SBN-BD: $\mathcal{O}(10 \text{ GeV})$ Proton Beam Dump at Fermilab's PIP-II Linac

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Abstract

Proton beam dumps are prolific sources of mesons enabling a powerful technique to search for vector mediator coupling of dark matter to neutral pion and higher mass meson decays. By the end of the decade the PIP-II linac will be delivering up to 1 MW of proton power to the FNAL campus. This includes a significant increase of power to the Booster Neutrino Beamline (BNB) which delivers 8 GeV protons to the Short Baseline Neutrino (SBN) detectors. By building a new dedicated beam dump target station, and using the SBN detectors, a greater than an order of magnitude increase in search sensitivity for dark matter relative to the recent MiniBooNE beam dump search can be achieved. This modest cost upgrade to the BNB would begin testing models of the highly motivated relic density limit predictions and provide novel ways to test explanations of the anomalous excess of low energy events seen by MiniBooNE.

1 Physics Goals and Motivation

Recent theoretical work has highlighted the motivations for sub-GeV dark matter candidates that interact with ordinary matter through new light mediator particles [1–3]. These scenarios constitute a cosmologically and phenomenologically viable possibility to account for the dark matter of the universe. Such sub-GeV (or light) dark matter particles are difficult to probe using traditional methods of dark matter detection, but can be copiously produced and then detected with neutrino beam experiments such as MiniBooNE, the Short Baseline Neutrino (SBN) Program, NOvA, and DUNE [4]. This represents a new experimental approach to search for dark matter and is highly complementary to other approaches such as underground direct detection experiments, cosmic and gamma ray satellite and balloon experiments, neutrino telescopes, and high energy collider experiments [1–3]. Furthermore, searches for light dark matter provide an additional important physics motivation for the current and future experimental particle physics research program at the Fermi National Accelerator Laboratory (FNAL).

The MiniBooNE experiment running at the FNAL Booster Neutrino Beamline (BNB) was originally designed for neutrino oscillation and cross section measurements. In 2014 a special beam dump run was carried out which suppressed neutrino produced backgrounds while enhancing the search for sub-GeV dark matter via neutral current scattering, resulting in new significant sub-GeV dark matter limits [5, 6]. The result clearly demonstrated the unique and powerful ability to search for dark matter with a beam dump neutrino experiment.

2 A New BNB Beam Dump Target Station and Running in the PIP-II Era

Leveraging the pioneering work of MiniBooNE's dark matter search, it has become clear that a significantly improved sub-GeV dark matter search can be performed with a new dedicated BNB beam dump target station optimized to stop charged pions which produce neutrino backgrounds to a dark matter search. The new beam dump target can be constructed within 100 m of the SBN Near Detector (SBND) that is currently under construction [7]. In the PIP-II era 8 GeV protons with higher power can be delivered to the BNB, up to 15 Hz and 115 kW, which is a significant increase from the current 5 Hz and 35 kW. In a five year run this would result in 6×10^{21} Proton on Target (POT) delivered to a new dedicated beam dumped while still delivering maximum levels of protons (35 kW) to the neutrino program. The five year sensitivity, shown in Figure 1, would be greater than an order of magnitude improvement on the MiniBooNE dark matter search due to the reduced neutrino background from the dedicated beam dump, the detector's close proximity to the beam dump, and higher protons on target. Furthermore, new vector and scalar/pseudoscalar dark sector models that couple to leptons or quark currents that explain the MiniBooNE low energy excess make unique prediction that can also be tested with SBND and the BNB beam dump [8].



Figure 1: Regions of relic abundance parameter (mixing strength) Y vs. dark matter mass m_{χ} for 6×10^{21} POT that could be achieved in a five year run with dedicated proton beam dump medium energy running in the PIP-II era. Left is the signal sensitivity for NC π^0 and right for NC-electron scattering with the SBND detector at 100 m from the dedicated beam dump. Both panels show regions where we expect 1–10 (light green), 10–1000 (green), and more than 1000 (dark green) scattering events. The solid black line is the scalar relic density line that can be probed.

3 A Kaon Decay-at-rest Sterile Neutrino Search

A new BNB beam dump target station also provides a unique opportunity to probe the sterile neutrino oscillation explanation of the MiniBooNE low energy excess using ν_{μ} disappearance. The KPIPE experimental concept, outlined in Ref. [9], calls for a very long (120 m) and thin (1.5 m radius) cylindrical detector close to and oriented radially outward from an intense beam-dump source of monoenergetic 236 Mev ν_{μ} from chargedkaon decay-at-rest ($K^+ \rightarrow \mu^+ \nu_{\mu}$, with branching ratio of 64%) to achieve sensitivity to short-baseline ν_{μ} disappearance. The idea is to search for an L/E-dependent oscillation wave using fixed-E neutrinos with minimal background and only modest detector requirements.

The KPIPE detector, relying on liquid scintillator and silicon photomultipliers (or PMTs), is designed to look for 236 MeV $\nu_{\mu}n \rightarrow \mu^{-}p$ interactions, which provide a unique double-flash coincidence due to the muon decay following the initial prompt event. Mapping these interactions as a function of distance along the detector pipe, with a nominal, no-oscillation expectation of a $1/r^2$ rate dependence, provides sensitivity to muon-flavor disappearance. Given a beam dump, decay-at-rest neutrino source, the beam-based ν_{μ} background (from decay-in-flight mesons) to these signal events is expected to be completely sub-dominant, at the 1-2% level. While cosmics can be considered a concern for such a surface or near-surface detector, this background can be mitigated by typical accelerator duty factors of ~ $10^{-6} - 10^{-5}$ combined with the short charged kaon lifetime (13 ns). The monoenergetic neutrino source, combined with low decay-in-flight background and small beam duty factor, means that the signal-to-background ratio is expected to be well over 50:1 in the scenarios considered. This large ratio means that the detector requirements, in particular the photocoverage, can be quite modest. In fact, a preliminary estimate at Ref. [10] predicts that the entire KPIPE detector would cost \$5M.

The KPIPE detector was originally envisioned to be paired with the 3 GeV, 730 kW (currently, with 1 MW planned) J-PARC Spallation Neutron Source. Aside from the primary proton energy, which is above the kaon production threshold, and the high power, this source is particularly attractive because the beam timing structure, two ~80 ns pulses separated by 540 ns at 25 Hz, provides an extremely low duty factor (4×10^{-6}) , essential for cosmic background rejection. The drawback of this source, however, is that the 3 GeV primary proton energy, while above threshold, is somewhat lower than optimal for charged kaon production per unit power: at 3 GeV, the MARS15 software package [11] predicts 0.007 KDAR ν_{μ} /POT. With an increase in proton energy to 8 GeV, for example, the production rate increases by a factor of 10 to 0.07 KDAR ν_{μ} /POT. Spatial and facility issues, especially in consideration of the existing materials-sciencefocused beamlines and experiments, also means that optimal detector placement, with KPIPE calling for a 120 m long detector with closest distance of 32 m from the neutrino source, is challenging.

The future Fermilab particle accelerator complex [12], including PIP-II [13] and eventually a new rapid cycling synchrotron (RCS) [14], can provide an optimal beam-dump/stopped-kaon neutrino source for KPIPE, in terms of beam energy (8 GeV), beam timing (~ 10^{-5} duty factor), and spatial considerations. Using the detector and Fermilab-accelerator assumptions shown in Table 1, and scaling based on the detailed study in Ref. [9], we expect KPIPE could achieve the sensitivity to short-baseline ν_{μ} disappearance shown in Figure 2. As can be seen, this sensitivity surpasses, and is highly complementary to, SBN (6 years) at $\Delta m^2 > 10 \text{ eV}^2$ for both scenarios considered and $\Delta m^2 > 1 \text{ eV}^2$ for the RCS upgrade era case.

Experimental assumptions	
Detector length	120 m
Active detector radius	1.45 m
Closest distance to source	32 m
Liquid scintillator density	$0.863 { m g/cm^3}$
Active detector mass	684 tons
Primary proton energy	$8 \mathrm{GeV}$
Target material	Hg or W
KDAR ν_{μ} yield (MARS15)	$0.07 \ \nu_{\mu}/\text{POT}$
$\nu_{\mu} \text{ CC } \sigma @ 236 \text{ MeV} (\text{NuWro})$	$1.3 \times 10^{-39} \text{ cm}^2/\text{neutron}$
KDAR signal efficiency	77%
Vertex resolution	80 cm
Light yield	4500 photons/MeV
Uptime (5 years)	5000 hours/year
$ \nu_{\mu} $ creation point uncertainty	$25~\mathrm{cm}$
PIP-II era assumptions	
Proton rate (0.08 MW)	$1.0 \times 10^{21} \text{ POT/year}$
Beam duty factor	1.6×10^{-5}
Cosmic ray background rate	110 Hz
Raw KDAR CC event rate	2.7×10^4 events/year
RCS upgrade era assumptions	
Proton rate (1.2 MW)	$1.5 \times 10^{22} \text{ POT/year}$
Beam duty factor	5.3×10^{-5}
Cosmic ray background rate	360 Hz
Raw KDAR CC event rate	4.0×10^5 events/year

Table 1: Summary of the relevant KPIPE experimental parameter assumptions.



Figure 2: The 90% CL sensitivities of the KPIPE at Fermilab scenarios considered here, in both the PIP-II and RCS upgrade eras. For reference, we also show the expected 90% CL SBN sensitivity (6 years) [15], existing 90% CL MiniBooNE+SciBooNE limit [16], and 99% allowed region from the Collin *et al.* global fit [17].

4 Required Infrastructure

The new PIP-II linac will be able to deliver a proton beam of significantly higher power to the Booster than the current linac. This will result in 15 Hz of beam to be delivered to the BNB achieving 115 kW, or about three times the power of current delivery. The BNB neutrino target and horn have a power limit of 35 kW, which leaves 80 kW of power for other uses. A new target station fed by the BNB, and on axis with the existing SBN neutrino experiment could be built relatively quick and at modest cost. Such a facility could be run concurrently with the SBN neutrino program, only using protons beyond the 35 kW limit. Events would be trivially separated on a pulse by pulse basis based on the which target the beam is being delivered too. The facility will require a Fe target about 2 m in length and 1 m in width to absorb the protons and resulting charged pions. Shielding and cooling requirements up to 80 kW are straightforward. Such a target would reduce backgrounds by another three orders of magnitude relative the regular neutrino running (see next section for details). Besides the higher power, the reduced neutrino flux background enables a significantly more sensitive search for dark matter relative to the MiniBooNE beam off target run.

5 Decay-in-flight Neutrino Flux Reduction with Improved Beam Dump

To leverage the increased dark matter signal rate production, a corresponding reduction in decay-in-flight neutrino-induced backgrounds is required. The MiniBooNE-DM beam-off-target run steered the protons past the Be target/horn and onto the 50 m absorber. This reduces the neutrino-induced background rate by a factor of \sim 50, but there was still significant production of neutrinos from proton interactions in the 50 m of decay pipe air and beam halo scraping of the target. Further reduction of neutrino production occurs by directing the proton beam directly onto a dense beam stop absorber made of Fe or W. This puts the end of the proton beam pipe directly onto the dump with no air gap. Detailed BNB dump beam line simulations, which have been verified by data [6], demonstrate that this would reduce neutrino-induced backgrounds by a factor of 1000 over Be-target neutrino running, which is a factor of twenty better than the 50 m absorber as demonstrated in Figure 3.



Figure 3: Detailed decay-in-flight neutrino flux estimation for neutrino running (solid black line), beam-off-target 50 m absorber running (dotted red line), and a dedicated new BNB beam dump target station (dotted brown line). In this final mode, the decay-in-flight neutrino flux reduction is a factor of 1000, or about 20 times better than 50 m absorber running.

6 Timescales, Costs, and Similar Facilities

The timescale for building a BNB beam dump target station is similar to the construction of PIP-II and the expected upgrade in protons once online. The SBN detectors are expected to run for at least 10 years. The new dedicated beam dump could be built sooner and begin running using the SBN detectors at a lower rate until the PIP-II upgrade is complete. Such a facility could be built quickly, 1-2 years, and at modest cost below \$5M. There are no other similar facilities in the world currently or planned in the next five years that can probe for dark matter masses up to 1 GeV with a proton beam.

References

- [1] Jim Alexander et al. Dark Sectors 2016 Workshop: Community Report. 8 2016.
- [2] Marco Battaglieri et al. US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report. In U.S. Cosmic Visions: New Ideas in Dark Matter, 7 2017.
- [3] Summary of the High Energy Physics Workshop on Basic Research Needs for Dark Matter Small Projects New Initiatives. In Basic Research Needs For Dark Matter Small Projects New Initiatives, 10 2018.
- [4] Patrick deNiverville, Maxim Pospelov, and Adam Ritz. Observing a light dark matter beam with neutrino experiments. Phys. Rev. D, 84:075020, 2011.
- [5] A. A. Aguilar-Arevalo et al. Dark Matter Search in a Proton Beam Dump with MiniBooNE. *Phys. Rev. Lett.*, 118(22):221803, 2017.
- [6] A.A. Aguilar-Arevalo et al. Dark Matter Search in Nucleon, Pion, and Electron Channels from a Proton Beam Dump with MiniBooNE. Phys. Rev. D, 98(11):112004, 2018.
- [7] Pedro AN Machado, Ornella Palamara, and David W Schmitz. The Short-Baseline Neutrino Program at Fermilab. Ann. Rev. Nucl. Part. Sci., 69:363–387, 2019.
- [8] Bhaskar Dutta, Doojin Kim, Adrian Thompson, Remington T. Thornton, and Richard G. Van de Water. Solutions to the MiniBooNE Anomaly from New Physics in Charged Meson Decays. 10 2021.
- [9] S Axani, G Collin, JM Conrad, MH Shaevitz, J Spitz, and T Wongjirad. Decisive disappearance search at high Δm^2 with monoenergetic muon neutrinos. *Phys. Rev. D*, 92(9):092010, 2015.
- [10] Cost Estimates for the KPIPE Experiment. https://dspace.mit.edu/bitstream/handle/1721.1/98388/Kpipecosts.pdf.

- [11] Nikolai Mokhov, Pertti Aarnio, Yury Eidelman, Konstantin Gudima, Alexander Konobeev, Vitaly Pronskikh, Igor Rakhno, Sergei Striganov, and Igor Tropin. MARS15 Code Developments Driven by the Intensity Frontier Needs. Prog. Nucl. Sci. Tech., 4:496–501, 2014.
- [12] Robert Ainsworth et al. An Upgrade Path for the Fermilab Accelerator Complex. 6 2021.
- [13] M. Ball et al. The PIP-II Conceptual Design Report. 3 2017.
- [14] Jeffrey Eldred, Valeri Lebedev, and Alexander Valishev. Rapid-Cycling Synchrotron for Multi-Megawatt Proton Facility at Fermilab. JINST, 14(07):P07021, 2019.
- [15] M. Antonello et al. A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam. 3 2015.
- [16] K. B. M. Mahn et al. Dual baseline search for muon neutrino disappearance at $0.5 \text{eV}^2 < \Delta m^2 < 40 \text{eV}^2$. Phys. Rev. D, 85:032007, 2012.
- [17] G. H. Collin, C. A. Argüelles, J. M. Conrad, and M. H. Shaevitz. First Constraints on the Complete Neutrino Mixing Matrix with a Sterile Neutrino. *Phys. Rev. Lett.*, 117(22):221801, 2016.