The NA62 RICH Detector

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***Abstract*—The CERN NA62 experiment aims to measure the ultra-rare charged kaon decay $K^+ \rightarrow \pi^+\nu\overline{\nu}$ with a 10% accuracy. For the reduction of the background from the decay of the $K^+ \rightarrow \mu^+\nu$ in muon-neutrino, a Neon-filled, RICH detector is being built, to have a good $\pi - \mu$ separation between 15 and 35 GeV/c. The final detector is described and the preliminary results from a test of a prototype equipped with 414 photomultipliers are presented.**

***Index Terms*—NA62, RICH, rare kaon decays**

I. Introduction

The decay $K^+ \rightarrow \pi^+\nu\overline{\nu}$,which has a branching ratio of the order of 10^{-10}. In the framework of the Standard Model (SM) the decay amplitude is, apart from well-known corrections, directly proportional to the product $|V_{ts} * V_{td}|$ of CKM matrix elements.

The theoretical uncertainties can reliably be estimated from other semileptonic decays and are of the order of a few per cent because of its low rate, its precise theoretical prediction inside the Standard Model, and the fact that the decay can only proceed via loop diagrams, possible contributions from physics beyond the Standard Model would easily be seen, provided a sufficient number of measured decays. The SM prediction for the BR values is $(8.5 \pm 0.7) \times 10^{-11}$[1]. Most of the existing theories of physics beyond the Standard Model predict a significant enhancement of the decay rate. However, so far only 7 events have been reported[2] by the E787/E949-Experiment at Brookhaven, which therefore can only set coarse limits on possible non-SM contributions.

Moreover, the study of this decay is complementary to the studies at the energy frontiers carried on at LHC; if LHC experiments will found hints of new physics in the next few years, a better knowledge of the BR of the decay $K^+ \rightarrow \pi^+\nu\overline{\nu}$ (and of the decay $K^0 \rightarrow \pi^0\nu\overline{\nu}$) will be fundamental to disentangle the nature of the physics beyond the Standard Model.

The NA62 experiment[3] aims to collect in two years ~100 events of the decay $K^+ \rightarrow \pi^+\nu\overline{\nu}$, with a final accuracy on the BR measurement at the level of 10%. For this purpose, a RICH detector to separate the signal from potential backgrounds from decays with a muon in the final state is essential.

In the next section the the beam and the detectors of the NA62 experiment is shortly described. Then the article focuses on the RICH detector, describing its final design and reporting the preliminary results of a test performed on May and June 2009.

II. The NA62 experiment

The NA62 experiment will operate at CERN exploiting a 400 GeV/c proton beam extracted from the SPS and impinging on a beryllium target to produce a secondary beam of charged particles. A schematic of the experimental layout is shown in Figure 1. The optics of the K12 beam will select an unseparated beam of particles with positive charge (mainly pions, $\sim 6\%$ kaons) at (75 ± 1) GeV/c. The estimated kaon flux is 5×10^{12} decays per year.

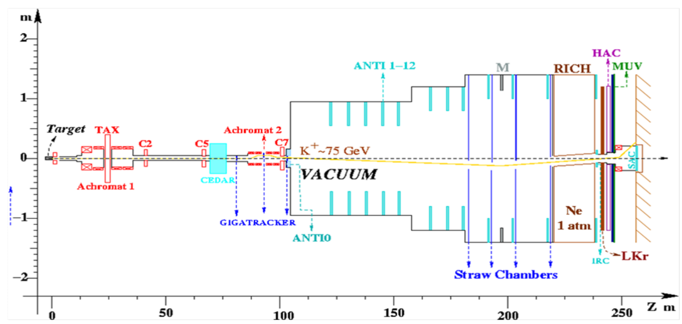

Fig. 1. Layout of the beam and the detector of the NA62 experiment.

Each particle in the beam will be tracked by 3 stations of silicon pixel detectors (measuring also the time of the track with a ~100 ps resolution). To identify kaons with respect to pions a differential Ring Čerenkov detector will be also used. After the fiducial decay region, the charged decay products will be reconstructed with a spectrometer composed by 4 stations of straw tubes, with a magnet (270 MeV/c p_T-kick) between the second and the third station. Several detectors will veto charged (outside the geometrical acceptance of the spectrometer) and neutral particles to reduce the background produced by other kaon decays.

The experimental layout is completed by a Muon detector and a ring Čerenkov (RICH) detector to reject channels with a muon in the final state. In fact, one of the most significant backgrounds for the measurement is the decay $K^+ \rightarrow \mu^+\nu$ (Kμ2) with a muon misidentified as a pion. Giving the Branching Ratio of this decay, $\sim 10^{10}$ times higher than the Branching Ratio of the signal, a rejection factor of at least 10^{-12} has to be achieved ion order to reduce the contamination to a few percents.

A factor 10^{-5} (see Figure 2) will be obtained with kinematic cuts on the squared missing mass between the decaying kaon and the outgoing charged track (under the assumption that it is a pion): $m^2_{miss} = (p_K - p_\pi)^2$. Another factor $\sim 10^{-5}$ against muon will be obtained from muon detector placed at the end of the experimental chain. Finally another factor lower than 10^{-2} must be obtained from the RICH detector exploiting the different angle for the emission of Čerenkov light between muon and pion at the same energy. The RICH detector is described in the next session.

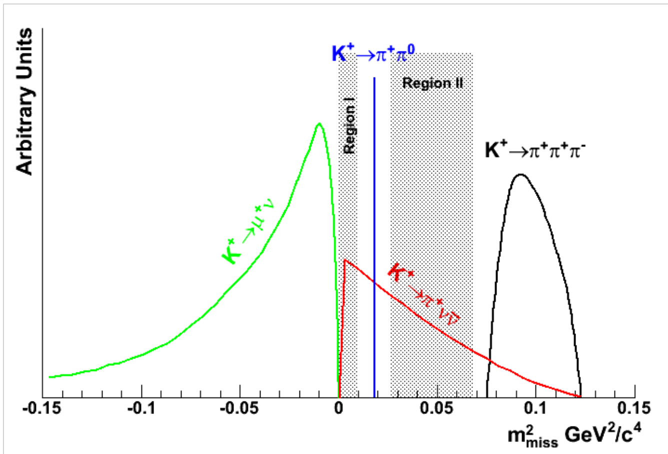

Fig. 2. Distribution of exact m^2_{miss} for the signal and the main backgrounds. The detector resolution produces a smearing of the m^2_{miss} distribution for the background channels, in this way background tails populate the two signal region.

III. The RICH detector

Kμ2 is the most frequent charged kaon decay and the event mis-reconstruction can contaminate the signal region. A fast RICH counter to further separate pions from muons in the range 15-35 GeV/c will be constructed. Under a particle mass hypothesis, the velocity measurement converts into a precise redundant measurement of the particle momentum. Conversely, if the momentum is measured by the magnetic spectrometer, the RICH can be used for particle identification. In the NA62 design the momentum of the outgoing particle is measured employing the magnetic spectrometer, and the RICH will be used purely for particle identification, to reduce the background originating from $K\mu2$ and $K \to \mu\nu\gamma$ to a negligible level.

Neon gas at roughly atmospheric pressure is chosen as Čerenkov radiating medium; a reasonable compromise between the number of produced photoelectrons (roughly linear with the length of the radiating medium) and the available space in the NA62 layout between the last straw chamber and the Liquid Krypton calorimeter (gas container no longer than 18 m in the beam direction). Moreover the refractive index n_{Ne}, $(n_{Ne} - 1) = 62.8 \times 10^{-6}$ at $\lambda = 300$ nm, guarantees small dispersion. The helium container is a tank (see Figure 3) composed by three sections with different diameters. The Čerenkov photons ($\theta_C^{\max} = 11.2$ mrad), reflected at the end of the tank by a mirror mosaic (17 m focal length), are detected in two focal planes by two flanges instrumented by $\sim$1000 photomultipliers each. The glass of the mirrors is 2.5 cm thick, 17 m focal length, with Aluminum deposit to maximize the reflectivity in the region of the light spectrum of interest. Piezo actuators are used for mirror alignment and a Carbon fiber plane (Honeycomb structure to minimize the radiation length) supports the mirrors. The final detector (see Figure 4) consists of 18 hexagonal mirrors plus 2 half hexagons in the beam pipe region, the focal planes are two in order to avoid Čerenkov photons to hit the beam pipe.

The Čerenkov light detection is performed by Hamamatsu

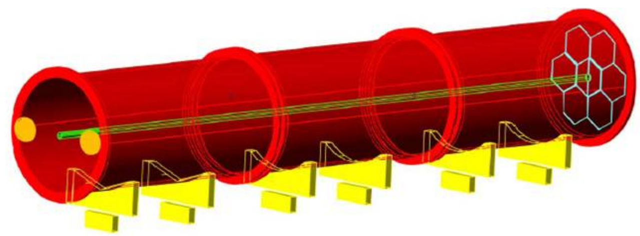

Fig. 3. Layout of the RICH tank.

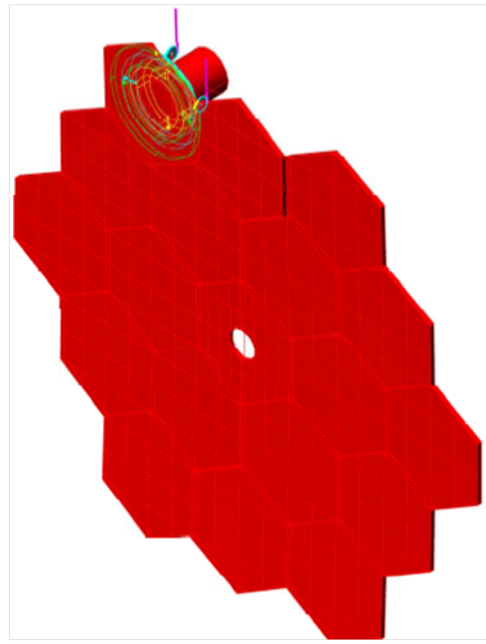

Fig. 4. The mirror mosaic for the final detector.

R7400 U-03 photomultipliers (Metal package tube, 8 dynodes) with a sensitivity range between 185 nm and 650 nm (peak sensitivity at 420 nm). These photomultipliers have an UV (transparent to Ultra Violet) glass window, the diameter is 16 mm, with an active window of 8 mm diameter. The photomultiplier gain at the applied Voltage (900 V) is $\sim 1.5 \times 10^6$ and the transit time is 5.4 ns (spread 0.28 ns), allowing to have a fast detector with an excellent time resolution. Light collection is improved with Winston Cones[4] (covered with Mylar) 22 mm high and wide from 18 mm to 7.5 mm (see fig. 5). The region with Neon is separated from the photochatodes by a 1 mm thick quartz window.

A. Readout and trigger

The analog signal out-coming from the photomultipliers is sent to a custom made current amplifier, and then to a Time-over-Threshold-discriminator, NINO[5] ASIC chip developed from the ALICE collaboration.

The digitalized signal produced by the NINO chip is received by a custom TDC board (based on the HPTDC [6] produced at CERN) with 100 ps less significant bit. Each TDC board houses HPTDC chips for a total of 128 TDCs per board. Four TDC boards are mounted on an FPGA based TELL1[7] mother board (developed by LHCb collaboration).

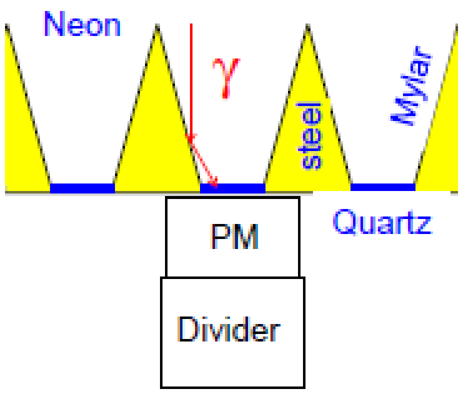

Fig. 5. The Winston cones with the quartz windows and a photomultiplier in place.

Then the TELL1 can operate 512 TDCs and four of such boards are enough to read out all the RICH channels. The TELL1 has 4 FPGAs, each one driving the output of the TDC boards, plus an FPGA driving general services and the connections to/from outside. In particular a four 1 Gigabit Ethernet ports allows to send incoming data to read-out PCs.

Trigger primitives based only on the RICH information (multiplicity) will be implemented in parallel with the readout chain on the same TELL1 board. The level 0 trigger must reduce the event rate from ∼10 MHz to ∼1 MHz (input rate for level 1).

IV. The test run on 2009

The test performed at CERN on May and June 2009 was exploiting a RICH prototype 18 m long with a diameter of 60 cm. The length of the prototype was equal to the one of the final detector, this allowed to have the same production (for equal particles at equal energy) and the same propagation of Čerenkov photons. In this way the $\pi-\mu$ separation and the time resolution can be studied under the same conditions of the final detector. The beam was parallel to the RICH axis with an angular spread of 20 μrad and a momentum spread of 1.5%. The Čerenkov light was reflected at the end of the tank by one single mirror 2.5 cm thick, with a focal length of 17 m and a diameter of 60 cm. On the focal plane, corresponding to the entrance window of the RICH prototype, a flange instrumented with 414 photomultipliers R7400 U-03 (chosen after a test performed on 2007[8]) was placed to detect Čerenkov light emitted by the charged particles of the beam. The exploited beam, produced by a primary proton beam extracted from the SPS and impinging on a Beryllium target, had a momentum ranging from 10 to 75 GeV/c, the beam composition was the following: mainly π^+, ∼15% of protons, few % of K^+, and a variable % of e^+ dependent from beam momentum (higher at lower momentum).

As the fraction of muons in the beam was negligible, in order to study the $\pi-\mu$ separation, the relation between the Čerenkov angle and the mass and momentum of a particle can be exploited. In fact, the emission angle θ_C is given by:

$$cos\theta_C = 1/(\beta n(\omega)) \tag{1}$$

Hence for two particles of different mass, in the same medium and with the same charge:

$$cos\theta_C^1 = cos\theta_C^2 \Leftrightarrow \beta_1 = \beta_2 \Leftrightarrow \frac{p_1}{m_1} = \frac{p_2}{m_2} \tag{2}$$

Since the emission probability and spectrum are unchanged if the charge and $beta$ of the particle are the same, the $\pi-\mu$ separation at a given momentum p can be studied from two pion samples; one collected at such momentum p and the other at a momentum $p' = p\cdot(m_\pi/m_\mu)$, that, from the point of view of Čerenkov light, is indistinguishable from a muon sample at momentum p.

Following this strategy, several samples of data were taken at different momenta, where each next point had a pion sample with the same β of a muon of the current momentum:

- first scan: 15.2, 20.1, 26.5, 35.0, 46.2, 61.2 GeV/c
- second scan: 17.7, 23.4, 31.0, 41.0, 54.2 GeV/c
- third scan: 28.7, 38.0, 50.3 GeV/c

The results of the test beam concerning $\pi-\mu$ separation and time resolution are presented in the next two sections.

A. $\pi-\mu$ separation

The Figures 6 and 7 show the distribution of reconstructed radius (obtained by fitting the positions of the photomultipliers giving a signal) for four momenta. The data collected at 15.2 GeV/c and 20.1 GeV/c respect the ratio $\cdot(m_\pi/m_\mu)$ and they can be used to measure the $\pi-\mu$ separation at 15.2 GeV/c, the same ratio is given by the data collected at 35 and 46.2 GeV/c, allowing to measure the $\pi-\mu$ separation at 35 GeV/c. The $\pi-\mu$ separation is better at low momenta with respect to higher momenta; the NA62 experiment will consider pion with momentum between 15 and 35 GeV/c.

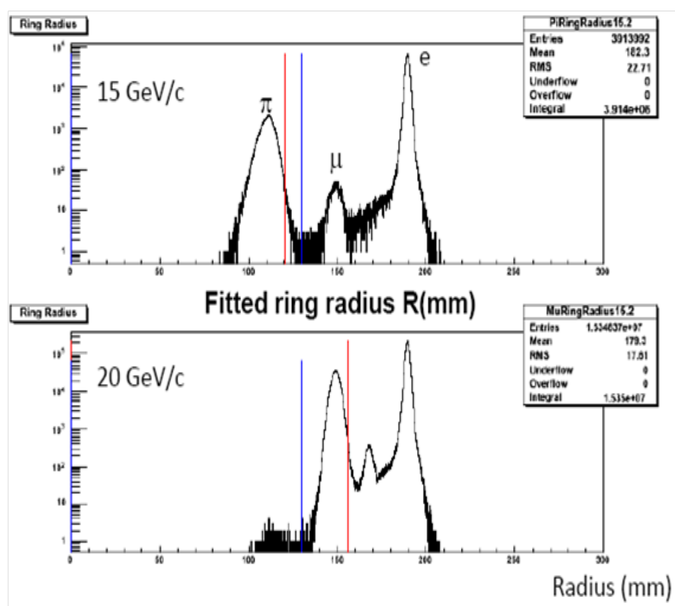

Fig. 6. Distribution of reconstructed beam at 15.2 GeV/c (top) and for 20.1 GeV/c (bottom). The half line between the pion and “muon” peaks is the blue one. In the plots are also visible the distributions for genuine muon strongly suppressed in the exploited beam.

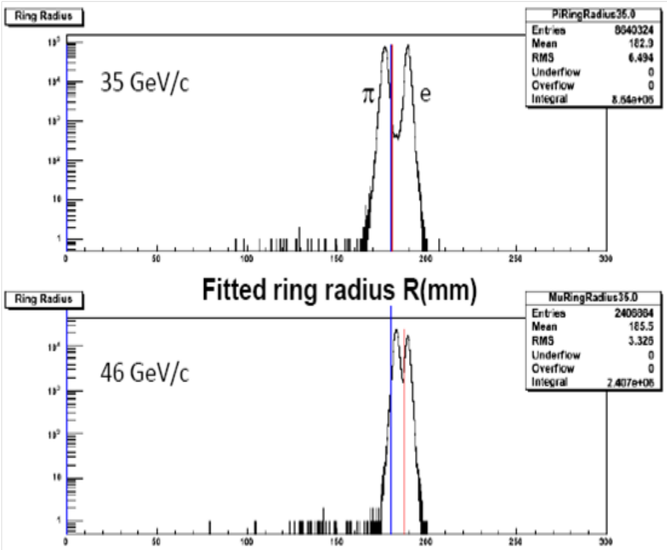

Fig. 7. Distribution of reconstructed beam at 15.2 GeV/c (top) and for 20.1 GeV/c (bottom). The half line between the pion and "muon" peaks is the blue one.

To calculate the $\pi - \mu$ separation the half line between the pion and "muon" (pion collected at higher momentum) peaks is considered. At lower momentum the events of the pion peak on the right tail above this line give the inefficiency of the separation procedure for the signal. At higher momentum the left tail of the "muon" peak belove the same line give the residual μ contamination on the signal sample. For each momenta we can then calculate the percentage of pion loss and of muon contamination (normalizing all the samples to the number of events in ± 3 standard deviation from the peaks position). The results are shown in Figure 8; integrating the residual contamination between 15 and 35 GeV/c a $(0.563 \pm 0.005)\%$ suppression factor for muons is obtained for the RICH prototype. This result is preliminary and further studies are going to determine the systematic uncertainty.

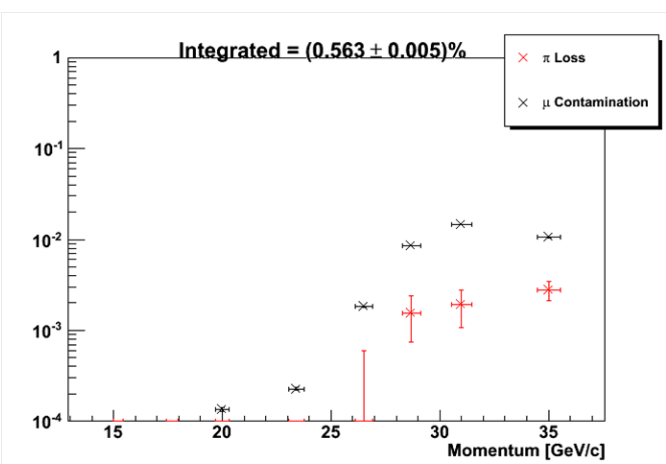

Fig. 8. Distribution of the rejection factor for muons (black) and of the inefficiency for pion identification (red) as a function of beam momentum.

B. Time resolution

On Figure 9 is reported the time resolution obtained for pions and electrons as a function of particle momentum. A single photomultiplier has a time resolution of ~350 ps. This value is achieved correcting for the dependence of the NINO response from the pulse-hight of the analog signal (slewing correction). Then the time resolution depends from the number of firing photomultipliers. In fact the probability of Čerenkov emission is proportional to the β of the charged particle; Then the time resolution for pions is momentum dependent ($p = \beta\gamma mc$). On the other hand the electrons, given their mass, can always be considered ultra-relativistic (β almost equal to 1), as a consequence their time resolution does not depend from momentum.

The time resolution for pions is always better than 95 ps while for electrons is ~60 ps on the whole momentum range (preliminary result).

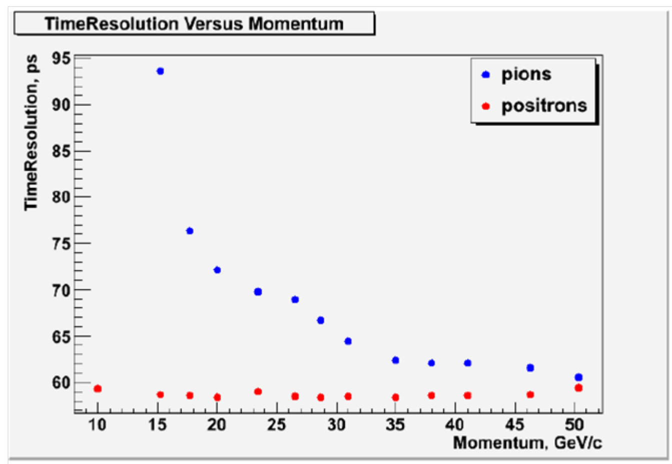

Fig. 9. Time resolution of the RICH prototype for pions and electrons as a function of beam momentum.

V. Conclusion

From the data collected during the test on June 2009 with a RICH prototype, a rejection factor against muon contamination of $(0.563 \pm 0.005)\%$ has been obtained. This preliminary result agrees with the requested performances for th final detector. A good time resolution, in agreement with previous measurement[8] and always better than 95 ps for pions with momentum between 15 and 35 GeV/c, has also been obtained.

Other studies were carried on during this test; two different mirrors were tested, in order to study the best procedure for Aluminium deposit. Pollution of the Neon with oxygen and CO_2 was also performed in order to understand the purity necessary to reach the requested performances.

Several data were also collected rotating the mirror in order to study the reflectivity of Winston cones and the uniformity on photocathode response. Analysis on these items is ongoing together with the finalization of the measurements here presented.

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