PROCEEDINGS OF SCIENCE

Prospects for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ observation at CERN in NA62

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The rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is an excellent process to probe Standard Model and indirectly search for new physics, complementary to the ongoing direct LHC searches. The NA62 experiment at CERN SPS aims to collect about 100 of such events in two years of data taking, keeping the background at the level of 10%. The physics motivation, experimental technique and status of the experiment are presented.

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1. Introduction

The rare decay $K^+ \to \pi^+ \nu\bar{\nu}$ is both theoretically very clean and highly sensitive to short-distance physics. Therefore, it plays a key role among flavour changing neutral current processes both in the Standard Model (SM) [1] and its extensions [2, 3] . The branching ratio (BR) of this process has been computed to a very high precision in the SM: $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (7.81 \pm 0.75 \pm 0.29) \times 10^{-11}$ [1]. The first error comes from the uncertainty of the CKM matrix elements, the second one is the pure theoretical uncertainty.

The $K^+ \to \pi^+ \nu\bar{\nu}$ decay has been observed by the E787/E949 experiments at the Brookhaven National Laboratory. The measured branching ratio value is based on the observation of seven candidate events and reads $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73\,^{+1.15}_{-1.05}) \times 10^{-10}$ [4]. High uncertainty of the experimental result motivates a new measurement of the branching ratio with an improved precision.

2. NA62 experimental strategy

The NA62 experiment at CERN [5, 6] aims to measure the branching ratio of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay at the 10% precision level. The experiment is expected to collect about 100 signal events in two years of data taking and to keep the total systematic uncertainty and backgrounds small. Assuming a 10% signal acceptance and the SM decay rate, the kaon flux should correspond to at least 10^{13} K^+ decays in the fiducial volume.

Unlike the experiments E787/E949 [4] which used separated K^+ beam with kaons stopped at a target, the NA62 experiment will use a high momentum (∼ 75 GeV/c) unseparated kaon beam produced by 400 GeV/c momentum protons delivered from the Super Proton Synchrotron (SPS) accelerator impinging on a beryllium target. Consequently, a decay in flight technique will be used to identify K^+ decay products.

The $K^+ \to \pi^+ \nu\bar{\nu}$ decay contains two undetectable neutrinos in the final state, which means that the signal signature is one π^+ track in the final state matched to one K^+ track in the beam with no other particles detected. In the NA62 experiment, the most important background processes to $K^+ \to \pi^+ \nu\bar{\nu}$ events are the main K^+ decay modes (see Tab. 1). In order to achieve a signal/background ratio ~ 10, a background rejection factor of the order of 10^{12} is required. Therefore, a precise measurement of the event kinematics, hermetic photon vetoes and particle identification are crucial for the success of the experiment.

Decay channel	Branching ratio (%)	Background rejection
$K^+ \to \mu^+ \nu_\mu$	63.55 ± 0.11	kinematics, μ ID
$K^+ \to \pi^+ \pi^0$	20.66 ± 0.08	kinematics, photon veto
$K^+ \to \pi^+ \pi^+ \pi^-$	5.59 ± 0.04	kinematics, charged particle veto
$K^+ \to \pi^0 e^+ \nu_e$	5.07 ± 0.04	E/p, photon veto
$K^+ \to \pi^0 \mu^+ \nu_\mu$	3.353 ± 0.034	photon veto, μ ID
$K^+ \to \pi^+ \pi^0 \pi^0$	1.761 ± 0.022	kinematics, photon veto

Table 1: Main K^+ decay modes and suppression strategy in the NA62 experiment.[5]

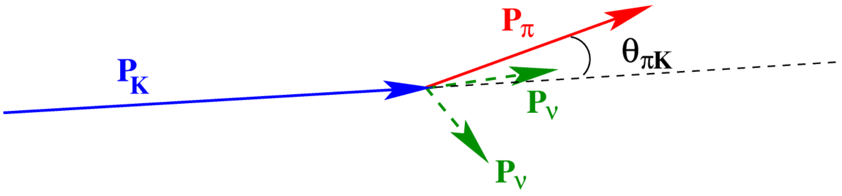

Figure 1: Kinematics of the $K^+ \to \pi^+ \nu \bar{\nu}$ decay.

The $K^+ \to \pi^+ \nu \bar{\nu}$ decay kinematics can be fully described by the variable $m^2_{miss} = (P_K - P_{\pi^+})^2$, where P_K and P_{π^+} are the four momenta of the kaon and pion candidates. The distribution of the m^2_{miss} variable allows a 92% separation of the signal and the main K^+ decay modes by defining two signal regions where a minimum background is expected. The signal regions are defined away from the $K^+ \to \pi^+ \pi^0$ peak and the $K^+ \to \pi^+ \pi^+ \pi^-$ threshold (see Fig. 2).

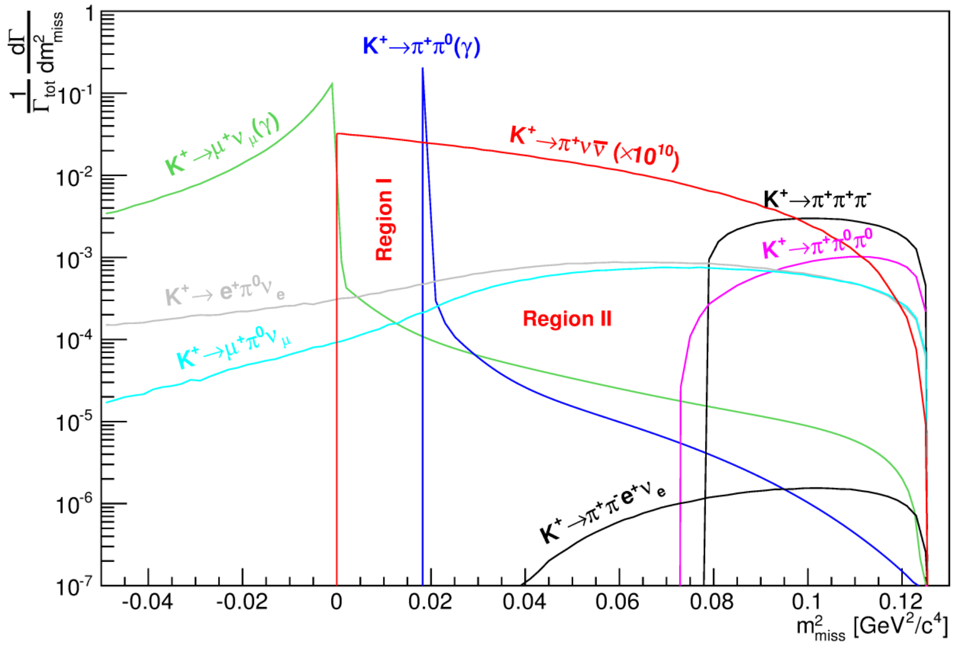

Figure 2: m^2_{miss} distribution for signal and backgrounds from the main K^+ decay modes. Backgrounds are normalized according to their BR; the signal is multiplied by a factor of 10^{10}. Region I: between 0 and $\pi^+ \pi^0$ peak; Region II: between $\pi^+ \pi^0$ peak and $\pi^+ \pi^+ \pi^-$ threshold.[7]

3. The NA62 detector

The NA62 experiment uses high energy protons from the SPS (400 GeV/c) to produce a secondary hadron beam (6% kaons) of momentum (75 ± 1.0) GeV/c and high intensity (750 MHz). The experimental set-up extends from the beryllium target to the beam dump over a distance of about 270 m. A schematic view of the NA62 experiment layout is presented in Fig. 3.

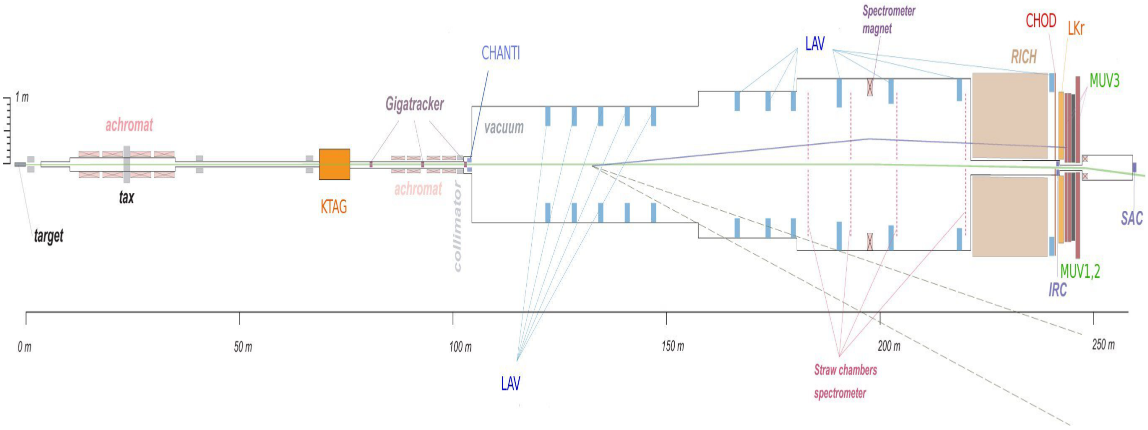

Figure 3: The NA62 detector layout. [6]

The first 100 m are covered by beam elements and two detectors measuring the incoming beam (KTAG and Gigatracker). The 65 m-long decay region is contained in a vacuum (at $< 10^{-6}$ mbar) cylindrical tank. Properties of decay products coming from the decay region are measured in detectors placed over a 170 m long region ending shortly before the beam dump.

The first detector traversed by the beam is KTAG, an upgraded differential Cherenkov (CEDAR) counter from the SPS at CERN. The KTAG identifies the K^+ component (45 MHz rate) in the beam with respect to the other beam particles with at least 95% efficiency and time resolution $\sigma_T \leq 100$ ps.

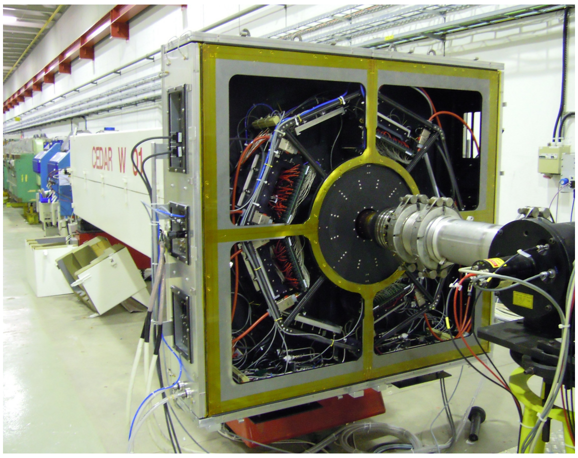

Figure 4: The KTAG detector.

The beam spectrometer, called Gigatracker (GTK), consists of three Si micro-pixel detectors matching the beam dimensions. These stations are placed in vacuum and are crossed by the full beam intensity of about 750 MHz. The GTK provides a time resolution better than 150 ps, which is vital to associate the right beam particle to the decay vertex. Four dipole magnets provide an achromatic (no net bending) spectrometer for particles of any momentum. The momentum resolution is expected to be 0.2% RMS and the angular resolution 15μrad. [8]

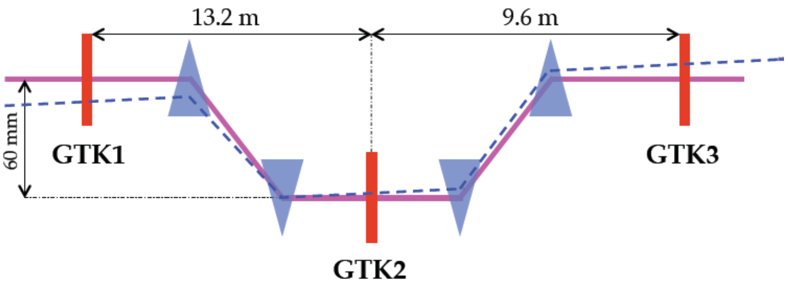

Figure 5: The GTK stations are mounted in the beam line between 4 achromat magnets measuring time, direction and momentum of all beam particles.

The GTK is followed by the CHANTI, which surrounds the beam just after the last GTK station. It is an anti-coincidence detector for charged particles whose main purpose is to detect inelastic interactions taking place in the third GTK station.

The Straw Tracker, made of 4 straw chambers and a dipole magnet measures the coordinates and momenta of secondary charged particles originating from the decay region. The magnet provides a vertical B-field of 0.36 T which corresponds to momentum kick $p_t = 270$ MeV/c. To minimize multiple scattering the chambers are built of ultra-light material and installed inside the vacuum tank. The momentum resolution is expected to be $\sigma(p)/p = (0.32 \oplus 0.008p)$.

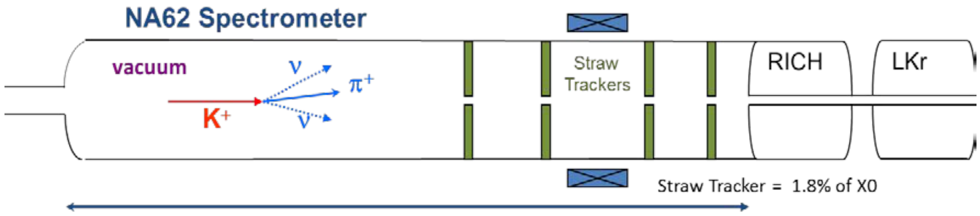

Figure 6: Schematic view of the Straw Tracker.

One of the main backgrounds to the $K^+ \to \pi^+ \nu \bar{\nu}$ decay is the $K^+ \to \pi^+ \pi^0$ decay. The requirement on the π^+ momentum (in the offline analysis) $p < 35$ GeV guarantees that the two photons from the π^0 have a total energy of ≈ 40 GeV. Thus, the NA62 experiment needs very high detection efficiency for high energy photons, the probability to miss both photons must be less than 10^{-8}. The veto system is composed of 3 sub-systems and covers an acceptance from 0 to 50 mrad from the K^+ decay vertex with respect to the beam line.

The Large Angle Veto (LAV) system consists of 12 stations distributed along the decay volume. These stations are made of lead-glass blocks with attached photo-multipliers (refurbished from the former OPAL electromagnetic calorimeter), providing the coverage from 8.5 mrad to 50 mrad.

The Liquid Krypton (LKr) calorimeter, a quasi-homogeneous ionisation chamber reused from the NA48 experiment [9] covers the forward region from 1.5 mrad to 8.5 mrad. To satisfy the NA62 rate requirements the calorimeter is equipped with new Calorimeter Readout Modules (called CREAM).

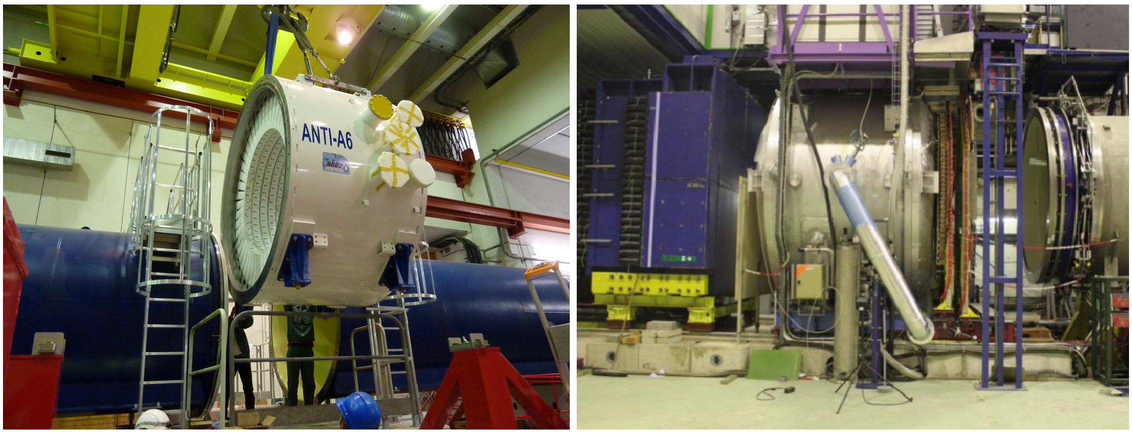

Figure 7: Photon veto detectors: one of the LAV stations (left) and LKr calorimeter (right).

The Small Angle Veto (SAV) system is composed of two shashlik calorimeters: the Intermediate Ring Calorimeter (IRC) and the Small Angle Calorimeter (SAC). The IRC covers the angular region close to the inner LKr radius, while the SAC is located behind the experimental cavern, preceded by a magnet to deflect the charged hadron beam.

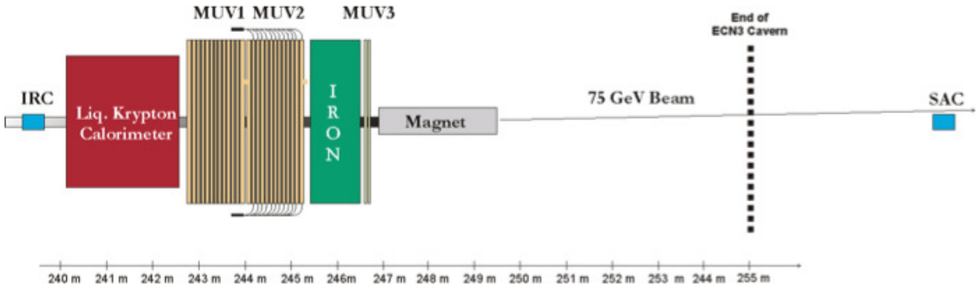

Figure 8: Downstream part of the NA62 detector.

The muon veto system (MUV) provides 10^5 rejection of muons from the most frequent kaon decay $K^+ \to \mu^+ \nu_\mu$. It is composed of three sub-detectors, called MUV1, MUV2, and MUV3. The first two modules follow directly the LKr calorimeter and work as hadronic calorimeters. Both modules are classic iron-scintillator sandwich calorimeters. The MUV3 detector, located after a 80 cm thick iron wall, is made of scintillator tiles. It serves as fast muon veto ($\sigma_T \leq 1$ ns) used in the Level-0 (L0) trigger.

The Ring Imaging Cherenkov detector (RICH) is required to improve the rejection of the background from the $K^+ \to \mu^+ \nu_\mu$ decay by providing positive identification of the μ in the background events and an identification of the π in the signal events. The RICH is situated between the last Straw station and the last LAV station. A cylindrical vessel with the beam pipe passing in its center is filled with Neon (1 atm). At the downstream end a mosaic hexagonal mirror focuses the Cherenkov light onto photo detectors located at the upstream end of the vessel. A dedicated test beam in 2009 showed that the RICH allows the required π/μ separation with μ misidentification probability $\sim 0.7\%$ and the time resolution better than 100 ps.[10]

Figure 9: The RICH detector: the vessel (left) and the mosaic mirror (right).

The particle rate in the detectors following the decay region is expected to be $\sim$ 10 MHz. Due to such high rate, the NA62 experiment requires high-performance triggering and data acquisition. These systems must minimize dead time while maximizing data collection reliability. The trigger is organized in three levels. The lowest hardware level (L0) is based on the input from a few sub-detectors and reduces the rate to 1 MHz while preserving most of the decays of interest. After a positive L0 signal is issued, most sub-detectors transfer data to dedicated PCs, where two trigger levels (L1 and L2) are applied via software, to reach a final rate of $\sim$ 10 kHz.

4. Conclusions and outlook

The first physics run of the NA62 experiment starts in October 2014. Lower beam intensity will be used for the detector commissioning. Full intensity beam and data taking is expected in years 2015 – 2017. Assuming the nominal intensity: $4.5 \times 10^{12}\, K^+$ decays in the fiducial region per year, the expected number of observed $K^+ \to \pi^+\nu\bar{\nu}$ decays together with expected background contribution is presented in the following table.

Decay	events / year
$K^+ \to \pi^+\nu\bar{\nu}$ [SM]	45
$K^+ \to \pi^+\pi^0$	5
$K^+ \to \mu^+\nu$	1
$K^+ \to \pi^+\pi^-\pi^+$	< 1
$K^+ \to \pi^+\pi^- e^+\nu$ + other 3-track decays	< 1
$K^+ \to \pi^+\pi^0\gamma\,(\mathrm{IB})$	1.5
$K^+ \to \mu^+\nu\gamma\,(\mathrm{IB})$	0.5
$K^+ \to \mu^+(e^+)\pi^0\nu$, others	negligible
Total background	< 10

Table 2: Signal and background estimated from the sensitivity studies. [7]

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