Letter of Interest:
Probing the Dark Sector at Kaon Factories

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August 30, 2020

Abstract

Measurements of rare kaon branching ratios are crucial probes of light dark sectors, and are set to be improved by the currently running kaon experiments NA62 and KOTO, and in future by KLEVER. In this letter we summarize the status of searches for kaon decays to light dark sectors, and discuss the experimental challenges and opportunities.

Introduction. Kaon factories are promising experiments to probe new physics beyond the standard model (BSM). Precision measurements of rare kaon decays are among the most powerful probes of heavy new physics, in which case the modifications of the kaon branching ratios can be systematically encoded in an effective field theory (EFT) framework [1]. On the other hand, new physics scenarios with light degrees of freedom, such as dark sector with mediators lighter than the kaon mass, are not captured by the general EFT analysis, and lead to a variety of model-dependent signals. This feature poses the theoretical challenges of *i)* classifying all the possible signals in kaon decays, *ii)* exploring benchmark models that can feature these signals, *iii)* comparing the reach of future measurements at kaon facilities with other experiments, *iv)* embedding the benchmark models in theory framework addressing Standard Model (SM) shortcomings and see what kaon facilities can teach us about them. The purpose of this Letter of Interest is to fully address the challenge *i)*, i.e., how to maximize in the short term the potential of the kaon experiments. The challenge *ii)* will also be explored, while regarding the challenge *iii)* one should note that kaon experiments have typically (for completely generic flavor structures) the greatest sensitivities for particles in a mass range MeV to GeV.

The two currently operating kaon experiments are NA62 at CERN and KOTO at J-PARC. The NA62 experiment collected a data sample equivalent to 6×10^{12} K^+ decays in the decay volume (2.2×10^{18} protons on target) during Run 1 in 2016–18 [2], and is expected to collect a 3 times larger data sample during Run 2 in 2021–24 [3]. While the main trigger line is designed for the $K^+ \to \pi^+\nu\bar{\nu}$ decay, trigger lines for events with multiple charged particles in the final state and pre-scaled control triggers are also in operation. The KOTO experiment collected a data sample equivalent to 1.6×10^{12} K_L decays (9.5×10^{19} protons on target) in 2015–19 [4] with the main goal of searching for the $K_L \to \pi^0\nu\bar{\nu}$ decay. Triggers for K_L decays to multiple photons are in operation, while charged particles are not measured. About 10 times more data is expected to be recorded by 2028 (to reach the SM sensitivity for $K_L \to \pi^0\nu\bar{\nu}$), and a new experimental setup (KOTO step-2) has been proposed aiming at observation of this decay [5]. Finally, the proposed KLEVER experiment at CERN aims to collect 60 SM $K_L \to \pi^0\nu\bar{\nu}$ events (similarly to KOTO step-2 but using a complementary technique) in 5 years operation [6].

Potential for the future. The ultra-rare decays $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ represent the main targets of NA62 and KOTO. At the same time, there are on-going and possible new searches that are sensitive to various models with light dark sector particles at the kaon experiments. The examples include:

a Production of a dark scalar (such as a Higgs portal scalar) or a QCD axion/axion-like particle (ALP), in $K^+ \to \pi^+X, \pi^+\pi^0X$ and $K_L \to \pi^0X, \pi^0\pi^0X$ decays. The BSM particles can either escape the detector, or decay invisibly (Higgs portal, ALPs), or decay to the SM final states as $X \to e^+e^-, \gamma\gamma$ (ALPs). The decay vertex can be displaced for ALPs [7–11]. The final state with e^+e^- can currently only be tested at NA62.

b Production of a dark scalar or a dark vector, such as leptonic force mediators, 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 $X \to \gamma\gamma$ [12–14]. These channels are particularly important to probe light muonic force carrier as a solution to the muon $g-2$ anomaly. The $K^+ \to e^+\nu X$ decay is another possibility, even though the NA62 reach in this channel will compete with direct production from electron/positron beams.

c Production of long-lived heavy neutral leptons in $K^+ \to (\pi^0)e^+N$ and $K^+ \to \mu^+N$ decays [15, 16].

d Production and decay of short-lived heavy neutral leptons, e.g., $K^+ \to \ell_\alpha N$, followed by the $N \to \ell_\beta^- \ell_\beta^+ \nu$ decay [17].

e Production of an invisible dark photon (γ') in $K^+ \to \pi^+ \pi^0 \gamma'$ decays [11, 18] or through $\pi^0 \to \gamma\gamma'$ where the π^0 is produced in $K^+ \to \pi^+ \pi^0 (\pi^0)$ or $K_L \to 3\pi^0$ decays.

f Processes violating the Grossmann-Nir bound: $K_L \to \gamma\gamma X_1, \gamma\gamma X_1 X_1$ and $K^+ \to \pi^+ X_1 X_1$. The $\gamma\gamma$ is emitted directly from K_L, or is from a decay of an intermediate particle, either π^0 or a new particle X_2, while X_1 is a massive stable particle [8, 19, 20]. Effective violation of the GN bound expects $K \to \pi X$ where a fraction of X decays to $\gamma\gamma$ [21].

g Similar processes violating the Grossmann-Nir bound but with $\ell^+\ell^-$ in the final state: $K_L \to \ell^+\ell^-\pi^0, \ell^+\ell^-(X_{\mathrm{NP}} \to \gamma\gamma), \ldots$, with K^+ decays suppressed.

h Production of two dark sector particles, $K \to \pi X X$. This is realized if a heavier scalar S is a portal to the dark sector (SXX) with a flavor violating coupling of $S\bar{s}d$. This scenario predicts an addition process, $K_L \to XX$, but it would not be detectable.

i Other more exotic scenarios can also be considered. For instance, lepton flavor violating decays such as $K^+ \to \pi^- \ell_1^+ \ell_2^+$ are already being searched for [22]. A more exotic, yet still viable possibility, are showers in the dark sector with final states decaying back to the SM, leading to prompt signals or displaced vertices (emergent jets).

Table 1 categorizes the examples based on the experimental signatures.

Experimental status. Most of the K^+ decays listed above can be studied with the existing NA62 Run 1 data set. Decays into $\mu^+\mu^-$ (e^+e^-) pairs are prescaled approximately by factors of 2 (10), while decays with a lone π^+ (μ^+) in the final state are prescaled by larger factors of about 200 (400). Several searches, namely $K^+ \to \pi^+ X$ with invisible X, invisible π^0 decays, and $K^+ \to e^+ N$ make use of the main $K^+ \to \pi^+ \nu\bar{\nu}$ trigger stream collected without prescaling, and have already been performed with partial or full Run 1 data set. While the size of data set available is well known, the level of background and the uncertainties on the background estimate require a dedicated study in each case. In general, decays with several undetected particles in the final state are affected by larger backgrounds. Some of the 1-track final states might benefit from more selective triggers; for example, an L0 trigger based on RICH pattern recognition may be useful to select low-momentum muons from the $K^+ \to \mu^+ N$ and $K^+ \to \mu^+ \nu X$ decays.

The KOTO experiment is not equipped with a tracking system, and is sensitive mainly to K_L decays with photons in the final state. The KLEVER experiment, whose baseline design does not involve a tracking system either, is expected to be able to test the KOTO physics cases with higher luminosity. A possibility of collecting a data set with a K_L beam and a setup allowing charged-particle measurements is considered within the CERN kaon programme [23].

Signature	$s \to dX_{\rm NP}$	$s \to dX_{\rm NP}X_{\rm NP}$	$\pi^0 \to \gamma X_{\rm NP}$
$K \to \pi + \text{inv}$	$s \to d(a/\gamma')$ [a,e]	$s \to d(aa/\gamma'\gamma'/\bar{N}N)$ [h]	–
$K \to 2\pi$+inv	$K \to 2\pi(a/\gamma')$ [a,e]	–	–
$K \to \pi\gamma + \text{inv}$	$s \to d(a \to \gamma\gamma')$ [i]	–	$K \to \pi(\pi^0 \to \gamma\gamma')$ [e]
$K \to 2\pi\gamma$+inv	$s \to d(a \to \gamma\gamma')$ [i]	–	$K \to 2\pi(\pi^0 \to \gamma\gamma')$ [e]
$K \to \pi\gamma\gamma$	$s \to d(a \to \gamma\gamma)$ [a,f]	–	–
$K \to \pi\ell^+_\alpha\ell^-_\alpha$	$s \to d(a/\gamma' \to \ell^+_\alpha\ell^-_\alpha)$ [a,e]	–	–
$K_L \to \gamma\gamma + \text{inv}$	$K_L \to \pi^0 a, \gamma\gamma a$ [f]	$K_L \to \pi^0(aa/\bar{N}N)$ [f]	–
		$K_L \to \gamma\gamma(aa/\bar{N}N)$ [f]	–
$K_L \to \ell^+\ell^-$+ inv	$K_L \to \ell^+\ell^-(a/\gamma')$ [g]	–	–
$K_L \to \ell^+\ell^-\gamma\gamma$	$K_L \to \ell^+\ell^-(a \to \gamma\gamma)$ [g]	–	–
$K^+ \to \ell^+_\alpha$+inv	$K^+ \to \ell^+_\alpha N, \ell^+_\alpha\nu(a/\gamma')$ [b,c]	–	–
$K^+ \to \ell^+_\alpha\ell^-_\beta\ell^+_\beta$	$K^+ \to \ell^+_\alpha\nu(a/\gamma' \to \ell^+_\beta\ell^-_\beta)$ [b,e]	–	–
+inv	$K^+ \to \ell^+_\alpha(N \to \ell^+_\beta\ell^-_\beta\nu)$ [d]		
$K^+ \to \ell^+_\alpha\gamma\gamma$+inv	$K^+ \to \ell^+_\alpha\nu(a \to \gamma\gamma)$ [b]	–	–
	$K^+ \to \pi^0\ell^+_\alpha N$ [c]		
$K^+ \to \pi^-\ell^+_\alpha\ell^+_\beta$	$u\bar{s} \to \ell^+_\alpha(N^* \to d\bar{u}\ell^+_\beta)$ [i]	–	–

Table 1: Common signatures expected in the $s \to dX$ decays, where X contains up to two new physics particles, $X_{\rm NP}$. For illustration these are taken to be either a dark (pseudo)scalar a, a dark vector γ', or a heavy neutral lepton N. The decay channels of these NP particles are indicated above. If the decays are not indicated, the particle is assumed to escape the detector.

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