Snowmass2021 - Letter of Interest

Search for low mass dark matter at ICARUS detector using NuMI beam

NF Topical Groups:

■ (NF3) Beyond the Standard Model

RF Topical Groups:

■ (RF6): Dark Sector Studies at High Intensities

CF Topical Groups:

■ (CF1) Dark matter: particle-like

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Abstract: This Letter of Interest discusses the opportunity to search for the low mass dark matter (LDM) at the ICARUS LArTPC detector at Fermilab Short-Baseline Neutrino (SBN) program, using the beam off-axis of the NuMI neutrino beam. Since ICARUS is situated about $5.7°$ off of the NuMI neutrino beam, at which LDM flux expects to peak in a wide range of mass with the neutrino flux greatly reduced, from which LDM searches would greatly benefit.

Introduction and Motivation: The proposed Short-Baseline Neutrino (SBN)[1] physics program at Fermilab will deliver rich and compelling physics opportunities, including the ability to resolve a class of experimental anomalies in neutrino physics. The ICARUS-T600 detector which functions as the far detector of the SBN program is in the final stage of installation and is being commissioned at FNAL. The main physics program of ICARUS detector is to deliver the most sensitive search to date for sterile neutrinos at the eV mass-scale through both appearance and disappearance oscillation channels and definitively resolve the LSND ν_e anomaly. Apart from sterile neutrino search, thanks to the superb performance of the detector, ICARUS can provide an excellent opportunity to study other Beyond Standard Model (BSM) physics scenarios, such as dark matter (DM).

During the past decade, the idea of a light dark sector containing (sub-)GeV-scale DM coupled to the Standard Model through a light mediator particle has emerged as a compelling framework for DM physics. These scenarios are cosmologically and phenomenologically viable, yet are challenging to probe using traditional search methods such as direct DM detection via nuclear recoil. On the other hand, such light DM could be copiously produced in high flux neutrino target for precision neutrino oscillation experiments. Indeed, it has recently been demonstrated that neutrino beam experiments have significant potential to search for sub-GeV dark sectors [4, 5]. In particular, the MiniBooNE-DM collaboration has carried out a dedicated beam dump mode run, leading to new constraints on light DM [2, 3]. Furthermore, several phenomenological studies have pointed out the potential of the Fermilab Short Baseline Experiments, including ICARUS, to probe light DM and mediator particles [6, 7, 8].

For DM in particular, the basic experimental principle is analogous to neutrino detection: i.e. light DM particles are produced in the primary proton-target collisions and subsequently travel to the near detector downstream and scatter elastically with electrons or nuclei, leaving a neutral current-like signature. This method of searching for DM is complementary to traditional search methods and in many scenarios provides the best sensitivity to light DM in sub-GeV mass range, interacting with quarks through a light mediator. The tantalizing prospect of searching for DM in this manner provides an important new motivation to the ICARUS experiment.

Benchmark Dark matter model: Minimal sub-GeV DM models are characterized by the mass scale and interaction strengths of the DM particle and the mediator that controls the coupling to ordinary matter. General effective field theory arguments suggest that the dominant interactions of a gauge singlet mediator will be through renormalizable couplings, of which only three are possible in the Standard Model – the so-called "portal" interactions. The benchmark "DM model" defined in this section describes only couplings of dark-sector states including the low-mass DM (denoted by χ).

The minimal "vector portal"-type scenario contains a (massive) dark-sector photon V_μ that mixes with the SM photon. The DM particle is assumed here to be a fermion for concreteness, though other options are possible. The relevant interaction Lagrangian is then given by

$$\mathcal{L}_{\text{int}} \supset -\frac{\epsilon}{2} V_{\mu\nu} F^{\mu\nu} + g_D \, V_\mu \, \bar{\chi} \gamma^\mu \chi + \text{H.c.}\,, \tag{1}$$

where $V^{\mu\nu}$ and $F^{\mu\nu}$ are the field strength tensors for the dark photon and the SM photon, respectively. We have here introduced the kinetic mixing parameter ϵ, while g_D is the $U(1)_D$ gauge coupling governing the interaction strenth of the dark photon and DM.

The opportunity : This letter summarizes the physics case and technical feasibility for a dedicated DM search at ICARUS using NuMI off-axis beam. The ICARUS detector is located off-axis to the NuMI beam with an angle of 5.7°, about 800m from the target. In this configuration, the relative flux ratio between neutrino over dark matter can be reduced significantly. This setup significantly reduces neutrino neutral current backgrounds that can mimic the scattering of DM off nucleons or electrons.

Accelerator-based neutrino facilities collide high-intensity proton beams with targets, producing large numbers of mesons whose leptonic decays generate a neutrino beam. Rare meson decays [4, 5] and proton bremsstrahlung [9] can produce light DM alongside the neutrino beam as mentioned above. The flux of DM produced via neutral meson decays – via on-shell V – may be estimated by[1]

$$N_\chi = 2N_{\mathrm{POT}} c_{\mathfrak{m}} \{\mathrm{Br}(\mathfrak{m} \to \gamma\gamma) \left[2\varepsilon^2 \left(1 - \frac{M_V^2}{m_{\mathfrak{m}}^2}\right)^3\right] \mathrm{Br}(V \to \chi\bar{\chi})\} g(M_\chi, M_V), \tag{2}$$

where N_{POT} is the number of protons on target delivered by the beam, $c_{\mathfrak{m}}$ is the average number of meson $\mathfrak{m}$ produced per POT, the term in braces is the branching fraction of $\mathfrak{m} \to \gamma V$ relative to $\gamma\gamma$, and $g(x, y)$ characterizes the geometrical acceptance fraction of DM reaching the ICARUS detector. $g(x, y)$ is determined by model parameters using Monte Carlo techniques. For the range of dark photon and DM masses for which ICARUS will set a competitive limit, the DM flux due to meson decays will dominate over the flux due to proton bremsstrahlung. Considering DM masses in the $\sim$1-300 MeV range, this will require production via the π^0 and η mesons. We use $c_{\pi^0} \approx 4.5$ and $c_\eta \approx 0.5$ in our simulations.

These DM particles can then be detected through their interactions with the nucleons and electrons of the neutrino detector, or if unstable and sufficiently long-lived, through their decays to visible particles. Electron scattering, in particular, provides one of the most promising signals for DM particles. If the DM reaches the ICARUS detector, it may scatter elastically off nucleons or electrons in the detector, via a t-channel dark photon. Due to its smaller backgrounds, we focus on scattering off electrons. The differential cross section of this scattering, as a function of the recoil energy of the electron E_e, is

$$\frac{d\sigma_{\chi e}}{dE_e} = 4\pi\epsilon^2 \alpha_D \alpha_{EM} \frac{2m_e E_\chi^2 - (2m_e E_\chi + m_\chi^2)(E_e - m_e)}{(E_e^2 - m_\chi^2)(m_V^2 + 2m_e E_e - 2m_e^2)^2}\,, \tag{3}$$

where E_χ is the incoming DM energy. The signal is an event with only one recoil electron in the final state. We may use the scattering angle and energy of the electron to distinguish between signal and background events as discussed in the following.

The background to the process consists of any processes involving an electron recoil. As the detector is located near the surface, background events, in general, can be induced by cosmic rays as well as by neutrinos generated from the beam. However, since majority of cosmic-induced backgrounds will be vetoed by triggers and timing information, the dominant background will be from neutrinos coming from the beam. The two neutrino-related backgrounds are $\nu_\mu - e^-$ scattering, which looks nearly identical to the signal, and ν_e CCQE scattering, which does not. While the latter has a much larger rate ($\sim$ 10 times higher) than the former, we expect that using the kinematical variable E_e and θ_e of the final state, where θ_e is the direction of the outgoing electron relative to the beam direction, will allow the ν_e CCQE background to be vetoed effectively. Preliminary sensitivity study using the NUMI off-axis beam (2×10^{21} POT) at ICARUS detector shows that the limits on the dark matter coupling parameters can be improved by an order of magnitude compared to current bounds[2, 3]. This letter includes the opportunity to study the trigger system for event selection, estimate of the backgrounds, and detailed beam and detector simulation.

Conclusions and outlook: A case for the physics and technical feasibility of a dedicated dark matter search at ICARUS using the NuMI off-axis beam is discussed. The ICARUS detector at SBN with 2 years (2×10^{21} POT) of NuMI (off-axis) beam will allow to probe a completely new range of dark matter model/parameter space. In addition, extending (2 to 3 years) the data taking beyond the current allocated POT for the SBN program would not only enhance the statistical precision and reduce systematic uncertainties, but also improve the sensitivity. Discovery of light dark matter would revolutionize our view of the universe and would have dramatic implications for the future of particle physics and cosmology.

[1] See Ref. [10] for a complete derivation of these expressions, including those for meson decays via off-shell V.

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