Snowmass2021 - Letter of Interest

Dark Matter Searches at the Next-Generation CEνNS and Neutrino Facilities: from Photon to Dark Photon

NF Topical Groups:

■ (NF3) Beyond the Standard Model

RF Topical Groups:

■ (RF6) Dark Sector Studies at High Intensities

TF Topical Groups:

■ (TF08) BSM model building
■ (TF09) Astro-particle physics & cosmology

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Abstract: This Letter of Interest discusses the opportunity of (light) dark matter searches at neutrino facilities which are featured by a very large flux of photons which can be converted into dark matter particles via the mixing with a dark photon. Two different classes of neutrino facilities are considered, CEνNS-type experiments using stopped pion sources and high-energy ($\gtrsim 10$ GeV) beam-produced neutrino experiments. Since the behaviors of neutrino-induced backgrounds in each type of experiments are different, we discuss different strategies to suppress them and hence improve the signal sensitivity.

Introduction: The paradigm of weakly interacting massive particles (WIMPs) has been a flagship in the research field of dark matter searches, as the lightest particle in various theories beyond the Standard Model resolving the hierarchy problem can be a natural candidate. An enormous amount of experimental and theoretical effort has been devoted to WIMPs and related physics opportunities, but none of the conclusive observations have been made in dark matter direct/indirect detection experiments and collider experiments. In particular, the sensitivity reaches of the conventional direct search experiments are getting close to the so-called neutrino floor below which the searches would be more challenging due to the coherent elastic neutrino-nucleus scattering (CEνNS) background [1].

In light of this situation, dark matter within the MeV-to-GeV mass range is receiving growing attention, as it can be thermally produced while it is less constrained by the existing dark matter searches. In order for them to be consistent with the observed dark matter relic abundance, "portal" particles such as dark photon are typically motivated to mediate the interactions between such dark matter and Standard Model (SM) particles. By construction, their coupling to the SM-sector particles is small/tiny, so high-intensity facilities (e.g., beam-dump experiments) are one of the ideal places to test relevant models.

An extensively explored scenario is dark photon production by meson decays (π^0, η, etc), bremsstrahlung of the particle beam, etc via the mixing between dark photon and the SM photon, followed by the decay of dark photon to dark matter. However, photons can be even more copiously produced via secondary cascade photons, in particular, in the neutrino experiments where a proton beam is incident on a target, inducing a lot of secondary activities of the produced primary particles [2]. Thus, the next-generation CEνNS and neutrino facilities will have great potential in exploring the models of light dark matter and light mediators.

We discuss light dark matter and light mediator searches and their future prospects at the next-generation neutrino experiments, utilizing the full list of photon sources. Two different classes of neutrino experiments are considered here in terms of the energy of the particle beam, which can provide complementary information to each other. Since we propose to search for dark matter at neutrino experiments, one major challenge is to remove the neutrino background (similar to the neutrino floor due to astrophysical neutrinos in the direct detection experiments). We need to come up with different strategies to remove the background.

Benchmark scenario and experimental signatures: As mentioned above, the signal process of interest is initiated by production of dark photon via the mixing with the SM photon. The dark photon then decays into dark matter which flies to a detector and leaves a scattering signature. In the neutrino experiments where a proton beam impinges on a fixed target, there are several ways of creating photons, hence dark photons:

1) Meson-induced production: Protons incident on a target can create mesons. Among them, light neutral mesons (e.g., π^0 and η) can decay into a pair of photons one of which could turn into a dark photon. By contrast, $\pi^\pm$ can be a good photon source via their absorption especially at stopped-pion experiments (e.g., CEνNS): for example, $\pi^- + p \to n + \gamma$ and $\pi^{+/-} + n/p \to p/n + \pi^0, \pi^0 \to 2\gamma$ with γ replaced by a dark photon.

2) Breamsstrahlung of beam protons: Incident protons can radiate off photons some of which could be converted to dark photons.

3) Cascade photons: Primary particles produced in the target by proton beam collision lose their energy by ionization, creating $e^\pm$ which subsequently undergo electromagnetic cascade showering. Expected are a copious number of cascade photons some of which may be replaced by a dark photon.

While the first two mechanisms except the charged pion absorption can be simulated by standard event generators like PYTHIA, the last one and the charged pion absorption can be evaluated by a dedicated simulation with GEANT4 or similar packages.

Searches at CEνNS-type experiments: These experiments (e.g., COHERENT, CCM, and JSNS^2) usually use an $\mathcal{O}(1)$ GeV proton beam so that not only neutrinos but dark matter particles are emitted from the target more or less isotropically. Their protons-on-target per year is as large as $\sim 10^{22} - 10^{23}$, resulting in a huge flux of dark matter (if any). Due to the beam energy and intensity, these experiments are expected to be particularly sensitive to dark matter candidates of the MeV-to-sub-GeV mass scale [2–7].

Neutrinos are an obvious background source, as they leave a similar signature. There are two types of neutrinos, "prompt" neutrinos from the (stopped) charged pion decay and "delayed" neutrinos from the longer-lived (stopped) muon decay. Due to kinematics, the recoil energy spectrum of prompt neutrinos is upper-bounded. By contrast, it was shown that dark matter signals are likely not only to be energetic but to reach the detector promptly [5]. Therefore, keeping only energetic events lying in prompt timing bins can significantly enhance the signal-over-background [2, 5]. We have demonstrated that the sensitivity reaches expected at COHERENT, CCM, and JSNS^2 can be significantly improved beyond the existing limits, using the above-described event selection scheme and all available photon sources [2].

Searches at "high-energy" neutrino experiments: These experiments (e.g., DUNE, SBN, and T2K/T2HK/T2HKK) use a more energetic ($\gtrsim$ 10 GeV) proton beam so that neutrino and dark matter fluxes are more forward-directed and it is possible to access to heavier dark matter. While neutrinos are the major background to the dark matter signal, there are no delayed neutrinos unlike the previous case. Therefore, the search strategy discussed in the previous section is no more relevant, motivating new strategies. While searches at off-beam-axis detectors (e.g., DUNE-PRISM and ICARUS in SBN) [8] are an interesting strategy, we would like to circumvent the background issue with a different strategy enabling us to execute nearly background-free searches.

As clear from the three major production mechanisms, dark matter particles would be produced inside the target and the flux of produced dark matter would lie along the beam direction. By contrast, in these experiments, most of the charged pions, muons etc decay to neutrinos outside the target. We envision the situation in which such charged particles are (uniformly) bent by an external magnetic field which would not affect the direction of the dark matter flux. As a result, neutrinos (typical backgrounds to dark matter signals) and dark matter particles would be separately transported to neutrino detectors and dark matter detectors, respectively. We are now planning to devise a magnet design to achieve this goal, in collaboration with experimentalists.

Summary and outlook: New physics opportunities at the next-generation neutrino experiments are receiving rising attention. The search for light dark matter and light mediators can be one of the core tasks that can be performed under the neutrino physics program in the next decade, as many of the relevant neutrino facilities start data collection or will be operational soon. While in this LOI we discussed the simple scenario where dark matter manifests itself by a target recoil only, upscattering of dark matter followed by the decay of the upscattered state to additional visible particles can be an equally interesting channel to investigate together. We strongly believe that the proposed dark matter searches in this LOI will deepen our understanding in dark matter physics.

References

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