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Searching for light Dark Matter with NA64−e and POKER at CERN

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Summary. — Light dark matter (LDM) is a theoretically well motivated model providing an attractive explanation for the observed relic dark matter density. In this scenario, LDM is composed of sub-GeV particles, feebly interacting with ordinary matter via a new force.
NA64-e is a *missing energy* experiment at CERN Super Proton Synchrotron (SPS), aiming to produce LDM particles using the 100-GeV SPS electron beam impinging on a thick, active target (electromagnetic calorimeter). Each impinging electron is tagged and its momentum is measured; the LDM production signature consists in a large difference between the initial electron energy and the measured energy deposition in the calorimeter. In last years, NA64-e collected data also with a positron beam, in order to exploit the $e^+ - e^-$ resonant annihilation process for the A' production, synergistically with the POKER (POsitron resonant annihilation into darK mattER) project. POKER is an ERC-funded effort, whose aim is to perform a preliminary missing-energy measurement with a multi-energy positron beam. POKER will exploit the NA64−e experimental setup, using a new high-resolution $PbWO_4$ electromagnetic calorimeter as an active target.
This document presents the status of the NA64-e experiment, its latest results and future prospects. Advances in the POKER program are reported, with a focus on the analysis of the latest positron data-takings performed during 2022 and 2023.

1. – Introduction to Light Dark Matter

Dark Matter (DM) is one of the hottest open questions of modern physics. Its existence is hinted by many astrophysical and cosmological observations, suggesting that the vast majority of the mass of the Universe is composed of a new kind of matter, not directly interacting with the Standard Model (SM) particles [1]. Among the many models proposed to explain DM, the Light Dark Matter (LDM) hypothesis has recently aroused the interest of the scientific community, being theoretically well motivated and still fairly unexplored. In this scenario, DM is composed of χ particles with masses in the 1 MeV − 1 GeV range, belonging to a Dark Sector (DS) of particles, charged under a new U(1) symmetry, whose gauge boson is usually called *dark photon, A'* [2, 3, 4, 5]. The interaction between the DS and the SM may be realized by a *kinetic mixing* between

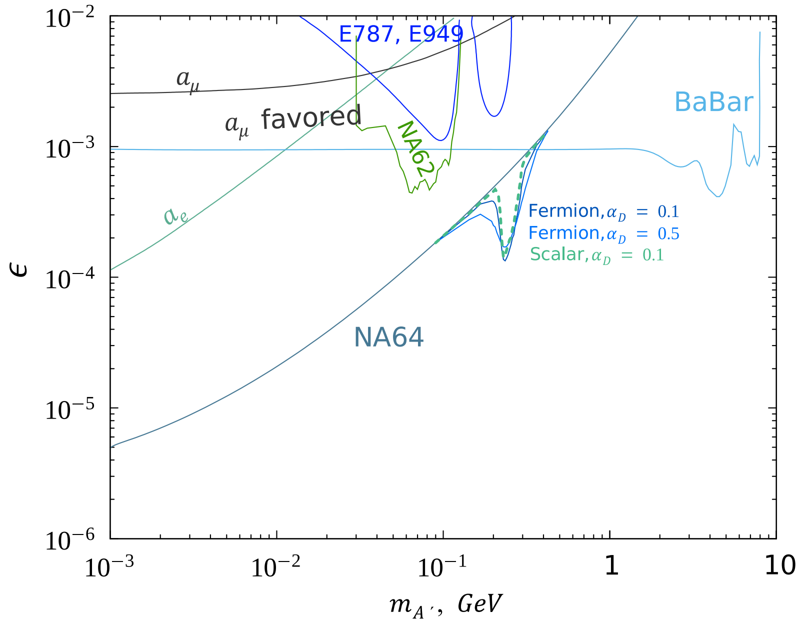

Fig. 1. – The most stringent current constraints (shaded regions) for an invisibly-decaying dark photon in the $\varepsilon - m_{A'}$ parameters space, reported by BaBar and by NA64 [7].

the A' and the SM photon. After field diagonalization and omitting the χ mass term, the DS lagrangian term reads:

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

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 strength of the kinetic mixing, $g_D = \sqrt{4\pi\alpha_D}$ is the dark gauge coupling and J^μ_χ is the current of DS particles. While it is reasonable to assume that $g_D \sim 1$, the range $\sim 10^{-4} - 10^{-2}$ ($\sim 10^{-6} - 10^{-3}$) is predicted for ε, considering a kinetic mixing generated in "Grand Unified Theories" at the one (two)-loop level [6]. This scenario can explain the currently observed DM abundance as a thermal relic from a primordial *freeze-out* mechanism, provided that the parameters of the model lie in a well defined region of the parameter space, called "thermal target". This can be easily expressed by defining the dimensionless quantity:

$$y \equiv \alpha_D \varepsilon^2 \left(\frac{m_\chi}{m_{A'}}\right)^4 \to y_{min} \simeq f \cdot 2 \cdot 10^{-14} \left(\frac{m_\chi}{1\,\text{MeV}}\right)^2 \quad ,$$

where $f \sim 1$ is a dimensionless quantity depending on the model specific details, i.e. the LDM quantum numbers and the $m_{A'}/m_\chi$ ratio. Given a m_χ value, a *minimum value* of y that experiments can probe is defined, resulting in a clear target to confirm or rule out the LDM theory. Experiments at accelerators at the *intensity frontier*, exploiting particle beams with moderate energies (10 – 100 GeV) are particularly well suited to explore the

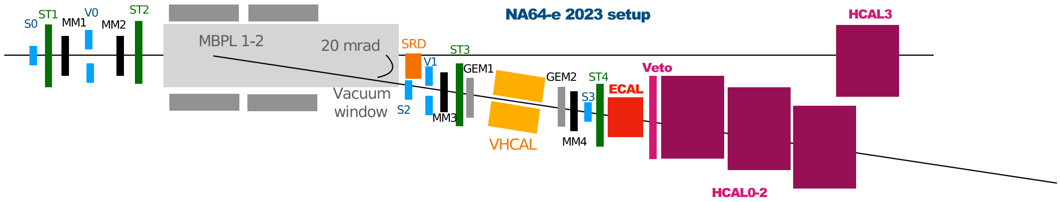

Fig. 2. – Experimental setup of NA64−e during the 2023 data taking.

LDM scenario; among these, the NA64−e experiment has set the most stringent limit in a large region of the parameter space (see Fig. 1).

2. – The NA64−e experiment

NA64−e is a thick-target experiment at CERN SPS (Super Proton Synchrotron), using the "missing energy" technique to search for LDM particles [7]. The layout of the experiment is shown in Fig. 2: 100-GeV electrons provided by the SPS at the H4 beamline impinge on a thick-active target, an electromagnetic calorimeter (ECAL), where they can produce LDM and feebly interacting particles; the time-structure of the beam is such that particles impinge on the target "one-by-one", allowing to tag and measure the momentum of each incoming e^- with a magnetic spectrometer. The ECAL is a 40-radiation-lengths long lead/scintillator (Pb/Sc) "shashlik" calorimeter, with energy resolution: $\frac{\sigma_E}{E} \simeq \frac{10\%}{\sqrt{E}} + 4\%$; the spectrometer (resolution $\frac{\Delta p}{p} \simeq 1\%$) consists in a set of straw tube detectors ($\mathrm{ST}_{1,4}$), micromegas ($\mathrm{MM}_{1,4}$) and gaseous electron multipliers ($\mathrm{GEM}_{1,2}$), located upstream and downstream a dipole magnet (MBPL), bending the beam by a $\theta \simeq 20$ mrad angle. Dark photons may be produced in the electromagnetic shower in the target and subsequently decay to LDM particles χ; given the weakness of the DS-DM interaction, χs leave the detector without depositing energy. The signature of LDM production is therefore a large difference between the energy of the beam and the energy deposited in the ECAL. In order to prevent SM penetrating particles that may be produced in the ECAL from escaping the detector, mimicking a signal, a high-efficiency plastic scintillator veto (VETO) and a large Pb/Sc hadronic calorimeter (HCAL) of ~ 30 nuclear interaction lengths are placed downstream the ECAL. Hadron contaminants in the beam such as $\pi,\ p, ...$ (hadron contamination level $\sim 1\%$ in electron beam mode) are rejected by means of a Pb/Sc sandwich syncrotron radiation detector (SRD), placed downstream the bending magnet: given the steep energy dependence of the irradiated power from the mass of the particle (for a given energy) the detection of the photons emitted by the particles of the beam in the magnetic filed allows for an efficient electron/hadron discrimination. Another possible background source originates from the interactions of the beam particles with beamline materials upstream the ECAL. These interactions may result in large-angle secondary hadrons emitted outside the detector acceptance, with the scattered electron hitting the ECAL with reduced energy deposition. To suppress this background, from 2023, a new hollow Pb/Sc hadronic calorimeter (VHCAL) was placed in front on the ECAL, vetoing large-angle emitted hadron.

NA64−e has been operating since 2016; the latest published results of the collaboration in the LDM scenario are based on 0.94×10^{11} electrons on target collected between 2016 and 2022 [7]. The data analysis was performed by defining the set of signal selec-

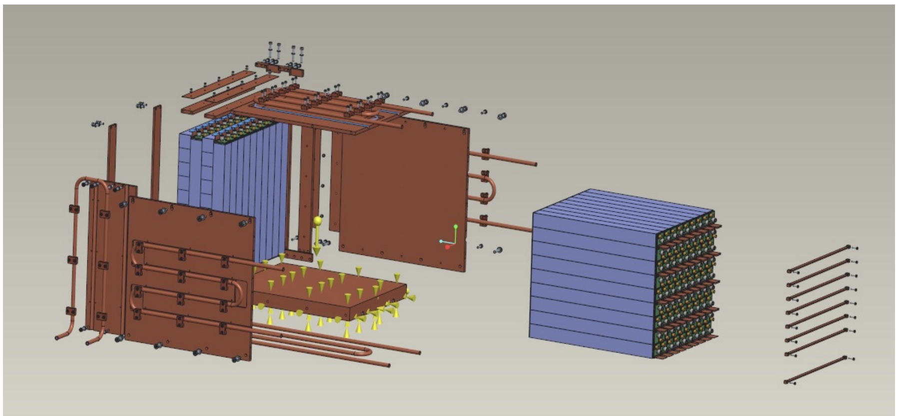

Fig. 3. – Exploded view of the PKR-cal detector. The $PbWO_4$ crystals are shown in blue, while the copper mechanical structure, with the serpentine pipes for water cooling, is drawn in brown.

tion criteria optimizing the experimental sensitivity, in a blind-analysis approach. The analysis cuts include the requirement of well-defined electron track, an in-time cluster in the SRD detector, an ECAL energy deposition consistent with the typical shape of an electromagnetic shower and negligible activity in the VETO and HCAL detectors. No events were observed in the signal region, defined as: $E_{ECAL} < 50$ GeV and $E_{HCAL} < 1$ GeV, resulting in the most stringent limits in the 1 MeV $< m_{A'} <$ 300 MeV range of the LDM scenario, as shown in Fig. 1.

3. – POKER - POsitron resonant annihilation into darK mattER

LDM production in NA64$-e$ occurs via two main reactions: the so-called A'*-strahlung*, a radiative process analogous to the SM bremsstrahlung, and the *resonant annihilation* of secondary positrons produced in the target: $e^+e^- \to A' \to \chi\bar{\chi}$. Where kinematically allowed, resonant annihilation features a larger cross section compared to A'-strahlung [8]; moreover, the energy of the outgoing LDM pair produced by this process is fixed, depending solely on the A' mass (neglecting the width of the A'). This latter feature provides a unique signal signature for an experiment such as NA64$-e$, since the missing-energy distribution has a Breit-Wigner shape, peaked at the value $E_{peak} = m_{A'}^2/2m_e$. This can be exploited to improve the experiment sensitivity via ad-hoc analysis techniques and, in case of a discovery, to measure $m_{A'}$ from data.

The idea behind the POKER (POsitron resonant annihilation into darK mattER) project is to exploit the full potential of the positron resonant annihilation, running the NA64$-e$ experiment with multi-energy positron beams, provided by the SPS. In order to fully exploit the Breit-Wigner-like signature of the process, the project involves the realization of a new high-resolution electromagnetic calorimeter (PKR-cal) composed of ~ 120 $PbWO_4$ crystals, to replace temporarily the Pb/Sc ECAL of NA64-e during the e^+ measurement. The design of the PKR-cal is shown in Fig. 3: the detector is divided in a pre-shower section, composed of 4-layers of 10 crystals each, oriented transversely with respect to the beam direction, and a 9×9 crystals matrix making the core of the detector. The dimension of the crystals in the pre-shower (matrix) is $2 \times 2 \times 20\,(22)$ cm^3, resulting

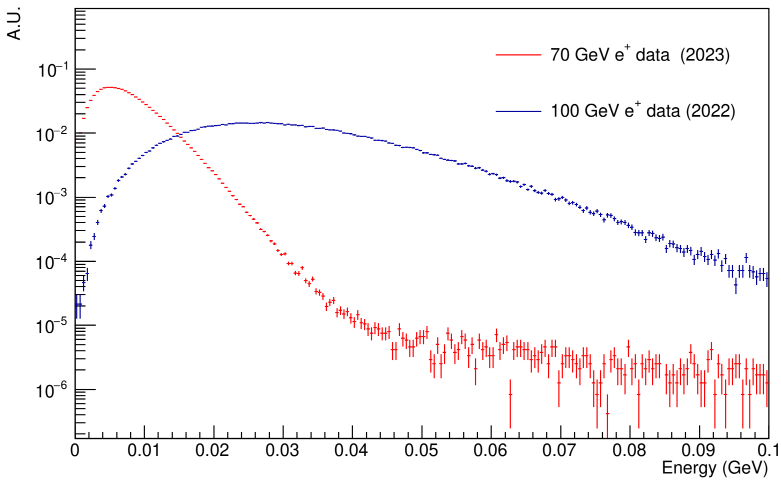

Fig. 4. – Measured distributions of the deposited energy in the SRD detector for 70 GeV (red markers) and 100 GeV (blue markers) positrons impinging on the detector. Both distributions have been normalized. The average energy deposition is reduced by a factor ~ 4 when passing from a 100-GeV to a 70-GeV beam.

in a total thickness of 33.7 radiation lenghts. The light readout will be performed with Silicon Photomultipliers (SiPM). The PKR-cal is currently being assembled; according to the tentative POKER schedule, the detector will be implemented in the NA64$-e$ setup for commissioning and a preliminary measurement during 2025. A possible measurement program with 60-GeV and 40-GeV positron beams, to be performed after CERN Long Shutdown 3, is currently being discussed within the NA64 collaboration.

Exploratory positron beam measurements at NA64−e. In parallel with the R&D of the new PKR-cal, the collaboration performed two preliminary data-takings with 100-GeV and 70-GeV positron beams, respectively during 2022 and 2023. In both cases, the NA64$-e$ detector was operated in its nominal configuration, with the Pb/Sc active target. These measurements, with a statistics of $\sim 10^{10}$ e^+ on target for both beam energies, had several purposes, such as the evaluation of the H4 beam contamination in positron mode and the assessment of the detector hermeticity at lower beam energies. Even with the limited statistics acquired, the analysis of the 100-GeV data sample proved the potential of the technique, motivating a full program with multi-energy e^+ beams [9].

A critical aspect of running the experiment at lower beam energies consists in the hadron contaminants identification via the SRD detector. Since the synchrotron radiation emitted by a relativistic particle accelerating in a magnetic field scales as the fourth power of the energy, the radiation emitted by a 70-GeV positrons is significantly reduced if compared to the 100-GeV case, as shown in Fig. 4. Still, the preliminary results of the analysis of the 70-GeV data suggest that, by applying a 2 MeV threshold on the SRD energy deposition, a signal efficiency of $\sim 92\%$ can be obtained preserving a high hadron rejection capability (hadron misidentification probability $< 2.5 \times 10^{-4}$). Figure 5 shows the preliminary sensitivity estimate, obtained accounting for the the

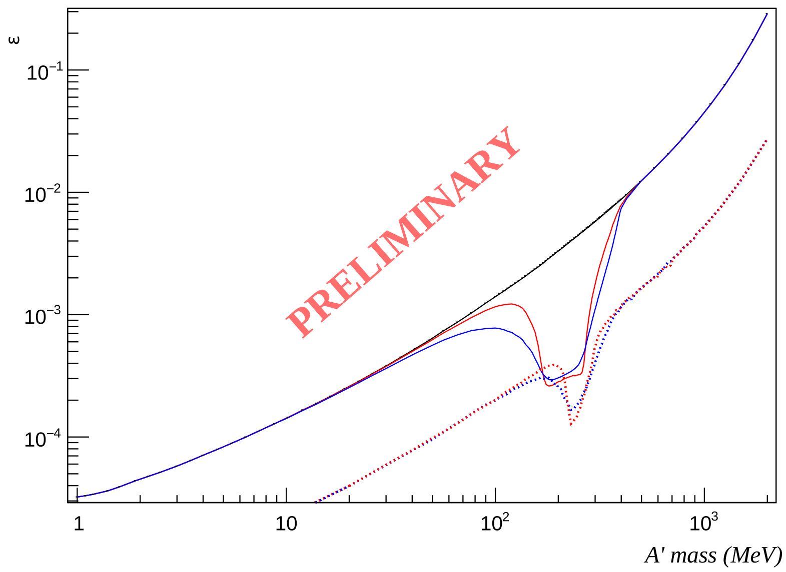

Fig. 5. – The solid lines show the projected sensitivity of the 70-GeV positron-beam measurement performed by NA64 in 2023, in the (ε, $m_{A'}$) parameters space, for $\alpha_D = 0.1$ (red) and $\alpha_D = 0.5$ (blue). The black line is the projected sensitivity without the contribution of the resonant annihilation to the total A' yield. The dashed lines are the current NA64 limits, reported as a comparison.

signal efficiency and the backgrounds estimation; despite the two-orders of magnitude difference in accumulated statistics, the projected sensitivity touches, in the 150 MeV $< m_{A'} <$ 250 MeV mass region, the current limits obtained by NA64$-e$ with an electron beam, proving again the potential of the resonant annihilation process in the search of LDM with positron beams.

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