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Searches for lepton flavour and lepton number violation in K+ decays

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The NA62 experiment at the CERN SPS is designed to conduct precision tests of the Standard Model by studying rare decays of charged kaons. NA62 took data in 2016-2018 and collected a large sample of charged kaon decays into final states with multiple charged particles. The sensitivity to a range of lepton flavour and lepton number violating kaon decays provided by this data set is improved over the previously reported measurements. Results from the searches of $K^+\to \pi^- l^+ l^+$ decays with a partial NA62 data sample are presented.

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1. Introduction

The existence of lepton number violating (LNV) and/or lepton flavour violating (LFV) processes are predicted by many scenarios beyond Standard Model (SM). The observation of $K^+ \rightarrow \pi^- l^+ l^+$ decays (where $l = e, \mu$), violating conservation of lepton number by two units, would verify the Majorana nature of the neutrino [1, 2]. The current limits at 90% CL on the branching fractions of these decays are $B(K^+ \rightarrow \pi^- e^+ e^+) < 6.4 \times 10^{-10}$ obtained by the BNL E865 experiment [3], and $B(K^+ \rightarrow \pi^- \mu^+ \mu^+) < 8.6 \times 10^{-11}$ obtained by the CERN NA48/2 experiment[4]. This search for $K^+ \rightarrow \pi^- l^+ l^+$ in about 30% of the data collected by the NA62 experiment at CERN in 2016-18 improves [5] the current best limits, and the results are summarized below.

2. The NA62 experiment

NA62 is a fixed target kaon experiment located on an extraction line from the CERN Super Proton Synchrotron (SPS). Protons of 400 GeV from the SPS impinge on a beryllium target producing a secondary hadron beam. There are upstream and downstream particle identification and spectrometer systems to measure K^+ beam and decay products respectively. The KTAG is a differential Cherenkov detector, which identify kaon component within the undecayed beam. The GigaTracker (GTK), an upstream spectrometer, is used to measure kaon beam momentum and direction. Downstream 4 STRAW chambers, located in the end of vacuum tank, and a large dipole magnet form a spectrometer, that provides momentum measurements and downstream tracks reconstruction. The Ring Imaging Cherenkov detector (RICH) provides identification for downstream particles π, μ and e in momentum range 15-35 GeV/c. A hermetic photon veto system consists of 12 large angle veto (LAV) stations surrounding the decay volume, the liquid krypton calorimeter (LKr). Additional particle identification can be obtained using the LKr and a fast scintillator detector, the MUV3 (muon veto), positioned after the LKr, two hadronic sampling calorimeters (MUV1 & MUV2) and an 0.8 m iron wall. The CHOD (charged hodoscope) detectors provide additional timing and triggering information. Detailed description and layout of NA62 detectors can be found in [6].

3. Data samples and event selection

Searches for $K^+ \rightarrow \pi^- l^+ l^+$ (denoted "LNV decays") and the flavour changing neutral current decays $K^+ \rightarrow \pi^+ l^+ l^-$ (denoted "SM decays") using the data sample acquired over three months of 2017 are performed. The SM decays with branching fractions, experimentally measured to a few percent precision [7, 4], are used for normalization. A blind analysis strategy is adopted. Dedicated two-level hardware (L0) [8] and software (L1) trigger lines have been used to collect considered data set. L0 trigger lines consist of multi-track, di-electron and di-muon trigger chains downscaled typically by factors of 100, 8 and 2, respectively. Requirements of the multi-track L0 trigger are RICH signal multiplicity and signal coincidence in two opposite CHOD quadrants. The di-electron L0 trigger selects 3-track events with at least 20 GeV energy deposition in the LKr. The di-muon L0 trigger requires a coincidence of signals from two

MUV3 tiles. Beam kaon identification by KTAG and reconstruction of a negatively charged track in STRAW are involved in software (L1) trigger.

Under the assumption of similar kinematic distributions for LNV and SM decays, this approach leads to first-order cancellation of the effects of detector inefficiencies, trigger inefficiencies and pileup. The condition of $K^+ \rightarrow \pi^- e^+ e^+$ ($K^+ \rightarrow \pi^- \mu^+ \mu^+$) event selection includes:

- constructing a vertex with charge +1 in the fiducial decay volume 105 m < Z_{vtx} < 180 m (114 m < Z_{vtx} < 180 m);
- the three charged track momenta in the range 8 GeV/c < p < 65 GeV/c (5 GeV/c < p < 65 GeV/c) and times within 15 ns (12 ns);
- the resulting final state momentum of 3-track compatible with beam nominal parameters (longitudinal and transverse momenta);
- particle identification through the reconstructed *E/p* ratio (with *E* being the energy deposited in LKr calorimeter and *p* being the track momentum measured by STRAW);

Electron ($e^{\pm}$) candidates are identified, when $0.9 < E/p < 1.1$. Muon ($\mu^{\pm}$) candidates require $E/p < 0.2$ (acting as minimum ionizing particles) and a signal in MUV3 is geometrically associated within 5 ns of the vertex time. *E/p* is broadly distributed for $\pi^{\pm}$ (depending on energy sharing between electromagnetic and hadronic shower components) and pion ($\pi^{\pm}$) candidates are selected, when $E/p < 0.85$. Positive identification of e^+ is also provided by RICH. Photon veto improves the rejection of background from neutral pion decays (like Dalitz decay $\pi^0 \rightarrow e^+ e^- \gamma$).

4. Backgrounds

The main source of $K^+ \rightarrow \pi^- l^+ l^+$ background comes from the $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ decays ($B(K^+ \rightarrow \pi^+ \pi^+ \pi^-) = (5.583 \pm 0.024)\%$). Acceptance and backgrounds evaluation are made using Monte Carlo (MC) simulation describing the detector geometry and data-driven techniques.

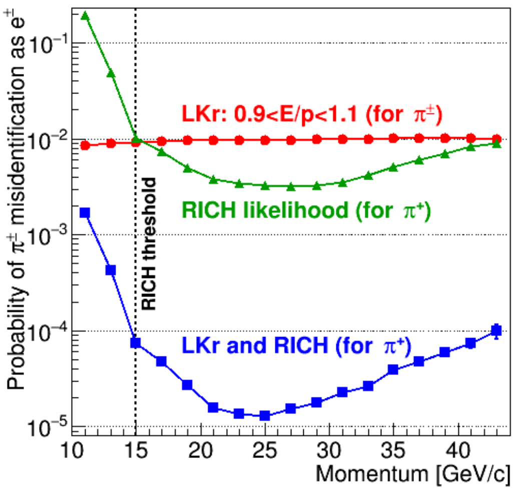

Figure 1: Measured probabilities of $\pi^{\pm}$ mis-identification as $e^{\pm}$ as functions of track momentum. LKr *E/p* condition alone (red), the RICH particle identification alone (green), the multiplication of the two (blue and dashed), LKr and RICH (blue and solid)

Particle mis-identification (mis-ID) and particle decays in flight are two main mechanisms of arising background. The major $K^+ \rightarrow \pi^- e^+ e^+$ background originates from $\pi^\pm$ mis-identification as $e^\pm$ and vice versa . Background estimation is based on simulations involving the measured pion ($\pi^\pm$) and electron ($e^\pm$) identification efficiencies, as well as pion to electron (and electron to pion) mis-ID probabilities. Each quantity is measured as a function of momentum using pion and positron samples obtained from kinematic selections of $K^+ \rightarrow \pi^+\pi^+\pi^-$ and $K^+ \rightarrow \pi^0 e^+ \nu$ decays. All measured inefficiencies and mis-ID probabilities are shown in Fig. 1.

Background in $K^+ \rightarrow \pi^- \mu^+ \mu^+$ sample arises mainly from $K^+ \rightarrow \pi^+\pi^+\pi^-$ with pion decays-in-flight to muons or pion mis-identified as muons. Background evaluation is performed with the same technique as for $K^+ \rightarrow \pi^- e^+ e^+$, using dedicated simulation based on control data samples.

5. Results

The invariant mass $M(\pi ll)$ spectra for SM and LNV $K \rightarrow \pi ll$ ($l = e, \mu$) candidates are shown in Fig. 2. In the SM $K^+ \rightarrow \pi^+ e^+ e^-$ signal mass region 470 MeV/c^2 < $M(\pi ee)$ < 505 MeV/c^2

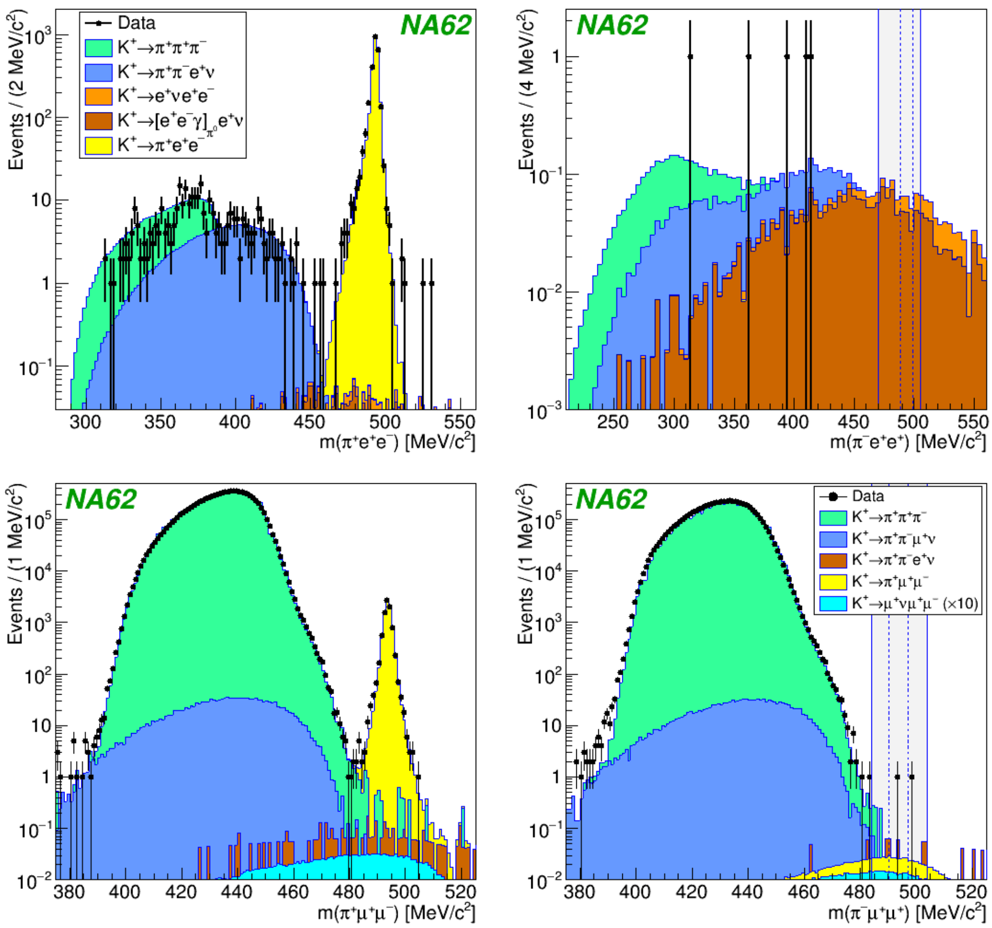

Figure 2: Reconstructed invariant πll mass spectra for selected samples of (top-left) SM $K^+ \rightarrow \pi^+ e^+ e^-$; (top-right) LNV $K^+ \rightarrow \pi^- e^+ e^+$; (bottom-left) SM $K^+ \rightarrow \pi^+ \mu^+ \mu^-$; (bottom-right) LNV $K^+ \rightarrow \pi^- \mu^+ \mu^+$. Data are overlayed with background estimates based on simulations. The shaded vertical bands indicate the regions masked during the analyses, which include the LNV signal regions bounded by dashed lines.

(also masked region for LNV mode) 2,484 $K^+ \rightarrow \pi^+e^+e^-$ candidates are observed with $M(ee)$ > 140 MeV/c^2 . The number of K^+ decays in fiducial volume is $N_K = (2.14 \pm 0.07) \times 10^{11}$. The signal acceptance for the LNV $K^+ \rightarrow \pi^-e^+e^+$ decay is 4.98%. The signal region for LNV mode is (493.7 ± 5.1) MeV/c^2. Total background estimate is (0.16 ± 0.03). After unbliding no candidate events are observed in the LNV $K^+ \rightarrow \pi^-e^+e^+$ signal region, and an upper limit is set on the branching fraction of the LNV mode using the CLs statistical treatment: $B(K^+ \rightarrow \pi^- e^+e^+) < 2.2\times10^{-10}$ at 90% confidence level.

In the SM $K^+ \rightarrow \pi^+\mu^+\mu^-$ signal mass region 484 MeV/c^2 < $M(\pi\mu\mu)$ < 504 MeV/c^2 (masked region for LNV mode) 8,357 $K^+ \rightarrow \pi^+\mu^+\mu^-$ candidates are observed. The number of K^+ decays is $N_K = (7.94 \pm 0.23) \times 10^{11}$. The signal acceptance for the LNV mode is 9.81%. Total background estimate is (0.91 ± 0.41). After unbliding 1 candidate event is observed in the LNV mode and an upper limit is set on the branching fraction of the LNV mode using the CLs statistical treatment: $B(K^+ \rightarrow \pi^-\mu^+\mu^+) < 4.2 \times 10^{-11}$ at 90% confidence level.

6. Conclusions

Searches for lepton number violating decays $K^+ \rightarrow \pi^-e^+e^+$ and $K^+ \rightarrow \pi^-\mu^+\mu^+$ have been performed using about 30% of the data collected by the NA62 experiment at CERN in 2016-2018. No signals are observed, but upper limits are improved on the previously reported measurements by factors of 3 and 2, respectively.

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