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Latest results from NA62 and NA48/2 experiments

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Abstract. Kaon physics at CERN has a long tradition, started in 1980s by the NA31 experiment and continued by the current NA48/2 and NA62 collaborations. New results have been presented by both, namely a new measurement of the branching ratio of $K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$ from NA48/2 and a set of new results from the broad physics programme of NA62.

1 Introduction

The NA48/2 and NA62 experiments at CERN are fixed target experiments located in the same experimental area. NA48/2 collected data in 2003 and 2004 with simultaneous K^+/K^- beams, then in 2016 the NA62 experiment started to take data with a positively charged particle beam and a new experimental apparatus. The layout of the two experiments is shown in fig. 1. A detailed description of the detectors can be found in [1] and in [2].

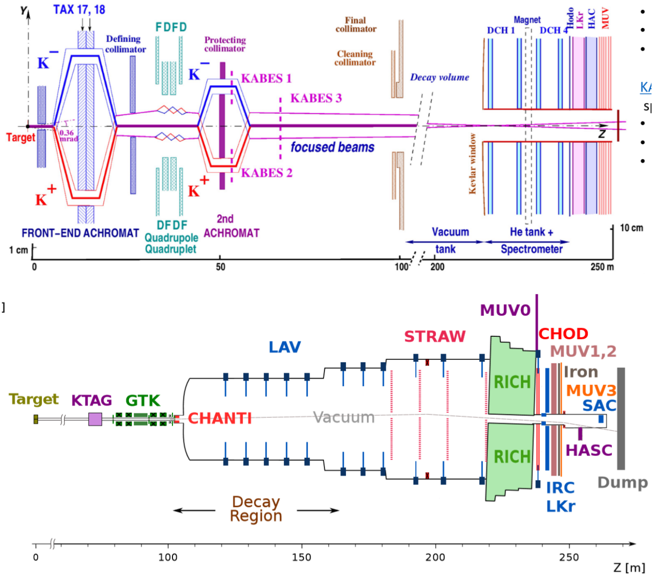

Figure 1. Experimental layout of the NA48/2 (top) and NA62 (bottom) experiments.

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2 Latest results from NA48/2 experiment

2.1 Measurement of the branching ratio for $K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$ ($BR(K^{00}_{\mu 4})$)

The semileptonic decays $K \to \pi\pi l\nu$ (K_{l4}) are described by the Cabibbo-Maksymowicz variables S_π (dipion mass), S_l (dilepton mass) and the angles θ_π, θ_l and ϕ. In general, the decay amplitudes depends on the form factors F, R, G and H; in the case of $K^{00}_{\mu 4}$ decay, assuming S-wave state for the dipion system, there is no dependance on $cos\theta_\pi$ and ϕ and therefore only F and R contribute to its branching ratio. The NA48/2 experiment already provided the best measurements for the branching ratios of K^{00}_{e4} and $K^{\pm}_{e4}$ decays, while $K^{00}_{\mu 4}$ has never been observed. In the muon modes, the largest source of background is represented by the $K \to \pi\pi\pi$ decays with subsequent decay in flight of a charged pion into a muon and a neutrino. For this measurement, the parametrization $F(S_\pi, S_l)$ from K^{00}_{e4} has been used profiting from lepton universality, while $R(S_\pi, S_l)$ is estimated by Chiral Perturbation Theory (ChPT) [3].

The signal is normalized to the $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$ decay, using a common selection: 4 isolated photons, compatible with a pair of pi0s are required in the electromagnetic calorimeter. The photons must be associated in time with a downstream track and the momentum of the total final state must be compatible with the decay of a beam kaon. For the signal the muon is identified by associating the track with hits in the muon system. Background events are rejected by cuts on the 3-pion invariant mass, p_t, $cos\theta_l$ and the missing mass. A data-driven background estimate is performed using the signal sidebands in the missing mass distribution.

The branching ratio is measured in the restricted phace space $S_l > 0.03$ GeV^2/c^4 and then extrapolated to the full phase space. The result is obtained from

$$BR(K^{00}_{\mu 4}) = \frac{N_S}{N_N} \cdot \frac{A_N}{A_S} \cdot K_{trig} \cdot BR(K^{00}_{3\pi}) \tag{1}$$

where N_S and N_N are the number of signal and background normalization events, A_N and A_S the selection acceptances, K_{trig} is a trigger correction factor and $BR(K^{00}_{3\pi})$ the BR of the normalization channel. After the background subtraction, $2083 \pm 59_{stat}$ signal events are observed, resulting in a measurement in the full phase space of:

$$BR(K^{00}_{\mu 4}) = (3.45 \pm 0.17) \times 10^{-6} \tag{2}$$

The result is compatible with the theoretical prediction when a non-zero contribution from the R form factor is taken into account (fig. 2).

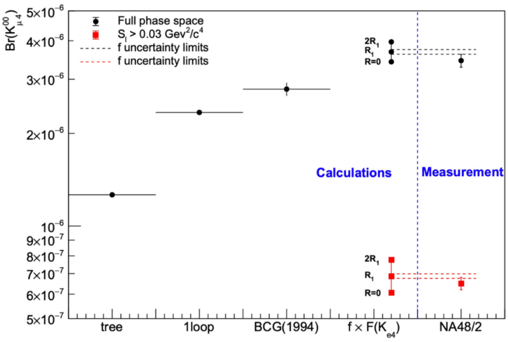


Figure 2. Result for $BR(K^{00}_{\mu 4})$ in the restricted (red) and full (black) phase space. The teoretical predictions in case of different contributions from the R form factor are also shown.

3 Latest results from NA62 experiment

3.1 Measurement of $BR(K^+ \to \pi^+ \nu\bar{\nu})$

The $K^+ \to \pi^+ \nu\bar{\nu}$ decay is a golden candidate to search for new physics in the kaon sector. It is a Flavour Changing Neutral Current (FCNC) process, suppressed in the Standard Model (SM) by the GIM mechanism, and therefore very sensitive to new physics effects. The decay amplitude is dominated by short-distance contributions, in particular from top quark loops, and the hadronic matrix element is linked by the isospin symmetry to those of the semileptonic kaon decays that are well measured. As a consequence, the theoretical prediction for its BR is very precise: $BR(K^+ \to \pi^+ \nu\bar{\nu})_{SM} = (8.4 \pm 1.0) \times 10^{-11}$.

The experimental signature is represented by one track in the initial state and one track in the final states, as the neutrinos are not detected. The main variable for the analysis is $m^2_{miss} = (P_K - P_\pi)^2$; from the m^2_{miss} distribution, two signal regions have been identified to discriminate the signal from the backgrounds. A blind analysis technique has been adopted, with the signal regions kept masked until the background evaluation was assessed using appropriate control regions. The experiment analyzed the data collected in 2016, 2017 and 2018: the data from 2018 have been divided into two subsamples S1 and S2, respectively before and after the installation of a new kaon beam collimator before the entrance of the decay volume, which reduced the background contribution from beam interactions in the last plane of the beam tracker. The sample S2, corresponding to ~ 80% of the 2018 sample, has been split into 6 pion momentum categories, from 15 to 45 GeV/c with a bin width of 5 GeV/c. Finally, data from 2016 and 2017 have been treated as two separate categories, for a total of 9.

The single event sensitivity (SES) is given by:

$$SES = \frac{BR(K^+ \to \pi^+ \pi^0)}{D \cdot N_{\pi\pi} \cdot \epsilon_{trig} \cdot \epsilon_{RV}} \frac{A_{\pi\pi}}{A_{\pi\nu\nu}} \tag{3}$$

where $N_{\pi\pi}$ are the number of events in the normalization channel, $A_{\pi\nu\nu}$ and $A_{\pi\pi}$ the acceptances of signal and normalization selections respectively, D is the downscaling factor between the signal and normalization trigger streams, ϵ_{trig} is the trigger efficiency and ϵ_{RV} is the random veto efficiency, namely the probability of not discarding an event because of accidental activity in the veto system. For the samples S1 and S2 the SES are $(0.54 \pm 0.04) \times 10^{-10}$ and $(0.14 \pm 0.01) \times 10^{-10}$ respectively. The backgrounds from the main kaon decays have been evaluated with dedicated background regions as $N^{exp}_{decay} = N_{bkg} \cdot f_{kin}$, where N_{bkg} is the number of events in each background region and f_{kin} is the fraction of events entering the signal region for that specific decay, estimated from MonteCarlo simulations. Beam-induced background ("upstream background") has been estimated using a data-driven technique, and the evaluation has been validated using a sample that is orthogonal to the signal sample.

After the background validation, the signal regions have been unblinded: 17 events have been found, which combined with the events found from the 2016 and 2017 analyses gives a total of 20 signal candidates. Taking into account the signal and background expectations, the resulting measurement of the branching ratio is [4]

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.5}|_{stat} \pm 0.3_{syst}) \times 10^{-11} \tag{4}$$

which corresponds to an observation of the decay at a significance of 3.4 standard deviations and is the most precise measurement of the branching ratio to date.

3.2 Measurement of $BR(K^+ \to \pi^0 e^+ \nu\gamma)$

The decay $K^+ \to \pi^0 e^+ \nu\gamma$ ($K_{e3\gamma}$) provides a good test of the Chiral Perturbation Theory (ChPT). In particular, its branching ratio is expressed in terms of the branching ratio of the non-radiative K_{e3} decay in different regions of the phase space defined by E_γ and $\theta_{e,\gamma}$, namely the energy of the radiative photon and the angle between the positron and the photon:

$$R_j = \frac{BR(K_{e3\gamma}|E^j_\gamma, \theta^j_{e,\gamma})}{BR(K_{e3})} \tag{5}$$

The most common definition of the restricted phase space regions are reported in table 1, together with the theoretical expectations from ChPT and the most recent results obtained by the ISTRA+ and OKA experiments.

Table 1. Definitions of R_j, preditions from ChPT and result from ISTRA+ and OKA experiments.

	E^j_γ	$\theta^j_{e,\gamma}$	$O(p^6)$ *ChPT*	ISTRA+	OKA
$R_1 \times 10^2$	$E_\gamma > 10$ MeV	$\theta_{e,\gamma} > 10°$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$
$R_2 \times 10^2$	$E_\gamma > 30$ MeV	$\theta_{e,\gamma} > 20°$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$
$R_3 \times 10^2$	$E_\gamma > 10$ MeV	$0.6 < \cos(\theta_{e,\gamma}) < 0.9$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$

The process can be used to study possible violations of T-parity by measuring the T-odd observable ξ and the relative asymmetry:

$$\xi = \frac{\vec{p}_\gamma \cdot (\vec{p}_e \times \vec{p}_\pi)}{M_K^3} \quad ; \quad A = \frac{N_+ - N_-}{N_+ + N_-} \tag{6}$$

In the second equation, N_+ and N_- correspond to the number of events with positive and negative values of ξ respectively.

The analysis is performed by using the $K(e3)$ decay as a normalization channel, in order to cancel out most of the systematic uncertainties. The main background is represented by K_{e3} events with accidental activity in the electromagnetic calorimeter, that can mimic the radiative photon. The background contribution has been evaluated on data using the signal sidebands.

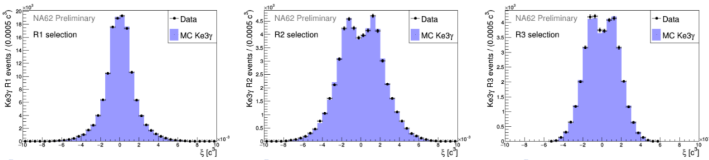
The preliminary results for the ratios R^j are:

$$R_1 = 1.684 \pm 0.005 \pm 0.010) \times 10^{-2} \tag{7}$$

$$R_2 = 0.599 \pm 0.003 \pm 0.005) \times 10^{-2} \tag{8}$$

$$R_3 = 0.523 \pm 0.003 \pm 0.003) \times 10^{-2} \tag{9}$$

In all cases, the results improved the experimental precision by a factor between 2 and 3 compared to the previous results. The asymmetries have been computed using (6) and corrected for the offset induced by the reconstruction and the selection, estimated using a MonteCarlo simulation. The results are reported in fig. 3. No statistically relevant differences with zero have been observed.



$A_\xi^{R_1} = (-0.1 \pm 0.3_{stat} \pm 0.2_{MC}) \times 10^2$ $A_\xi^{R_2} = (-0.3 \pm 0.4_{stat} \pm 0.3_{MC}) \times 10^2$ $A_\xi^{R_3} = (-0.9 \pm 0.5_{stat} \pm 0.4_{MC}) \times 10^2$

Figure 3. Data and MonteCarlo distribution for the ξ observables in the three restricted phase space regions. The corresponding results for the asymmetries are reported.

3.3 Measurement of $BR(K^+ \to \pi^+\mu^+\mu^-)$

$K^\pm \to \pi^\pm l^+ l^-$ decays are FCNC processes described through the exchange of a virtual photon, $K^\pm \to \pi^\pm \gamma^* \to \pi^\pm l^+ l^-$ involving long-distance hadronic effects. Much theoretical effort has been put into completely describing the processes involved out [7–9]. Precision measurements of the ($K_{\pi ll}$) branching ratios can provide important tests of Lepton Flavour Universality (LFU). The form factors are parametrized by the coefficients a_+ and b_+; NA62 has made a new measurement of the branching ratio for the $K^+ \to \pi^+\mu^+\mu^-$ ($K_{\pi\mu\mu}$) decay and of the two form factor parameters using data collected in 2017 and 2018.

The normalization channel is the $K^+ \to \pi^+\pi^+\pi^-$ decay and a common selection has been adopted, based on the reconstruction of a three-track vertex in the final state, matched with an upstream kaon, and on the absence of positrons in the downstream detectors. The signal and normalization channels have particle identification requirements. The muons in the signal channel are identified by activity in the MUV3 detector, compatible with a track in space and time. A track with no associated MUV3 activity is identified as a pion. This selection leads to a $K_{\pi\mu\mu}$ sample of 27679 events, with a signal acceptance of (8.688 ± 0.009)%. The invariant mass for the event passing the signal selection is reported in fig. 4.

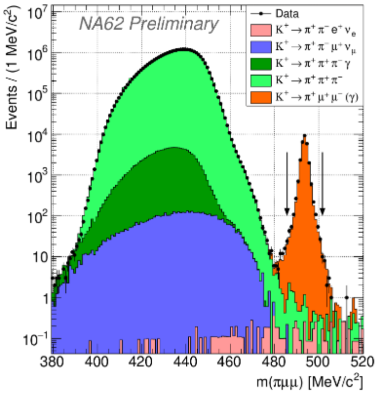


Figure 4. Invariant mass distribution for the event passing the $K_{\pi\mu\mu}$ selection. MC samples of the signal and the main background are shown.

The results for the branching ratio and for the form factor coefficients are reported in Table 2.

Table 2. Results obtained for the form factor coefficient and for $BR(K_{\pi\mu\mu})$.

	a_+	b_+	$BR(K_{\pi\mu\mu}) \times 10^8$
Best fit	−0.592	−0.699	9.27
Errors	δa_+	δb_+	$\delta BR(K_{\pi\mu\mu}) \times 10^8$
Statistical	0.013	0.046	0.07
Systematic			
Reconstruction efficiency	0.005	0.026	0.06
Beam and pileup simulation	0.005	0.024	0.05
Trigger efficiency	0.001	0.005	0.005
Background	-	0.001	0.004
Total systematic	0.007	0.035	0.08
External			
PDG error on $BR(K_{3\pi})$	0.001	0.003	0.04
Total	0.015	0.058	0.11

3.4 Searches for lepton number and lepton flavour violations

In the SM, Lepton Number (LN) and Lepton Flavour (LF) are conserved quantities not related to a symmetry principle of the theory and therefore considered as accidental symmetries. For this reason, many models of new physics beyond the SM contains LN and LF violating processes, mediated for instance by Majorana neutrinos, Z' bosons or leptoquarks.

Thanks to the large sample of K^+ decays collected, the NA62 experiment is able to perform many different searches for LNV and LFV in kaon and neutral pion decays. One of the most recent results obtained by NA62 in this context is the search for the LNV decays $K^+ \to \pi^-(\pi^0)e^+e^+$.

The signal rates have been measured normalizing to the SM decay $K^+ \to \pi^+e^+e^-$, which means most systematic uncertainties coming from detector or trigger inefficiencies and pileup activity in the experimental setup cancel. The common selection for both signal and normalization is based on the reconstruction of a 3-track vertex in the the final state, compatible with the decay of a kaon and made by one $\pi^\pm$ and two $e^\pm$; particles are identified by the measurement of the ratio E/p between the energy deposited in the electromagnetic calorimeter and the track momentum measured by the spectrometer. To suppress background from Dalitz decays of the $\pi 0$ events with in-time activity in the Large angle veto are rejected. Further e^+ identification requirements, using the RICH detector, are applied to reduce the background to the signal. Finally, a requirement on the invariant mass is performed and the signal region has been kept blind until the validation of the background estimate.

The main background contribution comes from $\pi^\pm$ mis-identification as $e^\pm$ and vice versa. Pion and positron mis-identification probabilities and identification efficiencies using the ratio E/p and the RICH have been estimated by data as a function of the particle momentum with pure $K^+ \to \pi^+\pi^+\pi^-$ and $K^+ \to \pi^0e^+\nu$ control samples respectively. The probabilities obtained from the control samples have been used as models in the MonteCarlo simulation.

The total number of K^+ decays selected is 10^{12}, obtained from 11041 SM $K^+ \to \pi^+e^+e^-$ events, which is the largest sample of the decay mode ever collected. After the validation of the background estimate, performed using control regions adjacent to the signal regions, no events have been found for both $K^+ \to \pi^-e^+e^+$ and $K^+ \to \pi^-\pi^0e^+e^+$ (fig. 5). As a result, the following 90% CL upper limits on the branching ratios of the LNV decay modes are obtained [10]:

$$BR(K^+ \to \pi^-e^+e^+) < 5.3 \times 10^{-11} \tag{10}$$

$$BR(K^+ \to \pi^-\pi^0e^+e^+) < 8.5 \times 10^{-10} \tag{11}$$

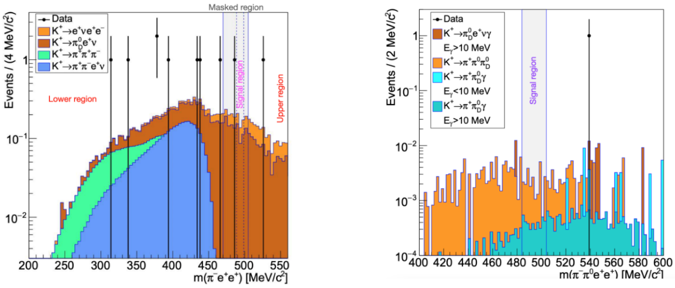


Figure 5. Invariant mass for $K^+ \to \pi^-e^+e^+$ (left) and $K^+ \to \pi^-\pi^0e^+e^+$ (right) decay modes. Signal regions and main background contributions are shown.

4 Conclusions

The first measurement of the $BR(K^{00}_{\mu 4})$ has been performed by the NA48/2 collaboration, showing an agreement with the theoretical expectation from ChPT. The NA62 experiment performed the most precise measurement of $BR(K^+ \to \pi^+ \nu\bar{\nu})$, based on the full Run1 sample (2016-2018) with a 3.4σ significance on the observation of the decay. The NA62 physics programme, however, is quite broad: and important results have been presented in the context of precision measurement of branching ratios of kaon decays ($K_{e3\gamma}$ and $K_{\pi\mu\mu}$), with improved precision in both cases with respect to previous results. In the searches for LNV decays from kaons and neutral pions, improved 90% CL upper limits have been obtained. Other LNV and LFV searches performed by NA62 can be found in [11].

The experiment restarted its data taking in 2021 and will continue until 2026, with the aim of measuring $BR(K^+ \to \pi^+ \nu\bar{\nu})$ to 10% precision.

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