Probing Dark Matter Dynamics with Long-Lived Particle Searches

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1 Introduction

Most dark matter searches at the Large Hadron Collider (LHC) focus on signals of monoj-X plus missing energy, predicted in traditional weakly interacting massive particle (WIMP) models. Over the past decade, physicists have realized that dark matter could be more complex and richer. In many newly proposed scenarios, dark matter resides a dark sector that contain its own interactions and particles, and they often predict novel signals that are not covered in the existing searches. In this LOI, we discuss such an example, self-interacting dark matter (SIDM) [1], a well-motived scenario that can solve long-standing problems of WIMPs in explaining galactic observations, and show that long-lived particle searches [2, 3] at the LHC provide a promising and complementary probe of the self-interacting nature of dark matter.

2 Dark matter bound states and displaced lepton jet signatures

High-energy particle colliders provide a powerful tool for searching dark matter. The traditional searches assume that dark matter is produced via its interaction with the standard model (SM) particles, and it escapes detectors without energy deposition, leaving only an imbalance of visible final state momentum. Beyond this minimal assumption, dark matter could live in a more complex dark sector where it has strong self-interactions, similar to the nuclear interactions. This possibility has been extensively studied in astrophysics for its success in resolving long-standing small-scale discrepancies of WIMPs on galactic scales. Fitting to astrophysical data provides hints at particle physics realizations of SIDM [1]. In many SIDM models, the dark force is carried by a new mediator that is much lighter than dark matter. In this scenario, two dark matter particles could form an on-shell bound state, leading to distinctive signatures at particle colliders. For example, we could construct invariant mass of visible final states in the bump hunt to measure dark matter mass directly. By comparing production rates of the bounded resonance process and the unbounded missing energy process, we could determine the dark coupling constant.

We studied searches for SIDM bound states at the LHC [4] [1]. The work assumes that SIDM particles are produced via a heavy pseudo-scalar portal with Yukawa-type couplings, and a light dark photon mediates a long-range interaction responsible for bound state formation. The dark photon has a small kinetic mixing with the SM photon, and it could decay to charged leptons, resulting in displaced vertices. The bound state production cross section could reach 1 fb in the allowed pseudoscalar mass region, if the SIDM mass is larger than about 110 (40) GeV and the dark coupling constant is larger than 0.2 (0.5). This means a few hundreds of bound states could be produced at LHC Run3. The bound state decay is dominated by the annihilation into two dark photons. The dark photon would eventually decay back into the charged leptons with a macroscopic decay length, due to a highly suppressed decay width and a large Lorentz boost. In the dark photon parameter region of our interest, final state leptons may originate from displaced vertices at a distance of a few meters without any inner detector information.

[1] See [5, 6, 7] for similar searches for different dark matter models.

This is a characteristic feature that does not appear in SM processes. Therefore, we focused on the Displaced Lepton Jet (DLJ) object from collimated leptonic decays, which is being searched for with non-conventional ATLAS triggers using only the hadronic calorimeter and the muon spectrometer. We found that the LHC is sensitive to SIDM parameter regions relevant for astrophysical observations. If positive signals are observed at LHC Run3, one can potentially fix all model parameters in a combined analysis of collider and astrophysical data. In additional, future LHCb and FASER experiments could also test the dark photon parameter region that gives such a detector size lifetime.

We may further improve our search strategy in future long-lived particle searches. The main background of DLJ search is the multi-jet event. Future background rejection power will be improved by both calorimeter resolution upgrade and larger control region data sample. In addition, we find that large suppression in signal efficiency mainly comes from the strict requirement that both dark photons decay after reaching the HCAL. This also limits our sensitivity to bound states that annihilate into long-lived particles. We expect more dedicated event triggers, for example those designed for non-pointing leptons, will help us optimize the efficiency. Furthermore, the SIDM model predicts another interesting phenomenon, i.e., dark photon radiation from dark matter, and the collinear dark photon decay products could form high multiplicity signals such as lepton jet, emerging jet and semi-visible jet.

3 Summary

We propose a Snowmass2021 study aimed at long-lived particle signals as a unique probe of dark matter dynamics. We have demonstrated the feasibility of this idea in the search of SIDM bound states at the LHC. It is of great interest to extend this analysis to other models that predict feebly interacting particles or degenerating mass spectrums. Aside from the ATLAS and CMS detectors, we could also study such kind of signals with existing and proposed forward physics facilities [8, 9, 10, 11]. Further studies on this topic may open up a new direction for dark matter searches at the LHC and other particle colliders.

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