PROCEEDINGS OF SCIENCE

The NA64-e experiment at CERN

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One of the most compelling arguments motivating the search for physics beyond the Standard Model (SM) is the need to explain the nature of Dark Matter (DM). Despite an extensive experimental program that combined direct, indirect, and detection at colliders, to date, no conclusive results about DM particle nature have been determined. Among the DM models, those predicting DM particles in the sub-GeV mass range (also called Light Dark Matter or LDM) represent a theoretically well-grounded option if a new DM-SM interaction is introduced. A simple hypothesis considers a new feeble force transmitted by a vector boson A' (called Dark Photon), kinetically mixed with the ordinary photon. In this scenario, the A' can be generated in the SM interactions of charged particles and subsequently decays either into SM or LDM particles. The NA64-e experiment at CERN exploits the 100 GeV SPS electron beam impinging on a thick active target focusing mostly on the production and detection of the A' to LDM decay. If an A' is produced in the target, the LDM daughter particles leave the detector carrying away a significant amount of energy, resulting in a missing energy event. To date, NA64-e has collected 2.84×10^{11} electrons on target. No events with missing energy greater than 50 GeV and no activity within the veto systems were observed. These results allowed the collaboration to set the most competitive limits in the LDM parameter space.

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1. Introduction

Various astronomical and cosmological observations suggest the need for an extension of the Standard Model (SM). These measurements, in addition to the observed anomalies in particle physics (such as the anomalous magnetic moment of the muon), may find an explanation within the hypothesis by which a new kind of matter, called Dark Matter (DM) [1] exists and not directly interacts with the electromagnetic field. Even if the nature of the DM is still unknown, gravitational measurements indicate that it may form the majority of the mass of the Universe. In the last decades, theoretical and experimental efforts in DM studies have primarily focused on the Weakly Interacting Massive Particles (WIMP) paradigm. This model predicts the existence of DM particles with masses in the range of 1 GeV - 1000 GeV, interacting with the Standard Model particles via the weak force. However, despite an extensive search program that combined direct, indirect, and detection at colliders, to date no conclusive signals supporting the existence of WIMPs have been found [2]. As a consequence, the DM search has extended to alternative models. In particular, the so-called "Light Dark Matter" (LDM) theories, by which LDM particles have mass in the sub-GeV range, are theoretically well-motivated if a new light mediator (neutral under the SM gauge group) is introduced. This light mediator acts as a "portal" connecting the SM and the Dark Sector. In this context, the SM gauge and Lorentz invariance strictly constrain the possible hypothesis about the introduced SM-DM interaction. The additional requirement of renormalizability further restricts the possible portals [3]. This work will be focused on the vector-mediated scenario whose model introduces a new massive gauge boson called "Dark Photon" or "Heavy Photon" (A'). This mediator interacts with the LDM particles (χ), charged under the new U$'(1)$ gauge symmetry. An effective coupling between the SM and the Dark Sector particles is generated by a kinetic mixing between the A' and the SM photon [4]. Such a theory can be described by the effective Lagrangian given below [5]:

$$\mathcal{L}_{LDM} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{m^2_{A'}}{2}A'_\mu A'^\mu + \bar{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi - e_D\bar{\chi}\gamma^\mu A'_\mu\chi + \frac{\varepsilon}{2}F'_{\mu\nu}F^{\mu\nu}.$$

Here $F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$ and $F_{\mu\nu}$ are respectively the Dark Photon and SM electromagnetic field strength, $m_{A'}$ is the A' mass, ε is the coupling constant between A' and the Standard Model photon, while $e_D \equiv \sqrt{4\pi\alpha_D}$ is the coupling constant for the χ-A' interaction. Thanks to the γ-A' mixing, an effective coupling arises between SM charged particles and the A' with intensity εq, being q the electric charge of the particle involved in the process. Here we focus on the so-called "invisible decay" scenario: in this hypothesis, being $m_{A'} > 2m_\chi$ and $\alpha_D \gg \alpha_{EM}\varepsilon^2$ the Dark Photon decays mainly into an LDM particle pair through an "invisible decay" channel ($A' \rightarrow \bar{\chi}\chi$). In conclusion, although the LDM parameters are unknown, the additional thermal origin hypothesis provides an indication for them. In particular, if one assumes that the current DM density results from a thermal relic abundance in the early universe, it is possible to constrain the LDM parameter space, identifying a specific region of parameters and providing a concrete experimental target, known as "thermal target" [5].

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2. LDM Seach at Accelerators: the Missing Energy Approach

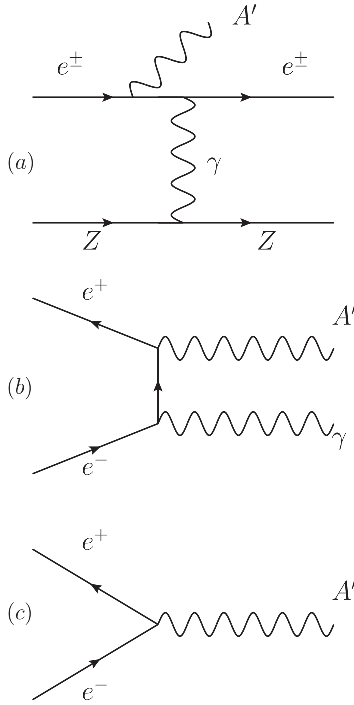
Because of the low mass of LDM candidates, direct search experiments, aiming to detect the nuclear recoil caused by the scattering of cosmogenic DM particles, present a limited sensitivity to this scenario. However, a significant experimental effort to overcome this challenge is currently ongoing [6], motivated by the fact that direct search is crucial to investigate the particle nature of Dark Matter. In parallel, during the last years, a broad experimental program to search for Light Dark Matter at accelerators has started. The controlled environment of accelerator-based experiments allows for optimized studies in specific regions of interest in the LDM parameter space, making this approach really promising. In addition, the LDM-SM interaction at low energies significantly depends on the details of the LDM theory (such as the quantum numbers of χ particles). For some models, this can result in a strong suppression of direct detection cross section. On the contrary, high-energy relativistic scattering processes are less affected by these details, making accelerator experiments particularly promising to explore different LDM hypotheses at the same time [3].

Among the accelerator-based studies, fixed-target experiments at medium beam energy (10 GeV - 100 GeV) are ideally suited to probe the LDM scenario. In this context, the A's can be produced in the collisions of electrons or positrons with a fixed target, through the processes shown in Fig.1 (left). Diagram (a), equivalent to the SM photon bremsstrahlung, is the dominant process in most of the LDM parameter space [7]. Processes (b) and (c) are the most intense A' production mechanisms in selected kinematic regions and can be fully exploited if a positron beam is used [12]. Once produced, the Dark Photon promptly decays into a Light Dark Matter particles pair $(\chi\bar{\chi})$ that leaves the detector without further interactions. This channel can be efficiently probed using a "missing energy" measurement.

The missing energy approach for LDM search exploits a beam impacting on a thick active target measuring the energy deposited by each impinging particle (Fig.1, right). If an A' is produced in the target by the electromagnetic shower generated by the primary beam particle, it promptly decays in LDM particles. This results in a sizable missing energy, defined as the difference between the beam and the measured energy. The target has to be thick enough to fully absorb the electromagnetic shower and the beam current has to be limited to reduce the pile-up effects: the time interval between the impact of two subsequent positrons has to be longer than the response time of the detector. Otherwise, an overlap between events occurs, and it is not possible to evaluate the missing energy event by event. Finally, such an experiment must consider the production of long-lived neutral and highly penetrating particles that can escape from the detector mimicking an LDM signal.

3. The NA64-e Experiment at CERN

The NA64-e experiment (Fig. 2) searches for Light Dark Matter using the 100 GeV electron beam provided by the Super Proton Synchrotron (SPS) at the H4 beam-line at CERN [8] [9] [11] [10]. The experiment exploits the "missing energy" technique described in the previous section. The electron beam impinges on a thick active target: a 40 X_0 radiation-length lead-scintillator (Pb/Sc) Shashlik electromagnetic calorimeter (ECAL) with a PMT-based readout. The first 4 X_0 of the ECAL forms the so-called "preshower"; the measured energy fraction, deposited



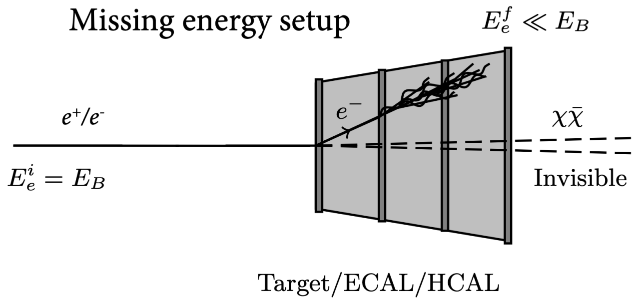


Figure 1: Left: Three different A' production channels in fixed target lepton beam experiments: (a) A'-strahlung in e^-/e^+-nucleon scattering; (b) $A'-$ strahlung in e^+e^-annihilation; (c) resonant A' production in e^+e^- annihilation [12]. **Right:** The missing energy experiment setup scheme. The $e^\pm$ beam impinges on a thick, active target. If produced, the LDM particles leave the detector carrying away a significant fraction of the beam energy.

within the preshower, plays an important role in rejecting backgrounds. The overall ECAL energy measurement has a resolution of $\frac{\sigma_E}{E} \simeq \frac{10\%}{\sqrt{E}} + 4\%$. The missing energy threshold defining signal events is $E_{miss} > 50$ GeV. The momentum of each impinging electron is measured using a magnetic spectrometer, composed of two successive dipole magnets (MBPL) that bend the beam by a 20 mrad angle, and a set of upstream and downstream tracking detectors (Micromegas, Strawtubes and Gaseous Electron Multipliers). The spectrometer allows for a momentum resolution of $\frac{\Delta p}{p} \simeq 1\%$.

The background sources affecting the NA64-e experiment can be divided into two main categories. The first one is due to the decay of muons and hadrons in the electron beam into $e + \nu$ that results in the deposition of a fraction of the beam energy in the ECAL. This kind of background is particularly significant for the NA64 experiment, which makes use of a secondary electron beam extracted from the primary proton beam of SPS. In particular, the electron beam at the H4 line presents hadronic contamination at the level of $\sim 1\%$. To reject this background, the NA64-e experiment features a Pb/Sc synchrotron radiation detector (SRD) placed ~ 16 m downstream of the MLBPs. The SRD detects the synchrotron radiation emitted by the charged particles of the beam passing through the magnetic field, allowing for the identification and rejection of hadrons. The NA64-e analysis uses a collection of cuts on the SRD signal and on the shape of the electromagnetic shower in the ECAL to discriminate electrons from pions, with an overall inefficiency of $\sim 10^{-4}$ [13]. The second background category is associated with the production of highly penetrating particles in

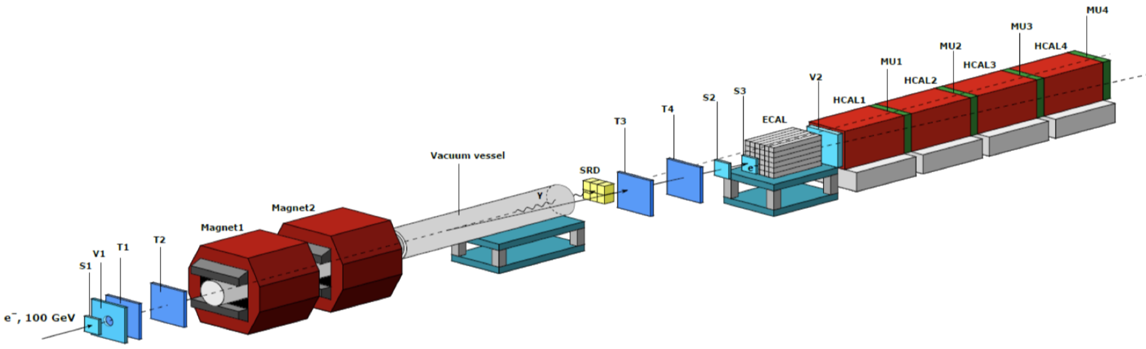


Figure 2: The NA64-*e* setup scheme [8].

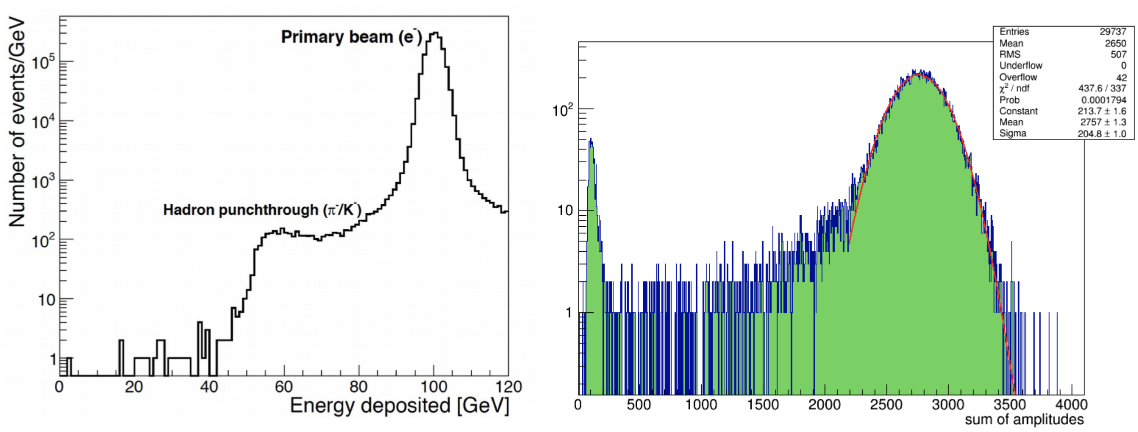


Figure 3: The typical NA64-*e* HCAL (left) and HCAL (right) observed spectra [13]. The left panel shows a $\sim$ 100 GeV deposition peak due to electron absorption in ECAL and a shoulder caused by the hadron beam contamination. The spectrum reported on the right panel shows that the fraction of hadron passing through a single HCAL module is about 10^{-3}.

the ECAL, such as muons, neutrinos, charged pions, and neutrons. To reject high-missing-energy events associated with the production of these SM particles, a high-efficiency veto system and a massive, hermetic hadronic calorimeter (HCAL) of $\sim$ 30 nuclear interaction lengths are positioned downstream of the ECAL. The veto system is composed of three side-by-side scintillator planes (5 cm thick), detecting charged particles impinging on the HCAL produced by upstream electron interactions. The HCAL is composed of 4 identical modules, consisting of alternating layers of iron and scintillating material separated by a gap of air. Each cell is composed of 48 layers for a total thickness of $\simeq 7\lambda_I$. The light readout is based on WLS fibres, embedded in the scintillator plates, and PMTs. Three HCAL modules are positioned in line with the ECAL, along the deflected electron beam direction, to detect muons and hadrons produced in the ECAL. The last module is positioned along the primary beam direction, to detect possible neutral hadrons produced in the beamline, crossing the magnetic dipole without changing trajectory.

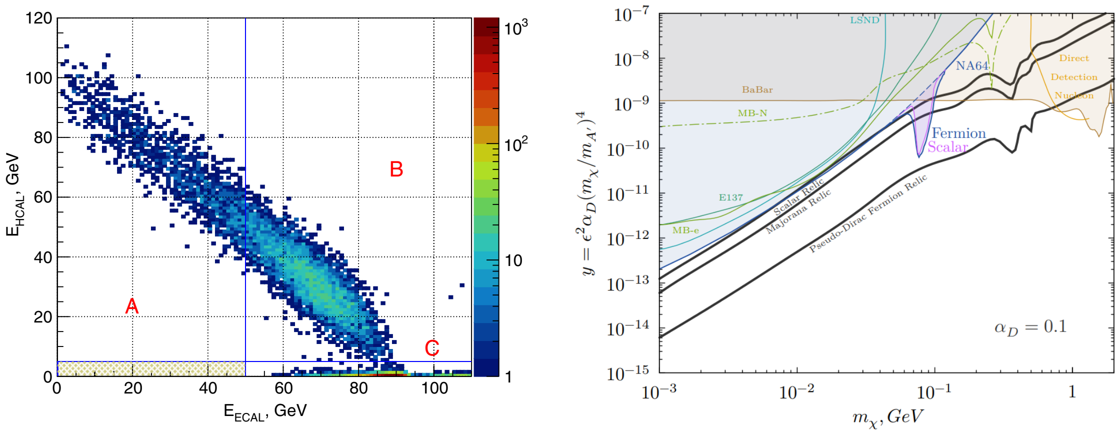


Figure 4: The left panel shows the measured distribution of events in the $(E_{ECAL}; E_{HCAL})$ after applying all selection criteria [11]. The shaded area is the signal box, which contains no events. The size of the signal box along the vertical axis is increased by a factor of 5 for a graphical reason. The sidebands A and C were used to estimate the background in the signal region. In the right panel, the exclusion limits of the NA64-*e* experiment in the A' LDM scenario are reported [14]. The sensitivity peak at $m_\chi \simeq 100$ MeV results from the contribution of the secondary e^+ resonant annihilation. The black lines are the predictions from the "thermal origin" hypothesis, for different LDM models.

4. The NA64-e Results

The NA64-*e* experiment's most recent results for Light Dark Matter search are based on data collected during the years 2016, 2017, and 2018, for a total of 2.83×10^{11} electrons on target (EOT). The signal selection cuts were determined through a blind analysis approach to maximize the experimental sensitivity. After applying cuts to data no events were found in the signal region $E_{CAL} < 50$ GeV and $E_{HCAL} < 1$ GeV, where E_{ECAL} and E_{HCAL} are the energy deposited in the ECAL and the HCAL. This observation is compatible with the expected number of background events ($\sim$ 0.5), evaluated through Monte Carlo simulation and extrapolations based on sideband studies (Fig.4, left) [11]. The performed analysis resulted in the most competitive exclusion limits in a large portion of the LDM parameters space (Fig.4, right). Both the contribution from A'-strahlung and, resonant annihilation production were considered, probing a portion of the "thermal target" region in the LDM parameter space that was not yet experimentally explored [14].

During fall 2022, the NA64-*e* collaboration collected 6×10^{11} EOT, more than doubling the previous statistics. These data are currently being analyzed and results are expected in mid-year 2023. A missing energy measurement with a positron beam has also been considered in NA64-e, in connection with the POKER (POsitron resonant annihilation into darK mattER) ERC project. The use of a positron beam allows for strong enhancing LDM production by exploiting the electron-positron annihilation process. This also provides a clean signal signature associated with the underlying resonant reaction dynamics, resulting in a peak in the missing energy distribution, whose position depends solely on the mass of the A'. The growing interest in this new approach motivated the NA64 collaboration to perform a preliminary feasibility study during fall 2022, running the experiment with a 100 GeV positron beam in the current experimental setup. These data are currently being analyzed by the collaboration; first results are expected in late 2023.

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