IL NUOVO CIMENTO **47 C** (2024) 91
DOI 10.1393/ncc/i2024-24091-2

Colloquia: IFAE 2023

Latest results from the NA62 experiment at CERN: Precision measurements and searches in beam-dump mode(*)

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received 13 February 2024

(*) IFAE 2023 - "Intensity Frontier session"
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Summary. — The NA62 experiment at CERN is designed to study the physics of the K^+ meson. After collecting data in 2016, 2017, and 2018, the experiment has resumed data taking in 2021 and has received approval for operations until the onset of long shutdown 3. The latest result from the NA62 experiment are presented with a focus on the studies performed in the framework of the Chiral Perturbation Theory and searches for production and decay of dark photons in beam-dump mode.

1. – The NA62 experiment at CERN SPS

NA62 at CERN is a fixed target experiment designed to measure the $K^+ \to \pi^+ \nu\bar{\nu}$ branching fraction [1]. The layout of the NA62 beamline and detector is described in [2].

The versatility of the experimental setup, combined with the multiple trigger chains available [3], enables the NA62 experiment to study a variety of K^+ mesons decays, including the decays $K^+ \to \pi^+\mu^+\mu^-$ and $K^+ \to \pi^+\gamma\gamma$.

The NA62 setup is also able to search for production and decay of dark photons into charged lepton pairs: $A' \to \mu^+\mu^-$ and $A' \to e^+e^-$. For this purpose, NA62 operates in beam-dump mode. Approximately 1.4×10^{17} protons have been collected in 10 days of data taking in beam-dump mode in 2021.

Other recent NA62 results are published in [4-7].

2. – The $K^+ \to \pi^+\gamma\gamma$ decay

The $K^+ \to \pi^+\gamma\gamma$ decay is dominated by long distance contributions and allows crucial tests of Chiral Perturbation Theory (ChPT). In the ChPT framework, the $K_{\pi\gamma\gamma}$ total rate can be written in terms of an unknown constant $\hat{c}$ and several low energy parameters known from other kaon modes. The main kinematic variable used to describe the $K_{\pi\gamma\gamma}$ decay is the normalized squared di-photon invariant mass $z = m^2_{\gamma\gamma}/m^2_K$.

NA62 has performed an analysis of the $K^+ \to \pi^+\gamma\gamma$ decay using the data collected in 2017-2018. About 4×10^3 signal candidates have been selected, with less than 10% background [8]. The main background sources in the signal region are decays like $K^+ \to \pi^+\pi^0\gamma$, in which two electromagnetic clusters are merged, and $K^+ \to \pi^+\pi^+\pi^-$ with two tracks not reconstructed. The di-photon mass z spectrum, shown in fig. 1, depends on $\hat{c}$ and exhibits a characteristic cusp due to the dominance of the pion loop amplitude.

A fit to the di-photon mass spectrum using ChPT at order $\mathcal{O}(p^6)$ allows the extraction of $\hat{c}$. The fit is limited to values of $0.2 < z < 0.51$. The background is extracted from simulation and validated with data in suitable control regions orthogonal to the signal. A model independent branching ratio is also evaluated as the sum over z bins of the signal normalized to the $K^+ \to \pi^+\pi^0$ decay, in the region $0.2 < z < 0.51$.

The $\hat{c}$ parameter is measured in the ChPT $\mathcal{O}(p^6)$ description to be

$$\hat{c}_6 = 1.144 \pm 0.069_{stat} \pm 0.034_{syst}.$$

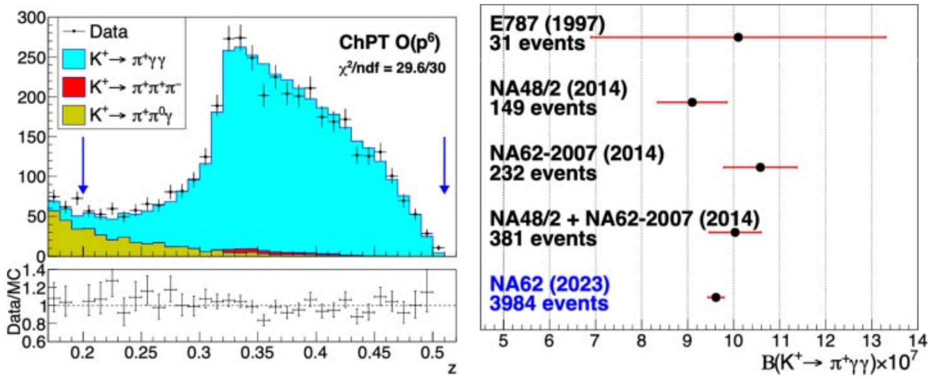

Fig. 1. – Left: reconstructed $z = m^2_{\gamma\gamma}/m^2_K$ spectrum for data compared to estimated signal and background components. The signal region is defined for $z > 0.2$. Right: Summary of the $\mathcal{B}$ measurements in the ChPT $\mathcal{O}(p^6)$ framework.

The corresponding branching ratio obtained by integration of the ChPT $\mathcal{O}(p^6)$ differential branching ratio over the full kinematic range is

$$\mathcal{B} = (9.61 \pm 0.15_{stat} \pm 0.07_{syst}) \times 10^{-7}.$$

The model-independent branching ratio in the region $0.2 < z < 0.51$ is

$$\mathcal{B}_{MI}(z > 0.2) = (9.46 \pm 0.19_{stat} \pm 0.07_{syst}) \times 10^{-7}.$$

The quantities $\hat{c}$ and $\mathcal{B}$ measured in the ChPT $\mathcal{O}(p^6)$ framework are compared to the previous measurements in fig. 1 (right panel).

3. – The $K^+ \to \pi^+\mu^+\mu^-$ decay

The $K^+ \to \pi^+\mu^+\mu^-$ process is a flavour changing neutral current decay theoretically described within the framework of ChPT. Dominant contributions to the $K_{\pi\mu\mu}$ are mediated by a virtual photon exchange $K^+ \to \pi^+\gamma^* \to \pi^+\mu^+\mu^-$ and involve long-distance effects described by a vector form factor W [9, 10].

ChPT provides a parametrization of the form factor $W(z)$ at $\mathcal{O}(p^6)$ in terms of two real parameters a_+ and b_+ and a complex function $W_{\pi\pi}(z)$, describing the contribution from a two-pion loop

$$W(z) = G_F\, m_K^2\, (a_+ + b_+\, z) + W^{\pi\pi}(z)$$

where z is the normalized di-lepton invariant mass $z = m^2(\mu^+\mu^-)/M_K^2$.

NA62 has studied the $K^+ \to \pi^+\mu^+\mu^-$ decay using data collected in 2017-2018 [13]. The $K^+ \to \pi^+\pi^+\pi^-$ decay is used as normalization channel allowing first-order cancellation of detector and trigger inefficiencies, thus reducing the systematic uncertainties in the measurement. In addition, the $K^+ \to \pi^+\pi^+\pi^-$ data sample is used to obtain the effective number of kaon decays.

The reconstructed mass spectrum of events satisfying the signal selection is shown in the left panel of fig. 2 for both data and simulation. The $m(\pi\mu\mu)$ signal region contains

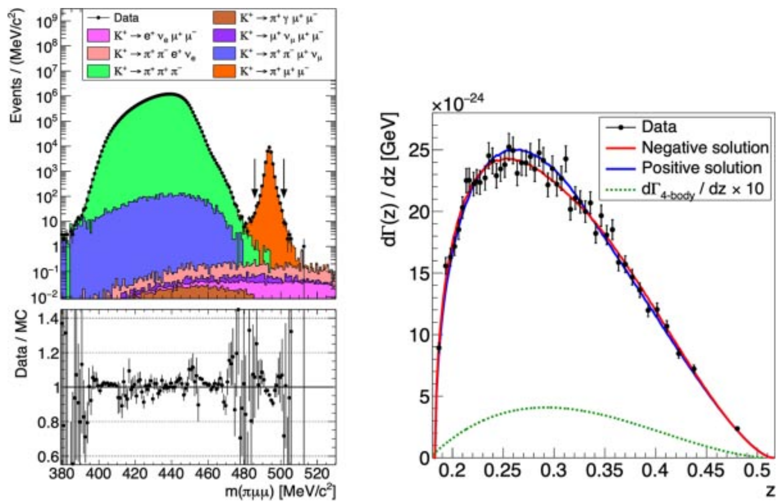

Fig. 2. – Left: reconstructed mass distribution of events satisfying the signal selection. The contribution from the simulated $K_{\pi\mu\mu}$ decay is scaled according to the PDG branching ratio [11]. The arrows indicate the selected mass region. Right: reconstructed $K_{\pi\mu\mu}$ differential decay width. The superimposed colored lines correspond to the form factor fit solutions. Figure from [13].

27679 data events with a background contamination of about 8 events, estimated from simulation.

The reconstructed differential decay width is plotted in 50 equi-populated bins in z, as shown in the right panel of fig. 2. $|W(z)|^2$ is computed in each bin, assuming a linear dependence on z within the bin. The form factor parameters a_+ and b_+ best describing the data are determined by a χ^2 fit of the data points.

The theoretically-preferred negative solution (with both parameters negative) is

$$a_+ = -0.575 \pm 0.013, \;\; b_+ = -0.722 \pm 0.043.$$

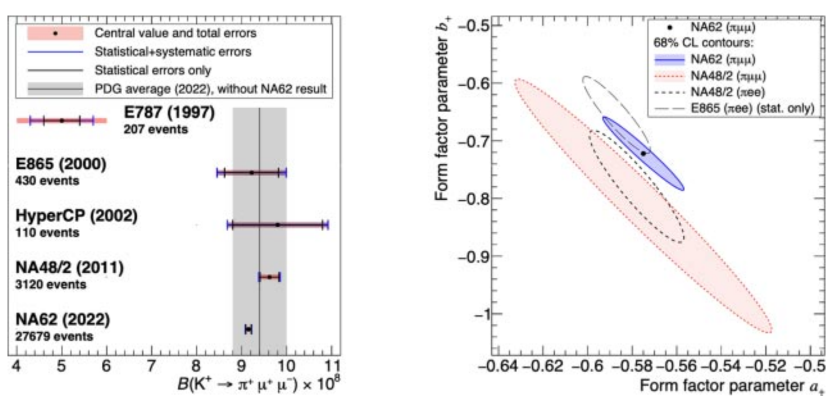

Fig. 3. – Comparison with earlier measurements. Left: the $K_{\pi\mu\mu}$ branching ratio, with the PDG [11] average as a shaded band. Right: combined statistical and systematic 68% confidence level (CL) contours in the $(a_+,\, b_+)$ plane for the muon and electron modes. Figure from [13].

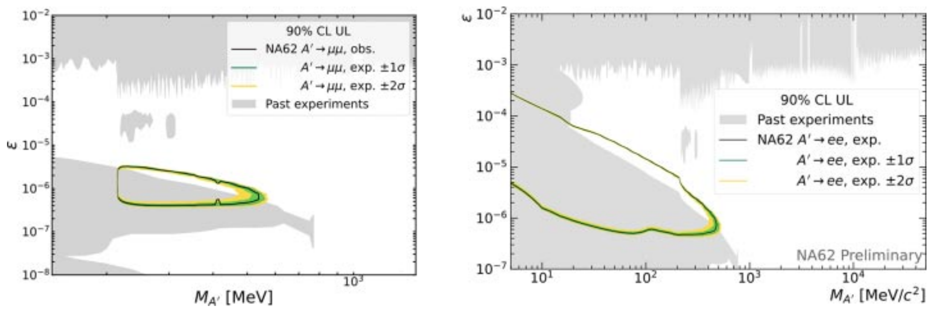

Fig. 4. – Left: $A' \to \mu^+\mu^-$. Right: $A' \to e^+e^-$. The region of the parameter space within the solid line is excluded at 90% CL. The colored filled area represent the expected uncertainty on the exclusion contour in absence of a signal: green (yellow) corresponds to a statistical coverage of 68% (95%).

The model-independent $K^+ \to \pi^+\mu^+\mu^-$ branching fraction

$$\mathcal{B}_{\pi\mu\mu} = (9.15 \pm 0.08) \times 10^{-8}$$

is obtained from the reconstructed binned differential decay width by integrating the spectrum over z and multiplying by $\tau_K/\hbar$.

The forward-backward asymmetry of the $K^+ \to \pi^+\mu^+\mu^-$ decay is also measured to be $A_{FB} = (0.0 \pm 0.7) \times 10^{-2}$.

4. – Dark photon searches with NA62 in beam-dump mode

The NA62 experimental setup can be used to investigate the production and decay of dark photons while operating in the beam-dump mode: the beam protons are dumped 80 m upstream of the NA62 decay volume. A search for dark photons decaying in flight to $\mu^+\mu^-$ pairs has been performed by NA62, based on a sample collected in 2021 [15]. A counting experiment through a cut-based, blind analysis has been performed. One event is found, with a possible interpretation as combinatorial background. No evidence of a dark photon signal is established. A region of the dark photon parameter space (coupling constant ϵ, mass $M_{A'}$) is excluded at 90% CL, extending the constraints set by previous experiments in the mass range 215-550 MeV/c^2 for coupling constants of the order of 10^{-6} (fig. 4, left panel). In addition, the result is interpreted in terms of the emission of axion-like particles in a model-independent approach. The result is found to improve on previous limits for masses below 280 MeV/c^2.

In addition to the searches for the $\mu^+\mu^-$ final state, a search for the dark photons decaying into e^+e^- pairs has been performed, with no events observed. The corresponding 90% CL upper limit translates into the excluded region visible in fig. 4 (right panel), which extends beyond past experiments for $20 < M'_A < 450$ MeV/c^2 and, correspondingly for values of the ϵ coupling constant from 8×10^{-5} to 8×10^{-7}. The details of this analysis and the preliminary results have been presented for the first time in March 2023 [16], and a publication with the final result is in preparation.

REFERENCES

[1] NA62 Collaboration, *JHEP*, **06** (2021) 093.
[2] NA62 Collaboration, *JINST*, **12** (2017) P05025.
[3] NA62 Collaboration, *JHEP*, **03** (2023) 122.
[4] NA62 Collaboration, *JHEP*, **09** (2023) 040.
[5] NA62 Collaboration, *Phys. Lett. B*, **846** (2023) 138193.
[6] NA62 Collaboration, *Phys. Lett. B*, **830** (2022) 137172.
[7] NA62 Collaboration, *Phys. Lett. B*, **838** (2023) 137679.
[8] NA62 Collaboration,, arXiv:2311.01837 (2023).
[9] D'Ambrosio G., Ecker G., Isidori G. and Portolés J., *JHEP*, **08** (1998) 004.
[10] D'Ambrosio G., Greynat D. and Knecht M., *JHEP*, **02** (2019) 049.
[11] Workman R. L. *et al.*, *Prog. Theor. Exp. Phys.*, **2022** (2022) 083C01.
[12] NA48/2 Collaboration, *Phys. Lett. B*, **697** (2011) 107.
[13] NA62 Collaboration, *JHEP*, **11** (2022) 011.
[14] D'Ambrosio G. and Portolés J., *Phys. Lett. B*, **386** (1996) 403.
[15] NA62 Collaboration,*JHEP*, **09** (2023) 035.
[16] Kleimenova A. (on behalf of the NA62 Collaboration), contribution at *La Thuile-Les Rencontres de Physique de la Vallée d'Aoste* (2023).