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Kaon experiments at CERN: NA48 and NA62

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Abstract

Searches for violation of lepton flavour universality and lepton number conservation in kaon decays by the NA62 and NA48/2 experiments at CERN, status and future plans of the CERN kaon programme are presented. A precision measurement of the helicity-suppressed ratio R_K of the $K^\pm \to e^\pm\nu$ and $K^\pm \to \mu^\pm\nu$ decay rates has been performed using the full data set collected by the NA62 experiment in 2007–2008. The result is $R_K = (2.488 \pm 0.010)\times 10^{-5}$, in agreement with the Standard Model expectation. An improved upper limit on the rate of the lepton number violating $K^\pm \to \pi^\mp\mu^\pm\mu^\pm$ decay from the NA48/2 experiment (2003–2004 data set) is presented. Finally, the NA62 project aiming at a measurement of the branching ratio of the ultra-rare decay $K^+ \to \pi^+\nu\bar{\nu}$ at 10% precision is discussed.

Keywords: Kaon decays, rare decays

1. Introduction

Decays of pseudoscalar mesons to light leptons ($P^\pm \to \ell^\pm\nu$, denoted $P_{\ell 2}$ in the following) are suppressed in the Standard Model (SM) by helicity considerations. Specific ratios of leptonic decay rates can be computed very precisely: in particular, the SM prediction for the ratio $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$ is [1]

$$\begin{aligned} R_K^{\rm SM} &= \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1 + \delta R_{\rm QED}) = \\ &= (2.477 \pm 0.001)\times 10^{-5}, \end{aligned}$$

where $\delta R_{\rm QED} = (-3.79 \pm 0.04)\%$ is an electromagnetic correction. Within certain two Higgs doublet models (2HDM type II), R_K is sensitive to lepton flavour universality violating effects via the charged Higgs boson ($H^\pm$) exchange [2], the dominant contribution being

$$\frac{R_K}{R_K^{\rm SM}} \simeq 1 + \left(\frac{m_K}{m_H}\right)^4 \left(\frac{m_\tau}{m_e}\right)^2 |\Delta_R^{31}|^2 \tan^6\beta,$$

where $\tan\beta$ is the ratio of the two Higgs vacuum expectation values, and $|\Delta_R^{31}|$ is the mixing parameter between the superpartners of the right-handed leptons, which can reach $\sim 10^{-3}$. This can enhance R_K by $\mathcal{O}(1\%)$ without contradicting any known experimental constraints. A precise R_K measurement based on the full data sample collected during the R_K phase of the CERN NA62 experiment in 2007–2008 (~ 10 times the world K_{e2} sample) is presented, superseding an earlier result [3] based on a partial data set.

The decay $K^\pm \to \pi^\mp\mu^\pm\mu^\pm$ violating lepton number conservation by two units can proceed via a neutrino exchange if the neutrino is a Majorana particle [4]; it has also been studied in the context of supersymmetric models with R-parity violation [5]. The most stringent limits on this and similar lepton flavour and number violating processes come from the BNL E865 experiment [6]. The NA48/2 experiment at CERN collected the world's largest $K^\pm \to \pi\mu\mu$ sample in 2003–2004, which allowed a significant improvement of the BNL upper limit on BR($K^\pm \to \pi^\mp\mu^\pm\mu^\pm$).

Among the flavour changing neutral current K and B decays, the ultra rare decays $K \to \pi\nu\bar{\nu}$ play a key role in the search for new physics through the underlying mechanisms of flavour mixing. These decays are strongly suppressed in the SM (highest CKM suppression), and are dominated by top-quark loop contributions. The SM branching ratios have been computed to an exceptionally high precision with respect to other loop-induced meson decays: BR($K^+ \to \pi^+\nu\bar{\nu}$) = $8.22(75) \times 10^{-11}$ and BR($K_L \to \pi^0\nu\bar{\nu}$) = $2.57(37) \times 10^{-11}$; the uncertainties are dominated by parametric ones, and the irreducible theoretical uncertainties are at a $\sim$ 1% level [7]. The extreme theoretical cleanness of these decays remains also in new physics scenarios like Minimal Flavour Violation (MFV) or non-MFV models, and even modest deviations of BRs from their SM values can be considered signals of new physics.

The $K^+ \to \pi^+\nu\bar{\nu}$ decay has been observed by the E787/E949 experiments at the BNL, and the measured branching ratio is $\left(1.73^{+1.15}_{-1.05}\right) \times 10^{-10}$ [8]. The achieved precision is inferior to that of the SM expectation. The main goal of the NA62 experiment at CERN is the measurement of the $K^+ \to \pi^+\nu\bar{\nu}$ decay rate at the 10% precision level, which would constitute a significant test of the SM.

2. Search for lepton flavour universality violation

The beam line and setup of the NA48/2 experiment [9] have been used during the NA62 R_K phase. The beam line was originally designed to deliver simultaneous narrow momentum band K^+ and K^- beams derived from the primary 400 GeV/c protons extracted from the CERN SPS. In 2007, mostly single beam configurations (with 74 GeV/c central momentum and 1.4 GeV/c rms spread) were used. The momenta of individual beam particles were not measured. The beam kaons decayed in a fiducial decay volume contained in a 114 m long cylindrical vacuum tank.

The momenta of charged decay products are measured in a magnetic spectrometer, housed in a tank filled with helium placed after the decay volume. The spectrometer comprises four drift chambers (DCHs), two upstream and two downstream of a dipole magnet which gives a horizontal transverse momentum kick of 265 MeV/c to singly-charged particles. Each DCH is composed of eight planes of sense wires. The measured spectrometer momentum resolution is $\Delta p/p = 0.48\% \oplus 0.009\% p$, where the momentum p is expressed in GeV/c. A plastic scintillator hodoscope (HOD) producing fast trigger signals and providing precise time measurements of charged particles is placed after the spectrometer. A 127 cm thick liquid krypton (LKr) electromagnetic calorimeter located further downstream is used for lepton identification and as a photon veto detector. Its 13248 readout cells have a transverse size of approximately 2×2 cm^2 each, without longitudinal segmentation.

The analysis strategy is based on counting the numbers of reconstructed K_{e2} and $K_{\mu2}$ candidates collected concurrently. Therefore the analysis does not rely on the absolute beam flux measurement, and several systematic effects cancel at first order. The study is performed independently for 40 data samples (10 bins of reconstructed lepton momentum and 4 samples with different data taking conditions) by computing the ratio R_K as

$$R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_{\rm B}(K_{e2})}{N(K_{\mu2}) - N_{\rm B}(K_{\mu2})} \cdot \frac{A(K_{\mu2})}{A(K_{e2})} \cdot \frac{f_\mu \times \epsilon(K_{\mu2})}{f_e \times \epsilon(K_{e2})} \cdot \frac{1}{f_{\rm LKr}},$$

where $N(K_{\ell2})$ are the numbers of selected $K_{\ell2}$ candidates ($\ell = e, \mu$), $N_{\rm B}(K_{\ell2})$ are the numbers of background events, $A(K_{\mu2})/A(K_{e2})$ is the geometric acceptance correction, f_ℓ are the efficiencies of e/μ identification, $\epsilon(K_{\ell2})$ are the trigger efficiencies, $f_{\rm LKr}$ is the global efficiency of the LKr calorimeter readout (which provides the information used for electron identification), and D is the downscaling factor of the $K_{\mu2}$ trigger. A Monte Carlo simulation is used to evaluate the acceptance correction and the geometric part of the acceptances for background processes entering the computation of $N_B(K_{\ell2})$. Particle identification, trigger and readout efficiencies and the beam halo background are measured directly from control data samples.

Two selection criteria are used to distinguish K_{e2} and $K_{\mu2}$ decays. Kinematic identification is based on the reconstructed squared missing mass assuming the track to be a electron or a muon: $M^2_{\rm miss}(\ell) = (P_K - P_\ell)^2$, where P_K and P_ℓ ($\ell = e, \mu$) are the kaon and lepton 4-momenta (Fig. 1). A selection condition $M_1^2 < M^2_{\rm miss}(\ell) < M_2^2$ is applied; $M^2_{1,2}$ vary across the lepton momentum bins depending on resolution. Lepton type identification is based on the ratio E/p of energy deposit in the LKr calorimeter to track momentum measured by the spectrometer. Particles with $(E/p)_{\rm min} < E/p < 1.1$ ($E/p < 0.85$) are identified as electrons (muons). Here $(E/p)_{\rm min}$ is 0.90 or 0.95, depending on momentum.

The largest background to the K_{e2} decay is the $K_{\mu2}$ decay with a mis-identified muon ($E/p > 0.95$) via the ‘catastrophic’ bremsstrahlung process in the LKr. To reduce the corresponding uncertainty, the muon mis-identification probability $P_{\mu e}$ has been measured as a function of momentum using dedicated data samples.

The numbers of selected K_{e2} and $K_{\mu2}$ candidates are 145,958 and 4.2817×10^7 (the latter pre-scaled at trigger level). Backgrounds in the K_{e2} sample integrated over lepton momentum are summarised in Table 1: they have been estimated with Monte Carlo simulations, except

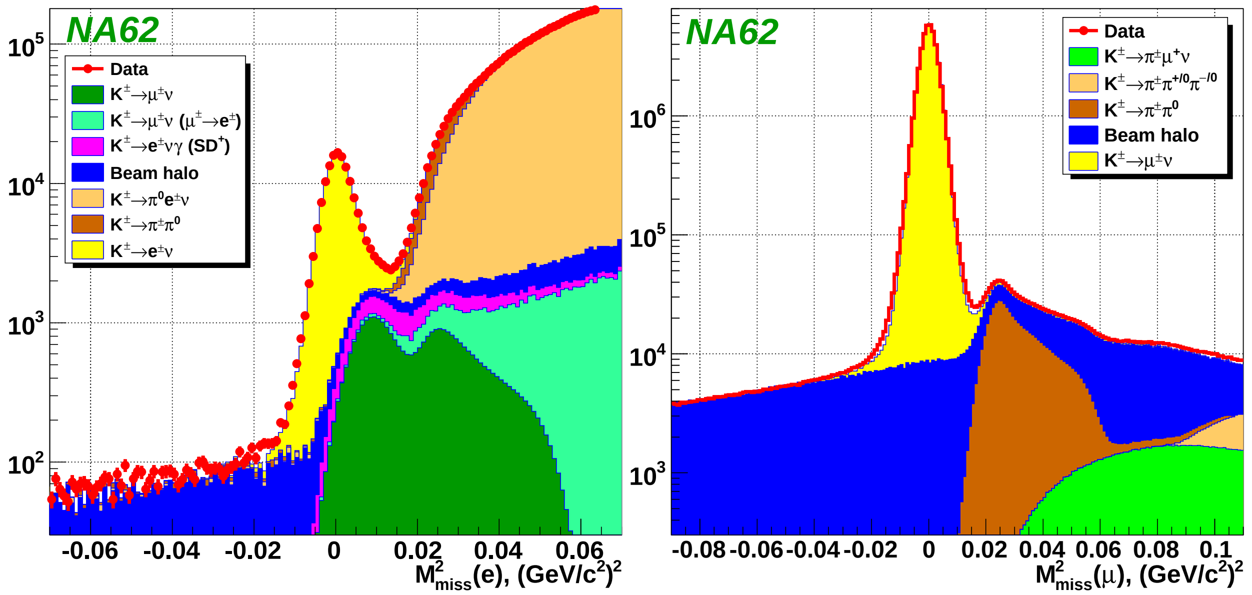

Figure 1: Distributions of the reconstructed squared missing mass $M^2_{\rm miss}(e)$ (left) and $M^2_{\rm miss}(\mu)$ (right) of the K_{e2} ($K_{\mu2}$) candidates compared with the sums of normalised estimated signal and background components. The double peak structure in the spectrum of the $K_{\mu2}$ background to K_{e2} decay is due to the momentum dependent particle identification criterion.

for the beam halo background measured directly with dedicated data samples. The contributions to the systematic uncertainty of the result include the uncertainties on the backgrounds, helium purity in the spectrometer tank (which influences the detection efficiency via bremsstrahlung and scattering), beam simulation, spectrometer alignment, particle identification and trigger efficiency. The final result of the measurement, combined over the 40 independent samples taking into account correlations between the systematic errors, is

$$\begin{aligned} R_K &= (2.488 \pm 0.007_{\rm stat.} \pm 0.007_{\rm syst.}) \times 10^{-5} = \\ &= (2.488 \pm 0.010) \times 10^{-5}. \end{aligned}$$

The stability of R_K measurements in lepton momentum bins and for the separate data samples is shown in Fig. 2. The result is consistent with the Standard Model expectation, and the achieved precision dominates the world average.

3. Search for lepton number conservation violation

The $K^\pm \to \pi^\mp\mu^\pm\mu^\pm$ decay has been searched for using a large sample of $K^\pm$ decays with at least three charged tracks in the final state collected by the NA48/2 experiment in 2003–2004. Three-track vertices with no significant missing momentum are reconstructed from the magnetic spectrometer information. Identification of pion and muon candidates is performed on the basis of energy deposition in the LKr calorimeter and the muon detector. The muon identification efficiency has been measured to be above 98% for $p > 10$ GeV/c.

Table 1: Summary of backgrounds in the K_{e2} sample.

Source	$N_B/N(K_{e2})$
$K_{\mu2}$	(5.64 ± 0.20)%
$K_{\mu2}$ ($\mu \to e$ decay)	(0.26 ± 0.03)%
$K^\pm \to e^\pm\nu\gamma$ (SD$^+$)	(2.60 ± 0.11)%
$K^\pm \to \pi^0 e^\pm \nu$	(0.18 ± 0.09)%
$K^\pm \to \pi^\pm\pi^0$	(0.12 ± 0.06)%
Beam halo	(2.11 ± 0.09)%
Decays of opposite sign K	(0.04 ± 0.02)%
Total	(10.95 ± 0.27)%

The invariant mass spectrum of the reconstructed $\pi^\pm\mu^\pm\mu^\mp$ and $\pi^\mp\mu^\pm\mu^\pm$ candidates is presented in Fig. 3. The observed $K^\pm \to \pi^\pm\mu^\pm\mu^\mp$ decay signal has been analyzed separately [10]. For the lepton number violating signature, 52 events are observed in the signal region $|M_{\pi\mu\mu} - M_K| < 8$ MeV/c^2. The background comes from the $K^\pm \to 3\pi^\pm$ decays with subsequent $\pi^\pm \to \mu^\pm\nu$ decay, is well reproduced by Monte Carlo simulation, and has been estimated by the simulation to be (52.6 ± 19.8) events. The quoted uncertainty is systematic due to the limited precision of MC description of the high-mass region, and has been estimated from the level of agreement of data and simulation in the control mass region

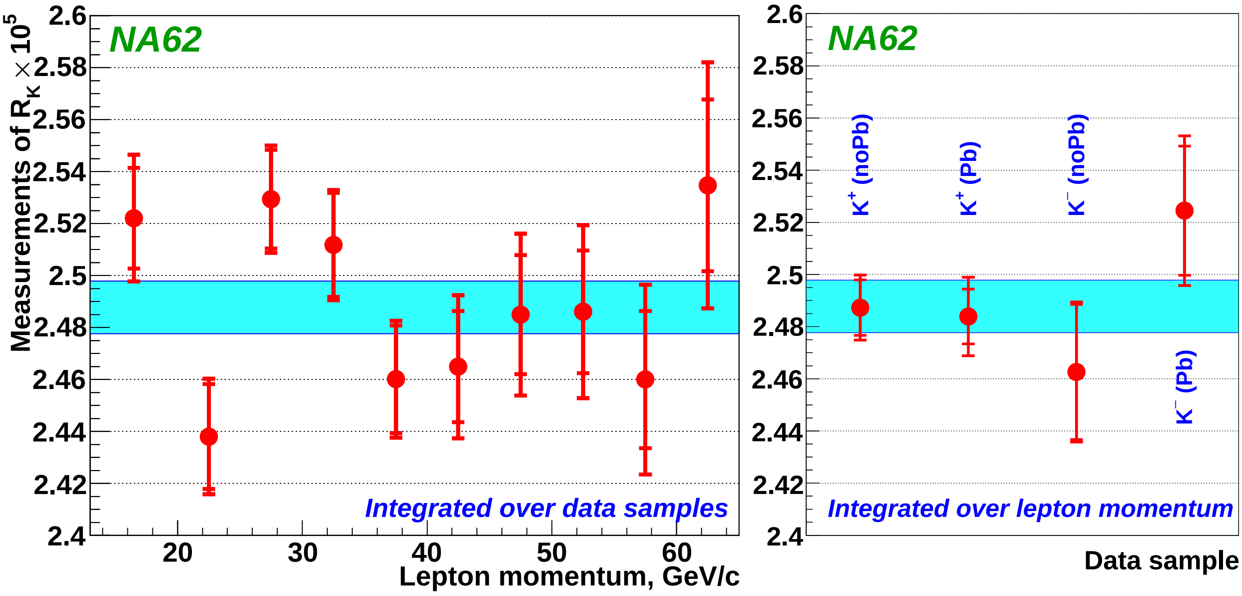

Figure 2: Stability of the R_K measurement versus lepton momentum and for independent data samples. The "Pb/noPb" labels indicate samples with present and absent lead wall covering a part of the LKr calorimeter in order to measure the muon mis-identification probability. The result of the combined fit over the 40 data bins is shown by horizontal bands.

of (465; 485) MeV/c^2. This background estimate has been cross-checked by fitting the mass spectrum with an empirical function in the region between 460 and 520 MeV/c^2, excluding the signal region between 485 and 502 MeV/c^2.

Conservatively assuming the expected background to be $52.6 - 19.8 = 32.8$ events to take into account its uncertainty, the upper limit for the possible signal is 32.2 events at 90% CL. The geometrical acceptance is conservatively assumed to be the smallest of those averaged over the $K^\pm \to \pi^\pm\mu^\pm\mu^\mp$ and $K^\pm \to 3\pi^\pm$ samples ($A_{\pi\mu\mu} = 15.4\%$ and $A_{3\pi} = 22.2\%$). This leads to an upper limit of BR($K^\pm \to \pi^\mp\mu^\pm\mu^\pm$) $< 1.1 \times 10^{-9}$ at 90% CL, which improves the best previous limit by almost a factor of 3. Further details of the analysis are presented in [10].

4. The ultra-rare decay $K^+ \to \pi^+\nu\bar{\nu}$

The principal goal of the NA62 experiment is the measurement of the branching ratio of the $K^+ \to \pi^+\nu\bar{\nu}$ decay to ∼ 10% precision. The experiment is expected to collect about 100 signal events in two years of data taking, keeping the systematic uncertainties and backgrounds low. Assuming a 10% signal acceptance and the SM decay rate, the kaon flux should correspond to at least 10^{13} K^+ decays in the fiducial volume. In order to achieve a small systematic uncertainty, a rejection factor for generic kaon decays of the order of 10^{12} is required, and the background suppression factors need to be measured directly from the data. In order to achieve the required kaon intensity, signal acceptance and background suppression, most of the existing NA48/NA62 apparatus will be replaced with new detectors.

The CERN SPS extraction line used by the NA48 experiment is capable of delivering beam intensity sufficient for the NA62. Consequently the new setup will be housed at the CERN North Area High Intensity Facility where the NA48 was located. The decay in flight technique will be used; optimisation of the signal acceptance drives the choice of a 75 GeV/c charged kaon beam with 1% momentum bite. The experimental setup is conceptually similar to the one used for NA48: a ∼ 100 m long beam line to form the appropriate secondary beam, a ∼ 80 m long evacuated decay volume, and a series of downstream detectors measuring the secondary particles from the K^+ decays in the fiducial decay volume.

The signal signature is one track in the final state matched to one K^+ track in the beam. The integrated rate upstream is about 800 MHz (only 6% of the beam particles are kaons, the others being mostly π^+ and protons). The rate seen by the detector downstream is about 10 MHz, mainly due to K^+ decays. Timing and spatial information are required to match the upstream and downstream track.

Backgrounds come from kaon decays with a sin-

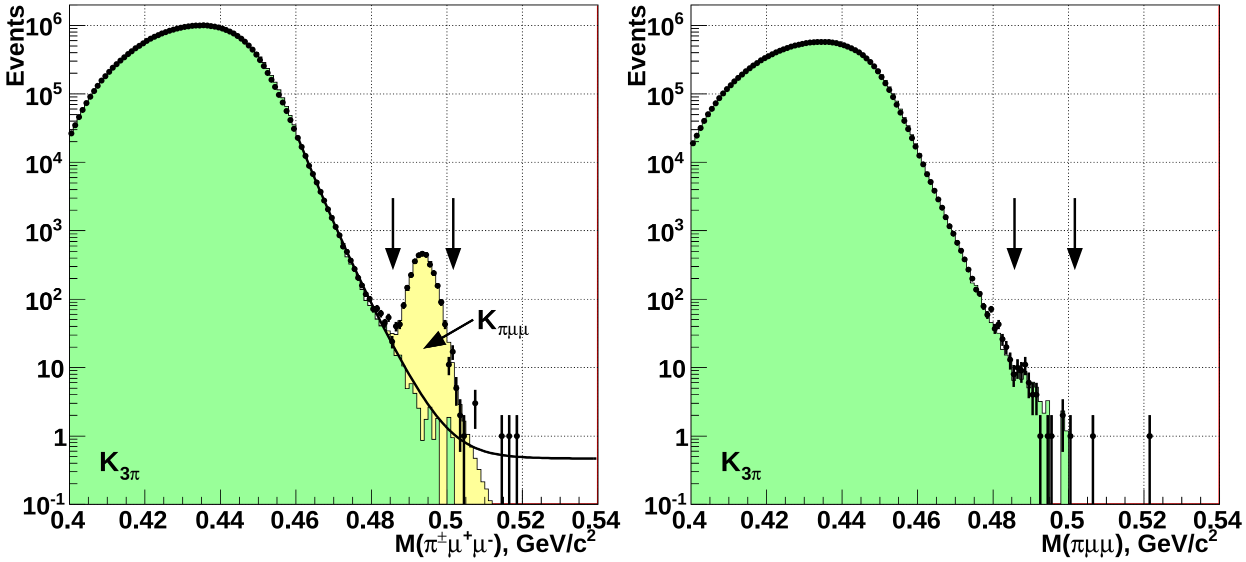

Figure 3: Reconstructed $M_{\pi\mu\mu}$ spectra of $K^{\pm} \to \pi^{\pm}\mu^{\pm}\mu^{\mp}$ (left) and lepton flavour violating $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ (right) candidates: data (dots), $K^{\pm} \to 3\pi^{\pm}$ and $K \to \pi\mu\mu$ MC simulations (filled areas); fit to background using the empirical parameterization. The signal regions are indicated with arrows.

gle reconstructed track in the final state, including accidentally matched upstream and downstream tracks. The background suppression profits from the high kaon beam momentum. A variety of techniques will be employed in combination in order to reach the required level of background rejection. They can be schematically divided into kinematic rejection, precise timing, highly efficient photon and muon veto systems, and precise particle identification systems to distinguish π^+, K^+ and positrons. The above requirements drove the design and the construction of the subdetector systems.

The main NA62 subdetectors are: a differential Cherenkov counter (CEDAR) on the beam line to identify the K^+ in the beam; a silicon pixel beam tracker; guard-ring counters surrounding the beam tracker to veto catastrophic interactions of particles; a downstream spectrometer composed of straw chambers operating in vacuum; a RICH detector to distinguish pions and muons; a scintillator hodoscope; a muon veto detector. The photon veto detectors will include a series of annular lead glass calorimeters surrounding the decay and detector volume, the NA48 LKr calorimeter, and two small angle calorimeters to keep the hermetic coverage for photons emitted at close to zero angle to the beam.

The design of the experimental apparatus and the R&D of the new subdetectors are complete. The experiment is under construction, and the first technical run is scheduled for October–December 2012.

5. Conclusions

The NA48/NA62 experiments at CERN recently accomplished a series of precision measurements of rare $K^{\pm}$ decays. The R_K phase of the NA62 experiment provided the most precise measurement of the lepton flavour parameter $R_K = (2.488 \pm 0.010) \times 10^{-5}$. This result is consistent with the SM expectation, and constrains multi-Higgs and fourth generation new physics scenarios. NA48/2 has improved the upper limit on the branching ratio of the lepton number violating decay $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$, which is now 1.1×10^{-9} at 90% CL. The ultra-rare $K^+ \to \pi^+\nu\bar{\nu}$ decay represents a unique environment to search for new physics. The NA62 experiment, aiming to collect $O(100)$ events of this decay, is being constructed and is preparing for a technical run in 2012.

References

[1] V. Cirigliano and I. Rosell, Phys. Rev. Lett. **99**, 231801 (2007).
[2] A. Masiero, P. Paradisi and R. Petronzio, JHEP **0811**, 042 (2008).
[3] C. Lazzeroni et al., Phys. Lett. B **698**, 105 (2011).
[4] K. Zuber, Phys. Lett. B **479**, 33 (2000).
[5] L.S. Littenberg and R. Shrock, Phys. Lett. B **491**, 285 (2000).
[6] R. Appel et al., Phys. Rev. Lett. **85**, 2877 (2000).
[7] J. Brod, M. Gorbahn and E. Stamou, Phys. Rev. **D83**, 034030 (2011).
[8] A.V. Artamonov et al., Phys. Rev. Lett. **101**, 191802 (2008).
[9] V. Fanti et al., Nucl. Instrum. Methods **A574**, 433 (2007).
[10] J.R. Batley et al., Phys. Lett. **B697**, 107 (2011).