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

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Abstract. The rare decays $K \rightarrow \pi \nu \bar{\nu}$ are excellent processes to probe the Standard Model and indirectly search for new physics complementary to the direct LHC searches. The NA62 experiment at CERN SPS aims to collect and analyse $\approx 10^{13}$ kaon decays before the CERN long-shutdown 2 (in 2018). This will allow to measure the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ branching ratio to a level of 10% accuracy. The experimental apparatus has been commissioned during a first run in autumn 2014.

1. Introduction

The rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is an excellent process to study the physics of flavour because of its very clean nature. The strong suppression to the Standard Model (SM) contributions and the remarkable theoretical precision of the SM rate makes this decay sensitive to possible new degrees of freedom. The NA62 experiment has been designed and built to study this decay mode for which the SM calculations [1] predict a branching ratio of: $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})(\text{SM}) = (7.8 \pm 0.7) \times 10^{-11}$.
The presence of two undetectable neutrinos in the final state reduces the signal signature to one high momentum charged track with nothing else, which has to be discriminated against background coming from all other kaon decays.

Figure 1 Schematic view of the NA62 experiment showing the main sub-detectors (not to scale). The main elements for the detection of the $K^+$ decay products are spread along a 170 m long region starting about $\sim 100$ m downstream of the beryllium target. Useful $K^+$ decays will be detected from a 65 m long fiducial region.

On the experimental side NA62 has chosen to use high momentum kaons (75 GeV/c) from a secondary beam produced by the CERN SPS accelerator with a technique of in-flight-decay. The high momentum of the incoming beam improves the background rejection and sets the longitudinal scale of the experiment. (see Figure 1). To achieve the required background suppression different principles have to be combined and the resulting requirements are outlined here:

- **High intensity and good timing**: a high intensity kaon beam is essential in order to reach sensitivity to a branching ratio of $\mathcal{O}(10^{-10})$. The incoming secondary beam from the SPS provides a particle rate of 750 MHz, containing about 6% of kaons delivering roughly $45 \times 10^6$ decays in the fiducial region per spill. Precise timing (in the range 100 - 150ps) of the $K^+$ and the $\pi^+$ allows precise matching of the particles in the decay. The time resolution is essential in order to keep wrong associations at level below 1%.

- **Low mass Tracking**: The most discriminating variable to distinguish the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ signal from background is the squared missing mass: $m^2_{\text{miss}} \equiv (p_K - p_\pi)^2$ where $p_K$ denotes the 4-momentum of the parent particle assumed to be a kaon and $p_\pi$ is the 4-momentum of the decay particle assumed to be a $\pi^+$. In order to exploit this variable, track position and momenta have to be measured with high accuracy in low mass detectors. Low mass detectors are essential because inelastic scattering of beam particles in the detector material can mimic an isolated $\pi^+$ appearing like a signal event and hence contribute to the background.

- **Hermetic vetoing for photons and muons**: the kinematic rejection must be accompanied by direct vetoing for photons (in particular for the $K^+ \rightarrow \pi^+ \pi^0$ background) requiring a typical
inefficiency of $10^{-4}$ for high energetic photons. The largest fraction of $K^+$ decays contain muons in the final state, therefore a muon veto system is mandatory both in the trigger and off-line. NA62 uses a plane of fast scintillators (MUV3) for direct muon vetoing, this system is complemented by two sampling hadron calorimeters (MUV1+2), which measure the deposited hadron energy in the event distinguishing hadron showers from muons.

- **Particle ID:** Several detectors (LKR, KTAG, RICH,…) complement the event information with direct evidence on the particle species. The RICH, for example, identifies positively the $\pi^-$ in the event providing another factor 100 in the suppression of muons. The LKR measures precisely the electro-magnetic energy with the possibility to identify positrons and pions by distinguished shower profiles. The KTAG tags the incoming kaon with 100ps time resolution and can reject pion or protons from beam gas interactions.

In order to reduce passive material in the acceptance region all the detectors upstream of the RICH are installed inside the beam vacuum. A side effect of the high intensity beam is that most detectors have to be able to cope with high particle rates. In particular the GTK is exposed to 750 MHz of beam particles and the KTAG/CEDAR has to deal with about 50 MHz of kaon rate. The downstream detectors are affected by muon flux of up to 11 MHz which are originating from particle decays or interactions in the target.

The main detectors are described in more detail in the following sections, for completeness, a short summary of all detectors and their features are outlined here (see Figure 1)[2]:

i) **The KTAG** identifies the $K^+$ component in the beam with respect to the other beam particles by employing an upgraded differential Cherenkov (CEDAR) counter;

ii) The GigaTracker (GTK) comprises three Si micro-pixel stations measuring, time, direction and momentum of the beam particles before entering the decay region.

iii) **The STRAW Tracker:** measures the coordinates and momentum of secondary charged particles originating from the decay region. To minimise multiple scattering the chambers are built of ultra-light material and are installed inside the vacuum tank. The four straw chambers are intercepted in the middle by a large aperture dipole magnet (MNP33), providing a vertical B-field of 0.36T.

iv) **The RICH:** is situated downstream of the last straw chamber. It consists of a 17 m long radiator filled with Neon Gas at 1 atm. allowing the separation of pions and muons between 15 and 50 GeV/c.

v) A system of Photon-Veto detectors ensured by:
   - the high-resolution Liquid Krypton electro-magnetic calorimeter (LKR),
   - supplemented, at small and forward angles, by an Intermediate Ring Calorimeter (IRC) and a Small-Angle Calorimeter, as well as
   - at large angles, by a series of 12 annular photon-veto detectors (LAV).

vi) The Muon-Veto Detectors (MUV) are composed of a two-part hadron calorimeter -from which only one module was installed in 2014- followed by additional iron and a scintillator tile array. This system supplements and provides redundancy with respect to the RICH in the detection and rejection of muons.

vii) **The CHANTI:** these detectors are ‘guard-ring’ scintillating counters surrounding the last GTK station to veto beam particles, which scatter inelastically in the material of GTK3.
viii) **The CHOD:** is a charged-particle hodoscope used in the trigger, covering the acceptance and located between the RICH and the LKR calorimeter.

ix) These detectors are operated and inter-connected with a high-performance trigger and data-acquisition system (**TDAQ**).

### 2. KTAG

The choice of using a high momentum beam (75 GeV/c) implies a secondary beam with mixed composition because at this energy kaons cannot be efficiently separated from pions and protons. In NA62 the beam intensity is about 17 times higher than the effective kaon rate and, in this context, accidental beam gas events in the vacuum tank can become a critical background for the signal. The KTAG is needed to measure precisely the timing of the mother particle in the decay in order to suppress quasi inelastic scattered beam particles, which enter the acceptance of the experiment.

The KTAG consists of a CERN SPS differential Cherenkov counter (called CEDAR) [3], which is upgraded with an external optics and new photo detectors. The CEDAR detectors are optimized to detect Cherenkov light at a specific angle and, at 75 GeV/c, kaons can be selected by choosing the N2 or H2 as radiator gas and the right pressure.

The front extension (called KTAG) is replacing the 8 original photomultipliers (PM’s) by light boxes containing each 48 PM’s (Figure 2). With this layout the detector can handle the high beam rate and achieves a time resolution of better than 100 ps.

Figure 2 Left: Schematic of the KTAG extension with the new optic and photo-detectors. Right: scatterplots of the 8 light spots (from the 2014 run).
The kaon spectrometer consists of three silicon pixel detectors installed perpendicular to the beam axis. The detectors are traversed by the full beam intensity of 750 MHz and mounted around four achromat magnets as shown in Figure 3 providing measurements of momentum, time and angle of the incoming kaon beam.

The GigaTracker is composed of hybrid silicon pixel detectors (GTK1,2 and 3) and is installed inside the beam vacuum. Each detector has an active area of about 60 x 27 mm² containing 18'000 pixels of 300x300 μm² size. The full-area sensor is bump bonded to 10 read-out ASIC chips (TDCpix) as shown in Figure 4. The expected fluence for a typical 100 day run time year is $2 \times 10^{14}$ 1 MeV n equivalent per cm² in the central region of the sensor [2].

The pixel dimensions and the distances between stations are adapted to deliver the required momentum and direction resolutions. But most important, and novel for a silicon pixel detector, is the excellent timing performance ($\sigma_t < 200\text{ps per station}$) allowing to separate sharply the incoming kaon from any other beam particle. To minimize hadronic interactions of the beam the total detector thickness is $\leq 0.5\text{mm}$ (see Figure 5) [4].

![Figure 3 Layout of the three GigaTracker stations with the accompanying achromat magnets.](image)

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### 3. GigaTracker (GTK)

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![Figure 4 Beam intensity distribution over GTK station 3 (units are MHz/mm²). One of the ten read-out chip is overlayed.](image)
### Component

| Material                      | Thickness [μm] | X₀ [%] |
|-------------------------------|----------------|--------|
| Sensor Si                     | 200            | 0.22   |
| Bump Bonds Pb-Sn              | ~25            | 0.001  |
| Readout Chip Si               | 100            | 0.11   |
| Micro Channel plate and cooling fluid Si + C₆F₁₄ | ≈150 | 0.16   |
| Total                         | < 500          | <0.5   |

Figure 5 Left side: Material Budget for one station. Right side: sketch of detector cross-section (red = sensor, blue ASIC, black = micro channel plate.

### 4. Straw Tracker

The purpose of the STRAW Tracker is to measure with good accuracy the direction and the momentum of secondary charged particles originating from the decay region. The spectrometer (see Figure 6) consists of four chambers interleaved in the middle by a large dipole magnet providing a transversal momentum kick of 270 MeV/c vertical B-field of 0.36T. Each chamber is equipped with 1’792 straw tubes, which are positioned in four “Views” providing measurements of four coordinates (see Figure 6 and Figure 7).

![Straw Tracker Diagram](image)

Figure 6 Longitudinal cross-section of the decay vacuum tank, the Straw Spectrometer and the RICH.

In order to minimise multiple scattering, the spectrometer is operated in vacuum without physical separation from the upstream decay volume. The straw tracker technology has been chosen notably because it can be designed without frames and flanges close to the beam, which limits interactions from accompanying beam particles.

The straws are made out of 36 μm thick polyethylene terephthalate film coated with thin layers of copper (50 nm) and gold (20 nm). The straws are fabricated from longitudinal foils through ultrasonic welding in the axial direction [2].
The straw readout is done with an FPGA based TDC imbedded in the front end and a tailored back-end read-out board (SRB) for data extraction and triggering [5].

5. The RICH

A Ring Imaging Cherenkov Counter (RICH) is used to distinguish pions from muons in the momentum range from 15 GeV/c to 35 GeV/c and to measure the arrival time of final state tracks to better than 100ps.

The RICH (see Figure 8) consists of a steel cylindrical radiator vessel, 17.5 m long and about 4 m in diameter. In the centre it is protruded by a thin aluminium pipe separating the beam vacuum from the radiator gas (neon at 1 atm.). Cherenkov photons are reflected on a mirror mosaic (made of 20 spherical mirrors) and, then, projected on to 2x1’000 photo-multipliers located at 3 and 9 o’clock on the upstream end of the vessel.
6. The Photon-Veto Detectors

Photon vetoes are required to suppress the dominant background originating from the decay $K^+ \rightarrow \pi^+\pi^0$ (BR=20.7%) to the specified level. The average inefficiency for the rejection of the $\pi^0$ should be smaller than $10^{-8}$. The photon vetoes need to have hermetic geometrical coverage up to 50 mrad for the photons originating from the kaon decays occurring in the decay region (from 5 to 70m after the final collimator). With such a configuration, only about 0.2 % of the $K^+ \rightarrow \pi^+\pi^0$ events have one photon from the $\pi^0$ left undetected [2].

The geometry of the experiment is partitioned into three different angular regions, each instrumented by three different detector technologies (see Figure 9):

- **Large Angle Vetoes (LAV)**, covering the angular region between 8.5 mrad and 50 mrad, distributed along the decay volume and spaced by $\approx 6$m in the upstream region and by $\approx 12$m downstream. The LAV is composed of 12 stations (11 inside the vacuum tank), each station consists of ring shaped assemblies of lead glass calorimeter elements with photomultipliers at the end (see Figure 10) [7].

- **The NA48 Liquid krypton calorimeter (LKR)**, covering angles between 1 and 8.5 mrad (see Figure 9) The LKr is a quasi-homogeneous electromagnetic calorimeter, which ensures a very good intrinsic energy and time resolution. Its key functions in the NA62 experiment are to veto photons from K decays and to enhance the hadron identification in conjunction with the muon veto system. For NA62 the LKR calorimeter has been equipped with new back-end electronics (Calorimeter REAdout Module named CREAM). The CREAMs (see Figure 11) provides 40 MHz sampling of 13248 calorimeter channels, data buffering during the SPS spill, zero suppression, and programmable trigger sums for the experiment trigger processor [8].

- **Small angle vetoes** covering the region down to zero degrees (SAC) and the zone around the inner radius of the LKR (IRC) calorimeter. These will have suitable overlap in the angular acceptance to cover the beam pipe and an inner radius smaller than that of the beam pipe (see Figure 9). Both detectors are sampling calorimeters with scintillating/iron layers and shashlik-type read-out [2].

![Figure 8 Schematic drawing of the RICH detector. The vessel is filled with neon gas at 1 atm.](image)
Figure 9 Longitudinal view of the experiment indicating the different region of the photon vetos.

Figure 10 Schematic drawing of one LAV station, the external cylinder is part of the vacuum tank housing inside the ring-shaped lead glass elements and the photomultipliers.
7. Experience from the commissioning run
NA62 has had a first commissioning run in autumn 2014 exploiting practically the complete detector at low beam intensity which was an important accomplishment for the first run. Practically all subsystem have been operated and could deliver data of the expected quality. The yet ongoing data analysis shows that the detector performances of the main new systems (e.g. photon and muon vetos, the RICH and the Straw Tracker) meet fully the expectations. Important learnings were obtained
concerning the data acquisition system, which will undergo further optimization to increase the acquisition rate, so that the beam intensity can be increased to its nominal rate in the future.

The first GigaTracker detectors were installed during the run and up to the end three GTK’s could be operated together. However, due to technical difficulties in the carrier board, these detectors could be read out only partially (10%), therefore, these data cannot be used in the physics analysis, but they are exploited for detector performance studies. Preliminary results show that the timing properties of the detectors are as expected.

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