PROCEEDINGS OF SCIENCE

Search for physics beyond the Standard Model at NA62

Renato Fiorenza[a,*] **for the NA62 collaboration**[†]

[a] *Scuola Superiore Meridionale, Università degli Studi di Napoli Federico II & INFN Sezione di Napoli Napoli, Italy*

E-mail: renato.fiorenza@cern.ch

The $K^+ \rightarrow \pi^+\nu\bar{\nu}$ decay is a golden mode for search of New Physics in the flavour sector. The Standard Model prediction of its branching ratio is less than 10^{-10}. The NA62 experiment at the CERN SPS is designed to study the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ decay, and provides the world's most precise investigation of this decay. NA62 is a multi-purpose high-intensity kaon decay experiment, and also carries out a broad rare-decay and hidden-sector physics programme with dedicated trigger lines.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

*Speaker

†A. Akmete, R. Aliberti, F. Ambrosino, R. Ammendola, B. Angelucci, A. Antonelli, G. Anzivino, R. Arcidiacono, M. U. Ashraf, T. Bache, A. Baeva, D. Baigarashev, L. Bandiera, M. Barbanera, V. Bautin, 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, N. Canale, T. Capussela, J. Carmignani, A. Ceccucci, P. Cenci, M. Ceoletta, V. Cerny, C. Cerri, X. Chang, 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, M. Francesconi, 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, M. Kolesar, 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, M. Medvedeva, A. Mefodev, E. Menichetti, E. Migliore, E. Minucci, M. Mirra, M. Misheva, N. Molokanova, M. Moulson, S. Movchan, Y. Mukhamejanov, A. Mukhamejanova, M. Napolitano, R. Negrello, 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, N. Saduyev, S. Sakhiyev, K. Salamatin, A. Salamon, J. Sanders, C. Santoni, G. Saracino, F. Sargeni, J. Schubert, 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, T. Velas, B. Velghe, S. Venditti, P. Vicini, R. Volpe, M. Vormstein, H. Wahl, R. Wanke, V. Wong, B. Wrona, O. Yushchenko, M. Zamkovsky, A. Zinchenko.

PoS(ICHEP2024)445

1. Introduction

NA62 is a fixed target experiment at the CERN SPS. Its main goal is to measure the branching ratio (BR) of the $K^+ \to \pi^+\nu\bar{\nu}$ decay. The NA62 apparatus is described in detail in [1]: its excellent performance [2] allows for a very broad physics programme, including precision measurements [3–6], searches for lepton number violating (LNV) and lepton flavour violating (LFV) decays [7–10], and a special beam-dump configuration to perform direct searches for new physics [11, 12]. NA62 collected data between 2016 and 2018 (Run1); it is currently in its second run of data taking (Run2), started in 2021 and expected to last until the CERN Long Shutdown 3.

We report the main NA62 results and the latest LFV / LNV decay search. Other recent results have been presented in dedicated contributions to this conference [13, 14].

2. Measurement of BR($K^+ \to \pi^+\nu\bar{\nu}$)

The $K^+ \to \pi^+\nu\bar{\nu}$ decay is driven by a flavour-changing neutral current. It is suppressed by the GIM mechanism, and it is dominated by short-distance contributions, which makes the Standard Model (SM) prediction of its BR, of the order of 8×10^{-11}, very precise, with an uncertainty of 5 to 10 % which is dominated by the knowledge of the CKM matrix parameters [15–18]. Many new physics models predict a deviation from this value [19].

Measuring this BR is very challenging, as the experimental signature of the signal is very weak due to the impossibility of detecting the neutrinos: the signal must be discriminated from the main kaon decays such as $K^+ \to \mu^+\nu$, $K^+ \to \pi^+\pi^0$, $K^+ \to \pi^+\pi^+\pi^-$.

The key kinematic variable for such discrimination is $m^2_{\text{miss}} = (P_K - P_\pi)^2$: using appropriate signal regions allows for a kinematic rejection of backgrounds of $O(10^4)$. The excellent performance of the particle identification system (muon rejection of $O(10^8)$) and of the photon veto system (π^0 rejection of $O(10^8)$) complements the kinematic discrimination.

The analysis is optimized in categories, depending on π^+ momentum and hardware configuration. The main background is the *upstream background*, which consists of an accidental matching between the K^+ and π^+ tracks. This is mainly due to decays of kaons, or beam interactions with the detector material, happening upstream of the fiducial volume. The estimation of the backgrounds is largely data-driven.

The analysis of Run1 data led to a single event sensitivity of $(0.839 \pm 0.053_{\text{syst}}) \times 10^{-11}$, corresponding to $10.01 \pm 0.42_{\text{syst}} \pm 1.19_{\text{ext}}$ SM events expected, and an observation of 20 events including $7.03^{+1.05}_{-0.82}$ estimated background events. This corresponded to a significance of the observation of 3.4σ and a measurement of

$$\text{BR}(K^+ \to \pi^+\nu\bar{\nu}) = \left(10.6^{+4.0}_{-3.8}\Big|_{\text{stat}} \pm 0.9_{\text{syst}}\right) \times 10^{-11},$$

which is the most precise so far[20].

3. 2021-2022 data analysis

Between 2018 and 2021, NA62 underwent a series of hardware upgrades, aimed at tackling the largest backgrounds, summarized in figure 2. A new detector (VetoCounter) was designed to detect

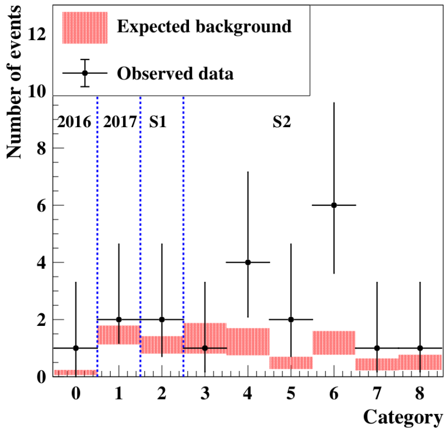

Figure 1: Results of Run1 data analysis. S1 and S2 correspond to subsets of 2018 data with different hardware. [20]

secondary products of kaon decays which would otherwise be absorbed in the final collimator before the entrance to the fiducial volume. Another detector (ANTI-0) was installed at the very entrance of the fiducial volume, to help reject background from halo particles. The beam line around the beam spectrometer was rearranged in order to sweep away upstream π^+ more efficiently, and a new station of the beam spectrometer (GTK0) was added, in order to increase the efficiency of beam track reconstruction and to improve the resilience against beam pileup tracks. A new detector (HASC2) was installed near the beam dump, which helps in rejecting a pathological class of $\mathrm{K}^+ \to \pi^+\pi^0$ events.

During 2021 and 2022, data was taken at 100 % of the nominal intensity: this corresponds to a rate of beam particles of around 600 MHz, and is an increase with respect to Run1, where the average beam intensity was about 60 % of the nominal. This demonstrated that the NA62 apparatus and TDAQ system is able to withstand such a high rate.

An improved trigger configuration, as well as various improvements in the analysis (including a refurbished reconstruction of the electromagnetic calorimeter, a new *Bayesian* classifier to match K^+ and π^+ tracks, and some retuning of selection cuts) improved the signal yield per SPS spill from 1.7×10^{-5} (for Run1 data) to 2.5×10^{-5} (for 2022 data). New procedures for the estimation of backgrounds were implemented and fully validated. The new VetoCounter improved the capability to reject the upstream background by a factor 2 compared to Run1.

Very recently, NA62 presented results of this analysis [21]: 31 events were observed in this dataset, with a signal sensitivity of $(0.84\pm0.03_{\mathrm{syst}})\times10^{-11}$ and $11.0^{+2.1}_{-1.9}$ background events expected. Combining with Run1 results, this led to the measurement

$$\mathrm{BR}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) = \left(13.0^{+3.0}_{-2.7}\Big|_{\mathrm{stat}}\ {}^{+1.3}_{-1.2}\Big|_{\mathrm{syst}}\right) \times 10^{-11},$$

and a significance for the observation of more than 5σ.

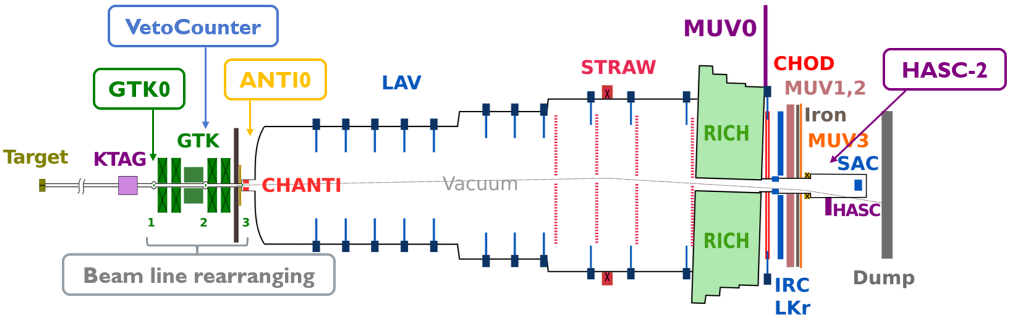

Figure 2: Summary of NA62 hardware improvements between 2018 and 2021.

4. First search for $K^+ \to \pi^0 \pi \mu e$ decays

The first search for the LNV decay $K^+ \to \pi^0\pi^-\mu^+e^+$ and the LFV decays $K^+ \to \pi^0\pi^+\mu^\pm e^\mp$ has been performed using Run1 data.

The effective number of kaon decays was computed to be $(1.97 \pm 0.02_{\text{stat}} \pm 0.02_{\text{syst}} \pm 0.06_{\text{ext}}) \times 10^{12}$, based on an effective number of 21401 $K^+ \to \pi^+e^+e^-$ events. The backgrounds, due primarily to misidentification and pileup of more than one kaon decay, are estimated with simulations. Figure 3 shows the reconstructed invariant mass of the final state of each of the three probed channels. No events were observed in the data for any of the three signal modes, leading to the 90 % CL upper limits [22]:

$$\text{BR}(K^+ \to \pi^0\pi^-\mu^+e^+) < 2.9 \times 10^{-10}\,,$$
$$\text{BR}(K^+ \to \pi^0\pi^+\mu^-e^+) < 3.1 \times 10^{-10}\,,$$
$$\text{BR}(K^+ \to \pi^0\pi^+\mu^+e^-) < 5.0 \times 10^{-10}\,.$$

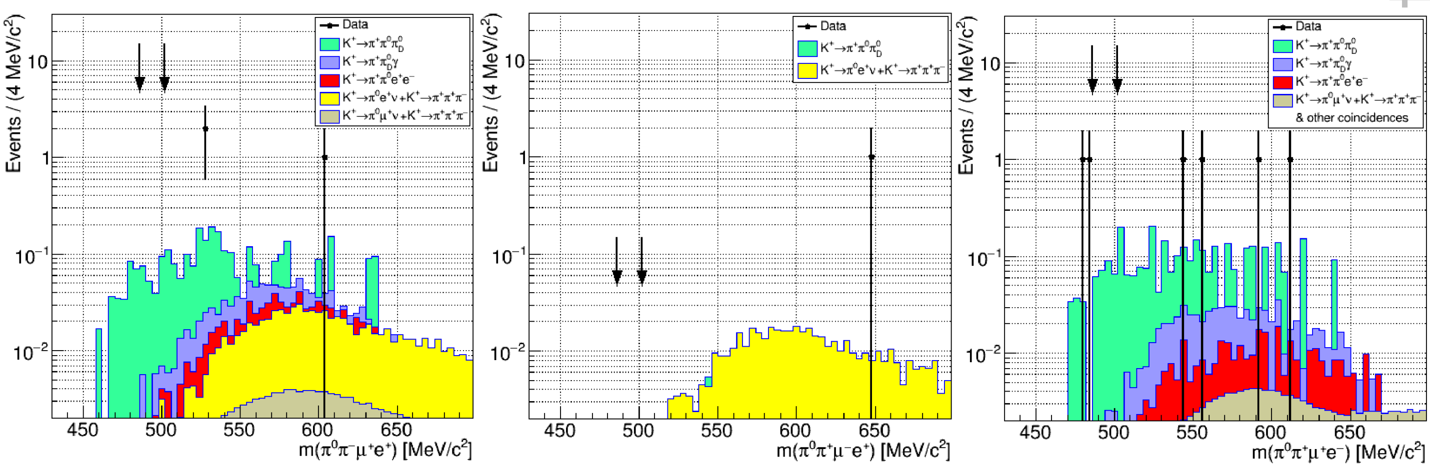

Figure 3: Reconstructed final state invariant mass distributions for $K^+ \to \pi^0\pi^-\mu^+e^+$ (left), $K^+ \to \pi^0\pi^+\mu^-e^+$ (middle), $K^+ \to \pi^0\pi^+\mu^+e^-$ (right). Arrows show the signal regions.

5. Conclusion

NA62 has collected the world's largest sample of K^+ decays, with which recently it observed the $K^+ \to \pi^+ \nu\bar{\nu}$ decay and showed the capability to measure $BR(K^+ \to \pi^+ \nu\bar{\nu})$ at 25 % precision. NA62 also has a broad physics programme, and it has covered 10 LNV / LFV decay searches to date.

References

[1] NA62 collaboration, *The beam and detector of the NA62 experiment at CERN*, *JINST* **12** (2017) P05025, arXiv:1703.08501 [physics.ins-det].

[2] NA62 collaboration, *Performance of the NA62 trigger system*, *JHEP* **03** (2023) 122, arXiv:2208.00897 [hep-ex].

[3] NA62 collaboration, *A measurement of the $K^+ \to \pi^+\mu^+\mu^-$ decay*, *JHEP* **11** (2022) 011, arXiv:2209.05076 [hep-ex].

[4] NA62 collaboration, *A study of the $K^+ \to \pi^0 e^+ \nu\gamma$ decay*, *JHEP* **09** (2023) 040, arXiv:2304.12271 [hep-ex].

[5] NA62 collaboration, *Search for K^+ decays into the $\pi^+e^+e^-e^+e^-$ final state*, *Phys. Lett. B* **846** (2023) 138193, arXiv:2307.04579 [hep-ex].

[6] NA62 collaboration, *Measurement of the $K^+ \to \pi^+\gamma\gamma$ decay*, *Phys. Lett. B* **850** (2024) 138513, arXiv:2311.01837 [hep-ex].

[7] NA62 collaboration, *Searches for lepton number violating K^+ decays*, *Phys. Lett. B* **797** (2019) 134794, arXiv:1905.07770 [hep-ex].

[8] NA62 collaboration, *Search for lepton number and flavor violation in K^+ and π^0 decays*, *Phys. Rev. Lett.* **127** (2021) 131802, arXiv:2105.06759 [hep-ex].

[9] NA62 collaboration, *Searches for lepton number violating $K^+ \to \pi^-(\pi^0)e^+e^+$ decays*, *Phys. Lett. B* **830** (2022) 132172, arXiv:2202.00331 [hep-ex].

[10] NA62 collaboration, *A search for the $K^+ \to \mu^+\nu e^+e^+$ decay*, *Phys. Lett. B* **838** (2022) 137679, arXiv:2211.04818 [hep-ex].

[11] NA62 collaboration, *Search for Leptonic Decays of Dark Photons at NA62*, *Phys. Rev. Lett.* **133** (2024) 111802, arXiv:2312.12055 [hep-ex].

[12] NA62 collaboration, *Search for dark photon decays to $\mu^+\mu^-$ at NA62*, *JHEP* **09** (2023) 035, arXiv:2303.08666 [hep-ex].

[13] A. Akmete (NA62 collaboration), *New results from analyses of rare kaon and pion decays at the NA62 experiment*, these proceedings. URL: https://indico.cern.ch/event/1291157/contributions/5878427/.

[14] S. Lezki (NA62 collaboration), *First NA62 search for long-lived new physics particle hadronic decays*, these proceedings. URL: https://indico.cern.ch/event/1291157/contributions/5887850/.

[15] A.J. Buras, D. Buttazzo, J. Girrbach-Noe and R. Knegjens, *$K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ in the Standard Model: status and perspectives*, *JHEP* **11** (2015) 033, arXiv:1503.02693 [hep-ph].

[16] J. Brod, M. Gorbahn and E. Stamou, *Updated Standard Model Prediction for $K \to \pi\nu\bar{\nu}$ and ϵ_K*, *PoS* **BEAUTY2020** (2021) 056, arXiv:2105.02868 [hep-ph].

[17] G. D'Ambrosio, A.M. Iyer, F. Mahmoudi and S. Neshatpour, *Anatomy of kaon decays and prospects for lepton flavour universality violation*, *JHEP* **09** (2022) 148, arXiv:2206.14748 [hep-ph].

[18] A.J. Buras and E. Venturini, *Searching for New Physics in Rare K and B Decays without $|V_{cb}|$ and $|V_{ub}|$ Uncertainties*, *Acta Phys. Polon. B* **53.6** (2022) A1, arXiv:2109.11032 [hep-ph].

[19] A.J. Buras, D. Buttazzo and R. Knegjens, *$K \to \pi\nu\bar{\nu}$ and ε'/ε in simplified new physics models*, *JHEP* **11** (2015) 166, arXiv:1507.08672 [hep-ph].

[20] NA62 collaboration, *Measurement of the very rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay*, *JHEP* **06** (2021) 093, arXiv:2103.15389 [hep-ex].

[21] J. Swallow, *A new measurement of* BR$(K^+ \to \pi^+ \nu\bar{\nu})$ *by the NA62 experiment*, CERN EP Seminar, 24 Sept. 2024. URL: https://indico.cern.ch/event/1447422/.

[22] NA62 collaboration, *First search for $K^+ \to \pi^0 \pi \mu e$ decays*, arXiv:2409.12981 [hep-ex].