PROCEEDINGS OF SCIENCE

Searches for hidden sectors and lepton flavour violation in kaon decays at the NA62 experiment

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The NA62 experiment provides unique opportunities to search for physics beyond the Standard Model. In this paper, recent results on searches for hidden sectors and lepton flavour violation in kaon decays are discussed.

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1. Introduction

Lepton Number (LN) and Lepton flavour (LF) are conserved and considered as accidental symmetries within the Standard Model (SM). Many SM extensions allow for LN and LF violating processes (LNV and LFV, respectively) mediated by new particles existing within the framework of such models. The existence of new mediators is also predicted by the hidden sector paradigm where these mediators are kinetically mixed with SM particles via portals. The hidden sector benchmark scenarios are described in [1].

The large sample of kaon decays collected by NA62 in 2016–2024 allows to look for physics beyond SM. In this paper, the most recent results on LFV/LNV and hidden sector searches are presented.

2. Experimental setup

NA62 is a fixed target experiment situated at the CERN SPS accelerator. Primary protons with 400 GeV/c momentum GeV/c momentum impinge on a beryllium target producing secondary particles. A 100 m long beam line collimates, focuses and transports charged particles of (75.0±0.8) GeV/c momentum to the decay volume. The kaon fraction in the secondary beam is 6%. Beam kaons are identified and timestamped by the KTAG, a differential Cherenkov detector placed on the beam and filled with nitrogen. The Gigatracker (GTK) detector, made of three silicon pixel stations, timestamps beam particles of all types and measures their momenta. The CHANTI detector, located after the GTK, vetoes beam interactions with the material in the last GTK station. The momenta of charged particles from kaon decays are measured by the spectrometer made of four straw chambers and a dipole magnet. A 17 m long RICH detector filled with neon at atmospheric pressure is used to identify π^+, μ^+ and e^+, and together with a scintillator hodoscope (CHOD), measures the downstream track time. Hadronic calorimeters (MUV1 and MUV2) and a fast scintillator muon veto (MUV3) aid in separating π^+ from μ^+. A system of photon veto detectors (12 LAV stations, LKr, IRC, SAC) is designed to reject extra electromagnetic activity, covering angles up to 50 mrad. A detailed description of the setup can be found in [2]. The experiment started to take data in 2016. The 2016–2018 period is referred to as Run 1 in the following.

3. Search for $K^+ \to \pi^+ X$ decays

The main goal of the NA62 experiment is the measurement of the branching ratio (BR) of a very rare decay $K^+ \to \pi^+ \nu\bar{\nu}$ [3]. As a by-product of this analysis, the search for a new particle X in the decay $K^+ \to \pi^+ X$ has been performed on Run 1 data in the mass range below and above the π^0 mass [4]. The upper limits on BR of the decay have been obtained for different hypotheses in terms of mass and lifetime, see Fig. 1 left. The analysis has been extended to the 2016–2022 data sample [5]. The search near the π^0 mass region [6] has been performed for partial (10%) Run 1 data, the results are shown in Fig. 1 right.

The obtained upper limits have been interpreted in terms of the dark scalar scenario (BC4 in [1]), see Fig. 2 left. Another benchmark scenario (BC11), where X could be an axion-like particle and decay to a couple of photons, has been tested in the $K^+ \to \pi^+ X, X \to \gamma\gamma$ decay [7]. The results are shown in Fig. 2 right.

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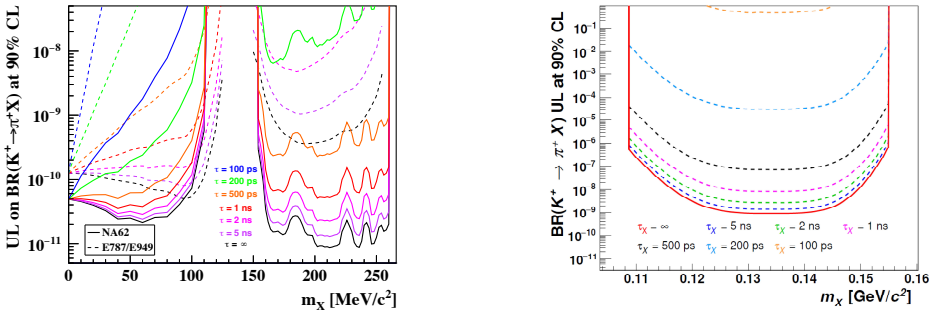

Figure 1: Upper limits of BR($K^+ \to \pi^+ X$) @90% CL for different (m, τ) hypotheses of X. Left: outside the π^0 mass region. Right: around the π^0 mass.

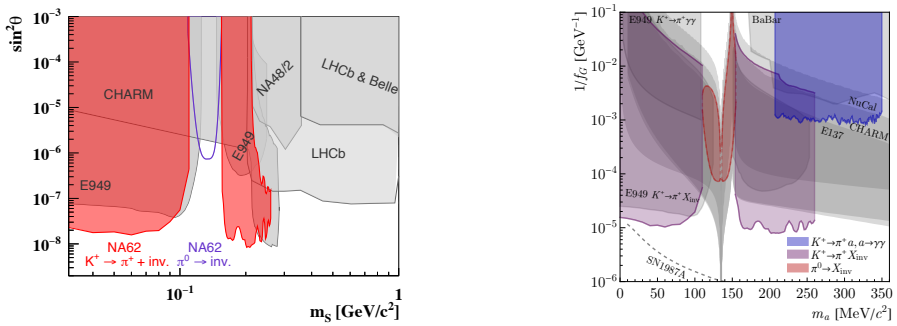

Figure 2: Upper limits @90% CL of coupling with hidden sector mediators. Left: dark scalar (BC4 scenario). Right: axion-like particle (BC11 scenario). The scenarios are described in [1].

4. Search for LFV/LNV kaon decays

Several decay signatures with three charged tracks in the final state have been studied. Obtained upper limits are summarized in Table 1.

4.1 $K^+ \to \pi^- e^+ e^+$ and $K^+ \to \pi^- \mu^+ \mu^+$

For the electron (muon) mode, the whole (partial) Run 1 data have been analyzed and the decay $K^+ \to \pi^+ e^+ e^-$ ($K^+ \to \pi^+ \mu^+ \mu^-$) is used for the normalization [8, 9]. The invariant mass $m_{\pi^- l^+ l^+}$ distributions are shown in Fig. 3. Previous limits have been improved by a factor of 8 (2).

4.2 $K^+ \to \pi \mu e$

The Run 1 data are used for this analysis [10]. The signal rates are normalized to the $K^+ \to \pi^+\pi^+\pi^-$ decay. In addition, a search for the $\pi^0 \to \mu e$ from the decay chain $K^+ \to \pi^+\pi^0, \pi^0 \to \mu e$ has been performed. The invariant mass $m_{\pi\mu e}$ distributions are shown in Fig. 4. An improvement in the upper limit of the BR by a factor of order 10 has been achieved compared to previous results.

4.3 $K^+ \to \pi^-\pi^0 e^+ e^+$, $K^+ \to \pi\pi^0 \mu e$ and $K^+ \to \mu^- \nu e^+ e^+$

The first search for the decay $K^+ \to \pi^-\pi^0 e^+ e^+$ has been published [11]. Another recent result is the upper limit of the BR of the $K^+ \to \pi^-\pi^0 \mu^+ e^+$, $K^+ \to \pi^+\pi^0 \mu^- e^+$ and $K^+ \to \pi^+\pi^0 \mu^+ e^-$

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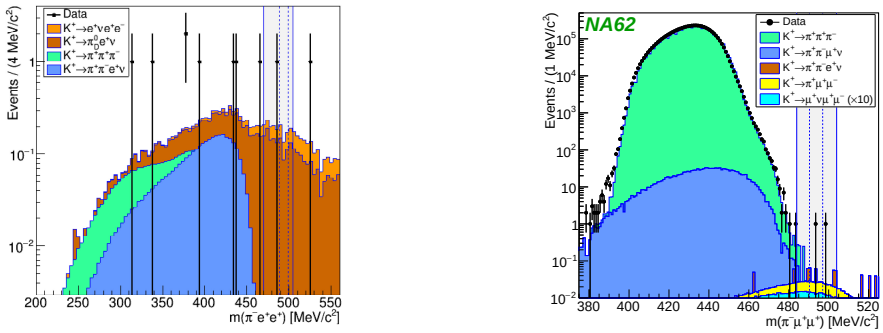

Figure 3: Reconstructed spectra for the data and simulated backgrounds. Left: $m_{\pi ll}$ for the $K^+ \to \pi^- e^+ e^+$ selection. Right: $m_{\pi ll}$ for the $K^+ \to \pi^- \mu^+ \mu^+$ selection.

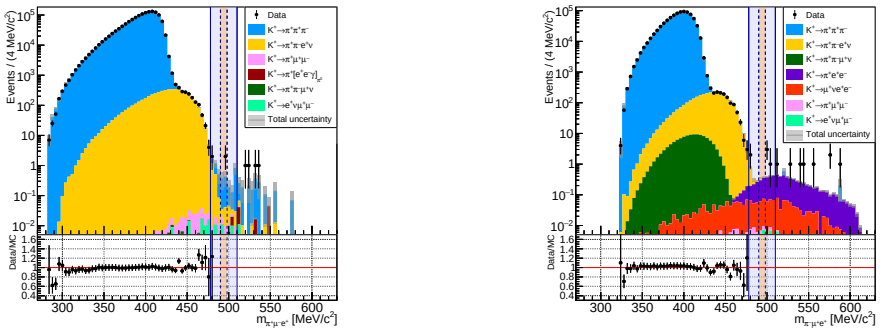

Figure 4: Reconstructed spectra for the data and simulated backgrounds. Left: $m_{\pi\mu e}$ for the $K^+ \to \pi^- \mu^+ e^+$ selection. Right: $m_{\pi\mu e}$ for the $K^+ \to \pi^+ \mu^- e^+$ selection.

decays [12]. The upper limit of the BR of the $K^+ \to \mu^- \nu e^+ e^+$ decay has been improved by a factor of 250 [13]. All searches use the whole Run 1 data sample and the $K^+ \to \pi^+ e^+ e^-$ decay for the normalization. The signal regions for some of them are shown in Fig. 5.

5. HNL production in kaon and pion decays

5.1 $K^+ \to l^+ N$

The HNL production search has been performed in $K^+ \to e^+ N$ [14] and $K^+ \to \mu^+ N$ [15] decays on Run 1 data. The results are interpreted in terms of the BC6 and BC7 scenarios [16] and are shown in Fig. 6.

5.2 $\pi^+ \to e^+ N$

Another search for HNL has been recently done in the $\pi^+ \to e^+ N$ decay using the 2016–2024 data sample [17]. The obtained upper limits of BR and the coupling with N are shown in Fig. 7.

6. Conclusions

The upper limits have obtained from $K^+ \to \pi^+ X$ and $K^+ \to l^+ N$ decays for various benchmark scenarios of hidden sector searches. Stringent upper limits have been set on several LFV/LNV decay

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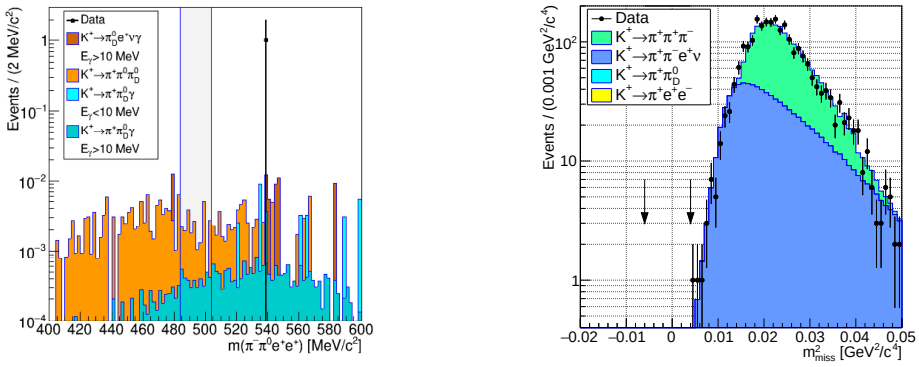

Figure 5: Reconstructed spectra for the data and simulated backgrounds. Left: $m_{\pi\pi ee}$ for the $K^+ \to \pi^-\pi^0 e^+ e^+$ selection. Right: missing mass squared $m^2_{miss} = (P_K - P_\mu - P_{e1} - P_{e2})^2$ for the $K^+ \to \mu^-\nu e^+ e^+$ selection.

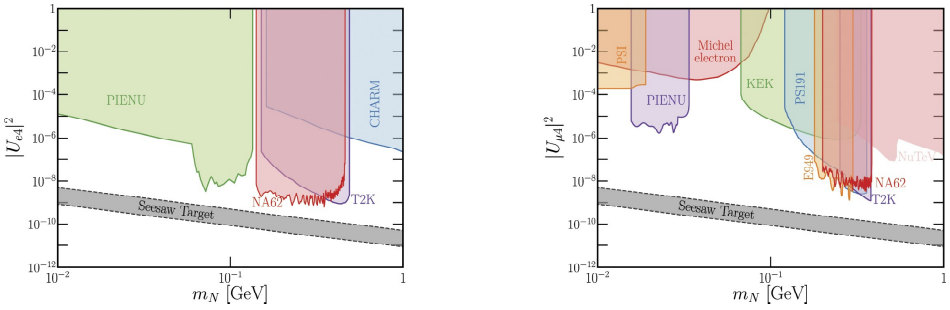

Figure 6: Upper limits @90% CL of HNL coupling U_{l4}. Left: $l = e$ (BC6 scenario). Right: $l = \mu$ (BC7 scenario).

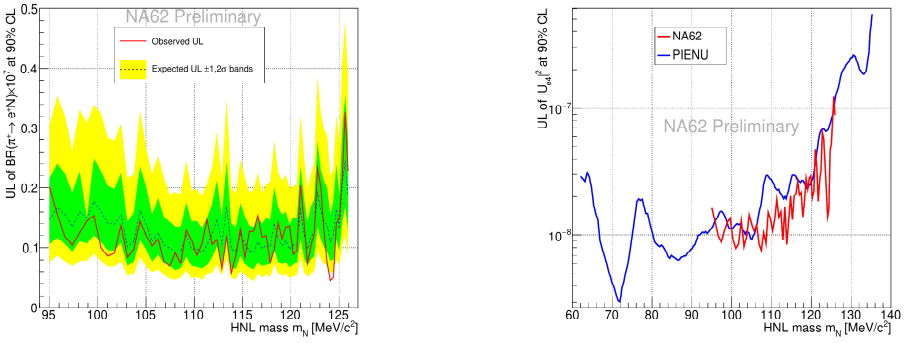

Figure 7: Upper limit @90% CL. Left: BR($\pi^+ \to e^+N$). Right: HNL coupling U_{e4}.

modes, the results are summarized in Table 1.

The NA62 experiment will continue data taking till 2026 and will be able to significantly improve the sensitivity with the upcoming data.

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Channel	UL(BR)@90% CL	Sample
$K^+ \to \pi^- e^+ e^+$	5.3×10^{-11}	Run 1
$K^+ \to \pi^- \mu^+ \mu^+$	4.2×10^{-11}	25% Run 1
$K^+ \to \pi^- \mu^+ e^+$	4.2×10^{-11}	Run 1
$K^+ \to \pi^+ \mu^- e^+$	6.6×10^{-11}	Run 1
$\pi^0 \to \mu^- e^+$	3.2×10^{-10}	Run 1
$K^+ \to \pi^- \pi^0 e^+ e^+$	8.5×10^{-10}	Run 1
$K^+ \to \mu^- \nu e^+ e^+$	8.1×10^{-11}	Run 1
$K^+ \to \pi^- \pi^0 \mu^+ e^+$	2.9×10^{-10}	Run 1
$K^+ \to \pi^+ \pi^0 \mu^- e^+$	3.1×10^{-10}	Run 1
$K^+ \to \pi^+ \pi^0 \mu^+ e^-$	5.0×10^{-10}	Run 1

Table 1: Summary of LFV/LNV searches.

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