Light dark matter searches with positrons

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This LOI presents two complementary approaches to search for light dark matter with a multi-GeV energy positron beam. Light dark matter is a new compelling hypothesis that identifies dark matter with new sub-GeV "hidden sector" states, neutral under standard model interactions and coupling to ordinary matter through a new force. Accelerator-based searches at the intensity frontier are uniquely suited to explore the dark sector.
Using a high-intensity and high-energy positron beam, and exploiting a novel light dark matter production mechanism—positron annihilation on atomic electrons—the proposed experiments will be able to explore new regions in the light dark matter parameter space, confirming or constraining the hypothesis.

Introduction

In recent years, a novel hypothesis for the nature of dark matter (DM) has been introduced. It predicts the existence of **light dark matter** (LDM) particles, with sub-GeV mass, interacting with standard model (SM) states through a new force. The simplest such model predicts LDM particles (denoted χ) with masses below 1 GeV, charged under a new force and interacting with SM particles via the exchange of a light spin-1 boson, usually referred to as a "heavy photon" or "dark photon" (A') (1–3). This picture allows for an entire new "dark sector" containing its own particles and interactions and is further compatible with the well-motivated hypothesis of DM thermal origin (4). This hypothesis assumes that, in the early Universe, DM and SM abundances reached thermal equilibrium through an annihilation mechanism. The present DM density, deduced from astrophysical measurements, is thus a relic remnant of its primordial abundance (4). The thermal origin hypothesis provides a relation between the currently observed DM density and the model parameters, resulting in a clear, predictive target for discovery or falsification (5).
This constraint, within the minimal A' model, is valid for every DM and mediator variation up to order-one factors, provided that $m_{\rm DM} < m_{\rm MED}$.

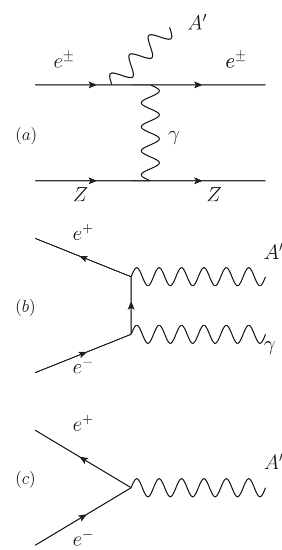

Fig. 1. Three different A' production modes in fixed-target lepton beam experiments: (a) A'-strahlung in e^-/e^+-nucleon scattering; (b) A'-strahlung in e^+e^- annihilation; (c) resonant A' production in e^+e^- annihilation.

Dark sector searches with positron beams on fixed targets

LDM particles can be produced in collisions of electrons or positrons of several GeV with a fixed target by the processes depicted in Fig. 1, with the final state A' decaying to a $\chi\overline{\chi}$ pair. For experiments with electron beams, diagram (a), analogous to ordinary photon bremsstrahlung, is the dominant process. However, for thick-target setups (where positrons are produced as secondaries from the developing electromagnetic shower), it has been recently shown that diagrams (b) and (c) actually give non-negligible contributions to select

regions of the available parameter space (6).[1]
In contrast, for experiments with positron beams, diagrams (b) and (c) play the most important role. In this LOI, we propose two complementary measurements to search for light dark matter with positron beams, relying on these processes. We first introduce the two approaches and then briefly discuss the experimental setup, measurement strategy, data analysis procedure, and foreseen results for each. Specifically, we consider here the possible 11 GeV positron beam to be developed in the near future at Jefferson Laboratory (7).

1. Thin-target measurement. This measurement exploits the A'*-strahlung* production in electron-positron annihilation described by diagram (b) (also called radiative annihilation). The primary positron beam impinges on a thin target, and a photon-A' pair is produced. By detecting the final-state photon momentum with an electromagnetic calorimeter, the missing mass M_{miss} per event can be computed:

$$M^2_{\text{miss}} = (P_{\text{beam}} + P_{\text{target}} - P_\gamma)^2 \quad . \qquad \mathbf{(1)}$$

The signal would appear as a peak in the missing mass distribution centered at the A' mass, on top of a smooth background resulting from SM processes with single photons measured in the calorimeter. The width of the signal peak is mainly determined by the energy and angular resolution of the calorimeter. Several experiments searching for A' with this approach have been proposed. PADME (Positron Annihilation into Dark Matter Experiment) at Laboratori Nazionali di Frascati (LNF) (8, 9) is one of the first experiments using the e^+ on thin-target approach to search for A'. It relies on a 550 MeV positron beam provided by the DAΦNE linac at LNF which then impinges on a thin diamond active target. PADME design can be used as a baseline for the future thin target measurements.

2. Active thick-target measurement. This measurement exploits the *resonant* A' *production* by positron annihilation on atomic electrons, described by diagram (c). The primary positron beam impinges on a thick active target, and the *missing energy* signature of produced and undetected χ is used to identify the signal (10). The active target measures the energy deposited by individual beam particles: when an energetic A' is produced, its *invisible* decay products—the $\chi\overline{\chi}$ pair—carry away a significant fraction of the primary beam energy, resulting in a measurable reduction of the expected deposited energy. Signal events are identified when the missing energy E_{miss}, defined as the difference between the beam energy and the detected energy, exceeds a minimum threshold. The signal has a distinct dependence on the missing energy through the relation $m_{A'} = \sqrt{2m_e E_{\text{miss}}}$. This leads to a specific experimental signature for the signal, appearing as a peak in the missing energy distribution; the peak location depends solely on the dark photon mass. Owing to the emission of soft Bremsstrahlung photons, the thick target causes an almost continuous energy loss in impinging positrons. Although the positron energy loss is a quantized process, the finite intrinsic width of the dark photon—much larger than the positron energy differences—and the electron energy and momentum spread induced by atomic motions (11) will counterbalance this effect. This allows the primary beam energy to be "scanned" through the full range of dark photon masses from the highest mass (corresponding to the loss of the entire beam energy), to the lowest allowed by the missing energy threshold (12). This approach exploits the presence of secondary positrons produced by the developing electromagnetic shower.

[1] Also see Ref. (5) for a comprehensive review of past and current experiments and future proposals.

1. Positron annihilation on a thin target

Signature and signal yield. The differential cross-section for dark photon production via positron annihilation on atomic electrons of the target, $e^+e^- \to A'\gamma$, is given by:

$$\frac{d\sigma}{dz} = \frac{4\pi\alpha^2\varepsilon^2}{s}\left(\frac{s-m^2_{A'}}{2s}\frac{1+z^2}{1-\beta^2z^2} + \frac{m^2_{A'}}{s-m^2_{A'}}\frac{1}{1-\beta^2z^2}\right).$$

Here, s is the $e^+\ e^-$ system invariant mass squared, z is the cosine of the A' emission angle in the center-of-mass (CM) frame, measured with respect to the positron beam axis, and $\beta = \sqrt{1-4m^2_e/s}$. This result has been derived at tree-level, keeping the leading m_e dependence to avoid non-physical divergences when $|z| \to 1$. The emission of the annihilation products in the CM frame is concentrated in the e^+e^- direction. This results in a forward-peaked angular distribution for the emitted γ in the laboratory frame. In the case of invisible decays, the A' escapes detection, while the γ can be detected in the downstream electromagnetic calorimeter (ECAL). The measurement of the photon energy and emission angle, together with the precise knowledge of the primary positron momentum, allows the computation of the missing mass kinematic variable via Eq. 1. The viable mass range is constrained by the available energy in the CM frame: with an 11 GeV positron beam A' masses up to ~ 106 MeV can be explored.
The signal yield has been evaluated using CALCHEP (13). The widths $\sigma(m_{A'})$ of the missing mass distributions due to the measured recoil photon momenta have been computed for six A' masses in the 1–103 MeV range. CALCHEP provides the total cross section of the process for $\varepsilon = 1$; the cross section as a function of ε is obtained by multiplying it by ε^2. Due to the kinematics in $e^+e^- \to \gamma A'$ discussed above, the missing mass resolution is best for large A' masses and degrades for lower A' masses ($m_{A'} < 50$ MeV).

Expected background. Processes resulting in a single γ striking the calorimeter constitute the backgrounds in the experiment, the most relevant ones being Bremsstrahlung and e^+e^- annihilation with two or three outgoing photons (where one or two photons are missed). In order to reduce the Bremsstrahlung background, the proposed detector features an active veto system composed of plastic scintillating bars. Positrons losing energy via Bremmstrahlung emission in the target are detected in the vetos, rejecting the event. However,

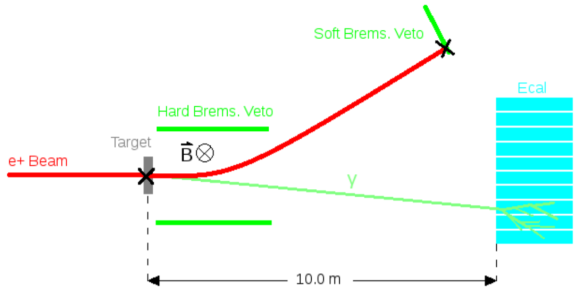

Fig. 2. Layout of the proposed thin target setup.

the high Bremsstrahlung rate is an issue for this class of experiments, limiting the maximum viable beam current. To evaluate this background, a full GEANT4 (14) Monte Carlo (MC) simulation of the positron beam impinging on the target, based on the PadmeMC simulation program (15), has been performed. For all Bremsstrahlung photons reaching the ECAL, the missing mass has been computed accounting for the assumed detector angular and momentum resolution. As a result of this study, it was found that Bremsstrahlung is a non-negligible source of background for this kind of experiment.

The $e^+e^- \to \gamma\gamma$ and $e^+e^- \to \gamma\gamma\gamma$ annihilation processes can produce background events whenever only one of the photons is detected in the ECAL. This contribution has been calculated by directly generating events with CALCHEP, which also provided the total cross sections for these processes. As with Bremsstrahlung, the missing mass spectrum was computed for events with a single photon hit in the ECAL. This study showed that, if one requires the measured energy to be greater than 600 MeV, the two-photon annihilation background becomes negligible. The reason is momentum conservation: asking for only one photon to fall within the ECAL geometrical acceptance translates into a strong constraint on its energy. However, the argument does not apply to the three-photon annihilation—this process generates an irreducible background in the experiment (albeit with a lower cross section).

Experimental Setup. The experimental setup of the proposed measurement is shown in Fig. 2. The 11 GeV positron beam impinges on an 100 µm thick carbon target, which features a good compromise between density and low Z/A ratio, thereby reducing the Bremsstrahlung rate. A magnet capable of generating a field of 1 T over a region of 2 m downstream of the target bends the charged particles (including non-interacting positrons) away from the ECAL, placed a few meters downstream. The ECAL is composed of high-density scintillating crystals arranged in a cylindrical shape. High segmentation is necessary to obtain a good angular resolution, which is critical for a precise missing mass computation. The optimal segmentation should be matched to the Moliére radius of the chosen material.

Since the high rate of Bremsstrahlung radiation at small angles from the beam axis would blind the central crystals of the calorimeter, the simplest solution is to carve out a hole at the center of the cylinder. Assuming a radius of 30 cm and a distance from the target of 6 m, a geometrical acceptance of ~ 50 mrad can be achieved. In addition to the ECAL, the experimental setup includes a veto system to tag and reject Bremsstrahlung events.

Further suppression of this background can be achieved by placing a photon detector, much faster than the main calorimeter, covering its central hole. Such a fast calorimeter can further help in the reduction of $\gamma\gamma$ and 3γ events with one or two photons lost.

Positron beam requirements. As mentioned, the A' mass range that the proposed thin target experiment can explore is strictly constrained by the available energy in the CM frame. A 11 GeV positron beam would therefore significantly extend the A' mass range relative to similar experiments, up to ~ 106 MeV. Since $e^+e^- \to \gamma A'$ annihilation is a rare process, the search sensitivity depends on the number of positrons on target (POT) collected. In this setup, the maximum current is limited by the Bremsstrahlung rate on the innermost crystals of the ECAL. Therefore, a continuous beam structure is preferable. In this study, a continuous 100 nA beam has been considered resulting in a manageable ~ 200 kHz rate per crystal in the inner ECAL. In this configuration, 10^{19} POT can be collected in 180 days, covering a new region in the A' parameter space. In the event that the available beam current is lower than 100 nA, similar results can be obtained by increasing the target thickness, at the expense of higher backgrounds due to multiple scattering.

The missing mass computation requires a precise knowledge of the primary positron momentum, which translates into certain beam quality requirements. Here, a beam energy dispersion of $\sigma_{E_{\text{Beam}}}/E_{\text{Beam}} < 1\%$ and angular dispersion of $\theta_{\text{Beam}} < 0.1$ mrad have been considered. With these assumptions, the missing mass resolution is dominated by the ECAL performance, with a negligible contribution from beam dispersion.

2. Positron annihilation on a thick active target

Signature and signal yield. The cross section for LDM production through positron annihilation on atomic electrons, $e^+e^- \to A' \to \chi\overline{\chi}$, is characterized by a resonant shape (16):

$$\sigma = \frac{4\pi\alpha_{EM}\alpha_D\varepsilon^2}{\sqrt{s}} \frac{q(s-4/3q^2)}{(s-m_{A'}^2)^2+\Gamma_{A'}^2 m_{A'}^2} \ , \qquad \textbf{(2)}$$

where s is the e^+e^- system invariant mass squared, q is the χ-$\overline{\chi}$ momentum transfer in the CM frame, and $\Gamma_{A'}$ is the A' width. The kinematics of the $e^+e^- \to \chi\overline{\chi}$ reaction in the *on-shell scenario* ($m_{A'} > 2m_\chi$) are strongly constrained by the underling dynamics. Since the A' decays invisibly, its energy is not deposited in the active target, and the corresponding experimental signature is the presence of a peak in the missing energy (E_{miss}) distribution. The peak position depends solely on the A' mass through the kinematic relation:

$$m_{A'} = \sqrt{2 m_e E_{\text{miss}}} \, . \qquad \textbf{(3)}$$

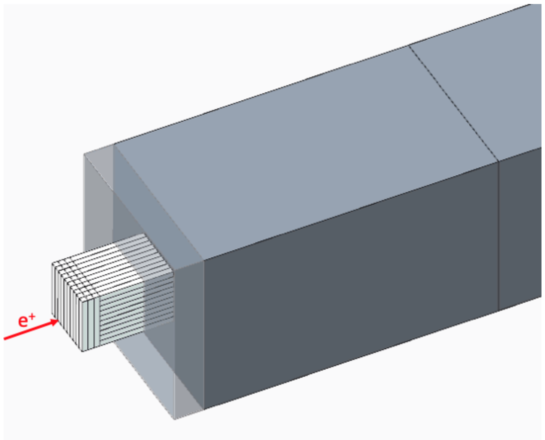

Fig. 3. Schematic layout of the active thick-target experimental setup, with the ECAL (white) followed and surrounded by the HCAL (gray). The semi-transparent portion of the HCAL in front is that installed all around the ECAL.

For a given A' mass, the expected signal yield is:

$$N_s = n_{\mathrm{POT}} \frac{N_A}{A} Z \rho \int_{E_{\mathrm{miss}}^{\mathrm{CUT}}}^{E_0} dE_e \, T_+(E_e)\, \sigma(E_e)\,, \qquad \textbf{(4)}$$

where A, Z, ρ, are (respectively) the target material atomic mass, atomic number, and mass density; E_0 is the primary beam energy; N_A is Avogadro's number; $\sigma(E_e)$ is the energy-dependent production cross section; n_{POT} is the number of impinging positrons; and $E_{\mathrm{miss}}^{\mathrm{CUT}}$ is the missing energy cut. Finally, $T_+(E_e)$ is the positron differential track-length distribution (17).

Positron beam requirements. A missing energy measurement requires low primary positron beam intensity, enough that individual positrons impinging on the active target can be distinguished. At the same time, the beam current has to be large enough to accumulate a sizeable number of POT. For example, a positron beam with time structure corresponding to 1 e^+/µs can accumulate more than 10^{13} POT/year, with an average time interval between positrons of 1 µs. In the following, we will present the sensitivity to LDM considering 10^{13} POT accumulated in one year of data-taking.

Experimental setup. The layout of the proposed measurement is schematically reported in Fig. 3. It features a homogeneous electromagnetic calorimeter (ECAL) acting as a thick target to measure the energy of each impinging positron, and a hadron detection system (HCAL) installed around and downstream of the active target to measure long-lived (e.g. neutrons and K_L) and high-penetration (e.g. muons and charged pions) particles escaping the ECAL.
The main requirement for the HCAL is hermeticity to long-lived particles exiting the ECAL. From a MC simulation of this setup, the probability of having one or more high-energy ($\gtrsim$1 GeV) hadrons leaving the active target is $\sim 10^{-4}$ per POT. This calls for an HCAL inefficiency of 10^{-10} or lower. The *preliminary* detector design uses a modular iron/scintillator calorimeter, with length corresponding to approximately 25 nuclear interaction lengths, partially surrounding the active target to decrease the energy leakage from the ECAL's transverse sides.

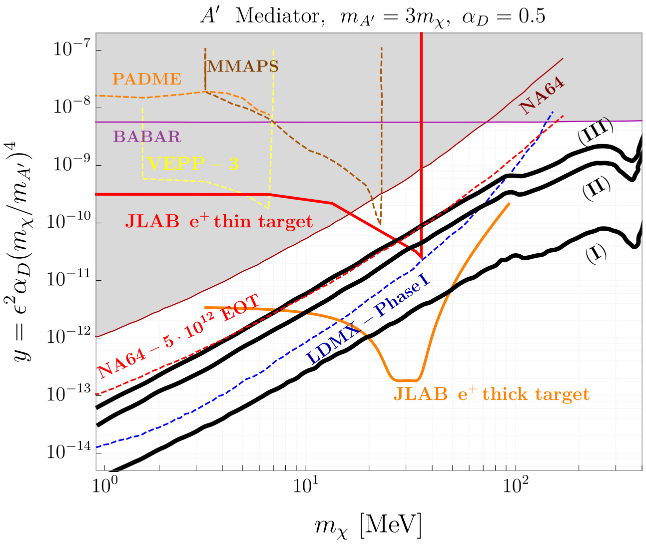

Fig. 4. The expected sensitivity for the thin-target (red) and thick-target (orange) measurements, compared to existing exclusion limits (gray area) and projections for future efforts (dotted lines). The black lines are the thermal targets for elastic and inelastic scalar LDM (I), Majorana fermion LDM (II), and pseudo-Dirac fermion LDM (III).

Results

The sensitivity of the two proposed measurements is shown in Fig. 4, compared with current exclusion limits (gray areas) and expected performance of other future missing-energy and missing-mass experiments (dashed curves). On the same plot, we show the thermal targets for significant variations of the minimal LDM model: elastic and inelastic scalar LDM (I), Majorana fermion LDM (II), and pseudo-Dirac fermion LDM (III). For the thin-target effort, the red curve reports the sensitivity estimate based on the realistic backgrounds that have been discussed before. In the thick-target case, the orange curve refers to the ideal scenario of a zero-background measurement. This hypothesis, following what was done in similar experiments (18, 19), will be investigated with MC simulations during the future experiment's design phase.
The two measurements presented in this document are characterized by varying sensitivity and design complexity. They can be considered as two complementary experiments addressing the light dark matter problem.
Specifically, with the availability of a 100 nA, 11 GeV positron beam at JLab, the thin-target experiment can start almost immediately, since no demanding requirements on the beam are present. The conceptual design is already mature, being based on realistic MC simulations. Furthermore, the detector can be based on an already-existing and working setup, the PADME experiment at LNF (8). The possibility of installing PADME at JLab, which would benefit both from existing equipment and from the experience in operating it, is a compelling possibility, allowing a successful run of thin-target measurements from day one.
The high energy and large intensity of the beam will allow

these two efforts to explore considerable untapped regions of the LDM parameter space, beyond that covered by current or planned experiments.

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