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The NA62 experiment at CERN for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

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The NA62 experiment to measure the branching ratio of the very rare kaon decay $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ at the CERN SPS is described. The proposed experiment aims to collect about 100 $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ events with a 10% of background. The status and the future perspectives for the experiment are discussed.

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1. Introduction

Among the many rare FCNC K and B decays, the rare decays $K \to \pi\nu\bar{\nu}$ play a key role in search for new physics through underlying mechanisms of flavour mixing. The SM branching ratio, in fact, can be computed to an exceptionally high degree of precision, thanks to the $O(G_F^2)$ electroweak amplitudes which exhibit a power-like GIM mechanism. The top-quark loops largely dominate the matrix element and can be computed with negligible theoretical uncertainty. The subleading charm-quark contributions affecting the $K^+ \to \pi^+\nu\bar{\nu}$ have been computed at NNLO order [1] and the irreducible uncertainty amounts to less than 3% on the amplitudes. This contribution and the knowledge of m_c are basically the only sources of theoretical uncertainties for the K^+ mode, since the hadronic matrix element can be extracted from the $K^+ \to \pi^0 e^+ \nu$ decays [2], whose branching ratio is well known experimentally [3]. The SM value is $(8.5 \pm 0.7) \times 10^{-11}$, where the error comes mainly from the experimental uncertainty of the CKM matrix element V_{td}. The extreme theoretical cleanness of these decays remain also in new physics scenarios like Minimal Flavour Violation (MFV) [4] or non-MFV models [5] and even not large deviations from the SM value (for example around 20%) can be considered clear signals of new physics.

The decay $K^+ \to \pi^+\nu\bar{\nu}$ has been observed by the stopping kaon experiments E787 and E949 at the Brookhaven National Laboratory and the corresponding measured branching ratio is $1.73^{+1.15}_{-1.05} \times 10^{-10}$ [6]. However only a measurement of the branching ratio with at least 10% accuracy can be a significative test of new physics. This is the main goal of the NA62 experiment at CERN-SPS [7, 8]. It aims to collect about 100 $K^+ \to \pi^+\nu\bar{\nu}$ events in about two years of data taking, keeping a background contamination around 10%.

2. The NA62 experiment

The NA62 experiment will be housed in the CERN North Area High Intensity Facility (NAHIF) where the NA48 [9] was located. It will use the same SPS extraction line and target of NA48 and a new high acceptance beam line will deliver a 50 times more intense secondary hadron beam of positive charge. The R&D of the experiment, started in 2007, will finish at the end of 2009. The construction of the apparatus will start in 2010 and the beginning of the data taking is foreseen in 2012-2013.

Figure 1 shows the layout of the experiment. The requirement of 100 events needs to 10% signal acceptance and at least to 10^{13} kaon decays. The required signal to background ratio demands a background suppression factor of at least 10^{13}. A high energy kaon beam and a decay-in-flight technique are the principles of the experiment. The decay-in-flight technique, in particular, should guarantee a suppression of the beam-induced background which mainly limits the accuracy of the stopping kaon experiments.

An intense 400 GeV/c proton beam, extracted from the SPS, produces a secondary charged beam by impinging on a Be target. A 100 m long beam line selects a 75 GeV/c momentum beam with 1% RMS momentum bite and an average rate of about 800 MHz integrated over an area of 14 cm^2. The beam is positron free and is composed by 6% of K^+. A system of subdetectors placed about 100 m downstream to the beginning of the decay region provides the detection of the K^+ decay products. The average rate seen by the downstream detectors integrated on their surface

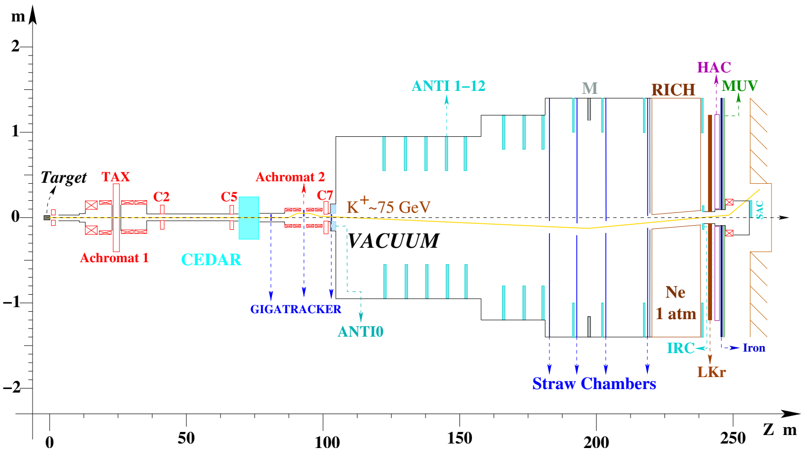

Figure 1: Layout of the experiment.

is ∼11 MHz. This rate is due to kaon decays and accidentals coming from the beam line. The described beam line provides 5×10^{12} K^+ decays, assuming 60 m decay region and 100 days of run at 60% of efficiency, which is a very realistic estimate based on the decennial NA48 experience at the SPS.

The key points of NA62 are: an accurate kinematic reconstruction to disentangle the signal; a precise timing to associate the π^+ with its K^+ parent; a system of efficient vetoes to reject events with γ and μ; a particle identification system to identify the kaons in the charged beam and to distinguish π^+ from μ^+ and e^+ in the final state.

2.1 Kinematic Rejection

The signature of the signal is one reconstructed positive track in the downstream spectrometer and one in the beam spectrometer. The main kinematic variable considered is the squared missing mass, defined as $m^2_{miss} \equiv (P_K - P_{track})^2$, where P are the 4-momenta of the particles and the track is assumed to be a π^+. It separates the signal from more than 90% of the background coming from K^+ decays, as shown in Figure 2. The signal can be selected in two regions almost background-

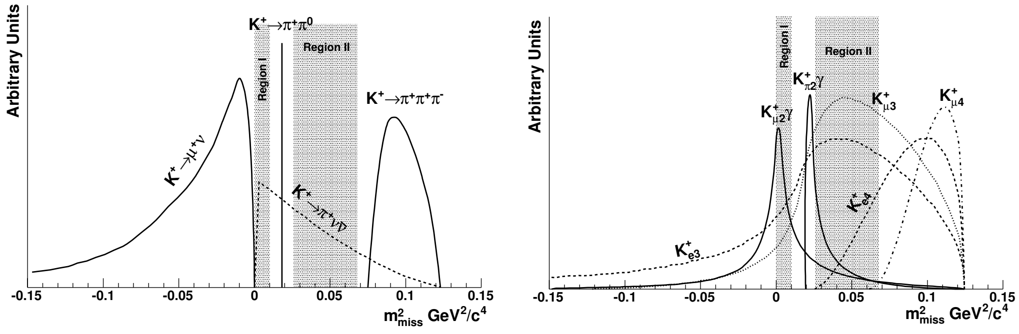

Figure 2: Squared missing mass for Kaon decays.

free divided by the $K^+ \rightarrow \pi^+\pi^0$ peak. Background may enter in the signal regions because of the finite resolution of the reconstructed kinematic thresholds. As a consequence low mass and high precision detectors placed in vacuum are required for the tracking. The very high rate in the beam detector (800 MHz) requires to associate the incoming kaon to the downstream pion track by means of tight spatial and time coincidences. Any mismatch between them, in fact, causes a loss of kinematic rejection power. A Cerenkov Threshold Counter (CEDAR) placed on the beam line, the beam tracker itself and a RICH, provide the timing of the experiment. Notably the beam tracker must reconstruct the beam tracks with at least 200 ps time resolution.

The designed beam spectrometer, called Gigatracker, consists of three Si pixels stations $60 \times 27\,\text{mm}^2$, made up by $300 \times 300\,\mu\text{m}^2$ pixels each of them composed by a $200\,\mu$m thick Si sensor. A sophisticated readout chip $100\,\mu$m thick constructed with a 0.13μm technology and bump-bonded on the sensor guarantees the requested time resolution. The total material budget amounts to less than 0.5% radiation length per station. Dedicated radiation damage tests on sensor prototypes proved the usage of this detector at an average rate of 60 MHz/cm^2.

Straw Tube is the building technology for the pion spectrometer. Four chambers placed in the same vacuum of the decay region form the detector. Each chamber includes four view-planes rotated by 45 degree one to another. Four staggered planes of straw tubes 2.1 m long form one view-plane. It provides the measurement of the coordinate of the impact point of the track perpendicular to the axis of the tube. A region free of tubes, 12 cm large, in the middle of each view-plane form an octagonal hole in each chamber where the intense charged beam of undecayed particles pass through. The NA48 dipole magnet, placed after the second chamber, gives a 256 MeV/c momentum kick in the horizontal plane to allow the momentum measurement. The chambers are displaced in the bending plane according to the 75 GeV/c positive beam path. A full length view-plane prototype has been successfully tested in vacuum on the NA48 beam line in 2007. It showed that the single coordinate can be reconstructed with a resolution better than 100 μm.

A Geant4 [15] Monte Carlo simulation predicted a resolution on kaon momentum of about 0.2%, on kaon direction of about 15 μrad, on pion momentum of about $0.33\% \pm 0.007\% \times P_{track}$ and on pion direction between 45 and 15 μrad. The expected kinematic rejection power against $K^+ \rightarrow \pi^+\pi^0$ and $K^+ \rightarrow \mu^+\nu_\mu$ decays is about 10^4 and 10^5, respectively. The limitation comes from the non gaussian multiple scattering in the detector materials and from a possible K^+-π^+ mismatching.

2.2 Vetoes

The kinematic rejection alone cannot provide the requested level of background suppression. An additional factor may come from γ and μ detection. Notably the $K^+ \rightarrow \pi^+\pi^0$ rejection drove the design of the photon veto system, giving a requirement of about 10^{-8} inefficiency for π^0 detection. The detectors designed for this purpose are: a system of calorimeters (LAV) covering the angle region between 10 and 50 mrad; an electromagnetic calorimeter for γ detection between 1 and 10 mrad, and a small angle calorimeter built with a shashlik technology covering the region below 1 mrad.

The key points to fulfill the experimental goal are: a cut at 35 GeV/c on the maximum π^+ momentum at analysis level to deal with π^0 of at least 40 GeV/c as a consequence of the 75 GeV/c kaon momentum; a detection inefficiency below 10^{-5} for γ's in the 1-10 mrad region above 10 GeV and, anyhow, within 10^{-3} for γ down to 1 GeV.

The electromagnetic calorimeter at liquid Kripton of NA48 will cover the 1-10 mrad region. Its inefficiency for single γ detection above 2.5 GeV has been measured on data collected by NA48/2 in 2004 and during a test beam in 2006 and found in perfect agreement with the requirements [8].

Twelve rings 50 cm thick surrounding the NA62 decay and detector regions and placed in vacuum form the LAV system. Each ring is made up of 5 staggered modules of lead glass blocks coming from the electromagnetic calorimeter of the dismantled LEP experiment OPAL [10]. Test beams performed at the Dafne Beam Test facility in Frascati provided a measurement of the lead glass block inefficiency for 471 MeV e^+ detection at 10^{-4} level, well suited for the NA62 purposes. A sector prototype was tested successfully in vacuum at CERN along the NA48 beam line in 2008. The first ring has been already mounted and will be tested at CERN at the end of 2009.

The muon detection system will make use of an upgraded version of the hadronic calorimeter of NA48 plus two planes of fast scintillators placed at the end of the apparatus after an iron wall. Monte Carlo simulations predicted an inefficiency of muon detection around 10^{-5}, achievable by exploiting the electromagnetic and hadronic shower separation capability of the hadronic calorimeter together with the LKr detector.

2.3 Particle Identification

The kinematic rejection and the muon veto alone, still cannot provide the rejection of backgrounds like $K^+ \to \mu^+ \nu_\mu (\gamma)$. A particle identification system different to the calorimeters must give the missing 10^2 factor in the background rejection.

A RICH has been designed to fulfill such a goal: it should separate π^+ from μ^+ with inefficiency below 1%. It must also provide the timing of the event with a resolution below 100 ps and it should be used as the main trigger of 1 track events. A vessel 17 m long placed after the pion spectrometer and filled with Ne at atmospheric pressure forms the detector. The vessel has a cylindrical shape around a 17 cm diameter beam tube used to let the undecayed particles to pass through in vacuum. A mosaic of mirrors at the end, having 17 m focal length, reflects the Cerenkov light towards two arrays of about 1000 phototubes each, placed on both the sides of the vessel at the entrance window. Hamamatsu phototubes of 1.8 cm diameter guarantee a quantum efficiency and time performances which fit the requirements.

A full length prototype of 50 cm diameter equipped with 96 phototubes has been tested at CERN on a 200 GeV hadron beam in 2007. About 17 optical photons per event were collected and the time resolution of a track was measured around 70 ps [11]. The same prototype equipped with 400 phototubes was tested at the SPS in 2009 on an hadron beam with momentum between 20 and 70 GeV/c. During this test a system formed by HPTDC's [13] mounted on one TELL1 board [12] was used for data acquisition. This apparatus has been developed by the NA62 collaboration itself in the framework of the NA62 trigger and DAQ R&D project [8]. The preliminary analysis of the data showed that a π^+/μ^+ separation with the requested purity can be reached in the 15-35 GeV/c momentum range.

2.4 Sensitivity

A preliminary analysis has been done using Geant3 [14], Geant4 and Fluka [16] based simulations. The total acceptance is about 14.4%, showing that the target of 10% of signal acceptance is safely achievable even taking into account additional losses occurring in a real data taking. The use of the RICH constrains the accepted pion tracks within the $(15,35)$ GeV/c momentum range. The higher cut is an important loss of signal acceptance, but assures that events like $K^+ \to \pi^+ \pi^0$ deposit at least 40 GeV of electromagnetic energy, making their rejection easier.

Many sources of background have been considered and just a simple counting of signal and background events in the signal regions indicates that the 10% background appears to be within reach.

3. Conclusions

The ultra-rare $K \to \pi \nu \nu$ decay is a unique environment where to search for new physics. The NA62 experiment at CERN-SPS proposes to follow this road by collecting $O(100)$ events of the $K^+ \to \pi^+ \nu \bar{\nu}$ decay. The CERN Research Board approved the experiment on December 2008. After two years of successful R&D program, the NA62 collaboration is starting to build the experiment.

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