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Recent results on dark sector searches at NA62

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Rare kaon decays are among the most sensitive probes of both heavy and light New Physics (NP) beyond the Standard Model (SM) thanks to the high precision of the SM predictions, to the availability of very large datasets and to the relatively simple decay topologies. The NA62 experiment at CERN SPS is a multi-purpose high-intensity kaon decay experiment, that carries out a broad rare-decay and hidden-sector physics program and has collected a large sample of K^+ decays during Run1 (2016-2017-2018) and the ongoing Run2 (started in 2021). Recent NA62 results on searches in Run1 data for hidden-sector mediators in kaon decays are here presented. NA62 can also 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/c protons from the SPS are dumped on an absorber. NP states feebly interacting with SM particles may be produced in the dump and reach the fiducial decay volume of the NA62 detector, that begins 80 m downstream of the absorber. More than 10^{17} protons on target have been collected in beam-dump mode in 2021. The results from the analysis of beam-dump data are also reported, with particular emphasis on dark photon and axion-like particle models.

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1. Introduction

NA62 is an high-intensity fixed target experiment at CERN SPS, aiming to measure the branching ratio (BR) of the ultra-rare $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay [1][2]. The large datasets collected during Run1 (2016-2017-2018) and the ongoing Run2 (restarted in 2021) allow NA62 for a broad physics program, both in flavor physics and in hidden sector searches, providing precise tests of the Standard Model (SM), as recentely published in [3] and [4], or searching for New Physics (NP). In the following, the focus will be on direct searches for new dark states.

Fixed target experiments such as NA62 usually operate at smaller center of mass energies with respect to collider experiments, for example. However, thanks to the availability of high intensity beams, they can collect larger statistics, that provides them with the leading sensitivities in searches for light NP states with feeble couplings to the SM particles. Feebly interacting particles (FIPs) arise in models with new hypothetical portal interactions between Dark Matter (DM) and ordinary matter, sometimes also providing an explanation to observations not accounted for in the SM. NA62 can directly search for FIPs with mass in the MeV/c^2-GeV/c^2 range via their production in K^+ decays or in a dedicated beam-dump program. NP particles could be produced in K^+ decays together with SM particles and could be reconstructed from the knowledge of the SM initial and final states, even if they don't decay to SM or if they escape detection. In dump-mode, NP physics states too heavy to be produced in kaon decays may arise in the interaction of the primary protons extracted from the SPS with the material of a dump and could be enough long-lived and feebly interacting to get indisturbed to the fiducial decay volume of the detector, starting $\sim$ 80 m downstream of the dump. They could be then detected by their decays to SM particles by the reconstruction of the final state.

NA62 dark sector searches in K^+ decays to the $\pi^+ e^+ e^- e^+ e^-$ final state will be detailed, together with the NA62 searches for $X \rightarrow l^+ l^-$ in beam-dump mode.

2. The NA62 experiment

The NA62 detector [5] was designed and optimized for the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ study. A 400 GeV/c proton beam extracted from the CERN SPS impinges on a beryllium target, producing a secondary hadron beam selected with 75 GeV/c momentum, the 6% of which are K^+. Beam kaons are identified by a Cherenkov differential counter (KTAG) [6] and their momenta are measured by a silicon pixel beam spectrometer (GTK), then they enter a 117 m long vacuum vessel. The K^+ decays that are reconstructed occur in the first 75 m of the vessel, that are usually referred to as fiducial volume (FV) of the detector. The momenta of the kaon decay products are measured by using the STRAW spectrometer, consisting of four straw stations and a 0.9 Tm magnet. The decay products are identified by a ring-imaging Cherenkov detector (RICH) [7], a liquid-kripton electromagnetic calorimeter (LKr) and two hadronic calorimeters. Muon identification is provided also by a scintillating-tile muon detector (MUV3), located behind an 80 cm thick iron wall. The Large Angle Veto (LAV) system, formed by twelve ring-shaped stations of lead-glass crystals, provides veto for photons emitted at large angles. In 2021 a new plane of scintillator tiles, the ANTI0, was intalled upstream of the FV to veto muons from the beam halo.

Figure 1 reports the two possible NA62 data-taking setups. In standard mode, the secondary beam is selected by using movable copper-iron collimators (TAX), located about 23 m from the beryllium target, as shown in the left hand side. To operate the experiment in beam-dump mode, the target is removed from the beam line and the TAX collimators are closed, effectively dumping the proton beam, as depicted on the right. Only neutrinos, muons and hypothetical NP particles that are produced in the interaction of the beam with the material of the TAX or in secondary particle decays can penetrate the collimators and get to the FV. Also, as one of the dominant backgrounds in the analyses of beam-dump data comes from the flux of halo muons, the currents of a set of dipole magnets used for the modulation of the secondary beam in the standard mode are set to produce magnetic fields in the same direction in beam-dump mode, to sweep the halo muons out from the FV acceptance. Thanks to the low particle rate, in beam-dump mode data can be collected at a beam intensity a factor ~1.5 higher than in the standard mode: $N_{POT} = (1.4 \pm 0.28) \times 10^{17}$ protons on target (POT) were collected in ~ 10 days of data taking in 2021.

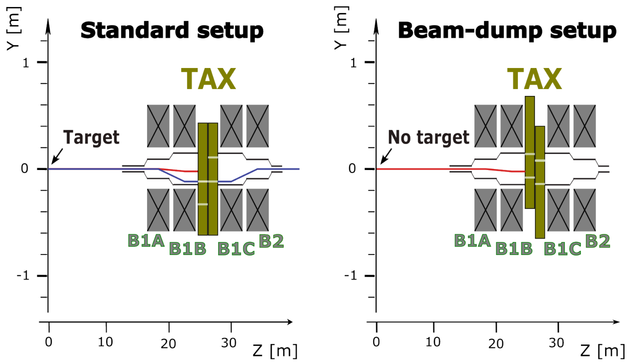


Figure 1: Configurations of the NA62 TAX achromat. Left: in the standard setup, used during kaon runs, the proton beam extracted from the SPS (red trajectory) impinges on a beryllium target; the interaction products are selected with positive charge and 75 GeV/c momentum (blue trajectory). Right: in beam-dump setup the target is removed and the movable collimators are misalligned; the proton beam is therefore dumped on 800 mm of copper followed by 2400 mm of iron (19.6 nuclear interaction lengths total).

3. Dark sector searches in K^+ decays to the $\pi^+e^+e^-e^+e^-$ final state

Kaon decays to final states with multiple charged leptons could provide hints of light NP, possibly probing regions of the yet unexcluded parameter space for different dark sector models, but have never been addressed to by experimentalists so far. NA62 searched for the first time for K^+ decays to the $\pi^+e^+e^-e^+e^-$ final state, aiming to probe two different scenarios: the existence of a short-lived QCD axion (a) with mass in the MeV/c^2 scale and decaying into an e^+e^- pair in the $K^+ \to \pi^+aa, a \to e^+e^-$ process; the existence of a dark scalar (S) promptly decaying into a pair of dark photons (A') through the cascade process $K^+ \to \pi^+S, S \to A'A', A' \to e^+e^-$. Moreover, as $BR(K^+ \to \pi^+aa) > 2 \times 10^{-8}$ [8] can be predicted for an axion mass of 17 MeV/c^2, the search for the $K^+ \to \pi^+aa, a \to e^+e^-$ process also offers the possibity for a conclusive test of the QCD axion explanantion of the "17 MeV" anomaly observed in the mass spectra of the e^+e^- pairs produced in the nuclear de-exitation of ^{8}Be.

NA62 searched for K^+ decays to the $\pi^+e^+e^-e^+e^-$ final state [9] in the Run1 data collected by the multi-electron trigger line [10], corresponding to an effective number of K^+ decays in the

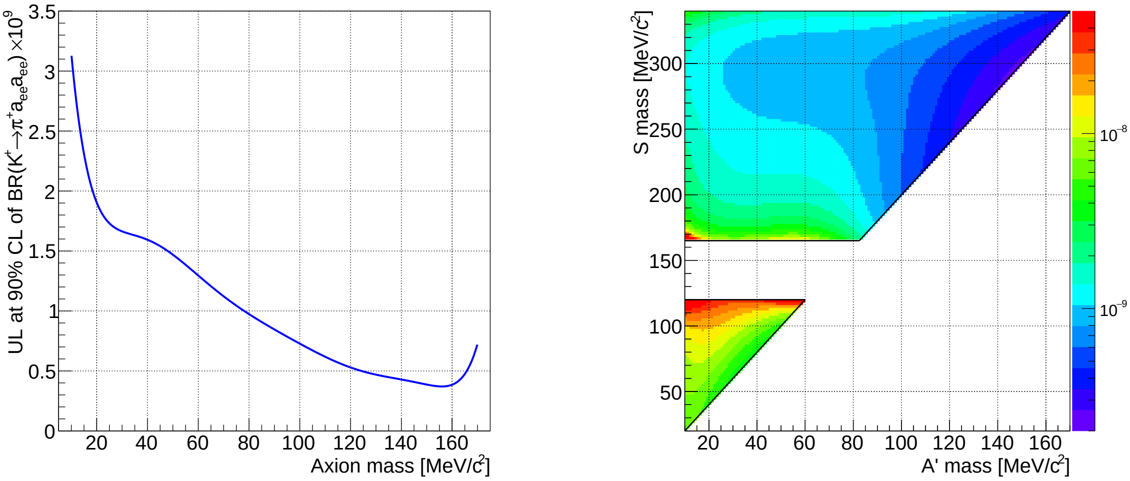


Figure 2: NA62 upper limits at 90% CL of the branching ratio of the prompt decay chain $K^+ \to \pi^+ aa, a \to e^+e^-$ as a function of the axion mass (left) and of the prompt cascade $K^+ \to \pi^+ S, S \to A'A', A' \to e^+e^-$ as a function of the dark-photon and dark-scalar masses (right) form the analysis of the Run1 data.

FV of $N_K = (8.58 \pm 0.19_{stat} \pm 0.07_{MC} \pm 0.41_{ext}) \times 10^{11}$, as obtained from a normalization procedure to the SM $K^+ \to \pi^+\pi^0, \pi^0 \to e^+e^-e^+e^-$ decay ($K_{2\pi DD}$), with $\pi^0 \to e^+e^-e^+e^-$ double Dalitz decay of the neutral pion. The invariant mass $m_{\pi 4e} = \sqrt{(P_{\pi^+} + P_{e_1^-} + P_{e_2^+} + P_{e_3^-} + P_{e_4^+})^2}$ is used as main discriminating variable to distinguish signal and backgrounds. A signal region (SR) $484 < m_{\pi 4e} < 504$ MeV/c^2 is defined in the $m_{\pi 4e}$ distribution, surrounding the K^+ mass value, and is kept masked until the final background validation. Details about the event selection and the Monte Carlo-driven background estimate can be found in [9]. Here we only point out that, due to the fact that K^+ decays with a five-track final state often produce tracks not fully contained in the geometric acceptance of the detectors downstream of the STRAW spectormeter, to avoid an order-of-magnitude loss of acceptance, the analysis relies on the STRAW information only. The reduction in selectivity caused by the lack of information from the downstream detectors is mitigated by the exploitation of several kinematic constraints on the five-track final state.

NA62 observes 0 events in the SR. Upper limits of $O(10^{-9})$ were set at 90% CL for the branching ratio of the $K^+ \to \pi^+ aa, a \to e^+e^-$ process in the QCD axion mass range 10-170 MeV/c^2 (Figure 2 left) and for the branching ratio of the $K^+ \to \pi^+ S, S \to A'A', A' \to e^+e^-$ cascade decay in the scalar mass range 20-340 MeV/c^2 (Figure 2 right). In particular, the upper limit $BR(K^+ \to \pi^+ aa) \times BR(a \to e^+e^-)^2 < 2.1 \times 10^{-9}$ for an axion mass of 17 MeV/c^2 excludes this hypothesis as an explanation for the "17 MeV" anomaly, according to the decay rate estimate reported in [8]. The interval 120-165 MeV/c^2 is excluded as dominated by the $K_{2\pi DD}$ mode.

It has to be mentioned that, within this analysis, NA62 also sets the first experimental upper limit for the SM non-resonant $K^+ \to \pi^+e^+e^-e^+e^-$ decay, that is strongly suppressed due to the resonant contribution from the π^0 double Dalitz decay in the $K_{2\pi DD}$ mode. Its branching ratio has a prediction of $(7.2 \pm 0.7) \times 10^{-11}$[11], but has never been measured so far. The NA62 result is: $BR_{NA62}(\text{non-res } K^+ \to \pi^+e^+e^-e^+e^-) < 1.4 \times 10^{-8}$ at 90% CL, a factor 200 larger than the prediction.

4. NA62 searches for $X \to l^+l^-$ in beam-dump mode

Due to their feeble couplings to the SM particles, exotic particles produced in the dump can punch through tens of meters of material before decaying. Decays to visible final states that occur in the FV of the detector can be reconstructed. In the dataset collected in 2021, NA62 searched for FIPs (X) in the $X \to l^+l^-$ decay, with $l = \mu, e$.

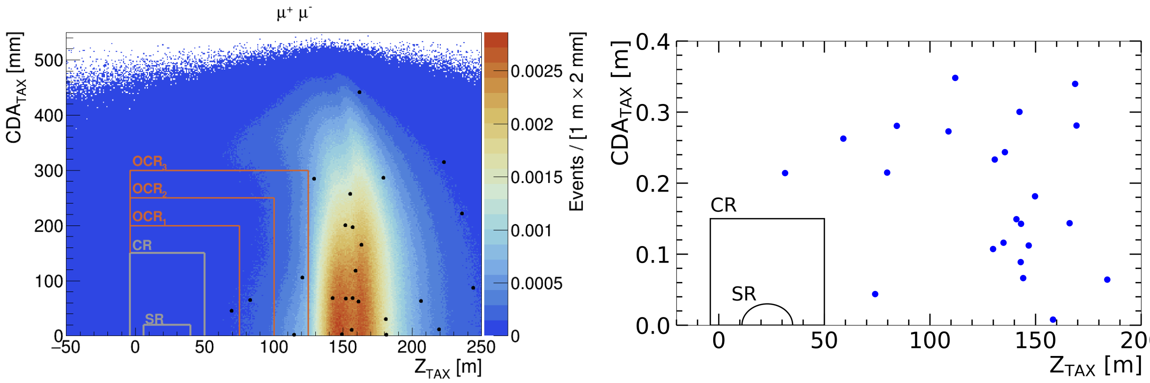


Figure 3: Examples of distributions of CDA_{TAX} vs Z_{TAX} from the NA62 $X \to l^+l^-$ analyses; CR and SR are masked. Left: data (dots) and expected background (colour-scale plot) from the $X \to \mu^+\mu^-$ analysis. Right: data distribution in the $X \to e^+e^-$ analysis after applying the full selection but the LAV and ANTI0 veto conditions. The full selection removes all the events outside the SR and CR.

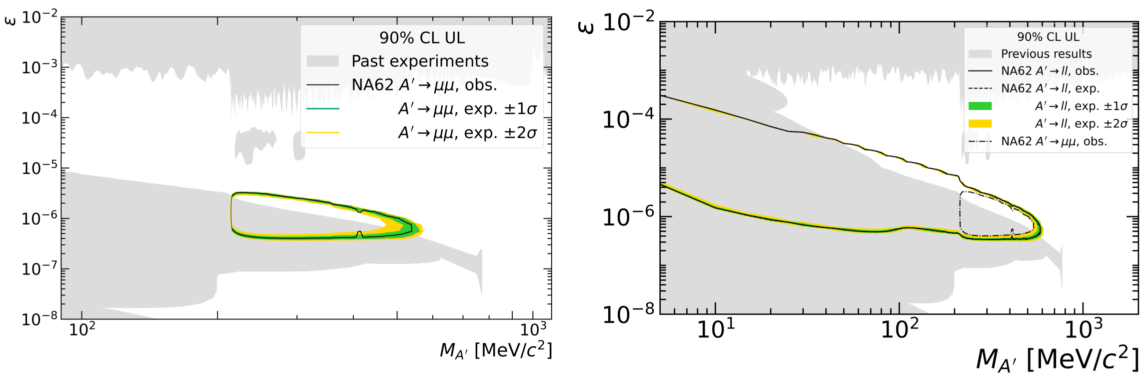
The $X \to l^+l^-$ process is characterised by a l^+l^- vertex reconstructed in the FV and by the back-extrapolation of the tracks total three-momentum pointing back to the X production position at the TAX. A signal region (SR) can therefore be defined in the plane (Z_{TAX}, CDA_{TAX}), where CDA_{TAX} is the closest distance of approach between the proton beam direction at the TAX entrance and the reconstructed direction of the exotic particle, and Z_{TAX} is the longitudinal position of the beam impact point on the dump. The SR is selected within $\pm 3\sigma$ in each axis: in the $\mu^+\mu^-$ analysis [12], it is defined as a box with $0 < CDA_{TAX} < 20$ mm and $6\text{ m} < Z_{TAX} < 40\text{ m}$ (Figure 3 left); in the e^+e^- analysis [13], an ellipse is defined centered in $CDA_{TAX} = 0$ and $Z_{TAX} = 23\text{ m}$ (Figure 3 right). A control region (CR) is used to validate the background estimate in the area outside the SR, satisfying $CDA_{TAX} < 150$ mm and $-4\text{ m} < Z_{TAX} < 50\text{ m}$. Both SR and CR are kept masked until the final validation of the background estimate. In both the analyses, the presence of two tracks of opposite charge coincident in time with the trigger and with each other is required. In the $\mu^+\mu^-$ analysis, for each selected track, the particle identification requires a single hit in the MUV3 muon detector and $E/p < 0.2$, where E is the energy deposited in the LKr calorimeter associated to the track and p the track momentum. In the e^+e^- analysis, the MUV3 detector is used as a veto and the track E/p ratio is expected to be around 1. Additionally, no in-time activity in the LAV stations is allowed to reduce the background from secondary interactions of halo muons and, in the e^+e^- analysis only, the ANTI0 detector is used for further background suppression.

The main background source in the $X \to \mu^+\mu^-$ analysis is due to the random pairing of halo muons from interactions of uncorrelated protons (combinatorial background). The second main background component is the so-called prompt background from secondary particles produced by interactions of halo muons with the material upstream of or inside the FV. This background has been evaluated as negligible. In the $X \to e^+e^-$ analysis, the prompt component is the dominant one, with the combinatorial background about one order of magnitude lower than it. Table 1 reports the expected backgrounds in the signal and control regions after applying the full selection, that are below 1 event in both the analyses.

	$\mu^+\mu^-$	e^+e^-
CR	0.17 ± 0.02	$9.7^{+21.3}_{-7.3} \times 10^{-3}$
SR	0.016 ± 0.002	$9.4^{+20.6}_{-7.2} \times 10^{-3}$

Table 1: Summary of expected $\mu^+\mu^-$ and e^+e^- background events in the CR and in the SR.

After opening the control regions, no events were found in either decay channels. After opening the $\mu^+\mu^-$ SR, one event with invariant mass of ~ 411 MeV/c^2 has been observed. As a counting experiment, the global significance of the event observed is 2.4σ. Note, however, that the tracks time difference is about two standard deviations from the value of zero expected for in-time tracks and that the back-extrapolation of the tracks total momentum to the beam impact point is barely in the SR, suggesting that the event found could be a combinatorial background event. After opening the e^+e^- SR, no events were found. These results can be interpreted in different FIPs scenarios.



(a)

Figure 4: NA62 observed and expected exclusion contours, at 90% CL, in the dark photon parameter space for the $X \to \mu^+\mu^-$ analysis (left) and for the combined $X \to \mu^+\mu^-$ and $X \to e^+e^-$ analyses (right). In gray, past exclusion limits are reported, adapted by PBC [14] and including the FASER results in [15].

The $X \to l^+l^-$ decay can occur in models where X is a dark photon A'. In minimal A' models, the interaction with the SM particles occurs via the kinetic mixing term: $\mathcal{L} \supset -\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$, where $F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$, $B^{\mu\nu}$ is the SM hypercharge field strength tensor, θ_W is the Weinberg angle and ϵ is the coupling constant. The dark photon could be produced in the NA62 beam-dump setup in proton-nucleus interactions via bremsstrahlung ($\gamma^* p \to A' p'$) or by secondary mesons in processes like $P \to A'\gamma$ or $V \to PA'$, with $P = \pi^0, \eta, \eta'$ and $V = \rho, \omega, \Phi$. The decay to the di-lepton final state is dominant for a dark photon mass $M_{A'} < 700$ MeV/c^2. The statistical combination of the NA62 $\mu^+\mu^-$ and e^+e^- analyses excludes new regions at 90% CL in the A' parameter space in the mass range from 50 to 600 MeV/c^2, as reported in Figure 4.

In another scenario, X can be interpreted as an axion-like particle (ALP) coupled to SM fermionic fields. Such an ALP (a) can be emitted in the decays of charged or neutral B mesons

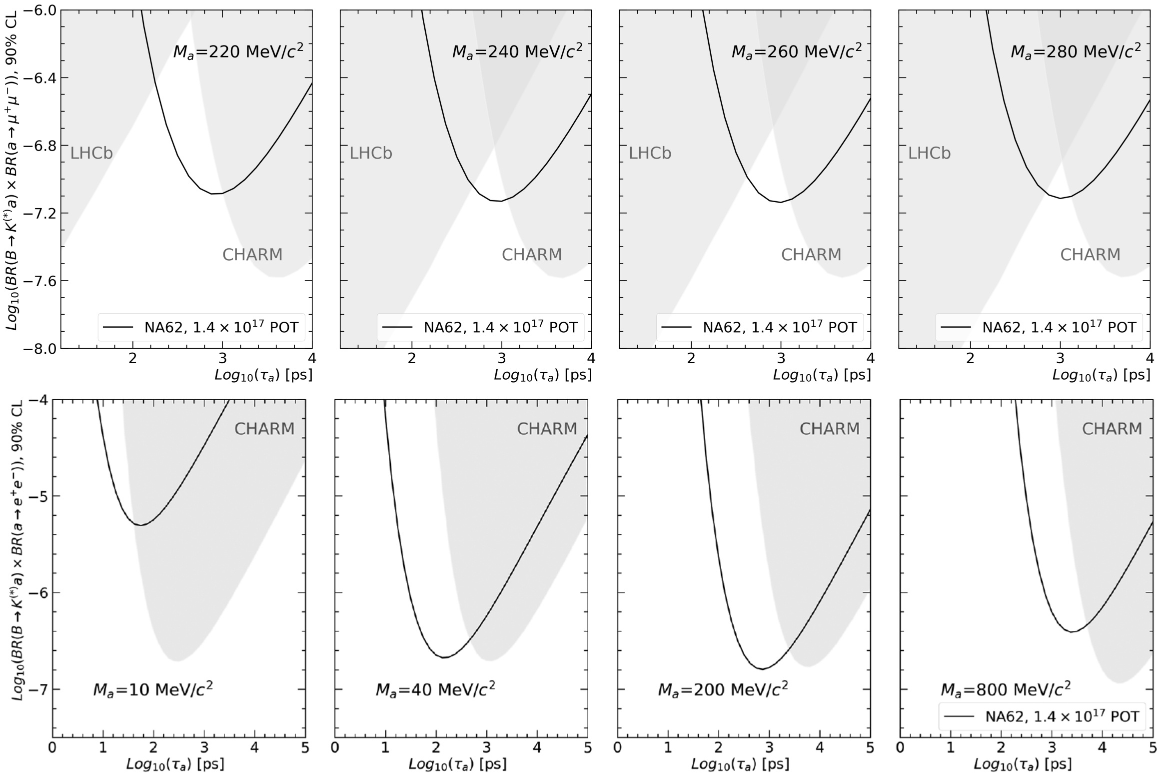


Figure 5: Exclusion limitis at 90% CL in a model-independent interpretation of the NA62 observations in the $X \to \mu^+\mu^-$ (top) and $X \to e^+e^-$ (bottom) searches in the scenario with an axion-like particle (a) produced in B meson decays.

produced in proton-nucleus interactions in the dump ($pN \to BY$, $B \to K^*a$). To address the general scenario in which the ALP coupling to SM fermionic fields is not uniform, exclusion limits are obtained by using a model-independent approach, in which the ALP mass (M_a) and lifetime (τ_A) and the product $BR(B \to K^*a) \times BR(a \to l^+l^-)$ are free parameters. In the $\mu^+\mu^-$ analysis, the NA62 result extends the exclusion limits from previous experiments for $M_a < 280$ MeV/c^2, as shown in the top row of Figure 5 for some ALP mass hypotheses. The bottom row of the same Figure reports some examples from the e^+e^- analysis, where the NA62 results extends the excluded regions in a mass range from 10 to 800 MeV/c^2.

5. Conclusion and prospects

NA62 is a multipurpose experiment exploiting an high intensity beam extracted from the CERN SPS. The search for K^+ decays to final states with multiple dark sector mediators in the $\pi^+e^+e^-e^+e^-$ final state in the NA62 Run1 data, allowed to set branching ratio upper limits at 90% CL of $O(10^{-9})$ for the $K^+ \to \pi^+aa, a \to e^+e^-$ and $K^+ \to \pi^+S, S \to A'A', A' \to e^+e^-$ prompt decay chains, with a QCD axion and $S(A')$ dark scalar (photon). The upper limit $BR(K^+ \to \pi^+aa) \times BR(a \to e^+e^-)^2 < 2.1 \times 10^{-9}$ for a mass of 17 MeV/c^2 excludes the QCD axion as a possible explanation for the "17 MeV" anomaly. By the dataset collected in dump-mode in 2021, new exclusion limits at 90% CL have been set by NA62 for the existence of dark photons and

ALPs coupling to fermions by searching for the $X \to l^+l^-$ final state. Other analyses are ongoing on beam-dump data considering, for example, the hadronic decay channels of the hypothetical NP particle.

The NA62 Run2 is ongoing, with new physics runs forseen until the third long shutdown of the CERN accelerator complex (LS3), providing new samples to be analysed. In particular, in dump-mode, NA62 aims to collect 10^{18} POT by the end of Run2, that will allow to further improve on the current results and probe other dark sector scenarios, such as Heavy Neutral Leptons and ALPs with di-photon final state.

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