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Searches for Lepton Number Violation and resonances in $K^{\pm} \to \pi\mu\mu$ decays at NA48/2

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Abstract. The NA48/2 experiment at CERN collected in 2003-2004 a large sample of charged kaon decays with multiple charged particles in the final state. A new upper limit on the rate of the lepton number violating decay $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ obtained from this sample is reported. Moreover searches for two-body resonances in the $K^{\pm} \to \pi\mu\mu$ decays (including heavy neutral leptons and inflatons) in the accessible range of masses and lifetimes are presented. During the 2016 run the NA62 experiment has collected data with a dedicated trigger for kaon decays with two muons in the final state. Preliminary results on the statistics collected during a period of two weeks for the decay $K^+ \to \pi^+\mu^+\mu^-$ will be presented. The NA62 experiment has good potential for the studies of rare K^+ decays in addition to its main goal, the measurement of the branching ratio of the decay $K^+ \to \pi\nu\bar{\nu}$.

1. Introduction

The observation of neutrino oscillations[1] has unambiguously demonstrated the massive nature of neutrinos, thus right-handed neutrino states must be included in the Standard Model (SM). A natural extension of the SM involves the inclusion of sterile neutrinos which mix with ordinary neutrinos to explain several open questions. An example of such a theory is the Neutrino Minimal Standard Model (νMSM)[2]. In this model, three massive right-handed neutrinos are introduced to explain simultaneously neutrino oscillations, dark matter and baryon asymmetry of the Universe: the lightest has mass O(1 keV) and is a dark matter candidate; the other two, with masses ranging from 100 MeV/c to few GeV/c, are responsible for the masses of the

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SM neutrinos (via the see-saw mechanism) and introduce extra CP-violating phases to account for baryon asymmetry. The νMSM can be further extended by adding a real scalar field, to incorporate inflation and provide a common source for electroweak symmetry breaking and for right-handed neutrino masses[3]. These SM extensions predict new particles, such as heavy neutrinos and inflatons, which could be produced in $K^{\pm} \to \pi\mu\mu$ decays. In this model the Lepton Number Violating (LNV) $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ decay, which is forbidden in the SM, could proceed via the production of on-shell Majorana neutrinos[4], while inflatons χ could be produced in $K^{\pm} \to \pi^{\pm}\chi$ decays, and promptly decaying to $\chi \to \mu^+\mu^-$[5, 6].

The NA48/2 experiments was taking data at CERN in 2003 and 2004. A detailed description of the NA48 detector is available elsewhere [7]. The main difference of the NA48/2 setup was the replacement of the neutral kaon beams with two high intensity secondary beams (K^+ and K^-) with a momentum of 60 GeV/c. The two beams were simultaneous, generated from the same primary proton beam (400 Gev/c momentum) extracted from the SPS. The ration between the K^+ and K^- fluxes was 1.8 and the rate of kaon decays was about 100 KHz. The main trigger used to collect the data analyzed in the study presented here was based on the selection of events with a decay vertex with three outgoing charged particles.

A neutral particle X produced in $K^{\pm} \to \mu^{\pm}X$ ($K^{\pm} \to \pi^{\pm}X$) will decay promptly to $\pi^{\pm}\mu^{\mp}$ ($\mu^+\mu^-$) and will produce a narrow spike in the invariant mass $M_{\pi\mu}$ ($M_{\mu\mu}$) spectrum. Therefore the invariant mass distributions of the collected $K^{\pm} \to \pi\mu\mu$ samples in NA48/2 have been scanned looking for such a signature. The results of these searches are presented, together with the prospects for the search for Lepton Number and Flavour Violation (LNFV) at the NA62 experiment, which aims to precisely measure the branching ratio of the $K^+ \to \pi^+\nu\bar{\nu}$ decay.

2. Event reconstruction, selection and final data samples

The event selection is based on the reconstruction of a three-track vertex: given the resolution of the vertex longitudinal position ($\sigma_{vtx} \simeq 50$ cm), the decays $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ ($K^{LNV}_{\pi\mu\mu}$ from now on, kaon decays violating lepton number) and $K^{\pm} \to \pi^{\pm}\mu^{\pm}\mu^{\mp}$ ($K^{LNC}_{\pi\mu\mu}$ from now on, kaon decays conserving lepton number) mediated by a short-lived ($\tau \leq 10$ ps) resonant particle are indistinguishable from a genuine three-track decay. The size of the selected $K_{\pi\mu\mu}$ sample is normalised relative to the abundant $K^{\pm} \to \pi^{\pm}\pi^+\pi^-$ channel (denoted $K_{3\pi}$ below). The $K_{\pi\mu\mu}$ and $K_{3\pi}$ samples are collected concurrently using the same trigger logic. Since the μ and π masses are close ($m_{\mu}/m_{\pi} = 0.7$), the signal and the normalisation final states have similar topologies. This leads to first order cancellation of the systematic effects induced by imperfect kaon beam description, local detector inefficiencies, and trigger inefficiency. The selections for signal and normalization modes have a large common part; a vertex must satisfy the following criteria:

- The total electric charge of the three tracks is $Q = \pm 1$

- The vertex longitudinal position is within the 98 m long fiducial decay volume (i.e. downstream the final collimator).

- Each of the vertex tracks must have momentum p within the range (5;55) GeV/c, the total momentum of the three tracks must be consistent with the beam nominal range (55;65) GeV/c, and the total transverse momentum of the three tracks with respect to the beam axis direction is $p_T < 10^{-2}$ GeV/c. If several vertices fulfill the above conditions, the one with the lowest fit χ^2 is considered. The vertex tracks are required to be consistent in time and to be in the geometric acceptance of the main detectors. Track separations are required to exceed 2 cm in the first drift chamber (DCH1) plane to suppress photon conversions, and 20 cm in the Electromagnetic Calorimeter (LKr) and in the muon detector (MUV) front planes, to minimize particle misidentification due to shower overlaps and to multiple Coulomb scattering.

The following criteria are used to select the $K_{\pi\mu\mu}^{LNV}$ ($K_{\pi\mu\mu}^{LNC}$) candidates:

- The vertex must be composed of one $\pi^\pm$ candidate (with the ratio of energy E in the LKr calorimeter to momentum p measured in the spectrometer $E/p < 0.95$ to suppress electrons, and no in-time associated hits in the MUV), and a pair of identically (oppositely) charged $\mu^\pm$ candidates (with $E/p < 0.2$ and associated hits in the MUV). The $\pi^\pm$ candidate is required to have momentum above 15 GeV/c to ensure high muon rejection efficiency (above 99%).

- The invariant mass of the three tracks in the $\pi^\mp\mu^\pm\mu^\pm$ ($\pi^\pm\mu^+\mu^-$) hypothesis must satisfy the requirement $|M_{\pi\mu\mu} - M_K| < 5$ MeV/c2 ($|M_{\pi\mu\mu} - M_K| < 8$ MeV/c2), where M_K is the nominal $K^\pm$ mass. This range corresponds to 2 (3.2) times the resolution on $M_{\pi\mu\mu}$.

An additional requirement is applied to the $K_{\pi\mu\mu}$ samples, when searching for resonances: $|M_{ij} - M_X| < 2\sigma(M_{ij})$, where M_{ij} is the invariant mass of the ij pair ($ij = \pi^\pm\mu^\mp$, $\mu^+\mu^-$), M_X is the assumed resonance mass, and $\sigma(M_{ij})$ is the resolution on the invariant masses M_{ij}. Independently, the following criteria are applied to select the $K_{3\pi}$ sample:

- The pion identification criterion described above is applied to the odd-sign pion only, to symmetrize the selection of the signal and normalisation modes.

- The invariant mass of the three tracks in the 3π hypothesis is in the range $|M_{3\pi} - M_K| < 5$ MeV/c2. This interval corresponds approximately to 3 times the resolution on $M_{3\pi}$.

No restrictions are applied to additional energy depositions in the LKr calorimeter, nor to extra tracks not belonging to the three-track vertex, to decrease the sensitivity to accidental activity. The invariant mass distributions of data and MC events passing the $K_{\pi\mu\mu}^{LNV}$ ($K_{\pi\mu\mu}^{LNC}$) selections are shown in Fig. 1. The signal mass regions are indicated with vertical arrows. One event is observed in the signal region after applying the $K_{\pi\mu\mu}^{LNV}$ selection, while 3489 $K_{\pi\mu\mu}^{LNC}$ candidates are selected with corresponding selection. The number of expected background events in the sample $K_{\pi\mu\mu}^{LNV}$ is $N_{bkg} = 1.163 \pm 0.867_{stat} \pm 0.116_{syst} \pm 0.021_{ext}$, the main source of which is the $K_{3\pi}$ decay with two subsequent $\pi^\pm \to \mu^\pm\nu$ decays. The estimated $K_{3\pi}$ background contamination in the $K_{\pi\mu\mu}^{LNC}$ sample is $(0.36 \pm 0.10)\%$, based on MC simulations. Such a level of purity allows to consider the $K_{\pi\mu\mu}^{LNC}$ decay as the only background for the resonance searches over the collected $K_{\pi\mu\mu}^{LNC}$ sample. The number of $K^\pm$ decays in the 98 m long fiducial decay region is computed as $N_K = (N(K_{3\pi}) \cdot D)/(BR(K_{3\pi}) \cdot A(K_{3\pi})) = (1.64 \pm 0.01) \times 10^{11}$, where $N(K_{3\pi}) = 1.37 \times 10^7$ is the number of data candidates reconstructed within the $K_{3\pi}$ selection, $D = 100$ is the downscaling factor of the trigger used to collect the $K_{3\pi}$ sample, $BR(K_{3\pi})$ is the nominal branching ratio of the $K_{3\pi}$ decay mode and $A(K_{3\pi}) = (14.955 \pm 0.004)\%$ is the acceptance of the $K_{3\pi}$ selection evaluated with MC simulations.

3. Search for two-body resonances
A peak search assuming different mass hypotheses is performed over the distributions of the invariant masses M_{ij} ($ij = \pi^\pm\mu^\mp$, $\mu^+\mu^-$) of the selected $K_{\pi\mu\mu}$ samples. The precise evaluation of the acceptance for $K^\pm \to \mu^\pm X$ ($K^\pm \to \pi^\pm X$) decays with subsequent $X \to \pi^\pm\mu^\mp$ ($X \to \mu^+\mu^-$) decay as a function of the resonance mass and lifetime has been performed with dedicated MC simulations. The mass steps of the resonance searches and the width of the signal mass windows around the assumed mass are determined by the resolutions $\sigma(M_{ij})$ on the invariant masses M_{ij} ($ij = \pi^\pm\mu^\mp$, $\mu^+\mu^-$). The mass step is set to be equal to $\sigma(M_{ij})/2$, while the half-width of the signal mass window is $2\sigma(M_{ij})$. Therefore, the results obtained in the neighbouring mass hypotheses are highly correlated, as the signal mass window is about 8 times wider than the mass step of the resonance scan. In total, 284 (267) and 280 mass hypotheses are tested respectively for the search of resonances in the $M_{\pi\mu}$ distribution of the $K_{\pi\mu\mu}^{LNV}$ ($K_{\pi\mu\mu}^{LNC}$) candidates and in the $M_{\mu\mu}$
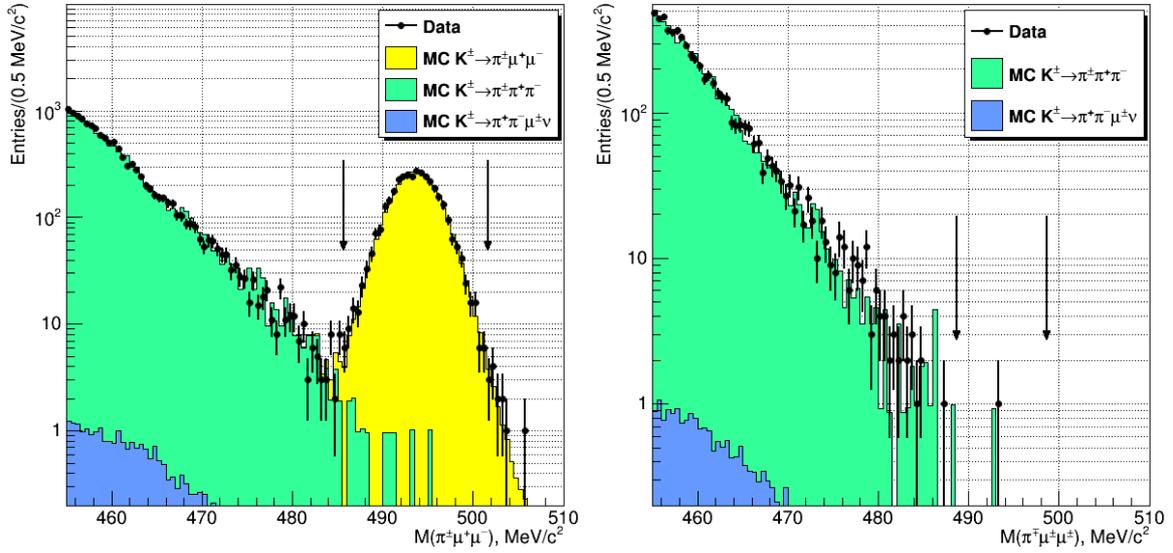
Figure 1. Invariant mass distributions of data and MC events passing the $K_{\pi\mu\mu}^{LNV}$ (left) and $K_{\pi\mu\mu}^{LNC}$ (right) selections. The boundaries of the signal mass regions are indicated with vertical arrows.

distribution of the $K_{\pi\mu\mu}^{LNC}$ candidates, covering the full kinematic ranges. The statistical analysis of the obtained results in each mass window is performed by using a quasi-Newton minimisation algorithm to find numerically the 90% confidence intervals for the case of a Poisson process in presence of unknown backgrounds, by applying an extension of the Rolke-Lopez method[8]. The upper limit at 90% CL on the number of signal events in the $K_{\pi\mu\mu}^{LNV}$ sample corresponding to the observation of one data event and a total number of expected background events N_{bkg} is obtained applying the Rolke-Lopez method to the total number of events in the KLNV sample: $N_{\pi\mu\mu}^{LNV} < 2.92$ at 90% CL. Using the values of the signal acceptance $A(K_{\pi\mu\mu}^{LNV}) = (20.62 \pm 0.01)\%$ estimated with MC simulations and the number N_K of kaon decays in the fiducial volume, the upper limit on the number of $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ signal events in the $K_{\pi\mu\mu}^{LNV}$ sample leads to a constraint on the signal branching ratio:

$$BR(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}) = \frac{N_{\pi\mu\mu}^{LNV}}{N_{3\pi} \cdot D} \cdot \frac{A(K_{3\pi})}{A(K_{\pi\mu\mu}^{LNV})} \cdot BR(K_{3\pi}) < 8.6 \times 10^{11} \ @ \ 90\% \ CL \qquad (1)$$

The total systematic uncertainty on the quoted upper limit is 1.5%. The largest source is the limited accuracy of the MC simulations (1.0%), followed by $BR(K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-})$ (0.8%), $BR(K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-})$ (0.73%), $BR(K^{\pm} \to \mu^{\pm}\mu^{+}\mu^{-}\nu)$ (0.24%) and $BR(K^{\pm} \to \mu^{\pm}\pi^{+}\pi^{-}\nu)$ (0.05%). This result improves the best previous limit[9] by more than one order of magnitude.

Concerning the search for two-body resonances, for each of the three resonance searches performed, the local significance $z = (N_{obs} - N_{exp})/\sqrt{\sigma N_{obs}^2 + \sigma N_{exp}^2}$ of the signal has been evaluated for each mass hypothesis, where N_{obs} is the number of observed events, N_{exp} is the number of expected background events, and σN_{obs} (σN_{exp}) is the statistical uncertainty of N_{obs} (N_{exp}). No signal is observed, as the local significances never exceed 3 standard deviations. In absence of a signal, upper limits on the product $BR(K^{\pm} \to p_1 X)BR(X \to p_2 p_3)$ ($p_1 p_2 p_3 = \mu^{\pm}\pi^{\mp}\mu^{\pm}, \mu^{\pm}\pi^{\pm}\mu^{\mp}, \pi^{\pm}\mu^{+}\mu^{-}$) as a function of several resonance lifetime τ are obtained for each mass hypothesis m_i and shown in Fig. 2.
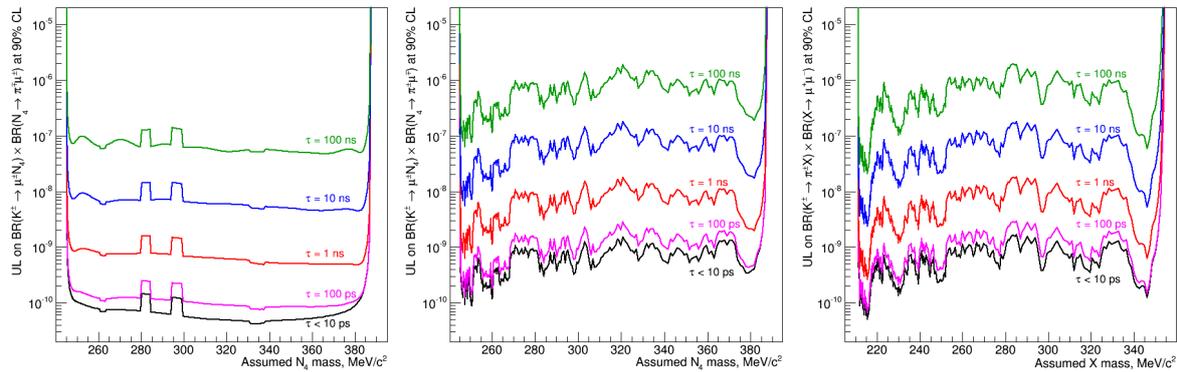
Figure 2. Obtained upper limits at 90% CL on the products of branching ratios as functions of the resonance mass and lifetime. $BR(K^{\pm} \to \mu^{\pm}N_4) \cdot BR(N_4 \to \pi^{\mp}\mu^{\pm})$ in the left; $BR(K^{\pm} \to \mu^{\pm}N_4) \cdot BR(N_4 \to \pi^{\pm}\mu^{\mp})$ in the center; $BR(K^{\pm} \to \mu^{\pm}\chi) \cdot BR(\chi \to \mu^{+}\mu^{-})$ in the right.

4. Prospects for the NA62 experiment

The NA62 experiment[10] has started to collect date in 2015 to perform the precise ($\sim 10\%$) measurement of the $K^{+} \to \pi^{+}\nu\bar{\nu}$ branching ratio. A total of $\sim 1.5 \times 10^{13}$ K^{+} decays is expected, with $\sim 3 \times 10^{12}$ π^{0} decays from $K^{+} \to \pi^{+}\pi^{0}$. Studies of the prospects for searches
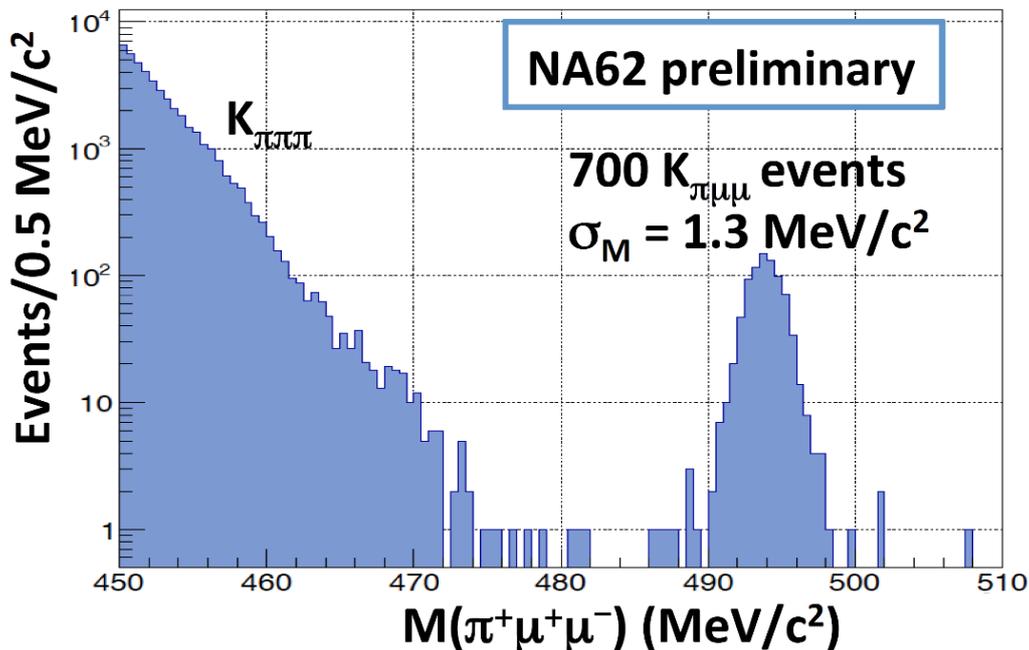
Figure 3. Sample of $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ collected by the NA62 experiment during 2 weeks in 2016.

for lepton-flavour (LF) or lepton-number (LN) violating and other forbidden decays with NA62 are underway. The expected acceptance for rare K^{+} (π^{0}) decays is $\sim 10\%$ (1%). Preliminary estimates of the single-event sensitivities (defined as the inverse of the number of accepted decays) give results at the level of 10^{-12} for K^{+} decays to states such as $\pi^{+}\mu^{\pm}e^{\mp}$ (LFV),

$\pi^-\mu^+e^+$ (LFNV), and $\pi^-e^+e^+$ or $\pi^-\mu^+\mu^+$ (LNV) and at the level of 10^{-11} for π^0 decays to $\mu^\pm e^\mp$. During the 2016 run the experiment has collected data with a dedicated trigger for events with two muons in the final state. In two weeks of data taking, at 24% of the nominal beam intensity of NA62, $\sim$700 $K^\pm \to \pi^\pm\mu^+\mu^-$ were collected as shown in Fig. 3. The resolution on the mass $M_{\pi\mu\mu}$ is 1.3 MeV/c^2, almost a factor two better than the one obtained in NA48/2. This will allow a better background rejection.

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