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Search for Dark Matter at NA62 and NA64 experiments

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Searches for Dark Matter with the NA62 and NA64 experiments at CERN are presented. In the NA62 experiment the search is in the decays $A' \to \mu\mu$ and $A' \to ee$, where A' is a new vector particle corresponding to a vector mediator field. The NA64 experiment looks for events with invisible decays of A' and thus having large missing energy. New upper limits have been set on models with such a vector mediator field.

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1. Dark Matter search at the NA62 experiment

1.1 Introduction

The existence of Dark Matter (DM) in the universe is predicted by several models with an additional U(1) gauge-symmetry sector [1, 2]. Such models introduce a vector mediator field A' often referred to as "dark photon" (DP) which is coupled to Standard Model fields through kinetic mixing, the mixing strength is characterised by a coupling constant ϵ.

Dark photons can be produced in proton-nucleus interactions via bremsstrahlung or decays of secondary mesons. For $M_{A'}$ below 700 MeV/c^2 the dark photon decay width is dominated by di-lepton final states.

1.2 Experimental setup and results

NA62 is a fixed target experiment situated at the CERN SPS accelerator. A detailed description of the setup can be found in [3]. In 2021 a fraction of the data was taken in dump mode, with Cu-Fe collimators closed and the target removed.

The proton beam was dumped on 800 mm of copper followed by 2400 mm of iron, corresponding to a total of 19.6 nuclear interaction lengths. Momenta and directions of charged particles are measured by a magnetic spectrometer. Two scintillator hodoscopes, consisting of a matrix of tiles and two orthogonal planes of slabs, perform track time measurements. Particle identification is provided by a quasi-homogeneous liquid krypton electromagnetic calorimeter (LKr), two hadron calorimeters, and a muon detector just downstream of a 80 cm thick iron absorber. A photon veto system includes the LKr, twelve ring-shaped lead-glass detectors and small angle calorimeters. A total of $(1.40 \pm 0.28) \cdot 10^{17}$ protons on target (POT) were collected.

Dark photons could be produced in beam interactions with the collimator material and could later decay into a pair of leptons within the detector acceptance. The NA62 setup is sensitive to decays of DP's with masses up to 600 MeV/c^2. The analysis strategy is to select events with a dilepton vertex in the decay fiducial volume and dilepton momentum pointing back to the collimators. The signal region is defined in terms of the closest distance of approach (CDA) between the beam and dilepton momentum and the Z coordinate of the point of closest approach. Signal events are concentrated at small CDA and Z around the collimator location. The signal region was kept masked during the analysis.

The main background for the $A' \to \mu\mu$ channel is composed of two uncorrelated "halo" muons forming a vertex, while for the $A' \to ee$ it comes from secondaries from a muon interaction with the traversed material. In both cases data driven techniques are applied to estimate the number of background events in the signal region. The expected background is 0.016 ± 0.002 events for the muon mode and $0.0094^{+0.049}_{-0.009}$ for the electron mode.

After unmasking the signal region, 0 events were observed for the electron mode and 1 event for the muon mode (2.4σ significance), see Fig. 1, left. Upper limits are set on the DP coupling and the excluded regions of the $(\epsilon, M_{A'})$ parameter space are shown in Fig. 1, right. The results have been published in [4] and [5].

It is planned to collect $O(10^{18})$ POT by 2025. Searches for exotic particles will be extended to decays with $\gamma\gamma$ and $\pi^+\pi^-\gamma$ final states.

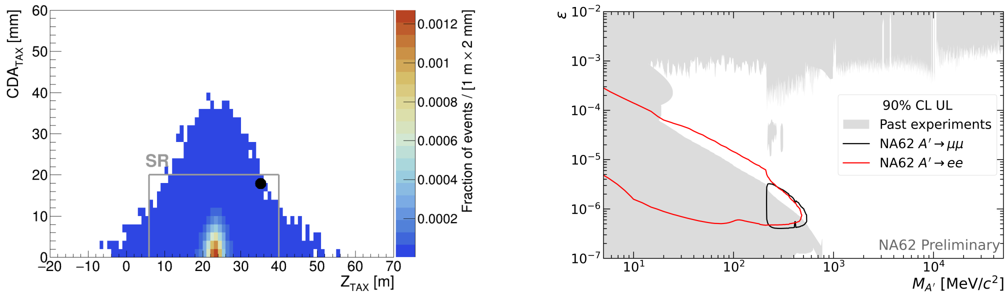

Figure 1: Left: signal region for the $A' \to \mu\mu$ search. Data (dots) and expected signal density (colour scale) are shown. Right: excluded regions for dark photon search in $A' \to ll$ decays.

2. Dark Matter search at the NA64 experiment

Thermal Light Dark Matter (LDM) models reliably predict the LDM [6, 7] parameters ("thermal target" [8]) starting from the observed relic DM density [9]. It is remarkable that with statistics accumulated by 2022 year the NA64 experiment becomes sensitive to parts of the region in the parameter space predicted by these models.

The fixed target experiment NA64 uses a technique of missing energy, arising from invisible decays of A' or some other LDM mediators, to search for LDM. It is located (Fig. 2) at the H4 beamline of the CERN SPS, capable of providing a 100 GeV electron or positron beam, see Ref. [10] and references therein. The most important part of the experiment is the active target: a 40 X_0 radiation-length lead-scintillator (Pb/Sc) Shashlik electromagnetic calorimeter (ECAL). The NA64 design allowed to use synchrotron radiation (SR) emitted in the MBPL magnets for the electron identification. The final pieces to ensure the maximal hermeticity of the detector are a high-efficiency veto counter VETO and three modules of Fe/Sc hadron calorimeter (HCAL).

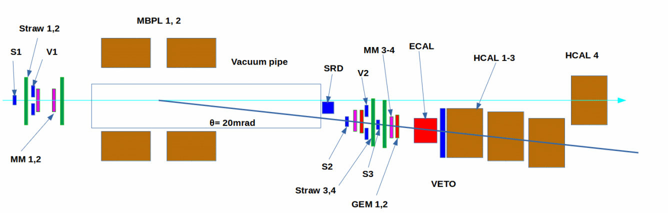

Figure 2: The scheme of the NA64 experimental setup in 2022.

In order to suppress the backgrounds the following main selection criteria were used [11]: (i) The incoming track quality and momentum requirements; (ii) The detected total SR energy should be in the range typical for electrons; (iii) The veto-like VETO and HCAL cuts. After optimization of the final cut $E_{ECAL} < 47-50$ GeV the acceptance for the signal was determined from the signal simulation using the dedicated package DMG4 [12]. In the signal simulation both Bremsstrahlung process and resonant annihilation production were taken into account.

As a result, no events were found after applying all selection criteria. We derived limits on the Dark Photon mixing parameters shown in Fig. 3. These limits are the most stringent to-date.

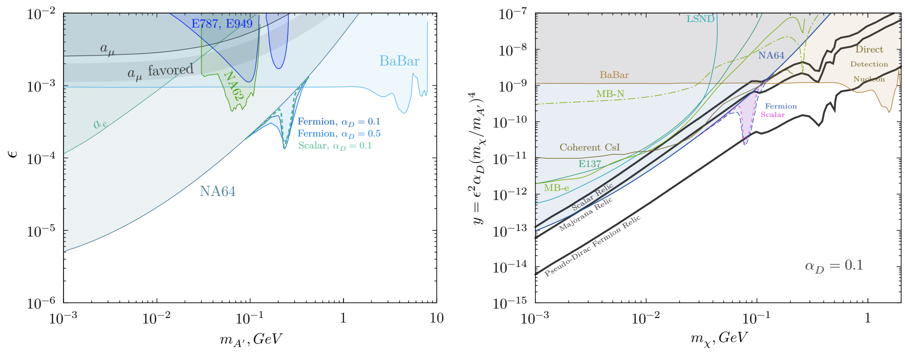

Figure 3: The exclusion limits of the NA64 experiment in the A' LDM scenario. In the left panel they are in terms of ϵ, with the sensitivity peak at $m_{A'} \simeq 250$ MeV from the contribution of the secondary e^+ resonant annihilation. In the right panel the limits are in "cosmological" variables. The black lines are the predictions from the "thermal origin" hypothesis, for different LDM models.

In summary, NA64 is a world leader in sensitivity in the searches for LDM mediators in the sub-GeV mass region. Apart from the most popular Dark Photon, the searches for other mediator types (Scalar, Pseudoscalar, Axial Vector) were performed. NA64 experiment searched also for other Feebly Interacting Particles FIP, such as light X boson decaying visibly into e^+e^- and Axion Like Particles (ALP). The experiment NA64μ on the CERN muon beam aiming at the search for a Z' boson of $L_\mu - L_\tau$ model was started in 2021, the first results are being prepared for publication. Another search direction is the invisible decays of η, η', K^0 in the hadron beam (NA64h).

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