The RICH detector of the NA62 experiment

F Brizioli and R Lollini, on behalf of the NA62 Collaboration.

Dipartimento di Fisica e Geologia dell’Università degli Studi di Perugia, Perugia, Italy
INFN, Sezione di Perugia, Perugia, Italy
E-mail: francesco.brizioli@pg.infn.it
E-mail: riccardo.lollini@pg.infn.it

Abstract.

The RICH detector of the NA62 experiment is one of the key detectors to achieve the muon rejection needed in the search for the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay, performed by NA62. Since $BR(K^+ \rightarrow \mu^+ \nu)$ is higher than $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ by more than 9 orders of magnitude, it represents one of the most relevant background contributions. Its rejection is performed with kinematic reconstruction of the event and identification of the charged particles in the final state ($\pi^+$ against $\mu^+$). The pion identification efficiency using the RICH detector is measured to be 83% in the momentum range between 15 and 35 GeV/c, with a misidentification probability for muons of 0.2%, while the track crossing time is measured with a resolution of 70 ps. The RICH detector is also exploited to provide trigger for charged particles with an efficiency greater than 99%.
1. NA62 and the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay
The ultra-rare $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay is a good environment to test the Standard Model in the Flavor Physics sector, its branching ratio is precisely computed in the Standard Model [1]:

$$BR^{SM}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (0.84 \pm 0.10) \cdot 10^{-10}.$$  

In addition, it is sensitive to several New Physics models.

The branching ratio measurement has already been performed by the BNL E787 and E949 experiments using kaon decays at rest $BR^{BNL}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \cdot 10^{-10}$. The goal of NA62 is to perform the measurement of the BR with a $\simeq 10\%$ precision, comparable with the Standard Model accuracy.

NA62 collected data in 2016, 2017 and 2018, and needs to run after CERN LS2 period to complete the measurement. The analysis of 2016 data-set led to the observation of 1 signal candidate [3], while in 2017 data-set 2 signal candidates have been detected. The preliminary combined (2016 and 2017 data) results from NA62 are [4]:

$$BR^{NA62}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 1.85 (2.44) \cdot 10^{-10} @ 90 (95)\% C.L. \quad (1)$$

$$BR^{NA62}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (0.47^{+0.72}_{-0.47}) \cdot 10^{-10} \quad (2)$$

The full description of the NA62 beam and detector (including RICH) is provided in [5].

2. The RICH detector
A schematic view of the RICH detector is shown in fig.1.

![Scheme of the RICH detector](image)

Figure 1. Scheme of the RICH detector.

The vessel is a vacuum proof tank, 17 m long and made of structural steel, with the beam pipe ($d = 168$ mm) passing through it (as shown in fig.1). It is divided in 4 cylindrical sections of decreasing diameter ($4 \div 3$ m) and different lengths.

The vessel is filled with the radiator: 200 m$^3$ of Neon (low atomic number to minimize $X_0$) at pressure slightly above 1 atm. The nominal refractive index is $(n-1) = 62.8 \times 10^{-6}$ at $\lambda = 300$ nm, with a corresponding Cherenkov threshold for charged pions: $P_{thres} = m/\sqrt{n^2-1} \simeq 12.5$ GeV/$c$.

At the downstream end of the vessel there is a mosaic of 20 spherical mirrors with curvature radius of 34 m: 18 of them are hexagonal mirrors with a 35 cm side, while 2 are semi-hexagonal mirrors with the hole for the beam pipe. Mirrors are made of 2.5 cm thick glass, with an aluminium coat and a MgF$_2$ protective layer. The average reflectivity is $\sim 90\%$ for $\lambda$ in 195-650 nm. The support structure is an aluminium honeycomb panel: each mirror is supported by a back dowel, two Al ribbons keep the mirror in equilibrium and allow its orientation while a third
ribbon prevents rotations. A system of piezo-motors, out of acceptance and remotely controlled, allows the alignment of each mirror, with a precision of $\sim 30 \, \mu$rad [6].

The Cherenkov photons are collected by two disks of 976 PMs (Hamamatsu R7400U-03) each. The PMs have 16 mm wide face, 8 mm active region, and are packed in hexagonal structure with 18 mm cell size. They are sensitive between 185 $\div$ 690 nm with a maximum quantum efficiency of 20% at $\lambda_{\text{peak}} \sim 420$ nm. Winston cones are exploited to increase the geometrical coverage.

3. RICH basic performance

The RICH space and time resolution, together with other basic performance, have been measured directly on data taken during the commissioning and the first physics run [5], [6]. In order to perform unbiased measurements, a clean sample of positrons have been exploited. Since the positron mass is negligible with respect to the momentum for $p > 10$ GeV/c ($\beta = 1$), the positrons are always above the Cherenkov threshold, and the Cherenkov ring radius and the number of hits do not depend on the particle momentum. Moreover, only events with the expected Cherenkov ring fully contained within the RICH geometrical acceptance have been taken into account. The positron sample has been collected selecting $K^+ \rightarrow \pi^0 e^+ \nu$ events, applying kinematic and calorimetric requirements.

The number of hits per positron ring, obtained fitting the distribution with the Poisson function, is: $\langle N_{\text{hits}} \rangle \simeq 13.8$. The positron ring radius, obtained fitting the distribution with the Gauss function, is: $\langle R_e \rangle \simeq 189.6$ mm, $\sigma_{R_e} \simeq 1.47$ mm.

![Figure 2. Distribution of the Pull variable (Left) and $T_1 - T_2$ (Right) of the RICH detector. For the definition of Pull and $T_1 - T_2$ see text.](image)

The measurement of the single hit space resolution is performed defining the quantity $\text{Pull} = (R - R^{\text{exp}}) \sqrt{\langle N_{\text{hits}} \rangle - 3}$, in order to weight the contribution to the resolution coming from each hit. $R$ is the reconstructed ring radius, $R^{\text{exp}}$ is the expected ring radius assuming the positron mass, $N_{\text{hits}}$ is the number of observed hits, 3 is the number of free parameters used in the $\chi^2$-based hits fit that reconstructs the ring (radius, X and Y center coordinates). Then $\sigma_{\text{Hit}} = \sigma_{\text{Pull}} \simeq 4.7$ mm (fig.2, left).

The ring time resolution is calculated by randomly dividing the hits of a single ring into two groups, defining the time of each group as the average hit time, and fitting $T_1 - T_2$ (fig.2, right). Then, the ring time resolution is: $\sigma_T = 0.5 \cdot \sigma_{T_1-T_2} \simeq 70$ ps.

4. RICH usage in $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ selection

In the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ selection the RICH plays a relevant role to reject background coming from kaon decays with a muon in the final state, typically the $K^+ \rightarrow \mu^+ \nu_\mu$ decay, that must be
suppressed by more than 10 orders of magnitude. In this section the RICH usage in the analysis of 2017 data is described.

In the left plot of fig.3 it is shown how the RICH detector works: the ring radius measured by the RICH, versus the momentum measured by the spectrometer, gives separated distributions for different particles, since the charged particle mass can be expressed as:

\[ m^2 = m^2(p, R) = p^2 \cdot \left( \frac{F^2 \cdot n^2}{F^2 + R^2} - 1 \right) \]

where \( p \) is the charged particle momentum, \( R \) is the ring radius, \( n \) is the refractive index and \( F \) the focal length.

\[ \text{Figure 3. Left: RICH reconstructed radius VS track momentum, for one-track selected events; the different distributions of positrons, muons, pions and kaons are marked with letters and the } \pi \nu \nu \text{ momentum region (15 – 35 GeV/c) is delimited by red lines. Right: one of the two RICH PM disk planes; the hits from Cherenkov photons are represented by black circles with a radius equal to the single hit resolution (4.7 mm). The ring reconstructed by the fit algorithm (black) is compared to the expected rings for electrons (magenta), muons (blue) and pions (red).} \]

The rings are reconstructed with two different analysis methods in order to optimize the signal acceptance and the background rejection (fig.3, right). In particular a stand-alone ring reconstruction is performed, and using the spectrometer momentum in eq. 3, the charged particle mass is computed (fig.4, left). Independently, the expected ring center is obtained by extrapolating the track to the PM plane (reflecting the track off the mirrors as if it were a photon); this information is used to compute different ring radii for different mass hypotheses, reverting eq. 3 and a likelihood discriminant is computed for each hypothesis (fig.4, right).

The optimized combination of cuts on the mass and the likelihoods (fig.4) gives the final RICH efficiency for signal and background (\( \epsilon(\pi) \) and \( \epsilon(\mu) \), respectively) in the momentum range 15-35 GeV/c:

\[ \epsilon(\pi) \simeq 83\% \text{ at } \epsilon(\mu) \simeq 0.2\%. \]

The RICH also contributes to the level-0 trigger chain [7], with an efficiency higher than 99%. 


Figure 4. Left: charged particle mass reconstructed by the RICH detector, for muons (blue) and pions (red) in the momentum range $15 - 35 \text{ GeV}/c$; the optimized cut applied in the $\pi\nu\nu$ selection (125 MeV/$c^2$) is shown in black. Right: highest likelihood discriminant of the not-pion hypotheses, reconstructed by the RICH detector, for muons (blue) and pions (red) in the momentum range $15 - 35 \text{ GeV}/c$; the optimized cut applied in the $\pi\nu\nu$ selection (0.12) is shown in black.

References

[1] Buras A J, Buttazzò D and Knegjens R J 2015 JHEP 1511 166
[2] Artamonov A V et al. [BNL-E949 Collaboration] 2009 Phys. Rev. D 79 092004
[3] NA62 Collaboration 2019 Phys. Lett. B 791 156166
[4] NA62 Collaboration 2019 Addendum I to P326: Continuation of the physics programme of the NA62 experiment CERN SPSC-2019-039/SPSC-P-326-ADD-1
[5] NA62 Collaboration 2017 JINST 12 P05025
[6] Anzivino G et al. 2018 JINST 13 no.07, P07012
[7] Ammendola R et al. 2019 NIM A 929 122