

Prospects for an experiment to measure $\text{BR}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$ at the CERN SPS

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Abstract. Precise measurements of the branching ratios for the $K \rightarrow \pi \nu \bar{\nu}$ decays can provide unique constraints on CKM unitarity and, potentially, evidence for new physics. It is important to measure both decay modes, $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$, since different new physics models affect the rates for each channel differently. We are investigating the feasibility of performing a measurement of $\text{BR}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$ using a high-energy secondary neutral beam at the CERN SPS in a successor experiment to NA62. The planned experiment would reuse some of the NA62 infrastructure, including possibly the NA48 liquid-krypton calorimeter. The mean momentum of K_L^0 mesons decaying in the fiducial volume is 70 GeV; the decay products are boosted forward, so that less demanding performance is required from the large-angle photon veto detectors. On the other hand, the layout poses particular challenges for the design of the small-angle vetoes, which must reject photons from K_L^0 decays escaping through the beam pipe amidst an intense background from soft photons and neutrons in the beam. We present some preliminary conclusions from our feasibility studies, summarizing the design challenges faced and the sensitivity obtainable for the measurement of $\text{BR}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$.

1. Introduction

The $K \rightarrow \pi \nu \bar{\nu}$ decays are flavor-changing neutral current (FCNC) processes that probe the $s \rightarrow d \nu \bar{\nu}$ transition via the Z -penguin and box diagrams shown in figure 1. They are highly GIM suppressed and their Standard Model (SM) rates are very small. For several reasons, the

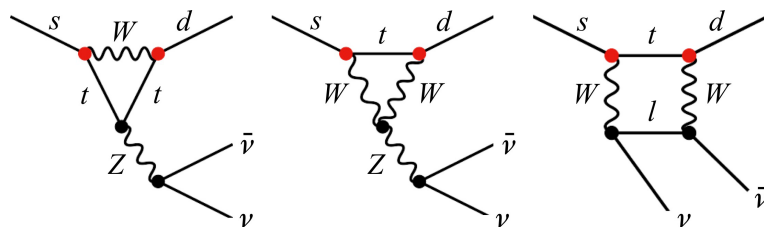


Figure 1. Diagrams contributing to the process $K \rightarrow \pi \nu \bar{\nu}$.

SM calculation for their branching ratios (BRs) is particularly clean (see [1] for a review):

- The loop amplitudes are dominated by the top-quark contributions. The neutral decay violates CP ; its amplitude involves the top-quark contribution only.

- The hadronic matrix element for these decays can be obtained from the precise experimental measurement of the K_{e3} rate.
- There are no long-distance contributions from processes with intermediate photons.

In the SM, $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$ and $\text{BR}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}$ [2]. The uncertainties are entirely dominated by the CKM inputs, which in this case are from tree-level observables. Without the parametric errors from this source, the uncertainties would be just 0.30×10^{-11} (3.5%) and 0.05×10^{-11} (1.5%), respectively. Because of corrections for lighter-quark contributions to the amplitudes, the intrinsic uncertainty is slightly larger for the charged channel.

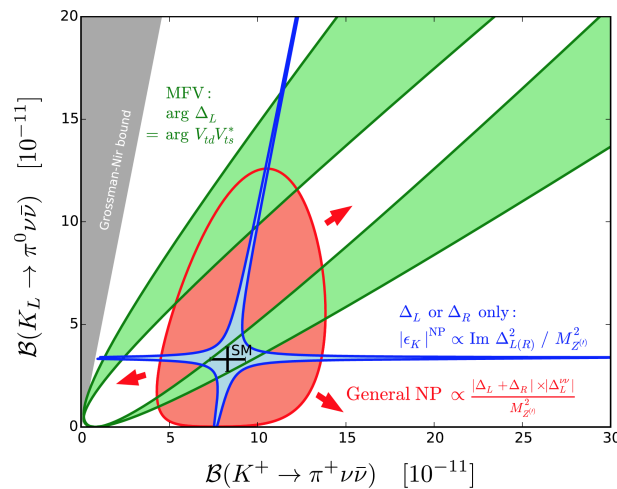


Figure 2. Schematic illustration of correlations between BRs for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ expected in different new-physics scenarios, from [3].

Because the SM rates are small and predicted very precisely, the BRs for these decays are sensitive probes for new physics. In general, $\text{BR}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$ and $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ are differently sensitive to modifications from a given new-physics scenario. If one or both BRs is found to differ from its SM value, it may be possible to characterize the physical mechanism responsible, as schematized in Figure 2, from [3]. For example, if the pattern of flavor-symmetry breaking from new physics were the same as in the SM (minimal flavor violation), the K_L^0 and K^+ BRs would lie along the band of correlation shown in green. If the new interaction were to couple to only left-handed or only right-handed quark currents, as expected for example in models with modified Z couplings or littlest Higgs models with T parity, the BRs would lie along one of the branches shown in blue. New physics without these constraints, as expected for example in models with large extra dimensions, could modify the K^+ and K_L^0 BRs in an arbitrary way, as illustrated in red.

The BR for the decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ has been measured by Brookhaven experiment E787 and its successor, E949. The combined result from the two generations of the experiment, obtained with seven candidate events, is $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.73^{+1.15}_{-1.05} \times 10^{-10}$ [4]. The goal of the NA62 experiment at the CERN SPS [5] is to measure $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ with a precision of about 10%. NA62 is currently running and is expected to collect ~ 100 signal events by the end 2018.

The decay $\text{BR}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$ has never been measured. The KOTO experiment at J-PARC has a good chance of observing it. The experiment makes use of a tightly collimated, low-energy neutral beam (peak momentum 1.4 GeV) and compact, hermetic detector. From a brief pilot run in 2013, KOTO obtained the limit $\text{BR}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) < 5.1 \times 10^{-8}$ (90% CL) [6]. The experiment has been running since 2015. From the preliminary analysis of 5% of the data collected so far,

KOTO has reached a single-event BR sensitivity of 5.9×10^{-9} ; background levels are still under evaluation [7]. By the end of 2015, the beam power reached 42 kW; it is expected to gradually increase to 100 kW. If this can be done, the experiment should reach single-event sensitivity for the SM BR by about 2019. In the longer term, KOTO strongly intends to upgrade the beam and experiment to perform a measurement with ~ 100 event sensitivity. A plan to do so was outlined in the original 2006 KOTO proposal, but there is no official Step 2 proposal yet. The Step 2 measurement would require construction of a new neutral beamline, a complete rebuild of the detector, and extension of the experimental hall; data taking would not be expected to begin before 2025.

2. KLEVER

Given the both the importance and the difficulty of the measurement of $\text{BR}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$, an experiment making use of a technique complementary to that used by KOTO is well motivated. We are evaluating the feasibility of an experiment at the CERN SPS to measure $\text{BR}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$ using a high-energy beam. This makes photon vetoing significantly easier, but increases considerably the size of the detector, and in particular, the volume to be covered with photon vetoes. On the other hand, since the photons from background K_L^0 are boosted forwards, the coverage of the large-angle photon vetoes may not need to extend beyond 100 mrad in the polar angle. The experiment could reuse some of the NA62 experimental infrastructure, and possibly the NA48 liquid-krypton calorimeter [8]. Given the time needed for R&D and construction, in addition to the constraints from the LHC running schedule, the natural target date for the experiment to turn on would be at the start of LHC Run 4, in early 2026.

2.1. Beam

Assuming the SM BR for $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ and an acceptance of 10% for decays within the experiment's fiducial volume (FV), 3×10^{13} K_L^0 decays would be required for the observation of 100 signal events. Extraction of the 400 GeV proton beam onto a $1\lambda_{\text{int}}$ beryllium target to produce a tightly collimated ($0.28 \mu\text{sr}$) neutral beam at an angle of 2.4 mrad (chosen to optimize the ratio of K_L^0 decays in the FV to neutrons in the beam) would result in a K_L^0 flux of 2.8×10^{-5} per proton on target (pot). About 2.2% of the K_L^0 mesons in the beam would decay in a 50-m FV with an average momentum of 70 GeV. The required integrated proton flux is then 5×10^{19} pot. Assuming that this is delivered in 5 years¹ the required primary beam intensity would be 2×10^{13} protons per pulse (ppp) with one pulse every 16.8 s. The sixfold increase in intensity relative to NA62 is made necessary by the tight beam collimation and long K_L^0 lifetime.

The maximum intensity that the SPS can deliver to the North Area is about 4×10^{13} ppp, but apart from competition for protons from the SPS, a primary beam intensity of 2×10^{13} ppp is not currently available on any of the North Area targets. Running with an intensity this high would require comprehensive upgrades to the current beamline cavern and experimental area, as well as the nearly 2 km long beam transport from the extraction point in the SPS to the production target of the experiment. An alternative could be to site the experiment at the North Area Beam Dump Facility under discussion in the context of the SHiP experiment. Either way, detailed solutions and meaningful cost estimates will require studies in collaboration with the CERN Accelerator and Technology Sector.

The layout of the secondary beamline is illustrated in figure 3. The 400-GeV beam is incident on the target at a downward angle of 2.4 mrad. Three collimators are used to obtain a neutral beam with an opening angle of 0.3 mrad: a moveable dump collimator at $z = 15$ m from the target, the defining collimator at $z = 60$ m, and a final collimator at $z = 105$ m with an aperture just larger than the angular limit of the background from the dump collimator, to

¹ 100 effective days of running per year, similar to a Snowmass year.

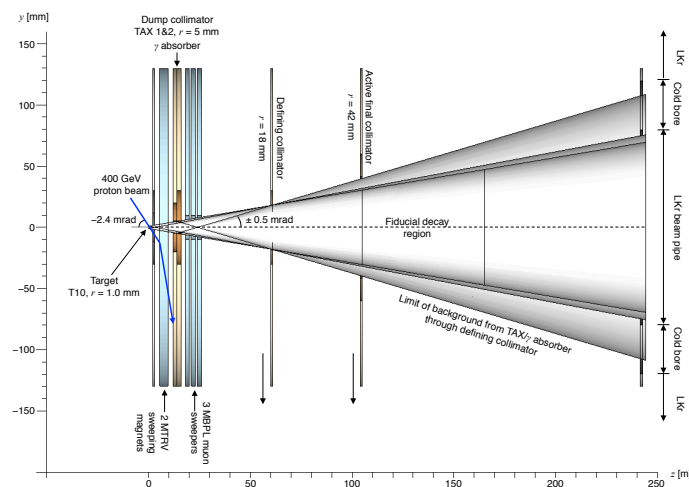


Figure 3. Layout of the neutral beamline.

remove particles showering on the edges of the defining collimator. The 45 m length between the defining and final collimators is equivalent to nearly 9 K_S^0 lifetimes at the mean beam momentum. Vertical sweeping magnets are located just upstream of the dump collimator, and horizontal muon-sweeping magnets are just downstream. A photon converter of high- Z material is placed in the center of the dump collimator, to reduce the flux of photons in the neutral beam.

The K_L^0 , photon, and neutron fluxes in this beamline have been simulated with Fluka and Geant4, with the former used for the beam-target interaction and the latter used for propagation of secondaries through the beamline. The simulation predicts 290 MHz of K_L^0 in the beam, about 50% more than the parameterizations used to estimate the intensity requirement would suggest. The simulation also predicts 230 MHz of photons with $E > 5$ GeV and 20 MHz of photons with $E > 30$ GeV, assuming a 30-mm iridium absorber in the dump collimator. More problematic is the fact that the simulation predicts 3 GHz of neutrons in the beam, which places stringent requirements on the insensitivity of the small-angle calorimeter to neutrons.

2.2. Detector

The experimental signature of the $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ decay consists of two photons with unbalanced transverse momentum in an event in which there are no additional particles. The only available kinematic constraint is on the two-photon invariant mass: $M(\gamma\gamma) = m_\pi^0$. The most dangerous background is from $K_L^0 \rightarrow \pi^0 \pi^0$ decays (which are about 3×10^7 times more abundant than the signal) with two lost photons. The centerpiece of the experiment is the NA48 liquid-krypton calorimeter, which is used both to reconstruct the π^0 for the signal decay and to veto any other photons present. The invariant mass constraint is imposed to obtain the z position of the $\gamma\gamma$ vertex. The layout of the detector elements is schematically illustrated in figure 4. The largest elements are about 3 m in diameter.

The vacuum volume begins 25 m upstream of the final collimator. Decays in this region for which two photons pass through the final collimator can give rise to background. The final collimator itself is thus an active detector, with the collimating surfaces made of LYSO surrounded by an electromagnetic calorimeter extending out to a radius of 1 m to provide upstream veto coverage.

The FV extends from $z = 105$ m (the position of the final collimator) to $z = 155$ m. The front face of the sensitive part of the LKr calorimeter is at $z = 241.5$ m. The 90-m distance from the downstream end of the FV to the LKr significantly aids with background rejection, since most

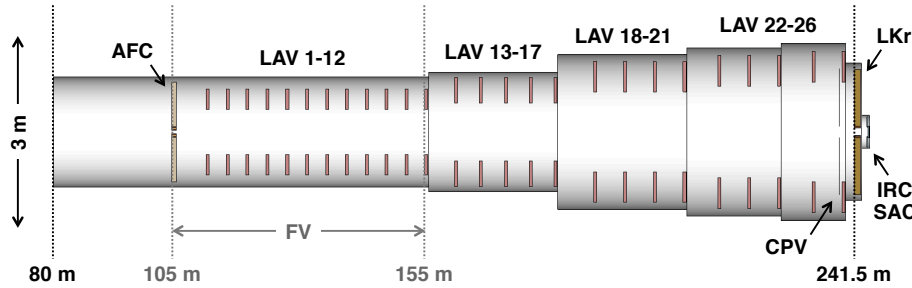


Figure 4. Schematic illustration of the experimental layout. The scales for transverse and longitudinal dimensions are in the ratio 10:1.

$K_L^0 \rightarrow \pi^0\pi^0$ decays with lost photons occur just upstream of the LKr. Even for $K_L^0 \rightarrow \pi^0\pi^0$ events in which the two detected photons are from different π^0 s, the vertex is almost always reconstructed downstream of the FV.

Besides the LKr, there are a total of 26 ring-shaped large-angle photon veto (LAV) stations in five different sizes, placed at intervals of 4 to 6 m to guarantee coverage out to $\theta = 100$ mrad. The LAV detectors are based on the lead/scintillating-tile design of the large-angle photon vetoes for the (canceled) CKM experiment at Fermilab [9].

The small-angle vetoes (IRC and SAC) on the downstream side of the LKr intercept photons from K_L^0 decays that pass through the beam pipe. The small-angle calorimeter (SAC) squarely intercepts the neutral beam. The intermediate-ring calorimeter (IRC) is a ring-shaped detector between the SAC and LKr that intercepts photons from downstream decays that make it through the calorimeter bore at slightly larger angles. Because of the high rates of neutrons and photons in the beam, the design of these detectors, in particular the SAC, is one of the most challenging aspects of the experiment. The task is made a little easier by the fact that photons from K_L^0 decays in the SAC acceptance have very high energy. The SAC can be blind to photons with $E < 5$ GeV, and need only have very high efficiency (99.99%) for photons with $E > 30$ GeV. The current design calls for a compact tungsten/silicon-pad sampling calorimeter with a crystal metal absorber. The coherent interaction of photons with the crystal lattice reduces the radiation length of the absorber, and hence the ratio X_0/λ_{int} (see, e.g., [10]), resulting in a calorimeter with better transparency to neutrons. The effect is greatest for high-energy photons; for 30 GeV photons incident at an angle of 2 mrad, the pair-production cross section is enhanced by a factor of about three. Preliminary Geant4 simulations indicate that perhaps 20% of the neutrons in the beam will interact in the SAC; information on the transverse and longitudinal shower spread and pulse shape information will be used to obtain additional neutron discrimination power.

In addition to the photon vetoes, the experiment makes use of charged-particle veto (CPV) detectors and a hadronic calorimeter downstream of the LKr (not shown in figure 4), to reject background from the copious K_L^0 decays into charged particles.

2.3. Expected performance

The rejection power for background from $K_L^0 \rightarrow \pi^0\pi^0$ events has been studied using a fast Monte Carlo, with statistics equivalent to those from five years of data taking. Signal candidates are required to have exactly two clusters on the LKr and no hits on any other detector. The decay vertex position in z is obtained from the separation between the clusters on the calorimeter and the cluster energies, and is required to be inside the FV. There is a substantial amount of background from upstream decays, but this can be eliminated by requiring that the clusters on the LKr lie outside of a radius of 35 cm from the beam axis. Figure 5 shows the distribution of the

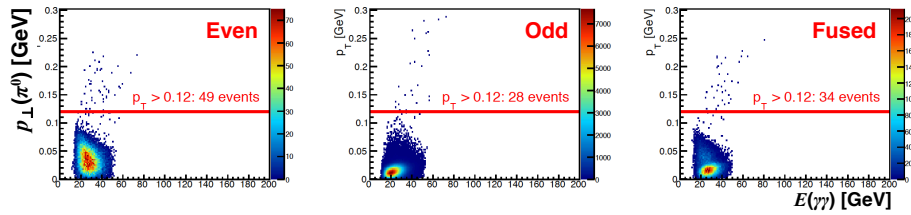


Figure 5. Distribution in $(p_{\perp\gamma\gamma}, E_{\gamma\gamma})$ plane of $K_L^0 \rightarrow \pi^0\pi^0$ events passing all selection cuts, from fast simulation: even events (left), odd events (center), and events with fused clusters (right).

remaining events in the plane of pair transverse momentum $p_{\perp\gamma\gamma}$ vs. pair energy $E_{\gamma\gamma}$ for events in which both photons come from the same π^0 (even pairing), different π^0 s (odd pairing), or in which one or both clusters contain overlapping LKr hits (fused). If $p_{\perp\gamma\gamma}$ for signal candidates is required to be larger than 0.12 GeV, 111 background events remain. Similar high-statistics studies of $K_L^0 \rightarrow \pi^0\pi^0\pi^0$ and $K_L^0 \rightarrow \gamma\gamma$ backgrounds give 15 and 0 counts, respectively ($K_L^0 \rightarrow \gamma\gamma$ is effectively eliminated by the p_{\perp} cut). The acceptance for $K_L^0 \rightarrow \pi^0\nu\bar{\nu}$ decays in the fiducial volume is about 9% (the $p_{\perp\gamma\gamma}$ cut retains 78% of signal events). In five years, 97 signal events are expected to be collected. The photon converter in the dump collimator may absorb or scatter as much as 35% of the beam. This effect is not simulated; taking it into account, at the SM BR, about 60 signal events per year are expected, together with a similar number of background events ($S/B \sim 1$).

3. Conclusions

The present results are highly preliminary. In particular, high-statistics background studies have been carried out only for a few channels. Some potential backgrounds, such as $nn \rightarrow nn\pi^0$ from interactions of beam neutrons on residual gas, need to be investigated. The detector concepts require validation, and the suitability of the LKr performance, in particular concerning photon detection efficiency and time resolution, needs to be verified. The possibility of adding charged-particle tracking to the experiment, which would provide more complete final-state reconstruction for efficiency estimation and systematic control, and which would allow significant expansion of the physics program, is under investigation. Finally, the available intensity and siting options at CERN need to be worked out. With these caveats, our preliminary design studies indicate that an experiment to measure $\text{BR}(K_L^0 \rightarrow \pi^0\nu\bar{\nu})$ can be performed at the SPS during LHC Run 4 (2026-2029). These ideas are under development in the context of the CERN Physics Beyond Colliders initiative [11], with the intention to move towards an official proposal within the next two years.

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