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Searching for light dark matter at fixed target experiments

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Searching for light dark matter at fixed target experiments

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Abstract. Nowadays deciphering the fundamental nature of dark matter is one of the foremost open questions in fundamental science. In the last years the dark matter experimental program is primarily focused on weakly-interacting massive particles (WIMPs), but in the recent years many innovative dark matter candidates have emerged. One of the most viable models takes into account DM particles in MeV-GeV mass range that are completely neutral under Standard Model forces, but interact through a new force. Small-scale fixed-target experiments at accelerators have unique sensitivities to fully explore these models. Indeed, accelerator experiments can both produce and detect new particles, such as dark matter and the particles mediating new interactions. This article reviews the various experimental techniques to search for light dark matter, i.e. beam dump, missing mass/energy, and visible mediator search experiments.

1. Introduction

The Dark Matter constitutes at least 85% of the mass of our Universe. The Dark Matter existence is ascertained thanks to many evidence come from cosmological and astrophysical measurements as: the shape of the cosmic microwave background (CMB) power spectrum, cluster and galactic rotation curves and gravitational lensing. On the other hand, its nature in terms of origin and compositions and the way its particles interact with the ordinary matter (apart gravitational interaction) is one of the foremost open questions in fundamental science.
A variety of DM candidates of various masses and subject to different kinds of interactions has been proposed over the years. In one of the most well known theoretical model, DM survives as a relic from an era of thermodynamic equilibrium with the SM in the early universe. In this scenario, theoretically well-motivated candidates are represented by Weakly Interacting Massive Particles (WIMPs): particles with mass range, from 10 GeV to 10 TeV interacting via SM weak force. The surprising match between the experimentally observed DM abundance and the value expected assuming the typical WIMP mass and interaction strength is called “WIMP miracle”. Due to the lack of evidence for WIMPs, other well motivated models of lighter DM candidates, in the sub-GeV range or even lower, gained recently the interest of the physics community. In the sub-GeV mass range, one of the simplest model conjures the existence of DM particle in MeV-GeV mass range that belong to a “hidden sector” secluded from the Standard Model, whose mutual interactions could be mediated by a vector massive boson A' called dark photon or heavy photon [1]. Dark photon can mix with the ordinary photon through kinetic mixing. The coupling ϵ of this additional gauge boson to the electric charge is expected to be less 10^{-2}. The kinetic mixing between the dark and the SM photon would provide a “portal” through which

the properties of the light dark matter (LDM) particles can be explored. The "vector-portal" scenario is regulated by four parameters: the LDM particles mass (m_χ), the dark photon mass ($m_{A'}$), the A'-SM electric charge coupling (ϵ), and the A'-LDM coupling (g_D). Depending on the relative values of the masses of the hidden gauge mediator and of the particles belonging to the hidden sectors, the dark photon can undergo visible or invisible decay. If $m_{A'} < 2\,m_\chi$, the decay in LDM is forbidden and the dark photon can only decay to SM particles: this is called "visible decay". On the contrary, if $m_{A'} > 2\,m_\chi$, the "invisible decay" is allowed and therefore A' can decay in a pair of light dark matter particles (χ).

2. Hidden sector searches at accelerators

A comprehensive LDM experimental program has been launched in the last few years, investigating both the existence of χ particles and dark photons [2]. This paper is focused on the fixed-target electron-beam experiments. In these experiments, an electron beam impinges on a high Z target, producing heavy photons that subsequently decay to pairs of fermions. The A' is then reconstructed by measuring the decay products momenta.
In particular, the experimental techniques described in the following sections will be ascribed to the two categories of visible and invisible decay searches.

2.1. Visible decay search

The visible decay search is focused on identifying the A' through its decay into SM particles. The production mechanisms include: annihilation process ($e^-e^+ \rightarrow \gamma A'$), the bremsstrahlung of an A' from an electron ($e^-Z \rightarrow e^-ZA'$). The mediator is searched through its leptonic decay $A' \rightarrow e^-e^+, \mu^-\mu^+$..... The main research techniques are: Bump hunting and Decay-vertex reconstruction.

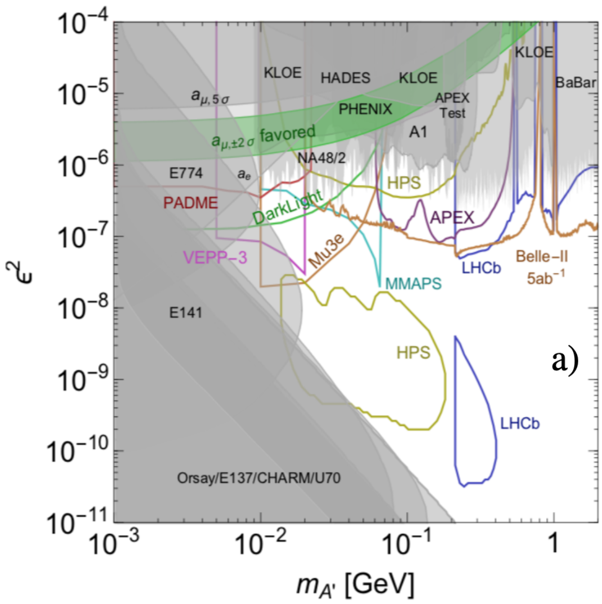

Figure 1. Existing bounds (shaded regions) and projected sensitivities of ongoing/proposed experiments (lines) for dark photon in visible decays in ϵ^2 vs $m_{A'}$

In Bump hunting the four-momentum of all the leptons from A' decay is measured and the l^-l^+ invariant mass is reconstructed. The dark photon will be show up as a narrow resonance over a huge background of QED events. Some examples of fixed-target experiments to search

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for visible decay are: HPS at JLAB [3], APEX at JLAB [4] .
Decay-vertex reconstruction allows to explore a region in the (ϵ^2, $m_{A'}$) plane corresponding to so small coupling parameter that the signal/background ratio is too unfavorable for a simple bump-hunt search. In this technique, a thin target is used to produce A' via, for example, a brehmsstrahlung emission from an incoming electron, and the vertexes of the l^-l^+ pairs produced in the beam-target interaction can be reconstructed. The selection of lepton-pair events with a displaced vertex allows to reduce the background from the prompt QED events. This strategy is used in HPS experiment at JLAB, in addition to bump hunting technique. Several constraints on the dark photon parameter space have been already set as shown in Fig.1.

2.2. Invisible decay search

In the invisible decay, A' decays in a pair of DM particles. The invisible decays can be detected by using missing-mass, missing-energy/momentum and beam dump experiments.

2.2.1. Missing mass In this class of experiments the DM is produced in exclusive reactions such as $e^-e^+ \to A' \to \chi\chi$ and identified as a narrow resonance over a smooth background in the recoil mass distribution. This approach requires a well-known initial state and the reconstruction of all particles besides the DM. The sensitivity of missing-mass experiments depends on the available luminosity, the momentum resolution and the hermeticity of the experimental set-up, which is especially critical to keep under control the background arises from reactions in which particle(s) escape undetected, mimicking an A' invisible decay. Examples of experiments based on this approach using a positron beam impinging on fixed target are: VEPP3 [6], PADME [5].

2.2.2. Missing energy/momentum In this approach the DM is produced in the fixed-target reaction as $e^-Z \to e^-ZA'$ and identified through the missing energy/momentum carried away by the escaping DM particles. The main challenge of this approach is an highly background rejection, which relies strongly on the detector hermeticity and, in most of the cases, on the exact knowledge of the initial and final state kinematics. An example of experiment based on missing energy approach is NA64 [7] where the dark mediator is produced in an active beam-dump, made by an electromagnetic calorimeter (ECAL) and the observable is the recoiling final state electron. Therefore the signal is defined as an energy deposition in the ECAL and null energy deposition in the downstream part of the detector (a second electromagnetic calorimeter and an hadronic calorimeter, plus veto detectors).
In a missing momentum experiment, as LDMX [8], the momentum of each incoming electron must be measured together with the energy and momentum of the outgoing particles. The experimental signature for an A' invisible decay consists of a soft electron scattered at wide angle with no other particles in the final state.

2.2.3. Beam Dump In this technique the A' invisible decay is probed by directly detecting the DM particles via $\chi e \to e\chi$ or $\chi N \to N\chi$ scattering in the downstream detector. This approach has the advantage of probing the DM interaction twice, providing sensitivity to the dark sector-mediator coupling. On the other hand, this involves a huge reduction of the expected signal yield. To (partially) compensate for the small scattering probability a large proton/electron beam flux is required.
The considerable sensitivity of beam-dump experiments to LDM is underscored by the reach of running neutrino experiments. A future experiment specifically designed and optimized to search for light DM by dumping an intense electron beam is BDX [9] (JLab). It is expected to run at JLAB in a dedicated underground facility located 20 m downstream of the Hall A beam-dump. It will make use of a 10.6 GeV e^- beam, provided by CEBAF, collecting up to 10^{22}

electrons on target. The detector consists of two main components: a CsI(Tl) electromagnetic calorimeter (Ecal) and a veto system used to reject the background. The expected signature of the DM interaction in the Ecal is a $\sim$GeV electromagnetic shower paired with a null activity in the surrounding active veto counters. In addition to the veto system, a specific shielding configuration installed between the dump and the detector will be used to suppress the high-energy component of the beam-related background.

3. Conclusion

In recent years, the field of dark matter has been characterized by the blossoming of many innovative ideas. Among these stand out hidden-sector Dark Matter candidates which are completely neutral under Standard Model forces, but interact through a new force. This article reviews the experimental approaches used to search for hidden-sector Dark Matter and, in particular, of the mediator of a still unknown new interaction, the dark photon. Most of the experiments based on these approaches can provide high sensitivity and precision results in well defined and so far unconstrained regions of the DM parameter space; as such, all of them are highly complementary and synergistic.

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