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First results on the $K^+ \to \pi^+ \nu\bar{\nu}$ decay search from NA62

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Abstract. The precise measurement of the branching ratio of an ultrarare decay $K^+ \to \pi^+ \nu\bar{\nu}$ ($\sim 10^{-10}$ according to the calculation within the Standard Model) allows to probe New Physics via indirect effects at mass scales higher than those accessible at the LHC. The NA62 experiment at the CERN SPS is aimed at measuring this branching ratio with the 10% precision. To achieve such level of precision, a novel decay-in-flight technique is used. The statistics collected during the first NA62 physics run in 2016 allowed to demonstrate the proof of the experimental method and obtain O(10^{-10}) single event sensitivity. The preliminary results based on the 2016 data set are described.

1 Introduction

The ultra rare decay $K^+ \to \pi^+ \nu\bar{\nu}$ proceeds via flavor changing neutral currents and is highly suppressed in the Standard Model (SM) due to the GIM mechanism. Within the SM, the main contribution to the branching ratio (BR) comes from box and penguin diagrams, which contain CKM matrix elements as external inputs. These elements give the largest uncertainty to the BR. Using tree-level observables, one obtains [1, 2]: $BR_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$.

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The $K^+ \to \pi^+\nu\bar{\nu}$ decay is extremely sensitive to physics beyond the SM, probing mass scales up to 100 TeV. Models with new sources of flavour violation give the largest deviations from SM [3, 4] due to weaker constraints from B physics.

The only experimental measurement is performed by the E787 and E949 experiments using the decay-at-rest technique [5]: $BR_{exp}(K^+ \to \pi^+\nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$.

2 NA62 experiment

The NA62 experiment at the CERN SPS is a new generation fixed target experiment which aims at measuring the BR of the $K^+ \to \pi^+\nu\bar{\nu}$ decay with the decay–in–flight technique. The schematic view of the setup if shown in Fig. 1. The detailed description of the apparatus can be found in [6]).

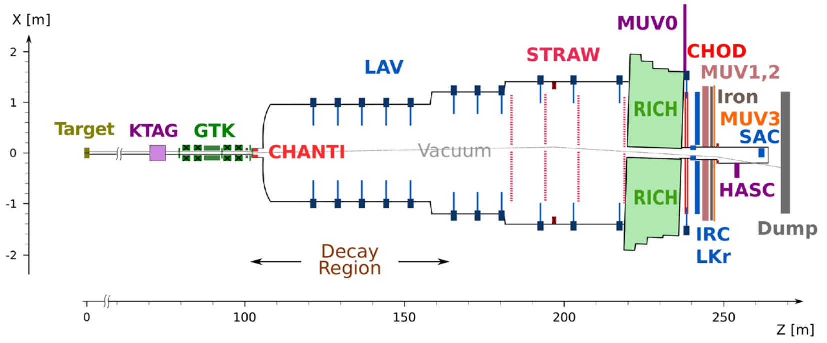

Figure 1. NA62 setup layout.

A hadron beam of 75 GeV/c and 1% momentum bite is produced by primary SPS protons impinging on a beryllium target and delivered to the NA62 setup. The fraction of K^+ in the beam is about 6%. Kaons are identified by a differential Cherenkov counter (KTAG), while the direction and momentum are measured by three stations of Si pixel detectors (GTK). Beam inelastic interactions in GTK are vetoed by the CHANTI detector. The decay volume is surrounded by the photon veto system (LAV) covering the photon angular range from 8.5 up to 50 mrad. Smaller angle photons are detected by the electromagnetic calorimeter LKr and small angle calorimeters IRC and SAC. The magnetic spectrometer is composed of four stations of straw chambers (STRAW) operating in vacuum and a dipole magnet providing a 270 MeV/c transverse kick. A RICH detector provides the time reference for the L0 trigger and identifies charged pions, muons and electrons. The scintillator hodoscope CHOD is used for timing measurements and for the minimum bias trigger. Additional pion and muon identification is performed by hadron calorimeters (MUV1,2) and a muon veto detector (MUV3).

The NA62 apparatus has been completely commissioned in the first half of the 2016 data taking period. In the second half, NA62 has collected about 4.5×10^{11} kaon decays at 20-40% of the nominal intensity suitable for the $K^+ \to \pi\nu\bar{\nu}$ analysis. The following sections describe the analysis of the 2016 data sample.

3 Measurement principle

The main kinematic variable used in the analysis is the missing mass squared:
$m^2_{miss} = (P_K - P_\pi)^2 \simeq m^2_K(1 - \frac{|p_\pi|}{|p_K|}) + m^2_\pi(1 - \frac{|p_K|}{|p_\pi|}) - |p_K||p_\pi|\theta^2_{\pi K}$. Here P_K and P_π are kaon and

pion 4-momenta, p_K and p_π are their 3-momenta and $\theta_{\pi K}$ is the angle between two particles in the laboratory frame.

Fig. 2 shows the distribution of this variable for the signal and backgrounds. The signal-enhanced region is constrained by the main background from the decays $K^+ \to \mu^+\nu_\mu$ (on the left), $K^+ \to \pi\pi\pi$ (on the right) and $K^+ \to \pi^+\pi^0$ (a peak from this decay splits the signal region into 2 halves).

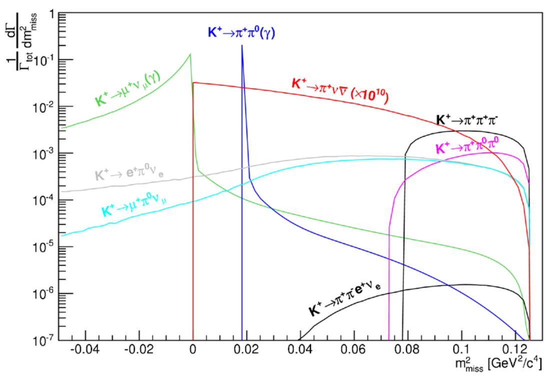

Figure 2. $m^2_{miss} = (P_K - P_\pi)^2$ for the signal and the most frequent background decay modes. The signal is multiplied by 10^{10}, background modes are normalized according to their BR.

The decay modes $K^+ \to \mu^+\nu_\mu$ and $K^+ \to \pi^+\pi^0$ enter the signal regions through non gaussian resolution and radiative tails of the m^2_{miss} distribution. More rare processes like $K^+ \to e^+\nu_e\pi^+\pi^-$ are broadly distributed across the signal regions due to the presence of neutrinos in the final state. Another background source comes from inelastic interactions or upstream decays of beam particles. For each source of background a different rejection procedure is required, depending on the kinematics and particle type in the final state. The background estimation is performed for each process individually. To validate the procedure, control regions are defined where possible.

For the 2016 data sample, a blind analysis is adopted. Both signal and control regions are kept masked as long as the evaluation of expected signal and background is not complete. The data sample has been collected with the dedicated $\pi\nu\nu$ trigger (PNN) and with a minimum bias trigger (control data).

4 Event selection

The main steps of the event selection are:

- define a K^+ decay with a charged particle in the final state;
- perform π^+ identification;
- reject events with photon(s) or any activity in the final state;
- perform kinematic selection and define signal regions.

The reconstructed track is spatially matched with signals in RICH, LKr and CHOD detectors, the latters define a pion time. A kaon is identified by the intime KTAG and GTK candidates. Kaon and pion candidates are matched in time and space, determining the decay vertex. The Z-coordinate of the vertex is required to be within a 50 m long fiducial decay region, starting from about 10 m downstream of the last GTK station.

The momentum range (15< P_π <35 GeV/c) is driven by the efficient rejection of events with π^0's in the final state, as well as the optimal π^+ identification. The latter is provided by calorimeters and the RICH. The achieved muon rejection is 0.6×10^{-5} for calorimeters and 2.1×10^{-3} for the RICH, the efficiencies are 78% and 82% respectively. The photon veto in the angular range between 0 and 50 mrad is ensured by LAV, LKr, IRC and SAC detectors. The achieved π^0 detection inefficiency is about 2.5×10^{-8}, measured on data.

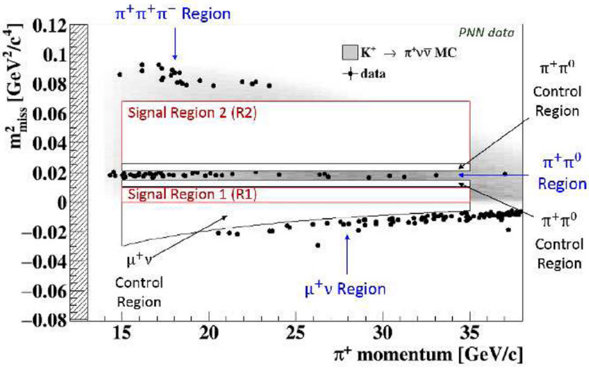

Figure 3. m^2_{miss} vs P_{π^+} for PNN trigger data events (dots) and signal MC (grey area). Red lines mark signal regions 1 and 2. Black lines define control regions. Signal and control regions are masked. Background regions are also shown.

Fig. 3 shows the distribution of surviving events in the (m^2_{miss} vs P_{π^+}) plane. Three background regions are defined, mostly populated by a certain decay mode. Signal regions are denoted as region 1 and region 2. Three control regions are located between signal and background, as shown in the Figure.

5 Single event sensitivity

The single event sensitivity (SES) is defined as $1/(N_K \cdot \epsilon_{\pi\nu\nu})$, where N_K is the number of K^+ decays and $\epsilon_{\pi\nu\nu}$ is the signal efficiency for the $K^+ \to \pi\nu\bar{\nu}$ selection. The number N$_K$ is measured on the normalization sample of $K^+ \to \pi^+\pi^0$ decays with similar selection criteria and is equal to $(1.21 \pm 0.02_{syst}) \times 10^{11}$. The main sources of the systematic uncertainty are data/MC disagreement and variations in the kaon flux as a function of the π^+ momentum.

The signal efficiency is the product of three terms: $\epsilon_{\pi\nu\nu} = A_{\pi\nu\nu} \cdot \epsilon_{RV} \cdot \epsilon_{trig}$. The selection acceptance $A_{\pi\nu\nu}$ is calculated from the Monte Carlo (MC), the efficiency ϵ_{RV} induced by the random activity in veto detectors is measured from the control data, as well as the PNN trigger efficiency ϵ_{trig}. To account for the momentum dependency, the signal efficiency is measured in four bins of momentum, 5 GeV/c wide each. The obtained numbers are 4% for $A_{\pi\nu\nu}$, 76% for ϵ_{RV} and 88% for ϵ_{trig}. The momentum and beam intensity dependence are illustrated in Fig. 4.

The obtained SES and the expected signal event number $N^{exp}_{\pi\nu\nu}$ (assuming the SM branching ratio) are: SES = $(3.15\pm 0.01_{stat}\pm 0.24_{syst}) \times 10^{-10}$, and $N^{expected}_{\pi\nu\nu} = 0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$. The systematic uncertainty of the SES is due to $A_{\pi\nu\nu}$ and ϵ_{RV} and is propagated to $N^{exp}_{\pi\nu\nu}$. The external error to $N^{exp}_{\pi\nu\nu}$ comes from the uncertainty of the $BR_{SM}(K^+ \to \pi^+\nu\bar{\nu})$.

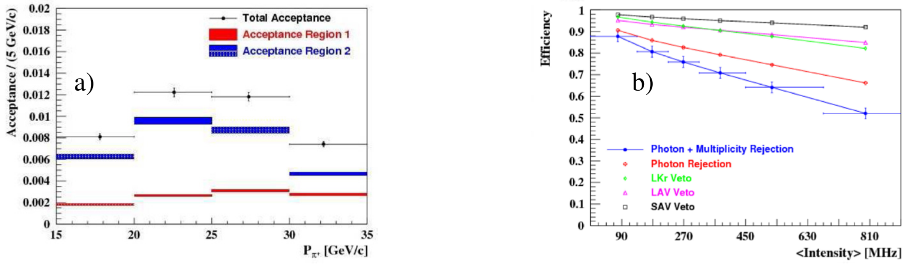

Figure 4. a) $A_{\pi\nu\nu}$ in momentum bins. Dots: region 1+2. Red: region 1. Blue: region 2. b) Signal efficiency as a function of the beam intensity. Different lines correspond to different selection stages described in the legend. The total efficiency $\epsilon_{\pi\nu\nu}$ is shown in blue.

6 Background estimation

The following decays modes contribute mostly to the background: $K^+ \to \mu^+\nu_\mu$, $K^+ \to \pi^+\pi^0$, $K^+ \to \pi^+\pi^-\pi^+$ and $K^+ \to e^+\nu_e\pi^+\pi^-$. The number of background events $N_{bkg}^{expected}$ in signal regions is calculated in the assumption that the kinematic selection (cuts on the m^2_{miss} defining two signal regions) is independent of the particle identification and the presence of π^0 in the selection. More specifically, $N_{bkg}^{expected} = N_{bkg} \times f_{kin}$, where N_{bkg} is the event number in the background region and f_{kin} is the ratio of the event number in the background region to the one in the signal region. The latter is calculated on control data samples that use a different particle identification (PID) or require a π^0 in the event selection. As mentioned above, f_{kin} is assumed to be the same for the PNN and for control sample event selection. The value of f_{kin} is also corrected for biases using dedicated MC samples. For decays $K^+ \to \mu^+\nu_\mu$ and $K^+ \to \pi^+\pi^0$ the procedure for calculating $N_{bkg}^{expected}$ is performed in four momentum bins. The same method is used to evaluate the expected event number in control regions N_{CR}.

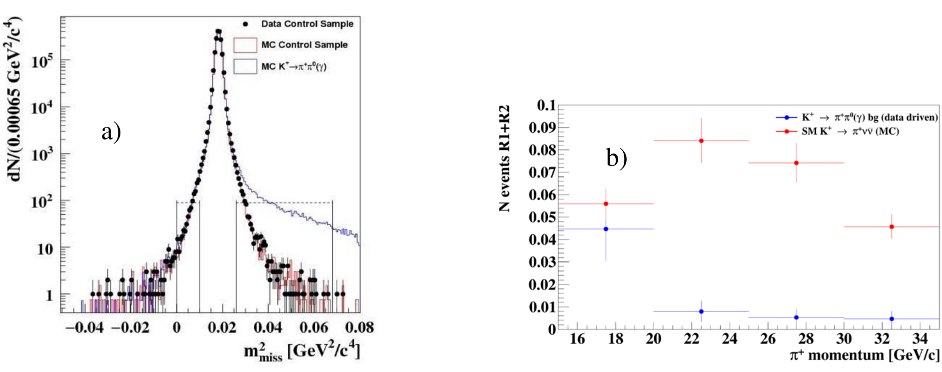

Figure 5. a) m^2_{miss} distribution for $K^+ \to \pi^+\pi^0(\gamma)$. Dots: control events (with π^0 tagging, see text for details). Red line: MC selected with π^0 tagging. Blue line: MC selected without π^0 tagging. b) expected $K^+ \to \pi^+\pi^0(\gamma)$ background in momentum bins (red) and expected number of signal events (blue).

In Fig. 5a the m^2_{miss} distribution is shown for $\boldsymbol{K^+ \to \pi^+\pi^0}$$(K2\pi)$ events with 2 photons in LKr (π^0 tagging). The π^0 tagging rejects the contribution from the radiative decay $K^+ \to$

$\pi^+\pi^0\gamma$ which is estimated from the MC simulation and evaluated by measuring the single photon detection efficiency. Fig. 5b illustrates the estimated event number in momentum bins. The total expected number in control regions is $N_{CR}^{K2\pi} = 1.46 \pm 0.16_{stat} \pm 0.06_{syst}$. After unblinding one event was observed.

Similar distributions for the $\boldsymbol{K^+ \to \mu^+\nu_\mu}(K\mu 2)$ background are shown in Fig. 6. Control events are selected with a muon PID instead of a pion one. The radiative contribution is included in measured tails. The expected number in a control region is $N_{CR}^{K\mu 2} = 1.02 \pm 0.16_{stat}$, with two events observed after unblinding.

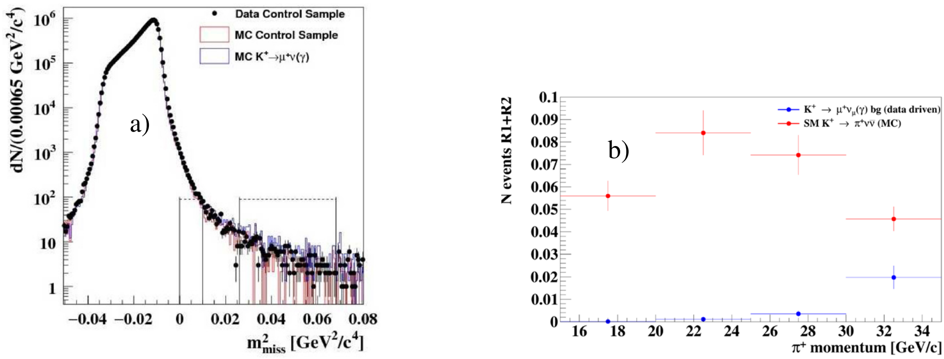

Figure 6. a) m^2_{miss} distribution for $K^+ \to \mu^+\nu_\mu(\gamma)$. Dots: control events (with muon PID, see text for details). Red line: MC selected with muon PID. Blue line: MC selected without muon PID. b) Expected $K^+ \to \mu^+\nu_\mu(\gamma)$ background in momentum bins (red) and expected number of signal events (blue).

The $\boldsymbol{K^+ \to \pi^+\pi^-\pi^+}$ ($K3\pi$) decays could mimic the signal in region 2. A procedure similar to $K\mu 2$ and $K2\pi$ is used for the estimation of the $K3\pi$ contribution which turns out to be negligible.

The estimation of $\boldsymbol{K^+ \to e^+\nu_e\pi^+\pi^-}$ ($Ke4$) background is performed using a dedicated MC sample of $Ke4$ decays. The validation of the sample was done on different $Ke4$ enriched event selections orthogonal to the signal one.

A very important contribution to the background comes from decays or interactions **upstream** the fiducial volume. The first scenario is a K^+ upstream decay between GTK stations 2 and 3 with a pion detected by downstream detectors and a pile-up kaon that is matched to this pion. In the second scenario a pile-up kaon is matched to a pion from beam inelastic interactions with the material of a GTK station (mostly 3). Finally, a kaon could be matched with a product if its upstream inelastic interaction or with a decay product of a neutral kaon. The estimation of the upstream background is data-driven and based on the geometrical cuts for enriching the fraction of such events. The total contribution is $N_{upstream}^{expected} = 0.15 \pm 0.09_{stat} \pm 0.01_{syst}$. The accuracy is limited by the statistics of the data sample.

All background contributions to the signal region are summarized in Table 1.

7 Result

After the evaluation of the background estimation procedure (the event number in control regions was in agreement with the expectations), signal regions were unblinded. One event was found in region 2, with the pion momentum of 15.3 GeV/c (see Fig. 7a). Fig. 7b shows the hit

Table 1. Summary of background estimation for the 2016 data sample. $K2\pi(\gamma)$ stands for the sum of $K^+ \to \pi^+\pi^0$ and $K^+ \to \pi^+\pi^0\gamma$; $K\mu2(\gamma)$ is the sum of $K^+ \to \mu^+\nu_\mu$ and $K^+ \to \mu^+\nu_\mu\gamma$.

Process	$N_{bkg}^{expected}$
$K2\pi(\gamma)$	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K\mu2(\gamma)$	$0.020 \pm 0.003_{stat} \pm 0.003_{syst}$
$K^+ \to e^+\nu_e\pi^+\pi^-$	$0.018^{+0.024}_{-0.017}\vert_{stat} \pm 0.009_{syst}$
$K^+ \to \pi^+\pi^-\pi^+$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
Upstream background	$0.050^{+0.090}_{-0.030}\vert_{stat}$
Total background	$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$

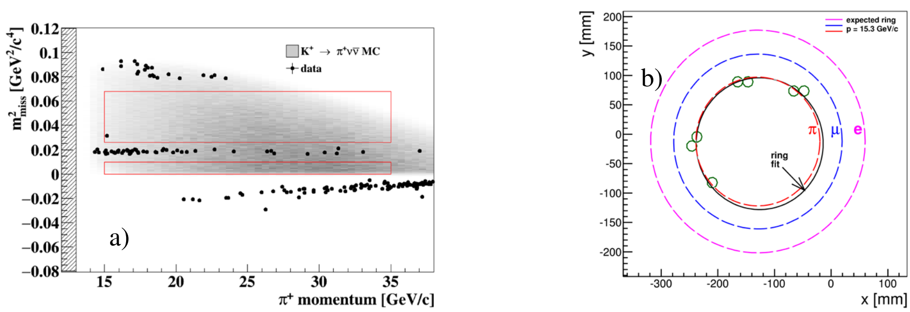

Figure 7. a) m^2_{miss} vs P_{π^+} for PNN trigger data events (dots) and signal MC (grey area). One event is observed in region 2. Red lines mark signal regions. b) Hit positions in the RICH (green circles). The ring fit (black line) and the predicted ring radii for different mass hypotheses (coloured lines) are shown.

distribution in the RICH which is compatible with the pion hypothesis for the observed pattern. The statistical interpretation of the results is done in the framework of a counting experiment with the expected $N_{\pi\nu\nu}^{expected}$ (see Section 6) and $N_{bkg}^{expected}$ (Table 1). A hybrid frequentist-bayesian prescription is used to account for the background uncertainty. The upper limit on the BR is calculated using the CLs method [7]: $BR(K^+ \to \pi^+\nu\bar{\nu}) < 14 \times 10^{-10}$ @95% CL.

8 Conclusion

The first results on the $K^+ \to \pi^+\nu\bar{\nu}$ search at the NA62 experiment have been presented, based on the data collected in 2016. The SES has been found to be 3×10^{-10}. The expected event numbers are 0.27 for signal and 0.15 for background. One event has been observed resulting in the upper limit: $BR(K^+ \to \pi^+\nu\bar{\nu}) < 14 \times 10^{-10}$ @95% CL. The ongoing analysis of the 2017 data sample will allow to increase statistics by the factor of 20.

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