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Light Dark Matter Analysis Using NOvA Near Detector

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Dark matter (DM) is believed to account for 85% of the matter content of the Universe. The leading dark matter candidate is the WIMP (weakly interacting massive particles). Light dark matter (LDM) refers to WIMP candidates with a mass of less than 1 GeV. The concept of LDM has been developed in order to explain the 511 keV γ-rays from the galactic bulge, as observed by the INTEGRAL satellite. There are a lot of candidates for light DM, and these candidates span a wide range of potential masses and couplings to the visible sector. Probing the vast parameter space of light-dark matter requires a correspondingly broad experimental program that can include neutrino fixed target experiments. NOvA is a high luminosity long-baseline fixed-target accelerator neutrino experiment at Fermilab that can provide a potentially interesting probe in searching for signatures of DM scattering with electrons in its near detectors. We aim to search for the MeV-scale dark matter particles that might be generated within the NuMI beam and produce detectable electron scattering signals in NOvA Near Detector. In this talk, we present our analysis of the single electron events using a simulated sample and show the sensitivity of the NOvA experiment.

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1. Introduction

Visible matter constitutes only 5% of the Universe, and the remaining major constituents are dark matter and dark energy. The concept of dark matter was initially introduced by Fritz Zwicky back in 1933 to explain the mismatch between theoretical and observed total mass density results. The evidence of dark matter comes from the Bullet Cluster, cosmic microwave background, rotation of the galaxies, and gravitational lensing. Unlike visible matter, dark matter does not interact with the electromagnetic field. Therefore, it does not absorb, reflect, or emit light, making it extremely hard to detect. The proposed candidates of dark matter are weakly interacting massive particles (WIMPs). Light dark matter is one of the WIMP candidates with a mass of less than 1 GeV.

NOvA is a long-baseline neutrino experiment at Fermilab [1]. The NOvA experiment is a mineral-oil based liquid scintillator detector. It consists of two detectors: a 300 metric-ton near detector at Fermilab and a much larger 14 metric-kiloton far detector in Minnesota. The main advantage lies in the high luminosity available, where NOvA Near Detector [2–5] has already accumulated more than 2.5×10^{21} protons on target (POT) since 2013, which allows for the production of a sizeable relativistic DM beam. It offers the possibility of probing a wide range of possible DM masses and couplings to the visible sector, complementary to underground direct detection experiments. In this analysis, we generate simulated samples in the NOvA Near Detector and show the sensitivity of the NOvA experiment to light dark matter.

2. Theoretical Framework

The vector portal model is the simple benchmark model that we considered in our analysis. In this model, the hidden sector couples to the Standard Model (SM) particles through a dark photon. The new dark $U(1)_D$ [6] gauge boson kinetically mixes with the ordinary photon, and a complex scalar χ charged under $U(1)_D$ that serves as DM candidates:

$$\mathcal{L}_{\text{DM}} = \mathcal{L}_V + \mathcal{L}_\chi. \tag{1}$$

The $\mathcal{L}_V$ can be written as:

$$\mathcal{L}_V = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_V^2 V^\mu V_\mu - \frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu}, \tag{2}$$

where ϵ is the DP-photon kinetic mixing, while:

$$\mathcal{L}_\chi = \frac{1}{2}ig_D V\mu J_\mu^\chi + \frac{1}{2}\partial_\mu\chi^\dagger\partial^\mu\chi - m_\chi^2\chi^\dagger\chi, \tag{3}$$

where $J_\mu^\chi = [(\partial_\mu\chi^\dagger - \chi^\dagger\partial_\mu\chi]$ and g_D is the $U(1)_D$ gauge coupling.

In this analysis, the physics is controlled by four unknown parameters: DM mass m_χ, DP mass m_V, kinetic mixing ϵ, and dark gauge coupling g_D. The Vector Portal model predicts the production of V mediators at high luminosity proton beam-dumps via indirect neutral meson decay or proton bremsstrahlung process, and then the decay of V into a pair of DM particles.

The NOvA Near Detector can explore the regions of the parameter space where $m_V > 2m_\chi$ and $g_D \gg \epsilon e$. The dark photon always decays into a $\chi\chi^\dagger$ pair. For the parameter space $m_V > 2m_\chi$, the annihilation cross section for a scalar DM particle can be written as:

$$\langle \sigma_{\text{ann}} v \rangle (\chi^\dagger \chi \to f\bar{f}) \sim \frac{8\pi v^2 Y}{m_\chi^2}, \tag{4}$$

where v is the relative DM velocity, and Y is a dimensionless self-annihilation parameter, which controls the DM annihilation cross-section and, in turn, the thermal relic abundance, which is defined as:

$$Y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_V} \right)^4, \tag{5}$$

where $\alpha_D \equiv g_D^2/4\pi$.

3. Analysis Details

3.1 Dark Matter Beam

The NuMI facility at Fermilab operates with access to the Main Injector's 120 GeV proton beam and delivers neutrinos to NOvA Near Detector. The beam of protons from Fermilab's Main Injector strikes a fixed graphite target, primarily producing πs and Ks, which are then focused toward the beam axis by two magnetic horns. The mesons decay into muons and neutrinos during their flight through a long decay tunnel as in FIG. 1. The muons are absorbed by the subsequent earth shield, while the neutrinos continue through it to the NOvA Near Detector. In the interaction of the proton beam with the target, dark photons may also be produced through rare decays of π^0, η, or for heavier masses, via the proton bremsstrahlung process. These dark photons decay promptly into DM particles, producing a "dark matter beam" along the neutrino beam. The NuMI facility could serve as a DM factory, and the NOvA Near Detector could be a DM detector.

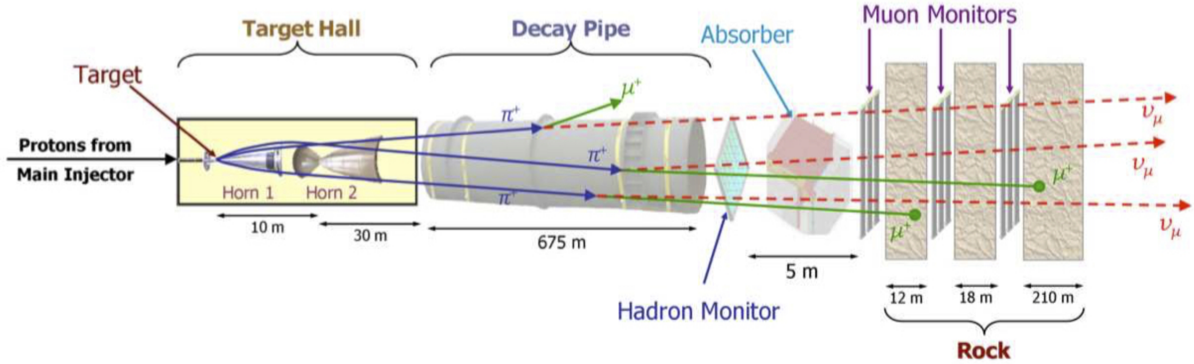

Figure 1: A Schematic picture of NuMI neutrino beam generation, and of the neutrino production, with the magnetic focusing horns, the decay pipe, and the NOvA Near Detector.

3.2 Signal Identification

The DM beam interacts with SM particles by elastically scattering off on a nucleon or electron inside the neutrino detector. The DM-electron elastic scattering is a purely leptonic process, and the kinematics are given by two body elastic collisions. The scattering angle θ_e of the outgoing electron with respect to the DM beam can be written as:

$$\cos\theta_{\rm e} = \frac{\rm E_\chi + m_e}{\rm E_\chi}\sqrt{\frac{\rm E_e}{\rm E_e + 2m_e}}, \tag{6}$$

where m_e is electron mass, E_e is the kinetic energy of the scattered electron, and E_χ is the DM energy. For high incoming particle energies of several GeV and small angle limit, $E_e\theta_e^2$ is small. This kinematic property of the scattered electron with small $E_e\theta_e^2$ shows the "forwardness" in the beam direction and can be used as an important signal selection criterion in this analysis. Therefore, the signal we are looking for is the single forward-going electromagnetic (EM) showers.

3.3 Background Study

The primary background in light-dark matter analysis is the EM showers from the neutrino-electron ($\nu - e$) elastic scatterings. In addition to that, we also have background events coming from the other beam-related events, such as ν_μ charged current (CC), ν_e CC, Neutral Current (NC), NC as well as CC quasi-elastic, meson exchange current (MEC) events, etc. Due to similar two-body elastic collision kinematics, the $\nu - e$ processes also have single, very forward-going EM showers with $E_e\theta_e^2$ peaking around zero. The DM particles tend to have higher mass than electrons, and the DM particle energy peaks around 10 GeV. Thus, the recoil energy of electrons scattering off the DM particles of higher energy will be more than the recoil energy of electrons scattering off the neutrinos. We have extended our interested energy region to incorporate higher $E_e\theta_e^2$ values than in $\nu - e$ analysis as shown in Fig 2

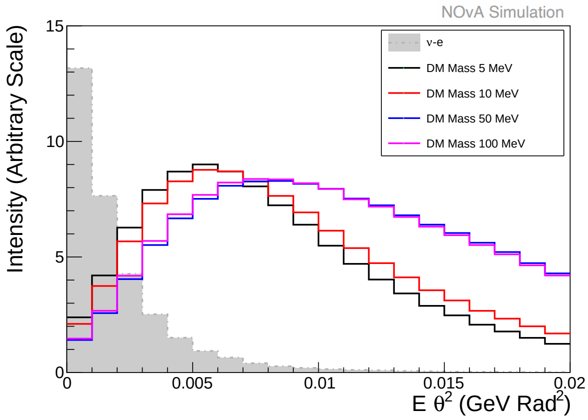

Figure 2: Signal and background pattern in $E\theta^2$ space. Arbitrary scales are used for the normalization to show the pattern difference clearly. Note, in this figure, only the ν-e background is plotted. In the high $E\theta^2$ region, other beam-related backgrounds start to dominate the total background

We simulate the DM particles for various masses ranging from 5 MeV to 450 MeV using the **BdNMC** software [7]. BdNMC helps in generating a "generic" distribution of electron recoil energy and scattering angle. These "generic" distributions are used as input to simulate NOvA detector response [8] to single electron events. In order to select the single electron events from the NOvA Near Detector, we have to remove our beam-related background events. To do so, we have our preselection cuts to remove obvious ν_μ-CC interactions produced in the detector. The preselection criteria utilized are:

- L < 800 cm, where L is the length of the longest prong (prong is a reconstructed particle candidate that has directional and reconstructed information).
- $N_{plane} < 120$, where N_{plane} is the number of plane of the longest prong
- $N_{cell} < 600$, where N_{cell} is the total number of cells
- Fiducial and Containment cuts, to suppress backgrounds that are induced by neutrino interaction with the rock and to make sure event interactions occur within the internal volume of the NOvA Near Detector
- The single particle requirement cuts, to make sure that the events selected are single particle
- A primary shower energy cut, to select the electron candidates with specific shower energy
- Two particle ID cuts are used to select single electrons and further reject the background.
  - NuoneID:identify $\nu - e$ elastic scattering events
  - Epi0ID: reject background with π^0 in the final state

With our selection criteria, the overall selection efficiency of the beam-related background is around 0.3%.

4. Results

In this analysis, the DM mass parameter space for $5 < m_\chi < 200$ MeV window has been scanned to generate 2D confidence limits. In Fig 3, we have shown the sensitivity for Y as a function of m_χ, assuming $\alpha_D = 0.5$ and $m_V = 3m_\chi$, using NOvA simulation. In the plot, we have projected the sensitivity of light DM using both neutrino and antineutrino fake data. It suggests new parameter space will be excluded using the Vector Portal DM model for the DM mass between 5 and 100 MeV if no signal events are observed.

5. Conclusion

In this analysis, we did a preliminary study of the DM-electron scattering signatures in the NOvA Near Detector using the MC samples. The results obtained here don't include systematics. The sensitivity plot obtained suggests that in the 5 to 100 MeV DM mass window, NOvA can explore so far unprobed regions of the parameters space (Y, m_χ) reaching down to the thermal relic line for the value $\alpha_D = 1/2$ for a complex scalar DM candidate. Thus, we will be able to represent a significant improvement over existing experimental measurements, like LSND, E137, NA64, MiniBooNE, and COHERENT. We would like to extend our study in order to include the systematics and study the excess of single EM showers from NOvA true dataset in the future.

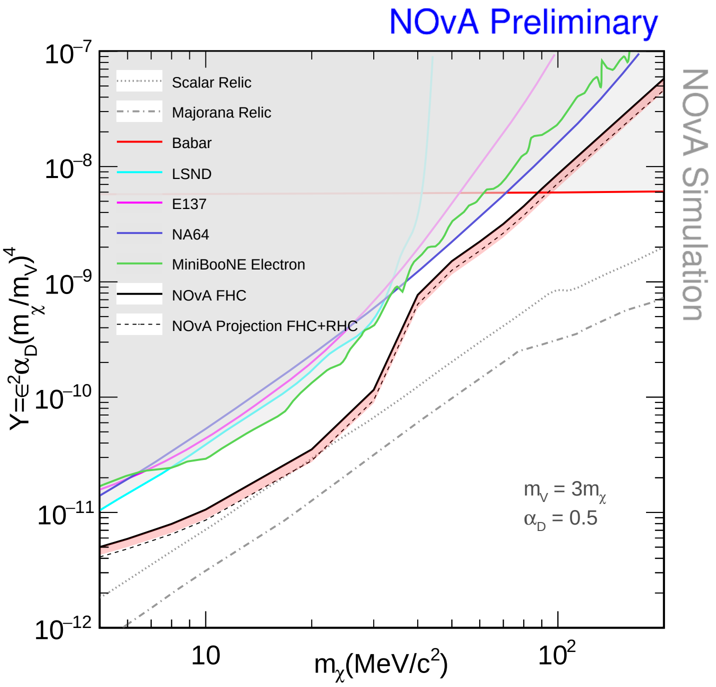

Figure 3: Comparison of NOvA sensitivity to other experiments for Y as a function of m_χ, assuming $\alpha_D = 0.5$ and $m_V = 3m_\chi$. The black solid line is the sensitivity drawn from the neutrino (simulated) data analysis. The dashed line shows the estimated projection if we combine the neutrino and anti-neutrino in the analysis

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