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Physics beyond the Standard Model with NA62

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Abstract: The NA62 experiment at CERN took data in 2016–2018 with the main goal of measuring the $K^+ \to \nu\bar{\nu}$ decay. The NA62 dataset is also exploited to search for light feebly interacting particles produced in kaon decays. Searches for $K^+ \to e^+N$ and $K^+ \to \mu^+N$ decays, where N is a massive invisible particle, are performed. The N particle is assumed to be a heavy neutral lepton, and the results are expressed as upper limits of $O(10^{-8})$ the neutrino mixing parameter $|U_{l4}|^2$, where $l = e, \mu$. Dedicated trigger lines were employed to collect di-lepton final states, which allowed stringent upper limits to be established for the rates lepton flavor and lepton number violating kaon decays. Upper limits on the rates of several K^+ decays violating lepton flavour and lepton number conservation, obtained by analysing this dataset, are presented here.

Keywords: Large detector systems for particle and astroparticle physics; Large detector-systems performance

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1 Introduction

The main experimental goal of the NA62 experiment at CERN is the measurement of the Branching Ratio (BR) for $K^+ \to \pi^+ \nu\bar{\nu}$, which would represent an extremely high precision test of the Standard Model (SM). The experiment is presented in section 2. A summary of the present and future analysis strategy for $K^+ \to \pi^+ \nu\bar{\nu}$ will be given in section 3. Other physics goals of the experiment are studies of rare and forbidden decays, including the search for lepton flavor and lepton number violation, which will be discussed in section 4. Another branch of research performed at NA62, presented in section 5, is "hidden sector" searches, i.e. searches for New Physics below the electroweak scale and feebly coupled to SM particles, such as dark scalars or heavy neutral leptons N from K^+ decays. A possible experiment upgrade and its physics case will be presented in section 6.

2 The NA62 experiment

The NA62 experiment at CERN exploits the SPS primary proton beam, which impinges on a Be target. After the target, 75 GeV/c momentum secondary hadrons are selected; of those approximately 6% are K^+, whose decays are studied in the experiment. The NA62 beam line and detector are described in detail in [1]. The NA62 experiment has been optimized to be sensitive to the $K^+ \to \pi^+ \nu\bar{\nu}$ in-flight decay. The upstream part of the experiment is dedicated to the measurement of the energy and momentum of the selected K^+ (primarily in the KTAG differential Cherenkov detector and the GTK Si pixel tracker). A collimator, preceding the last layer of the GTK, is intended to intercept background outside the beam acceptance. Shortly after the start of the 2018 datataking, the original collimator was replaced with a larger one. The detectors in the second part of the experiment, after the beginning of the K^+ decay fiducial volume, measure the momentum and direction of the pion (in the STRAW tube spectrometer), perform the pion particle identification (in the RICH and the LKr calorimeter) and veto other K^+ decays into muons, photons (in the Large Angle Veto, Small Angle

Veto and IRC photon detectors) and multi pions. Excellent timing from the detectors, at the level of 150 ps, allows for $K-\pi$ matching. Muon and π^0 suppression are essential for removing background events from other K^+ decays and the suppression factors reach a level of 10^{-8} after applying the analysis selection.

3 Search for the $K^+ \to \pi^+\nu\bar{\nu}$ decay

The flavor changing neutral current loop suppressed $K^+ \to \pi^+\nu\bar{\nu}$ decay has a SM predicted BR of (8.4±1.0) $\times 10^{-11}$ as estimated in [2]. Figure 1 (left) shows the missing squared invariant mass as a function of the pion momentum for events passing the signal selection. It is possible to see the events in the sidebands and the unblinded events in the signal regions 1 and 2: the number of observed events in the signal regions is 17. The BR is computed normalized to the $K^+ \to \pi^+\pi^0$ channel, which shares the same secondary track as the signal, but unlike the signal does not require a photon veto and has been collected with a down-scaled minimum bias trigger where no muon/photon vetoes are applied:

$$BR(K^+ \to \pi^+\nu\bar{\nu}) = \frac{N_{\pi\nu\nu} \cdot BR(K^+ \to \pi^+\pi^0) \cdot A_{\pi\pi} \cdot \epsilon_{\text{trig}}^{MB}}{D \cdot N_{\pi\pi} \cdot A_{\pi\nu\nu} \cdot \epsilon_{RV} \cdot \epsilon_{\text{trig}}^{\pi\nu\nu}}, \tag{3.1}$$

where $N_{\pi\nu\nu}$ is the number of selected signal events, $N_{\pi\pi}$ is the number of the events selected in the normalization channel and D is the down-scaling factor for the minimum bias trigger. The ratio of the total efficiencies for the signal and normalization selection takes into account for the different acceptances A, the different efficiency ϵ for the trigger conditions for the signal and the normalization channel and the efficiency ϵ_{RV} of the random veto due to the photon rejection that is required for the signal selection but not for the normalization channel. Using the ratio guarantees the cancellation of systematic effects for particle identification, detector efficiencies, kaon association and beam-related uncertainties. The BR has been calculated by performing a maximum likelihood fit dividing the data into eight categories to increase sensitivity. Categories 0 and 1 correspond to the 2016 and 2017 datasets, category 2 is for the so called "S1" dataset, i.e. the 2018 dataset collected before changing the collimator (roughly 20% of the whole 2018 dataset). Categories 3 to 8 correspond to the six 5 GeV/c wide momentum bins of the "S2" subset (2018 dataset after the new collimator). Figure 1 (right) shows the number of the data events observed and the expected background, divided into the categories used to perform the BR maximum likelihood fit, which results in $BR(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}(\text{stat.}) \pm 0.9(\text{syst})) \cdot 10^{-11})$. The BR differs from zero with a 3.4 σ significance (i.e. evidence of the decay) and it is compatible with the SM expectation for $BR(K^+ \to \pi^+\nu\bar{\nu})$. The significance is still not enough to put stringent limits on the different beyond SM theories that foresee a deviation of $BR(K^+ \to \pi^+\nu\bar{\nu})$ from the SM value (Minimal Supersymmetric SM, Simplified Z, Z', LF Universality violation models [2, 5–7]). The Run II datataking is crucial for NA62: the experiment resumed collecting data in summer 2021 and will continue till 2025 with the aim of achieving a measurement of the BR with 15% statistical precision. Section 6 will discuss how the BR measurement can be further improved in the future years and the possible discrimination among some Beyond SM (BSM) models.

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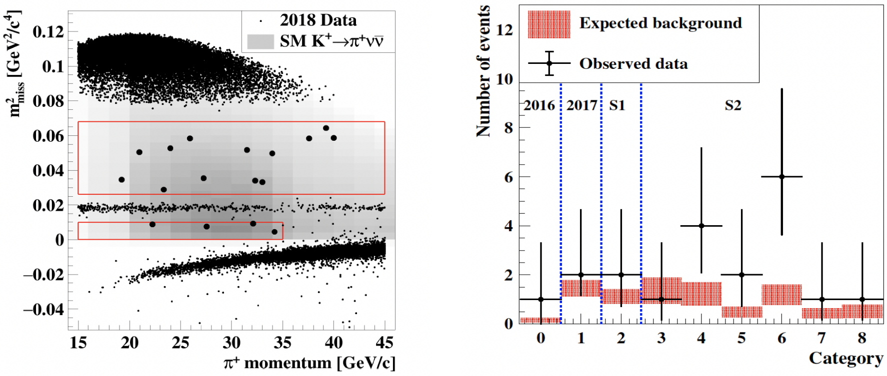

Figure 1. Left: the reconstructed missing squared invariant mass as a function of the pion momentum for events satisfying the $K^+ \to \pi^+ \nu\bar{\nu}$ selection criteria. The intensity of the grey shaded area reflects the variation of the SM signal acceptance in the plane. The two boxes represent the signal regions. The events observed outside the signal regions are background and control regions. Right: expected number of background events and number of events observed in the nine categories used to extract the $K^+ \to \pi^+ \nu\bar{\nu}$ BR. The observed data for each category are indicated by black markers with Poissonian statistical errors. The shaded boxes show the expected numbers of background events and the corresponding uncertainties. Reproduced from [3]. CC BY 4.0.

4 Lepton flavour and lepton number violation searches

Lepton Number Violation (LNV) and Lepton Flavour violation (LFV) are foreseen in some BSM theories as SM conservation laws are not imposed by any local gauge symmetry. The observation of neutrino oscillations provided the first proof of LFV, however no evidence of LNV has been observed yet. Searches for LFV/LNV K decays are powerful probes of BSM models at mass scales up to $O(100\,\text{TeV})$. The K meson decay searches at NA62 complement searches for quark-lepton or purely lepton LFV and LNV decays performed by other experiments. Thanks to the ability to control the background of mis-identified particles, NA62 is able to set world-leading 90% C.L. limits in seven decay channels: $BR(K^+ \to \pi^-\mu^+\mu^+) < 4.2 \times 10^{-11}$ [8], $BR(K^+ \to \pi^- e^+ e^+) < 5.3 \times 10^{-11}$ [9], $BR(K^+ \to \pi^-\pi^0 e^+ e^+) < 8.5 \times 10^{-10}$ [9], $BR(K^+ \to \pi^-\mu^+ e^+) < 4.2 \times 10^{-11}$ [10], $BR(K^+ \to \pi^+\mu^- e^+) < 6.6 \times 10^{-11}$ [10], $BR(\pi^0 \to \mu^- e^+) < 3.2 \times 10^{-10}$ [10] and $BR(K^+ \to \mu^-\nu e^+ e^+) < 8.1 \times 10^{-11}$ [11]. These results improve on previous results for these decay modes by one order of magnitude. These LFV/LNV results depend on the phase space density assumptions; a uniform space density has been assumed.

5 Heavy neutral leptons and feebly interacting particle searches

Neutrinos are massless in the SM, contrary to the well established observation of neutrino oscillations. Right-handed neutrinos, i.e. Heavy Neutral Leptons (HNLs), if they exist could generate neutrino masses via the see-saw mechanism with "low scale" HNL masses of order of 100 MeV. A decay involving a HNL has a similar experimental signature to the $K^+ \to l^+\nu$ SM decay, where l^+ is the charged lepton (e^+ or μ^+). The expected branching fraction for $K^+ \to l^+ N$, where N is the HNL, is given by $BR(K^+ \to l^+ N) = BR(K^+ \to l^+\nu) \cdot \rho_l(m_N) \cdot |U_{l4}|^2$, where $|U_{l4}|^2$ is the mixing parameter and $\rho_l(m_N)$ is a kinematic factor which depends on the HNL mass. Complete details of the analysis are reported in [12, 13]. Search for $K^+ \to l^+ N$, decays in the HNL mass range 144–462 MeV/c^2 for the electron channel and in the range 200–384 MeV/c^2 for the muon channel have been performed. The upper limits obtained on $|U_{e4}|^2$ at 90% C.L. improve on the existing limits from production searches over the whole mass range considered, while the $|U_{\mu 4}|^2$ 90% C.L. limit is comparable to the results from earlier searches.

Feebly interacting scalar or pseudoscalar $X_{\rm inv}$ particles from the decay $K^+ \to \pi^+ X_{\rm inv}$ have the same signature as $K^+ \to \pi^+ \nu\bar{\nu}$. Various scenarios of interpretation of $X_{\rm inv}$ are possible according to the portals connecting SM particles to the new mediators [14]. In the BC4 benchmark scenario of such classification the $X_{\rm inv}$ is a scalar S decaying into visible SM particles and mixing with the Higgs boson according to mixing parameter $\sin^2\theta$: figure 2 (left) shows the excluded regions at 90% C.L. in the $(m_S, \sin^2\theta)$ parameter space for run I. For $m_S < 2m_\pi$ the search proceeds with direct extension of the $K^+ \to \pi^+ \nu\bar{\nu}$ search. For $m_S > 2m_\pi$ the analysis looks for $K^+ \to \pi^+ S, S \to \mu\mu$. A dedicated analysis has been performed for $m_S \approx m_\pi$.

6 The proposed High Intensity Kaon Experiment and physics analysis prospects

Discrimination amongst BSM scenarios through the $K^+ \to \pi^+ \nu\bar{\nu}$ decay may start only when the BR is measured at the 5–10% level. In order to obtain this measurement a new experiment, the High Intensity Kaon Experiment (HIKE) is at proposal stage [15]. The new experiment will be an upgrade from the current NA62 experiment in three stages. In Phase I (after LS3–2029), K^+ decays will be produced with an intensity 4 times higher than currently: ≈ 500 $K^+ \to \pi^+ \nu\bar{\nu}$ decays are expected. The upgrade will require that new state of the art detectors will replace most of the present systems, due to the higher intensity. The timing requirements will be $O(100\,\text{ps})$ to achieve the correct $K - \pi$ matching. Also the photon veto detectors need improved timing performance from the present 1 ns to 200 ps to keep ϵ_{RV} at least to the same level as now. Transitional programs will see a K_L beam in phase II and a dedicated experiment to measure $K^0 \to \pi^0 \nu\bar{\nu}$ in Phase III. Regarding the $K^+ \to \pi^+ \nu\bar{\nu}$ (and $K^0 \to \pi^0 \nu\bar{\nu}$) BR measurement, some theories allow large deviations from the SM prediction due to the effect played by the third generation neutrinos [16]. In other BSM scenarios, the measurable BR for $K^+ \to \pi^+ \nu\bar{\nu}$ is formed of two components: the experimentally measured BR may be given by a combination of the SM BR with purely vector nature and a scalar LNV process [4, 17]. A comprehensive review of the possible phenomenological models and the status of the searches for kaon decay channels is available here [18]. This review also covers the exploration of the light dark sectors, which are not reported here as the focus is on rare kaon decays. For comparison only in figure 2 (right), we report the complementary sensitivity for a new scalar S in the BC4 model obtained from $B \to K^{(*)} S$ in beam dump mode vs the same search looking for $K^+ \to \pi^+ X_{\rm inv}$.

The NA62 experiment is both contributing to flavor physics and complements BSM searches. Evidence for the $K^+ \to \pi^+ \nu\bar{\nu}$ decay has been seen in Run I with the BR measured with $\sim 40\%$ uncertainty. A $O(15\%)$ uncertainty measurement is targeted at the end of Run II (2025). Large improvements to the upper limits down to $O(10^{-11})$ for several LN and LF violating K^+ and π^0 decays have been performed. A search for HNL production in K^+ decays to leptons has been performed, imposing upper limits on the $|U_{4l}|^2$ down to 10^{-9} covering a large mass range. A new experiment, HIKE, is at the proposal stage with exciting prospects: BSM physics could be discriminated with a $BR(K^+ \to \pi^+ \nu\bar{\nu})$ measurement more precise than 10%. LN and LF violating decays are limited by statistics: improvements are expected with Run2 and HIKE.

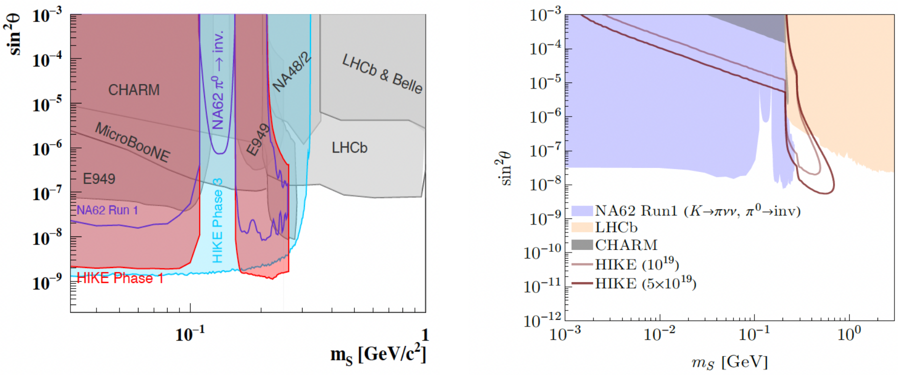

Figure 2. Left: excluded regions at 90% C.L. of the $(m_S, \sin^2(\theta))$ parameter space for a dark scalar S of the BC4 model. The purple lines are the present NA62 results. The red lines are the projected HIKE Phase 1 sensitivities. Right: 90% C.L. exclusion limits obtained in simulation for the BC4 model in HIKE beam-dump mode. Reproduced from [4]. CC BY 4.0.

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