 Searches for lepton number violation and resonances in $K^\pm \rightarrow \pi \mu \mu$ decays at the NA48/2 experiment

Letizia Peruzzo 1
Johannes Gutenberg University, Mainz, Germany
E-mail: lperuzzo@uni-mainz.de

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 $K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm$ obtained from this sample is reported. Searches for two-body resonances in the $K^\pm \rightarrow \pi \mu \mu$ decays (including heavy neutral leptons and inflatons) in the accessible range of masses and lifetimes are presented.

1. Introduction
The massive nature of neutrinos has unambiguously been demonstrated by the observation of neutrino oscillations, although, within the Standard Model (SM), neutrinos are massless and right-handed neutrino states are not included. The possibility to include right-handed neutrinos is provided, for example, by the Neutrino Minimal Standard Model ($\nu$MSM) [1, 2], a SM extension in which sterile neutrinos mix with ordinary neutrinos. In the $\nu$MSM three massive right-handed neutrinos are introduced to explain neutrino oscillations, dark matter and the baryon asymmetry of the Universe. The lightest among the three massive neutrinos, with mass of $O(1 \text{ keV}/c^2)$, is a dark matter candidate; the other two, with masses in the range of 100 MeV/$c^2$ to a few GeV/$c^2$, give masses to the SM neutrinos via the see-saw mechanism and introduce extra CP violating phases to explain the baryon asymmetry.

In a further extension of the $\nu$MSM a real scalar field is added to the theory in order to incorporate inflation and provide a common source for electroweak symmetry breaking and for right-handed neutrino masses [3].

The $\nu$MSM and its extension predict the existence of new particles which could be produced in kaon decays. In particular, a Majorana neutrino $N_4$ is produced on shell in $K^\pm \rightarrow N_4 \mu^\pm$ and then decays to $N_4 \rightarrow \pi \mu$ in both the Lepton Number Violating decay (LNV) $K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm$, which is forbidden in the SM, and in the Lepton Number Conserving decay (LNC) $K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\mp$ [4]. An inflaton $\chi$ could be produced in the Lepton Number Conserving (LNC) $K^\pm \rightarrow \pi^\pm \chi$ decay with the subsequent decay $\chi \rightarrow \mu^+ \mu^-$ [5, 6].

The large statistics of kaon decays with multiple charged particles in the final state collected in 2003–2004 by the NA48/2 experiment allows to search for the forbidden LNV $K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm$ decay, as well as for two-body resonances in $K^\pm \rightarrow \pi \mu \mu$ decays. The search for the

1 On behalf of the NA48/2 Collaboration:
Cambridge, CERN, Dubna, Chicago, Edinburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Wien
\[ K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm \] together with the limits on the products of branching fractions \( BR(K^\pm \rightarrow \mu^\pm N_4)BR(N_4 \rightarrow \pi \mu) \) and \( BR(K^\pm \rightarrow \pi^\pm \chi)BR(\chi \rightarrow \mu^+ \mu^-) \) [7] are presented here.

2. The NA48/2 apparatus and data taking conditions

The NA48/2 experiment was located in the north area (NA) of the CERN SPS accelerator facility and was a successor of the NA48 experiment with almost the same detector setup. The primary goal of NA48/2 was the search of direct CP violation in \( K^\pm \rightarrow \pi^\pm \pi^+\pi^- \) and \( K^\pm \rightarrow \pi^\pm \pi^0\pi^0 \) decays [4] with about 100 days of effective data taking in 2003–2004. The experiment used 400 GeV/c protons provided by the SPS which, hitting on a Beryllium target, produced a secondary hadronic beam. Thanks to a system of magnets and collimators only charged particles with momenta of \((60 \pm 3) \text{ GeV/c}\) were selected and aligned with the longitudinal axis of the detector within 1 mm and with a transverse size of about 1 cm. The experiment was recording the decays of \( K^+ \) and \( K^- \) mesons inside the fiducial decay region located in a 114 m long cylindrical vacuum tank. After the vacuum tank a thin Kevlar window separated the vacuum from a helium vessel at atmospheric pressure in which a magnetic spectrometer was located.

The spectrometer consisted of four drift chambers (DCH) and a dipole magnet, placed between the second and the third chamber, which provided a horizontal momentum kick of \( p_t = 120 \text{ MeV/c} \) for charged particles. Each chamber had four different views and a spatial resolution of \( \sigma_{x,y} = 90 \text{ \mu m} \). The nominal momentum resolution of the spectrometer was \( \sigma_p/p = (1.02 \oplus 0.044 \text{ p})\% \) where \( p \) is given in GeV/c. A scintillating hodoscope (HOD) followed the spectrometer. It was divided in four quadrants by a horizontal and a vertical plane of strip-shaped counters. The HOD was used in the trigger chain to provide a fast time measurement for charged particles with a 150 ps time resolution. A quasi homogeneous electromagnetic calorimeter filled with liquid krypton (LKr) and a depth of \( 27X_0 \) was used both for photon detection and particle identification. It had an energy resolution of \( \sigma_E/E = 0.032/\sqrt{E + 0.09}/E \oplus 0.0042 \) (\( E \) in GeV) corresponding to \( \sigma_E/E = 0.94\% \) at 20 GeV. The particle identification was completed by a hadronic calorimeter and a muon veto system (MUV). The hadronic calorimeter consisted of alternated iron and scintillator planes, while the MUV of three plastic scintillator strips planes each of them preceded by a 80 cm iron wall. A more detailed description of the experiment can be found in Ref. [5].

3. Events selection

Two different samples are selected on the data: candidates for the Lepton Number Violating decay \( K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm (K^\pm_{\mu\mu,\text{LNV}}) \) and Lepton Number Conserving \( K^\pm \rightarrow \pi^\pm \mu^+\mu^- (K^\pm_{\mu\mu,\text{LNC}}) \) events for the search of resonances. Due to the decay vertex resolution, the signature given by a particle \( X \) produced in \( K \rightarrow \mu X \) (\( \pi X \)) and promptly decaying to \( X \rightarrow \pi \mu \) (\( X \rightarrow \mu^+\mu^- \)) is indistinguishable from a real three-track decay. Therefore the trigger logic of three-track events (the main trigger of the experiment) can be used for the searches presented here.

The \( K^\pm \rightarrow \pi^\pm \pi^+\pi^- (K^\pm_{3\pi}) \) decay is used as a normalization channel: the same three-track topology and the small difference in mass between \( \pi \) and \( \mu \) allow a first order cancellation of systematic effects due to possible imperfect kaon beam description and detector and trigger inefficiencies.

The three-track event selection requires a total charge of the three tracks equal to one and a vertex inside the 98 m long fiducial decay region. For each track a momentum between 5 and 55 GeV/c is required and a total momentum for the three tracks inside the range 55-65 GeV/c, compatible with the beam momentum. A cut is applied to the total transverse momentum of the three tracks with respect to the beam direction, that is measured using the \( K^\pm_{3\pi} \) sample \( (p_t < 10 \text{ MeV/c}) \). The three tracks forming the vertex must be consistent in time with the trigger and within 10 ns from the average time of the three tracks. Each track is required to be inside the geometric acceptance of the DCH, HOD, LKr and MUV detectors. If more than one
vertex satisfies the requirements above only the one with the lowest fit $\chi^2$ is taken into account. The $K_{\pi\mu\mu}$ signal candidates are selected applying particle identification and kinematic constraints. The three tracks have to consist of a $\pi^\pm$ candidate and two muons with the same/opposite sign for $K_{\pi\mu\mu}^{LNV}$ and $K_{\pi\mu\mu}^{LNC}$, respectively. The pion candidate is selected by requiring the ratio between the energy deposited in the LKr and the momentum measured in the spectrometer to be $E/p < 0.95$ and that no in-time associated hits are in the MUV. For muon identification $E/p < 0.2$ and associated hits in the first two planes of the MUV are required.

The signal region satisfies $|M_{\pi\mu\mu} - M_K| < 5(8)$ MeV/$c^2$ where $M_{\pi\mu\mu}$ is the invariant mass of the three tracks in the $\pi^+\mu^+\mu^- (\pi^\pm\mu^\mp\mu^-)$ hypothesis and $M_K$ is the nominal $K^\pm$ mass [10].

The selected region corresponds to $\pm 2$ and $\pm 3.2$ times the resolution of $M_{\pi\mu\mu}$ respectively for $K_{\pi\mu\mu}^{LNV}$ and $K_{\pi\mu\mu}^{LNC}$, where $\sigma_{M(\pi\mu\mu)} = 2.5$ MeV/$c^2$. The different cuts on the mass resolution is due to the different background composition in the two samples. The data/Monte Carlo agreement is studied in the control region $456 \text{ MeV}/c^2 < M_{\pi\mu\mu} < 480 \text{ MeV}/c^2$.

For the $K_{3\pi}$ normalization channel the pion identification criteria used for the signal is applied only for the track with opposite electric charge with respect to the kaon and the invariant mass of the three pions must satisfy $|M_{3\pi} - M_K| < 5 \text{ MeV}/c^2$ that corresponds to $\pm 3\sigma_{3\pi}$ (± 5.1 MeV/$c^2$) where the three-pion mass resolution is 1.7 MeV/$c^2$. The number of $K^\pm$ decays in the fiducial region is measured to $N_K = 1.637 \times 10^{11}$ using the normalization channel $K_{3\pi}$ with $N_{3\pi} = 1.367 \times 10^7$ and the acceptance $A_{3\pi} = 14.96\%$.

The events passing the signal selection are shown in Figure 1 for both data and Monte Carlo simulation. Only one event is observed in the signal region for the $K_{\pi\mu\mu}^{LNV}$ sample while 3489 candidates are selected in the $K_{\pi\mu\mu}^{LNC}$ sample.

![Figure 1](image-url)

**Figure 1.** $M_{\pi\mu\mu}$ mass distribution for data and Monte Carlo simulation for events that pass the $K_{\pi\mu\mu}^{LNV}$ (a) and the $K_{\pi\mu\mu}^{LNC}$ (b) selection.

4. Upper limit on $BR(K^\pm \rightarrow \pi^\pm\mu^\mp\mu^\pm)$

Only one event remains after applying the signal selection. The background expectation is $N_{bkg} = 1.16 \pm 0.87_{\text{stat.}} \pm 0.12_{\text{syst.}}$. The background is evaluated with Monte Carlo simulation and is mostly composed of $K_{3\pi}$ events in which two pions decay into muons. Since no signal is
observed an upper limit is set on $\mathcal{B}(K^{\pm} \rightarrow \pi^{\mp} \mu^{\pm} \mu^{\pm})$ applying the Rolke-Lopez method [11] to find the 90% confidence intervals for the case of a Poisson process in presence of multiple Poisson backgrounds with unknown mean:

$$\mathcal{B}(K^{\pm} \rightarrow \pi^{\mp} \mu^{\pm} \mu^{\pm}) = \frac{N^{LNV}_{\pi \mu \mu} \cdot A_{3\pi} \cdot \mathcal{B}(K_{3\pi})}{N_{3\pi} \cdot D \cdot A(K^{LNV}_{\pi \mu \mu})} < 8.6 \times 10^{-11},$$

where $D = 100$ is the trigger downscaling, $N^{LNV}_{\pi \mu \mu} < 2.92$ the upper limit on the signal events at 90% CL and $A(K^{LNV}_{\pi \mu \mu}) = (20.62 \pm 0.01)\%$ the signal acceptance evaluated with Monte Carlo simulation.

5. Search for two-body resonances

The search for the two-body resonances is performed on all events that survived $K^{\pm} \rightarrow \mu^{\pm} X(X \rightarrow \pi \mu)$ and $K^{\pm} \rightarrow \pi^{\mp} X(X \rightarrow \mu^{+} \mu^{-})$ in the $K^{LNV}_{\pi \mu \mu}$ and $K^{LNC}_{\pi \mu \mu}$ selections respectively. Figure 2 shows the obtained signal acceptances as a functions of the resonance mass and lifetime.

![Figure 2. Signal acceptance as a function of the resonances mass and lifetime hypothesis.](image)

(a) $K^{LNV}_{\pi \mu \mu}$ selection for $K^{\pm} \rightarrow \mu^{\pm} N_{4}(N_{4} \rightarrow \pi^{\mp} \mu^{\pm})$; (b) $K^{LNC}_{\pi \mu \mu}$ selection for $K^{\pm} \rightarrow \mu^{\pm} N_{4}(N_{4} \rightarrow \pi^{\mp} \mu^{\pm})$; (c) $K^{LNC}_{\pi \mu \mu}$ selection for $K^{\pm} \rightarrow \pi^{\pm} \chi(\chi \rightarrow \mu^{+} \mu^{-})$.

In the scan of the invariant mass $M_{ij}(ij = \pi \mu, \mu^{+} \mu^{-})$ the mass step are given by $\sigma(M_{ij})/2$, where $\sigma(M_{ij})$ is the mass resolution, and the signal window by $\pm 2\sigma(M_{ij})$ at each mass $M_{ij}$. This means that the results obtained in neighbouring mass hypotheses are highly correlated, as the signal mass window is 8 times larger than the mass step.

In total, 284 and 267(280) mass hypotheses have been tested, covering the full kinematic range of the $M_{\pi \mu}(M_{\mu \mu})$ distributions for the $K^{LNV}_{\pi \mu \mu}$ and $K^{LNC}_{\pi \mu \mu}$ candidates.

In the $K^{LNC}_{\pi \mu \mu}$ selection a total of 3489 candidates is observed where the background contamination from $K_{3\pi}$ is estimated to be $(0.36 \pm 0.10)\%$ using Monte Carlo simulation. This level of purity allows to consider $K^{LNC}_{\pi \mu \mu}$ as the only background for resonance searches in that sample. For the search of two-body resonances also the Rolke-Lopez statistical method is used.

The number of considered background events for the $K^{LNV}_{\pi \mu \mu}$ ($K^{LNC}_{\pi \mu \mu}$) candidates is N=4 (N=1). The number of observed events and the obtained upper limits at 90% confidence level are shown in Figure 3.
Figure 3. The numbers of observed data (black) and expected background events ($K^\pm \rightarrow \pi^\pm \pi^\mp \pi^\pm$ in green, $K^\pm \rightarrow \pi^\pm \mu^+\mu^-$ in red) are shown for (a) $M_{\pi\mu}$ with the $K^{LNV}_{\pi\mu\mu}$ selection; (b) $M_{\pi\mu}$ with the $K^{LNC}_{\pi\mu\mu}$ selection; (c) $M_{\mu\mu}$ with the $K^{LNC}_{\pi\mu\mu}$ selection (big plots). The light blue line represents the obtained upper limits at 90% CL on the numbers of signal candidates. In the separated figure the local significances (blue line) are shown for each resonance mass value.
For each mass hypothesis of the three resonance searches the local significance $z$ is evaluated as

$$z = \frac{N_{\text{obs}} - N_{\text{exp}}}{\sqrt{\delta N_{\text{obs}}^2 + \delta N_{\text{exp}}^2}},$$

where $N_{\text{obs}}$ and $N_{\text{exp}}$ are the number of observed and expected background events with their uncertainties $\delta N_{\text{obs}}$ and $\delta N_{\text{exp}}$. The results for $z$ are also shown in Figure 3. Since the local significances never exceed 3 standard deviations no signal is observed, and upper limits are set on the product $\mathcal{BR}(K^\pm \rightarrow p_1X)\mathcal{BR}(X \rightarrow p_2p_3)$, with the three possibilities $p_1p_2p_3 = \mu^\pm \pi^\pm \mu^\pm, \mu^\pm \pi^\pm \mu^\pm, \pi^\pm \mu^\pm \mu^-$. The upper limits are calculated as a function of the resonance lifetime $\tau$ for each mass hypothesis $m_i$ by using the values of the signal acceptances (these also depend on the resonances mass and lifetime) and the upper limits on the number of signal events in each mass hypothesis.

$$\mathcal{BR}(K^\pm \rightarrow p_1X)\mathcal{BR}(X \rightarrow p_2p_3)|_{m_i,\tau} = \frac{N_{\text{sig}}^i}{N_{3\pi} \cdot D} \cdot \frac{A_{3\pi}}{A_{\pi\mu\mu}(m_i, \tau)} \cdot \mathcal{BR}(K_{3\pi})$$

The obtained upper limits on the products $\mathcal{BR}(K^\pm \rightarrow p_1X)\mathcal{BR}(X \rightarrow p_2p_3)$ are shown in Figure 4.

6. Conclusions
The NA48/2 collaboration has performed searches for the lepton number violating $K^\pm \rightarrow \pi^\pm \mu^\pm \mu^\pm$ decay and resonances in $K^\pm \rightarrow \pi\mu\mu$ decays, using the data collected in 2003-2004. In those searches (LNV decay and resonances) no signals are observed. For the LNV $K^\pm \rightarrow \pi^\pm \mu^\pm \mu^\pm$ decay an upper limit is set of $\mathcal{BR} < 8.6 \times 10^{-11}$ [7], which improves the previous limit [12] by more than one order of magnitude. Upper limits are also set on the products $\mathcal{BR}(K^\pm \rightarrow \mu^\pm N_4)\mathcal{BR}(N_4 \rightarrow \pi^\pm \mu^\pm)$ and $\mathcal{BR}(K^\pm \rightarrow \pi^\pm \chi)\mathcal{BR}(\chi \rightarrow \mu^\pm \mu^-)$ as function of the resonance lifetimes and masses. These upper limits are in the range $10^{-10} - 10^{-9}$ for resonance lifetimes $\tau < 100$ ps.
Figure 4. Obtained upper limits at 90% CL on the products of branching ratios as functions of the resonance mass and lifetime: (a) $\mathcal{BR}(K^\pm \rightarrow \mu^\pm N_4)\mathcal{BR}(N_4 \rightarrow \pi^\mp \mu^\pm$); (b) $\mathcal{BR}(K^\pm \rightarrow \mu^\pm N_4)\mathcal{BR}(N_4 \rightarrow \pi^\pm \mu^\mp$); (c) $\mathcal{BR}(K^\pm \rightarrow \pi^\pm \chi)\mathcal{BR}(\chi \rightarrow \mu^+ \mu^-$).

References
[1] Asaka T and Shaposhnikov M 2005 Phys. Lett. B620 17.
[2] Asaka T, Blanchet S and Shaposhnikov M 2005 Phys. Lett. B631 151.
[3] Shaposhnikov M and Tkachev I 2006 Phys. Lett. B639 414.
[4] Atre A, Han T, Pascoli S and Zhang B 2009 JHEP 0905 030.
[5] Bezrukov F and Gorbunov D 2010 JHEP 1005 010.
[6] Bezrukov F and Gorbunov D 2014 Phys. Lett. B736 494.
[7] Batley J R et al (NA48/2 collaboration), arXiv:1612.04723.
[8] Batley J R et al (NA48/2 collaboration) 2007 Search for direct CP violating charge asymmetries in $K^\pm \rightarrow \pi^\pm \pi^\mp \pi^\pm$ and $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ decays Eur. Phys. J. C52 875.
[9] Fanti V et al (NA48 collaboration) 2007 Nucl. Instrum. Methods A574 433.
[10] Patrignani C et al (Particle Data Group) 2016 Chin. Phys. C40 100001.
[11] Rolke W A and Lopez A M 2001 Nucl. Instrum. Meth. A458 745.
[12] Batley J R et al. (NA48/2 collaboration) 2011 Phys. Lett. B697 107.