PROCEEDINGS OF SCIENCE

Dark Sector searches with electron and positron beams at NA64@CERN

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Several astrophysical observations indicate that the majority of the mass of the Universe is made of a new type of matter, called Dark Matter, not interacting with light. DM may be composed of a dark sector of new particles, charged under a new U(1) gauge boson kinetically mixed with the ordinary photon, called dark photon. The NA64e experiment at CERN aims to produce and detect DS particles using a 100 GeV electron beam impinging on a thick active target (electromagnetic calorimeter). The detection of DS particles in NA64e occurs through the "missing energy" technique. So far, NA64e sets the most competitive limits in the 1 MeV $< m_\chi <$ 100 MeV parameters space, with an accumulated statistic of $9.37 \cdot 10^{11}$ electrons on target. In conjunction with the ERC-funded project POKER, from 2022 NA64e started collecting data also with positron beams, to exploit the DS production yield enhancement due to the positron resonant annihilation process. This work presents the latest results of the NA64e measurements, both with electron and positrons beams.

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1. Introduction

Over the past decades, cosmological and astrophysical observations have suggested that ~85% of the matter in our Universe is composed of Dark Matter (DM), a novel form of matter that interacts gravitationally with Standard Model (SM) particles but neither emits nor absorbs light [1]. Despite extensive research, the nature of DM particles remains unknown. Thermal light dark matter is one of the proposed models to explain DM's origin. In this framework, DM consists of particles (denoted as χ) with masses below the electroweak scale (m$_\chi \ll 100$ GeV) which were in thermal equilibrium with SM particles in the early Universe. At the beginning, when the Universe temperature T was large, the two forms of matter annihilated into each other at equal rates. Later, when the temperature dropped below m$_\chi$, only the annihilation into SM particles was possible, resulting in an exponential suppression of the DM density. Finally, when the Universe expansion rate overcame the DM annihilation rate, also this process ceased, leading to the currently observed DM density (according to the so-called "freeze-out" mechanism) [2]. Considering LDM particles with masses within 1-100 MeV, the observed relic abundance can be explained by introducing a novel force between Standard Model (SM) particles and DM, mediated by a new U(1) gauge boson known as the Dark Photon (A') [3]. A' couples to the SM photon through a kinetic mixing term, according to the following lagrangian density (omitting the DM mass term):

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_{\mu}A'^{\mu} - \frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu} - g_D A'_{\mu}J^{\mu}_D$$

where $m_{A'}$ is the A' mass, $F'_{\mu\nu} \equiv \partial_\mu A'_\nu - \partial_\nu A'_\mu$ is the A' field strength tensor, $F_{\mu\nu}$ is the SM electromagnetic field strength, $g_D \equiv \sqrt{4\pi\alpha_D}$ is the dark gauge coupling, and J^μ_D is the LDM current under $U(1)_D$. The strength of the kinetic mixing is given by the parameter ε, assumed to be $\ll 1$. The strength of the coupling of the A' to the χ particles is described by $\alpha_D = e^2_D/4\pi$. The adimentional parameter y, proportional to the annihilation cross-section, can be introduced:

$$y = \frac{\varepsilon^2 \alpha_D m^4_\chi}{m^4_{A'}}.$$

In the parameter space $y - m_\chi$ it is possible to define thermal targets (see Fig. 2), i.e. regions compatible with the freeze-out hypothesis, providing experimental targets. To date, the most stringent exclusion limits in the LDM parameter space have been established by experiments conducted at accelerators and colliders [4]. In this work, we report the latest results of the NA64e experiment on the search of A' at the CERN Super Proton Synchrotron (SPS) accelerator, using the "missing energy" technique [5] to explore the A' invisible decay ($m_{A'} = 3m_\chi$).

2. The NA64e experiment at CERN

NA64e is an experiment designed to search for LDM located at the line H4 of the SPS accelerator in CERN's North Area. The experiment utilizes 100 GeV electron beams and employs the missing energy technique to detect LDM particles, which are produced through prompt $A' \to \chi\chi$ decays. These particles carry away a substantial portion of the energy, leading to a significant discrepancy between the initial and the in-target measured energy. LDM particle production occurs via A'-strahlung ($e^- Z \to e^- Z A'$) or resonant annihilation ($e^+e^- \to A' \to \chi\bar{\chi}$) [6], with secondary positrons generated by the electromagnetic shower in the target. LDM particles then leave the detector without depositing any energy. A diagram of the experimental setup can be seen in Fig. 1. The beamline is equipped with several scintillators (S_{0-3}) and veto (V_{0-1}) counters devoted to

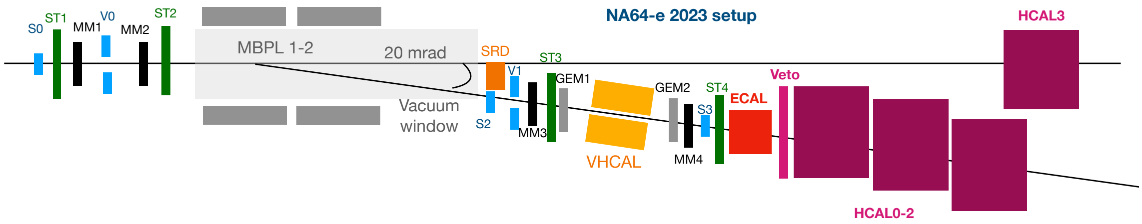

Figure 1: Schematic illustration of the NA64e experiment setup for the 2023-2024 data taking.

particle tagging, while particle tracking is performed using specialized detectors like MicroMegas (MM), Straw Tubes (ST), and Gaseous Electron Multipliers (GEMs). The momentum of the particles is measured by a magnetic spectrometer, which consists of two dipole magnets ($MBPL_{1-2}$), together with the trackers. This allows a precision of $\Delta p/p \simeq 1\%$. Here, the incoming electrons are deflected by 22 mrad. The Synchrotron Radiation Detector (SRD) plays a crucial role in background detections, as it measures the Synchrotron Radiation (SR) light emitted by the incoming particles in the MBPL magnetic field; the SRD has a "fake-positive" probability of 10^{-5} for pions. The NA64e active thick target is a Shashlik-like electromagnetic calorimeter (ECAL), made of lead and plastic scintillator; the whole detector is ≃40 radiation length, with the first 4 serving as pre-shower. The energy resolution is $\sigma_E/E = 10\%/\sqrt{E} \oplus 4\%$. The ECAL is then followed by a plastic scintillator Veto and 4 iron-plastic scintillator hadronic calorimeter (HCAL) modules, devoted to tagging the muons or hadronic secondaries produced in the target and escaping from it carrying a large fraction of the beam energy and thus mimicking the signal. The $HCAL_{0-2}$ is 30 nuclear interaction length; the zero-degree $HCAL_3$ is devoted to rejecting events associated with secondary neutral hadrons. The Veto-HCAL (VHCAL) detector was recently implemented in the NA64e experiment to tag large-angle hadronic secondaries coming from upstream interactions.

3. NA64e$^-$ latest results

During the 2016-2022 data taking runs, NA64e collected $9.37 \cdot 10^{11}$ electrons on target, thereby establishing the most stringent limits in the 1 MeV < m_χ < 100 MeV parameter space (right image in Fig. 2). The data analysis uses a series of selection cuts: the incoming particles should have a momentum equal to 100±10 GeV/c; the particles deflection must stay within an angular tolerance of 3 mrad. The SR energy of the incoming particles must stay in a 1-100 MeV range. There must be no energy deposition in the Veto and in the VHCAL. For what concerns the ECAL, we select the events which exhibit a shower shape consistent with the one expected for the signal [4]. Once the selection cuts are applied, the data are examined using a "hermeticity" plot (see the left image in Fig. 2), which includes a blind signal box which extends from 0 to 50 GeV in the ECAL and from 0 to 1 GeV in the HCAL.

The main sources of background (e.g., dimuon losses or decays in the ECAL, μ, K, and π decays along the beamline, upstream e$^-$ interactions, and punchthrough events, where particles

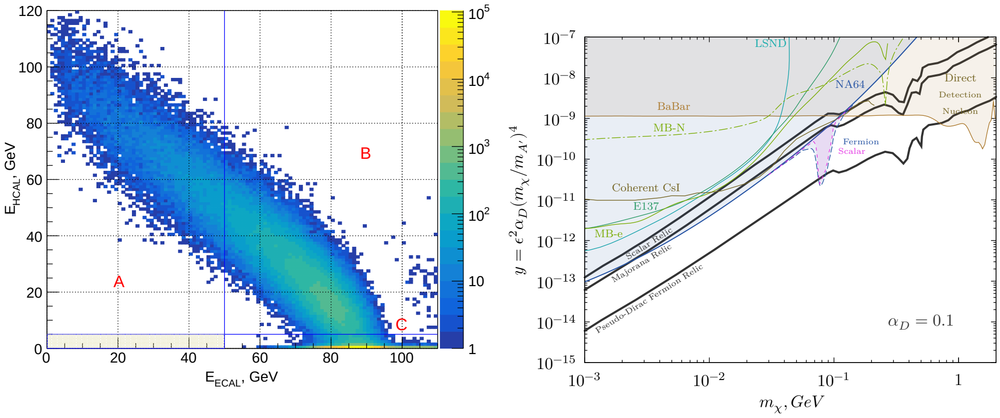

Figure 2: Left: Distribution of events surviving the selection cuts. The X-axis shows the energy deposited in the ECAL (in GeV), while the Y-axis shows the energy in the HCAL (in GeV). The yellow box in the bottom-left corner represents the signal box, with boundaries $0 < E_{ECAL} < 50 \,\&\, 0 < E_{HCAL} < 1$. Here, the signal box size along the HCAL axis is increased for illustration purposes. Right: Current limits set by NA64e in the y(m_χ) parameter space (with $\alpha_D = 0.1$). The sharp peaks correspond to the resonant annihilation process, while the continuous distribution is due to the A'-strahlung mechanism [4].

pass undetected through the detectors) come upstream interaction of the beam particles with the beamline materials or beam contamination [7]. To date, NA64 did not detect any events within the signal region.

4. The POKER project: the positron beams program

The resonant annihilation channel for dark photon production ($e^+e^- \to A' \to \chi\bar{\chi}$) is a highly effective mechanism in the search for LDM, characterized by a distinctive Breit-Wigner-like signature, which displays a narrow peak at the resonant energy, specifically at $E_{\text{res}} = m_{A'}^2/2m_e$ (as shown in the up-left image in Fig. 3).

The ERC-funded POKER (POsitron resonant annihilation into darK mattER) project aims to exploit this mechanism to enhance the NA64e physics program using lower-energy positron beams (40 and 60 GeV). To test this approach, POKER conducted an initial run with 100 GeV positron beams, accumulating $1.017 \cdot 10^{10}$ positron on target with the results shown in Fig. 3 (top-right) [8]. The aquired data were analized following the standard NA64 approach with electron beam: the particles momentum was required to stay in a [97, 103] GeV range; the total energy deposition in the SRD had to be ≥ 2.5 MeV. Again, no energy had to be deposited in the Veto, and the shape of the electromagnetic shower in the ECAL was required to be compatible with that expected for the signal. Finally, the same $E_{ECAL} < 50$ GeV, $E_{HCAL} < 1$ GeV signal window conditions were applied. Another measurement using 70 GeV/c positron beams was performed during 2023, whose analysis is still ongoing.

To perform the measurements using low-energies beams, a new ECAL (PKR-Cal) with higher energy resolution is needed. The new PKR-Cal will be composed of a 9×9 matrix of $PbWO_4$ crystals, each 22 cm long, plus a pre-shower part. The required energy resolution is $\sigma_E/E \simeq 2.5\%/\sqrt{E} \oplus 0.5\%$.

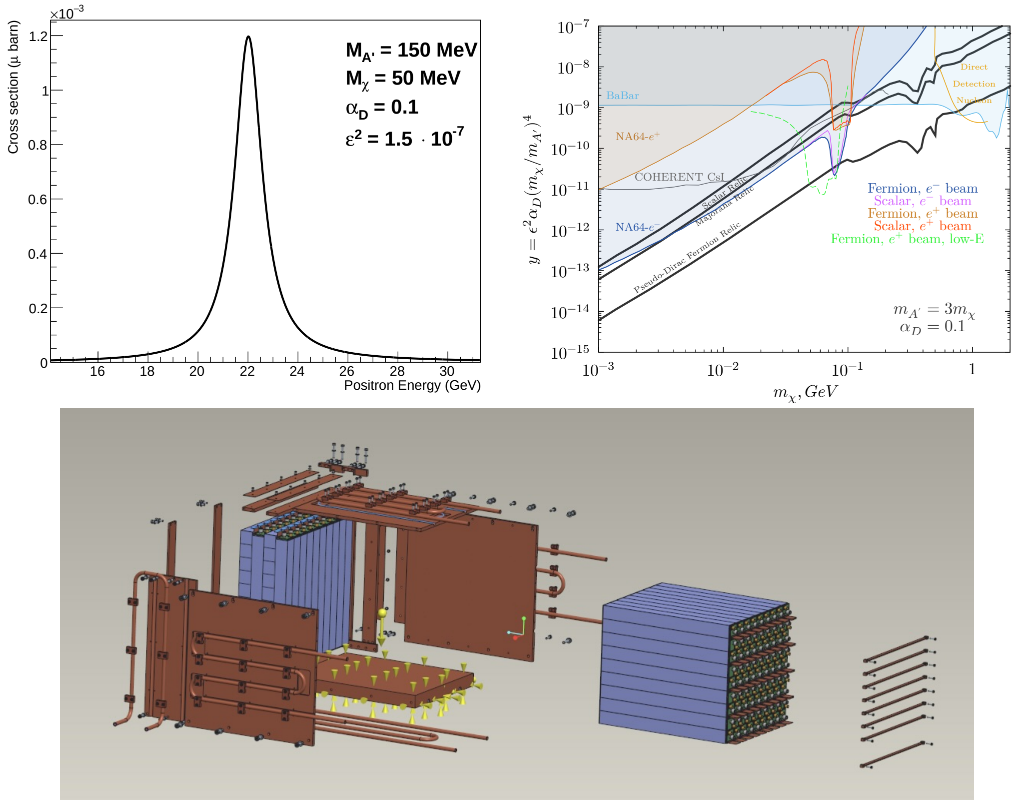

Figure 3: Top-left: Shape of the resonant annihilation signature. Top-right: Initial results from the POKER project. The green line indicates the projected limits using low-energy positron beams (with $\alpha_D = 0.1$). Bottom: CAD drawing of the PKR-Cal. The crystals (in blue) are coupled to SiPM matrices (green); the first 4 crystal layers (placed transverse to the beam axis) form the "pre-shower" section. The detector is placed in a copper structure which hosts copper pipes to allow the cooling.

Each crystal will be paired with 4 silicon photomultipliers (SiPMs). The calorimeter will be housed within a copper structure designed to interface with an appropriate cooling system for the SiPMs (as shown in the bottom image of Fig. 3). The first PKR-Cal run is scheduled for Summer 2025.

5. Conclusions

NA64e is a leading experiment in the global search for LDM, operating at CERN's SPS accelerator and utilizing the missing energy technique with 100 GeV electron beams. With its extensive physics program, NA64e is capable of setting the most stringent limits on the 1 MeV < m_χ < 100 MeV parameter space. POKER, an ERC-funded project, aims to search for LDM using lower-energy positron beams to enhance the resonant production channel for A'. To validate this new approach, a preliminary run was conducted using a 100 GeV/c positron beam with the current NA64e setup. The distinct resonant signature shape allowed us to approach the limits set by NA64e$^-$ with less accumulated statistics. This result demonstrates the potential of the NA64e experiment to search for LDM particles using the H4 line at CERN in positive mode. To achieve this goal, a new electromagnetic calorimeter (PKR-Cal), consisting of a 9×9 matrix of $PbWO_4$ crystals coupled to SiPM arrays, is necessary. The first run of PKR-Cal is foreseen for Summer 2025.

Acknowledgments

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