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Precision tests of the Standard Model with Kaon decays at CERN

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Abstract

Effects of new physics in flavor could be found both in Flavor Changing Neutral Current (FCNC) processes and in Lepton Flavor Violation (LFV) modes. The former offer the possibility to deeply test the standard model in a clean environment, while the latter are sensitive to contribution from several models beyond the standard model. In the Kaon sector both FCNC and LFV will be investigated in the NA62 experiment. In addition the kaons sector is an ideal place where to look for new particles and tiny effects, in the region of hundreds of MeV/c^2. In this paper prospects for exotic searches in NA62 will be presented, together with recent results from NA48/2 and NA62-RK on LFV kaon decays modes.

1. Introduction

After the Higgs discovery and the direct search of new particles at the energy frontier, it is becoming increasingly evident that the flavor physics provides a complementary tool to investigate the physics beyond the standard model. In this context the kaon system, in spite of its relative simplicity (relatively few decay channels, low final state multiplicities), offers several opportunities to study deeply the Standard Model (SM). On one side the processes of flavor changing neutral current (FCNC) are a unique laboratory for studying flavor dynamics as described by the CKM matrix and possible extensions, on the other hand processes that violate lepton flavor (LFV) conservation are particularly sensitive to the effects of new physics. Thanks to the availability of high intensity hadron beams at the SPS accelerator, the kaon physics at CERN is continuing an extensive research program.

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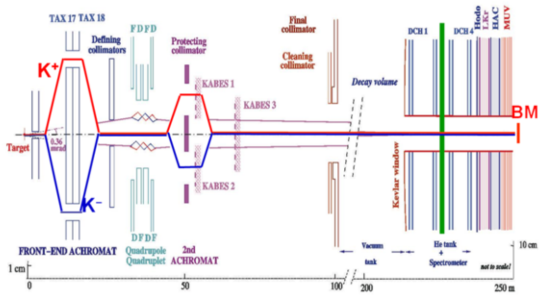

Figure 1: Layout of the NA48/2 experiment at CERN.

In this paper we will describe, in particular, recent results obtained from the NA48/2 and NA62-RK experiments and the prospectives of NA62 experiment, which begins data taking in fall 2014.

The NA48/2 experiment beam line was designed to measure the CP violating charged asymmetry in the $K \rightarrow 3\pi$ decay [1]. Simultaneous positive and negative kaon beams were produced by 400 GeV/c protons from the SPS accelerator impinging on a beryllium target. Particles of opposite charge with a central momentum of (60 ± 3) GeV/c were selected by two systems of dipole magnets (achromats) and focused $\sim 200m$ downstream by a complex system of magnets, at the end of the $\sim$ 100m long decay region. In fig.1 a schematic view of the beam line is shown. Both K^+ and K^- decays are collected concurrently in the NA48 detector, described in details elsewhere [2]. The main detectors used for events reconstruction, particle identification and trigger are: the magnetic spectrometer to measure the charged particle momentum, consisting of a magnet dipole with 120 MeV/c momentum kick and two sets of two drift chambers (DCH), the momentum resolution is $\sigma(p)/p = (1.02 \oplus 0.044 \cdot p)\%$ (with p in GeV/c) and the position resolution is about $\sim 100\mu m$; the electromagnetic calorimeter (LKr) to measure electromagnetic energy deposition of photons and electrons with a resolution of $\sigma(E)/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$ (with E in GeV); the hodoscope (CHOD) to give a fast trigger signal for charged particle (the time resolution per track is $\sim 150ps$); the muon detector system (MUV), made of three scintillator planes shielded by a 80 cm thick iron wall, to collect muons with high efficiency.

The NA62-RK experiment collected data in 2007-2008. It was essentially based on the NA48/2 detector with minor changes. The trigger system has been adapted to collect single track leptonic modes. The beam momentum was (75 ± 3) GeV/c and the momentum resolution of the spectrometer was $\sigma(p)/p = (0.48 \oplus 0.009 \cdot p)\%$ due to the higher magnetic field used.

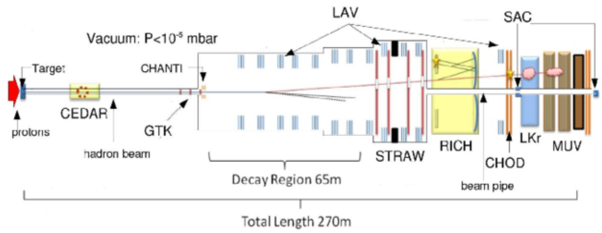

Figure 2: Layout of the NA62 experiment at CERN.

The NA62 started to collect data in fall 2014 with main goal of measuring the ultra-rare process $K^{\pm} \rightarrow \pi^+ \nu \bar{\nu}$. The layout of the NA62 experiment is shown in fig.2 . The unseparated 75 GeV/c hadron beam is obtained by the primary 400 GeV/c proton beam from the SPS accelerator, impinging on a beryllium target. About $\sim$ 6% of the total amount of particles in the secondary 75 GeV/c beam are kaons (the rest are mainly pions ($\sim$ 70%), protons ($\sim$ 23%) and positrons ($\sim$ 1% after filtering through a W foil)). The identification of the kaons in the beam is done in a differential hydrogen Cerenkov counter (CEDAR) followed by a silicon pixel beam spectrometer (Gigatracker) to measure the momentum and the direction of the particles. The decay region is housed in a $\sim 80m$ long $\sim 2.5m$ diameter evacuated tube (10^{-6} mbar). The charged particles produced in kaon decays (pions, muons and electrons) are measured by a straw tubes spectrometer (STRAW) integrated directly inside the evacuated decay region. The Straw spectrometer is very thin (< 0.5 X0 per chamber) to minimize the interactions with the photons coming from the kaon decays. A liquid krypton electromagnetic calorimeter (LKr) is devoted to measure photons and electrons in the forward direction, while a complex of 12 rings of lead glass blocks(LAVs) are placed along the decay region to identify the large angle photons. A 1 atm Neon RICH is used to distinguish among muons and pions in the 15-35 GeV/c range, increasing the particle identification power of the muon identification system (MUVs) placed just beyond the LKr. At nominal intensity the main detectors will be exposed at a rate of 10 MHz of events. A multilevel trigger system is designed to reduce such intensity at few kHz. Further details on the NA62 experiment can be found in Sergi's proceedings for the same conference.

2. LFV in Kaon Sector

The lepton flavor conservation (LF) is an accidental symmetry of the SM, in the sense that there is no a fun-

Process	Upper Limit (90% CL)	Experiment	Ref.
$K^+ \to \pi^+\mu^+e^-$	1.3×10^{-11}	BNL 777/865	[10]
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	BNL 865	[11]
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}	BNL 865	[11]
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}	BNL 865	[11]
$K^+ \to \pi^-\mu^+\mu^+$	1.1×10^{-9}	NA48/2	[12]
$K^+ \to \mu^-\nu e^+e^+$	2.0×10^{-8}	Geneva-Saclay	[13]

Table 1: Current status of searches for the main LFV modes in Kaon decays.

damental reason prevents its possible violation. Many attempts to improve upon the SM introduce new interactions that may give rise to violation of lepton flavor and/or number conservation in specific processes, including supersymmetry [3] [4], mechanisms for dynamical electroweak symmetry breaking with strong coupling such as extended technicolor [5], Little Higgs models [6], models that introduce heavy neutrinos into the SM [7], models featuring large extra dimensions [8] [9], and more. Thanks to the availability of high intensity kaon beams and the clear experimental signature with respect to background processes, the LFV search in kaon sector have reached upper limits to the BR at level of 10^{-10}. As a result, kaon decay experiments have reached sensitivities to branching ratios as low as 10^{-12}, which, by simple dimensional arguments, can provide access to mass scales upwards of 100 TeV in the search for new physics at tree level (e.g., a new gauge boson mediating the tree-level $s \to dme$ transition). In table 1 we summarize the present status for the main LFV decay channels in charged kaon decays.

2.1. R_K

The SM allows a very precise determination of the ratio of $P^\pm \to l^\pm\nu$ (P_{l2}, with $l = \mu, e$) decay amplitudes of the same meson in different lepton flavors, like $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu2})$. Including internal Bremsstrahlung (IB) the prediction for R_K is [14]:

$$R_K^{SM} = \left(\frac{M_e}{M_\mu}\right)^2 \left(\frac{M_K^2 - M_e^2}{M_K^2 - M_\mu^2}\right)^2 (1 + \delta R_{QED})$$

where δR_{QED} is an electromagnetic correction. Models of new physics including sources of lepton flavor violation, predict sizable deviation of R_K from the SM (R_K^{SM}) [15][16][17].

The NA62-RK experiment collected data in 2007-2008 to measure R_K with a precision better than 0.5%.

The K_{e2} and $K_{\mu2}$ events are collected concurrently: in this way R_K does not depend on the absolute kaon flux and the ratio allows for a first order cancellation of several systematic effects, like reconstruction and trigger efficiencies and time dependent biases.

Experimentally, R_K can be defined as:

$$R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu2}) - N_B(K_{\mu2})} \cdot \frac{A(K_{\mu2}) f_\mu \varepsilon(K_{\mu2})}{A(K_{e2}) f_e \varepsilon(K_{e2})} \cdot \frac{1}{f_{LKr}}$$

where $N(K_{l2})$ and $N_B(K_{l2})$ are the number of selected K_{l2} events and expected background events, respectively; D is the downscaling factor applied to the $K_{\mu2}$ trigger; $A(K_{l2})$ the geometrical acceptance of the selected K_{l2} mode; f_l the identification efficiency; $\varepsilon(K_{l2})$ the trigger efficiency; f_{LKr} the global LKr efficiency. The acceptance correction and the geometric part of the acceptances for most of the background processes are evaluated with a Monte Carlo (MC) simulation, while the beam halo background, the particle identification and the readout and trigger efficiencies are measured directly from data. Both f_l and $\varepsilon(K_{l2})$ are well above 99%. The selection criteria of the single track topology are in common between K_{e2} and $K_{\mu2}$. The kinematics of the event and the lepton identification, instead, are effective to separate K_{e2} and $K_{\mu2}$. The kinematic identification is based on the squared missing mass $M^2_{miss} = (P_K - P_l)^2$, where P_K and P_l are the kaon and lepton 4-momenta respectively. The mean P_K is measured on spill basis using fully reconstructed $K^+ \to \pi^+\pi^+\pi^-$ decays; P_l is computed in the electron or muon mass hypothesis. A cut on the M^2_{miss}, according to the M^2_{miss} resolution and dependent on the lepton momentum, selects the K_{l2} candidates. The ratio between the energy deposited by the lepton in the calorimeter and the lepton momentum measured in the spectrometer (E/P) allows

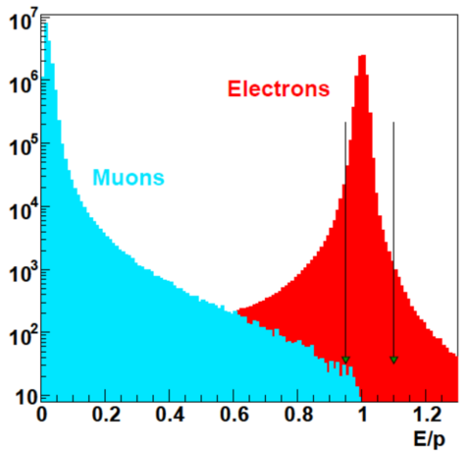

Figure 3: Electromagnetic energy divided by momentum (E/p) is used for particle identification.

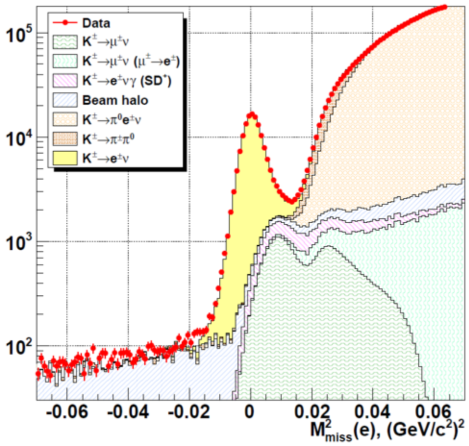

Figure 4: Distributions of reconstructed squared missing masses for reconstructed K_{e2} events.

the lepton identification. A cut on E/P between 0.95 (0.9 at $P_l < 25$ GeV/c) and 1.1 identifies the electrons; those tracks with $E/P < 0.8$ are classified as muons.

The total numbers of selected K_{e2} and $K_{\mu2}$ candidates are 145958 and 4.2862×10^7, respectively. Figure 4 shows the distribution of the M^2_{miss} of reconstructed K_{e2} events with the backgrounds superimposed. The $K_{\mu2}$ background in the K_{e2} sample, is caused, mainly, from muon misidentification due to hard bremsstrahlung in the LKr calorimeter. It has been addressed by a dedicated measurement of the misidentification probability, $P_{\mu e}$, based on a sample of muons from $K_{\mu2}$ decays traversing a lead bar placed in front of the calorimeter. A dedicated Geant4 [18] simulation allowed the evaluation of this momentum-dependent correction. The correspondent measured background relative to the K_{e2} sample, integrated over the different samples, is $(5.64 \pm 0.20)\%$.

The geometrical part of the signal acceptances have been estimated by a MC simulation. The electron and positron identification inefficiency averaged over the K_{e2} sample is $(0.72 \pm 0.05)\%$. It has been measured on data using a sample of $K^\pm \to \pi^0 e^\pm \nu$ and $K_L \to \pi^\pm e^\mp \nu$. The analysis is performed independently for 40 data samples (10 bins of reconstructed lepton momentum and 4 different data samples). The R_K value is obtained through a χ^2 fit to the measurements in the lepton momentum bins and data taking periods ($\chi^2/ndf = 47/39$). The result is: $R_K = (2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5} = (2.488 \pm 0.010) \times 10^{-5}$. The result is stable within the errors versus lepton momentum and for the independent data samples. The main systematics are summarized in table 2. The main contribution comes from the evaluation of the backgrounds. The result is consistent with the SM expectation and the achieved precision dominates the world average. Further details on data analysis and results can be found in [19].

Source	$R_K \times 10^5$
$K_{\mu2}$	0.004
BR($K_{e2\gamma}(SD+)$)	0.002
Beam halo	0.002
$K_{e3}, K_{\pi2}$	0.003
Material	0.002
Acceptance	0.002
DHC alignment	0.001
Electron ID	0.001
LKr read. ineff.	0.001
Trigger	0.001

Table 2: Summary of the main sources of systematics error.

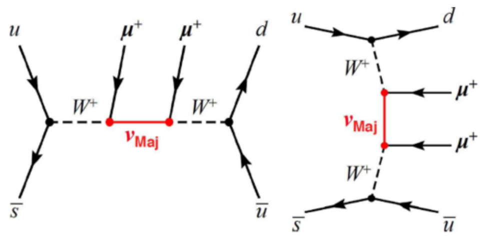

Figure 5: Feynmann diagram for LFV $K+ \to \pi^-\mu^+\mu^+$ mode.

2.2. $K^+ \to \pi^-\mu^+\mu^+$

The existence of the $K+ \to \pi^-\mu^+\mu^+$ process is particularly interesting because, as discussed in [20][21], the lepton number violation in this decay would imply that the virtual neutrino exchanged is a Majorana fermion, i.e., it is its own antiparticle, as illustrated in the diagram of fig.5. This is similar to the case of neutrino-less nuclear double beta decay, providing a tool to study Majorana neutrinos in second generation. In this scenario, the existence of heavy-neutrino mass eigenstates that participate in the neutrino mixing to form sterile, right-handed neutrino flavor eigenstates would also be predicted. Before the NA48/2 analysis, the most stringent limit on the branching ratio for this decay was from the E865 decay-in-flight experiment at Brookhaven [11]. This result is based on the analysis of a few hundred events reconstructed in the magnetic spectrometer and passing the trigger selection. Analysis of the invariant-mass distribution with assigned particle identification $M(\pi^-\mu^+\mu^+)$ gives 5 candidates in the signal window around $M_K^\pm$ with an expected background (from sidebands) of 5.3 events. This is used to set the

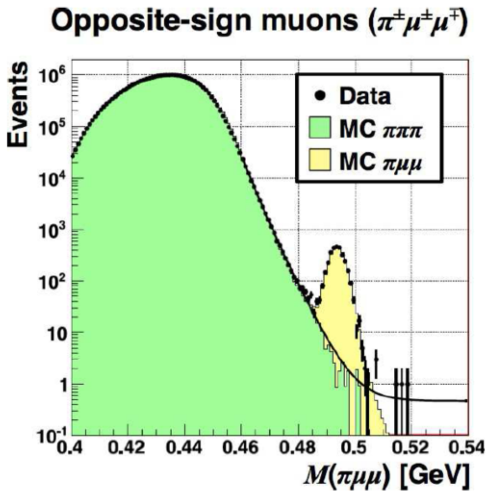

Figure 6: $M(\pi\mu\mu)$ distribution for opposite sign muons events.

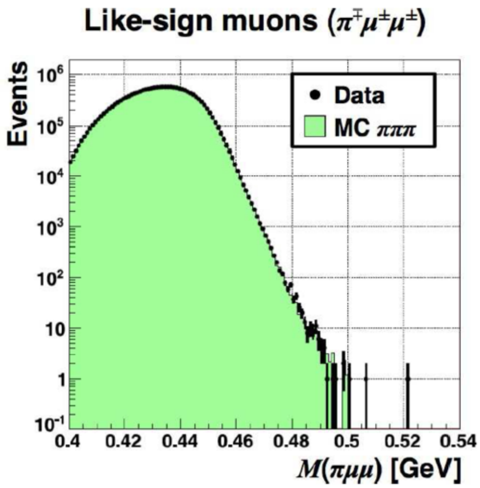

Figure 7: $M(\pi\mu\mu)$ distribution for same sign muons events.

limit $BR(K+ \to \pi^-\mu^+\mu^+) < 3.0 \times 10^{-9}$ (90% CL). The data collected in NA48/2 within the three tracks trigger sample has been used to measure both the lepton flavor conserving and the violating mode. For both signal and normalization events, reconstruction of the three-track vertex with strict quality criteria was required. For signal events, two tracks were further required to be identified as muons by hits in the MUV. The experimental configuration and the analysis are further described in [12].

For the Flavor changing neutral current mode ($K^{\pm} \to \pi^{\pm}\mu^{\pm}\mu^{\mp}$) NA48/2 collected about 3000 signal candidates, visible as the peak near $M(\pi\mu\mu) = m_{K^{\pm}}$ in fig. 6. Normalized MC distributions for signal and background

Process	Acceptance
$K^+ \to \pi^+\mu^+e^-$	$\sim 10\%$
$K^+ \to \pi^+\mu^-e^+$	$\sim 10\%$
$K^+ \to \pi^-\mu^+e^+$	$\sim 10\%$
$K^+ \to \pi^-e^+e^+$	$\sim 5\%$
$K^+ \to \pi^-\mu^+\mu^+$	$\sim 20\%$
$K^+ \to \mu^-\nu e^+e^+$	$\sim 2\%$
$\pi^0 \to \mu^-e^+$	$\sim 2\%$
$\pi^0 \to \mu^+e^-$	$\sim 2\%$
$\pi^+ \to \mu^-e^+e^+\nu$	$\sim 2\%$

Table 3: Estimated acceptance for K^+ and π^0 LFV modes.

are shown as the yellow- and green-shaded regions. In the distribution for events with like-sign muons, which violate lepton number conservation, the signal peak is largely absent (fig. 7). There are 52 signal candidates in the region near $M(\pi\mu\mu) = m_{K^{\pm}}$ and 52.6 ± 19.8 background events expected from MC. This gives the upper limit $BR(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}) < 1.1 \times 10^{-9}$ (90% CL), which improves upon the E865 result by about a factor of three. In NA48/2 the main background has been recognized as due to the pion decay in flight inside the spectrometer. This increase the apparent value of $M(\pi\mu\mu)$, in the signal region. In NA62 the invariant mass resolution will be about 1.1 MeV/c^2, more than a factor 2 better with respect to NA48/2. A factor 100 or 1000 improvement in the upper limit of the BR is expected in NA62.

3. Forbidden and exotics

The search for $K^+ \to \pi^-\mu^+\mu^+$ will be performed with the new NA62 apparatus, together with other relevant LFV modes both in kaons and pions, as summarized in table 3. A rough estimation of the expected sensitivity is around $\sim 10^{-11} - 10^{-12}$ for most of the processes. Dedicated triggers will be used to collect data parasitically with respect to the $K \to \pi^+\nu\bar{\nu}$, eventually by using online computing on GPU [22]. In addition to LFV modes other searches of exotics particles and forbidden processes will be carried out by the NA62 experiment. The existence of low mass boson, for instance, is requested by several theories to explain some of the SM anomalies (excess of positrons in cosmic rays [23], Dama/Libra dark matter signal [24] , $(g-2)_\mu$ anomaly [25]). In the same way right handed neutral leptons can be invoked to explain several open questions in particle physics. The kaons provide an ideal laboratory to study the rare effects and to look for elusive particles in the range of hundreds of MeV/c^2.

3.1. Sterile Neutrinos

In recently introduced models [26][27] , sterile neutrinos are invoked to explain several open questions. In this model there are three right handed neutrinos, the first (N_1) with low mass could be a candidate for dark matter, the others (N_2, N_3), with masses ranging from 100 MeV/c^2 to few GeV/c^2, are the responsible of the standard neutrinos masses, through seesaw mechanism, and introduce extra CP violating phases to account for baryon asymmetry, Experimentally, there are two ways to look for possible heavy sterile neutrino (N) in kaon decays: either in production or in decay. In the first case one analyzes the momentum spectrum of a decay in which there are missing energy, such as $K_{\mu 2}$, for kinematic evidence of the presence of unseen massive particles. The second strategy imply the exclusive reconstruction of possible decays of the sterile neutrino in a hypothetical final state. NA62-RK is investigating the possibility of performing a production search for heavy neutrinos in $K_{\mu 2}$ decay with a subset of the 2007 $K_{\mu 2}$ sample used for the measurement of R_K, discussed above. The limits of such measurement in NA62-RK are related to the missing mass resolution and the background, mainly from beam pions and muon halo. In NA62 the missing mass resolution will improve at least of a factor two, thanks to the low mass spectrometer in vacuum, and the background will be better controlled thanks to the full coverage veto system. NA62 should be able to improve on the limits from production searches up to $M_N \sim 350$ MeV/c^2 by orders of magnitude with respect to the present studies [28].

3.2. Dark Photon

An hypothetical spin-1 massive U boson (also known as Dark Photon) has been introduced as possible mediator for SM particle interaction with dark matters constituents. The same object can be invoked to explain the $> 3\sigma$ discrepancy in the muon anomaly [29]. The mass of the dark photon is not predicted, but should be in the range of few MeV/c^2. Experimentally, one interesting prospect is to examine e^+e^- final states of π^0. A U boson with a mass of less than $M_U < M_{\pi^0}/2$ might be directly observable in $\pi^0 \rightarrow U\gamma$ decays with $U \rightarrow e^+e^-$. NA48/2 collected about $\sim 10^{10}$ π^0decays. A preliminary result has been presented in [30], after the ICHEP conference. In the mass range 10-60 (MeV/c^2)^2 the exclusion region is improved, by this result. for coupling constants (ε^2) ranging from 10^{-6} to 6×10^{-7}. NA62 will collect $\sim$ 50 times more π^0, with 10^8 e^+e- pairs per year; moreover, NA62 has good invariant-mass resolution for the ee pair: about 1 MeV/c^2 even before any attempt at kinematic fitting. Both statistics and better systematics control could allow to exclude the U boson up to $\varepsilon^2 \sim 10^{-7}$ in the mass range kinematical accessible from kaon decays ($<$ 100 MeV/c^2).

3.3. Conclusions

In the flavor sector LFV and FCNC decays are powerful tool for new physics discovery. The kaon decays provide a clean environment to look for tiny SM deviation and possible extensions. We presented in this paper analysis performed by NA48/2 and NA62-RK and prospects from NA62, for some of the most interesting processes to discover new physics effects in the kaon sector.

The most precise measurement of R_K to date has been performed from a sample of about $\sim 150 \times 10^3$ candidates collected by the NA62-RK experiment. The result is $R_K = (2.488\pm0.010)\times10^{-5}$, consistent with the earlier measurements and with the SM expectation. The experimental uncertainty on R_K is still an order of magnitude larger than the uncertainty on the SM prediction. The NA48/2 experiment measured the $BR(K^\pm \rightarrow \pi^\mp\mu^\pm\mu^\pm)$ upper limit with a precision a factor three better with respect to the previous result. The incoming NA62 will be able to measure LFV modes, sterile neutrinos and dark photons improving previous results by order of magnitude thanks to higher statistics, better resolution and cleaner experimental environment.

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