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S. Recksiegel, A. Hoang, S. Paul

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The NA48/3 Experiment at CERN

GiuseppeRuggiero
CERN
PH Department
Geneva, Switzerland

1 Introduction

The $K^+ \to \pi^+ \nu\overline{\nu}$ decay is a flavour changing neutral current process which proceeds through box and purely electroweak penguin diagrams. The short distance contributions largely dominate in the matrix element, while c-quark contributions have been evaluated at NNLO order giving an uncertainty of about 5% [1]. This is the only source of theoretical error because the hadronic matrix element can be parametrized in terms of the branching ratio of the $K^+ \to \pi^0 e^+ \nu$ decay, which is well known experimentally [5]. The computed value is $(8.0 \pm 1.1) \times 10^{-11}$, where the error is dominated by the uncertainty in the knowledge of the CKM matrix elements. Such extreme theoretical clarity, unique in K and B physics, makes this decay, together with the $K_L \to \pi^0 \nu\overline{\nu}$ decay, extremely sensitive to new physics contributions both in MVF and non-MFV scenarios [2–4]. As a by-product, it allows also a measurement of the CKM element V_{td} independent on the value extracted from B oscillation measurements.

Up to now 3 $K^+ \to \pi^+ \nu\overline{\nu}$ events have been observed [6], but a 10% accuracy measurement of the branchig ratio is required to provide a significative test of new physics scenarios. This is the goal of the proposed NA48/3 experiment at CERN-SPS [7]. It aims to collect about 80 $K^+ \to \pi^+ \nu\overline{\nu}$ events keeping the background contamination at the level of 10%.

2 The P-326 proposal

The NA48/3 experiment will be based on the NA48 apparatus at CERN and will make use of the same CERN-SPS beam line which produced the kaon beam for the NA48 experiment. The R&D program for this experiment, started in 2006, will continue in 2007. The data taking should start in 2010.

The layout of the experiment is shown in figure 1. The goal of the experiment can be achieved by exploiting a decay in flight technique which allows 10% signal

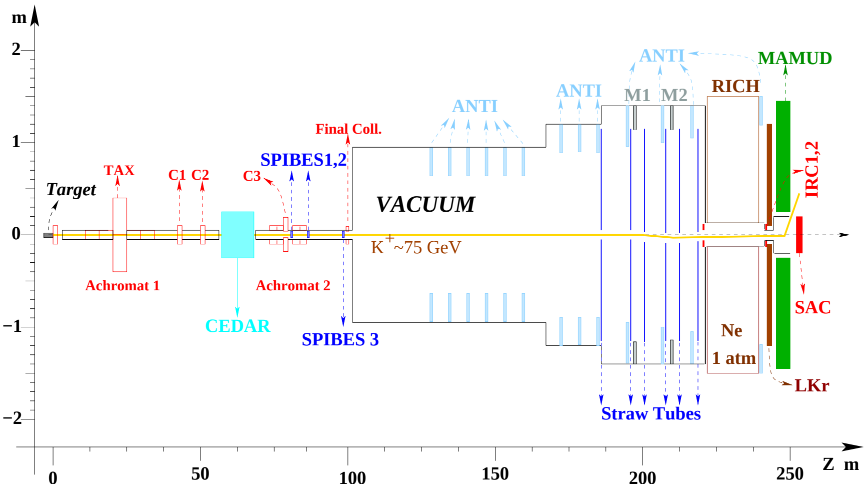

Figure 1: Layout of the experiment.

acceptance and by using a beam line able to provide of the order of 10^{13} kaon decays.

The experimental signature of a $K^+ \to \pi^+\nu\overline{\nu}$ is one reconstructed positive track in the downstream detector. A beam and a pion tracking detectors provide a precise reconstruction of the kinematics, since the squared missing mass allows a kinematical separation between the signal and more than 90% of the total background, as shown in figure 2. In particular two signal regions can be defined where the backgrounds from $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu_\mu$ enter only because of non-gaussian tails in the squared missing mass resolution. The kinematics alone cannot provide a 10^{13} background rejection. A system of calorimeters for photon vetoes, muon veto and a RICH for positron, pion and muon separation is designed to fulfill these needs. Moreover, the detector layout gives redundancy both in kinematics reconstruction and particle identification allowing the background estimation directly from data.

2.1 The beam line

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 16 cm^2. However, since the beam is composed by 6% of K^+ and 94% of π^+, e^+ and protons, the kaon decay rate downstream to the final collimator is only about 6 MHz. Some MHz of accidentals coming from the beam, mainly composed by muon, accompany the kaon decays, resulting in a total $\sim$11 MHz average rate seen by the downstream detectors integrated on their surface.

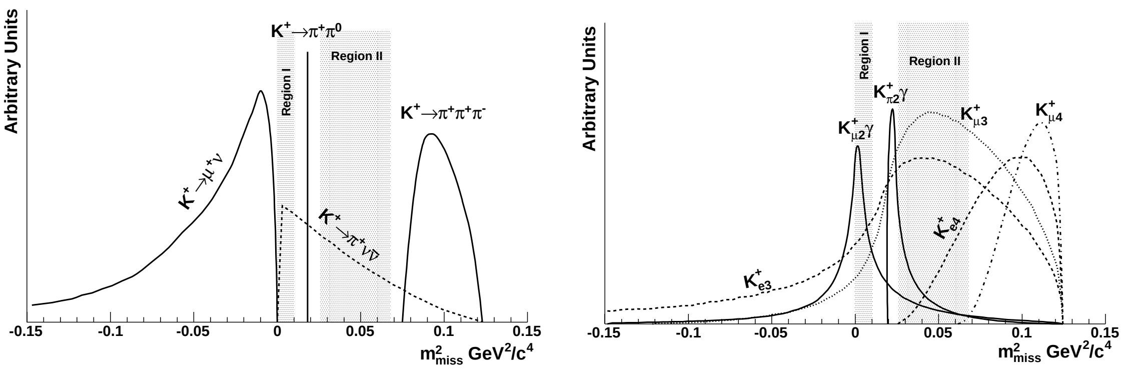

Figure 2: Squared missing mass for Kaon decays. The squared missing mass is defined as the square of the difference between the 4-momentum of the kaon and of the decayed track in the hypothesis that it is a pion.

Thanks to a significant increase of the secondary beam acceptance with respect to the beam used in NA48/2, the beam line is able to provide about 5×10^{12} K^+ decays in a 60 m decay region, in 100 days of run at 60% of efficiency, which is a very realistic estimate based on the decennial NA48 experience at the SPS. As a consequence the experiment will be able to collect $O(100)$ Standard Model events in two years of data taking.

Since the experiment uses an unseparated charged beam, a differential Cerenkov counter, the CEDAR [8], is required to provide the kaon identification. This detector is available at CERN, but upgrades are needed to adapt it to the new beam conditions. The R&D is started with a test beam run in November 2006, mainly devoted to the study of the timing capability.

The precise kinematical reconstruction requires a beam tracker highly performing in terms of time and spatial resolution and able to sustain a particle rate of about 60 $\mathrm{MHz\,cm^{-2}}$. To limit the amount of interactions one is faced with severe constraints on the material budget. The detector under study consists of three Si pixels stations $36 \times 48\,\mathrm{mm}^2$ large, made up by $300 \times 300\,\mu\mathrm{m}^2$ pixels each of them composed by a $200\,\mu$m thick Si sensor and a chip $100\,\mu$m thick, bump-bonded on the sensor and built using a $0.13\,\mu$m CMOS technology. The characteristics of the detector and a careful design of the readout chip should provide 200 ps time resolution per station, enough for an efficient tagging of the kaon track. A mis-tagging of the kaon, in fact, may be source of background because it spoils the kinematical resolution of the squared missing mass. The design of the readout chip and the project of a cooling system is under way. Radiation damage tests on sensor prototypes took place in 2006.

Downstream of the beam tracker, the decay region consists of the existing 80 m long iron tube of NA48. Tests performed in 2006 demonstrated that one is able to achieve a vacuum level of less than 10^{-5} mbar after a substantial improvement of the pumping system. Fluka [9] and Geant3 [10] based simulations showed that such a vacuum is enough to keep the background from the interaction of the particles with the residual gas at a fraction of one event.

2.2 The downstream detectors

Since the multiple scattering is the main limitation to the kinematics reconstruction, the minimization of the material budget is the driven parameter for the downstream spectrometer. As a consequence, the proposed detector is made by six straw chambers which can be placed directly in the same vacuum of the decay region. Two magnets space pairs of chambers, providing redundant measurements of the particle momentum. The R&D program is started in 2006 and a reduced-size prototype will be built for the end of 2007. Each chamber consists of tubes assembled in a way to ensure up to four views for a single hit reconstruction and the 36 μm thick mylar foil which forms the 1 cm diameter tubes allows the chamber thickness not to exceed 0.5% radiation lentgh. Moreover the overall resolution on hit position must be within 100 μm. Tests on gas leakage and tube expansion started in 2006 are in progress and preliminary results indicate no major problem in the use of the straws in vacuum, providing a suitable control of their mechanical stability. The layers must be packed to leave an octagonal 10 cm diameter hole in the middle of the chamber to let the intense undecayed beam to pass through. The center of each station must be displaced in the bending plane of the magnets according to the path of the 75 GeV/c positive beam. This arrangement allows the individual chambers to be used as a veto for negative particles up to 60 GeV/c, needed for the rejection of backgrounds like $K^+ \rightarrow \pi^+\pi^-e^+\nu$ and $K^+ \rightarrow \pi^+\pi^+\pi^-$. Each station will operate at about 45 KHz per tube on average, but, due to the beam halo, the region close to the hole will suffer up to 0.5 MHz rate.

A 18 m long RICH located after the spectrometer and filled with Ne at atmospheric pressure is the core of the particle identification. A 11 cm radius beam pipe crosses the RICH and two tilted mirrors at the end reflect the Cerenkov light toward an array of about 2000 phototubes placed in the focal plane. Because of the Cerenkov threshold, the RICH is able to identify pions with momentum greater than 15 GeV/c. Simulations showed that up to 40 photo electrons can be collected per track. Using phototubes of 1 cm diameter a better than 3σ separation for tracks with momentum below 35 GeV/c is achievable, where the size of the phototubes is the main limitation to the Cerenkov angle resolution. As a by-product the detector has also the function of an auxiliary spectrometer. The RICH must work also as a timing detector for the downstream track with a requested time resolution of 100 ps. The timing performances depend on the phototubes. To this purposes a set of phototubes were tested on a Cerenkov device during a test beam performed at CERN in November

2006. The construction and test of a full-length prototype of the RICH is planned for 2007.

A combination of calorimeters covering up to 50 mrad serves to identify the photons produced in kaon decays. Thirteen ring-shaped calorimeters cover the angular region between 10 and 50 mrad. They should guarantee the detection of photons down to 50 MeV with 10^{-4} inefficiency at most and must be placed in vacuum. Tests on prototypes of detectors built using lead scintillator tiles and scintillating fibers are scheduled for 2007 using a $\gamma-$tagged facility at LNF. Moreover tests on the out-gassing rate performed at CERN in 2006 showed the possibility to place these calorimeters directly in the high vacuum of the decay region. The existing NA48 liquid Kripton calorimeter (LKr) [11] covers the region between 1 and 10 mrad. A data analysis performed on $K^+ \to \pi^+\pi^0$ decays collected by NA48/2 in 2004 shows that the inefficiency of the LKr is lower than 10^{-5} for photons with energy greater than 10 GeV. A test run was performed in October 2006 at the SPS using the NA48 apparatus. This run used a well known momentum electron beam which passed through the NA48 apparatus, making photon bremsstrahlung in the detector material. These data allows the LKr inefficiency below 10 GeV to be addressed. First results indicate that the LKr matches our requests in terms of efficiency on the overall photon energy range. Finally a program of consolidation and update of the readout electronics of the LKr is under way. Two rings calorimeter (IRCs) around the beam pipe and a 20×20 cm^2 calorimeter (SAC) behind the muon veto cover the low angle region. Only photons with energy larger than 10 GeV/c illuminate these detectors, making a 10^{-5} inefficiency achievable. A SAC prototype based on shashlyk technology was built and tested with electrons on the NA48 beam line in 2006.

A 6 m long hadronic sampling calorimeter (MAMUD) provides a 10^5 rejection of muons. It is composed by 8 sections divided in 19 iron planes 2 cm thick separated by planes of extruded scintillators. The longitudinal shower development allows the separation between pion and muon. The detector should be used also as a fast trigger for muons. A 20×30 cm^2 aperture in the center lets the beam to pass through. Two coils provide a 5 Tm magnetic field integral in the hole to deflect the beam out of the acceptance of the SAC.

3 Performances

A preliminary analysis using Geant3 and Geant4 [12] based simulations of the apparatus gives an acceptance of about 17%, 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

	Total	Region I	Region II
Signal	65	16	49
$K^+ \to \pi^+\pi^0$	2.7	1.7	1.0
$K^+ \to \mu^+\nu$	1.2	1.1	< 0.1
$K^+ \to e^+\pi^-\pi^+\nu$	2	*negligible*	2
Other three track decays	1	*negligible*	1
$K^+ \to \pi^+\pi^0\gamma$	1.3	*negligible*	1.3
$K^+ \to \mu^+\nu\gamma$	0.4	0.2	0.2
K_{e3}, $K_{\mu3}$, others	*negligible*	–	–
Total background	8.6	3.0	5.6

Table 1: List of the expected signal events and the expected background events from kaon decays per year of data taking.

electromagnetic energy, making their rejection easier.

Main sources of background have been considered and the results per year of data taking are shown in table 1. Just a simply counting of the signal and background events in the signal regions indicates that the 10% background level is nearly achievable.

4 Conclusions

The ultra-rare $K \to \pi\nu\nu$ decay is a unique environment where to search for new physics. The NA48/3 experiment at CERN-SPS proposes to follow this road by collecting $O(100)$ events of the $K^+ \to \pi^+\nu\overline{\nu}$ decay. The overall experimental design requires a sophisticated technology for which an intense R&D program is started. Actually we are designing an experiment able to reach a 10^{-12} sensitivity per event employing existing infrastructures and detectors at CERN.

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