PROCEEDINGS OF SCIENCE

# Dark sector searches at NA64$-e$

**Andrea Celentano**[a,*] **on behalf of the NA64 collaboration**

[a] *INFN, Sezione di Genova, Via Dodecaneso 33, Genova, Italia*

*E-mail:* andrea.celentano@ge.infn.it

The Light Dark Matter (LDM) hypothesis identifies dark matter particles with new sub-GeV "Hidden Sector" states, neutral under Standard Model interactions and interfacing with our world through a new force. In the simplest model, the new interaction is mediated by a massive vector particle, also called "dark photon" ($A'$), kinetically mixed with the ordinary photon.

The NA64-$e$ experiment at CERN North Area conducts a dedicated search for Light Dark Matter by running a missing energy measurement with high energy electron and positron beams from SPS impinging on a active thick target. With a total statistics of about $10^{12}$ electrons-on-target already accumulated during the 2016-2022 period, NA64$-e$ was able to probe for the first time the target region of the parameter space motivated by cosmology for scalar and Majorana LDM, in the $A'$ mass range between 1 MeV and 100 MeV.

In parallel to the main electron-beam program, NA64$-e$ recently completed a first pilot run with a 100 GeV positron beam. The goal of the test was to experimentally demonstrate this new technique, characterized by an enhanced $A'$ production by resonant annihilation of positrons with atomic electrons. With a total accumulated statistics of about $10^{10}$ positrons on target, the pilot run allowed NA64$-e$ to set competitive exclusion limits in the LDM parameter space.

This document provides a summary of the latest results obtained by the aforementioned NA64$-e$ efforts, together with a description of the future plans for the experiment.

*Workshop Italiano sulla Fisica ad Alta Intensità (WIFAI2023)*
*8-10 November 2023*
*Dipartimento di Architettura dell'Università Roma Tre, Rome, Italy*



[*] Speaker

## 1. Introduction

The existence of Dark Matter (DM) is unambiguously proved by a variety of multiple, independent astrophysical and cosmological measurements. Unveiling the DM particle content is one of the most prominent questions of contemporary physics. Specifically, since the Standard Model (SM) of elementary particles does not include any viable DM particle candidate, an extension of the latter is required, with new fields and forces not yet experimentally observed. So far, the main efforts to explain DM focused on the WIMPs (Weakly Interacting Massive Particles) scenario. However, null results in direct detection experiments of galactic halo DM and in high-energy accelerator searches at the LHC call for an alternative explanation to the current paradigm [1].

The light dark matter (LDM) hypothesis conjectures the existence of a new class of lighter elementary particles, not charged under the SM interactions. The simplest model predicts LDM particles (denoted as $\chi$) with masses below 1 GeV/c$^2$, charged under a new force in Nature and interacting with the SM particles via the exchange of a light spin-1 boson, usually referred to as "heavy photon" or "dark photon" ($A'$), kinetically mixed with SM charged particles [2]. In this picture, the new Lagrangian term extending the SM, omitting the LDM mass term, reads:

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

where $m_{A'}$ is the dark photon mass, $F'_{\mu\nu} \equiv \partial_\mu A'_\nu - \partial_\nu A'_\mu$ is the dark photon 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 between the $A'$ and LDM, $J^\mu_D$ is the LDM current under $U(1)_D$, and $\varepsilon$ parametrizes the mixing strength. While the specific values of the model parameters are not predicted by the theory, by assuming a LDM thermal origin in the early Universe it is possible to obtain a relation between them [3, 4]:

$$y \simeq f \cdot 2 \cdot 10^{-14} \left(\frac{m_\chi}{1\,\text{MeV}}\right)^2 \quad , \tag{2}$$

where $y \equiv \alpha_D \varepsilon^2 \left(\frac{m_\chi}{m_{A'}}\right)^4$, and $f \sim 1$ is a dimensionless quantity that depends on model specific details. For a given value of $m_\chi$, it follows that there is a *target value* of $y$ that experiments should probe, resulting in a clear, predictive target to confirm or rule out the LDM theory.

## 2. The NA64-$e$ experiment at CERN

NA64-$e$ at CERN North Area is a "missing energy" LDM search exploiting the 100 GeV electron beam from the H4 beamline [5]. In the experiment, particles impinge at $\simeq$ MHz rate on an active thick target (electromagnetic calorimeter), measuring the energy deposited therein. In this approach, the $A'$ production signature consists in a clean electron track associated with a large *missing energy* $E_{miss}$, i.e. the difference between the nominal beam energy $E_0$ and the one deposited in the active target $E_{ECAL}$, with no activity in other downstream detectors [6].

A schematic view of the NA64−$e$ detector is shown in Fig. 1. Incoming particles are detected by a set of three plastic scintillator counters (S1, S2 ,S3) and two veto counters (V1, V2). The setup involves a magnetic spectrometer used to measure particle momentum, made of tracking detectors (GEMs, MicroMegas, and Straw Tubes) placed before and after two dipole magnets with a total

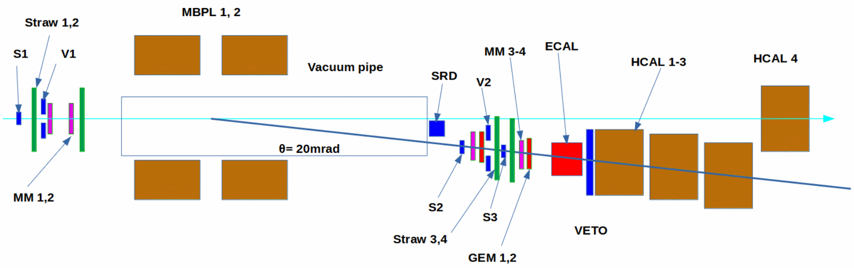


**Figure 1:** Schematic illustration of the NA64 setup to search for invisible decays of the $A'$s produced by the interaction of the 100 GeV impinging $e^+$ with the material of the active ECAL target.

magnetic strength of approximately 7 T·m, resulting to a momentum resolution $\delta p/p$ of about 1%. Particle identification is achieved by detecting synchrotron radiation emitted by electrons deflected by a magnetic field through a compact Pb/Sc calorimeter (SRD). The NA64 active target is a Pb/Sc calorimeter with a thickness of 40 $X_0$, arranged in a $5 \times 6$ matrix of $3.82 \times 3.82$ cm$^2$ cells. Each cell has independent PMT readout and is segmented into a $4X_0$ pre-shower section (ECAL0) and a main section (ECAL1). Downstream of the ECAL, a hermetic Fe/Sc hadron calorimeter (HCAL), consisting of three modules, with a total length of approximately 21 $\lambda_I$, is installed to detect secondary hadrons and muons produced in the ECAL and in upstream beamline elements, with a fourth module installed at zero degrees. Additionally, a high-efficiency plastic scintillator counter (VETO) is placed between the ECAL and HCAL to further minimize background signals.

During the 2016-2022 period, NA64−$e$ collected a total statistics of $\simeq 10^{12}$ electrons-on-target at beam energy $E_0 = 100$ GeV, setting stringent limits for the LDM model [5]. The beam intensity was gradually increased during the different data-taking periods, benefiting from better detector response knowledge and beam quality, up to $\simeq 6 \times 10^6$ electrons per SPS spill of 4.8 s. A blind-analysis approach was adopted, with all the selection cuts optimized by maximizing the experiment sensitivity to the LDM signal. Specifically, the final selection algorithm required the presence of a well identified electron track with momentum $100 \pm 10$ GeV, paired with an in-time energy deposition in the SRD detector in the range $\simeq 1 - 100$ MeV. Furthermore, the ECAL energy deposition in the different cells have to be compatible with the one expected for an electro-produced $A'$ [7]. Finally, no activity should be observed in the VETO and in the HCAL detector, with the corresponding 1 GeV threshold set just above the detector noise level. The value of the ECAL missing energy threshold defining the signal box, $E_{ECAL} < E^{thr}_{ECAL}$ was optimized independently for each particular run period, accounting for small differences in the detector response and in the observed background levels, resulting to $E^{thr}_{ECAL} \sim 47 - 50$ GeV. The ECAL-vs-HCAL energy distribution for all selected events for the 2021-2022 run period is reported in Fig. 2, left panel.

The most critical background source for the experiment is associated with upstream interactions of the impinging particle with beamline materials, with the low-energy scattered electron releasing a small energy in the ECAL and with secondary neutral hadrons produced at large angle, outside the HCAL acceptance. The corresponding yield was evaluated directly from data, considering events lying in the sideband region $E_{HCAL} \simeq 0$, $E_{ECAL} < E_0$ (region "C" in Fig. 2). The corresponding ECAL energy distribution was extrapolated in the signal region through an exponential model, and

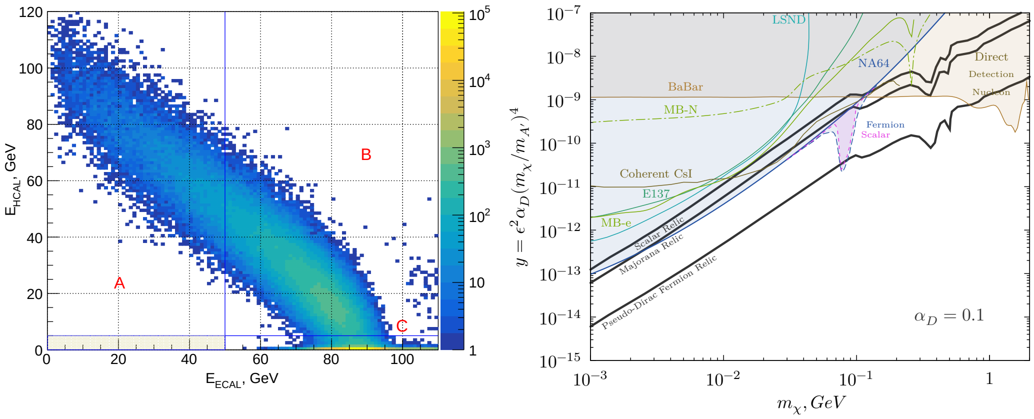


**Figure 2:** Left: the ECAL-vs-HCAL energy distribution for events measured during the 2021-2022 NA64−$e$ run, selected by the analysis cuts. The gray area represents the signal box - the HCAL threshold has been amplified by a factor for better readability. Right: the NA64−$e$ upper limits in the (y;$m_\chi$) plane obtained for $\alpha_D = 0.1$, considering the whole 2016-2022 statistics.

the integral therein was evaluated. For the 2021-2022 runs, corresponding to the larger accumulated statistics for the whole experiment, the result reads $\simeq 0.16$ background events.

After scrutinizing the signal box, no events were observed. Based on this null result, an upper limit for the $A'$ signal was determined. The LDM yield in the signal window was estimated through a full Geant simulation of the NA64 setup, employing the DMG4 package [8]. Two main LDM production mechanisms were accounted for: the radiative emission of an $A'$ by the interaction of an electron/positron of the electromagnetic shower with the atoms of the active target ($e^\pm Z \to e^\pm Z A'$), followed by the invisible $A'$ decay [6], and the resonant annihilation of a secondary positron with an atomic electron ($e^+e^- \to A' \to \chi\chi$) [9]. While the first process, for a given $m_{A'}$ value, corresponds to a broad missing energy distribution, the second results to a peak for $E^{miss} = m^2_{A'}/(2m_e)$, due to the $s-$channel dynamics of the reaction.

The results are reported in Fig. 2, right panel, for $\alpha_D = 0.1$ and for $m_{A'} = 3m_\chi$, considering a fermionic (blue) or scalar (pink) LDM model. The black lines report the predicted value of the $y$ parameter for a given $m_\chi$, given by Eq. 2. Thanks to the sizeable accumulated statistics, NA64 was able to exclude scalar and Majorana LDM for masses 1 MeV$\lesssim m_\chi \lesssim$ 100 MeV. Exploiting the yield enhancement provided by the $e^+e^-$ annihilation production channel, NA64−$e$ was able for the first time to exclude Pseudo-Dirac LDM in a narrow interval close to $m_\chi \simeq 80$ MeV.

### 2.1 Positron-beam measurements

The NA64 collaboration recently started a dedicated missing-energy program with positron beams[1]. The driving idea is the observation that in a thick-target positron-beam experiment, thanks to the contribution of the primary $e^+$ impinging on the target, the positrons track-length distribution $T_+(E)$ is strongly enhanced at large energy, close to $E_0$ (see Fig. 3, left panel). It follows that a large

[1]This program is supported by a dedicated ERC Grant (POKER, "POsitron resonant annihilation into darK mattER").

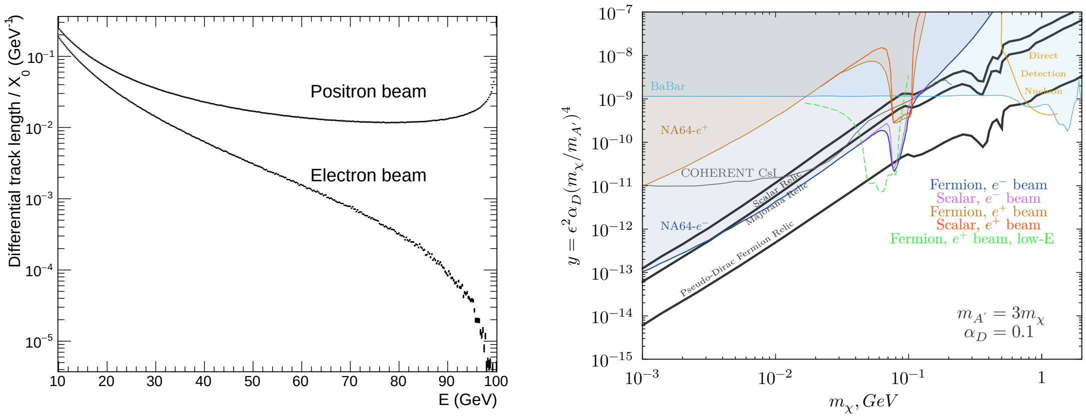


**Figure 3:** Right: differential positrons track-length distribution in a thick target for an impinging 100 GeV $e^+$ beam, normalized to the radiation length $X_0$. For comparison, the same distribution in case of an $e^-$ beam is also reported. Left: exclusion limits for the NA64 positron-beam test run in the $(m_\chi, y)$ plane, for $\alpha_D = 0.1$. The other curves and shaded areas report already-existing limits in the same parameter space. The green dashed line shows the sensitivity for a future positron-beam effort at lower energy.

sensitivity to $\varepsilon$ is obtained within the $A'$ mass range rigidly delimited by the experimental threshold on the missing energy and the energy of the beam [9], $E^{miss}_{thr} \lesssim m^2_{A'}/(2m_e) \lesssim E_0$.

In 2022 a first positron-beam missing-energy pilot measurement was performed using the same detector configuration previously introduced, with a total statistics of about $N_{e^+OT} = (10.1 \pm 0.1) \times 10^9$ 100 GeV positrons-on-target. In analogy with the electron-beam measurement, a blind-analysis approach was adopted. The final cuts configuration required the presence of an accurately identified 100 GeV/c ± 3 GeV/c impinging track, in coincidence with a total energy deposition in each SRD cell of at least 2.5 MeV. The VETO energy was required to be less than 17 MeV for each panel. A 500 MeV threshold on the ECAL0 energy deposition was applied, and the shape of the electromagnetic shower in the ECAL was required to be compatible with that expected for the $A'$ signal. Finally, the $E_{ECAL} < 50$ GeV, $E_{HCAL} < 1$ GeV signal region conditions were applied.

When the H4 beamline is operated at 100 GeV/c in positive-charge mode, a large hadronic contamination of about $\simeq$ 4% is present [10]. As a consequence, the largest background source was from the $K^+ \to e^+\pi^0\nu_e$ decay of a misidentified kaon occurring upstrem of the ECAL, if the neutrino energy is larger than 50 GeV and the $e^+\gamma\gamma$ particles produce a single low-energy EM shower in the calorimeter. The corresponding expected yield was about 0.06 events.

After scrutinizing the signal box, no events were found, and upper limits were set for the $A'$ signal. The result is shown in Fig. 3, right panel, for $\alpha_D = 0.1$. Despite the accumulated statistics being two orders of magnitude lower, the obtained limits are comparable to those from the $e^-$ measurement, thanks to the yield enhancement induced by the $e^+e^-$ resonant annihilation.

## 3. Conclusions

By running a dedicated missing-energy electron-beam measurement, NA64−$e$ at CERN obtained world-leading bounds for the existence of LDM in the mass range 1 MeV $\lesssim m_{A'} \lesssim$ 350 MeV, probing for the first time the thermal LDM curves for scalar and Majorana models. In the next years, before CERN LS3, NA64 plans to accumulate further statistics, with up to $3 \times 10^{12}$ EOT, to further explore the LDM scenario. A dedicated detector upgrade is also foreseen during the LS3 period, with an improved DAQ system enabling to run the experiment at even higher intensity, up to $10^7$ $e^-$/spill. This will allow NA64 to reach the final goal of $\simeq 10^{13}$ EOT, to probe the whole LDM parameter space down to the Pseudo-Dirac target.

In parallel to this effort, a positron-beam missing-energy program was recently started. A first dedicated test was successfully completed in 2022, and the collaboration is now looking forward to a future multi-energy $e^+$ experimental program, to fully exploit the peculiarities of the resonant $A'$ production and "scan" the LDM parameter space.

## References

[1] G. Arcadi, M. Dutra, P. Ghosh, M. Lindner, Y. Mambrini, M. Pierre et al., *The waning of the WIMP? A review of models, searches, and constraints*, *Eur. Phys. J. C* **78** (2018) 203 [1703.07364].

[2] S. Knapen, T. Lin and K.M. Zurek, *Light Dark Matter: Models and Constraints*, *Phys. Rev. D* **96** (2017) 115021 [1709.07882].

[3] A.R. Liddle, *An introduction to modern cosmology* (1998).

[4] A. Berlin, N. Blinov, G. Krnjaic, P. Schuster and N. Toro, *Dark Matter, Millicharges, Axion and Scalar Particles, Gauge Bosons, and Other New Physics with LDMX*, *Phys. Rev. D* **99** (2019) 075001 [1807.01730].

[5] NA64 collaboration, *Search for Light Dark Matter with NA64 at CERN*, *Phys. Rev. Lett.* **131** (2023) 161801 [2307.02404].

[6] S.N. Gninenko, N.V. Krasnikov, M.M. Kirsanov and D.V. Kirpichnikov, *Missing energy signature from invisible decays of dark photons at the CERN SPS*, *Phys. Rev. D* **94** (2016) 095025 [1604.08432].

[7] NA64 collaboration, *Search for vector mediator of Dark Matter production in invisible decay mode*, *Phys. Rev. D* **97** (2018) 072002 [1710.00971].

[8] M. Bondi, A. Celentano, R.R. Dusaev, D.V. Kirpichnikov, M.M. Kirsanov, N.V. Krasnikov et al., *Fully Geant4 compatible package for the simulation of Dark Matter in fixed target experiments*, *Comput. Phys. Commun.* **269** (2021) 108129 [2101.12192].

[9] L. Marsicano, M. Battaglieri, M. Bondí, C.D.R. Carvajal, A. Celentano, M. De Napoli et al., *Novel Way to Search for Light Dark Matter in Lepton Beam-Dump Experiments*, *Phys. Rev. Lett.* **121** (2018) 041802 [1807.05884].

[10] Y.M. Andreev et al., *Measurement of the intrinsic hadronic contamination in the NA64−e high-purity e+/e− beam at CERN*, *Nucl. Instrum. Meth. A* **1057** (2023) 168776 [2305.19411].