The RICH detector of the NA62 experiment at CERN

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***Abstract*–A long focus RICH counter has been proposed as the key element for particle identification in the NA62 experiment at CERN. The purpose of this detector is threefold: to identify and reduce muons contaminating pion samples at the level or less then than 1%; to measure the arrival time of charged tracks with a precision better than 100 ps; to provide a fast signal for the level-zero trigger. The design parameters of the detector and the results of test beams performed at CERN with a prototype are described in this paper.**

I. INTRODUCTION

The NA62 experiment [1][2] at CERN aims at the measurement of the ultra-rare process $K^+ \to \pi^+ \nu\bar{\nu}$ with 10% accuracy. Among many decays of kaons and B mesons mediated by Flavor Changing Neutral Currents, the $K \to \pi\nu\nu$ mode plays a key role in searching for new physics through underlying mechanisms of flavor mixing. According to the Standard Model (SM), the branching ratio of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay is BR = $(0.85 \pm 0.07) \times 10^{-10}$ [3]. The only measurement, BR = $(1.73^{+1.15}_{-1.05}) \times 10^{-10}$ [4], compatible with the SM prediction within errors, is based on 7 events observed at the BNL AGS by the E959 and E787 experiments, which detected this decay for the first time in 1997 [5]. Sizable deviations from the SM are predicted in a variety of models [6][7].

The goal of NA62 is to collect about 100 signal events in 2 years, with a background over signal fraction of about 10%. The experimental strategy of NA62 is based on an accurate kinematic reconstruction to disentangle the signal, a precise timing to associate the π^+ with the parent K^+, a system of efficient vetoes to reject events with γ and μ, a particle identification system to identify kaons in the charged beam and to distinguish π^+ from μ^+ and e^+ in the final state. The R&D of the experiment, started in 2007, is almost completed. The construction of the apparatus has already started and the beginning of the data taking is foreseen in 2012-2013.

The kinematic rejection and the muon veto alone are still unable to suppress at the required level the main background process $K^+ \to \mu^+ \nu$ ($K_{\mu 2}$), whose branching ratio is BR = $(63.55 \pm 0.11) \times 10^{-2}$ [8]. A further muon rejection factor of at least 10^2 should be provided by identifying π and μ among the K^+ decay products in a Ring Imaging Cherenkov (RICH) detector in the momentum range 15 GeV/c to 35 GeV/c.

The RICH proposed for the NA62 experiment is contained in a vessel about 18 m long and 4 m wide, filled with Neon gas at atmospheric pressure. The Cherenkov light is read by about 2000 single-anode fast photomultipliers assembled into two regions, left and right of the beam pipe. Fig. 1 is a schematic drawing of the NA62 RICH detector.

II. THE NA62 RICH DETECTOR DESIGN

In a RICH detector [9] 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 a 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.

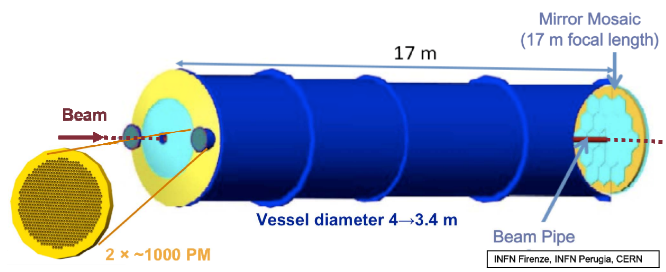

Fig. 1. Schematic drawing of the NA62 RICH detector (not to scale): the downstream section of the vessel is cut to show the mirrors and the beam pipe; the upstream section shows the PM assembly.

In order to identify π and μ in the momentum range between 15 GeV/c and 35 GeV/c achieving a muon rejection factor better that 10^2, the NA62 RICH should have a Cherenkov angle θ_c resolution better than 80 μrad. In addition, it should provide a measurement of the crossing time of the π^+ produced in K^+ decays with a resolution better than 100 ps, to suppress accidental coincidences with an upstream beam detector. Finally, it must provide a fast signal in presence of a charged particle at the level-zero trigger.

The best π-μ separation is obtained when the lowest accepted momentum is close to the Cherenkov threshold. Since full efficiency is achieved at momenta slightly higher than the threshold, a Cherenkov threshold of about 12 GeV/c for pions is well suited for the NA62 RICH: this corresponds to a refraction index $(n\text{-}1) \approx 60 \times 10^{-6}$. Neon gas has the appropriate refractive index at atmospheric pressure and fulfils this requirement; it also guarantees a good light transparency in visible and near-UV and a small chromatic dispersion [10].

The low emission rate of Cherenkov photons per unit length, due to the smallness of $(n\text{-}1)$, should be compensated with a long radiator. The RICH of NA62 will make use of the maximum space available along the beam line i.e. about 18 m.

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The NA62 RICH will be given by a cylindrical vessel in ferro-pearlitic structural steel, about 17 m long. It will consist of 4 longitudinal sections with decreasing diameter (4 to 3.4 m) and a centered beam pipe passing through. The total volume will be about 200 m^3. The entrance end-cap will host two flanges holding the photomultipliers (PM), left and right of the beam pipe. The beam windows will be in aluminium alloy in order to keep the minimum material thickness in the kaon decay region. Fig. 2 illustrates the top view of the vessel: the red lines identify the acceptance region for the Cherenkov light, the PM flanges and the mirror plane are also shown.

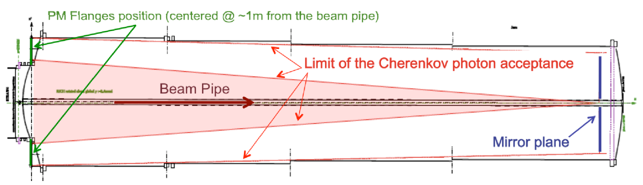

Fig. 2. Schematic drawing of the vessel of the NA62 RICH (top view, beam entering from the left): the red lines show the limit of the acceptance region for the Cherenkov photons; the PM flanges are shown in green on the entrance end-cap, left and right of the beam pipe; the mirror plane is represented in blue, close to the downstream section of the vessel.

The vessel should not be out-gassing; the non-reflectivity and the cleanliness of its inner surface will be ensured by a mat epoxy coating. Neon gas at about atmospheric pressure will be used as radiator, corresponding to 5.6% of a radiation length. Due to mechanical reasons, the gas pressure will be adjusted slightly above the atmospheric value: the maximum overpressure will be 150 mbar, with ±1 mbar accuracy on the pressure regulation. The vessel will be first filled with clean carbon dioxide CO_2 to replace air and clean the inner surface. The gas will circulate in closed loop mode and the Neon introduced only later, while absorbing the CO_2 in a molecular sieve filter. When the residual air in the radiator will reach the required level, the inlet flow will be switched to Neon. The Neon will be kept in the vessel for long data taking periods, with a gas leak rate below 10^{-2} std. cc/s. The gas density stability will be below 1%; gas impurities will not exceed 1%.

In order to achieve full acceptance coverage for the Cherenkov photons emitted by pions and muons, the total surface of the mirror layout will have a diameter of about 3 m. A mosaic given by spherical mirrors with hexagonal shape, 35 cm side, will be built. The layout will consist of 18 hexagons and 2 half hexagons, to fit the beam pipe crossing the centre of the RICH. The mirrors, with 17 m focal length, will be made of 2.5 cm thick glass, coated with a thin dielectric film in order to protect the surface and improve the reflectivity. Fig. 3 is a schematic drawing of the final mirror layout.

Each mirror will be individually supported and adjusted for alignment. A carbon fiber honeycomb structure will hold the mirrors; piezo actuators will be used for the movement. The initial mirror alignement will be accomplished using a laser, starting from one reference mirror. The laser beam, originating in the focal plane, will point towards the reference mirror: the reflected light will be directed on a well-selected point in the focal plane, by changing the mirror orientation. An iterative procedure will allow to align all the mirrors with respect to the first one, keeping parallel the laser beam by means of telescopic optical devices. The mirror alignment will be further checked during the data taking periods by selecting particles with Cherenkov rings completely contained in a single mirror and by measuring the track angle in the magnetic spectrometer.

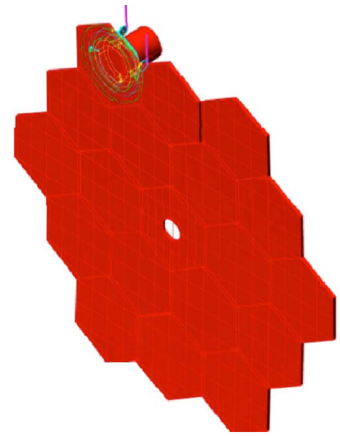

Fig. 3. A schematic drawing of the NA62 RICH mirror layout with a detail of the support for one mirror.

The mirrors should have a high optical quality: the D_0 parameter[1] will be less than 4 mm and the average reflectivity will be better than 90% in the wavelength range from 195 nm to 650 nm. In order 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 about 1000 PM each, out of the detector acceptance. The centre of each PM region is about 1 m far from the beam pipe axis (see Fig. 1 and Fig. 2).

The Hamamatsu[2] R7400-U03 PM type, shown in Fig. 4, was chosen as final light readout device, after test results. The PM of the R7400 series have been selected for their compactness, the small dimension and the good timing properties. 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. They have good timing characteristics: the transit time jitter is 0.28 ns (FWHM) and the typical rise time is 0.78 ns. The wavelength sensitivity ranges between 185 nm and 650 nm, with maximum response at 420 nm and quantum efficiency of about 20%. The gain is about 1.5×10^6 at the operating voltage of 900 V.

[1] D_0 is the minimum diameter of a circle which collects the 95% of the light of a point-like source placed in the curvature center.

[2] Hamamtsu Photonics K. K., Japan, http://www.hamamatsu.com

Fig. 4. The Hamamatsu R7400-U03 photomultiplier.

In order to improve the light collection, Winston cones [11] covered with aluminized mylar will be used as Cherenkov light guides towards the active area of the PM; a quartz window will separate the PM from the Neon radiator.

The PM assembly will consist of two independent flanges installed on the entrance end-cap of the vessel. A stainless steel flange, holding quartz windows, will separates the Neon gas from the PM. The PM will be mounted on an aluminium flange, in front of the quartz windows, isolated from the environment light and water cooled. The mechanical detail of the PM assembly, as used in the RICH prototype beam tests, is shown in Fig. 5.

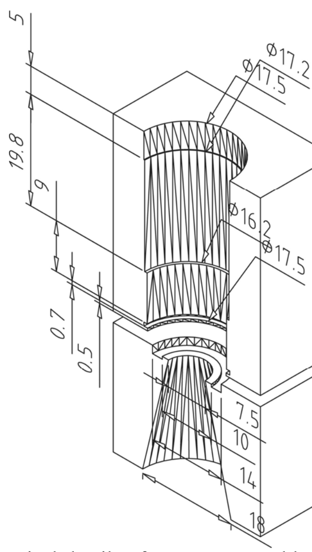

Fig. 5. Mechanical details of one PM assembly module, showing the two parts of the PM flange used in the RICH prototype test: the first part (bottom), in stainless steel, houses Winston's cones and quartz windows, separating Neon from air; the second part (top), in aluminium, holds the PM, the voltage divider, a water based cooling system and the O-ring used for light tightness.

The PM high voltage system is based on CAEN[3] SY1527 and SY2527 main frames, equipped with A1733N and A1535S boards. The PM signals are sent to custom-made current amplifiers with differential output. The amplifiers feed NINO ASIC chips [12][13] used as fast discriminators operating in time-over-threshold mode, with LVDS output and an intrinsic resolution of 50 ps. The RICH readout consists of custom-made TDC boards (TDCB) [14], equipped with 128 channels of TDC based on HPTDC chips with about 100 ps LSB [15]. The NINO output signals are sent to FPGA based mother boards [14], evolution of the TELL1 boards [16] developed for the LHCb experiment at CERN, housing 4 TDCB each. A total of 512 TDC channels are available in each mother board. The trigger primitives will be constructed in parallel with the readout on the same mother board [14][17].

A fast simulation of the NA62 RICH detector has been developed taking into account the generation of Cherenkov photons, the geometry of the mirrors and the PM performance. A full GEANT4 [18] based Monte Carlo simulation of the prototype was also developed and validated with the purpose of correctly simulating the final detector and evaluating its performance. Generation, full optical propagation and detection of Cherenkov photons have been taken into account in the latter program, as well as smaller effects such as Neon scintillation, reflectivity of the vessel and of the PM flange.

III. The RICH Prototype

The RICH prototype [19] consists of a full longitudinal scale stainless steel vessel made by 5 different sections, filled with Neon gas at roughly atmospheric pressure. The vessel total length is about 18 m; the diameter is about 60 cm. A photo of the prototype installed on the K12 beam line in the CERN North Area High Intensity Facility, where also the NA62 detector will be housed, is show in Fig. 6.

Fig. 6. The RICH prototype tested at CERN in 2007 and 2009

A single spherical glass mirror, 2.5 cm thick, with 50 cm diameter and 17 m focal length, was installed inside the vessel, without a beam pipe. The mirror, built by the MARCON[4] company, which will also provide the mirrors for the final detector, was moved by high precision stepping motors, remotely controlled. A laser was used to align the detector along the beam line before mounting the mirror and

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

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

to adjust the mirror position. The final mirror alignment was done with the beam. Special care was taken to keep a good Neon purity inside the vessel and to monitor the stability of the temperature and the pressure during the tests.

The RICH prototype was first tested in fall 2007 at CERN. The Cherenkov light was read by 96 PM's (RICH-100). The RICH-100 prototype was installed on the K12 beam line and tested with a 200 GeV/c hadron beam, mainly given by pions. The PM were installed in the mirror focal plane, along the ring expected for pions at 200 GeV/c momentum. A standard VME CAEN V1190 TDC, based on HPTDC chips with 100 ps LSB, was used as readout. The aim of the test was the measurements of the number of photoelectrons per each event and of the Cherenkov angle and time resolutions, needed to validate the RICH detector design parameters. The prototype and the analysis of the 2007 test beam data are described in detail in [19]. The performance of the detector in terms of number of photoelectrons per event, time resolution and Cherenkov angle resolution are in 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 this test.

An improved prototype with 414 PM (RICH-400) and the new readout electronics, based on TELL1 and TDCB boards, was tested in 2009 at CERN on the same K12 beam line. The purpose of this test was to validate the π-μ separation figure, to check the functioning of the PM cooling system and that of the final readout electronics. The upstream flange of the vessel was arranged in order to accommodate the 414 PM and the water cooling system, based on copper pipes. The PM flange was split into two parts: one, in stainless steel, housing Winston cones and fused silica windows and separating the Neon from air; the other, in aluminium, holding the PM, the voltage dividers, the cooling system and the O-rings used for light tightness (see the mechanical details in Fig. 5).

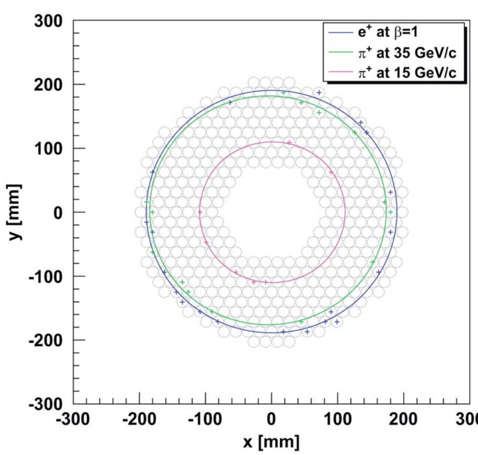

Fig. 7. Ring image of a typical event (RICH-400 prototype test, see text)

A positive hadron beam, produced by the SPS primary protons at 400 GeV/c, was exploited at different momenta, in the 10 GeV/c to 75 GeV/c range, with a momentum byte of 1.5% Δp/p and a negligible angular spread. The beam was mainly given by pions, with a small quantity of protons, a few percent of kaons and variable fractions of positrons. The prototype performance has been checked under different conditions, by changing the beam momentum and the rate, the mirror orientation, the TELL1 firmware version and in presence of known quantities of gas contaminants (air and CO_2). The measurements have been repeated using a new mirror similar to the final ones, produced by MARCON and later aluminized and coated at CERN. Special runs have been dedicated to collect data useful for checking the trigger algorithms, the effect of accidentals at higher intensities and for measuring the efficiency of the ring fitting procedures. The results of the 2009 test have been recently published [20].

Fig. 7 shows a typical event with well separated reconstructed ring images due to, in order of decreasing radii: positrons (β=1, blue), pions at 35 GeV/c (green) and pions at 15 GeV/c (violet).

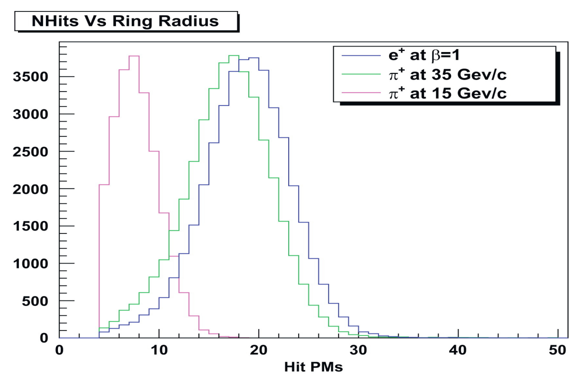

Fig. 8. Distribution of the number of hit PM in a single ring; the cut at 4 is due to the software trigger algorithm.

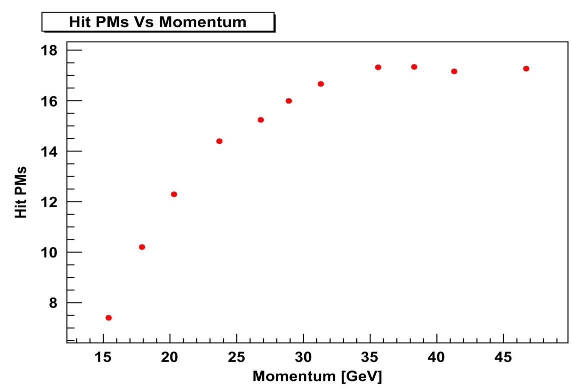

Fig. 9. Average number of hit PM per ring as a function of momentum.

The average number of PM hits in a single ring, given by the peaks in the corresponding distributions in Fig. 8, is about 20 for positrons (blue), 17 for pions at 35 GeV/c (green) and 8 for pions at 15 GeV/c (violet), with a 30% firing probability for a PM crossed by a Cherenkov ring in the centre. The distribution of PM hits per ring as a function of the momentum for 15 GeV/c to 35 GeV/c pions is given in Fig. 9. In this distribution a dip is visible at high momenta, mainly due to the geometry of the PM assembly: in fact, a higher sensitivity to dead regions is achieved in case of particles at β=1 when the reconstructed rings are not exactly centered in the beam and, hence, do not cross the PM center.

Fig. 10 shows the pion time resolution as a function of the momentum in the range 15 GeV/c to 35 GeV/c. The PM signals are properly aligned in time and corrected for slewing effects. The time resolution is defined as the average root mean square of the distribution of the selected hit time with respect to the average hit time: a value below 100 ps has been measured over the whole momentum range.

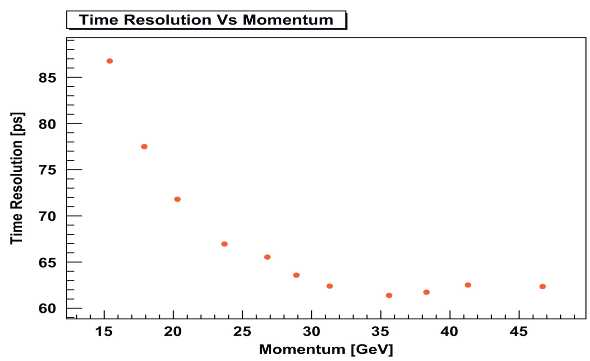

Fig. 10. Pion time resolution as a function of momentum. The resolution is defined as the average root mean square of the selected hit times with respect to their average.

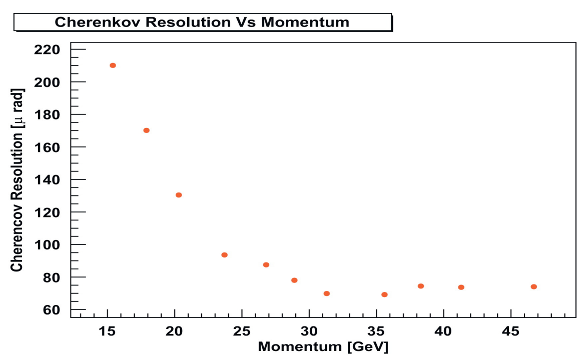

Fig. 11. Cherenkov angle resolution defined as the standard deviation σ of the Gaussian fit to the radius distributions.

The Cherenkov angle resolution as a function of the pion momentum is reproduced in Fig. 11. The standard deviation σ is estimated by a Gaussian fit to the radius distribution, excluding tails: the resolution decrease to a constant value of about 70 μrad for β=1 particles. Time and Cherenkov angle resolutions are strongly correlated to the number of hit PM per ring, i.e. to the number of Cherenkov photons and to the their collection and the detection efficiencies. Both the time and the angle resolution exhibit an effect at high momenta similar to the one shown in Fig. 9, due to the same reason: when the particle β is close to 1, any change in the Cherenkov angle, hence in the ring radius, is small. In this case, the ring reconstruction becomes sensible to small variations in the light acceptance and gives, as a result, a fine scan of the honeycomb structure of the PM assembly.

The following method was used to measure the π-μ separation in the momentum range between 15 GeV/c and 35 GeV/c. For each momentum bin, the reconstructed Cherenkov ring radius for pions has been compared with the ring radius of pions at a higher momentum and the same β of muons of the initial momentum bin. The ring radius distributions of Fig. 12 allow to better explain the method: Fig. 12, in fact, shows the superposition of the fitted Cherenkov ring radius distributions at 15 GeV/c (left) and 35 GeV/c (right) for pions, muons simulated with higher energy pions as explained above and positrons, which populate the peak at higher radii in both plots. A better π-μ separation is expected at lower momenta, due to the increasing of the distance between muon and pion ring radii, as Fig. 12 also indicates.

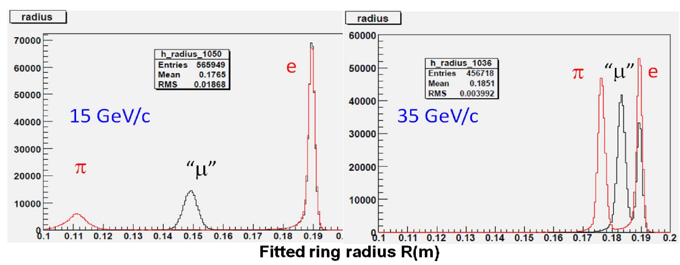

Fig. 12. Recontructed ring radius distributions at 15 GeV/c (left) and at 35 GeV/c (right) for pions, muons simulated with pions at higher momentum (see text) and positrons.

The quantitative evaluation of the π-μ separation is based on the measurements of the muon contamination in the pion sample and of the pion losses out of it, done in momentum bins and later integrated over the whole momentum range. In addition to the ring radius, the distribution of the reconstructed squared mass of the particle has also been used as a further check for the same calculation. The measurements are repeated under different conditions, by changing the mirror orientation and the analysis cuts to confirm the final results.

Fig. 13 shows some of the distributions used for the π-μ separation measurement at two different momentum bin: 15 GeV/c (left) and 35 GeV/c (right). On the top part of the figure, the fitted Cherenkov ring radius distribution is represented: the peaks correspond to pions, real muons due to pion decays and positrons at 15 GeV/c (left) and at 35 GeV/c (right) momenta. The bottom part of the figure represents the muon samples, simulated with pions at higher momenta with the same β of muons at 15 GeV/c (left) and 35 GeV/c (right). After defining the pion signal as given by all the events within +3σ from the peak of the distribution (red lines in Fig. 13), a cut is set at half way between the π and the μ signal peaks (blue lines in Fig. 13) in order to calculate the pion loss and the muon contamination.

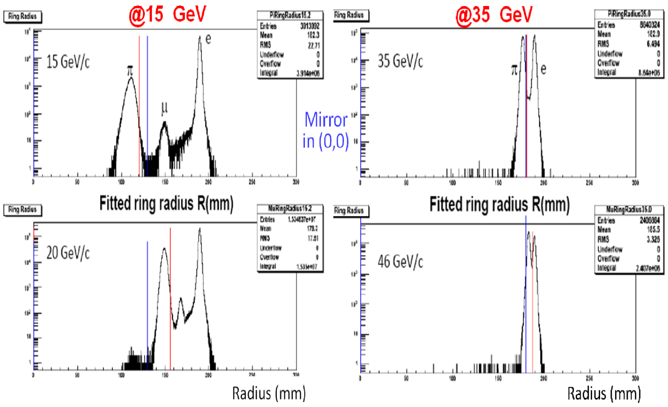

Fig. 13. Reconstructed ring radius distributions used for the measurement of π-μ separation at 15 GeV/c (left) and 35 GeV/c (right). See text for details.

Fig. 14 shows the muon misidentification probability as a function of the momentum for four different alignment positions of the mirror, in order to take into account possible displacements of the ring center.

Fig. 15 represents the same measurement repeated with different event selections and ring reconstruction methods: the upper and the lower limits are the 3σ constraint on the position of the fitted ring center.

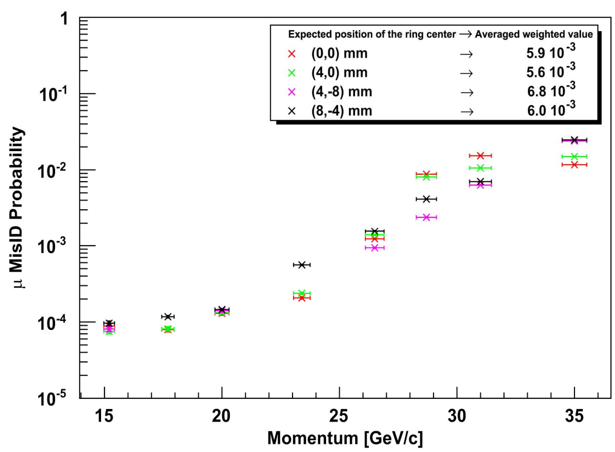

Fig. 14. Muon misidentification probability as a function of momentum for four different alignment positions of the mirror.

The analysis of the data of the RICH-400 prototype beam test leads to a muon misidentification probability lower that 10^{-2} over the whole momentum range, measured in many different conditions. The overall integral corresponds to a 0.7% residual contamination of muons in the pion sample, i.e. to a muon suppression factor of the order or better than 10^2, in agreement with the requirements of the NA62 RICH detector.

Further details on the results of the test of the RICH-400 prototype can be found in [20]. More studies and analyses of the test data are still going on in order to optimize the RICH working conditions and to possibly improve its performace.

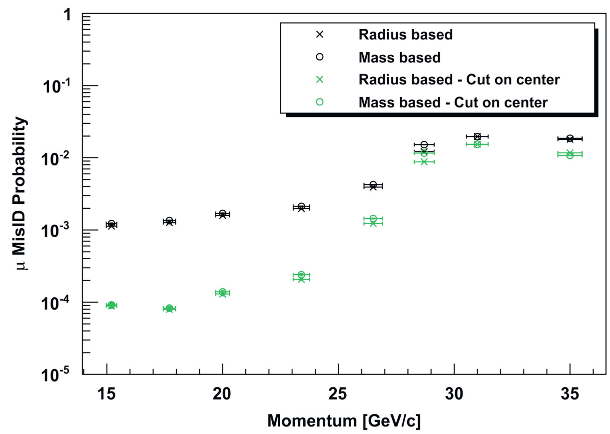

Fig. 15. Muon misidentification probability as a function of momentum for different cuts and ring reconstruction methods: the upper and the lower limits are the 3σ constraint on the position of the fitted ring center.

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IV. Conclusion

The design parameters of the NA62 RICH detector have been validated by the positive results of the test beams of a full longitudinal scale prototype, held at CERN in 2007 and 2009. The project matches the requirements expected for the NA62 experimental program.

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