Searches for lepton flavor and lepton number violation in K^+ decays with NA62

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Abstract. The NA62 experiment at the CERN SPS provides unique opportunity to study rare and forbidden decays of K^+ mesons. Using the data collected in 2017 a search for the lepton number violating decays $K^+ \to \pi^- \mu^+ \mu^+$ and $K^+ \to \pi^- e^+ e^+$ has been performed. New upper limits on the branching ratio have been obtained: 4.2×10^{-11} for the muon and 2.2×10^{-10} for the electron mode (90% confidence level). These results improve the existing limits by factors of 2 and 3 respectively.

1. Introduction

A lot of scenarios beyond the Standard Model (SM) allow for lepton flavor violating (LFV) and lepton number violating (LNV) processes. For example, in the kaon sector the decays $K^+ \to \pi^- \mu^+ \mu^+$ and $K^+ \to \pi^- e^+ e^+$ could exist under the assumption that there is a massive Majorana neutrino [1, 2]. If such processes were observed, this would lead to the clear evidence of physics beyond the SM.

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The best upper limits obtained so far come from the CERN NA48/2 experiment for the muon mode [3] ($BR(K^+ \to \pi^-\mu^+\mu^+) < 8.6 \times 10^{-11}$) and from BNL E865 for the electron mode [4] ($BR(K^+ \to \pi^-e^+e^+) < 6.4 \times 10^{-10}$). A new search for both modes [5] with 30% of the data collected by NA62 is reported below.

2. NA62 experiment

The NA62 experiment which is currently running at the CERN SPS is aimed at the 10% precision measurement of the branching fraction of the ultra rare decay $K^+ \to \pi^+\nu\bar{\nu}$. The experiment has been taking data since 2016 and offers a wide physics program beyond the baseline: tests of Chiral perturbation theory, lepton flavor universality in kaon decays, hidden sector searches (dark photons, dark scalars, heavy neutral leptons), searches for rare and forbidden K^+ and π^0 decays [6, 7].

The experimental setup is described in detail in [8] and shown in Figure 1.

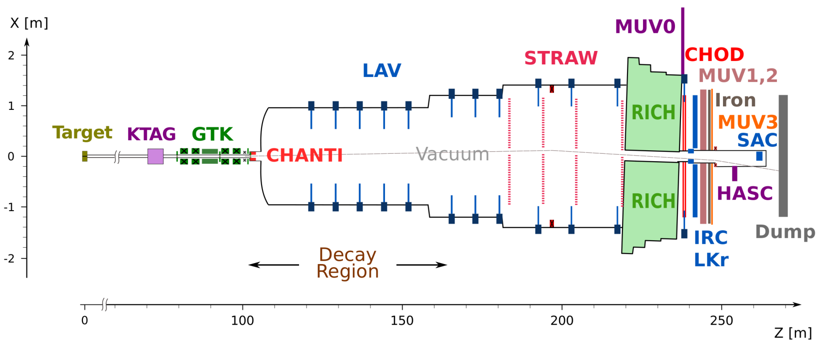

Figure 1. NA62 setup. The beam goes in the positive Z direction.

The secondary unseparated hadron beam (p = 75 GeV/c) is created by SPS protons (p = 400 GeV/c) impinging on a beryllium target. The beam is composed of π^+ (70%), K^+ (6%) and protons (24%) with the total particle rate of 750 MHz at the nominal beam intensity. Kaons decay in a fiducial volume (FV) contained in a vacuumed (10^{-6} mbar) cylindrical tank to minimise beam interactions with the residual gas.

The tracking system consists of the beam spectrometer Gigatracker (GTK), made of three stations of silicon pixel detectors, and the straw spectrometer (STRAW) composed of four stations each having four views. The beam particle identification is performed by a Cherenkov differential counter (KTAG), while a Ring Imaging Cherenkov (RICH) detector is used for the separation of pions and muons produced in kaon decays, as well as for the precise timing. The liquid Krypton (LKr) calorimeter is responsible for the electron identification and together with intermediate (IRC) and small angle (SAC) calorimeters provides the photon detection at small emission angles (up to 15 mrad). Large angles (up to 50 mrad) are covered by 12 stations of large angle vetoes (LAV), distributed over the length of the decay volume. Hadron calorimeters MUV1 and MUV2 complement the pion identification. Finally, the MUV3 detector is aimed at detecting/vetoing muons.

3. Data sample and event selection

For the present study a subset ($\sim$ 30%) of the data collected by the NA62 experiment is used. The sample has been taken in 2017 and contains about 2.3×10^5 SPS spills. Typical beam intensity in 2017 was 2×10^{12} protons per SPS spill, corresponding to the 450 MHz particle rate at the FV entrance and 3.5 MHz K^+ decay rate in FV.

Dedicated trigger lines were used to select di-muon and di-electron final states. The L0 conditions [9] are based on the RICH multiplicity and a requirement of the signal presence in two opposite quadrants of the charged hodoscope. The di-muon L0 trigger in addition requires a coincidence of signals from at least two MUV3 tiles, while the di-electron L0 trigger at least 20 GeV energy deposit in the LKr calorimeter. The L1 trigger conditions require the beam kaon identification by the KTAG and the reconstruction of a negatively charged track in STRAW.

A blind analysis strategy is adopted for the search for LNV decay modes, the normalisation modes being the corresponding flavour changing neutral current (FCNC) decays $K^+ \to \pi^+\mu^+\mu^-$ and $K^+ \to \pi^+e^+e^-$. The branching ratios of the normalisation modes are measured to a few percent precision [10, 11]. Signal and normalisation modes are collected concurrently, using the same trigger lines. Assuming similar kinematic distributions, this approach allows for the first order cancellation of the detector and trigger inefficiencies, as well as the event pileup.

The event selection starts with the requirement on the presence of a good quality 3-track vertex reconstructed in the fiducial volume: 114 m $< Z_{vtx} <$ 180 m for the muon mode (105 m $< Z_{vtx} <$ 180 m for the electron mode) and the total charge equal to +1 e. Track momenta must be in the range 5 GeV/c$< p <$45 GeV/c (8 GeV/c $< p <$ 45 GeV/c). Track times are required to be consistent with each other within 15 ns. The particle identification (PID) is based on the E/p ratio which is required to be $0.9 < E/p < 1.1$ for $e^\pm$, $E/p < 0.90$ (0.85) for $\pi^\pm$ and $E/p < 0.2$ for $\mu^\pm$. The RICH is used for the additional e^+ identification for the electron mode. To reject the background from the decay chain $K^+ \to \pi^+\pi^0, \pi^0 \to e^+e^-\gamma$, all photon detectors are used in the veto mode. Muon candidates are required to have at least one MUV3 hit associated in time and space with the track reconstructed by the STRAW spectrometer.

4. Backgrounds

The dominant background source for both electron and muon mode is the decay $K^+ \to \pi^+\pi^+\pi^-(K_{3\pi})$ (BR = 5.58%) where two pions either decay in flight ($\pi \to \mu\nu_\mu$) or are misidentified as muons or electrons. To estimate the contribution from the $K_{3\pi}$ decay with two pion decays, a dedicated Monte-Carlo (MC) sample was produced where events were preselected at the generator level to have at least two potential pion decays. The background from $K_{3\pi}$ with one pion decay and one misidentified pion (two misidentified pions) is evaluated using MC simulation and forced misidentification of a pion (two pions). The misidentification (misID) probabilities are measured with the data as a function of the momentum, using dedicated selections. The LKr response is known to be the same for electrons and positrons and the momentum dependence of the misID probability is weak. For the RICH, the misID probability is higher at lower momentum due to the Cherenkov threshold and at higher momentum where electron and pion rings become almost identical. The combined probability reaches a minimum values of 10^{-5} at 25 GeV/c, and increases up to 2×10^{-3} at 10 GeV/c, and to 10^{-4} at 45 GeV/c, see Figure 2.

5. Results

The distributions of the invariant mass $M(\pi ll)$ for the signal and normalisation are shown in Figure 3. For the muon mode the number of candidates for the normalisation mode is 8357 resulting in the number of K^+ decays in the fiducial volume $N_K = (7.94 \pm 0.23) \times 10^{11}$. The evaluated signal acceptance for the LNV decay is 9.81%. The single event sensitivity is found to be SES $= (1.28 \pm 0.04) \times 10^{-11}$. The total background estimate in the LNV signal region is 0.91 $\pm$ 0.41. After unblinding 1 event is observed in the LNV $K^+ \to \pi^-\mu^+\mu^+$ signal region, and an upper limit is set on the branching ratio of the LNV mode using the CLs statistical treatment: $BR(K^+ \to \pi^-\mu^+\mu^+) < 4.2 \times 10^{-11}$ at 90% confidence level.

The event selection for $K^+ \to \pi^+e^+e^-$ includes the RICH PID for e^+. An auxiliary selection without RICH PID is used for the validation of background estimates. For this selection the

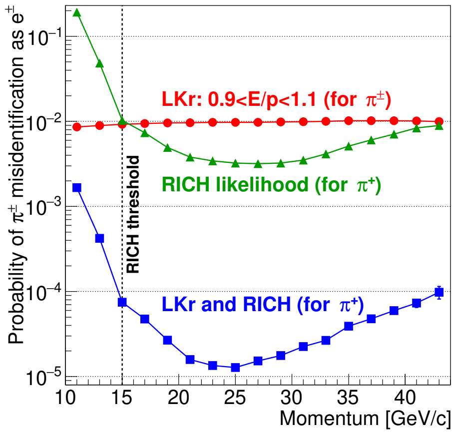

Figure 2. Measured misID probabilities of $\pi^{\pm}$ as $e^{\pm}$ as a function of the track momentum.

sensitivity is limited by the background from the decay chain $K^+ \to \pi^+\pi^0, \pi^0 \to e^+e^-\gamma$. The usage of RICH allows to reduce the background by the factor of 6. The expected background estimate in the LNV $K^+ \to \pi^-e^+e^+$ signal region is 0.16 ± 0.03, where the error is dominated by the systematic uncertainty of the background description after including the RICH PID. For the normalisation mode, 2484 candidates are observed which leads to $N_K = (2.14 \pm 0.07) \times 10^{11}$. The signal acceptance for the LNV $K^+ \to \pi^-e^+e^+$ decay is calculated from MC under the assumption of the uniform phase space: A = 4.98%. A single event sensitivity defined as $SES = 1/(N_K \cdot A)$ is found to be $(0.94 \pm 0.03) \times 10^{-10}$. After unblinding zero events are observed in the LNV $K^+ \to \pi^-e^+e^+$ signal region, and an upper limit is set on the branching fraction of the electron mode using the CLs statistical treatment: $BR(K^+ \to \pi^-e^+e^+) < 2.2 \times 10^{-10}$ at 90% confidence level.

6. Conclusions

The search for the lepton flavor and lepton number violation decays $K^+ \to \pi^-\mu^+\mu^+$ and $K^+ \to \pi^-e^+e^+$ has been performed using the NA62 partial data sample. No signal is observed, the obtained upper limits are 4.2×10^{-11} for the muon mode and 2.2×10^{-10} for the electron mode. The low level of background does not affect much the sensitivity, hence using the full data sample collected in 2016–2018 should lead to the improvement (by a factor of 3) of the obtained upper limits. Other ongoing analyses of the LFV/LNV decays have the potential to significantly improve the existing limits, e.g. $K^+ \to \pi^-\mu^+e^+$, $K^+ \to \pi^+\mu^-e^+$, $K^+ \to e^-\nu\mu^+\mu^+$ (SES$\sim 5 \times 10^{-11}$ for each decay) and $K^+ \to \mu^-\nu e^+e^+$ (SES$\sim 1 \times 10^{-10}$).

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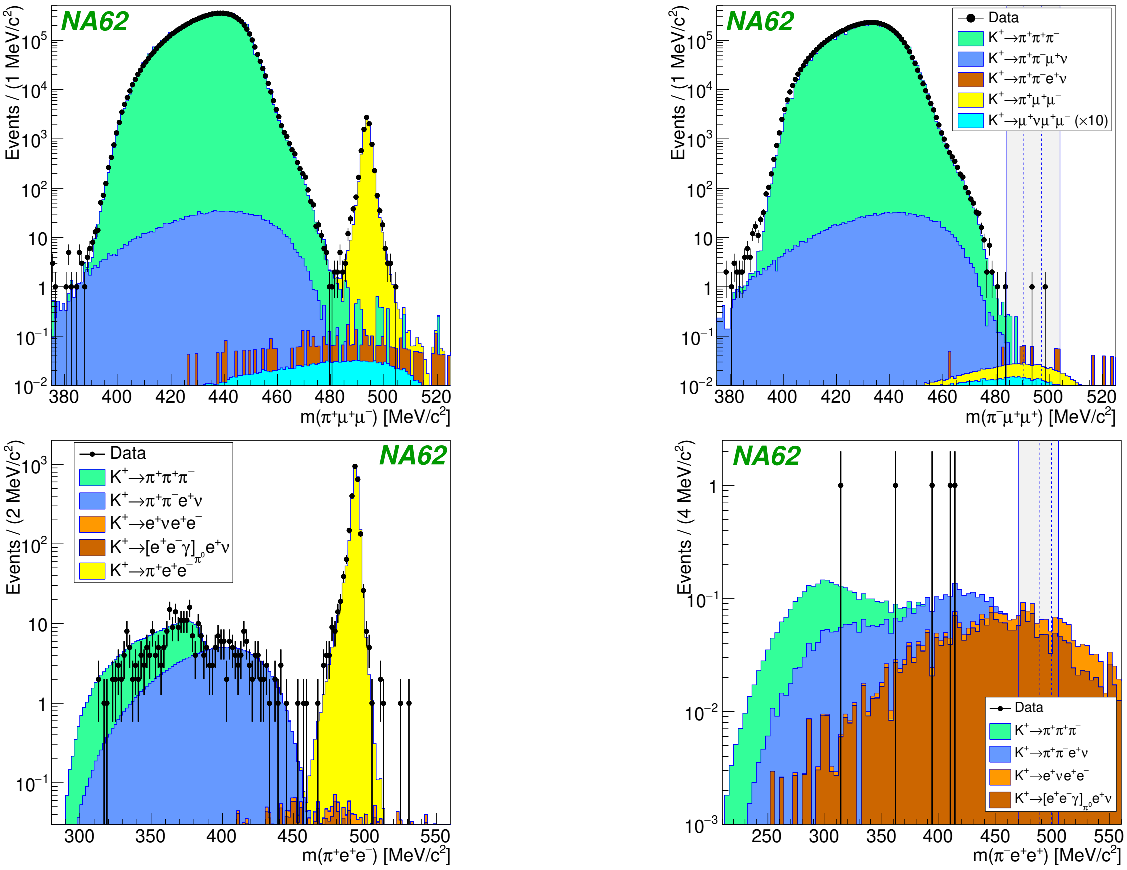

Figure 3. Reconstructed invariant mass $M(\pi ll)$ for selected samples of (top-left) SM $K^+ \to \pi^+\mu^+\mu^-$; (top-right) LNV $K^+ \to \pi^-\mu^+\mu^+$; (bottom-left) SM $K^+ \to \pi^+e^+e^-$; (bottom-right) LNV $K^+ \to \pi^-e^+e^+$. Data are overlayed with background estimates. The shaded vertical bands indicate the regions blinded during the analyses, the LNV signal regions are bounded by dashed lines.