# The NA62 RICH Detector

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## Abstract

The NA62 experiment at CERN aims to measure the ultra-rare decay $K^+ \to \pi^+ \nu\bar{\nu}$ with a 10% accuracy; the main background, $K^+ \to \mu^+ \nu$, is suppressed using kinematical cuts and exploiting the different stopping power of $\pi^+$ and $\mu^+$. A further 0.5% suppression will be provided by a RICH detector, in a momentum range between 15 and 35 GeV/c. In this paper the design parameters of a RICH detector that fulfills the NA62 experiment requirements will be described, as well as results from two different beam tests.

*Key words:* RICH, PID, timing
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## 1. Introduction

The CERN NA62 experiment [1] aims to measure the Branching Ratio of the ultra-rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay with a 10% accuracy. The main background, the decay $K^+ \to \mu^+ \nu$ ($BR \sim 63\%$), must be suppressed by a rejection factor of $4 \times 10^{-13}$. This can be accomplished using a combination of kinematical cuts ($8 \times 10^{-6}$), the different power of penetration through matter of pions and muons ($10^{-5}$) and a further $5 \times 10^{-3}$ suppression factor will be provided by a RICH detector, in a momentum range between 15 and 35 GeV/c. The RICH detector must also provide the pion crossing time with a resolution of the order of 100 ps in order to minimize wrong matching with the parent particle measured by an upstream detector. The details of the RICH project will be described. A RICH prototype of the same length as the final detector, equipped with 96 PM's was built and tested using a pion beam at CERN in October 2007: the results of this test beam as well as results from a second test performed in 2009 using a larger number of PM's and several beam configurations will be presented. The final RICH detector is supposed to be completed in time for the NA62 commissioning run foreseen in 2011.

## 2. The RICH detector design

In a RICH detector [2] the Cherenkov light, emitted at an angle $\theta_C$ by a charged particle of velocity $\beta c$, larger than the speed of light in the crossed medium, is imaged by means of a spherical mirror onto a ring on its focal plane. In the case of small index of refraction $n$, as is typical of gas radiators, the ring radius, $r$, is related to the Cherenkov angle by $\theta_C = r/f$, where $f$ is the mirror focal length.

The NA62 RICH [3] is an ~18 m long tube, ~3 m in diameter, filled with neon at atmospheric pressure and room temperature, equipped with a segmented mirror of 17 m focal length, at the downstream end, and about 2000 PhotoMultipliers (PM's), at the upstream end. In order to achieve the required $\pi - \mu$ separation, the NA62 RICH must have a Cherenkov angle resolution better than 80 $\mu$rad. Moreover, it must provide the crossing time of the pion produced in the $K^+$ decay with a resolution of less than 100 ps and it should give a fast signal for the first level trigger for a charged particle. The best $\pi - \mu$ separation is obtained when the lowest accepted momentum is close to the Cherenkov threshold. However, in order to have full efficiency for a 15 GeV/c momentum pion, the threshold should be about 20% smaller, i.e. 12.5 GeV/c; this corresponds to $(n-1)=62\times10^{-6}$, which matches almost exactly the index of refraction of neon at atmospheric pressure, and this also guarantees a small dispersion. The smallness of (n-1) implies a low emission of Cherenkov photons per unit length, which should be compensated with a long radiator. The NA62 RICH will make use of the maximum space available along the beam line: a stainless steel cylindrical vessel is foreseen, 18 m long and about 3.7 m in diameter, with the beam pipe passing through. It will be filled with neon gas at atmospheric pressure, corresponding to 5.6% $X_0$. In order to achieve full acceptance coverage for the Cherenkov photons emitted by pions and muons, the total surface of the mirrors will have a diameter of about 3 m. To avoid absorption of reflected light on the beam pipe, the mirrors are divided into two spherical surfaces: one with the center of curvature to the left and one to the right of the beam pipe. The total reflective surface exceeds 6 m$^2$, therefore a matrix of 20 mirrors, 18 hexagonal (each inscribed inside a 70 cm diameter circle) and 2 semi-hexagonal, will be used. The PM's are equally distributed to instrument these two regions, each about 1 m away from the beam pipe axis; Winston's cones [4] are used to enhance the ratio between sensitive and instrumented area.

The Hamamatsu[1] R7400U-03 metal package PM has been chosen as light detector for its fastness (280 ps FWHM transit time jitter), small dimension (16 mm wide with an active diameter of 8 mm) and relative cheapness; thanks to the UV-glass window and bialkali cathode the PM has good response up to the near ultraviolet with a peak quantum efficiency of about 20% at 420 nm. The PM will be operated at about 900 V negative voltage, with a gain of about $1.5 \times 10^6$. The High Voltage system consists of a CAEN[2] SY2527 crate equipped with A1733N boards. The PM signal is sent to custom-made current amplifiers with differential output. The amplifiers feed NINO chips [5] used as discriminators operating in time-over-threshold mode, providing a fast LVDS signal. The RICH readout is a compact, high-performance TDC-based integrated readout and trigger system, partly based on existing hardware developed for LHC experiments. The mother board is the TELL1 [6], a customizable, general-purpose readout board which can house up to four custom daughter-cards, each of them served by a FPGA and a large amount of dynamic memory. A TDC daughter-card was developed for NA62, based on CERN HPTDC chips [7], working in 100 ps LSB resolution mode. A single daughter card houses 128 channels, for a total of 512 channels per board. The trigger primitives will be constructed in parallel with the readout on the same TELL1 board. A fast simulation of the NA62 RICH detector was developed taking into account the generation of Cherenkov photons, the geometry of the mirrors and the PM performance. A full GEANT4 based Monte Carlo of the prototype was later developed and validated with the purpose to simulate the final detector and evaluate its performance. Generation, full optical propagation and detection of Cherenkov photons have been taken into account, as well as smaller effects such as neon scintillation, reflectivity of the vessel and of the PM flange.

## 3. Prototype test beam results

A RICH prototype was built and tested at CERN. A stainless steel vessel, 17 m long and 60 cm wide (divided in 5 sections) and vacuum resistant, was installed along the K12 beam line in the SPS North Area. A single mirror, 50 cm wide, 2.5 cm thick, with a focal length of 17 m, built by Marcon[3], was used. The mirror was placed at the downstream end of the vessel, mounted on a support structure which could be moved by means of two remotely controlled step motors. At the upstream end a stainless steel flange was placed to house the photomultipliers, arranged in a hexagonal lattice (honeycomb). Each PM was separated from neon by a 1 mm thick quartz window; a Winston cone, covered with a thin mylar foil, was used to convey the light to each PM, as it is foreseen for the final detector.

### *3.1. RICH-100 prototype*

A first beam test was performed in October 2007. The RICH prototype was exposed to a 200 GeV/c momentum negative beam, composed mainly of pions. The detector was equipped with a limited number of PM's (96), placed in the region where the 200 GeV/c pion Cherenkov ring was expected. Hamamatsu R7400 PM's of types U03, U04 and U06 were tested. U04 turned out to be too inefficient for the experiment needs. The U03 type was chosen because U06 is more expensive, has a worse time resolution and does not provide a significantly higher number of photoelectrons. The results from data analysis confirm the Monte Carlo expectations and fully match the detector design: an average single PM time resolution of 310 ps was found (Fig. 1, top) while the RMS of the average event time was measured to be about 65 ps (Fig. 1, bottom). The pion Cherenkov angle resolution turned out to be better than 60 $\mu$rad and the average number of PM's that fired per event was found to be 17. The prototype construction and the beam test results are described in detail in [8].

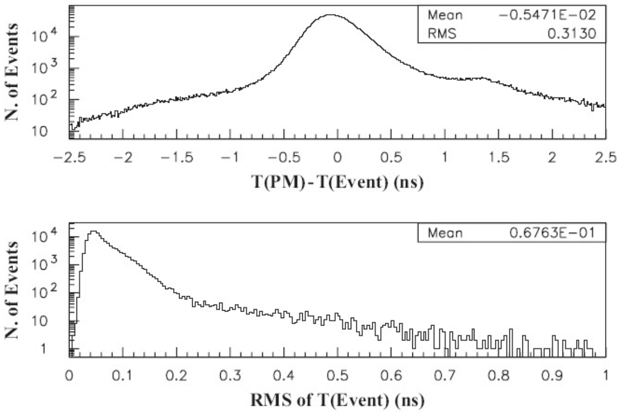

Figure 1: Top: Difference between each PM time and the event time, Bottom: RMS of the event time.

### *3.2. RICH-400 prototype*

The RICH prototype was tested again at CERN in May-June 2009. The main differences with respect to the previous test were a larger number of PM's, a cooling system and new read-out electronics. The upstream flange of the vessel was redesigned to accomodate 414 PM's, in order to cover the whole acceptance for Cherenkov light produced by $\pi^+$ with momentum $\geq$15 GeV/c passing through the detector along its axis, and to house a cooling system also usable in the final detector. Positive hadron beams, produced by the SPS primary 400 GeV/c protons, were used at several different momenta in the 10 GeV/c to 75 GeV/c range in order to measure the $\pi - \mu$ separation, to check the detector performance and to validate the design of the final readout electronics. The beam was composed mainly of pions, with a small quantity of protons, a few percent of kaons and a variable fraction of positrons. The prototype performances were tested under various conditions: beam momenta, mirror orientation, rates, TELL1 firmware versions and gas contamination (adding air and $CO_2$ to neon). The measurements were repeated with a new mirror, similar to the final ones. Fig. 2 shows the PM illumination during a 15 GeV/c run; two rings are clearly visible, as expected.

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[1] Hamamatsu Photonics, Japan, http://www.hamamatsu.com

[2] CAEN S.p.A., Italy, http://www.caen.it

[3] MARCON Costruzioni Ottico Meccaniche, Italy, http://www.marcontelescopes.com

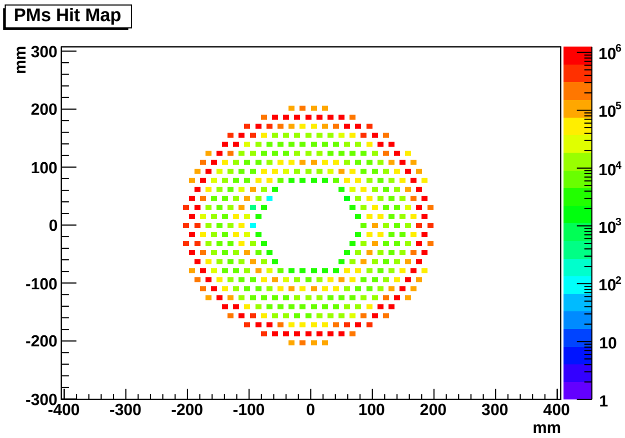

Figure 2: PM illumination for a 15 GeV/c run; two Cherenkov rings are visible: the outer, due to $e^+$, at $\beta = 1$ and the inner, due to $\pi^+$.

### 3.2.1. *Time and Cherenkov angle resolutions*

The number of hit PM's per ring as a function of the momentum is shown in Fig. 3.

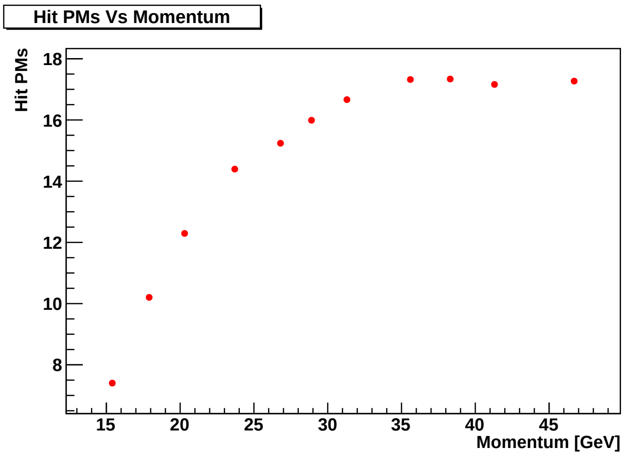

Figure 3: Average number of hit PM's for a single ring.

Both time and Cherenkov resolution are strongly correlated to the number of hit PM's per ring, hence to the number of Cherenkov photons and to the collection and the detection efficiencies. In the momentum range of interest, a time resolution, defined as the average root mean square of selected hits, well below 100 ps was measured (Fig. 4) and a Cherenkov angle resolution below 200 $\mu$rad was found (Fig. 5), in good agreement with the Monte Carlo expectations. The small rising trend in the high momentum region is associated to variation in light acceptance, as a result of geometrical effects due to the honeycomb structure.

### 3.2.2. $\pi - \mu$ *separation*

The $\pi/\mu$ separation in the momentum range 15-35 GeV/c was measured using only $\pi^+$, since the $\mu^+$ content in the beam was negligible. The following method was used: the fitted Cherenkov ring radius for pions at a given momentum was compared with the radius of pions at higher momentum, with the same $\beta$ as that of muons of the original momentum. The $\pi - \mu$ separation was parametrized by the probability to misidentify a $\mu$ as a $\pi$. In each momentum bin, a signal region ($\pi$) was defined and the fraction of $\mu$ in that region was evaluated. The procedure to calculate the misidentifcation probability is the following: a Gaussian fit, excluding tails, to both peaks was used to extract their average values and their widths; the normalization for $\mu$'s is taken as the number of events within 3 standard deviations from its average, while a cut half-way between the two peaks is used to separate signal and background regions. Since the $\pi - \mu$ separation has been calculated using two data samples at two different momenta, the systematic effect due to its knowledge can be estimated by comparing the results obtained using two different variables.

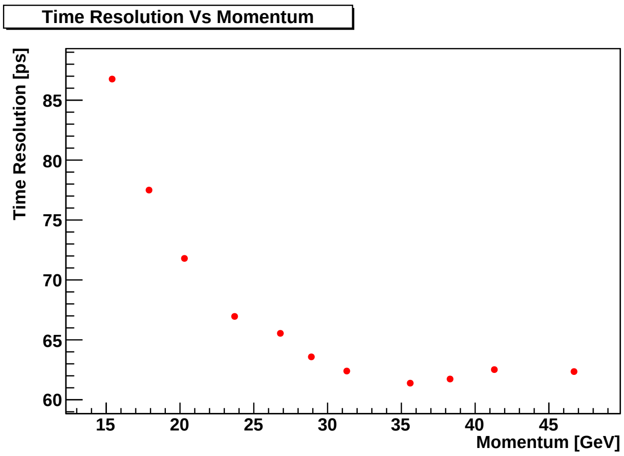

Figure 4: Time resolution as a function of momentum.

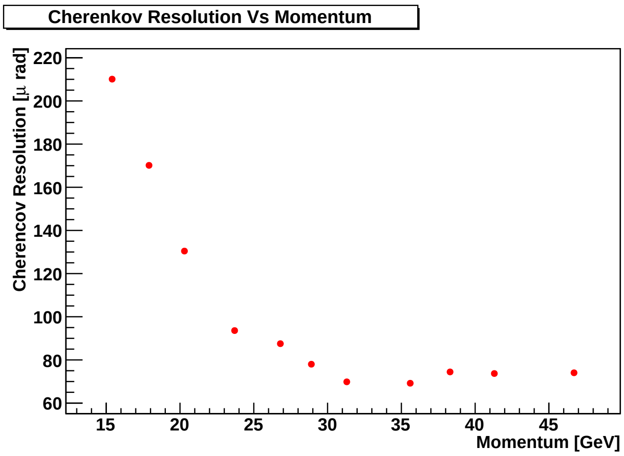

Figure 5: Cherenkov angle resolution as a function of momentum.

Fig. 6 shows the Cherenkov ring radius distributions for 35 GeV/c pions (top) and muons (bottom) simulated with pions at slightly higher momentum, with the same $\beta$ as 35 GeV/c muons. Positrons populate the peak at highest radius. The clear $\pi - \mu$ separation is even more evident at lower momentum, due to the increase of the distance between muon and pion ring radii, as can be seen in Fig. 7 where the fitted ring radius for 15 GeV/c (top) and 20 GeV/c (bottom) pions, equivalent to muons at 15 GeV/c is shown.

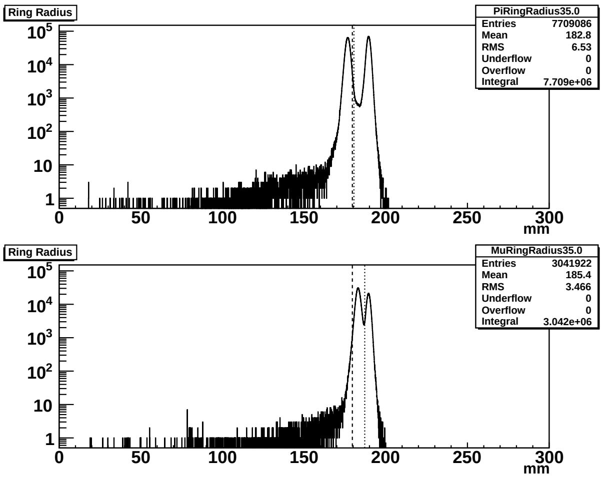

Figure 6: Ring radius at 35 GeV/c. The dotted and dashed lines define the upper edge of the normalization and the signal regions, respectively. The leftmost peak is due to pions. The rightmost peak is due to positrons. Top and bottom plots are for $\pi$ dataset and $\mu$ dataset, respectively.

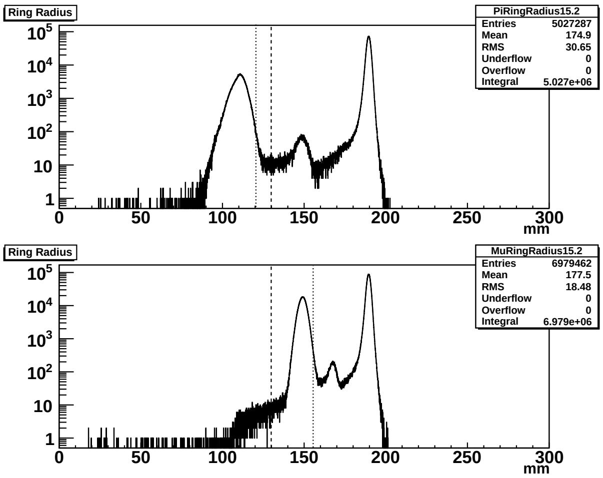

Figure 7: Ring radius at 15 GeV/c. The dotted and dashed lines define the upper edge of the normalization and the signal regions, respectively. The leftmost peak is due to pions. The small peak at low values is given by true $\mu$ from $\pi$ decays. The rightmost peak is due to positrons. Top and bottom plots are for $\pi$ dataset and $\mu$ dataset, respectively.

The quantitative evaluation of the $\pi - \mu$ separation is based on the integral of many measurements done at different momenta and experimental conditions, i.e. mirror orientation, analysis cut, etc. After defining pion and muon signals, a cut is set at half way between the two signal peaks in order to calculate the pion loss and the muon contamination. Fig. 8 shows the muon contamination and pion loss distributions as a function of the particle momentum, measured with the mirror centered along the beam line. This corresponds to a muon suppression factor of about 0.56%, averaged over the whole momentum range. The overall integral of the measurements gives a preliminary muon suppression factor of $\sim 0.7\%$.

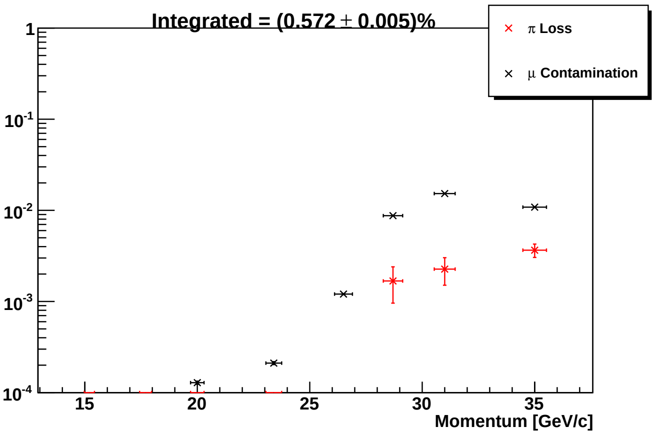

Figure 8: Muon mis-identification probability (upper symbols) and pion loss (lower symbols) as a function of the particle momentum

## 4. Acknowledgments

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