PROCEEDINGS OF SCIENCE

Physics Beyond the Standard Model with the NA62 experiment at CERN

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Abstract. The first measurement of the branching ratio of the ultra-rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay and the searches for production of feebly interacting particles predicted by dark scalar models from the NA62 experiment at CERN are presented. The results of a search for in-flight decays of dark photon to $\ell^+\ell^-$ pairs with data collected in beam-dump mode in 2021 are also reported.

XVIII International Conference on Topics in Astroparticle and Underground Physics 2023
28.08. – 01.09.2023
University of Vienna

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PoS(TAUP2023)040

1. The NA62 experiment at CERN SPS

NA62 at CERN is a fixed target experiment designed to measure the $K^+ \to \pi^+ \nu\bar{\nu}$ branching fraction. The layout of the NA62 beamline and detector is described in [1].

The versatility of the experimental setup, combined with the multiple trigger chains available [2], enables the NA62 experiment to study a variety of K^+ mesons decays, including the multi-track $K^+ \to \pi^+ e^+ e^- e^+ e^-$ decay.

The NA62 setup is also able to search for production and decay of dark photons into charged lepton pairs: $A' \to \mu^+\mu^-$ and $A' \to e^+e^-$. For this purpose, NA62 operates in beam-dump mode. Approximately 1.4×10^{17} protons have been collected in 10 days of data taking in dump-mode in 2021.

Other recent NA62 results are published in [3, 4].

2. The $K^+ \to \pi^+ \nu\bar{\nu}$ decay

The $K^+ \to \pi^+ \nu\bar{\nu}$ decay is one of the best environments to test the Standard Model in the Flavour Physics sector, because it is very sensitive to Physics beyond the Standard Model and its very small branching ratio is precisely predicted by theory: $\mathcal{B}_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}$ [5]. The most relevant physics quantity for this study is the squared missing mass: $m^2_{miss} = (P_K - P_\pi)^2$, where P_K and P_π are the measured 4-momenta of the beam particle (kaon) and of the decaying particle under the assumption that it is a pion, respectively.

NA62 has analysed the data taken in RUN1 (2016-2018), 20 $K^+ \to \pi^+ \nu\bar{\nu}$ candidates are observed, with $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$ expected SM events and $7.03^{+1.05}_{-0.82}$ expected background events [6]. This is the first evidence of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay with a significance of 3.4σ, and leads to a measured branching ratio $\mathcal{B} = (10.6^{+4.0}_{-3.4}\,|_{stat} \pm 0.9_{syst}) \times 10^{-11}$.

3. Feebly Interacting Particles searches in the $K^+ \to \pi^+ e^+ e^- e^+ e^-$ decay

Dark-sector models can be tested via the process $K \to \pi^+ e^+ e^- e^+ e^-$. In this context, NA62 has recently published the result of a study of the $K^+ \to \pi^+ e^+ e^- e^+ e^-$ decay using the dataset collected in 2017-2018 [7].

In the dark sectors framework, the $K^+ \to \pi^+ e^+ e^- e^+ e^-$ could proceed through two short-lived QCD axions, a, decaying into e^+e^- pairs, through to the sequence $K^+ \to \pi^+ aa$, $a \to e^+e^-$. This mechanism could provide a possible explanation of the observed "17 MeV anomaly" in the mass spectra produced by the de-excitation of specific nuclei [8]. Also, the same final state could be obtained from the cascade $K^+ \to \pi^+ S$, $S \to A'A'$, $A' \to e^+e^-$, where S and A' are a dark scalar and vector, respectively [9].

The $K^+ \to \pi^+ e^+ e^- e^+ e^-$ signal has a 5-track final state topology. The relevant kinematic variables to select the signal and the normalization ($K^+ \to \pi^+ \pi^0_D \pi^0_D$, $\pi^0_D \to e^+e^-\gamma$) are the five-track mass, $m_{\pi 4e}$, the four-electron mass, m_{4e}, and the squared missing mass, $m^2_{miss} = (P_K - P_\pi)^2$, where P_K is the kaon four-momentum computed using the central beam momentum and P_π is the reconstructed π^+ four-momentum. $K^+ \to \pi^+ e^+ e^- e^+ e^-$ candidates are selected outside the π^0 peak of m_{4e}, in order to reduce the $K^+ \to \pi^+ \pi^0_D \pi^0_D$ background.

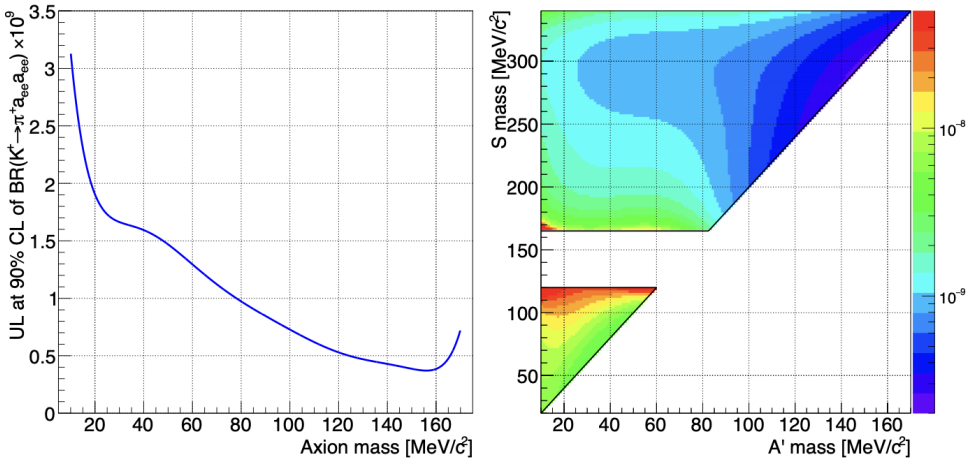

Figure 1: Left: upper limit at 90% CL of the branching ratio of the prompt decay chain $K^+ \to \pi^+ aa$, $a \to e^+e^-$ as a function of the assumed axion mass. **Right:** upper limit at 90% CL of the branching ratio of the prompt decay chain $K^+ \to \pi^+ S$, $S \to A'A'$, $A' \to e^+e^-$ as a function of the assumed dark-photon and dark-scalar masses.

The signal region definition requires the $m_{\pi 4e}$ value to lie within 10 MeV/c^2 of the kaon mass. Additional criteria are set to select the $K_{\pi aa}$ and $K_{\pi S}$ decay chains: the electrons and positrons are grouped into two pairs and the combination with m_{ee} values most consistent with each other is chosen.

The QCD-axion mediated decay is looked for through a scan of the di-electron invariant mass in steps of 5 MeV/c^2. The mass scan is performed from 5 to 175 MeV/c^2 and the upper limit is shown in Figure 1, left panel. A similar technique is used to look for the dark cascade process. In this case the search is performed in the di-vector and scalar mass spectrum. The result in the S versus A' mass plane is shown in Figure 1, right panel.

4. Dark photon searches with NA62 in beam dump mode

The NA62 experimental setup can be used to investigate the production and decay of dark photons while operating in the beam-dump mode: the beam protons are dumped 80 m upstream of the NA62 decay volume.

A search for dark photons decaying in flight to $\mu^+\mu^-$ pairs has been performed by NA62, based on the beam-dump sample collected in 2021 [10]. A counting experiment through a cut-based, blind analysis has been performed. One event is found, with a possible interpretation as combinatorial background. No evidence of a dark photon signal is established. A region of the dark photon parameter space (coupling constant ϵ, mass $M_{A'}$) is excluded at 90% CL, extending the constraints set by previous experiments in the mass range 215-550 MeV/c^2 for coupling constants of the order of 10^{-6} (Figure 2, left panel). In addition, the result is interpreted in terms of the emission of axion-like particles in a model-independent approach. The result is found to improve on previous limits for masses below 280 MeV/c^2.

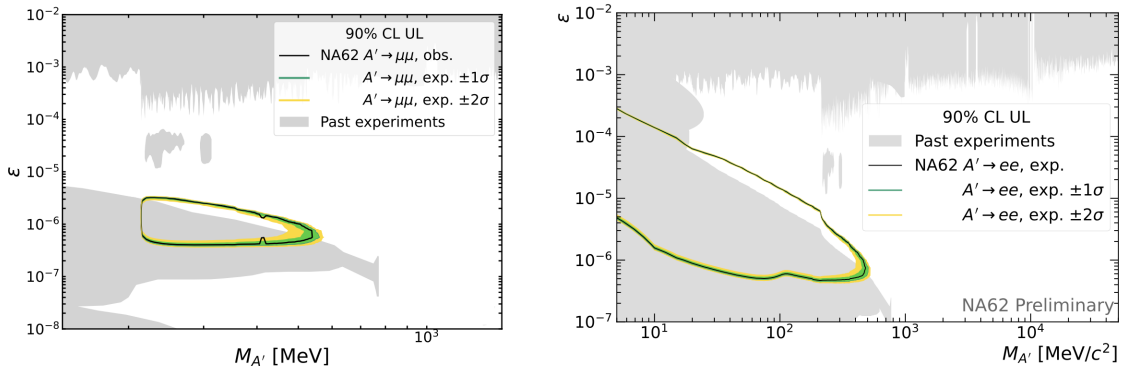

Figure 2: Left: $A' \to \mu^+\mu^-$. **Right:** $A' \to e^+e^-$. The region of the parameter space within the solid line is excluded at 90% CL. The colored filled area represent the expected uncertainty on the exclusion contour in absence of a signal: green (yellow) corresponds to a statistical coverage of 68% (95%).

In addition to the searches for the $\mu^+\mu^-$ final state, a search for the dark photons decaying into e^+e^- pairs has been performed, with no events observed. The corresponding 90% CL upper limit translates into the excluded region visible in Figure 2 (right panel), which extends beyond past experiments for $20 < M'_A < 450$ MeV/c^2 and, correspondingly for values of the ϵ coupling constant from 8×10^{-5} to 8×10^{-7}. The details of this analysis are presented in [11].

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