Snowmass2021 - Letter of Interest

Search for Boosted Dark Matter in DUNE-like experiments

NF Topical Groups:

■ (NF3) Beyond the Standard Model

CF Topical Groups:

■ (CF1) Dark matter: particle-like

TF Topical Groups:

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

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Abstract: In this Letter of Interest, we discuss the prospects for detecting boosted dark matter (BDM) in DUNE-like experiments. BDM is a class of models in which there is a flux of (semi-)relstivistic dark matter, in addition to the usual flux of non-relativistic relic dark matter. The signals arising from BDM can differ significantly from those of elastically scattering relic DM, leading to new opportunities for searches at a broader set of experiments. Large-volume neutrino detectors offer particularly interesting possibilities in several scenarios. The detection capabilities of liquid argon time-projection chambers make them a leading technology in the search for BDM.

Introduction. The search for Weakly Interacting Massive Particle (WIMP) dark matter (DM) will continue over the next decade via direct, indirect, and collider searches. While this remains a flagship piece of the search for non-gravitational DM interactions, recently there has been substantial effort in exploring DM candidates beyond the WIMP paradigm. Many of these new DM scenarios require new search strategies beyond the conventional, WIMP-motivated ones. Among the well-motivated new possibilities, boosted dark matter (BDM) has been proposed [1] which introduces the generic possibility that a small fraction of DM produced at late times is (semi-)relativistic today. BDM is a phenomenon that can generically arise from dark sector models with non-minimal structure, e.g., through DM annihilating to a lighter secondary dark state, DM semi-annihilation or DM decay. We will elaborate some of these possibilities in the following. In terms of phenomenology, the distinctive feature of BDM models is the energetic SM particles that are typically produced due to the scattering of BDM on SM targets, which can be followed by secondary signatures depending on the model details [2] and parameter region [3] . Because of the energetic nature of the final states, neutrino detectors are found to be a particularly promising arena for BDM searches. In the recent years, BDM has become an emerging area of interest for major neutrino experiments such as Super-Kamiokande [4] and Deep Underground Neutrino Experiment (DUNE) [5, 6], and has opened up a range of new research directions for the coming years.

The defining feature of BDM models is that a component of dark matter is boosted with (semi-)relativistic velocities generated by mechanisms discussed below. In most of the well-motivated parameter regions and scenarios, energy deposits of the relativistic incoming BDM are typically much larger than those in the interactions of standard non-relativistic WIMPs. This allows to probe BDM signals both in neutrino experiments [1–18] such as DUNE, Super/Hyper-Kamiokande (SK/HK), IceCube Neutrino Observatory (IceCube), and Short-Baseline Neutrino program (SBN), and in ton-scale dark matter direct detection experiments [18–21]. In particular, the kiloton scale underground neutrino experiments enable the detection of such astroparticles with low fluxes.

Sources of BDM. A typical channel of production of BDM is via annihilation processes due to unique dark sector structures determining the relic abundance [22, 23], whereas other energetic light dark matter productions via cosmic-ray acceleration [24–26], solar reflection [27], nucleon decay in the Sun [28], and dark-sector decays [9, 10, 29, 30] are as well possible and associated phenomenological features would be similar. The annihilation mechanisms include the assisted freeze-out mechanism in two-component scenarios [22] and the semi-annihilation mechanism in the scenarios with a Z_3 symmetry [23]. In both of these cases, non-relativistic relic DM particles are annihilating, so the flux is dominantly generated in locations with a high concentration of relic DM. These locations include the galactic center (GC) [1, 2] and dwarf spheroidal galaxies [12], as well as the Sun [1, 7, 8] in cases where hadronic- and/or DM self-interactions allow the Sun to capture relic DM particles.

Experimental signatures. BDM energetically scatters off targets inside the neutrino detectors. Depending on the type of the recoiling target particle and transferred energy, we can categorize the BDM signals by electron recoiling (e-recoil), nucleon recoiling (N-recoil), and deep/resonant inelastic scattering. Further, the BDM models allowing "upscattering" processes of BDM or bremsstrahlung of a dark gauge boson result in multi-particle signatures with a secondary vertex [2, 3].

Taking advantage of different experimental technologies, we can develop strategies specifically targeting each BDM signal [18]. For example, as the momentum of BDM candidates is correlated with that of the BDM source, a detector providing their directions will allow us to discriminate signal from background, typically by neutral current scatterings of atmospheric neutrinos. Liquid-argon time-projection chambers, such as DUNE [2, 3, 5, 12, 13, 16–18], its protoype ProtoDUNE [14, 15], and SBN [15], hold a great potential for BDM searches, as discussed below. On the other hand, searches at other experiments, such as SK/HK [1, 2, 4, 7, 8, 12, 13, 18], IceCube [1, 8–11, 18], and various ton-scale dark matter detectors [18–21], can probe complementary parameter space.

Detection prospects at DUNE. The underground, multiple tens kiloton far detector of the DUNE experiment is of particular interests in BDM search owing to its millimeter spatial resolution, calorimetry, and the detection threshold of a few tens of MeV kinetic energy for hadrons.

BDM interacting with electrons is expected to give rise to a relatively clean signature, i.e., an electron recoil, so some of the earlier works were devoted to the sensitivity studies of such BDM at DUNE. Examples include BDM from GC [12, 13] and dwarf galaxies [12] in the two-component BDM scenario and BDM from the Sun [13] in the self-interacting BDM scenario. These studies showed the ability of DUNE to probe parameter space of the associated models, e.g., maximum electron recoil energy vs. scattering cross section of BDM off an electron and BDM mass vs. halo DM mass.

In the scenarios where BDM interacts predominantly with hadrons, the interactions include elastic scattering yielding a recoiling nucleon, deep inelastic scattering yielding multi-hadron final states, and resonant scattering producing excited baryons such as the Δ baryons [18, 31]. The newly developed Monte-Carlo (MC) based simulation [16, 31] offers the most accurate description of hadronic BDM interaction thus far. Studies on a benchmark model can be found in Ref. [16], where it demonstrates that DUNE has leading sensitivity in a significant range in the parameter space. In addition, more sophisticated models can be probed applying these MC tools and the analysis method to complementary data sets from DUNE and other neutrino and dark matter experiments.

In non-minimal models which allow "upscattering" of BDM, inelastic BDM (iBDM) [2], and dark-strahlung [3], the experimental signature is enriched by the presence of multiple particles and a secondary interaction vertex, in both cases of electron and hadron scatterings. Along with other BDM cases, the high-resolution imaging capabilities of DUNE detector enable the detailed reconstruction of these unique features, enhancing background rejection and resulting in sensitivity competitive with/complementary to other experiments such as HK [18]. This potential has been already shown in Ref. [17].

Ongoing and future developments: To realize DUNE's potential for BDM search, comprehensive scrutiny of signal topology, background processes, and detector resolution is crucial. While e-recoil can be calculated analytically in the regime relevant to BDM, the hadronic interactions involve nuclear effects which smear the signatures and complicate their topology. Better understanding on nuclear effects is therefore relevant to the BDM search via hadronic interactions. Similar to other analyses, developments on data acquisition/triggering, event reconstruction, detector calibration, and analysis techniques are all important to maximize the sensitivity of BDM searches [17] and distinguish underlying model dynamics.

Summary: The idea of boosted dark matter is receiving increasing attention, as it provides an alternative dark-sector scenario beyond WIMP and can be tested in various immediate and intermediate future experiments. In terms of phenomenology, BDM signals represent *the high recoil energy regime of possible DM dynamics*. This is in contrast to conventional DM direct detection searches for relic DM that are focused on low recoil energy events. DUNE, a next-generation neutrino experiment, has a great potential in the search for BDM signals, allowing for various physics opportunities within BDM. Therefore, dedicated investigation of BDM signal sensitivities and development of related physics tools for DUNE will be important aspects of the neutrino physics and the cosmic-frontier physics programs in the next decade and beyond.

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