Fixed-Target Searches for New Physics with $\mathcal{O}$(1 GeV) Proton Beams at Fermi National Accelerator Laboratory

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I. PHYSICS GOALS AND MOTIVATION

Two recent developments in particle physics clearly establish the need for a GeV-scale high energy physics (HEP) beam dump facility. First, theoretical work has highlighted not only the viability of sub-GeV dark sectors models to explain the cosmological dark matter abundance but also that a broad class of these models can be tested with accelerator-based, fixed-target experiments, which complement growing activity in sub-GeV direct dark matter detection [1–3]. Second, the observation of coherent elastic neutrino-nucleus scattering (CEvNS) [4, 5] by the COHERENT experiment [6] provides a novel experimental tool that can now be utilized to search for physics beyond the standard model in new ways, including in searches for light dark matter [7] and active-to-sterile neutrino oscillations [8], which would provide smoking-gun evidence for the existence of sterile neutrinos.

The completion of the PIP-II superconducting LINAC at Fermilab as a proton driver for DUNE/LBNF in the mid 2020s creates an attractive opportunity to build such a dedicated beam dump facility at Fermilab. A unique feature of this Fermilab beam dump facility is that it can be optimized from the ground up for HEP. Thus, relative to spallation neutron facilities dedicated to neutron physics and optimized for neutron production operating at a similar proton beam power, a HEP-dedicated beam dump facility would allow for better sensitivity to dark sector models, sterile neutrinos, and CEvNS-based NSI searches, and more precise measurements of neutrino interaction cross sections relevant for supernova neutrino detection. For example, the Fermilab facility could be designed to suppress rather than maximize neutron production and implement a beam dump made from a lighter target such as carbon, which can have a pion-to-proton production ratio up to ∼2 times larger than the heavier Hg or W targets used at spallation neutron sources. The facility could also accommodate multiple, 100-ton-scale high energy physics experiments located at different distances from the beam dump and at different angles with respect to the incoming proton beam. This flexibility would allow for sensitive dark sector and sterile neutrino searches, which can constrain uncertainties in expected signal and background rates by making relative measurements at different distances and angles.

II. PROTON BEAM CHARACTERISTICS

The continuous wave capable PIP-II LINAC at Fermilab can simultaneously provide sufficient protons to drive megawatt-class $\mathcal{O}$(GeV) proton beams as well as the multi-megawatt LBNF/DUNE beamline. By coupling the PIP-II LINAC to a new Booster-sized, permanent magnet or DC-powered storage ring, the protons can be compressed into pulses suitable for a proton beam dump facility (∼320 ns goal) with a rich physics program. The storage ring could be located in a new or existing beam enclosure and be designed to operate at 800 MeV but with an upgrade path allowing for future operation in the GeV range. The storage ring would initially provide 100 kW of beam power, limited by stripping foil heating, and have a $\mathcal{O}(10^{-5})$ duty factor. Upgrading the beam energy to 1 GeV would allow for a factor of ∼1.3 increase in storage ring intensity and implementing laser stripping technology would allow the beam power to increase by another factor of ∼4, at the expense of an increase in duty factor by an equivalent factor. One such storage ring making use of the existing Booster enclosure, and which could be implemented on the timescale of the completion of PIP-II, has been proposed in [9].

III. DARK SECTOR SEARCHES

Proton beam dump experiments are potentially sensitive to any dark sector models that produce light dark matter directly through hadronic interactions or through the subsequent decay of light mesons. This includes, for example, both standard vector portal dark matter models that can be probed with beam proton and electron

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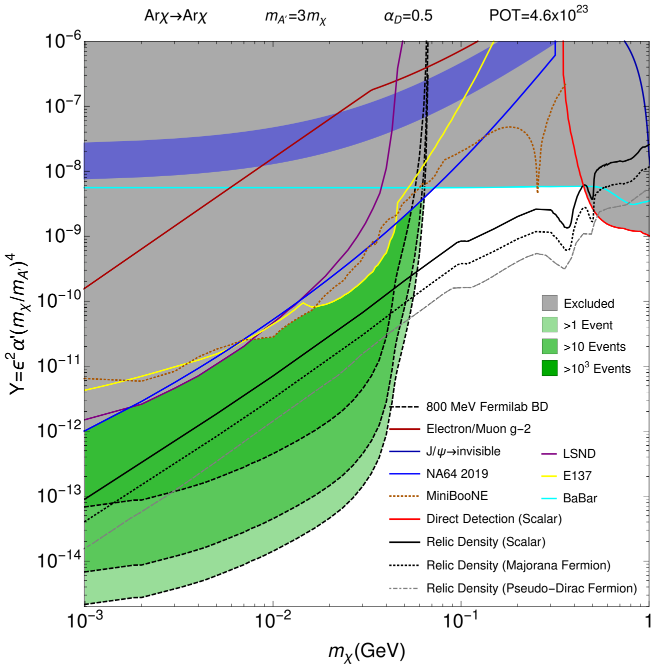

FIG. 1. Fermilab beam dump facility argon recoil event sensitivity curves for 4.6×10^{23} protons on target compared to thermal relic density targets and existing 90% exclusion limits as a function of the dimensionless scaling variable $Y = \epsilon^2\alpha(m_\chi/m_{A'})^4$, assuming $\alpha = 0.5$ and $m_A = 3m_\chi$.

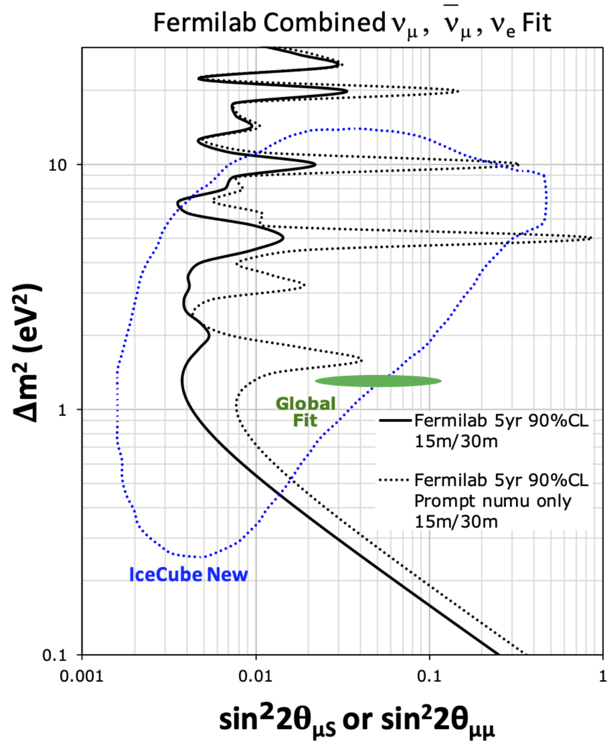

FIG. 2. Fermilab beam dump facility 90% confidence limits on active-to-sterile neutrino mixing assuming a 5 year run. Also shown are the 90% confidence limits for $\nu_\mu \to \nu_\mu$ disappearance, assuming the $\bar{\nu}_\mu$ and ν_e can be detected with similar assumptions as for the ν_μ, the 90% confidence limit from IceCube [19], and a recent global fit [20].

beams as well as other models, such as hadrophilic dark matter models, for which proton beams provide unique sensitivity [10]. Some of the best limits on vector portal dark matter for dark matter masses in the 10–100 MeV range come from reinterpretations [11–13] of ν_e-electron elastic scattering measurements made by the high power, 800-MeV proton beam dump experiment LSND [14]. While an LSND-like experiment optimized for dark matter searches at the Fermilab beam dump facility could likely improve on existing bounds [15], CEvNS provides an additional channel with which to search for dark matter [7].

The COHERENT collaboration recently reported the first detection of CEvNS on argon using an $\mathcal{O}(10$ kg) liquid argon scintillation detector achieving a 20 keV recoil energy threshold [16]. Studies of the sensitivity of an upgraded 750-kg liquid argon scintillation detector to scalar light dark matter models indicate the importance of larger mass detectors, utilizing the angular dependence of the dark matter flux, and reduced flux uncertainty (which can be addressed with relative measurements at different angles using identical or moveable detectors), to expand the reach of these searches [17]. We consider here a 100-ton LAr detector placed on-axis, 18 m downstream from a carbon proton beam dump with a 50 keV recoil energy threshold (to suppress neutrino backgrounds) and an efficiency of 70%. Assuming a 5-year run of the upgraded 1 GeV proton storage ring with laser stripping and a 75% uptime, we generate dark matter signal estimates using the BdNMC [18] simulation and obtain the argon recoil event sensitivity curves shown in Fig. 1, which probe thermal relic density targets for Pseudo-Dirac and Majorana fermion dark matter in addition to scalar dark matter.

IV. STERILE NEUTRINO SEARCHES

Decay-at-rest neutrinos from a stopped pion beam dump provide an excellent source of ν_μ, $\bar{\nu}_\mu$, and ν_e with a time structure that can separate ν_μ from $\bar{\nu}_\mu$ and ν_e. Using a lightly-doped oil Cerenkov detector, the LSND experiment found evidence for an excess of $\bar{\nu}_e$ 30 m downstream from a high-powered, 800 MeV proton beam dump, which can be interpreted as evidence for short-baseline $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations driven by a light sterile neutrino with a $\Delta m^2 \sim 1$ eV^2 mass-squared splitting [21]. A larger, follow-up experiment could be mounted at the Fermilab beam dump facility as a direct test of the LSND anomaly, using the same technology as LSND but located far off-axis and taking advantage of the low duty factor [22]. On the other hand, CEvNS provides a unique tool to definitively establish the existence of sterile neutrinos through active-to-sterile neutrino oscillations [8].

Using CEvNS, we can explore both mono-energetic ν_μ disappearance with $E_\nu = 30$ MeV and the summed disappearance of ν_μ, $\bar{\nu}_\mu$, and ν_e to ν_S, which can also put constraints on $\nu_\mu \to \nu_e$ oscillation parameters in a 3+1 sterile neutrino model. We consider here a setup consisting of identical 100-ton LAr scintillation detectors, located 15 m and 30 m away from a carbon proton beam dump with a 20 keV recoil energy threshold and an efficiency of 70%. We assume the neutron background in this dedicated facility could be suppressed to a negligible level for this experiment and that the signal-to-noise ratio for the remaining steady-state backgrounds is 1:1. In Fig. 2, we calculate the 90% confidence limits on the $\nu_\mu \to \nu_S$ mixing parameter $\sin^2 2\theta_{\mu S}$ for a 5-year run of the upgraded 1 GeV proton storage ring with laser stripping and a 75% uptime, assuming a 9% normalization systematic uncertainty correlated between the two detectors and a 36 cm path length smearing. Also shown are the 90% confidence limits for $\nu_\mu \to \nu_\mu$ disappearance assuming the $\bar{\nu}_\mu$ and ν_e can be detected according to similar assumptions as for the ν_μ.

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