Conference Paper

Search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at NA62

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Received: 25 December 2017
Accepted: 2 February 2018
Published: 9 April 2018

Publishing services provided by Knowledge E

Selection and Peer-review under the responsibility of the ICPPA Conference Committee.

Abstract

$K \rightarrow \pi \nu \bar{\nu}$ is one of the theoretically cleanest meson decay where to look for indirect effects of new physics complementary to LHC searches. The NA62 experiment at CERN SPS is designed to measure the branching ratio of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay with 10% precision. NA62 took data in 2015-2017; the analysis of a partial data set allows to reach the Standard Model sensitivity. The status of the experiments will be here reviewed, and prospects will be presented.

How to cite this article: Silvia Martellotti, (2018), "Search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at NA62" in *The 3rd International Conference on Particle Physics and Astrophysics*, KnE Energy & Physics, pages 372–378. DOI 10.18502/ken.v3i1.1769

1. Introduction

The $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ are flavour changing neutral current decays proceeding through box and electroweak penguin diagrams as shown in Fig.1. A quadratic GIM mechanism and strong Cabibbo suppression make these processes extremely rare. Using the value of tree-level elements of the Cabibbo-Kobayashi-Maskawa (CKM) triangle as external inputs, the Standard Model (SM) predicts[1][2]:

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11},\ BR(K_L \to \pi^0 \nu\bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}.$$

The theoretical accuracy is at the percent level, because short distance physics dominates thanks to the top quark exchange in the loop. The hadronic matrix elements cancel almost completely in the normalization of the $K \to \pi\nu\bar{\nu}$ branching ratios to the precisely measured BR($K^+ \to \pi^0 e^+ \nu_e$). Experimental knowledge of the external inputs dominate the uncertainties on these predictions. The dependence on CKM parameters partially cancels in the correlation between $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$. Therefore simultaneous measurements of the two BRs would allow a theoretically clean investigation of the CKM triangle using kaons only. The $K \to \pi\nu\bar{\nu}$ decays are extremely sensitive to physics beyond the SM, probing the highest mass scales among the rare meson decays. The largest deviations from SM are expected in models with new sources of flavour violation, owing to weaker constraints from B physics [3][4]. The experimental value of ϵ_K, the parameter measuring the indirect CP violation in neutral kaon decays, limits the range of variation expected for $K \to \pi\nu\bar{\nu}$ BRs within models with currents of defined chirality, producing typical correlation patterns between charged and neutral modes[5]. Results from LHC direct searches strongly limit the range of variation, mainly in supersymmetric models[6][7]. In any case, due to the suppression of this decay in the SM, significant variations of the $K \to \pi\nu\bar{\nu}$ BRs from the SM predictions induced by new physics at mass scales up to 100 TeV are still observable by experiment with at least 10% precision, even with existing constraints from other measurements in K physics.

The most precise experimental result has been obtained by the dedicated experiments E787 and E949 at the Brookhaven National Laboratory which collected a total of 7 events using a decay-at-rest technique. Only the charged mode has been observed so far, and the present experimental status is[8][9][10]:

$$BR(K^+ \to \pi^+ \nu\bar{\nu})_{exp} = (17.3^{+11.5}_{-10.5}) \times 10^{-11},\ BR(K_L \to \pi^0 \nu\bar{\nu})_{exp} < 2.6 \times 10^{-8}\ 90\% CL,$$

still far from the precision of the SM prediction.

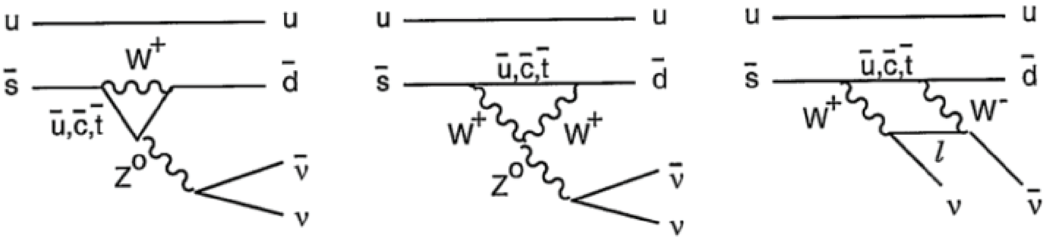

Figure 1: Box diagram and Z-penguin diagrams contributing to the process $K \to \pi\nu\bar{\nu}$.

2. The NA62 experiment at CERN.

The NA62 experiment at CERN[11][12] aims to measure the $BR(K^+ \to \pi^+\nu\bar{\nu})$ with 10% precision. Therefore it needs to collect about $10^{13}K^+$ decays using 400 GeV/c protons from SPS for a 10% signal acceptance. Keeping the background to signal ratio about 10% requires the use of almost independent experimental techniques to suppress unwanted final states. With a single event sensitivity of 10^{-12} NA62 can afford also a broader physics program[13]. NA62 is running with the apparatus fully operational since 2016.

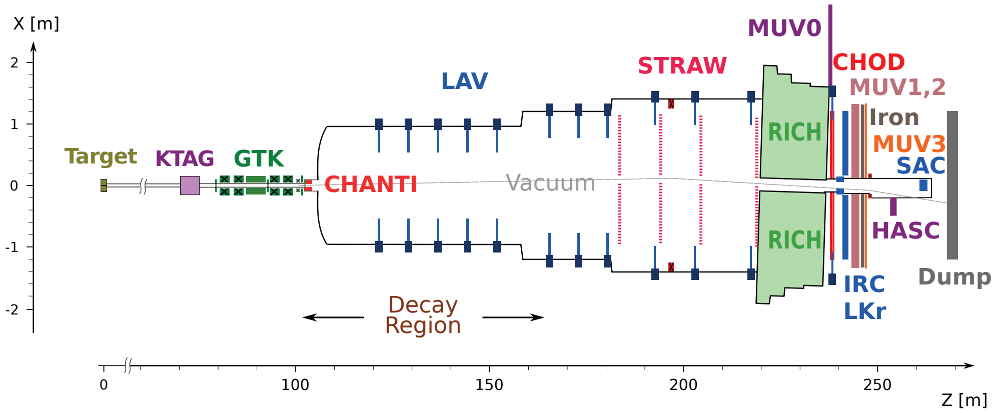

Figure 2: Schematic layout of the NA62 experiment in the xz plane.

NA62 adopts a kaon decay-in-flight technique. Fig.2 shows a schematic view of the apparatus. Primary SPS protons strike a target from which a secondary charged hadron beam of 75 GeV/c and 1% momentum bite is selected and transported to the decay region. The detailed descriptions of the apparatus can be found in[14]. The incoming kaon is positively identified by a differential Cerenkov counter (KTAG) and its momentum and direction are measured by three stations of Si pixel detectors (GTK). About 6% of beam particles are K^+. A guard ring detector (CHANTI) vetoes beam inelastic interactions occurring in GTK. A decay tank at vacuum (10^{-6} mbar) is surrounded by ring-shaped lead-glass calorimeters designed to intercept photons at polar angles of up to 50 mrad (LAV). Four stations of straw chambers (STRAW) in vacuum track downstream charged particles, with a dipole magnet providing a 270 MeV/c transverse kick for momentum analysis. A RICH counter time-stamps and identifies charged particles; plastic scintillators (CHOD) are used for triggering and timing. Photon rejection in the forward region is provided by an electromagnetic calorimeter of liquid krypton (LKr) and two small angle calorimeters (IRC and SAC). Hadron calorimeters (MUV1,2) and a plastic scintillator detector (MUV3) are used to suppress muons. At full intensity, the SPS delivers 3.3×10^{12} protons per pulse to NA62, corresponding to a particle rate of 750 MHz in the GTK. Information from CHOD, RICH, MUV3 and LKr are built up online to issue level zero trigger conditions. Software-based variables from KTAG, CHOD, LAV and STRAW provide higher level trigger requirements. $K^+ \to \pi^+\nu\bar{\nu}$-triggered data are taken concurrently with downscaled samples of data for rare kaon decays studies and minimum bias. The NA62 apparatus has been commissioned in 2015 and 2016. Low intensity data have been taken in 2015 with a minimum bias trigger to study detector performances and to perform physics analysis. In fall 2016 NA62 has collected about 4.5×10^{11} kaon decays for $K^+ \to \pi^+\nu\bar{\nu}$ at 20-40% of nominal intensity. A four-month run dedicated to $K^+ \to \pi^+\nu\bar{\nu}$ has taken place in 2017 at 50-60% of the nominal intensity and another one is scheduled in 2018.

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

The analysis of 5% of the 2016 dataset corresponding to 2.3×10^{10} kaons is presented here. The $K^+ \to \pi^+\nu\bar{\nu}$ signature is one track in the initial and final state with two missing neutrinos. The main kinematic variable is $m^2_{miss} = (P_K - P_\pi)^2$, where P_K and P_π are the 4-momenta of the K^+ and π^+ respectively.

The theoretical shapes of the m^2_{miss} distribution for the main K^+ background decay modes are compared to the $K^+ \to \pi^+\nu\bar{\nu}$ on Fig.3. The analysis is done in the π^+ momentum range between 15 and 35 GeV/c to leave at least 40 GeV of electromagnetic energy in the calorimeters in the case of $K^+ \to \pi^+\pi^0(K_{\pi2})$ decay. Two regions are used: region 1 between $K^+ \to \mu^+\nu_\mu(K_{\mu2})$ and $K_{\pi2}$ and region 2 between $K_{\pi2}$ and $K^+ \to \pi^+\pi^+\pi^-(K_{\pi3})$. The main backgrounds entering those regions are $K_{\mu2}$ and $K_{\pi2}$ decays through non gaussian resolution and radiative tails; $K_{\pi3}$ through non-gaussian resolution; $K^+ \to \pi^+\pi^-e^+\nu_e(K_{e4})$ and $K^+ \to {}^+\pi^0\nu_l(K_{l3})$ by not detecting the extra π^-, e^+, π^0 particles. Another important source of background is the beam-related background coming from upstream decays and beam-detector interactions. Each of the background processes requires a different rejection procedure depending on its kinematics and type of charged particle in the final state. The main requirements for the analysis are

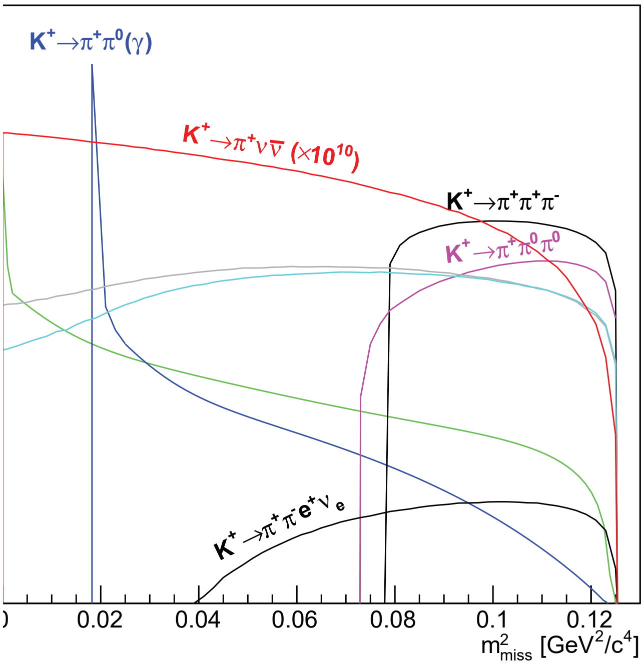

Figure 3: m^2_{miss} distributions for signal and backgrounds of the main K^+ decay modes are shown in log scale: the backgrounds are normalized according to their branching ratio; the signal is multiplied by a factor 10^{10}.

excellent kinematic reconstruction to reduce kinematic tails; precise timing to reduce the kaon mis-tagging probability; no extra in-time activity in all of the electromagnetic calorimeters to suppress $K^+ \to \pi^+\pi^0$ decays with $\pi^0 \to \gamma\gamma$ (photon rejection); clear separation between $\pi/\mu/e$ tracks to suppress decays with μ^+ or e^+ in the final state (particle identification). Low multiplicity cuts in the downstream detectors are used to further suppress decays with multiple charged tracks in the final state. The parent K^+ track is reconstructed and time-stamped in the GTK with 100 ps resolution; the daughter π^+ track is reconstructed in the STRAW. The CHOD and RICH measure π^+ time with resolution below 100 ps. The pion is associated in time to a KTAG kaon signal. The timing and the closest distance of approach between GTK and STRAW tracks allow a precise $K^+ - \pi^+$ matching. The kaon mistagging probability at 40% of nominal intensity is below 2%, signal acceptance about 75%.

Decays are selected within a 50 m fiducial region beginning 10 m downstream of the last GTK station (GTK3) to reject events originated from interactions of beam particles in GTK and kaon decays upstream of GTK3. Figure 4 (left) exemplifies the kinematics of the selected events. The resolution of m^2_{miss} drives the choice of the boundaries of the signal regions. Reconstruction tails from $K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu_\mu$ and $K^+ \to \pi^+\pi^+\pi^-$ set the level of background in signal regions. To reduce it, signal regions are restricted to

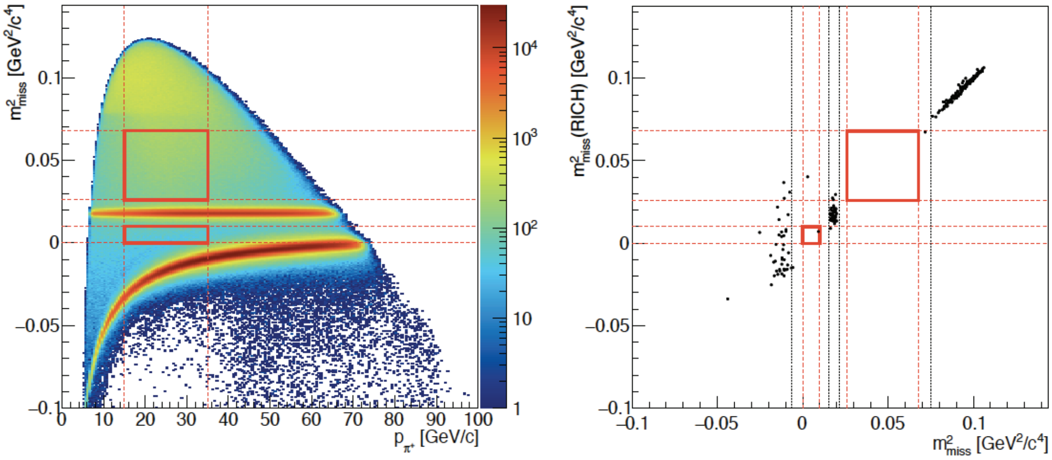

Figure 4: Left: distribution of m^2_{miss} vs track momentum for events selected on minimum bias data; the bands corresponding to $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu$ decays are clearly visible; the signal regions (red box) are drawn for reference. Right: distribution in the (m^2_{miss}(RICH), m^2_{miss}) plane of $K^+ \to \pi^+\nu\bar{\nu}$-triggered events passing the selection, except for the cut on m^2_{miss}(No-GTK); signal regions (red tick boxes) and lines defining background regions (light dashed lines) are drawn; the event in region 1 has m^2_{miss}(No-GTK) outside the signal region.

boxes within a 3D space, defined by i) m^2_{miss}; ii) the same quantity computed using the momentum of the particle measured by the RICH under π^+ hypothesis, rather than the straws (m^2_{miss}(RICH)); iii) the same quantity computed replacing the 3-momentum of the kaon measured by the GTK with the nominal 3-momentum of the beam m^2_{miss}(No-GTK). The probability for $K^+ \to \pi^+\pi^0$ ($K^+ \to \mu^+\nu_\mu$) to enter the signal regions is 6×10^{-4} (3×10^{-4}), as measured with data. Calorimeters and RICH separate π^+, μ^+, and e^+. A multivariate analysis combines calorimetric information and provides $10^5 \mu^+$ suppression and 80% π^+ efficiency. RICH quantities are used to infer particle types, giving $10^2 \mu^+$ suppression and 80% π^+ efficiency. The two methods are independent and therefore able to suppress μ^+ by 7 orders of magnitude while keeping 65% of π^+. Remaining events after π^+ identification are primarily $K^+ \to \pi^+\pi^0$. Photon rejection exploiting timing coincidences between π^+ and calorimetric deposits suppresses them further. The resulting π^0 rejection inefficiency is $(1.2 \pm 0.2) \times 10^{-7}$, as measured from minimum bias and $K^+ \to \pi^+\nu\bar{\nu}$-triggered events before and after γ rejection, respectively. Random losses are in the 15-20% range.

A sample of $K^+ \to \pi^+\pi^0$ from minimum bias is used for normalization. About 0.064 $K^+ \to \pi^+\nu\bar{\nu}$ events are expected over $2.3 \times 10^{10} K^+$ decays. Figure 4 (right) shows the distribution of residual events in the m^2_{miss}(RICH) versus m^2_{miss} plane. Backgrounds from $K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu_\mu$ and $K^+ \to \pi^+\pi^+\pi^-$ are 0.024, 0.011 and 0.017, respectively. They are estimated directly from events outside signal regions, with the measured kinematic tails used for extrapolation in signal regions. Simulation studies indicate that background from other processes is lower or negligible. The analysis is still ongoing together with an optimization of the selection to further reduce backgrounds and increase signal acceptance. No events are observed in signal regions.

4. Conclusions

The kaon experiment NA62 at CERN is running to search for physics beyond the SM through the ultra rare $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decay. The performance of the experiments is within expectations. No events were found after the analysis of $2.3 \times 10^{10} K^+$ decays corresponding to 5% of the full 2016 dataset. NA62 is expected to reach the SM sensitivity ($\mathcal{O}(1)$) from the analysis of the 2016 full dataset and to select some tens of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ events from the analysis of the data taken in 2017 and from the already scheduled 2018 run.

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