PROCEEDINGS OF SCIENCE

Searches for lepton flavor/lepton number violation and hidden sectors in kaon decays at the NA62 experiment

Ilaria Panichi[a,b,*] **for the NA62 Collaboration**[†]

[a] *INFN Sezione Firenze, Via Bruno Rossi 1, 50019 Sesto Fiorentino (FI), Italy*

[b] *Dipartimento di Fisica e Astronomia, Università degli Studi di Firenze, Via Giovanni Sansone 1, 50019 Sesto Fiorentino (FI), Italy*

E-mail: ilaria.panichi@unifi.it

Rare kaon decays are among the most sensitive probes of both heavy and light physics beyond the Standard Model (SM) thanks to the high precision of the SM predictions, the availability of very large datasets and the relatively simple decay topologies. NA62 is the CERN multi-purpose fixed-target kaon decay experiment, carring out a broad rare decay and hidden sector physics program. Recent NA62 searches for lepton flavor and lepton number violation and for the production of hidden sector mediators in K^+ decays, along with their future prospects, are presented.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

*Speaker

†A. Akmete, R. Aliberti, F. Ambrosino, R. Ammendola, B. Angelucci, A. Antonelli, G. Anzivino, R. Arcidiacono, T. Bache, A. Baeva, D. Baigarashev, L. Bandiera, M. Barbanera, J. Bernhard, A. Biagioni, L. Bician, C. Biino, A. Bizzeti, T. Blazek, B. Bloch-Devaux, P. Boboc, V. Bonaiuto, M. Boretto, M. Bragadireanu, A. Briano Olvera, D. Britton, F. Brizioli, M.B. Brunetti, D. Bryman, F. Bucci, T. Capussela, J. Carmignani, A. Ceccucci, P. Cenci, M. Ceoletta, V. Cerny, C. Cerri, B. Checcucci, A. Conovaloff, P. Cooper, E. Cortina Gil, M. Corvino, F. Costantini, A. Cotta Ramusino, D. Coward, P. Cretaro, G. D'Agostini, J.B. Dainton, P. Dalpiaz, H. Danielsson, B. De Martino, M. D'Errico, N. De Simone, D. Di Filippo, L. Di Lella, N. Doble, B. Döbrich, F. Duval, V. Duk, D. Emelyanov, J. Engelfried, T. Enik, N. Estrada-Tristan, V. Falaleev, R. Fantechi, V. Fascianelli, L. Federici, S. Fedotov, A. Filippi, R. Fiorenza, M. Fiorini, O. Frezza, J. Fry, J. Fu, A. Fucci, L. Fulton, E. Gamberini, L. Gatignon, G. Georgiev, S. Ghinescu, A. Gianoli, R. Giordano, M. Giorgi, S. Giudici, F. Gonnella, K. Gorshanov, E. Goudzovski, C. Graham, R. Guida, E. Gushchin, F. Hahn, H. Heath, J. Henshaw, Z. Hives, E.B. Holzer, T. Husek, O. Hutanu, D. Hutchcroft, L. Iacobuzio, E. Iacopini, E. Imbergamo, B. Jenninger, J. Jerhot, R.W. Jones, K. Kampf, V. Kekelidze, C. Kenworthy, D. Kereibay, S. Kholodenko, G. Khoriauli, A. Khotyantsev, A. Kleimenova, A. Korotkova, M. Koval, V. Kozhuharov, Z. Kucerova, Y. Kudenko, J. Kunze, V. Kurochka, V. Kurshetsov, G. Lanfranchi, G. Lamanna, E. Lari, G. Latino, P. Laycock, C. Lazzeroni, G. Lehmann Miotto, M. Lenti, E. Leonardi, S. Lezki, P. Lichard, L. Litov, P. Lo Chiatto, R. Lollini, D. Lomidze, A. Lonardo, P. Lubrano, M. Lupi, N. Lurkin, D. Madigozhin, I. Mannelli, A. Mapelli, F. Marchetto, R. Marchevski, S. Martellotti, P. Massarotti, K. Massri, E. Maurice, A. Mazzolari, M. Medvedeva, A. Mefodev, E. Menichetti, E. Migliore, E. Minucci, M. Mirra, M. Misheva, N. Molokanova, M. Moulson, S. Movchan, M. Napolitano, I. Neri, F. Newson, A. Norton, M. Noy, T. Numao, V. Obraztsov, A. Okhotnikov, A. Ostankov, S. Padolski, R. Page, V. Palladino, I. Panichi, A. Parenti, C. Parkinson, E. Pedreschi, M. Pepe, M. Perrin-Terrin, L. Peruzzo, P. Petrov, Y. Petrov, F. Petrucci, R. Piandani, M. Piccini, J. Pinzino, I. Polenkevich, L. Pontisso, Yu. Potrebenikov, D. Protopopescu, M. Raggi, M. Reyes Santos, K. Rodriguez Rivera, M. Romagnoni, A. Romano, I. Rosa, P. Rubin, G. Ruggiero, V. Ryjov, A. Sadovsky, A. Salamon, J. Sanders, C. Santoni, G. Saracino, F. Sargeni, S. Schuchmann, V. Semenov, A. Sergi, A. Shaikhiev, S. Shkarovskiy, M. Soldani, D. Soldi, M. Sozzi, T. Spadaro, F. Spinella, A. Sturgess, V. Sugonyaev, J. Swallow, A. Sytov, G. Tinti, A. Tomczak, S. Trilov, M. Turisini, P. Valente, B. Velghe, S. Venditti, P. Vicini, R. Volpe, H. Wahl, R. Wanke, V. Wong, B. Wrona, O. Yushchenko, M. Zamkovsky, A. Zinchenko.

https://pos.sissa.it/

PoS(EPS-HEP2023)335

1. The NA62 experiment at CERN

NA62 is a fixed-target kaon experiment at CERN. Its main goal is to measure the branching ratio (BR) of the ultra rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay [1], providing a stringent test of the Standard Model (SM) and of several New Physics (NP) models.

The experimental layout [2] was designed and optimized for the $K^+ \to \pi^+ \nu\bar{\nu}$ study. The $400\,GeV/c$ protons beam extracted from the CERN Super Proton Synchrotron impinges on a beryllium target producing a secondary beam of unseparated $\pi^+(70\%)$, $p(24\%)$ and $K^+(6\%)$, selected with $75\,GeV/c$ momentum ($\Delta p/p \sim 1.1\%$). The kaon component is identified by a differential Cherenkov counter (KTAG). The particles of the secondary beam are measured by a Si-pixel beam spectrometer (GTK), then travel in the vacuum of the fiducial decay volume (FV) of the experiment. K^+ decays occurring in the FV are reconstructed by measuring the momentum of the charged particles produced in the decay with a four-chamber spectrometer of STRAW tubes, and by identifying particles with a Ring Imaging Cherenkov (RICH) detector [3], a liquid kripton (LKr) electromagnetic calorimeter and a muon veto system. Large (LAV) and small angle (IRC, SAC) photon detectors system are included to veto photons that are outside the LKr acceptance.

NA62 took data during 2016, 2017 and 2018 (Run1) and collected around 6.2×10^{12} K^+ decays, allowing for a broad kaon physics program, which includes searches for lepton flavor (LF) and lepton number (LN) violation and for direct production of hidden sector mediators in K^+ decays.

2. LF and LN violation searches at NA62

Lepton number (L) and lepton flavor (L_e, L_μ, L_τ) are accidentally conserved quantities within the SM and the observation of processes violating these conservation laws constitutes a clear indication of physics beyond the Standard Model (BSM). LN violation has never been observed, while neutrino oscillations constitutes the first evidence of LF violation. LF and LN violating processes involving charged leptons are expected to occur in perturbation theory, via virtual effects, and kaon decays are perfect probes to investigate the NP responsible for them at mass scales up to $O(100\ TeV/c^2)$. For example, in LN violating decays, such as $K^+ \to \pi^- e^+ e^+$ ($\Delta L = -2$), Majorana neutrinos may be exchanged, as in the neutrino-less double β decay [4]. LF violating processes like $K^+ \to \pi^+ \mu^- e^+$ ($\Delta L_e = -1 = \Delta L_\mu$) may occur via the exchange of a Z' boson [5] or in SM extensions with light pseudoscalar bosons [6].

Thanks to dedicated di-lepton and multi-track trigger lines [7], running concurrently with the main $K^+ \to \pi^+ \nu\bar{\nu}$ trigger line, NA62 has the world's leading sensitivity to most LF/LN violating K^+ decays and has already set stringent BR upper limits (UL) for a variety of processes, all listed in Tab.1. Based on results from Run 1 only, NA62 has improved on previous limits by at least a factor two up to a factor greater than $O(10^2)$, depending on the process, and provided the first limit for the $BR(K^+ \to \pi^- \pi^0 \mu^+ e^+)$. The NA62 LF/LN violating searches on Run1 data are still ongoing, with the promising prospect of setting the very first limit for the LFV $K^+ \to \pi^- \pi^0 \mu^+ e^+$ and the LFV/LNV $K^+ \to e^- \nu \mu^+ \mu^+$ decays.

PoS(EPS-HEP2023)335

	Previous UL (90%C.L.)		NA62 UL (90%C.L.)	
$BR(K^+ \to \pi^- \mu^+ \mu^+)$	$< 8.6 \times 10^{-11}$	[8]	$< 4.2 \times 10^{-11}$	[9]
$BR(K^+ \to \pi^- e^+ e^+)$	$< 6.4 \times 10^{-10}$	[10]	$< 5.3 \times 10^{-11}$	[11]
$BR(K^+ \to \pi^- \pi^0 e^+ e^+)$	none		$< 8.5 \times 10^{-10}$	[11]
$BR(K^+ \to \pi^- \pi^0 \mu^+ e^+)$	none		analysis started	
$BR(K^+ \to \pi^- \mu^+ e^+)$	$< 5.0 \times 10^{-10}$	[10]	$< 4.2 \times 10^{-11}$	[12]
$BR(K^+ \to \pi^+ \mu^- e^+)$	$< 5.2 \times 10^{-10}$	[10]	$< 6.6 \times 10^{-11}$	[12]
$BR(\pi^0 \to \mu^- e^+)$	$< 3.4 \times 10^{-9}$	[10]	$< 3.2 \times 10^{-10}$	[12]
$BR(K^+ \to \pi^+ \pi^0 \mu^- e^+)$	none		analysis started	
$BR(K^+ \to \mu^- \nu e^+ e^+)$	$< 2.1 \times 10^{-8}$	[13][14]	$< 8.1 \times 10^{-11}$	[15]
$BR(K^+ \to e^- \nu \mu^+ \mu^+)$	none		analysis ongoing	

Table 1: Summary of the NA62 Run1 program on LF and LN violation searches. The first five decays are LN violating, the central three are LF violating and the last two are LF or LN violating, depending on the neutrino flavor. The result in [9] is obtained by the analysis of ~30% of Run1 sample.

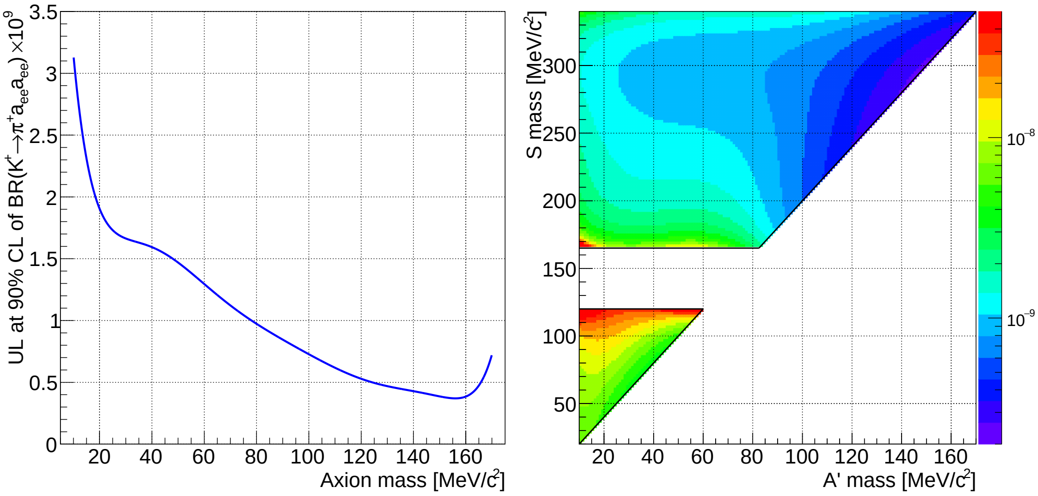
.

3. Hidden sector searches in the K^+ into $\pi^+ e^+ e^- e^+ e^-$ final state at NA62

Kaon decays to multiple dark states can probe unexplored regions of the parameter space for different dark sector models [16]. Analysing the data collected in Run1, NA62 performed the first search for K^+ decays to multiple dark states through the $\pi^+ e^+ e^- e^+ e^-$ final state, that can be produced, for example, by the $K^+ \to \pi^+ aa$ with prompt $a \to e^+ e^-$ decay, where a is a short lived QCD axion with mass in the MeV scale, or by the prompt dark cascade $K^+ \to \pi^+ S$, $S \to A' A'$, $A' \to e^+ e^-$, involving a dark scalar (S) promptly decaying into dark photons (A'). The QCD axion is also accounted for as possible explanation for the 17 MeV/c^2 anomaly observed in the mass spectra of the $e^+ e^-$ pairs produced in the nuclear de-excitation of ^{8}Be. As the lower limit $BR(K^+ \to \pi^+ aa) > 2 \times 10^{-8}$ [17] can be predicted for $m_a = 17\, MeV/c^2$, a conclusive test of the QCD axion explanation for the anomaly can be performed. Moreover, within the SM, the non-resonant $K^+ \to \pi^+ e^+ e^- e^+ e^-$ decay is strongly suppressed, with a prediction of $BR_{SM}(non\, res.\, K^+ \to \pi^+ e^+ e^- e^+ e^-) = (7.2 \pm 0.7) \times 10^{-6}$ at leading order in QED and Chiral Perturbation Theory [18]. A measurement of this BR, which has not yet been made, could hint at BSM physics through deviations with respect to its prediction.

The NA62 strategy to search for the K^+ into $\pi^+ e^+ e^- e^+ e^-$ final state relies on a fully kinematic analysis. Momentum, direction of flight, track time and electric charge are the only information used to define the kinematic selection and to identify the final state particles, and they are all measured by the STRAW spectrometer. This approach is necessary in order to have the highest possible acceptance for the multiple soft tracks of the final state. The invariant mass $m_{\pi 4e} = \sqrt{P_{\pi^+} + P_{e_1^+} + P_{e_1^-} + P_{e_2^+} + P_{e_2^-}}$, is defined as discriminating variable. P_i is the four-momentum of the final state particle calculated by using the measured momentum of the selected track and the mass assignment in the subscript. The momentum excess $\Delta p = p_{vtx} - p_{beam}$ between the total momentum of the five reconstructed tracks coming from the K^+ decay vertex (p_{vtx}) and the central beam momentum (e.i. the K^+ momentum) p_{beam}, is also used to distinguish between signal and background. p_{beam} is measured with fully reconstructed $K^+ \to \pi^+\pi^+\pi^-$ decays and monitored during the run. The conditions $|\Delta p| < 2\, GeV/c$, ensuring the compatibility of the total reconstructed momentum with the beam, and $484\, MeV/c^2 < m_{\pi 4e} < 504\, MeV/c^2$ define a two dimensional signal region, which is kept closed until the final background validation in the control region $\Delta p < -2\, GeV/c$. The expected background in the signal region is estimated by MC simulations. Backgrounds due to particle mis-identification and/or lost tracks coming from five-track and seven-track SM K^+ decays, and from the time coincidence of two three-track SM K^+ decays, are taken into account. The major background comes from the $K^+ \to \pi^+\pi^0$ with $\pi^0 \to e^+e^-e^+e^-$ double Dalitz decay ($K_{2\pi DD}$), which is otherwise used for the normalization: branching ratios are measured relative to a SM decay with known BR and similar topology to the final state. This normalization procedure allows to estimate the effective number of K^+ decays in the FV (N_K) and a first order cancellation of systematic uncertainties. Including the whole Run1, $N_K = (8.58 \pm 0.19_{stat} \pm 0.007_{MC} \pm 0.41_{ext}) \times 10^{11}$, with uncertainties coming from the size of the NA62 data sample, from the $K_{2\pi DD}$ acceptance (estimated with MC) and from the knowledge of the $K_{2\pi DD}$ decay BR (external error). The analysis is fully described in [19].

After the unblinding no data events are observed in the signal region. The upper limit $BR(non\, res.\, K^+ \to \pi^+e^+e^-e^+e^-) < 1.4 \times 10^{-8}$ is established at 90% C.L., a factor $O(200)$ greater than the SM expectation in [18]. Fig.1a and Fig.1b shows BR UL for $K^+ \to \pi^+aa$, $a \to e^+e^-$ and $K^+ \to \pi^+S$, $S \to A'A'$, $A' \to e^+e^-$ as a function of the QCD axion and dark particles mass, respectively. In particular, assuming $a \to e^+e^-$ as the main decay mode, $BR(K^+ \to \pi^+aa,$ $a \to e^+e^-) < 2.1 \times 10^{-9}$ at $m_a = 17\, MeV/c^2$ excludes the QCD axion as possible explanation of the 17 MeV/c^2 anomaly, given the 10 times higher predicted lower limit in [17].



(a) (b)

Figure 1: NA62 upper limits at 90% C.L. of $BR(K^+ \to \pi^+aa,\ a \to e^+e^-)$ (left) and $BR(K^+ \to \pi^+S,\ S \to A'A',\ A' \to e^+e^-)$ (right). Results comes from the analysis of Run1 statistics. The whole kinematicaly allowed range $2m_e \le m_a \le (m_K - m_\pi)/2$ ($2m_e \le m_{A'} \le m_S/2 \le (m_K - m_\pi)/2$) is considered for the axion a (dark scalar S and dark photon A'); $120 \le m_S \le 165\, MeV/c^2$ is excluded from the search as dominated by the background process $K^+ \to \pi^+\pi^0$ with $\pi^0 \to e^+e^-e^+e^-$ double Dalitz decay. See [19] for details.

PoS(EPS-HEP2023)335

4. Future and prospects

In 2021, after the second long shutdown of the CERN accelarator complex (LS2), NA62 resumed the data taking, aiming to improve the precision of the $BR(K^+ \to \pi^+ \nu\bar{\nu})$ measurement to $O(15\%)$. NA62 Run2 is expected to last until LS3 and is ongoing with about a factor two increased beam intensity with respect to Run1. As all the searches presented are statistics dominated, the current experimental sensitivities (e.g. $O(10^{-11})$ for LF/LN violating decays) are expected to improve at least by a factor two by combining the Run1 and Run2 data.

The HIKE (High Intensity Kaon Experiments) proposal [20] is under discussion at CERN for a long term kaon physics program after LS3. HIKE will run with a beam intensity 4 to 6 times higher than NA62 and will pursue a multi-phase physics program with charged K^+ and neutral K_L beams planned in different phases. HIKE are ultimately to measure the $BR(K^+ \to \pi^+ \nu\bar{\nu})$ with $O(5\%)$ precision (Phase 1) and the $BR(K_L \to \pi^0 l^+ l^-)$ with $O(20\%)$ precision (Phase 2). Beyond the studies of these golden channels, HIKE will continue the campaign, started by NA62, to make precision studies of rare and forbidden kaon decays and hidden sector searches in kaon decays, with an enriched program and higher expected sensitivities (e.g. LF/LN violation searches with sensitivities of $O(10^{-12})$).

5. Conclusions

NA62 is the CERN multi-purpose fixed-target kaon decay experiment, carring out a broad rare decay and hidden sector physics program. Through the analysis of the data collected during Run1, NA62 set stringent branching ratio upper limits for a variety of LF and LN violating K^+ decays, improving on the existing limits or establishing a limit for the first time, depending on the channel, and recently performed the first search for K^+ decays into the final state $\pi^+ e^+ e^- e^+ e^-$. The first experimental limit for the branching ratio of the SM non-resonant contribution to the $K^+ \to \pi^+ e^+ e^- e^+ e^-$ was established, together with upper limits of $O(10^{-9})$ in the kinematically allowed mass range for the pair-production of short-lived QCD axions in the $K^+ \to \pi^+ aa$, $a \to e^+ e^-$ decay and for the prompt decay chain $K^+ \to \pi^+ S$, $S \to A'A'$, $A' \to e^+ e^-$ with S (A') dark scalar (dark photon). The observed limit $BR(K^+ \to \pi^+ aa,\ a \to e^+ e^-)^2 < 2.1 \times 10^{-9}$ at $m_a = 17\ MeV/c^2$ excludes the QCD axion as possible explanation of the 17 MeV/c^2 anomaly observed in the nuclear de-excitation of ^{8}Be. Other recent results from NA62 Run1 analysis are published in [21],[22],[23].

NA62 Run2 is ongoing at higher intensities, providing additional data for the searches, and the HIKE proposal is under discussion for the future.

References

[1] NA62 Collaboration, *Measurement of the very rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay.* *JHEP* **06**(2021)093

[2] NA62 Collaboration, *The beam and detector of the NA62 experiment at CERN.* *JINST* **12**(2017)P05025

[3] G. Anzivino *et al*, *Light Detection System and Time Resolution of the NA62 RICH.* *JINST* **15**(2020)P10025

[4] A. Atre *et al*, *The search for heavy Majorana neutrinos.* *JHEP* **05**(2009)030

[5] P. Langacker, *The physics of heavy Z' gauge bosons.* *Rev. Mod. Phys.* **81**, 1199

[6] C. Cornella, P. Paradisi, O. Sumensari, *Hunting for ALPs with Lepton Flavor Violation.* *JHEP* **01**(2020)158

[7] NA62 Collaboration, *Performnance of the NA62 triger system.* *JHEP* **03**(2023)122

[8] NA48/2 Collaboration, *Searches for lepton number violation and resonances in $K^{\pm} \to \pi\mu\mu$ decays.* *Phys. Lett. B* **769** (2017) 67

[9] NA62 Collaboration, *Searches for lepton number violating K^+ decays.* *Phys. Lett. B* **797** (2019) 134794

[10] R. Appel *et al*, *Search for Lepton Flavor Violation in K^+ Decays into a Charged Pion and Two Leptons.* *Phys. Rev. Lett.* **85** 2877 (2000)

[11] NA62 Collaboration, *Searches for lepton number violating $K^+ \to \pi^-(\pi^0)e^+e^+$ decays.* *Phys. Lett. B* **830** (2022) 137172

[12] NA62 Collaboration, *Search for lepton number and flavor violation in K^+ and π^0 decays.* *Phys. Rev. Lett.* **127**, 131802 (2021)

[13] A.M. Diamant-Berger *et al*, *Study of some rare decays of the K^+ meson.* *Phys. Lett. B* **62** (1976) 485

[14] R.L. Workman *et al*, *Review of Particle Physics* *PTEP* **2022** (2022), 083C01

[15] NA62 Collaboration, *A search for the $K^+ \to \mu^-\nu e^+e^+$ decay.* *Phys. Lett. B* **838** (2022) 137679

[16] M. Hostert, M. Pospelov, *Novel multilepton signatures of dark sectors in light meson decays.* *Phys. Rev. D* **105** (2022) 015017

[17] D. M. S. Alves, *Signals of the QCD axion with mass of* 17 MeV$/c^2$*: Nuclear transitions and light meson decays.* *Phys. Rev. D* **103** (2021) 055018

[18] T. Husek, *Standard Model estimate of $K^+ \to \pi^+ 4e$ branching ratio.* *Phys. Rev. D* **106** (2022) L071301

[19] NA62 Collaboration, *Search for the K^+ decays into the $\pi^+e^+e^-e^+e^-$ final state.* *Phys. Lett. B* **846** (2023) 138193

[20] HIKE Collaboration, *High Intensity Kaon Experiments (HIKE) at the CERN SPS: Proposal for Phases 1 and 2.* CERN-SPSC-2023-031

[21] NA62 Collaboration, *A measurement of the $K^+ \to \pi^+\mu^+\mu^-$ decay.* *JHEP* **11**(2022)011

[22] NA62 Collaboration, *Search for dark photon decays to $\mu^+\mu^-$ at NA62.* *JHEP* **09**(2023)035

[23] NA62 Collaboration, *A study of the $K^+ \to \pi^0 e^+\nu\gamma$ decay.* *JHEP* **09**(2023)040