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

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The rare decay $K^+ \to \pi^+ \nu\bar{\nu}$ is an excellent process to make tests of new physics at the highest scale complementary to LHC thanks to its theoretical cleanness. The NA62 experiment at CERN SPS aims to collect of the order of 100 events in two years of data taking, keeping the background at the level of 10%. Part of the experimental apparatus has been commissioned during a technical run in 2012. The physics prospects and the status of the experiment are reviewed in light of the pilot run which occurred in October-December 2014.

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1. Introduction

The main aim of the NA62 experiment is the study of the ultra rare decay $K^+ \to \pi^+ \nu\bar{\nu}$. The final goal is to measure the Branching Ratio of this process with a 10% accuracy, in order to provide a stringent test of the Standard Model (SM) predictions or lead to a discovery of deviations from the SM which turns into evidence of new physics.
Among the many rare flavour changing neutral current (FCNC) decays, the ultra rare decays $K \to \pi\nu\bar{\nu}$ play a key role in the search for new physics through underlying mechanisms of flavour mixing. The Branching Ratio can be computed to an exceptionally high degree of precision: the current prediction for the $K^+ \to \pi^+ \nu\bar{\nu}$ channel is $(0.911 \pm 0.072) \times 10^{-10}$ [1], the error coming from the uncertainty on the CKM matrix elements in addition to the intrinsic theoretical uncertainty. This decay is one of the best probes for new physics effects complementary to direct searches, and an important portal to scales beyond those explored by the LHC experiments. Since the theoretical cleanness of these decays holds also in these scenarios [2][3][4], even deviations from the SM value at the level of 20% can be considered signals of new physics.
The decay $K^+ \to \pi^+ \nu\bar{\nu}$ has been observed by the dedicated experiments E787 and E949 at the Brookhaven National Laboratory. The combined measured Branching Ratio is $(1.73^{+1.15}_{-1.05}) \times 10^{-10}$, based on a total of 7 events collected using a decay-at-rest technique [5].

2. Experimental strategy

NA62 uses a decay-in-flight technique, differently from the kaon decay at rest approach which was at the basis of the previous experiments. The experimental setup consists of a 100 m long beam line to select the appropriate secondary beam component produced by protons from the SPS CERN accelerator, followed by a 80 m long evacuated volume which defines the decay region. The detectors are designed to measure the K^+ and the secondary particles from kaon decays occurring in the decay volume.
The signature of the signal is one track in the final state matched with one K^+ track in the beam. The kinematics of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay is fully described by the squared missing mass:

$$m^2_{\text{miss}} = (P_K - P_\pi)^2 = (E_K - E_\pi)^2 - (|\vec{p}_K|^2 + |\vec{p}_\pi|^2 - 2|\vec{p}_K||\vec{p}_\pi|\cos\theta_{\pi K})$$

The measurable quantities are $\vec{p}_K$ (kaon momentum), $\vec{p}_\pi$ (pion momentum) and the angle $\theta_{\pi K}$ (angle between the pion and the kaon).
The distribution of m^2_{miss} (with the hypothesis that the charged decay product is a pion) allows a separation of the signal from the main K^+ decay modes by defining two signal regions where a limited background coming from the other decays is expected (figure 1):

- region I: $0 < m^2_{\text{miss}} < m^2_{\pi^0} - (\Delta m)^2$
- region II: $m^2_{\pi^0} + (\Delta m)^2 < m^2_{\text{miss}} < \min[m^2_{\text{miss}}(K^+ \to \pi^+\pi^+\pi^-)] - (\Delta m)^2$

where $(\Delta m)^2$ represents the resolution on the squared missing mass.
Nevertheless, the total background in these regions is still several order of magnitude larger than the $K^+ \to \pi^+ \nu\bar{\nu}$ signal, as a consequence of the main decay modes leaking there via resolution

effects and radiative tails, and more than 2-body decays, like semi-leptonic decays and rare decays, whose kinematics cannot be constrained by the m^2_{miss} variable.

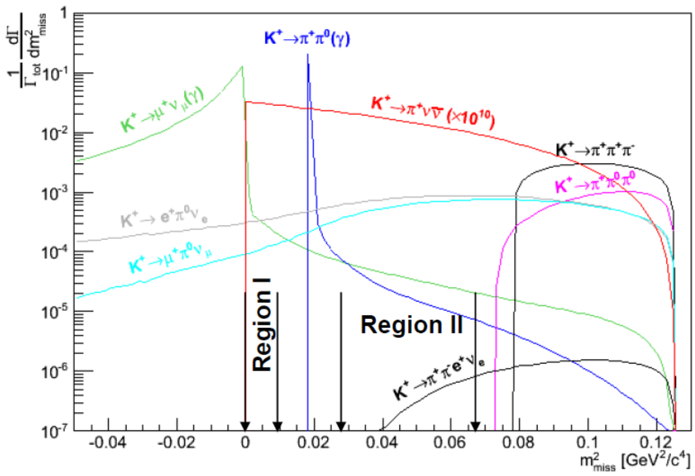

Figure 1: Distribution of m^2_{miss} for main kaon decay modes and the signal, with the hypothesis that the charged decay product is a pion.

2.1 Signal selection

The presence of one track reconstructed in the downstream spectrometer matched in space and time with one track reconstructed in the beam spectrometer is the first requirement for a signal selection. A set of criteria for pion identification allows the suppression of the decay modes with muons and positrons, by means of a RICH counter and hadronic calorimeters. The same requirements are also effective for controlling the backgrounds with more than one charged track in the final state. A hermetic photon veto system is also important to suppress decay modes with photons in the final state: these are decays with one or more neutral pions as well as radiative decays. A signal in the Čerenkov counter on the beam line ensures the presence of a kaon in time with the tracks in beam spectrometer and in the downstream spectrometer. This allows the suppression of most of the accidental tracks coming from the interactions of the pions in the beam with the material along the beam line. Finally two global requirements are applied: the kaon decay has to take place in the first 60 m of the decay volume; the measured momentum of the downstream pion must be between 15 and 35 GeV/c.
Table 1 summarises the expected results on the sensitivity of NA62, combining all the rejection factors coming from kinematics, particle identification and vetoes. The Standard Model Branching Ratio is assumed for the signal.

3. NA62 experimental setup

The schematic layout of the NA62 experiment is shown in figure 2.
The experimental setup consists in tracking devices for both K^+ and π^+, and calorimeters to veto photons, positrons and muons. Furthermore, a powerful particle identification system to identify

Decay	event/year
$K^+ \to \pi^+ \nu\bar{\nu}$	45
$K^+ \to \pi^+ \pi^0$	5
$K^+ \to \pi^+ \pi^+ \pi^+$	1
$K^+ \to \pi^+ \pi^- e^+ \nu$	<1
$K^+ \to \pi^+ \pi^0 \gamma$	<1
$K^+ \to \mu^+ \nu\gamma$	1.5
other rare decays	0.5
Total backgrounds	<10

Table 1: Expected signal and background from K^+ decays estimated from NA62 sensitivity studies.

the incident kaons and distinguish π^+ from μ^+ and e^+ complements the tracking and veto detectors to reach the required sensitivity and to guarantee redundancy.

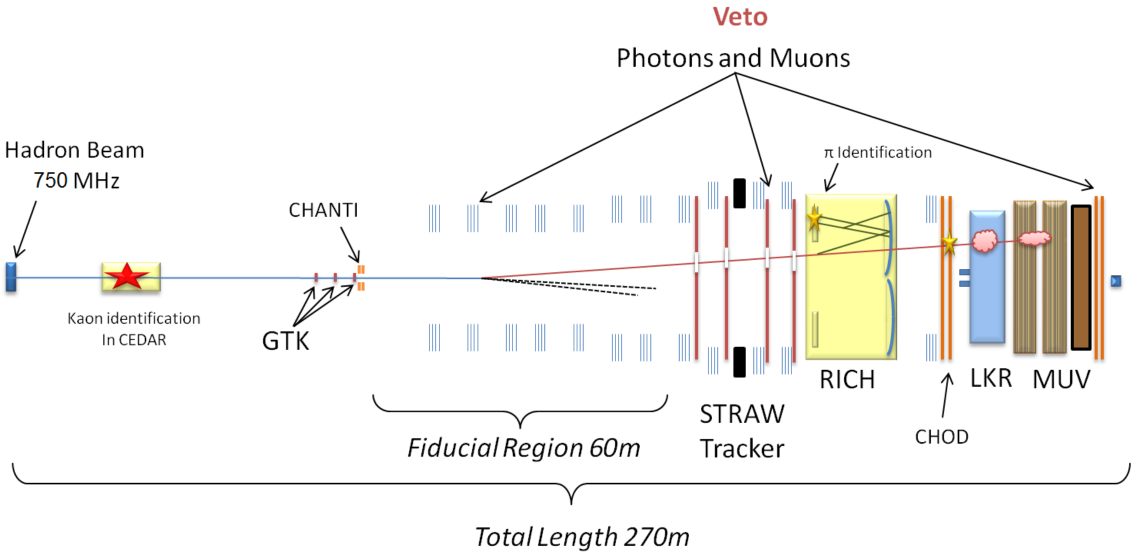

Figure 2: Layout of the NA62 experimental setup (not to scale).

The beam feeding the NA62 experiment is a secondary hadron beam produced from SPS primary protons with a momentum of 400 GeV/c and impinging on a beryllium target located at the beginning of the NA62 experimental hall. The central momentum of the kaon beam is 75 GeV/c, chosen as a result of a compromise between particle flux at production and fraction of kaons decaying within the 60 m long fiducial region. In addition, this value fits well with the characteristics of the detectors for particle identification: the useful range of momenta for a π^+ decay product to be distinguished from a background μ^+ is between 15 and 35 GeV/c, and this means that other particles associated with an accepted pion must carry an energy above 40 GeV/c, for which the veto system has an adequate efficiency.
The kaon component represents only 6% of the secondary beam; the remaining particles are mainly pions (70%) and protons (23%). Given the nominal hadron beam rate of 750 MHz, about 5 MHz of kaon decays are expected in the 60 m long fiducial region, for a total of about 4.5×10^{12} kaon decays per year.

Kaon tagging and tracking

A CEDAR filled with nitrogen gas is placed in the incoming beam to positively identify the kaon component in the high rate environment. It is designed to identify particles of a specific mass by making the detector blind to the Čerenkov light produced by particles of different mass. The KTAG upgrade of NA62 acts in the Čerenkov light detection stage: to cope with the expected 45 MHz kaon rate, 384 photomultipliers (PMTs) grouped in 8 light boxes are placed behind the 8 annular slits. A preliminary analysis of 2014 data shows a kaon identification efficiency better than 95% and a time resolution below 100 ps.
The GigaTracker (GTK) is a spectrometer composed of three stations placed along the beam line just before the fiducial region. Each GTK station is a hybrid silicon pixel detector with a total number of 18000 $300 \times 300\ \mu\text{m}^2$ pixels grouped in 10 read-out chips. The expected performances on the track measurement are a 0.4% resolution for the momentum, 16 μrad for the direction and 200 ps for the timing. One chip per station has been commissioned during the 2014 run.

Pion tracking and identification

A STRAW magnetic spectrometer measures the direction and momentum of secondary charged particles originating from the decay region. It is composed of four chambers, two on each side of a large aperture dipole magnet. Each chamber is equipped with 1792 straw tubes which are arranged in four “views” providing measurements of four coordinates x, y, u, v. The requirements for the detector performances are a relative momentum resolution of 1%, a spatial resolution of 130 μm per coordinate and a very low track reconstruction inefficiency. The detector has been fully commissioned during the 2014 run.
The RICH gives an additional rejection of the muon background in the selected momentum range. It is a 17 m long cylindrical tank, filled with Neon at atmospheric pressure. The Čerenkov light is reflected by a system of hexagonal spherical mirrors placed at the downstream end of the tank and detected by 2x960 photomultipliers located in the upstream end of the detector. The μ suppression factor is 10^{-2} averaged over the momentum range of interest, and a time resolution of 65 ps has been measured.
A further reduction of the muon background comes from hadronic calorimeters (MUV1-2), used for the measurement of energy deposits and shower shapes of incident particles. The two modules are iron-scintillator sandwich calorimeters with scintillator strips alternately oriented in the horizontal and vertical directions. One full module has been commissioned in 2014.
A charged hodoscope (CHOD) is placed right after the RICH tank, with the main purpose of detecting possible photo-nuclear reactions in the RICH mirror plane. It is composed of two planes made of 64 plastic scintillators, one with vertical and one with horizontal slabs. The CHOD can provide the timing of charged decay products with a resolution of about 200 ps.

Veto system

The MUV3 is a plane of fast scintillator tiles placed after an iron wall and is used to detect non-showering muons. Each tile is read by 2 PMTs to avoid the effect of Čerenkov photons on time resolution. Data from the 2014 run show a time resolution below 500 ps.
The CHANTI detector is used to detect beam particles undergoing inelastic interactions in the GTK

material. It consists of six stations of x-y plastic scintillator bars surrounding the beam, covering an angle between 0.034 and 1.38 rad. The expected efficiency in vetoing signal-like events is 99%. Preliminary 2014 data analysis shows a time resolution of the order of 1 ns.
The photon veto system provides an overall inefficiency of about 10^{-8} for $\pi^0 \to \gamma\gamma$ detection covering an acceptance from 0 to 50 mrad. The NA48 liquid Krypton (LKr) calorimeter covers intermediate angles between 1 and 8.5 mrad. It is divided in 13248 cells and the electromagnetic showers are fully detected through ionisation of low energy charged particles. The reconstructed shower time resolution is 500 ps, and the space resolution of the order of 1 mm; the total inefficiency for 10 GeV photons is below 10^{-5}. The new readout has been validated during the 2014 run.
The LAV system provides full coverage for decay photons with polar angles from 8.5 to 50 mrad, with an inefficiency of $10^{-3} \div 10^{-4}$ on photons down to 150 MeV. It consists of 12 stations, whose diameter increases with distance from the target, containing 4 or 5 layers of azimuthally staggered lead glass blocks, for a total of 2500 channels. The time resolution observed in 2014 run is about 1 ns.
The SAC and IRC give photon coverage below 1 mrad. Both detectors are made of consecutive lead and plastic scintillator plates. The inefficiency for 1 GeV photons is below 10^{-4}. A time resolution of 3 ns was measured in the 2014 run.

The TDAQ system

The NA62 experiment has a unified trigger and data acquisition system, in order to achieve an efficient data collection at high rates with a low-level selection for a first background reducing stage. The trigger logic is made of three levels: the hardware L0 trigger is implemented digitally using the data themselves, and provides a reduction from the initial 10 MHz data rate to 1 MHz; it is followed by software high-level triggers (L1 and L2) with a final output rate of 10 kHz.

4. 2014 pilot run

The majority of the NA62 setup was involved in the pilot run (October-December 2014). Two weeks of run were dedicated to data taking for preliminary physics studies. The beam intensity was 5% of the nominal one and two triggers have been used to collect a minimum bias sample and a $\pi\nu\nu$-like without photon rejection sample. The data analysis is at a preliminary stage: about 1% of the available data have been studied, not including the GTK, with partial spectrometer and with preliminary LKr calibration.
The distribution of the angle between the kaon and the secondary track as a function of the track momentum is shown in figure 3 (left), for events with only 1 track in the spectrometer and after requiring the presence of a kaon in the KTAG. A reasonable agreement can be observed if compared with the expectations for the main kaon decays (right): the suppression of the $K^+ \to \mu^+ \nu$ component is due to the muon rejection at trigger level.
The intersection between the track and the nominal beam direction is used to reconstruct the vertex and suppresses the background from kaon interactions. After requiring the vertex in the fiducial region, and selecting the track momentum between 15 and 35 GeV/c, the squared missing mass distribution shown in figure 4 (left) is obtained.

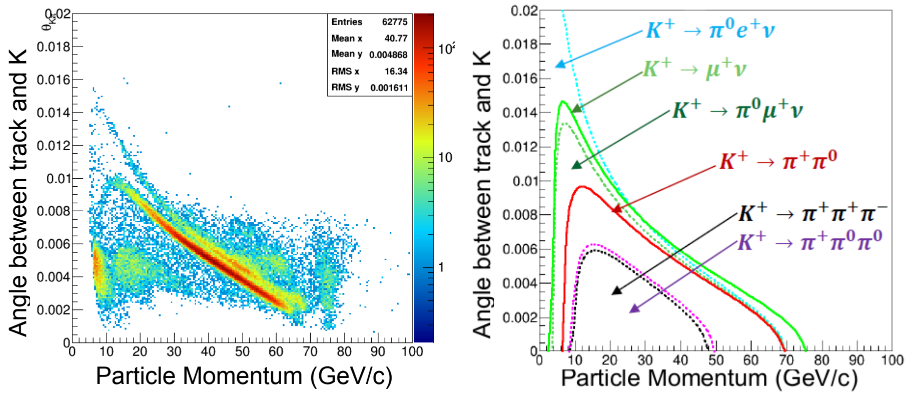

Figure 3: Distribution of the angle between the kaon and the charged particle as a function of the particle momentum for 2014 data (left) compared to the analytic distributions from main kaon decays (right).

The minimum bias sample has been used to reconstruct kaon decay modes as control samples with the liquid Krypton calorimeter only. Figure 4 (right) shows a reconstructed $K^+ \to \pi^+ \pi^0$ sample in good agreement with Monte Carlo expectations.

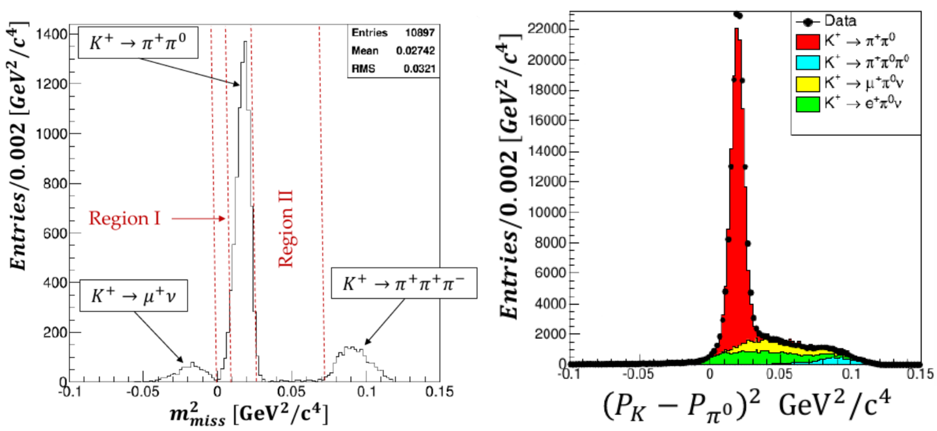

Figure 4: Distribution of the squared missing mass with the hypothesis that the charged particle is a pion, for events with vertex in the fiducial region and track momentum between 15 and 35 GeV/c (left). $K^+ \to \pi^+ \pi^0$ control sample reconstructed using the LKr (right).

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