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Searches for lepton flavour and lepton number violating K^+ decays at the NA62 experiment

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Abstract. The NA62 experiment at CERN collected the world's largest dataset of charged kaon decays to di-lepton final states in 2016-2018, using dedicated trigger lines. Upper limits on the rates of several K^+ decays violating lepton flavour and lepton number conservation, obtained by analysing this dataset, are reported.

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1. Introduction

Lepton number (LN) L is a charge corresponding to an accidental $U(1)$ symmetry of the Standard Model (SM). Moreover, it is conserved for each flavour L_e, L_μ, L_τ in SM processes. A notable example of lepton flavour violation (LFV) is the observation of neutrino oscillations which requires that the SM has to be extended. The various extensions of the SM, which aim to explain the SM neutrino properties, often also result in LNV and LFV in charged processes [1, 2]. For example a heavy Majorana neutrino could mediate a $K^+ \to \pi^-\ell^+\ell^+$ type of decays [3] while the decay $K^+ \to \pi^+\ell_1^+\ell_2^-$ with ℓ_1 and ℓ_2 of different flavours could be mediated by a leptoquark [4]. Therefore, observing this type of interactions would not only reveal more about the underlying mechanism generating the neutrino masses but it could give us more insight into the other properties of the SM and possibly also of the evolution of the Early Universe.

2. NA62 experiment

The NA62 experiment is a fixed-target experiment at the CERN SPS (north area). Its main purpose is the measurement of the branching ratio of the very rare $K^+ \to \pi^+\nu\bar{\nu}$ decay with 10% precision. Moreover, NA62 serves as a multi-purpose experiment covering a broad kaon and beam-dump physics programme. About 4×10^{12} kaon decays have been collected during the data-taking period 2016-2018 (Run 1) and the result of the corresponding $\mathcal{B}_{K^+\to\pi^+\nu\bar{\nu}}$ measurement is $\mathcal{B}_{K^+\to\pi^+\nu\bar{\nu}} = (10.6 \pm 4.0) \times 10^{-11}$ [5].

In standard data-taking, the experiment uses 75 GeV/c beam with $\sim$ 750 MHz particle rate and consisting of 6% K^+. The kaons in the beam are selected using a Cherenkov counter detector (KTAG), which also provides the timing for the kaon tracks, while their momenta are measured by a silicon pixel spectrometer (GTK). The particle beam then enters a 117 m long vacuum vessel where about 14% of the beam kaons decay in the fiducial volume (FV) which occupies the first about 75 m of the vacuum vessel. The momenta of the kaon decay products are measured using the STRAW spectrometer, consisting of 4 straw stations and a 0.9 Tm magnet. The vacuum vessel is followed by a ring-imaging Cherenkov counter (RICH) optimized for the momentum range 15-35 GeV/c in order to separate the final state π^+ and μ^+ [6]. Further particle identification (PID) is given by a sequence of calorimeters: the electromagnetic calorimeter (LKr) and hadronic calorimeters (MUV1 and MUV2). The muon identification is given by a scintillating-tile muon detector (MUV3), located behind 80 cm thick iron wall. The RICH and the charged hodoscope (CHOD) also provide the timing for the tracks of the final state particles. The overall time resolution of the experiment reaches $\mathcal{O}(100)$ ps [7].

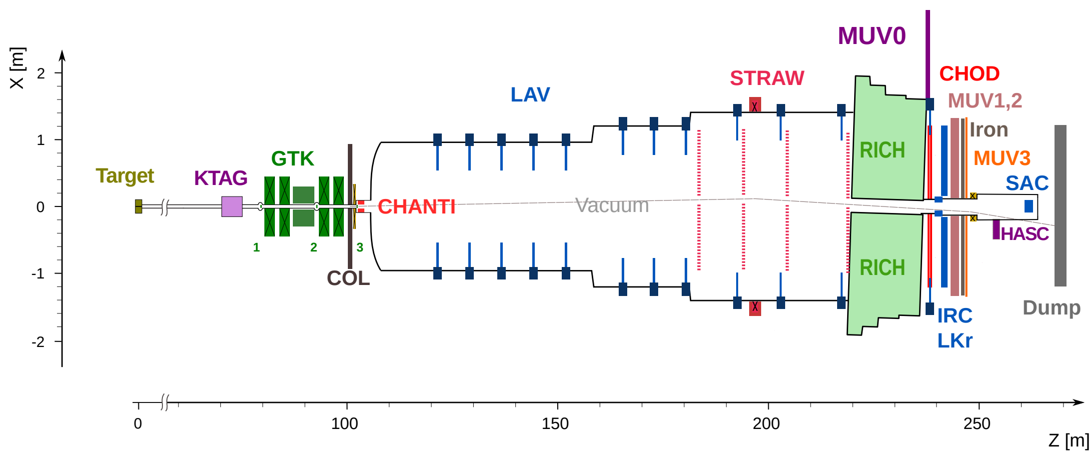

Figure 1. Schematic layout of the NA62 experiment in the X-Z plane in 2018 [7].

3. Search for the $K^+ \to \pi^-\mu^+\mu^+$ decay

The $K^+ \to \pi^-\mu^+\mu^+$ decay has been searched for in data collected during about 3 months of operation in 2017 ($\sim$ 25% of Run 1 data). The hardware level (L0) trigger used was an in-time signal in two MUV3 tiles (so-called *di-muon* trigger) with a downscaling factor (D) of 2. The software level (L1) trigger required a K^+ identified by the KTAG and a negative track reconstructed by STRAW. The SM $K^+ \to \pi^+\mu^+\mu^-$ decay with $\mathcal{B}_{K^+\to\pi^+\mu^+\mu^-} = (9.4\pm0.6)\times10^{-8}$ [8] was used for the normalization in order to reach a low systematic error as it has a similar kinematic distribution to the target decay resulting in a first-order cancellation of detector inefficiencies.

The signal region (SR), defined in terms of the reconstructed $\pi\mu\mu$ invariant mass $484 < m_{\pi\mu\mu} < 504$ MeV/c^2, was kept blinded during the analysis until the selection criteria were fixed. The number of candidates observed in the SM channel is $N^{\text{obs}}_{\pi\mu\mu} = 8357$, see fig.2, left. The signal acceptance is $A_{\pi\mu\mu} = 10.93\%$ and the single event sensitivity (SES) yields $S_{\pi\mu\mu} = (1.28 \pm 0.04) \times 10^{-11}$. The expected number of background events in the SR is $N^{\text{exp}}_{\text{bg}} = 0.91 \pm 0.41$ and after the unblinding we observe $N^{\text{obs}} = 1$ in the SR (see fig.2, right) which results in an upper limit at 90% CL for $\mathcal{B}_{K^+\to\pi^-\mu^+\mu^+}$ of 4.2×10^{-11}.

4. Search for the $K^+ \to \pi^-(\pi^0)e^+e^+$ decays

The full NA62 Run 1 data sample has been used in this analysis. The L0 trigger requires a RICH signal multiplicity and an in-time signal in two opposite CHOD quadrants (so-called multi-track or *MT* trigger) with $D = 100$, together with an *eMT* trigger with the additional condition $E_{\text{LKr}} > 20$ GeV with $D = 8$. The L1 trigger definition is the same as for the $K^+ \to \pi^-\mu^+\mu^+$ decay. The SM $K^+ \to \pi^+e^+e^-$ ($K_{\pi ee}$) decay with $\mathcal{B}_{K^+\to\pi^+e^+e^-} = 3 \times 10^{-7}$ is used for the normalization.

For the SM $K_{\pi ee}$ decay, the SR defined by requiring that $m_{\pi ee}$ is within the range 470–505 MeV/c^2 while for the LNV decay, we use a tighter definition 488.6 MeV/c^2 $< m_{\pi ee} <$ 498.8 MeV/c^2. The number of SM candidates observed is $N^{\text{obs}}_{\pi ee} = 11041$, see fig.3 left. The signal acceptance $A_{\pi ee} = (3.62\pm0.02)\%$ and the SES $S_{\pi ee} = (2.28\pm0.07)\times10^{-11}$. The expected background in the SR of the LNV decay yields $N^{\text{exp}}_{\text{bg}} = 0.43 \pm 0.09$ and after the unblinding, we observe $N^{\text{obs}} = 0$, see fig.3 right. An upper limit $\mathcal{B}_{K^+\to\pi^-e^+e^+} < 5.3 \times 10^{-11}$ is obtained at 90% CL.

For the $K^+ \to \pi^-\pi^0e^+e^+$ decay, additional selection conditions are applied based on the π^0 reconstruction. The signal acceptance is $A_{\pi\pi ee} = (0.271 \pm 0.003)\%$ and the SES

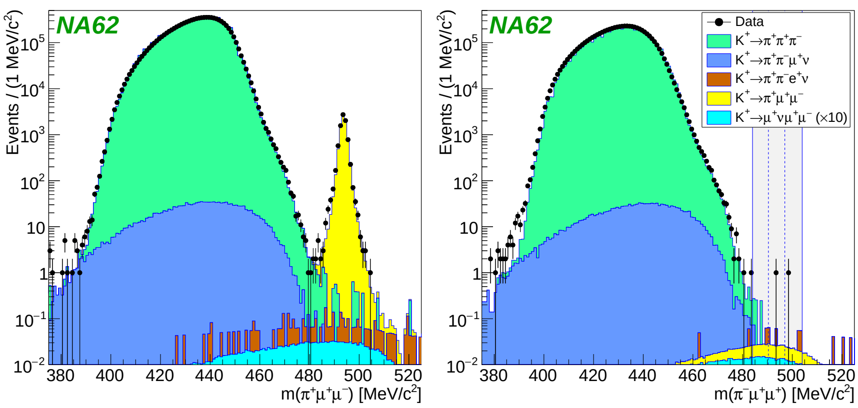

Figure 2. $\pi\mu\mu$ final state mass spectra, data overlaid with simulated background estimates [9]. Left: SM normalization channel $\pi^+\mu^+\mu^-$. Right: LNV channel $\pi^-\mu^+\mu^+$.

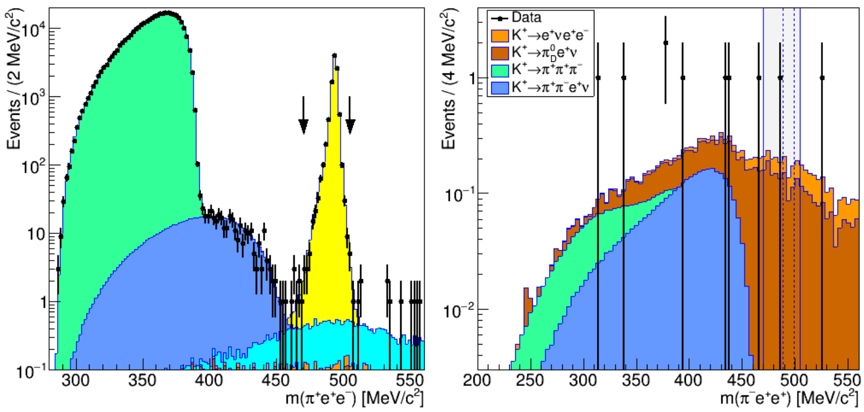

Figure 3. πee final state mass spectra, data overlaid with simulated background estimates [10]. Left: SM normalization channel $\pi^+e^+e^-$. Right: LNV channel $\pi^-e^+e^+$.

$S_{\pi\pi ee} = (3.68 \pm 0.12) \times 10^{-10}$. The expected background in the SR yields $N_{\rm bg}^{\rm exp} = 0.044 \pm 0.020$ and, after the unblinding, we observe $N^{\rm obs} = 0$ in the SR, resulting in an upper limit $\mathcal{B}_{K^+\to\pi^-\pi^0e^+e^+} < 8.5 \times 10^{-10}$ at 90% CL.

5. Search for the $K^+ \to \pi^\pm\mu^\mp e^+$ and $\pi^0 \to \mu^-e^+$ decays

This analysis has been performed on a combined 2017–18 dataset. Three L0 trigger lines are used MT ($D = 100$), eMT ($D = 8$) and μMT ($D = 8$) where μMT is the MT trigger with an additional requirement on MUV3 hits and at least 10 GeV deposited in the LKr. For the former two L0 triggers, the L1 definiton is the same as for previous analyses while for the μMT L0 an additional veto condition requiring less than 3 in-time signals in LAV2–11 is applied at L1. The SM $K^+ \to \pi^+\pi^+\pi^-$ decay collected with the MT trigger is used for the normalization.

For the $\pi^0 \to \mu^-e^+$ decay, the $\pi^+\mu^-e^+$ selection is used, assuming the decay $K^+ \to \pi^+\pi^0$. The signal region is defined for $K^+ \to \pi^\pm\mu^\mp e^+$ as $490 < m_{\pi\mu e} < 498$ MeV$/c^2$ and the observed number of candidates in the normalization channel $K_{3\pi}$ is $N_{3\pi}^{\rm obs} = 2.73 \times 10^8$. The following table summarizes the results of the analysis for the three LFV decays.

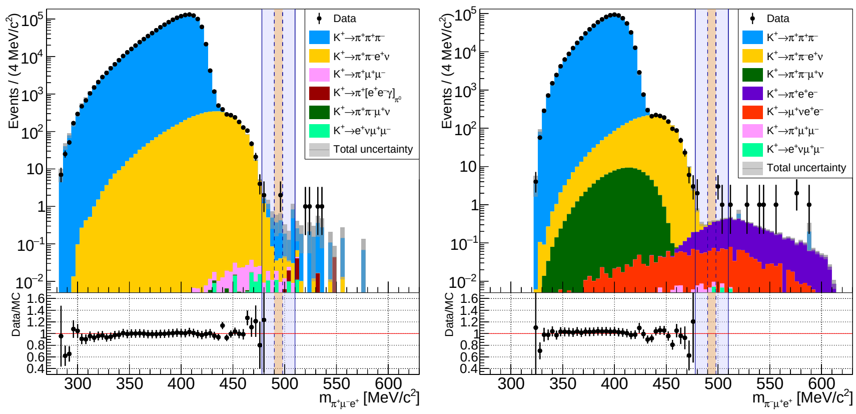

Figure 4. $m_{\pi\mu e}$ spectra, data overlaid with simulated background estimates and ratio between data events and MC simulations [11]. Left: $K^+ \to \pi^+\mu^-e^+$ decay, right: $K^+ \to \pi^-\mu^+e^+$ decay.

Decay channel	signal acceptance	SES	$N_{\mathrm{bg}}^{\mathrm{exp}}$	N^{obs}	$\mathcal{B}[10^{-11}]$
$K^+ \to \pi^- \mu^+ e^+$	$(4.90 \pm 0.02)\%$	$(1.82 \pm 0.08) \times 10^{-11}$	1.07 ± 0.20	0	4.2
$K^+ \to \pi^+ \mu^- e^+$	$(6.21 \pm 0.02)\%$	$(1.44 \pm 0.05) \times 10^{-11}$	0.92 ± 0.34	2	6.6
$\pi^0 \to \mu^- e^+$	$(3.11 \pm 0.02)\%$	$(1.39 \pm 0.09) \times 10^{-10}$	0.23 ± 0.15	0	32

6. Search for the $K^+ \to \mu^- \nu e^+ e^+$ decay

This analysis has been performed on the full Run 1 data set collected with the same trigger lines as in the previous analysis. The SM $K^+ \to \pi^+ e^+ e^-$ decay is used for the normalization.

The SR is defined in terms of the reconstructed invariant mass 470 MeV$/c^2 < m_{\pi ee} <$ 505 MeV$/c^2$ for the SM $K_{\pi ee}$ decay and in terms of the square of the missing invariant mass m^2_{miss} for the target $K_{\mu\nu ee}$ decay: -0.006 GeV$^2/c^4 < m^2_{\mathrm{miss}} < 0.004$ GeV$^2/c^4$. We observe $N_{\pi ee} = 10975$ decays in the SM channel. The signal acceptance is $A_{\mu\nu ee} = 1.44\%$ and the SES $S_{\mu\nu ee} = (3.53 \pm 0.12) \times 10^{-11}$. The expected background in the SR of the LNV decay is $N^{\mathrm{bg}}_{\mathrm{exp}} = 0.26 \pm 0.04$ and we observe $N_{\mathrm{obs}} = 0$, resulting in an upper limit $\mathcal{B}_{K_{\mu\nu ee}} < 4.2 \times 10^{-11}$ at 90% CL.

7. Conclusions

Results of various analysis performed on NA62 Run 1 data set have been presented, showing no signs of lepton number or lepton flavour violation in the K^+ decays studied. These results set the current world's most stringent upper limits on the branching ratios. The improvement factors, obtained from the comparison of the measured branching ratio upper limit to the previous measurements, are shown in the following summary table. The single event sensitivities of the NA62 Run 1 data set for decays $K^+ \to \pi^+ \mu^+ e^-$ and $\pi^0 \to \mu^+ e^-$ are not competitive with previous searches [13, 14].

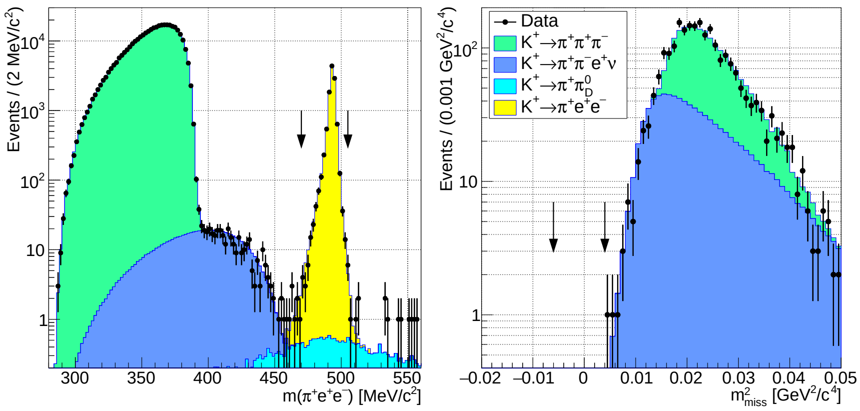

Figure 5. Left: $m_{\pi ee}$ spectra from $K_{\pi ee}$ selection, data overlaid with simulated background estimates. Right: m^2_{miss} spectra from $K_{\mu\nu ee}$ selection. [12]

Decay channel	Previous $\mathcal{B}$ UL [8]	NA62 $\mathcal{B}$ UL	improvement
$K^+ \to \pi^-\mu^+\mu^+$	8.6×10^{-11} [15]	4.2×10^{-11} [9]	$\sim$ factor 2
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10} [16]	5.3×10^{-11} [10]	$\sim$ factor 12
$K^+ \to \pi^-\pi^0e^+e^+$	–	8.5×10^{-11} [10]	first search
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10} [16]	4.2×10^{-11} [11]	$\sim$ factor 12
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10} [16]	6.6×10^{-11} [11]	$\sim$ factor 8
$\pi^0 \to \mu^-e^+$	3.4×10^{-9} [16]	3.2×10^{-10} [11]	$\sim$ factor 10
$K^+ \to \mu^-\nu e^+e^+$	2.1×10^{-8} [17]	8.1×10^{-11} [12]	$\sim$ factor 250

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