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

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Searches for visible decays of exotic mediators can be performed by the NA62 experiment, when running in "beam-dump" mode. The analysis presented in this work, focuses on in-flight decays of dark photons to $\mu^+\mu^-$ pairs, using the data collected in 2021, corresponding to more than 10^{17} dumped protons.

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1. Introduction

Several New Physics (NP) models ("portals") have been proposed as extensions of the Standard Model (SM). Among them the focus of this work is on the vector portal or dark photon (DP), defined by the introduction of a new vector field, $F'_{\mu\nu}$, symmetric under U(1) and feebly interacting with SM fields. In a minimal scenario the interaction can be reduced to the kinematic mixing with SM hypercharge $B^{\mu\nu}$ [1, 2]:

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

where $F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$, θ_W is the Weinberg angle and $\varepsilon \ll 1$. In this model both the DP mass, $M_{A'}$ and the coupling ε are free parameters. Such DP models have the following phenomenological features: the DP can be emitted after a proton-nucleus interaction through a "direct" A'-bremsstrahlung-like process or a meson-mediated tertiary production; for masses $M_{A'}$ below 700 MeV/c^2 the DP decay width is dominated by decays to lepton-antilepton final states.

In this work the search for A' production and decay into $\mu^+\mu^-$ pairs within the NA62 experiment is presented. The data analysed have been collected in 2021 in the so-called "beam-dump" mode and approximately 1.4×10^{17} dumped protons have been collected.

2. The NA62 beam line and detector

The NA62 experiment is located at CERN in the north area. It is a fixed target experiment using 400 GeV/c protons from the SPS and it is dedicated to the study of rare and forbidden K^+ decays. The NA62 experiment can also be operated in the so-called "beam-dump" mode. In this case the Beryllium target (called T10), used to produced the kaon beam in the standard running mode, is removed and the proton beam impinges on the movable collimators (TAX), located 23 m downstream of T10 and 80 m upstream of the NA62 detector. In addition the beam line is optimised to reduce the muons flux induced by charged pion decays within the TAX [3]. A schematic of the NA62 experiment is presented in Fig. 1 and a detailed description can be found in [4]. For the analysis described in this work the momenta and directions of charged particles are measured by a magnetic spectrometer (STRAW) composed of two pairs of straw tube chambers on either side of a dipole magnet, with a momentum resolution σ_P/P between 0.3% and 0.4%. Time measurements are provided by a ring-imaging Cherenkov detector (RICH) and two scintillator hodoscopes, CHOD and NA48-CHOD, with 600 and 200 ps resolution, respectively. Particle identification is based on information from the energy deposited by the tracks in the quasi-homogeneous liquid Kripto electromagnetic calorimeter (LKr) and in the hadronic calorimeters (MUV1,2) and from the presence of signals in the muon detector (MUV3), located downstream of a 80 cm thick iron absorber (Iron). A photon veto system includes the LKr, twelve ring-shaped lead-glass detectors (LAV) and two small angle calorimeters (IRC and SAC). The trigger system is composed of two levels: an hardware trigger level (L0), provided by fast detectors and a software trigger level (L1).

The data sample considered in this analysis was collected in 2021. Three trigger lines were implemented using only L0 conditions, because of the low particle rate: Q1/20, triggered by events with at least one signal in the CHOD and downscaled by a factor 20; H2, triggered by events with

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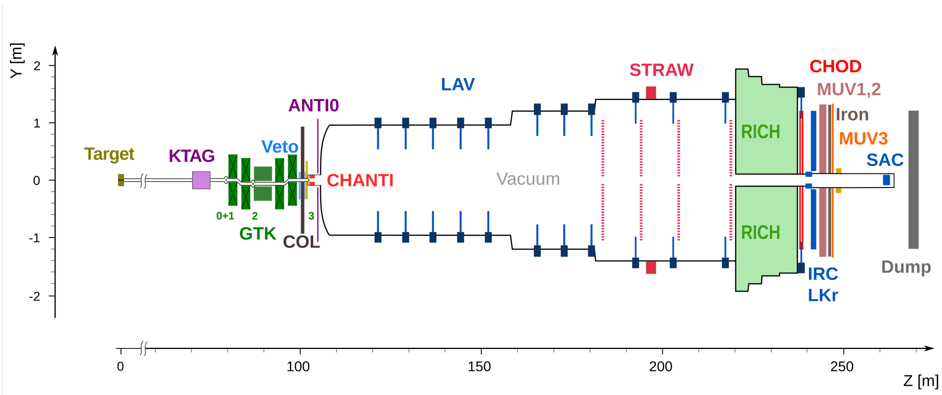

Figure 1: Schematic view on the Y-Z plane of the NA62 detector.

at least two in time signals in two different tiles of the CHOD and E1, selecting events with more than 1 GeV energy deposited in the LKr and one or more reconstructed LKr cluster.
As the proton beam is dumped on the TAX, its intensity can be set well above that for the standard NA62 data taking. During the 2021 run the average beam intensity was 66×10^{11} protons per spill of 4.8 seconds effective duration, approximately 1.5 times that of the nominal standard beam. The approximate rate for the Q1/20, H2 and E1 trigger lines are 14 kHz, 18 kHz and 4 kHz, respectively.

3. Analysis

After a proton interaction, a dark photon can be emitted via a bremsstrahlung process or after the decay of secondary mesons. Bremsstrahlung production is due to the scattering process $\gamma^* p \to A'p'$, where the virtual photon γ^* is exchanged between the incoming proton and a nucleus in the dump, as described in [5]. The meson-mediated production chain can be summarised as: $pN \to MX$, where $M = \pi^0, \eta^{(\prime)}, \rho, \omega, \Phi$, followed by $M \to M'A'$ with $M' = \gamma, \pi^0, \eta$, depending on the meson, M, emitted. The expected DP yield (N_{exp}) for each mass and coupling is computed using the NA62 Monte Carlo (MC) simulation from the following equation:

$$N_{\text{exp}} = \text{POT} \times \chi(pp \to A') \times \mathcal{B}(A' \to ll) \times P_{RD}(\varepsilon) \times A_{\text{acc}} \times A_{\text{trig}} \tag{2}$$

where POT is the total number of proton dumped on the TAX, $\chi(pp \to A')$ is the DP emission probability, $\mathcal{B}(A' \to ll)$ is the branching fraction for DP decays to two leptons, $P_{RD}(\varepsilon)$ is probability of the DP reaching the NA62 fiducial decay volume (FV) and decaying therein, and A_{acc} and A_{trig} are the selection and trigger efficiency, respectively.

Given the signal topology, events triggered by H2 are used for the search presented in this work. Signal-like events are filtered by selecting vertices formed between two tracks of opposite charge reconstructed within the NA62 FV. Particle identification (PID) conditions are applied, to isolate $\mu^+\mu^-$ final states, based on the LKr calorimeter and MUV3 information. To reduce the background from secondary interactions of muons with the material traversed, a veto condition on in time activity in all LAV stations is applied. A primary vertex of good quality must be reconstructed as a minimum distance of approach between the total momentum of the selected track pair and

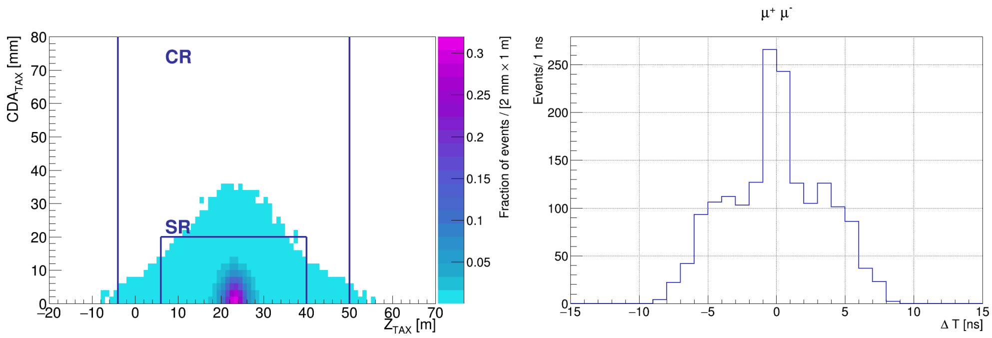

Figure 2: Left: Distance of closest approach (CDA_{TAX}) plotted against the longitudinal position of the primary vertex (Z_{TAX}) for MC signal events. Right: time difference between the two selected tracks before applying the LAV veto condition. The two background sources are well distinguished: the peak around zero is due to the prompt background, while the flat distribution is due to combinatorial background

the nominal direction of the proton beam. The primary vertex must be close to the beam impact point on the TAX. Both a signal region (SR) and a control region (CR) are defined in the plane between the longitudinal position of the primary vertex (Z_{TAX}) and the distance of closest approach (CDA_{TAX}) as shown in Fig. 2 (left). The analysis is blind to the SR and CR content until the final validation.

4. Background

Two sources of background have been identified: prompt background and combinatorial background (see Fig. 2 right). The first derives from secondary particles coming from muon interactions with the traversed material upstream of and within the FV and it is characterised by in time muons. The combinatorial background is due to random superposition of halo muons from interactions of uncorrelated protons and it is characterised by a flat distribution of the time difference between two muons. For these type of searches, to understand the background through a MC simulation alone would require a full simulation of 10^{17} POT and this is not a viable strategy, therefore a mixture of data-driven and MC methods is used. The prompt background has been derived using both data and MC simulation: single muon kinematic distributions have been extracted from data and used for the backward-forward MC simulation. To correct for the spread induced by the simulation, mostly due to multiple scattering, an unfolding technique is applied. From this study the prompt background is found to be negligible with respect to the combinatorial background.

The combinatorial background has been derived using a data-driven method: single muon events have been selected from a data sample orthogonal to the one used in the analysis and track pairs have been artificially built to emulate the random superposition of muons, requiring the same conditions as for the signal. A weight is applied to each track pair in order to take into account the 10 ns time window used to built vertices in the FV. The validation of the combinatorial background estimation has been performed using $\mu^+\mu^+$ and $\mu^-\mu^-$ control samples. The distribution of the CDA_{TAX} vs Z_{TAX} expected for $\mu^+\mu^-$ combinatorial events is shown in Fig. 3. Data events are superimposed as full black dots. Validation of the background for signal-like events is performed

Table 1: Summary of the expected di-muon events from combinatorial background ($N_{\rm exp}$), the related systematic error ($\delta N_{\rm exp}$), the observed events in data ($N_{\rm obs}$) and the probability to obtain a likelihood L for data-MC compatibility equal or worse than that corresponding to $N_{\rm obs}$ ($P_{\rm L \leq L_{obs}}$).

Mode	Region in $\mathrm{CDA_{TAX}}$ vs $Z_{\rm TAX}$	$N_{\rm exp} \pm \delta N_{\rm exp}$	$N_{\rm obs}$	$P_{\rm L \leq L_{obs}}$
$\mu^+\mu^-$	Outside CR	26.3 ± 3.4	28	0.74
	$\mathrm{CR_3}$	1.70 ± 0.22	2	0.68
	$\mathrm{CR_2}$	0.58 ± 0.07	1	0.44
	$\mathrm{CR_1}$	0.29 ± 0.04	1	0.25
	$\mathrm{CR_{1+2+3}}$	2.57 ± 0.33	4	0.34
$\mu^+\mu^-$	CR	0.17 ± 0.02	–	–
	SR	0.016 ± 0.002	–	–

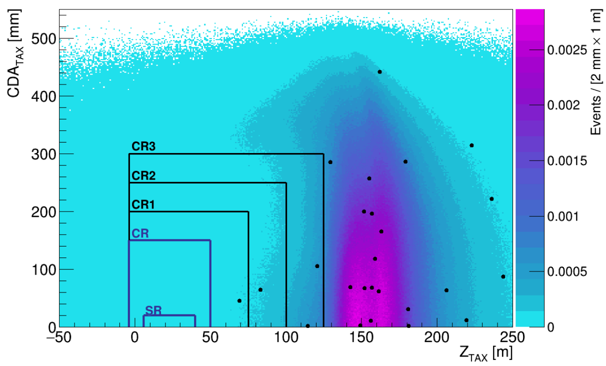

Figure 3: Expected combinatorial background (color-scale plot) and events from data (full black dots). Possible data within the control or signal regions (CR, SR) are masked. Additional control regions surrounding the CR are also shown by the black lines.

in three control regions closer and closer to the CR and labelled as CR3,CR2 and CR1. A summary of the expected and observed events is presented in Tab. 1 and shows a good agreement.

5. Result

The expected DP yield is evaluated using Eq. 2, where the number of POT is derived from the measurement of the beam flux, registered for each spill. The POT measurement takes into account the real duration of each spill and has a 20% uncertainty. The selection and trigger efficiencies are determined by MC as a function of the DP mass, $M_{A'}$ and coupling ε, for each production process and the corresponding total relative uncertainty is below 3%. The expected DP yield is computed as a function of $M_{A'}$ and ε and the bremsstrahlung process is expected to dominate over the meson-mediated production for most of the parameter space. The expected total number of background events in the SR is 0.016 ± 0.002. Under the hypothesis of no signal, no observed data events are expected in the SR at 90% CL coverage. After opening the SR, one event has been observed corresponding to a muon pair invariant mass of 411 MeV/c^2. The event found might

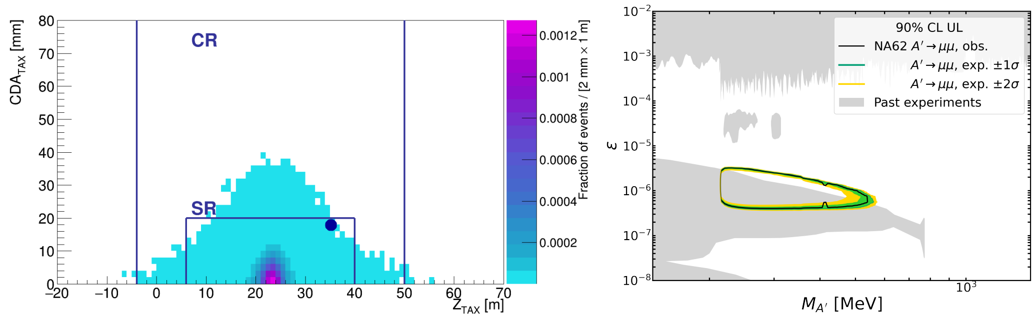

Figure 4: Left: distance of closest approach between the beam direction at the TAX entrance and the total momentum of the two tracks (CDA_{TAX}) vs the longitudinal position of the minimum approach (Z_{TAX}). Data (dots) vs expected fraction of signal MC events (colour density) . Right: the region of the parameter space within the solid line is excluded at 90% CL. The colour filled area represents the expected uncertainty on the exclusion contour in absence of a signal: green (yellow) corresponds to a statistical coverage of 68% (95%).

be due to combinatorial background, since the track time difference is away from zero and the extrapolation to the TAX impact point is barely within the SR as shown in the left panel of Fig. 4. The corresponding observed 90% CL upper limit is represented by the region enclosed within the black contour in the right panel of Fig. 4. As a counting experiment, the event found corresponds to a $2.4 - \sigma$ global significance.

6. Conclusion

The first search for production and decay of dark photons at the NA62 experiment, using the beam-dump running mode has been presented. A counting experiment cut-based blind analysis has been performed, focusing on $\mu^+\mu^-$ final states. The sample analysed corresponded to 1.4×10^{17} POT. No evidence for a DP signal has been observed. A new region of the parameter space of DP coupling and mass has been explored and excluded at 90% CL. Other searches for dark photon, axion-like particles, using the data sample collected in 2021 are ongoing and new results are expected.

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