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The NA62 RICH detector

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Abstract

The CERN NA62 experiment aims to measure the ultra-rare charged kaon decay $K^+ \to \pi^+ \nu\bar{\nu}$ (branching fraction $O(10^{-10})$) with a 10% accuracy. The detector must be able to reject background events from decay channels of which the branching fractions are up to 10 orders of magnitude larger than the signal and with similar experimental signature. To totally suppress the main background from $K^+ \to \mu^+ \nu$ decay (BR ~ 63%), NA62 will need a further μ rejection factor better than 5×10^{-3}. This will be provided by a gas RICH detector for π/μ separation in a momentum range between 15 and 35 GeV/c. The details of the RICH project will be described and the results of two beam tests performed at CERN with prototypes will be presented.

Keywords: RICH; PID;

1. Introduction

The NA62 experiment [1,2] will be installed at CERN in the North Area on an extracted beam from the SPS accelerator. The experiment aims to measure the Branching Ratio (BR) of the ultra-rare decay $K^+ \to \pi^+ \nu\bar{\nu}$ with high accuracy (10%). The Standard Model (SM) prediction BR = $(0.85 \pm 0.07) \times 10^{-10}$ [3] is very accurate and the only experimental result, BR = $(1.73^{+1.15}_{-1.05}) \times 10^{-10}$ [4], based on 7 events observed at the BNL AGS by the E959 and E787 experiments, is still compatible with the SM prediction within errors. A new measurement of the BR with higher precision will allow to perform a stringent test

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of the SM and probe possible new degrees of freedom beyond the SM. Sizable deviations from the SM are predicted by several models [5,6].

The goal of NA62 is to collect ~100 events in two years of data taking, with a background over signal fraction of about 10%. The experimental strategy 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's and μ's and a particle identification system to identify kaons in the charged beam and to distinguish pions from muons in the final state. The R&D of the experiment, started in 2007, is completed. The construction of the different detectors of the apparatus is in a well advanced state and the beginning of the data taking is foreseen in 2012-2013.

The main background is the decay $K^+\rightarrow\mu^+\nu$ (BR ~ 63%) that must be suppressed by a rejection factor of 4×10^{-13}. This can be accomplished using a combination of kinematical cuts (8×10^{-6}), the different power of penetration through matter of pions and muons (10^{-5}) and a further 5×10^{-3} suppression factor will be provided by a Ring Imaging Cherenkov (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.

2. The NA62 RICH detector design

The NA62 RICH is a ~17 m long tube, ~3 m in diameter, filled with Neon at atmospheric pressure and room temperature, equipped with a segmented mirror of 17m focal length, at the downstream end, and about 2000 photomultipliers (PM), at the upstream end. The schematic drawing of the NA62 RICH detector is shown in Fig. 1.

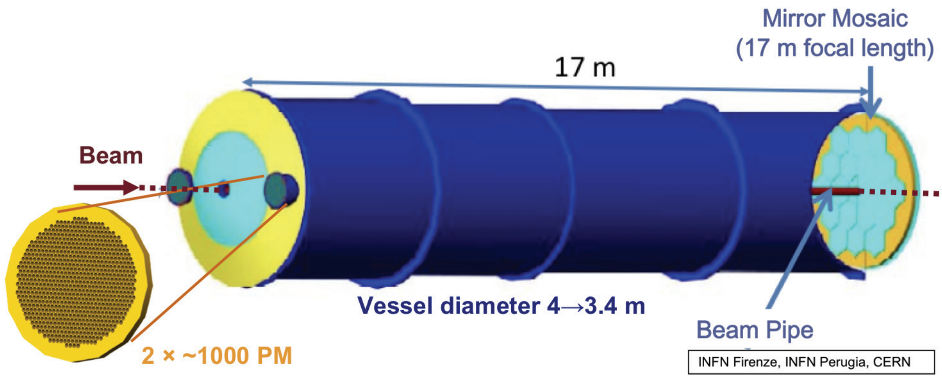

Fig. 1. Schematic drawing of the NA62 RICH detector; the downstream section of the vessel is cut to show the mirrors and the beam pipe; the upstream section shows the PM assembly.

In a RICH detector [7] 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.

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 than 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-0 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. The smallness of (n-1) implies a low emission of Cherenkov photons per unit length which should be compensated with a long radiator, therefore the NA62 RICH will make use of the maximum space available along the beam line, about 18 m.

The NA62 RICH consists of a cylindrical vessel in ferro-pearlitic structural steel, about 17 m long and made of 4 longitudinal sections with decreasing diameter (4 to 3.4 m) with the beam pipe passing through. The entrance end-cap will host two flanges holding the photomultipliers, left and right of the beam pipe. The total volume of about 200 m^3 will be filled with Neon gas, in slight overpressure w.r.t. the external atmosphere; the total radiation length corresponds to 5.6% X_0. The non-reflectivity and the cleanliness of its inner surface will be ensured by a mat epoxy coating. After a vacuum cleaning procedure, Neon will be inserted and kept for long data taking periods. No gas recirculation and purification system is foreseen. In case of opening of the vessel, the entire volume of gas will be replaced. The gas density variation will be below 1% and 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 vessel. 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. 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. To avoid absorption of reflected light on the beam pipe, the mirrors are divided into two spherical surfaces: one with the centre of curvature to the left and one to the right of the beam pipe, thus defining two regions in the focal plane to be equipped with about 1000 PM each, out of the detector acceptance.

The Hamamatsu R7400-U03 PM type 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 and Winston's cones [8] are used to enhance the ratio between sensitive and instrumented area. 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. The PM's are separated from the Neon by means of 1mm thick quartz windows. The PM high voltage system is based on CAEN 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 [9,10] 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) [11], equipped with 128 channels of TDC based on HPTDC chips with about 100 ps LSB [12]. The NINO output signals are sent to FPGA based mother boards [11], evolution of the TELL1 boards [13] 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.

The full NA62 detector simulation is based on GEANT4 [14]. A Montecarlo simulation of the prototype (based on the same toolkit) was also developed and validated with the purpose of simulating the final detector and evaluating 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

The RICH prototype [15] 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 17 m and the diameter is about 60 cm. The prototype was installed on the K12 beam line in the CERN North Area High Intensity Facility, where also the NA62 detector will be housed.

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 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 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 Cherenkov light was read by 96 PM's (RICH-100).

An improved prototype [16] with 414 PM (RICH-400) and the new readout electronics, based on TELL1 and TDCB boards, was built: 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.

4. Test beam results

The RICH-100 prototype was first tested in fall 2007 at CERN: it was installed on the K12 beam line and tested with a 200 GeV/c hadron beam containing mainly 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. This test was mainly devoted to the assessment of the final choice of the PM and to the measurement of the time resolution and Cherenkov angle resolution, needed to validate the RICH detector design parameters. The U03 and U06 types of the Hamamatsu R7400 PM were tested. Type U03 was chosen, because the U06 type had a larger cost, worse time resolution and did not provide a significantly higher number of photoelectrons. An average single PM time resolution of 310 ps was found, while the RMS of the average event time was measured to be about 65 ps. The pion Cherenkov angle resolution turned out to be better than 60 μrad and the average number of fired PM per event was found to be 17. The prototype and the analysis of the 2007 test beam data are described in detail in [15]. 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 RICH-400 prototype 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. A positive hadron beam, produced by the SPS primary protons at 400 GeV/c, was used at different momenta, in the 10 GeV/c to 75 GeV/c range, with a momentum bite of

1.5% Δp/p and a negligible angular spread. The beam contained mainly 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 [16].

Fig. 2(left) shows a typical event with well separated reconstructed ring images for, in order of decreasing radii, positrons (β=1), pions at 35 GeV/c and pions at 15 GeV/c. The average number of PM hits in a single ring, shown in Fig. 2(right), is about 20 for positrons (blue, rightmost histogram), 17 for pions at 35 GeV/c (green, middle histogram) and 8 for pions at 15 GeV/c (violet, leftmost histogram).

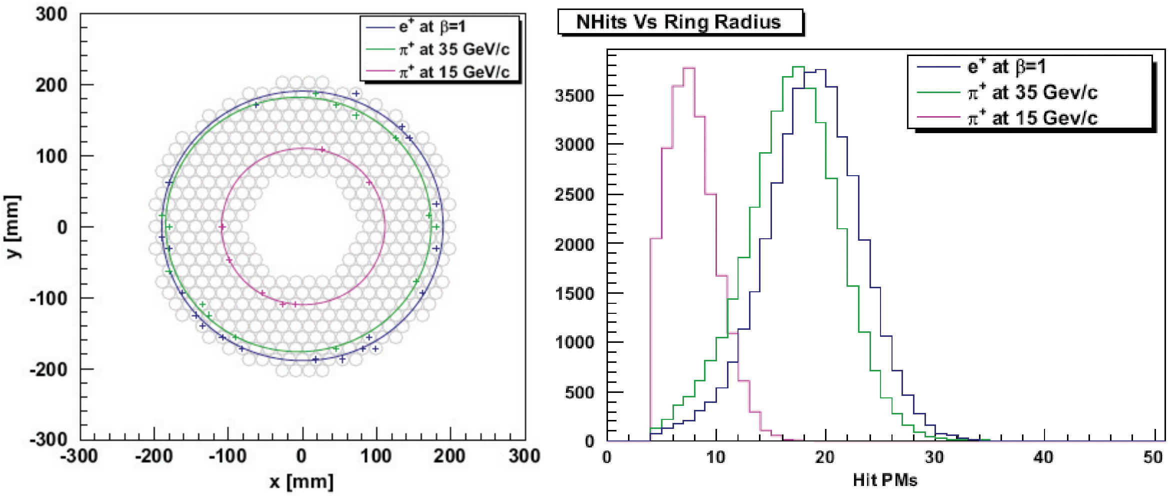

Fig. 2. (a) Reconstructed ring images for, in order of decreasing radii, positrons (β=1), pions at 35 GeV/c and pions at 15 GeV/c; (b) Distribution of the number of hit PM in a single ring; the cut at 4 is due to the software trigger algorithm.

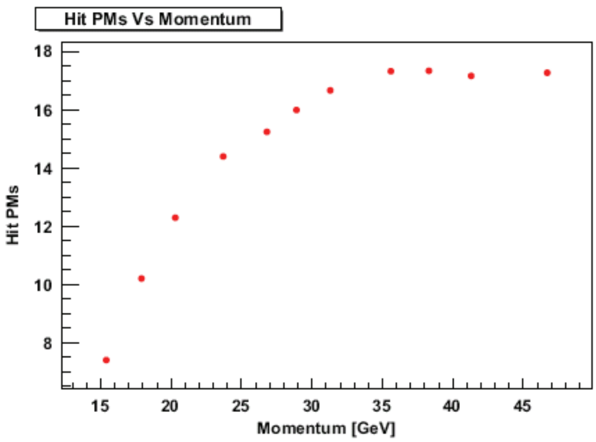

Fig. 3. Average number of hit PM per ring as a function of momentum. Error bars are smaller than the dot size.

The time resolution, shown in Fig 4(a), is defined as the average root mean square of the distribution of the selected hit times with respect to the average hit time: a value below 100 ps has been measured over the momentum range of interest.

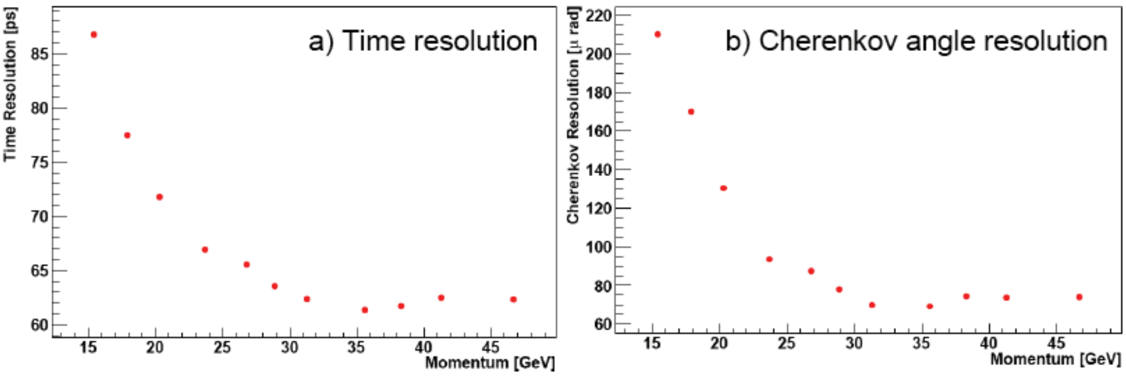

Fig. 4. (a) Pion time resolution as a function of momentum. (b) Pion Cherenkov angle resolution as a function of pion momentum. Error bars are smaller than the dot size.

The Cherenkov angle resolution as a function of the pion momentum is presented in Fig. 4(b). The standard deviation is estimated by a Gaussian fit to the radius distribution, excluding tails; the resolution decreases to a constant value of about 70 μrad for β=1 particles. Time and Cherenkov angle resolution are strongly correlated to the number of hit PM per ring, i.e. to the number of Cherenkov photons and 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. 3, due to the same reason: when the β of the particle is close to 1, any change in the Cherenkov angle, hence in the ring radius, is small. In this case, the ring reconstruction becomes sensitive to small variations in the light acceptance and gives, as a result, a fine scan of the honeycomb structure of the PM assembly.

The *π-μ* separation, parameterized as the probability to mis-identify a μ as a π, was measured in the momentum range 15-35 GeV/ using only pions, since the muon content in the beam was negligible. The following method was used: for each momentum bin, the fitted Cherenkov ring radius for pions was compared to the radius of pions at higher momentum and with the same β that a muon would have at the original momentum. For example, the ring radius of pions at 15.2 GeV has been compared with the ring radius of pions at 20.0 GeV (fake muons) as listed in Table 1.

π	15.2	17.7	20.0	23.4	26.5	28.7	31.0	35.0
"μ"	20.0	23.4	26.5	31.0	35.0	38.0	41.0	46.3

Table 1. beam momenta (Gev/c) used in the analysis; the "μ" are π at the velocity a μ woud have at the momentum indicated in the π line.

The π-μ mis-identification probability is evaluated in each momentum bin defining a signal region in the pion sample and evaluating the muon fraction contained in it. Results are then 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. 5 shows some of the distributions used for the π-μ separation measurement in 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 for the pion sample 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 (dashed lines), a cut is set at half way between the π and the μ signal peaks (full lines) in order to calculate the pion loss and the muon contamination.

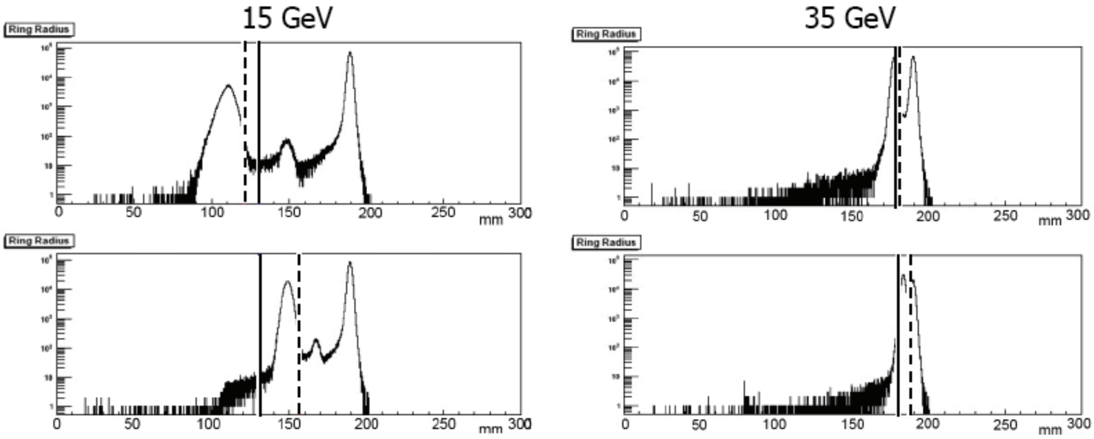

Fig. 5. Reconstructed ring radius distributions used for the measurement of π-μ separation at 15 GeV/c (left) and 35 GeV/c (right). See text for details.

A clear π-μ separation is more evident at lower momentum, due to the large difference of the distance between muon and pion ring radii. Figure 6(left) shows the muon misidentification probability as a function of the particle momentum, measured for four different positions of the mirror w.r.t. the beam line, in order to take into account possible displacements of the ring center. Figure 6(right) 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.

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}, satisfying the requirements for the NA62 RICH detector. Further details on the results of the test of the RICH-400 prototype can be found in [16].

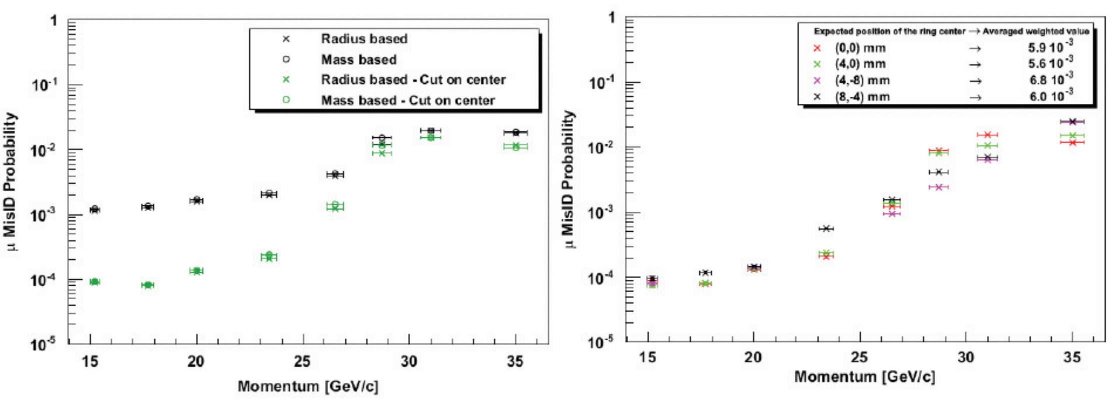

Fig. 6. (a) Muon misidentification probability as a function of momentum for different cuts and ring reconstruction method. (b) Muon misidentification probability as a function of momentum for four different alignment positions of the mirror.

5. Conclusions

The design parameters of the NA62 RICH detector have been validated by the positive results obtained with a full longitudinal scale prototype in two beam tests held at CERN in 2007 and 2009. The design matches the requirements needed for the NA62 experimental program. 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 performance.

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