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Design, performance and perspective of the NA62-RICH

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Abstract: NA62 is an experiment designed to measure the branching fraction of the ultra-rare decay of the positively charged kaon into a pion and a neutrino-antineutrino pair. The specialties of its Ring Imaging Cherenkov detector (RICH) are the muon-pion separation, the sub-nanosecond timing and the participation in the lowest level trigger of the experiment. These characteristics made the NA62-RICH crucial for the physics data taking that run in the three-year period 2016–2018. Two aspects are currently under consideration to increase the impact of RICH in the broad NA62 physics program: a better time resolution to cope with higher intensity beam and the online extraction of high level features to be used in the trigger logic. This paper describes the RICH detector and presents its possible upgrades.

Keywords: Cherenkov detectors; Particle identification methods

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1 The NA62 experiment

NA62 is a challenging experiment designed to study the rarest decay modes of the K meson with an innovative decay-in-flight technique. The first goal of the experiment is to probe the channel $K^+ \to \pi^+ \nu\bar{\nu}$. Such a process is strongly suppressed and its branching ratio has an extremely clean theoretical prediction [1] equal to $(8.4 \pm 0.1) \times 10^{-11}$. Therefore its experimental determination constitutes an excellent test for the predictive power of Standard Model and can shed a light on the physics beyond it. In order to keep small the systematic uncertainty and collect enough statistics required to measure such a tiny quantity NA62 has been designed with two main characteristics: the ability to handle a very high intensity beam and a strong background rejection performance.

A layout of the apparatus is illustrated in figure 1, it took physics quality data in 2016, 2017 and 2018. The complete analysis is currently ongoing while a first physics result obtained on a partial

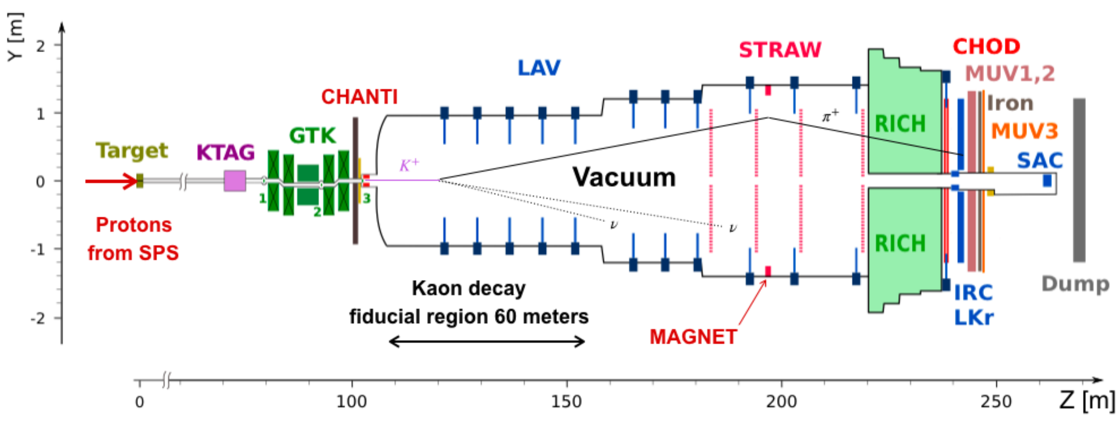

Figure 1. Schematic view of NA62 detectors.

sample was published in 2019 [2]. The beam and the detectors are comprehensively described in a dedicated publication [3], here a short description of the main elements is provided to introduce the RICH role in the experiment.

NA62 is a fixed target experiment located in the North Area of CERN where protons extracted from the SPS complex are exploited to produce a positively charged hadron beam of 75 GeV/c momentum using a beryllium target. Hadrons are received in spills of 3.5 seconds duration with a nominal rate of 750 MHz. The presence of a kaon is determined by means of a differential Cherenkov counter (KTAG) while a magnetic spectrometer made of silicon pixels (Gigatracker, GTK) is used to measure the particle direction and momentum before its decay. In addition a scintillator system (CHANTI) placed after the last tracking station is used to veto possible inelastic scattering in the GTK.

The beam contains 6% of kaons and only 10% of them are expected to decay in the 60 meters long fiducial region. However the particle rate on the detectors involved in the final state determination is as high as 10 MHz. These detectors are an ultra light magnetic spectrometer composed by 4 straw chambers (STRAW), a fully hermetic large angle gamma veto system (LAV), an electromagnetic calorimeter (LKr) for small angle gammas, a plane of scintillator tiles behind an iron block to veto muons (MUV3), a group of hadronic calorimeters to identify pions (MUV1,2) and the Ring Imaging Cherenkov (RICH) detector.

The RICH is placed after the last STRAW chamber and is designed to suppress muon contamination in the pion sample by a factor 100 in the momentum range from 15 to 35 GeV/c. Being very precise in time and practically free from random coincidences the RICH has been used offline to realize the time match with the originating kaon and online to determine the presence of charged particles in the decay products with a simple multiplicity based algorithm.

2 The RICH detector

The RICH project started long ago with the aim to provide NA62 with an extra muon rejection factor on top of kinematics and calorimetry. In fact the main source of background is the process $K^+ \to \mu^+\nu$ with a branching fraction of 63.6% that is ten orders of magnitude larger than the signal expectation. Thus an impressive rejection power at the level of 10^{-12} is required to keep the experimental uncertainty at 10%, comparable with Standard Model prediction. Given an estimated rejection factor of 10^{-5} from kinematics and 10^{-5} from hadronic calorimeters, the RICH was required to provide a muon suppression of the order of 10^{-2}. After an initial Montecarlo simulation finalized the geometry optimization, an intense test campaign with two prototypes of increasing complexity was conducted to validate the project and its constituting elements [4, 5].

A summary of the design and two key performances are presented here. For a complete description of the RICH characterization and optimization please refer to [6] which was recently published.

2.1 Design

The Ring Imaging Cherenkov (RICH) is a classical focusing RICH with 17 meters focal length and neon gas as radiator ($n - 1 = 62.8 \times 10^{-6}$ at 300 nm and 0.996 atm). Neon guarantees a

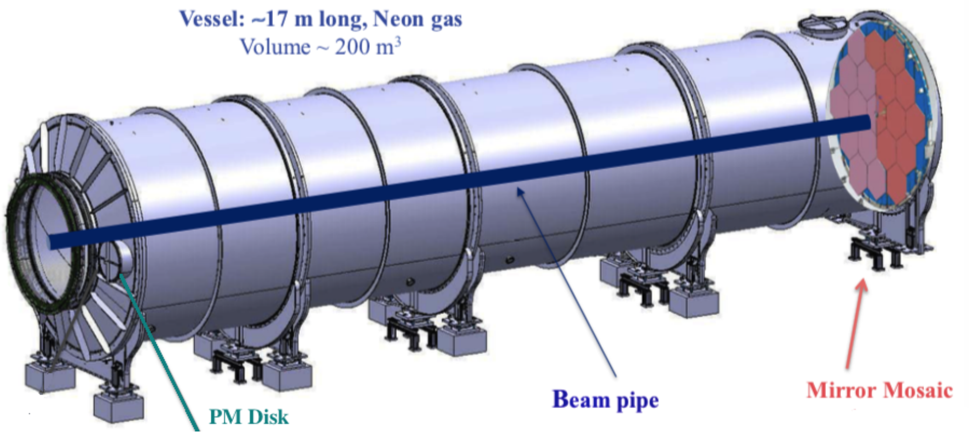

Figure 2. Pictorial view of the RICH detector.

pion threshold of 12.5 GeV/c and minimizes the multiple scattering for downstream detectors, but imposes an impressive longitudinal length because of the small value of the refractive index.

The passage of undecayed beam particles takes place through an inner pipe (10^{-5} mbar) as sketched in figure 2. Consequently a dual optics setup composed by a mosaic of spherical mirrors has been chosen together with two identical photo-detection surfaces (Disk) located at the opposite endcap of the vessel. Details on the mirror system are presented in [7] and an exhaustive description of the iterative alignment procedure can be found in [8]. The orientation of each mirror is adjusted until a deviation smaller than 1 mm is found on the focal plane between the Cherenkov ring center and the expected position predicted by track extrapolation from the STRAW spectrometer. Considering the 17 meters of focal length, this corresponds to a final angular precision of 30 μrad.

Light is detected using 1952 compact photomultiplier devices (PM) with near UV extended photocathode response, 20% quantum efficiency at peak wavelength (420 nm), 280 ps transit time spread and a minimum gain of 1.5×10^6 at 900 Volts (Hamamatsu R7400U-03). Because of the small active area (8 mm diameter) a light funnel system was adopted resulting in a 18 mm pixel pitch and a minimum dead space on the PM Disks. Frontend electronics are mounted at the proximity rack and organized in 32-channel custom boards. They are built around the 8-channel NINO discriminator ASIC [9] offering 25 ps time jitter for charge greater than 200 fC and LVDS outputs.

Four boards are used to read out the logic pulses, process the data and encapsulate them in UDP packets for transmission over the NA62 acquisition network. Called TEL62, they are general purpose readout boards housing FPGA devices (Altera Stratix III) and large memory buffers to provide flexibility in hardware design and handle the quite uncommon 1 ms trigger latency requirement of the experiment. A fifth TEL62 is used for triggering purpose reading out the RICH with coarse granularity (244 cells). Timestamping is obtained by means of TDC boards called TDCB, a CERN standard module for LHC providing 100 ps resolution.

In 2017 and 2018 an interesting pilot project ran parasitically to test a possible online reconstruction of the Cherenkov rings based on custom high speed network interface called NaNet [10] and a Graphical Processor Units (NVidia Pascal P100 GPU). A description of the TEL62 board with detailed information on hardware, baseline trigger logic and RICH-GPU trigger implementation can be found in [11].

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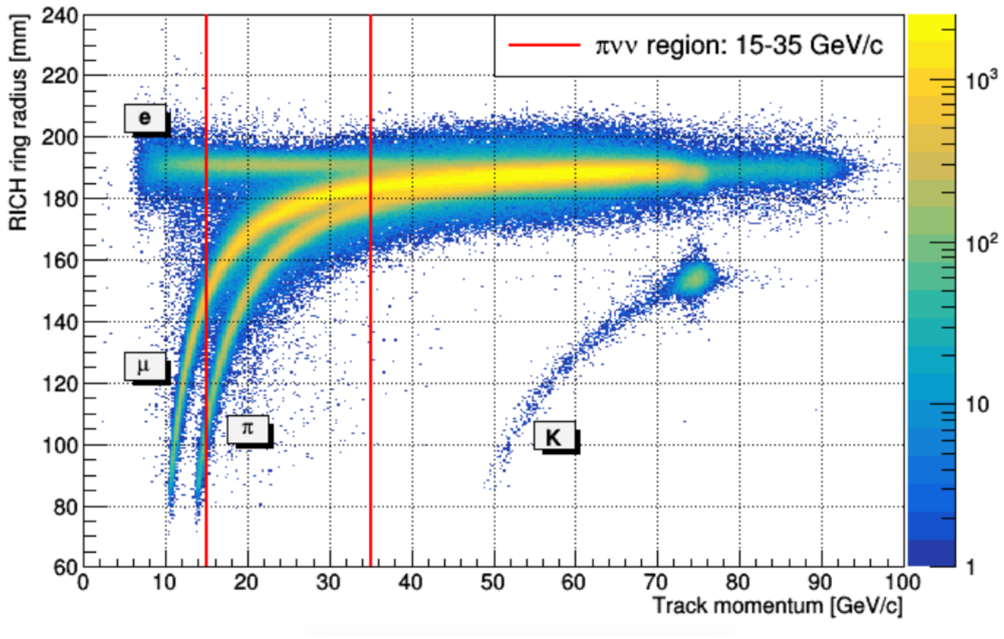

Figure 3. PID performance using 2017 data.

2.2 Performance

The discrimination power of the RICH detector for the $\pi\nu\bar{\nu}$ study can be appreciated in figure 3 where the offline reconstructed ring radii are plotted against the particle momentum from the STRAW magnetic spectrometer. The distributions due to different particles are clearly visible. In particular the separation between pions and muons is evident in the momentum range from 15 to 35 GeV/c indicated by the two vertical red lines.

Even more interesting is the ring time resolution which measures how blurred is the ring image in time. This figure of merit is calculated by randomly splitting the hits of a ring in two groups, getting the time centroid of each group (T_1, T_2), plotting the time difference between the two values and getting half sigma of the fitted distribution. Figure 4 shows a typical example of this calculation where a clean positron sample was used to get a result independent from the momentum range ($\beta = 1$). From data analised so far the ring time resolution is always at the level of 70 ps. A more rough estimation can be obtained dividing the transit time spread of the PM quoted by the manufacturer (i.e. 280 ps) by the square root of the average number of hits, which in the case of 2017 data is equal to $\langle Nhit \rangle = 14.1$, giving about 74 ps. The two values are pretty in agreement indicating that the major source of degradation is the jitter introduced by PMs.

During 2019 the software calibration suite of the RICH detector was expanded with new tools to perform periodical checks and prevent sub-optimal running conditions. In dedicated tests with the hadron beam off, it was verified that PMs are operating in an almost saturated regime and only a small improvement in detection efficiency (at the level of 0.1%) can be achieved by refining the discrimination thresholds. On the other hand 1% of useful detection area (less than 20 PMs) can be recovered by replacing noisy electronic channels and low gain PMs with spares in view of the data taking restart in 2021.

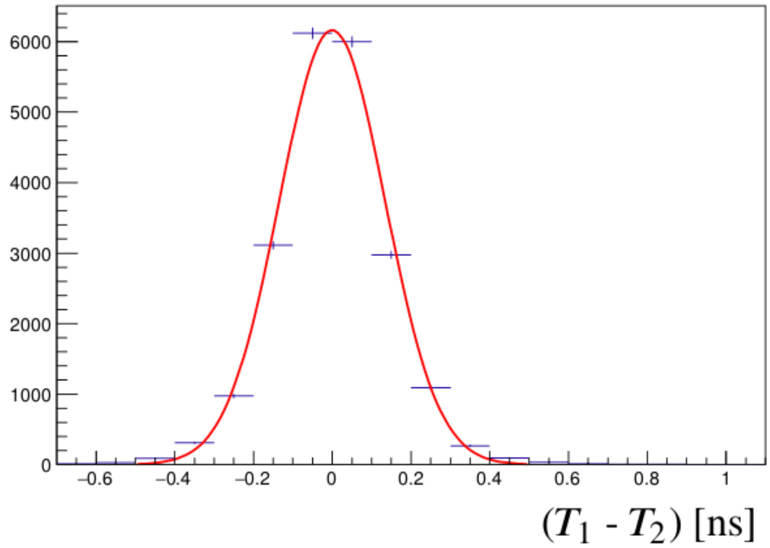

Figure 4. Distribution of $(T_1 - T_2)$ for a positron sample from 2017 data. The gaussian fit gives a standard deviation $\sigma \simeq 0.14$ ns. For the definition of $(T_1 - T_2)$ see text.

3 Perspective

The NA62 collaboration plans to scale at 100% beam intensity in 2021 (before it was typically 60%) in order to reach $O(10^{13})$ kaon decays for the $\pi\nu\bar{\nu}$ analysis and test solutions for a possible increase of a factor 4 in NA62 beam intensity.

With a higher beam intensity a better RICH time resolution would be required to cope with increased particle rates and accidental backgrounds. This could be achieved by improving the time resolution of individual readout channels and by increasing the number of hits per ring as discussed in 2.2. The lighter impact solution involving the readout system is to replace the installed PMs with more recent devices (Hamamatsu R9880U model) having the same form factor but offering smaller transit time spread (200 ps) and higher quantum efficiency (30%). In this scenario the maximum obtainable performance is estimated to be at the level of 50 ps. Only a change in the photo-detection technology and consequently a complete redesign of electronics and services would allow the detector performance to go well below this value.

The most promising development line is related to the RICH role in future trigger strategies of the experiment. Together with the $\pi\nu\bar{\nu}$ measurement completion, the search for exotic particles are growing in importance seen the potentiality of NA62 in performing rare physics detection. In particular, with its low noise, the RICH can identify events with more than one lepton in the final state. In this view the real-time extraction of high level features like number and geometry of the rings can increase the purity of the selection, save readout bandwidth for additional physics or control samples and eventually increase the possibility of new discoveries. Three factors could open the way to get an online rings reconstruction at a rate higher than 10 MHz: the use of a custom fixed latency link like the one adopted in the past years for the GPU-based reconstruction pilot project, the availability of latest generation acceleration boards with their huge density of programmable logic and the use of High Level Synthesis (HLS) tools that allow specialized hardware design starting from C/C++ code instead of using traditional Hardware Description Language (HDL) techniques.

4 Conclusion

NA62 took $K^+ \to \pi^+ \nu\bar{\nu}$ data in the three-year period 2016–2018 with the RICH as a crucial detector. The RICH provided additional muon rejection on top of calorimetry based particle identification. Moreover the RICH participated in the lower level trigger logic with a simple algorithm based on the number of hits and provided the experiment with a high resolution time reference on the passage of charged particles at the level of 70 ps.

In view of a high luminosity running condition a drastic improvement of the RICH time resolution can be obtained only with a significant upgrade of the photosensor technology and related frontend electronics.

Thanks to the experience gained in the past with custom fixed latency link and GPU-based ring reconstruction and considering the presently large availability of fast data transmission links, parallel configurable devices and High Level Synthesis tools, the RICH can play an important role in rare physics search by providing real time high level features information to the lowest level trigger of the NA62 experiment.

References

[1] A.J. Buras, D. Buttazzo, J. Girrbach-Noe and R. Knegjens, *$K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ in the Standard Model: status and perspectives*, *JHEP* **11** (2015) 033 [arXiv:1503.02693].

[2] NA62 collaboration, *First search for $K^+ \to \pi^+ \nu\bar{\nu}$ using the decay-in-flight technique*, *Phys. Lett. B* **791** (2019) 156 [arXiv:1811.08508].

[3] NA62 collaboration, *The Beam and detector of the NA62 experiment at CERN*, 2017 *JINST* **12** P05025 [arXiv:1703.08501].

[4] G. Anzivino et al., *Construction and test of a RICH prototype for the NA62 experiment*, *Nucl. Instrum. Meth. A* **593** (2008) 314.

[5] B. Angelucci et al., *Pion-muon separation with a RICH prototype for the NA62 experiment*, *Nucl. Instrum. Meth. A* **621** (2010) 205.

[6] G. Anzivino, M. Barbanera, A. Bizzeti, F. Brizioli, F. Bucci, A. Cassese et al., *NA62 RICH performance: measurement and optimization*, *Nucl. Instrum. Meth. A* **952** (2020) 161736.

[7] D. Aisa et al., *Mirror system of the RICH detector of the NA62 experiment*, 2017 *JINST* **12** P12017.

[8] G. Anzivino et al., *Precise mirror alignment and basic performance of the RICH detector of the NA62 experiment at CERN*, 2018 *JINST* **13** P07012 [arXiv:1809.04026].

[9] F. Anghinolfi, P. Jarron, A.N. Martemyanov, E. Usenko, H. Wenninger, M.C.S. Williams et al., *NINO: An ultra-fast and low-power front-end amplifier/discriminator ASIC designed for the multigap resistive plate chamber*, *Nucl. Instrum. Meth. A* **533** (2004) 183.

[10] A. Lonardo et al., *NaNet: a configurable NIC bridging the gap between HPC and real-time HEP GPU computing*, 2015 *JINST* **10** C04011.

[11] R. Ammendola et al., *The integrated low-level trigger and readout system of the CERN NA62 experiment*, *Nucl. Instrum. Meth. A* **929** (2019) 1 [arXiv:1903.10200].

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The NA62 collaboration

R. Aliberti, F. Ambrosino, R. Ammendola, B. Angelucci, A. Antonelli, G. Anzivino, R. Arcidiacono, T. Bache, M. Barbanera, J. Bernhard, A. Biagioni, L. Bician, C. Biino, A. Bizzeti, T. Blazek, B. Bloch-Devaux, V. Bonaiuto, M. Boretto, M. Bragadireanu, D. Britton, F. Brizioli, M.B. Brunetti, D. Bryman, F. Bucci, T. Capussela, J. Carmignani, A. Ceccucci, P. Cenci, V. Cerny, C. Cerri, B. Checcucci, A. Conovaloff, P. Cooper, E. Cortina Gil, M. Corvino, F. Costantini, A. Cotta Ramusino, D. Coward, G. D'Agostini, J. Dainton, P. Dalpiaz, H. Danielsson, N. De Simone, D. Di Filippo, L. Di Lella, N. Doble, B. Dobrich, F. Duval, V. Duk, J. Engelfried, T. Enik, N. Estrada-Tristan, V. Falaleev, R. Fantechi, V. Fascianelli, L. Federici, S. Fedotov, A. Filippi, M. Fiorini, J. Fry, J. Fu, A. Fucci, L. Fulton, E. Gamberini, L. Gatignon, G. Georgiev, S. Ghinescu, A. Gianoli, M. Giorgi, S. Giudici, F. Gonnella, E. Goudzovski, C. Graham, R. Guida, E. Gushchin, F. Hahn, H. Heath, E.B. Holzer, T. Husek, O. Hutanu, D. Hutchcroft, L. Iacobuzio, E. Iacopini, E. Imbergamo, B. Jenninger, J. Jerhot, R.W. Jones, K. Kampf, V. Kekelidze, S. Kholodenko, G. Khoriauli, A. Khotyantsev, A. Kleimenova, A. Korotkova, M. Koval, V. Kozhuharov, Z. Kucerova, Y. Kudenko, J. Kunze, V. Kurochka, V. Kurshetsov, G. Lanfranchi, G. Lamanna, E. Lari, G. Latino, P. Laycock, C. Lazzeroni, M. Lenti, G. Lehmann Miotto, E. Leonardi, P. Lichard, L. Litov, R. Lollini, D. Lomidze, A. Lonardo, P. Lubrano, M. Lupi, N. Lurkin, D. Madigozhin, I. Mannelli, G. Mannocchi, A. Mapelli, F. Marchetto, R. Marchevski, S. Martellotti, P. Massarotti, K. Massri, E. Maurice, M. Medvedeva, A. Mefodev, E. Menichetti, E. Migliore, E. Minucci, M. Mirra, M. Misheva, N. Molokanova, M. Moulson, S. Movchan, M. Napolitano, I. Neri, F. Newson, A. Norton, M. Noy, T. Numao, V. Obraztsov, A. Ostankov, S. Padolski, R. Page, V. Palladino, A. Parenti, C. Parkinson, E. Pedreschi, M. Pepe, M. Perrin-Terrin, L. Peruzzo, P. Petrov, Y. Petrov, F. Petrucci, R. Piandani, M. Piccini, J. Pinzino, I. Polenkevich, L. Pontisso, Yu. Potrebenikov, D. Protopopescu, M. Raggi, A. Romano, P. Rubin, G. Ruggiero, V. Ryjov, A. Salamon, C. Santoni, G. Saracino, F. Sargeni, S. Schuchmann, V. Semenov, A. Sergi, A. Shaikhiev, S. Shkarovskiy, D. Soldi, V. Sugonyaev, M. Sozzi, T. Spadaro, F. Spinella, A. Sturgess, J. Swallow, S. Trilov, M. Turisini, P. Valente, B. Velghe, S. Venditti, P. Vicini, R. Volpe, M. Vormstein, H. Wahl, R. Wanke, B. Wrona, O. Yushchenko, M. Zamkovsky and A. Zinchenko.

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