PROCEEDINGS OF SCIENCE

Status and prospects of rare decay searches at NA62

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The $K^+ \to \pi^+ \nu\bar{\nu}$ decay is a golden mode for flavour physics. Its branching ratio is predicted with high precision by the Standard Model to be less than 10^{-10}, and this decay mode is highly sensitive to indirect effects of new physics up to the highest mass scales. A new measurement of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay by the NA62 experiment at CERN using data collected in 2021 and 2022 is presented. This new dataset was collected after modifications to the beamline and detectors and at a higher instantaneous beam intensity with respect to the previous 2016−2018 data taking. Using the complete datasets from 2016−2022, for the first time, the $K^+ \to \pi^+ \nu\bar{\nu}$ decay is observed with a significance exceeding 5σ.

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1. Introduction

The NA62 experiment [1] at CERN features a broad physics program. Its main goal is to measure the branching ratio of the $K^+ \to \pi^+\nu\bar{\nu}$ decay, providing an extremely high-precision test of the Standard Model (SM). A summary of the analysis strategy and results will be presented in sections 2.1-2.3. Other key objectives of the experiment include studies of rare and forbidden decays, such as searches for violations of lepton flavor and lepton number [2–6, 8]. Another area of research at NA62 is the "hidden sector", focusing on searches for new physics below the electroweak scale, weakly coupled to SM particles, such as axion-like particles, dark photons, or decays of heavy neutral leptons [9–13].

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

The $K^+ \to \pi^+\nu\bar{\nu}$ decay is a flavour changing neutral current process, which is forbidden at tree level in the SM. It occurs through electroweak box and penguin diagrams, with the process being dominated by t-quark exchange. This decay is highly suppressed both due to the GIM mechanism and the CKM suppression of the $t \to d$ quark transition. The decay is dominated by the short distance contribution, thus the intrinsic theoretical uncertainty accounts for approximately only 3%. Using tree-level measurements of the CKM matrix elements as external inputs, the SM branching ratio was predicted to be $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (8.4\pm1.0)\times10^{-11}$ [14]. The largest contribution to the uncertainty comes from the CKM input parameters. Recently, new predictions for the SM branching ratio have been calculated based on different assumptions. In [15], the $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (8.60\pm0.42)\times10^{-11}$ derived only from meson mixing processes to eliminate the strong dependence on $|V_{cb}|$, while using a full CKM parameter fit [16] $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (7.86 \pm 0.61) \times 10^{-11}$. The $K^+ \to \pi^+\nu\bar{\nu}$ decay is sensitive to a variety of Beyond SM (BSM) effects, probing new physics at mass scales up to $O(100$ TeV) [14]. Several BSM scenarios predict significant deviations of the branching ratio from the SM prediction, as well as correlations with other flavour observables and the corresponding decay mode of the neutral kaon. The direct upper limit of $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) < 2.2 \times 10^{-9}$ at 90% CL, set by the KOTO experiment [17], is two orders of magnitude above the SM predictions. However, this significance is still not sufficient to impose stringent limits on the various beyond SM theories that predict a deviation of $K^+ \to \pi^+\nu\bar{\nu}$ from the SM value (Minimal Supersymmetric SM, Simplified Z, Z', LF Universality violation models [15, 22–25]).

The NA62 experiment has already published results on previous data taking periods: the 2018, 2017 and 2016 data analysis have been respectively published in [18], [19] and [20]. From the combination of the 2016−2018 datasets, NA62 has produced the first evidence for this decay with a significance of 3.4 σ, measuring $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (10.6 + 4.1 - 3.5) \times 10^{-11}$, which has an uncertainty of approximately 35%. Recently, the analysis of the 2021-2022 dataset has been released [21] and it will be reported in the following sections. The beam intensity in 2021-2022 has increased by ≈35% with respect to the 2018 conditions, being approximately 600 MHz.

2.1 Selection criteria and signal sensitivity

The analysis uses a decay-in-flight technique: the K^+ and π^+ reconstruction starts at the first trigger level (level 0) by requiring the presence of charged particles and by applying a muon and a

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photon veto, depending on the specific case. The trigger level 1 enforces K^+ identification and an additional photon or extra activity veto. Three trigger lines are used, building up on more stringent condition [26]: the Minimum Bias, used to collect control samples of $K^+ \to \mu^+\nu$ decays; the Normalisation (NORM), to collect a normalisation sample of $K^+ \to \pi^+\pi^0$ decays; and the Signal (PNN), to collect signal $K^+ \to \pi^+\nu\overline{\nu}$ candidates. Excellent timing from the main detectors (the Cherenkov KTAG kaon tagger, the RICH pion identifier and the GTK kaon tracker), at the level of 100 ps, allows for $K-\pi$ matching. The kaon and downstream particle directions and momentum are measured respectively by the GTK and STRAW spectrometers. Muon suppression and π^0 suppression are essential for removing background events from other K^+ decays, both achieve a level of 10^{-8} after applying the complete analysis selection. The missing invariant mass squared $m^2_{\rm miss}$ is computed using the four-momenta of the kaon and the secondary track, which is assumed to be a pion. This is used with the pion momentum p_π to define two kinematic regions used for the signal search (Region 1 and Region 2) and identify control and validation/sideband regions. Region 1 requires: $0 < m^2_{miss} < 0.010$ GeV$^2/c^4$ and 15 GeV$/c < p_\pi < 35$ GeV$/c$ and Region 2 covers the phase-space with $0.026 < m^2_{miss} < 0.068$ GeV$^2/c^4$ and 15 GeV$/c < p_\pi < 45$ GeV$/c$. The signal regions are further divided into six categories corresponding to 5 GeV$/c$ bins of pion momentum in the range 15–45 GeV$/c$.

The branching ratio $\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu})$ is computed normalized to the $K^+ \to \pi^+\pi^0$ channel which shares the same secondary track as the signal, but unlike the signal does not require photon veto and has been collected with a down-scaled NORM trigger with no photon veto applied:

$$\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu}) = N_{\pi\nu\overline{\nu}} \cdot \mathcal{B}^{\rm SES} = \frac{N_{\pi\nu\overline{\nu}} \cdot \mathcal{B}(K^+ \to \pi^+\pi^0) \cdot A_{\pi\pi}}{D \cdot N_{\pi\pi} \cdot A_{\pi\nu\overline{\nu}} \cdot \epsilon_{RV} \cdot \epsilon_{trig}}, \tag{1}$$

where $N_{\pi\nu\nu}$ is the number of selected signal events, $\mathcal{B}^{\rm SES}$ is the Single Event Sensitivity, i.e. the branching ratio corresponding to the expectation of 1 event, $N_{\pi\pi}$ is the number of the events selected by the normalization channel and D is the down-scaling factor for the NORM trigger. The ratio of the total efficiencies for the signal and normalization selection accounts for the different acceptances A, the different efficiency ϵ_{trig} for trigger ratio of the signal divided by the normalization channel ($\epsilon_{trig} = \epsilon_{\rm PNN}/\epsilon_{\rm NORM}$) and the efficiency ϵ_{RV} of the random veto due to the photon rejection required for the signal selection but not for the normalization channel. Extracting the branching ratio normalized to a different channel guarantees the cancellation of systematic effects for particle identification, detector efficiencies, kaon association and beam-related uncertainties. All terms that are computed in equation 1 but the down-scaling factor for the NORM trigger and the ϵ_{RV} have a dependence on the p_i pion momentum bin: the values for the terms, summed or averaged over momentum bins, are summarised in table 1. By inverting equation 1, the number of expected signal events given the SM expectation for the $\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu}) = 8.4 \times 10^{-11\cdot}$ is 9.91 ± 0.34.

2.2 Background evaluation

The background estimate has a crucial role in the analysis, given that the background from other K^+ decays is several orders of magnitude higher than the signal.

For $K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu$ and $K^+ \to \pi^+\pi^+\pi^0$ backgrounds, a data driven estimate has been performed: the number of background events in the sidebands has been reweighted by the ratio of the signal to sideband region in the recorded control samples. The estimation of the $K^+ \to \pi^+\pi^- e^+\nu_e$

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$N_{\pi\pi}$	Effective number of normalisation events	$(1.953 \pm 0.005) \times 10^8$
$A_{\pi\pi}$	Normalisation acceptance	$(13.410 \pm 0.005)\%$
N_K	Effective number of K^+ decays	$(2.85 \pm 0.01) \times 10^{12}$
$A_{\pi\nu\bar{\nu}}$	Signal acceptance	$(7.62 \pm 0.22)\%$
ϵ_{trig}	Trigger efficiency ratio	$(85.9 \pm 1.4)\%$
ϵ_{RV}	Random veto efficiency	$(63.2 \pm 0.6)\%$
$\mathcal{B}^{\mathrm{SES}}$	Single event sensitivity	$(8.48 \pm 0.29) \times 10^{-12}$
$N_{\pi\nu\bar{\nu}}$	Number of expected $K^+ \to \pi^+\nu\bar{\nu}$ events	9.91 ± 0.34

Table 1: Signal sensitivity inputs for the total 2021–2022 data sample. $N_{\pi\nu\bar{\nu}}$ is evaluated assuming $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = 8.4 \times 10^{-11}$.

background relies entirely on MC simulations normalized to the normalization channel. The radiative decays $K^+ \to \pi^+\pi^0\gamma$ and $K^+ \to \mu^+\nu\gamma$ have been considered and a suppression based on the missing square mass using the four-momentum P of $(P_K - P_\mu - P_\gamma)$ has been applied.

In addition to the background coming from K^+ decays, there is a beam related background, defined as upstream background, i.e. a background where a secondary track coming from a decay of a K^+ before the start of the fiducial volume is erroneously associated with a beam particle passing close by at the same time. Given that the average beam intensity is at its maximum for the 2022-2023 data collection period, an increase in upstream background is anticipated. Mitigation is provided by the installation of an additional veto detector in the upstream part of the experiment. The upstream background represents the largest background contribution and has been estimated from data. The evaluation uses a background enriched sample obtained by inverting the requirement on the closest distance of approach of the $K - \pi$ candidates and weighting this distribution by the mistag probability evaluated in data.

A summary of the background expectations is given in table 2. Background expectations have been validated with respect to observations in data sidebands, used as control regions, as visible in figure 1 (left). The global p-value of the comparison is 0.80, the lowest single-region p-value is 0.24. The upstream background computation has been validated on specific either interaction or accidental enriched validation samples (figure 1, right). The global p-value is 0.97, the lowest single-sample p-value is 0.14.

Background	Events
$K^+ \to \pi^+\pi^0(\gamma)$	0.83 ± 0.05
$K^+ \to \mu^+\nu(\gamma)$	1.70 ± 0.47
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03
$K^+ \to \pi^+\pi^- e^+\nu$	$0.89^{+0.33}_{-0.27}$
$K^+ \to \pi^+\gamma\gamma$	0.01 ± 0.01
$K^+ \to \pi^0\ell^+\nu$	< 0.001
Upstream	$7.4^{+2.1}_{-1.8}$
Total	$11.0^{+2.1}_{-1.9}$

Table 2: Background expectations for 2021–2022 data, averaged over the six π^+ momentum bins.

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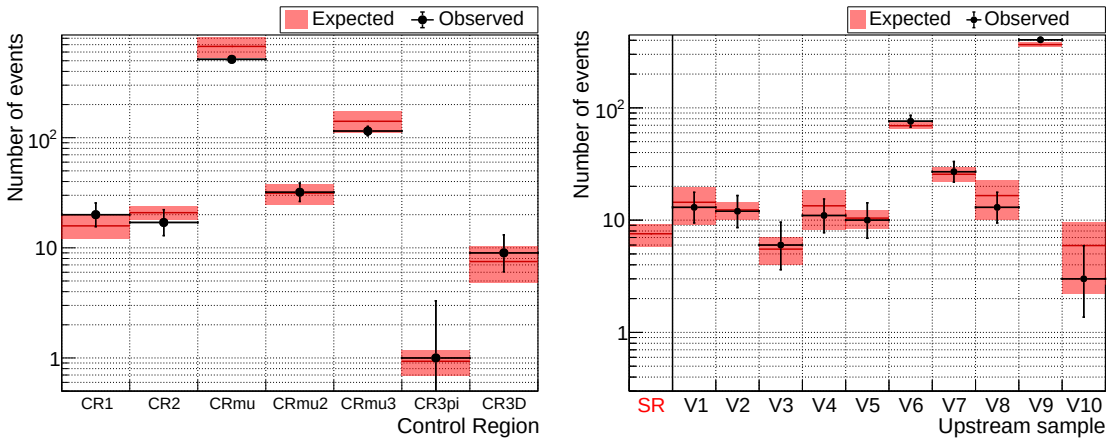

Figure 1: Left: expected and observed numbers of events in the control regions. Right: expected and observed numbers of events in the upstream validation samples. The first bin is the signal region and therefore only the expectation is displayed.

2.3 Results

Figure 2 left shows the (p_{π^+}, $m^2_{\rm miss}$) distribution of the observed data events after the signal selection criteria are applied. Six events are observed in Region 1 and twenty-five in Region 2. The $m^2_{\rm miss}$ projection including the background spectra and SM signal expectation is shown in figure 2 right.

The branching ratio measurement is performed using a profile likelihood ratio test statistic, using $N_{\rm cat}$ categories, considered independent. The analysis of 2021–2022 data is performed using $N_{\rm cat} = 6$, corresponding to the six π^+ momentum bins defined above. The resulting measurement of the branching ratio is

$$\mathcal{B}^{2021-2022}(K^+ \to \pi^+\nu\bar{\nu}) = (16.2^{+4.9}_{-4.3}|_{\rm stat}\ ^{+1.4}_{-1.4}|_{\rm syst}) \times 10^{-11} = (16.2^{+5.1}_{-4.5}) \times 10^{-11}.$$

The six categories of the 2021–2022 data have been combined with the nine categories of the for the 2016–2018 dataset for a total $N_{\rm cat} = 15$ for the combined 2016–2022 branching ratio result. The combined measured $\mathcal{B}$ is:

$$\mathcal{B}^{2016-2022}(K^+ \to \pi^+\nu\bar{\nu}) = (13.0^{+3.0}_{-2.7}|_{\rm stat}\ ^{+1.3}_{-1.3}|_{\rm syst}) \times 10^{-11} = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$$

The relative uncertainty is rougly 25%, limited by the statistical contribution. The p-value of the background-only hypothesis is evaluated to be 2×10^{-7}. Therefore, for the first time, the background-only hypothesis is rejected with a significance above 5σ and the $K^+ \to \pi^+\nu\bar{\nu}$ decay is observed.

3. Conclusions

The $K^+ \to \pi^+\nu\bar{\nu}$ decay has been observed for the first time with a significance above 5σ, and its branching ratio has been measured to be $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ =$(13.0^{+3.3}_{-3.0}) \times 10^{-11}$. The relative

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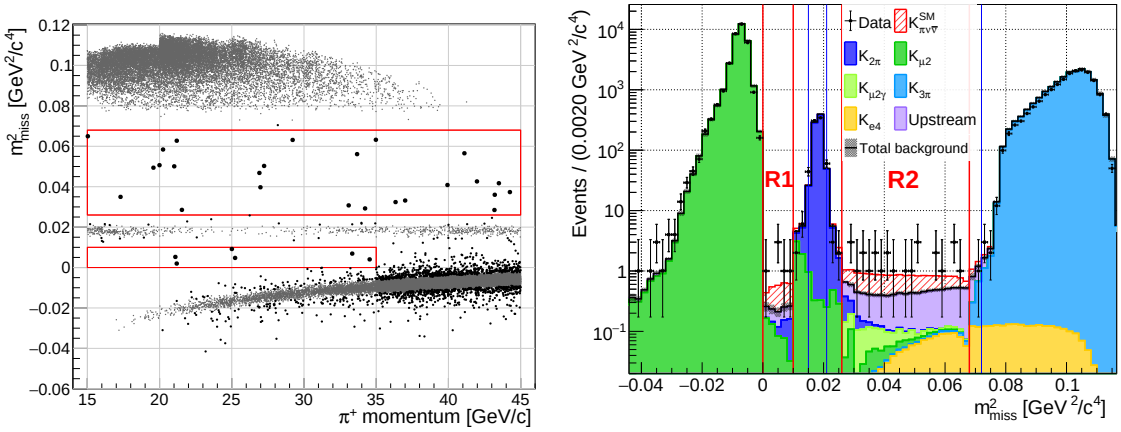

Figure 2: Left: Distribution of the data events satisfying the signal selection criteria in the $(p_{\pi^+}, m^2_{\rm miss})$ plane. Events in the background, control and signal regions are shown by small grey, small black and large black markers, respectively. Right: 1-D $m^2_{\rm miss}$ projection including SM signal events (assuming $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$= 8.4×10^{-11}) and background expectations from $K^+ \to \pi^+\pi^0$ (K2π), $K^+ \to \mu^+\nu$ (Kμ2), $K^+ \to \mu^+\nu\gamma$ (Kμ2 γ), $K^+ \to \pi^+\pi^+\pi^-$ (K3π), $K^+ \to \pi^+\pi^- e^+\nu$ (Ke4) and upstream. The total expected background and its uncertainty are shown by the black line and hatched bars.

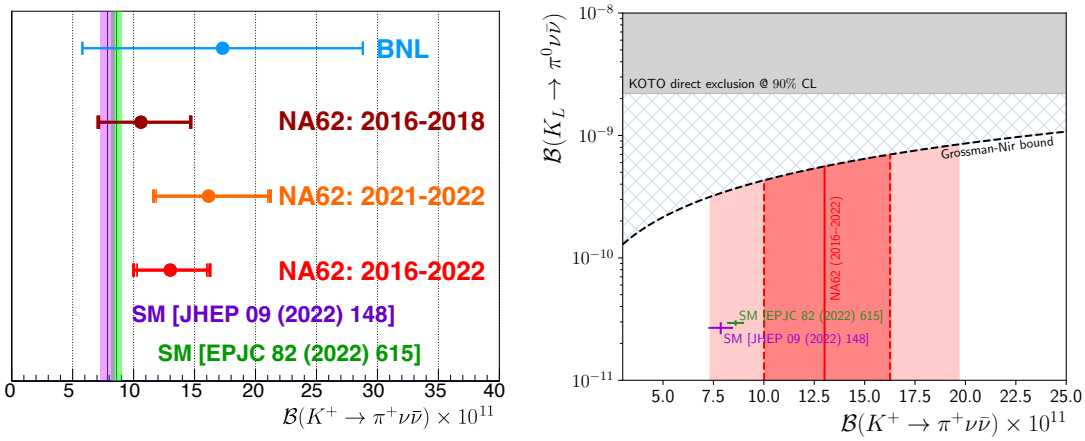

Figure 3: Left: Comparison of the $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio measurements from the BNL E787 and E949 experiments and the NA62 experiment using the 2016–2018, 2021–2022 and 2016–2022 data. Statistical and total uncertainties are shown by thinner and thicker vertical bars, respectively. The two recent SM predictions are also reported. Right: global status of the $K^+ \to \pi^+\nu\bar{\nu}$ decay modes, showing the present $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ upper limit from the KOTO collaboration, the Grossman-Nir bound, the two recent SM predictions, and the $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ result from the combined 2016–2022 NA62 dataset (the 1 and 2 σ ranges are displayed in darker and lighter shaded areas, respectively).

uncertainty in the branching ratio measurement has been improved from 40% (2016–2018) to 25% (2016–2022). The NA62 measurements for the different data periods are consistent among themselves and compatible with the results from the previous BNL E787 and E949 experiment results, as visible in figure 3 left. The 2016–2022 NA62 combined measurement agrees with the SM predictions within 1.5-1.7σ, depending on the considered SM prediction. With more data to

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be analysed (corresponding to the 2023-2024 data, which have already been collected and possibly other 2 extra years of running), NA62 aims to reach a branching ratio measurement with a relative precision better than 20%. Since August 2023, the beam intensity has been lowered to 75% of its maximum with the aim of (i) maximize the signal yield, which follows a paralizable model and decreases at higher intensities, (ii) lower the expected upstream background, (iii) increase the overall data acquisition efficiency. Agreement or tension with respect to the SM expectation will become clearer thanks to extra data and foreseen enhancements to the analysis techniques.

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