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First NA62 search for long-lived new physics particle hadronic decays

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Abstract. The NA62 experiment at CERN, designed to measure the highly-suppressed decay $K^+ \to \pi^+ \nu\bar{\nu}$, has the capability to collect data in a beam-dump mode, where 400 GeV protons are dumped on an absorber. In this configuration, new physics (NP) particles, including dark photons, dark scalars and axion-like particles, may be produced and reach a decay volume starting 80 m downstream of the absorber. A search for NP particles decaying in flight to hadronic final states is reported, based on a blind analysis of a sample of 1.4×10^{17} protons on target collected in dump mode in 2021.

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1. Search for new physics with fixed target experiments

Fixed-target experiments offer a complementary approach to collider experiments in the search for new physics (NP) particles. While collider experiments are typically designed to explore mass scales around $\mathcal{O}(1)$ TeV, fixed-target setups operate at high intensity in a low-background environment, allowing them to probe NP particles with masses m_X up to a few tens of GeV/c^2, weakly coupled with the Standard Model (SM) particles. This capability to explore regions of small masses and weak couplings is especially relevant for models involving hypothetical mediators between dark matter (DM) and SM particles, collectively referred to as Dark Sector portals. Such mediators enable interactions between the SM and DM sectors and could help explain several phenomena that remain unexplained within the SM framework.

The most common portals [1], along with the SM final states that can be investigated in NP particle decays at fixed-target experiments, are summarised in Table 1. In this work the following models (BCs) are considered:

- $BC1$: a new $U(1)$ symmetry gauge boson A', called dark photon (DP), interacts through a kinetic mixing with the photon, ε is the mixing parameter characterizing the interaction strength;
- $BC4-5$: a new dark scalar S (DS), mix with the SM Higgs boson through an angle $\theta \simeq \mu v/(m_h^2 - m_S^2)$;
- $BC9-11$: an axion-like particle a (ALP), can couple to SM fermions and gauge bosons proportionally to C_{ff} and C_{VV}, respectively.

Model	**SM portal**	**PBC**	**Decay modes**
HNL (N_I)	$F_{\alpha I}(\bar{L}_\alpha H)N_I$	BC6–8	$\pi\ell$, $K\ell$, $\ell_1\ell_2\nu$
Dark Photon (A')	$-(\varepsilon/2\cos\theta_W)F'_{\mu\nu}B^{\mu\nu}$	BC1–2	$\ell^+\ell^-$, 2π, 3π, 4π, $2K$, $2K\pi$
Dark scalar (S)	$(\mu S + \lambda S^2)H^\dagger H$	BC4–5	$\ell^+\ell^-$, 2π, 4π, $2K$
Axion/ALP (a)	$(C_{ff}/\Lambda)\partial_\mu a\, \bar{f}\gamma^\mu\gamma^5 f$	BC10	$\ell^+\ell^-$, $2\pi\gamma$, 3π, 4π, $2\pi\eta$, $2K\pi$
	$(C_{VV}/\Lambda)g_a V_{\mu\nu}\tilde{V}^{\mu\nu}$	BC9,11	$\gamma\gamma$

Table 1: Summary of BSM portals, PBC benchmark cases and decay modes.

2. The NA62 experiment at CERN SPS

NA62 is a multi-purpose fixed-target experiment at the CERN SPS designed to measure the $K^+ \to \pi^+\nu\bar{\nu}$ branching fraction [2, 3]. The layout of the NA62 beamline and detector is described in [4]. The versatility of the experimental setup, combined with the multiple trigger chains available [5], allows NA62 to study a variety of K^+ meson decays [6–12].

The NA62 setup is also suitable for searching for production of New Physics (NP) particles in the target area and their decay in the detector into observable final states. For this purpose, NA62 operates in beam-dump mode. The proton beam is then directed onto a set of movable copper-iron

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collimators (TAX), positioned 23 meters downstream of T10 SPS target, between two pairs of dipole magnets, as shown in Fig. 1-right. Approximately 1.4×10^{17} protons have been collected in 10 days of data taking in beam-dump mode in 2021. The analysis of 2021 data also led to the first searches for feebly interacting particles decaying into hadronic final states. Two trigger lines 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.

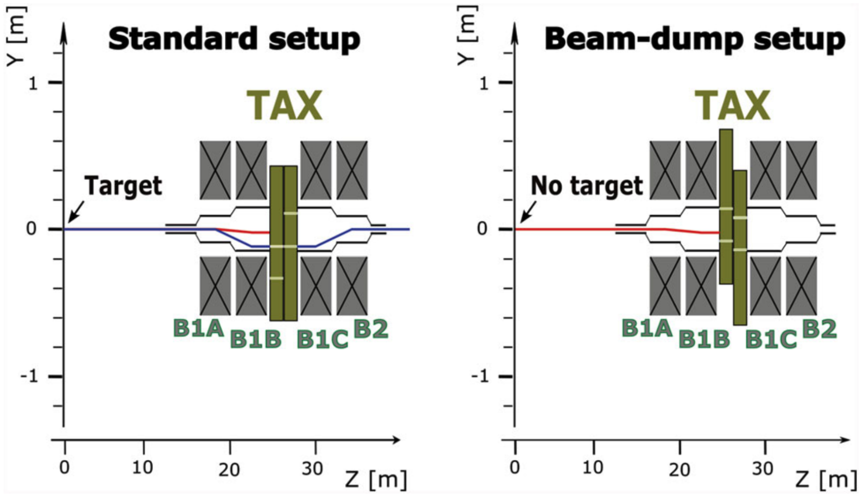

Figure 1: Schematic side view of the NA62 achromat area in the standard (left) and beam-dump (right) setups. The trajectory of a 75 GeV/c positively charged particle is drawn in blue while the trajectory of a 400 GeV/c proton is drawn in red

3. Search for long-lived new physics particle hadronic decays

From the NA62 Monte Carlo simulation a model-independent estimate of the expected number of NP particles X can be obtained. Several production mechanisms are evaluated, 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 process i and decay channel j, the number of expected signal events is evaluated as a function of the particle mass m_X and lifetime τ_X as

$$\begin{aligned} N_{\text{exp}}(m_X, \tau_X, i, j) = N_{\text{POT}} \times \chi^i_{pp \to X}(m_X) \times P^i_{\text{RD}}(m_X, \tau_X) \\ \times A^{ij}_{\text{acc}}(m_X, \tau_X), \end{aligned} \tag{1}$$

where N_{POT} is the number of protons on target, $\chi^j_{pp \to X}$ is the probability of NP particle production, P_{RD} is the probability for the NP particle to reach the fiducial volume and decay therein, and A^{ij}_{acc} is the signal selection acceptance. The decay channels j are listed in Table 1 for each NP particle, amounting to 36 combinations of production i and decay channels j simulated.

The signal selection is applied to events triggered by the H2 trigger line. Exactly one vertex, formed by two good quality opposite-charged STRAW tracks, is required inside the fiducial volume

(FV). No in-time signals are allowed both in the LAV, SAV, or ANTI0 detectors in order to suppress backgrounds and avoid signal event mis-reconstruction. Particle identification (PID) is based on a boosted decision tree (BDT) using information from the LKr and MUV1,2,3 detectors. Additionally, the information from the RICH is used to identify K^+ and classify the event as K^+K^--like; otherwise, it is assumed to be $\pi^+\pi^-$-like. Neutral decay products are reconstructed using the LKr by identifying clusters that are in time with the event and not associated with charged tracks. The invariant mass of two in-time photon candidates selects events with additional π^0, η or $2\pi^0$, allowing the reconstruction of all possible decays from Table 1.

The three-momentum of the NP particle candidate is obtained as sum of the three-momenta of the reconstructed decay products and used to extrapolate the primary vertex location based on the minimum distance between the primary beam and extrapolated NP particle trajectories. The signal region (SR) is the area inside an ellipse centered at the TAX impact point with semi-axes of 23 m and 40 mm, while the control region (CR) is a rectangle surrounding the SR with $-7\,\mathrm{m} < z < 53\,\mathrm{m}$ and a closest distance of approach between the NP particle trajectory and the beam axis lower than 150 mm. The CR and SR are kept masked in the data sample until the backgrounds are validated.

4. Background determination

Four types of background components have been identified: neutrino-induced, combinatorial, prompt, and upstream backgrounds. A biased MC simulation of the neutrino-induced background indicates that this contribution is negligible. The combinatorial background, originating from the pairing of beam induced upstream particles, was evaluated using single tracks collected by the Q1 trigger. This component is found to be lower by two orders of magnitude than the already small background in the analysis with e^+e^- final states [13]. The prompt background, arising from muons traversing detector material upstream of the NA62 fiducial volume, has been evaluated using Muons are propagating muons backwards accounting for the expected energy loss and bending induced by magnetic fields [14]. K^+ and K_S passing through the center of ANTI0, missing the veto, and decaying in the fiducial volume constitutes the dominant source of upstream background. The K^+ component has been simulated using kaons selected in events triggered by the Q1 trigger line. A 3σ window around the K_S mass is kept masked until the full simulation of this 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 number of events N_{obs} required to claim for a p-value larger than 5σ under the background-only hypothesis is shown in Table 2.

5. Results

After unmasking all CRs and SRs, no events have been observed [15]. The public tool `Alpinist` [16] is used for the model-independent interpretation of the result, calculating $N_{\mathrm{exp}}(m_X, C_X)$ by combining the individual values of $N^{ij}_{\mathrm{exp}}(m_X, \tau_X)$.

The axion-like particle exclusion contours in the plane $(m_a, C_a/\Lambda)$, shown in Fig. 2, are evaluated assuming a UV scale $\Lambda = 1$ TeV. The results for BC1 (dark photon) and BC4 (dark scalar) are shown in Figs. 3 and 4, respectively.

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

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

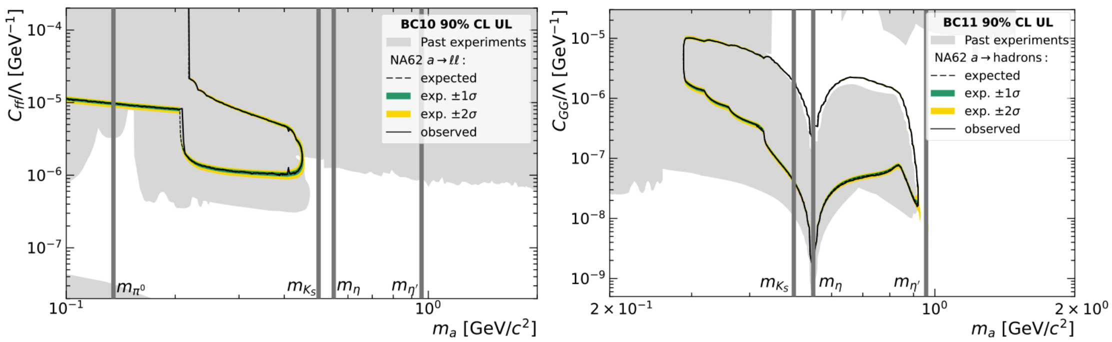

Figure 2: The observed 90% CL exclusion contours in the plane $(m_a, C_a/\Lambda)$ in the fermion-coupled axion-like particle $BC10$ (left) and gluon-coupled axion-like particle $BC11$ (right) benchmark cases, evaluated assuming $\Lambda = 1$ TeV. Expected $\pm 1\sigma$ and $\pm 2\sigma$ bands correspond to the uncertainty in the number of protons on TAX (theory uncertainty not included)

6. Conclusions

A search for new physics particles decaying 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 has been conducted with the NA62 experiment 2021 beam-dump data sample, corresponding to a statistic of $N_{POT} = 1.4 \times 10^{17}$.

The combination of this result with the previous search for NP particles decaying into di-lepton final states shows no evidence of a new physics signal. New regions of dark photon, dark scalar and axion-like particle parameter spaces have been excluded, improving on previous experimental searches.

The NA62 experiment continues to operate until the CERN Long Shutdown 3, and a sample of 10^{18} protons on target in beam-dump mode is ready to be analyzed. This dataset will help to improve the sensitivity and extend the exploration to other new physics scenarios, such as heavy neutral leptons (HNLs) and ALPs with di-photon final states.

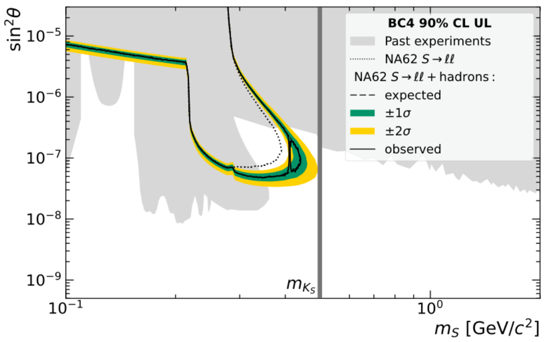

Figure 3: The observed 90% CL exclusion contours in the plane $(m_S, \sin^2\theta)$ in dark scalar $BC4$ benchmark case combining hadronic and di-lepton channels compared to the NA62 di-lepton result. Expected $\pm 1\sigma$ and $\pm 2\sigma$ bands correspond to the uncertainty in the number of protons on TAX (theory uncertainty not included).

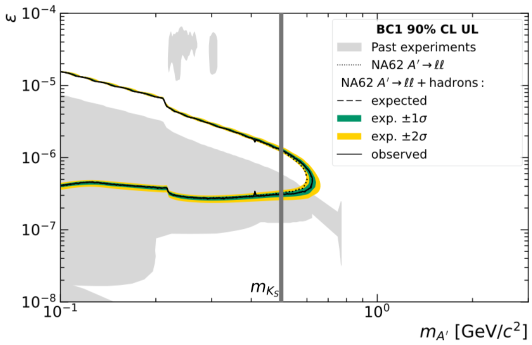

Figure 4: Observed 90% CL exclusion contours in the plane (m_A, ϵ) in dark photon BC1 benchmark case combining hadronic and di-lepton channels compared to the updated NA62 di-lepton result. Left: result using bremsstrahlung production without the time-like form factor.

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