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New results from analyses of rare K^+ and π decays at NA62(*)

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Summary. — The CERN NA62 experiment is dedicated to rare kaon decays. Data collected during Run1 (2016-2017-2018) already constitute the largest sample ever of detected K^+ decays and offer unprecedented opportunities to test the SM or to search for New Physics in a variety of rare kaon and pion decays. The preliminary NA62 precision measurement of the $\pi^0 \to e^+e^-$ decay branching fraction is reported in the following, together with the recently published study of the $K^+ \to \pi^+\gamma\gamma$ decay and the first search for an axion-like particle (a) coupling to gluons in the decay chain $K^+ \to \pi^+ a, a \to \gamma\gamma$.

1. – NA62, the K^+ experiment at CERN

NA62 is a fixed target experiment [1] at CERN Super Proton Synchrotron dedicated to the study of the rare decays of the K^+ meson, aiming to measure the branching ratio (BR) of the $K^+ \to \pi^+\nu\bar{\nu}$ decay [2] with a precision comparable to its Standard Model (SM) prediction: $(7.86 \pm 0.61) \times 10^{-11}$ [3]. The availability of an high-intensity secondary beam selected with 75 GeV/c momentum, 6% of which are K^+, allowed NA62 to collect, by several trigger lines running in parallel [4], the largest sample ever of K^+ decays. Run1 (2016-2017-2018) data provide unprecedented opportunities to test the SM or to search for New Physics in a variety of kaon and pion rare decays. Several results have already been published as, for example, the precision measurements of the $K^+ \to \pi^+\mu^+\mu^-$ [5] and $K^+ \to \pi^0 e^+\nu\gamma$ [6] decays, the first search for the $K^+ \to \pi^+e^+e^-e^+e^-$ [7] decay, or the searches for the lepton flavor violating $K^+ \to \pi^+\mu^-e^+$ and $\pi^0 \to \mu^-e^+$ decays and for the lepton number violating $K^+ \to \pi^-\mu^+e^+$ mode [8].

In the following, the new measurement of the $\pi^0 \to e^+e^-$ decay and the recentely published study of the $K^+ \to \pi^+\gamma\gamma$ decay are reported, together with the first search for an axion like particle (a) with gluon coupling in the channel $K^+ \to \pi^+ a, a \to \gamma\gamma$.

To be mentioned that, thanks to the possibility to run the experiment in dump mode, NA62 program goes also beyond the K^+ physics, searching for direct production of exotic particles at higher mass scales as, for example, in [9] and [10].

2. – Precision measurement of the $\pi^0 \to e^+e^-$ decay

Within the SM, the $\pi^0 \to e^+e^-$ decay is $\mathcal{O}(10^7)$ suppressed with respect to the most abundant $\pi^0 \to \gamma\gamma$ mode ($BR = (98.823 \pm 0.034)\%$) [11]) and a precision measurement of its branching ratio would constitute a direct probe of the SM. However, as radiative photons can be present in the final state, the observable is $BR(\pi^0 \to e^+e^-(\gamma), x > 0.95)$, the branching ratio inclusive of the final state radiation, with a cut-off on $x \equiv (m_{ee}^2/m_{\pi^0}^2)$, with m_{ee} di-electron invariant mass. The cut-off is needed in order to reduce the otherwise dominat $\pi_D^0 \to \gamma e^+e^-$ Dalitz decay to about 3.3% with respect to $\pi^0 \to e^+e^-(\gamma)$. By using radiative corrections calculations, the measurement can then be extrapolated to the full x range to obtain the exclusive $BR(\pi^0 \to e^+e^-, no-rad)$ to be compared with theory. The latest previous measurement was performed by the Fermilab KTeV E799-II experiment [12]: $BR_{\mathrm{KTeV}}(\pi^0 \to e^+e^-(\gamma), x > 0.95) = (6.44 \pm 0.33) \times 10^{-8}$, extrapolated to $BR_{\mathrm{KTeV}}(\pi^0 \to e^+e^-, no - rad) = (6.85 \pm 0.35) \times 10^{-8}$ once the latest radiative

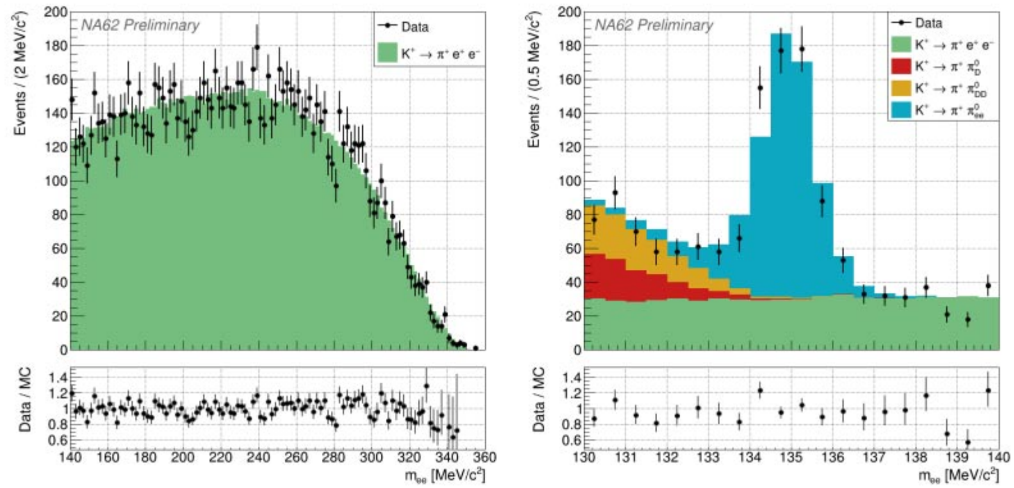

Fig. 1. – Di-electron invariant mass from the $\pi^0 \to e^+e^-$ NA62 measurement. Left: $K^+ \to \pi^+e^+e^-$ normalization sample; it has a purity $> 99\%$. Right: NA62 data after $K^+ \to \pi^+\pi^0_{ee}$ signal selection superimposed to the sum of MC samples. The preliminary NA62 measurement of the $\pi^0 \to e^+e^-$ branching ratio is used to normalize Monte Carlo signal events to data.

calculatios are taken into account [13-15]. The $\sim 2\sigma$ tension of this result with respect to the most precise theoretical prediction $BR_{SM}(\pi^0 \to e^+e^-, no{-}rad) = (6.25{\pm}0.03){\times}10^{-8}$ [15] motivates a new measurement at NA62.

NA62 analysed data collected in 2017 and 2018 with the multi-track electron trigger line, searching the $\pi^0 \to e^+e^-$ mode in the $K^+ \to \pi^+\pi^0, \pi^0 \to e^+e^-$ decay chain ($K^+ \to \pi^+\pi^0_{ee}$), referred to as signal here on. Monte Carlo simulations including the latest radiative corrections [13,14] are used to estimate the expected background and the acceptances. Figure 1 reports the final distributions of the reconstructed m_{ee}, the chosen discriminating variable. The left hand side plot shows the di-electron mass spectra for the normalization sample of selected $K^+ \to \pi^+e^+e^-$ events, used to determine the effective number of K^+ decays in the analysed data: $N_K = (8.62 \pm 0.08_{stat} \pm 0.26_{ext}) \times 10^{11}$. Since the $K^+ \to \pi^+e^+e^-$ has the same topology as signal, measuring the branching ratio with respect to this known SM mode allows a first order cancellation of systematic uncertainties. For the normalization selection, $140 < m_{ee} < 360\,\mathrm{MeV/c^2}$ is considered, well above the π^0 mass, where the signal is expected to peak, while for the signal selection $130 < m_{ee} < 140\,\mathrm{MeV/c^2}$ is required, where $K^+ \to \pi^+e^+e^-$ constitutes a flat and irreducible background. The normalization and the signal selections are described in detail in [16]. Other backgrouds entering the signal selection come from $K^+ \to \pi^+\pi^0, \pi^0 \to \gamma e^+e^- (\equiv K^+ \to \pi^+\pi^0_D)$, due to the tail at large x of the π^0_D decay, and from $K^+ \to \pi^+\pi^0, \pi^0 \to e^+e^-e^+e^- (\equiv K^+ \to \pi^+\pi^0_{DD})$, due to the double Dalitz π^0 decay with two undetected $e^\pm$. The right hand side of fig 1 reports the signal region; signal MC sample is scaled according to NA62 measurement of the inclusive $\pi^0 \to e^+e^-$branching ratio, obtained from a maximum likelihood fit of simulated samples to the m_{ee} data distribution. The branchig ratios of the other decays are taken as known external inputs from [11]. The fitted signal event yield is $597 \pm 29\,(\chi^2/ndf : 25.3/19,\ p - value : 0.152)$, and the preliminary measurement of the inclusive branching ratio is $BR_{\mathrm{NA62}}(\pi^0 \to e^+e^-(\gamma), x > 0.95) = (5.86 \pm 0.30_{\mathrm{stat}} \pm 0.11_{\mathrm{sys}} \pm 0.19_{\mathrm{ext}}) \times 10^{-8} = (5.86 \pm 0.37) \times 10^{-8}$. When extrapolating using the latest radiative corrections [13, 14]: $BR_{\mathrm{NA62}}(\pi^0 \to e^+e^-, no - rad) = (6.22 \pm 0.39) \times 10^{-8}$. NA62 inclusive measurement is compatible with the KTeV one, with similar precision but lower central value, leading to an NA62 exclusive measurment in agreement with the theoretical expectations in [15]. The measurement is limited by the statistics, that will be increased by including data collected during Run2 (2021 to long shutdown 3 of CERN accelerator complex) by an optimized multi-track electron trigger line, with reduced downscaling with respect to Run1. Also, as the total external uncertainty is dominated by the knowledge of $BR(K^+ \to \pi^+e^+e^-)$, an analysis is planned at NA62 to get a new measurement of this mode.

3. – Measurement of the $K^+ \to \pi^+\gamma\gamma$ decay

Radiative non-leptonic kaon decays constitute crucial tests of the Chiral Perturbation Theory (ChPT), which describes low-energy QCD processes. In particular, for the $K^+ \to \pi^+\gamma\gamma$ decay, the ChPT description has been developed at both leading ($\mathcal{O}(p^4)$) and next-to-leading order ($\mathcal{O}(p^6)$) [17-19], and depends on a single unkonwn a priori real parameter ($\hat{c}$). At $\mathcal{O}(p^6)$ the $K^+ \to \pi^+\gamma\gamma$, decay rate depends also on external parameters, fixed according to [20].

NA62 recently performed a new study of the $K^+ \to \pi^+\gamma\gamma$ decay [21] on data collected during 2017 and 2018 by the minimum-bias trigger lines. The main discriminating variable of the study is related to the di-photon invarinat mass $z = (m_{\gamma\gamma}/m_K)^2$, with $m_{\gamma\gamma} = \sqrt{(q_1 + q_2)^2}$ and $q_{1,2}$ reconstructed photons four-momenta. The interval $0.20 < z < 0.51$ is considered as signal region, while the range $0.04 < z < 0.12$ is used for the estimate of the effective number of K^+ decays ($N_K = (5.55 \pm 0.03) \times 10^{10}$) as it is dominated by the abundant $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$ decay ($z = 0.075$ if $m_{\gamma\gamma} = m^0_{\pi}$), chosen as normalization mode. The signal and normalization selections are described in details in [21]. After the signal selection 3984 events are observed in data with an expected background of 291 ± 14 events, estimated from simulations.

Figure 2 shows the observed di-photon mass spectrum in the signal region after the signal selection, together with the results of the $min\,\chi^2$ fits to data performed assuming the $\mathcal{O}(p^4)$ (left) and $\mathcal{O}(p^6)$ (right) ChPT descriptions for the MC simulation of the $K^+ \to \pi^+\gamma\gamma$ decay. The main background contributions are also showed, the dominant one coming from the merging of the energy deposits in the NA62 homogeneous electromagnetic LKr calorimeter produced by overlapping showers from the photons of the $K^+ \to \pi^+\pi^0(\gamma), \pi^0 \to \gamma\gamma$ decay chain. The observed mass spectrum is not well reproduced if the ChPT description at the leading order is assumed ($p - value = 2.7 \times 10^{-8}$) and provides the first experimental evidence for the need of a description at least at the next-to-leading order ($p - value = 0.49$). The NA62 fitted value of the $\hat{c}$ parameter is $\hat{c}_{ChPT\,\mathcal{O}(p^6)\,\mathrm{NA62}} = 1.144 \pm 0.069_{stat} \pm 0.034_{sys}$, and $BR_{ChPT\,\mathcal{O}(p^6)\,\mathrm{NA62}}(K^+ \to \pi^+\gamma\gamma) = (9.61 \pm 0.15_{stat} \pm 0.07_{sys}) \times 10^{-7}$ from the intregration of the analytical differential amplitude over the whole possible kinematic range once $\hat{c} = \hat{c}_{ChPT\,\mathcal{O}(p^6)\,\mathrm{NA62}}$ is fixed. The value of the branching ratio is consistent with the most precise previous measurement [22] but with a precision improved by a factor ¿ 3. NA62 provided also a model-independent estimate of the branching ratio, obtained in bins of z in the signal region and then integrated: $BR_{\mathrm{M.I.,\ NA62}}(K^+ \to \pi^+\gamma\gamma|z > 0.20) = (9.46 \pm 0.19_{stat} \pm 0.07_{sys}) \times 10^{-7}$.

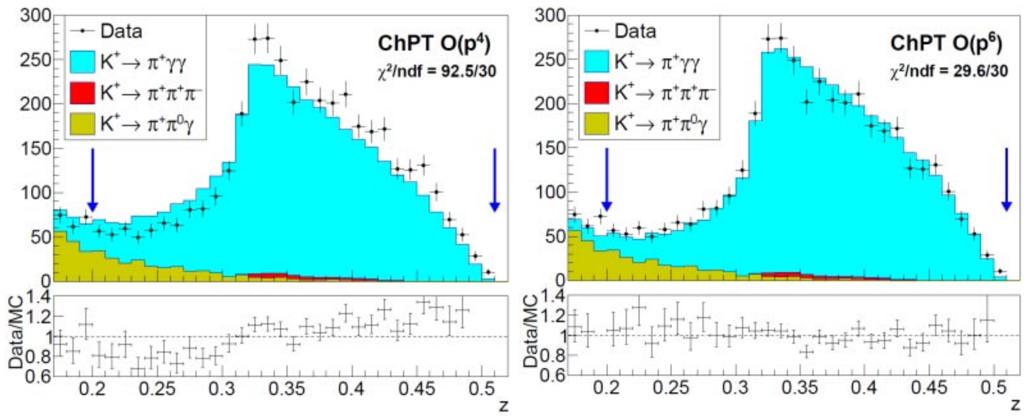

Fig. 2. – Reconstructed z spectrum after the $K^+ \to \pi^+\gamma\gamma$ selection. NA62 data are superimposed with summed signal and background MC samples. $K^+ \to \pi^+\gamma\gamma$ spectra are simulated fixing $\hat{c}$ to the result of the min χ^2 fit assuming the leading order (left) or the next-to-leading (right) order ChPT description. Blu arrows indicate the region used for the fits.

4. – First search for NP in the $K^+ \to \pi^+ a, a \to \gamma\gamma$ decay

The first search for an axion like particle (ALP) with gluon coupling in the channel $K^+ \to \pi^+ a, a \to \gamma\gamma$ was also performed starting from the sample of data selected by the $K^+ \to \pi^+\gamma\gamma$ selection [21]. Assuming the $K^+ \to \pi^+\gamma\gamma$ as the main background and a prompt $a \to \gamma\gamma$ decay, a peak search is performed in the distribution of the missing mass $m_{miss} = \sqrt{(P_K - P_\pi)^2}$, with $P_{K(\pi)}$ reconstructed four-momentum of the $K(\pi^+)$, in the interval $(207, 350)\,\mathrm{MeV/c^2}$ in steps of $0.5\,\mathrm{MeV/c^2}$. The ALP mass resolution ranges from 2.0 to $0.2\,\mathrm{MeV/c^2}$ over the whole range considered. Figure 3 left shows the upper limit at 90% C.L. of $BR(K^+ \to \pi^+ a) \times BR(a \to \gamma\gamma)$ as a function of the ALP mass (m_a) obtained once the upper limit on the number of signal events is estimated for each considered m_a by using the CLs method [24]; the expected background and signal acceptances ($< 8\%$ for every m_a) are estimated from simulations.

These results can be extended to the case of ALP with finite lifetime and, assuming a BC11 new physics scenario [23], the red region of parameter space shown in fig. 3 right is exluded by NA62. Other regions of the same parameter space were already excluded by the NA62 searches for new particles long lived or decaying into invisible (X_{inv}) in the $K^+ \to \pi^+ X_{\mathrm{inv}}$ decay [2] and $\pi^0 \to X_{\mathrm{inv}}$ decay [25].

5. – Conclusions

The new NA62 measurement $BR(\pi^0 \to e^+e^-,\, no{-}rad) = (6.22 \pm 0.39) \times 10^{-8}$ is in full agreement with the latest SM predictions and does not confirm the $\sim 2\sigma$ tension observed by KTeV. NA62 provided the first evidence for a next-to-leading order ChPT description to reproduce the observed di-photon mass spectrum of the $K^+ \to \pi^+\gamma\gamma$ decay, and measured $\hat{c}_{ChPT\,\mathcal{O}(p^6)} = 1.144 \pm 0.077$ and $BR_{ChPT\,\mathcal{O}(p^6)}(K^+ \to \pi^+\gamma\gamma) = (9.61 \pm 0.17) \times 10^{-7}$. The first search for an ALP with gluon coupling in the $K^+ \to \pi^+ a, a \to \gamma\gamma$ mode was also performed, excluding new regions of the BC11 model parameter space.

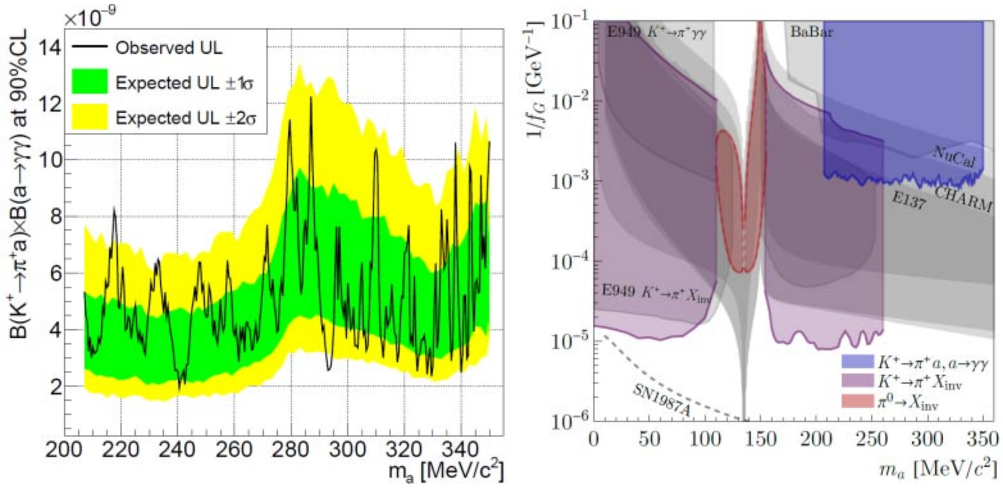

Fig. 3. – Left: $K^+ \to \pi^+ a, a \to \gamma\gamma$ branching ratio upper limit at 90% C.L. as a function of the ALP mass for prompt $a \to \gamma\gamma$ decay. Right: parameter space of a BC11 ALP; red regions are excluded by NA62 by the generalization to finite ALP lifetime of the upper limits on the left plot. To be noted that the relation $1/f_G \sim \sqrt{\tau_a}$ exists between the ALP coupling to gluons (f_G) and its lifetime (τ_a).

REFERENCES

[1] NA62 Collaboration, *JINST*, **12** (2017) P05025.
[2] NA62 Collaboration, *JHEP*, **06** (2021) 093.
[3] D'Ambrosio G. *et al.*, *JHEP*, **09** (2022) 148.
[4] NA62 Collaboration, *JHEP*, **03** (2023) 122.
[5] NA62 Collaboration, *JHEP*, **11** (2022) 011.
[6] NA62 Collaboration, *JHEP*, **09** (2023) 040.
[7] NA62 Collaboration, *Phys. Lett. B*, **846** (2023) 138193.
[8] NA62 Collaboration, *Phys. Rev. Lett.*, **127** (2021) 131802.
[9] NA62 Collaboration, arXiv.2312.12055 [hep-ex], to be published in *Phys. Rev. Lett.*
[10] NA62 Collaboration, *JHEP*, **09** (2023) 035.
[11] Paricle Data Group (Workman R. L. *et al.*), *Prog. Theor. Exp. Phys.*, **2022** (2022) 083C01.
[12] KTeV-E799-II Collaboration, *Phys. Rev. D*, **75** (2007) 012004.
[13] Vaško P. and Novotný J., *JHEP*, **10** (2011) 122.
[14] Husek T., Kampf K. and Novotný K., *Eur. Phys. J. C* , **74** (2014) 3010.
[15] Hoferichter M. and Teubner T, *Phys. Rev. Lett.*, **128** (2022) 172004.
[16] Brizioli F. for the NA62 Collaboration, *New results from analyses of rare kaon and pion decays at the NA62 experiment*, *Moriond EW 2024 Conference*.
[17] Ecker G. *et al.*, *Nucl. Phys. B*, **303** (1988) 665.
[18] D'Ambrosio G. *et al.*, *Phys. Lett. B*, **386** (1996) 403.
[19] Gérard J. M. *et al.*, *Nucl. Phys. B*, **730** (2005) 1.
[20] D'Ambrosio G. *et al.*, *Phys. Lett. B*, **835** (2022) 137594.
[21] NA62 Collaboration, *Phys. Lett. B*, **850** (2024) 138513.
[22] NA62 Collaboration, *Phys. Lett. B*, **732** (2014) 65.
[23] Beacham J. *et al.*, *J. Phys. G*, **47** (2020) 010501.
[24] Read A. L. *et al.*, *J. Phys. G*, **28** (2002) 2693.
[25] NA62 Collaboration, *JHEP*, **02** (2021) 201.