

R_K and $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ with NA62 at CERN SPS¹

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1 Introduction

In the Standard Model (SM) the decays of charged pseudo scalar mesons into lepton neutrino ($P^\pm \rightarrow l^\pm \nu$, denoted P_{l2}) are helicity suppressed. The SM allows a very precise determination of the ratio of P_{l2} decay amplitudes of the same meson in different lepton flavours, like $R_K \equiv \Gamma(K_{e2})/\Gamma(K_{\mu2})$. The prediction for R_K inclusive of internal bremsstrahlung (IB) radiation is [1] $R_K = (2.477 \pm 0.001) \times 10^{-5}$. Deviations of R_K from the SM require new physics models with sources of lepton flavour violation (LFV) [2, 3, 4]. The present PDG value [5] of R_K , $R_K = (2.488 \pm 0.012) \times 10^{-5}$, is largely dominated by the result of the analysis of a partial sample of the data set collected by the NA62 experiment at CERN in 2007 [6]. A new measurement of R_K based on the full data sample collected by NA62 is reported here (section 2).

Among the many rare flavour changing neutral current K and B decays, the ultra rare decays $K \rightarrow \pi \nu \bar{\nu}$ play a key role in the search for new physics through underlying mechanisms of flavour mixing. The SM branching ratio can be computed to an exceptionally high degree of precision. The prediction for the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ channel is $(7.81 \pm 0.75 \pm 0.29) \times 10^{-11}$ [8]. The first error comes from the uncertainty on the CKM matrix elements, the second one is the pure theoretical uncertainty. This decay is one of the best probe for new physics effects complementary to the LHC, especially within non Minimal Flavour Violation models [9, 10]. Since the extreme theoretical cleanness of these decays remains also in these scenarios, even deviations from the SM value at the level of 20% can be considered signals of new physics. Also, the decay can be used for a measurement of V_{td} free from hadronic uncertainties and independently from that obtained with B mesons decays. The decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ has been observed by the experiments E787 and E949 at the Brookhaven National Laboratory and the measured branching ratio is $1.73_{-1.05}^{+1.15} \times 10^{-10}$ [11]. However only a measurement of the branching ratio with at least 10% accuracy can be a significant test of new physics. This is the main goal of the NA62 experiment at CERN-SPS [12] (section 3).

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2 Measurement of R_K with NA62

The NA62 experiment at CERN collected data in 2007-08 for measuring R_K using the same beam line and experimental set-up of the NA48/2 experiment [13]. The experiment made use of a 400 GeV/c primary proton beam, extracted from the SPS accelerator at CERN and producing a secondary charged kaon beam after impinging on a beryllium target. A 100 m long beam line selected the momentum of the secondary beam to (75 ± 3) GeV/c. Finally the beam entered a decay volume, housed in a 100 m long vacuum tank. The detector was designed to see the products of the kaons decaying in the vacuum region. A magnetic spectrometer, consisted of four drift chambers separated by a dipole magnet, tracked the charged particles. An array of scintillators (hodoscope) gave the time reference for the other detectors and the main trigger for the event topologies including charged particles. A quasi-homogeneous electromagnetic calorimeter with liquid Krypton as active material (LKr) [7], was used mainly for particle identification.

The analysis strategy for measuring R_K is based on counting the numbers of reconstructed K_{e2} and $K_{\mu2}$ events collected concurrently. Consequently R_K does not depend on the absolute kaon flux and the ratio allows for a first order cancellation of several systematic effects, like reconstruction and trigger efficiencies and time dependent biases. The basic formula is:

$$R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu2}) - N_B(K_{\mu2})} \cdot \frac{A(K_{\mu2})f_{\mu}\epsilon(K_{\mu2})}{A(K_{e2})f_e\epsilon(K_{e2})} \cdot \frac{1}{f_{LKr}}. \quad (1)$$

Here $N(K_{l2})$ and $N_B(K_{l2})$ are the number of selected K_{l2} events and expected background events, respectively; D is the downscaling factor applied to the $K_{\mu2}$ trigger; $A(K_{l2})$ the geometrical acceptance of the selected K_{l2} mode; f_e and f_{μ} the identification efficiencies of electrons and muons, respectively; $\epsilon(K_{l2})$ the trigger efficiencies for the selected K_{l2} events; f_{LKr} the global LKr efficiency. A Monte Carlo simulation is used to evaluate the acceptance correction and the geometric part of the acceptances for most of the background processes. The beam halo background, the particle identification and the readout and trigger efficiencies are measured directly from data. Both f_l and $\epsilon(K_{l2})$ are well above 99%. The analysis is performed independently for 40 data samples (10 bins of reconstructed lepton momentum and 4 samples with different data taking conditions).

A large part of the selection is in common between K_{e2} and $K_{\mu2}$, because of the similar single-track topology. The event kinematics and the lepton identification, instead, are effective to separate K_{e2} and $K_{\mu2}$. The kinematic identification is based on the squared missing mass $M_{miss}^2 = (P_K - P_l)^2$, where P_K and P_l are the kaon and lepton 4-momenta respectively. The mean P_K is monitored on spill basis using fully reconstructed $K^+ \rightarrow \pi^+\pi^+\pi^-$ decays; P_l is computed in the electron or muon mass hypothesis. A cut on the M_{miss}^2 , according to the M_{miss}^2 resolution and dependent on the lepton momentum, selects the K_{l2} candidates.

The numbers of selected K_{e2} and $K_{\mu2}$ candidates are 145958 and 4.2817×10^7 , respectively. The total background is $10.95 \pm 0.27\%$. The $M_{miss}^2(K_{e2})$ and the background contamination as a function of lepton momentum are shown in figure 1.

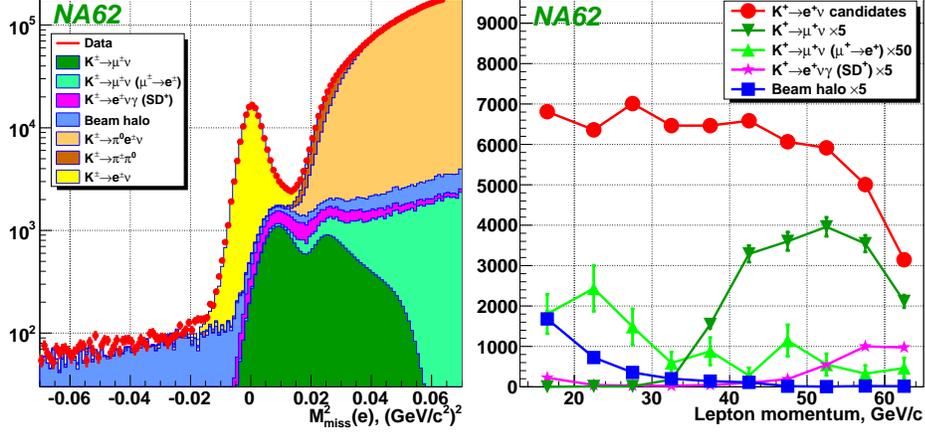


Figure 1: Left: reconstructed $M_{miss}^2(K_{e2})$ for K_{e2} and backgrounds. Right: lepton momentum distributions of the K_{e2} candidates and the dominant backgrounds.

The background is strongly momentum dependent. In particular for momenta higher than 35-40 GeV/c , the $K_{\mu2}$ with a muon mis-identified as a positron becomes the largest background source. A large energy loss as a consequence of a hard bremsstrahlung of the muon in or in front of the LKr is the dominant source of the muon-positron mis-identification. The corresponding probability is measured on data as a function of lepton momentum by making use of a set of data collected in 2007 with a $9.2 X_0$ lead bar in front of the LKr, covering about 20% of the total geometrical acceptance. This set-up allowed the collection of a muon sample free from electron contamination due to $\mu \rightarrow e$ decays.

The R_K value is extracted from a χ^2 fit to the measurements in the lepton momentum bins and data taking periods. The contributions to the systematic uncertainty include the uncertainties on the backgrounds, the acceptance evaluation, the beam simulation, the spectrometer alignment, the particle identification and the trigger efficiency measurement. The result is:

$$R_K = (2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5} = (2.488 \pm 0.010) \times 10^{-5}. \quad (2)$$

The result is consistent with the SM expectation and the achieved precision dominates the world average.

3 The measurement of the $\text{BR}(K \rightarrow \pi\nu\nu)$: future prospects at NA62

The goal for the future of the NA62 experiment is the measurement of the branching ratio of the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ decay with 10% precision. Therefore NA62 aims to collect of the order of 100 $K^+ \rightarrow \pi^+\nu\bar{\nu}$ events in about two years of data taking and to keep the total systematic uncertainty smaller than the statistical one. To this purpose, at least 10^{13} K^+ decays are required, assuming a 10% signal acceptance and a $K^+ \rightarrow \pi^+\nu\bar{\nu}$ branching ratio of 10^{-10} . The need of keeping the systematic uncertainty small requires a rejection factor for generic kaon decays of the order of 10^{12} and the possibility to measure efficiencies and background suppression factors directly from data. In order to match the above required kaon intensity, signal acceptance and background suppression, new detectors must replace the existing NA62 apparatus.

The same CERN-SPS extraction line already used for the R_K measurement, can deliver the required intensity asking for 30% more SPS protons on target only. Considerations about signal acceptance drive the choice of a 75 GeV/c charged kaon beam with 1% momentum bite. The use of a decay-in-flight technique to identify K^+ decay products is the experimental principle of NA62.

The experimental set-up is close to the one used for the measurement of R_K : a 100 m beam line selects the appropriate beam; a 80 m evacuated decay volume follows the beam line and the detectors are placed downstream to measure the secondary particles from the kaon decays occurring in the decay volume. The secondary beam is composed of kaons (6%), π^+ and protons and the rate is about 800 MHz integrated over a 16 cm^2 area. The rate seen by the detector downstream is about 10 MHz, mainly due to K^+ decays. The main subdetectors forming the NA62 layout are: a differential Cerenkov counter on the beam line to identify the K^+ in the beam; a Si-pixel beam tracker; a guard-ring counter surrounding the beam tracker to veto inelastic interactions of particles; a downstream spectrometer made of straw chambers in vacuum; a RICH to distinguish pions from muons; a charged hodoscope; a system of photon vetoes including a series of annular lead glass calorimeters surrounding the decay and detector volume, the NA48 LKr calorimeter and a small angle calorimeter to achieve the hermetic coverage for photons emitted at zero angle; an hadronic calorimeter to identify pions and veto muons.

The signature of the signal is one track in the final state matched to one K^+ track in the beam. Backgrounds come from all the kaon decays with one track left in the final state and from accidental tracks reconstructed downstream matched by chance to a track upstream. Let P_K and P_π be the measured four-momenta of the K^+ and π^+ , respectively. The variable $M_{miss}^2 \equiv (P_K - P_\pi)^2$ defines two regions (namely region I and region II) almost free of the backgrounds coming from the main K^+ decay modes (see fig 2). The residual sources of background contamination are: tails

to the M_{miss}^2 of the main K^+ decay channels due to the detector resolution and to the corresponding radiative processes; semileptonic K^+ decays like $K^+ \rightarrow e^+\pi^0\nu_e$; rare decays like $K^+ \rightarrow \pi^+\pi^-\pi^+\nu_e$.

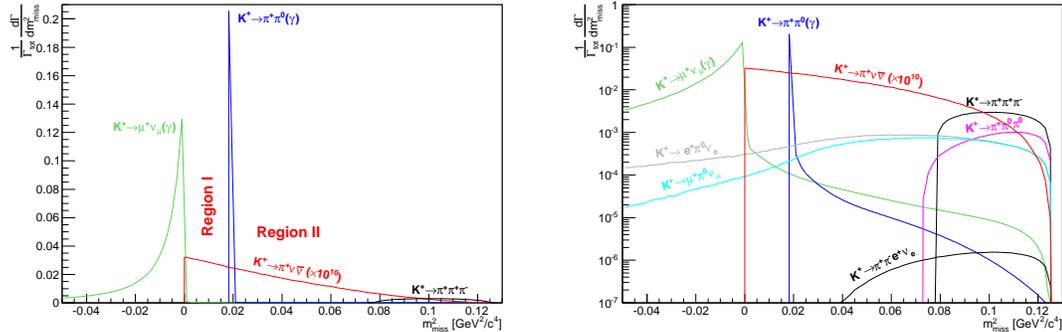


Figure 2: Shape of the squared missing mass for signal and background events under the hypothesis that the charged track is a pion.

Different techniques have to be employed in combination in order to reach the required level of background rejection. Schematically they can be divided into: kinematic rejection, precise timing, high efficient photon vetoes, precise particle identification systems to distinguish π^+ , μ^+ and positrons. The kinematic rejection requires a minimal material budget for the kaon and pion tracking systems. The precise timing is required for a proper kaon-pion matching, given the different rate environments upstream and downstream. The high energy of the K^+ beam, the offline requirement of having a reconstructed track of maximum 35 GeV/c momentum, a photon detector coverage up to 50 mrad and a photon detection inefficiency at the level of 10^{-5} for photons above 10 GeV in the LKr calorimeter guarantee a large enough π^0 suppression. The combined use of a RICH and a calorimetric technique allows a muon/pion separation suitable for the $K^+ \rightarrow \mu^+\nu$ rejection.

Part of the subdetectors and the final beam line have been commissioned during a technical run at the end of 2012. The overall construction is on schedule for the first physics run in autumn 2014.

4 Conclusions

The NA62 experiment at CERN provided in 2007 the most precise measurement of the lepton flavour parameter R_K : $R_K = (2.488 \pm 0.010) \times 10^{-5}$. The ultra-rare $K \rightarrow \pi\nu\bar{\nu}$ decay is a unique environment where to search for new physics. The NA62 experiment at CERN-SPS will follow this road by collecting $O(100)$ events of the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ decay. The first physics run is scheduled for autumn 2014.

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