Searches for lepton number violation and resonances in $K^{\pm} \rightarrow \pi \mu \mu$ 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 $K^{\pm} \rightarrow \pi^{\mp} \mu^{\pm} \mu^{\pm}$. Searches for two-body resonances like heavy neutral leptons and inflatons in the $K^{\pm} \rightarrow \pi \mu \mu$ 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 (νMSM)[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 $\mathcal{O}(1)$ keV and is a potential dark matter candidate. The other two have masses in the range between 100 MeV/c² to few GeV/c² and could account for the baryon asymmetry in the universe by introducing additional CP violating phases. The νMSM 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 $K^\pm \to \pi^+ \mu^- \mu^+$ 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 $K^\pm \to \pi^\pm \mu^+ \mu^-$, 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 $X \to \mu^+ \mu^-(X \to \pi^\pm \mu^\pm)$, 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 $K^+ \to \pi^+ \pi^- \pi^0$ and $K^- \to \pi^- \pi^+ \pi^0$ 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 $\sigma_p/p = (1.02 \pm 0.044 p)\%$ ($p$ 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 $\sigma(E)/E = 0.032/\sqrt{E + 0.09}/E \oplus 0.0042 (E$ in GeV). The spatial resolution for isolated electromagnetic showers was $\sigma_x = \sigma_y = (0.42/\sqrt{E} \oplus 0.06) \text{ cm}$ ($E$ in GeV).
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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 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 ($\sigma_{\text{vtx}} = 50$ cm), $K^\pm \rightarrow \pi^\pm \mu^\mp \mu^\mp$ ($K_{\pi\mu\mu}^{LNV}$) and $K^\pm \rightarrow \pi^\pm \mu^+ \mu^-$ ($K_{\pi\mu\mu}^{LNC}$) decays mediated by a short-lived ($\tau \leq 10$ ps) resonant particle are indistinguishable from a genuine three-track decay. The mode $K^\pm \rightarrow \pi^\pm \pi^\mp \pi^-$ ($K_{3\pi}$) 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 ± 0.01) × 10^{11} using $N_{3\pi} = 1.37 \times 10^7$ reconstructed $K_{3\pi}$ events with a down-scaled trigger.
4. Search for LFV in $\mathcal{B}(K^\pm \to \pi^\pm \mu^\pm \mu^\pm)$

The invariant mass distribution after the full event selection is shown on Fig. 1. After unblinding the Signal Region for the $K_{\pi\mu}^{LNV}$ selection one event is observed with a background expectation of $N_{bkg} = 1.16 \pm 0.87_{stat} \pm 0.02_{syst} \pm 0.12_{syst}$. The background in the $K_{\pi\mu}^{LNV}$ 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 $\mathcal{B}(K^\pm \to \pi^\pm \mu^\pm \mu^\pm)$ is set applying the statistical analysis described in Section 5 to the total number of events in the $K_{\pi\mu}^{LNV}$ sample: $N_{LNV} < 2.92$ at 90% CL. The results are presented in Fig. 3. Using the signal acceptance of $A(K_{\pi\mu}^{LNV}) = (20.62 \pm 0.01)%$ estimated with MC simulations and the number $N_K$ of kaon decays in the fiducial volume, the upper limit on the number of $K^\pm \to \pi^\pm \mu^\pm \mu^\pm$ signal event leads to a limit on the signal branching ratio of

$$\mathcal{B}(K^\pm \to \pi^\pm \mu^\pm \mu^\pm) = \frac{N_{LNV}^{K_{\pi\mu}^{LNV}}}{N_{3\pi} \cdot D \cdot A(K_{3\pi}) \cdot A(K_{\pi\mu}^{LNV})} \cdot B(K_{3\pi}) < 8.9 \times 10^{-11} \quad \text{at } 90\% \text{ CL} \quad (4.1)$$

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 $\mathcal{B}(K^\pm \to \pi^\pm \mu^\pm \mu^-)(0.8%), \mathcal{B}(K^\pm \to \pi^\pm \pi^- \pi^-)(0.73%)$ and $\mathcal{B}(K^\pm \to \pi^\pm \pi^- \nu_v)(0.05%)$.

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 $M_{ij}$ ($ij = \pi^\pm \mu^\pm, \pi^\pm \mu^\pm, \mu^+ \mu^-$) after the $K_{\pi\mu}$ 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 $K_{\pi\mu}^{LNC}$ as the only background for the selection. The acceptances for $K^\pm \to \mu^+ X$ followed by $X \to \pi^\pm \mu^\pm$ and the decays $K^\pm \to \mu^+ X (K^\pm \to \pi^\pm X)$ followed by $X \to \pi^\pm \mu^\pm (X \to \pi^\pm \mu^\pm)$ (top left; the $M_{\mu\mu}$ cut with the $K_{\pi\mu}^{LNC}$ selection (top right); the $M_{\mu\mu}$ cut with the $K_{\pi\mu}^{LNC}$ 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.
\( \mu^+ \mu^- \) 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 \( K^{LNV} \pi \mu \) and \( K^{LNC} \pi \mu \) 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 \( K^{LNC} \pi \mu \) selection. The background contamination from \( K^{3\tau} \) in the \( K^{LNC} \pi \mu \) sample is estimated to be \((0.36 \pm 0.10)\%\) using MC simulation. Such a level of purity allows to consider \( K^{LNC} \pi \mu \) as the only background for resonance searches in \( K^{LNC} \pi \mu \).

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 \( K^{LNV}(K^{LNC}) \) candidates is \( N = 4(N = 1) \). The values \( N_{obs} \), the normalized number of background events \( \hat{N}_{bkg}^i = N^i_{bkg}/\tau_i \), 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

\[
z = \frac{N_{obs} - N_{exp}}{\sqrt{\delta N^2_{obs} + \delta N^2_{exp}}},
\]

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 $\mathcal{B}(K^\pm \rightarrow p_1 X) \mathcal{B}(X \rightarrow p_2 p_3) (p_1 p_2 p_3 = \mu^\pm \pi^\mp \mu^\pm, \mu^\pm \pi^\mp \mu^\mp)$ as a function of the resonance lifetime $\tau$ for each mass hypothesis $m_i$, and are computed as

$$\mathcal{B}(K^\pm \rightarrow p_1 X) \mathcal{B}(X \rightarrow p_2 p_3) |_{m_i, \tau} = \frac{N_{sig}^i}{N_{3\pi}^i} \cdot \frac{A(K_{3\pi})}{A_{\pi\mu\mu}(m_i, \tau)} \cdot \mathcal{B}(K_{3\pi}). \quad (5.2)$$

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

6. Conclusions

A search for the LFV decay $K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm$ and two-body resonances in $K^\pm \rightarrow \pi \mu \mu$ decays has been performed using the data collected by the NA48/2 experiment in 2003 and 2004, corresponding to $1.6 \times 10^{11}$ 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 $\mathcal{B}(K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm) < 8.6 \times 10^{-11}$ 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 $K \rightarrow \pi \mu \mu$ decays are performed. Upper limits are set on the products of branching ratios $\mathcal{B}(K^\pm \rightarrow \mu^\pm N_4) \mathcal{B}(N_4 \rightarrow \pi^\mp \mu^\pm)$ and $\mathcal{B}(K^\pm \rightarrow \pi^\pm X) \mathcal{B}(X \rightarrow \mu^+ \mu^-)$ as functions of the resonance mass and lifetime. These limits are in the $10^{-10} - 10^{-9}$ range for resonance lifetimes below 100 ps.

References