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Boosted Dark Matter at DUNE

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We discuss the search for boosted dark matter scattered off either electron or proton in the Deep Underground Neutrino Experiment. We particularly focus on the case where such boosted dark matter up-scatters to a heavier dark-sector unstable state which subsequently decays back to the dark matter and additional visible particles. The benchmark model to describe the interactions between the Standard Model and dark-sector particles includes a dark photon. We study the experimental sensitivity to the relevant signal in the plane of the dark photon mass and the kinetic mixing parameter.

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1. Introduction

While the existence of dark matter in the universe is compelling and supported by a large amount of cosmological and astrophysical evidence, none of the dark matter-induced signatures via non-gravitational interactions have been observed yet. Conventional approaches including dark matter direct searches assume elastic scattering of non-relativistic, weakly-coupling dark matter with weak-scale mass, focusing on detection of halo dark matter. Alternative approaches are receiving increased attention nowadays. Along the line, in this work, we imagine inelastic (or up-scattering) processes of boosted/relativistic dark matter with sub-GeV/MeV-range mass via a dark photon scenario under the assumption that the relevant dark sector consists of multiple dark matter species and unstable heavy states. More specifically, we consider two-component dark matter scenarios [1] where the heavier component (denoted by χ_0) consists of cosmological dark matter and is allowed to pair-annihilate only to a pair of lighter components (denoted by χ_1) which couple to Standard Model (SM) particles. Under this model setup, lighter dark matter can be boosted in the universe today and leave relativistic scattering signatures in terrestrial detectors. In typical models, the expected flux of boosted χ_1 is not sizable enough for small-volume detectors (e.g. in conventional dark matter direct search experiments) to possess signal sensitivity, so large-volume detectors are better motivated. We consider far detectors in the Deep Underground Neutrino Experiment (DUNE) among such detectors and study detection prospects of boosted dark matter signal in this work.

2. Model and Signatures

To define a model to describe interactions between SM-sector and dark-sector particles, we employ the following benchmark model including a dark photon X and Dirac-fermionic dark-sector matter particles:

$$\mathscr{L} \supset -\frac{\varepsilon}{2}F_{\mu\nu}X^{\mu\nu} + g_{11}\bar{\chi}_1\gamma^\mu\chi_1X_\mu + (g_{12}\bar{\chi}_2\gamma^\mu\chi_1X_\mu + \text{h.c.}), \tag{2.1}$$

where $F_{\mu\nu}$, $X_{\mu\nu}$, and ε denote SM photon field strength tensor, dark photon field strength tensor, and kinetic mixing parameter, respectively. χ_2 is a dark-sector unstable state heavier than χ_1, so g_{11} and g_{12} parameterize the coupling strengths of flavor-conserving and flavor-changing interactions, correspondingly.

This model conceives the processes that the incident χ_1, which is boosted by pair-annihilation of χ_0 in the universe today, scatters off either the electron or proton target, elastically to χ_1 [1, 2] or inelastically χ_2 [3, 4, 5], via virtual dark photon exchange. The process accompanying χ_2 is often called inelastic boosted dark matter (iBDM) process. Since χ_2 is unstable, it decays back to χ_1 and e.g. an electron-positron pair through either on-shell or off-shell dark photon intermediate state depending on the mass spectrum among χ_2, χ_1, and X. Therefore, in an iBDM event, there are a primary recoil target (e^- or p) and secondary decay products (e^-e^+) in the final state. Indeed, the secondary decay point may be displaced from the primary scattering point due to either long-lived χ_2 or X, again depending on the parameter choice. In our phenomenological study, we focus on the iBDM signal as the relevant SM background is expected to be almost absent due to some unique signal features such as multiple visible particles and displaced vertices.

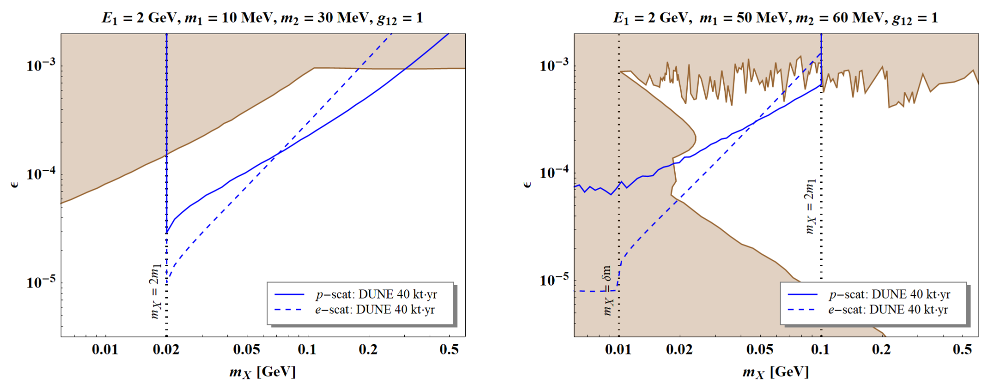

Figure 1: Experimental sensitivities to the iBDM signal under consideration. The results are displayed in the plane of $m_X - \varepsilon$ for the cases of $m_X > 2m_1$ (left panel) and $m_X < 2m_1$ (right panel).

3. Phenomenology and Conclusions

As an example study, we investigate the experimental sensitivity in the usual $m_X - \varepsilon$ plane with m_i being the mass of species i. Exclusion reaches differ from the case of $m_X > 2m_1$ to $m_X < 2m_1$, so we perform two separate analyses, showing our results for the former (latter) in the left (right) panel of Figure 1. All the results are reported by 90% C.L. for a zero-background assumption with 1-year exposure at DUNE far detectors of 40 kt fiducial mass. The momentum threshold for detecting an electron (proton) with an angular resolution of 1° (5°) is set 30 MeV (200 MeV) throughout all analyses. The chosen parameter values are shown in the top frame of each plot. The brown shaded regions denote the present limits. We find that DUNE can probe unexplored parameter space with ε values smaller by about an order of magnitude. We also see that the signal sensitivities in proton and electron channels are different in m_X, i.e. two channels are complementary to each other.

In conclusion, the search for (in)elastic boosted dark matter is promising and can provide a new avenue to investigate dark matter phenomenology. Many theoretical/phenomenological studies have been actively conducted and in progress. These ideas can be tested in various ongoing and projected experiments including DUNE.

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