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$K^+ \to \pi^+ \nu\bar{\nu}$ with NA62: 2016 results and prospects

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Summary. — The ultra rare $K \to \pi\nu\bar{\nu}$ process is one of the theoretically cleanest meson decay where to look for a stringent test of the Standard Model (SM). The NA62 experiment at CERN SPS is designed to measure the branching ratio of the $K^+ \to \pi^+\nu\bar{\nu}$ decay with 10% precision. After commissioning, in 2016 first data set good for physics has been collected. The data taking is foreseen till the LS2 at the end of 2018. Results obtained with the full 2016 data sample will be presented togheter with prospects for 2017 and 2018 data sets.

1. – Introduction

The $K^+ \to \pi^+\nu\bar{\nu}$ is a flavour changing neutral current decay proceeding through box and electroweak penguin diagrams as shown in fig. 1. A quadratic GIM mechanism and strong Cabibbo suppression make this process extremely rare. Using the value of tree-level elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix as external inputs, the Standard Model predicts [1]:

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

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 ratio to the precisely measured BR($K^+ \to \pi^0 e^+\nu_e$). Experimental knowledge of the external inputs dominates the uncertainties on this prediction. The $K^+ \to \pi^+\nu\bar{\nu}$ decay is extremely sensitive to physics beyond the SM, probing the highest mass scales among the rare and ultra 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 [2, 3]. 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 [4]. The most precise experimental result has been obtained by the E787 and E949 Collaborations at the Brookhaven National Laboratory which collected a total of 7 events using a decay-at-rest technique. The present experimental status is [5, 6]: $BR(K^+ \to \pi^+\nu\bar{\nu})_{exp} = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$, still far from the precision of the SM prediction.

2. – The NA62 experiment at CERN

The NA62 experiment at CERN [7] aims to measure the $BR(K^+ \to \pi^+\nu\bar{\nu})$ with 10% precision. In order to achieve its goal, it needs to collect about 10^{13} K^+ decays using 400 GeV/c protons from SPS. Keeping the background to signal ratio about 10% requires the use of almost independent experimental techniques to suppress unwanted final states. NA62 is running with the apparatus fully operational since 2016 and it adopts a kaon decay-in-flight technique. Figure 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

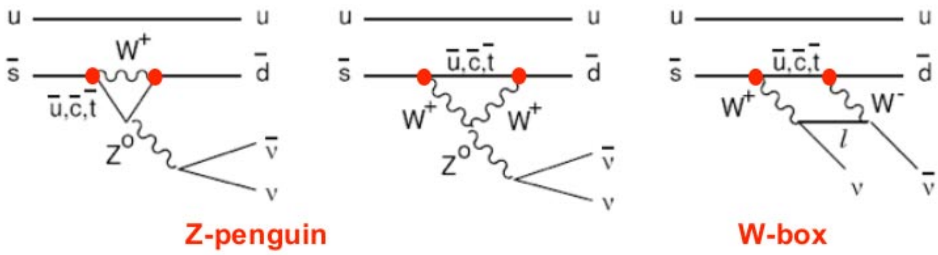

Fig. 1. – Box and Z-penguin diagrams contributing to the process $K \to \pi\nu\bar{\nu}$.

and 1% momentum bite is selected and transported to the decay region. About 6% of beam particles are K^+. The detailed descriptions of the apparatus can be found in [7]. 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). A guard ring detector (CHANTI) vetoes beam inelastic interactions occurring in GTK stations (in particular in the third). 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, between the second and the third station, providing a 270 MeV/c momentum kick. 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 about 750 MHz in the GTK. Information from CHOD,

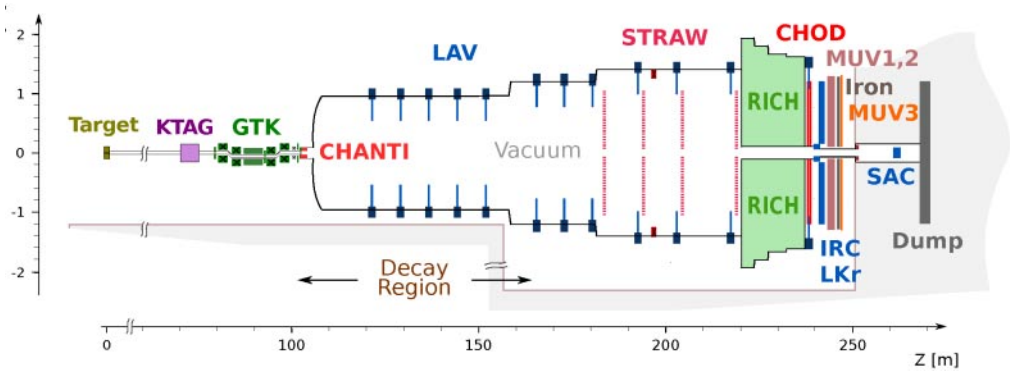

Fig. 2. – Schematic layout of the NA62 experiment in the xz plane.

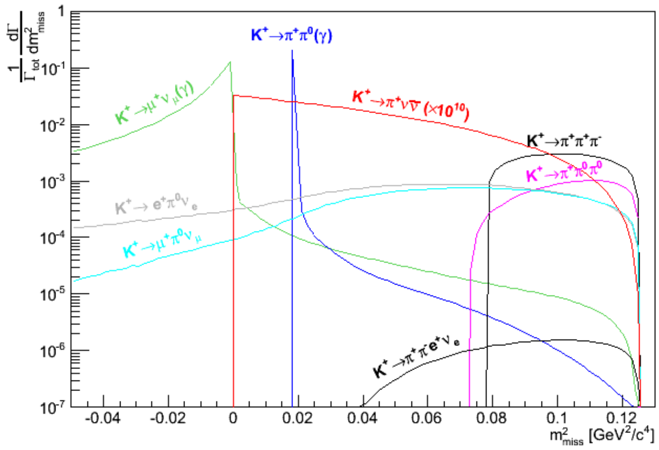

Fig. 3. – Squared missing mass distributions for signal and backgrounds of the main K^+ decay modes are shown in log scale: the backgrounds are normalized according to their branching ratio; the signal is multiplied by a factor 10^{10}.

RICH, MUV3 and LKr are built up online, in an hardware L0 trigger processor [8], to issue level zero trigger conditions [9]. Software-based variables from KTAG, 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. In fall 2016, NA62 started its data taking with the full commissioned detector 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 at 60–70% in 2018 in a seven-month run.

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

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 the squared missing mass $m^2_{miss} = (P_K - P_\pi)^2$, 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 and to optimize the $\pi^+ - \mu^+$ identification with the RICH. For the signal selection, 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 $K^+ \to l^+\pi^0\nu_l(K_{l3})$ 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.

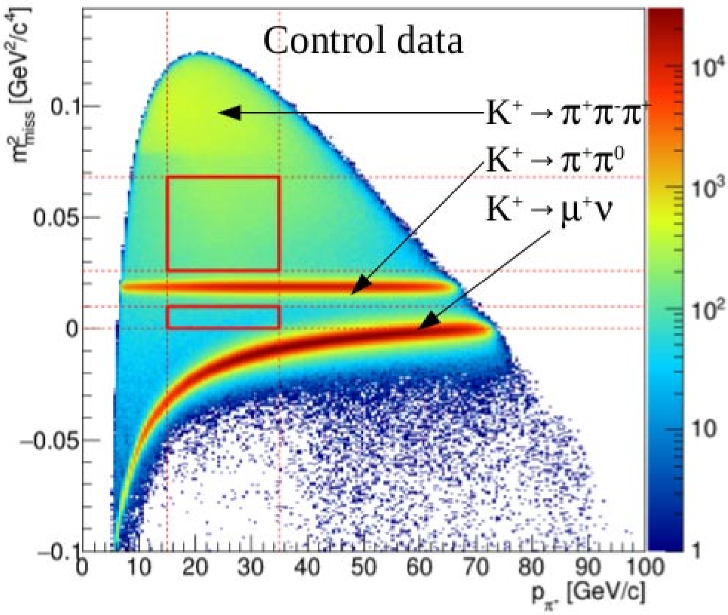

Fig. 4. – Distribution of m^2_{miss} as a function of pion momentum for kaon events selected on control data. The signal regions (red box) in the (m^2_{miss}, P_{π^+}) plane are drawn for reference. The small box is region 1 and the biggest is region 2.

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 excellent kinematic reconstruction to reduce tails in the squared missing mass; precise timing between upstream and downstream detectors to reduce the kaon mis-tagging probability and to match the incoming kaon and the outcoming charged pion; no extra in-time activity in all of the electromagnetic calorimeters to suppress decays with at least 2 photons in the final state, in particular $K^+ \to \pi^+\pi^0$ 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 incoming K^+ track is reconstructed and time-stamped in the GTK with 100 ps time resolution; the outcoming π^+ track is reconstructed in the STRAW. The 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. 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. 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 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

TABLE I. – *Summary of the expected number of signal and background events in region 1 and region 2 after the full selection. Errors are added in quadrature to obtain the uncertainty on the total expected background.*

Process	Expected events
$K^+ \to \pi^+\nu\bar{\nu}$(SM)	$(0.267 \pm 0.001_{stat} \pm 0.020_{sys} \pm 0.032_{ext})$
$K^+ \to \pi^+\pi^0\gamma$(IB)	$(0.064 \pm 0.007_{stat} \pm 0.006_{sys})$
$K^+ \to \mu^+\nu\gamma$(IB)	$(0.020 \pm 0.003_{stat} \pm 0.006_{sys})$
$K^+ \to \pi^+\pi^-e^+\nu$	$(0.013^{+0.017}_{-0.012}{}_{stat} \pm 0.009_{sys})$
$K^+ \to \pi^+\pi^+\pi^-$	$(0.002 \pm 0.001_{stat} \pm 0.002_{sys})$
Upstream background	$(0.050^{+0.090}_{-0.030}{}_{stat})$
Total background	$(0.152^{+0.092}_{-0.033}{}_{stat} \pm 0.013_{sys})$

(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)). Calorimeters and RICH separate π^+, μ^+, and e^+. A multivariate analysis combines calorimetric information and toghter with RICH quantities are used to infer particle types. The two methods, calorimeters and RICH, are independent and therefore able to give 10^8 μ^+ suppression while keeping 64% of π^+. At the end of the selection the $K^+ \to \pi^+\nu\bar{\nu}$ acceptance is 1% in region 1 and 3% in region 2.

Assuming a number of kaons decayed in the fiducial decay volume, $N_K = (1.21 \pm 0.02) \times 10^{11}$, measured with a sample of $K^+ \to \pi^+\pi^0$ selected with a Control Trigger (based on signal coming from the CHOD), the single event sensitivity (SES) has been evaluated, $SES = (3.15 \pm 0.02_{stat} \pm 0.24_{sys}) \times 10^{-10}$ obtained from the following formula:

$$SES = \frac{1}{N_k \times \sum_j (A^j_{\pi\nu\nu} \times \epsilon^j_{RV} \epsilon^j_{trig})}$$

where $A^j_{\pi\nu\nu}$ is the signal acceptance in momentum bin j, ϵ^j_{RV} is the random veto efficiency in the same momentum bin and ϵ^j_{trig} is the trigger efficiency again in the same bin. Using the value of the single event sensitivity and the SM prediction of the Branching Ratio the number of expected Standard Model $K^+ \to \pi^+\nu\bar{\nu}$ events is:

$$N_{\pi\nu\bar{\nu}}(SM) = (0.267 \pm 0.001_{stat} \pm 0.020_{sys} \pm 0.032_{ext})$$

the external error is due to the SM prediction.

4. – Results

In table I the background contributions are reported for the single decays. A part the $K^+ \to \pi^+\pi^-e^+\nu$ where the background estimation has been evaluated with Monte Carlo, all the other contributions have been obtained with a data driven procedure and the result has been checked in control regions around the two signal regions.

After un-masking one event is found in signal region 2, see fig. 5. The $K^+ \to \pi^+\nu\bar{\nu}$ candidate event has 15.3 GeV/c momentum and is perfectly consistent with a charged

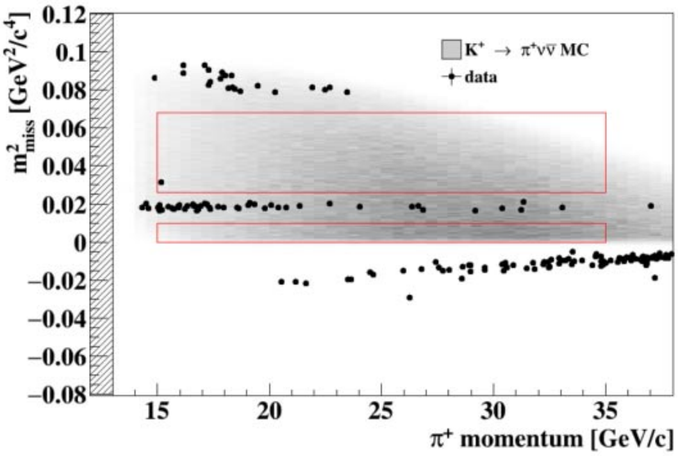

Fig. 5. – Distribution of m^2_{miss} as a function of pion momentum at the end of signal selection. One event in region 2 is visible.

pion track in the RICH detector. Upper limit on the branching ratio of the $K^+ \to \pi^+\nu\bar{\nu}$ decay has been obtained using the CLs method [10]:

$$BR(K^+ \to \pi^+\nu\bar{\nu}) < 14 \times 10^{-10} 95\% \text{ CL}.$$

5. – Prospects

In order to mitigate the background coming from upstream decays the following two actions have been taken. First during the last part of the 2017 data taking an additional shielding has been installed in the beam line. Second, in the middle of 2018 data taking a new final collimator has been installed with the same aim of mitigation of the upstream contribution.

The analsysis of the 2017 data sample is ongoing and preliminary results indicates that the background contribution is stable, not increasing with the intensity and the actions taken to reduce the upstream decays are effective.

The NA62 Collaboration is planning to resume the data taking after the long shutdown 2 (2019–2020) to complete its $\pi\nu\bar{\nu}$ program and reach the 10% precision.

6. – Conclusions

The first NA62 $K^+ \to \pi^+\nu\bar{\nu}$ result [11], based on the analysis of the full 2016 data set, has been reported demostrating that the decay in-flight technique works. Considering $(1.21 \pm 0.02) \times 10^{11}$ kaon decays in the fiducial volume we expect $(0.267 \pm 0.001_{stat} \pm 0.020_{sys} \pm 0.032_{ext})$ $K^+ \to \pi^+\nu\bar{\nu}$ assuming the SM prediction. One event has been observed in the region 2 providing an upper limit of 14×10^{-10} at 95% CL for the Branching Ratio. The analysis of the 2017 data samples is ongoing and we expect improvements in the background rejection.

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