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# Searches for lepton number violation and resonances in $K^{\pm} \to \pi\mu\mu$ decays with the NA48/2 experiment

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The NA48/2 experiment at CERN collected a large sample of charged kaon decays into final states with multiple charged particles in 2003-2004. An upper limit of $8.6 \times 10^{-11}$ at 90 % CL is set on the branching ratio of the lepton number violating decay $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$. Searches for two-body resonances like heavy neutral leptons and inflatons in the $K^{\pm} \to \pi\mu\mu$ decays in the accessible range of masses and lifetimes are also presented.

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## 1. Introduction

The discovery of neutrino oscillations [1] is a direct evidence that neutrinos cannot be massless and that right-handed neutrino states must be present. A natural extension of the SM that includes them is the so-called Neutrino Minimal Standard Model ($\nu$MSM)[2]. In this model three right-handed sterile neutrinos are proposed to explain simultaneously neutrino oscillations and the observed baryon asymmetry of the universe. One has a mass of $\mathscr{O}(1)$ keV and is a potential dark matter candidate. The other two have masses in the range between 100 MeV/c$^2$ to few GeV/c$^2$ and could account for the baryon asymmetry in the universe by introducing additional *CP* violating phases. The $\nu$MSM can be further extended by adding a scalar field, which helps to incorporate inflation, to provide a common source for electroweak symmetry breaking and right-handed neutrino masses [3]. These models predict new particles like heavy Majorana neutrinos and inflatons, which could be produced in $K^{\pm} \to \pi\mu\mu$ decays. In particular the decay $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ is Lepton Number Violating (LNV) and is not allowed in the SM, but could proceed via on-shell Majorana neutrinos. While inflatons $\chi$, on the other hand can be produced in $K^{\pm} \to \pi^{\pm}\chi$ processes with $\chi$ decaying to two muons $\chi \to \mu^+\mu^-$ .

The NA48/2 experiment at CERN collected in 2003-2004 charged kaon decays into final states with multiple charged particles. The huge statistics of this sample allows searching for the forbidden LNV decay $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$, as well as for two-body resonances in $K^{\pm} \to \pi\mu\mu$ decays. If a particle $X$ is produced in $K^{\pm} \to \pi^{\pm}X (K^{\pm} \to \mu^{\pm}X)$ decays followed by prompt decay $X \to \mu^+\mu^- (X \to \pi^{\mp}\mu^{\pm})$, it would appear as sharp resonance in the $M_{\mu\mu} (M_{\pi\mu})$ invariant mass spectra, therefore Mass scans in the invariant mass distributions of the collected $K^{\pm} \to \pi\mu\mu$ sample were performed, whose results are presented.

## 2. The NA48/2 detector

The NA48/2 experiment at the CERN SPS was a multi-purpose $K^{\pm}$ experiment, whose main goal was the search for direct CP violation in $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ and $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ decays [4]. Simultaneous and colinear $K^+$ and $K^-$ beams of the same momentum of (60 $\pm$ 3.7) GeV/$c$ were produced by the 400 GeV/c SPS primary proton beam impinging on a Beryllium target, and were steered into a 114 m long decay region, contained in a cylindrical vacuum tank. The downstream part of the vacuum tank was sealed by a convex Kevlar window, that separated the vacuum from helium at atmospheric pressure inside the helium vessel a magnetic spectrometer was installed, which was formed of 4 drift chambers (DCHs) and a dipole magnet providing a horizontal momentum kick $p_t$ = 120 MeV/$c$. The spatial resolution of each DCH was $\sigma_x = \sigma_y = 90$ $\mu$m. The nominal spectrometer momentum resolution was $\sigma_p/p = (1.02 \oplus 0.044p)\%$ ($p$ in GeV/$c$).

The magnetic spectrometer was followed by a scintillating hodoscope (HOD) used to provide fast time measurements of charged particles used in the trigger chain. The HOD consisted of a plane of horizontal and a plane of vertical strip-shaped counters.

The HOD was followed by a quasi-homogeneous, $27X_0$ deep electromagnetic calorimeter filled with liquid krypton (LKr), which was used for photon detection and particle identification. The calorimeter had an energy resolution $\sigma(E)/E = 0.032/\sqrt{E} \oplus 0.09/E \oplus 0.0042$($E$ in GeV). The spatial resolution for isolated electromagnetic showers was $\sigma_x = \sigma_y = (0.42/\sqrt{E} \oplus 0.06)$ cm ($E$ in

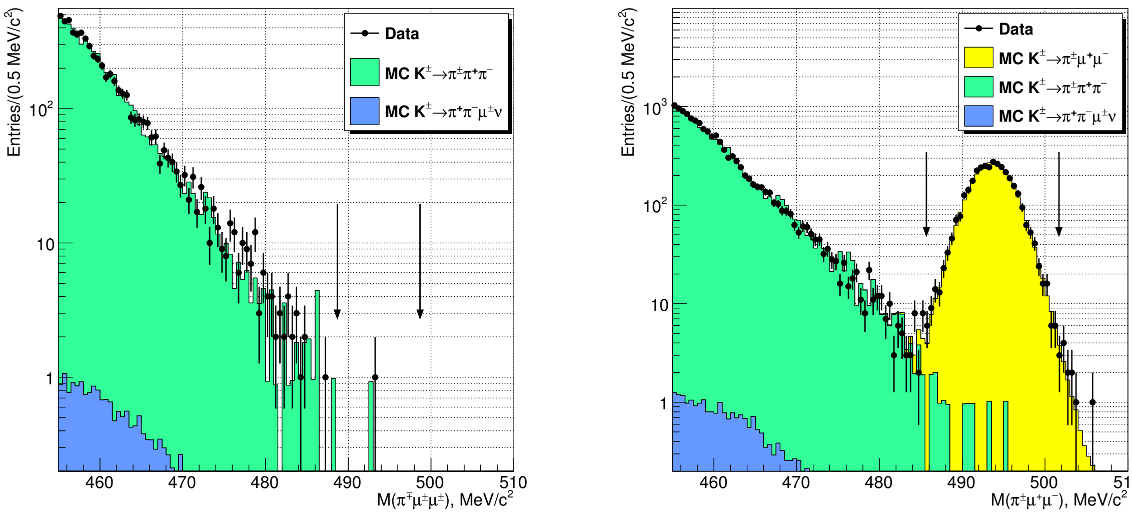


**Figure 1:** Invariant mass distributions of data and MC events passing the $K^{LNV}_{\pi\mu\mu}$ (left) and $K^{LNC}_{\pi\mu\mu}$ (right) selections. The signal mass regions are indicated with vertical arrows.

GeV) for the transverse coordinates $x$ and $y$ and a single shower time resolution of $\sigma_t = 2.5$ ns$/\sqrt{E}$. The LKr was followed by a hadronic calorimeter (not used for the present measurement) and a muon detector (MUV). The MUV consisted of three planes made of plastic scintillator strips, read out by photomultipliers on both ends. Each plane was preceded by a 80 cm thick iron wall to provide absorption of hadrons. A more detailed detector description can be found in [5].

## 3. Event selection procedure

The event selection is based on the reconstruction of a three-track vertex: given the resolution of the vertex longitudinal position ($\sigma_{vtx} = 50$ cm), $K^\pm \to \pi^\mp\mu^\pm\mu^\pm$ ($K^{LNV}_{\pi\mu\mu}$) and $K^\pm \to \pi^\pm\mu^+\mu^-(K^{LNC}_{\pi\mu\mu})$ decays mediated by a short-lived ($\tau \leq 10$ ps) resonant particle are indistinguishable from a genuine three-track decay. The mode $K^\pm \to \pi^\pm\pi^+\pi^-(K_{3\pi})$ was chosen as normalization for the $K_{\pi\mu\mu}$, because the topologies of the final states of both decays are similar. This leads to first order cancellation of systematic effects due to a possible imperfect kaon beam description a detector and trigger inefficiencies.

A large part of the selection is common for both $K_{\pi\mu\mu}$ and $K_{3\pi}$ modes. The three-track vertex is required to have a total charge $|Q| = \pm 1$, and to be within the 98 m fiducial decay volume. Each track has to be within the geometrical acceptance of the DCH, HOD, LKr, and MUV detectors, to have a momentum $p$ within the range (5;55) GeV/$c$, the sum of the three momenta should be consistent with kaon momentum in the range (55;65) GeV/$c$ and the total transverse momentum of the three-tracks with respect to the beam axis to be $p_T < 10$ MeV/$c$. A more detailed description of the selection can be found here [6].

The total number of kaon decays over the 98 m long decay volume was determined to $(1.64 \pm 0.01) \times 10^{11}$ using $N_{3\pi} = 1.37 \times 10^7$ reconstructed $K_{3\pi}$ events with a down-scaled trigger.

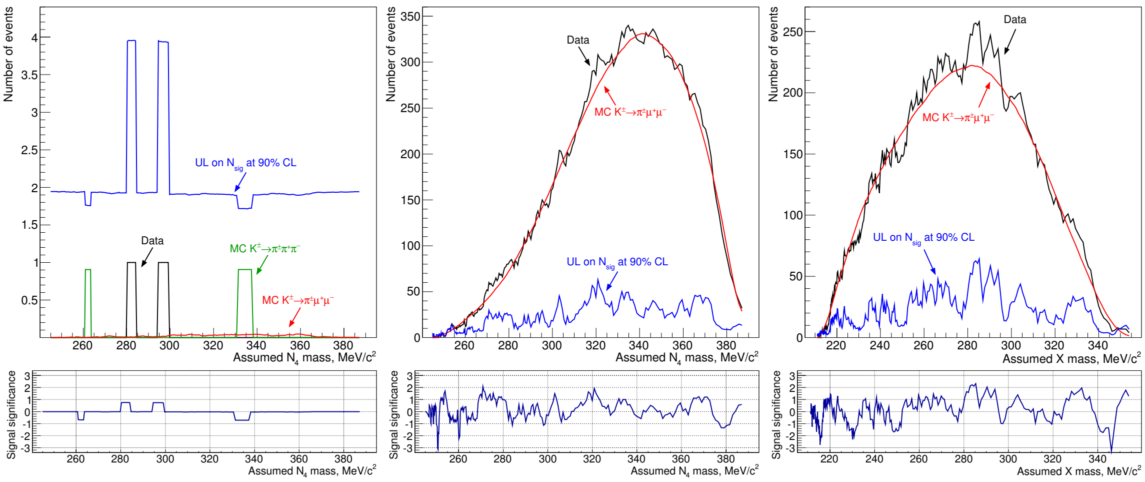


**Figure 2:** Numbers of observed data events (black) and expected background events ($K^{\pm} \to \pi^{\pm}\pi^{-}\pi^{+}$ in green, $K^{\pm} \to \pi^{\pm}\mu^{-}\mu^{+}$ in red) passing the $M_{\pi\mu}$ cut with the $K^{LNV}_{\pi\mu\mu}$ selection (top left); the $M_{\pi\mu}$ cut with the $K^{LNC}_{\pi\mu\mu}$ selection (top center); the $M_{\mu\mu}$ cut with the $K^{LNC}_{\pi\mu\mu}$ selection (top right). The obtained upper limits at 90% CL on the numbers of signal candidates (light blue) and the local significances of the signal (dark blue, bottom figures) are also shown for each resonance mass value.

## 4. Search for LFV in $\mathscr{B}(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm})$

The invariant mass distribution after the full event selection is shown on Fig.1. After unblinding the Signal Region for the $K^{LNV}_{\pi\mu\mu}$ selection one event is observed with a background expectation of $N_{bkg} = 1.16 \pm 0.87_{stat.} \pm 0.02_{ext.} \pm 0.12_{syst.}$. The background in the $K^{LNV}_{\pi\mu\mu}$ selection is composed of $K_{3\pi}$ events with two subsequent $\pi^{\pm} \to \mu^{\pm}\nu_{\mu}$ decays. No signal is observed and a 90% upper limit on the branching ratio $\mathscr{B}(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm})$ is set applying the statistical analysis described in Section 5 to the total number of events in the $K^{LNV}_{\pi\mu\mu}$ sample: $N^{LNV}_{\pi\mu\mu} < 2.92$ at 90% CL. The results are presented in Fig.3. Using the signal acceptance of $A(K^{LNV}_{\pi\mu\mu}) = (20.62 \pm 0.01)\%$ 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 event leads to a limit on the signal branching ratio of

$$\mathscr{B}(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}) = \frac{N^{LNV}_{\pi\mu\mu}}{N_{3\pi} \cdot D} \cdot \frac{A(K_{3\pi})}{A(K^{LNV}_{\pi\mu\mu})} \cdot \mathscr{B}(K_{3\pi}) < 8.9 \times 10^{-11} \quad @\ 90\%\ CL \qquad (4.1)$$

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 $\mathscr{B}(K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-})(0.8\%)$, $\mathscr{B}(K^{\pm} \to \pi^{\mp}\pi^{+}\pi^{-})(0.73\%)$ and $\mathscr{B}(K^{\pm} \to \pi^{+}\pi^{-}\mu^{\pm}\nu)(0.05\%)$.

## 5. Search for resonances in $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$

A signal search was performed assuming different mass hypotheses using distributions of invariant mass $M_{ij}$ ($ij = \pi^{\mp}\mu^{\pm}, \pi^{\pm}\mu^{\mp}, \mu^{+}\mu^{-}$) after the $K_{\pi\mu\mu}$ selection. The background contamination from $K_{3\pi}$ is estimated to be $(0.36 \pm 0.10)\%$ using MC simulation. Such a level of purity allows to consider $K^{LNC}_{\pi\mu\mu}$ as the only background for the selection. The acceptances for $K^{\pm} \to \mu^{\pm}X$ followed by $X \to \pi^{\mp}\mu^{\pm}$ and the decays $K^{\pm} \to \mu^{\pm}X(K^{\pm} \to \pi^{\pm}X)$ followed by $X \to \pi^{\pm}\mu^{\mp}(X \to$

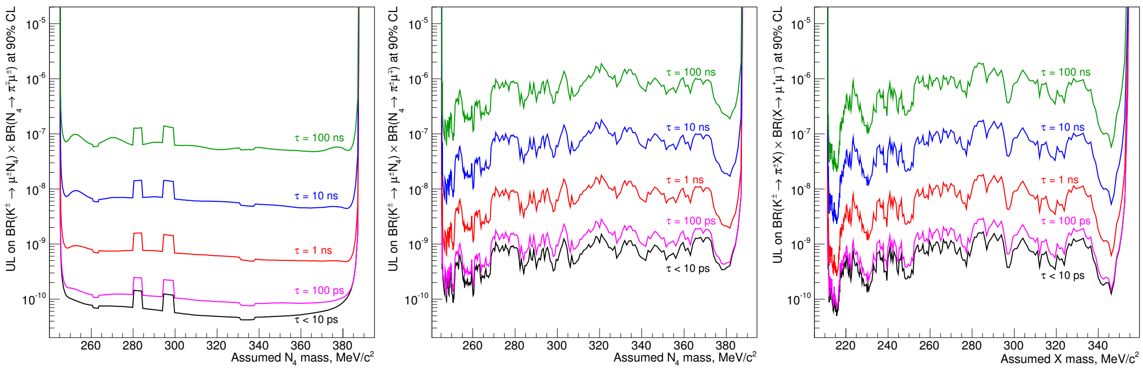


**Figure 3:** Obtained upper limits at 90% CL on the products of branching ratios as functions of the resonance mass and lifetime: $\mathscr{B}(K^{\pm} \to \mu^{\pm}N_4)\mathscr{B}(N_4 \to \pi^{\mp}\mu^{\pm})$ (left);$\mathscr{B}(K^{\pm} \to \mu^{\pm}N_4)\mathscr{B}(N_4 \to \pi^{\pm}\mu^{\mp})$ (center);$\mathscr{B}(K^{\pm} \to \pi^{\pm}\chi)\mathscr{B}(\chi \to \mu^{+}\mu^{-})$. The upper limits are presented for a $N_4$ sterile Majorana neutrino described by the " type I see-saw mechanism" [7] (left) and (center), and for an inflaton $\chi$ [3].

$\mu^+\mu^-$) have been evaluated as function of the resonance mass and lifetime using dedicated MC simulation and are in the range of $10\% - 25\%$ for $\tau < 100$ ps.

The width of the signal mass window and the scanning step are determined by the invariant mass resolution $\sigma(M_{ij})$, which are functions of the invariant mass itself. The half-width of the window is chosen to be $2\sigma(M_{ij})$ and the step $\sigma(M_{ij})/2$. 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 hypothesis have been tested, covering the full kinematic range of the $M_{ij}$ distributions for the $K^{LNV}_{\pi\mu\mu}$ and $K^{LNC}_{\pi\mu\mu}$ candidates.

A statistical analysis in each mass window is performed by applying an extension of the Rolke-Lopez method [8] to numerically estimate the 90% confidence intervals in case of a Poisson background.

A total of 3489 candidates is observed in the $K^{LNC}_{\pi\mu\mu}$ selection. The background contamination from $K_{3\pi}$ in the $K^{LNC}_{\pi\mu\mu}$ sample is estimated to be $(0.36 \pm 0.10)\%$ using MC simulation. Such a level of purity allows to consider $K^{LNC}_{\pi\mu\mu}$ as the only background for resonance searches in $K^{LNC}_{\pi\mu\mu}$.

In the generic case of $N$ considered backgrounds, the Rolke-Lopez computation performed requires $2N+1$ inputs for each mass hypothesis: the number $N_{obs}$ of observed data events in the signal mass window; the number $N^i_{bkg}$of MC events for the considered background $i$ observed in the signal mass window, and the size of the MC sample with respect to the data volume $\tau_i$ used to evaluate $N^i_{bkg}$ for the background source $i$. The number of considered backgrounds for the $K^{LNV}_{\pi\mu\mu}$ ($K^{LNC}_{\pi\mu\mu}$) candidates is $N = 4 (N = 1)$. The values $N_{obs}$, the normalized number of background events $\tilde{N}^i_{bkg} = N^i_{bkg}/\tau_i$ , and the upper limit (UL) at 90% confidence level (CL) on the number $N_{sig}$ of signal events obtained are shown for each mass hypothesis of the resonance searches in Fig.2.

For each of the three resonance searches a local significance $z$ of the signal has been evaluated for each mass hypothesis

$$z = \frac{N_{obs} - N_{exp}}{\sqrt{\delta N^2_{obs} + \delta N^2_{exp}}}, \tag{5.1}$$

where $N_{obs}$ is the number of observed events, $N_{exp}$ is the number of expected background events, and $\delta N_{obs}(\delta N_{exp})$ is the statistical uncertainty on $N_{obs}(N_{exp})$. The results are shown in Fig. 2. The local significance never exceeds 3 standard deviations, therefore no signal is observed.

In absence of any signal, upper limits have been set on the product $\mathscr{B}(K^{\pm} \to p_1X)\mathscr{B}(X \to p_2p_3)(p_1p_2p_3 = \mu^{\pm}\pi^{\mp}\mu^{\pm}, \mu^{\pm}\pi^{\pm}\mu^{\mp}, \pi^{\pm}\mu^{+}\mu^{-})$ as a function of the resonance lifetime $\tau$ for each mass hypothesis $m_i$, and are computed as

$$\mathscr{B}(K^{\pm} \to p_1X)\mathscr{B}(X \to p_2p_3)|_{m_i,\tau} = \frac{N^i_{sig}}{N_{3\pi} \cdot D} \cdot \frac{A(K_{3\pi})}{A_{\pi\mu\mu}(m_i,\tau)} \cdot \mathscr{B}(K_{3\pi}). \tag{5.2}$$

The ULs corresponding to the observed signal events for the $i^{th}$ hypothesis $N^i_{sig}$ for the three resonance searches for several lifetimes $\tau$ are presented in Fig 3.

## 6. Conclusions

A search for the LFV decay $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ and two-body resonances in $K^{\pm} \to \pi\mu\mu$ decays has been performed using the data collected by the NA48/2 experiment in 2003 and 2004, corresponding to $1.6\times10^{11}$ kaon decays in the fiducial volume of the experiment. No signal is observed. An upper limit on the branching ratio of the LNV decay of $\mathscr{B}(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}) < 8.6 \times 10^{-11}$ has been set, improving the previous best limit [9] by more than one order of magnitude.

Searches for Majorana Neutrinos, Heavy Neutral Leptons and Inflaton two-body resonances in $K \to \pi\mu\mu$ decays areperformed. Upper limits are set on the products of branching ratios $\mathscr{B}(K^{\pm} \to \mu^{\pm}N_4)\mathscr{B}(N_4 \to \pi^{\mp}\mu^{\pm})$ and $\mathscr{B}(K^{\pm} \to \pi^{\pm}X)\mathscr{B}(X \to \mu^{+}\mu^{-})$ as functions of the resonance mass and lifetime. These limits are in the $10^{-10} - 10^{-9}$ range for resonance lifetimes below 100 ps.

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