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Recent NA62 results

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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 including the data collected in 2021 and 2022 is presented: the branching ratio has been measured to be $\mathcal{B}^{2016-2022}(K^+ \to \pi^+\nu\bar{\nu}) = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$. It is consistent with the Standard Model theoretical prediction within 1.7σ.

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1. Introduction

The NA62 experiment [1] exploits the SPS proton beam at CERN to produce a secondary 75 GeV hadron beam containing about 6% K^+. The primary goal of the experiment is the measurement of the branching ratio of the $K^+ \to \pi^+\nu\bar{\nu}$ decay, providing a high-precision test of the Standard Model (SM). In addition, rare and forbidden decays of K^+ and π^+ are studied, including searches for violations of lepton flavor and lepton number [2–8]. Another key research focus is the hidden sector, which encompasses searches for new physics below the electroweak scale that is weakly coupled to SM particles, such as axion-like particles, dark photons, and decays of heavy neutral leptons both in a dedicated beam dump mode [9–11] and from K^+ decays [12–16].

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

The $K^+ \to \pi^+\nu\bar{\nu}$ decay is a flavour-changing neutral current process that is forbidden at tree level within the SM. It proceeds via electroweak loop diagrams, specifically box and penguin diagrams, and is predominantly mediated by top-quark exchange. The decay is highly suppressed due to the combined effects of the Glashow–Iliopoulos–Maiani mechanism and the Cabibbo–Kobayashi–Maskawa (CKM) suppression of the $t \to d$ quark transition. Owing to its dependence on short-distance contributions, the theoretical prediction for the branching ratio is particularly clean, with an intrinsic uncertainty of approximately 3%.

Using tree-level determinations of CKM matrix elements as external inputs, the SM prediction for the branching ratio is $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$ [17], where the dominant uncertainty arises from the CKM input parameters. More recent evaluations refine this estimate under different assumptions: Ref. [18] reports $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}$ using meson mixing observables to reduce dependence on $|V_{\text{cb}}|$, while a global CKM fit yields $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (7.86 \pm 0.61) \times 10^{-11}$ [19].

The $K^+ \to \pi^+\nu\bar{\nu}$ decay serves as a powerful probe of physics beyond the Standard Model (BSM), with sensitivity to new phenomena at mass scales up to $\mathcal{O}(100\text{ TeV})$ [17]. Numerous BSM scenarios predict sizable deviations of the $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio from the SM predicted one, often accompanied by correlations with other flavour observables, notably the neutral kaon decay mode $K_L \to \pi^0\nu\bar{\nu}$. The most stringent direct upper limit on this decay, established by the KOTO experiment, is $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) < 2.2 \times 10^{-9}$ at 90% confidence level [20], which remains approximately two orders of magnitude above the SM prediction. Although this limit does not yet impose stringent constraints on BSM models, it is particularly relevant for scenarios such as the Minimal Supersymmetric Standard Model (MSSM), Simplified Z and Z' models, and frameworks involving lepton flavour universality violation [18, 21–24].

The NA62 experiment has published results from multiple data-taking campaigns. Analyses of the 2016, 2017, and 2018 datasets were presented in Refs. [25], [26], and [27], respectively. By combining these datasets, NA62 reported the first evidence for the decay $K^+ \to \pi^+\nu\bar{\nu}$ with a significance of 3.4σ, corresponding to a measured branching ratio of $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.1}_{-3.5}) \times 10^{-11}$, with an overall uncertainty of approximately 35%. More recently, the collaboration released the analysis of the 2021–2022 dataset [28], collected under enhanced intensity beam conditions and corresponding to $(2.85 \pm 0.01) \times 10^{12}$ K^+ decays. During this period, the beam intensity was increased by approximately 35% relative to 2018, reaching a nominal rate of about 600 MHz.

The signal sensitivity of the analysis and the branching ratio itself are determined relative to the normalization to the $K^+ \to \pi^+\pi^0$ decay channel. Based on this method, the expected number of SM events in the 2021-2022 data sample is estimated to be 9.91 ± 0.34. The corresponding single event sensitivity (SES), defined as the branching ratio equivalent to one observed signal event, is calculated to be $(8.48 \pm 0.29) \times 10^{-12}$. The background contribution is categorized into two main components: backgrounds arising from dominant K^+ decay modes, and the so-called upstream background, which originates from kaon decays occurring upstream of the fiducial volume but reconstructed with a fake vertex within the fiducial region. A revised, fully data-driven methodology has been employed to estimate the upstream background, which constitutes the dominant source. For the 2021-2022 dataset, the expected contribution from upstream background is $7.4^{+2.1}_{-1.8}$ events, while the total expected background amounts to $11.0^{+2.1}_{-1.9}$ events. The resulting measurement of the branching ratio for the $K^+ \to \pi^+\nu\bar{\nu}$ decay, based on this partial dataset, is:

$$\mathcal{B}^{2021-2022}(K^+ \to \pi^+\nu\bar{\nu}) = (16.2^{+5.1}_{-4.5}) \times 10^{-11}.$$

In the full 2016-2022 dataset, a total of 51 signal candidate events have been observed, with an estimated background contribution of 18^{+3}_{-2} events. The expected number of signal events under the SM hypothesis is 20 ± 1 events. The combined measurement of the branching ratio is derived using a profile likelihood ratio test statistic, incorporating 15 distinct analysis categories. These categories are defined based on the data-taking period and, for years with higher statistics, further subdivided according to the reconstructed pion momentum. This categorization strategy enhances the sensitivity of the analysis by exploiting variations in detector performance and background composition across different data subsets.

The combined result for the full 2016–2022 dataset yields a measurement of the branching ratio of $K^+ \to \pi^+\nu\bar{\nu}$ equal to:

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

with a total relative uncertainty of approximately 25%, predominantly driven by statistical fluctuations. This represents a significant improvement in precision compared to the previous result based on the 2016-2018 dataset, which had a relative uncertainty of 40%.

The p-value of the background-only hypothesis is 2×10^{-7}, corresponding to a significance above 5σ. This marks the first observation of the $K^+ \to \pi^+\nu\bar{\nu}$ decay.

A comparison of the branching ratio measurements across different data-taking periods has been performed to verify the internal consistency of the results. The NA62 measurements for the individual data subsets are mutually consistent and in agreement with the results obtained by the previous BNL E787 and E949 experiments, as illustrated in Figure 2 (left). The combined NA62 measurement for the full 2016-2022 dataset is compatible with the SM predictions within 1.5–1.7σ, depending on the specific theoretical prediction considered, as shown in Figure 2 (right). Although the measured value shows a slight excess relative to the SM expectation, this deviation is not statistically significant and is interpreted as a fluctuation. Overall, the NA62 results remain consistent with the SM within the current experimental uncertainties.

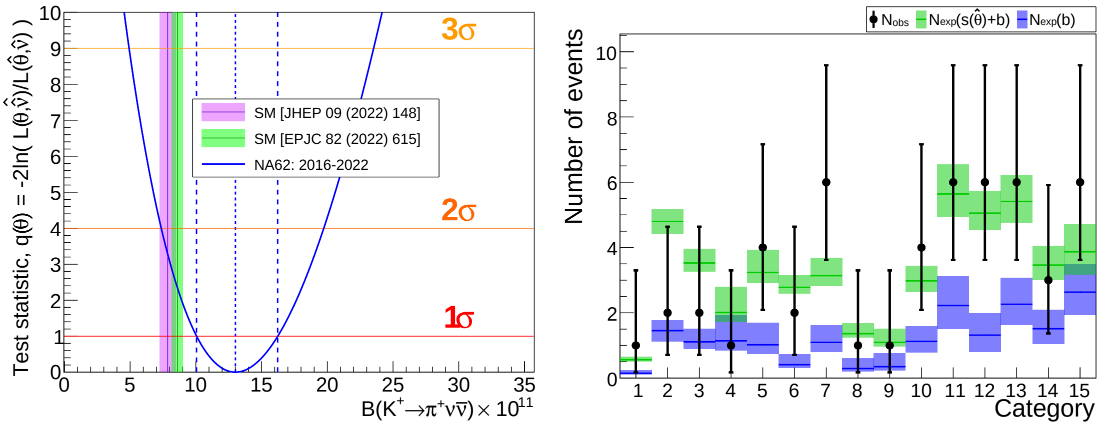

Figure 1: Left: test statistics as a function of the $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio for 2016-2022 data. Right: numbers of expected and observed events in the 15 categories used for the statistical analysis of 2016-2022 data. The background expectation is shown in blue, while the signal (using the measured value of the branching ratio) plus background expectation is shown in green.

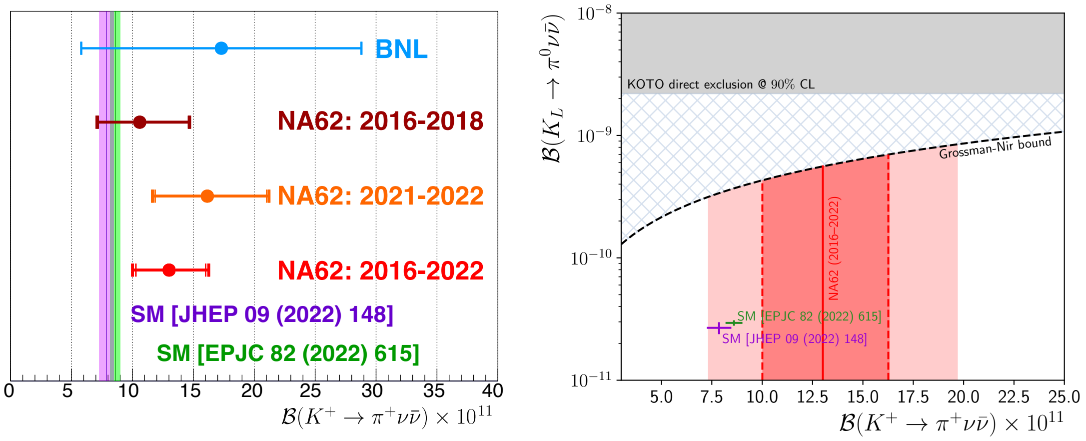

Figure 2: Left: Comparison of the $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio measurements from the BNL E787 and E949 experiments and the NA62 experiment using the 2016–2018, 2021–2022 and 2016–2022 data. Statistical and total uncertainties are shown by thinner and thicker vertical bars, respectively. 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 1σ and 2σ ranges are displayed in darker and lighter shaded areas, respectively).

The $K^+ \to \pi^+\nu\bar{\nu}$ analysis could be interpreted as a $K^+ \to \pi^+X$ decay, where X is a scalar or pseudo-scalar particle [27]. Interpretation of the new dataset is ongoing [29].

3. Conclusions

The NA62 experiment has reported the first observation of the ultra-rare $K^+ \to \pi^+\nu\bar{\nu}$ decay, with a measured branching ratio of $\mathcal{B}^{2016-2022}(K^+ \to \pi^+\nu\bar{\nu}) = (13.0^{+3.3}_{-3.0})$, corresponding to a total relative uncertainty of approximately 25%. This result is based on the full dataset collected between 2016 and 2022. Looking ahead, the analysis of the already acquired 2023–2024 dataset along with two additional years of planned data-taking through 2026, is expected to at least double the current statistics thus further improving the precision of the branching ratio measurement. The goal is to achieve a relative uncertainty below 20% with the full final dataset. Since August 2023, the beam intensity has been reduced to 75% of its nominal value to optimize the experimental conditions. This strategy aims to: (i) maximize the signal yield, which follows a paralyzable model and decreases at higher intensities; (ii) reduce the upstream background contribution; and (iii) enhance the overall data acquisition efficiency. Currently, the full 2016-2022 dataset analysis shows a slight excess in the measured branching ratio, corresponding to a deviation of 1.5–1.7 standard deviations above the SM prediction. As discussed in [24], certain new physics scenarios, particularly those involving enhanced couplings to third-generation leptons, could potentially account for both the NA62 mild excess and similar anomalies observed in some B-meson decays. However, the level of agreement or tension with respect to the SM will become clearer with the inclusion of additional data and the implementation of improved analysis techniques.

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