PROCEEDINGS OF SCIENCE

Probing the Dark Sector with NA64 and POKER at CERN SPS

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Despite its great successes, the Standard Model (SM) of particle physics is far from complete, as suggested by many facts, such as the astrophysical evidences of Dark Matter, the baryon asymmetry observed in the universe and the unsolved problem of the origin of the neutrino masses. The search for DM, in particular, is one of the hottest topics of modern physics. Despite the various astrophysical and cosmological observations proving its existence, its particle properties remain to date unknown. In a theoretically motivated and largely unexplored scenario, DM could interact with the SM through a new force, mediated by a new vector boson (dark photon or A'), kinetically mixed with the SM photon. The NA64-e experiment at CERN aims to produce DM particles using the 100 GeV SPS electron beam impinging on a thick electromagnetic calorimeter. The DM production signature consists in a large observed missing energy, defined as the difference between the energy of the 100 GeV primary electron and the energy deposited in the calorimeter, coupled with no activity in the downstream veto systems. NA64-e its a versatile experiment, featuring a significant sensitivity to several beyond SM extensions involving new feebly interacting particles, as proved by the exclusion limits set by the NA64 collaboration in the ALPs and $L_\mu - L_\tau$ scenarios. In the last years, the collaboration has performed preliminary studies with the aim to run the experiment with a positron beam, in order to exploit the potential of the $e^+ - e^-$ resonant annihilation for the A' search, according with the ERC-funded POKER (POsitron resonant annihilation into darK mattER) project. This work presents the latest NA64-e results and its future prospects, reporting the sensitivity of the experiment to different theoretical scenarios. Finally, the progresses and prospects of the POKER project are presented.

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1. Introduction

The Standard Model (SM) of particle physics is one of the greatest success of modern physics, describing and predicting many physical processes with great precision. Still, different astrophysical and cosmological observations support the case for extensions of the SM. These anomalies could be reconciled with theory assuming the existence of a new kind of matter, not directly interacting with the SM, called Dark Matter (DM) [1]. Astrophysical observations indicates that DM makes the vast majority of the mass of the Universe; however, the fundamental properties of DM, remain to date unknown. Among the different models proposed over the years, the so-called light Dark Matter (LDM) paradigm as recently gathered the interest of the particle physics community, being theoretically well motivated and largely unexplored. In a representative model, DM is composed of "Dark Sector" particles χs with masses in the 1 MeV - 1 GeV mass range, charged under a new U(1) symmetry. The mediator of this new interaction, is a massive vector boson, called "heavy photon" or "dark photon" (A'), kinetically mixed with the SM photon [2]. The corresponding lagrangian density, after field diagonalization and omitting the χ mass term, reads:

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

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 χ particles. This representative model is consistent with the hypothesis of DM thermal origin, provided that the model parameters lie in a constrained region. This provides a target for discovery or falsifiability - the so called "thermal target" [3]. To date, the most stringent exclusion limits in the vector-mediated LDM parameter space have been set by experiments at accelerators and colliders. Fixed-target experiments exploiting particle beams with moderate energies (10÷100 GeV) are particularly well suited to probe this scenario.

2. The NA64-e Experiment

NA64-e is an electron-beam fixed-target experiment at CERN SPS (Super Proton Synchrotron). The experiment, whose detector layout is shown in Fig. 1, exploits a 100 GeV electron beam impinging on a thick active target to produce LDM and feebly interacting particles, such as χ particles resulting from the decay of dark photons. The time structure of the e^- beam is such that electrons impinge on the target "one-by-one", allowing for their tagging and momentum measurement with a magnetic spectrometer (resolution $\frac{\Delta p}{p} \simeq 1\%$). The spectrometer is composed of a dipole magnet (MBPL), bending the beam by a $\theta \simeq 20$ mrad angle, and a set of straw tube detectors ($\mathrm{ST}_{1,4}$), micromegas ($\mathrm{MM}_{1,4}$) and gaseous electron multipliers ($\mathrm{GEM}_{1,2}$). From the interaction of the electrons of the beam on the target, i.e. a 40-radiation-lengths long lead/scintillator (Pb/Sc) electromagnetic calorimeter (ECAL), an electromagnetic shower is initiated. LDM particles may result from the decay of dark photons produced in the shower and subsequently, given the weakness of the DS-DM interaction, leave the detector area without depositing energy. The signature of the production of χs is therefore a large missing energy, i.e. the difference between the energy of the beam and the energy deposited in the ECAL (ECAL energy resolution: $\frac{\sigma_E}{E} \simeq \frac{10\%}{\sqrt{E}} + 4\%$). Such an experiment is affected by two main kinds of background:

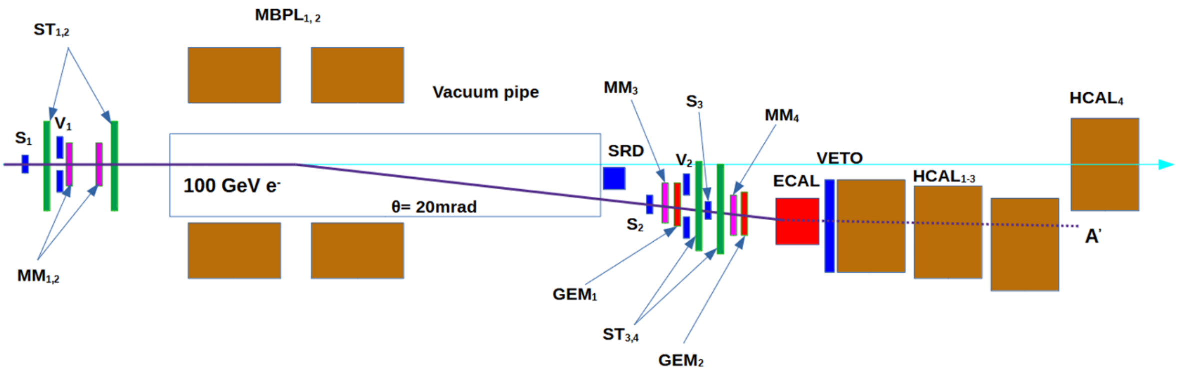

Figure 1: Schematic view of the NA64-*e* detector in the 2022 configuration for the light DM search. See text for the acronym definitions.

- hadron contaminants in the beam such as $\pi,\ p, ...$ (at the level of $\sim 1\%$ in the electron beam) punching through the ECAL;
- events where energetic, highly penetrating particles ($\mu, \nu, n, ...$) produced in the target escape from the detector.

The first background source is rejected by means of a Pb/Sc sandwich syncrotron radiation detector (SRD), placed downstream the bending magnet; the detection of the photons emitted by the charged particles passing through the magnetic field allows for the electron identification and rejection of hadron contaminants. In order to detect all SM penetrating particles that may be produced in the ECAL and escape from it, a high-efficiency plastic scintillator veto (VETO) and a large Pb/Sc hadronic calorimeter (HCAL) of $\sim$ 30 nuclear interaction lengths are placed downstream the ECAL. NA64 has been operating since 2016, collecting $\sim 1.5 \cdot 10^{12}\ e^-$ on target (EOT) [4]. Event selection in the data analysis was defined by optimizing the experiment sensitivity, adopting a blind-analysis approach. The selection criteria include the requirement of well defined track in the spectrometer, an in-time cluster in the SRD detector, and an energy deposition in the ECAL with the shape compatible with an electromagnetic shower. After applying all selection cuts, no events were observed in the signal region: $E_{ECAL} < 50$ GeV and $E_{HCAL} < 1$ GeV. This result allowed the NA64 collaboration to set the most stringent limits in a large portion of the vector-mediated LDM scenario, as shown in Fig. 2.

Besides the search for dark photons decaying to LDM *invisible* states, NA64 also collected data with a slightly modified detector setup, optimized for the detection of A' decays to electron/positron pairs. This "*visible* decay scenario has recently gathered a significant interest, since it could explain the X17 or "beryllium anomaly" [5]. During 2018, NA64-*e* collected $\sim 3 \times 10^{10}$ EOT with the "visible" setup, (see [6] for a detailed description of the apparatus). Since no signal-like events were observed, NA64-*e* could set stringent limits on the A' parameter space compatible with the X17 observation; in order to completely exclude this hypothesis, new detector upgrades, currently under discussion, are required [6].

NA64$-e$ can explore other beyond SM scenarios, besides vector-mediated LDM: data collected by the experiment up to 2018 have been re-analyzed searching for a new muon-philic mediator (Z')

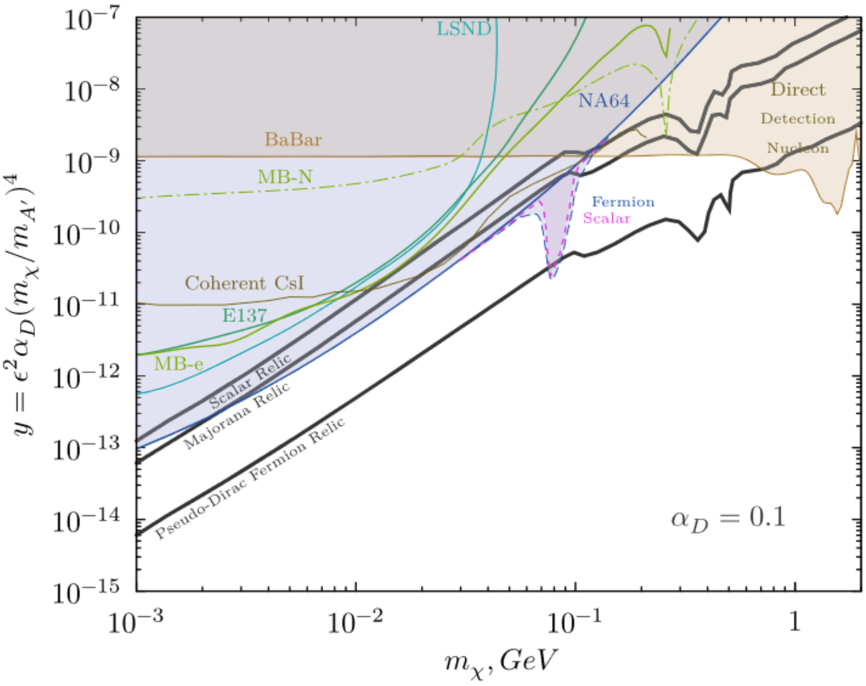

Figure 2: Latest published exclusion limits of NA64$-e$ in the LDM parameter space, for $\alpha_D = 0.1$. See [4] for more details.

in the $L_\mu - L_\tau$ scenario [7] , and axion like particles (ALPs) [8] . Figure 4 shows the exclusion limits set by NA64$-e$ in the Z' (left panel) and ALPs (right panel) parameter spaces; see [7, 8] for a thorough description of the analysis procedure and the theoretical scenarios involved. The re-analysis of the data collected by NA64 from 2019 to 2022 for these models is currently being performed; updated limits are expected soon.

3. POKER - POsitron resonant annihilation into darK mattER

Electron-positron resonant annihilation in χ particles ($e^+e^- \to A' \to \chi\bar{\chi}$) is an efficient mechanism to explore the vector-mediated LDM scenario. Where kinematically allowed, it features a large cross section compared to other production processes[9]; in addition, the energy of the outgoing LDM pair is fixed by the A' mass (neglecting the width of the A'). This feature results in a unique signal signature for a missing-energy experiment: the resulting E_{miss} distribution has a Breit-Wigner-like shape, peaked at the value $E_{peak} = m^2_{A'}/2m_e$. This provides a way to measure $m_{A'}$ from data and can be exploited to improve the experiment sensitivity, by using ad-hoc analysis techniques. POKER (POsitron resonant annihilation into darK mattER) fits into this context: it is an ERC-funded project aiming to perform a missing-energy measurement with the positron beam provided by the CERN SPS, within the experimental setup of NA64-e. According to the project, a new electromagnetic calorimeter composed of $\sim$ 120 $PbWO_4$ crystals will be built to replace temporarily the ECAL of NA64-e during the POKER measurement. The improved energy resolution of such detector, currently under construction, will permit to better exploit the distinct Breit-Wigner signature of the resonant annihilation [10]. During 2022, a first data set of $\sim 10^{10}$ e^+

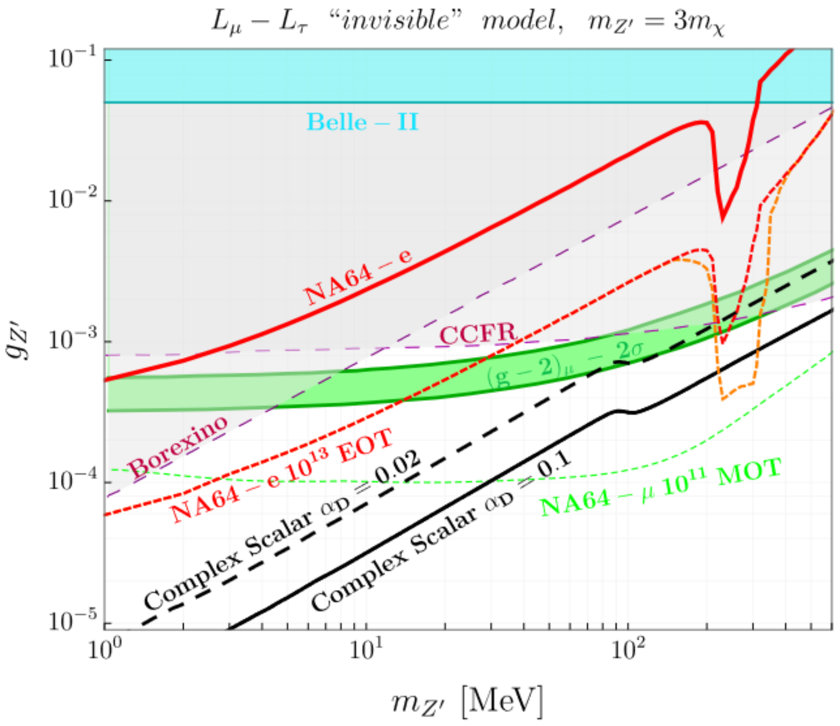

Figure 3: Latest published limits of NA64 in the $L_\mu - L_\tau$ parameter space (solid red line). The plot includes projection for a future 10^{13} electron (dashed red line) and positron (orange dashed line) beam measurement.

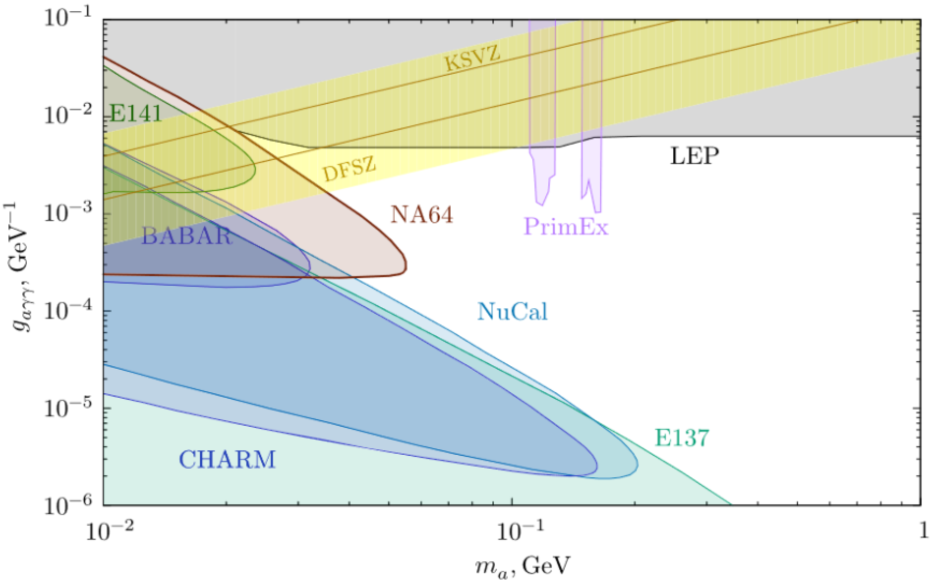

Figure 4: Exclusion limits of NA64−e in the ALPs parameter space.

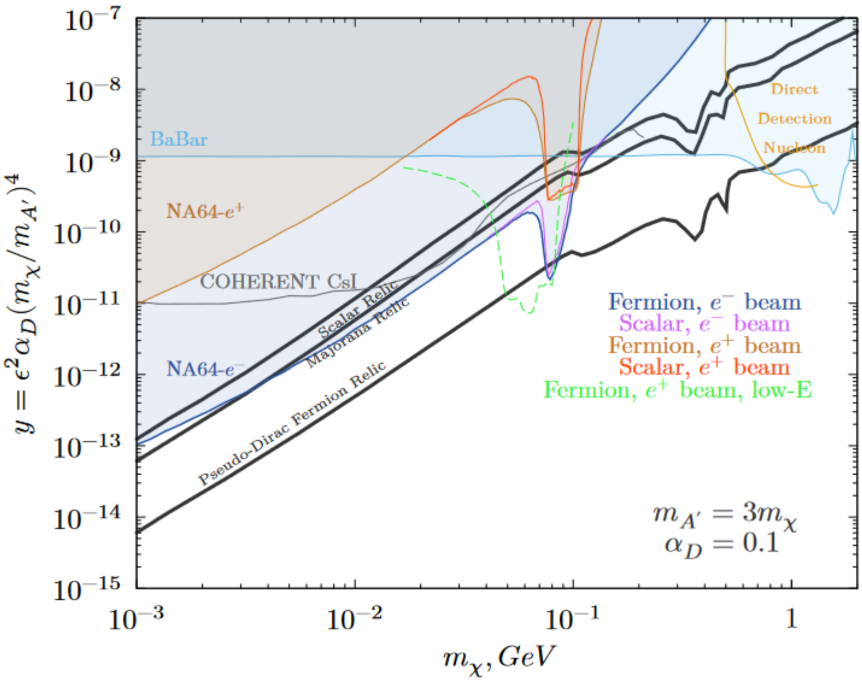

Figure 5: The red and orange solid lines show the exclusion limits resulting from the 2022 NA64 e^+ measurement, for $\alpha_D = 0.1$. The green dashed line show the projected sensitivity for a future multi-energy positron beam run (see [10] for more details).

has been collected with the current NA64-*e* setup; Fig. 5 shows the exclusion limits resulting from this preliminary measurement, as well as projections from future positron-beam runs at NA64.

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