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

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The NA62 experiment at CERN took data in 2016–2018 with the main goal of measuring the $K^+ \to \pi^+ \nu\bar{\nu}$ decay. In this talk we report on the search for visible decays of exotic mediators from data taken in "beam-dump" mode with the NA62 experiment. NA62 can be run as a "beam-dump" experiment by removing the kaon production target and moving the upstream collimators into a "closed" position. In this configuration 400 GeV protons are dumped on an absorber and New Physics (NP) particles, including dark photons, dark scalars and axion-like particles, may be produced and reach a decay volume beginning 80 m downstream of the absorber. More than 10^{17} protons on target have been collected in "beam-dump" mode by NA62 in 2021. Recent results from analysis of this data, with a particular emphasis on Dark Photon and Axion-like particle Models, are presented. We also report new results on the first NA62 search for long-lived NP particles decaying in flight to hadronic final states based on a blind analysis of a sample of 1.4×10^{17} protons on dump collected in 2021.

31st International Workshop on Deep Inelastic Scattering (DIS2024)
8–12 April 2024
Grenoble, France

*Speaker

PoS(DIS2024)132

1. Introduction

Fixed-target experiments offer a complementary approach to collider experiments in the search for new physics (NP) particles. While most collider experiments are designed to explore mass scales around $O(1\text{TeV})$, fixed-target experiments focus on much lower energies, allowing them to probe particle masses m_X up to a few GeV. These experiments benefit from high-intensity beams and operate in low-background environments, making them sensitive to very small couplings C_X between NP particles X and the Standard Model (SM). The ability to probe small mass and coupling parameter space is especially relevant for models involving hypothetical mediators between dark matter (DM) and SM particles, often referred to as Dark Sector portals. These mediators facilitate interactions between the SM and DM sectors and may help explain various observations that remain unexplained by the SM.

Table 1 summarises the most common portals [1], along with the SM final states that can be searched for in NP particle decays at fixed-target experiments. The list includes ALPs that can couple to the SM fermions and gauge bosons proportionally to C_{ff} and C_{VV}, dark photons (DP) characterised by a mixing parameter ε with the photon, dark scalars (DS) characterised by a mixing parameter $\theta \simeq \mu v/(m_h^2 - m_S^2)$ with the SM h-boson and heavy neutral leptons model (HNL) characterised by a mixing parameter with the SM neutrinos.

Table 1: Summary of new physics particle types, portals and decay channels relevant for fixed-target experiments. Highlighted are the hadronic final states studied in this work.

NP Particle	type	portal (dim ≤ 5)	decay channels	
ALP (a)	pseudoscalar	$(C_{VV}/\Lambda)aV_{\mu\nu}\tilde{V}^{\mu\nu}$ $(C_{ff}/\Lambda)\partial_\mu a\bar{f}\gamma^\mu\gamma^5 f$	$\gamma\gamma$, $\ell\ell$	$\boldsymbol{2\pi\gamma, 3\pi, 4\pi, 2\pi\eta, 2K\pi}$
DP (A'_μ)	vector	$-(\varepsilon/2\cos\theta_W)F'_{\mu\nu}B^{\mu\nu}$	$\ell\ell$	$\boldsymbol{2\pi, 3\pi, 4\pi, 2K, 2K\pi}$
DS (S)	scalar	$(\mu S + \lambda S^2)H^\dagger H$	$\ell\ell$	$\boldsymbol{2\pi, 4\pi, 2K}$
HNL (N_I)	fermion	$F_{\alpha I}(\bar{L}_\alpha H)N_I$	$\pi\ell$,$K\ell$,$\ell_1\ell_2\nu$	

The high-intensity proton beam, extracted from the CERN SPS, and the detector setup, makes NA62 a perfect place to search for the NP signatures outlined in Table 1. For these searches, NA62 has to be operated in beam-dump mode, where protons are directed onto an absorber 80 metres upstream of the decay volume. In 2021, approximately 1.4×10^{17} protons were dumped onto the movable collimators (TAX) over ten days, providing a substantial dataset to search for beyond the SM signatures.

2. The NA62 beamline and detector

The NA62 experiment is a fixed-target experiment located in the north area of the CERN SPS. NA62 uses 400 GeV/c protons delivered by the SPS to study rare and forbidden K^+ decays. During beam-dump operation, the T10 target, typically employed to generate the standard secondary hadron beam, is removed from the beam line. The proton beam is then directed onto the TAX positioned 23 metres downstream of T10 between two pairs of dipole magnets. In contrast with the kaon mode of data-taking, in the beam-dump configuration, the currents of the second pair of dipoles are adjusted to generate magnetic fields in the same direction.

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The detailed description of the NA62 beamline and detector setup can be found in [2]. Only the detectors relevant to these analyses are described here. The magnetic spectrometer (STRAW) comprises straw chambers and a dipole magnet. It is employed for precise momentum measurement with a resolution $\sigma p/p$ between 0.3% and 0.4%. The CHOD and NA48-CHOD, made of SiPM-readout tiles and scintillating slabs, respectively, serve for triggering and timing with resolutions of 600 ps and 200 ps. Particle identification is performed using information provided by the quasi-homogeneous liquid krypton electromagnetic calorimeter (LKr), hadronic calorimeters (MUV1,2) and muon detector (MUV3) located downstream of an 80 cm thick iron absorber (Iron). A photon veto system consists of the LKr, twelve ring-shaped lead-glass detectors (LAV) and small angle calorimeters (IRC and SAC). The energy, E, resolution (in GeV) provided by the LKr is $\sigma_E/E = (4.8/\sqrt{E} \oplus 11/E \oplus 0.9)\%$. The spatial and temporal resolutions are 1 mm and between 0.5 and 1 ns, depending on the quantity and type of energy released. Signals from an additional hodoscope (ANTI0) are used to mitigate the effect of activity before the fiducial volume.

The data sample used in this work was collected in 2021 with the experiment in beam-dump mode. Three trigger lines were employed during operation, two of which are used to identify charged particles: Q1, triggered by events with at least one signal in the CHOD and downscaled by 20 and H2, triggered by events with two in-time signals in different tiles of the CHOD.

3. Search for hadronic final states

A model-independent estimation of the expected number of NP particles X is derived using the NA62 Monte Carlo simulation. Various production channels are simulated, including B-meson-mediated decays for DSs and ALPs, meson mixing and Primakoff production for ALPs, and light-meson-mediated decays as well as proton Bremsstrahlung for DPs. For each production i and decay channel j the expected number of NP particles X is computed as a function of the particle mass m_X and lifetime τ_X as

$$\begin{aligned} N_{\text{exp}}(m_X, \tau_X, i, j) =& N_{\text{POT}} \times \chi_{pp\to X}(C_X, i) \times P_{\text{RD}}(m_X, \tau_X, i) \\ & \times A_{\text{acc}}(m_X, \tau_X, i, j) \times A_{\text{trig}}(m_X, \tau_X, i, j) \ , \end{aligned} \tag{1}$$

where N_{POT} is the number of protons on target, $\chi_{pp\to X}$ is the production probability for the reference value of coupling C_X, P_{RD} is the probability for the NP particle to reach the fiducial volume and decay therein, $A_{\text{acc}} \times A_{\text{trig}}$ are the signal selection and trigger efficiencies. P_{RD} and $A_{\text{acc}} \times A_{\text{trig}}$ depend on the X mass, lifetime and the kinematic variables specific to the given production and decay channel. The decay channels j are highlighted in Table 1 for each NP particle, amounting to 36 combinations of production i and decay channels j simulated.

The analysis uses events triggered by the H2 condition. Exactly one vertex, formed by two opposite-charge STRAW tracks, is requested in the decay volume. LAV,SAV and ANTI0 are used as a veto to suppress backgrounds and to avoid signal event mis-reconstruction. Particle identification (PID) is based on a BDT employing information from LKr and MUV1,2,3, which is used to select hadrons. Additionally, if a positively charged hadron is identified by the RICH as a K^+, the event is classified as K^+K^--like. Otherwise, it is assumed to be $\pi^+\pi^-$-like.

Additional neutral final states are reconstructed using the LKr by identifying clusters that are in time with the event and not associated with the charged tracks. The invariant mass of two in-time

Table 2: Number of expected events N_{exp} at 68% CL in CR and SR after full selection and minimum number of observed events N_{obs} for p-value larger than 5σ in the background-only hypothesis in the SR and SR+CR.

Channel	$N_{\text{exp,CR}} \pm \delta N_{\text{exp,CR}}$	$N_{\text{exp,SR}} \pm \delta N_{\text{exp,SR}}$	$N^{p>5\sigma}_{\text{obs,SR}}$	$N^{p>5\sigma}_{\text{obs,SR+CR}}$
$\pi^+\pi^-$	0.013 ± 0.007	0.007 ± 0.005	3	4
$\pi^+\pi^-\gamma$	0.031 ± 0.016	0.007 ± 0.004	3	5
$\pi^+\pi^-\pi^0$	$(1.3^{+4.4}_{-1.0}) \times 10^{-7}$	$(1.2^{+4.3}_{-1.0}) \times 10^{-7}$	1	1
$\pi^+\pi^-\pi^0\pi^0$	$(1.6^{+7.6}_{-1.4}) \times 10^{-8}$	$(1.6^{+7.4}_{-1.4}) \times 10^{-8}$	1	1
$\pi^+\pi^-\eta$	$(7.3^{+27.0}_{-6.1}) \times 10^{-8}$	$(7.0^{+26.2}_{-5.8}) \times 10^{-8}$	1	1
K^+K^-	$(4.7^{+15.7}_{-3.9}) \times 10^{-7}$	$(4.6^{+15.2}_{-3.8}) \times 10^{-7}$	1	2
$K^+K^-\pi^0$	$(1.6^{+3.2}_{-1.2}) \times 10^{-9}$	$(1.5^{+3.1}_{-1.2}) \times 10^{-9}$	1	1

photon candidates selects events with additional π^0, η or $2\pi^0$, which allows the reconstruction of all possible decays from Table 1. The reconstructed momentum of the NP candidate allows the reconstruction of the primary vertex location based on the minimum distance between the primary beam and extrapolated NP particle trajectories. The signal region (SR) is defined as the area inside the ellipse centred at the TAX impact point and semi-axes 23 m and 40 mm respectively, while the control region (CR) is a box outside of the SR with $-7\,\text{m} < z < 53\,\text{m}$ and a distance smaller than 400 mm. The contents of CR and SR are kept masked in the data sample until the backgrounds are validated.

4. Background determination

In this analysis, four main background components have been identified: neutrino-induced, combinatorial, prompt, and upstream background. A biased MC simulation of the neutrino-induced background indicates that the contribution of this background is negligible. The combinatorial background originating from uncorrelated pairs of upstream particles was evaluated using single upstream tracks selected from the data. This component is found to be lower by two orders of magnitude than the already small background to the analysis with e^+e^- final states [3]. The prompt background arising from muons traversing detector material upstream of the NA62 fiducial volume has been evaluated using a data-driven backwards MC [4]. K^+ and K_S passing through the centre of ANTI0, missing the ANTI0 veto and decaying in the fiducial volume are found to be the main source for the upstream background. The K^+ component has been simulated using kaons selected in the events triggered by the Q1 trigger line. A 3σ window around the K_S mass is kept masked until the full simulation of this last component is available. A summary of the number of expected background events in the CR and SR N_{exp} for each decay channel and the numbers of events that have to be observed N_{obs} to surpass the 5σ global significance is shown in Table 2.

5. Results

After unmasking all CRs and SRs, no events have been observed. The model-independent interpretation of the result has been performed with the help of a public tool ALPINIST [5], calculating $N_{\text{exp}}(m_X, C_X)$ by combining the individual $N_{\text{exp}}(m_X, \tau_X, i, j)$, varying the NP particle lifetimes, branching ratios and production probabilities for all the channels as a function of the respective

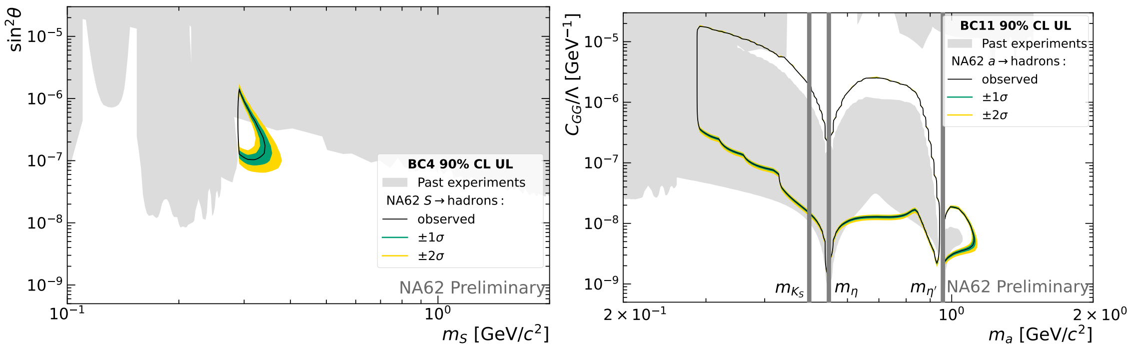

Figure 1: The observed 90% CL exclusion contours in DS (left) and gluon-couple ALP (right) benchmarks together with the expected $\pm 1\sigma$ and $\pm 2\sigma$ bands corresponding to the total experimental uncertainty coming from the trigger and signal selection efficiencies and statistics.

couplings C_X and masses m_X. A standalone observed exclusion contour from $X \to$ hadrons decays, shown in Figure 1, is obtained for DSs and gluon-coupled ALPs. A statistical combination with the $X \to \ell\ell$ results is in progress, potentially excluding new regions in the DP parameter space.

6. Conclusions

This work outlines the search for the decays of New Physics particles into $\pi^+\pi^-$, $\pi^+\pi^-\gamma$, $\pi^+\pi^-\pi^0$, $\pi^+\pi^-\pi^0\pi^0$, $\pi^+\pi^-\eta$, K^+K^- and $K^+K^-\pi^0$ final states at the NA62 experiment, using data collected in beam-dump mode. A counting experiment through a cut-based blind analysis of data equivalent to 1.4×10^{17} protons on target was performed. As a result of this search, no evidence of a New Physics signal was observed. New regions of dark scalar and axion-like particle parameter spaces have been excluded, improving on previous experimental searches. The work on the full statistical combination of this result with the result of the di-lepton searches is ongoing.

The NA62 experiment continues to operate until the CERN long shutdown 3, and it expects to collect a sample of 10^{18} protons on target. This sample will allow improvement of the current results and probing of other New Physics scenarios, such as HNLs and ALPs.

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