Research Article
DUNE Prospect for Leptophobic Dark Matter

Sabeeha Naaz [ID], Jyotsna Singh, and R. B. Singh

Department of Physics, University of Lucknow, Lucknow 226007, India

Correspondence should be addressed to Sabeeha Naaz; sabeehanaaz0786@gmail.com

Highly energetic proton/electron beam fixed-target experiments extend an opportunity to probe the sub-GeV dark matter and associated interactions. In this work, we have explored the sensitivity of DUNE (Deep Underground Neutrino Experiment) for sub-GeV leptophobic dark matter, i.e., this dark matter barely couples with the leptons. Baryon number gauge theory can predict the existence of leptophobic cold dark matter particle candidates. In our work, the dark matter candidate is considered to be scalar whose mass is defined by the symmetry breaking of new baryonic gauge group $U(1)_B$. In this scenario, a light scalar dark matter couples with the standard model candidates via vector boson mediator V_B which belongs to the baryonic gauge group $U(1)_B$. This leptophobic dark matter dominantly couples to the quarks. Under this scenario, new parameter space for α_B is explored by DUNE for leptophobic dark matter candidates. This new parameter space allowed α_B to get a lower value than the present exiting constraint value of α_B, i.e., 10^{-6}.

1. Introduction

Existence of dark matter (DM) particle is supported by many gravitational phenomena in astrophysics and cosmology, but the nature of the dark matter is still to be discovered. These gravitational evidences motivate the physicist to know about the dark matter (DM) particle candidates and their interactions with ordinary matter if any. None of the running experiments is able to probe the DM candidates; hence, different theoretical assumptions or models are floating in the scientific community to describe their nature. DM candidates are assumed to be nonbaryonic, weakly interacting, and stable.

On the basis of DM mass and their velocities, DM candidates can be broadly classified into two categories: hot and cold dark matter. All relativistic and superrelativistic DM particles are called hot DM, whereas all nonrelativistic DM particles are known as cold DM. Most part of the DM is cold because they move with nonrelativistic speed, and they are capable of forming small structure galaxies rather than massive galaxies. While hot DM cannot form small structure of galaxies by the free streaming process. As we observe small structure galaxies, hence, it is assumed that DM is a mixture of small amount of hot DM with predominant cold DM. Dif-

ferent DM physics models need different experimental environment for the detection of DM. The experimental techniques proposed for dark matter detection can be broadly classified into three categories.

1.1. Direct Detection. In the direct detection technique, we suggest that the DM candidates can be detected by the measurement of recoil energy of nucleons, but this detection technique becomes less sensitive for the detection of sub-GeV dark matter because in this mass range of DM the recoil energy of nucleons decreases below the detector threshold value of the detector.

1.2. Indirect Detection. In indirect detection, the standard model (SM) particles produced via annihilation of DM particles are studied.

1.3. Collider Technique. Beam collider technique looks for the missing transverse energy in an event, for the DM detection.

In this work, we have focused on the MeV to GeV mass range of DM because a lot of work has been done for mass range 1 GeV to 10 TeV (WIMP (weakly interactive massive particles) as a DM candidate) at direct detection experiments, but these experiments have estimated null results for WIMP [1–5]. Hence, sub-GeV mass DM particles can be potential

candidates of the DM family and the sub-GeV DM candidates can be explored by direct detection, in neutrino laboratories. To improve the sensitivity of DM candidates, fixed-target approach is considered in direct detection experiment, but one major drawback of this approach is the presence of huge neutrino background. These particles (neutrinos) can mimic the DM signatures hence for the detection of DM neutrino background reduction becomes necessary. To mitigate the neutrino background in our DM detection work, we have considered DUNE running in beam dump mode. For the first time, neutrino experiment in the beam dump mode was carried by MiniBooNE in 2014 [6, 7]. The fixed-target experiment in beam dump mode opens the door for the study of DM and hidden sector physics via different DM portals.

A large number of DM studies [6, 8–14] have focused on the kinetic mixing scenario, in which DM of hidden sector couples with the SM particles via kinetic mixing parameter (ε), which kinetically mixes the dark photon (γ_D) mediator of hidden sector and ordinary photon. This is one of the possible ways of interaction of DM with SM particles, but there are other large number of scenarios of DM interaction with SM particles. These scenarios need to be probed for imposing better constraints on DM parameter space. In one of these scenarios, DM candidates of hidden sector interacts with the SM particles via a new massive vector gauge boson mediator (V_B) of new baryonic gauge group $U(1)_B$. This vector gauge boson V_B dominantly couples with the quarks and is called leptophobic dark matter.

In our work, using fixed-target experiment in beam dump mode, we have estimated the sensitivity of DUNE (Deep Underground Neutrino Experiment) [15] for capturing the signatures of leptophobic dark matter. A highly energetic proton beam of energy 120 GeV is used to produce a boosted dark matter beam through vector boson mediator V_B. Here, three modes of DM production are taken into consideration in our analysis. These modes are pseudomeson decay, bremsstrahlung, and parton-level production channels. The DM signatures are captured in DUNE near detector by looking at DM-nucleon elastic scattering.

This paper is organized as follows. In Section 2, we have described the leptophobic DM model considered in our analysis which is followed by a note on DUNE near detector. In Section 3, we have discussed different modes of DM production. Section 4 takes up the expression for scattering cross-section of leptophobic DM. We have briefly summarized all the essential parameters that are used in our analysis and discussed about the expression of DM signal rates in Section 5. Section 6 illustrates several experimental and theoretical constraints which are relevant for leptophobic sub-GeV DM. In Section 7, we have briefly discussed the BdNMC simulation tool which is used for DM simulation in our analysis, and sensitivity results of DUNE for leptophobic sub-GeV DM are discussed. At the end, we have concluded our work, in Section 8.

2. Leptophobic Dark Matter Model and DUNE near Detector

The model considered for sub-GeV leptophobic scalar DM candidates, which are charged under a new baryonic gauge group $U(1)_B$, couples with the SM particles through a new vector boson mediator V_B which dominantly interacts with quarks. We have used generation independent coupling of V_B with quarks to make the model simple as it avoids the tree level flavor changing neutral current interactions. In this consideration, to allow the renormalizable Yukawa couplings of quarks to the Higgs boson of SM, coupling of V_B with right and left-handed quarks should be the same. Our considered model, due to the addition of new gauge group $U(1)_B$ to the standard model gauge group, suffers from gauge anomalies [16, 17] and can be considered as nonrenormalizable effective field theory with a cutoff Λ_{UV} [18]. New states, either at or below this cutoff ($\sim m_{V_B}/g_B$), must be introduced for the theory to remain consistent. The simplest choice for the addition of new states is new chiral heavy fermion which helps in the cancellation of the anomaly.

Here, in this work, our focus is on GeV scale phenomenology; hence, the exact details of the UV completion can be ignored, and we can focus our attention on low-energy effective field theory of a local $U(1)_B$ symmetry under which the DM is charged. The Lagrangian of leptophobic scalar DM for low-energy effective field theory can be expressed as

$$
\begin{aligned}
\mathscr{L}_{DM} = & \left| D_\mu \chi \right|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} \left(F_B^{\mu\nu} \right)^2 + \frac{1}{2} m_{V_B}^2 \left(F_B^\mu \right)^2 \\
& - \frac{\varepsilon}{2} F_B^{\mu\nu} F_{\mu\nu} + g_B F_B^\mu J_{B\mu} + \cdots
\end{aligned}
\tag{1}
$$

where $F_{\mu\nu} = [\partial_\mu F_\nu - \partial_\nu F_\mu]$ is the field of SM, $F_B^{\mu\nu} = [\partial^\mu V_B^\nu - \partial^\nu V_B^\mu]$ is the field strength of $U(1)_B$, $D = \partial - ig_B q_B V_B$, g_B is the baryonic gauge coupling, and q_B is the baryonic charge of $U(1)_B$. The J_B^μ represents the sum of baryonic current over all quark species, i.e., $J_B^\mu = 1/3 \sum_i \bar{q}_i \gamma^\mu q_i$. Above Lagrangian includes baryonic coupling (g_B) scenario as well as kinetic mixing (ε) interaction scenario. Two different scenarios at a time are possible and may give some interesting results, but for most cases, either the baryonic coupling scenario or the kinetic mixing scenario will dominate. Therefore, for leptophobic DM scenario, we have set the value of kinetic mixing parameter $\varepsilon \rightarrow 0$ as we want to check constraint on DM parameter space in the presence of baryonic coupling.

The search of MeV scale dark matter in beam dump mode was first performed at the near detector of MiniBooNE, and this search developed the hope for DM searches at fixed-target experiments. The MiniBooNE experiment used 8 GeV accelerated proton beam to produce the DM beam, but the DM signal decreased after the mediator mass became greater than 1 GeV. The upcoming DUNE will use 120 GeV proton beam produced at Fermilab main injector for physics studies of neutrino oscillation hence providing higher energies for the study of dark matter. The far detector of DUNE is proposed to study precise neutrino oscillation physics, whereas the near detector will be capable of probing physics beyond the standard model, sterile neutrinos, nonstandard interaction, low mass DM, etc.

In this manuscript, we have focused on the possibility of upcoming DUNE to probe the dark matter sensitivity. The 120 GeV proton beam after hitting the Beryllium target

produces charged mesons and neutral mesons. The neutral mesons further decay into a pair of DM via baryonic mediator V_B. In beam dump mode, charged mesons get absorbed into thick steel pipe before they can decay into neutrinos. The produced dark matter will hit the 1 ton near detector made up of Ar + CH$_4$ with the ratio of (Ar + CH$_4$: 90 : 10) which will be placed at a distance of 574 m downstream from the center of the Beryllium target. This detector is a 5-m-long cylinder with 5 m diameter [19]. We have considered 90% efficiency of DUNE near detector for sub-GeV dark matter candidates [20].

3. Production of Leptophobic Dark Matter

We have focused on three production channels of leptophobic dark matter for DUNE. The considered production modes are as follows:

(i) Pseudoscalar meson decay

(ii) Bremsstrahlung process

(iii) Parton-level production

3.1. Pseudoscalar Meson Decay. This production channel dominates overall production modes of dark matter at lower masses of vector boson mediator V_B. In this mode, vector boson mediator V_B is produced via radiative decay of pseudoscalar mesons $\rho = \pi^0, \eta$ [8, 9]. These secondary mesons are produced from the primary interaction of $p(p)$ and $p(n)$.

$$p + p(n) \rightarrow X + \pi^0/\eta \rightarrow X + \gamma + V_B \rightarrow X + \gamma + \chi + \chi^\dagger. \quad (2)$$

The pseudoscalar mesons coupling with vector boson V_B takes place under the gauged Wess-Zumino-Witten (WZW) lagrangian [21–23]. If the mass of the secondary meson is greater than the mass of the vector boson mediator V_B, i.e., $m_{V_B} < m_\rho$ or if the mass of DM particle produced is such that $2m_\chi < m_{V_B} < m_\rho$, then V_B will be produced on-shell, and further, it will decay into a pair of DM candidates. Branching ratio of pseudoscalar meson decay to dark matter particles is calculated using narrow width approximation [9] which is equal to the product of mesons decay to V_B and decay of V_B to dark matter.

$$Br(\varrho \rightarrow \gamma\chi\chi^\dagger) = Br(\varrho \rightarrow \gamma V_B)Br(V_B \rightarrow \chi\chi^\dagger),$$

$$Br(\varrho \rightarrow \gamma V_B) = 2\left(c_\varrho \frac{g_B}{\varrho} - \varepsilon\right)^2 \left(1 - \frac{m_{V_B}^2}{m_\varrho^2}\right)^3 Br(\varrho \rightarrow \gamma\gamma). \quad (3)$$

Where g_B is the baryonic coupling constant, g is the electromagnetic coupling constant, m_ρ is the mass of the pseudoscalar mesons, and the value of c_ρ is different for different mesons, i.e., $c_{\pi^0} = 1$ and $c_\eta \approx 0.11$ [24]. We have used the BMPT (Beryllium Material Proton Target) distribution fits [25] in rejection sampling to simulate the momentum and angular distribution of mesons. For the detailed calculation, check the reference [26].

3.2. Bremsstrahlung Process. For intermediate masses of vector boson mediator V_B, resonant vector mesons $R = \omega$ decay by the bremsstrahlung process dominates over other decay processes. Here, the mass of V_B is close to the mass of resonant vector mesons.

$$p + p(n) \rightarrow p + p(n) + V_B \rightarrow . \cdots + \chi + \chi^\dagger. \quad (4)$$

In this process, vector mesons mix with vector boson mediator V_B. This process generates a nearly collimated beam of vector boson V_B. The four momentum of incident proton of mass m_p is $q = (E_p, 0, 0, Q)$ where $E_p = Q + (m_p^2/2Q)$. The four momentum of outgoing vector boson mediator of mass m_{V_B} is $q_{V_B} = (E_{V_B}, q_\perp \cos(\phi), q_\perp \sin(\phi), Q.z)$ where $E_{V_B} = Q.z + (q_\perp^2 + m_{V_D}^2/2Q.z)$, $Q.z = q_\parallel$, and z is a fraction of proton beam momentum carried away by outgoing vector boson V_B in the direction of proton beam. Here, $q_\perp$ and $q_\parallel$ are transverse and longitudinal components of the momenta of V_B.

By Weizsäcker-Williams approximation, the rate of production of vector boson V_B production per proton is as follows [14, 27, 28]:

$$\frac{d^2 N_{V_B}}{dz dq_\perp^2} = \frac{\sigma_{pA}[2m_p(E_p - E_{V_B})]}{\sigma_{pA}(2m_p E_p)} F_{1,N}^2(q^2) f_{yx}(z, q_\perp^2), \quad (5)$$

here, $\sigma_{pA} = f(A)\sigma_{pp}$, $f(A)$ is a function of atomic number A, and $f_{yx}(z, q_\perp^2)$ is a splitting weight-function of photon which relates before and after differential scattering cross-section [27]

$$f_{yx}(z, q_\perp^2) = \frac{\alpha_B}{2\pi H}\left[\frac{1 + (1-z)^2}{z} - 2z(1-z)\left(\frac{2m_p^2 + m_{V_B}^2}{H} - z^2\frac{2m_p^4}{H^2}\right)\right.$$
$$\left. + 2z(1-z)(z + (1-z)^2)\frac{m_p^2 m_{V_B}^2}{H^2} + 2z(1-z)^2\frac{m_{V_B}^4}{H^2}\right], \quad (6)$$

here, $H = q_\perp^2 + (1-z)m_{V_B}^2 + z^2 m_p^2$.

Since radiative V_B has time-like momentum and time-like form factor $F_{1,N}(q^2)$ expresses off-shell mixing of vector bosons with vector mesons in appropriate kinematic region. Baryonic vector portal considers both proton form factor $F_{1,p}(q^2)$ and neutron form factor $F_{1,n}(q^2)$ [29]. These incorporate only isoscalar Breit-Wigner components [29] ω-like in the spacelike regime, and this form factor is not completely resolved for ω. Above 1 GeV, the form factors suppresses the rate of production of virtual bosonic mediator; hence, above this energy, direct parton-level production dominates over other channels.

To calculate the dark photon production rate, equation (5) must be integrated over $p_\perp$ and z in a range that satisfies

some kinematic conditions [27] expressed as

$$E_p, E_{V_B}, E_P - E_{V_B} \gg m_p, m_{V_B}, |q_\perp|. \tag{7}$$

Using the above equation, $z \in [0.2, 0.8]$ and $|p_\perp| = 0.4$ are selected for DUNE in the present work.

3.3. Parton-Level Production of Dark Matter. Above 1 GeV of vector boson mediator V_B mass, this channel becomes significant. This process works under the narrow width approximation via $q\bar{q} \rightarrow V_B$ and can be written as

$$p + p(n) \rightarrow X + V_B \rightarrow X + \chi\chi^\dagger. \tag{8}$$

Dark matter pair production cross-section at parton-level can be expressed as

$$\sigma(pp(n) \rightarrow X + V_B \rightarrow X + \chi\chi^\dagger) = \sigma(pp(n) \rightarrow V_B)Br(V_B \rightarrow \chi\chi^\dagger), \tag{9}$$

where $\sigma(pp(n) \rightarrow V_B)$ cross-section for the production of vector boson V_B and can be written as

$$\sigma(pp(n) \rightarrow V_B) = \frac{\pi}{3m_{V_B}^2} \sum_q \left(\frac{g_B}{3} - \varepsilon g Q_q\right)^2 \int_\zeta^1 \frac{dx}{x} \tau \left[f_{\frac{q}{p}}(x) f_{\frac{\bar{q}}{p(n)}} \right.$$
$$\left. \cdot \left(\frac{\zeta}{x}\right) + f_{\frac{\bar{q}}{p}}(x) f_{\frac{q}{p(n)}}\left(\frac{\zeta}{x}\right) \right], \tag{10}$$

where $\zeta = m_{V_B}^2/s$, $\sqrt{s}$ is the hadron-level center of mass energy, and Q_q is quark charge in the unit of positron electric charge. To calculate the cross-section of the DM production, we have used CTEQ6.6 PDFs [30] and have set $Q = m_{V_B}$ which is allowed to vary from $m_{V_B}/2$ to $2m_{V_B}$. In above equation, $f_{q/p(n)}(x)$ is the parton distribution function (PDF) which gives the probability of extraction of quarks and gluons with longitudinal momentum fraction x from a proton (neutron). Details of the cross-section calculation are discussed in the references [10, 14, 26].

4. Scattering Cross-Section of Leptophobic Dark Matter

In the considered leptophobic dark matter model, dark matter dominantly interacts with the quarks, whereas it does not couple with the leptons. In our work, we have focused on the neutral current elastic scattering of dark matter with nucleons present in the DUNE near detector. The differential cross-section of neutral current DM-nucleon elastic scattering which is similar to the neutrino-nucleon neutral current scattering [31, 32] can

be expressed as

$$\frac{d\sigma_{\chi N \rightarrow \chi N}}{dE_\chi}$$
$$= \alpha_B q_B^2 \times \frac{\tilde{F}_{1,N}^2(Q^2)A(E, E_\chi) + \tilde{F}_{2,N}^2(Q^2)B(E, E_\chi) + \tilde{F}_{1,N}(Q^2)\tilde{F}_{2,N}(Q^2)C(E, E_\chi)}{\left(m_{\gamma_D}^2 + 2m_N(E - E_\chi)\right)^2 \left(E^2 - m_\chi^2\right)}, \tag{11}$$

where E and E_χ represent energy of the incoming and outgoing DM, m_N is the mass of nucleons $(N = p, n)$, and $Q^2 = 2m_N(E - E_\chi)$ is the momentum transfer. The $\tilde{F}_{1,N}^2(Q^2)$ and $\tilde{F}_{2,N}^2(Q^2)$ are monopole and dipole form factors [26], and the values of kinematic functions for complex scalar DM are listed as

$$A = 2m_N E E_\chi - m_\chi^2(E - E_\chi),$$
$$B = \frac{1}{4}(E - E_\chi)\left[(E + E_\chi)^2 - 2m_N(E - E_\chi) - 4m_x^2\right],$$
$$C = -(E - E_\chi)\left(m_N(E - E_\chi) + 2m_\chi^2\right). \tag{12}$$

5. Signal Rates

To simulate the DM event rates, it is essential to incorporate the relevant cuts of detector geometry and energy resolution in the simulation tool. In this work, the detector limitations are listed below [14]:

The expression for the DM events produced by the pseudoscalar mesons and vector mesons can be stated as

$$N_{\chi N \rightarrow \chi N} = n_A \varepsilon_{\text{eff}} \sum_{M=\pi^0, \eta, \omega} \left[N_M Br(M \rightarrow V_B + \cdots) Br(V_B \rightarrow \chi\chi^\dagger) \right.$$
$$\left. \times \left(\frac{1}{N_{\chi M}} \sum_i L_i \sigma_{\chi N, i}\right) \right], \tag{13}$$

where n_A is the atomic number density of detector material, ε_{eff} is the detector efficiency, N_M is the total number of mesons produced in the target, $N_{\chi M}$ is the total number of DM trajectories produced by relevant production channels, and L_i is the length of DM trajectory in the detector. The DM-nucleon elastic scattering cross-section $\sigma_{\chi N}$ is defined as

$$\sigma_{\chi N}(E) = \int_{E_\chi^{\min}}^{E_\chi^{\max}} dE_\chi \sum_{N=p,n} f_N \frac{d\sigma_{\chi, N}}{dE_\chi}, \tag{14}$$

where E represents the energy of incoming dark matter, E_χ represents the energy of outgoing dark matter, and $E_\chi^{\min/\max}$ is the minimum and maximum energy of outgoing DM which is calculated by the relevant experimental cuts that are derived by the experimental data of nucleon recoil

momentum q ($q = \sqrt{2m_N(E - E_\chi)}$). In baryonic vector portal, we take $f_{p,n} = A$ (A is atomic number) for the elastic or quasielastic scattering of DM. For parton-level production channel, we have substituted N_{V_B} (total number of produced vector bosons) in place of $N_M Br(M \to V_B + \cdots)$ in the above equation (13). Total DM events are evaluated by adding the DM events produced via three different channels considered in this work.

6. Constraints on the Leptophobic Dark Matter

In this paper, we are checking the sensitivity of DUNE fixed-target experiment in beam dump mode for leptophobic DM. Several essential constraints that need to be considered for checking the DUNE sensitivity for leptophobic DM are listed below in brief.

6.1. Thermal Relic Dark Matter. In large class of models where DM is considered to be a thermal relic, its cosmological abundance is calculated by the correct thermal relic density of DM (~ 22% of the energy density of the universe) which can be obtained by the measurement of s-wave annihilation cross-section $\langle \sigma_s \rangle \sim 3 \times 10^{-26} \mathrm{cm}^3/s$ during freeze-out. The s-wave annihilation of DM into charged SM particles, in particular, rules out DM masses below 10 GeV, but by adding the p-wave process into the annihilation cross-section of DM, the DM of masses less than 10 GeV can be produced. For the correct reproduction of DM annihilation cross-section with only s-wave process, the most viable annihilation mode of DM is its annihilation into neutrino like states. In this annihilation process, because of the weak interaction of baryonic neutrinos with matter, they are unable to ionize the hydrogen and helium gases; hence, the problem of energy injection around redshift $z \sim 100 - 1000$ is completely ignored, during and after the recombination. In this scenario, the required annihilation cross-section of thermal relic DM (of ~ pb order) can be achieved. The required value of annihilation cross-section imposes constraints on the on-shell production mode and off-shell production mode of DM candidates. In off-shell production mode ($m_{V_B} < m_\chi$; m_{V_B} is the mass of vector boson mediator V_B and m_χ is the DM mass), $\chi \chi^\dagger \to V_B^* \to \nu_b \bar{\nu}_b$ annihilation process can achieve thermal relic DM annihilation cross-section $\langle \sigma v \rangle \sim 1 pb$ by imposing $\alpha_B^2 \sim 10^{-11}(m_\chi/100 \, \mathrm{MeV})^2$ bound. Whereas for the on-shell production mode ($m_{V_B} > m_\chi$), baryonic fine structure constant α_B would require a slightly larger value. In both production modes, baryonic constant $G_B = 4\pi\alpha_B/m_{V_B}^2$ would necessarily be greater than the weak Fermi constant G_F, $G_B \sim (10^2 - 10^3) \times G_F$ [33, 34].

6.2. Direct Detection. Direct detection experiments probe the cross-section of DM-nucleon elastic scattering. The CRESST-II [2] experiment provides the best limit on the recoil energy of nucleons. The CRESST-II experiment can explore the sensitivity of DM masses below 0.5 GeV with detection threshold of nuclear recoil 307 eV. The DM-nucleon scattering cross-section for baryonic current can be expressed as

$$\sigma_{\chi N} \sim \frac{16\pi\alpha_B^2 \mu_{\chi,N}^2}{m_{V_B}^4}, \tag{15}$$

where $\mu_{\chi,N}$ is the reduced mass of DM and nucleons.

6.3. Constraints on Masses of the Vector Boson Mediator V_B. The CDF (Collider Detector at Fermilab) collaboration imposes a rigorous constraints on monojet, $pp \to$ jet + missing energy. The limit imposed on the quarks coupling $g_u < 0.026$ and $g_d < 0.04$ is largely independent of vector boson mass m_{V_B} 10 GeV [35, 36].

6.4. $\pi^0 \to \gamma$ + invisible. The Brookhaven alternating gradient synchrotron [37] imposes limit on the branching ratio $Br(\pi^0 \to \gamma V_B) < 5 \times 10^{-4}$.

6.5. $K^+ \to \pi^+$ + invisible. Dimension-4 coupling of new light vector to the SM state leads to enhance the production rates; however, the current they couple to is conserved. These rare processes allow us to probe new and better constraints on the coupling of such vectors. These new limits arise from range of processes such as K-decays, B-decays, rare Z-decays, and changing meson decays. B-decays constraints will be very useful at B-factories and LHC experiment. For our work, we have considered K-decays only [38–41]. The K-decay imposes a limits on the branching ratio of $Br(K^+ \to \pi^+ V_B) < 10^{-6}$ for $m_{V_B} = 1.8$ MeV and $Br(K^+ \to \pi^+ V_B) < 7 \times 10^{-7}$ for $m_{V_B} = 100$ MeV [42, 43].

6.6. $J/\psi \to$ invisible. BES (Beijing Spectrometer) collaboration imposes a constraint on the branching ratio $Br(J/\psi \to$ invisible) $< 7 \times 10^{-4}$ for larger value of m_{V_B} [44].

6.7. Angular Dependence in Neutron Scattering. The constraints imposed by neutron scattering on the baryonic fine structure constant α_B ($\alpha_B = g_B^2/4\pi$) which couples the DM candidates and SM particles for mediator vector boson mass $m_{V_B} > 1$ MeV is expressed below [45, 46]:

$$\alpha_B < 3.4 \times 10^{-11} \left(\frac{m_{V_B}}{MeV} \right)^4. \tag{16}$$

Existing constraints on the leptophobic DM model are shown in Figures 1 and 2. The plot (4) shows the constraints on the $U(1)_B$ model in the $\alpha_B - m_{V_B}$ parameter space, while the plot (5) shows the constraints on the $U(1)_B$ model in the $\alpha_B - m_\chi$ parameter space for 10 MeV DM mass and $\varepsilon = 0$. The other constraints plotted in Figures 1 and 2 are taken from $K^+ \to \pi^+ \nu \bar{\nu}$, $\pi^0 \to \gamma$ + invisible, Monojet(CDF), Neutron Scattering, and $J/\psi \to$ invisible experiments.

7. Simulation and Results

We have used BdNMC (Beam dump Neutrino Monte Carlo) [47] simulation tool to compute the sensitivity of DUNE near detector for leptophobic DM. This simulation tool works on
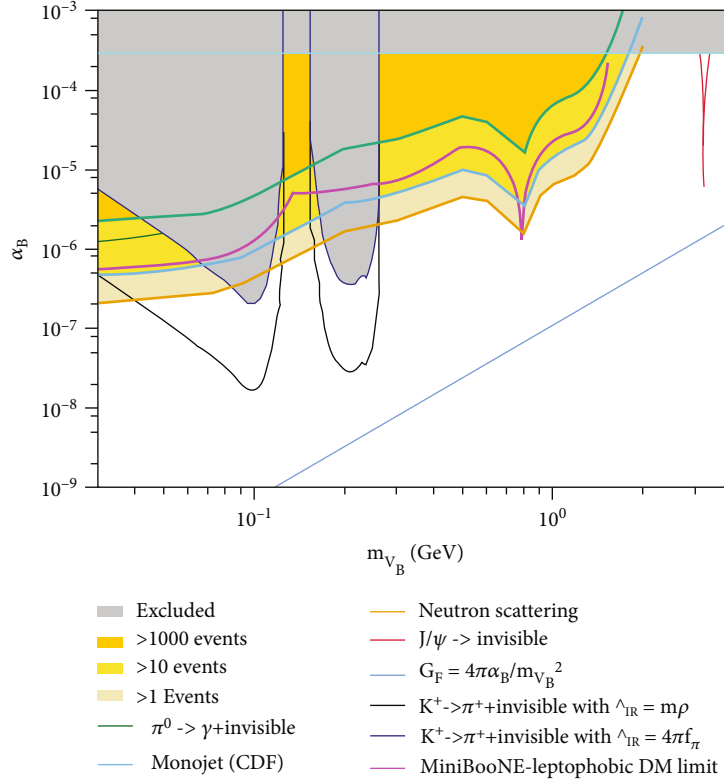
FIGURE 1: Comparison of the DUNE contour sensitivity plots for light dark matter signatures in the parameter space of $\alpha_B - m_{V_B}$ with MiniBooNE confidence level (magenta line) plot [48] and other important experimental exclusion regions. These dark matters are produced from distinct channels by using 120 GeV proton beam. Here, we have considered $m_\chi = 0.01$ GeV, $\varepsilon = 0$ and POT $= 1.1 \times 10^{21}$. In the above plot, the gray regions are excluded by existing constraints, while the yellow contours indicate 1, 10, and 1000 events.

the direct detection technique to probe the sensitivity of the considered experiment running in beam dump mode.

The 120 GeV proton beam of DUNE produces charged and neutral mesons after hitting the beryllium target. These mesons are allowed to propagate through the decay pipe which is made up of steel. The neutral mesons quickly decays in the decay pipe, while charged mesons propagate further and get absorbed in the decay pipe before they decay. The neutral mesons decay into vector mediator V_B which further decays into a pair of DM candidates in the center of mass frame of V_B. The total DM particles produced via distinct production channels (visit Section 3) reach the DUNE near detector which is a cylinder of length 5 m, diameter 5 m, and 1 ton (Ar : CH$_4$::90 : 10) fiducial mass [19]. Using BdNMC simulation tool, the DM event rate is estimated by imposing production distribution function $f(p, \theta)$, specific geometric cuts [19], and recoil energy cuts on nucleons $E_R \in [0.1,2]$ in equation (13). The trajectory of each DM particle which intersects the fiducial mass of near detector is recorded in the form of the energy of DM candidates.

In Figure 3, we have explored the signatures of DM-nucleon scattering events with varying mass of the vector boson mediator m_{V_B} for a fixed value of DM mass, i.e., 10 MeV. From this piece of work, we have observed that the DM signatures coming from the DM produced via mesons decay channel, parton-level production channel, and brems-

strahlung are $\sim 94\%$, $\sim 4\%$, and $\sim 2\%$, respectively, in the mass range from 10 MeV to 300 MeV of V_B. For intermediate mass range of V_B, i.e., from 300 MeV to 1 GeV, the DM events arising by DM produced via resonance decay channel are approximately $\sim 96\%$. Whereas the DM signatures coming from the DM produced via parton-level production channel and mesons decay channel are negligible. For $m_{V_B} > 1$ GeV, the main contribution of DM events arises from parton-level production channel. In this plot, we notice a sharp peak around $m_{V_B} = 3m_\chi \sim m_\omega \sim 800$ MeV which can be attributed to the resonance production via bremsstrahlung process at this point.

In Figure 1, we have presented the sensitivity of DUNE for leptophobic DM scenario in $m_{V_B} - \alpha_B$ parameter space where m_{V_B} is allowed to vary between 0.03 GeV and 2 GeV, and baryonic fine structure constant α_B has been varied from 10^{-9} to 10^{-3}. This study is performed for the DM mass 10 MeV and kinetic mixing parameter $\varepsilon = 0$. The threshold values for recoil nucleons and other essential parameters that have been used in simulation are mentioned in the Table 1. The DM-nucleon elastic scattering event contours for 1, 10, and 1000 events are shown in Figure 1 along with other experimental constraints which are shown by different line colors as mentioned in legends. From Figure 1, we have observed that the allowed parameter space between two sensitivity contours 1 and 10 events is
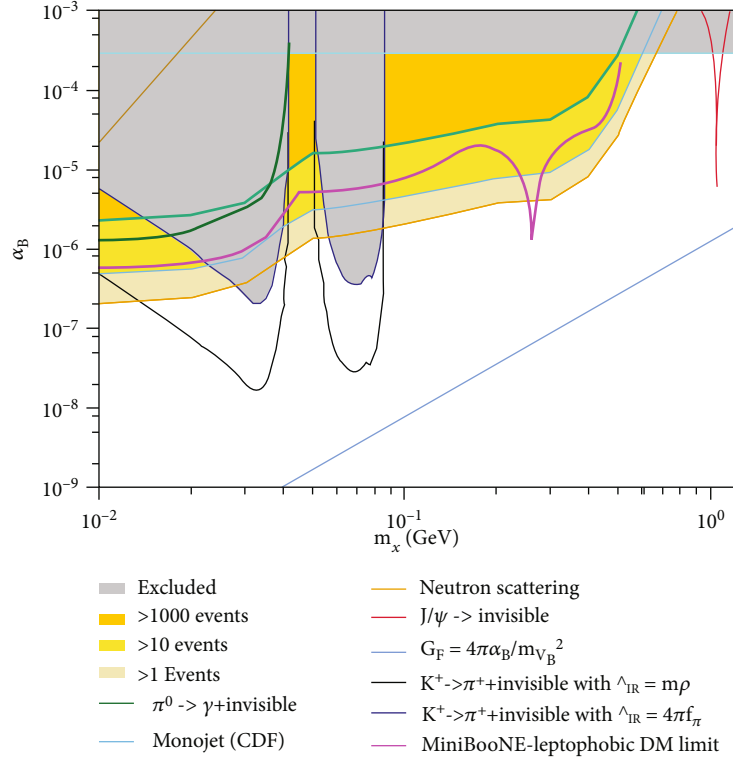
FIGURE 2: Comparison of the DUNE contour sensitivity plots for light dark matter signatures in the parameter space of $\alpha_B - m_\chi$ with MiniBooNE confidence level (magenta line) plot [48] and other important experimental exclusion regions. These dark matters are produced from distinct channels by using 120 GeV proton beam. Here, we have considered $m_{V_B} = 3m_\chi$ GeV, $\varepsilon = 0$, and POT = 1.1×10^{21}. In the above plot, the gray regions are excluded by existing constraints, while the yellow contours indicate 1, 10, and 1000 events.
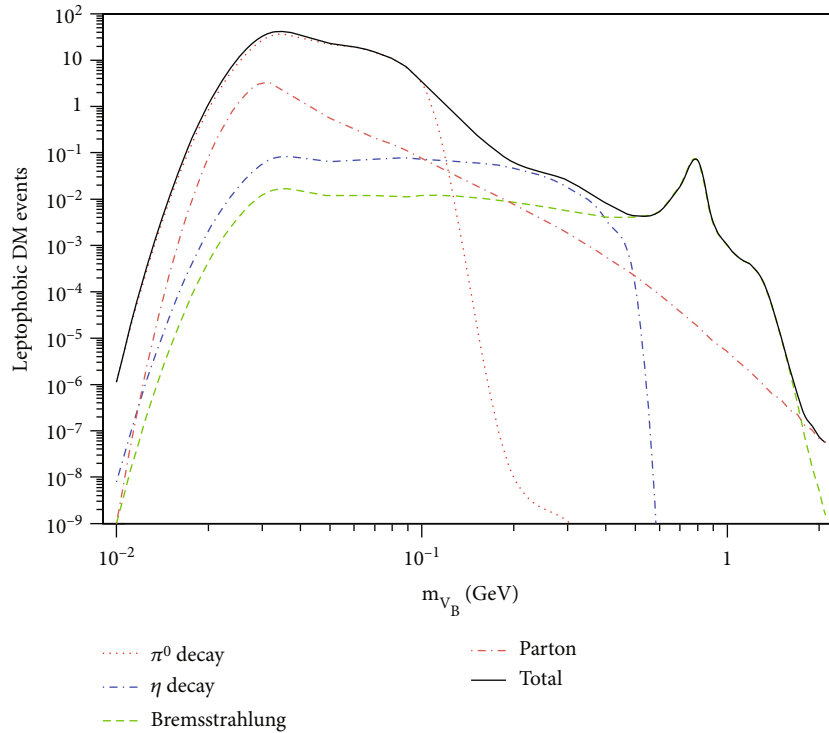

FIGURE 3: Dark matter-nucleon scattering event plot with the variation of mediator vector boson mass for all distinct channels. Here, m_χ = 0.01 GeV, ε =0, $\alpha_B = 10^{-6}$, and POT =1.1×10^{21}.

Table 1: Essential parameters for DUNE near detector.

Name	Target material	E_{beam}	POT	Detector mass (fiducial)	Distance	Angle	Efficiency (ε_{eff})	Cuts on the recoil energy of nucleons
DUNE	Ar + CH$_4$	120 GeV	1.1×10^{21}	1 ton (900 kg + 100 kg)	574 m	0	0.9 [8]	$E_R \in [0.1,2]$ GeV

$[m_{V_B} \in (0.03,1.5)\text{GeV}, \alpha_B \in (2 \times 10^{-7}, 2 \times 10^{-4})]$, the allowed parameter space between two sensitivity contours 10 and 100 events is $[m_{V_B} \in (0.03,1.5)\text{GeV}, \alpha_B \in (3 \times 10^{-7}, 2 \times 10^{-4})]$, and the allowed parameter space for DM events greater than 1000 events is $[m_{V_B} \in (0.1,1.5)\text{GeV}, \alpha_B \in (3 \times 10^{-6}, 2 \times 10^{-4})]$. A sharp peak around $m_{V_B} \sim m_\omega \sim 800$ MeV which can be attributed to the resonance production via bremsstrahlung process at this point. This plot shows that DUNE can probe DM for baryonic fine structure coupling below the existing bound on the coupling value $\alpha_B \simeq 10^{-6}$; these lower coupling values are present for mass of vector boson mediator V_B less than 200 MeV.

Figure 2 shows the contour plot of DM-nucleon elastic scattering events in $m_\chi - \alpha_B$ plane where the variation of m_χ is from 0.01 GeV to 1 GeV and α_B is varied from 10^{-9} to 10^{-3}. This study is performed for kinetic mixing parameter $\varepsilon = 0$ and vector boson mass $m_{V_B} = 3m_\chi$. The threshold values for recoil nucleons and other essential parameters that are used in simulation for probing DM events are mentioned in Table 1. The three contours of Figure 2 represent the 1, 10, and 1000 events in the parameter space of $m_\chi - \alpha_B$. From Figure 1, we have observed that the allowed parameter space between two sensitivity contours 1 and 10 events is $[m_\chi \in (0.01,0.7)\text{GeV}, \alpha_B \in (2 \times 10^{-7}, 2 \times 10^{-4})]$, the allowed parameter space between two sensitivity contours 10 and 100 events is $[m_\chi \in (0.01,0.7)\text{GeV}, \alpha_B \in (3 \times 10^{-7}, 2 \times 10^{-4})]$, and the allowed parameter space for DM events greater than 1000 events is $[m_\chi \in (0.04,0.7)\text{GeV}, \alpha_D \in (3 \times 10^{-6}, 2 \times 10^{-4})]$. A sharp peak around $m_\chi \sim (m_\omega/3) \sim 800$ MeV which can be attributed to the resonance production via bremsstrahlung process at this point. In this study, we observe that the vector boson mediator V_B shows weak coupling (below the existing limit of $\alpha_B = 10^{-6}$) for DM masses less than 250 MeV.

Figures 1 and 2 shows that like DUNE, $\pi^0 \to \gamma$ + invisible and $K^+ \to \pi^+$ + invisible can also explore the DM signatures at lower coupling values, but DUNE can explore DM signatures for higher values of V_B as compared to the stated experiments. The MiniBooNE sensitivity for leptophobic DM at 90% C.L. is also plotted for comparative study.

8. Conclusion

In our work, we have explored the sensitivity of DUNE in beam dump mode for leptophobic DM. In the considered DM model, DM candidates couple with the SM particles via vector boson mediator V_B of a new baryonic gauge group $U(1)_B$ with coupling strength α_B. The leptophobic DM signatures are observed via DM-nucleon elastic scattering in the parameter space of $m_{V_B} - \alpha_B$ and $m_\chi - \alpha_B$. The analysis of Figures 1 and 2 illuminates that the DUNE sensitivity for leptophobic light DM is better as the constraint imposed on the coupling value α_B by DUNE is lower than the present constraint value of the coupling value $\alpha_B \simeq 10^{-6}$. These lower coupling values can be explored by DUNE for vector boson mediator mass $m_{V_B} < 200$ MeV. Therefore, DUNE in beam dump mode will be able to provide the new results for leptophobic DM. DUNE potential to probe dark matter for lower dark matter coupling values is better than the MiniBooNE potential. These results will help us to understand the nature of DM and its interactions.

Data Availability

All my data are self generated by the dark matter simulation tool "BdNMC".

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] E. Aprile, M. Alfonsi, K. Arisaka et al., "Dark matter results from 225 live days of XENON100 data," 2013, https://arxiv.org/abs/1207.5988v2.

[2] G. Angloher, A. Bento, C. Bucci et al., "Results on light dark matter particles with a low-threshold CRESST-II detector," 2016, https://arxiv.org/abs/1509.01515v2.

[3] R. Agnese, A. J. Anderson, T. Aramaki et al., "WIMP-search results from the second CDMSlite run," 2016, https://arxiv.org/abs/1509.02448v2.

[4] A. Tan, M. Xiao, X. Cui et al.et al., "Dark matter results from first 98.7 days of data from the PandaX-II experiment," 2016, https://arxiv.org/abs/1607.07400v3.

[5] D. S. Akerib, S. Alsum, H. M. Araújo et al., "Results from a search for dark matter in the complete LUX exposure," 2017, https://arxiv.org/abs/1608.07648v3.

[6] A. A. Aguilar-Arevalo, B. Batell, R. Cooper et al., "Low mass WIMP searches with a neutrino experiment: a proposal for further MiniBooNE running," 2012, https://arxiv.org/abs/1211.2258v1.

[7] P. de Niverville and C. Frugiuele, "Hunting sub-GeV dark matter with NOνA near detector," 2018, https://arxiv.org/abs/1807.06501v1.

[8] B. Batell, M. Pospelov, and A. Ritz, "Exploring portals to a hidden sector through fixed targets," 2009, https://arxiv.org/abs/0906.5614v2.

[9] P. de Niverville, M. Pospelov, and A. Ritz, "Observing a light dark matter beam with neutrino experiments," 2013, https://arxiv.org/abs/1107.4580v3.

[10] P. de Niverville, D. McKeen, and A. Ritz, "Signatures of sub-GeV dark matter beams at neutrino experiments," 2012, https://arxiv.org/abs/1205.3499v1.

[11] E. Izaguirre, G. Krnjaic, P. Schuster, and N. Toro, "New electron beam-dump experiments to search for MeV to few-GeV dark matter," 2013, https://arxiv.org/abs/1307.6554v2.

[12] M. D. Diamond and P. Schuster, "Searching for light dark matter with the SLAC millicharge experiment," 2013, https://arxiv.org/abs/1307.6861v1.

[13] E. Izaguirre, G. Krnjaic, P. Schuster, and N. Toro, "Physics motivation for a pilot dark matter search at Jefferson Laboratory," 2014, https://arxiv.org/abs/1403.6826v1.

[14] S. Naaz, J. Singh, and R. B. Singh, "DUNE potential for sub-GeV dark matter in proton beam dump mode," 2019, https://arxiv.org/abs/1912.08468v3.

[15] R. Acciarri, M. A. Acero, A. Adamowski et al., "Long-baseline neutrino facility (LBNF) and deep underground neutrino experiment (DUNE)," 2016, https://arxiv.org/abs/1601.02984v1.

[16] B. A. Dobrescu and C. Frugiuele, "Hidden GeV-scale interactions of quarks," 2014, https://arxiv.org/abs/1404.3947v2.

[17] M. Duerr, P. F. Perez, and M. B. Wise, "Gauge theory for baryon and lepton numbers with leptoquarks," 2013, https://arxiv.org/abs/1304.0576v2.

[18] J. Preskill, "Gauge anomalies in an effective field theory," *Annals of Physics*, vol. 210, no. 2, pp. 323–379, 1991.

[19] "High-Pressure Argon gas TPC Option for the DUNE Near Detector, DUNE HPgTPC WGFermi National Accelerator Laboratory, Batavia, IL, USA.

[20] G. Brown, *Sensitivity Study for Low Mass Dark Matter Search at DUNE*, 2018.

[21] J. Wess and B. Zumino, "Consequences of anomalous Ward identities," *Physics Letters B*, vol. 37, no. 1, pp. 95–97, 1971.

[22] E. Witten, "Global aspects of current algebra," *Nuclear Physics B*, vol. 223, no. 2, pp. 422–432, 1983.

[23] Ö. Kaymakcalan, S. Rajeev, and J. Schechter, "Non-Abelian anomaly and vector-meson decays," *Physical Review D*, vol. 30, no. 3, pp. 594–602, 1984.

[24] K. J. Kelly and Y.-D. Tsai, "Proton fixed-target scintillation experiment to search for minicharged particles," 2018, https://arxiv.org/abs/1812.03998v2.

[25] M. Bonesini, A. Marchionni, F. Pietropaolo, and T. Tabarelli de Fatis, "On particle production for high energy neutrino beams," *The European Physical Journal C*, vol. 20, no. 1, pp. 13–27, 2001.

[26] B. Batell, P. de Niverville, D. McKeen, M. Pospelov, and A. Ritz, "Leptophobic dark matter at neutrino factories," 2014, https://arxiv.org/abs/11405.7049v1.

[27] J. Blümlein and J. Brunner, "New exclusion limits on dark gauge forces from proton bremsstrahlung in beam-dump data," 2013, https://arxiv.org/abs/1311.3870v1.

[28] D. Gorbunov, A. Makarov, and I. Timiryasov, "Decaying light particles in the SHiP experiment: signal rate estimates for hidden photons," 2015, https://arxiv.org/abs/1411.4007v2.

[29] A. Faessler, M. I. Krivoruchenko, and B. V. Martemyanov, "Once more on electromagnetic form factors of nucleons in extended vector meson dominance model," 2010, https://arxiv.org/abs/0910.5589v1.

[30] P. M. Nadolsky, H.-L. Lai, Q. -H. Cao et al., "Implications of CTEQ global analysis for collider observables," 2008, https://arxiv.org/abs/0802.0007v3.

[31] A. A. Aguilar-Arevalo, C. E. Anderson, A. O. Bazarko et al., "Measurement of the neutrino neutral-current elastic differential cross section, Phy," 2010, https://arxiv.org/abs/1007.4730v1.

[32] T. Leitner, *Neutrino Interactions with Nucleons and Nuclei*, Thesis, Giessen U, 2005.

[33] M. Pospelov, "Neutrino physics with dark matter experiments and the signature of new baryonic neutral currents," *Physical Review D*, vol. 84, no. 8, article 085008, 2011.

[34] B. W. Lee and S. Weinberg, "Cosmological lower bound on heavy-neutrino masses," *Physical Review Letters*, vol. 39, no. 4, pp. 165–168, 1977.

[35] I. M. Shoemaker and L. Vecchi, "Unitarity and monojet bounds on models for DAMA, CoGeNT, and CRESST-II," 2012, https://arxiv.org/abs/1112.5457v3.

[36] H. An, X. Jia, and L.-T. Wange, "Light dark matter and Z' dark force at colliders," 2012, https://arxiv.org/abs/1202.2894v1.

[37] M. S. Atiya, I. H. Chiang, J. S. Frank et al., "Search for the decay $\pi^0 \to \gamma + X$," *Physical Review Letters*, vol. 69, no. 5, pp. 733–736, 1992.

[38] J. A. Dror, R. Lasenby, and M. Pospelov, "Dark forces coupled to non-conserved currents," https://arxiv.org/abs/1707.01503v2.

[39] A. A. Aguilar-Arevalo, M. Backfish, A. Bashyal et al., "Dark matter search in a proton beam dump with MiniBooNE," https://arxiv.org/abs/1702.02688v3.

[40] J. A. Dror, R. Lasenby, and M. Pospelov, "New constraints on light vectors coupled to anomalous currents," https://arxiv.org/abs/1705.06726v2.

[41] P. Ilten, Y. Soreq, M. Williams, and W. Xue, "Serendipity in dark photon searches," https://arxiv.org/abs/1801.04847v2.

[42] A. E. Nelson and N. Tetradis, "Constraints on a new vector boson coupled to baryons," *Physics Letters B*, vol. 221, no. 1, pp. 80–84, 1989.

[43] A. V. Artamonov, B. Bassalleck, B. Bhuyan et al., "Study of the decay $K^+ \to \pi^+ \nu \bar{\nu}$ in the momentum region $140 < P_\pi < 199$ MeV/c," 2009, https://arxiv.org/abs/0903.0030v1.

[44] M. Ablikim, J. Z. Bai, Y. Ban et al., "Search for invisible decays of the J/ψ in $\psi(2S) \to \pi^+ \pi^- J/\psi$," 2008, https://arxiv.org/abs/0710.0039v2.

[45] R. Barbieri and G. Curci, "On the Higgs coupling to nucleons and pions," *Physics Letters B*, vol. 219, no. 4, pp. 503–506, 1989.

[46] S. Tulin, "MCTP-14-08 New weakly-coupled forces hidden in low-energy QCD," 2014, https://arxiv.org/abs/1404.4370v1.

[47] P. de Niverville, C. -Y. Chen, M. Pospelov, and A. Ritz, "Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and SHiP," 2017, https://arxiv.org/abs/1609.01770v3.

[48] A. A. Aguilar-Arevalo, M. Backfish, A. Bashyal et al., "Dark matter search in nucleon, pion, and electron channels from a proton beam dump with MiniBooNE," *Physical Review D*, vol. 98, no. 11, 2018.