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PHYSICS BEYOND THE STANDARD MODEL WITH THE NA62 EXPERIMENT AT CERN[*]

Mattia Soldani

on behalf of the NA62 Collaboration[†]

INFN Laboratori Nazionali di Frascati, Frascati, Italy

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The NA62 experiment at CERN is a high-intensity kaon decay experiment with a very broad physics program. Between 2016 and 2018, it collected the world's largest dataset of K^+ decays, which led to the first measurement of the branching ratio of the rare $K^+ \to \pi^+ \nu \bar{\nu}$ (PNN) decay, observed with a significance of 3.4σ. At the same time, several other new-physics (NP) studies are carried out. For example, the experiment is very active in the search for lepton-flavour/number-violating kaon decays, the most recent result concerning the $K^+ \to \mu^- \nu e^+ e^+$ channel. Moreover, limits were recently set on the existence of evidence of a dark (pseudo-) scalar in the PNN dataset and hidden-sector mediators are sought in the $K^+ \to \pi^+ e^+ e^+ e^- e^-$ channel. In 2021, the experiment was run in beam-dump mode for the first time. This allows for new searches for exotic particles — for instance, a massive dark photon which decays into a $\mu^+ \mu^-$ pair is sought.

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1. Introduction

Over the last 70 years, measurements of kaon decays have played a central role in testing the Standard Model (SM) and searching for New Physics (NP). Indeed, the kaon sector proves a powerful probe at the intensity frontier, given the small number of decay modes, the rather simple final states, and the accessibility of intense kaon beams [1].

The NA62 experiment is currently carrying on the successful series of kaon decay experiments at the CERN North Area [2]. It makes use of a 400 GeV/c primary proton beam extracted from the Super Proton Synchrotron. The primary beam impinges on a beryllium target, thus producing a secondary, unseparated positive hadron beam, with a total rate

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[†] The list of the NA62 Collaboration members can be found at the end of the article.

of 750 MHz consisting of approximately 70% charged pions, 23% protons, and 6% charged kaons. The 75 GeV ± 1% momentum component of the secondary beam is used by the experiment.

The NA62 apparatus consists of an instrumented decay volume with a strong focus on an excellent time resolution for the precise matching of the incident kaon with the decay output tracks, a powerful and redundant charged-particle identification (PID) system, and a hermetic coverage of the decay volume, in order to fully reconstruct the signal kinematics and to efficiently veto the background events — especially those involving final-state photons from π^0 decays. The experimental setup is described in extensive detail in [1].

2. $K^+ \to \pi^+\nu\overline{\nu}$ and $K^+ \to \pi^+X$

The $K^+ \to \pi^+\nu\overline{\nu}$ (PNN) decay (as well as its neutral counterpart, $K_\mathrm{L} \to \pi^0\nu\overline{\nu}$) is a flavour-changing neutral current process that proceeds via Z-penguin and double-W-box diagrams [3]. Rather clean theoretical predictions can be done in the framework of the SM: a branching ratio of $\mathrm{BR}^\mathrm{SM}_\mathrm{PNN} = (7.86 \pm 0.61) \times 10^{-11}$ was calculated [4]. Other theoretical predictions are given in [5, 6]. The PNN decay may prove highly sensitive to flavour NP, including, *e.g.*, non-SM behaviour due to new sources of flavour violation, direct CP violation, lepton–flavour non-universality, and leptoquarks.

Events with an input K^+ track matching an output π^+ track inside the fiducial volume with some missing transverse momentum (due to the neutrinos) are selected. In the reconstructed $(p_\pi, m^2_\mathrm{miss})$ plane (Fig. 1, left) two boxes are identified as the signal regions, and several other validation and background evaluation regions are identified. The $K^+ \to \pi^+\pi^0$ decay is also used as a normalization channel. The analysis procedure is described in further detail in [7–9].

Analyzing the data collected in 2016 [7], 2017 [8], and 2018 [9], 20 PNN candidates have been observed in the signal region, to be compared to the expected sum of $10.01 \pm 0.42_\mathrm{syst} \pm 1.19_\mathrm{ext}$ PNN events and $7.03^{+1.05}_{-0.82}$ background events. This leads to $\mathrm{BR}^\mathrm{meas}_\mathrm{PNN} = (10.6^{+4.0}_{-3.4}|_\mathrm{stat} \pm 0.9_\mathrm{syst}) \times 10^{-11}$ at 68% C.L., which is the most precise measurement to date, and corresponds to 3.4σ evidence for the existence of the decay channel.

The event sample selected in the PNN analysis has been used to constrain the branching ratio of the $K^+ \to \pi^+X$ decay as a function of the mass of X, a dark scalar or pseudo-scalar. X can be stable, decay to other invisible particles or live long enough to decay outside the NA62 apparatus. All the events observed in the PNN signal regions are assumed to be background events — the $K^+ \to \pi^+\nu\overline{\nu}$ events themselves constituting the main background source. Upper limits are established on BR($K^+ \to \pi^+ X$) for different X mass and lifetime hypotheses. Further details can be found in [9].

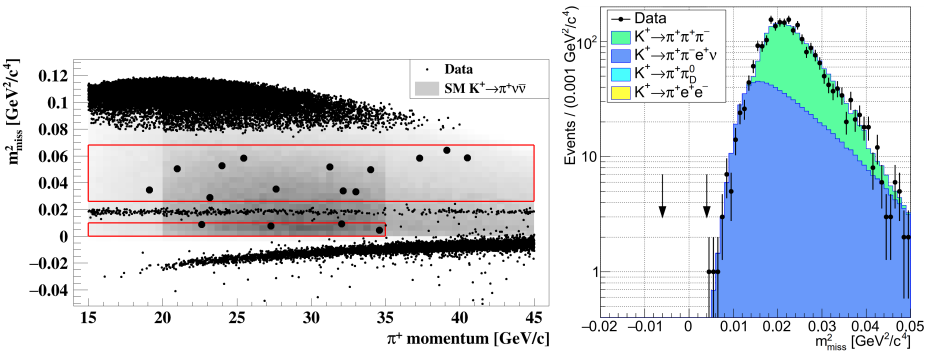

Fig. 1. (Colour on-line) Left: PNN candidate events from the 2018 dataset in the $(p_\pi, m^2_{\rm miss})$ plane. The intensity of the grey shaded area reflects the variation of the SM signal acceptance. The signal regions are highlighted in red (black boxes). From [9]. Right: Reconstructed $m^2_{\rm miss}$ spectra obtained with the $K_{\pi ee}$ selection from the $K^+ \to \mu^- \nu e^+ e^+$ data and MC. The signal region is indicated with black arrows. From [10].

3. $K^+ \to \mu^- \nu e^+ e^+$

The $K^+ \to \mu^- \nu e^+ e^+$ ($K_{\mu\nu ee}$) decay is not allowed in the SM by either lepton-flavour or lepton-number conservation, depending on the flavour of the neutrino in the final state. Its observation would demonstrate the existence of NP and, in the lepton-number-violating case, would provide evidence for the Majorana nature of the neutrino.

A search for this decay was performed on the 2016–2018 data. The event selection (see, *e.g.*, Fig. 1, right) is based on kinematic constraints and on the identification of electrons, muons, and charged pions (in the normalization channel $K^+ \to \pi^+ e^+ e^-$ and in most of the main background channels), which is done by means of the ratio between the energy deposited in the LKr and the momentum measured by the spectrometer. Extensive details of the analysis can be found in [10].

No events were observed within the signal selection cuts. The upper limit $\mathrm{BR}^{\rm meas}_{\mu\nu ee} < 8.1 \times 10^{-11}$ at 90% C.L. was estimated. This corresponds to an improvement of the result of previous searches [11] by a factor of ~ 250.

4. $K^+ \to \pi^+ e^+ e^- e^+ e^-$

The $K^+ \to \pi^+ e^+ e^- e^+ e^-$ decay exists in the SM in resonant form ($K_{2\pi\mathrm{DD}}$ — through the double-Dalitz decay of an intermediate π^0), with a branching ratio $\mathrm{BR}^{\mathrm{meas}}_{2\pi\mathrm{DD}} = (6.9 \pm 0.3) \times 10^{-6}$ [12], and in non-resonant form ($K_{\pi 4e}$), with a branching ratio $\mathrm{BR}^{\mathrm{theo}}_{\pi 4e} = (7.2 \pm 0.7) \times 10^{-11}$ [13]. This channel is also suitable for dark sector searches: it may proceed, *e.g.*, through an intermediate state involving two dark axions or a dark scalar that decays into two dark photons.

The characteristic kinematics of the final state allows for this study to rely exclusively on the analysis of the output kinematics. Omitting the information from the PID detectors and calorimeters reduces the selectivity, which is feasible because strong kinematic constraints can be used. The $K_{2\pi\mathrm{DD}}$ channel is used for normalization, whereas the signal events are sought in the non-resonant part. Extensive details of the event selection procedure are provided in [14].

No signal candidates were observed within the signal selection cuts applied to the 2017–2018 data. This corresponds to the upper limit of $\mathrm{BR}^{\mathrm{meas}}_{\pi 4e} < 1.4 \times 10^{-8}$ at 90% C.L., which is ~ 200 times larger than the SM expectation [14]. Upper limits were also estimated for decay chains initiating from axions and scalar dark-sector particles as a function of the masses of the dark mediators involved. In particular, the QCD axion model is excluded as a possible explanation of the $X17$ observations [15].

5. $A' \to \mu^+ \mu^-$ in beam-dump mode

Dark photons A' could be produced in proton interactions in a target via bremsstrahlung or secondary-meson decays. Due to their extremely feeble interaction with SM matter, they could freely propagate through tens of meters of material before decaying. Simple SM extensions which encompass dark photons [16] predict that, at a mass scale of hundreds of MeV, the decay width is dominated by di-lepton final states.

The $A' \to \mu^+ \mu^-$ decay can be searched for by the NA62 experiment operated in dump mode [17]. In summary, in this mode, the beryllium target on which the 400 GeV/c protons from the SPS impinge in order to generate the hadron beam used during normal operations is removed, the beam collimators (TAXes — 800 mm of copper and 2400 mm of iron) are fully closed, the proton beam intensity is significantly increased (170% of the normal-mode value), and the magnetic optics surrounding the TAXes is optimized for better muon halo elimination.

The search was performed using the dataset collected in a $\sim$ 10-day-long dump-mode session in 2021. Essentially, the event reconstruction proceeds by identifying two muon tracks in the final state. The event selection proceeds with cuts on the longitudinal position of the decay vertex (Z_{TAX}) and on the closest distance of approach between the dark photon line of flight and the proton nominal beam direction ($\mathrm{CDA}_{\mathrm{TAX}}$). Figure 2 shows the events observed in the ($\mathrm{Z}_{\mathrm{TAX}}, \mathrm{CDA}_{\mathrm{TAX}}$) plane. Two background sources are identified: the so-called prompt background, which consists of lepton pairs that originate from interactions of halo muons in the material upstream of or within the decay volume, and the so-called combinatorial background, *i.e.*, di-muon vertices formed by unrelated tracks that are randomly paired. The total background expected in the signal region is 0.016 ± 0.002, dominated by the combinatorial part. Further details can be found in [17].

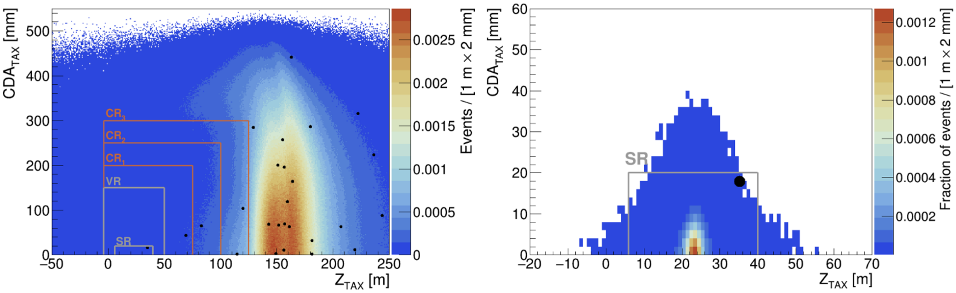

Fig. 2. (Colour on-line) Events of the 2021 beam-dump dataset in the ($\mathrm{Z}_{\mathrm{TAX}}, \mathrm{CDA}_{\mathrm{TAX}}$) plane. The colour scale plot reflects the expected distribution of $\mu^+\mu^-$ background (left) and signal (right) event density. The dots correspond to the observed events. From [17].

One event was observed in the signal region, with a mass of 411 MeV/c^2, which would correspond to a 2.4σ global significance. The probability of background observation within the signal cuts is 1.6%. Indeed, the observed event could be interpreted as an instance of combinatorial background, as it is close to the border of the selection box in the ($\mathrm{Z}_{\mathrm{TAX}}, \mathrm{CDA}_{\mathrm{TAX}}$) plane and the time difference between its two tracks is 2 standard deviations away from the mean for signal events. Overall, no evidence of a dark photon signal is established.

6. Conclusions and outlook

The NA62 experiment explores the kaon sector with unparalleled performance, especially with the PNN decay channel measurement and with the numerous searches for NP through dark mediators and lepton-flavour- and lepton-number-violating processes. Other recent results are published in [18–21]. The experiment will continue its operations until CERN Long Shutdown 3, expected in late 2025.

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The list of the NA62 Collaboration members:

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, 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. Dainton, P. Dalpiaz, H. Danielsson, M. D'Errico, N. De Simone, D. Di Filippo, L. Di Lella, N. Doble, B. Dobrich, 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, 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, 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, M. Lenti, G. Lehmann Miotto, E. Leonardi, 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, M. Romagnoni, A. Romano, P. Rubin, G. Ruggiero, V. Ryjov, A. Sadovsky, A. Salamon, 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.