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Searches for Lepton Flavour and Number Violation and Hidden Sector Particles at NA62

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Rare kaon decays are among the most sensitive probes of both heavy and light new physics beyond the Standard Model (SM) description thanks to high precision of the Standard Model predictions, availability of very large datasets, and the relatively simple decay topologies. The NA62 experiment at CERN is a multi-purpose high-intensity kaon decay experiment, and carries out a broad rare-decay and hidden-sector physics programme. Recent NA62 results on searches for violation of lepton flavour and lepton number in kaon decays, and searches for production in hidden-sector mediators in kaon decays, are presented. Future prospects of these searches are discussed.

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1. The NA62 experiment at CERN

The NA62 experiment at CERN is located in the North Area where it started data collection in 2016 and will operate until the beginning of Long Shutdown 3 (LS3). The experiment is designed to measure the branching ratio (BR) of the ultra-rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay [1]. In addition, other trigger lines are available to select different final state topologies. NA62 is served by the SPS accelerator and operates with a Kaon-rich (6%) hadronic beam with mean momentum of 75 GeV/c; it can also operate in Beam Dump mode for exotic searches. A schematic of the experimental setup is shown in Figure 1. NA62 employs a novel "in-flight decay" approach. High timing resolution, state-of-the-art Particle Identification techniques (PID) and a hermetic γ veto allow for full reconstruction of both initial and final states. Incoming beam particles are tagged by a Differential Cherenkov counter (KTAG), which provides timing ($\sigma_t \approx 70$ ns) and PID; momentum and trajectory information is provided by a multi-layer pixel Si tracker (GTK) with $\sigma_\theta \approx 16$ µrad. Beam particles then propagate within the fiducial volume and decay products are characterized with a magnetic spectrometer (STRAW) and a Ring Imaging Cherenkov Detector (RICH). A hodoscope for charged particles (CHOD) is used within the trigger system while further information for PID is provided by a Liquid Krypton calorimeter (LKr), a set of hadronic calorimeters (MUV1-2) and a muon detector (MUV3). The γ veto is built with 12 Large Angle Veto (LAV) stations, the LKr and a set of two shashlik calorimeters (IRC-SAC). A more in-depth description of the NA62 experiment can be found in [2].

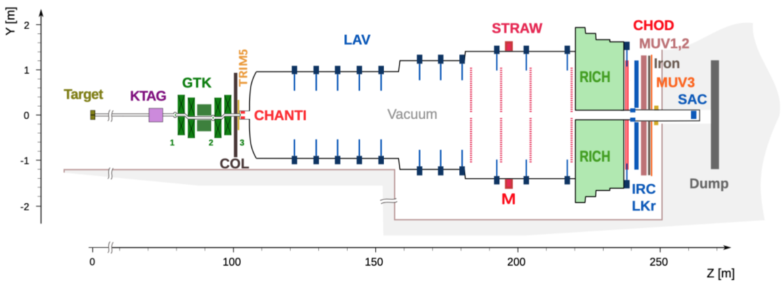

Figure 1: Layout of NA62 in 2016

2. $K^+ \to \pi^+ \nu\bar{\nu}$ decay at NA62

The $K^+ \to \pi^+ \nu\bar{\nu}$ ($\pi\nu\nu$) decay is an extremely rare channel with a predicted SM branching ratio of $\sim 10^{-10}$. It is a Flavor Changing Neutral Current (FCNC) process forbidden at tree level and happening only through box and penguin diagrams [3]. The $\pi\nu\nu$ decay is one of the very few theoretically clean channels, i.e. its SM BR uncertainty is dominated by the contribution from CKM matrix elements. The decay is an exceptional probe for Beyond SM physics, with an accessible mass scale that is the largest among meson decays. Large deviations from the SM BR are predicted by models including new sources of flavour violation.

NA62 has published the best measurement of $\pi\nu\nu$ BR using data acquired during NA62 Run1 (2016-2018) [4].

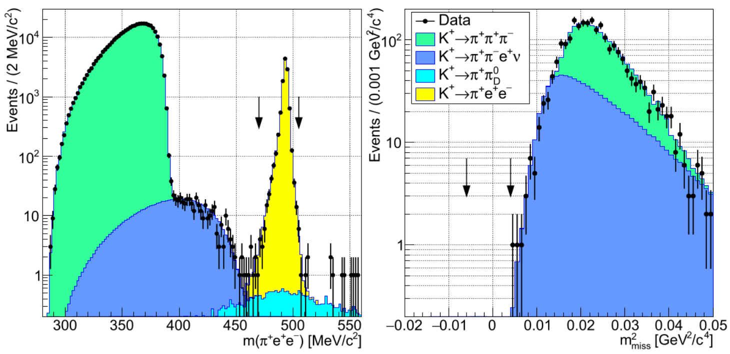

Figure 2: Left: reconstructed $m_{\pi ee}$ spectra for the data and MC samples obtained with the normalization selection. Right: reconstructed m^2_{miss} spectra for the data and MC samples obtained with the signal selection. The normalisation and signal mass regions are indicated by vertical arrows

3. Search for Lepton Flavor/Lepton Number violation in $K^+ \to \mu^- \nu e^+ e^+$

Searches for Lepton Flavor and Lepton Number violation (LFV/LNV) in K physics can probe energy scales up to $\mathcal{O}(100\text{ TeV})$. NA62 is a good candidate to study these due to its PID system, hermetic veto and dedicated multi-lepton and multi-track trigger lines. An observation of LFV/LNV decays such as $K^+ \to \mu^- \nu e^+ e^+$ would provide evidence of the Majorana nature of neutrinos [5]. Moreover, several ALP and Z' models predict an LFV [6] [7]. In the SM, $K^+ \to \mu^- \nu e^+ e^+$ is forbidden by either LN or LF conservation depending on the emitted ν flavor. The previous best limit for the BR is 2.1×10^{-8} [8] [9].

The NA62 measurement is based on data collected in 2016-2018 with multi-track and multi-lepton trigger lines. The decay $K^+ \to \pi^+ e^+ e^-$ is used as normalization channel; since both can be acquired with the same trigger lines systematic trigger inefficiencies are negligible.

The selection is performed based on the final state signature; that is three well separated, STRAW tracks with $Q = 1$ form a vertex in the decay volume. In order to suppress Dalitz-like decays, photon veto is applied downstream of the vertex. Due to the presence of a neutrino in the signal channel, stricter photon veto and vertex position conditions are applied with respect to the normalization.

The signal region for this search is defined in $m^2_{\text{miss}} = (P_K - P_\mu - P_{e1} - P_{e2})^2$ as $-6 \times 10^{-3}\text{GeV}^4/\text{c}^2 < m^2_{\text{miss}} < 4{\times}10^{-3}\text{GeV}^4/\text{c}^2$. The asymmetry comes from m^2_{miss} resolution constraints and background rejection. Concerning the normalization, events are selected within $470\,\text{MeV}/\text{c}^2 < m_{\pi ee} < 505\text{ MeV}/\text{c}^2$; with $N' = 21401$ normalization events in the fiducial volume $N_K \approx 2 \times 10^{12}$ kaon decays are expected. The signal and normalization regions are shown in Figure 2, the expected background in the signal region is $N_B = 0.26 \pm 0.04$.

Single event sensitivity is estimated to be $\mathcal{B}_{\text{ses}} = (3.53 \pm 0.12) \times 10^{-11}$ using an uniform phase space, which implies [10]:

$$\text{BR}(K^+ \to \mu^- \nu e^+ e^+) < 8.1 \times 10^{-11} \quad \text{at } 90\%\text{ CL.} \tag{1}$$

The sensitivity is not background-limited. With an improvement of a factor ~ 250 over the previous estimates this search probes physics beyond SM, but the achieved sensitivity is not yet sufficient to obtain new constraints on Majorana neutrino or ALP and Z' models.

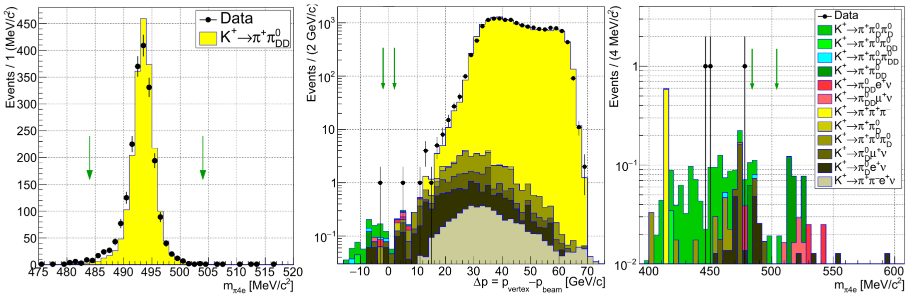

Figure 3: Left: Normalization region. Center/Right: Signal regions in Δp and $m_{\pi ee}$. Backgrounds are shown if their BR > 10^{-8}.

4. Hidden sector searches with $K^+ \to \pi^+ e^- e^+ e^- e^+$

Until recently, dark sector searches in meson decays focused on single dark particle production [11] [12]. However, it is possible to also probe pair production [13] [7]. In kaon physics a prominent example is given by $K \to \pi X(\to e^+e^-)X(\to e^+e^-)$, a process not yet studied. In the SM, the final state is reachable from common $K^+ \to \pi^+\pi^0$ decay followed by a double Dalitz decay ($\pi^+ \to e^+e^-e^+e^-$); the overall process having BR = 6.9×10^{-6}. An expected contribution is also given by photon exchanges and has BR = $(7.2 \pm 0.7) \times 10^{-11}$ [14]. An accurate measurement of the non-resonant contribution may provide evidence for several dark-sector models, notably:

- A pair production of QCD axions (a) promptly producing e^+e^- pairs $K^+ \to \pi^+ aa$ with $a \to e^+e^-$. This mode may also provide an explanation of the «17 MeV» anomaly in nuclear spectra [15]; if $m_a := 17$ MeV the process $K^+ \to \pi^+ aa$ has a lower bound of BR > 2×10^{-8} [13].
- A cascade process involving dark photons A' and dark scalars S with $m_S \geq 2m_{A'}$, that is $K^+ \to \pi^+ S$, $S \to A'A'$ with $A' \to e^+e^-$ [13].

For this search events with five tracks forming a vertex with the Kaon track and consistent with the beam momentum and direction are selected and classified as normalization (from Double Dalitz) and signal (non resonant). The normalization region, defined in the $m_{\pi 4e}$ variable and centered around the K^+ mass, is shown in Figure 3 (left). The signal selection is based on the assumption that the e^+e^- are pair produced from a parent particle. The momentum excess $p_{\text{vertex}} - p_{\text{beam}}$ and the reconstructed final state mass ($m_{\pi 4e}$) are shown in Figure 3 center and right, respectively, with the signal region highlighted by the green arrows.

In the signal region the total background, given the size of the analyzed dataset of $N_K \sim 8.6 \times 10^{11}$ decays in the fiducial volume, is $N_B = 0.18 \pm 0.14$. Meanwhile, considering m_X (Where X is the dark sector particle) in the range $[10 - 170]$ MeV/c^2 the background for each mass hypothesis is:

$$N_B = (0.4 \pm 0.4) \times 10^{-3}. \tag{2}$$

The uniform phase space signal acceptances for $K^+ \to \pi^+ aa$ and $K^+ \to \pi^+ S(S \to A'A', A' \to ee)$ are estimated to reach maxima of 7.1×10^{-3} (m_a = 155 MeV/c^2) and 1.2×10^{-2} ($m_{A'}$ =

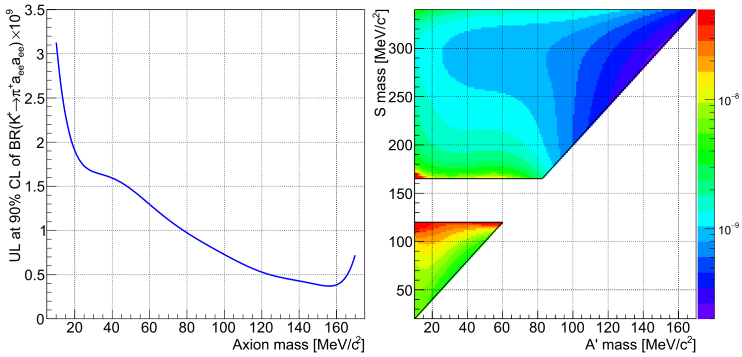

Figure 4: Left: Upper Limit at 90% CL for the $K^+ \to \pi^+ aa$ with $a \to e^+e^-$ decay chain as function of m_a hypothesis. Right: UL at 90% CL for the $K\pi S$ decay chain as function of $m_{A'}$ and m_S hypotheses.

150 MeV/c^2, m_S = 300 MeV/c^2) respectively. No events have been observed in the signal region after unblinding, leading to an upper limit on the non-resonant channel of:

$$\mathrm{BR} < 1.4 \times 10^{-8}. \quad (3)$$

Upper limits for the $K\pi aa$, $K\pi S$ processes are shown in Figure 4 [16]. Note that BR $<$ 2.1×10^{-9} for m_a = 17 MeV/c^2 excludes an ALP as source of the 17 MeV anomaly.

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