

# NA62 Experiment: Measurement of $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$

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**Abstract.** The NA62 experiment aims to measure the very rare kaon decay  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  at the CERN SPS. The expected branching ratio has been recently estimated within the Standard Model to be  $(8.22 \pm 0.84) \times 10^{-11}$ . From the experimental side, 7 events has been found by E787/949 experiments at BNL providing a measurement of the branching ratio of  $(1.73^{+1.15}_{-1.05}) \times 10^{-10}$ . The aim of NA62 is to collect  $\sim 100$  events in two years of data taking with a 10% background. A description of the setup and the R&D program is presented.

## 1. Introduction

The  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  decay is a flavor changing neutral current process which proceed through box and purely electroweak penguin diagrams. It is very clean theoretically because of the dominance of short distance dynamics.

This decay is one of the so called Golden Modes in Kaon decays in which a kaon decays into a pion and two leptons. During past years, branching ratio of these channels have been computed up to NNLO [1][2], and the hadronic matrix elements have been parametrized in terms of the  $K^+ \rightarrow \pi^0 e^+ \bar{\nu}$  branching ratios that is well known experimentally. The overall theoretical error obtained is of the order of 10% and is largely dominated by the relative poor knowledge of CKM matrix elements. The branching ratio expectations within Standard Model are presented in Table 1.

**Table 1.** Theoretical Predictions for Golden Mode decays

Decay	Short Distance Contribution	Branching Ratio	Reference
$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$	99%	$(2.76 \pm 0.40) \times 10^{-11}$	[2]
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	88%	$(8.22 \pm 0.84) \times 10^{-11}$	[2]
$K_L^0 \rightarrow \pi^0 e^+ e^-$	38%	$(3.54^{+0.98}_{-0.85}) \times 10^{-11}$	[1]
$K_L^0 \rightarrow \pi^0 \mu^+ \mu^-$	28%	$(1.41^{+0.28}_{-0.26}) \times 10^{-11}$	[1]

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ , together with  $K_L \rightarrow \pi^0 \nu \bar{\nu}$ , is then extremely sensitive to new physics contributions through contributions in the penguin loop. Within the SM, the mediator is basically the top quark. Precise measurement of this channel will allow a precise measurement

of the CKM parameter  $V_{td}$ , independent from B oscillation measurements. In case of the existence of new particles, such as for instance in the framework of supersymmetric models, new box- and penguin-diagram contributions involving particles as charged Higgs, charginos or stops can contribute significantly to any deviation of the measured branching ratios from SM expectations.

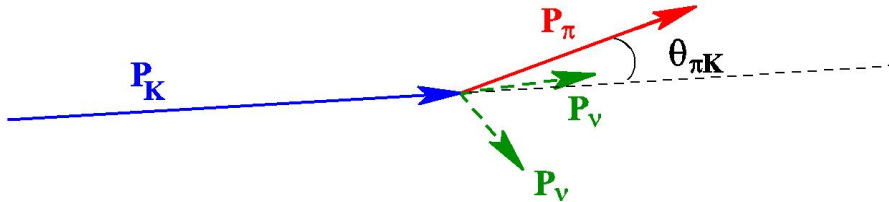
From the experimental point of view the existing measurement, based on 7 events from E787/949 experiments at BNL, is  $(1.73^{+1.15}_{-1.05}) \times 10^{-10}$  [3], compatible with the SM within errors. In order to provide a significative test of new physics scenarios, as well as an estimation of  $V_{td}$  a 10% accuracy measurement of the  $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$  are needed. This is precisely the goal of NA62 experiment at the CERN SPS, collect about 100 events in two years of data taking, keeping background contamination lower than 10%.

The experiment will be based on the NA48 apparatus and will use the same CERN-SPS beam line which produced the kaon beam for NA48. The experiment is being designed to reach  $10^{-12}$  sensitivity per event, exploiting a decay in flight technique. The detector requires a sophisticated technology for which an intense R&D program started in 2006. The flux of  $K^+$  will be about 2 orders of magnitude higher than for NA48, opening many other physics opportunities, specially in the field of radiative kaon decays. The status of the project, the R&D program and the perspectives of the experiment will be discussed.

## 2. Principle of the measurement

The principle of the measurement is based in the  $10^{12}$  rejection factor between the signal and the rest of  $K^+$  decays. This rejection factor is obtained with a decay in flight technique in which kinematical constraints and particle identification are combined.

The boost of the events will have two main effects: the first is that outgoing particles from decay will still have enough energy to be detected in the downstream detectors. The second is that the event will be mainly in the forward region, allowing to concentrate all instrumentation in this region leaving almost no dead zones.



**Figure 1.** Kinematics of  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  decay in NA62.

The signal topology (see Figure 1) is a three-body decay in which only the incoming track and one of the outgoing tracks can be detected. Reconstructing the square missing mass:

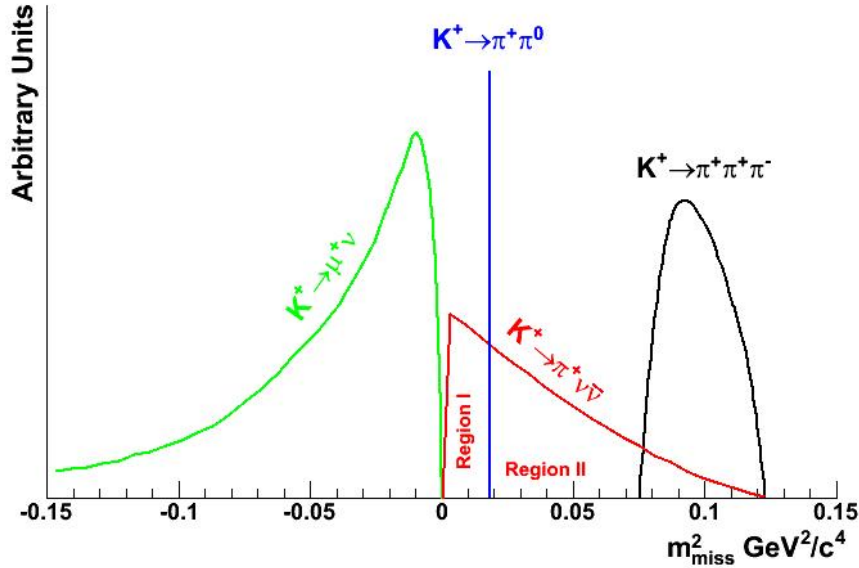
$$m_{miss}^2 \approx m_K^2 \left(1 - \frac{|P_\pi|}{|P_K|}\right) + m_\pi^2 \left(1 - \frac{|P_K|}{|P_\pi|}\right) - |P_K| |P_\pi| \theta_{\pi K}^2$$

will allow to define two kinematical regions where the two main backgrounds ( $K^+ \rightarrow \pi^+ \pi^0$ ,  $K^+ \rightarrow \mu^+ \nu$  and  $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ ) enter because of non-gaussian tails in the missing mass reconstruction.

- Region I:  $0 < m_{miss}^2 < m_{miss}^2 < m_{\pi^0}^2 - (\Delta m)^2$
- Region II:  $m_{\pi^0}^2 + (\Delta m)^2 < m_{miss}^2 < \min(m_{miss}^2(\pi^+ \pi^+ \pi^0)) - (\Delta m)^2$

where  $(\Delta m)$  depends on the  $m_{miss}^2$  resolution. This resolution has been estimated by simulation studies and is believed to be  $(\Delta m)^2 \simeq 8 \times 10^{-3} \text{GeV}^2/c^4$

In figure 2 is shown the definition of these regions as well as the expected contribution of main backgrounds. This kinematical reconstruction requires then a precise tracking of both the kaon beam and the decay pion. Then two spectrometers called kaon spectrometer and pion spectrometer should be available in the experiment.



**Figure 2.** Squared missing mass for Kaon decays defined as the square of the difference of 4-momentum of the kaon and the decayed particle with the hypothesis that it is a pion

Besides the kinematical rejection, that it has been estimated in the order of  $10^{-8}$ , particle identification based in a set of calorimeters for photon vetoes, muon identification and a RICH for positron, pion and muon will provide the required  $10^{12}$  rejection factor.

### 3. Experimental setup

NA62 experiment [4][5] is based on the expertise and the infrastructures created for NA48 experiment. Then NA62 will be at the same location as NA48 and will inherit part of the infrastructures, notably the secondary beam instrumentation, the 140 m long decay channel and the excellent calorimeters built for NA48. In order to suppress the main backgrounds, a new set of detectors are being developed. We can divide them in tracking detectors, particle id detectors and veto detectors. In figure 3 it is shown the layout of the NA62 beam line and detector.

Since 2006 beam time has been granted to the collaboration to test under beam conditions both different detectors prototypes and the feasibility of the kinematic fit. In order to prove this last, a measurement of the ratio

$$R_K = \frac{BR(K^+ \rightarrow e^+ \nu)}{BR(K^+ \rightarrow \mu^+ \nu)}$$

was proposed. A sample of 150k  $K^+ \rightarrow e^+ \nu$  candidates was recorded during years 2007 and 2008. With this sample an ongoing analysis will allow to determine this ratio better than 0.5%. A fully description of the method and preliminary results can be found in reference [6].

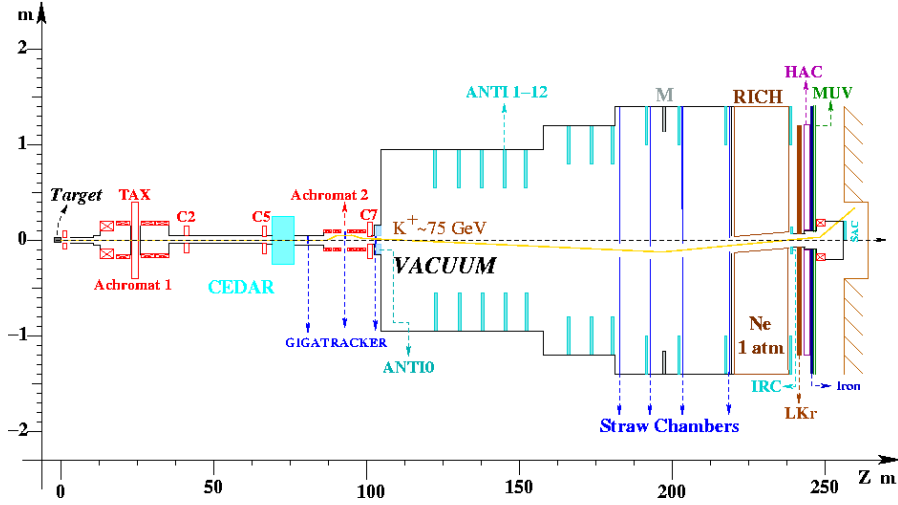


Figure 3. NA62 experiment layout

### 3.1. Beam line

Beam chosen for the experiment is an intense 400 GeV/c protons from SPS ( $3.3 \times 10^{12}$  protons/pulse) impinging on a Be target. A 102 m long beam line will select 75 GeV/c momentum of positive hadrons with a narrow acceptance of  $\sim 1.2\% \Delta p/p$ . Beam will be composed by 6% of  $K^+$ , 23% of protons, 70% of  $\pi^+$ , 1% of muons and less than 0.01% of positrons. With respect to NA48 beam, the incoming proton beam will be 3 times more intense and the magnetic acceptance will be 30 times larger. All these improvements in the beam line will give a factor 50 more kaons in the proposed configuration with respect to NA48 beam. The expected rate at different detectors will be  $\sim 800$  MHz in those located in the beam line and  $\sim 10$  MHz for those around beam line in the decay channel. A total of  $4.5 \times 10^{12}$   $K^+$  decays are expected per year, assuming 100 days of data taking with an overall efficiency of 60%. All these estimations are believed to be realistic based on the experience for more than ten years with NA48.

### 3.2. Decay Vacuum Tank

One of the main elements of the experiment is the 140 m long decay vacuum tank. In this tank the vacuum achieved can be better than  $6 \times 10^{-8}$  mbar. This low pressure in the decay tunnel will keep the background to less than one fake event per year. The vacuum system needed to achieve this vacuum is going to be upgraded. Inside this vacuum tank will be placed most of the detectors, notably the straw chambers of the pion spectrometer. The kevlar window present in the NA48 setup is going to be removed as well as the He gas surrounding the NA48 spectrometer.

### 3.3. Tracking detectors

Tracking will be assured by two spectrometers: the kaon spectrometer that will measure the incoming kaon beam and pion spectrometer that will measure the particles from kaon decays. Two new tracking detectors will be part of these spectrometers, the Gigatracker in the kaon spectrometer and the Straw Tracker in the pion spectrometer.

The Gigatracker is composed of three planes of pixel detectors of  $60\text{mm} \times 27\text{mm} \times 200\mu\text{m}$  composed by 18000  $300\mu \times 300\mu\text{m}$  pixels in 45 columns and readout by bump-bonded dedicated readout chips  $100\mu\text{m}$  thick. Together with four achromat magnets it will form the kaon spectrometer. This spectrometer will be placed just before the entrance of the decay vacuum

tank. The average particle rate impinging this detector is  $\sim 800$  MHz ( $\sim 50$  MHz/cm<sup>2</sup>). In order to track single particles in this beam, an overall temporal resolution of 200 ps is required. This requirement together with the limited material budget ( $< 1\%$   $X_0$ ) makes this device technologically quite challenging. For the readout two different readout chips have been designed and will be available in spring 2009 as well as the sensor. Beam tests to decide the final configuration will be performed at the end of 2009.

The pion spectrometer will be composed by four planes of straw chambers placed around two magnets. Each plane is composed by four views rotated 45 degrees each. Each view is composed by two layers of staggered planes of 9.6 mm diameter and a maximum length of 2.3 m. With this configuration any possible ambiguity can be removed. The assembly of the views will leave a hole of around 10 cm in to let pass the undecayed kaon beam. This region not covered will correspond to an acceptance loss of 10%. The rate due to beam halo is expected to be less than 10 MHz. Straw tubes walls are made by two layers of kapton with a total thickness of less than 40  $\mu$ m. These planes are going to be placed in the vacuum tank to reduce multiple scattering. R&D for this detector started in 2006 and since then, gas thickness has been proved. In 2007 a prototype was tested at the NA48/2 beam line and in 2008 a prototype with the final mechanics was placed in the beam.

### 3.4. Particle identification

CEDAR is a differential Cerenkov detector built in the 70's to be used with the SPS secondary beams. NA62 is going to use one of these CEDAR with two changes: use of H instead of He as radiator and provide them with new photon detectors (SiPM) and readout electronics. This detector will tag incident  $K^+$  with a rate of 50MHz.

A Ring Imaging Cerenkov (RICH) will be placed in the decay channel after the magnetic spectrometer and just before the end of tunnel calorimeters. It will be composed of a He radiator 17 m long and a segmented mirror that will reflect Cerenkov light to two focal planes equipped with  $\sim 2000$  1 cm diameter photomultipliers. It will detect cerenkov light of pions with an energy greater than 10 GeV, and will allow to separate pions and muons up to 35 GeV.

### 3.5. Veto detectors

The veto system is composed by a series of calorimeters that are going to assure photon detection in order to suppress backgrounds down to 10%. The system is going to cover the forward region up to 50 mrad. Some of the calorimeters as the Liquid Krypton has been inherited from NA48, while other calorimeters like the Large Angle Veto will be constructed to assure NA62 hermeticity.

A set of calorimeters (IRCs,SAC) located at the end of the vacuum tank and built with the shashlyk technology will cover the region below 1 mrad. As only photons with an energy greater than 10 can illuminate this region inefficiencies lower than  $10^{-5}$  can be achieved.

The NA48 Liquid Krypton calorimeter is going to be used as photon veto covering the region between 1 and 10 mrad. It's located in the end of the decay channel. The inefficiency of this calorimeter has been measured and is lower than  $10^{-5}$  for photons with an energy greater than 10 GeV. The readout electronics of this calorimeter is going to be updated in order to make it compatible with the DAQ foreseen for NA62.

Large Angle Veto (LAV) consist of a set of 12 rings made with the lead glass crystals from OPAL electromagnetic calorimeters. These vetoes will cover the region between 10 and 50 mrad. The rings will be located along the length of the vacuum tank and they should assure photon detection down to 50 MeV with less than  $10^{-4}$  inefficiency. First prototypes of these detectors have been already tested on NA48 beam in 2008.

In order to identify muons a 6 meters long hadronic sampling calorimeter is located after the Liquid Krypton calorimeter. It can reject muons with an inefficiency of  $10^{-5}$

#### 4. Conclusions

NA62 is going to measure the rare decay  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  at the CERN-SPS with a 75 GeV/c  $K^+$  beam. This experiment is the continuation of NA48, and it uses the existing infrastructures built for it. NA62 expects to collect  $\sim 100$  events in two years of data taking with less than 10% contamination. An intensive R&D program has been set up to reach the  $10^{-12}$  sensitivity per event needed. Since 2006, different test beams have allowed the collaboration to test innovative detector prototypes and prove the validity of the kinematical measurement collecting 150.000  $K^+ \rightarrow e^+ \nu$  decay candidates that will determine the ratio  $R_k$  better than 0.5%.

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