligned} f_e^L &= g_e^L + \varepsilon_e^L, \\ f_e^R &= g_e^R + \varepsilon_e^R, \end{aligned} \quad (14)$$

with the new contributions written as

$$\begin{aligned} \varepsilon_e^L &= 2\gamma \hat{s}_Z^2 \rho_{\nu e} \left(\frac{3c_\beta}{2\sqrt{6}} + \frac{s_\beta}{3} \sqrt{\frac{5}{8}} \right)^2, \\ \varepsilon_e^R &= 2\gamma \hat{s}_Z^2 \rho_{\nu e} \left(\frac{c_\beta}{2\sqrt{6}} - \frac{s_\beta}{3} \sqrt{\frac{5}{8}} \right) \left(\frac{3c_\beta}{\sqrt{24}} + \frac{s_\beta}{3} \sqrt{\frac{5}{8}} \right), \end{aligned} \quad (15)$$

and γ defined as previously in the CE ν NS case. Here, it is interesting to note that, for $\cos\beta = -\sqrt{5/32}$, the coupling constants are equal to zero, so there is no sensitivity to new physics in this case [65].

III. EXPERIMENTAL SETUPS

We now examine a number of conceivable experimental setups that may be used to probe for the existence of new neutral gauge bosons. In particular, we consider CE ν NS experiments employing both SNS and reactor neutrinos with various possible targets, as well as a future $\nu_e - e^-$ scattering experiment using a ^{51}Cr source.

A. CE ν NS from accelerator and reactor neutrinos

For the case of CE ν NS experiments, the total number of events between the threshold T_{th} and the maximum nuclear

recoil energy allowed by the kinematics, $T_A^{\text{max}} = 2E_\nu^2/m_A$, can be expressed as [49]

$$\begin{aligned} N_{\text{theor}} &= \sum_{\nu_\alpha} \sum_{x=\text{isotope}} \mathcal{F}_x \int_{T_{\text{th}}}^{T_A^{\text{max}}} \int_{\sqrt{m_A T_A/2}}^{E_\nu^{\text{max}}} \lambda_{\nu_\alpha}(E_\nu) \mathcal{E}(T_A) \\ &\times \left(\frac{d\sigma_x}{dT_A}(E_\nu, T_A) \right)_{\text{tot}} dE_\nu dT_A. \end{aligned} \quad (16)$$

As indicated, the sum is taken over the detector isotopes, x , and the neutrino flavors, α . In this expression, $\mathcal{F}_x = N_{\text{targ}}^x \Phi_\nu$ denotes the corresponding luminosity on the detector. This depends on the neutrino flux at the detector, $\Phi_\nu(L)$, and the number of target nuclei, N_{targ}^x , (see Table II). The efficiency function $\mathcal{E}(T_A)$ for each given experiment is taken according to Table II as well.

For the pion decay at rest (π -DAR) neutrinos, relevant for the COHERENT experiment, the neutrino energy distributions are adequately described by the Michel spectrum [68],

$$\begin{aligned} \lambda_{\nu_\mu}(E_\nu) &= \delta\left(E_\nu - \frac{m_\pi^2 - m_\mu^2}{2m_\pi}\right), \\ \lambda_{\bar{\nu}_\mu}(E_\nu) &= \frac{64E_\nu^2}{m_\mu^3} \left(\frac{3}{4} - \frac{E_\nu}{m_\mu} \right), \\ \lambda_{\nu_e}(E_\nu) &= \frac{192E_\nu^2}{m_\mu^3} \left(\frac{1}{2} - \frac{E_\nu}{m_\mu} \right). \end{aligned} \quad (17)$$

For reactor-based neutrino experiments, we consider the corresponding antineutrino energy distribution $\lambda_{\bar{\nu}_e}(E_\nu)$ resulting from the fission products² of ^{235}U , ^{238}U , ^{239}Pu , and ^{241}Pu [69], while for $E_{\bar{\nu}_e} < 2$ MeV, we rely on the theoretical spectrum given in Ref. [70].

²Note that for the noncommercial reactor used by MINER, only the ^{235}U contribution is considered.

B. Neutrino-electron scattering from a ^{51}Cr source

Another experimental configuration that we have studied uses neutrinos from an artificial neutrino source, as suggested in [59].³ Following Ref. [61], we consider, for this case, a cylindrical LXe detector with height $h = 1.38$ m, diameter $d = 1.38$ m, located at $L = 1$ m above a 1 MCi radioactive ^{51}Cr source with a flux $\phi_0 = 2.94 \times 10^{15}$ ν / (MCi $\text{m}^2 \text{s}$). The emitted neutrino spectra consist of two monochromatic beams with energies $E_{\nu_1} = 430$ keV and $E_{\nu_2} = 750$ keV with a relative strength $\alpha_1 = 10\%$ and $\alpha_2 = 90\%$, respectively. Due to the exponentially decaying nature of the source within a time interval Δt , we take the time-averaged activity [61],

$$\langle R_{\text{Cr51}} \rangle = \frac{\tau R_{\text{Cr51}}^0}{\Delta t} [1 - e^{-\Delta t/\tau}], \quad (18)$$

where R_{Cr51}^0 denotes the initial radioactivity and $\tau = 39.96$ days is the mean lifetime of ^{51}Cr . The number of neutrino-electron scattering events within a bin i with recoil energy in the range $[T_{e,i}, T_{e,i} + \delta T_e]$ and maximum recoil energy $T_e^{\text{max}} = 2E_\nu^2 / (2E_\nu + m_e)$ is given by

$$N_{\text{events}}^i = \mathcal{F} \int_{T_{e,i}}^{T_{e,i} + \delta T_e} \left[\alpha_1 \frac{d\sigma}{dT_e}(E_{\nu_1}, T_e) + \alpha_2 \frac{d\sigma}{dT_e}(E_{\nu_2}, T_e) \right] dT_e, \quad (19)$$

with $\mathcal{F} = \Phi_{\text{avg}}^{51\text{Cr}} V n_e \Delta t$. Here, V represents the detector fiducial volume, n_e is the electron density of the target material, while the factor $\Phi_{\text{avg}}^{51\text{Cr}} = \phi_0 \frac{1 \text{ m}^2}{r_{\text{avg}}^2} \langle R_{\text{Cr51}} \rangle$ represents the average neutrino flux. Finally, due to its cylindrical geometry, the average distance r_{avg} between the source and the detector is written as [72]

$$r_{\text{avg}} = \left[\frac{4L}{d^2 h} \log \frac{L^2(d^2 + 4(h+L)^2)}{(d^2 + 4L^2)(h+L)^2} + \frac{4}{d^2} \log \frac{d^2 + 4(h+L)^2}{4(h+L)^2} - \frac{4}{dh} \tan^{-1} \left(\frac{2L}{d} \right) + \frac{4}{dh} \tan^{-1} \left(\frac{2(h+L)}{d} \right) \right]^{-1/2}. \quad (20)$$

As a test case, in our calculations, we assume the three configurations assumed in Ref. [72], (A, B, C): with $R_{\text{Cr51}}^0 = (5, 5, 10)$ MCi ^{51}Cr and a time interval $\Delta t = (100, 50, 50)$ days, respectively.

³For a study focusing on $\bar{\nu}_e - e^-$ scattering at the TEXONO experiment, see Ref. [71].

IV. NUMERICAL RESULTS

We now perform a statistical analysis of the different experimental configurations discussed in the previous sections. Our present study is based on a χ^2 fit of the measured (COHERENT with CsI detector) or expected (other CE ν NS experiments) number of events. We minimize over the nuisance parameters and probe the Z' mass by computing $\Delta\chi^2(\mathcal{S}) = \chi^2(\mathcal{S}) - \chi_{\text{min}}^2(\mathcal{S})$ with $\mathcal{S} \equiv \{M_{Z'}, \beta\}$. Our statistical analysis of the COHERENT data relies on the χ^2 function [24],

$$\chi^2(\mathcal{S}) = \min_{\bar{a}_1, \bar{a}_2} \left[\frac{(N_{\text{meas}} - N_{\text{theor}}(\mathcal{S})[1 + \bar{a}_1] - B_{0n}[1 + \bar{a}_2])^2}{(\sigma_{\text{stat}})^2} + \left(\frac{\bar{a}_1}{\sigma_{\bar{a}_1}} \right)^2 + \left(\frac{\bar{a}_2}{\sigma_{\bar{a}_2}} \right)^2 \right], \quad (21)$$

with $N_{\text{meas}} = 142$ (measured number of events), $\sigma_{\bar{a}_1} = 0.28$ (normalization uncertainty on the signal events), and $\sigma_{\bar{a}_2} = 0.25$ (normalization uncertainty on the background events). N_{theor} denotes the calculated number of events in the left-right or E_6 model. The statistical uncertainty is calculated as $\sigma_{\text{stat}} = \sqrt{N_{\text{meas}} + B_{0n} + 2B_{ss}}$ with $B_{0n} = 6$ and $B_{ss} = 405$ being the prompt-neutron and steady-state background events, respectively (see Refs. [24,66] for more details).

For the analysis of future CE ν NS data expected at the Ge, LAr and NaI detector subsystems at COHERENT, as well as at the different reactor-based experiments, we consider a single nuisance parameter a and assign conservative values for the systematic uncertainty, namely $\sigma_{\text{sys}} = 0.2$. Although quite simplified, we think this analysis is justified at present. The χ^2 function in this case reads

$$\chi^2(\mathcal{S}) = \min_a \left[\frac{(N_{\text{SM}} - N_{\text{theor}}(\mathcal{S})[1 + a])^2}{(\sigma_{\text{stat}})^2} + \left(\frac{a}{\sigma_{\text{sys}}} \right)^2 \right], \quad (22)$$

where N_{SM} represents the number of events assuming purely Standard Model interactions and, as previously, N_{theor} is the calculated number of events in the presence of LR and E_6 interactions, while the estimated statistical uncertainty is taken to be $\sigma_{\text{stat}} = \sqrt{N_{\text{SM}} + N_{\text{bg}}}$. We assume a flat steady-state background $N_{\text{bg}} = \sigma_{\text{bg}} N_{\text{SM}}$, with $\sigma_{\text{bg}} = 0.2$. It should be noted that, for the CONUS experiment, a realistic background level of 1–3 cpd has been previously assumed [73] while, for the case of Ricochet, a likelihood analysis with a binned uncertainty following a Poisson distribution has been considered in Ref. [56]. For other reactor-based experiments, background-related information is given in Ref. [74].

As a first step, we obtain the sensitivity on $M_{Z'}$ in the framework of the LR-symmetric model from the available data of COHERENT in terms of a χ^2 fit as described above.

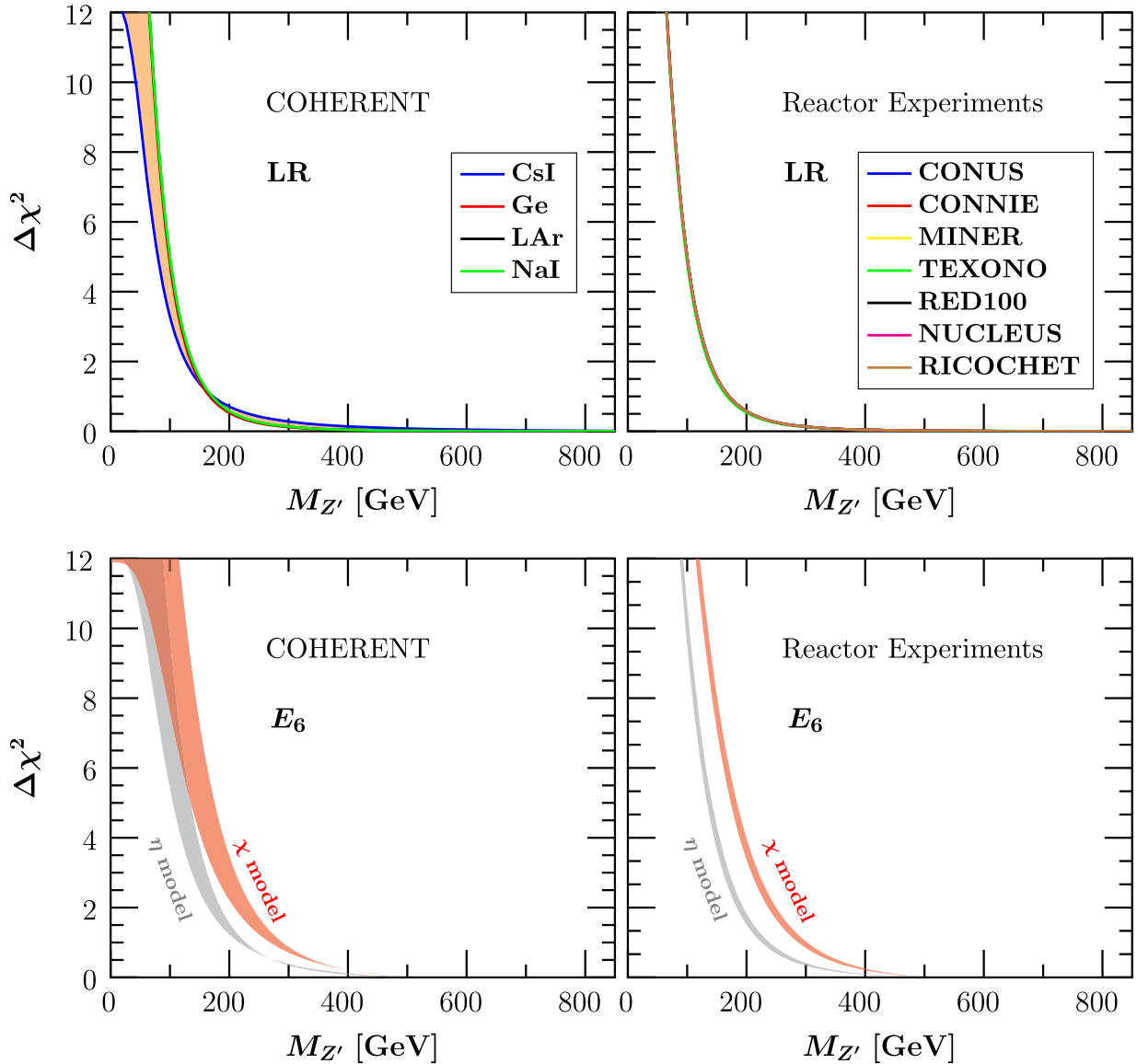


FIG. 1. $\Delta\chi^2$ profiles for the Z' mass in the left-right-symmetric model (upper panel) and E_6 models (lower panel). The results correspond to $\text{CE}\nu\text{NS}$ at the SNS (left) and at reactor-based experiments (right). For the case of E_6 models the red (gray) band corresponds to the sensitivity on $M_{Z'}$ in the χ (η) model.

In a similar manner, we estimate the projected sensitivities at the future SNS and reactor experiments looking for $\text{CE}\nu\text{NS}$ events. The results are presented in the upper-left (upper-right) panel of Fig. 1 for the case of SNS (reactor) experiments. From this analysis, it becomes evident that for all the setups, the sensitivities are rather poor compared to current bounds from the LHC [6]; i.e., we find that $M_{Z'} \gtrsim 125$ GeV at 90% C.L.

We now turn to the Z' models obtained in the context of E_6 symmetry. In particular, we explore the corresponding sensitivity on $M_{Z'}$ in the (χ, ψ, η) realizations of E_6 by fixing $\cos\beta = (1, 0, \sqrt{3}/8)$. For each model, we extract the sensitivity on $M_{Z'}$ assuming the available $\text{CE}\nu\text{NS}$ data as well as the data expected in the future. The results obtained

are presented in the lower panel of Fig. 1, where the red (gray) band corresponds to the χ (η) model. Note that in comparison with the upper plots in Fig. 1, here the color labels corresponding to each experiment are dropped. The band width illustrates the sensitivity range considering all the experiments: for the COHERENT experiment, the least (most) constraining detector is the CsI (NaI), as can be seen in the upper panel of Fig. 1, while for reactor-based facilities, one finds that essentially all experiments have the same sensitivity. In both cases, the sensitivity to the Z' mass at 90% C.L. is slightly below (above) 200 GeV for the η (χ) model. A summary of the obtained limits at 90% C.L. is listed in Table III. Notice that $\text{CE}\nu\text{NS}$ is not sensitive to the ψ model, since the $\epsilon_p^V = 2\epsilon_u^V + \epsilon_d^V$ and $\epsilon_n^V = \epsilon_u^V + 2\epsilon_d^V$

TABLE III. Sensitivity at 90% C.L. on the Z' mass for all experimental configurations assumed in the present study (see Table II and the text). The values of the reported limits are given in GeV units. We also present results for the proposed ^{51}Cr -LXe experiment, corresponding to the scenarios (A, B, C).

Model	COHERENT				Reactor experiments							$\nu_e - e^-$
	CsI	LAr	Ge	NaI	CONUS	CONNIE	MINER	TEXONO	RED100	NUCLEUS	RICOCHET	^{51}Cr -LXe
χ	183	220	215	217	218	228	223	215	215	222	221	(510, 481, 564)
η	144	170	166	168	169	177	173	167	166	172	171	(487, 459, 540)
ψ	...	...	...	...	...	...	...	...	...	...	...	(224, 211, 250)
LR	110	124	122	125	125	125	124	123	125	125	125	(483, 455, 534)

couplings⁴ are vanishing; see Eq. (13). Before closing this discussion, we should note that some of our results could, in principle, be extracted by remapping the NSI bounds derived from the current and future CE ν NS data [35,41,49]. However, the importance of probing for new neutral gauge bosons more than justifies a dedicated study.

A. Improving the sensitivities on the Z' mass with future CE ν NS experiments

We now explore to what extent the control of uncertainties will offer improved sensitivities on the vector mediator mass. Note that the quenching factor uncertainty is nuclear isotope dependent. For example, the current uncertainty on CsI is 18.9% [24], while for LAr, it is 2% [67]. Hence, after considering the uncertainties on the flux (10%), the form factor (5%), and the acceptance function (5%), the corresponding total systematic uncertainties for CsI and LAr experiments read 28% and 12.4%, respectively. The latter indicates that our earlier assumption of $\sigma_{\text{sys}} = 20\%$ might not be always accurate. To this purpose, we perform a χ^2 analysis assuming different values for the systematic uncertainty σ_{sys} , while keeping all other detector specifications fixed according to Table II. Reducing the systematic uncertainty is not unreasonable by combining improved quenching factor measurements with a better understanding of the nuclear form factors and neutrino fluxes, as well as from the expected substantial improvements on detector technologies aimed at the future CE ν NS experiments. Our results are presented in the upper and lower panel of Fig. 2 for the LR symmetric and E_6 models, respectively. As shown previously, the left and right panels show the sensitivities of SNS and reactor CE ν NS experiments. Focusing on the LR symmetric model, it can be seen that, for very low uncertainty, the LAr and NaI detectors perform better while, for larger uncertainty, the CsI detector is optimal. Similarly, for the case of reactor-based CE ν NS experiments, the xenon-based RED100 (Ge-based TEXONO) appears to have the best (worst) performance. The same conclusions are drawn for the case of E_6 models where, for convenience, only the bands are displayed. In both cases, one sees the improvement with respect to Fig. 1.

⁴Note that $\varepsilon_q^V = \varepsilon_q^L + \varepsilon_q^R$ with $q = \{u, d\}$.

At this point, we turn to the impact of neutrino luminosities on improving the attainable sensitivities on the Z' mass at future CE ν NS experiments. We do this by scaling up the number of events, assuming a correspondingly larger detector mass and running period. This information is encoded in the future detector luminosity factor, that we denote here as \mathcal{F}' . We have checked that, with the chosen values of statistical and systematic uncertainties [see Eq. (22)], the sensitivity shown in Fig. 1 remains practically unaffected by an increase in the exposure. Indeed, the sensitivity on the Z' mass is dominated by the systematic uncertainty at all experiments. Figure 3 illustrates the projected sensitivity on $M_{Z'}$ at 90% C.L. as a function of the ratio \mathcal{F}'/\mathcal{F} , where \mathcal{F} corresponds to the current or proposed luminosity of each experiment in Table II and $\sigma_{\text{sys}} = 5\%$. This level of systematic uncertainty can only be reached through a substantial improvement on the quenching factor uncertainty, an improved determination of the nuclear form factors, and a better understanding of the neutrino energy distribution. We therefore conclude that higher intensity CE ν NS experiments will offer only slightly improved results with respect to those expected from the current experimental setups. Moreover, one sees that the expected sensitivity for the χ model is better than that expected in the η or LR symmetric models.

B. Improved Z' sensitivities with future neutrino-electron scattering experiments

We now expand our analysis by including also information coming from neutrino-electron scattering, which involves both neutral and charged currents. As a concrete example, we focus on new interesting proposals that aim to measure neutrino-electron scattering events by employing a LXe detector exposed to neutrino emissions from a radioactive ^{51}Cr source [61]. Our statistical analysis in this case is based on the χ^2 function,

$$\chi^2 = \sum_i \left(\frac{N_{\text{SM}}^i - N_{\text{th}}^i}{\delta N_{\text{SM}}^i} \right)^2, \quad (23)$$

with $\delta N_{\text{SM}}^i = \sqrt{N_{\text{SM}}^i}$. Since we are dealing with a large number of events, here we have binned the sample with

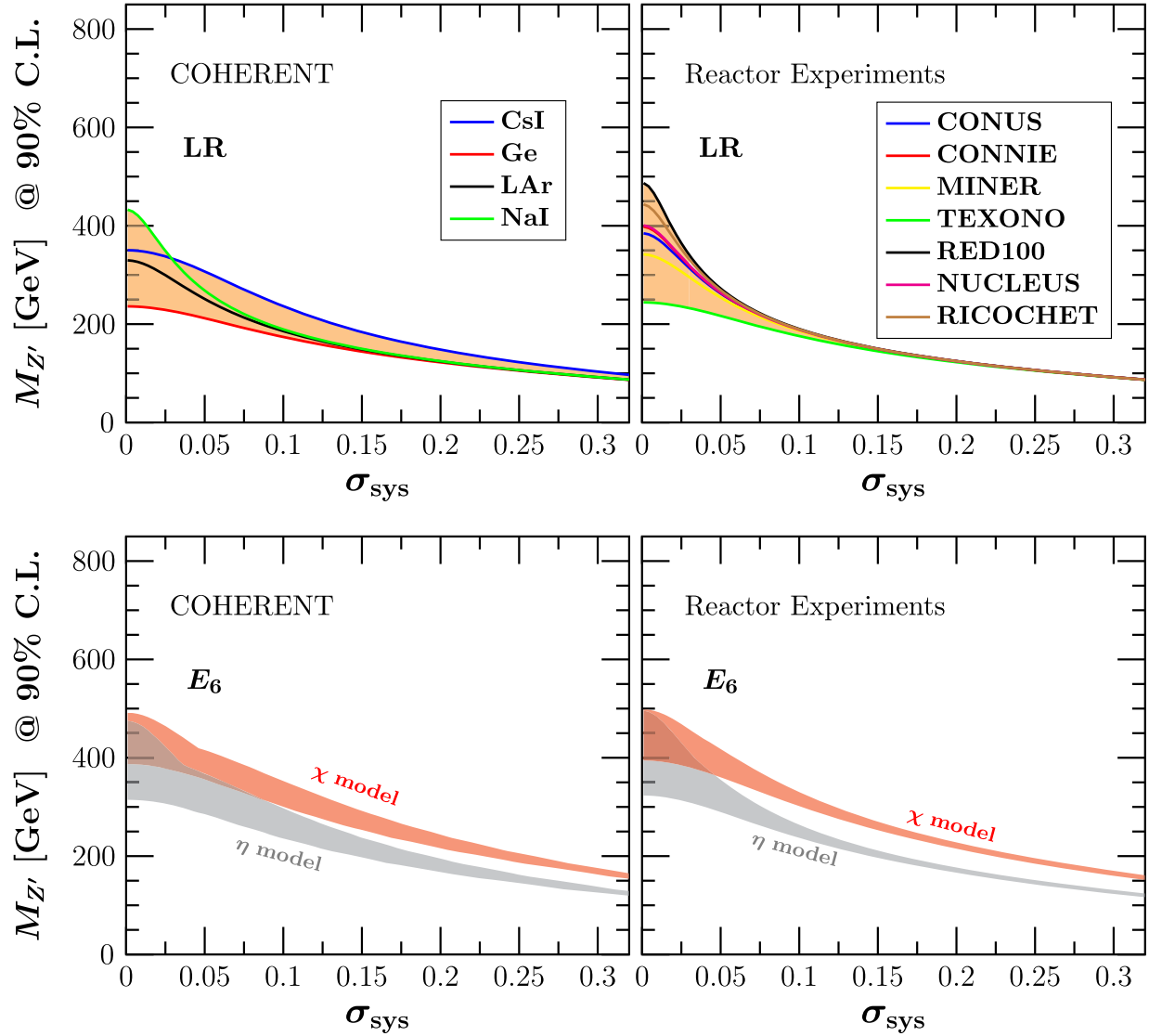


FIG. 2. 90% C.L. sensitivity on the Z' mass as a function of the systematic uncertainty σ_{sys} . The analysis assumes CE ν NS experiments at the SNS (left) and at reactor facilities (right). The upper (lower) panel shows the results for the left-right symmetric (E_6) model.

$\delta T_e = 5$ keV, assuming 120 bins in the range $[0, T_e^{\text{max}}]$. The sensitivities on $M_{Z'}$ for the LR symmetric and E_6 models is shown in the left and right panel of Fig. 4, respectively. As previously, the χ model (dashed lines) is more sensitive to $M_{Z'}$ compared to the η model (solid lines), while the ψ model (dotted lines) is the least sensitive. Our results indicate that neutrino-electron scattering within 50–100 days will reach a sensitivity of the order of 200–600 GeV, i.e., more competitive with respect to the one extracted from the purely neutral-current CE ν NS.

We can obtain the sensitivity contours in the $(\cos \beta, M_{Z'})$ plane, where β is the parameter defining a one-parameter family of E_6 theories, as shown in Fig. 5. The left panel illustrates the allowed regions obtained from CE ν NS at the SNS and at reactor experiments, indicated by the shaded blue and green bands, respectively. The right panel shows

the corresponding regions from a neutrino-electron scattering experiment using a ^{51}Cr source, for the different configurations assumed (A, B, and C). The following conclusions can be extracted from the figure: concerning CE ν NS, the SNS facilities are less sensitive compared to the reactor-based ones, while neutrino-electron scattering at LXe with a ^{51}Cr source is the optimum choice, since it can exclude a larger region of the parameter space. Notice as well the presence of two special β values for which CE ν NS experiments have no sensitivity to $M_{Z'}$, since the Z' couplings vanish in this case. Likewise, one sees that neutrino-electron scattering presents only one such special β value with no Z' sensitivity. These results are in agreement with our discussion in Sec. II B.

One sees that the potential for probing a new Z' mediator from low-energy measurements of neutrino-electron

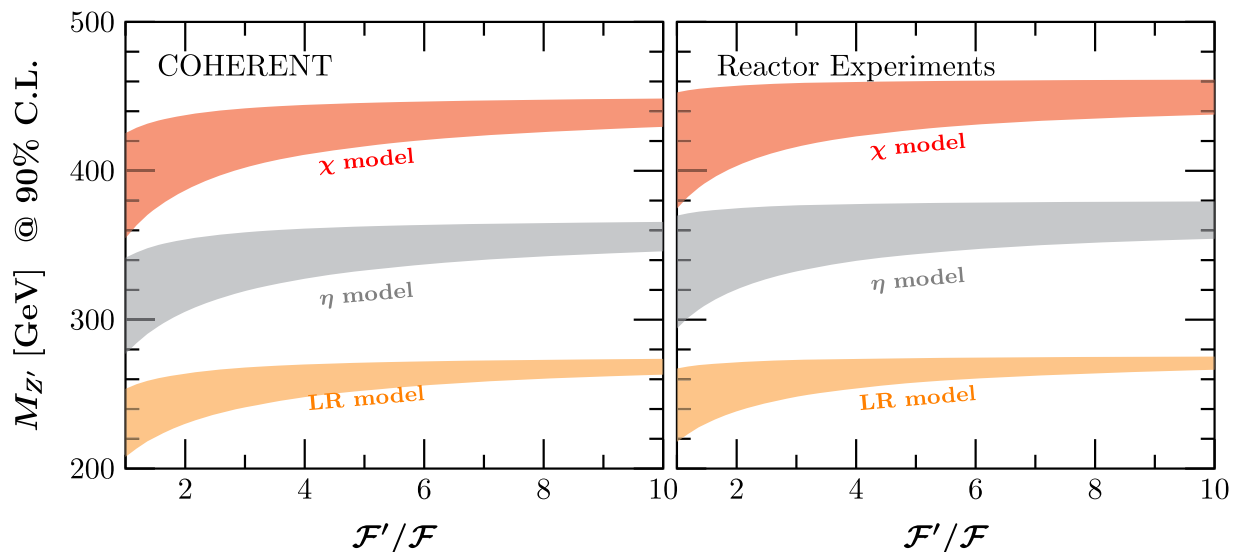


FIG. 3. 90% C.L. sensitivity on the Z' mass as a function of the total luminosity at a given detector. The results for the E_6 and LR symmetric models are shown for the case of CE ν NS experiments at the SNS (left) and at reactor facilities (right).

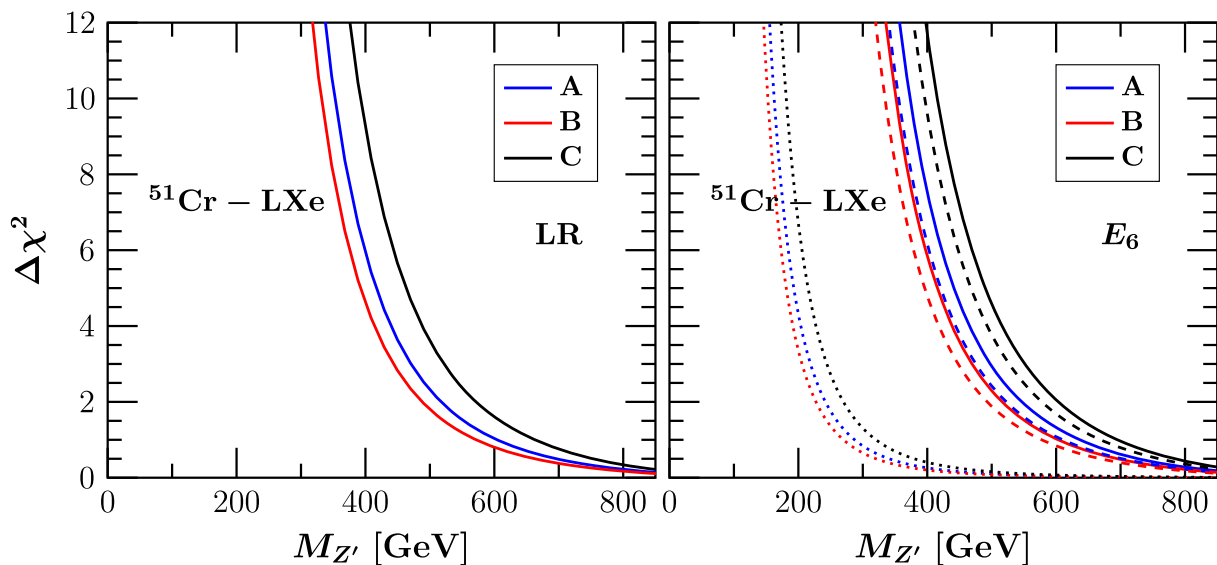


FIG. 4. Same as Fig. 1 but from the analysis of neutrino-electron scattering using a ^{51}Cr source. The left panel shows the results for left-right symmetric models. In the right panel, corresponding to E_6 models, the solid (dashed) [dotted] curves correspond to the χ (η) [ψ] model. The different lines A, B, and C correspond to different assumptions for the activity of the source and the exposure, see the text for details.

scattering or CE ν NS seems to lie well below the sensitivity reached by direct searches at the LHC; i.e., the search for high-mass dilepton resonances produced *a la* Drell-Yan [6]. However, our analysis has been very conservative, as it relies only on the proposed experimental configurations of the first generation of CE ν NS experiments. Moreover, we have presented the sensitivity range expected from the various experiments of each type, considering one experiment at a time.

C. Combined expected sensitivities on the Z' mass

So far our strategy has been to explore the potential in probing Z' physics within a given low-energy experiment. However, one may explore the phenomenological potential of high intensity low-energy experiments by performing a combined analysis of CE ν NS and $\nu_e - e^-$ scattering experiments. Due to the lack of experimental data, however, only the COHERENT-CsI, CONNIE, and ^{51}Cr -LXe experiments are taken into account. While considering only

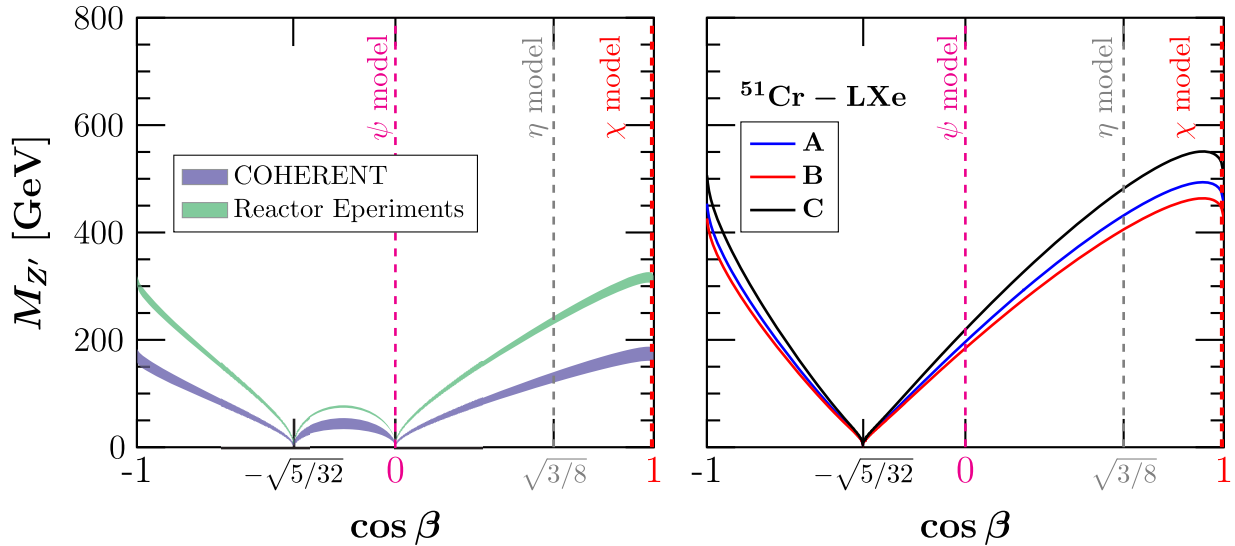


FIG. 5. 90% C.L. allowed regions in the $(\cos \beta - M_{Z'})$ plane for CE ν NS (left) and neutrino-electron scattering (right) experiments.

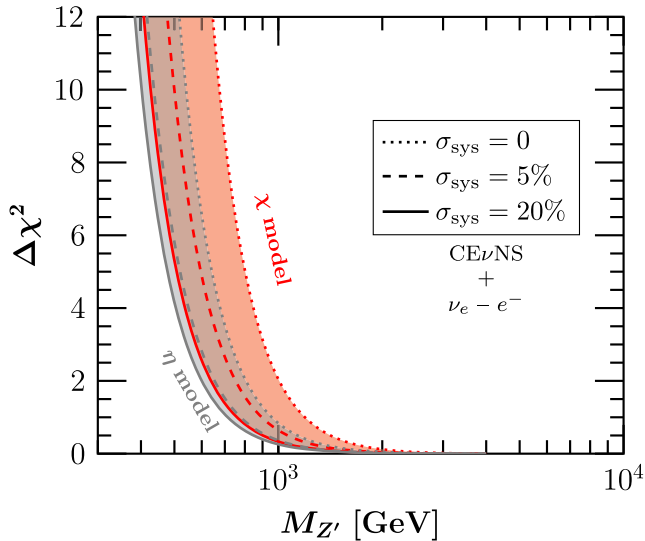


FIG. 6. Projected sensitivity for the χ and η models of E_6 from a future combined analysis of CE ν NS and neutrino-electron scattering data (see text).

three experiments for this particular analysis, we however note that different neutrino sources and detector materials are assumed, minimizing the impact of correlation effects of the present analysis. The corresponding results are illustrated in Fig. 6 for the χ and η models of E_6 , assuming different choices of systematic uncertainties ranging from 20% to zero. Notice that different experimental uncertainties are assumed for the case of CE ν NS experiments, while for neutrino-electron scattering, the C configuration is assumed. As before, one can also present the sensitivities to the various gauge bosons of E_6 models associated to different values of β . One sees that future neutrino-electron scattering and high-intensity CE ν NS data with a better

control of uncertainties have promising prospects for reaching few TeV scale. This is the scale currently probed at the high energy frontier experiments, such as the LHC.⁵ It follows that low-energy measurements may offer new probes of Z' parameters, complementary to the high-energy frontier approach.

V. CONCLUSIONS AND OUTLOOK

In this work, we have quantified the attainable sensitivities on extra neutral gauge bosons Z' that can be reached at high-intensity, low-energy facilities. We focused on existing and next generation coherent-elastic neutrino-nucleus scattering (CE ν NS) as well as neutrino-electron scattering experiments. As neutrino sources, we have discussed the spallation neutron source as well as reactor neutrinos and neutrinos from radioactive sources. We have concentrated on compelling models that predict the existence of a new neutral vector boson mediator, such as string-inspired E_6 schemes and models with left-right symmetry. The Z' contributions to the CE ν NS and neutrino-electron scattering in this class of theories were studied. Current Z' limits are obtained from Fig. 1 and given in Table III. Future Z' sensitivities from individual CE ν NS at SNS and reactor experiments are given in Figs. 2 and 3. A comparison with the expected sensitivity from a future neutrino-electron scattering using a ^{51}Cr source and a ton-scale liquid xenon detector is also given in Fig. 4. Expected sensitivities for an arbitrary E_6 model are presented in Fig. 5. Finally, combined global sensitivities were presented in Fig. 6. The high-intensity, low-energy approach is not only complementary to the high-energy frontier

⁵Notice that LHC constraints usually assume the Z' to have SM-strength couplings and should be adequately rescaled as a function of β .

measurements at colliders, but could also become competitive in the long run, as shown in Fig. 6.

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- [1] M. Tanabashi *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **98**, 030001 (2018).
- [2] J. Schechter and J. W. F. Valle, Neutrino masses in $SU(2) \times U(1)$ theories, *Phys. Rev. D* **22**, 2227 (1980).
- [3] J. Schechter and J. W. F. Valle, Neutrino decay and spontaneous violation of Lepton number, *Phys. Rev. D* **25**, 774 (1982).
- [4] R. N. Mohapatra and G. Senjanovic, Neutrino masses and mixings in gauge models with spontaneous parity violation, *Phys. Rev. D* **23**, 165 (1981).
- [5] M. Gell-Mann, P. Ramond, and R. Slansky, Complex Spinors Unified Theories **C790927**, 315 (1979).
- [6] G. Aad *et al.* (ATLAS Collaboration), Search for high-mass dilepton resonances using 139 fb^{-1} of pp collision data collected at $\sqrt{s} = 13 \text{ TeV}$ with the ATLAS detector, *Phys. Lett. B* **796**, 68 (2019).
- [7] M. Gonzalez-Garcia and J. W. F. Valle, Updated constraints on a new neutral gauge Boson, *Nucl. Phys.* **B345**, 312 (1990).
- [8] M. Gonzalez-Garcia and J. W. F. Valle, Neutral current and LEP constraints on an extra $E(6)$ neutral gauge boson: A Global fit to electroweak parameters, *Phys. Lett. B* **259**, 365 (1991).
- [9] P. Langacker, The Physics of heavy Z' gauge Bosons, *Rev. Mod. Phys.* **81**, 1199 (2009).
- [10] S. Das, F. F. Deppisch, O. Kittel, and J. W. F. Valle, Heavy neutrinos and Lepton flavour violation in left-right symmetric models at the LHC, *Phys. Rev. D* **86**, 055006 (2012).
- [11] F. F. Deppisch, N. Desai, and J. W. F. Valle, Is charged lepton flavor violation a high energy phenomenon?, *Phys. Rev. D* **89**, 051302 (2014).
- [12] O. G. Miranda, V. Semikoz, and J. W. F. Valle, Neutrino electron scattering and electroweak gauge structure: Tests, *Phys. Rev. D* **58**, 013007 (1998).
- [13] E. Garces, O. G. Miranda, M. Tortola, and J. W. F. Valle, Low-energy neutrino-electron scattering as a Standard Model probe: The potential of LENA as case study, *Phys. Rev. D* **85**, 073006 (2012).
- [14] J. C. Pati and A. Salam, Lepton number as the fourth color, *Phys. Rev. D* **10**, 275 (1974).
- [15] R. N. Mohapatra and R. Marshak, Local B-L Symmetry of Electroweak Interactions, Majorana Neutrinos and Neutron Oscillations, *Phys. Rev. Lett.* **44**, 1316 (1980).
- [16] M. Singer, J. W. F. Valle, and J. Schechter, Canonical neutral current predictions from the weak electromagnetic gauge group $SU(3) \times U(1)$, *Phys. Rev. D* **22**, 738 (1980).
- [17] C. Hati, S. Patra, M. Reig, J. W. F. Valle, and C. A. Vaquera-Araujo, Towards gauge coupling unification in left-right symmetric $SU(3)_c \times SU(3)_L \times SU(3)_R \times U(1)_X$ theories, *Phys. Rev. D* **96**, 015004 (2017).
- [18] E. K. Akhmedov, M. Lindner, E. Schnapka, and J. W. F. Valle, Dynamical left-right symmetry breaking, *Phys. Rev. D* **53**, 2752 (1996).
- [19] E. K. Akhmedov, M. Lindner, E. Schnapka, and J. W. F. Valle, Left-right symmetry breaking in NJL approach, *Phys. Lett. B* **368**, 270 (1996).
- [20] C. T. Hill and E. H. Simmons, Strong dynamics and electroweak symmetry breaking, *Phys. Rep.* **381**, 235 (2003).
- [21] M. Cvetič and P. Langacker, Implications of Abelian extended gauge structures from string models, *Phys. Rev. D* **54**, 3570 (1996).
- [22] M. Reig, J. W. F. Valle, C. Vaquera-Araujo, and F. Wilczek, A model of comprehensive unification, *Phys. Lett. B* **774**, 667 (2017).
- [23] M. Malinsky, J. Romao, and J. W. F. Valle, Novel Supersymmetric $SO(10)$ Seesaw Mechanism, *Phys. Rev. Lett.* **95**, 161801 (2005).
- [24] D. Akimov *et al.* (COHERENT Collaboration), Observation of coherent elastic neutrino-nucleus scattering, *Science* **357**, 1123 (2017).
- [25] D. Papoulias, T. Kosmas, and Y. Kuno, Recent probes of standard and non-standard neutrino physics with nuclei, *Front. Phys.* **7**, 191 (2019).
- [26] J. Liao and D. Marfatia, COHERENT constraints on nonstandard neutrino interactions, *Phys. Lett. B* **775**, 54 (2017).
- [27] C. Giunti, General COHERENT constraints on neutrino nonstandard interactions, *Phys. Rev. D* **101**, 035039 (2020).
- [28] P. Coloma, I. Esteban, M. Gonzalez-Garcia, and M. Maltoni, Improved global fit to non-Standard neutrino interactions using COHERENT energy and timing data, *J. High Energy Phys.* **02** (2020) 023.
- [29] D. Aristizabal Sierra, V. De Romeri, and N. Rojas, COHERENT analysis of neutrino generalized interactions, *Phys. Rev. D* **98**, 075018 (2018).
- [30] M. Cadeddu, C. Giunti, Y. Li, and Y. Zhang, Average CsI Neutron Density Distribution from COHERENT Data, *Phys. Rev. Lett.* **120**, 072501 (2018).
- [31] D. Papoulias, T. Kosmas, R. Sahu, V. Kota, and M. Hota, Constraining nuclear physics parameters with current and future COHERENT data, *Phys. Lett. B* **800**, 135133 (2020).
- [32] B. Canas, E. Garces, O. G. Miranda, A. Parada, and G. S. Garcia, Interplay between nonstandard and nuclear

- constraints in coherent elastic neutrino-nucleus scattering experiments, *Phys. Rev. D* **101**, 035012 (2020).
- [33] M. Cadeddu, C. Giunti, K. Kouzakov, Y. Li, A. Studenikin, and Y. Zhang, Neutrino charge radii from COHERENT elastic neutrino-nucleus scattering, *Phys. Rev. D* **98**, 113010 (2018).
- [34] O. G. Miranda, D. Papoulias, M. Tórtola, and J. W. F. Valle, Probing neutrino transition magnetic moments with coherent elastic neutrino-nucleus scattering, *J. High Energy Phys.* **07** (2019) 103.
- [35] O. G. Miranda, G. Sanchez Garcia, and O. Sanders, Coherent elastic neutrino-nucleus scattering as a precision test for the Standard Model and beyond: The COHERENT proposal case, *Adv. High Energy Phys.* **2019**, 3902819 (2019).
- [36] C. Blanco, D. Hooper, and P. Machado, Constraining sterile neutrino interpretations of the LSND and MiniBooNE anomalies with coherent neutrino scattering experiments, [arXiv:1901.08094](https://arxiv.org/abs/1901.08094).
- [37] J. M. Berryman, Constraining sterile neutrino cosmology with terrestrial oscillation experiments, *Phys. Rev. D* **100**, 023540 (2019).
- [38] S.-F. Ge and I. M. Shoemaker, Constraining photon portal dark matter with Texono and coherent data, *J. High Energy Phys.* **11** (2018) 066.
- [39] B. Dutta, R. Mahapatra, L. E. Strigari, and J. W. Walker, Sensitivity to Z -prime and nonstandard neutrino interactions from ultralow threshold neutrino-nucleus coherent scattering, *Phys. Rev. D* **93**, 013015 (2016).
- [40] J. B. Dent, B. Dutta, S. Liao, J. L. Newstead, L. E. Strigari, and J. W. Walker, Probing light mediators at ultralow threshold energies with coherent elastic neutrino-nucleus scattering, *Phys. Rev. D* **96**, 095007 (2017).
- [41] J. Billard, J. Johnston, and B. J. Kavanagh, Prospects for exploring new physics in coherent elastic neutrino-nucleus scattering, *J. Cosmol. Astrophys. Phys.* **11** (2018) 016.
- [42] A. Datta, B. Dutta, S. Liao, D. Marfatia, and L. E. Strigari, Neutrino scattering and B anomalies from hidden sector portals, *J. High Energy Phys.* **01** (2019) 091.
- [43] P. B. Denton, Y. Farzan, and I. M. Shoemaker, Testing large non-standard neutrino interactions with arbitrary mediator mass after COHERENT data, *J. High Energy Phys.* **07** (2018) 037.
- [44] Y. Farzan, M. Lindner, W. Rodejohann, and X.-J. Xu, Probing neutrino coupling to a light scalar with coherent neutrino scattering, *J. High Energy Phys.* **05** (2018) 066.
- [45] D. A. Sierra, V. De Romeri, and N. Rojas, CP violating effects in coherent elastic neutrino-nucleus scattering processes, *J. High Energy Phys.* **09** (2019) 069.
- [46] B. Dutta, S. Liao, S. Sinha, and L. E. Strigari, Searching for Beyond the Standard Model Physics with COHERENT Energy and Timing Data, *Phys. Rev. Lett.* **123**, 061801 (2019).
- [47] D. A. Sierra, B. Dutta, S. Liao, and L. E. Strigari, Coherent elastic neutrino-nucleus scattering in multi-ton scale dark matter experiments: Classification of vector and scalar interactions new physics signals, *J. High Energy Phys.* **12** (2019) 124.
- [48] G. Arcadi, M. Lindner, J. Martins, and F. S. Queiroz, New physics probes: Atomic parity violation, polarized electron scattering and neutrino-nucleus coherent scattering, [arXiv:1906.04755](https://arxiv.org/abs/1906.04755).
- [49] D. Papoulias and T. Kosmas, COHERENT constraints to conventional and exotic neutrino physics, *Phys. Rev. D* **97**, 033003 (2018).
- [50] D. Akimov *et al.* (COHERENT Collaboration), COHERENT 2018 at the spallation neutron source, [arXiv:1803.09183](https://arxiv.org/abs/1803.09183).
- [51] J. Hakenmüller *et al.*, Neutron-induced background in the CONUS experiment, *Eur. Phys. J. C* **79**, 699 (2019).
- [52] A. Aguilar-Arevalo *et al.* (CONNIE Collaboration), Exploring low-energy neutrino physics with the coherent neutrino nucleus interaction experiment, *Phys. Rev. D* **100**, 092005 (2019).
- [53] G. Agnolet *et al.* (MINER Collaboration), Background Studies for the MINER coherent neutrino scattering reactor experiment, *Nucl. Instrum. Methods Phys. Res., Sect. A* **853**, 53 (2017).
- [54] H. T. Wong, Neutrino-nucleus coherent scattering and dark matter searches with sub-keV germanium detector, *Nucl. Phys.* **A844**, 229C (2010).
- [55] D. Akimov *et al.*, RED-100 detector for the first observation of the elastic coherent neutrino scattering off xenon nuclei, *J. Phys. Conf. Ser.* **675**, 012016 (2016).
- [56] J. Billard *et al.*, Coherent neutrino scattering with low temperature bolometers at Chooz reactor complex, *J. Phys. G* **44**, 105101 (2017).
- [57] G. Angloher *et al.* (NUCLEUS Collaboration), Exploring $CE\nu NS$ with NUCLEUS at the Chooz nuclear power plant, *Eur. Phys. J. C* **79**, 1018 (2019).
- [58] M. Lindner, F. S. Queiroz, W. Rodejohann, and X.-J. Xu, Neutrino-electron scattering: General constraints on Z' and dark photon models, *J. High Energy Phys.* **05** (2018) 098.
- [59] I. Barabanov, P. Belli, R. Bernabei, V. I. Gurentsov, V. N. Kornoukhov, O. G. Miranda, V. B. Semikoz, and J. W. F. Valle, Testing for new physics with low-energy anti-neutrino sources: LAMA as a case study, *Nucl. Phys.* **B546**, 19 (1999).
- [60] C. Bellenghi, D. Chiesa, L. Di Noto, M. Pallavicini, E. Previtali, and M. Vignati, Coherent elastic nuclear scattering of ^{51}Cr neutrinos, *Eur. Phys. J. C* **79**, 727 (2019).
- [61] P. Coloma, P. Huber, and J. M. Link, Combining dark matter detectors and electron-capture sources to hunt for new physics in the neutrino sector, *J. High Energy Phys.* **11** (2014) 042.
- [62] J. Barranco, O. G. Miranda, and T. Rashba, Probing new physics with coherent neutrino scattering off nuclei, *J. High Energy Phys.* **12** (2005) 021.
- [63] D. W. L. Sprung and J. Martorell, The symmetrized Fermi function and its transforms, *J. Phys. A* **30**, 6525 (1997).
- [64] J. Polak and M. Zralek, Updated constraints on the neutral current parameters in left-right symmetric model, *Nucl. Phys.* **B363**, 385 (1991).
- [65] J. Barranco, O. G. Miranda, and T. Rashba, Low energy neutrino experiments sensitivity to physics beyond the Standard Model, *Phys. Rev. D* **76**, 073008 (2007).

- [66] D. Akimov *et al.* (COHERENT Collaboration), COHERENT Collaboration data release from the first observation of coherent elastic neutrino-nucleus scattering, <https://dx.doi.org/10.5281/zenodo.1228631>.
- [67] D. Akimov *et al.* (COHERENT Collaboration), First constraint on coherent elastic neutrino-nucleus scattering in argon, *Phys. Rev. D* **100**, 115020 (2019).
- [68] W. Louis, Searches for muon-to-electron (anti) neutrino flavor change, *Prog. Part. Nucl. Phys.* **63**, 51 (2009).
- [69] G. Mention, M. Fechner, Th. Lasserre, Th. A. Mueller, D. Lhuillier, M. Cribier, and A. Letourneau, The reactor antineutrino anomaly, *Phys. Rev. D* **83**, 073006 (2011).
- [70] V. Kopeikin, L. Mikaelyan, and V. Sinev, Spectrum of electronic reactor anti-neutrinos, *Phys. At. Nucl.* **60**, 172 (1997).
- [71] B. Sevda *et al.*, Constraints on nonstandard intermediate boson exchange models from neutrino-electron scattering, *Phys. Rev. D* **96**, 035017 (2017).
- [72] J.M. Link and X.-J. Xu, Searching for BSM neutrino interactions in dark matter detectors, *J. High Energy Phys.* **08** (2019) 004.
- [73] M. Lindner, W. Rodejohann, and X.-J. Xu, Coherent neutrino-nucleus scattering and new neutrino interactions, *J. High Energy Phys.* **03** (2017) 097.
- [74] D. Yu. Akimov, V. A. Belov, A. Bolozdynya, Yu. V. Efremenko, A. M. Konovalov, A. V. Kumpan, D. G. Rudik, V. V. Sosnovtsev, A. V. Khromov, and A. V. Shakirov, Coherent elastic neutrino scattering on atomic nucleus: recently discovered type of low-energy neutrino interaction, *Phys. Usp.* **62**, 166 (2019).