Dark sector searches at the CERN high-intensity kaon beam facility

NA62 and KLEVER Collaborations

1 Introduction

CERN hosts the NA62 kaon physics experiment, whose primary purpose is the precise measurement of the rare decay $K^+ \to \pi^+ \nu\bar{\nu}$. The experiment took data for this measurement in 2016–18, and will soon restart for the period 2021–24. Longer term plans for kaon physics experiments at CERN involve a high-intensity facility operating with K^+ and K_L beams. This includes the proposed KLEVER experiment to measure the ultra-rare decay $K_L \to \pi^0 \nu\bar{\nu}$ [1]. For details of these future plans, we refer to the Snowmass input [2] for a high-intensity kaon facility at CERN.

While these experiments are designed to test the Standard Model, two features make them significant players in probing dark sector physics as well: 1) high-intensity kaon beams allow high statistics to be collected for a number of decay modes, enabling searches for rare outliers; 2) redundant PID systems and precise timing allow for a wide range of searches with various final states, outlined below.

2 Dark sector searches in charged kaon decays

In 2016–18, the NA62 experiment collected a data sample equivalent to 6×10^{12} K^+ decays in the decay volume [3]. The main trigger line was developed for the $K^+ \to \pi^+ \nu\bar{\nu}$ decay. However, triggers for K^+ decays into multiple charged particles, as well as pre-scaled control triggers, were also enabled. To complete the NA62 $K^+ \to \pi^+ \nu\bar{\nu}$ programme, it is expected to collect a data sample approximately 3 times larger in 2021–24 [4]. Plans for a kaon facility beyond 2026 are outlined in [2].

The data samples already collected, together with those to be collected, provide unique sensitivity to the production of hidden-sector mediators in kaon decays. The models to be probed include:

- production of a dark scalar in $K^+ \to \pi^+ S$ decays [5, 6];
- production and decay of a MeV-scale QCD axion: $K^+ \to \pi^+ a$ followed by a prompt $a \to e^+e^-$ decay [7];
- production of dark scalar and vector particles in the $K^+ \to \mu^+ \nu X$ decay, where X is either invisible or decays promptly via $X \to \mu^+\mu^-$, $X \to e^+e^-$, or $X \to \gamma\gamma$ [8, 9];
- production of massless dark photons and invisible light axions in $K^+ \to \pi^+\pi^0 X$ decays [10, 11];
- production of long-lived heavy neutral leptons in $K^+ \to (\pi^0)e^+N$ and $K^+ \to \mu^+ N$ decays [12];
- production and decay of short-lived heavy neutral leptons, e.g., $K^+ \to \mu^+ N$ followed by $N \to e^+e^-\nu$ with a displaced vertex [13].

Pilot results obtained with the K^+ data samples already collected are already available. They include searches for $K^+ \to \pi^+ X$ decays with a long-lived scalar or axion-like particle in the final state in the

0–110 MeV/c^2 and 154–260 MeV/c^2 mass ranges (PBC [5] models BC4 and BC10) [14]; π^0 decays to an invisible final state, also interpreted in terms of $K^+ \to \pi^+ X$ decays involving a long-lived X particle in the 110–155 MeV/c^2 mass range (again probing the models BC4 and BC10) [15]; $\pi^0 \to \gamma A'$ decay with an invisible dark photon in the final state [16]; and heavy neutral lepton production in $K^+ \to e^+ N$ and $K^+ \to \mu^+ N$ decays [17, 18].

3 Visible final states of dark sector particles produced upstream

Dark sector particles can be produced not only in kaon decays but also upstream of the experiment, as, for example, in the collisions of protons with the material of the main upstream collimator. Visible final states of dark sector particles produced upstream can be probed in at least two different ways.

First, a dark sector particle produced upstream of the decay volume can reach it and decay therein during normal data taking with the kaon beam. Unlike the kaons, dark sector particles do not follow the magnet system of the beamline and mostly decay away from the beam axis. Consequently, e.g. di-lepton events originating away from the kaon beam path might signal a dark sector particle decay.

Second, final states of dark sector particle decays that are more challenging to detect, such as into di-photon or kinematically open channels, might be measured when running the experiment as a beam-dump, by moving the main upstream collimators into the closed position and removing the beryllium target for K^+ production.

During 2016–18 data taking, NA62 collected the following data samples for dark sector searches.

- (2–3)$\times 10^{16}$ protons-on target (POT) in beam-dump mode with trigger lines for both charged and neutral particles. Analysis of this data set is ongoing. A particular challenge in operation in beam-dump mode is the accurate understanding of the halo-muon flux [19] and its induced secondary processes for optimal background rejection.
- 7×10^{17} POT in parasitic mode for the di-muon search and 2×10^{17} POT for the search for $\pi\mu$ final states. Analysis of this data set is ongoing.

NA62 plans to collect 10^{18} POT in beam-dump mode in 2021–24. The corresponding sensitivity to several benchmark models has been studied in the context of the Physics Beyond Colliders study [5].

It is planned to continue taking data with the parasitic trigger lines for dark sector searches insofar as they remain compatible with the requirements for the main physics programme. As described in [5], the data set collected with parasitic trigger lines during 2021–24 data taking is expected to be globally competitive if $\gtrsim 10^{18}$ POT are collected; see also [20, 21] for figures with further NA62-specific prospects.

In the longer term (after 2026), the use of parasitic trigger lines, as well as the prospects for dark sector searches in general, can be reevaluated based on the experience of the 2021–24 run and the status and results of dedicated dark sector experiments such as CODEX-b and FASER2.

4 Dark sector searches with KLEVER

When running as KLEVER, to optimize the measurement of BR($K_L \to \pi^0 \nu\bar{\nu}$), the experiment will have no secondary tracking and only limited PID capability. KLEVER's sensitivity to dark-sector particles is principally through an apparent increase in BR($K_L \to \pi^0 \nu\bar{\nu}$) because of the contribution from $K_L \to \pi^0 X$. The sensitivities achievable with 5×10^{19} POT were estimated for decays to dark photons (BC4), Higgs-mixed scalars (BC5), and axion-like particles with fermion couplings (BC10) as part of the Physics Beyond Colliders study [5]. As part of the broader physics program, we also foresee the possibility of taking data with the downstream detectors configured for charged-particle measurements, but with a neutral beam. This would enable the experiment to look for K_L decays to charged particles with displaced vertices, for example, in data collected for the measurement of $K_L \to \pi^0 \ell^+ \ell^-$ decays.

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