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Status and future prospects for rare kaon decay measurements at NA62

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The NA62 experiment at the CERN SPS is designed to study the $K^+ \to \pi^+ \nu\bar{\nu}$ decay: the analysis of data collected in 2021–2022 and the combination of previous results based on 2016–2018 data, are presented. Recent preliminary results on studies of the $K^+ \to \mu^+\nu\mu^+\mu^-$, $K^+ \to e^+\nu\gamma$ and $K^+ \to \pi^+\pi^+\pi^-\gamma$ decays are also shown.

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1. The NA62 experiment

NA62 is a high-precision kaon experiment located at CERN SPS, employing a fixed-target and a decay-in-flight technique. The main goal of the experiment is to measure the branching ratio (BR) of the ultra-rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay; the excellent performance of its detector also allows for a very broad physics programme [1–12].

An extensive description of the apparatus can be found in [13–15]; during CERN Long Shutdown 2, upgrades to the setup were performed, most notably to include vetoes for beam particle interactions and decays upstream of the fiducial volume.

2. $K^+ \to \pi^+ \nu\bar{\nu}$

The $K^+ \to \pi^+ \nu\bar{\nu}$ decay is short-distance dominated, and suppressed by the GIM mechanism. A Standard Model (SM) prediction of its BR, using tree-level measurements of the CKM matrix elements, gave $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$ [16]; more recently, the value $(8.60 \pm 0.42) \times 10^{-11}$ was calculated independently of $|V_{cb}|$ uncertainties [17], while a different calculation using a full CKM parameter fit obtained $(7.86 \pm 0.61) \times 10^{-11}$ [18]. This decay mode is highly sensistive to physics beyond the SM, and can probe existence of new physics at mass scales up to $O(100\,\text{TeV})$ [19].

During 2021 and 2022, data were collected at the design mean instantaneous intensity of about 580 MHz. Samples of normalization $K^+ \to \pi^+\pi^0$ decays, and of signal candidates, are collected using dedicated trigger lines, denoted NORM and PNN respectively. Events in both the signal and the normalization samples are required to pass selection criteria compatible with a beam K^+ entering the fiducial volume (FV) and a π^+ emerging from it, making a vertex; vetoes are applied against interactions and decays upstream of the FV. Signal candidates are also required to pass photon veto and multiplicity veto criteria. Kinematic regions, shown in figure 1-left, are defined in terms of $m^2_{\text{miss}} = (P_K - P_\pi)^2$ (where P_K and P_π are the 4-momenta of the K^+ and π^+ candidates) and p_{π^+} (the π^+ candidate momentum): signal events are required to lie in either of the signal regions, R1 and R2, while normalization events are required to lie within the regions CR1, $K_{2\pi}R$, or CR2.

An effective number of K^+ decays $N_K = (2.85 \pm 0.01) \times 10^{12}$ is calculated from the number of background-subtracted normalization events observed, the downscaling factor applied to the NORM trigger line, the branching ratio of the normalization $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$ decay chain, and the normalization selection acceptance $A_{\pi\pi} = (13.410 \pm 0.005)$ %, evaluated with simulations. The single event sensitivity is $\mathcal{B}_{\text{SES}} = (N_K A_{\pi\nu\bar{\nu}} \varepsilon_{\text{trig}} \varepsilon_{\text{RV}})^{-1} = (8.48 \pm 0.29) \times 10^{-12}$, where: $A_{\pi\nu\bar{\nu}} = (7.62 \pm 0.22)$ % is the signal selection acceptance, evaluated with simulations; $\varepsilon_{\text{trig}} = (85.9 \pm 1.4)$ % is the trigger efficiency ratio of the PNN and NORM trigger lines for the signal and normalization samples; $\varepsilon_{\text{RV}} = (63.2 \pm 0.6)$ % is the *random veto efficiency*, accounting for signal losses from the veto of unrelated activity, measured from a data control sample of $K^+ \to \mu^+\nu$ decays (figure 1-right). Assuming a BR of $\mathcal{B}^{\text{SM}}_{\pi\nu\bar{\nu}} = 8.4 \times 10^{-11}$, the number of SM signal events expected is $N^{\text{SM}}_{\pi\nu\bar{\nu}} = \mathcal{B}^{\text{SM}}_{\pi\nu\bar{\nu}} / \mathcal{B}_{\text{SES}} = 9.91 \pm 0.34$.

Non-gaussian tails of the m^2_{miss} resolution contribute to background from $K^+ \to \mu^+\nu$, $K^+ \to \pi^+\pi^0$ and $K^+ \to \pi^+\pi^+\pi^-$ decays in the FV, which are estimated based on the number of events

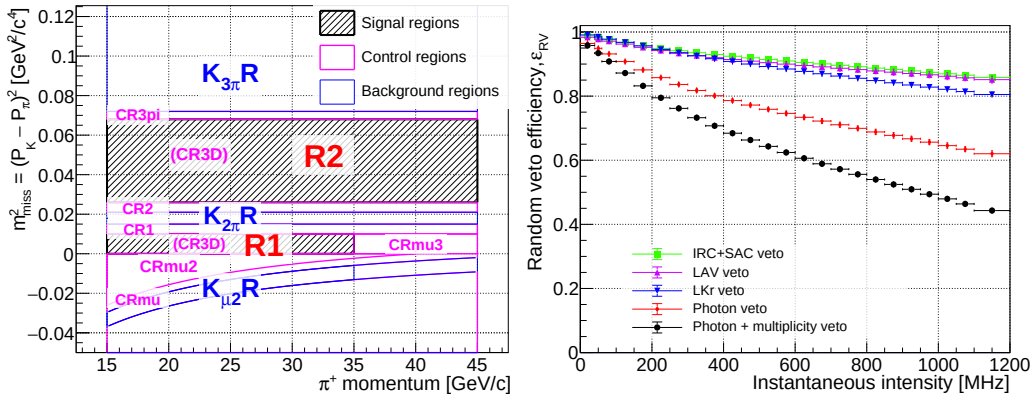

Figure 1: Left: definitons of kinematic regions in the $(p_{\pi^+}, m^2_{\text{miss}})$ plane. The definitions of R1 and R2 include additional constraints on alternative measurements of the squared missing mass; CR3D is obtained by inverting such constraints, and overlaps them in this projection. Right: random veto efficiency as a function of the instantaneous beam intensity.

observed in the corresponding background region, and the distribution of the reconstructed m^2_{miss} in dedicated control samples. Background from $K^+ \to \pi^+\pi^-e^+\nu$ and $K^+ \to \pi^+\gamma\gamma$ decays are estimated by using simulations. A fully data-driven strategy is used to estimate the *upstream background*, arising from decays and interactions upstream of the FV with misreconstruction or mismatching of the candidate π^+ downstream, which produces a fake reconstructed vertex. This is the dominant background, at $7.4^{+2.1}_{-1.8}$ events estimated. The total number of background events estimated is $11.0^{+2.1}_{-1.9}$.

After the signal selection, 6 events are observed in R1 and 25 in R2 (figure 2-left). Performing the analysis in six 5 GeV/c wide bins of p_{π^+} separately and using a profile likelihood ratio test statistic to combine them together with the nine categories spanning 2016–2018 data [20], the measurement

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = \left(13.0^{+3.0}_{-2.7}\big|_{\text{stat}}\ {}^{+1.3}_{-1.3}\big|_{\text{syst}}\right) \times 10^{-11} = \left(13.0^{+3.3}_{-3.0}\right) \times 10^{-11}$$

was obtained [21]. With a total expectation of 18^{+3}_{-2} background events and a total observation of 51 events, the background-only hypothesis is rejected with a significance above 5σ, which marks the first observation of the $K^+ \to \pi^+\nu\bar{\nu}$ decay. To date, this is the smallest branching ratio measured with a signal significance above 5σ.

This result has been recently reinterpreted as a search for the $K^+ \to \pi^+X$ decay, where X is a feebly-interacting new particle [22].

3. Recent preliminary results

Data collected in 2017–2024 are analyzed to measure the BR of the $K^+ \to \mu^+\nu\mu^+\mu^-$ decay. The $K^+ \to \pi^+\mu^+\mu^-$decay is used as a normalization channel, giving an effective number of kaon decays of $\left(1.475 \pm 0.005_{\text{stat}}\right) \times 10^{13}$. The number of observed data candidates is 8227, with an estimated total background from $K^+ \to \pi^+\mu^+\mu^-$, $K^+ \to \pi^+\pi^+\pi^-$ and $K^+ \to \mu^+\nu\pi^+\pi^-$ decays of

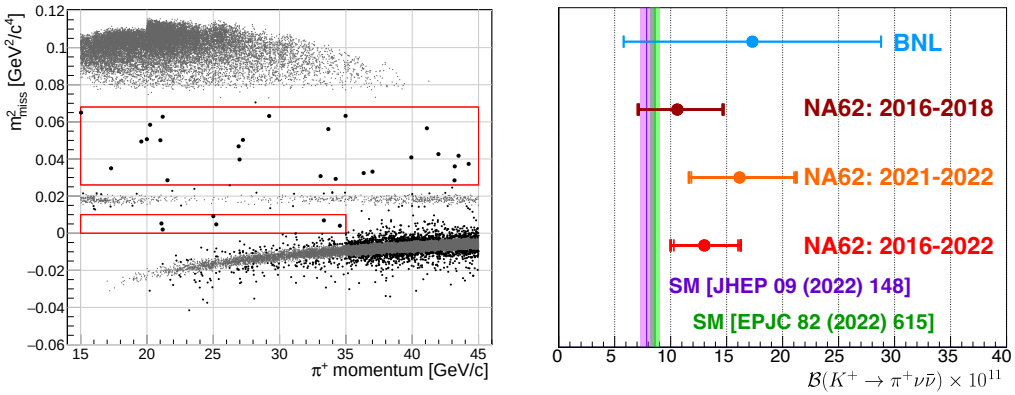

Figure 2: Left: distribution of events satisfying the signal selection in the $(p_{\pi^+}, m^2_{\rm miss})$ plane. Right: history of $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ measurements [20, 21, 23] and recent SM predictions [17, 18].

$892 \pm 11_{\rm stat} \pm 54_{\rm syst}$, and an acceptance computed using an $O(p^6)$ chiral perturbation theory (ChPT) prediction of $(3.821 \pm 0.004_{\rm stat})$ %. The obtained preliminary measurement is

$$\begin{aligned}\mathcal{B}(\mathrm{K}^+ \to \mu^+\nu\mu^+\mu^-) &= \left(1.301 \pm 0.017_{\rm stat} \pm 0.012_{\rm syst} \pm 0.012_{\rm ext}\right) \times 10^{-8} \\ &= (1.301 \pm 0.024) \times 10^{-8}\,,\end{aligned}$$

can be compared to ChPT [24] and lattice QCD [25, 26] predictions. This constitutes the first observation of the last missing $\mathrm{K}^+ \to \ell^+\nu\ell'^+\ell'^-$ decay [27, 28].

The structure dependent component of the $\mathrm{K}^+ \to \mathrm{e}^+\nu\gamma$ decay with positive γ helicity (denoted SD^+) is studied with data collected in 2017–2018. The normalization channel used is $\mathrm{K}^+ \to \mathrm{e}^+\nu\pi^0$, giving an effective number of kaon decays of about 2.9×10^{10}. The signal selection includes the kinematic criteria $X = 2E^*_{\rm e}/m_{\rm K} > 0.2$ and $Y = 2E^*_\gamma/m_{\rm K} > 0.93$ (where $E^*_{\rm e}$ and E^*_γ are the energies of the e^+ and γ in the K^+ rest frame, respectively, and $m_{\rm K}$ is the K^+ mass); 18929 signal candidates are selected, with an estimated background of 72 ± 8 events. The extrapolated preliminary branching ratio measurement is

$$\begin{aligned}\mathcal{B}\left(\mathrm{K}^+ \to \mathrm{e}^+\nu\gamma\ (\mathrm{SD}^+)\right) &= \left(0.466 \pm 0.003_{\rm stat} \pm 0.003_{\rm syst} \pm 0.004_{\rm ext}\right) \times 10^{-5} \\ &= (0.466 \pm 0.006) \times 10^{-5}\,.\end{aligned}$$

Furthermore, the measurement $R_\gamma = \Gamma\left(\mathrm{K}^+ \to \mathrm{e}^+\nu\gamma\ (\mathrm{SD}^+)\right)/\Gamma(\mathrm{K}^+ \to \mu^+\nu) = (1.59 \pm 0.02) \times 10^{-5}$ is more precise than previous theoretical [29–31] and experimental [32, 33] results.

The $\mathrm{K}^+ \to \pi^+\pi^+\pi^-\gamma$ decay is studied by analyzing data collected in 2017–2018. The normalization channel is $\mathrm{K}^+ \to \pi^+\pi^+\pi^-$, giving an effective number of kaon decays of $(7.3997 \pm 0.0013_{\rm stat} \pm 0.0319_{\rm ext}) \times 10^{10}$. The branching ratio is measured as function of the γ energy in the K^+ rest frame; in the range $10 < E^*_\gamma/\mathrm{MeV} < 60$, 87648 signal candidate events are selected with an estimated background of 156 ± 28, leading to the preliminary measurement

$$\mathcal{B}(\mathrm{K}^+ \to \pi^+\pi^+\pi^-\gamma, 10 < E^*_\gamma/\mathrm{MeV} < 60) = (6.30 \pm 0.04) \times 10^{-5}\,.$$

In the $30 < E^*_\gamma/\mathrm{MeV} < 60$ range, results agree with the OKA experiment [34] and with theoretical predictions [35].

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