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$K^+ \to \pi^+ \nu\bar{\nu}$ first NA62 results

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The $K^+ \to \pi^+ \nu\bar{\nu}$ decay is characterised by a very precise prediction in the Standard Model (SM). Its branching ratio, which is expected to be less than 10^{-10} is one of the best candidates to indicate indirect effects of new physics beyond SM at the highest mass scales. The NA62 experiment at CERN SPS is designed to measure the branching ratio of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay with an in-fight technique, never used before for this measurement. NA62 is taking data since in 2016 with the goal to reach the SM sensitivity, an accuracy of the order of 10%. In 2017 it has then collected 10 times more statistics and a similar amount of data is expected from the 2018 run. The preliminary result on $K^+ \to \pi^+ \nu\bar{\nu}$ from the full 2016 data set and prospects for future developments are presented.

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1. $K^+ \to \pi^+ \nu\bar{\nu}$ decay: theoretical prediction and experimental status

The rare decay $K^+ \to \pi^+ \nu\bar{\nu}$ ($K_{\pi\nu\bar{\nu}}$) is a golden channel for high-precision tests of the Standard Model (SM). It is a Flavour Changing Neutral Current (FCNC) process, forbidden at the tree-level in the SM. The decay can be described by a short-distance effective hamiltonian in which the main contribution comes from top quark loops with a sub-leading contribution from charm. The hadronic matrix element can be related via isospin symmetry to the one of K^+_{e3} decay, measured with good accuracy. For this reason, the prediction is essentially not affected by hadronic uncertainties. This makes the $K_{\pi\nu\bar{\nu}}$ very clean theoretically and sensitive to physics beyond the SM. The SM prediction for the Branching Ratio (BR) of $K_{\pi\nu\bar{\nu}}$ is [1]:

$$BR(K_{\pi\nu\bar{\nu}}) = (8.4 \pm 1.0) \times 10^{-11}. \tag{1.1}$$

The knowledge of the external inputs dominate the uncertainties on the predictions. Experiments E787 and E949 at Brookhaven National Laboratory performed a measurement of this BR using stopped kaons; the result was [2]:

$$BR(K_{\pi\nu\bar{\nu}}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}. \tag{1.2}$$

The branching ratio is $\sim 1\sigma$ away from the SM prediction, but the measurement was based on only few events and the experimental uncertainties are large.

1.1 The NA62experiment at CERN

The fixed target NA62 experiment aims at measuring the branching ratio of the decay $K_{\pi\nu\bar{\nu}}$ with a 10% precision. A sample of about 10^13 kaon decays should be collected in few years and a maximum of 10% of background contamination is required, necessitating a background rejection factor of the order of 10^12. The experiment is located in the North Area of CERN; here, a primary beam of protons with a momentum of 400 GeV/c hits a beryllium target to create a non-separated beam of hadrons of 75 GeV/c momentum. This secondary beam, made of pions (70%), protons (23%) and kaons (6%) reaches the 260 m long apparatus of NA62, shown in Figure1. The

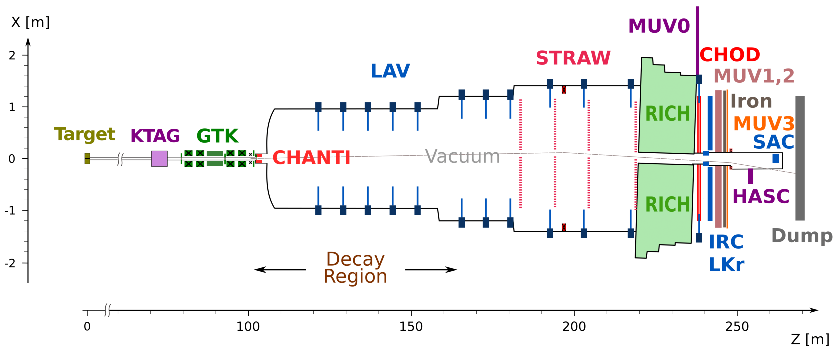

Figure 1: A schematic illustration of NA62 apparatus in x-z plane.

experimental technique used by NA62 is the in-flight detection of kaon decays in a 80 m long fiducial volume. Kaons are identified by a Cherenkov differential counter (KTAG) which also provides timestamps for them. Kaon momentum is measured by the GigaTracKer (GTK), a three-station silicon spectrometer. To reject background coming from inelastic interactions between the kaons and the GTK, a veto detector (CHANTI) is located downstream the last station of the tracker. The momenta of the downstream particles are measured by a straw tubes spectrometer; (STRAW) a Ring Imaging CHerenkov detector (RICH) provides π^+ identification and reject e^+ and μ^+. Fast timing informations come from the RICH and a scintillation hodoscope (CHOD), placed downstream to it. A background rejection factor at the order of 10^{12} is required to separate the signal from the other kaon decays, whose BRs are several order of magnitudes higher than the signal, like $K^+ \to \mu^+\nu$ ($K_{\mu 2}$, $BR = 63\%$) and $K^+ \to \pi^+\pi^0$ ($K_{\pi 2}$, $BR = 21\%$). Two hadronic calorimeters (MUV1 and MUV2) and a fast scintillator array (MUV3) provide further separation between π^+ and μ^+. A set of photons vetoes (LAVs, LKr, IRC, SAC) hermetically cover angles up to 50 mrad to reject extra electromagnetic activity. A more detailed description of NA62 apparatus can be found in [3] .

2. $K_{\pi\nu\bar{\nu}}$ analisys

The analysis of the complete 2016 data set, corresponding to a total number of kaon decays in the fiducial decay region $N_K = 1.21(2)\times 10^{11}$, is presented. The $K_{\pi\nu\bar{\nu}}$ decay signature is one track with two missing neutrinos. The main kinematic variable is $m^2_{miss} \equiv (p_K - p_{\pi^+})^2$, where p_K and p_{π^+} are the 4-momenta of the K^+ and π^+ respectively. The theoretical shape of the principal K^+ background decay modes are compared to the $K_{\pi\nu\bar{\nu}}$ in Figure2-left. The analysis is performed in

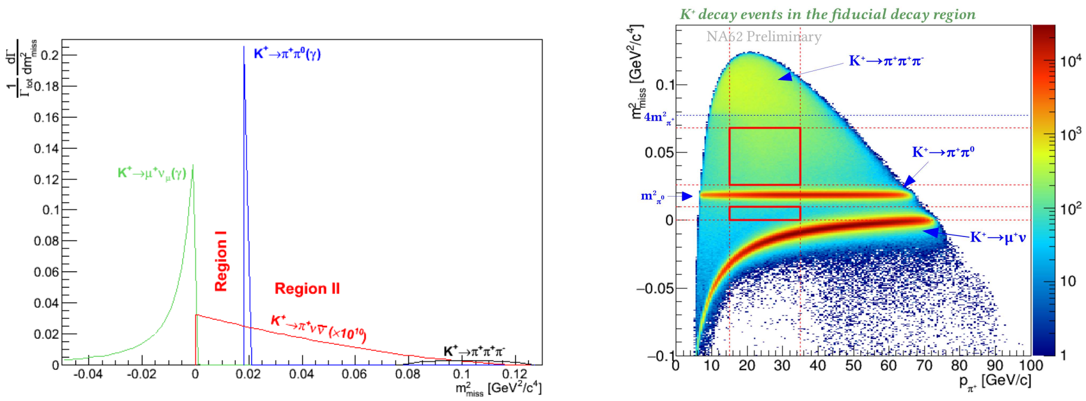

Figure 2: Left: m^2_{miss} shapes for signal and $K_{\mu 2}$ and $K_{\pi 2}$ backgrounds: the backgrounds are normalised according to their branching ratio; the signal is multiplied by a factor 10^{10}. Right: Distribution of m^2_{miss} as a function of track momentum for events selected on minimum bias data; The bands corresponding to $K_{\mu 2}$ and $K_{\pi 2}$ decays are clearly visible; the signal regions (red box) are drawn for reference.

two separate regions: Region 1 (R1), between the $K_{\mu 2}$ and $K_{\pi 2}$ contribution, and Region 2 (R2) between $K_{\pi 2}$ and $K \to \pi^+\pi^+\pi^-(K_{3\pi})$ contribution. The main backgrounds in these regions are $K_{\mu 2}$ and $K_{\pi 2}$ decays characterised by non-gaussian resolution or radiative tails , $K_{3\pi}$ decays characterised by non-gaussian momentum resolution, $K \to \pi^+\pi^- e^+ \nu_e$ (K_{e4}) decays, K^+ decays upstream of the GTK3 station and inelastic beam-detector interactions. Each of the background processes requires different rejection procedure according to its kinematics and to the type of charged particle

in the final state. Events with single track topology are selected using the downstream detectors STRAW, CHOD and RICH. The track is required to match with the CHOD and to have a reconstructed ring in the RICH, which is characterised by a time resolution of the order of 100 ps. The downstream track is then associated to an in-time kaon in the KTAG detector and associated to a the corresponding K^+ track in the GTK detector. A kaon decay vertex is created at the intersection point of the GTK and STRAW tracks. The kaon decays within a 50 m fiducial region, beginning 10 m downstream to the last GTK station (GTK3), are selected (figurename2-right). The calorimeters and the RICH identify the π^+ tracks providing 10^8 μ suppression with $64\%\pi^+$ efficiency. These performances are measured on kinematically selected $K_{\mu 2}$ and $K_{\pi 2}$ decays on control-trigger data. Events passing the π^+ identification criteria are mainly $K_{\pi 2}$ decays, which are further suppressed by looking for energy deposits in the electromagnetic calorimeters in-time with the π^+. The π^0 suppression is of the order of 3×10^8, as measured directly on data. Signal region definitions are driven by the m^2_{miss} resolution $\sigma_{m^2_{miss}}$ = 10^3 GeV^2/c^4. The total $K_{\pi\nu\bar{\nu}}$ acceptance, taking into account signal region definition and selection cuts, is 4%, R1(1%) and R2(3%).
The probability of the $K_{\mu 2}$ ($K_{\pi 2}$) decays to enter the signal regions 3×10^{-4} (1×10^{-3}). This kinematic suppression factor is measured using $K_{\mu 2}$ ($K_{\pi 2}$) decays selected with $K_{\pi\nu\bar{\nu}}$ like selection on a control-trigger data sample.
The Single Event Sensitivity (SES) for a SM $K_{\pi\nu\bar{\nu}}$ decay is SES = $(3.15\pm0.01_{stat}\pm0.24_{syst})\times10^{-10}$, dominated by systematic uncertainty. Summary of the systematic uncertainties on the SES is presented in Table1.

Source	δ SES (10^{-10})
Random veto	$\pm$ 0.17
Denition of $\pi^+\pi^0$ region	$\pm$ 0.10
$A_{\pi\nu\bar{\nu}}$	$\pm$ 0.09
N_K	$\pm$ 0.05
Trigger efficiency	$\pm$ 0.04
Extra activity	$\pm$ 0.02
Pileup simulation	$\pm$ 0.02
Momentum spectrum	$\pm$ 0.01
Total	$\pm$ 0.024

Table 1: Sources of systematic uncertainties to SES: The uncertainty is dominated by random veto losses induced by the π^0 rejection, stability of the SES estimation varying the $\pi^+\pi^0$ normalisation region, simulation of the π^+ losses due to interactions in the detector material upstream of the hodoscopes.

The behaviour of the $K_{\pi 2(\gamma)}$ and $K_{\mu 2(\gamma)}$ background decays is shown in Figure3 as a function of the P_{π^+} momentum and compared to the signal expectation. The $K_{\pi 2(\gamma)}$ ($K_{\mu 2(\gamma)}$) background is dominating at low (high) P_{π^+}. A MC simulation of 400 million generated K_{e4} decays is used to estimate the expected background. The upstream background is estimated using a data driven method.

3. Results

One event has been found in R2 after un-blinding the signal regions. The $K_{\pi\nu\bar{\nu}}$ candidate

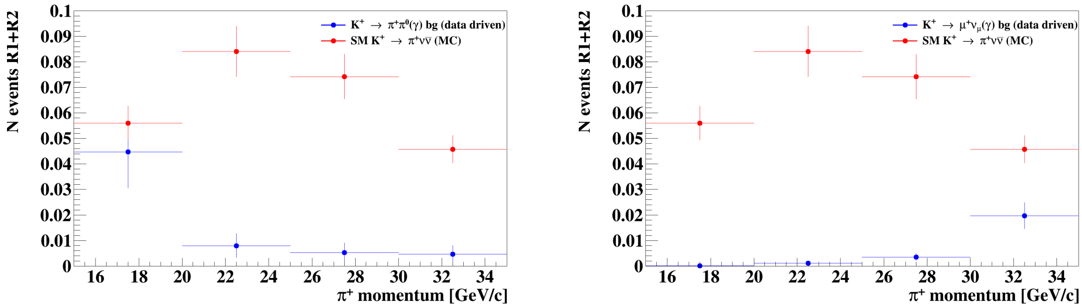

Figure 3: Left: Expected number of $K_{\pi 2(\gamma)}$ background events in R1 and R2 in bins of P_{π^+} compared to the expected number of SM $K_{\pi\nu\bar{\nu}}$ events. Right: Expected number of $K_{\mu 2(\gamma)}$ background. Uncertainties on the background estimations are statistical only, while on expected signal are mostly systematic.

Process	Expected events in R1+ R2
$K_{\pi\nu\bar{\nu}}$ (SM)	$0.267 \pm 0.001_{stat} \pm 0.020_{syst}$ pm 0.032_{ext}
$K_{\pi 2(\gamma)}$ IB	$0.604 \pm 0.007_{stat} \pm 0.006_{syst}$
$K_{\mu 2(\gamma)}$ IB	$0.020 \pm 0.003_{stat} \pm 0.003_{syst}$
K_{e4}	$0.018^{+0.024}_{-0.017}\|_{stat} \pm 0.009_{syst}$
$K_{3\pi}$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
Upstream Background	$0.050^{+0.090}_{-0.030}\|_{stat}$
Total Background	$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$

Table 2: Expected number of signal and background events in R1 and R2 on the complete 2016 data set.

event, Figure4-left, is consistent with a π^+ track in the RICH detector, Figure4-right.

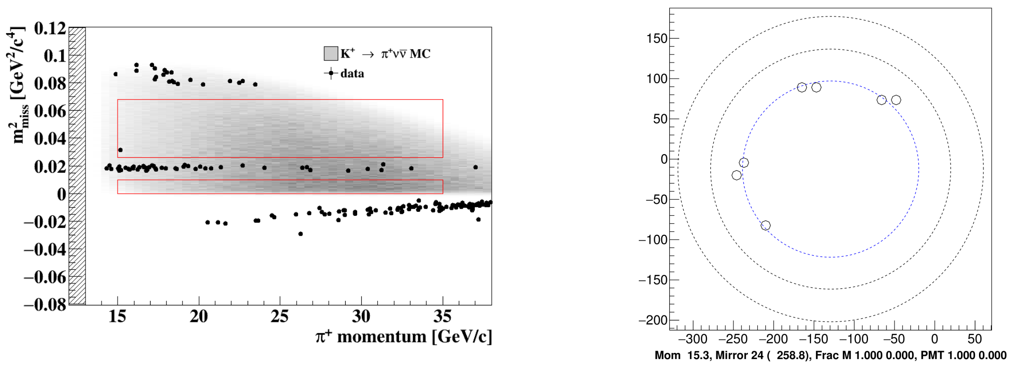

Figure 4: Left: m^2_{miss} as a function of P_{π^+} after applying the $K_{\pi\nu\bar{\nu}}$ selection, but the cuts on m^2_{miss} and P_{π^+}. The grey area is given by $K_{\pi\nu\bar{\nu}}$ MC events. The red lines correspond to the signal regions. The event observed in R2 is shown. Right: Position of the hits in the RICH forming the ring associated to the π^+ track for the observed event in R2. The circles illustrate the positron (outermost ring), muon and pion (the innermost ring) hypothesis, showing a perfect agreement with the pion hypothesis.

Upper limit on the branching ratio of the $K_{\pi\nu\bar{\nu}}$ decay are obtained using the CLs method:

$$BR(K_{\pi\nu\bar{\nu}}) < 11 \times 10^{-10} @ 90\% CL \quad (3.1)$$

$$BR(K_{\pi\nu\bar{\nu}}) < 14 \times 10^{-10} @ 95\% CL \quad (3.2)$$

A measurement of the branching ratio at 68% CL is also computed

$$BR(K_{\pi\nu\bar{\nu}}) = 2.8^{+4.4}_{-2.3} \times 10^{-10} @ 68\% CL \tag{3.3}$$

The branching ratio estimation has been shown only for comparison with the Standard Model prediction, Equation 1.1, and with the result obtained by the BNL E949 collaboration, Equation 1.2. This result is in agreement with both the SM prediction and previous measurements. Improvements at both hardware and analysis level are foreseen to reduce the background and improve signal efficiency. NA62 should observe about 20 SM $K_{\pi\nu\bar{\nu}}$ events with the complete data set, considering the statistics collected in 2017 and expected in 2018.

References

[1] A. J. Buras, D. Buttazzo, J. Girrbach-Noe and R. Knegjens, "$K^+ \to \pi^+ \nu\overline{\nu}$ and $K_L \to \pi^0 \nu\overline{\nu}$ in the Standard Model: status and perspectives," JHEP **1511** (2015) 033 doi:10.1007/JHEP11(2015)033 [arXiv:1503.02693 [hep-ph]].

[2] A. V. Artamonov *et al.* [BNL-E949 Collaboration], "Study of the decay $K^+ \to \pi^+ \nu\bar{\nu}$ in the momentum region $140 < P_\pi < 199$ MeV/c," Phys. Rev. D **79** (2009) 092004 doi:10.1103/PhysRevD.79.092004 [arXiv:0903.0030 [hep-ex]].

[3] E. Cortina Gil *et al.* [NA62 Collaboration], "The Beam and detector of the NA62 experiment at CERN," JINST **12** (2017) no.05, P05025 doi:10.1088/1748-0221/12/05/P05025 [arXiv:1703.08501 [physics.ins-det]].