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Latest results from precision measurements at the NA62 experiment

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Then NA62 experiment at CERN collected the world's largest dataset of charged Kaons, the main goal being the measurement of the $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$. New results from the analyses of rare kaon and pion decays using data samples collected in 2017-2018 are presented. A sample of $\pi^0 \to e^+e^-$ decays was collected and preliminary results of the branching ratio are reported. Also, a sample of $K^+ \to \pi^+\gamma\gamma$ decays was collected and measurement of the branching ratio, study of the di-photon mass spectrum, and the first search for production and prompt decay of an axion-like particle with gluon coupling in the process $K^+ \to \pi^+ A$, $A \to \gamma\gamma$ are reported.

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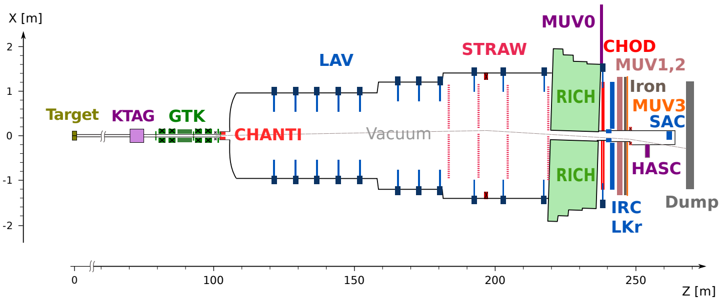

Figure 1: Schematic side view of the NA62 beam line and detector used in 2018

1. The NA62 experiment

The NA62 is a fixed target experiment at CERN's SPS North Area which has the goal to measure the branching ratio of the ultra-rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay with 10% precision [1]. A schematic view of the NA62 detector is show in Figure 1 and more details regarding the apparatus can be found in [2].

Besides the $K^+ \to \pi^+ \nu\bar{\nu}$, thanks to the multiple trigger lines [3] and the versatility of the experiment, mutiple K^+ decays can be studied. Other NA62 recent results are published in [4] and [5].

2. Measurement of the $\pi^0 \to e^+e^-$ decay

The primary focus of studying the decay $\pi^0 \to e^+e^-$ is to determine its branching ratio. Experimentally, additional radiative photons may appear in the final state. Consequently, the observable branching ratio includes final-state radiation, making radiative corrections crucial in the analysis. Due to this, a kinematic variable related to the di-electron invariant mass $x = m_{ee}^2/m_\pi^2$ is defined. The branching ratio to be measured is $\mathcal{B}(\pi^0 \to e^+e^-(\gamma), x > x_{\text{cut}})$ where the selected value of x_{cut} must be sufficiently large to suppress the effects of the Dalitz decay $\pi^0 \to e^+e^-\gamma$, which dominates in the low-x region. For $x_{\text{cut}} = 0.95$ the partial Dalitz decay branching ratio represents about 3.3% of the $\mathcal{B}(\pi^0 \to e^+e^-(\gamma))$. The previous best measurement conducted by the KTeV-E799-II experiment [6] reported $\mathcal{B}_{\text{KTeV}}(\pi^0 \to e^+e^-(\gamma), x > 0.95) = (6.44 \pm 0.25 \pm 0.28) \times 10^{-8}$. By using the latest radiative corrections ([7], [8]) and extrapolating the result to the value of the branching ratio without the final-state radiation, $\mathcal{B}_{\text{KTeV}}(\pi^0 \to e^+e^-, \text{no-rad}) = (6.84 \pm 0.35) \times 10^{-8}$ was obtained, resulting in a 2σ disagreement with the latest theoretical prediction $\mathcal{B}_{\text{KTeV}}(\pi^0 \to e^+e^-, \text{no-rad}) = (6.25 \pm 0.03) \times 10^{-8}$ [9].

The 2017 and 2018 data samples are used by NA62 for this measurement, selecting the $K^+ \to \pi^+\pi^0, \pi^0 \to e^+e^-$ decay, containing the latest radiative corrections in the Monte-Carlo sample, with the $K^+ \to \pi^+e^+e^-$ decay used for normalization. Due to the identical final state of the signal and normalization decay modes, the cancellation of certain several systematic effects is achieved. A dedicated multi-track electron trigger line, reduced by a factor of 8, was employed to collect both $K^+ \to \pi^+\pi^0, \pi^0 \to e^+e^-$ and $K^+ \to \pi^+e^+e^-$ events with an overall trigger efficiency is of ~90% for both the signal and normalization selections.

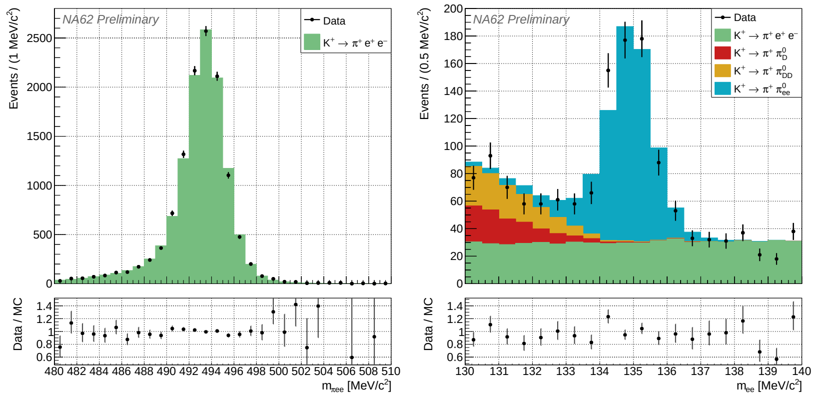

Figure 2: Left: $m_{\pi ee}$ distribution for candidates satisfying the normalization conditions. Right: m_{ee} distribution for signal selection

The selection of signal and normalization events involves the following criteria: a three-track vertex topology must be identified using data from the STRAW, combined with kinematic constraints on the total and transverse momenta of the vertex, and time coincidence information from the CHOD and KTAG detectors. The tracks are identified using the energy deposited in the LKr (E) and the momentum measured by the STRAW (p): An $E/p < 0.9$ is required for the π^+ tracks and $E/p \in (0.9, 1.1)$ condition is required for the $e^\pm$ tracks. For the signal events the dielectron invariant mass, m_{ee} is required to be in the (130, 140) MeV/c^2 range, while for the normalization events, the range is (140, 360) MeV/c^2. The total invariant mass, $m_{\pi ee}$ is required to be in the (480, 510) MeV/c^2 range (Figure 2 - Left).

For the normalization sample a negligible background was achieved (>99.9% sample purity) while for the signal sample the following background are present: $K^+ \to \pi^+ e^+ e^-$ which is irreducible and flat in the signal region, close the π^0 mass, $K^+ \to \pi^+\pi^0, \pi^0 \to e^+e^-\gamma$ which is either the irreducible large x-tail of the π^0 Dalitz decay or a photon conversion in the STRAW with an $e^\pm$ track selected from the conversion, this background being suppressed using STRAW hit information in the photon conversion case, and $K^+ \to \pi^+\pi^0, \pi^0 \to \pi^+e^+e^-e^+e^-$ where two $e^\pm$ tracks are not reconstructed and events with a track segment reconstructed in the first two STRAW chambers compatible with the vertex are rejected to suppress this background.

A total of 12160 normalization candidates were selected, with $A(K^+ \to \pi^+e^+e^-) = (4.70 \pm 0.01_{\text{stat}})\%$ based on simulations. The effective number of Kaon decays is $N_K = (8.62 \pm 0.08_{\text{stat}} \pm 0.26_{\text{ext}}) \times 10^{11}$, where the external uncertainty is attributed to the limited accuracy of the normalization branching ratio ($\mathcal{B}(K^+ \to \pi^+e^+e^-) = (3.00 \pm 0.09) \times 10^{-7}$) [10].

Regarding the signal selection, using $x_{\text{true}} > 0.95$, the acceptance is $A(K^+ \to \pi^+\pi^0, \pi^0 \to e^+e^-) = (5.72 \pm 0.02_{\text{stat}})\%$. The preliminary branching ration obtained is $\mathcal{B}_{\text{NA62}} = (\pi^0 \to e^+e^-(\gamma), x > 0.95) = (5.86 \pm 0.30_{\text{stat}} \pm 0.11_{\text{syst}} \pm 0.19_{\text{ext}}) \times 10^{-8}$ determined using maximum likelihood fit of the Monte-Carlo samples to the m_{ee} spectrum observed in the data with the branching ratio being the parameter of interest (Figure 2 - Right). The obtained signal event yield from the fit is 597 ± 29 events.

The preliminary results can be extrapolated to $\mathcal{B}_{\text{NA62}}(\pi^0 \to e^+e^-, \text{no-rad}) = (6.22 \pm 0.39) \times 10^{-8}$ using the latest radiative corrections. The NA62 measurement has a precision comparable to the KTeV-E799-II measurement, and the two results are consistent. However, the central value of the NA62 preliminary result is lower and aligns with theoretical expectations.

The precision of the $\mathcal{B}(\pi^0 \to e^+e^-)$ measurement is expected to improve due to NA62's ongoing data collection, which will continue until CERN's Long Shutdown 3. Additionally, a new measurement of $K^+ \to \pi^+e^+e^-$ is planned with the data collected by NA62, aiming to enhance the precision of the $\mathcal{B}(K^+ \to \pi^+e^+e^-)$ measurement.

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

Experimental investigations of radiative kaon decays provide a mean to test Chiral Perturbation Theory (ChPT), which explains low-energy QCD processes. For the $K^+ \to \pi^+\gamma\gamma$ decay, using an unknown real parameter $\hat{c}$ and additional external parameters, the ChPT was developed at both leading and next-to-leading orders.

From the 2017 and 2018 NA62 dataset, a sample of 3984 $K^+ \to \pi^+\gamma\gamma$ decay candidates was selected with an estimated background of 291 ± 14 events [11]. The primary background comes from the $K^+ \to \pi^+\pi^0\gamma, \pi^0 \to \gamma\gamma$ decays, where photons produce overlapping showers in the LKr calorimeter leading to the reconstruction of merged clusters, background estimated with simulations and validations of the simulations of cluster merging on a dedicated data sample. The $K^+ \to \pi^+\pi^0, \pi^0 \to \gamma\gamma$ decays were used as normalization sample. The next-to-leading order contribution $O(p^6)$ in the ChPT is necessary to describe the observed di-photon invariant mass by fitting the distribution of the observable $z = m^2_{\gamma\gamma}/m^2_K$ (Figure 3 - Left). The following value of $\hat{c}$ was obtained: $\hat{c} = 1.144 \pm 0.069_{\text{stat}} \pm 0.034_{\text{syst}}$. By integration of the ChPT $O(p^6)$ differential branching ratio in the full kinematic range, the following branching ratio was obtained $\mathcal{B} = (9.61 \pm 0.15_{\text{stat.}} \pm 0.07_{\text{syst.}}) \times 10^{-7}$.

In the region $0.2 < z < 0.51$, by summing over the z bins, the model independent branching ratio is found to be $\mathcal{B}_{\text{MI}}(z > 0.2) = (9.46 \pm 0.19_{\text{stat.}} \pm 0.07_{\text{syst.}}) \times 10^{-7}$.

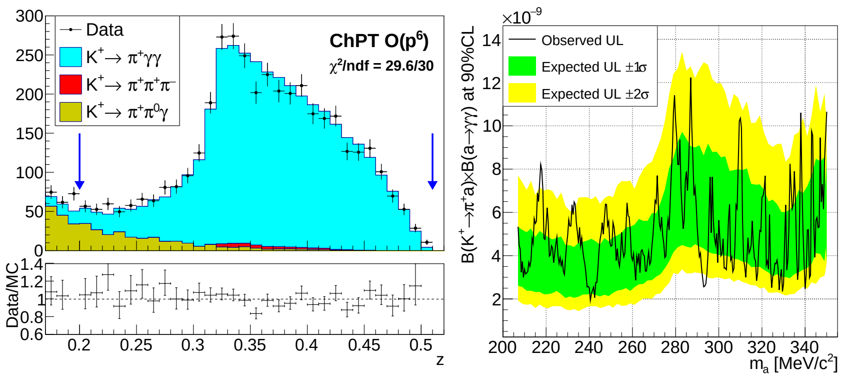

Figure 3: Left: Reconstructed z spectrum of the $K_{\pi\gamma\gamma}$ candidates, estimated background contributions and simulated signal spectra in the ChPT $O(p^6)$ description. Right: $\mathcal{B}(K^+ \to \pi^+a) \times \mathcal{B}(a \to \gamma\gamma)$ upper limits at 90% CL with their expected bands assuming prompt ALP decays

A first search for an axion-like particle a (ALP) in $K^+ \to \pi^+a, a \to \gamma\gamma$ was performed with the same selected events, by peak search in 287 mass hypotheses in the 207 − 350 MeV/c^2 range with a step of 0.5 MeV/c^2, with a variable m_a resolution from 2.0 MeV/c^2 to 0.2 MeV/c^2. For each hypothesis concerning m_a, the background is estimated through simulation. Upper limits on the number of signal events and the corresponding branching ratio (assuming prompt $a \to \gamma\gamma$ decay) are determined using the CL$_s$ method [12] method (Figure 3 - Right). Also, in the BC11 scenario, limits on the coupling strengths of the ALP to gluons ($1/f_G$) are also set, with the ALP proper mean lifetime scaling as $\tau_a \sim f_G^2$.

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