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Hunt for sub-GeV dark matter at neutrino facilities: A survey of past and present experiments

Luca Buonocore,[1,2,*] Claudia Frugiuele,[3,4,†] and Patrick deNiverville[5,6,‡]
[1]*Dipartimento di Fisica, Università di Napoli Federico II and INFN,*
Sezione di Napoli, I-80126 Napoli, Italy
[2]*Physik Institut, Universität Zürich, CH-8057 Zürich, Switzerland*
[3]*CERN, Theoretical Physics Departments, Geneva, Switzerland*
[4]*INFN, Sezione di Milano, Via Celoria 16, I-20133 Milano, Italy*
[5]*Center for Theoretical Physics of the Universe, IBS, Daejeon 34126, Korea*
[6]*T2, Los Alamos National Laboratory (LANL), Los Alamos, New Mexico, USA*

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We survey the sensitivity of past and present neutrino experiments to MeV-GeV scale vector portal dark matter and find that these experiments possess novel sensitivity that has not yet fully explored. Taking $\alpha_D = 0.1$ and a dark photon to dark matter mass ratio of three, the combined recast of previous analyses of Big European Bubble Chamber and a projection of NOνA's sensitivity are found to rule out the scalar thermal target for dark matter masses between 10 and 100 MeV with existing data, while CHARM-II and MINERνA place somewhat weaker limits. These limits can be improved by off-axis searches using the NuMI beam line and the MicroBooNE, MiniBooNE, or ICARUS detectors and can even begin to probe the Majorana thermal target. We conclude that past and present neutrino facilities can search for light dark matter concurrently with their neutrino program and reach a competitive sensitivity to proposed future experiments.

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I. INTRODUCTION

A program for the direct detection of light dark matter (LDM) in the keV-GeV mass range has recently been advanced as many current dark matter searches are insensitive to DM below a few GeV in mass. This program has already borne fruit despite being only a few years old. It was shown that a new generation of DM direct detection experiments could be built with current or near-future technologies [1] and the first dedicated sub-GeV direct detection experiment (SENSEI) has already begun taking data [2]. It is timely to pose the question of how we can efficiently search for LDM in our laboratories. While high energy colliders have limited sensitivity to light, ultraweakly coupled particles, accelerator experiments such as fixed-target experiments and low energy colliders (the so-called *intensity frontier*) represent an ideal playground [3], with the advantage that the DM is produced with relativistic energies [4–7]. This has stimulated a wave of interest in accelerator-based LDM searches leading to the proposal of many new dedicated experiments (e.g., SHiP [8], LDMX [9–11], BDX [12,13]), which are under study by major laboratories. The neutrino program is extensive, with many experiments currently running and even more in preparation, such as the Fermilab program at the booster beam line with three liquid argon detectors: SBND, MicroBooNE, and ICARUS [14]. However, the attempt to make full use of existing neutrino fixed-target experiments for DM searches is limited to a few experiments, analysis techniques, and DM signatures [6,15–28], with the strongest sensitivity coming from the NOνA [25] experiment at Fermilab [25]. We also discuss the possibilities offered by experiments aiming to measure the coherent neutrino-nucleus scattering [29,30]. In particular, a recent analysis of released COHERENT CsI data [31], which made use of a novel strategy based on timing spectra in a pulsed proton beam, hints at a roughly 2σ excess in the region where dark matter scattering would be expected. Coherent CAPTAIN-Mills [32] has recently completed an engineering run at Los Alamos National Laboratory and will publish a dark matter analysis sometime in 2020.

In the present paper, we will thoroughly investigate the potential of electron-DM scattering signatures at neutrino fixed-target experiments, considering for the first time the sensitivity of past experiments such as CHARM-II [33], Big European Bubble Chamber (BEBC) [34], and MINERνA [35], We also revisit the sensitivity of current

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[*]luca.buonocore@na.infn.it
[†]claudia.frugiuele@cern.ch
[‡]pgdeniverville@gmail.com

experiments such as MiniBooNE, MicroBooNE, and ICARUS to vector portal dark matter when treated as off-axis detectors for the NuMi beam line (see Refs. [36] for some other dark sector searches using the aforementioned detectors and the NuMI beam line).

The paper is organized as follows: in Sec. II, we define a benchmark LDM model. Section III summarizes the main aspects of DM searches at neutrino facilities, and Sec. IV presents the results of the sensitivity studies.

II. VECTOR PORTAL

We consider as a benchmark model a dark sector coupled to the Standard Model through the vector portal. Specifically, we introduce a dark photon (DP) [37–39] A'_μ as the gauge boson of a new dark gauge group $U(1)_D$ kinetically mixed with the photon, and a scalar χ charged under $U(1)_D$ that serves as a DM candidate,

$$\mathcal{L}_{\mathrm{DM}} = \mathcal{L}_{A'} + \mathcal{L}_{\chi}, \tag{2.1}$$

where

$$\mathcal{L}_{A'} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{m_{A'}^2}{2}A'^{\mu}A'_{\mu} - \frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu}, \tag{2.2}$$

where ϵ is the DP-photon kinetic mixing, while

$$\mathcal{L}_{\chi} = ig_D A'^{\mu}J^{\chi}_{\mu} + \partial_\mu\chi^\dagger\partial^\mu\chi - m_\chi^2\chi^\dagger\chi, \tag{2.3}$$

where $J^{\chi}_{\mu} = [(\partial_\mu\chi^\dagger)\chi - \chi^\dagger\partial_\mu\chi]$ and g_D is the $U(1)_D$ gauge coupling. The region of the parameter space to which neutrino facilities are most sensitive is $m_{A'} > 2m_\chi$ and $g_D \gg \epsilon e$, which implies that the DP decays promptly into a $\chi\chi^\dagger$ pair.

We focus on the region where χ is a thermal relic compatible with the observed DM relic energy density. A complex scalar dark matter candidate χ is safe from constraints from precise measurements of the temperature anisotropies of the cosmic microwave background (CMB) radiation [40,41]. Other compelling choices for DM not in tension with the CMB include a Majorana fermion or pseudo-Dirac fermion with a mass splitting. In the following, we will also comment on these other candidates since the sensitivity of neutrino experiments to LDM does not significantly depend on its spin.

For $m_{A'} > 2m_\chi$, the annihilation cross section for a scalar dark matter particle can be written as [42]

$$\sigma(\chi\chi \to f\bar{f})v \sim \frac{8\pi v^2 Y}{m_\chi^2}, \tag{2.4}$$

where v is the relative DM velocity and Y is defined as

$$Y \equiv \epsilon^2\alpha_D\left(\frac{m_\chi}{m_{A'}}\right)^4. \tag{2.5}$$

We will present the sensitivity of neutrino facilities in the (Y, m_χ) plane, since this allows us to identify the so-called thermal targets, regions of the parameter space where, for a certain scenario, the correct DM thermal abundance is obtained [3,42].

We consider as benchmark point $\alpha_D = 0.1$ following [43], for which the most important existing constraints on the (Y, m_χ) are as follows:

(i) Laboratory bounds: The strongest laboratory constraints for $m_\chi > 60$ MeV come from a monophoton search performed by *BABAR* [44] that excludes the existence of a DP with $\epsilon > 10^{-3}$ and $m_{A'} < 8$ GeV decaying into $\chi\bar{\chi}$. For a complex scalar with our benchmark parameters, *BABAR* bounds constrain thermal relics to be lighter than 100 MeV [44]. The NA64 Collaboration has recently published very strong limits for DP masses below 150 MeV [45] via a missing energy analysis. For large α_D, experiments looking at electron-DM scattering such as LSND [46,47], MiniBooNE [20,21], E137 [48–50], and NOνA [25] and capable of competing with NA64 for dark matter masses below few tens of MeV.

(ii) Direct detection: In the region where the χ relic abundance corresponds to the observed DM abundance and for large values of α_D, CRESST-II and III place strong constraints on $m_\chi > 500$ MeV [51–54]. However, as direct detection experiments lose sensitivity if DM is a Majorana or pseudo-Dirac fermion, we will not present the constraints coming from direct detection in our sensitivity plots. As was already mentioned in the Introduction, many new ideas to probe the sub-GeV thermal DM parameter space via a direct detection experiment have been proposed [3]. For example, SENSEI can discover or exclude the scalar thermal target for DM masses below 100 MeV [2] in the near future, and Refs. [55,56] detail a new fermionic dark matter signal that can potentially probe MeV-scale dark matter masses.

(iii) Astrophysical and cosmological bounds: The $U(1)$ gauge coupling α_D is bounded by the constraint on the DM self-scattering cross section coming from halo shape and bullet cluster observations, that is,

$$\frac{\sigma}{m_\chi} \lesssim \text{few} \times \mathrm{cm}^2/\mathrm{g}. \tag{2.6}$$

In the whole MeV-GeV region values $\alpha_D \lesssim 0.1$ are allowed, while for $m_\chi > 10$ MeV even larger values of α_D up to $\alpha_D \lesssim 0.5$ which is the upper bound suggested by the running of α_D [57]. Furthermore, for the minimal DP model considered here, a complex scalar lighter than 6.9 MeV is ruled out [58] by the Planck measurement of N_{eff} [41].

III. DM PRODUCTION AND DETECTION AT NEUTRINO FACILITIES

Fixed-target neutrino facilities collide high-intensity proton beams with thick targets, producing large numbers of mesons whose leptonic decays generate a neutrino beam. The properties of the neutrino beam may be studied in both near and far detectors, located anywhere from tens of meters to hundreds of kilometers downstream of the target. Depending on the detector, both electron-neutrino and nucleon-neutrino interactions may be observed. Near detectors with relatively short baseline distances and large volumes can also serve as ideal LDM experiments [6]. Rare meson decays (see Refs. [59,60] for a previous approach to dark photon production through rare meson decays at the SPS for NOMAD, PS191 and CHARM-I) and bremsstrahlung can produce LDM alongside the neutrino beam mentioned above. These LDM particles can then be detected through their interactions with the nucleons and electrons of the neutrino detector, or if unstable and sufficiently long-lived, through their decays to visible particles. Electron scattering, in particular, provides one of the most promising signals for LDM particles with masses below 100 MeV [21,25,47].

The total number of DM particles produced through the decay of some pseudoscalar meson ϕ is given by

$$N_\chi = 2N_{\mathrm{POT}} N_{\phi/\mathrm{POT}} \mathrm{Br}(\phi \to \chi\chi^\dagger), \tag{3.1}$$

while the total number of DM particles produced in the target via bremsstrahlung is

$$N_\chi = \frac{2N_{\mathrm{POT}}}{\sigma_{\mathrm{T}}(pp)} \sigma_{\mathrm{T}}(pp \to A'X), \tag{3.2}$$

where the factor of 2 takes into account the production of the $\chi\bar{\chi}$ pair, N_{POT} is the number of protons on target, and $\sigma_{\mathrm{T}}(pp)$ is the total proton-proton cross section.

A. Electron-DM scattering inside the near detector

DM-electron scattering is a very promising signature for new physics searches due to the suppressed neutrino signal that can be further reduced with the appropriate cuts. We can approximate the inclusive electron-neutrino scattering cross section by [61]

$$\sigma(\nu_l e) \sim 10^{-42} \left(\frac{E_\nu}{\mathrm{GeV}}\right) \mathrm{cm}^{-2}, \tag{3.3}$$

while for $E_\chi \gg m_V$ the DM-electron elastic cross section is

$$\sigma(\chi e) \sim \frac{4\pi\alpha_D \alpha \epsilon^2}{m_{A'}^2} \sim 10^{-27} \alpha_D \epsilon^2 \left(\frac{100\ \mathrm{MeV}}{m_{A'}}\right)^2 \mathrm{cm}^{-2}, \tag{3.4}$$

such that for $\epsilon \sim 10^{-4}$–10^{-5} and a light DP the DM-electron scattering cross section is still orders of magnitude larger than the neutrino-electron cross section. Hence, we write the number of signal events $S_{\chi e \to \chi e}$ as

$$S_{\chi e \to \chi e} = L_d n_e \int \frac{dN_{\mathrm{T}}(E_\chi)}{d_{E_\chi}} \sigma(\chi e) dE_\chi, \tag{3.5}$$

where L_d is the longitudinal length of the detector, n_e is the electron number density inside the detector, while $dN_{\mathrm{T}}(E_\chi)/dE_\chi$ is the differential number of dark matter particles per unit energy incident on the detector, written generically as

$$\frac{dN_{\mathrm{T}}(E_\chi)}{dE_\chi} = \epsilon_{\mathrm{det}} 2N_{\mathrm{POT}} \left(\frac{1}{\sigma_{\mathrm{T}}(pp)} \frac{d\sigma_{\mathrm{T}}(pA \to \chi\bar{\chi})}{dE_\chi}\right). \tag{3.6}$$

In the formula above, ϵ_{det} indicates the acceptance of the detector under investigation, $\sigma_{\mathrm{T}}(pp)$ is again the total interaction cross section between a proton and the target material, and $\sigma_{\mathrm{T}}(pA \to \chi\bar{\chi})$ is the dark matter production cross section in proton-A collisions, where A is the target material.

It is challenging experimentally to distinguish an electron shower from the (large) neutral current (NC) events background. However, elastic scattering events are characterized by no hadronic activity near the interaction vertex, and

$$E\theta^2 < 2m_e, \tag{3.7}$$

and indeed imposing this cut could reduce the NC background to a manageable level. This level of background reduction, however, requires detectors with good angular resolution. A handful of experiments (LSND [46], CHARM-II [33,62], MINERνA [35], NOνA, MiniBooNE (MB) [21], and MicroBooNE (MC) [63]) are equipped to distinguish such a signal. In the following section, we will study their sensitivity. Moreover, a new generation of liquid argon detectors will soon be running at Fermilab. ICARUS is being installed and commissioned, and SBND is in the design and construction phase, and as such, we will also evaluate their future reach.

(i) CHARM-II [33,62] was a CERN-based experiment which performed runs with proton energies of 400 and 450 GeV. It took data from 1987 to 1991, collecting a total of 2.5×10^{19} POT. The target calorimeter was 36 m long and consisted of 420 modules with cross sections of $3.70 \times 3.70\ \mathrm{m}^2$. The total detector mass was 692 tons with a fiducial mass of 450 tons (see Table I for important geometrical information). CHARM-II performed a dedicated analysis of $\nu - e$ scattering [64], which can be recast to obtain its sensitivity to the sub-GeV DM parameter space.

We took the number of π^0 (η) mesons to be $6.35 \times \mathrm{POT}$ ($0.726 \times \mathrm{POT}$), with their momenta and

TABLE I. Summary of experiments and their geometry. Beneath the name of each experiment is the energy of the proton beam incident upon its target. POT stands for the total number of protons on target, and d indicates the distance of the detector from the target. In the last two columns, the selection requirements applied to signal events and the number of neutrino background events which pass the same criteria are reported. The BEBC, CHARM-II, and MINERνA detectors are located on axis with respect to the beam line, while MB, MC, and ICARUS are located off axis by an angle of $\theta = 6.5°, 5.7°$, and $7.5°$ from the NuMi beam line, respectively. For the latter, we consider a background free analysis, as an off-axis signal should have greatly reduced beam-related backgrounds.

Experiment	d (m)	n_{det} (g/cm^3)	Mass (tons)	POT	Cuts	n_{bkg}
MB NuMI [67] 120 GeV	745	0.69	800	6×10^{20}	$\cos\theta > 0.99$ $E^{\mathrm{rec}} > 75$ MeV	~ 0
MC NuMI [63] 120 GeV	684	1.4	89	10^{21}	$\cos\theta > 0.99$ $E^{\mathrm{rec}} > 75$ MeV	~ 0
MINERνA [35] 120 GeV	980	0.9	6.1	3.43×10^{20}	$E^{\mathrm{rec}}\theta^2 < 3.2\,\mathrm{MeV}$ $E^{\mathrm{rec}} > 0.8$ GeV	137 ± 17 [35]
CHARM-II [33] 450 GeV	871	1.4	692	2.5×10^{19}	$E^{\mathrm{rec}} \in [3, 24]$ GeV $E^{\mathrm{rec}}\theta^2 < 1\,\mathrm{MeV}$	5429 ± 170 [68]
BEBC/WA66 [34] 400 GeV	406	0.69	11.5	2.72×10^{18}	$E^{\mathrm{rec}}\theta^2 < 2m_e$ $E^{\mathrm{rec}} > 0.8$ GeV	1 ± 1 [65]
ICARUS NuMI [69] 120 GeV	789	1.4	500	10^{21}	$\cos\theta > 0.99$ $E^{\mathrm{rec}} > 75$ MeV	~ 0

angular distribution determined by a PYTHIA8 simulation (see Sec. III B for further details). We selected dark matter-electron scattering events with electron recoil energies between 3 and 24 GeV and assumed a reconstruction efficiency of 0.73. We placed a 90% limit on 340 dark matter induced electron recoil events.

(ii) BEBC/WA66 [34]: The WA66 experiment used the BEBC, a large detector located at CERN and installed in the early 70s, to detect neutrinos produced by dumping 400 GeV protons from the CERN SPS into a copper block large enough to contain almost the entire hadronic cascade. This long target suppresses the standard neutrino flux by almost 3 orders of magnitude (i.e., emitted by pion or kaon decays), while prompt neutrinos (for instance, those created by D-meson decays) were still copiously produced and reached the detector. This specific feature makes this experiment suitable for new physics searches, and hence a new physics analysis is available to be recast [65].

Compared to CHARM-II, BEBC operated with a slightly lower energy beam (400 GeV, equal to the lower energy run of CHARM-II) and produced slightly fewer mesons as a result, with $N_{\pi^0} = 6.15 \times \mathrm{POT}$ and $N_\eta = 0.703 \times \mathrm{POT}$. The analysis cuts used were $E\theta^2 < 2m_e$, $E^{\mathrm{reco}}_{\mathrm{min}} > 0.8$ GeV with a reconstruction efficiency of 0.8. The 90% confidence limit corresponds to 3.5 new physics events.

(iii) NOνA [35] is a Fermilab-based long-baseline neutrino experiment located slightly off axis from the NuMI beam. Its near detector is located 990 m downstream of the NuMI target with 125 tons of active mass. The reach of the existing neutrino-electron analysis [66] was previously studied in Ref. [25]. The following cuts were applied: $E\theta^2 < 5\ \mathrm{MeV\,rad}^2$ and the recoil energy was considered in the range 0.5–5 GeV. The reconstruction efficiency was taken to be 50% with a total background of ~ 580 events for 2.97×10^{20} POT [25,66].

(iv) MINERνA [35] is a neutrino scattering experiment currently running that uses the NuMI beam line at Fermilab. It performed a neutrino electron scattering analysis [35] intending to improve the precision in measuring the neutrino flux. However, the possible new physics contribution arising from DM-electron scattering was not taken into account. We will study here for the first time whether the sensitivity to LDM might be significant. The number of mesons produced by the NuMI beam line was estimated by PYTHIA to be $N_{\pi^0} = 4.176 \times \mathrm{POT}$ and $N_\eta = 0.474 \times \mathrm{POT}$. We applied the following cuts $E\theta^2 < 3.2\ \mathrm{MeV\,rad}^2$ in our analysis and placed a 90% exclusion on 41 dark matter induced recoil events.

(v) MiniBooNE off-axis (MBOA) is a Fermilab-based 800-ton detector. It collected data both as an on-axis detector from the booster beam line (8.9 GeV) and as a detector located 6.5° off axis from the NuMI beam line (120 GeV) [67]. An analysis considering DM-electron scattering was recently published by the MiniBooNE Collaboration [21] considering an 8.9 GeV run in beam dump mode. Here, we consider instead the possible sensitivity of the off-axis NuMI data with the same meson production estimates as those quoted for MINVERνA above. We applied the same cuts as [21] ($\cos\theta > 0.99$, $E^{\mathrm{reco}}_{\mathrm{min}} > 75$ MeV), assumed a reconstruction efficiency of 0.35, and considered a background free analysis, as an off-axis signal should have greatly reduced beam related backgrounds.

(vi) MicroBooNE off-axis MicroBooNE is the first large liquid-argon time projection chamber (LArTPC) to acquire a high statistics sample of neutrino interactions. It is located at a 7.5° angle relative to the NuMI beam line. We consider the same cuts and production rates as MiniBooNE off-axis.

(vii) ICARUS off-axis ICARUS is a 600-ton (500-ton fiducial) LArTPC that serves as the far detector of the SBND program. It is located at a 5.7° angle relative to the NuMI beam line. We consider the same cuts and production rates as MiniBooNE off-axis.

The sensitivity of the six experiments described above relies heavily on angular cuts to differentiate between background and signal. Electron recoils from dark matter scattering are very peaked in the forward direction, meaning that a large fraction of dark matter events will easily satisfy even very tight angular cuts. However, we have not accounted for the angular resolution of the experiments themselves in our analysis. A poor angular resolution would tend to smear dark matter events at small angles to larger angles more often than the reverse, reducing the efficiency with which dark matter events satisfy the cuts and depressing the measured sensitivity. A more comprehensive detector simulation may be able to account for this by determining the expected efficiency loss for a given set of dark matter parameters, but that is beyond the scope of our effort.

The cuts used for BEBC, CHARM-II, and MINERνA were those adopted by the experiments themselves, and we would expect their angular resolution to be sufficiently small for the angular cuts to remain meaningful. The CHARM-II experiment provides a plot of their angular resolution in Fig. 15 of Ref. [62], and it does become quite poor low energies, with $\sigma_\theta \approx 12$ mrad for $E^{\mathrm{rec}} = 3$ GeV, where the cut requires $\theta < 18$ mrad for such an energy. The BEBC analysis of Ref. [34] does not discuss their angular resolution, but they do mention angular measurements as small as 3 mrad. MINERνA cites an average angular resolution of between 7.2 and 7.5 mrad depending on the direction in Ref. [35].

The cuts for MicroBooNE and ICARUS are based on the angular cut proposed for the MiniBooNE dark matter search detailed in Ref. [21]. A $\cos(\theta) > 0.99$ cut is quite generous compared to the experiments discussed above, and MiniBooNE demonstrated in its previous analysis that such a cut could be satisfied with little loss of sensitivity due to its angular resolution. However, ICARUS and MicroBooNE use new detector technology and are not guaranteed to be able to attain the same performance. A more detailed study using the ICARUS and MicroBooNE detector simulations would therefore be valuable in improving the reliability of our signal estimates.

B. Simulation of the signal

In the parameter space relevant for fixed-target neutrino experiments, the generation of signal events can be modeled as a three-step process:

(1) (Prompt) production of dark matter particles in the target or proton beam dump.

(2) Propagation (as free particles) from the production point to the detector.

(3) Interaction within the active volume[1] of the detector.

The production rate of DM particles is dominated by the interaction of the incoming protons within the first few interaction lengths in the dump, with the most relevant mechanisms given, as mentioned above, by prompt radiative meson decays and proton bremsstrahlung. We neglect effects related to the geometry of the production target (and secondary particle interactions), as its characteristic length is far smaller than the distance between the beam dump and the detector, and we assume that the production is localized to a point at the center of the target. The simulation of the full production and propagation process was performed using two different available tools, BdNMC [70] and MadDump [71]. They both provide a complete framework to handle all the three-particle generation steps in a transparent and mostly automatic fashion.

Nonetheless, the two tools differ in many aspects regarding their actual implementation, providing a powerful test of the robustness of our prediction. In particular, they handle the DM scattering process inside the detector (step 3) following two different strategies. BdNMC works event-by-event and decides if each DM particle reaching the detector will interact according to an acceptance-rejection criterion. If an event is rejected, a new one is generated, and the procedure is iterated until the requested number of sample events is reached. In MadDump, the intermediate results of step 1 and step 2 are used to build a fake DM beam, characterized by its bidimensional flux distribution in energy and angle, which interacts within the detector acceptance. In this way, the interaction probability (cross section) can be computed by exploiting standard Monte Carlo methods, and the final signal events can be generated through an efficient unweighting procedure (as provided by the MadGraph framework [72]).

Limiting our focus to the cases relevant to this work, we have found a reasonably good agreement, within a few percent, between the predictions of BdNMC and MadDump on the total signal rates with and without applying the

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[1] Given the weakness of the interaction of LDM with ordinary matter, we neglect here any loss in its propagation from the production point to the active volume of the detector. In particular, we do not consider the interactions within the passive components of the detector. In the case where these interactions could lead to a detectable signature, they will actually increase the signal yield and improve the sensitivity. On the other hand, if they are not detectable, this might lead to a loss of the LDM flux if they occur before reaching the active volume. We expect that this effect does not alter significantly our estimations as we consider very long interaction lengths for the LDM. A complete simulation that takes into account the realistic features of the detector is beyond the scope of this work, but it should be part of a dedicated analysis by the experimental collaborations.

selection cuts on the electron recoil. The level of agreement is below the main experimental and theoretical systematics. One of the primary sources of uncertainty is given by the modeling of the meson spectra produced in the proton dump, which represents an input for our tools. Indeed, BdNMC and MadDump handle only the decay of the mesons into DM particles within an effective field theory approach. External data must be supplied, and one can either rely on full event-generator such as PYTHIA [73] or adopt a phenomenological parametrization such as those provided in Ref. [74], which represents the default choice in BdNMC. We have found that for the relatively high energy beams of the neutrino experiments investigated in this work, the difference in the final rates can be as large as a factor of 2, with the distribution given by PYTHIA being softer and with a larger angular spread. We assume a pragmatic approach adopting the more conservative result given by PYTHIA, which has been investigated in Ref. [75].

IV. SENSITIVITY TO SUB-GEV DM OF PAST AND CURRENT EXPERIMENTS

In Fig. 1, we present the comparison of the sensitivity of all different neutrino experiments described above, including also previous results such as NOνA [25] and MB on axis [21], while in Fig. 2, we compare the strongest ones to existing constraints described in Sec. II.

We find the following:

(i) In the small mass region $m_\chi \lesssim 50$ MeV, the best sensitivity is reached by MB off-axis, which can rule out part of the thermal targets both for scalar and Majorana DM. NOνA is capable of excluding some parameter space for $m_\chi \approx 10$ MeV. ICARUS will further improve on this result reaching a sensitivity to the Majorana target even better, while MicroBooNE has more limited reach, although the off-axis run still could improve over the beam dump dark matter run using the 8.9 GeV booster beam line. Both the MicroBooNE and ICARUS analyses assume zero background based upon the results of the MiniBooNE electron scattering analysis, but this may be too optimistic. MicroBooNE and ICARUS use different detector medium and technology than MiniBooNE and may not be able to attain the same level of background rejection as MiniBooNE was capable of during its beam dump dark matter search. Conversely, the off-axis position considered should greatly reduce the number of neutrinos reaching the detector, which may improve the potential sensitivity of all three experiments. Similar sensitivity could potentially be achieved by repeating the MiniBooNE-DM beam dump run [21] with the ICARUS and MicroBooNE detectors, but we have not performed a full analysis for this work.

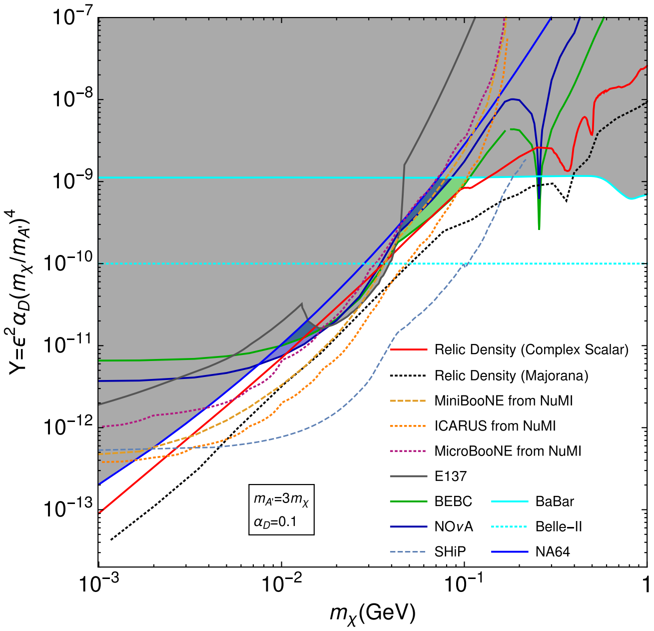

FIG. 2. We show a slice of the vector portal dark matter parameter space with $\alpha_D = 0.1$ and $m_{A'} = 3m_\chi$. The solid (dotted) black lines show the parameter space for which a complex scalar (Majorana) dark matter candidate coupled to a DP reproduces the observed dark matter relic density. The blue shaded region is excluded by the NOνA experiment, while the gray shaded region is excluded by a recast of a physics analysis of BEBC. The other dotted lines show the projected sensitivity of a new physics analysis of 10^{21} POT of data for MiniBooNE, ICARUS, and MicroBooNE taking data from the NuMI beam line. SBN is too far off axis to provide much sensitivity to vector portal dark matter produced by the NuMI beam line and is not shown.

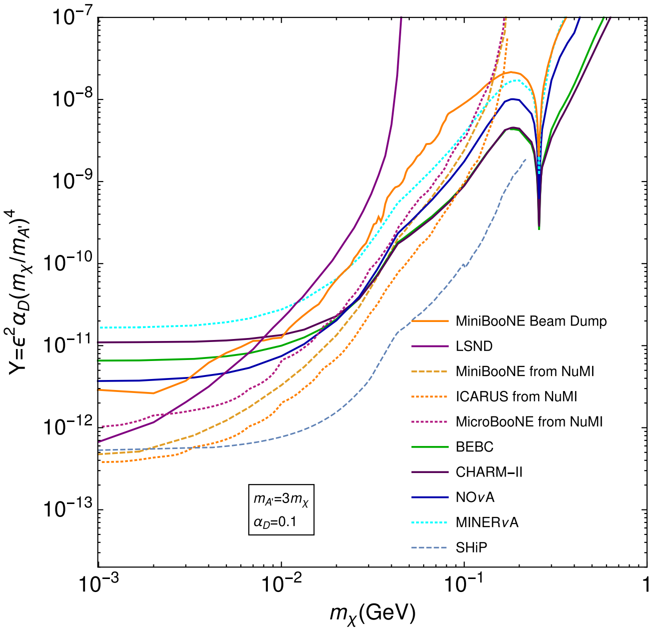

FIG. 1. All limits and projections from existing fixed-target neutrino experiments. Limits based on existing data and analyses are given by solid lines, while projections are dotted.

(ii) For higher masses, the best reach among fixed-target experiments instead comes from old SPS experiments like BEBC and CHARM-II. In particular, the recast of the previous new physics search using BEBC [65] eliminates some existing parameter space not covered by E137, NA64, and *BABAR*.

(iii) MINERνA is less sensitive to new physics than other existing experiments, but for sufficiently high mass, it can surpass the sensitivity of the MiniBooNE beam dump search [21]. However, both NOνA and the old SPS experiments (CHARM-II and BEBC) have a significantly better reach.

V. CONCLUSIONS

In this paper, we surveyed the reach of past and present neutrino facilities. We found the following:

(i) NOνA and BEBC exclude a significant range of masses for the scalar thermal target. A dedicated DM analysis by NOνA is important, as it could further improve on this result.

(ii) An analysis performed on the existing data of MB from the NuMi beam could rule out most of the remaining parameter space and even reach the Majorana thermal target, substantially improving on the reach of the MB beam dump dedicated run. However, as such an analysis may not occur, it is critical that the potential of existing and future experiments such as MicroBooNE and ICARUS be exploited. We also find that the signal improves as the threshold for the electron recoil energy is decreased, a trait that could be targeted by future analyses.

(iii) The derived limits hold for ratios of the dark photon mass to the dark matter mass larger than three, as both the limits and the relic density curves are squeezed to smaller dark matter masses by this change, but are otherwise unchanged. The limits may not hold for smaller mass ratios, as the relic density curve moves to smaller values of the kinetic mixing when the dark photon mass approaches twice the dark matter mass due to resonant enhancement of the annihilation cross section. Further complicating matters, visible decay channels will begin to compete with the invisible dark matter channel, introducing new constraints on the parameter space. The relic density curve is unaffected in terms of Y by changes in α_D, while the other constraint lines will move to lower values of Y as α_D declines, though the exact scaling is dependent on the signal.

(iv) ICARUS rules out the Majorana thermal target for masses between 6 and 50 MeV. This result is highly complementary to Belle II and not far from the reach of SHiP [43], as shown in Fig. 2. We limit our off-axis analyses to MicroBooNE and ICARUS, as SBND was found to be too far off axis to achieve good acceptance.

(v) Our final conclusion is that existing and past facilities can compete with future and proposed experiments sensitivity [43] in a completely parasitic way to their neutrino program.

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[1] R. Essig, A. Manalaysay, J. Mardon, P. Sorensen, and T. Volansky, First Direct Detection Limits on sub-GeV Dark Matter from XENON10, Phys. Rev. Lett. **109**, 021301 (2012).
[2] M. Crisler, R. Essig, J. Estrada, G. Fernandez, J. Tiffenberg, M. S. haro, T. Volansky, and T.-T. Yu(SENSEI Collaboration), SENSEI: First Direct-Detection Constraints on sub-GeV Dark Matter from a Surface Run, Phys. Rev. Lett. **121**, 061803 (2018).
[3] M. Battaglieri *et al.*, US cosmic visions: New ideas in dark matter 2017: Community report, arXiv:1707.04591.
[4] J. D. Bjorken, R. Essig, P. Schuster, and N. Toro, New fixed-target experiments to search for dark gauge forces, Phys. Rev. D **80**, 075018 (2009).
[5] B. Batell, M. Pospelov, and A. Ritz, Probing a secluded U(1) at B-factories, Phys. Rev. D **79**, 115008 (2009).
[6] B. Batell, M. Pospelov, and A. Ritz, Exploring portals to a hidden sector through fixed targets, Phys. Rev. D **80**, 095024 (2009).
[7] R. Essig, R. Harnik, J. Kaplan, and N. Toro, Discovering new light states at neutrino experiments, Phys. Rev. D **82**, 113008 (2010).
[8] S. Alekhin *et al.*, A facility to search for hidden particles at the CERN SPS: The SHiP physics case, Rep. Prog. Phys. **79**, 124201 (2016).
[9] T. Åkesson *et al.* (LDMX Collaboration), Light Dark Matter eXperiment (LDMX), arXiv:1808.05219.
[10] A. Berlin, N. Blinov, G. Krnjaic, P. Schuster, and N. Toro, Dark matter, millicharges, axion and scalar particles, gauge bosons, and other new physics with LDMX, Phys. Rev. D **99**, 075001 (2019).

[11] J. Mans (LDMX Collaboration), The LDMX experiment, EPJ Web Conf. **142**, 01020 (2017).

[12] E. Izaguirre, G. Krnjaic, P. Schuster, and N. Toro, New electron beam-dump experiments to search for MeV to few-GeV dark matter, Phys. Rev. D **88**, 114015 (2013).

[13] E. Izaguirre, G. Krnjaic, P. Schuster, and N. Toro, Physics motivation for a pilot dark matter search at Jefferson laboratory, Phys. Rev. D **90**, 014052 (2014).

[14] M. Antonello *et al.* (MicroBooNE, LAr1-ND, and ICARUS-WA104 Collaborations), A proposal for a three detector short-baseline neutrino oscillation program in the Fermilab booster neutrino beam, arXiv:1503.01520.

[15] P. deNiverville, M. Pospelov, and A. Ritz, Observing a light dark matter beam with neutrino experiments, Phys. Rev. D **84**, 075020 (2011).

[16] P. deNiverville, D. McKeen, and A. Ritz, Signatures of sub-GeV dark matter beams at neutrino experiments, Phys. Rev. D **86**, 035022 (2012).

[17] R. Dharmapalan *et al.* (MiniBooNE Collaboration), Low mass WIMP searches with a neutrino experiment: A proposal for further MiniBooNE running, arXiv:1211.2258.

[18] B. Batell, P. deNiverville, D. McKeen, M. Pospelov, and A. Ritz, Leptophobic dark matter at neutrino factories, Phys. Rev. D **90**, 115014 (2014).

[19] D. E. Soper, M. Spannowsky, C. J. Wallace, and T. M. P. Tait, Scattering of dark particles with light mediators, Phys. Rev. D **90**, 115005 (2014).

[20] A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration), Dark Matter Search in a Proton Beam Dump with MiniBooNE, Phys. Rev. Lett. **118**, 221803 (2017).

[21] A. A. Aguilar-Arevalo *et al.* (MiniBooNE DM Collaboration), Dark matter search in nucleon, pion, and electron channels from a proton beam dump with MiniBooNE, Phys. Rev. D **98**, 112004 (2018).

[22] B. A. Dobrescu and C. Frugiuele, GeV-scale dark matter: Production at the main injector, J. High Energy Phys. 02 (2015) 019.

[23] P. Coloma, B. A. Dobrescu, C. Frugiuele, and R. Harnik, Dark matter beams at LBNF, J. High Energy Phys. 04 (2016) 047.

[24] C. Frugiuele, Probing sub-GeV dark sectors via high energy proton beams at LBNF/DUNE and MiniBooNE, Phys. Rev. D **96**, 015029 (2017).

[25] P. deNiverville and C. Frugiuele, Hunting sub-GeV dark matter with the NOνA near detector, Phys. Rev. D **99**, 051701 (2019).

[26] G. Magill, R. Plestid, M. Pospelov, and Y.-D. Tsai, Millicharged Particles in Neutrino Experiments, Phys. Rev. Lett. **122**, 071801 (2019).

[27] A. de Gouvéa, P. J. Fox, R. Harnik, K. J. Kelly, and Y. Zhang, Dark tridents at off-axis liquid argon neutrino detectors, J. High Energy Phys. 01 (2019) 001.

[28] V. De Romeri, K. J. Kelly, and P. A. N. Machado, DUNE-PRISM sensitivity to light dark matter, Phys. Rev. D **100**, 095010 (2019).

[29] P. deNiverville, M. Pospelov, and A. Ritz, Light new physics in coherent neutrino-nucleus scattering experiments, Phys. Rev. D **92**, 095005 (2015).

[30] D. Akimov *et al.* (COHERENT Collaboration), Sensitivity of the COHERENT experiment to accelerator-produced dark matter, arXiv:1911.06422.

[31] B. Dutta, D. Kim, S. Liao, J.-C. Park, S. Shin, and L. E. Strigari, Dark Matter Signals from Timing Spectra at Neutrino Experiments, Phys. Rev. Lett. **124**, 121802 (2020).

[32] R. Van de Water, Searching for sterile neutrinos with the coherent CAPTAIN-Mills detector at the Los Alamos neutron science center, APS April Meeting 2019, Vol. **64** (2019), http://meetings.aps.org/Meeting/APR19/Session/Z14.9.

[33] K. De Winter *et al.* (CHARM-II Collaboration), A detector for the study of neutrino—electron scattering, Nucl. Instrum. Methods Phys. Res., Sect. A **278**, 670 (1989).

[34] H. Grässler, W. Dröge, U. Idschok, H. Kreutzmann, B. Nellen, B. Wünsch *et al.*, Prompt neutrino production in 400 GeV proton copper interactions, Nucl. Phys. **B273**, 253 (1986).

[35] J. Park *et al.* (MINERvA Collaboration), Measurement of neutrino flux from neutrino-electron elastic scattering, Phys. Rev. D **93**, 112007 (2016).

[36] A. de Gouvêa, P. J. Fox, R. Harnik, K. J. Kelly, and Y. Zhang, Dark tridents at off-axis liquid argon neutrino detectors, J. High Energy Phys. 01 (2019) 001.

[37] L. Okun, Limits of electrodynamics: Paraphotons?, Sov. Phys. JETP **56**, 502 (1982).

[38] P. Galison and A. Manohar, Two Z's or not two Z's?, Phys. Lett. **136B**, 279 (1984).

[39] B. Holdom, Two U(1)'s and epsilon charge shifts, Phys. Lett. **166B**, 196 (1986).

[40] T. Lin, H.-B. Yu, and K. M. Zurek, On symmetric and asymmetric light dark matter, Phys. Rev. D **85**, 063503 (2012).

[41] P. A. R. Ade *et al.* (Planck Collaboration), Planck 2015 results. XIII. Cosmological parameters, Astron. Astrophys. **594**, A13 (2016).

[42] E. Izaguirre, G. Krnjaic, P. Schuster, and N. Toro, Analyzing the Discovery Potential for Light Dark Matter, Phys. Rev. Lett. **115**, 251301 (2015).

[43] J. Beacham *et al.*, Physics beyond colliders at CERN: Beyond the standard model working group report, J. Phys. G **47**, 010501 (2020).

[44] J. P. Lees *et al.* (*BABAR* Collaboration), Search for Invisible Decays of a Dark Photon Produced in e^+e^- Collisions at BABAR, Phys. Rev. Lett. **119**, 131804 (2017).

[45] D. Banerjee *et al.* (NA64 Collaboration), Search for vector mediator of dark matter production in invisible decay mode, Phys. Rev. D **97**, 072002 (2018).

[46] L. B. Auerbach *et al.* (LSND Collaboration), Measurement of electron—neutrino—electron elastic scattering, Phys. Rev. D **63**, 112001 (2001).

[47] P. deNiverville, M. Pospelov, and A. Ritz, Observing a light dark matter beam with neutrino experiments, Phys. Rev. D **84**, 075020 (2011).

[48] B. Batell, R. Essig, and Z. Surujon, Strong Constraints on Sub-GeV Dark Sectors from SLAC Beam Dump E137, Phys. Rev. Lett. **113**, 171802 (2014).

[49] L. Marsicano, M. Battaglieri, M. Bondí, C. D. R. Carvajal, A. Celentano, M. De Napoli, R. De Vita, E. Nardi, M. Raggi, and P. Valente, Novel Way to Search for Light Dark Matter in Lepton Beam-Dump Experiments, Phys. Rev. Lett. **121**, 041802 (2018).

[50] L. Marsicano, M. Battaglieri, M. Bondí, C. D. R. Carvajal, A. Celentano, M. De Napoli, R. De Vita, E. Nardi, M. Raggi, and P. Valente, Dark photon production through

positron annihilation in beam-dump experiments, Phys. Rev. D **98**, 015031 (2018).

[51] G. Angloher *et al.* (CRESST-II Collaboration), Results on low mass WIMPs using an upgraded CRESST-II detector, Eur. Phys. J. C **74**, 3184 (2014).

[52] R. Agnese *et al.* (SuperCDMS Collaboration), Search for Low-Mass Weakly Interacting Massive Particles Using Voltage-Assisted Calorimetric Ionization Detection in the SuperCDMS Experiment, Phys. Rev. Lett. **112**, 041302 (2014).

[53] J. Barreto, H. Cease, H. T. Diehl, J. Estrada, B. Flaugher, N. Harrison *et al.*, Direct search for low mass dark matter particles with CCDs, Phys. Lett. B **711**, 264 (2012).

[54] F. Petricca *et al.* (CRESST Collaboration), First results on low-mass dark matter from the CRESST-III experiment, J. Phys.: Conf. Ser. **1342**, 012076 (2020).

[55] J. A. Dror, G. Elor, and R. Mcgehee, Directly Detecting Signals from Absorption of Fermionic Dark Matter, Phys. Rev. Lett. **124**, 181301 (2020).

[56] J. A. Dror, G. Elor, and R. Mcgehee, Absorption of Fermionic dark matter by nuclear targets, J. High Energy Phys. 02 (2020) 134.

[57] H. Davoudiasl and W. J. Marciano, Running of the U(1) coupling in the dark sector, Phys. Rev. D **92**, 035008 (2015).

[58] C. Boehm, M. J. Dolan, and C. McCabe, A lower bound on the mass of cold thermal dark matter from Planck, J. Cosmol. Astropart. Phys. 08 (**2013**) 041.

[59] S. N. Gninenko, Stringent limits on the $\pi^0- > \gamma X, X- > e + e-$ decay from neutrino experiments and constraints on new light gauge bosons, Phys. Rev. D **85**, 055027 (2012).

[60] S. N. Gninenko, Constraints on sub-GeV hidden sector gauge bosons from a search for heavy neutrino decays, Phys. Lett. B **713**, 244 (2012).

[61] J. Formaggio and G. Zeller, From eV to EeV: Neutrino cross sections across energy scales, Rev. Mod. Phys. **84**, 1307 (2012).

[62] D. Geiregat, P. Vilain, G. Wilquet, U. Binder, H. Burkhardt, W. Flegel *et al.* (CHARM II Collaboration), Calibration and performance of the CHARM-II detector, Nucl. Instrum. Methods Phys. Res., Sect. A **325**, 92 (1993).

[63] B. Fleming (MicroBooNE Collaboration), Fermilab The MicroBooNE technical design report No. FERMILAB-DESIGN-2012-04.

[64] T. Layda (CHARM II Collaboration), New results from the CHARM-II experiment, in *26th Rencontres de Moriond: Electroweak Interactions and Unified Theories* (1991), pp. 79–86, https://inspirehep.net/literature/327986.

[65] A. M. Cooper-Sarkar, S. Sarkar, J. Guy, W. Venus, P. O. Hulth, and K. Hultqvist, Bound on the tau-neutrino magnetic moment from the BEBC beam dump experiment, Phys. Lett. B **280**, 153 (1992).

[66] B. Wang, J. Bian, T. E. Coan, S. Kotelnikov, H. Duyang, A. Hatzikoutelis, Muon neutrino on electron elastic scattering in the nova near detector and its applications beyond the standard model, J. Phys. Conf. Ser. **888**, 012123 (2017).

[67] P. Adamson *et al.* (MiniBooNE and MINOS Collaboration), First Measurement of ν_μ and ν_e Events in an Off-Axis Horn-Focused Neutrino Beam, Phys. Rev. Lett. **102**, 211801 (2009).

[68] P. Vilain *et al.* (CHARM-II Collaboration), Precision measurement of electroweak parameters from the scattering of muon-neutrinos on electrons, Phys. Lett. B **335**, 246 (1994).

[69] S. Amerio *et al.* (ICARUS Collaboration), Design, construction and tests of the ICARUS T600 detector, Nucl. Instrum. Methods Phys. Res., Sect. A **527**, 329 (2004).

[70] P. deNiverville, C.-Y. Chen, M. Pospelov, and A. Ritz, Light dark matter in neutrino beams: Production modelling and scattering signatures at MiniBooNE, T2K and SHiP, Phys. Rev. D **95**, 035006 (2017).

[71] L. Buonocore, C. Frugiuele, F. Maltoni, O. Mattelaer, and F. Tramontano, Event generation for beam dump experiments, J. High Energy Phys. 05 (2019) 028.

[72] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, MadGraph 5: Going beyond, J. High Energy Phys. 06 (2011) 128.

[73] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, An introduction to PYTHIA8.2, Comput. Phys. Commun. **191**, 159 (2015).

[74] M. Bonesini, A. Marchionni, F. Pietropaolo, and T. Tabarelli de Fatis, On particle production for high-energy neutrino beams, Eur. Phys. J. C **20**, 13 (2001).

[75] B. Döbrich, J. Jaeckel, and T. Spadaro, Light in the beam dump. Axion-like particle production from decay photons in proton beam-dumps, J. High Energy Phys. 05 (2019) 213.