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LFV/LNV searches at the NA62 experiment

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The NA62 experiment at CERN has collected a large sample of K^+ decays in flight during several data-taking periods in 2016 – 2017 – 2018 (Run1) and the ongoing Run2, which started in 2021. Dedicated lepton-pair trigger lines have enabled a broad rare and forbidden decay programme. A review of searches for lepton flavour and number violating K^+ and π^0 decays with the NA62 Run1 lepton-pair dataset is presented. Ten final states have been investigated, improving on the world data in each case. Upper limits of the decay branching fractions are obtained typically at the 10^{-11} level, and the sensitivities are not limited by backgrounds. Prospects of the searches with the full NA62 dataset are also discussed.

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1. The NA62 experiment and its physics programme

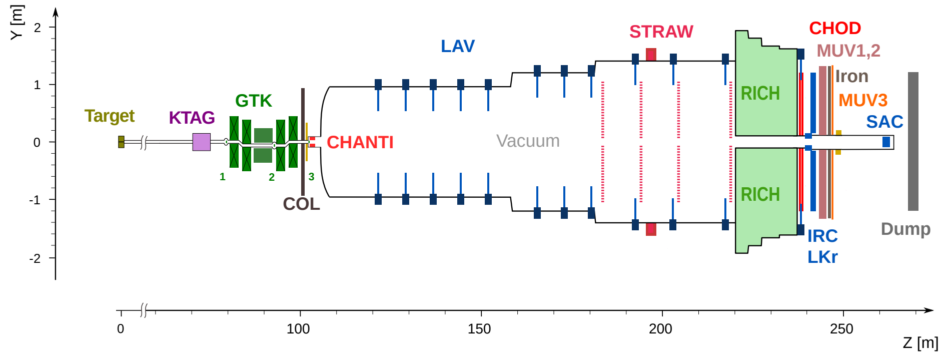

Figure 1: Schematic side view of the NA62 beam line and detector used in 2018

NA62 is an experiment at CERN SPS designed to measure the branching ratio (BR) of the ultra-rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay [1]. The experiment employs a 75 GeV/c positively charged hadron beam with a ~6% K^+ component, produced by the SPS 400 GeV/c protons impinging on a beryllium target. A schematic of the detector is shown in Figure 1, while a detailed description can be found in [2]. Beam kaons are identified by a differential Cherenkov counter (KTAG) [3] and their momenta are measured by a silicon pixel spectrometer (GTK). Reconstructed K^+ decays occur in a ~75 m long vacuum fiducial volume (FV), from 105 to 180 m downstream of the target, with the charged products detected by the scintillator planes of the CHOD (Charged particles Hodoscope) and their momenta measured by a straw-chamber spectrometer (STRAW). Particle identification (PID) is provided by a Ring Imaging Cherenkov detector (RICH) [4], an electromagnetic calorimeter (LKr), hadronic calorimeters (MUV1,2), and a muon detector (MUV3). The LKr, together with twelve ring-shaped lead-glass detectors (LAV) and two small-angle shashlik calorimeters (IRC and SAC), ensures vetoing of photons emitted at angles up to 50 mrad relative to the beam direction. NA62 operates at high rates (~650 MHz in the GTK) and employs a flexible and selective trigger system [5]. Multiple trigger lines run concurrently with the $K^+ \to \pi^+ \nu\bar{\nu}$ one, recording a variety of event topologies, and allowing NA62 to collect the world's largest K^+ decay dataset during its Run1 (2016 – 2017 – 2018). This dataset enables a broad physics programme, including precision tests of the Standard Model (SM), searches for rare or symmetry-forbidden decays and direct searches for hidden-sector particles; recently published results can be found, for example, in [6][7][8][9]. NA62 can also operate in beam-dump mode, where the proton beam is stopped in a dense copper-iron absorber, enabling direct searches also for new particles with masses above the K^+ scale in a dedicated dataset [10][11][12].

In the following an overview of the NA62 searches for lepton flavour violating (LFV) and lepton number violating (LNV) K^+ and π^0 decays in the Run1 data is reported.

2. Searches for LFV/LNV kaon decays: motivations

Lepton number (L) and lepton flavour (L_e, L_μ, L_τ) are accidentally conserved quantum numbers within the SM, and their violation would be a clear indication of physics beyond it. The observation of neutrino oscillations provides the first evidence of LFV and implies non-zero neutrino masses, opening the possibility to probe the Dirac or Majorana nature of neutrinos. In particular, the observation of lepton number violating processes such as $K^+ \to \pi^- l^+ l^+$ with $l = e, \mu$ and $\Delta L = -2$ would strongly support the Majorana hypothesis [13]. LFV kaon decays with $\Delta L_e = \pm 1 = -\Delta L_\mu$ of the form $K^+ \to \pi^+ l_1^+ l_2^-$, where $l_{1,2} = e, \mu$ and $1 \neq 2$, are also predicted in several beyond SM (BSM) scenarios, including theories with axion-like particles and Z' bosons [14][15]. Rare kaon decays violating lepton number or lepton flavour thus provide powerful probes of BSM physics, with sensitivity to mass scales up to $O(100\ \text{TeV}/c^2)$. Their study takes advantage of the availability of high kaon fluxes and of the relatively simple decay topologies and clean experimental signatures. In addition, channels such as $K^+ \to \pi^+ \pi^0$ allow π^0 tagging and enable precision studies of π^0 decays alongside dedicated searches for LNV and LFV effects in neutral pion decays.

3. LFV and LNV at NA62

During Run1, NA62 recorded $O(10^{12})$ kaon decays by using dedicated di-lepton trigger lines. This dataset is particularly well suited for searches for LFV and LNV kaon decays and provides NA62 with the world-leading sensitivities to several of these rare processes. Ten channels have been investigated in a model-independent way: the LNV $K^+ \to \pi^- \mu^+ \mu^+$ [17], $K^+ \to \pi^- (\pi^0) e^+ e^+$ [18], $K^+ \to \pi^- \pi^0 \mu^+ e^+$ [19] and $K^+ \to \pi^- \mu^+ e^+$ [20] decays, the LFV $K^+ \to \pi^+ \mu^- e^+$ [20], $\pi^0 \to \mu^- e^+$ [20] and $K^+ \to \pi^+ \pi^0 \mu^\mp e^\pm$ [19] decays, and the $K^+ \to \mu^+ \nu e^- e^+$ decay [21], that can be LNV or LFV depending on the neutrino flavour. All these studies adopt a cut-and-count approach within a blind analysis framework. In the following only a few general remarks about the analysis strategy are reported, further details can be found in the corresponding references.

The branching ratio of a LFV/LNV process (signal) is measured relative to a normalisation channel, a SM decay with similar topology to the signal, collected by the same trigger lines and selected with common conditions to it. This ensures first-order cancellation of systematic effects and trigger inefficiencies. The common event selection is usually based on the reconstruction of a three-track vertex within the FV, with total charge $Q = +1$ (in units of electronic charge). The reconstructed vertex momentum is required to be consistent with the average K^+ beam momentum p_{beam}, that is measured from data by a sample of SM $K^+ \to \pi^+ \pi^- \pi^+$ decays. Particle identification relies on the E/p ratio, where E is the energy of the electromagnetic cluster associated with the track in the LKr and p is the track momentum measured by the STRAW. Signals in the MUV3 detector are also used to distinguish muons from electrons and pions. LAV signals provide veto against extra photons in the final state (for e.g. radiative photons). The signal and normalisation selections then include specific conditions depending on the decay final state. In particular, if a π^0 is present in the final state, it is reconstructed in the LKr by the $\pi^0 \to \gamma\gamma$ decay. To distinguish between signal (normalisation) and background, a signal (normalisation) region is defined surrounding the nominal K^+ mass value in the invariant mass distribution of the reconstructed decay products. As an example, the left hand side of Figure 2 reports the distribution of the reconstructed $m(\pi^+ e^+ e^-)$ mass after the normalisation selection defined to select SM $K^+ \to \pi^+ e^+ e^-$ ($K_{\pi ee}$) events. 21401 $K_{\pi ee}$ candidates are observed in the normalisation region, and are used to get an estimate of the kaon flux: $(1.97 \pm 0.02_{stat} \pm 0.02_{syst} \pm 0.06_{ext}) \times 10^{12}$ K^+ decays in the FV. This normalisation sample has been used, for instance, within the searches for the $K^+ \to \pi\pi^0 \mu e$ modes. Figure 3 clearly shows the

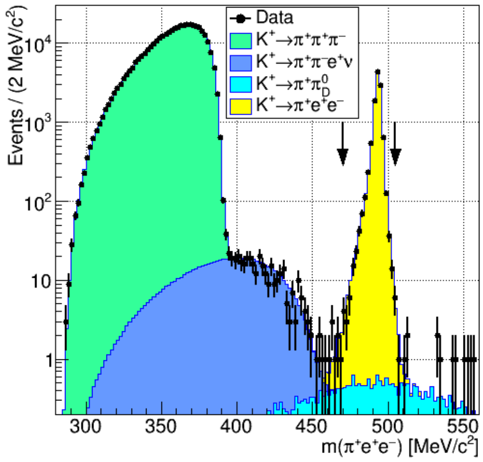

Figure 2: Invariant mass spectrum after the normalisation selection defined in [19] to select $K^+ \to \pi^+ e^+ e^-$ events is applied to the NA62 Run1 data and MC samples. Black arrows indicate the normalisation region.

signal regions defined in the $m(\pi^-\mu^+e^+)$ and $m(\pi^+\mu^-e^+)$ mass spectra after the LNV $K^+ \to \pi^-\mu^+e^+$ (right) and LFV $K^+ \to \pi^+\mu^-e^+$ (left) selections, respectively. It should be noted that the previously mentioned LFV $\pi^0 \to \mu^-e^+$ mode is investigated by searching for the $K^+ \to \pi^+\pi^0$ ($\pi^0 \to \mu^+e^-$) decay chain, therefore the corresponding signal region is defined as in Figure 3 right with the additional constraint of consistency of the reconstructed di-lepton invariant mass $m(\mu^-e^+)$ with the nominal π^0 mass value. For the $K^+ \to \mu^+\nu e^-e^+$ decay, the presence of a final-state neutrino prevents full kinematic reconstruction and the invariant mass of the detected daughter particles to be used as discriminating variable. The squared missing mass $m^2_{\text{miss}} \equiv (P_K - (P_\mu + P_{e1} + P_{e2}))^2$ is used instead, where P_i denotes the reconstructed four-momentum of the particle i, with a signal region centered around the neutrino mass.

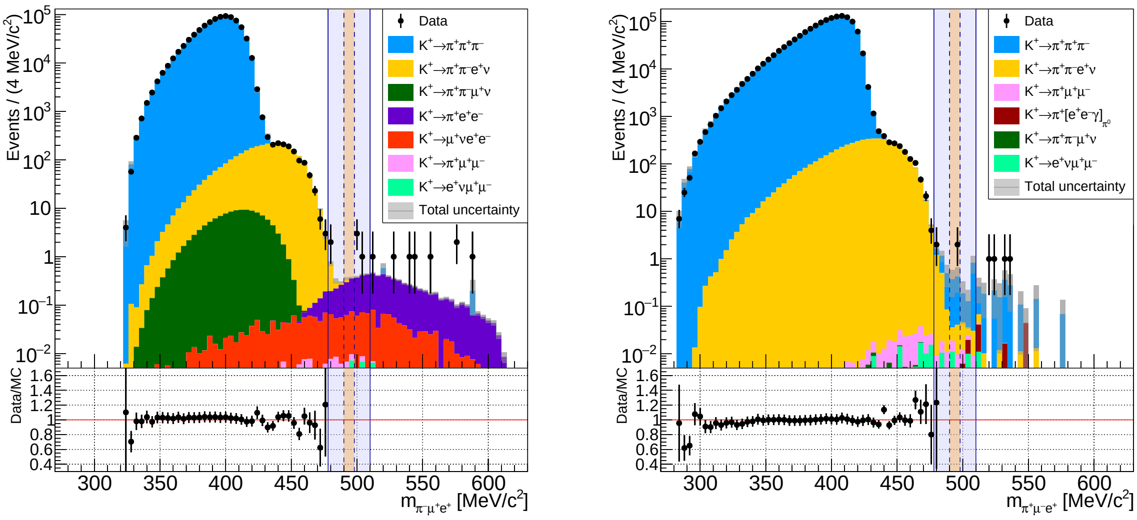

Figure 3: Invariant mass distributions after the LNV $K^+ \to \pi^-\mu^+e^+$ (right) and LFV $K^+ \to \pi^+\mu^-e^+$ (left) selections were applied to the NA62 Run1 data and MC samples. The dashed lines indicate the signal regions; the blue bands indicate some control regions used for background validation. Details in [20].

	Previous UL (90%C.L.)		NA62 UL (90%C.L.)	
$BR(K^+ \to \pi^- \mu^+ \mu^+)$	$< 8.6 \times 10^{-11}$	[23]	$< 4.2 \times 10^{-11}$	[17]
$BR(K^+ \to \pi^- e^+ e^+)$	$< 6.4 \times 10^{-10}$	[24]	$< 5.3 \times 10^{-11}$	[18]
$BR(K^+ \to \pi^- \pi^0 e^+ e^+)$	none		$< 8.5 \times 10^{-10}$	[18]
$BR(K^+ \to \pi^- \pi^0 \mu^+ e^+)$	none		$< 2.9 \times 10^{-10}$	[19]
$BR(K^+ \to \pi^- \mu^+ e^+)$	$< 5.0 \times 10^{-10}$	[24]	$< 4.2 \times 10^{-11}$	[20]
$BR(K^+ \to \pi^+ \mu^- e^+)$	$< 5.2 \times 10^{-10}$	[24]	$< 6.6 \times 10^{-11}$	[20]
$BR(\pi^0 \to \mu^- e^+)$	$< 3.4 \times 10^{-9}$	[24]	$< 3.2 \times 10^{-10}$	[20]
$BR(K^+ \to \pi^+ \pi^0 \mu^- e^+)$	none		$< 3.1 \times 10^{-10}$	[19]
$BR(K^+ \to \pi^+ \pi^0 \mu^+ e^-)$	none		$< 5.0 \times 10^{-10}$	[19]
$BR(K^+ \to \mu^- \nu e^+ e^+)$	$< 2.1 \times 10^{-8}$	[25][26]	$< 8.1 \times 10^{-11}$	[21]

Table 1: Summary of the NA62 Run1 programme on lepton flavour and lepton number violation searches; the result in [17] is obtained by the analysis of ~30% of the Run1 sample. The NA62 model-independent upper limits at 90% C.L. are compared with previous limits.

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Background estimate fully relies on Monte Carlo simulations. The dominant contributions come from particle mis-identification, especially of pions as electrons and viceversa. A dedicated data-driven particle identification model [18] is employed in the simulations: $\pi^\pm$ and $e^\pm$ (mis)identification probabilities measured with $K^+ \to \pi^+\pi^-\pi^+$ and $K^+ \to \pi^0 e^+ \nu_e$ decay samples are applied as weights to simulated events. This approach allows to avoid the GEANT4[22]-based modelling of the E/p quantity, that is sensitive to the simulation of the hadronic showers. In the searches for the $K^+ \to \pi\pi^0\mu e$ final states, backgrounds from coincidences of pairs of K^+ decays are also non-negligible and are strongly suppressed by including a cut on the momentum difference $\Delta p = p_{\pi\pi^0\mu e} - p_{beam}$, with $p_{\pi\pi^0\mu e}$ the sum of the reconstructed total final state momenta. The momentum difference is expected to be larger than 3 GeV/c if the selected charged tracks come from concurrent K^+ decays, with the regions of large Δp populated exclusively by backgrounds from coincidences, as shown in the left column of Figure 4. Combinations of pairs of decays having product of BR as low as $O(10^{-6})$ were included in the studies, and normalised by using the region with $\Delta p > 10$ GeV/c and accounting for the mean probability of coincidence of two decays in the selection time window.

The results of the analyses are summarized and put in context in Table 1. NA62 upper limits (UL) at 90% C.L. improve upon the existing ones by factors ranging from two up to two orders of magnitude, and provide the first experimental limits for the $K^+ \to \pi^-\pi^0 e^+ e^+$, $K^+ \to \pi^-\pi^0\mu^+ e^+$, $K^+ \to \pi^+\pi^0\mu^- e^+$ and $K^+ \to \pi^+\pi^0\mu^- e^+$ decays.

4. Conclusion and prospects

From the analysis of the data collected during Run1, NA62 established world-leading limits on ten LFV and LNV decay modes. All the searches are not limited by the background and the results are dominated by statistics. NA62 data taking resumed in 2021 (Run2), after the second long shutdown (LS2) of the CERN accelerator complex. The new datasets, that will be collected

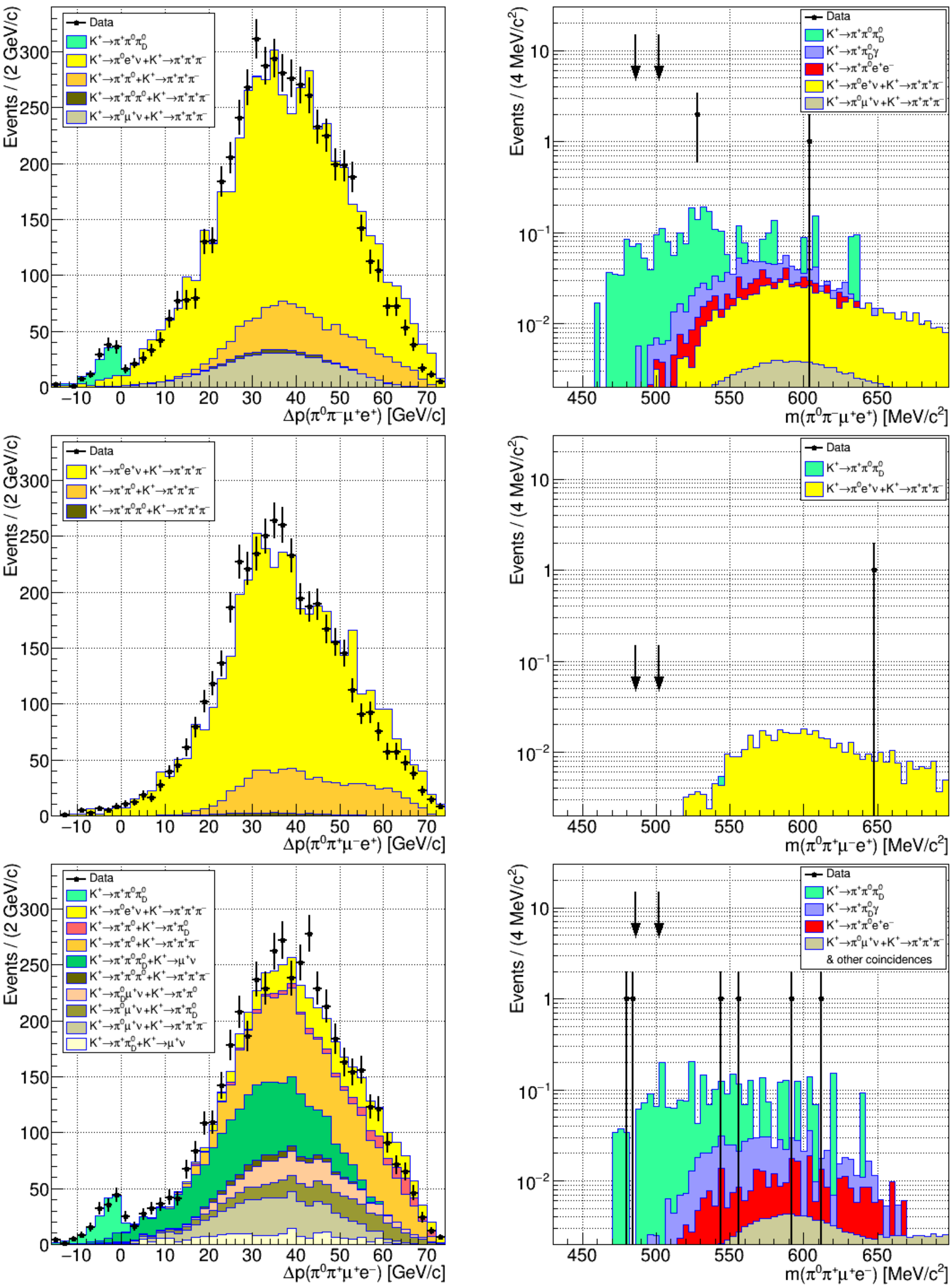

Figure 4: From the $K^+ \to \pi^-\pi^0\mu^+e^+$ (top), $K^+ \to \pi^+\pi^0\mu^-e^+$ (middle) and $K^+ \to \pi^+\pi^0\mu^-e^+$ (bottom) searches [19]. Left: momentum difference (Δp) distributions for NA62 Run1 data and MC samples after a loose selection without the $\Delta p < 3$ GeV/c cut and including only events outside the signal region. Right: reconstructed mass spectra after the corresponding full signal selection; black arrows indicate the signal regions.

until LS3, benefit from an increased beam intensity with respect to Run1 and from upgraded trigger configurations and algorithms. In particular, the downscaling factors for the di-lepton trigger lines, previously ranging from a few units up to 100, depending on the stream, were reduced to 1 by late 2023. As the reported searches are not background limited, the combined Run1 and Run2 di-lepton dataset is expected to correspond to $O(10^{13})$ kaon decays. This will provide about an order of magnitude improvement in sensitivity, reaching the level of $10^{-11}-10^{-12}$ in branching ratio. The larger statistics will also allow to explore additional decay modes, such as $K^+ \to \pi^+\mu^+e^-$ and $\pi^0 \to \mu^+e^-$, for which the sensitivity obtained using Run1 data alone is comparable to the existing limits.

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