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Non-minimal dark matter search in dark matter colliders

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Abstract. In the scenarios of dark matter (DM) with a non-minimal dark sector, we revisit a new detection strategy of observing two or three simultaneous signals from inelastic scattering of a boosted DM [1]. The relativistically incoming DM can scatter off inelastically to a heavier unstable dark sector particle which decays back in to the DM associated with visible Standard Model particles inside large volume neutrino detectors. The existence of the secondary procedure renders us to separate it from conventional neutrino scattering background. The relativistically incoming DM can come from the universe by the annihilation of heavy DM component in an inelastic boosted DM scenario or produced by the beam bombardments in fixed target experiments.

1 Introduction

Dark matter (DM) is a key element constituting our universe with energy density about five times larger than that of the Standard Model (SM) particles. Reminding that the SM sector is composed of seventeen elementary particles with various mass spectrum, it is natural to imagine that the dark sector may be also flavorful containing many particles with a variety of mass spectrum. Furthermore, one may consider the scenarios with multiple DM components (with multiple symmetries for the stability of each component) where the right thermal relic can be expected from mechanisms different from that in conventional scenario of weakly interacting massive particle (WIMP).[1]

As a promising strategy to examine non-minimal dark sector directly, we focus on the possibility of observing *relativistic* DM scattering signal with targets, inspired from ordinary collider experiments [1]. Such relativistic scattering may arise either from a DM component which is produced with a relativistic velocity in the universe in a boosted DM (BDM) scenario or from a direct production of light DM inside the laboratory in fixed target experiments. In the framework of BDM, there are at least two DM components (heavy and light) which are stable each other [8–11] and the right thermal relic is obtained via assisted freeze-out mechanism [7]. The mass difference of the two DM particles is huge so that the light DM pair produced from the annihilation of the heavy DM pair in the *present* universe have relativistic velocities (the ratio of the heavy DM mass to the light one is the boost factor). The heavy DM particles do not interact with the SM particles directly but only through the light

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[1]Null signal observation in DM detection experiments has motivated various non-conventional DM scenarios such as secluded DM [2–6] and non-minimal dark sector models including assisted freeze-out [7], boosted DM (BDM) [8–11], and DM transporting mechanism for cosmic-ray excesses [12].

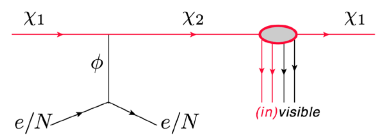

Figure 1. Inelastic boosted DM direct detection scenarios considered in Ref. [1].

DM component so what we can observe in the terrestrial experiments are (in)direct signals of (heavy) light DM. The flux of the relativistic light DM produced from the annihilation of the heavy DM is as small as $\mathcal{O}(10^{-7}\,\mathrm{cm}^{-2}\,s^{-1})$ for the heavy DM mass of $\mathcal{O}(10\,\mathrm{GeV})$ so large volume neutrino detectors are usually considered to observe the signals [8]. On the other hand, a direct production of light DM particles inside the laboratory is possible for any kind of DM scenarios as long as they include a light DM below the center of mass energy of the fixed target experiments.

In this proceeding based on Ref. [1], we discuss the channel that the incoming boosted DM (χ_1) scatters off inelastically to a heavier (unstable) dark sector particle (χ_2) which decays back into the DM χ_1 associated with visible SM particles by the decay of the mediator ϕ inside the detectors of our interest, as depicted in Fig. 1. The decay of the excited state χ_2 into χ_1 and SM particles, resembling typical cascade decay signatures in collider experiments, provides a unique secondary signature separated from conventional neutrino scattering signals.

2 Model framework and kinematic features

A variety of DM model frameworks can be considered to realize the process in Fig. 1. As a toy model for a concrete analysis, we consider a model of Dirac fermionic DM χ_1 which interacts with target SM electron or nucleus via a vector mediator ϕ. The vector mediator is assumed to be a dark gauge boson X_μ from the toy model Lagrangian satisfying a dark $\mathrm{U(1)_X}$ gauge symmetry.

$$\mathcal{L}_X \supset -\frac{\sin\epsilon}{2} F_{\mu\nu}X^{\mu\nu} + g_{12}\bar{\chi}_2\gamma^\mu\chi_1 X_\mu + h.c.\,, \tag{1}$$

where the kinetic mixing between $\mathrm{U(1)_X}$ and $\mathrm{U(1)_{EM}}$ [2, 13–15] is parameterized by ϵ. The off-diagonal gauge interaction $\chi_1\chi_2X_\mu$ with coupling g_{12} can be obtained, e.g., from the mixing in the dark sector with different $\mathrm{U(1)_X}$ charge assignments to χ_1 and χ_2 (see Ref. [16] as an example for the SM quark sector). The red-circled blob in Fig. 1 shows a sequential cascade process of χ_2. For simplicity, we consider a single-step cascade of $\chi_2 \to \chi_1\phi$.

The maximum mass of χ_2 is $\sqrt{s} - m_T$ where m_T is the target mass and $\sqrt{s}$ is the overall center-of-mass energy ($s = m_T^2 + 2E_{\chi_1}m_T + m_{\chi_1}^2$). Then, we get

$$m_{\chi_2} \le \sqrt{m_T^2 + 2E_{\chi_1}m_T + m_{\chi_1}^2} - m_T\,. \tag{2}$$

For χ_1 much heavier than the target ($m_{\chi_1} \gg m_T$) along with a decent boost factor γ_{χ_1}, the above is approximately rewritten as

$$m_{\chi_2} \lesssim m_{\chi_1} + (\gamma_{\chi_1} - 1)m_T\,, \tag{3}$$

which is the case of our e-scattering. On the other hand, if $m_{\chi_1} \ll m_T$, we obtain

$$m_{\chi_2} \lesssim \gamma_{\chi_1} m_{\chi_1}\,, \tag{4}$$

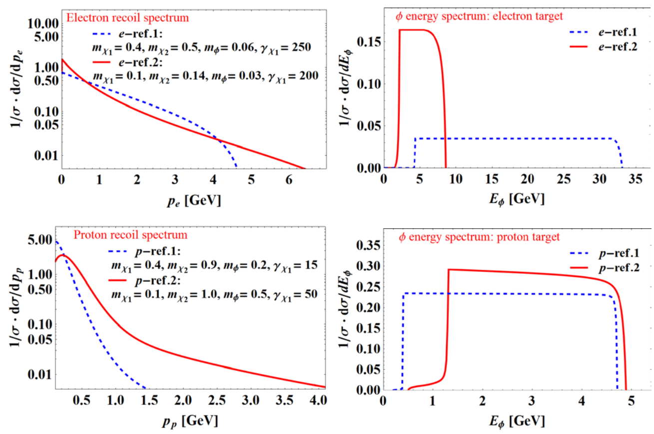

Figure 2. Expected unit-normalized energy spectra of the recoiling target particles from the primary vertex (left panels) and outgoing mediators from the secondary vertex (right panels) for e-scattering (top panels) and p-scattering (bottom panels). The reference masses are in unit of GeV. See Ref. [1] for the details.

Exp.	Volume [Mt]	$p_e^{\rm th}$ [GeV]	$p_p^{\rm th}$ [GeV]	$\theta_e^{\rm res}$ [°]	$\theta_p^{\rm res}$ [°]
SK	0.0224	0.1	1.07	3	3
HK	0.56	0.1	1.07	3	3
DUNE	0.04	0.03	0.05	1	5

Table 1. The volume, threshold (kinetic) energy and angular resolution of SK [19], HK [20] and DUNE [21].

which makes it possible that χ_2 is much heavier than χ_1, corresponding to our p-scattering.

The expected unit-normalized recoil energy spectra for our four reference points (e-ref.1, e-ref.2, p-ref.1, and p-ref.2), written in the plots, are shown in the left panels of Fig. 2. Note that the recoiling energy in large volume neutrino experiments corresponds to the magnitude of the spatial momentum (equivalently, the kinetic energy) of the recoiling target, i.e., $p_T = \sqrt{E_T^2 - m_T^2}$. The reference parameters are chosen to satisfy various experimental bounds [17]. The right panels show the expected (unit-normalized) energy spectra of ϕ produced in the cascade process for our reference points.

Throughout this proceeding and in Ref. [1], we assume that ϕ predominantly decays into e^+e^-. Then the decay length of $\chi_2 \to \chi_1\phi \to \chi_1 e^+e^-$ is at most $\lesssim 1$ cm for our reference points. This is below the detector resolutions (e.g., a few cm for Deep Underground Neutrino Experiment (DUNE) [18]) so the secondary process will be observed as a prompt process in those detectors for the reference points. Note that an appreciable displaced vertex can e also expected for a different choice of parameters of m_ϕ and ϵ.

3 Detection prospects

In order for our signal to be sensitive even with small flux, we choose large volume neutrino detectors such as Super-Kamiokande (SK), Hyper-Kamiokande (HK) and DUNE. The latter two experiments are future proposals which have much attention. Table 1 summarizes the volume, threshold (kinetic) energy and angular resolution of each experiment. Note that our process depicted in Fig. 1 can also

Exp.	Run time	e-ref.1	e-ref.2	p-ref.1	p-ref.2
SK	13.6 yr	170	7.1	3500	5200
HK	1 yr	88	3.7	1900	2800
HK	13.6 yr	6.7	0.28	140	210
DUNE	1 yr	190	9.0	150	1600
DUNE	13.6 yr	14	0.69	11	120

Table 2. Required fluxes in 10^{-7} cm^{-2} s^{-1} in order to make our reference points sensitive in various experiments.

exist in any kind of model with a light DM χ_1 and additional heavier unstable dark sector state χ_2 in fixed target experiments such as LBNF/DUNE [18], SHiP [22] and T2HKK [23]). Note that the threshold energy for p-scattering is much higher that that for e-scattering in Cherenkov light detectors, i.e., SK and HK. This is because a large amount of momentum transfer is needed from χ_1 to boost proton with mass $m_p = 0.938$ GeV. However, this condition is enormously relaxed in liquid Ar TPC detectors like DUNE. From Fig. 2, we see that the differential cross section gets larger for smaller momentum transfer so that the e-scattering is preferred over p-scattering in SK and HK. We also impose an upper limit $p_p \lesssim 1.8$ GeV in order to avoid more concrete analysis on deep inelastic scattering, for simplicity.

The angular resolution separating the primary and secondary signal is also an important feature to observe our signal. For the e-scattering, a huge energy is needed to produce an exited state χ_2 from the initial scattering. Thus, the primary (recoiled e target) and secondary signals can be highly collimated. The angular separation levels between these are shown in Fig. 3 of Ref. [1] for our reference parameters. The results imply that a detector with the angular resolution about 3°, such as SK/HK, can separate the primary and secondary signals for our reference point e-ref.2 with momentum values of the recoiling electron $p_e \in [0.1, 0.3]$ GeV.[2]

On the other hand, much clearer angular separation is possible for p-scattering because the incoming energy of χ_1 only about m_p is enough to produce χ_2 so that the produced particles are not so much boosted. Also, the opening angle of ϕ decay products is large enough as estimated in Ref. [1].

Because the observation of two or three separate (but correlated) signals, expected from our e-scattering and p-scattering processes, is usually not expected in neutrino scattering, it is fair to assume there is no background events. So, in Table 2, we show the experimental sensitivities by requiring three signal events which correspond to the 95% C.L. upper limit under the assumption of a null observation over a null background with Poisson statistics (see also Refs. [24, 25] for useful information). Considering the fact that the typical flux of χ_1 in the minimal BDM scenario is $\mathcal{O}(10^{-7})$ cm^{-2} s^{-1} for $E_{\chi_1} = \mathcal{O}(20\,\text{GeV})$ [8], we see that e-ref. 2 is very promising. Note that the p-scattering processes are much more sensitive in DUNE than SK/HK because of low p_p^{th} of DUNE. The flux can be increased in a modified BDM scenario (e.g., up to $\mathcal{O}(10^{-4})$ cm^{-2} s^{-1} [10, 11]) or probed in fixed target experiments with much higher intensity.

Conclusions

In this proceeding, we revisited the novel proposal of DM detection strategy for the scenarios with non-minimal dark sector: relativistic and inelastic scattering of DM with the targets in terrestrial experiments [1]. The existence of primary and secondary signals provides a unique feature of this process separating the DM signal events from large number of background events (e.g., conventional

[2]For e-ref.1, detecting events with separable signatures is very challenging, which requires future detailed analysis.

neutrino scattering in large volume neutrino experiments). The source of relativistically incoming DM can be the light DM component produced from the annihilation of heavy DM components at the current universe in BDM scenarios or a light DM (in any kind of DM scenarios) produced inside the laboratory in fixed target experiments. A phenomenologically promising feature comes from the secondary cascade process which makes us utilizing the knowledge in collider phenomenology.

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