Future Experiments of Kaon Physics

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Abstract. Several new experiments to study Kaon physics have been taken into operation in the recent years or are being planned at the moment. All of them aim to measure ultra-rare FCNC Kaon decays like $K \to \pi\nu\bar{\nu}$, $K_L \to \pi^0 l^+ l^-$, or $K^0 \to \mu^+\mu^-$, which all are extremely sensitive to possible new physics beyond the Standard Model. This report gives an overview on the status and the physics reaches of currently running and future Kaon physics experiments.

1 Golden Kaon Decays

Kaons, discovered more than 75 years ago, have played a crucial role in uncovering new physics phenomena, including the discovery of CP violation in $K_L \to \pi^+\pi^-$, the suggestion of the GIM mechanism through the suppression of $K^0 \to \mu^+\mu^-$ and $K^+ \to \pi^+ l^+ l^-$ decays, and the confirmation of CP violation within the Standard Model (SM) through the measurement of $\mathrm{Re}(\epsilon'/\epsilon)$.

In the past decade, interest has shifted to ultra-rare, flavour-changing neutral current (FCNC) decays with branching ratios of $O(10^{-10})$ or smaller. These decays, often referred to as *golden decays*, proceed via penguin or box diagrams. The short-distance (SD) contributions to their SM decay rates are closely linked to CKM matrix elements of the unitarity triangle (Fig. 1). Consequently, their decay rates can be precisely predicted based on measurements from other processes, such as B decays. Due to the extremely small SM decay rates of these processes (see Table 1), they are uniquely sensitive to potential physics beyond the SM. Although long-distance contributions typically dominate in Kaon physics, these contributions can be estimated to a few-percent level by isospin rotation (using $K \to \pi l \nu$ for $K \to \pi\nu\bar{\nu}$) or from well-measured related decays, as illustrated in Fig. 1.

To measure branching ratios of $O(10^{-10})$ or smaller, an unprecedented amount of Kaon decays is necessary. Assuming typical acceptances of $O(1\,\%)$, approximately 10^{13}-10^{14} decays need to be produced and measured. This is achievable only by current experiments (NA62, KOTO, LHCb) or future experiments (KOTO-2).

2 Currently Running Experiments

Currently, three experiments are actively collecting data on rare and ultra-rare Kaon decays. The NA62 experiment at CERN aims to measure the $K^+ \to \pi^+\nu\bar{\nu}$ decay with a precision of approximately 20 %. The KOTO experiment at J-PARC is working towards a single event

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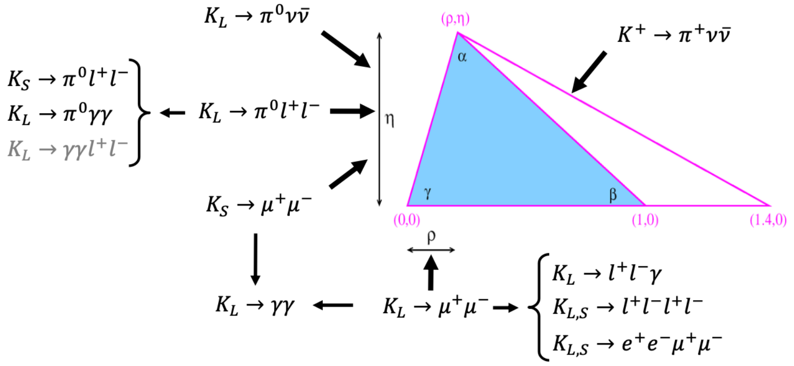

Figure 1. The relationship between rare Kaon decay modes and the parameters ρ and η of the unitarity triangle (UT) [1]. The direct link between decay modes and the UT indicates that short-distance contributions, dependent on ρ and η, contribute to the corresponding decay amplitudes. Decays not directly connected to the UT are relevant to interpret the experimental results of the decay modes to which they are related.

Table 1. Predicted Standard Model branching fractions of ultra-rare FCNC Kaon decays. For the $K_L \to \pi^0 l^+ l^-$ decays, positive interference between the direct and indirect CP-violating contributions is assumed. For $K_L \to \mu^+\mu^-$, positive interference between short-distance and long-distance contributions is assumed.

Decay	SM Branching Ratio	Ref.
$K_L \to \pi^0 \nu\bar{\nu}$	$(2.94 \pm 0.15) \times 10^{-11}$	[2]
$K^+ \to \pi^+ \nu\bar{\nu}$	$(8.60 \pm 0.42) \times 10^{-11}$	[2]
$K_L \to \pi^0 e^+ e^-$	$(3.5^{+1.0}_{-0.9}) \times 10^{-11}$	[3]
$K_L \to \pi^0 \mu^+ \mu^-$	$(1.4 \pm 0.3) \times 10^{-11}$	[3]
$K_L \to \mu^+ \mu^-$	$(6.8^{+0.8}_{-0.2}) \times 10^{-9}$	[4]

sensitivity of 10^{-10} for $K_L \to \pi^0 \nu\bar{\nu}$. Additionally, the LHCb experiment at CERN is focusing on rare K_S decays involving muons. Other experiments either lack sufficient Kaon statistics or, as in the case of other LHC experiments, do not have a dedicated triggers to collect rare Kaon decays.

2.1 NA62

The NA62 experiment [5] at the CERN SPS has been in operation since 2016 and is approved to run until CERN's Long Shutdown 3 (2025). Its primary goal is to measure the $K^+ \to \pi^+ \nu\bar{\nu}$ branching ratio with about 20 % precision by detecting approximately 100 $K^+ \to \pi^+ \nu\bar{\nu}$ candidates with a signal-to-background (S/B) ratio of roughly 1.

In its first analysis phase (2016-18), prior to CERN's Long Shutdown 2, the NA62 Collaboration expected a Standard Model signal of 10.0 events against a background expectation of 7.0. A total of 20 $K^+ \to \pi^+ \nu\bar{\nu}$ candidates were observed [6], leading to a significance of 3.4 σ for the decay. The branching ratio was determined to be $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4} \pm 0.9) \times 10^{-11}$, approximately one standard deviation above the SM prediction.

During the ongoing run period (2021-2025), NA62 expects to collect four to five times more Kaon decays compared to the 2016-18 data, with a similar S/B ratio. Most of this data has already been recorded and is under analysis. Assuming smooth data-taking in future runs, a total precision of approximately $\pm 1.8 \times 10^{-11}$ on $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ is anticipated, corresponding to a relative uncertainty of about 20 % on the branching fraction.

2.2 KOTO

The KOTO experiment [7] at the J-PARC Hadron Facility searches for the rare Kaon decay $K_L \to \pi^0 \nu\bar{\nu}$. It has been operational since 2013 and is expected to run until 2027. Over this period, the beam power has increased from 20 kW to approximately 80 kW as of 2024, with an expected rise to 100 kW in the near future.

The most recent result from KOTO is based on data collected in 2021, which profit from several detector improvements with respect to previous running periods. After unblinding the signal region no candidate event was observed and an upper limit was set to $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) < 2.0 \times 10^{-9}$ at 90 % CL [8]. The result is still preliminary, but a publication is in preparation.

In the coming years, the beam power is expected to reach 100 kW, resulting in a 10-fold increase in the number of protons on target over four years of data collection compared to the 2021 run. Combined with improvements in acceptance and background suppression — enabled by an optimized hadron beam structure — KOTO aims to set an upper limit on $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$ as low as 1.0×10^{-10}, approximately three times the SM prediction.

2.3 LHCb

The LHCb experiment at CERN is also capable of searching for very rare Kaon decays, although it faces challenges due to the environment of proton-proton collisions at $\sqrt{s} \approx 14$ TeV. Only a limited number of Kaon decay modes can be selected by the trigger and reconstructed in this high-track-density environment. These modes are mainly K_S (and partially K_L) decays to muons, where a well-separated secondary vertex facilitates the trigger by the presence of multiple muons.

Using 9 fb^{-1} of data, LHCb has set an upper limit of $\mathcal{B}(K_S \to \mu^+\mu^-) < 2.1 \times 10^{-10}$ [9], and with 5 fb^{-1} of data, it has obtained $\mathcal{B}(K_S \to \mu^+\mu^-\mu^+\mu^-) < 5.1 \times 10^{-12}$ [10] at 90 % CL[1].

The projections of the final LHCb sensitivities on $K_S \to \mu^+\mu^-$ and $K_S \to \mu^+\mu^-\mu^+\mu^-$ are shown in Fig. 2. While in $K_S \to \mu^+\mu^-$ it will be difficult to reach the SM prediction, $K_S \to \mu^+\mu^-\mu^+\mu^-$ looks a bit more optimistic. However, if new physics should have similar contributions to one of the two decay rates as the SM, there is a good chance that it will be detected even with currently projected sensitivities. In addition to these two decays, LHCb is also planning to look for other Kaon decays like e.g. $K_S \to \pi^0\mu^+\mu^-$ or $K_S \to \pi^+\pi^-e^+e^-$ [11].

3 Future Kaon Experiments

3.1 Future Kaon Experiments at CERN

Since the expected NA62 sensitivity on $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ will not reach the precision of the SM prediction, large parts of the NA62 Collaboration proposed a successor experiment, called HIKE (High Intensity Kaon Experiments) [1]. The HIKE experiment was planned to use the same experimental hall as NA62 and to reuse large parts of the NA62 detector. In a first K^+ phase the beam intensity should be increased by a factor of 4 with respect to the NA62 beam to reach, together with detector improvements, a precision of about 5 % on $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$. In a second phase, a K_L beam would have been employed to precisely measure $K_L \to \pi^0 e^+ e^-$

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[1] The latter analysis also yields a limit of $\mathcal{B}(K_L \to \mu^+\mu^-\mu^+\mu^-) < 2.3 \times 10^{-9}$ at 90 % CL.

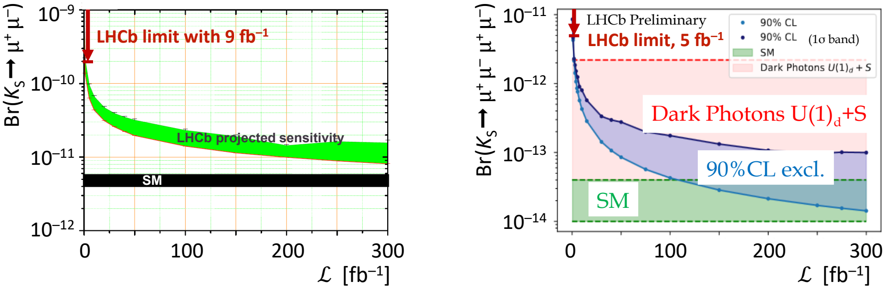

Figure 2. Perspectives on LHCb searches on $K_S \to \mu^+\mu^-$ (left, [11]) and $K_S \to \mu^+\mu^-\mu^+\mu^-$ (right, [12]) for luminosities up to the data size of 300 fb^{-1} that is planned to be collected by the LHCb experiment. Plotted are also the current upper limits [9, 10].

and $K_L \to \pi^0\mu^+\mu^-$ among many other K_L decays. Again, large parts of the detector could have been reused. Finally, a third phase with a completely new detector was considered to precisely measure $K_L \to \pi^0\nu\bar{\nu}$ decays.

Despite the broad Kaon Physics program envisioned for the next 15-20 years, CERN management made a strategic decision to prioritize a future beam dump experiment in the experimental hall, thus not approving HIKE. Therefore, with the end of the NA62 run, there will be no mid- or long-term experimental Kaon Physics program at CERN, apart from the LHCb searches for rare K_S decays as described earlier.

3.2 KOTO-2 at J-PARC

The reach of KOTO is limited not by the available beam power, but by the number of useful K_L decays per primary proton. Due to constraints in the beam and target setup in the experimental hall, which houses many different experiments, the extraction angle of 16° for the neutral beam relative to the initial proton beam is quite large. An optimal extraction angle of 5° would increase the K_L flux per proton per steradian by a factor of 5 while maintaining the same S/B ratio for the neutron background. Moreover, the mean K_L momentum would increase by a factor of 2 to about 3 GeV/c, facilitating the detection of $K_L \to \pi^0\nu\bar{\nu}$. However, it is not possible to change the extraction angle in the existing hadron facility.

Thus, an extension of the J-PARC hadron facility has been proposed. This extension would house a second proton target, T2, serving a new $K_L \to \pi^0\nu\bar{\nu}$ experiment (KOTO-2) along with other new experiments (see Fig. 3). This would allow for a K_L extraction angle of 5° and provide sufficient space for a longer neutral beamline and a larger detector. The hadron hall extension has not yet been approved. A proposal for the extension and for KOTO-2 is expected to be submitted in 2025, aiming to realize the experiment in the 2030s.

The proposed KOTO-2 detector has a layout similar to KOTO but is significantly larger (Fig. 4). The fiducial decay volume will be extended from 2 m to 12 m, resulting in a threefold increase in the K_L decay probability, despite the higher K_L momenta. The entire detector would measure about 20 m in length (without detectors in the exiting neutral beam), compared to about 6 m for KOTO. The transverse size would also be enlarged from 2 m to 3 m.

A comparison of the properties of KOTO and KOTO-2 is shown in Table 2. Due to the increased length of the neutral beamline, the stereo angle of the neutral beam is smaller for KOTO-2, which eats up a part of the increased K_L intensity, though it still leaves an improvement factor of 2.6. The largest improvement, however, comes from the selection

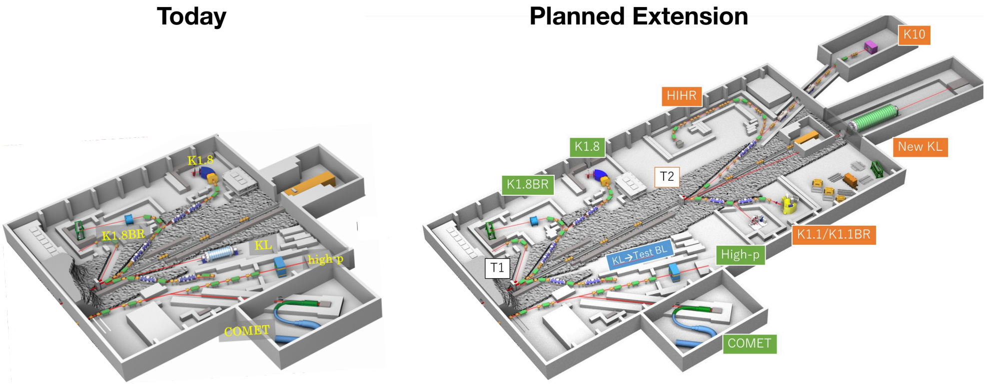

Figure 3. Left: Existing Hadron Facility at J-PARC with the KOTO experiment (“KL”). Right: Hadron Facility with the planned extension and the KOTO-2 experiment (“New KL”) [13, 14].

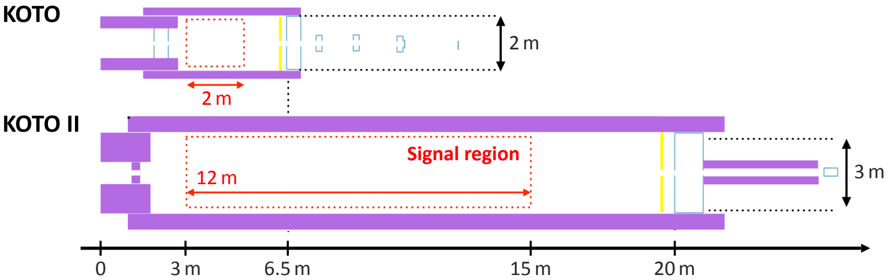

Figure 4. Comparison of the layouts of the existing KOTO and the planned KOTO-2 detector.

efficiency: Due to the cleaner environment and an improved detector, many selection criteria can be relaxed, resulting in an almost ninefold increase in signal acceptance. Overall, a factor of 190 improvement in signal yield per incident proton is expected for KOTO-2 compared to KOTO.

To estimate the expected reach of KOTO-2, we assume a proton beam power of 100 kW, as in KOTO, and a running time of 3×10^7 s, corresponding to 3-5 calendar years. These

Table 2. Improvements of KOTO-2 in the $K_L \to \pi^0 \nu\bar{\nu}$ measurement compared to KOTO. The overall improvement is a factor of 190 in precision for the same number of protons on target.

	KOTO	**KOTO-2**	**Improvement**
K_L yield (arb. units)	1	2.6	2.6
Decay probability	3.3 %	10 %	3.0
Geometrical acceptance	26 %	24 %	0.9
Selection efficiency	3 %	26 %	8.7
1 − accidental loss	64 %	39 %	1.7
1 − backsplash loss	50 %	91 %	21.8
Total			**190**

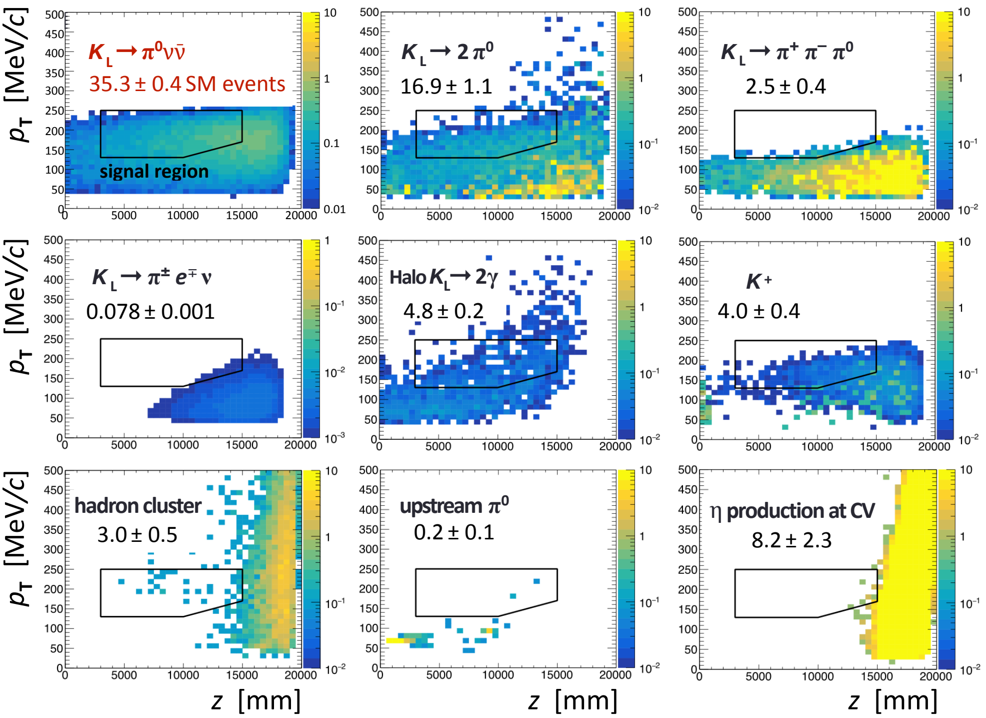

Figure 5. Signal (upper left) and various background expectations for KOTO-2 [8]. The estimates correspond to the expected event numbers in the signal box over the entire KOTO-2 lifetime.

assumptions translate into a total of 6.3×10^{20} protons on target, and ultimately into an expectation of 35 SM $K_L \to \pi^0\nu\bar{\nu}$ events (see Fig. 5 (upper left)). The background estimate includes a variety of sources, such as other K_L decays like $K_L \to \pi^0\pi^0$, $K_L \to \pi^+\pi^-\pi^0$, and $K_L \to \pi^\pm e^\mp \nu$, as well as halo $K_L \to \gamma\gamma$, K^+ creation by charge exchange at the collimator, scattered neutrons, upstream π^0 sources, and η production on the charged veto plane in front of the calorimeter (Fig. 5). The total background is expected to be about 40 ± 3 events, leading to an S/B ratio of approximately 0.9, which corresponds to a 5.6 σ discovery significance for SM $K_L \to \pi^0\nu\bar{\nu}$.

The design of the KOTO-2 detector is progressing towards a realistic geometry (Fig. 6), which is being used for Monte Carlo simulations, as well as weight and cost estimations. The detector will mainly consist of completely new components. Only the CsI calorimeter, originally used in the KTeV experiment, is likely to be reused, though it will need to be enlarged to accommodate the larger diameter of the new experiment. Additionally, possible improve-

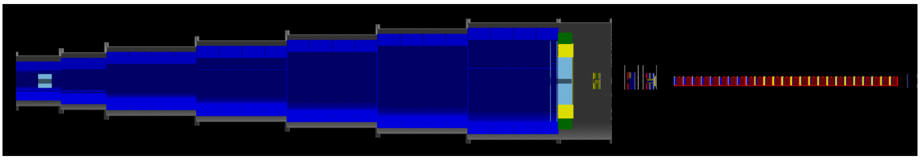

Figure 6. Cutaway view of the KOTO-2 detector.

ments to the calorimeter, such as the capability to measure shower directions for background suppression, are under discussion. Most of the other components, although similar to KOTO, have not yet been defined in detail.

An intriguing possibility is the operation of the experiment in two phases. In the first phase, the $K_L \to \pi^0 \nu\bar{\nu}$ measurement would be performed with a detector composed primarily of the calorimeter and vetoes for charged and neutral particles. In the second phase, a tracking detector and potentially other components would be added to measure $K_L \to \pi^0 e^+ e^-$, $K_L \to \pi^0 \mu^+ \mu^-$, and possibly $K_{L,S} \to \mu^+ \mu^-$. These options are currently being discussed within the collaboration.

4 Summary

Current and future Kaon experiments focus on ultra-rare FCNC decays. These decays, notably $K \to \pi\nu\bar{\nu}$, $K_L \to \pi^0 l^+ l^-$, and $K_{L,S} \to \mu^+\mu^-$, are highly sensitive to new physics beyond the SM. From the currently running experiments — NA62, KOTO, and LHCb — only NA62 has access to one of these decays, $K^+ \to \pi^+ \nu\bar{\nu}$, rather than merely setting limits. LHCb may have the potential to access $K_S \to \mu^+\mu^-$ in the long term.

After the cancellation of the proposed NA62 successor, HIKE, the remaining future experiment is the KOTO successor, KOTO-2. The projected sensitivity of NA62 and KOTO/KOTO-2 in the $K_L \to \pi^0 \nu\bar{\nu}$ versus $K^+ \to \pi^+ \nu\bar{\nu}$ parameter space is shown in Fig. 7. While the precision of the SM prediction cannot be achieved, there remains significant sensitivity to non-SM physics.

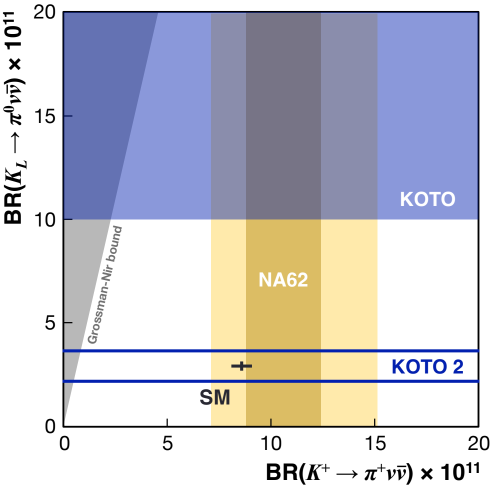

Figure 7. The expected $1\,\sigma$ precision or 90 % CL, respectively, of NA62 (brown), KOTO (blue), and KOTO-2 (blue lines) together with the SM prediction [2] in the plane of $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ versus $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$. The existing NA62 measurement is shown in light brown. The final NA62 band assumes the same branching fraction as the existing NA62 measurement, while for KOTO-2 the SM branching fraction has been taken. The grey region is excluded when assuming lepton flavor conservation and isospin symmetry [15].

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