PROCEEDINGS OF SCIENCE

Measurement of the very rare $K^+ \to \pi^+\nu\bar{\nu}$ decay at the NA62 experiment at CERN

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The NA62 experiment reports the branching ratio measurement $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})$ at 68 % CL, based on the observation of 20 signal candidates with an expected background of 7.0 events from the total data sample collected at the CERN SPS during 2016-2018. This provides evidence for the very rare $K^+ \to \pi^+\nu\bar{\nu}$ decay, observed with a significance of 3.4σ. The experiment achieves a single event sensitivity of $(0.839 \pm 0.054) \times 10^{-11}$, corresponding to 10.0 events assuming the Standard Model branching ratio of $(8.4 \pm 1.0) \times 10^{-11}$. The result represents the most accurate measurement achieved so far of this ultra-rare decay. Future prospects and plans for data taking from 2021 will also be presented.

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1. Introduction

The $K^+ \to \pi^+ \nu\bar{\nu}$ decay is an ultra-rare process, which, according to the Standard Model (SM), proceeds via box and electroweak penguin diagrams. Its branching ratio is very cleanly predicted by the SM to be

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{SM}} = (8.4 \pm 1.0) \times 10^{-11},$$

where the uncertainty is dominated by the uncertainty on CKM parameters [1]. This process is sensitive to new physics beyond the SM and probes higher mass scales than other rare meson decays [2, 3]. A previous measurement of this branching ratio, using a decay-at-rest technique, was performed by the experiments E787 and E949 at BNL, giving $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(17.3^{+11.5}_{-10.5}\right) \times 10^{-11}$ [4].

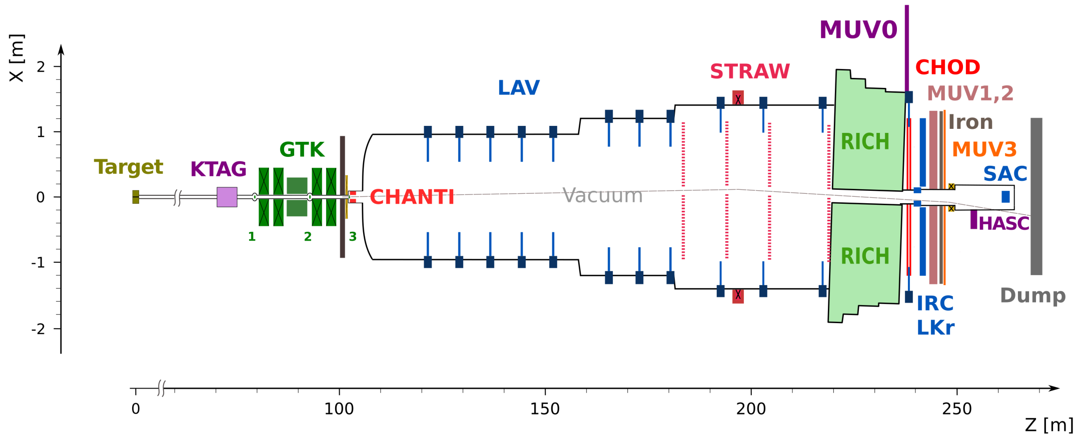


Figure 1: Schematic top view of the NA62 beam line and detector.

2. The NA62 detector

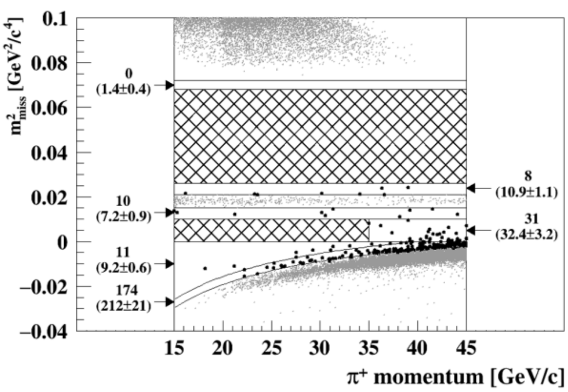
The NA62 beam line and apparatus are shown in figure 1. The NA62 beam originates from the collision of the 400 GeV/c proton beam coming from SPS with a beryllium target, and it consists of positively charged particles of (75.0 ± 0.8) GeV/c momentum, of which the K^+ component is 6 %. The KTAG, a differential Cherenkov detector filled with nitrogen, identifies kaons in the beam. The momentum and direction of beam particles is then measured by the Gigatracker (GTK), composed of three silicon pixel stations of $6 \times 3\,\mathrm{cm}^2$. Inelastic interactions between the beam and the last GTK station (GTK3) are tagged by the CHANTI. The charged particles coming from K^+ decays are detected downstream by a magnetic spectrometer, using four STRAW chambers, to measure their momentum and direction. A 17 m long RICH discriminates π^+, μ^+ and e^+, and, with an array of scintillators (CHOD), provides a measure of the time of the decay products with a 100 ps resolution. In order to further separate π^+ and μ^+, two hadronic calorimeters (MUV1,2) and a fast scintillator array (MUV3), are used. Calorimetric information is provided by a LKr calorimeter, which complements a photon veto system (LAV, IRC, SAC) that hermetically covers angles up to 50 mrad from the beam axis. A much more detailed description of the NA62 apparatus is found in [5].

3. $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ analysis

The experimental signature of a $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ event is an incoming K^+ and an outgoing π^+, with missing energy in the final state. In order to kinematically discriminate the signal from other K^+ decays, the squared missing mass $m^2_{\mathrm{miss}} = (p_{\mathrm{K}} - p_\pi)^2$ is used, where p_{K} and p_π are, respectively, the 4-momenta of the K^+ and of the downstream charged particle, in the π^+ mass hypothesis.

The criteria used to select signal events are described in the following. The downstream detectors STRAW, CHOD and RICH are used to select events with a single-track decay topology: the track, reconstructed with the STRAW, must have a matching pair of slabs in CHOD and a matching reconstructed ring in the RICH. This downstream charged track is then associated to an in-time signal in the KTAG detector and to a GTK track, defining a K^+. The kaon decay vertex is defined via the GTK and STRAW tracks, and is required to be inside a 60 m long fiducial volume, starting 10 m downstream of GTK3. π^+ identification is provided by two complementary algorithms: one is cut-based, using a track-driven likelihood discriminant and using the particle mass as determined by the RICH; the other is a multivariate analysis with boosted decision trees, using energy deposition, energy sharing and shower shape profiles in LKr and MUV1,2, and signals from MUV3. In this manner, a π^+ identification efficiency of 68 % and a μ^+ misidentification probability of $O(10^{-8})$ are attained. Finally, photon and multi-charged particle rejection are applied, based on signals in the photon veto system and in the CHOD.

The 2016 and 2017 data analysis is described in more detail in [6] and [7]. The 2018 data set is divided in two subsamples, S1 and S2, corresponding to before and after the installation of a new collimator which mitigates the background from K^+ decays upstream of GTK3 (upstream background) entering the fiducial volume through the aperture of the last dipole of the beam achromat. The analysis of S1 is similar to the analysis of the 2017 data, but with optimized fiducial



(a)

Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

(b)

Figure 2: Background evaluation for the 2018 sample. (a) Reconstructed m^2_{miss} in selected events, as function of the π^+ momentum. Events in the background regions are displayed as light grey dots. The control regions, populated by the solid black markers, are adjacent to the background regions. Next to the control regions, the observed and expected number of background events are reported. The signal regions (hatched rectangles) are kept blind until the completion of the analysis. (b) Expected number of background events in the signal regions.

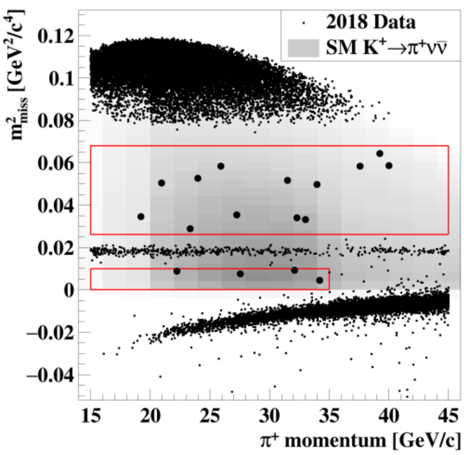
volume and signal region definitions, while the analysis of S2, which benefits from the presence of the new collimator, includes major improvements, that increase signal acceptance while retaining a good separation between signal and upstream background. The S2 sample, containing 80 % of the 2018 data set, is subdivided into 6 categories, defined by 5 GeV/c wide momentum bins, and the selection is optimized separately for each category.

The single event sensitivity (SES) is calculated via the following expression:

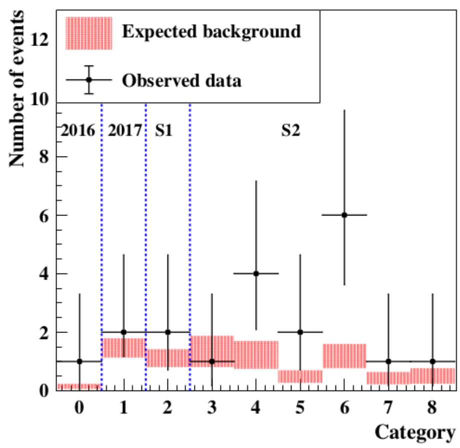
$$\mathrm{SES} = \frac{\mathrm{BR}(\mathrm{K}^+ \to \pi^+\pi^0)}{N_{\pi\pi}\varepsilon_{\mathrm{trig}}\varepsilon_{\mathrm{RV}}} \frac{A_{\pi\pi}}{A_{\pi\nu\bar{\nu}}},$$

where: $N_{\pi\pi}$ is the number of $\mathrm{K}^+ \to \pi^+\pi^0$ normalization events collected (selected from a minimum bias sample with a selection similar to the signal but without photon and multi-charged particle rejection applied); $\varepsilon_{\mathrm{trig}}$ is the trigger efficiency; $1 - \varepsilon_{\mathrm{RV}}$ is the random veto inefficiency, induced by the photon and multi-charged particle rejection, and is estimated from data; $A_{\pi\pi}$ and $A_{\pi\nu\bar{\nu}}$ are the signal and normalization acceptances, respectively, evaluated via Monte Carlo simulations. The use of $\mathrm{K}^+ \to \pi^+\pi^0$ as a normalization channel results in cancellation of systematic effects.

The expected number of background events for the 2018 sample is summarized in figure 2b. Background from $\mathrm{K}^+ \to \pi^+\pi^0$, $\mathrm{K}^+ \to \mu^+\nu$ and $\mathrm{K}^+ \to \pi^+\pi^+\pi^-$ enters the signal regions if m^2_{miss} is misreconstructed; the estimation of these backgrounds is data-driven, and uses selections that are assumed to be independent of m^2_{miss}. Background from $\mathrm{K}^+ \to \pi^+\pi^-\mathrm{e}^+\nu$, $\mathrm{K}^+ \to \pi^+\gamma\gamma$ and semileptonic decays is evaluated via simulations. The background prediction for K^+ decays is validated by unmasking control regions (figure 2a). The upstream background is also estimated from data, and the prediction is validated using a separate sample orthogonal to the signal selection, obtained by inverting some of the selection criteria.



(a)



(b)

Figure 3: $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ candidate events. (a) Reconstructed m^2_{miss} in 2018 data, as function of the π^+ momentum, after unmasking the signal regions (represented as red boxes). The intensity of the grey shaded area reflects the expected SM distribution of signal events. (b) Expected and observed numbers of background events in the nine categories of data. Categories 3 to 8 correspond to the six 5 GeV/c wide momentum bins of S2.

4. Results and prospects

After unblinding the signal regions, 17 events have been found in the 2018 dataset, distributed as shown in figure 3a. Combining the result of the $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ analysis performed on 2016 [6], 2017 [7] and 2018 [8] data, 20 candidate $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ events are observed in total.

The SES and the expected numbers of signal and background events are, respectively, SES = $(0.839 \pm 0.053_{\mathrm{syst}}) \times 10^{-11}$, $N^{\mathrm{exp}}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{\mathrm{syst}} \pm 1.19_{\mathrm{ext}}$, and $N^{\mathrm{exp}}_{\mathrm{bg}} = 7.03^{+1.05}_{-0.82}$. The statistical uncertainty in the SES and in $N^{\mathrm{exp}}_{\pi\nu\bar{\nu}}$ are negligible, and the external uncertainty in the latter is due to the SM prediction of $\mathrm{BR}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$).

In order to obtain the final branching ratio, a maximum likelihood fit is performed using the signal and background expectation in the 9 categories shown in figure 3b. The resulting measurement is

$$\mathrm{BR}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.5}\big|_{\mathrm{stat}} \pm 0.3_{\mathrm{syst}}) \times 10^{-11} \text{ at } 68\,\%\ \mathrm{CL}\,.$$

The result is compatible with the SM prediction within one standard deviation, and corresponds to a significance of 3.4σ, estimated using the CLs method. This is the most precise measurement of this branching ratio so far.

NA62 is currently in its second run of data taking, and will continue acquiring data until 2024 at a greater intensity. New subdetectors have been added with the aim of further reducing the upstream background; the improvement of Monte Carlo simulations and the implementation of machine learning techniques will also be important in order to improve the signal sensitivity.

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