

Probing the ν_R -philic Z' at DUNE near detectors

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ABSTRACT: We consider a hidden $U(1)$ gauge symmetry under which only the right-handed neutrinos (ν_R) are charged. The corresponding gauge boson is referred to as the ν_R -philic Z' . Despite the absence of direct gauge couplings to ordinary matter at tree level, loop-induced couplings of the ν_R -philic Z' via left-right neutrino mixing can be responsible for its experimental accessibility. An important feature of the ν_R -philic Z' is that its couplings to neutrinos are generally much larger than its couplings to charged leptons and quarks, thus providing a particularly interesting scenario for future neutrino experiments such as DUNE to probe. We consider two approaches to probe the ν_R -philic Z' at DUNE near detectors via (i) searching for Z' decay signals, and (ii) precision measurement of elastic neutrino-electron scattering mediated by the Z' boson. We show that the former will have sensitivity comparable to or better than previous beam dump experiments, while the latter will improve current limits substantially for large neutrino couplings.

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1 Introduction

The discovery of neutrino oscillations has established non-zero neutrino masses on a firm footing [1]. It also clearly points towards the presence of Beyond the Standard Model (BSM) physics. There has been monumental progress to understand the standard 3×3 neutrino mixing paradigm by measuring the mixing parameters with ever-increasing accuracy but we are yet to understand the neutrino mass mechanism. There have been several proposals in the literature (for reviews, see e.g. Refs. [2, 3]), which always come with new interactions of neutrinos. Some of these ideas might be testable with the upcoming high-intensity frontier experiments in the near future [4].

In this work, we consider a BSM scenario with a hidden $U(1)$ gauge symmetry under which only the right-handed neutrinos (ν_R) are charged. These right-handed neutrinos interact with SM particles only through their mixing with the active neutrinos. As a result, the new gauge boson Z' associated with the hidden $U(1)$ symmetry can interact with the SM particles only through the left-right neutrino mixing and through $W^\pm/Z$ -loop induced couplings (see Fig. 1). A noteworthy feature of the ν_R -philic Z' is that its couplings to neutrinos (including the light ones via mixing) are generically larger than its loop-induced couplings to electrons. This is directly useful for probing this scenario at the intensity frontier neutrino experiments like DUNE [5]. Therefore, unlike most Z' models for which there are already severe constraints from beam dump experiments and e^+e^- colliders, and hence, little space for DUNE to probe,

the ν_R -philic Z' presents significantly better prospect in neutrino experiments. In our case, due to stronger coupling to neutrinos than quarks, Z' is primarily produced through charged pion decays instead of neutral pion decays. This is in stark contrast to the typical Z' models in literature, e.g. $B - L$ model, where neutral pion decay is the dominant production mode for light Z' [6, 7].

In this work, we study the detection prospects for the ν_R -philic Z' model at the near detector complex of DUNE [8] in two different ways: (i) elastic ν - e scattering, and (ii) using DUNE as a beam dump experiment. The process of elastic ν - e scattering has been widely used to constrain new interactions of neutrinos in the literature [9–15], due to its rather small theoretical uncertainties compared to the neutrino-nucleus scattering, although the neutrino-electron scattering cross section is much smaller than the neutrino-nucleus scattering cross section.¹ Nevertheless, a large neutrino flux at DUNE offers a significant statistical advantage to probe BSM physics at the near detector. In addition to neutrino scattering, the Z' can be directly produced from proton bremsstrahlung and decay of charged/neutral mesons produced from proton beam striking the target. In this way, DUNE can also be modeled as a beam dump experiment [6].

A number of studies have shown that beam dump experiments in general have great capabilities to constrain Z' with very weak couplings, provided that its visible decay width is not too small [23–27]. For the ν_R -philic Z' , the comparatively large couplings to neutrinos would suppress the visible decay width but enhance the production rate. Both aspects will be taken into account in this work.

The rest of paper is organized as follows: In Sec. 2, we discuss the framework for the neutrinophilic scenario considered in this work. In Sec. 3, we study prospects for this scenario at DUNE through neutrino-electron scattering. In Sec. 4, we analyze the role of DUNE as a beam dump experiment in constraining the neutrinophilic scenario. In Sec. 5, we discuss the implications of the combined analysis from neutrino scattering and beam dump. Finally we conclude in Sec. 6. Some details on the Z' production via proton bremsstrahlung are relegated to Appendix A.

2 Model Framework

We consider a Z' vector boson that is coupled to n right-handed neutrinos (ν_R) as follows:²

$$\mathcal{L} \supset g' Z'_\mu \sum_{i=1}^n \nu_{R,i}^\dagger \bar{\sigma}^\mu Q_{R,i} \nu_{R,i}, \quad (2.1)$$

where g' is the gauge coupling and $Q_{R,i}$ is the $U(1)'$ charge of $\nu_{R,i}$. For brevity, we will rewrite Eq. (2.1) in the matrix form:

$$\mathcal{L} \supset g' Z'_\mu \nu_R^\dagger \bar{\sigma}^\mu Q_R \nu_R, \quad (2.2)$$

¹Since the successful observation of coherent elastic neutrino-nucleus scattering (CE ν NS) [16], neutrino-nucleus scattering has also been used to constrain new physics, see e.g. [17–22].

²Following the same notations as in Ref. [28], we adopt two-component Weyl spinors for all chiral fermions.

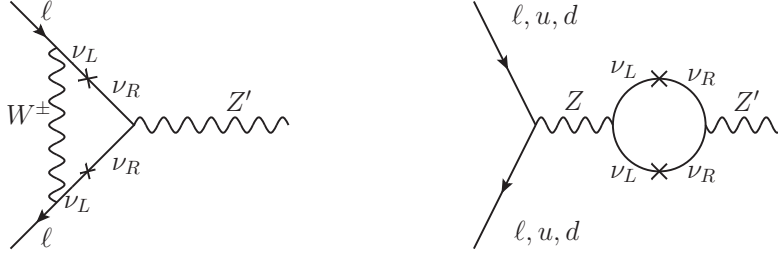


Figure 1. Loop-induced couplings of the ν_R -philic Z' to charged leptons (ℓ) and quarks (u and d). The $\times$ denotes the Dirac mass insertion.

with $Q_R = \text{diag}(Q_{R,1}, Q_{R,2}, Q_{R,3}, \dots)$ and $\nu_R = (\nu_{R,1}, \nu_{R,2}, \nu_{R,3}, \dots)^T$.

If ν_R are the only fermions charged under $U(1)'$, the cancellation of chiral anomalies requires $\sum_i Q_{R,i}^3 = 0$. Therefore, one often introduces pairs of ν_R with opposite charges to attain the cancellation [29–31]. Alternatively, one may consider other charge assignment such as $Q_R = (1, 1, 1, -4, -4, 5)$ or $(3, 4, 5, -6)$ which also satisfies $\sum_i Q_{R,i}^3 = 0$. We refrain from further discussions on the charge assignment as this can be rather model-dependent while the results in this work can be simply rescaled by a factor of $\mathcal{O}(Q_R)$.

The ν_R sector is connected to left-handed neutrinos ν_L via Dirac mass terms. In addition, ν_R may have Majorana mass terms. Formulated in the matrix form, the Dirac and Majorana mass terms are given by

$$\mathcal{L} \supset \nu_L^T m_D \nu_R + \frac{1}{2} \nu_R^T m_R \nu_R + \text{h.c.}, \quad (2.3)$$

where m_D is a $3 \times n$ matrix and m_R is a $n \times n$ matrix.

2.1 Loop-induced coupling

In the presence of the Z' couplings given by Eq. (2.2) and the neutrino mass terms in Eq. (2.3), there are loop-induced couplings of Z' to the SM charged leptons (ℓ) and quarks (u and d) generated by the diagrams in Fig. 1. The loop-induced couplings are finite (i.e. not UV divergent) when both light and heavy neutrino mass eigenstates are included in the loop integral.

For illustration, let us first discuss the case with only one ν_L and one ν_R so that m_D and m_R are 1×1 matrices. In this case, the loop-induced couplings read [28]:

$$\mathcal{L}_{\text{loop}} = \sum_f g_f f^\dagger \bar{\sigma}^\mu Z'_\mu f, \quad (2.4)$$

where f denotes SM chiral fermions and g_f is determined as follows:

$$g_f = \begin{cases} g_f^{(W)} + g_f^{(Z)} & f = \ell_L \\ g_f^{(Z)} & \text{otherwise} \end{cases}, \quad (2.5)$$

with

$$g_f^{(W)} = -\frac{\sqrt{2}G_F m_D^2}{8\pi^2} g' Q_R, \quad (2.6)$$

$$g_f^{(Z)} = \frac{\sqrt{2}G_F m_D^2}{8\pi^2} g' Q_R Q_f^{(Z)}. \quad (2.7)$$

Here the superscripts (W) and (Z) indicate contributions from the W and Z diagrams in Fig. 1, respectively. The result of the Z diagram depends on the so-called Z charge in the SM, defined as $Q_f^{(Z)} \equiv I_3 - Q_{\text{em}} s_W^2$ with I_3 the isospin and Q_{em} the electric charge (e.g. $Q_{\nu_L}^{(Z)} = 1/2$, $Q_{e_L}^{(Z)} = -1/2 + s_W^2$, $Q_{e_R}^{(Z)} = s_W^2$), and $s_W \equiv \sin \theta_W$, where θ_W is the weak mixing angle.

Eqs. (2.6) and (2.7) are derived under the approximation that $m_D/m_R \ll 1$. The results are proportional to m_D^2 which can be understood from Fig. 1 since each diagram needs two mass insertions to connect ν_L and ν_R lines. If Z' is replaced with a scalar, then the diagrams would be proportional to m_R^{-1} , leading to more suppressed loop-induced couplings [32].

For $3\nu_L + n\nu_R$, the loop-induced couplings are also finite and of the same order of magnitude as Eqs. (2.6) and (2.7). However, with the most general mass matrices, the loop-induced couplings cannot be written into compact and simple forms—see Eqs. (3.8) and (3.9) in Ref. [28]. Besides, a large number of free parameters in the flavor structure make it more difficult to obtain simple correlations among the loop-induced couplings. For simplicity, we concentrate on the case of $n = 3$ and assume that m_D and m_R can be simultaneously diagonalized as follows:³

$$U_L^T m_D U_R = m_D^{(d)}, \quad (2.8)$$

$$U_R^T m_R U_R = m_R^{(d)}, \quad (2.9)$$

where U_L and U_R are 3×3 unitary matrices, $m_D^{(d)}$ and $m_R^{(d)}$ are diagonal matrices.

The full neutrino mass matrix can be diagonalized by a 6×6 unitary matrix U :

$$\begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} = U \begin{pmatrix} \nu_{1,2,3} \\ \nu_{4,5,6} \end{pmatrix}, \quad (2.10)$$

$$U^T \begin{pmatrix} 0 & m_D \\ m_D^T & m_R \end{pmatrix} U = \text{diag}(m_1, \dots, m_6). \quad (2.11)$$

Eqs. (2.8) and (2.9) allow us to write U as

$$U = \begin{pmatrix} U_L & \\ & U_R \end{pmatrix} U', \quad U' = \begin{pmatrix} -i \text{diag}(c_1, c_2, c_3) & \text{diag}(s_1, s_2, s_3) \\ i \text{diag}(s_1, s_2, s_3) & \text{diag}(c_1, c_2, c_3) \end{pmatrix}, \quad (2.12)$$

where $(s_i, c_i) = (\sin \theta_i, \cos \theta_i)$ and $\theta_i = \arctan \sqrt{m_i/m_{i+3}}$.

³That m_D and m_R can be simultaneously diagonalized is a rather common feature in flavor symmetry models—see e.g. Refs. [33–35].

With the above assumption, the loop-induced couplings previously computed in Ref. [28] can be reformulated into the following matrix form:

$$g_f^{(W)} = -\frac{\sqrt{2}G_F \left[m_D \hat{Q}_R m_D^\dagger \right]_{\alpha\beta}}{8\pi^2} g', \quad (2.13)$$

$$g_f^{(Z)} = \frac{\sqrt{2}G_F \text{tr} \left[m_D \hat{Q}_R m_D^\dagger \right]}{8\pi^2} g' Q_f^{(Z)}, \quad (2.14)$$

where $\hat{Q}_R \equiv U_R \text{diag}(Q_{R,1}, Q_{R,2}, Q_{R,3}) U_R^\dagger$ and $(\alpha, \beta) \in \{e, \mu, \tau\}$ are flavor indices. Eq. (2.13) implies that flavor-changing couplings could be generated by the W diagram. It can be flavor diagonal if the charge assignments $(Q_{R,1}, Q_{R,2}, Q_{R,3})$ and $m_D^{(d)}$ satisfy

$$\left[m_D^{(d)} \right]^2 \text{diag}(Q_{R,1}, Q_{R,2}, Q_{R,3}) \propto I_{3 \times 3}. \quad (2.15)$$

In this case, we define

$$\bar{m}_D^2 \equiv \frac{1}{3} \text{tr} \left\{ \left[m_D^{(d)} \right]^2 \text{diag}(Q_{R,1}, Q_{R,2}, Q_{R,3}) \right\}, \quad (2.16)$$

$$\epsilon_{\text{loop}} \equiv \frac{\sqrt{2}G_F \bar{m}_D^2}{8\pi^2}, \quad (2.17)$$

and rewrite Eqs. (2.13) and (2.14) as

$$g_f^{(W)} = -\epsilon_{\text{loop}} g', \quad (2.18)$$

$$g_f^{(Z)} = 3 \epsilon_{\text{loop}} g' Q_f^{(Z)}. \quad (2.19)$$

2.2 Neutrino flavor states at low energies

Neutrinos in most experiments are produced via charged-current interactions. Since ν_L are the eigenstates of such interactions, one might expect that neutrinos at production are simply ν_L . However, due to a small fraction of heavy neutrino components in ν_L , only a quantum superposition of light mass eigenstates (ν_1, ν_2, ν_3) can be produced if the heavy mass eigenstates are heavier than the masses of the particles responsible for neutrino production (typically $\pi^\pm, K^\pm, \mu^\pm$, etc.). This implies that a neutrino state produced in the laboratory is slightly different from ν_L . To account for the difference, we define neutrino flavor states at low energies as follows:

$$\nu_\alpha^{\text{lab}} = \sum_{i=1}^3 (U_L)_{\alpha i} \nu_i, \quad \alpha \in \{e, \mu, \tau\}. \quad (2.20)$$

Further, we introduce a set of orthogonal states $\nu_\alpha^{\perp \text{lab}} = \sum_{i=4}^6 (U_R)_{\alpha i} \nu_i$ to complete the basis so that $(\nu^{\text{lab}}, \nu^{\perp \text{lab}})$ and (ν_L, ν_R) are connected by a unitary transformation:

$$\begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} = \begin{pmatrix} -iC_L & S \\ iS^\dagger & C_R \end{pmatrix} \begin{pmatrix} \nu^{\text{lab}} \\ \nu^{\perp \text{lab}} \end{pmatrix}, \quad (2.21)$$

where

$$C_{L,R} = U_{L,R} \text{diag}(c_1, c_2, c_3) U_{L,R}^\dagger, \quad (2.22)$$

$$S = U_L \text{diag}(s_1, s_2, s_3) U_R^\dagger. \quad (2.23)$$

Since $c_i \approx 1$ and $s_i \sim m_D/m_R \ll 1$, the unitary matrix in Eq. (2.21) performs only a small rotation from $(\nu^{\text{lab}}, \nu^{\perp\text{lab}})$ to (ν_L, ν_R) . In the basis of (ν_L, ν_R) , the Z' couplings to the neutrino sector (including loop-induced couplings to ν_L) read:

$$\mathcal{L} \supset g' (\nu_L, \nu_R) \begin{pmatrix} \frac{3}{2} \epsilon_{\text{loop}} I_{3 \times 3} \\ Q_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}. \quad (2.24)$$

Applying the basis transformation in Eq. (2.21), we obtain the effective couplings of Z' to ν^{lab} :

$$\mathcal{L}_{Z', \nu^{\text{lab}}} = g' Z'_\mu (\nu^{\text{lab}})^\dagger \bar{\sigma}^\mu \left[\frac{3}{2} \epsilon_{\text{loop}} C_L C_L^\dagger + S Q_R S^\dagger \right] \nu^{\text{lab}}. \quad (2.25)$$

2.3 Effective Z' couplings

Let us summarize the effective couplings of Z' to normal matter and neutrinos:

$$\begin{aligned} \mathcal{L} \supset & \bar{\psi}_q [g_{qL} \gamma^\mu P_L + g_{qR} \gamma^\mu P_R] Z'_\mu \psi_q \\ & + \bar{\psi}_e [g_{eL} \gamma^\mu P_L + g_{eR} \gamma^\mu P_R] Z'_\mu \psi_e + \bar{\psi}_\nu [g_\nu \gamma^\mu P_L] Z'_\mu \psi_\nu, \end{aligned} \quad (2.26)$$

where $q = u$ or d and we use ψ to denote four-component Dirac spinors. For neutrinos, the left-handed part of ψ_ν is the neutrino state produced in the laboratory, i.e. $P_L \psi_\nu = \nu^{\text{lab}}$ where ν^{lab} has been introduced in Sec. 2.2. Combining the previous results, we have the following couplings:

$$g_\nu = g' \left[\frac{3}{2} \epsilon_{\text{loop}} C_L C_L^\dagger + S Q_R S^\dagger \right], \quad (2.27)$$

$$(g_{eL}, g_{eR}) = 3 \epsilon_{\text{loop}} g' (s_W^2 - 5/6, s_W^2), \quad (2.28)$$

$$(g_{uL}, g_{uR}) = \epsilon_{\text{loop}} g' (1/2 - 2s_W^2, -2s_W^2), \quad (2.29)$$

$$(g_{dL}, g_{dR}) = \epsilon_{\text{loop}} g' (s_W^2 - 5/2, s_W^2). \quad (2.30)$$

For later convenience, we also define

$$g_e \equiv \sqrt{g_{eL}^2 + g_{eR}^2}, \quad g_q \equiv \sqrt{g_{qL}^2 + g_{qR}^2}, \quad (2.31)$$

and

$$r \equiv \frac{g_\nu}{g_e}. \quad (2.32)$$

Note that all effective couplings are of the order of $\epsilon_{\text{loop}} g'$ except for the mixing-induced part $S Q_R S^\dagger$ which is of $\mathcal{O}(\sin^2 \theta_i)$ where the mixing angles θ_i are defined below Eq. (2.12). According to Refs. [36, 37], for heavy neutrino masses above the electroweak scale, the current

constraints on $\sin^2 \theta_i$ typically vary from 10^{-3} for 10^{-2} , depending on lepton flavors. This allows for the scenario that the mixing-induced part dominates over the loop-induced part ($\epsilon_{\text{loop}} C_L C_L^\dagger$) in g_ν . More concretely, if we consider $m_R \sim G_F^{-1/2}$, $\sin^2 \theta_i \sim m_D^2/m_R^2$ should be of the same order as $G_F m_D^2$, which is about a factor of $8\pi^2 \sim \mathcal{O}(10^2)$ larger than the loop-induced part $\epsilon_{\text{loop}} C_L C_L^\dagger$. In this case, one expects that $g_\nu \sim \mathcal{O}(10^2) g_e$. For larger m_R with fixed m_D , the mixing-induced part decreases and eventually loses its dominance, leading to $g_\nu \sim g_e$. Taking $m_R^2 \in [1, 10^2] G_F^{-1}$ and $\sin^2 \theta_i = 10^{-3}$ for example (neglecting the flavor structure), we roughly have $m_D^2 \in [10^{-3}, 10^{-1}] G_F^{-1}$ and $\epsilon_{\text{loop}} \in [1.8 \times 10^{-5}, 1.8 \times 10^{-3}]$. Therefore, as a benchmark in this work, we can consider

$$C_L C_L^\dagger \rightarrow 1, \quad S Q_R S^\dagger \rightarrow 10^{-3}, \quad \epsilon_{\text{loop}} \in [10^{-5}, 10^{-3}]. \quad (2.33)$$

3 DUNE as a neutrino scattering experiment

Having formulated the effective couplings of Z' to neutrinos and electrons, we now study the sensitivity of the DUNE near detector to the signal of elastic neutrino-electron scattering⁴ caused by Z' .

For a general Z' with the effective couplings given by Eq. (2.26), the differential cross section of elastic neutrino-electron scattering including both the SM and the new physics contributions reads [10, 13, 38]:

$$\frac{d\sigma}{dT} = \frac{2m_e G_F^2}{\pi} \left[c_L^2 + c_R^2 \left(1 - \frac{T}{E_\nu} \right)^2 - c_L c_R \frac{m_e T}{E_\nu^2} \right], \quad (3.1)$$

where

$$c_L = c_L^{(\text{SM})} + \frac{g_{eL} g_\nu}{2\sqrt{2} G_F (2m_e T + m_{Z'}^2)}, \quad c_L^{(\text{SM})} = -\frac{1}{2} + s_W^2 + \delta_{\alpha e}, \quad (3.2)$$

$$c_R = c_R^{(\text{SM})} + \frac{g_{eR} g_\nu}{2\sqrt{2} G_F (2m_e T + m_{Z'}^2)}, \quad c_R^{(\text{SM})} = s_W^2. \quad (3.3)$$

Here T denotes the recoil energy of the electron; c_L and c_R are dimensionless quantities consisting of the SM and the new physics contributions, as given by Eqs. (3.2) and (3.3). We have added $\delta_{\alpha e}$ (where α denotes the incoming neutrino flavor) in Eq. (3.2) to take account of the SM charged current interaction: $\delta_{\alpha e} = 1$ for $\alpha = e$ and $\delta_{\alpha e} = 0$ for $\alpha = \mu$ or τ . Note that $c_R^{(\text{SM})}$ is not affected by the presence of the charged current contribution. For anti-neutrino scattering ($\bar{\nu}_\alpha + e$), Eq. (3.1) should be modified with the interchange $c_L \leftrightarrow c_R$ while Eqs. (3.2) and (3.3) remain the same. In this work, we neglect flavor transition in neutrino scattering since the contribution is suppressed due to the loss of interference with the SM processes.

⁴Neutrino trident scattering could also be used to probe Z' . However, for our model the sensitivity is weaker than elastic neutrino-electron scattering, as can be expected from Fig. 7 of Ref. [12].

The event rate of elastic neutrino-electron scattering at the detector is computed by [10, 13]:

$$\frac{dN}{dT} = N_e \lambda_{\text{POT}} \int \Phi(E_\nu) \frac{d\sigma(T, E_\nu)}{dT} \Theta(T_{\text{max}} - T) dE_\nu, \quad (3.4)$$

where N_e is the total electron number in the fiducial mass of the detector; λ_{POT} is the number of protons-on-target (POT) at the neutrino production facility; Φ is the neutrino flux per POT; Θ is the Heaviside theta function with the maximal recoil energy T_{max} determined by

$$T_{\text{max}}(E_\nu) = \frac{2E_\nu^2}{m_e + 2E_\nu}. \quad (3.5)$$

The event number in a given recoil energy bin $T \in [T_i, T_i + \Delta T]$ is computed as

$$N_i = \int_{T_i}^{T_i + \Delta T} \frac{dN}{dT} dT. \quad (3.6)$$

The electron number N_e can be computed as $N_e = 18M_{\text{Ar}}/m_{\text{Ar}}$ where the factor 18 comes from the fact that each Ar atom has 18 electrons, M_{Ar} is the fiducial detector mass and $m_{\text{Ar}} = 39.95u = 37.21 \text{ GeV}$ is the atomic mass of ^{40}Ar . For the fiducial mass, we consider only the liquid argon time-projection chamber (LArTPC) near detector which has a fiducial mass of $M_{\text{Ar}} = 67.2 \text{ ton}$ [4]. For the number of POT, we take $\lambda_{\text{POT}} = 5 \times 1.1 \times 10^{21}$ for each of the neutrino and anti-neutrino modes, corresponding to the Long Baseline Neutrino Facility (LBNF) at Fermilab operating at 1.2 MW intensity for five years in each mode. The neutrino flux Φ can be obtained from the latest DUNE Technical Design Report⁵.

With the above setup, we compute the event numbers⁶ and perform the sensitivity study with the following χ^2 function previously adopted in Ref. [17]:

$$\chi^2 = \left(\frac{a}{\sigma_a}\right)^2 + \sum_i \left(\frac{(1+a)N_i - N_i^0}{\sigma_i}\right)^2, \quad (3.7)$$

where a is a scale factor introduced to take into account the normalization uncertainty (we assume that the dominant systematic uncertainty arises from the normalization of event rates); σ_a denotes the uncertainty of a for which we set $\sigma_a = 2\%$; the summation goes over all T bins; N_i denotes the event number evaluated from Eq. (3.6) with N_i^0 the corresponding SM value; and $\sigma_i \approx \sqrt{N_i}$ denotes the statistical uncertainty on N_i . Here a is treated as a nuisance parameter which in the *frequentist treatment* [1] is marginalized by minimizing χ^2 with respect to a . For Eq. (3.7), the value of a at the minimum, a_{min} , can be computed analytically [17]:

$$a_{\text{min}} = \frac{\sum_i (N_i^0 - N_i) N_i / \sigma_i^2}{\sigma_a^{-2} + \sum_i N_i^2 / \sigma_i^2}. \quad (3.8)$$

We set the T bins as follows: the interval $T \in [0, 8] \text{ GeV}$ is divided evenly to 5 bins, and events above 8 GeV are collected in a single bin. Each bin has a sufficiently large event number so that the use of $\sigma_i \approx \sqrt{N_i}$ is justified. The χ^2 functions for neutrino and anti-neutrino modes are computed separately and then combined.

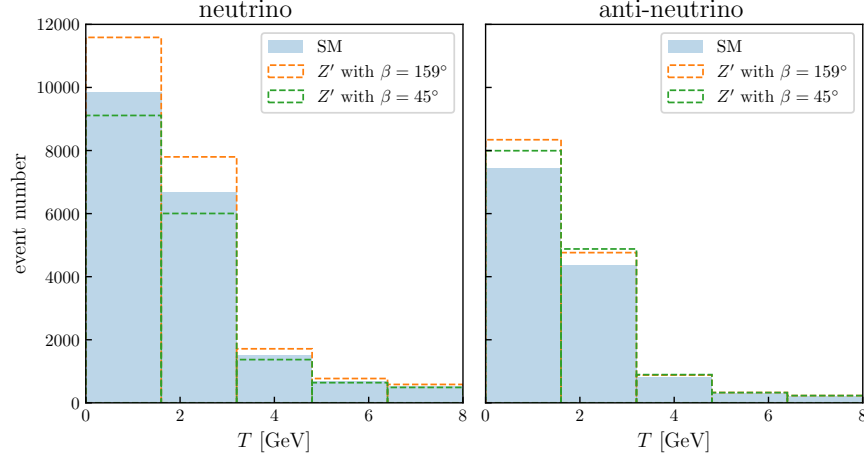


Figure 2. The events numbers for elastic neutrino-electron scattering at DUNE near detector LArTPC. Depending on the angle β defined in Eq. (3.9), a generic Z' can lead to an excess or deficit in the event numbers.

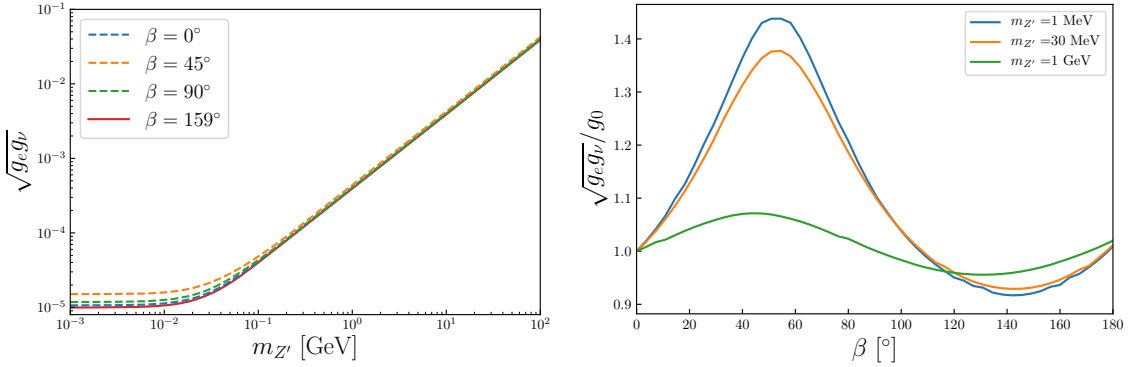


Figure 3. Left: the sensitivity of DUNE as a neutrino scattering experiment to a generic Z' for several selected values of β defined in Eq. (3.9). Right: the dependence of the results on β .

Fig. 2 shows the expected event numbers computed in the SM and in the new physics scenario of a generic Z' . We parametrize the ratio of g_{eL} to g_{eR} as

$$(g_{eL}, g_{eR}) = (\cos \beta, \sin \beta) g_e. \quad (3.9)$$

In our model, the couplings in Eq. (2.28) correspond to $\beta = 159^\circ$. This leads to excesses of event numbers in both neutrino and anti-neutrino modes, as shown by the orange points in Fig. 2. For comparison, we also show an example with $\beta = 45^\circ$ (corresponding to $g_{eL} : g_{eR} = 1 : 1$) which could cause excesses in the anti-neutrino mode but deficits in the neutrino mode. The two new physics examples assume $m_{Z'} = 100$ MeV and $\sqrt{g_e g_\nu} = 10^{-4}$.

⁵See Fig. 5.4 in Ref. [39], Fig. 2.15 in Ref. [8], and Fig. 2 in Ref. [40].

⁶Our code is publicly available at <https://github.com/xunjiexu/Zprime-at-DUNE>.

In the left panel of Fig. 3, we present the 90% C.L. sensitivity reach of DUNE-LArTPC for a few selected values of β . As one can see, the curves nearly overlap for $m_{Z'} \gtrsim 100$ MeV and show small differences for $m_{Z'} \lesssim 10$ MeV. To further check whether varying β could cause significant changes, in the right panel we investigate the dependence of the results on β with three representative values of $m_{Z'}$ and find that the sensitivity reach varies at most by a factor of $\sqrt{g_e g_\nu}/g_0 \in [0.91, 1.44]$ for $\beta \in [0, \pi]$, where g_0 is defined as the value of $\sqrt{g_e g_\nu}$ at $\beta = 0$. For larger $m_{Z'}$, the results are more insensitive to β . Fig. 3 can be considered as a model-independent analysis for Z' with rather general couplings to left-/right-handed electrons and neutrinos.

4 DUNE as a beam dump experiment

At the neutrino production site of DUNE, Z' can be produced from the proton beam striking the target. Due to its weak couplings to SM fermions, the produced Z' boson can be long-lived and penetrate through the shielding and earth between the near detector and the target. This possibility allows us to consider DUNE as a beam dump experiment (like E137, E141, Orsay) to probe Z' [6, 7].

We consider the DUNE Multi-Purpose Detector (MPD) which is a High-Pressure Ar gas TPC (HPgTPC)⁷ for the detection of Z' in this work. The DUNE MPD will be located 579 m away from the target, with a diameter of 5 m and a length of 5 m [6]. Therefore, for Z' particles produced at the target to cause observable signals at the DUNE MPD, the transverse momentum, $p_\perp$, compared to the Z' momentum, $p_{Z'}$, needs to be sufficiently small:

$$\frac{p_\perp}{p_{Z'}} < \frac{R}{L_1} \approx 4.3 \times 10^{-3} \equiv \theta_{\max}, \quad (4.1)$$

where $R = 2.5$ m is the radius of the detector and $L_1 = 579$ m is the distance of the detector to the target.

There are several processes responsible for the production of Z' in our model, namely meson decays ($\pi^0 \rightarrow Z'\gamma$, $\eta \rightarrow Z'\gamma$, $\pi^\pm \rightarrow \ell^\pm \nu Z'$, $K^\pm \rightarrow \ell^\pm \nu Z'$) and proton bremsstrahlung ($pp \rightarrow ppZ'$). The latter can be computed using an approximate formula in Ref. [41]—see Appendix A for a brief review. The former requires the production rates of relevant mesons, which can be obtained from Monte-Carlo simulations of high-energy protons scattering off nucleons. We adopt the production rates from Ref. [6] (neutral meson results from Fig. 4.1, charged meson results from Fig. 5.2) and rescale them according to the effective couplings of Z' in our model.

Fig. 4 shows the number of Z' bosons produced (denoted as $N_{\text{prod.}}$) via the aforementioned processes for $r = 100$, within the small angle determined by Eq. (4.1). Since in this case Z' is dominantly coupled to neutrinos, in the low-mass regime the dominant production processes

⁷Compared to LArTPC, HPgTPC has the advantage of lower (roughly 50 times smaller) backgrounds. Hence it is more suitable for new physics searches that do not require interactions with the content filled in the detector.

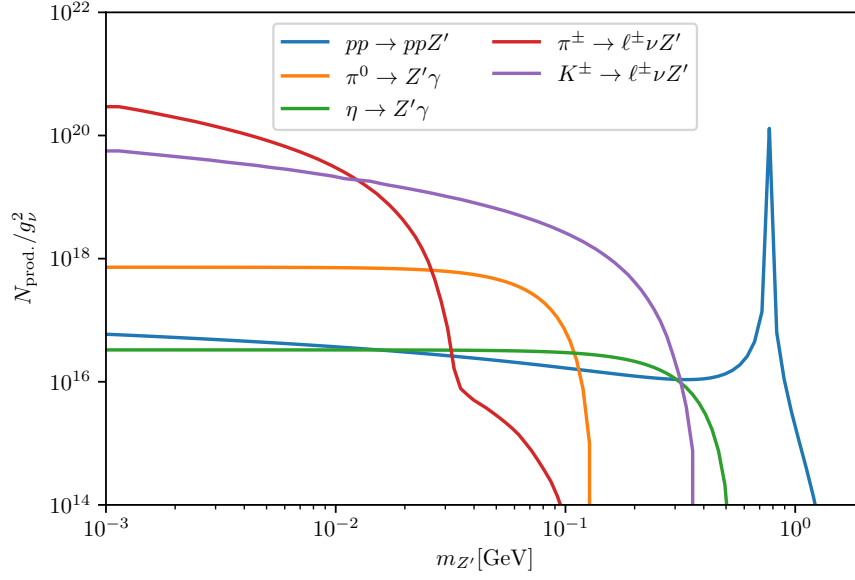


Figure 4. The number of Z' bosons produced via meson decays ($\pi^0 \rightarrow Z'\gamma$, $\eta \rightarrow Z'\gamma$, $\pi^\pm \rightarrow \ell^\pm \nu Z'$, $K^\pm \rightarrow \ell^\pm \nu Z'$) and proton bremsstrahlung ($pp \rightarrow ppZ'$) assuming $r = 100$ and 1.47×10^{22} POT from a 120 GeV proton beam.

are those with neutrino final states ($\pi^\pm \rightarrow \ell^\pm \nu Z'$, $K^\pm \rightarrow \ell^\pm \nu Z'$). Note, however, that these three-body decay processes are more suppressed in the phase space than neutral meson decays ($\pi^0 \rightarrow Z'\gamma$, $\eta \rightarrow Z'\gamma$). Hence if all the couplings are of the same order of magnitude, neutral meson decays would dominate over charged meson decays [7]. When $m_{Z'}$ is greater than the meson masses, proton bremsstrahlung starts to dominate. In particular, the blue curve in Fig. 4 peaks at $m_{Z'} \approx 0.8$ GeV due to the resonance caused by the ρ/ω meson [42, 43].

The number of detectable events, $N_{\text{det.}}$, can be computed by [27]

$$N_{\text{det.}} = \int dp_{Z'} \frac{dN_{\text{prod.}}(p_{Z'})}{dp_{Z'}} P_{\text{decay}}(p_{Z'}) \text{BR}_{Z' \rightarrow \text{vis.}}, \quad (4.2)$$

where $\text{BR}_{Z' \rightarrow \text{vis.}}$ denotes the branching ratio of Z' decaying to visible states and P_{decay} denotes the probability that a single Z' particle travels from the target to the detector and then decays in the detector. The momentum distribution of Z' at the production, $dN_{\text{prod.}}/dp_{Z'}$, includes contributions from meson decay processes and proton bremsstrahlung. The latter is elaborated in Appendix A and the former can be obtained by combining the kinematics of meson decays at rest and Lorentz boosts according to the meson momentum distributions taken from Fig. 4 in Ref. [44]. The probability P_{decay} is computed by [27]

$$P_{\text{decay}} = e^{-L_1/L_{Z'}} \left(1 - e^{-L_2/L_{Z'}} \right), \quad (4.3)$$

with $L_1 = 579$ m, $L_2 = 5$ m, and $L_{Z'}$ denotes the distance of flight before Z' decay. The physical meaning of Eq. (4.3) is manifest: it is the probability of Z' not decaying in L_1

multiplied by the probability of Z' decaying in L_2 . The distance of flight, $L_{Z'}$, is computed by

$$L_{Z'} = \frac{\tau_{Z'} v}{\sqrt{1 - v^2}}, \quad (4.4)$$

where $1/\sqrt{1 - v^2}$ is the Lorentz boost factor with the velocity $v = p_{Z'}/\sqrt{m_{Z'}^2 + p_{Z'}^2}$. The lifetime $\tau_{Z'}$ takes into account all decay modes:

$$\tau_{Z'}^{-1} = \Gamma_{Z'} = \Gamma_{Z' \rightarrow \text{had.}} + \sum_{f \neq q} \Gamma_{Z' \rightarrow f \bar{f}}, \quad (4.5)$$

where $\Gamma_{Z' \rightarrow \text{had.}}$ denotes the decay width of Z' to hadronic states. The decay widths to other states $\Gamma_{Z' \rightarrow f \bar{f}}$ ($f \neq q$) are computed analytically (see e.g. Ref. [41]):

$$\Gamma_{Z' \rightarrow f \bar{f}} = \frac{g_f^2}{12\pi} m_{Z'} \left(1 + 2 \frac{m_f^2}{m_{Z'}^2} \right) \sqrt{1 - \frac{4m_f^2}{m_{Z'}^2}}. \quad (4.6)$$

The hadronic decay width, $\Gamma_{Z' \rightarrow \text{had.}}$, can be computed using experimental measurements of the hadron-to-muon cross section ratio in e^+e^- collisions. For $\Gamma_{Z' \rightarrow \text{had.}}$, we adopt the same method previously used in Ref. [27]. The visible decay width in Eq. (4.2) takes the form

$$\text{BR}_{Z' \rightarrow \text{vis.}} \equiv 1 - \frac{\Gamma_{Z' \rightarrow \nu \bar{\nu}}}{\Gamma_{Z'}}. \quad (4.7)$$

The effective coupling to neutrinos, g_ν , plays a particularly important role here because it reduces the visible decay width of Z' . When $g_\nu \gg g_e$ and g_q , we have $\text{BR}_{Z' \rightarrow \text{vis.}} \ll 1$ and hence a significantly suppressed event rate.

Using Eq. (4.2) with each ingredient explicated above, we compute the sensitivity reach of DUNE MPD for our model. The results are presented in Fig. 5 with $r = g_\nu/g_e$ fixed at several benchmark values (1, 5, 10, 100). As expected, when r increases, due to the aforementioned suppression of the visible decay width, the DUNE MPD sensitivity becomes weaker.

5 Combined results and discussions

In this section, we compare the estimated sensitivities of DUNE-LArTPC (via ν - e scattering) and DUNE-MPD (which could detect Z' decay) with existing bounds. We focus on the mass range $1 \text{ MeV} \leq m_{Z'} \leq 100 \text{ GeV}$ where the DUNE experiment shows competitive sensitivities.

For masses below 100 GeV, direct searches for Z' at BaBar, LHCb, and NA48 put the strongest collider bounds. For masses ranging from MeV to GeV, there are constraints from beam dump experiments such as E137, E141, and Orsay. For these existing collider and beam dump bounds, we use the DARKCAST package [25] to recast the published bounds and obtain the shaded exclusion regions in Fig. 6.

Since Z' is effectively coupled to charged leptons, the muon and electron anomalous magnetic moments can be used to set constraints, which are presented in Fig. 6, being labelled

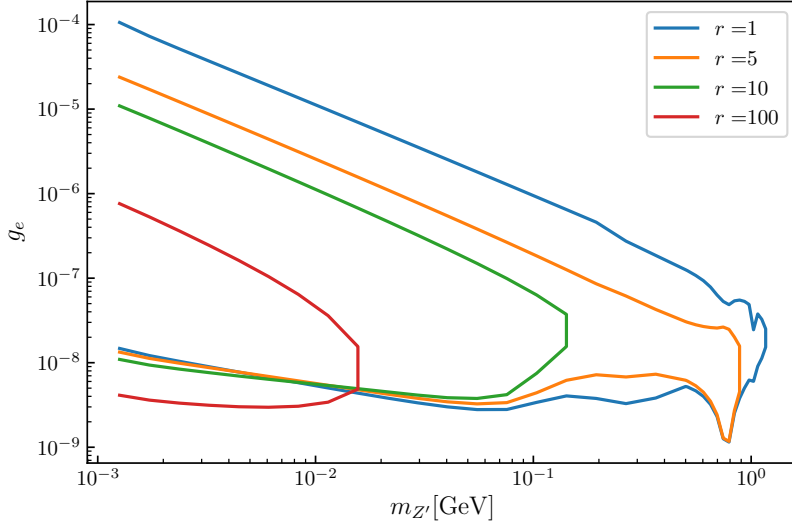


Figure 5. The sensitivity reach of DUNE MPD to the ν_R -philic Z' with loop-induced couplings. The results depend on the ratio r defined in Eq. (2.32).

as $(g-2)_\mu$ and $(g-2)_e$, respectively. These curves are obtained by setting $\Delta\alpha_\mu \leq 5.5 \times 10^{-9}$ (5σ) [45] and $\Delta\alpha_e \leq 13.8 \times 10^{-13}$ (3σ) [46] where $\Delta\alpha_\ell$ ($\ell = \mu, e$) is computed by [27, 47]

$$\Delta\alpha_\ell = \frac{g_\ell^2}{4\pi^2} \left(\frac{m_\ell}{m_{Z'}} \right)^2 \int_0^1 \frac{(1-x)x^2}{1-x+x^2(m_\ell/m_{Z'})^2} dx. \quad (5.1)$$

There are also strong constraints on low-mass Z' from astrophysics and cosmology. The most relevant one comes from the supernova event SN1987A. Studies on SN1987A energy loss criteria have put restrictive constraints on weakly coupled Z' below $\mathcal{O}(100)$ MeV [48–50]. In Fig. 6, we adopt the combined SN1987A bound from Ref. [51] for the $B-L$ gauge boson and rescale it accordingly. Near the MeV mass scale or lower, there are constraints from stellar cooling [52] and the effective number of relativistic degrees of freedom (N_{eff}) [53]. We do not show the N_{eff} constraints as they are marginally relevant to the mass range considered here.

From Fig. 6, we see that the ratio $r \equiv g_\nu/g_e$ is crucial when comparing bounds from DUNE and the existing experiments. When g_ν and g_e are comparable ($r = 1$), neutrino-electron scattering at DUNE-LArTPC (dotted line) does not show a significant advantage over other experiments. Nevertheless, there is a mass range from 10 MeV to 200 MeV for DUNE-LArTPC to probe. When r increases, both the DUNE-LArTPC sensitivity and collider bounds become weaker, since they all depend on g_e and/or g_q which is decreasing, given fixed mixing angles and hence fixed g_ν/g' . However, as one can see, for large r , DUNE-LArTPC shows significantly better sensitivity than other non-neutrino experiments because the former relies on the product $g_e g_\nu$ while the latter typically relies on g_e^2 or g_q^2 . We emphasize here that the main feature of our framework is the dominance of neutrino couplings in the ν_R -philic Z' model, which provides an excellent prospect for DUNE to probe.

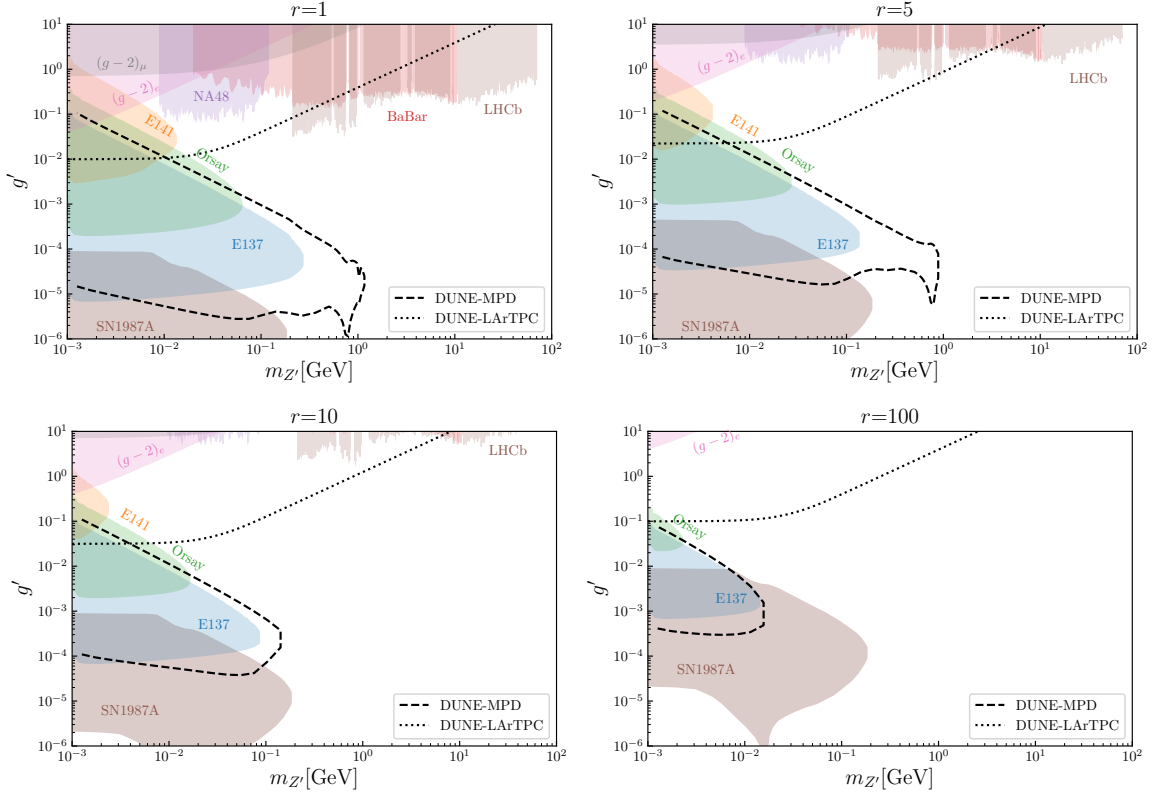


Figure 6. Combined results of the DUNE sensitivity to the ν_R -philic Z' . All bounds depends on the ratio $r \equiv g_\nu/g_e = \{1, 5, 10, 10^2\}$.

As previously discussed in Sec. 4, DUNE-MPD can be used to probe Z' like a beam dump experiment. The sensitivity reach is shown as dashed curves in Fig. 6. In this case, g_ν plays a positive role in production (it leads to additional contributions of Z' production from meson decays with neutrino final states), but a negative role in detection because it increases the invisible decay width of Z' . In particular, for $r \gg 1$, Z' dominantly decays to neutrinos. Overall, large g_ν reduces the sensitivity of DUNE-MPD. Therefore, when r increases, DUNE-MPD together with all other beam dump experiments quickly loses sensitivity to the weak-coupling regime ($g' \sim 10^{-4}, 10^{-5}$). Consequently, the DUNE-MPD sensitivity region shrinks quickly as we increase r in Fig. 6.

6 Conclusion

Hidden $U(1)$ symmetries in the right-handed neutrino (ν_R) sector are theoretically well motivated and would give rise to an inherently dark gauge boson which we refer to as the ν_R -philic Z' . Due to the loop-suppressed couplings to normal matter and comparatively larger couplings to neutrinos, neutrino experiments are the most suited to probe the ν_R -philic Z' .

In this work we studied the sensitivity of the future DUNE experiment to the ν_R -philic Z' . We considered two complementary near detectors, DUNE-LArTPC and DUNE-MPD (HPgTPC), which could be sensitive to Z' signals via elastic ν - e scattering and via Z' decay respectively. We stress here that the ratio of electron and neutrino couplings, $r = g_\nu/g_e$, which is practically a free parameter in the model, plays a crucial role. Larger neutrino couplings lead to higher elastic ν - e scattering rates in DUNE-LArTPC but make Z' decay less visible in DUNE-MPD due to the enhanced invisible decay width. The combined results are shown in Fig. 6 and compared with existing bounds. For $r = 1$ or 5, DUNE-MPD exhibits a significant advantage over other beam dump experiments in the mass range $0.1\text{GeV} \lesssim m_{Z'} \lesssim 1\text{GeV}$. On the other hand, for larger r such as $r = 10$ or 100, DUNE-LArTPC as a scattering experiment will be able to generate the leading constraints, exceeding the collider bounds from BaBar, LHCb, etc. We conclude that there is an excellent prospect of DUNE probing new physics hidden in the sector of right-handed neutrinos.

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A The proton bremsstrahlung formula

For Z' emitted via proton bremsstrahlung ($pN \rightarrow pNZ'$), there is an approximate formula often used in the literature [6, 41, 42, 54]⁸:

$$\frac{d^2 N_{\text{brem}}}{dz dp_\perp^2} = N_{\text{POT}} \frac{\sigma_{pN}(s')}{\sigma_{pN}(s)} |F_{1,N}(m_{Z'}^2)|^2 w_{ba}(z, p_\perp^2), \quad (\text{A.1})$$

with

$$w_{ba}(z, p_\perp^2) = \frac{g_p^2}{8\pi^2 H} \left[\frac{1 + (1-z)^2}{z} - 2z(1-z) \left(\frac{2m_p^2 + m_{Z'}^2}{H} - z^2 \frac{2m_p^4}{H^2} \right) + 2z(1-z) \left[1 + (1-z)^2 \right] \frac{m_{Z'}^2 m_p^2}{H^2} + 2z(1-z)^2 \frac{m_{Z'}^4}{H^2} \right], \quad (\text{A.2})$$

$$H \equiv p_\perp^2 + (1-z)m_{Z'}^2 + z^2 m_p^2. \quad (\text{A.3})$$

⁸We note that there is a discrepancy between the expressions of w_{ba} in Refs. [41, 54] and Refs. [6, 42]. We adopt the former since this is consistent with the matrix element given by Eq. (6) in Ref. [41].

Here the kinematic variable z is the ratio of the outgoing Z' momentum to the incoming proton momentum ($0 < z < 1$); $p_\perp$ is the transverse component of the Z' momentum; σ_{pN} is the proton-nucleus cross section evaluated at $s = 2m_p E_p$ and $s' \approx 2m_p(E_p - E_{Z'})$; $F_{1,N}(m_{Z'}^2)$ is the vector form factor of the nucleus evaluated at $q^2 = m_{Z'}^2$ (timelike); and g_p is the effective coupling of Z' to the proton. Since the beam energy is high, one can approximately view the target as free protons and neutrons at rest. According to the simulations in Ref. [6], the difference between neutron and proton being the target particle is negligible at this energy, which allows us to replace σ_{pN} with the proton-proton cross section, σ_{pp} , and replace $F_{1,N}$ with the corresponding form factor of the proton, $F_{1,p}$. The cross section σ_{pp} is computed via an approximate formula from Ref. [41], and the form factor $F_{1,p}$ is taken from Ref. [42].

Due to the small angle in Eq. (4.1) which implies $p_\perp^2 \ll H$, we can integrate out $p_\perp^2$ in Eq. (A.1), which leads to

$$\frac{dN_{\text{brem}}}{dz} = N_{\text{POT}} \frac{\sigma_{pN}(s')}{\sigma_{pN}(s)} |F_{1,N}(m_{Z'}^2)|^2 w_{ba}(z), \quad (\text{A.4})$$

where

$$w_{ba}(z) = \int_0^{E_p^2 \theta_{\text{max}}^2} w_{ba}(z, p_\perp^2) dp_\perp^2 = \frac{g_p^2 \theta_{\text{max}}^2 E_p^2}{8\pi^2} \frac{z(z^2 - 2z + 2)}{[m_p^2 z^2 + m_{Z'}^2(1 - z)]}. \quad (\text{A.5})$$

Note that, though w_{ba} in Eq. (A.2) diverges at $z \rightarrow 0$, the integrated form of w_{ba} in Eq. (A.5) at $z \rightarrow 0$ has been regularized by $m_{Z'}^2$, i.e. $\lim_{z \rightarrow 0} w_{ba}(z) = 0$ as long as $m_{Z'}^2 \neq 0$.

The proton bremsstrahlung formula presented above is valid only if the incoming and outgoing protons as well as the Z' boson are ultra-relativistic [41]. Typically in the literature one imposes upper and lower bounds on z , $z_{\text{min}} < z < z_{\text{max}}$. For instance, previous studies on the SHiP experiment often take $(z_{\text{min}}, z_{\text{max}}) = (0.1, 0.9)$ [42, 54]. For the DUNE setup, we set $z_{\text{min}} = 5m_{Z'}/E_p$ so that the outgoing Z' is relativistic. If z is very close to 1, the outgoing proton would be non-relativistic. Hence we set the upper bound $z_{\text{max}} = 1 - 5m_p/E_p$. The factor 5 here is chosen so that the relativistic approximation holds and meanwhile the width of the integration interval ($z_{\text{max}} - z_{\text{min}} \approx 1$) is not significantly reduced. We have checked that varying this factor does not change the result significantly, provided that the two conditions are satisfied.

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