Accelerator-Produced Dark Matter Search using MiniBooNE

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Cosmology observations indicate that our universe is composed of 25% dark matter (DM), yet we know little about its microscopic properties. Whereas the gravitational interaction of DM is well understood, its interaction with the Standard Model is not. Direct detection experiments, the current standard, have a nuclear recoil interaction, low-mass sensitivity edge of order 1 GeV. To detect DM with mass below 1 GeV, either the sensitivity of the experiments needs to be improved or use of accelerators producing boosted low-mass DM are needed. Using neutrino detectors to search for low-mass DM is logical due to the similarity of the DM and ν signatures in the detector. The MiniBooNE experiment, located at Fermilab on the Booster Neutrino Beamline, has produced the world’s largest collection of ν and ν̄ samples and is already well understood, making it desirable to search for accelerator-produced boosted low-mass DM. A search for DM produced by 8.9 GeV/c protons hitting a steel beamdump has finished, collecting $1.86 \times 10^{20}$ POT. Analysis techniques along with predicted sensitivity will be presented.

PRESENTED AT

XXXIV Physics in Collision Symposium
Bloomington, Indiana, September 16–20, 2014

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1 Introduction

Since the first proposal of dark matter (DM) by Zwicky [1] there has been overwhelming cosmological evidence of its existence [2]. To determine how DM interacts with the Standard Model of particle physics (SM), extensive searches for DM have been done. These searches include looking for a nuclear recoil signature in direct detection experiments. Direct detection experiments have a DM mass threshold around 1 GeV. Boosting the DM will help probe masses less than a GeV. A study for DM masses less than a GeV is necessary to understand DM in general.

The MiniBooNE detector [3] is a $\nu$ detector filled with 800 tons of mineral oil acting as a Cherenkov/scintillator detector. The light is read out by 1280 inner and 240 veto PMTs. MiniBooNE has been taking data for over 10 years obtaining $6.5 \times 10^{20}$ POT ($11.3 \times 10^{20}$ POT) in $\nu(\bar{\nu})$ mode. Publications include results for $\nu$- [4] and $\bar{\nu}$- [5] nucleon current elastic scatting (NCel). Because it is such a well-understood detector, it is a good candidate to search for production of a vector mediator produced in a beamstop decaying into a DM particle which is detected in the MiniBooNE detector 490 m away. The beam is composed of 8.9 GeV/c protons.

2 Benchmark Theoretical Model

The benchmark model is a vector portal model of light DM. It was initially developed by Boehm and Fayet [6] in order to solve the 511 keV spectrum line seen from the galactic bulge. The theory consists of $V$ a vector mediator with a mass $m_V$ less than 1 GeV and the DM particle $\chi$ with a mass $m_\chi$. The following is added to the SM Lagrangian [7]:

\[ L = L_\chi - \frac{1}{4} F^\mu_\nu F^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu - \frac{\kappa}{2} F^\mu_\nu F^{\mu\nu} \\
L_\chi = \begin{cases} 
\bar{\chi} (\partial^\mu - ig' V^\mu) \chi - m_\chi \bar{\chi} \chi & \text{Dirac fermion DM} \\
|\partial^\mu - ig' V^\mu| \chi|^2 - m_\chi^2 |\chi|^2 & \text{Complex scalar DM}
\end{cases} \tag{1}
\]

which leads to four new free parameters, (i) $m_\chi$, (ii) $m_V$, (iii) kinetic mixing angle between DM and SM, $\kappa$, and (iv) a coupling constant for DM and $\chi$, $\alpha' = g'/4\pi$. When $V < 2m_\chi$ the decay is practically visible, into leptons or photons, and invisible otherwise. The production of $V$ can be produced in beamlines from either through Bremsstrahlung or decay of neutral mesons. References [8] apply the benchmark theory to several neutrino experiments, predicting the experiments sensitivity. MiniBooNE has the best sensitivity, in the interesting parameter regions, when the decay is invisible (Fig. [1]), where the signature of $\chi$ is either NCel off a nucleon or an electron. Due to detector efficiency and background, MiniBooNE is most sensitive when the reconstruction nuclear recoil is between 40 and 250 MeV (Fig. [2]).
Figure 1: Regions of DM-nucleon scattering cross section (corresponding to non-relativistic spin-independent coherent scattering on nuclei) vs. DM mass. In this plot we have fixed $V = 300$ MeV and $\alpha' = 0.01$. Constraints are shown from monojet searches ($pp \rightarrow j + inv$) [9], excessive contributions to (g-2)$_\mu$ [10], precision electroweak measurements [11], a monophoton search ($e^+e^- \rightarrow \gamma + inv$) [12] (labeled BaBar), and low-mass limits from DM direct detection experiments, DAMIC [13] (1-3 GeV), CDMSlite [14] (3-5 GeV) and XENON10 [15] (5-10 GeV). Note that a slightly stronger exclusion contour to XENON10 has recently been obtained by LUX [16]. The light blue band represents the region where the current $\sim 3\sigma$ discrepancy in (g-2)$_\mu$ is alleviated by the 1-loop contribution from the vector mediator [10]. The solid black line indicates where the relic density of the DM matches observations—the structure in this contour is due to $s$-channel $V^*$ resonant enhancement in the DM annihilation cross section for $m_\chi \sim m_V/2$. For $m_\chi > m_V/2$, new annihilation channels open up and this relation is modified. The left panel shows regions where we expect 1–10 (light green), 10–1000 (green), and more than 1000 (dark green) elastic scattering events off nucleons in the MiniBooNE detector with $1.75 \times 10^{20}$ POT. The right panel shows the same for elastic scattering off electrons.
Figure 2: Nucleon kinetic energy from DM scattering for various model parameters (left). Reconstructed nucleon kinetic energy for both DM and neutrino scattering after corrected for detector efficiency (right).

3 Beamdump Mode

Running MiniBooNE in beamdump mode reduces $\nu$-induced events, which are a background to a DM measurement, by having the beam hit a steel beamdump 50 m downstream instead of hitting the Be target (Fig. 3). A reduction factor of $\sim$40 from beam on-target with the horn in neutrino mode to beamdump mode is seen by comparing the $\nu_\mu$CCQE analyses. $\nu_\mu$CCQE is also used to determine if an extra scale factor to the simulations is needed.

4 Semi-Blind Preliminary Results

A semi-blind analysis is being done. The first $3.2 \times 10^{19}$ POT of total $1.86 \times 10^{20}$ POT is used to adjust cuts and understand predictions from simulations. For the nucleon analysis, two observables will be used to compare to theory, nuclear recoil energy and DM time of flight. Using both observables will reduce backgrounds and give better information about the DM mass; there is a correlation between DM time of flight and
mass. We use the same event selection as [5] except the nuclear recoil energy is now 35–250 MeV. With these cuts, we see the results in Fig. 4.

![Figure 4: Time of events inside the proton bunch (left). Energy distributions for data and background (middle). Table showing integral of the energy distributions (right).](image)

**5 Conclusion**

MiniBooNE has finished a beamdump run, accumulating a total of $1.86 \times 10^{20}$ POT. The motivation of this run was to search for DM particles with a mass less than 1 GeV. In the light DM model, MiniBooNE has been shown to be able to add to the exclusion plots. Doing a semi-blind analysis, preliminary results on $\chi$-nucleon NCel shows a consistency with null. Final results expected fall 2015.

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