Snowmass2021 - Letter of Interest

Feebly interacting Dark Matter at colliders and Early Universe Cosmology

Thematic Areas:

■ (EF10) BSM: Dark Matter at colliders
■ (CF1) Dark Matter: Particle Like
■ (TF07) Collider phenomenology
■ (TF09) Astro-particle physics and cosmology

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Context

The origin of dark matter is still an unsolved issue in the Standard Model of particle physics and cosmology. Assuming dark matter is constituted by a new particle beyond the Standard Model (BSM), it is important to explore the mechanisms under which it could have been produced in the early universe and how to probe its existence in current and future experiments. A popular paradigm is the so called WIMP (weakly interacting massive particle) where dark matter is a new particle interacting with the SM through a weak-like interaction. In this scenario DM is in thermal equilibrium with the SM in the early Universe and the relic abundance is obtained typically through the freeze-out mechanism. The WIMP scenario has a very rich phenomenology and, depending on the specific model, can be tested in direct/indirect detection experiments as well as in colliders.

Here we focus on a different scenario, the so called FIMP (feebly interacting massive particle), where DM has only tiny couplings with the SM. In this case the dynamics and the production mechanism in the early Universe can be qualitatively very different than for the WIMP. A typical scenario is where the FIMP is not in thermal equilibrium with the SM in the early Universe and it is produced through the freeze-in mechanism[1], but also more unconventional mechanisms could occur (e.g.[3–5]).

Proposed project

Given the absence of new physics signals in standard searches for dark matter, it is important to investigate systematically unconventional DM paradigms and analyze the strategies through which they can be tested in current and future experiments. The focus of this LOI is the investigation of new directions in FIMP phenomenology. We identify two main goals which will have overlapping outcomes and impact

1) FIMP production mechanism in the early universe As mentioned, FIMP production in the early Universe can occur through different mechanisms, such as freeze-in (decay and/or scattering), co-scattering, conversion driven freeze-out, etc . . . . It is important to explore if new realizations exist, and at the same time investigate whether these mechanisms can be realized in concrete simplified models with natural explanations of the feeble couplings and/or of the mass hierarchies involved. This also involves a classification of simplified models and possible connection with UV completions of the SM.
Furthermore, FIMP models often assume that DM production occurs in the Standard ΛCDM cosmological model with Big Bang Nucleosynthesis preceded by a period of radiation dominated era all the way to reheating time. Relaxing this assumption can lead to different predictions for the DM relic abundance and open new regions of parameters space and signatures. A detailed study of the FIMP phenomenology and associated signatures can thus provide indirect probes of the cosmological history of the early Universe.

2) FIMP phenomenology and long-lived signatures at colliders The feeble couplings involved in FIMP models implies that often new particles in the dark sector have a macroscopic lifetime in their decay into DM and other (dark or not) particles. Such *mediators* can also have sizeable couplings with gauge fields or matter in the SM, and could hence represent the portal to explore the dark sector in experiments. They can be produced at colliders and give rise to exotic BSM signatures involving long-lived particles or displaced decays with missing energy. The connection between long-lived particles and feebly interacting DM has received a renewed interest in the last years[2]. Indeed, in view of the large amount of data that is already collected and will be gathered by the LHC in the next runs, there is an effort in the collider community to explore further BSM models associated to such exotic signatures[6]. New inputs from investigations of alternative DM production mechanisms can then lead to new experimental probe of DM models. For instance, the freeze-in production in a matter dominated era naturally lead to lifetime compatible with displaced signals at the LHC[7;8]. Here we plan to reinterpret existing LHC searches in terms of simplified FIMP models and constraint accordingly the cosmology parameters. Moreover, unexplored topologies such as *kinked tracks* could also emerge from these model classifications, for which dedicated sensitivity studies can be performed. Finally, FIMP models and their associated exotic collider signatures represent important physics cases for future proposed leptonic and hadronic colliders and collider experiments, such as e.g. Mathusla[9], or other detectors including e.g. beam dump experiments. In addition, because FIMP models can allow for light DM candidates, their number density can be large and potentially give rise to large detection rates in direct or indirect DM searches experiments that is also worth to explore.

Our current investigation[8] includes: 1) a classification of models characterized by a three body interaction (DM-mediator-SM), 2) the resulting prediction for the DM relic abundance in different regimes of parameters (including freeze-in through decay and scattering contributions) and in different cosmological history, and 3) the long-lived/displaced signatures at the LHC. The analysis cover in particular the case of an early matter dominated era (in the spirit of[7]), and contains previously unexplored models (with e.g. non renormalizable interactions). We study in details the impact of a modification of the reheating temperature of the Universe on the FIMP relic abundance. In particular we show that by measuring mediator lifetime and mass (cross section), and assuming the correct DM relic abundance, one can infer an upper bound on the reheating temperature.
In the near future we plan to extend such analysis to include the reach for future LHC runs and for different possible future detectors, to start exploring the impact of (proposed) future experiments to the feebly interacting DM paradigm.

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