THE RICH DETECTOR OF THE NA62 EXPERIMENT AT CERN

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The RICH detector of the NA62 experiment is proposed for π-μ separation and level 0 trigger. The design parameters of the detector and the results of test beams performed at CERN in 2007 and 2009 with a prototype are described.

1. Introduction

The NA62 experiment[1] at CERN aims at the measurement of the ultra-rare process $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ with 10% accuracy. According to the Standard Model (SM), the branching fraction of this mode is[2]: BR = $(0.85 \pm 0.07) \times 10^{-10}$. The most recent experimental measurement, based on 7 events observed by the E787 and the E959 Collaborations at the BNL AGS, is[3]: BR = $(1.73^{+1.15}_{-1.05}) \times 10^{-10}$. Sizable deviations from SM are predicted in a variety of models[4-5].

The goal of NA62 is to collect about 100 signal events in 2 years, starting in 2011, with a background over signal ratio of about 10%. This requires a rejection factor of the main background process $K^+ \rightarrow \mu^+ \nu$ ($K_{\mu 2}$) better than 10^{-12}, achievable by combining different methods. According to the NA62 Monte Carlo simulation, $K_{\mu 2}$ events are reduced by a factor of at least 10^{-5} through kinematical cuts. A muon rejection factor of the order of 10^{-5} is achieved with muon veto detectors, by exploiting the different stopping power of muons and pions through matter. A further muon suppression factor, better than 10^{-2}, will be provided by identifying muons and pions with momenta between 15 GeV/c and 35 GeV/c in a Ring Imaging Cherenkov (RICH) detector.

The RICH proposed for the NA62 experiment is filled with Neon gas at atmospheric pressure, contained in a vessel about 18 m long and 3.7 m wide. The Cherenkov light is read by about 2000 single-anode fast photomultipliers.

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2. The RICH detector design

In a RICH detector[6] the Cherenkov light, emitted at an angle θ_c by a charged particle of velocity βc, 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. For small index of refraction n, as in case of gas radiators, the ring radius r is related to the Cherenkov angle as $\theta_c = r/f$, where f is the mirror focal length.

In order to achieve the required π-μ separation, the NA62 RICH must have a Cherenkov angle θ_c resolution better than 80 μrad. Moreover, it must provide the crossing time of the pion produced in the K^+ decay with a resolution of less than 100 ps, useful to suppress accidental coincidences with an upstream beam detector. Finally, it should give the level-zero fast trigger for a charged particle.

The NA62 RICH must identify pions and muons in the momentum range 15 GeV/c to 35 GeV/c with a muon suppression factor better that 10^{-2}. The best π-μ separation is obtained when the lowest accepted momentum is close to the Cherenkov threshold. However, full efficiency is achieved at momenta about 20% higher than the threshold. For the above reason, the Cherenkov threshold should be about 12 GeV/c for a pion, i.e. the index of refraction n must be given by $(n\text{-}1) \approx 60 \times 10^{-6}$. Neon gas at atmospheric pressure fulfils this requirement; it also guarantees a small dispersion[7].

However, 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, i.e. about 18 m. A stainless steel cylindrical vessel is foreseen, about 3.7 m large and 18 m long, with the beam pipe passing through. It will be filled with Neon gas at atmospheric pressure, corresponding to 5.6% radiation lengths.

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. A mosaic given by 20 hexagonal mirrors with 17 m focal length, made of 2.5 cm thick glass, each one inscribed inside a 70 cm diameter circle, will be used. Two mirrors will be obtained from one single hexagonal mirror cut in the middle, with a central hole to fit the beam pipe containing the primary particle beam and crossing the centre of the RICH. The mirrors must have very high optical quality. To avoid the beam pipe shadow on the reflected Cherenkov photons, one half of the mirrors will be oriented towards the right side of the beam pipe and one half towards the left one, thus defining two regions in the focal plane to be equipped with photomultipliers, out of the detector acceptance. The centre of each PM region is about 1 m far from the beam pipe axis.

The Hamamatsu R7400-U03 photomultipliers[a] have been chosen as light readout device, after test results. They are metal packaged single-anode PM with 8 stages, UV glass window and cylindrical shape, 16 mm wide and 11.5 mm long. The active region has a diameter of 8 mm. The R7400 typical rise time is 0.78 ns; the transit time is 5.4 ns and the transit time jitter is 0.28 ns (FWHM). The wavelength sensitivity ranges between 185 nm and 650 nm, with maximum response at 420 nm and quantum efficiency of about 20%. Winston cones[8] covered with aluminized mylar will be used as Cherenkov light guides toward the active area of the PM. The PM will be operated at 900 V, with a gain of about 1.5×10^6. The HV system consists of a CAEN[b] SY2527 crate equipped with A1733N boards. Four PM will be feed by one HV channel.

The PM signal is sent to custom-made current amplifiers with differential output. The amplifiers feed NINO chips[9] used as discriminators operating in time-over-threshold mode. The RICH readout consists of custom made TDC boards (TDCB)[10], equipped with 128 channels of TDC based on HPTDC chips[11]. The NINO output signals are sent to FPGA based TELL1 mother boards[12] housing 4 TDCB (512 channels) each. 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[13] based Monte Carlo of the prototype was later developed and validated with the purpose of 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. The RICH prototype: test beam results

The RICH prototype consists of a full longitudinal scale stainless steel vessel made by 5 sections, filled with Neon gas at roughly atmospheric pressure[14]. The vessel total length is about 18 m; the diameter is about 60 cm. A single spherical glass mirror built by Marcon[c], 2.5 cm thick, with 50 cm diameter and 17 m focal length, is installed to reflect the Cherenkov light toward the PM, without a beam pipe. The mirror can be moved by high precision stepping motors, remotely controlled. A laser is used to align the detector along the beam line before the mirror mounting and, later, to orient the mirror itself. The final mirror alignment

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[a] HAMAMATSU PHOTONICS K.K., Japan, http://www.hamamatsu.com .
[b] CAEN S.p.A., Italy, http://www.caen.it .
[c] MARCON Costruzioni Ottico Meccaniche, Italy, http://www.marcontelescopes.com .

is done with the beam. Special care was taken to obtain and keep a good Neon purity inside the vessel and to monitor temperature and pressure during the tests.

The RICH prototype was first tested in 2007 at CERN, with hadron beams. The Cherenkov light was read by 96 PM (RICH-100 prototype). The aim of the test was the measurements of the number of photoelectrons in each event and of the Cherenkov angle and time resolutions, in order to validate the RICH detector design. The results[14] well agree with Monte Carlo expectations.

An improved prototype with about 400 photomultipliers (RICH-400) and a new readout electronics has been tested in 2009. The main purpose of this test was to validate the π-μ separation and the final readout electronics design.

3.1. *The RICH-100 prototype*

The RICH-100 prototype was installed at CERN along the K12 beam line and tested in 2007 with a 200 GeV/c hadron beam (mainly pions) produced by the SPS primary 400 GeV/c proton beam. The 96 photomultipliers available at that time were mounted in the mirror focal plane, along the ring expected for pions at 200 GeV/c momentum (see Figure 1, left). A standard VME CAEN V1190 TDC, based on HPTDC chips with ~100 ps LSB, was used as readout.

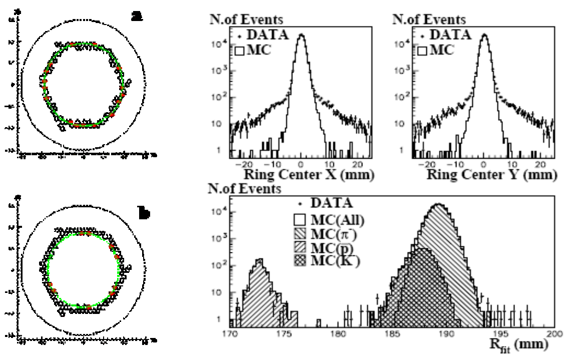

Figure 1: RICH-100 prototype performance. *Left:* the ring image for pions (a) and protons (b). *Right:* fitted ring centre (top) and radius (bottom) for different particles.

The performances of the detector in terms of Cherenkov angle resolution, number of photoelectrons per event and time resolution are in good agreement with the Monte Carlo expectations and fully match the detector design. The choice of the final PM type was validated by the results of the test[14].

The average number of PM hits per events was 17 for a pion and 6 for an antiproton, with 30% probability for a PM to fire, if crossed in the centre by a

Cherenkov ring: the ring images for a pion and an antiproton candidate event are shown in Figure 1, left. The ring centre position was fitted with a resolution of 1.9 mm (RMS) on each coordinate, as shown in Figure 1, right-top. The pion Cherenkov angle resolution turned out to be about 50 μrad after a cut on the fitted ring centre. The pion and antiproton rings are well separated and agree well with the Monte Carlo prediction, as shown in Figure 1 (right-bottom).

The PM signals were properly time aligned and corrected for slewing effects: an average single PM time resolution of 310 ps was found (Figure 2, left) after cutting the single PM time with respect to the average time; the RMS of the average event time was measured to be about 65 ps (Figure 2, right).

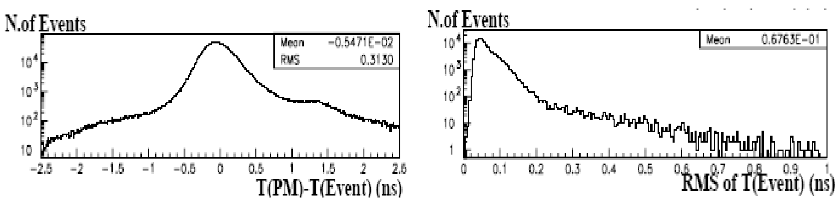

Figure 2: RICH-100 prototype time resolution. *Left:* difference between each photomultiplier time and the event time. *Right:* RMS of the average event time (right).

3.2. *The RICH-400 prototype*

The improved version of the RICH prototype was installed at CERN on the K12 beam line and tested in may-june 2009. The upstream flange of the vessel was arranged in order to accommodate 414 PM. New readout electronics similar to the final one, based on TELL1 boards and TDCB, has been used.

Positive hadron beams, produced by the SPS primary 400 GeV/c protons, have been used at different momenta in the 10 GeV/c to 75 GeV/c range in order to measure the π-μ separation, to check the detector performance and to validate the design of the final readout electronics. The beam was given mainly by pions, with a small quantity of protons, a few percent of kaons and a variable fraction of positrons. The prototype performances have been tested under different conditions: beam momenta, mirror orientation, rates, TELL1 firmware versions and gas contamination (adding air and CO_2 to the Neon gas). The measurements have been repeated with a new mirror, similar to the final ones. Special data samples at higher intensities have been collected to study trigger algorithms and accidental events and to check the efficiency of ring fitting.

Data analysis is in progress and the first results are encouraging. The preliminary distributions of PM hits per event as a function of momentum for pions (blue) and positrons (red) are shown in Figure 3 (left). Acceptance corrected (full dots) and uncorrected (circles) data are shown. The PM hits for positrons is constant as expected for relativistic particles at β=1 with constant Cherenkov ring radius; the number of PM for pions increases with momentum. Figure 3 (right) shows the preliminary time resolution for pions (blue) and positrons (red) as a function of momentum. Although the corrections for time offsets and slewing effect are not final yet, an event time resolution better than 100 ps is found, confirming the results of the previous test. No difference was found between the CAEN TDC measurements and the new electronics prototype, thus validating the performance of the final RICH readout system.

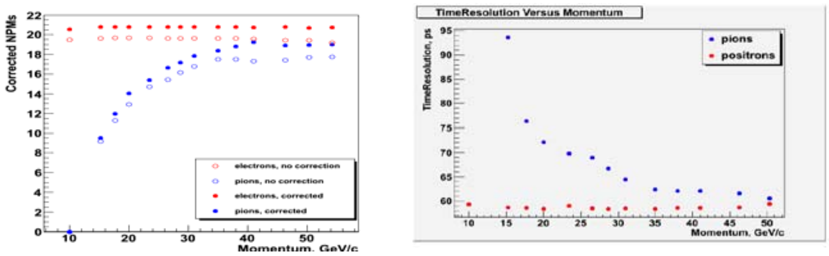

Figure 3: RICH-400 prototype, preliminary results. *Left:* number of photomultiplier hits per event as a function of momentum for pions (blue) and positrons, uncorrected (circles) and corrected (full dots) for acceptance. *Right:* time resolution vs momentum for pions (blue) and positrons (red).

The following method has been used to measure the π-μ separation at particle momenta between 15 GeV/c and 35 GeV/c. The fitted Cherenkov ring radius for pions at a given momentum has been compared with that of pions at higher momentum, which have the same β of muons of the initial given momentum. Figure 4 (left) show the superposition of the Cherenkov ring radius distributions of 35 GeV/c pions (red) and muons simulated with pions at slightly higher momentum, with the same β as 35 GeV/c muons (black). Positrons populate the peak at highest radius in both distributions. A clear π-μ separation is shown at 35 GeV/c; a better separation is expected at lower momentum, due to the increasing of the distance between muon and pion ring radii.

The quantitative evaluation of the π-μ separation is based on the integral of many measurements done at different momentum 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. Figure 4 (right) shows an example of pion loss and muon contamination distributions as a function of the particle momentum, found with the mirror centered along the beam line. These data correspond to a muon suppression factor of about 0.56%, averaged over the whole momentum range. The overall integral of such measurements gives a preliminary muon suppression factor of about 0.7%.

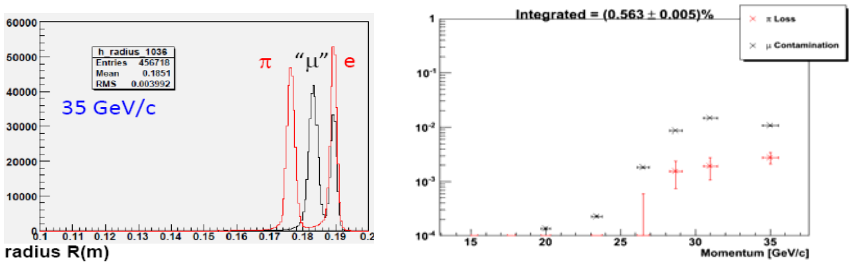

Figure 4: RICH-400 prototype, preliminary results. *Left:* π-μ separation at 35 GeV/c (see text). *Right:* pion loss (red) and muon contamination (black) vs momentum (mirror centered on beam line).

4. Conclusions

The design parameters of the NA62 RICH detector are validated by the results of the test beams of a full longitudinal scale prototype, held at CERN in 2007 and in 2009. The project matches the NA62 experiment requirements. The preliminary results of the 2009 test beam look very promising. The analysis is in progress: a paper reporting the achievements of the 2009 test is in preparation.

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