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# Search for lepton number and flavour violation in $K^+$ and $\pi^0$ decays

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The NA62 experiment at CERN collected a large sample of charged kaon decays into final states with multiple charged particles in 2016-2018. This sample provides sensitivities to rare decays with branching ratios as low as $10^{-11}$. Searches for the lepton number violating $K^+ \to \pi^- \mu^+ e^+$ decay and the lepton flavour violating $K^+ \to \pi^+ \mu^- e^+$ and $\pi^0 \to \mu^- e^+$ decays are reported. No evidence for these decays is found and upper limits of the branching ratios are obtained at 90% confidence level. These results improve by one order of magnitude over previous results for these decay modes.

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## 1. Introduction

Lepton Number (LN) and Lepton Flavor (LF) are conserved quantum numbers in the standard model (SM), nevertheless their conservation is not imposed by any local gauge symmetry. LN violation have never been observed so far. LF violations arise from neutrino oscillations while the charged sector is still not subject to these observations. LN and LF violations are foreseen by several new physics models built to explain experimental results which are not described by the SM, as the neutrino oscillations or the possible flavor anomalies in B physics [1]. Kaon and pion decays are convenient environment to search for such violations and their observation would be a clear indication of physics beyond the SM. This document reports the results on the search for LNV through the decay $K^+ \to \pi^-\mu^+e^+$ and on the search for LFV through the decay $K^+ \to \pi^+\mu^-e^+$ and $\pi^0 \to \mu^-e^+$, obtained analysing the data collected by the NA62 experiment [2] at CERN SPS in 2017-2018. The previous 90% CL upper limits for the branching ratios of these decays are: $\mathcal{B}(K^+ \to \pi^-\mu^+e^+) < 5.0\times10^{-10}$, $\mathcal{B}(K^+ \to \pi^+\mu^-e^+) < 5.2\times10^{-10}$ and $\mathcal{B}(\pi^0 \to \mu^-e^+) < 3.4\times10^{-9}$ [3].

## 2. The NA62 experiment and analysis strategy

The NA62 experiment has been designed to measure with high precision the branching ratio $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$, a schematic view is in Fig.1 and the details of the beam line and detectors are described in [2]. In the following only an overview of the main detectors used in this work is given. The 400 GeV/$c$ proton beam provided by the SPS accelerator impinges a berillyum target

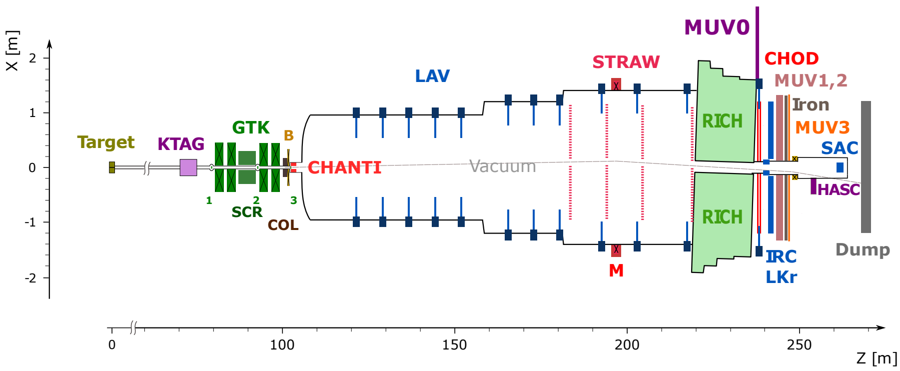


**Figure 1:** Schematic side view of the NA62 beamline and detector.

giving rise to a secondary beam composed of only 6% of kaons with a nominal momentum of 75 GeV/$c$. They are identified by a differential Cherenkov counter (KTAG) with a 70 ps resolution. A magnetic spectrometer (STRAW) measures the momenta and directions of the charged particles produced by the decays of the kaons in a 75 m long fiducial volume (FV). The detectors used in the particle identification of these analyses are the quasi-homogeneous liquid krypton electromagnetic calorimeter (LKr) and a muon detector (MUV3). A hermetic photon veto system is composed by the LKr and a twelve ring-shaped lead-glass detectors (LAV).
The details of the analysis are described in [4] and the results are based on data collected in 2017 and 2018 with a mean $K^+$ decay rate in the fiducial volume (FV) of 3.7 MHz.

The trigger system is composed of a hardware level (L0) and a software level (L1). Three trigger streams dedicated to this analysis run simultaneously with the trigger chain needed for the primary goal of the experiment: the multi-track (MT) which select at least three tracks, the electron multi-track ($e$MT) which requires in addition to the tracks an energy deposit in the LKr of at least 20 GeV (LKr20), and the muon multitrack ($\mu$MT) which requires also an energy deposit in the calorimeter of at least 10 GeV (LKr10) and a muon. These three trigger chains are run in logical $OR$ depending on the particular channel and are downscaled with factors depending on the particular run periods. The typical factors are: $D_{MT} = 100$, $D_{eMT} = 8$, and $D_{\mu MT} = 8$.
The signal event selection requires three tracks which are in time with the trigger time, form a vertex in the fiducial volume defined by the $105 < Z_{vtx} < 180$ m and are in coincidence with the presence of an upstream kaon detected by the KTAG. In addition a LAV photon veto is applied.
The decay $K^+ \to \pi^+\pi^+\pi^-$ is used as normalization channel. This sample is selected with the trigger stream $MT$ and the offline selection requires that the 3 tracks invariant mass is within $3\sigma_{3\pi}$ from the kaon mass, where $\sigma_{3\pi} = 0.9$ MeV/c$^2$.
The particle identification (PID) is obtained with information from the LKr, the muon detector (MUV3) and the variable $E/p$, where $E$ is the energy of the LKr cluster and $p$ is the momentum measured by the STRAW. For the $K^+ \to \pi^-\mu^+e^+$ channel the additional condition $m(\pi^-e^+) > 140\text{MeV}/c^2$ is used to reduce other kaon decays background.
The distribution of the invariant mass of the three tracks $m_{\pi\mu e}$ is divided in several regions: $m_{\pi\mu e} < 478$ MeV$/c^2$ is used for the optimization and definition of the analysis, while the signal region (490-498 MeV$/c^2$) and two control regions, CR1 (478-490 MeV$/c^2$) and CR2 (498-510 MeV$/c^2$), are kept masked during the optimization of the selection. For the channel $\pi^0 \to \mu^-e^+$ the additional requirement $|m_{\mu e} - m_{\pi^0}| < 2\text{MeV}/c^2$ is applied.
The trigger efficiency is measured with minimum bias data. The Monte Carlo (MC) does not reproduce accurately the energy deposited by the pion in the LKr, therefore a correction is applied to the simulation samples. Table.1 reports the trigger efficiencies used in the analysis. The lower efficiency for the $\pi^0$ decay channel with respect to the two kaon decay channels is due to the softer $e^+$ spectrum as it is clear in Fig.2(left). There are two main sources of background: $K^+$ decays with particle misidentification (mis-ID) and $\pi^\pm \to l^\pm\nu_l$, $(l = \mu, e)$, decay in flight. The mis-ID $\pi^\pm \Leftrightarrow e^\pm$ probabilities arise from the $E/p$ measurement and are estimated with data collected with minimum bias trigger. They depend on the momentum of the particle and are shown in Fig.2(right). Mis-ID of $\pi^\pm$ as $\mu^\pm$ arise from the accidental matching between tracks and signal in MUV3, they depend on the momentum and position and are evaluated with simulation to be 2-3 $\times 10^{-3}$. Mis-ID of $\mu^\pm$ as $\pi^\pm$ is due to the MUV3 inefficiency and evaluated with a $K^+ \to \mu^+\nu_\mu$ sample and is $1.5 \times 10^{-3}$. $e^\pm$ is misidentified as $\mu^\pm$ when it is absorbed upstream ot the LKr and corresponds to $O(10^{-8})$. The contribution to the background of the decays in flight is found considering the decay $K^+ \to \pi^+\pi^+\pi^-$ occurring within the FV and the probability that at least one of the pions decays upstream of the LKr, which is obtained with simulation.
The single event sensitivity ($\mathcal{B}_{SES}$) is defined as the branching ratio corresponding to the observation of one signal event and is computed for each process and for each data-taking period $i$, with the

corresponding effective trigger downscaling factor $D_i^{eff}$:

$$D^i_{eff} = \left[1 - \left(1 - \frac{1}{D^i_{MT}}\right)\left(1 - \frac{1}{D^i_{\mu MT}}\right)\left(1 - \frac{1}{D^i_{eMT}}\right)\right]^{-1}. \tag{1}$$

The number of kaon decays in the FV, $N^i_K$, is found using the number of events of the normalisation channel $K^+ \to \pi^+\pi^+\pi^-$, $N_{3\pi}$, the selection acceptance $A_n = 10.18 \times 10^{-2}$, the trigger efficiency $\epsilon_n$ and the branching ratio $\mathcal{B}(K_{3K}) = (5.583 \pm 0.024) \times 10^{-2}$.
Therefore $\mathcal{B}^i_{SES}$ can be written as:

$$\mathcal{B}^i_{SES} = \frac{1}{N^i_K A_S \epsilon^i_S} = \mathcal{B}(K_{3\pi})\frac{A_n D^i_{eff}}{A_S N^i_{3\pi} D^i_{MT}} \frac{\epsilon_n}{\epsilon^i_S} \tag{2}$$

where $A_S$ are the signal acceptances, $\epsilon^i_S$ are the trigger efficiencies.
The total number of kaon decays in the FV used in the analysis is:

$$N_K = \sum_i N_K = \frac{1}{B(K_{3K})A_n\epsilon_n} \cdot \sum_i \left(N^i_{3\pi} \frac{D^i_{MT}}{D^i_{eff}}\right) = (1.33 \pm 0.02) \times 10^{12} \tag{3}$$

| | $K^+ \to \pi^-\mu^+e^+$ | $K^+ \to \pi^+\mu^-e^+$ | $\pi^0 \to \mu^-e^+$ |
|---|---|---|---|
| $A_S \times 10^2$ | $4.90 \pm 0.02$ | $6.21 \pm 0.02$ | $3.11 \pm 0.02$ |
| $\epsilon_{LKr10} \times 10^2$ | $97.5 \pm 1.3$ | $97.5 \pm 1.3$ | $92.9 \pm 1.2$ |
| $\epsilon_{LKr20} \times 10^2$ | $74.1 \pm 1.6$ | $73.3 \pm 1.6$ | $45.3 \pm 1.0$ |
| $\mathcal{B}_{SES} \times 10^{11}$ | $1.82 \pm 0.08$ | $1.44 \pm 0.05$ | $13.9 \pm 0.9$ |

**Table 1:** Signal acceptances $A_S$, trigger efficiencies $\epsilon_{LKr10}$ and $\epsilon_{LKr20}$, and single event sensitivities $\mathcal{B}_{SES}$ for each signal channel.

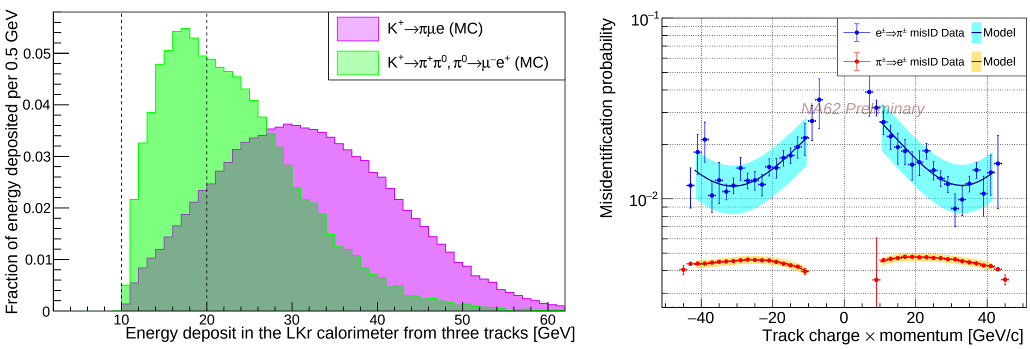


**Figure 2:** Left: MC Distributions, after data-driven corrections, of energy deposited in the LKr associated with the three selected tracks. Right: Probabilities of misidentify $\pi^{+/-}$ as $e^{+/-}$ (blue) and of $e^{+/-}$ as $\pi^{+/-}$ (red).

The background evaluation is performed with MC samples corrected with the corresponding mis-ID probabilities and the possible data-simulation discrepancies.

## 3. Results

The distributions of the background contributions in the invariant mass $m_{\pi\mu e}$ variable are shown in Fig.3 together with the distribution of observed events. There is a clear agreement between the expected and observed events outside the masked region. A good agreement is observed also after the unmasking of the control regions CR1 and CR2. Therefore the signal regions could be unmasked giving a number of observed events consistent with the background predictions, reported in Table 2. Upper limits at 90% CL to the branching ratios are obtained with the $CL_S$ method with a likelihood ratio test statistic and are reported in the same table. These results improve on previous searches by one order of magnitude.

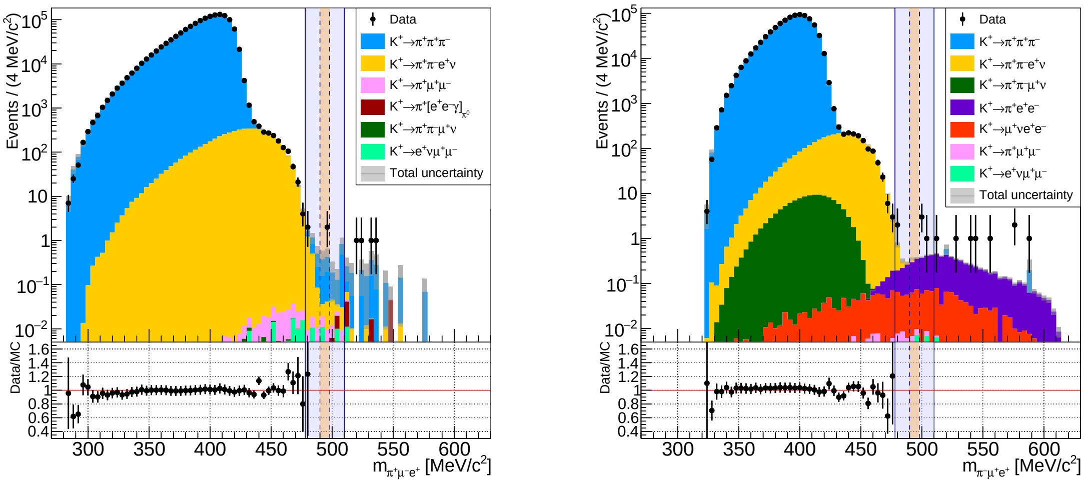


**Figure 3:** Three particle invariant mass distribution for $K^+ \to \pi^-\mu^+e^+$ (left) $K^+ \to \pi^+\mu^-e^+$ (right) samples.

| Decay | $n_{bkg}$ | $n_{obs}$ | BR upper limit at 90% CL |
|---|---|---|---|
| $K^+ \to \pi^-\mu^+e^+$ | $1.07 \pm 0.20$ | 0 | $4.2 \times 10^{-11}$ |
| $K^+ \to \pi^+\mu^-e^+$ | $0.92 \pm 0.34$ | 2 | $6.6 \times 10^{-11}$ |
| $\pi^0 \to \mu^-e^+$ | $0.23 \pm 0.15$ | 0 | $3.2 \times 10^{-10}$ |

**Table 2:** Number of background, observed events and resulting upper limit at 90% CL for the three signal channels.

## References

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