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Status and Prospects of $K \to \pi\nu\bar{\nu}$ at NA62 and KOTO

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The ultra-rare $K \to \pi\nu\bar{\nu}$ decays are considered golden modes in flavour physics. The charged $K^+ \to \pi^+\nu\bar{\nu}$ decay mode is under investigation by the NA62 fixed-target experiment at CERN. NA62 collected the world's largest dataset of charged kaon decays in 2016-2018, leading to the first measurement of the branching ratio BR($K^+ \to \pi^+\nu\bar{\nu}$) based on 20 signal candidates. This provides evidence for the ultra-rare $K^+ \to \pi^+\nu\bar{\nu}$ decay, observed with a significance of 3.4σ. NA62 restarted operation in 2021, and will continue taking data until CERN long shutdown 3, with the main goal of improving the precision on the measurement of BR($K^+ \to \pi^+\nu\bar{\nu}$). The search for the neutral $K_L \to \pi^0\nu\bar{\nu}$ mode is currently being addressed by the KOTO experiment, located at the J-PARC accelerator complex in Japan. KOTO is expected to reach the Standard Model sensitivity for the $K_L \to \pi^0\nu\bar{\nu}$ decay in three to four years of data taking. The status of and prospects for $K \to \pi\nu\bar{\nu}$ measurements at NA62 and KOTO experiments are reviewed.

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1. Introduction

The $K \to \pi\nu\bar{\nu}$ decays are Flavour Changing Neutral Current (FCNC) processes and are therefore of particular interest in the study of the physics of flavour. In the Standard Model (SM) these decays are extremely rare due to the quadratic GIM mechanism and the $t \to d$ Cabibbo suppression; they can only proceed through Z penguin and W box (one-loop) diagrams. The decay amplitudes are dominated by short-distance dynamics, with the leading SM contribution generated by top quark loops. Additionally the $K \to \pi\nu\bar{\nu}$ decay rates are computed with negligible theoretical uncertainty, as the hadronic matrix element can be extracted from the precisely measured $K^+ \to e^+\pi^0\nu_e$ decay rate. The SM predictions for the branching ratios using elements of the CKM matrix extracted from tree-level processes are [1][2]: $BR(K^+ \to \pi^+\nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$ and $BR(K_L \to \pi^0\nu\bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}$, with uncertanties dominated by the knowledge of the external inputs. The $K \to \pi\nu\bar{\nu}$ decays are excellent probes of flavour physics. Their strong suppression within the SM leads to high sensitivity to possible New Physics (NP) scenarios [3]. NP predictions include tree-level FCNC processes mediated by a heavy gauge boson (Z) [4], for which the combined measurement of BR($K^+ \to \pi^+\nu\bar{\nu}$) and BR($K_L \to \pi^0\nu\bar{\nu}$) would show specific correlations. In NP models with Lepton Flavour Universality (LFU) violation [5] the $K^+ \to \pi^+\nu\bar{\nu}$ could be linked to the anomalies observed in semileptonic B meson decays, and can constrain lepto-quark models [6].

2. The NA62 experiment at CERN

The NA62 experiment at the CERN SPS is a fixed target detector specifically designed to study the ultra-rare $K^+ \to \pi^+\nu\bar{\nu}$ decay. The NA62 experiment aims to precisely measure BR($K^+ \to \pi^+\nu\bar{\nu}$) using a novel decay-in-flight technique. The NA62 strategy is to collect at least $10^{13}K^+$ decays and achieve a background rejection factor at the level of 10^{12}. So far NA62 has collected the world's largest dataset of K^+ decays ($\sim 6 \times 10^{12}$) in a period called RUN1 (2016-2018). In NA62 a secondary unseparated hadron beam of central momentum (75.0 ± 0.8) GeV/c is produced from SPS primary protons at 400 GeV/c directed on a beryllium target. The total particle rate is about 600 MHz, of which ~ 6% are K^+. About 10% of the K^+ decay in a 60 m fiducial volume (FV). The schematic layout of the NA62 experiment comprising the target, secondary beam line, and detectors is shown in Fig. 1 and described in [10]. The tracking system is composed of three stations of silicon micro-pixel GigaTracker (GTK) beam spectrometer and a four straw chamber spectrometer (STRAW) responsible for the tracking of particles upstream and downstream of the FV, respectively. A differential Cherenkov counter is used for K^+ identification in the hadron beam (KTAG [11]), a Ring Imaging Cherenkov (RICH [12]) detector provides π/μ separation and timing, liquid Krypton electromagnetic (LKr) and hadronic (MUV1,2) calorimeters ensure $\pi/\mu/e$ separation. The photon veto system is composed by several detectors covering photon emission angles up to 50 mrad: the LKr, intermediate ring (IRC) and small angle (SAC) calorimeters, as well as twelve stations of large angle vetoes (LAV) distributed over the whole length of the FV. The veto system also comprises plastic scintillators (MUV3) to suppress muons. Detector redundancy is necessary to reach a background rejection at the required level of 10^{12}. Information from several detectors is combined into hardware and software conditions to provide multi-level trigger requirements [13][14].

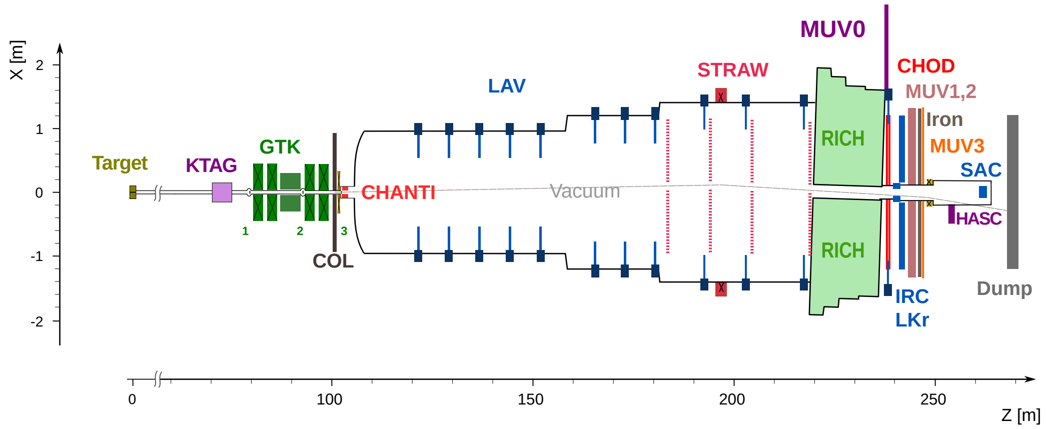
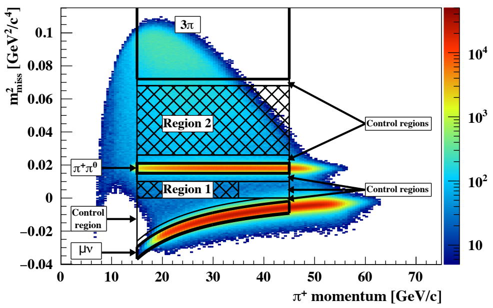


Figure 1: Schematic layout of the NA62 experiment in the xz plane.

3. The $K^+ \to \pi^+\nu\bar{\nu}$ analysis

The $K^+ \to \pi^+\nu\bar{\nu}$ analysis with NA62 2016 and 2017 data demonstrated the validity of the kaon decay-in-flight technique [7][8]. The results presented here are based on the analysis of NA62 data collected in the full RUN1 (2016-2018) [9]. The experimental signature of a $K^+ \to \pi^+\nu\bar{\nu}$ event is an incoming K^+ and an outgoing π^+ with missing energy in the final state. The kinematics of the $K^+ \to \pi^+\nu\bar{\nu}$ decay can be fully described by the squared missing mass variable $m^2_{miss} = (P_K - P_\pi)^2$, where P_K and P_π are the 4-momenta of the K^+ candidate and of the downstream charged particle, in the charged pion mass hypothesis. The m^2_{miss} variable is used to kinematically discriminate the signal from the other K^+ decays. For K^+ decays in the FV with single track topology the π^+ mass is assigned to the downstream track, and the distribution of the reconstructed m^2_{miss} as a function of the downstream track momentum is shown in Fig. 2. Features due to the main K^+ decays ($K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu_\mu$, $K^+ \to \pi^+\pi^-\pi^+$) are clearly visible; in particular the negative part of the distribution from $K^+ \to \mu^+\nu_\mu$ ($\mu\nu$) where a π mass has been assigned to the downstream track, the peak from $K^+ \to \pi^+\pi^0$ ($\pi^+\pi^0$), and the upper bound from $K^+ \to \pi^+\pi^-\pi^+$ (3π) decays. Two kinematic signal regions are defined for the analysis (Region 1, Region 2), and several control regions are considered to validate the background estimation. Signal, control and background regions are drawn in Fig. 2. The signal selection proceeds through π^+ identification and rejection of photons and multitrack events. The π^+ tracks are identified by combining the information from the RICH detector and the calorimeters (LKr, MUV1-2-3). Events with in-time extra energy deposits in the LKr are rejected if the corresponding clusters are more than 10 cm away from the impact position of the π^+ on the LKr. Events with in-time activity in either the LAV, SAV, IRC or downstream counters are rejected. Combining information from the STRAW, CHODs and LKr, events with extra charged particles in the final state not reconstructed in the spectrometer or with photons interacting in the material before reaching LKr, LAV and SAV are also rejected. The 2018 dataset is divided in two samples, S1 and S2, corresponding to before and after the installation of a new collimator (COL) which reduces the background from K^+ decays upstream of GTK3 entering the fiducial volume (upstream background). The S2 sample is subdivided into six sub-samples, defined by 5 GeV/c wide momentum bins, and the selection is optimised separately for each data sample.



	S1	S2
SES $\times 10^{10}$	0.54 ± 0.04	0.14 ± 0.01
$N_{\pi\nu\nu}$	$1.56 \pm 0.10 \pm 0.19_{ext}$	$6.02 \pm 0.39 \pm 0.72_{ext}$
$K^+ \to \pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$K^+ \to \mu^+\nu_\mu$	0.19 ± 0.06	0.45 ± 0.06
$K^+ \to \pi^+\pi^- e^+\nu_e$	0.10 ± 0.03	0.41 ± 0.10
$K^+ \to \pi^+\pi^-\pi^+$	0.05 ± 0.02	0.17 ± 0.08
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$

Figure 2: Left: m^2_{miss} observable as a function of the momentum of the downstream charged particle, used to define the two signal regions, the background regions of the main K^+ decay channels and the control regions. Right: expected SM signal and background events in signal regions for the two 2018 samples.

3.1 Results

The number of expected $K^+ \to \pi^+\nu\bar{\nu}$ SM events, $N_{\pi\nu\nu}$, is estimated as:

$$N_{\pi\nu\nu} = N_{\pi\pi} \cdot D \cdot \frac{A_{\pi\nu\nu} \cdot \epsilon_{trg} \cdot \epsilon_{RV}}{A_{\pi\pi}} \frac{BR(\pi\nu\nu)}{BR(\pi\pi)}$$

where $N_{\pi\pi}$ is the number of $K^+ \to \pi^+\pi^0$ decays, used as normalization, selected from minimum bias data with trigger downscaling factor D. The same offline selection criteria are used to select the normalization sample, except for the photon rejection cuts and requiring the m^2_{miss} in the $K^+ \to \pi^+\pi^0$ region. The symbols ϵ_{trg} and ϵ_{RV} denote the trigger and the random veto efficiencies, both measured with data. In particular $(1 - \epsilon_{RV})$ is defined as the probability for a signal event to be randomly rejected by the photon veto conditions. The selection acceptances, $A_{\pi\nu\nu}$ and $A_{\pi\pi}$, for signal and $K^+ \to \pi^+\pi^0$ decays are estimated from MonteCarlo simulations. The branching ratios, $BR(\pi\nu\nu)$ and $BR(\pi\pi)$, are the SM prediction and measured value of $K^+ \to \pi^+\nu\bar{\nu}$ and $K^+ \to \pi^+\pi^0$ decays, respectively. By definition, the single event sensitivity (SES) is equal to $BR(\pi\nu\nu)/N_{\pi\nu\nu}$. Background from $K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu_\mu$ and $K^+ \to \pi^+\pi^-\pi^+$ enters the signal regions if m^2_{miss} is mis-reconstructed; the estimation of these backgrounds is data-driven and validated via kinematic control regions. Background from $K^+ \to \pi^+\pi^- e^+\nu_e$ is evaluated via simulations. The upstream background is also estimated from data. The results obtained with 2018 data are reported in the table of Fig. 2.

Opening the signal regions, 17 signal candidates are observed in the full 2018 dataset, distributed as shown in the left panel of Fig. 3. This result can be combined with those from the analyses of 2016 and 2017 data, where 1 and 2 signal candidates were observed, respectively. To obtain the final branching ratio measurement, a maximum likelihood fit is performed using the signal and background expectations, and the number of observed events in the nine data samples defined for the analysis (right panel of Fig. 3). The resulting measurement is:

$$BR(K^+ \to \pi^+\nu\bar{\nu}) = (1.06^{+0.40}_{-0.34}|_{stat} \pm 0.09|_{syst}) \cdot 10^{-10} \text{ @ } 68\%\ CL.$$

The result is compatible with the SM prediction within one standard deviation, and corresponds to a significance of 3.4σ in terms of observation of this ultra-rare process. It is the most precise measurement of this branching ratio so far.

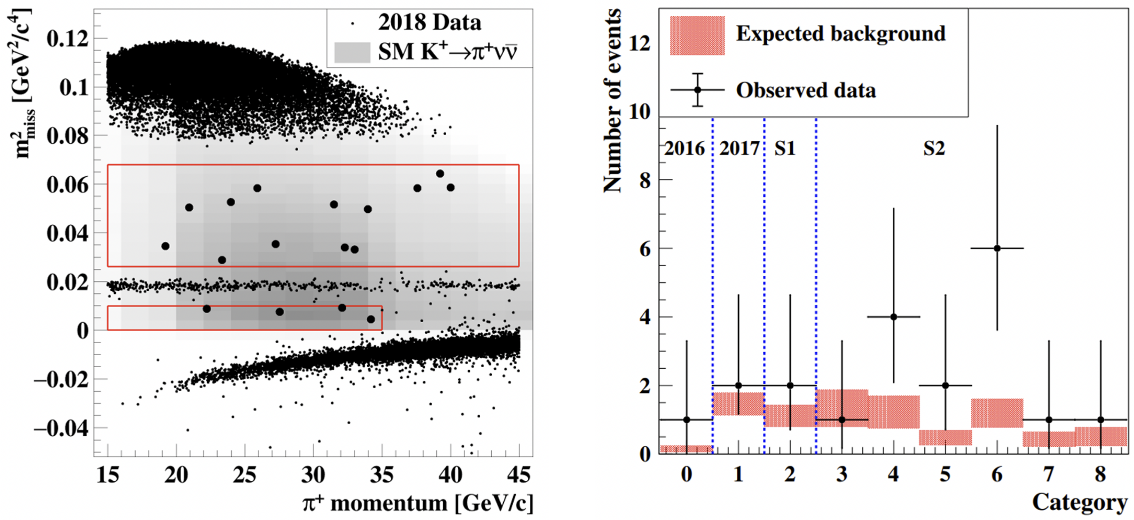


Figure 3: Left: m^2_{miss} as function of the π^+ momentum for events selected in 2018 data, after unblinding the signal regions (red boxes). The grey shaded area reflects the expected SM distribution of signal events. Right: numbers of expected background and observed signal candidates in the nine data samples of RUN1.

4. The KOTO experiment at J-PARC

The KOTO experiment [15] at J-PARC is aiming to observe the $K_L \to \pi^0\nu\bar{\nu}$ decay. A schematic view of the KOTO detector is shown in Fig. 4. Primary protons at 30 GeV/c are extracted from the Main Ring accelerator and directed onto a 66 mm-long gold target. K_L with a peak momentum of 1.4 GeV/c are produced at an angle of 16 degrees with respect to the proton beam; the neutral beam also contains neutrons and photons. A halo of neutrons originating from scattering inside the collimators on the beam line, and travelling outside the nominal beam solid angle, is present. The K_L decay volume is 3 m-long and is hosted inside the detector along the beam direction. To suppress π^0 produced in the interactions of beam neutrons with residual gas, the decay volume is kept at 5×10^{-7} mbar. The main subsystem of the KOTO detector is the electromagnetic calorimeter made of undoped CsI crystals, which detects the $\pi^0 \to \gamma\gamma$ decay in the final state of the signal. Several veto counters ensure that no other detectable particles are emitted in the K_L decay; the lead-scintillator sandwich counters cover the gaps between the cylinder and the crystals of the calorimeter. The outside region of the decay volume is surrounded by the Main Barrel (MB), which is a sandwich-type shower counter with lead and plastic scintillator sheets responsible for the detection of extra particles from $K_L \to \pi^0\pi^0$ and $K_L \to \pi^0\pi^0\pi^0$. The upstream end of the decay region is covered by the Front Barrel (FB) and the Neutron Collar Counter (NCC). The former is a lead-scintillator sandwich counter and the latter is made of CsI crystals. Both these veto counters are used for the detection of photons from K_L decays upstream the decay region. The KOTO experiment has set the most stringent upper limit on the $K_L \to \pi^0\nu\bar{\nu}$ branching ratio to be 3.0×10^{-9} at 90% C.L. with data collected in 2015 [16]. The results of the analysis with the 2016-2018 data revealed new background sources which prevented an improvement of the experimental sensitivity [17]. To reduce this background new detectors were installed after 2018, and improved analysis methods were developed. The results of the analysis of 2016-2018 data are reported here.

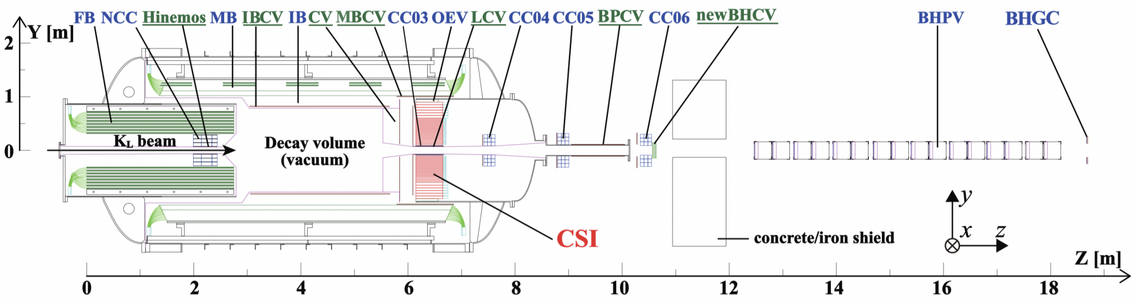


Figure 4: Cross-sectional side view of the KOTO detector. The K_L beam comes in from the left hand side. Also shown is the coordinate system: x is the horizontal, y is the vertical, and z is the beam directions, respectively. The origin of the coordinate is set at the upstream end of the Front Barrel (FB).

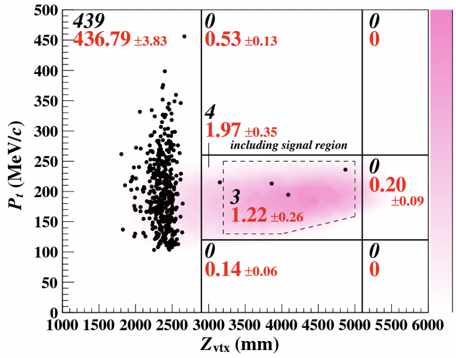
5. The $K_L \to \pi^0\nu\bar{\nu}$ analysis

The $K_L \to \pi^0\nu\bar{\nu}$ decay signature is two photons from a π^0 decay, with no other particles detected. Events with two photons in the final state are selected in the KOTO analysis for π^0 reconstruction. Assuming that the $\pi^0 \to \gamma\gamma$ decay occurred on the beam axis, then the decay vertex position (Z_{vtx}) along the beam axis is calculated. The CsI calorimeter information and Z_{vtx} are used to determine the transverse momentum (P_T) and the π^0 decay time. The signal region for $K_L \to \pi^0\nu\bar{\nu}$ is defined by the Z_{vtx} of the reconstructed π^0 and P_T.

The results of the 2016-2018 analysis are represented in the left panel of Fig. 5, three signal candidate events in the signal box are found, and they are statistically consistent with the number of background events estimated to be 1.22 ± 0.26. A single event sensitivity (SES) of $(7.20 \pm 0.05_{stat} \pm 0.66_{sys}) \times 10^{-10}$ is reached, that is 1.8 times better than the SES from the analysis of 2015 data. However, the resultant upper limit on the branching ratio of the $K_L \to \pi^0\nu\bar{\nu}$ decay is 4.9×10^{-9} at 90% C.L., and is larger than the previous result due to the new background contamination found after examining the blind region. The largest background contribution is due to $K^\pm$ decay events, where the charged kaons are generated in the collisions of K_L with the downstream collimator, and entered the decay region. Among $K^\pm$ decay modes, the $K^\pm \to \pi^0 e^\pm \nu_e$ channel is the dominant source because of the high kinematic limit of 228 MeV/c on the transverse momentum of the π^0 in the final state and the difficulty of detecting the low energy $e^\pm$ emitted in the backward direction. The number of $K^\pm$ background events is estimated to be 0.87 ± 0.25. The second largest background contribution is due to halo $K_L \to 2\gamma$ events, where K_L particles scatter at the surface of the collimators and enter the decay region with a large incident angle. The reconstructed transverse momentum for these K_L decays can be large if the vertex position is mis-reconstructed on the beam axis when the actual K_L decays position is displaced from the beam axis. The number of halo $K_L \to 2\gamma$ background events is estimated to be 0.26 ± 0.07.

6. Prospects for $K \to \pi\nu\bar{\nu}$

NA62 resumed data taking in 2021 after CERN Long Shutdown 2 (LS2) and is approved for operation till LS3. This second period is called RUN2. NA62 recorded $\sim 3 \times 10^{18}$ protons on target in RUN1 and is expected to record twice that number in RUN2. The main goal of NA62 RUN2 is



Source		Number of events
K_L	$K_L \to 3\pi^0$	0.01 ± 0.01
	$K_L \to 2\gamma$ (beam halo)	0.26 ± 0.07[a]
	Other K_L decays	0.005 ± 0.005
$K^\pm$		0.87 ± 0.25[a]
Neutron	Hadron cluster	0.017 ± 0.002
	CV η	0.03 ± 0.01
	Upstream π^0	0.03 ± 0.03
Total		1.22 ± 0.26

[a]Background sources studied after looking inside the blind region.

Figure 5: Left: Reconstructed π^0 transverse momentum (P_T) versus π^0 decay vertex position (Z_{vtx}) plot of the events after imposing the $K_L \to \pi^0\nu\bar{\nu}$ selection criteria. The region surrounded by dotted lines is the signal region. The black dots represent observed events, and the shaded contour indicates the $K_L \to \pi^0\nu\bar{\nu}$ distribution from the MC simulation. The black italic (red regular) numbers indicate the number of observed (background) events for different regions. In particular, 1.22±0.26 (1.97±0.35) is the background expectation for the three (four) events observed inside the signal (blind) region. Right: Summary of the numbers of background events with a central value estimate taken from [17].

to improve the precision of the measurement of BR($K^+ \to \pi^+\nu\bar{\nu}$). Several detector upgrades have been implemented during LS2 to this purpose. A 4th station of GTK was added to improve the $K-\pi$ matching and lower the probability of reconstructing a fake vertex. A veto hodoscope (ANTI0) before the decay volume, and additional veto counters around the beam pipe, were installed to improve the detection of upstream background. A first preliminary analysis of the data collected in 2022 exhibits a sensitivity similar to that of the whole RUN1. A measurement of BR($K^+ \to \pi^+\nu\bar{\nu}$) with a precision of the order of 15% is achievable by LS3, assuming a beam delivery similar to that of 2022 in the upcoming years.

The future 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 kaon sector. The High Intensity Kaon Experiments (HIKE) [18] is a proposal for a long-term multi-purpose kaon physics programme at CERN SPS after LS3. HIKE will profit from a beam intensity increase by a factor 4 with respect to the current NA62 beam. The proposed HIKE program consists of multiple phases and includes both a charged beam (K^+) phase and a neutral beam (K_L) phase. The NA62 apparatus will be replaced by cutting-edge detectors able to cope with the higher intensity. Several detectors will serve both the K^+ and a K_L phase, to guarantee a smooth experimental transition between the two phases. The HIKE physics programme will cover all the main aspects of rare kaon decays and searches accessible via kaon physics, from ultra-rare kaon decays to precision measurements and searches for new phenomena, with unprecedented world-leading sensitivity.

Between 2018-2020 several KOTO detector upgrades were completed with the aim of suppressing background events to $K_L \to \pi^0\nu\bar{\nu}$. With these upgrades, preliminary results from the analysis of 2021 data show that the $K^\pm$ and halo $K_L \to 2\gamma$ backgrounds are suppressed to less than 0.1 event, and the largest residual background is now due to $K_L \to \pi^0\pi^0$ events [19]. The slow extraction for the Hadron Experimental Facility resumed in 2023 and the beam power is being gradually increased from 60 kW to 100 kW. The KOTO experiment is expected to reach the SM sensitivity for the $K_L \to \pi^0\nu\bar{\nu}$ decay in three to four years of data taking.

The KOTO II experiment at J-PARC is a next-generation experiment aiming at the measurement of BR($K_L \to \pi^0\nu\bar{\nu}$) [20]. KOTO II is planned in the extended Hadron Experimental Facility at J-PARC using a second production target. A K_L extraction angle of 5 degrees is chosen instead of 16 degrees in order to obtain a larger K_L flux and harder K_L momentum spectrum, while keeping the same ratio of neutron and K_L fluxes. The KOTO II detector has a longer decay volume to increase the probability that the K_L decays inside the FV, and a larger calorimeter to improve the acceptance of the K_L decay. With the designed beam line and detector, KOTO II aims to collect 40 SM $K_L \to \pi^0\nu\bar{\nu}$ events with 60 background events in a running period of 3×10^7 s, allowing for a $\sim 5\sigma$ discovery of the decay.

7. Conclusions

The NA62 experiment at CERN SPS collected the world's largest dataset of charged kaon decays in 2016-2018, the so called RUN1, and performed the most precise measurement of the branching ratio of the ultra-rare $K^+ \to \pi^+\nu\bar{\nu}$ decay. The NA62 measurement is:

$$BR(K^+ \to \pi^+\nu\bar{\nu}) = (1.06^{+0.40}_{-0.34}|_{stat} \pm 0.09|_{syst}) \cdot 10^{-10} \text{ @ } 68\% \; CL.$$

The result is compatible with the SM prediction within one standard deviation, and corresponds to a significance of 3.4σ in terms of observation of this ultra-rare process. NA62 is approved to take data until LS3, and should more than double the statistics collected in RUN1. The future of kaon physics at CERN relies on the HIKE proposal for a multi-purpose physics programme able to address both charged and neutral kaon decays. The ultra-rare $K_L \to \pi^0\nu\bar{\nu}$ decay is studied with data collected by the KOTO experiment at J-PARC in 2016-2018. With a single event sensitivity of $(7.20 \pm 0.05_{stat} m \pm 0.66_{sys}) \times 10^{-10}$, three candidate events are observed in the signal region, and an upper limit of 4.9×10^{-9} at 90% C.L. is set on the branching ratio of $K_L \to \pi^0\nu\bar{\nu}$. The KOTO experiment resumed operation with upgraded detectors to reduce background, and is expected to reach the SM sensitivity for the $K_L \to \pi^0\nu\bar{\nu}$ decay in three to four years of data taking.

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