

Cosmology tests in rare kaon decays

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Abstract.

The Standard Model (SM) of particle physics is an extremely successful theory that effectively describes strong and electroweak interactions up to the energies presently accessible. Still, the SM does not explain the observed parameters of neutrino oscillations, baryon asymmetry of the Universe and Dark Matter (DM), and contains a fine-tuning of 16 orders of magnitude (the gauge hierarchy problem). Various New Physics (NP) models beyond the SM have been developed in order to address the above limitations. This paper concentrates on several models related to cosmology and their tests in rare kaon decays. In particular, recent NA48/2 results on the search for heavy neutrinos, light inflatons and dark photons are presented. Prospects for the ongoing NA62 experiment are discussed.

1 Introduction

For many years kaon physics has been a powerful tool both to explore the flavor sector of the SM and to search for NP. A very high experimental sensitivity (down to $O(10^{-12})$) comes from the possibility to create high-intensity kaon beams, clear decay signatures and low background environment. From the theoretical side, precise predictions are available for various processes.

NP manifestations in kaon sector could be indirect or direct. An example of the former is the deviation from the SM values in the branching ratios (BR) for rare decays (e.g. $K \rightarrow \pi\nu\bar{\nu}$, $K \rightarrow e\nu$) or form factor distributions (e.g. $K \rightarrow e\nu_e\pi^0$, $K \rightarrow \mu\nu_\mu\pi^0$). The direct manifestations include peak searches ($K \rightarrow eX$, $K \rightarrow \mu X$, $K \rightarrow \pi X$) where a new particle X escapes from the detector and decay searches where X decays to known particles (leptons, pions) that can be detected.

Among various NP scenarios that can be probed by kaon decays, we will concentrate on those related to cosmology. One of the simplest extensions of the SM is the ν MMSM model [1]. The model contains three additional leptons N_1 , N_2 and N_3 and explains observed parameters of neutrino oscillations, baryon asymmetry of the Universe (BAU) and the existence of DM. The lightest lepton N_1 ($m \sim \text{keV}$) constitutes DM, while N_2 and N_3 (m up to a few GeV) are responsible for neutrino oscillations and BAU and can be searched for in kaon decays $K \rightarrow lN(l = e, \mu)$.

Light inflaton models explain inflation in the early Universe and together with the ν MMSM form a complete extension of the SM [2, 3]. In this class of models an additional scalar particle χ coupling to the SM Higgs boson is introduced and can be searched for in the decay $K \rightarrow \pi\chi$.

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Another example of models that can be probed in kaon decays is a class of models with extra U(1) gauge symmetry where the interaction between DM and the SM particles is mediated by a hypothetical gauge boson A' through the kinetic mixing [4]. A possible observation channel of this boson is the decay chain $K \rightarrow \pi\pi^0, \pi^0 \rightarrow \gamma A'$.

Recently several results on the topic have been obtained by the NA48/2 collaboration which is one of two most recent kaon experiments at CERN, the second one being the NA62 experiment currently running in the CERN North Area.

In the following sections a brief description of the NA48/2 setup is given, then the results on heavy neutrino, light inflation and dark photon search are presented. Finally, prospects for the NA62 experiment are discussed.

2 NA48/2 experiment

The NA48/2 is a fixed-target kaon experiment at CERN SPS that recorded a large data set of kaon decays in 2003–2004. The schematic view of the setup is shown in Fig. 1.

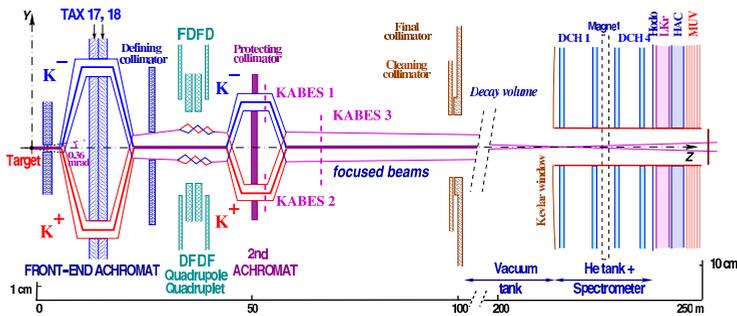


Figure 1. NA48/2 experimental setup.

The experiment used simultaneous beams of K^+ and K^- produced by 400 GeV/c protons from SPS hitting a beryllium target. Charged particles were selected by an achromate system containing four dipole magnets. The kaon momentum was 60 ± 3 GeV/c. After the selection and collimation, the beam particles entered a 114 m long decay volume. The momentum of secondary particles was measured by the magnetic spectrometer located downstream the decay volume. The spectrometer consisted of a dipole magnet, two drift chambers upstream the magnet (DCH1, DCH2) and two chambers downstream it (DCH3, DCH4). The spectrometer was followed by a plastic scintillator hodoscope (Hodo) creating a fast trigger for charged particles passing through it. The electromagnetic (LKr) and hadronic (HAC) calorimeters were used for the particle identification. They were followed by a muon detector (MUV). The detailed description of the setup can be found in [5].

3 Heavy neutrino search

Searches for heavy neutrinos are performed either by looking for the evidence of their production (a peak in the decays $K \rightarrow lN$, $l = e, \mu$) or by detecting their decay products. The ν_{MSM} heavy neutral leptons N_2, N_3 can be searched for in the following processes: $K^\pm \rightarrow \mu^\pm N$, $N \rightarrow \pi^\pm \mu^\mp$ or $K^\pm \rightarrow \mu^\pm N$, $N \rightarrow \pi^\mp \mu^\pm$.

The NA48/2 has recently set limits on the $N_{2,3}$ decays to pions and muons [6]. In this analysis, 3-track decays were selected with the invariant mass close to the kaon one. Then, a peak search was performed in the $\pi^\pm\mu^\mp$ or $\pi^\mp\mu^\pm$ invariant mass. The obtained upper limits are shown in Fig. 2. In the first case there is an irreducible background $K^\pm \rightarrow \mu^\pm\pi^\pm\mu^\mp$, while for the second decay mode the background is much lower, because the decay $K^\pm \rightarrow \mu^\pm\pi^\mp\mu^\pm$ is prohibited in the SM due to lepton number violation.

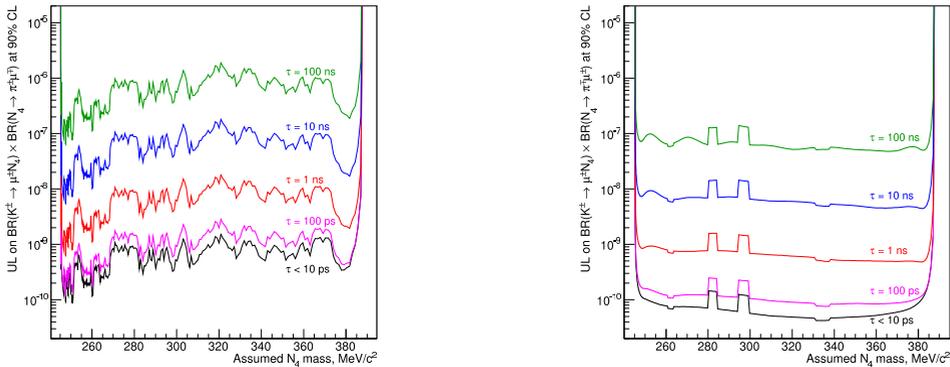


Figure 2. Upper limits on $BR(K^\pm \rightarrow \mu^\pm N, N \rightarrow \pi^\pm \mu^\mp)$ (left) and $BR(K^\pm \rightarrow \mu^\pm N, N \rightarrow \pi^\mp \mu^\pm)$ (right) for different lifetimes of N .

4 Light inflaton search

Light inflaton models contain two free parameters [2, 3]. The parameter values are constrained both by theory and experimental searches [3]. In the context of experimental tests it is straightforward to exploit the following three variables: inflaton mass m_χ , its lifetime τ_χ and the Higgs-inflaton squared mixing angle θ^2 characterizing the effective inflaton coupling to SM fields (and hence branching ratios of SM particle decays to inflaton). Any two parameters can be considered as free, e.g. for given τ_χ and m_χ , the value θ^2 is known. The expected inflaton decay modes and current limits on the inflaton phase space are shown in Fig. 3 (left).

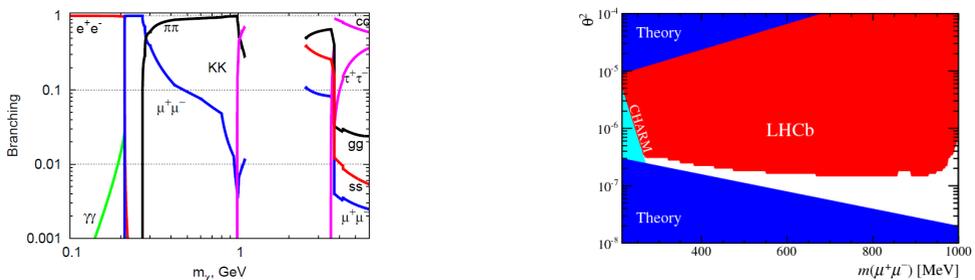


Figure 3. Light inflaton decay modes (left) and current limits on θ^2 (right).

The most promising processes for light inflaton search are the rare meson decays $B \rightarrow K\chi$ and $K \rightarrow \pi\chi$. The first search in the B sector has recently been published by the LHCb experiment at CERN [7]. The exclusion plot is shown in Fig.3 (right). The mass range $265 \text{ MeV} < m_\chi < 350 \text{ MeV}$ is currently outside the experimental reach in the B sector but can be covered in the kaon sector by the decay $K \rightarrow \pi\chi, \chi \rightarrow \mu^+\mu^-$ ($\chi \rightarrow \mu^+\mu^-$ is a dominant decay mode in this mass range, as can be seen in Fig. 3, left). This region contains inflatons with $\tau < 10^{-9} \text{ s}$ and $\theta^2 = (2 \div 3) \times 10^{-7}$, corresponding to branching ratios $BR(K \rightarrow \pi\chi) \times BR(\chi \rightarrow \mu^+\mu^-) < 3 \times 10^{-10}$.

The NA48/2 event selection for the inflaton search was the same as for heavy neutrino search [6]. After selecting 3-track candidates, the scan over the the invariant mass of two muons $M_{\mu\mu}$ was performed. The obtained upper limits are shown in Fig. 4.

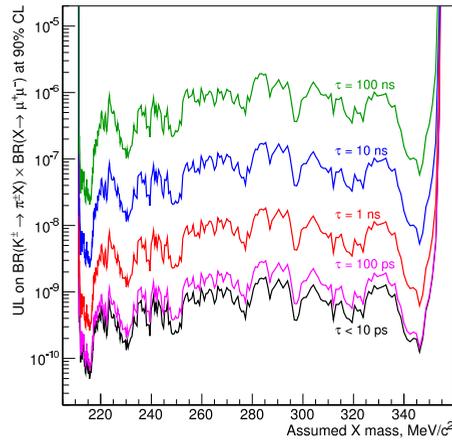


Figure 4. Upper limits on $BR(K^\pm \rightarrow \pi^\pm\chi, \chi \rightarrow \mu^+\mu^-)$ for different lifetimes of χ .

5 Dark photon search

In 2003–2004 the NA48/2 experiment collected a large set of π^0 's tagged from kaon decays $K^\pm \rightarrow \pi^\pm\pi^0$ and $K^\pm \rightarrow \mu^\pm\nu_\mu\pi^0$ which allows to search for the dark photon (DP)[8]. The BR of the DP production is $BR(\pi^0 \rightarrow \gamma A') = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right) \times BR(\pi^0 \rightarrow \gamma\gamma)$ [9]. Here ϵ is the mixing parameter, $m_{A'}$ is the DP mass. The only allowed decay mode of the DP in the mass range $2m_e < m_{A'} < m_{\pi^0}$ is $A' \rightarrow e^+e^-$. Thus, the DP search was performed by selecting Dalitz decays $K^\pm \rightarrow \pi^\pm\pi_D^0$ and $K^\pm \rightarrow \mu^\pm\nu_\mu\pi_D^0$, where $\pi_D^0 \rightarrow e^+e^-\gamma$. These decays have the same signature as the DP signal and therefore reproduce irreducible background.

The distribution over the invariant mass M_{ee} for $K^\pm \rightarrow \pi^\pm\pi_D^0$ is shown in Fig. 5 (left). A DP signal would correspond to a narrow peak in this distribution. A scan over the mass range $9 \text{ MeV}/c^2 < m_{A'} < 120 \text{ MeV}/c^2$ was performed. The range limits are due to the limited accuracy of the $\pi_D^0 \rightarrow e^+e^-\gamma$ simulation (left side) and not competitive sensitivity to the mixing parameter ϵ^2 (right side).

In total 404 mass hypotheses were tested. For none of them the local statistical significance exceeded 3σ . Upper limits at 90% CL on ϵ^2 were calculated for each mass hypothesis. The results compared to other exclusion limits are presented in Fig. 5(right). The world limits on the mixing parameter ϵ with DP are improved in the range 9–70 MeV/c^2 .

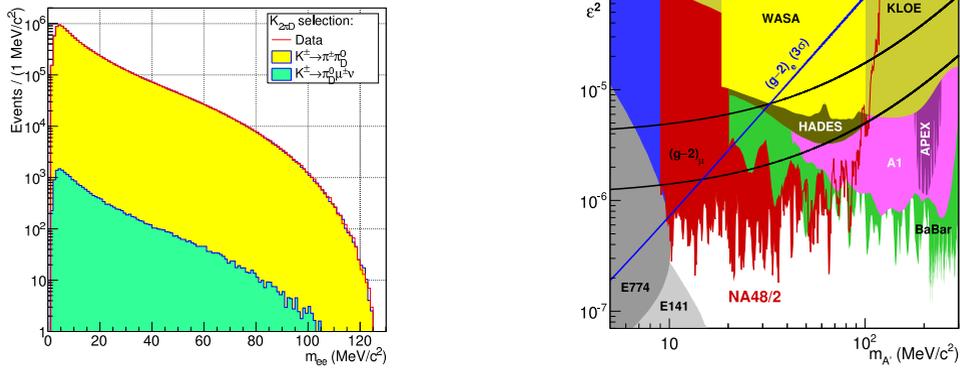


Figure 5. Invariant mass M_{ee} for $K^{\pm} \rightarrow \pi^{\pm} \pi_D^0$ (left) and current limits on DP search (right).

6 Prospects for the NA62 experiment

The NA62 experiment is aimed at measuring the $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ with $\sim 10\%$ precision. It is expected to collect $\sim 10^{13}$ K^+ decays (~ 50 times more than the NA48/2 statistics) in 2016–2018. The schematic view of the setup is shown in Fig. 6. The high-intensity (750 MHz) unseparated ($\sim 6\%$ of positively charged kaons) hadron beam with a 75 GeV/c momentum is obtained from the SPS primary beam (protons with 400 GeV/c momentum) impinging on a Be target. Kaons are identified by a differential Cerenkov counter (CEDAR). The momentum and direction of beam particles are measured by a silicon pixel beam spectrometer (Gigatracker). The vacuumed decay region has a length of ~ 65 m. The momentum of secondary charged particles (produced in kaon decays) is measured by a magnetic spectrometer composed of four stations of straw tubes and a magnet with $p_T \sim 270 \text{ MeV}/c$. The energy of secondary photons and electrons flying at small angles with respect to the beam axis is measured by a liquid krypton electromagnetic calorimeter, while large angle photons are detected by a system of 12 rings of lead-glass blocks (Large angle photon veto). The identification of secondary particles is done in the RICH detector filled with Ne at atmospheric pressure, liquid krypton calorimeter, hadron calorimeter (both calorimeters were previously used in the NA48/2 experiment). A highly segmented muon identification system (Muon veto) is located behind the krypton calorimeter.

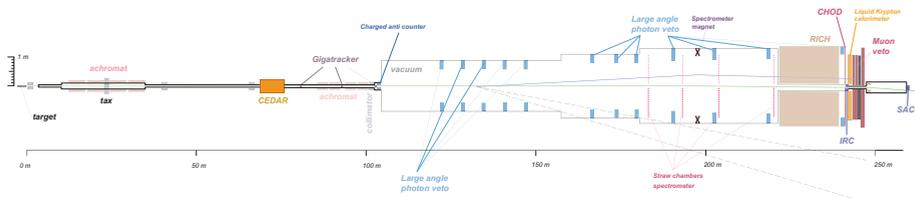


Figure 6. NA62 experimental setup.

The detailed description can be found in [10]. A new spectrometer operated in vacuum will allow to significantly improve the momentum resolution crucial for the searches discussed above (at least by a factor of two). The kaon identification by the KTAG detector will reduce the muon halo contribution. In addition to the decay searches, it is expected to improve the current world limits on

the heavy neutrino production in $K^+ \rightarrow \mu^+ N$ decay, at least for neutrino masses above $300 \text{ MeV}/c^2$. The advantage of this mode is that the production searches are model-independent.

7 Conclusions

Various NP models that allow to solve existing problems in cosmology can be tested in kaon decays, among them the ν MSM, light inflaton models and models with dark photons. Recently new upper limits were set by the NA48/2 experiment on the BR of related processes $K^\pm \rightarrow \mu^\pm N$, $N \rightarrow \mu^\pm \pi^\mp$; $K^\pm \rightarrow \mu^\pm N$, $N \rightarrow \pi^\pm \mu^\mp$ and $K^\pm \rightarrow \pi^\pm \chi$, $\chi \rightarrow \mu^+ \mu^-$. The new limits on the mixing parameter ϵ with DP are obtained in the range $9\text{--}120 \text{ MeV}/c^2$. The ongoing NA62 experiment should have significantly better sensitivity due to larger statistics and better performance of the detectors.

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