HIKE: High Intensity Kaon Experiments at the CERN SPS

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Abstract. The availability of high intensity kaon beams at the CERN SPS North Area gives rise to unique possibilities for sensitive tests of the Standard Model in the quark flavor sector. Precise measurements of the branching ratios for the flavor-changing neutral current decays $K \rightarrow \pi\nu\bar{\nu}$ can provide unique constraints on CKM unitarity and, potentially, evidence for new physics. Building on the success of the NA62 experiment, plans are taking shape at CERN for a comprehensive program that will include experimental phases to measure the branching ratio for $K^+ \rightarrow \pi^+\nu\bar{\nu}$ to $\sim 5\%$ and to $K_L \rightarrow \pi^0\nu\bar{\nu}$ to $\sim 20\%$ precision. These planned experiments would also carry out lepton flavor universality tests, lepton number and flavor conservation tests, and perform other precision measurements in the kaon sector, as well as searches for exotic particles in kaon decays. We overview the physics goals, detector requirements, and project status for the next generation of kaon physics experiments at CERN.

1. Introduction
Rare kaon decays provide information on the unitary triangle, as illustrated in Figure 1. These are flavor-changing neutral current processes (FCNC) that probe the $s \rightarrow d\nu\bar{\nu}$ or $s \rightarrow d\ell^+\ell^-$ transitions. They are highly GIM-suppressed and their SM rates are very small. The $K \rightarrow \pi\nu\bar{\nu}$ decays are the least affected by long-distance physics. The branching ratios (BRs) for the $K \rightarrow \pi\nu\bar{\nu}$ decays are among the observable quantities in the quark-flavor sector most sensitive to new physics.

![Figure 1. Determination of the unitary triangle with rare kaon decays.](image)

In the SM, the uncertainties on the $K \rightarrow \pi\nu\bar{\nu}$ rates are entirely dominated by the uncertainties on the CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$ and the angle $\gamma$. Using values for these parameters
from the analysis of tree-level observables, Buras et al. obtain [1]

\[
\begin{align*}
\text{BR}(K_L \to \pi^0\nu\bar{\nu}) &= (3.4 \pm 0.6) \times 10^{-11}, \\
\text{BR}(K^+ \to \pi^+\nu\bar{\nu}) &= (8.4 \pm 1.0) \times 10^{-11}.
\end{align*}
\]

(1)

Assuming no new-physics effects in \(\epsilon_K\) and \(\sin 2\beta\) from \(B \to J/\psi K_S\), the BRs can be determined independently of \([V_{cb}]\) as \(\text{BR}(K_L \to \pi^0\nu\bar{\nu}) = (2.94 \pm 0.15) \times 10^{-11}\) and \(\text{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}\) [2]. The intrinsic theoretical uncertainties, if the CKM parameters are taken to be exact, are about 1.5% and 3.5%, respectively.

Because the amplitude for \(K^+ \to \pi^+\nu\bar{\nu}\) has both real and imaginary parts, while the amplitude for \(K_L \to \pi^0\nu\bar{\nu}\) is purely imaginary, the decays have different sensitivity to new sources of CP violation. Measurements of both BRs would therefore be extremely useful not only to uncover evidence of new physics in the quark-flavor sector, but also to distinguish between new physics models. More generally, measurement of all of the FCNC kaon decays would allow the unitarity triangle to be overconstrained as illustrated in Figure 1, potentially providing evidence of new physics independently of and in comparison to results from \(B\) and \(D\) meson decays and providing important information about the flavor structure of that physics.

2. The NA62 experiment

NA62 is a fixed-target experiment at the CERN SPS, the goal of which is to measure \(\text{BR}(K^+ \to \pi^+\nu\bar{\nu})\) to within 10% [3]. The secondary positive beam, consisting of 6% \(K^+\) with a total rate of 750 MHz, is derived from the 400-GeV primary proton beam from the SPS incident at zero angle on a beryllium target at a rate of \(3 \times 10^{12}\) protons per pulse (ppp). The \(K^+ \to \pi^+\nu\bar{\nu}\) decay is detected in flight. The signature is a \(K^+\) entering the experiment and a \(\pi^+\) leaving the decay vertex, with missing momentum at the vertex and no other particles observed in the final state. Principal backgrounds include those from the abundant decays \(K^+ \to \mu^+\nu\) and \(K^+ \to \pi^+\pi^0\), as well as backgrounds from upstream decays and interactions. The signal decay is identified via selection in the \((p_\pi, m_{\text{miss}}^2)\) plane to exclude the abundant two-body decays, where \(p_\pi\) is the momentum of the candidate pion track and \(m_{\text{miss}}^2\) is the squared missing mass at the vertex. The distinguishing features of the experiment include high-rate, precision tracking for both the beam and secondary particles, redundant particle identification systems and muon vetoes, and hermetic photon vetoes, including a high-performance EM calorimeter.

Between 2016 and 2018, NA62 observed more than \(4 \times 10^{12}\) \(K^+\) decays in its fiducial volume, with the expectation of observing 10 signal events and 7 background events, principally from upstream decays and interactions. A total of 20 events were observed, establishing the \(K^+ \to \pi^+\nu\bar{\nu}\) decay with 3.4\(\sigma\) significance and providing the most precise measurement to date for the branching ratio [4]:

\[
\text{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}\text{stat} \pm 0.9\text{syst}) \times 10^{-11}.
\]

NA62 resumed data taking in July 2021 with a number of key modifications to the beamline and detector to reduce background from upstream decays and interactions and to allow data to be taken at the full nominal beam intensity. The experiment is approved for data taking up to LHC Long Shutdown 3 (LS3), currently foreseen for the end of 2025, and is expected to measure \(\text{BR}(K^+ \to \pi^+\nu\bar{\nu})\) to 10% precision by then. In the longer term, fixed-target runs in the SPS North Area are foreseen at least through 2040. There is therefore an opportunity at the SPS for an integrated program to pin down new physics in the kaon sector via measurement of all rare kaon decay modes—both charged and neutral.
3. The HIKE physics program

The HIKE program (High Intensity Kaon Experiments at the CERN SPS) [5] is foreseen to include three experimental phases for the comprehensive, high-precision study of rare kaon decays during the period from the end of LS3 to the FCC era:

- **Phase 1:** A $K^+$ experiment running at four times the intensity of NA62 ($1.2 \times 10^{13}$ ppp) to measure $\text{BR}(K^+ \to \pi^+ \nu \bar{\nu})$ to 5% precision. Phase 1 will also focus on studies of lepton universality/number/flavor violation through observables such as $R_K = \Gamma(K^+ \to e^+ \nu)/\Gamma(K^+ \to \mu^+ \nu)$ and $K^+ \to \pi^+ \ell \ell$, and searches for decays such as $K^+ \to \pi^- \ell^+ \ell^+$ and $K^+ \to \pi^+ \mu e$. The experiment will also make precision measurements of leptonic and semileptonic, radiative, and Dalitz decays and chiral parameters of the kaon system.

- **Phase 2:** An experiment with a neutral beam and tracking and PID systems optimized for the measurement of decays like $K_L \to \pi^0 \ell^+ \ell^-$ and $K_L \to \mu^+ \mu^-$, as well as studies of lepton universality/number/flavor violation in $K_L$ decays, radiative $K_L$ decays and precision measurements, and measurements of $K_L$, $n$, and $\Lambda$ fluxes in the neutral beam and halo to prepare for the final phase.

- **Phase 3:** An experiment to measure $\text{BR}(K_L \to \pi^0 \nu \bar{\nu})$ to 20%, also known as KLEVER [6].

In addition, periodic runs will be taken in beam-dump mode, with the target out and the collimator in the secondary beam line closed, to allow sensitive searches for the decays of exotic, long-lived particles produced in the decays of mesons from interactions in the beam dump, with the goal of collecting $10^{19}$ protons on target (pot) in Phase 1 and up to $5 \times 10^{19}$ pot by the end of Phase 3.

The experimental setup for all three phases will rely to the maximum extent possible on the reuse of the same detectors in different configurations. In particular, when a detector for HIKE is newly built or extensively upgraded, if at all possible, it is designed to meet the performance requirements for all successive phases.

3.1. HIKE Phase 1

The four-fold increase in primary intensity needed for the measurement of $\text{BR}(K^+ \to \pi^+ \nu \bar{\nu})$ to 5% will require major upgrades of the primary and secondary beamlines, as discussed in [7]. From the standpoint of the experiment, the success of NA62 has validated the measurement technique and proves that the background can be handled. The key challenge from the intensity increase is that the time resolution of the detectors must be improved across the board by a factor of four in order to maintain the loss of events from accidental coincidence (random veto) to acceptable levels ($\lesssim 25\%$), which must be achieved while maintaining other key performance specifications such as space-time reconstruction performance, low material budget, high single
photon efficiencies, etc. The experimental setup, shown in Figure 2, is not very different from that of NA62, but most detectors will need to be rebuilt or extensively overhauled to secure the needed performance.

Of particular interest, the NA62 beam tracker (Gigatracker, GTK), consisting of three stations of silicon pixel detectors, will need to be upgraded to track at 3 GHz. A time resolution of better than 50 ps will be required, and the detector will have to be able to handle rates of 8 MHz/mm² and be radiation resistant up for particle fluences of more than $2 \times 10^{15} \text{n eq/cm}^2/\text{yr}$. An excellent candidate technology is provided by the timeSPOT project [8, 9], which is developing hybrid 3D-trenched pixels in which the pixel electrode geometry is optimized for timing performance.

The experiment’s rate capability for secondary particles must be improved as well. New straw-tube designs are being developed at CERN, based on past collaboration with Dubna, that will allow straw chambers for use in vacuum to be developed with 5-mm diameter straws with wall thickness of 20 µm.

It is natural to inquire whether the NA48 liquid-krypton (LKr) calorimeter [10] used in NA62 can be reused for any of the HIKE phases. NA48-era studies suggest and NA62 experience confirms that the photon detection efficiency is sufficient for at least Phases 1 and 2. The time resolution, however, is insufficient for the high-intensity program and would require improvement by at least a factor of four. Two directions are being pursued. The first is to examine whether the LKr can be used for HIKE Phase 1. In addition to necessary consolidation work, this would require upgrades to make the calorimeter faster, including an increase in the operating voltage to increase the drift velocity and faster signal shaping and digitizers for the readout system. For the $K_L$ phases, the diameter of the LKr inner bore limits the solid angle of the beam that can be used, so a new calorimeter would be necessary in any case. The new calorimeter could also be used in Phase 1, if it is ready in time. An ideal choice of technologies appears to be the fine-sampling shashlyk design used for the KOPIO and PANDA calorimeters [11], which has been shown to provide excellent energy and time resolution. For HIKE, PID capability could be added by including independently read out, 1-cm-thick “spy tiles” at key points in the shashlyk stack (for example, at the front of the calorimeter for charged-particle identification, at shower maximum, and deep in the stack). Prototypes with this design have been tested at Protvino and DESY. Another option under investigation is to construct the calorimeter with new-generation, nanocomposite scintillators [12], which offer high light output, fast response, and good radiation robustness.

### 3.2. HIKE Phase 2

![Experimental setup for HIKE Phase 2](image)

**Figure 3.** Experimental setup for HIKE Phase 2

For HIKE Phase 2, a new neutral beamline is required. The baseline design is the original
120-m beamline for KLEVER [13], featuring four collimation stages, including an active final collimator that is incorporated into the experiment and an oriented-crystal-metal photon converter at the center of the dump collimator to reduce the flux of prompt photons in the beam [14]. The collimation system defines a beam opening angle of 0.4 mrad. The neutral beam is produced at $\theta = 2.4$ mrad; $K_L$ mesons in the beam have an average momentum of 79 GeV, while those decaying in the fiducial volume (FV) have an average momentum of 46 GeV. Relative to the Phase-1 experiment, in addition to the changes to the beamline and the removal of the beamline detectors for charged particles, the RICH is removed and the spectrometer is moved further downstream to increase the acceptance for decays such as $K_L \to \pi^0 \ell^+ \ell^-$. The beamline and experimental setup are illustrated in Figure 3.

At a primary intensity of $2 \times 10^{13}$ ppp (a six-fold increase with respect to NA62), nearly $2 \times 10^{14}$ kaon decays will be observed in the FV in five years of running. This will allow single-event sensitivities for $K_L \to \pi^0 \ell^+ \ell^-$ to be improved by two orders of magnitude with respect to the current best limits from KTeV [15, 16]. There are topologically identical backgrounds to these channels from $K_L \to \gamma \gamma \ell^+ \ell^-$, with BRs that are 3–4 orders of magnitude greater than for $K_L \to \pi^0 \ell^+ \ell^-$ [17]. Suppression of these backgrounds relies on the excellent energy resolution of the HIKE EM calorimeter for the reconstruction of the $\pi^0$ mass peak for the signal decay. HIKE Phase 2 will be well positioned to make the first observation of the $K_L \to \pi^0 \ell^+ \ell^-$ decay, as well as to measure $\text{BR}(\Lambda \to \mu^+ \mu^-)$ with a statistical precision of 0.2%, improving on the current best result from BNL-E871 [18], and should also achieve BR sensitivities of $O(10^{-12})$ for a broad range of rare and forbidden $K_L$ decays, such as lepton-flavor violating processes, representing improvement on current best limits from BNL-E871 by up to a factor of 60.

3.3. HIKE Phase 3

HIKE Phase 3 is a dedicated experiment, known as KLEVER, to measure $\text{BR}(K_L \to \pi^0 \nu \bar{\nu})$ to 20%. Specifically, with a total exposure of $6 \times 10^{19}$ pot in five years at an intensity of $2 \times 10^{13}$ ppp, the KLEVER goal is to detect 60 signal events at the Standard Model branching ratio, with a signal-to-background ratio $S/B \sim 1$. The experiment is complementary to KOTO, in the sense that the beam energy is significantly higher. As a result, photons from $K_L$ decays receive a significant boost, which makes photon vetoing easier. On the other hand, the length of the experiment is much greater, and a very long beamline is required to allow $\Lambda$ baryons and $K_S$ mesons to decay upstream of the fiducial volume. Relative to the Phase-2 beamline, the KLEVER beamline needs to be extended by an additional 150 m from target to final collimator. This in turn requires a downstream extension of the ECN3 hall by a similar amount. For KLEVER running, the production angle for the neutral beam will be increased from 2.4 to 8.0 mrad: this decreases the $n/K_L$ and $\Lambda/K_L$ ratios for the beam and softens the momentum
spectra so that the average $K_L$ momentum is 39 GeV at production (26 GeV for $K_L$ mesons that decay in the FV). This also decreases the absolute $K_L$ flux, which is further reduced by the need to collimate the beam more tightly ($\Delta \theta = 0.256$ mrad) for the extended beamline. The need for additional construction to extend the ECN3 hall is a major factor in scheduling KLEVER towards the end of the HIKE program. Cost estimates are in progress.

From the standpoint of the experiment, the layout of the vacuum tank and fiducial volume is roughly the same as for the other HIKE phases. The spectrometer will be removed and the number of large-angle photon veto detectors will be increased from 12 to 25 to extend the polar angle coverage out to 100 mrad (from 50 mrad for Phases 1 and 2). The HIKE large-angle vetoes themselves will be fine-segmented lead/scintillating tile detectors similar to the VVS detectors for the planned but never realized CKM experiment [19]. One particularly challenging detector for KLEVER is the small-angle calorimeter (SAC), which sits in the neutral beam at the downstream end of the experiment and which must reject photons from background decays such as $K_L \rightarrow \pi^0\pi^0$ that would otherwise escape via the beam exit. The SAC must have good photon detection efficiency, especially for high energy photons (e.g., the inefficiency must be $< 10^{-4}$ for photons with $E > 30$ GeV) while being as insensitive as possible to the accidental coincidence of nearly 600 MHz of neutral hadrons ($n$ and $K_L$) in the beam. The SAC must also have $\sigma_t < 100$ ps, be able to separate two pulses a few ns apart, and be radiation hard to $10^{14} n/cm^2$ and $10^5$–$10^6$ Gy. Our proposed solution is an ultra-fast, high-Z crystal calorimeter based on a Cerenkov radiator like PbF$_2$ or an ultra-fast scintillator such as PWO-UF [20], which has a dominant emission component with $\tau < 0.7$ ns. The SAC will have transverse and longitudinal segmentation for $\gamma/n$ discrimination. From an engineering standpoint, it will be very similar to the CRILIN calorimeter [21], and R&D is proceeding in concert between the HIKE and CRILIN collaborations. An additional possibility under investigation is to exploit the coherent interactions of high-energy photons in oriented crystals to stimulate early pair conversion, allowing the calorimeter to be realized with reduced thickness, increasing the transparency to neutral hadrons while maintaining high detection efficiency for photons [22].

4. Conclusions
The HIKE project consists of a three-phase experimental program for the comprehensive study of flavor physics in the kaon sector. The experimental apparatus changes over time with a staged approach, allowing HIKE to evolve and adapt its physics scope, an important feature for a project that embraces a time scale of more than decade, during which the physics landscape could change. Thanks to the successful experience of NA62 and its predecessor NA48, the experimental techniques are well established and robust expectations of sensitivity can be obtained from the extrapolation of existing data. The HIKE Letter of Intent was submitted to the CERN SPSC at the beginning of November 2022 [5]. A formal proposal is in preparation for submission in fall 2023.

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