

# The kaon identification system in the NA62 experiment at the CERN SPS

NA62 Collaboration

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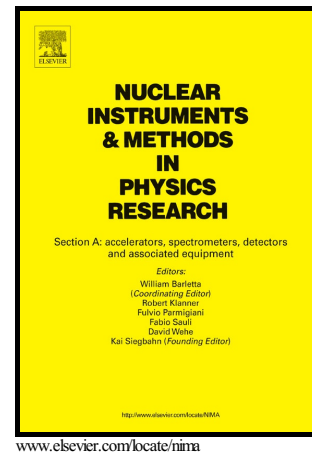
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# The kaon identification system in the NA62 experiment at the CERN SPS

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## Abstract

The fixed target experiment NA62 at CERN aims at measuring the ultra-rare decay  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ , whose branching ratio is of the order of  $10^{-11}$ . The main challenges faced by the experiment to achieve a 10% precision measurement are the required beam intensity and background rejection factor. The differential Cherenkov detector KTAG must be able to tag charged kaons in an unseparated hadron beam with an average particle rate of 750 MHz, of which 45 MHz are kaons, with a time precision of at least 100 ps and an efficiency higher than 95%. The additional pion contamination must be kept lower than  $10^{-4}$ .

The RICH has been designed to separate charged pions from muons in the momentum range  $15 < p < 35$  GeV/ $c$ , contributing to a further muon rejection factor of 100. In order to match the upstream and downstream activity, a time resolution similar to the one of KTAG must be achieved. The RICH is also used as a primitive trigger generator for the level-0 trigger system.

The construction and commissioning of both detectors was completed and their performances were studied during the 2014–2015 runs.

*Keywords:* Cherenkov detectors, Fast timing, Photomultiplier, NA62, KTAG, RICH

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<sup>1</sup>Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, Glasgow, Liverpool, Louvain, Mainz, Merced, Moscow, Naples, Perugia, Pisa, Prague, Protvino, Rome LS, Rome TV, San Luis Potosi, SLAC, Sofia, TRIUMF, Turin, Vancouver

## 1 1. The NA62 Experiment at the CERN SPS

2 NA62 is a fixed target Kaon decay experiment located at the CERN SPS.  
 3 The main goal is to measure the branching fraction of the ultra-rare decay  
 4  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  with a precision of  $\sim 10\%$  and a ratio signal/background  $> 10$ .  
 5 This process plays a key role in the search for new physics. With a dominant  
 6 contribution coming from the short-distance  $t$  quark, and small  $c$  quark and  
 7 long-distance corrections, this decay is theoretically very clean. The standard  
 8 model prediction is computed to an exceptionally high degree of precision [1]:

$$Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{SM}} = (9.11 \pm 0.72) \times 10^{-11}$$

9 The main uncertainty arises from the CKM matrix elements, and the pure  
 10 theoretical uncertainty is at the 1% level. An experimental measurement of the  
 11 branching ratio at a similar level of precision can constrain new physics scenarios  
 12 because many of them predict effects on this branching ratio.  
 13 On the experimental side, the best available measurement [2]:

$$Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{exp}} = 1.73_{-1.05}^{+1.15} \times 10^{-10}$$

14 is extracted from the 7  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  candidate events observed by the E797  
 15 and E949 experiments at the Brookhaven National Laboratory. The achieved  
 16 precision is not sufficient, however, to be a significant test of new physics.  
 17 The aim of NA62 is to collect around 50  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  events per year of data  
 18 taking with  $\sim 10\%$  accuracy and less than 10% background. To achieve this  
 19 ambitious goal, two challenges must be faced: a large sample of kaon decays must  
 20 be considered and a sufficient fraction of the background must be rejected. The  
 21 former is fulfilled by a high intensity beam providing  $4.5 \times 10^{12}$   $K^+$  decays/year  
 22 within the 10% detector acceptance. The beam is extracted from the primary  
 23 400 GeV/ $c$  SPS beam line impacting on a Beryllium target. The secondary  
 24 beam reaching the experiment is an unseparated hadron beam at 75 GeV/ $c$   
 25 with a momentum bite of 1%. The composition of the beam is roughly  $K^+ \sim$   
 26 6%,  $\pi^+ \sim 72\%$ ,  $p \sim 22\%$ . The second requirement is to achieve a rejection

27 factor greater than  $10^{12}$  on other kaon decays acting as background to the  
28 measurement. This is accomplished by a combination of kinematic rejection,  
29 efficient particle identification and veto systems and a good time resolution to  
30 match upstream and downstream activity. The kinematic rejection is mainly  
31 driven by the performances of the GigaTracker spectrometer for beam particles  
32 and the Straw spectrometer for the charged decay products.

## 33 **2. The Kaon Identification System**

34 As the beam entering the experiment has a total particle rate of 750 MHz  
35 and contains only  $\sim 6\%$   $K^+$  it is important to tag them to reduce the event rate.  
36 The Kaon identification system is the first detector, located at the beginning  
37 of the experiment and is expected to sustain a flux of 45 MHz of kaons while  
38 providing a positive identification efficiency greater than 95% and less than  
39 0.1% mis-tagging probability. It should also provide a time resolution better  
40 than 100 ps for the downstream event matching.

41 The CEDAR/KTAG system is an upgrade of the Cherenkov Differential counter  
42 with Achromatic Ring focus West (CEDAR West) build in the 1970s for the SPS  
43 beam lines [3]. The vessel is filled with nitrogen as radiator gas. The Cherenkov  
44 light is transported outside the gas volume by the internal optics through a  
45 diaphragm and 8 quartz windows. The optics comprise a spherical Mangin  
46 mirror and elements for focusing and correcting chromatic errors. The optical  
47 axis must be precisely aligned with the beam axis. This also requires the beam  
48 divergence to be small: of the order of 100  $\mu$ rad. The design of the detector  
49 only allows to select a fixed Cherenkov angle and the aperture of the diaphragm  
50 permits to tune the tolerance around that angle. As the beam is monochromatic,  
51 it is sufficient to adjust the gas pressure to select the particle mass to which the  
52 CEDAR is sensitive. The CEDAR is enclosed in a cooled, thermally insulated  
53 volume and the environmental conditions are constantly monitored.

54 *2.1. The KTAG upgrade*

55 The original version of the CEDAR is neither able to withstand the rate  
56 requirements nor to yield the desired time resolution. The KTAG upgrade de-  
57 signed to improve the performance is twofold: an upgrade of the light collection  
58 and detection and the replacement of the entire readout.

59 The original photomultipliers placed after the exit windows were replaced by  
60 focusing lenses and convex spherical mirrors reflecting the light radially. Thanks  
61 to this change the detection planes were moved farther from the axis, leaving  
62 more space and allowing to spread the light on wider areas. The photon rate  
63 per unit area is lower, reducing the strain on the readout. The detection planes  
64 are instrumented with 8 insulated and cooled light boxes. The entrance of the  
65 box is formed by a matrix of closely spaced light collection cones covered with  
66 aluminized Mylar, machined in spherical convex aluminium plates. An array of  
67 48 small, fast Hamamatsu photomultipliers (32 of type R9880 in the centre and  
68 16 of type R7400 on the edges) is placed at the exit of the cones. The box also  
69 contains the high voltage distribution board and the front-end electronics.

70 A custom printed circuit board extracts a differential signal from the anode  
71 and the last cathode of the photomultiplier. Each light box houses a mother  
72 board with 8 NINO ASIC chip [4] mezzanines. They perform a fast Time-over-  
73 Threshold on the 64 input channels and output a Low Voltage Differential Signal  
74 (LVDS). A splitter board collects the signals from all sectors and redistributes  
75 them on the readout based on the common acquisition system of the experiment.  
76 The TEL62 mother board [5] is used as integrated trigger and data acquisition  
77 and hosts 4 daughter boards (TDCB). Each of these TDCB is equipped with  
78 4 high-performance analogue time to digital conversion (HPTDC) chips with  
79 32 channels each [6]. The times of both the leading and trailing edges are  
80 recorded, providing the width of the signal time for slewing corrections in the  
81 analysis. KTAG uses 6 similarly equipped TEL62 boards where the channels  
82 are distributed in such a way that the data rate is equalized amongst them. The  
83 maximum sustainable rate is  $\sim 5$  MHz per PMT.

84 The detector was tested on a beam line at CERN in 2011. The CEDAR was

85 equipped with both its old readout, and prototypes of the new photomultipliers  
 86 and front-end electronics. The results of this test were used as input to carry out  
 87 detailed simulations of the transport of Cherenkov photons inside the CEDAR,  
 88 using all the available information concerning the optical components. As seen  
 89 in Figure 1, the separation in angular distribution of the Cherenkov photons on  
 90 the diaphragm is sufficient to isolate the kaons and pions. A diaphragm aper-  
 91 ture of 1.5 mm provides the required kaon efficiency and pion rejection. More  
 92 details can be found in [7].

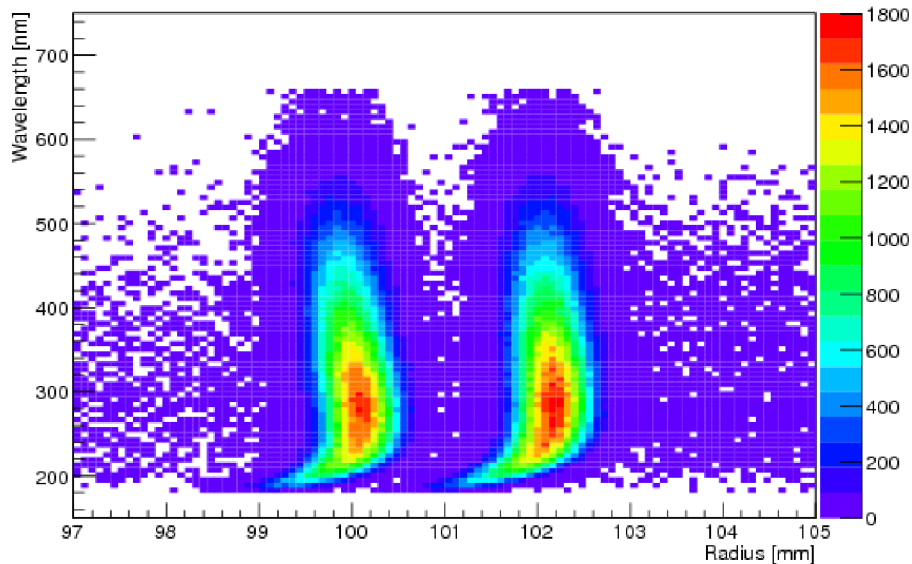


Figure 1: Distribution of Cherenkov photons on the diaphragm plane in  $N_2$ . The accumulation around 100 mm is due to kaons while the one around 102 mm is due to pions.

### 93 2.2. Performance

94 The KTAG performance was studied on multiple occasions. A first test of  
 95 a partially equipped KTAG was performed during a technical run with beam  
 96 at 1% intensity in 2012. Only 4 sectors were instrumented with 32 PMTs of  
 97 type R7400 each. A pressure scan was performed. The extrapolation of the  
 98 pion contamination under the kaon peak is done by looking at the tails of the

99 pion peak. It permits to estimate the pion mis-identification probability, and  
 100 is found to be  $\sim 10^{-4}$ . The single photon time resolution after corrections is  
 101 measured to be  $\sigma_t(\gamma) = 280$  ps.

102 The commissioning was completed during the 2014/2015 physics run. The  
 103 KTAG was fully instrumented and the expected performance has been con-  
 104 firmed. An average of  $N_\gamma = 20$  photons per kaon are detected. The time  
 105 resolution for kaons is  $\sigma_t(K) = \sigma_t(\gamma)/\sqrt{N_\gamma} = 70$  ps. The efficiency is studied  
 106 by reconstructing a sample of  $K^+ \rightarrow \pi^+\pi^0$  using only information from the  
 107 Liquid Krypton calorimeter (LKr). These events are compared with the frac-  
 108 tion of events for which the CEDAR does not have a matching candidate as a  
 109 function of the number of fired sectors. The efficiency is better than 95% for 5  
 110 or more sectors fired. Finally a pressure scan was performed at the beginning  
 111 of 2015 for different diaphragm apertures. The result is presented in Figure 2.  
 112 A diaphragm aperture of 1.5 mm and a pressure of 1.745 bar have been chosen  
 113 in order to maximise the kaon identification efficiency.

### 114 3. The RICH detector

115 Many background events contain muons and the experiment needs a reliable  
 116 way of identifying them. This is the purpose of the RICH detector. It needs  
 117 to provide a muon suppression factor of better than 100 for charged tracks in  
 118 the range  $15 < p < 35$  GeV/ $c$ . As for the CEDAR the time resolution on the  
 119 pion crossing time must be of the order of 100 ps. It must also provide a level-0  
 120 trigger for charged tracks.

121 The detector is a Ring Imaging Cherenkov detector placed at the exit of the  
 122 vacuum volume. The vessel is 17.5 m long and the diameter varies from 4.2 m  
 123 at the entrance to 3.2 m at the exit. It is closed at each end by thin (2–4 mm)  
 124 aluminium windows. A beam pipe starts at the entrance window and exits at  
 125 the downstream side through an O-ring allowing longitudinal movement.

126 In order to be fully efficient at 15 GeV/ $c$  the Cherenkov threshold should be at  
 127 12.5 GeV/ $c$ , which corresponds to a refractive index of  $(n - 1) = 62 \times 10^{-6}$ .



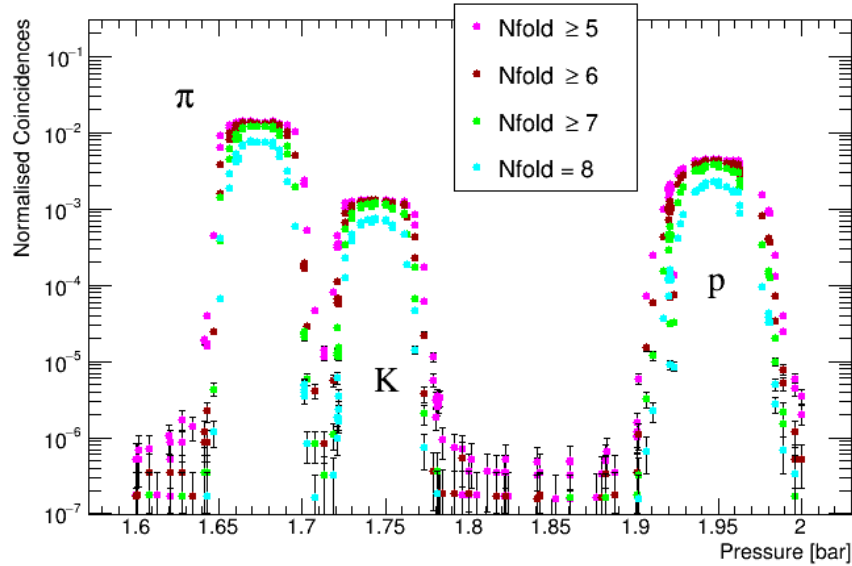


Figure 2: Pressure scan at 1.5 mm diaphragm aperture in log scale. The 1st peak corresponds to the pion peak, the 2nd to the kaon peak, and the 3rd one to the proton peak.

128 Neon has been chosen as radiator gas and has two advantages. Its refractive  
 129 index at atmospheric pressure matches almost exactly the requirements and it  
 130 is sensitive to wavelengths above 190 nm, rendering the detector insensitive to  
 131 the main impurities (H<sub>2</sub>O and oxygen). All other impurities, like CO<sub>2</sub>, are  
 132 naturally not present and can be kept low. The gas is kept at 990 mbar in  
 133 the sealed volume without continuous renewal. Small losses due to leaks are  
 134 compensated by occasionally topping up.

135 An array of hexagonal mirrors of 35 cm side length (18 full hexagons and 2  
 136 semi-hexagonal ones with a circular opening around the beam pipe) are placed  
 137 on the downstream endcap to reflect the light on the photo-detectors. They  
 138 are spherical with a radius of curvature of  $(34 \pm 0.2)$  m and a focal length of  
 139 17 m. They are made of 2.5 cm thick glass with an aluminium coating and a  
 140 thin dielectric film for protection and to increase the reflectivity. Their average  
 141 reflectivity is better than 90%. To reduce the material budget, a 5 cm thick

142 aluminium honeycomb structure is supporting them. They are connected to  
143 the support by a dowel with a spherical head inserted in a hole drilled on the  
144 non-reflecting surface at the back of the mirrors. Two thin aluminium ribbons  
145 keep them in position and are connected to piezo-electric actuators allowing  
146 remote control for fine alignment. To avoid light reflection on the beam pipe,  
147 the left and right subset of mirrors are oriented towards the detection spots on  
148 their respective sides.

149 Thanks to the larger radius at the entrance window, the photon detection system  
150 is located outside of the acceptance and concentrated on two aluminium disks  
151 on the left and on the right of the beam pipe. The detection planes support  
152 a total of 1952 Hamamatsu R7400U-03 photomultiplier tubes placed behind a  
153 light collection system made of Winston cones covered with aluminized Mylar  
154 foils. They are separated from the neon by 1 mm quartz windows.

155 Similarly to the KTAG, the custom made amplifiers provide differential output  
156 signals, which are fed to 64 front-end boards. Each of these accommodates 32  
157 channels and uses 4 NINO ASIC chips in time-over-threshold mode. The LVDS  
158 output signal is sent to TEL62 boards as already described in 2.1. The readout  
159 is performed by four TEL62 and a fifth one is used to generate level-0 primitives  
160 using the digital OR of 8 channels provided by the NINO chip.

### 161 *3.1. Performance*

162 The RICH was fully commissioned during the 2014–2015 run. A sample of  
163 positive pions from  $K^+ \rightarrow \pi^+\pi^0$  is selected. A  $\pi^0$  is reconstructed using the  
164 information from the LKr and the missing mass of the charged track must cor-  
165 respond to the  $\pi^+$  mass. Detected photons belonging to the same Cherenkov  
166 ring are divided into two groups and the time difference of the average between  
167 the two groups is plotted. The ring time resolution is  $\sim 70$  ps, half the sigma  
168 of that curve. The average number of detected photons varies between 8 and  
169 16 as a function of the track momentum.

170 A preliminary mirror alignment was performed with a laser after their instal-  
171 lation. However, a fine alignment should be performed using data. The Straw

172 spectrometer was not fully operational in 2014 and could not provide tracking,  
 173 delaying the mirror fine-tuning to the 2015 run. The track properties are mea-  
 174 sured in the Straw detector and the expected ring centre ( $p_{\text{track}}$ ) in the RICH is  
 175 predicted by extrapolating the track position on the mirror plane. The position  
 176 of the centre of the ring ( $p_{\text{fit}}$ ) is fitted from the RICH hits. The track and ring  
 177 are matched by requiring the distance between these two positions to be smaller  
 178 than 20 mm

$$d_{\text{fit-track}} = |p_{\text{fit}} - p_{\text{track}}| < 20 \text{ mm}$$

179 The mirror fine alignment is performed by minimising  $d_{\text{fit-track}}$  for the rings  
 180 that are fully contained in a single mirror.

181 During the 2015 run, the RICH showed a good separation between pions, muons  
 182 and electrons in the range of interest ( $15 < p < 35 \text{ GeV}/c$ ) as seen in Figure 3.  
 183 It has been assessed that the RICH reached a muon rejection factor of 50 and  
 184 a pion detection efficiency of 83%. The ring radius resolution is dominated by  
 185 the mirror alignment and a final alignment campaign foreseen in 2016 will push  
 186 the RICH to its design efficiency.

#### 187 4. Conclusion

188 The NA62 experiment uses two Cherenkov detectors for particle tagging and  
 189 identification. The KTAG detector is an upgrade of a differential Cherenkov de-  
 190 tector (CEDAR West) whose purpose is to tag 45 MHz of charged kaons in a  
 191 beam of 750 MHz of particles with 100 ps time resolution. The RICH provides  
 192 separation between pions and muons in the momentum range between 15 and  
 193 35  $\text{GeV}/c$  with a similar time resolution.

194 The installation of both detectors has been completed. A first data taking  
 195 campaign was performed in 2014–2015 during which these detectors were com-  
 196 missioned. The displayed performance in terms of time resolution, identification  
 197 efficiency or contamination either reached the design values or was close to the  
 198 expectations but some improvements are still possible during the upcoming runs.

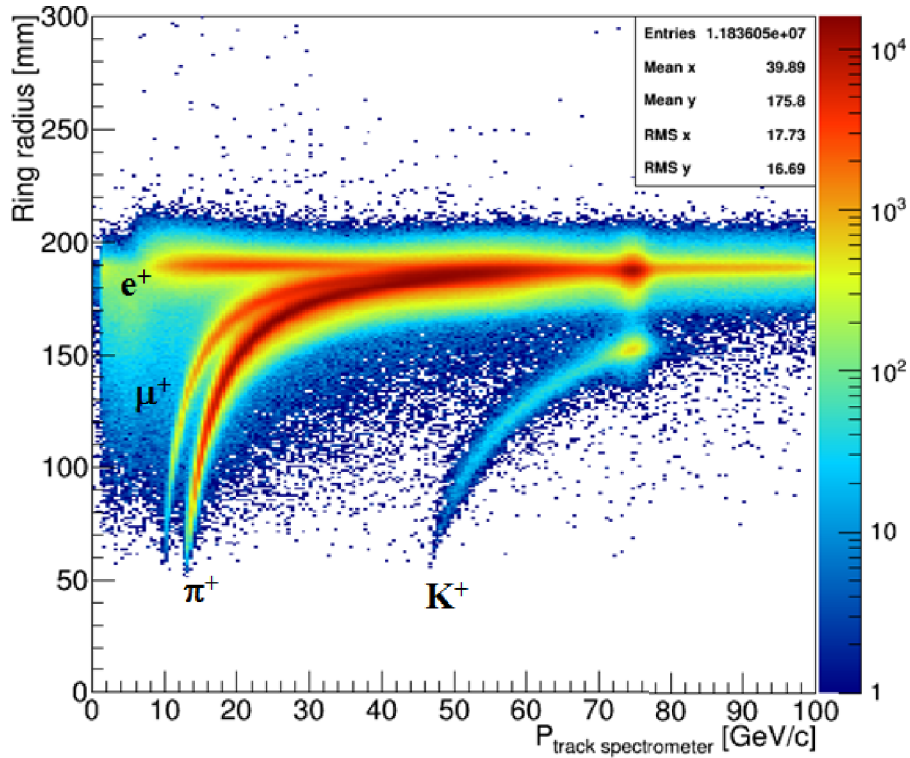


Figure 3: Track distribution as a function of reconstructed momentum and fitted ring radius. The RICH shows good separation between particles in the range  $15 < p < 35$  GeV/c. A small beam component can also be observed at 75 GeV/c

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