PROCEEDINGS OF SCIENCE

Recent results from the NA62 experiment at CERN

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Abstract. The NA62 experiment at CERN SPS is designed to study the $K^+ \to \pi^+\nu\bar{\nu}$ decay. 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 LS3. The first search for the lepton number violating decay $K^+ \to \pi^0\pi^-\mu^+e^+$ and lepton flavour violating decays $K^+ \to \pi^0\pi^+\mu^+e^-$, $K^+ \to \pi^0\pi^+\mu^-e^+$ is reported. More recent results from NA62 analyses of $K^+ \to \pi^+\gamma\gamma$ and $\pi^0 \to e^+e^-$ decay are also reported. Additionally, the search for New Physics in the data collected during the beam-dump mode in 2021 will be discussed.

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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, 2]. The layout of the NA62 beamline and detector is described in [3].

The versatility of the experimental setup, combined with the multiple trigger chains available [4], allows NA62 to study a variety of K^+ meson decays [5–8], including the $K^+ \to \pi^+\gamma\gamma$, the lepton number violating decay $K^+ \to \pi^0\pi^-\mu^+e^+$ and lepton flavour violating decays $K^+ \to \pi^0\pi^+\mu^+e^-$, $K^+ \to \pi^0\pi^+\mu^-e^+$, as well as π^0 decays, such as $\pi^0 \to e^+e^-$.

The NA62 setup is also suitable for searching 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.

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

The $K^+ \to \pi^+\gamma\gamma$ decay is dominated by long distance contributions and is a crucial test of the 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 decay modes. The main kinematic variable used to describe the $K_{\pi\gamma\gamma}$ decay is the normalized squared di-photon invariant mass $z = m^2_{\gamma\gamma}/m^2_K$.

Using the data collected in 2017-2018, NA62 performed the analysis of the $K^+ \to \pi^+\gamma\gamma$ decay. About 4×10^3 signal candidates were selected, with less than 10% background [9]. 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 Figure 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 $O(p^6)$, 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, in the ChPT $O(p^6)$ description, is found to be $\hat{c}_6 = 1.144 \pm 0.069_{\text{stat}} \pm 0.034_{\text{syst}}$. The corresponding branching ratio, obtained by integration of the ChPT $O(p^6)$ differential branching ratio over the full kinematic range, is $\mathcal{B} = (9.61 \pm 0.15_{\text{stat}} \pm 0.07_{\text{syst}}) \times 10^{-7}$. The model-independent branching ratio in the region $0.2 < z < 0.51$ is $\mathcal{B}_{MI}(z > 0.2) = (9.46 \pm 0.19_{\text{stat}} \pm 0.07_{\text{syst}}) \times 10^{-7}$.

The result for $\mathcal{B}(K^+ \to \pi^+\gamma\gamma)$ could be reinterpreted in terms of the search for an axion-like particle (ALP, a) in the $K^+ \to \pi^+ a$, $a \to \gamma\gamma$ decay chain. A peak search over $m_a = \sqrt{(P_K - P_\pi)^2}$ in the range 207-350 MeV/c^2 in steps of 0.5 MeV/c^2 is performed. The resolution of m_a goes from 2.0 MeV/c^2 to 0.2 MeV/c^2 across the mass search range. In each mass hypothesis, the background is estimated from simulations and an upper limit on the number of signal events is set using CLs method. Upper limits at 90% CL for $\mathcal{B}(K^+ \to \pi^+ a) \times \mathcal{B}(a \to \gamma\gamma)$ in the prompt decay assumption with their expected bands are shown in the right panel of Figure 1.

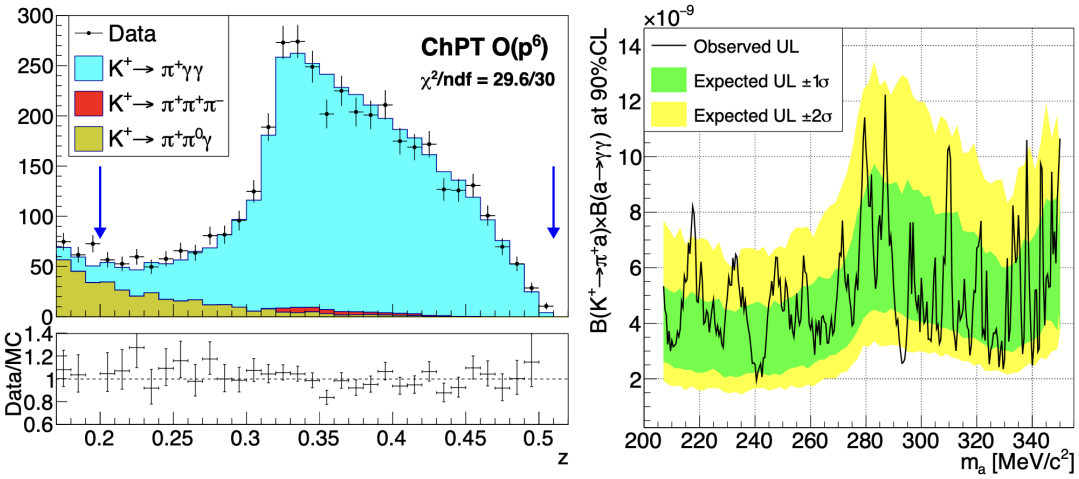

Figure 1: Left: reconstructed $z = m^2_{\gamma\gamma}/m^2_K$ spectrum for data compared to estimated signal and background components. The signal region is defined for $0.2 < z < 0.51$. **Right:** upper limits at 90% CL of $\mathcal{B}(K^+ \to \pi^+ a) \times \mathcal{B}(a \to \gamma\gamma)$ in the prompt decay assumption with their expected bands.

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

The $\pi^0 \to e^+e^-$ decay is $O(10^7)$ suppressed with respect to $\pi^0 \to \gamma\gamma$. Moreover, from the experimental point of view, the e^+e^- final state is particularly difficult to identify, given the presence of additional radiative photons. The $x = m^2_{ee}/m^2_{\pi^0}$ kinematic variable is essential to discriminate between the $\pi^0 \to e^+e^-$ and the $\pi^0 \to e^+e^-\gamma$ decay. The branching ratio $\mathcal{B}(\pi^0 \to e^+e^-, x > x_{cut})$ can be measured, where x_{cut} is chosen in order to suppress the $\pi^0 \to e^+e^-\gamma$ decay, which is dominant in the low-x region. The previous best measurement of this branching ratio, performed by the KTeV experiment, is $\mathcal{B}_{\rm KTeV}(\pi^0 \to e^+e^-, x > 0.95) = (6.44 \pm 0.25 \pm 0.22) \times 10^{-8}$ [10]. Applying the latest radiative corrections [11, 12], it is possible to extrapolate to the branching ratio without radiative photons in the final state, resulting in $\mathcal{B}_{\rm KTeV}(\pi^0 \to e^+e^-, \text{no-rad}) = (6.84 \pm 0.35) \times 10^{-8}$. This value has a 2σ discrepancy with the latest theoretical prediction, $\mathcal{B}_{\rm theory}(\pi^0 \to e^+e^-, \text{no-rad}) = (6.25 \pm 0.03) \times 10^{-8}$ [13].

The data sample used in this measurement was collected by NA62 in 2017 and 2018, selecting as signal decay mode the $K^+ \to \pi^+\pi^0$ with $\pi^0 \to e^+e^-$ decay chain. The $K^+ \to \pi^+e^+e^-$ decay is used for normalization. The invariant mass of the e^+e^- pair, is required to be in the range (130-140) MeV/c^2 for the signal selection. The main background sources for the signal are the irreducible decay $K^+ \to \pi^+e^+e^-$, flat near the π^0 mass, and the $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-\gamma$ process with a lost or converted γ. Another source of background is the double Dalitz decay $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-e^+e^-$ with two undetected $e^\pm$.

The number of signal events, obtained by a maximum likelihood fit of MC samples to the m_{ee} (Figure 2), is 597 ± 9 leading to a preliminary branching ratio of $\mathcal{B}_{\rm NA62}(\pi^0 \to e^+e^-, x > x_{cut}) = (5.86 \pm 0.30_{\rm stat} \pm 0.11_{\rm syst} \pm 0.19_{\rm ext}) \times 10^{-8}$. After applying radiative corrections, the extrapolation to the branching ratio without final-state radiation is $\mathcal{B}_{\rm NA62}(\pi^0 \to e^+e^-, \text{no-rad}) = (6.22 \pm 0.39) \times 10^{-8}$ [14].

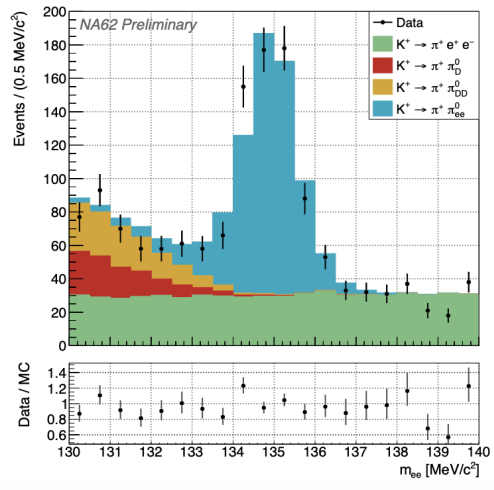

Figure 2: m_{ee} distribution for events passing the signal selection.

The result is compatible with the KTeV measurement and in agreement with the theoretical expectations when the extrapolation using radiative corrections is performed.

4. LNV and LFV searches at NA62

The first search for the lepton number violating decay $K^+ \to \pi^0\pi^-\mu^+e^+$ and lepton flavour violating decays $K^+ \to \pi^0\pi^+\mu^+e^-$, $K^+ \to \pi^0\pi^+\mu^-e^+$ has been performed using a dataset collected in 2016–2018.

The rates of the possible signal decays $K^+ \to \pi^0\pi\mu e$ are measured with respect to the rate of the normalisation decay $K^+ \to \pi^+e^+e^-$. Mass spectra for data and simulated background samples obtained with the full $K^+ \to \pi^0\pi\mu e$ selection are shown in Figure 3.

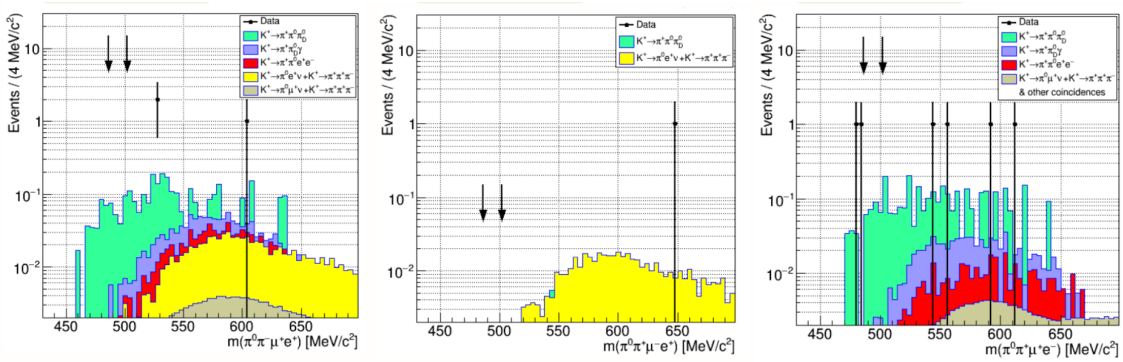

Figure 3: mass spectra for data and simulated background samples obtained with the full $K^+ \to \pi^0\pi\mu e$ selection. **Left**: $K^+ \to \pi^0\pi^-\mu^+e^+$ mode; **middle**: $K^+ \to \pi^0\pi^+\mu^-e^+$ mode; **right**: $K^+ \to \pi^0\pi^+\mu^+e^-$ mode

Upper limits of 2.9×10^{-10}, 3.1×10^{-10} and 5.0×10^{-10}, respectively, are obtained at 90% CL for the branching ratios of the three decays on the assumption of uniform phase-space distributions [15].

5. 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.

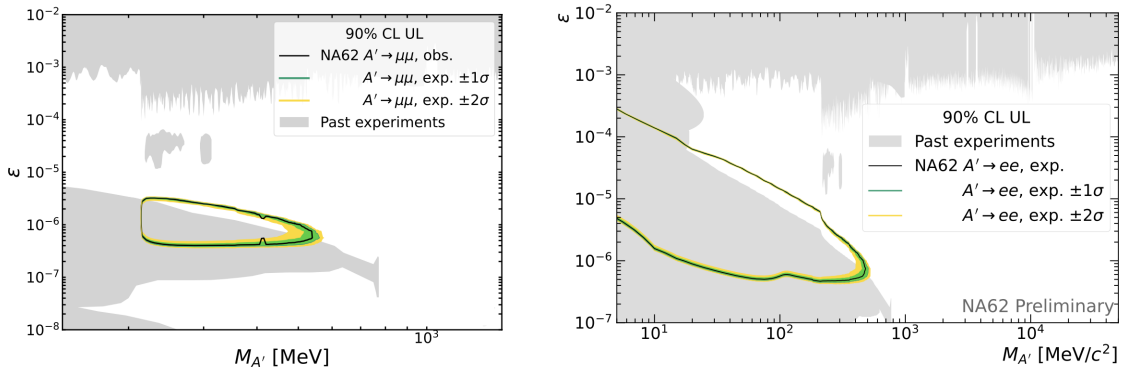

Figure 4: Left: $A' \to \mu^+\mu^-$. **Right:** $A' \to e^+e^-$. The region of the parameter space within the solid line is excluded at 90% CL. The colored filled area represent the expected uncertainty on the exclusion contour in absence of a signal: green (yellow) corresponds to a statistical coverage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

A search for dark photons decaying in flight to $\mu^+\mu^-$ pairs has been performed by NA62, based on the beam-dump sample collected in 2021 [16]. 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} (Figure 4, left panel).

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 Figure 4 (right panel), which extends beyond past experiments for $20 < M'_A < 450$ MeV/c^2 and, correspondingly for values of the coupling constant ϵ from 8×10^{-5} to 8×10^{-7}. The details of this analysis can be found in [17].

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