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Latest results and future prospects of the NA64 experiment at CERN SPS

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The search for Dark Matter (DM) is one of the hottest topics of modern physics. Despite the various astrophysical and cosmological observations proving its existence, its elementary properties remain to date unknown. In addition to gravity, DM could interact with ordinary matter through a new force, mediated by a new vector boson (Dark Photon, Heavy Photon or A'), kinetically mixed with the Standard Model photon. The NA64-e experiment at CERN fits in this scenario, aiming to produce DM particles using the 100 GeV SPS electron beam impinging on a thick active target (electromagnetic calorimeter). In this setup the DM production signature consists in a large observed missing energy, defined as the difference between the energy of the incoming electron and the energy measured in the calorimeter, coupled with null activity in the downstream veto systems. Recently, following the growing interest in positron annihilation mechanisms for DM production, the NA64 collaboration has performed preliminary studies with the aim to run the experiment with a positron beam, as planned within the POKER (POsitron resonant annihilation into darK mattER) project. This work presents the latest NA64-e results and its future prospects, reporting on the progresses in the positron beam run and discussing the sensitivity of the experiment to alternative variations of to the dark photon paradigm.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

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PoS(ICHEP2022)174

1. Introduction

Several astrophysics observations support the case for extensions of the Standard Model (SM). These anomalies, as well as tensions in particle physics (e.g. the anomalous magnetic moment of the muon) could be reconciled with theory assuming the existence of a new kind of matter, not directly interacting with the electromagnetic field, called Dark Matter (DM) [1]. While gravitational effects of DM suggest that it may compose the vast majority of the mass of the Universe, the DM particle nature remains to date unknown. Intensive experimental efforts - leading so far to no conclusive evidence - have been devoted to the detection of cosmogenic DM in the so called WIMP (Weakly Interacting Massive Particles) paradigm, by which DM is made of particles with masses in the $1 \div 1000$ GeV range, interacting with the SM particles via the weak force. In the wake of the null results in the WIMP search, interest towards alternative DM models has progressively grown; among these, vector-mediated Light Dark Matter (LDM) is theoretically well motivated and still largely unexplored. In the simplest representative model, a Dark Sector (DS) of χ particles in the MeV - GeV mass range makes the $\sim 85\%$ of the mass of the Universe. Dark Sector particles are charged under a new *U(1)* symmetry, whose mediator is a massive vector boson, called "heavy photon" or "dark photon" (A'). An effective coupling between the SM and the DS particles arises from a kinetic mixing between the A' and the SM photon [2], as modeled in the corresponding lagrangian density, here reported after field diagonalization and omitting the χ mass term:

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

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 determines the magnitude of the kinetic mixing, $g_D = \sqrt{4\pi\alpha_D}$ is the dark gauge coupling and J^μ is the current of DS particles. This scenario is theoretically well justified with the assumption that DM has a thermal origin, provided that the model parameters lie in a constrained region, which provides a target for discovery or falsifiability - the so called "thermal target" [3]. The direct search for cosmogenic LDM with *á la* WIMP techniques presents significant difficulties, given the low mass of the LDM candidates compared to WIMPs; while a significant experimental effort to overcome this challenge is currently ongoing, the most stringent exclusion limits in the LDM parameter space have been set so far by experiments at accelerators and colliders. In particular, thick and thin fixed-target experiments at moderate beam energy (10÷100 GeV) are well suited to probe the LDM scenario.

2. The NA64-*e* experiment at CERN SPS

NA64-*e* is an experiment searching for Light Dark Matter at Cern North Area [4], making use of the 100 GeV electron beam provided by the SPS (Super Proton Synchrotron) at he H4 beam-line. The experiment aims to detect LDM particles through the *missing energy* technique. The electron beam impinges on a thick active target, a 40 radiation-lengths lead-scintillator (Pb/Sc) electromagnetic calorimeter (ECAL), where it gives rise to an electromagnetic shower; LDM particles χ are produced by electrons and positrons in the shower, via the "A'-strahlung" radiative process or via resonant annihilation ($e^+e^- \to A' \to \chi\bar{\chi}$) [5], and subsequently leave the detector area without depositing energy. The momentum of each impinging electron is measured via a

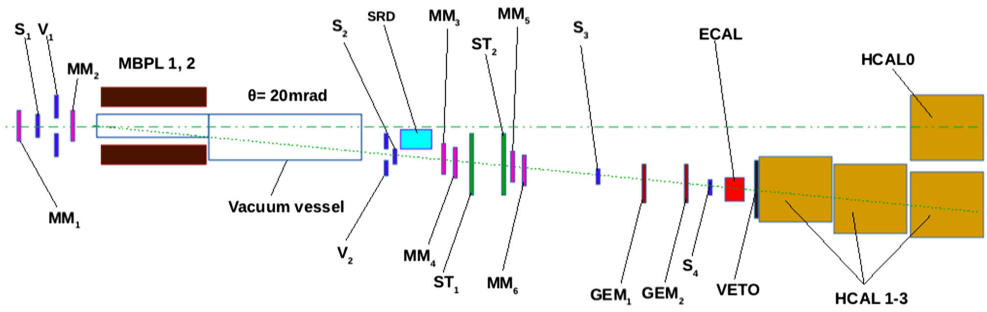

Figure 1: Schematic view of the NA64-e detector in the nominal configuration for the LDM search. See text for the acronym definitions.

magnetic spectrometer consisting of two successive dipole magnets (MBPL), bending the beam by a 20 mrad angle, and a set of upstream and downstream tracking detectors (see Fig. 1 for a detailed scheme of the experimental setup), Micromegas (MM), Strawtubes (ST) and Gaseous Electron Multipliers (GEM), allowing for a momentum resolution $\frac{\Delta p}{p} \simeq 1\%$. The signature of LDM production consists in a large measured missing energy $E_{miss} > 50$ GeV, defined as the difference between the impinging electron energy and the energy deposited in the ECAL (ECAL energy resolution: $\frac{\sigma_E}{E} \simeq \frac{10\%}{\sqrt{E}} + 4\%$). The backgrounds affecting this measurement can be divided in two main categories:

- hadron contaminants in the beam, such as proton and pions, punching through the ECAL;
- events associated with the production of highly penetrating particles in the the ECAL, such as muons, neutrinos, charged pions and neutrons.

In order to reject background events caused by hadron contaminants in the beam (at the level of $\sim 1\%$ in the H4 electron beam), NA64-e features a Pb/Sc sandwich syncrotron radiation detector (SRD), placed ~ 16 m downstream the MLBPs; by detecting the synchrotron radiation emitted by the charged particles of the beam passing through the magnetic field, the SRD allows for the identification and rejection of hadrons. The combination of cuts on the SRD signal with cuts on the shape of the electromagnetic shower in the ECAL, results in a e^-/π discrimination with a $\sim 10^{-4}$ inefficiency. To reject high-missing-energy events associated with the production of penetrating SM particles, a high-efficiency veto and a massive, hermetic hadronic calorimeter (HCAL) of ~ 30 nuclear interaction lengths are positioned downstream the ECAL. The veto is a plane of scintillator counters used to detect charged secondaries incident on the HCAL detectors from upstream e^- interactions. The HCAL, composed of lead and scintillator layers, is divided into 4 different modules of equal length. Three modules(HCAL 1-3) are positioned in line with the ECAL, along the bent electron beam direction, to detect muons and hadronic secondaries produced in the ECAL. The last module (HCAL 0) is positioned along the unbent beam direction, to detect possible neutral hadrons produced along the beam-line and crossing the magnetic dipole with unaltered trajectory.

2.1 NA64-e "visible mode" setup

Aside from the nominal setup described in the previous section, the NA64-e detector can be adapted to perform measurements of the so-called "visible" dark photon decay $A' \to e^+e^-$.

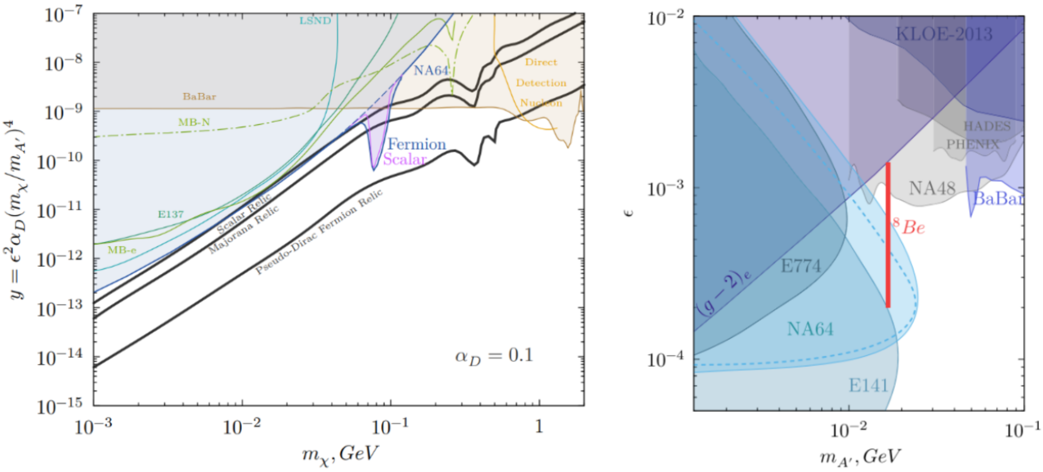

Figure 2: Left: exclusion limits of the NA64-e experiment in the A'-mediated LDM scenario. The tooth-shaped region at $m_\chi \simeq 100$ MeV results from the contribution of the secondary e^+ resonant annihilation. Right: NA64-e exclusion limits in the parameter space of the A' visible-decay scenario. The red line represents the region in the parameter space compatible with the particle explanation of the beryllium anomaly.

The study of this channel is particularly relevant since it could explain the recent observation of a $\sim 7\sigma$ excess of events in the angular distribution of e^+e^- pairs produced in the nuclear transitions of the excited ^{8}Be* nuclei to the ground state via internal e^+e^- pair creation [6]. The "visible" setup features a tungsten/scintillator sandwich calorimeter (WCAL) and a set of ST and GEM trackers located upstream the ECAL (see [7] for a detailed description of the apparatus). In this configuration, the A' can be produced in the WCAL and travel few mm before decaying in a e^+e^- pair, whose energy can be measured with the ECAL. In case of a signal event, the trackers located between the WCAL and the ECAL can be used to measure the opening angle of the e^+e^- pair, allowing to determine the invariant mass.

3. NA64-e Recent Results

The most updated NA64-e exclusion limits in the LDM parameter space, reported in Fig. 2, left panel, result from the analysis of the data sets collected during the years 2016, 2017 and 2018, for a total of 2.83×10^{11} electrons on target (EOT). After applying all the selection cuts, determined through a blind analysis approach by maximizing the experimental sensitivity, no events were found in the signal region, defined by the requirements: $E_{CAL} < 50$ GeV and $E_{HCAL} < 1$ GeV, where E_{ECAL} and E_{HCAL} are the energy deposited in the ECAL and the HCAL, respectively. In the signal evaluation, both the contribution from A'-strahlung and resonant annihilation production have been considered [8]. During fall 2022 NA64-e has collected additional $\sim 6 \times 10^{11}$ EOT, more than doubling the previous statistics. These data are currently being analyzed; results are expected in mid-year 2023.

In addition to the LDM search, during 2018 NA64-e collected 3×10^{10} EOT in "visible mode". Since no signal-like events were observed [7], an exclusion limit was set in the visible-

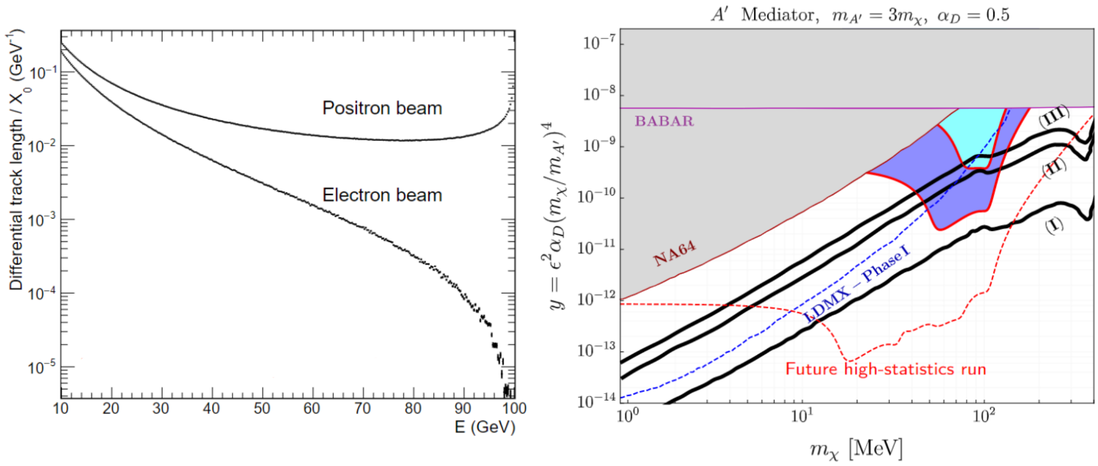

Figure 3: Left: differential track-length of positrons in the active target of NA64-e (ECAL), with a primary electron or positron beam. Right: projected sensitivity of the POKER effort, for different scenarios. Cian: baseline scenario, 5×10^{10} e^+OT, 50 GeV missing energy threshold. Violet: aggressive scenario, 3×10^{11} e^+OT, 25 GeV missing energy threshold. Dashed red line: future experimental program with multiple 10^{13} e^+OT runs at different energies.

decay A' parameter space (see Fig. 2, right panel). The limits cast by NA64-e partially excluded the preferred region for the particle explanation of the ^{8}Be anomaly; the remaining space can be explored increasing the statistics, provided that the experimental setup is updated to increase the detection efficiency and the missing mass resolution for a short lived A', as described in the next section.

4. Future prospects of the experiment

4.1 Positron beam - POKER

Electron-positron resonant annihilation into a LDM particles pair ($e^+e^- \to A' \to \chi\bar{\chi}$) is a powerful mechanism for the exploration of the vector-mediated LDM scenario [5]. In the A' mass region where it is kinematically allowed, it features a significantly larger cross section compared to A'-strahlung; in addition, given the closed kinematics of the $e^+e^- \to A'$ annihilation, the energy of the outgoing LDM pair is fixed by the A' mass (neglecting the width of the A'). From the point of view of a missing-energy experiment, this feature results in a unique signal signature: the E_{miss} distribution of resonant-annihilation events has a Breit-Wigner-like shape, peaked at the value $E_{peak} = m^2_{A'}/2m_e$. Other than providing a way to infer $m_{A'}$ from data, the presence of a peak allows the use of tailored analysis techniques to improve the signal/background ratio and therefore the experiment sensitivity. As illustrated in Fig. 2, left panel, reporting latest NA64-e results in the LDM parameter space, positron annihilation plays an important role for NA64-e, given the large number of secondary e^+ produced by the e^- beam in the ECAL. A 100 GeV positron beam would result in a much larger track length of high-energy e^+ in the ECAL, therefore enhancing A' production via resonant annihilation (see Fig. 3, left panel). The POKER (POsitron resonant annihilation into darK mattER) effort, funded with *ERC Starting Grant* fits into this context: the project aims to perform a preliminary missing-energy measurement with the 100 GeV e^+ beam available at the CERN H4 beam-line, within the experimental setup of NA64-e. The measurement will be performed using a newly-built electromagnetic calorimeter composed of $\sim$ 120 $PbWO_4$ crystals, replacing temporarily the ECAL of NA64-e. The use of $PbWO_4$ is motivated by the higher achievable energy resolution compared to the Pb/Sc solution, allowing to resolve the distinct Breit-Wigner signature of the resonant annihilation (see Fig. 3, right panel, for the projected sensitivity of the POKER effort).

During fall 2022 the collaboration has performed a test measurement with a small-scale prototype of the POKER calorimeter, in order to validate the technical solutions chosen for the detector; in anticipation of the full POKER measurement, whose schedule is currently being discussed with the NA64 management, a first data set of $\sim 10^{10}$ positrons has been collected with the current NA64-e setup. This data, other than provide valuable information for POKER, will allow to set new limits in the LDM parameter space.

4.2 Visible mode upgrade

An upgrade of the NA64-e visible setup has been proposed to explore the remaining areas in the A' visible-decay parameter space which are compatible with the particle explanation of the ^{8}Be anomaly. In these regions of the parameter space the A' is very short lived, resulting in a mean free path at 100 GeV of the order of few millimeters. The detection efficiency is therefore suppressed since the produced A's decay before leaving the WCAL. Moreover, the small opening angle of the e^+e^- pair makes impossible to separate the two tracks in the current setup. In the proposed upgrade, these issues are addressed introducing new components: a new, thinner WCAL, to increase the probability of the A' to exit from it to at least 20%; a 18 m long decay tube following the WCAL; a dipole magnet with a 2.6 $T \cdot m$ integrated field to separate the e^+e^- pair. According to Monte Carlo simulations, with this upgrade NA64-e could definitively probe ^{8}Be anomaly by collecting $\sim 7 \times 10^{11}$ EOT. The implementation of the upgrades and the time schedule of the measurement are currently under discussion by the NA64 collaboration.

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