Search for Dark Matter in the beam-dump of a proton beam with MiniBooNE

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Abstract. A search for the production of sub-GeV dark matter via vector boson mediators was carried out using 8 GeV protons from the Fermilab Booster in a dedicated run where \(1.86 \times 10^{20}\) protons were delivered to the steel beam dump of the Booster Neutrino Beam (BNB). The MiniBooNE detector, 490 m downstream of the beam dump, is sensitive to the elastic scattering of dark matter particles off nucleons in the detector mineral oil, and neutrinos are an irreducible background. Here, a description of the detection principle and the analysis method of this novel and powerful technique to search for dark matter is given, and the results of a search in the context of a vector portal model of dark matter, as well as future prospects, are discussed.

1. Introduction
The strong evidence for dark matter (DM) from observations in a wide range of gravitational phenomena [1], and the lack of positive results from direct searches in the mass range from a few GeV to 10s of TeV [2] have motivated considering extensions of the Standard Model (SM) that include Dark Sectors (new fields with no charges under the symmetries of the SM) as an explanation for this major component of the Universe. Under appropriate assumptions, dark sector scenarios are able to provide DM candidates with sub-GeV masses. Models that connect the dark sector to the SM and are constrained by the SM symmetries are called portals, of which only three renormalizable versions exist: (i) the vector portal (the mediator is a vector), (ii) the Higgs portal (the mediator is a scalar), and (iii) the neutrino portal (the mediator is a fermion). Vector portal models are the most viable for thermal sub-GeV DM. Despite its sound theoretical motivation, sub-GeV DM has been significantly less explored experimentally, and is accessible, among others, with accelerator beam dump experiments [3].

The MiniBooNE (MB) experiment at Fermilab completed its original physics program on neutrino oscillation and cross section measurements in 2012. A special run was carried out in 2013-2014 where neutrino production was suppressed, enhancing the sensitivity to sub-GeV DM. The recently published results of this search [4] demonstrate the unique and powerful ability to search for DM with a neutrino experiment.
2. The minimal kinetically mixed dark photon (MKMDP) model
A minimal extension to the SM featuring a single \( U(1)_D \) (\( D \) for dark) gauge boson, dubbed the dark photon, and a dark matter candidate \( \chi \), has the effective Lagrangian \[ L_{V,\chi} = |D_{\mu}\chi|^2 - m_\chi^2|\chi|^2 - \frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_V^2V_{\mu\nu}^2 + \epsilon V_{\mu\nu}F_{\mu\nu} + \ldots \right. , \]
where \( F^{\mu\nu} \) is the electromagnetic field-strength tensor of the SM, and \( V_{\mu\nu} \) is the corresponding object associated with the dark photon field \( V_\mu \). Only four parameters control the physics: the DM particle mass \( m_\chi \), the mediator particle mass \( m_V \), the kinetic mixing parameter \( \epsilon \), and the dark photon interaction coupling strength \( \alpha_D \). A \( U(1)_D \) mediator can increase the DM annihilation cross section to give the observed relic density. Furthermore, a dark photon with a mass of \( \mathcal{O} \sim 10^{-1} \) MeV could explain the \( (g-2)_\mu \) anomaly [5].

3. Dark matter beam and detection
The DM production can be achieved in high-energy collisions of SM particles (e.g. protons), and the detection by elastic scattering of the DM particles in a sensitive detector. Figure 1 shows possible mechanisms. In the MKMDP model the event rate scales as \( \epsilon^4 \alpha_D \), when \( m_V > 2m_\chi \) (invisible decay of the \( V \)) which will be considered in what follows.

Neutrino interactions in the detector constitute an irreducible background to the DM search, hence neutrino production must be suppressed. Unlike a standard neutrino production target, a beam dump is a large piece of high-Z material where charged mesons will be either absorbed or stopped before decay, reducing the neutrino flux significantly.

4. The BNB and the MiniBooNE Detector
In its standard \( \nu \)-mode configuration, the BNB delivers 8 GeV protons to a 1.75 interaction length Be target in pulses with \( (3-5) \times 10^{12} \) protons and 1.6 \( \mu \)s in duration, creating a large flux of charged mesons (predominantly \( \pi \)'s). A focusing horn produces a pulsed toroidal magnetic field of 1.5 T, which focuses the charged mesons along a 1 m-diameter, 50 m-long decay pipe that terminates in a steel beam dump. This creates a large neutrino flux at the detector location, 541 m from the target. The polarity of the horn can be switched in order to create a beam of neutrinos or antineutrinos.
Figure 2. Schematic of the experimental setup in off-target mode. Taken from [4].

The MB detector is a 12.2 m-diameter spherical tank filled with 818 tons of mineral oil (CH$_2$). An inner wall at 5.5 m radius is lined with 1280 photomultiplier tubes (PMTs) that view the main tank volume. An optically separate 35 cm-thick outer shell viewed by 240 PMTs arranged in pairs comprises the veto region. PMT pulses with signal $>0.1$ photoelectron are digitized in a 19.2 $\mu$s time window around the 1.6 $\mu$s proton pulses of the BNB. MB is primarily a Cherenkov detector, but is sensitive to sub-Cherenkov particles via a small amount of scintillation light emitted as these traverse the mineral oil. The detector is very well understood; it ran for more than 10 years in neutrino ($\nu^-$) and antineutrino ($\bar{\nu}^-$) modes producing 27 publications on neutrino oscillations, cross section measurements and other physics topics. Most relevant for this search are the measurements of the Charged Current Quasi-Elastic (CCQE) [6] and Neutral Current Elastic (NCE) [7] scattering, on which the DM search analysis relies.

5. Dark Matter search in beam dump mode
For this DM search, the beam line was configured in “off-target” mode, with the protons steered off the Be production target, keeping the magnetic horn powered off, and going directly into the steel beam dump, see Figure 2. This reduces the neutrino flux at the detector, 490 m from the beam dump, by a factor of $\sim 30$ compared to $\nu$−mode, while the event rate for CCQE events is $\sim 50$ times smaller. A total of $1.86 \times 10^{20}$ POT (protons on target) were collected over a running period of 9 months between November 2013 and September 2014.

DM candidate events in the off-target data were selected as in the MB $\bar{\nu}$−NCE analysis [7], adding a reconstructed nucleon kinetic energy cut of $35 < T_n < 600$ MeV. This requires one time-cluster of hits in coincidence with the beam window having a time and spatial distribution consistent with a single nucleon and no pions. The selection criteria applied to the off-target data yields 1465 $\pm$ 38 events. In order to constrain the off-target neutrino flux, which gives rise to an irreducible background of neutrino-induced NCE events, a sample of CCQE events was selected from the off-target data using the cuts developed for the CCQE cross-section measurement [6]. In addition, and because NCE and CCQE cross sections are not known independently of MB data, two other large samples with the same NCE and CCQE cuts as for the off-target data were selected from previously collected $\nu^-$ mode data. The three “constraint” samples provide an improved estimate of beam-related backgrounds.

Prior to any constraints, a total background of 1579 $\pm$ 529 events (34% uncertainty) was expected. This is composed of 697 events from beam-unrelated backgrounds (measured with an out-of-beam random trigger), 775 events from detector beam-related backgrounds (dominated by NCE neutrino interactions in the detector), and 107 events from beam-related “dirt” backgrounds (neutrino-induced neutrons created outside the detector entering the main volume). The error estimates considered correlations between the different energy bins and samples. A combined background-only fit to the three constraint samples and the off-target sample yields
Figure 3. Left: Reconstructed nucleon kinetic energy distribution of DM candidates. Center: The 90% C.L. limit on $\epsilon^2 \alpha_D$ for each point in the $m_\chi$ vs $m_V$ plane obtained with this search. Right: The limit on the annihilation parameter $Y = \epsilon^2 \alpha_D (m_\chi/m_V)^4$ that results from assuming the relation $m_V = 3m_\chi$ and $\alpha_D = 0.5$, compared to other results. The forthcoming results from BABAR [9] are expected to be stronger, especially for smaller values of $\alpha_D$.

a constrained background prediction of 1548 ± 198 events (13% uncertainty).

The BdNMC DM simulation [8] was used to generate the energy distribution of the nucleons in $\chi N$ scattering events for different values of $\epsilon^4 \alpha_D$, $m_V$, and $m_\chi$, which was passed on to the MB detector simulation. Corrections for bound nucleons were included using an effective efficiency calculated from the MB simulation.

6. Results

The signal prediction was included in a combined fit to the $Q^2$ distributions of the four mentioned samples, and subjected to a frequentist method to determine the 90% C.L. limit on $\epsilon^4 \alpha_D$ for given $m_V$ and $m_\chi$. The results are shown in Figure 3. Fixing other DM parameters allows comparisons of experiments employing different methods. In the right-hand-side plot of the figure values of the annihilation cross-section parameter $Y = \epsilon^2 \alpha_D (m_\chi/m_V)^4$ with $m_V = 3m_\chi$ and $\alpha_D = 0.5$ are plotted for this search and compared to other experimental results. Within the vector portal DM model and the chosen parameter constraints, the MB result excludes a vector mediator particle solution to the $(g-2)_\mu$ anomaly and sets stringent limits on DM with sub-GeV masses two orders of magnitude lower than attainable in nucleon direct detection experiments.

7. Lessons and future perspectives

Several lessons learned from this search are already proving useful for the planning of future measurements. Access to a decade-worth of data from a well characterized detector allowed for a good understanding of the backgrounds affecting the DM search. Having a large detector with a veto to tag incoming particles, reduced the events originating in the surrounding dirt. Being able to accurately measure the beam-unrelated backgrounds was crucial. Modeling the nuclear effects on the DM interaction with nucleons is an important characteristic that cannot be avoided in a realistic estimate of the experiment’s sensitivity. Finally, the use of several constraint samples which may be correlated helps to reduce systematic uncertainties to a manageable level.

The collaboration is currently developing two analyses that will increase the sensitivity to vector portal DM with the off-target data, using new interaction channels: the “$e$-DM” analysis, where the DM particles elastically scatter off electrons, and the “inelastic $\pi^0$” analysis, where it will search for resonant production of $\pi^0$’s in DM-nucleon interactions. An additional improvement will be the use of the timing structure of the Booster proton beam to look for
characteristic intra-bunch (out of time) events in the detector associated subluminal massive DM particles, which is expected to increase the sensitivity to DM masses $> 70$ MeV.

Simulations have shown that replacing the BNB target assembly with a dedicated Fe or W beam dump, hence removing 50 m of air along the protons flight path, would reduce the neutrino flux by more than one order of magnitude compared to off-target mode. This would represent a non-trivial upgrade to the BNB and could entail an enhancement of the goals of the Fermilab Short Baseline Neutrino (SBN) Program to include a sub-GeV DM search. In this scenario, the SBN near detector (SBND), at 110 m from such beam dump, could achieve an order of magnitude better sensitivity in the $e$-DM and inelastic π0 channels, with a short run collecting $2 \times 10^{20}$ POT. An SBND with an improved beam dump would be most sensitive to leptophobic models, where the DM does not couple to electrons. These ideas have been put forward in presentations to the community [10, 11] and a recent LOI submitted to the Fermilab PAC.

8. Conclusions
The successful MB beam dump run is an example of the kind of low-cost sub-GeV DM searches that can be done with proton accelerators by re-tooling existing neutrino experiments. The MB result clearly establishes that such searches are achievable and lessons learned can be used to improve future measurements. A highly motivated and timely search for sub-GeV DM can be performed at Fermilab over a short 6-12 months run collecting data with the SBN near detector. This will require a modest investment for an improved beam dump, with an increased return in science, leveraging on the existing current neutrino program of the laboratory.

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