Fixed-Target Searches for New Physics with $\mathcal{O}$(10 GeV) Proton Beams at Fermi National Accelerator Laboratory

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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. In the next five years the PIP-II linac will be delivering up to 1 MW of proton power to the FNAL campus. This includes 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 sensitively 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.

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][2][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, Short Baseline Neutrino (SBN), 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][2][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]. 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 charge pions which produce neutrino backgrounds to a dark matter search. The new beam dump target can be constructed within 100m of the SBN Near Detector (SBND) that is currently under construction [6]. 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 would be greater than an order of magnitude better than current MiniBooNE dark matter sensitivity 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.

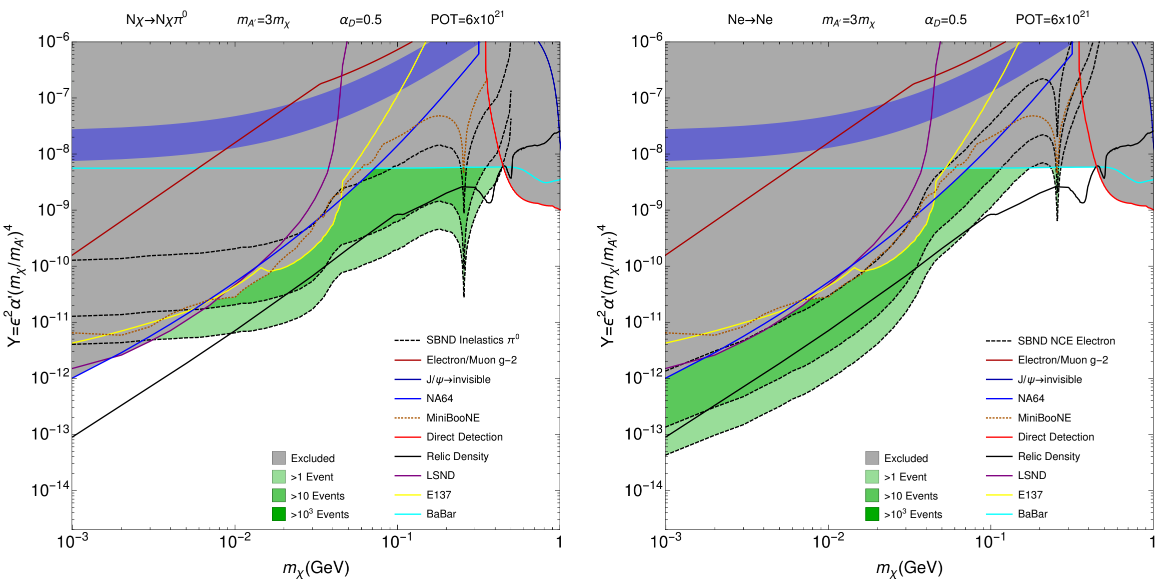

Figure 1: Regions of relic abundance parameter (mixing strength) Y vs. dark matter mass m_χ for 6×10^{21} POT that could be achieved in a five year run with dedicated proton beam dump medium energy running in the PIP-II era. Left is the signal sensitivity for NCπ^0 and right for NC-electron scattering 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 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 the neutrino 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.

4 Neutrino Flux Reduction with Improved Beam Dump

To leverage the increased signal rate production, a corresponding reduction in 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 ∼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

[5], 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 2.

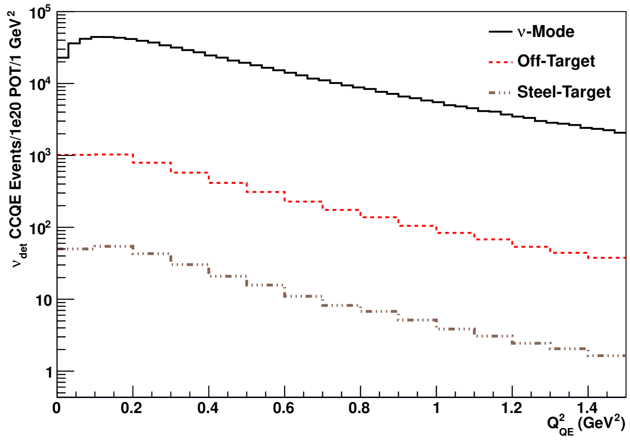

Figure 2: Detailed neutrino flux estimation for neutrino running (solid black line), beam-off-target 50 m absorber running (dotted red line), and a dedicated new BNB beam dump target station (dotted brown line). In this final mode, the neutrino flux reduction is a factor of 1000, or about 20 times better than 50 m absorber running.

5 Timescales, Costs, and Similar Facilities:

The timescale 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

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