

# NEW MEASUREMENT OF THE $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ BRANCHING RATIO AT THE NA62 EXPERIMENT\*

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A new measurement of the  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  decay by the NA62 experiment at the CERN SPS is presented, using data collected in 2021 and 2022. Combining the NA62 datasets from 2016–2022, the decay branching ratio is measured to be:  $\text{BR} = (13.0_{-3.0}^{+3.3}) \times 10^{-11}$ . For the first time, the decay is observed with a significance exceeding  $5\sigma$ . The reinterpretation of the result as a  $K^+ \rightarrow \pi^+ X$  search, where  $X$  is a feebly interacting particle, is also discussed.

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## 1. Introduction

One of the golden modes for flavour physics is the  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  decay. It is a flavour-changing neutral current process whose amplitude is dominated by short-distance contributions and is highly suppressed due to the GIM mechanism and due to a small value of the CKM matrix element for the  $t \rightarrow d$  quark transition. The decay branching ratio is calculated within the Standard Model (SM) with a precision of few %, and the uncertainty depends mainly on CKM parameter inputs. Using tree-level measurements of the CKM matrix elements,  $\text{BR} = (8.4 \pm 1.0) \times 10^{-11}$  [1] was calculated. A more recent calculation has been performed, which is independent of  $V_{cb}$  uncertainties:  $(8.60 \pm 0.42) \times 10^{-11}$  [2]. If an alternative strategy from a full CKM parameter fit is used, a value of  $(7.86 \pm 0.61) \times 10^{-11}$  was obtained [3].

The decay also allows us to probe New Physics beyond the SM at mass scales up to  $O(100 \text{ TeV})$  [1]. Several scenarios predict significant modifications of the branching ratio with respect to the SM value, as well as correlations with other flavour observables [1, 4, 5].

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## 2. NA62 experimental setup

NA62 is a fixed-target experiment situated at the CERN SPS accelerator. Primary protons with 400 GeV/c momentum impinge on a beryllium target producing secondary particles. A 100 m long beam line collimates, focuses, and transports charged particles of  $(75.0 \pm 0.8)$  GeV/c momentum to the decay volume. The kaon fraction in the secondary beam is 6%. Beam kaons are identified and timestamped by the KTAG, a differential Cherenkov detector placed on the beam and filled with hydrogen. The Gigatracker (GTK) detector, made of four silicon pixel stations, timestamps beam particles of all types and measures their momenta. The CHANTI detector, located after the GTK, vetoes beam interactions with the material in the last GTK station. The momenta of charged particles from kaon decays are measured by the spectrometer made of four straw chambers and a dipole magnet. A 17 m long RICH detector filled with neon at atmospheric pressure is used to identify  $\pi^+$ ,  $\mu^+$ , and  $e^+$ , and together with a scintillator hodoscope (CHOD), measures the downstream track time. Hadronic calorimeters (MUV1 and MUV2) and a fast scintillator muon veto (MUV3) aid in separating  $\pi^+$  from  $\mu^+$ . A system of photon veto detectors (12 LAV stations, LKr, IRC, SAC) is designed to reject extra electromagnetic activity, covering angles up to 50 mrad. A detailed description of the setup (schematically shown in Fig. 1) can be found in [6]. The experiment started to take data in 2016.

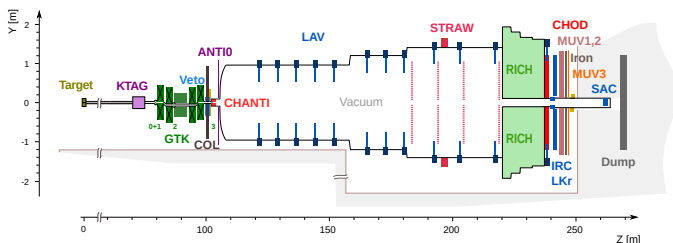


Fig. 1. The scheme of the NA62 experimental setup in 2021.

## 3. Analysis principles

The branching ratio of the signal decay is ten orders of magnitude smaller than that of the main  $K^+$  decays:  $\text{BR}(K^+ \rightarrow \mu^+\nu) = (63.56 \pm 0.11)\%$ ,  $\text{BR}(K^+ \rightarrow \pi^+\pi^0) = (20.67 \pm 0.08)\%$ , and  $\text{BR}(K^+ \rightarrow \pi^+\pi^+\pi^-) = (5.58 \pm 0.02)\%$ . To suppress the background from these decays the following requirements must be satisfied:

- Time-matching between key detectors with  $O(100)$  ps resolution.
- Kinematic suppression by a factor of  $O(10^4)$ . Two signal regions R1 and R2 (shown in red/grey boxes in Fig. 2, left) are defined using

the  $\pi^+$  momentum and the squared missing mass defined as  $m_{\text{miss}}^2 = (P_K - P_\pi)^2$ , where  $P_K$  and  $P_\pi$  are 4-momenta of  $K^+$  and  $\pi^+$ .

- Muon rejection by a factor of  $> 10^7$ . The required factor is achieved by combining particle identification of the RICH and calorimeters. For 2021–2022 data, the rejection is  $(1.3 \pm 0.2) \times 10^{-8}$ , while the identification efficiency is 73% [7].
- Suppression by a factor of  $> 10^7$  of  $\pi^0$  from the  $K^+ \rightarrow \pi^+ \pi^0$  decay. The rejection is provided by photon veto detectors and found to be  $(1.72 \pm 0.08) \times 10^{-8}$  for 2021–2022 data [7].

#### 4. NA62 previous results on the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay search

Three results were published by NA62 using data collected in 2016 [8], 2017 [9], and 2018 [10]. The expected background in the combined 2016–2018 sample was  $7.03_{-0.82}^{+1.05}$  events. The expected number of SM events was calculated assuming  $\text{BR} = (8.4 \pm 1.0) \times 10^{-11}$  and was found to be  $10.01 \pm 0.42$ . In total, 20 candidates were observed in the signal region which corresponds to the  $p$ -value of the background-only hypothesis of  $3.4 \times 10^{-4}$  and the significance of  $3.4\sigma$ . The branching ratio was measured to be  $\text{BR} = (10.6 \pm 4.1) \times 10^{-11}$ , with the total relative uncertainty of 40%.

#### 5. Analysis of the 2021–2022 dataset

The analysis of 2016–2018 data demonstrated the effectiveness of the NA62 detector and strategy. To further improve the experiment performance, several changes were done before the 2021 data taking.

First, the instantaneous beam intensity was increased from 400 to 600 MHz. Then, a number of detector upgrades were performed to reduce the largest “upstream background” due to decays and interactions of particles upstream of the decay volume. In particular, the Veto Counter and ANTI0 detectors were installed, which allowed us to improve the rejection by more than a factor of 2.

Comparing the latest 2021–2022 analysis to the 2016–2018 one, the signal acceptance was improved by 20%. The changes in the trigger configuration led to the improvement in the accuracy of the trigger efficiency measurement by a factor of 3:  $\epsilon_{\text{trig}, 2018} = (89 \pm 5)\%$  versus  $\epsilon_{\text{trig}, 2021-22} = (85.9 \pm 1.4)\%$ . The higher beam intensity for the 2021–2022 data-taking would result in a decrease of  $\epsilon_{\text{RV}}$  ( $1 - \epsilon_{\text{RV}}$  is the probability for a single event to be vetoed by accidental activity). However, significant modifications in the selection criteria allowed to maintain  $\epsilon_{\text{RV}}$  at a similar level:  $\epsilon_{\text{RV}, 2018} = (66 \pm 1)\%$  versus  $\epsilon_{\text{RV}, 2021-22} = (63.2 \pm 0.6)\%$ . The expected number of SM signal

events is  $N_{\pi\nu\nu}^{\text{SM}} = 9.91 \pm 0.34$ , which is roughly equal to that of the 2016–2018 dataset. The total expected background is  $N_{\text{bkg}} = 11.0_{-1.9}^{+2.1}$  with the dominant upstream background ( $7.4_{-1.8}^{+2.1}$ ). The details can be found in [7]. In total, 31 events were observed in the signal regions, see Fig. 2, left.

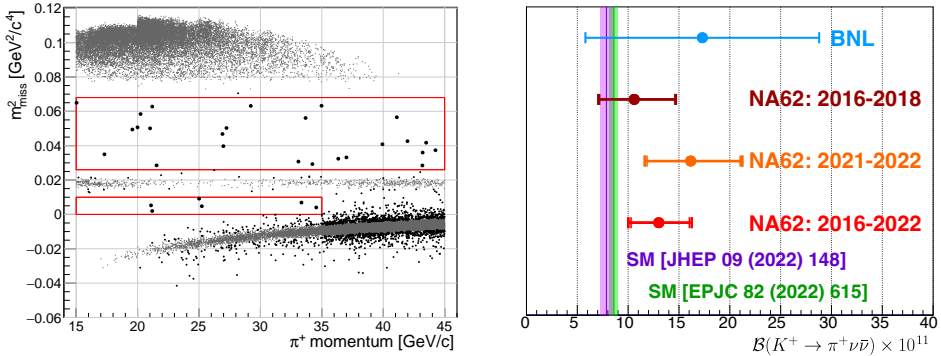


Fig. 2. (Colour on-line) Left: Distribution of the observed data events satisfying the signal selection criteria in the  $(\pi^+$  momentum,  $m_{\text{miss}}^2$ ) plane. Signal regions R1 and R2 are shown in red/grey boxes. Right: History of  $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$  measurements.

## 6. Combination of results from 2016–2022 data

The total number of background events is expected to be  $N_{\text{bkg}} = 18_{-2}^{+3}$ , while 51 candidates were observed. The  $p$ -value of the background-only hypothesis is  $2 \times 10^{-7}$ , which corresponds to its rejection with a significance above  $5\sigma$ . This is the first observation of the  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  decay. The statistical combination of all samples yields the branching ratio  $\text{BR} = (13.0_{-3.0}^{+3.3}) \times 10^{-11}$ , measured with a 25% relative precision, see Fig. 2, right.

## 7. Interpreting $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ as $K^+ \rightarrow \pi^+ X$ search

The  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  measurement has been reinterpreted as a search for a new feebly interacting particle  $X$  in the  $K^+ \rightarrow \pi X$  decay [11]. The new particle  $X$  could either be stable, or decay into particles (SM or invisible) which escape the experimental setup. In this case, the signal signature would be identical to that of  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ , with a peak in the  $m_{\text{miss}}^2$  distribution corresponding to  $m_X^2$ . A peak search on the  $m_{\text{miss}}^2$  spectrum (Fig. 3, left) has been performed, and the model-independent constraints are set for the scenario when  $X$  decays into visible particles.



The upper limits on the branching ratio are calculated for different ( $m_X, \tau_X$ ) hypotheses (see Fig. 3, right) and reinterpreted as exclusion limits for the case that  $X$  is a vector, scalar, axion-like particle (ALP) with fermion coupling, and ALP with gluon coupling respectively, as shown in Fig. 4.

## 8. Conclusions

Using the 2016–2022 dataset, the NA62 experiment was able to provide, for the first time, observation of the  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  decay with a significance in excess of 5 standard deviations and measured the branching ratio to be  $\text{BR} = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$ , with a relative uncertainty of 25%. This result has been reinterpreted as a search for the  $K^+ \rightarrow \pi^+ X$  decay, where  $X$  is a feebly interacting new particle.

The full NA62 dataset is expected to be collected by the end of 2026, aiming at tripling of the data sample with respect to the 2016–2022 one. With this full dataset, a branching ratio measurement with a precision of 15–20% is expected.

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