The NA62 Hadron Calorimeter

Riccardo Aliberti
Johannes Gutenberg Universitat - Mainz
E-mail: aliberti@uni-mainz.de

Abstract. NA62 is a fixed target experiment located in the north area of CERN. The ambitious aim of the experiment is the measurement of the branching ratio ($Br$) of the very rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ within 10% precision using a decay-in-flight technique. The branching ratio of this decay is very well calculated in the standard model as $(9.11 \pm 0.72) \times 10^{-11}$ and the measurement of this channel represents one of the most promising fields for the search of new physics beyond the standard model. The presence of just one detectable track in the final state is an enormous challenge for any experiment. The decay is fully reconstructed, which leads to a strong background suppression. Still the detector resolution, combined with the tiny branching ratio of the signal, makes the $K^+ \rightarrow \mu^+ \nu$ decay (whose $Br$ is 0.64) a critical source of background. The NA62 detector was therefore designed to perform an excellent $\pi/\mu$ separation using a very efficient particle identification system. A major role is played by the calorimeters that provides a muon rejection factor of the order of $10^5$ through the measurement of energy and shape of the hadronic showers. The calorimetric system consists of an electromagnetic calorimeter filled with liquid krypton and a hadron calorimeter. This presentation, after illustrating the HAC structure, reports on the calibration procedure of the detector response and preliminary results of the performance of the hadronic energy reconstruction.

1. Introduction

NA62 is a fixed target experiment located at the North Area of the European Center for Nuclear Research (CERN). The proton beam from the SPS accelerator is used to produce a secondary hadron beam and perform flavor physics studies mainly in the charged kaon sector. NA62 is the successor of the NA48\cite{1} experiment and acquired for the first time data in 2007\cite{2} using the same beam line and apparatus as in NA48. Starting from 2008 the experiment underwent an intense phase of R&D and construction of a almost completely new apparatus. The new detector was optimized for the precise measurement of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ branching ratio and in 2014/2015 has taken data for the first time.

2. The Search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

The rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is a Flavor Changing Neutral Current (FCNC) process dominated by short distance interactions and therefore highly suppressed. The clean theoretical environment allows to have a precise computation within the standard model (SM) to $Br_{SM}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11}$\cite{6}, where the main sources of uncertainty are the CKM matrix parameters. Many theoretical models of physics beyond the SM predict deviations for this branching ratio. The high sensitivity of this process to the existence of new leptons or heavy mesons up to the 100 TeV scale makes it a golden channel in the search of physics beyond the SM. Only one previous measurement exists, the E787 and E949 experiments at Brookhaven National
Laboratories (BNL) obtained $Br_{exp} = (17.3^{+11.3}_{-10.5}) \times 10^{-11}$ \cite{7,8}. The measurement is based on the observation of 7 candidate events and the uncertainty does not allow to precisely probe the standard model validity.

3. Measurement Strategy and NA62 Apparatus
The aim of the NA62 experiment is to collect around 100 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ signal events until end of 2018 in order to measure the branching ratio with 10% accuracy \cite{9,10}. The experiment plans to collect in total $10^{13}$ kaon decays using the 400 GeV/c proton beam from the CERN SPS accelerator. Assuming a 10% acceptance the background signal ratio should be kept below 20% to achieve the design sensitivity. This implies a background suppression at the level of $10^{12}$ \cite{11}.

The tiny branching ratio combined with the weak signature of the signal makes the rejection of the main $K^+$ decay modes very challenging. The keys to achieve the foreseen sensitivity are: the rejection of beam induced background, a precise measurement of kinematics, an efficient particle identification and a hermetic photon detection.

![Figure 1. The NA62 apparatus](image)

**Beam induced background**  The 400 GeV protons beam from SPS impinge on a Beryllium target resulting in a secondary hadron beam which reaches the experiment with a central momentum of $(75 \pm 0.8)$ GeV/c. The kaons represent 6% of the total 750 MHz particle rate. The remaining components are protons (10%) and pions (74%). A Cherenkov detector filled with Nitrogen (Cedar) provides the kaon identification with 100 ps resolution. The precise timing from the Cedar allows to reject $\pi^+ \rightarrow \mu^+ \nu$ that could mimic the signal. A series of scintillator arrays (CHANTI) around the beam line are used to veto the interaction of particles inside the beam spectrometer.

**Measurement of the Decay Kinematics**  The suppression of background from the reconstruction of kinematic variables is required to be at the level of $10^{-5}$ on the main kaon decays. Precise measurements of both $K^+$ and $\pi^+$ directions and momenta with a sub-percent resolution are performed by two spectrometer systems. The beam spectrometer Gigatracker (GTK), placed right after the Cedar detector, is composed by three, 300 $\mu$m thick, silicon pixel stations. The GTK faces the full beam rate and for this reason the timing performances are crucial, the single hit time resolution is at the level of 200 ps. A magnetic spectrometer is used to track the kaon decay products. It is composed of 4 stations of straw tube chambers resulting in a relative momentum resolution ($\sigma_p/p$) better than 0.3%. The combined data from the GTK and STRAW detectors allow a reconstructed vertex resolution at the mm level. The last station of the GTK define the start of the fiducial decay region, which ends at the first station of the STRAW tube spectrometer.

**Particle Identification**  The kaon decay $K^+ \rightarrow \mu^+ \nu$ with a branching ratio of $63.6\%$ \cite{12} represents the main background source for the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ measurement. In order to keep this
background under control a muon suppression factor of $10^8$ is required. The NA62 detector has been designed in order to provide a very efficient Particle Identification (PID). The system includes a Ring Cherenkov detector (RICH), 17 m long, filled with Neon and a system of calorimeters which allows to disentangle $\pi/\mu/e$ by studying the energy share between the electromagnetic calorimeter (LKr) and the hadron calorimeter (HAC). Following a 80 cm thick iron wall a fast muon veto (MUV3) provides an online veto trigger with a 300 ps time resolution.

**Photon Veto** A hermetic coverage of the experiment against photons is fundamental to veto all the kaon decays containing a $\pi^0$ in the final state ($Br \sim 30\%^{[12]}$) with an efficiency at the level of $10^{-8}$. The NA62 experiment is equipped with three different type of detectors devoted to the photon detection from 0 up to 50 mrad: 12 stations of Large Angle Veto (LAV), an electromagnetic calorimeter (LKr) and two Small Angle Vetoes (IRC and SAC) for photons down to 0 mrad.

4. **The Hadron Calorimeter (HAC)**

The Hadron Calorimeter is a sampling calorimeter using iron as absorber material. It counts in total almost 8 interaction lengths, presenting therefore minimal energy losses even for pions of momenta beyond 100 GeV/$c$, divided in two independent modules. The front module was newly built for the NA62 experiment with a fine transverse segmentation in order to better disentangle hadronic and electromagnetic shower components. The back module is the front module of the old NA48 hadron calorimeter. Each of the two modules present 24 iron planes interleaved with scintillators in alternated horizontal and vertical orientation. The strips covering the same area are read out by the same photomultiplier. In the front most of the strips span the full detector width. Wave length shifting fibers are used to readout the scintillators on both ends. The transverse segmentation of the front module is 6 cm.

Each scintillator strip in the back module covers half of the detector width and they are therefore readout on one side only. The light collection in the back module is performed via light guides and the transverse segmentation is 6 cm.

5. **HAC Calibration**

The performances required for the hadron calorimeter can only be achieved after a precise calibration of the detector response. The calibration procedure consists of four different steps: photomultiplier gain equalization, correction for attenuation inside the scintillators, estimation of the energy scale from muon pulses, and determination of pion energy corrections.

**Gains Equalization and Attenuation in Scintillators** The adjustment of the gain is performed channel-by-channel by a scan of the supply voltage during the data taking with a muon-based trigger. The single channel response to muon pulses is evaluated as a function of the supply voltage. A major role in the energy resolution of the HAC is played by the correction for the impact point of the particle. To precisely determine the scintillator contribution dedicated runs with only muon tracks are performed. The tracks reconstructed in the STRAW spectrometer are extrapolated to and matched with the HAC. The distribution of the charge collected as a function of the position is then parameterized with a double exponential function to take in account reflections inside the scintillators. Figure 2 shows the effect of the impact point corrections on charge collected in muon events for the front (left) and the back module (right).

**Energy Scale** The absolute energy scale for the calorimeter is determined independently for the two modules by fitting the collected charge distribution with a Landau function convoluted with a gaussian. The landau distribution describes the energy deposition by minimum-ionizing particles, while the gaussian is used to parameterized the smearing effect from the resolution.
Figure 2. Charge collected by the front (left) and back (right) module when crossed by a muon. The charge distributions are shown before (solid) and after (dashed) the impact point correction.

The energy scale is derived by dividing the peak of energy deposit from Monte Carlo simulation by the most probable value of the fitted landau distribution. The energy scale factors where estimated as 317 keV/pC for the front and 450 keV/pC for the back module.

Pion Calibration Front and back module of the HAC have slightly different structure which results in a different response to impinging pions. In particular the sampling fraction of the front module is almost twice bigger than for the back one. The consequence of the different structure is that the two modules have to be calibrated separately. The calibration is performed by analyzing dedicated MC simulations of \( K^+ \rightarrow \pi^+ \nu \bar{\nu} \) without the LKr and only one of the two HAC modules present. The ratio between the energy deposited in the calorimeter modules and the pion momentum is shown as a function of the momentum in figure 3.

Figure 3. Fraction of visible energy in the front (left) and back (right) HAC module for pions as a function of the momentum.

Showers from hadrons have a development which can vary between two extremes: a full electromagnetic and a full hadronic development. To estimate the contribution from the two components, a weighting parameter (W) was defined as the ratio between the sum of the energy collected in each channel squared and the total energy collected in the module squared: 
\[
W = \frac{\sum_i E_i^2}{E_{\text{mod}}^2}.
\]
A small weight indicates a dominance of the hadronic component while a weight parameter near to 1 an electromagnetic shower.

The scale factor for the visible pion energy takes into account the mean contribution by the hadronic and electromagnetic component and is applied dependently to the weight parameter following a Fermi-Dirac function as shown in equation 1.
\[ E_{\text{HAC Module Corrected}} = E_{\text{HAC Module}} + E_{\text{Invisible HAC Module}} \times (1 + F(W)) \] (1)

The calibration is checked in the data by applying the corrections in a step by step basis and verifying the improvement in terms of resolution and linearity of the response. On left of figure 4 it is possible to notice the improvement of the HAC response from before any correction (red line), after applying the visible energy correction (in blue) and after the modulation of the invisible energy correction by the weighting parameter (in green). The resolution was estimated as:

\[ \frac{\sigma_E}{E} = (0.115 \pm 0.003) \oplus \frac{0.38 \pm 0.05}{\sqrt{E}} \oplus \frac{1.37 \pm 0.17}{E} \] (2)

**Figure 4.** Linearity of the energy response (left) and energy resolution (right). In red before any correction, blue after visible energy scaling and green after the weighting correction. The red dotted line shows the fit to the energy resolution (see formula 2)

**Acknowledgments**

Thanks to the NA62 Collaboration for the support to this work.

**References**

[1] V. Fantini et al. (NA48 Collaboration), *Nucl. Instrum. Methods A* 574, 433 (2007).
[2] C. Lazzeroni et al. (NA62 Collaboration), *Phys. Lett. B* 719, 326 (2013).
[3] M. Gell-Mann and F. Zachariasen, *Phys. Rev. D* 124, 953 (1961).
[4] T. Husek and S. Leupold, *Eur. Phys. J C* 75, 586 (2015).
[5] T. Husek et al., *Phys. Rev. D* 92, 054027 (2015).
[6] A.J. Buras, D. Buttazzo, J. Girrbach-Noe and R. Knegjens, *JHEP* 1511, 33 (2005).
[7] S. Adler et al. (E949 and E787 Collaborations), *Phys. Rev. D* 77, 052003 (2008).
[8] S. Adler et al. (E949 and E787 Collaborations), *Phys. Rev. D* 79, 092004 (2009).
[9] G. Anelli et al., CERN-SPSC-2005-013; SPSC-P-326.
[10] NA62 Technical Design Document, NA62-10-07; https://cdsweb.cern.ch/record/14049857.
[11] G. Ruggiero (NA62 Collaboration), *PoS KAON* 13 032 (2013).
[12] C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016).