RECENT RESULTS ON RARE KAON DECAYS FROM NA48/2 AND NA62 EXPERIMENTS AT CERN SPS

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Abstract. The branching fractions of $K^\pm \to \pi^\pm e^+ e^-$ and $K^\pm \to \pi^\pm \mu^+ \mu^-$ rare decays have been measured by the NA48/2 collaboration at CERN SPS. An improved upper limit has been set on the Lepton Number Violating decay $K^\pm \to \pi^\mp \mu^\pm \mu^\pm$. The branching ratio $R_K = \Gamma(K^\pm \to e^\pm \nu)/\Gamma(K^\pm \to \mu^\pm \nu)$ has been measured by the NA62 collaboration at CERN SPS with an unprecedented accuracy, allowing a precise test of lepton flavour universality.

The NA62 experiment is now undergoing a major upgrade in order to measure the branching fraction of the very rare $K^+ \to \pi^+ \nu \bar{\nu}$ decay with a 10% precision.

1 Introduction

Rare Kaon decays provide unique opportunities to search for effects of physics beyond the Standard Model. In fact, the suppression of these decays in the SM makes them very sensitive to loop-level contributions of virtual heavy particles.

NA48/2 collected several thousands of $K^\pm \to \pi^\pm e^+ e^-$ and $K^\pm \to \pi^\pm \mu^+ \mu^-$ decays, obtaining upper limits on CP violating charge asymmetries and on the branching fraction of the Lepton Number violating decay $K^\pm \to \pi^\mp \mu^\pm \mu^\pm$.

Lepton flavour universality has been investigated by NA62 measuring the ratio $R_K = \Gamma(K^\pm \to e^\pm \nu)/\Gamma(K^\pm \to \mu^\pm \nu)$ with unprecedented accuracy. The branching fraction ($\simeq 10^{-10}$) of the ultra-rare FCNC decay $K^+ \to \pi^+ \nu \bar{\nu}$ is predicted by the SM [1] with a theoretical uncertainty much smaller than present experimental accuracy. NA62 will measure this BR with a 10% precision.

2 The NA48/2 and NA62 experiments

The NA48/2 and NA62 experiments at CERN SPS collected data in 2003–2004 and in 2007–2008, respectively, using the same experimental setup and a beam line able to deliver simultaneous K^+ and K^- beams.

After momentum selection, cleaning and collimation, the beams enter the fiducial decay volume, housed in a 114 m long vacuum tank, with a negligible angular divergence and a r.m.s. transverse size below 1 cm. The beams contain between 10^7 and 10^8 particles per SPS pulse (4.8 s duration), and about 5% of them are kaons.

The charged particle reconstruction is provided by a magnetic spectrometer, consisting of a dipole magnet and four drift chambers. A plastic scintillator hodoscope provides fast signals for triggering on charged particles and precise time

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measurement. The energy and position of photons and electrons are precisely measured by a liquid krypton electromagnetic calorimeter (LKr), consisting of a $27X_0$ almost homogeneous ionization chamber with high-granularity tower read-out. A muon detector (MUV) composed of iron absorbers and three planes of scintillator is used to identify muons. An iron-scintillator hadron calorimeter and several photon veto counters complete the experimental apparatus, a detailed description of which can be found in Ref. [2].

3 $K^\pm \to \pi ee$, $K^\pm \to \pi\mu\mu$ and search for Lepton Number Violation

The large NA48/2 data sample collected in 2003–2004 to measure charge asymmetries in $K^\pm \to 3\pi$ decays [3] gives the opportunity to study the $K^\pm \to \pi^\pm e^+ e^-$ and $K^\pm \to \pi^\pm \mu^+ \mu^-$ rare decays and to search for the Lepton Number Violating (LNV) decay $K^\pm \to \pi^\mp \mu^\pm \mu^\pm$.

Three-track vertices are reconstructed extrapolating the segments from the spectrometer, taking into account the measured residual magnetic fields and multiple scattering. For each track, the ratio E/p of the associated energy deposit in the LKr calorimeter to its momentum measured by the magnetic spectrometer is used for particle identification, as described below.

3.1 $K^\pm \to \pi^\pm e^+ e^-$

The $K^\pm \to \pi^\pm e^+ e^-$ rate is measured relative to the more abundant $K^\pm \to \pi^\pm \pi^0_D$ normalization channel (where $\pi^0_D \to e^+ e^- \gamma$ is the so-called Dalitz decay), whose final state contains the same charged particles as the signal events.

Candidate events are required to have one $\pi^\pm$ track ($E/p < 0.85$) and a pair of oppositely charged electrons ($E/p > 0.95$); their total momentum is required to be consistent with that of beam particles. Kinematic suppression of the main background channel ($K^\pm \to \pi^\pm \pi^0_D$) is achieved by requiring the e^+e^- invariant mass to be above the π^0 mass: $z \equiv (M_{ee}/M_K)^2 > 0.08$. Finally, the $\pi^\pm e^+ e^-$ invariant mass is required to be consistent with the $K^\pm$ mass.

A total of 7253 events has been obtained, with a 1.0% background.

The branching fraction has been measured to be $\mathrm{BR}(K^\pm \to \pi^\pm e^+ e^-) = (3.11 \pm 0.12) \times 10^{-7}$. The first simultaneous observation of both charged kaon decays into $\pi^\pm e^+ e^-$ allows to establish an upper limit for the CP violating charge asymmetry $A_{\mathrm{CP}} = (\mathrm{BR}^+ - \mathrm{BR}^-)/(\mathrm{BR}^+ + \mathrm{BR}^-) : |A_{\mathrm{CP}}| < 2.1 \times 10^{-2}$ at 90% CL. More details on this analysis can be found in [4].

3.2 $K^\pm \to \pi^\pm \mu^+ \mu^-$

The $K^\pm \to \pi^\pm \mu^+ \mu^-$ rate is measured relative to the abundant $K^\pm \to \pi^\pm \pi^+ \pi^-$ normalization channel (denoted $K_{3\pi}$ below). The $K^\pm \to \pi^\pm \mu^+ \mu^-$ and $K_{3\pi}$ samples are collected concurrently using the same trigger logic.

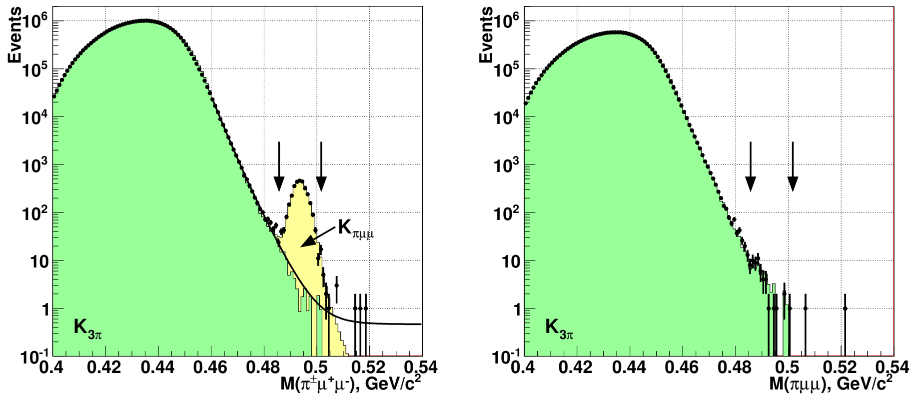

Figure 1: Invariant mass distribution of (left) $\pi^\pm\mu^+\mu^-$ and (right) $\pi^\mp\mu^\pm\mu^\pm$ candidates: data (dots), $K_{3\pi}$ and $K_{\pi\mu\mu}$ simulations (filled areas). Arrows indicate the signal region.

Candidate events are required to have one $\pi^\pm$ track (with $E/p < 0.95$ and no correlated hits in the MUV) and a pair of oppositely charged muons ($E/p < 0.2$ and associated hit(s) in the MUV); their total momentum is required to be consistent with that of beam particles. The $\pi^\pm\mu^+\mu^-$ invariant mass is required to be consistent with the $K^\pm$ mass (see Fig. 1(left)).

A total of 3120 events has been obtained, with a background of $(3.3 \pm 0.7)\%$. The branching fraction has been measured to be $\mathrm{BR}(K^\pm \to \pi^\pm\mu^+\mu^-) = (9.62 \pm 0.25) \times 10^{-8}$, improving the precision by a factor ~ 3 with respect to the most precise earlier measurement. The branching ratios have been measured separately for K^+ and K^-, allowing to establish an upper limit on the CP violating charge asymmetry $A_{\mathrm{CP}} = (\mathrm{BR}^+ - \mathrm{BR}^-)/(\mathrm{BR}^+ + \mathrm{BR}^-)$: $|A_{\mathrm{CP}}| < 2.9 \times 10^{-2}$ at 90% CL.

The forward-backward asymmetry $A_{\mathrm{FB}} = \frac{\Gamma(\cos\theta_{\mathrm{K}\mu}>0) - \Gamma(\cos\theta_{\mathrm{K}\mu}<0)}{\Gamma(\cos\theta_{\mathrm{K}\mu}>0) + \Gamma(\cos\theta_{\mathrm{K}\mu}<0)}$ in the angle $\theta_{K\mu}$ between the kaon and the opposite-sign lepton in the di-lepton rest frame has also been measured, resulting in an upper limit $|A_{\mathrm{FB}}| < 2.3 \times 10^{-2}$. More details on this analysis can be found in [5].

3.3 Search for lepton number violation

The same selection criteria described above for $K^\pm \to \pi^\pm\mu^+\mu^-$ decays have been used to select events with same-sign muons.

The $\pi\mu\mu$ invariant mass distribution of the selected $K^\pm \to \pi^\mp\mu^\pm\mu^\pm$ candidates is shown in Fig. 1(right). As in the $K^\pm \to \pi^\pm\mu^+\mu^-$ sample, the main background comes from $K_{3\pi}$ decays: a Monte Carlo simulation has given 52.6 ± 19.8 background events in the signal region (Kaon mass window) where

52 events are found in the data sample.

Conservatively assuming the expected background to be $(52.6 - 19.8) = 32.8$ events we obtain an upper limit of 32.2 signal events at 90% CL. This corresponds to an upper limit on the branching fraction $\mathrm{BR}(K^\pm \to \pi^\mp\mu^\pm\mu^\pm) < 1.1 \times 10^{-9}$ at 90% CL, with a factor 3 improvement over the best previous limit.

4 Lepton Flavour Universality test with $K^\pm \to l^\pm\nu$ decays

The measurement is based on counting the number of K_{e2} and $K_{\mu 2}$ in-flight decays collected concurrently from an unseparated beam of (74 ± 1.4) GeV/c momentum. Data have been collected in 2007–2008 by the NA62 experiment. A result based on part of the 2007 data sample has already been published [6].

The ratio R_K is measured independently for 40 data samples (10 bins of lepton momentum and 4 samples with different data taking conditions). A large part of the selection is common for K_{e2} and $K_{\mu 2}$ decays, with two main differences. K_{l2} kinematic identification is based on the reconstructed squared missing mass assuming the track to be an electron or a muon: $M^2_{\mathrm{miss}}(l) = (P_K - P_l)^2$, where P_K and P_l are the kaon and lepton 4-momenta. Particle identification is based on the ratio E/p of the track energy deposit in the LKr calorimeter to its momentum measured by the spectrometer. Particles with $0.95 < E/p < 1.1$ ($E/p < 0.85$) are identified as electrons (muons). The squared missing mass distributions of $K_{\mathrm{e}2}$ and $K_{\mu 2}$ candidates are shown in Fig.2.

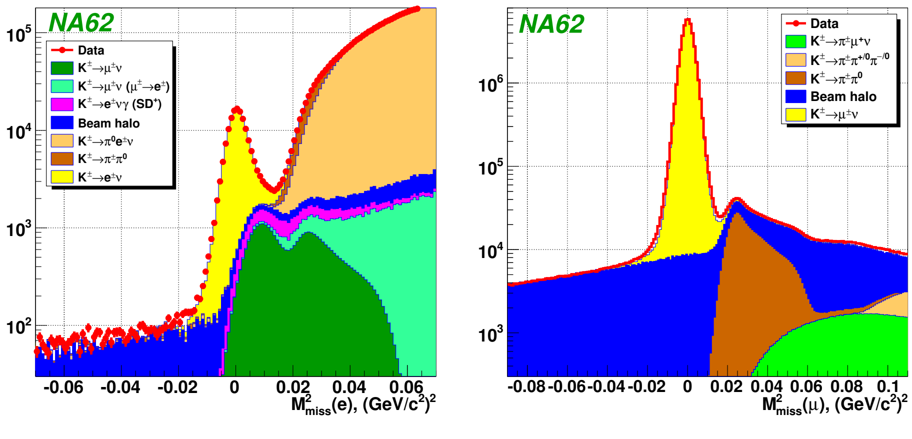

Figure 2: Reconstructed squared missing mass distributions for: (left) $K^\pm \to e^\pm\nu$ and (right) $K^\pm \to \mu^\pm\nu$ candidates: data (dots), signal and background components (filled areas).

The largest background to the K_{e2} decay comes from $K_{\mu 2}$ events where the muon is mis-identified ($E/p > 0.95$) due to 'catastrophic' bremsstrahlung in the LKr. In order to reduce the corresponding uncertainty, the muon misidentification probability $P_{\mu e}$ has been measured as a function of momentum using dedicated samples. The numbers of selected K_{e2} and $K_{\mu 2}$ candidates are 145 958 and 4.2817×10^7, respectively (the latter pre-scaled at trigger level).

The final result of the measurement, combined over the 40 independent samples taking into account correlations between the systematic errors, is $R_K = (2.488 \pm 0.007_{\mathrm{stat}} \pm 0.007_{\mathrm{syst}}) \times 10^{-5} = (2.488 \pm 0.010) \times 10^{-5}$. This result is consistent with the Standard Model expectation [7] $R_K = (2.477 \pm 0.001) \times 10^{-5}$ and its precision dominates the world average.

5 The ultra-rare $K^+ \to \pi^+ \nu \bar{\nu}$ decay

The primary goal of the NA62 experiment [8] is the measurement of the branching fraction of the $K^+ \to \pi^+ \nu \bar{\nu}$ decay with 10% precision. In order to obtain this precision, NA62 aims to collect at least 100 $K^+ \to \pi^+ \nu \bar{\nu}$ decays in about two years of data taking. At least 10^{13} K^+ decays are needed, assuming a $\approx 10\%$ signal acceptance and a branching ratio of $\approx 10^{-10}$. To keep the systematic uncertainty small, a rejection factor $\approx 10^{-12}$ is required for the main K^+ decay modes, as well as the possibility to measure efficiencies and rejection factors directly from data. In order to match the above requirements new detectors must replace most of the existing apparatus.

The experimental setup consists of an unseparated positive beam of 75 GeV/c $\pm 1\%$ momentum, a ~ 80 m long evacuated decay volume and detectors downstream to identify and measure the kaon decay products.

The signature of the $K^+ \to \pi^+ \nu \bar{\nu}$ decay is one π^+ track in the final state matched to one K^+ track in the beam, and no other detectable particle. The beam intensity rate is about 800 MHz (only 6% of the beam particles are kaons, the others are π^+ and protons). The rate seen by the detectors downstream is about 10 MHz, mainly due to K^+ decays.

Backgrounds come from all kaon decays with one track in the final state. Different techniques will be combined in order to reach the required level of rejection: kinematic rejection, precise timing, highly efficient photon and muon vetos, precise particle identification systems to distinguish π^+, μ^+ and e^+.

The layout of the NA62 detector is sketched in Fig. 3. The main subdetectors are: a differential Čerenkov counter (CEDAR) to identify the K^+ in the beam; a Silicon pixel beam tracker (GTK); guard-ring counters (CHANTI) surrounding the beam tracker to veto catastrophic interactions of particles in the tracker; a downstream spectrometer made of STRAW chambers in vacuum; a RICH Čerenkov counter to distinguish pions and muons; a plastic scintillator hodoscope (CHOD); a system of photon vetos including a series of annular lead glass calorimeters (LAV) surrounding the decay and detector volume, the NA48 LKr calorimeter and a small angle calorimeter (SAC) to complete the hermetic coverage for photons emitted at very small angles (down to zero); a

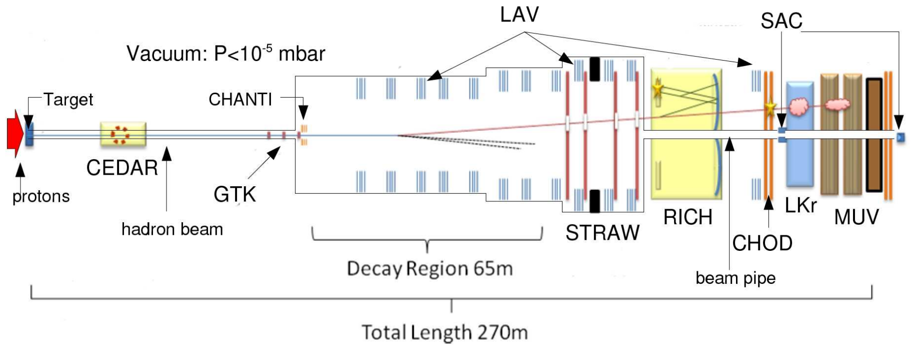

Figure 3: Schematic lateral view of the NA62 experimental setup

muon veto detector (MUV).

The design of the experimental apparatus and the R&D of the new subdetectors have been completed in 2010. The experiment is under construction and the first technical run is foreseen at the end of 2012.

6 Conclusions

The NA48/2 experiment at CERN SPS has measured the branching ratios of $K^\pm \to \pi^\pm e^+ e^-$ and $K^\pm \to \pi^\pm \mu^+ \mu^-$ decays with a few percent relative precision and has also improved the upper limit on the branching ratio of the lepton number violating decay $K^\pm \to \pi^\mp \mu^\pm \mu^\pm$: BR$< 1.1 \times 10^{-9}$ at 90% CL.

Using the same detector, the NA62 experiment has obtained the most precise measurement of the ratio $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2}) = (2.488 \pm 0.010) \times 10^{-5}$, in agreement with the Standard Model prediction.

The ultra-rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay is a unique environment where to search for new physics. The NA62 experiment aims to measure its branching ratio with a 10% accuracy. After three years of successful R&D, all subdetectors are now under construction.

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