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New results for searches of exotic decays with NA62 in beam dump mode

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The NA62 experiment at CERN has been taking data since 2016 with the main goal of measuring the decay $K^+ \to \pi^+ \nu \bar{\nu}$. The NA62 experiment can be run as a *beam dump experiment* by removing the kaon production target and moving the upstream collimators into a closed position. We report on the search for visible decays of exotic mediators from data taken in beam dump mode with the NA62 experiment. More than 10^{17} protons on target have been collected in this way during a week long data taking campaign by the NA62 experiment. We report on new results from analysis of this data, with a particular emphasis on the *dark photon* model.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

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PoS(EPS-HEP2023)045

1. Introduction

To explain observed shortcomings of the Standard Model of Particle Physics (SM), additional degrees of freedom can be introduced, commonly referred to as exotic particles. One ansatz to explain the abundance of dark matter is an extra $U(1)$ gauge symmetry mediated by a massive vector boson A', the *dark photon* (DP). In a simple realisation [1, 2] of this model, A' interacts with the SM through a kinetic mixing Lagrangian term

$$-\varepsilon \frac{1}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}, \tag{1}$$

where $F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$, $B^{\mu\nu}$ is the SM $U(1)$ hypercharge gauge field, θ_W is the Weinberg angle, and $\varepsilon \ll 1$ quantifies the coupling suppression. In principle, the mass $M_{A'}$ and coupling suppression ε are free parameters of the model. However, the MeV to GeV mass region with ε at around 10^{-6} to 10^{-3} is particularly well motivated. Here, the DP can, by itself, account for a significant part of the cosmologically required dark matter [3].

The DP phenomenology is rich[1], but the relevant features for this search can be summarised as follows

- Dark photons can be produced in proton-nucleus interactions via bremsstrahlung or decays of secondary mesons.
- For ε from 10^{-7} to 10^{-3} with $M_{A'}$ in the MeV to GeV range, the DP decay lengths for momenta above 10 GeV span from tens of metres to tens of kilometres. For these parameters, they can traverse tens of metres of material with minimal scattering due to their feeble interaction with the SM.
- For masses below 700 MeV, the DP decays predominantly into dilepton final states.

This paper will discuss the experimental set up in section 2, followed by the data selection in section 3, and dedicated search strategy in section 4. The results of the search for exotic decays are presented in section 5, with concluding remarks in section 6 and the main result in figure 3. Further information can be found in the accompanying publications [5, 6].

2. The NA62 experiment and the beam dump configuration

The NA62 experiment is located in the North Area of CERN receiving a 400 GeV proton beam from the Super Proton Synchroton (SPS). It was first conceived in order to accurately measure the very rare decay $K^+ \to \pi^+\nu\bar{\nu}$ [7]. To reach the background suppression necessary to resolve such a rare event, the apparatus was designed with hermiticity as the driving concept. Figure 1 (top) shows the principle components of the NA62 detector array, the exact workings of which are explained in great detail elsewhere [8, 9]. In what follows, we will restrict ourselves to superficially introducing the most important components for the searches described in this work.

The most upstream detector relied upon in these searches is the ANTI0 scintillator hodoscope, used to detect particles from outside the vacuum pipe. The downstream 117 m long vacuum tank – evacuated to 10^{-6} mbar – is encased by twelve ring shaped lead glass detectors (LAV) for the first 80.6 m, and subsequently houses the STRAW, two pairs of straw chamber stations on either

[1] See e.g. [4] for a recent review.

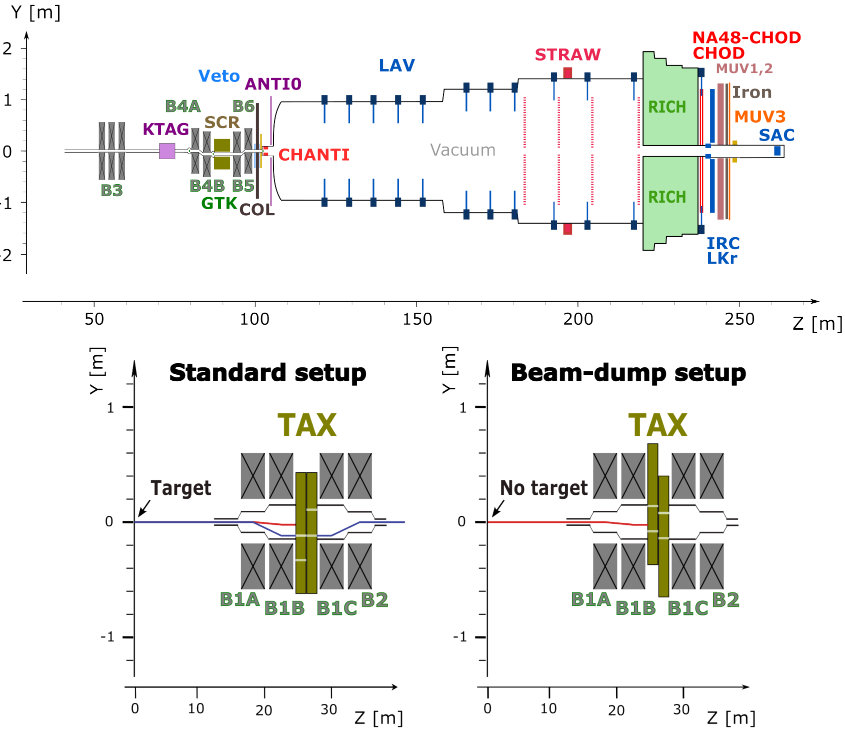

Figure 1: Schematic layout of the NA62 experiment's detector array (top) and layout of TAX achromat for standard (bottom left) and beam dump (bottom right) operation. The trajectory of a 400 GeV proton beam incident from the left is shown in red, while that of a secondary 75 GeV beam is shown in blue.

side of a dipole magnet, which measures momentum vectors. Two scintillator hodoscopes (CHOD and NA48-CHOD), consisting of a matrix of tiles and two orthogonal planes of slabs, provide time measurements with 600 and 200 ps resolution respectively. Particle identification is performed using the electromagnetic calorimeter (LKr), as well as a muon detector (MUV3).

As the main goal of the experiment is to measure rare kaon decays, the standard setup is optimised for kaon production. However, the experiment can alternatively be run in *beam dump mode*, optimised for detecting decays of long lived exotic particles also above the kaon mass. The main modification when changing into dump mode is schematically shown in figure 1 (bottom) and constitutes the removal of the T10 beryllium target and the closing of the TAX collimators. In this mode, the 400 GeV SPS proton beam is dumped on 800 mm of copper followed by 2400 mm of iron, corresponding to a total of 19.6 nuclear interaction lengths. Another, important difference in operation is that in beam dump mode the currents of the B1C and B2 dipoles are set to produce magnetic fields in the same direction. This allows the flux of *halo muons* produced by upstream interactions to be minimised. Thanks to the strong background rejection provided by the NA62 detector array, in combination with the high intensities of protons on target (PoT) possible at the SPS, the resulting experimental setup is sensitive to a broad variety of long lived exotic particles with world leading parameter reach [10, 11].

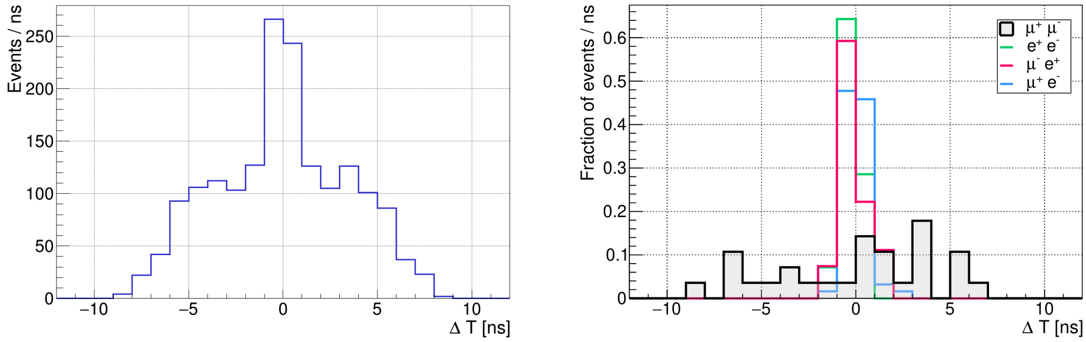

Figure 2: Event count of incident particles time differences for $\mu^+\mu^-$ before (left) and multiple final states after (right) LAV veto.

3. Data selection

The data presented here constitutes a total of 1.4×10^{17} PoT with three trigger lines employed during data taking. These require

Q1 at least one signal in the CHOD (downscaled by a factor of 20),

H2 at least two signals within 5 ns in different tiles of the CHOD,

C3 a total energy above 1 GeV in the LKr with one or more reconstructed clusters.

Particles were identified by the ratio of LKr cluster energy to associated STRAW track momentum, and associated MUV3 signal as

μ if zero or one LKr cluster with $Ep^{-1} < 0.2$ and one associated MUV3 signal,

π if one LKr cluster with $0.2 < Ep^{-1} < 0.9$ and no associated MUV3 signal,

e if one LKr cluster with $0.95 < Ep^{-1} < 1.05$ and no associated MUV3 signal.

For the e^+e^- search, the upper π and lower e limit were refined for high energies. Overall, the resulting efficiency of signal selection and trigger is in the order of 95 % for e^+e^- and 90 % for $\mu^+\mu^-$ with a total uncertainty below 3 % in both cases.

4. Search strategy

The search presented here looked for the closed dilepton final states of a long lived exotic decay, which is the predominant dark photon decay channel in the relevant mass region as mentioned in section 1. Thus, the full dark photon kinematic information can be recovered with the detector setup described in section 2. This can be exploited to reduce backgrounds by pointing back to its production vertex, using the kinematics and decay vertex position reconstructed from the final states. A signal and control region (SR, CR) are defined in terms of the reconstructed primary vertex location in coordinates along the axis given by the protons incident on the TAX and closest distance of approach to this beam line. Both regions were kept masked up to the point of collaboration approval. Another major factor in reducing backgrounds is the veto of any in time activity in the LAV, which for the e^+e^- final state also extends to any in time activity in the ANTI0 hodoscope. This excludes a large part of background due to scattering processes of upstream halo particles.

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Figure 2 shows the measured time difference of muons coalesced by the vertex reconstruction algorithm before and after the applied LAV veto. Before applying the LAV veto, we can identify two main categories of backgrounds. Firstly, *prompt* background is clustered around the centre of the distribution and is mostly generated by secondary scattering of incident muons in the material traversed and subsequent decays into a muons (ie. $\pi \to \mu$). *Combinatorial* background makes up the second main category with a distribution fully satisfying the H2 trigger requirement and is due to accidental combination of unrelated muons by the vertex reconstruction.

The combinatorial background was estimated using random in-time coincidence of single track events from a different trigger line and cross checked against data of same sign dimuon pairs. To estimate the prompt background in the $\mu^+\mu^-$ search, data points from single track events were traced back through the detector using backward MC, generating an input distribution for the standard forward MC at the upstream face of the B5 magnet. For the e^+e^- search, the individual rejection powers involved were deduced from cut inverted samples. Based on these, a Cousins-Highland estimation was employed to evaluate the probability of nonzero background events in the signal region. The expected number of background events in the signal region for the $\mu^+\mu^-$ final state is dominated by combinatorial background with 0.16 ± 0.002 expected events, while the expected prompt background only contributes < 0.011 expected events. For the e^+e^- final state, the reverse is true. Here, the probability for nonzero event counts in absence of signal of 1.6 % is dominated by the prompt background, while the combinatorial background expectation is below 10^{-3}.

5. Results

Upon opening the SR for $\mu^+\mu^-$ a single event was observed. However, the event was an outlier both in terms of timing coincidence ($\sim 2\sigma$ away from $\Delta t = 0$) and the expected primary vertex location (expected fraction of events more than 10 times smaller than global maximum in associated $1\,\mathrm{m} \times 2\,\mathrm{mm}$ bin). Consequently, the event can be interpreted as a combinatorial background event.[2] For the e^+e^- final state, no event was observed in the SR. For both searches, there was a probability of 1.6 % for nonzero event observation in absence of signal.

6. Conclusion

A data set corresponding to 1.4×10^{17} PoT at the NA62 experiment in beam dump mode was analysed for exotic decays to a dilepton final state. No conclusive signal events were observed. We exclude parts of the possible parameter space for dark photons as shown in figure 3 at a confidence level of 90 % for the individual searches presented in this work. The statistical combination of the two results into a single exclusion limit is work in progress.

Acknowledgments

JLS is partially supported through the European Research Council under grant ERC-2018-StG-802836 (AxScale project).

[2]For further detail on the event and classification decision, please find the dedicated publication [5].

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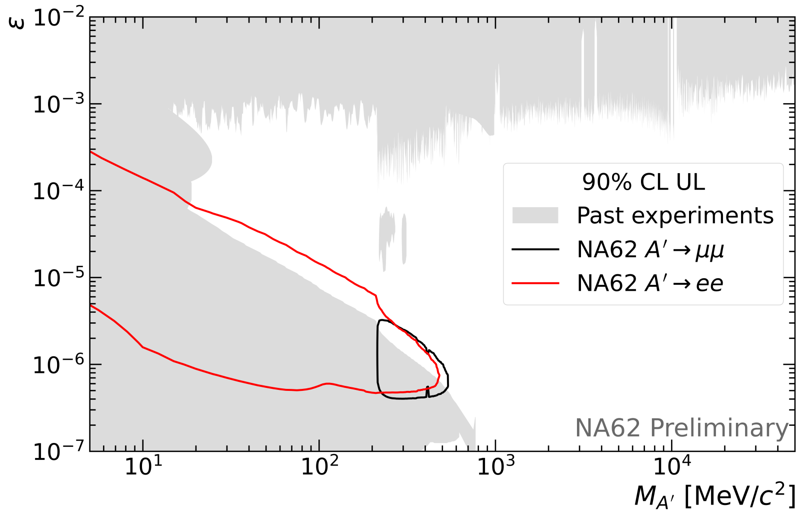

Figure 3: Parameter space exclusion at 90 % confidence level for dark photon from this search (excluded inside contours).

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