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Rare kaon decay measurements in the experiments NA48/2 and NA62

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The NA48/2 and NA62 (R_K-phase) experiments at CERN SPS collected a large sample of charged kaon decays in 2003–2008, allowing one to study these decays with a high precision. The first result of the helicity-suppressed decay ratio $R_K = Br(K_{e2})/Br(K_{\mu 2})$ measurement based on the data collected in NA62 (R_K-phase) experiment is presented. The result is in agreement with the Standard Model expectation. Using the data from both experiments collected with a minimum bias trigger in 2004 and in 2007, a large sample of $K^\pm \to \pi^\pm \gamma\gamma$ decays has been selected and analyzed. This analysis led to a precision test of the Chiral Perturbation Theory. The first evidence for the rare decay $K^\pm \to \pi^\pm \pi^0 e^+ e^-$ is obtained in the NA48/2. The study of rare decay $K^\pm \to e^\pm \nu\gamma$ is performed in the NA62 (R_K-phase) experiment. The presented results are preliminary.

The NA62 experiment at CERN SPS aims to collect of the order of 100 $K^\pm \to \pi^\pm \nu\bar{\nu}$ events in two years of data taking, keeping the background at the level of 10%. The physics prospects and the status of the construction of the experiment are presented as well.

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1. Introduction and the NA48/2 detector

Experimental studies of rare and very rare charged kaon decays provide a test of Chiral Perturbation Theory (ChPT) at higher orders of calculations, a precise test of the Standard Model (SM), and could give an indication to the physics beyond the SM.

Large samples of charged kaon decays were collected with the NA48/2 detector at two slightly different conditions: the NA48/2, and NA62 (R_K-phase) experiments. The NA48/2 experiment was aimed to search for CP violating asymmetries in $K^{\pm}$ decays [1] and to study its rare decays. The simultaneous K^+ and K^- beams with a momentum of (60 ± 3) GeV/c were produced by 400 GeV primary protons from the CERN/SPS at Be target and selected by two "achromats". At the entrance of 114 m long decay volume the flux ratio K^+/K^- of the beams is $R \simeq 1.8$. The detector major parts are [2]: magnetic spectrometer providing the momentum resolution of $\sigma(p)/p = (1.02 \oplus 0.044p)\%$ (p in GeV/c); a liquid-krypton calorimeter (LKr) with the transverse segmentation into 13248 projective cells ($2x2cm^2$ each) and the 27 radiation length thickness, measuring electrons and photons with an energy resolution of $\sigma(E)/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$ (E in GeV) and a transverse position resolution for isolated showers $\sigma_x = \sigma_y = (0.42/\sqrt{E} \oplus 0.06)cm$; two planes of scintillator hodoscope used for the trigger, with a time resolution of $\sim 150ps$; the muon veto counters. In the NA62 (R_K phase) experiment the following conditions were changed: the beam mean momentum was (74 ± 2) GeV/c, the momentum resolution $\sigma(p)/p = (0.48 \oplus 0.009p)\%$ (p in GeV/c) (improved by the larger magnetic field), and a flux ratio K^+/K^- of $\simeq 2.0$.

2. The measurement of decay mode ratio: $R_K = Br(K_{e2})/Br(K_{\mu 2})$

The leptonic decays of pseudoscalar mesons are suppressed in the SM by helicity conservation. The ratios of decay rates can be computed very precisely [3]. Within extensions of the SM involving charged Higgs doublet, R_K is sensitive to lepton flavour violating effects induced by loop processes with the charged Higgs boson ($H^{\pm}$) exchange [4]. A recent study has concluded that R_K can be enhanced by $O(1\%)$ within the Minimal Supersymmetric Standard Model (MSSM) [5].

The presented result is obtained using the data collected in 2007-2008 in the NA62 (R_K-phase) experiment. The ratio is computed independently for 10 bins of reconstructed lepton momentum (each at 4 samples with different data taking conditions) as

$$R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu 2}) - N_B(K_{\mu 2})} \cdot \frac{A(K_{\mu 2})}{A(K_{e2})} \cdot \frac{f_\mu \times \varepsilon(K_{\mu 2})}{f_e \times \varepsilon(K_{e2})} \cdot \frac{1}{f_{LKr}},$$

where $N(K_{\ell 2})$ are the numbers of selected $K_{\ell 2}$ candidates ($\ell = e, \mu$), $N_B(K_{\ell 2})$ are the numbers of background events, $A(K_{\mu 2})/A(K_{e2})$ is the geometric acceptance correction, f_ℓ are the efficiencies of e/μ identification, $\varepsilon(K_{\ell 2})$ are the trigger efficiencies, f_{LKr} is the global efficiency of the LKr calorimeter readout (which provides the information used for electron identification), and D is the downscaling factor of the $K_{\mu 2}$ trigger. The K_{e2} and $K_{\mu 2}$ candidates have been collected concurrently. Therefore the result does not rely on the absolute beam flux measurement, and several systematic effects cancel at first order. A Monte Carlo (MC) simulation is used to evaluate the acceptance correction and the geometric part of the acceptances for most background processes. Particle identification, trigger and readout efficiencies and the beam halo background are measured directly from control data samples.

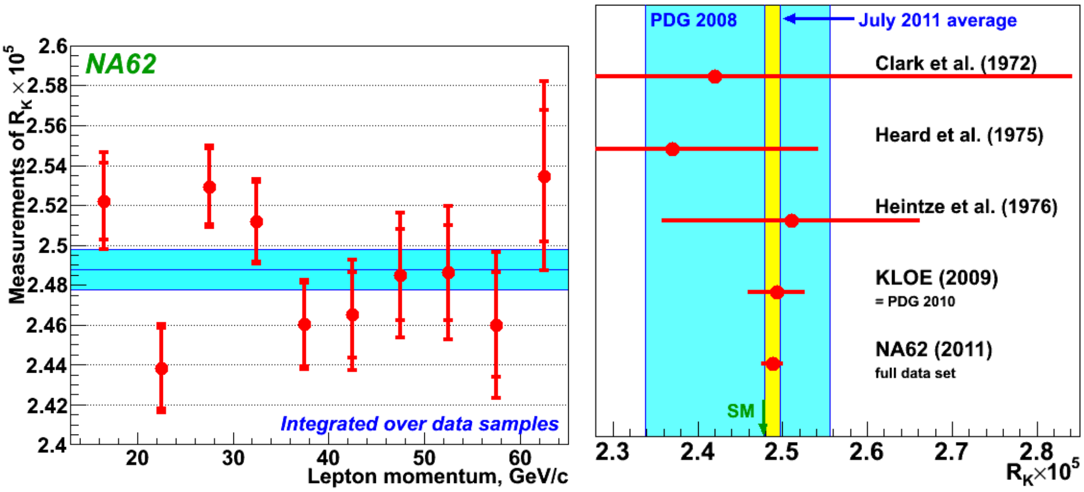

Figure 1: *left*: R_K obtained in different samples; *right*: comparison of obtained R_K with the SM and other experiments.

To distinguish K_{e2} and $K_{\mu 2}$ decays two sets of selection criteria are used. The first one limits on the reconstructed squared neutrino mass assuming the track to be e or μ and varying criteria with the lepton momentum depending on resolution. The second one limits on the ratio E/p of energy deposit in the LKr calorimeter to track momentum: particles with $(E/p)_{min} < E/p < 1.1(E/p < 0.85)$ are identified as $e(\mu)$, where $(E/p)_{min}$ is 0.90 or 0.95, depending on momentum.

The numbers of selected K_{e2} and $K_{\mu 2}$ candidates are 145,958 and 4.2817×10^7, respectively (the latter are pre-scaled at trigger level). The background contamination in the K_{e2} sample has been estimated by MC simulations and, where possible, by the direct measurements. Finally it has been obtained to be $(10.95 \pm 0.27)\%$. The largest background contribution is the $K_{\mu 2}$ decay with a mis-identified muon via the "catastrophic" bremsstrahlung process in the LKr. The contributions to the systematic uncertainty of the result include the uncertainties on the backgrounds, helium purity in the spectrometer tank (which influences the detection efficiency via bremsstrahlung and scattering), beam simulation, spectrometer alignment, particle identification and trigger efficiency. The obtained ratio is combined over the 10 lepton momentum samples (see Fig.1(left)) taking into account correlations between the systematic errors:

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

The result is consistent with the SM expectation, and the achieved precision dominates the world average (Fig.1(right)). No evidence of the MSSM or charged Higgs doublet model contributions is found.

3. The $K^{\pm} \to \pi^{\pm}\gamma\gamma$ decay

Measurements of radiative non-leptonic kaon decays provide crucial tests for the ability of the Chiral Perturbation Theory (ChPT) to describe weak low energy processes.

In the ChPT framework, the $K^{\pm} \to \pi^{\pm}\gamma\gamma$ decay receives two non-interfering contributions at lowest non-trivial order $O(p^4)$: the pion and kaon loop amplitude depending on an unknown

O(1) constant $\hat{c}$ representing the total contribution of the counter terms, and the *pole amplitude* [6]. Higher order $O(p^6)$ unitarity corrections from $K^\pm \to 3\pi^\pm$ decays have been found to modify the $K^\pm \to \pi^\pm\gamma\gamma$ decay rate and spectrum of diphoton invariant mass ($m_{\gamma\gamma}$) significantly, leading, in particular, to non-zero differential decay rate at $z = (m_{\gamma\gamma}/m_K)^2 = 0$ [7], [8]. Experimentally, the only published $K^+ \to \pi^+\gamma\gamma$ observation is that of 31 candidates (K^+ decays) in the large diphoton mass region by the BNL E787 experiment [9].

The decay has been studied using minimum bias data sets collected in special NA48/2 run in 2004 and NA62 (R_K-phase) run in 2007. Signal events were selected in the region $z \geq 0.2$ to minimize the $K^\pm \to \pi^\pm\pi^0$ background. Reconstructed invariant mass ($\pi^\pm\gamma\gamma$) spectra, with the MC simulation expectations of the signal and background contributions, are displayed in Fig.2: 147 (175) decay candidates are observed in the 2004 (2007) data set, with the backgrounds contaminations of $K^\pm \to \pi^\pm\pi^0(\pi^0)(\gamma)$ decays with a merged photon clusters in the LKr calorimeter. The obtained spectrum of z clearly exhibits the cusp at two-pion threshold as predicted by the ChPT. The values of the $\hat{c}$ parameter in the framework of the ChPT $O(p^4)$ and $O(p^6)$ parameterizations according to [7] have been measured by the performing of likelihood fits to the data. The preliminary results of the fits are presented in Table1: they are in agreement with the earlier BNL E787 ones. The uncertainties are dominated by the statistical ones; the systematic errors are mainly due to uncertainties of the background estimates. The combined results take into account the large positive correlation of the systematic uncertainties of the two measurements.

The model-dependent branching ratio in the framework of $O(p^6)$ model in the full kinematic range is:

$$BR(K^\pm \to \pi^\pm\gamma\gamma) = (1.07 \pm 0.04_{stat} \pm 0.08_{sys}) \cdot 10^{-6}.$$

It is compatible with less precise measurement of experiment E787 based on 31 events [9].

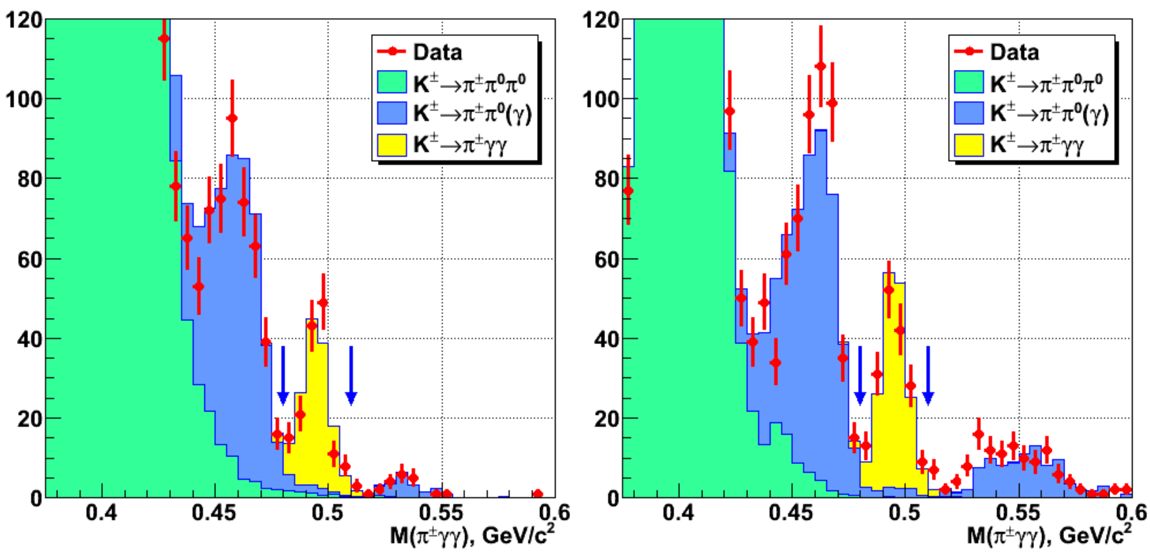

Figure 2: Reconstructed invariant mass of $\pi^\pm\gamma\gamma$ for NA48/2 (left) and NA62 (right) data; histograms present for the MC simulated signal and various backgrounds.

Table 1: *Results of $\hat{c}$ obtained by fitting the $z = (m_{\gamma\gamma}/m_K)^2$ distributions*

$\hat{c}$	NA48/2	NA62 (2007)	combined
$O(p^4)$	$1.36 \pm 0.33_{stat} \pm 0.007_{syst}$	$1.71 \pm 0.29_{stat} \pm 0.06_{syst}$	$1.56 \pm 0.22_{stat} \pm 0.007_{syst}$
	$= 1.36 \pm 0.34$	$= 1.71 \pm 0.30$	1.56 ± 0.23
$O(p^6)$	$1.67 \pm 0.39_{stat} \pm 0.009_{syst}$	$2.21 \pm 0.31_{stat} \pm 0.008_{syst}$	$2.00 \pm 0.24_{stat} \pm 0.09_{syst}$
	$= 1.67 \pm 0.34$	$= 2.21 \pm 0.32$	2.00 ± 0.26

4. The first observation of $K^\pm \to \pi^\pm \pi^0 e^+ e^-$ decay

The decay $K^\pm \to \pi^\pm \pi^0 e^+ e^-$ can be described as an internal γ conversion of $K^\pm \to \pi^\pm \pi^0 \gamma$ and depends on electric and magnetic form factors [10], [11]. This decay could be sensitive to the CP violation and new physics phenomena. The first evidence of this decay as detected by the NA48/2 experiment is reported here, with about 4500 candidates as can be seen in Fig.3(left). The result is preliminary, analysis is in progress.

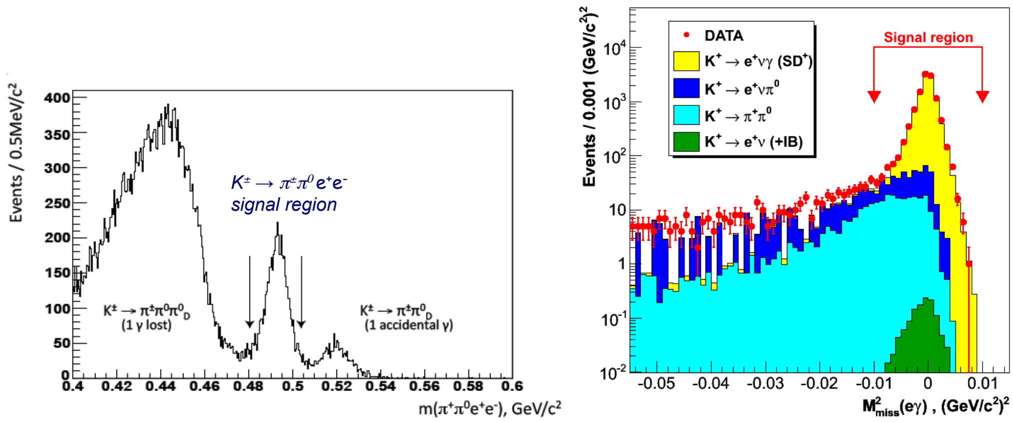

Figure 3: *left*: the invariant mass of $(\pi^\pm \pi^0 e^+ e^-)$ distribution for the data collected in the NA48/2 experiment; *right*: the squared missing mass for the $K^\pm \to e\nu\gamma$ decay candidates obtained in the NA62 (R_K-phase) experiment and the MC simulation of the background.

5. The study of $K^\pm \to e^\pm \nu\gamma$ decay

The $K^\pm \to e^\pm \nu\gamma$ decay receives three contributions to the total decay amplitude: Inner Bremsstrahlung (IB), Structure-Dependent (SD) and a term of interference INT between these two components [12], [13]. The IB part is purely electromagnetic and to the lowest order can be predicted on general grounds (Low theorem). The SD part receives electro-weak and hadronic contributions, is a dominating part and is sensitive to the kaon structure. The SD$^+$ process with positive helicity photon has a clear kinematic signature and has been calculated to $O(p^6)$ [14]. The $K_{e2\gamma}$ (IB) component has the same final state of the signal but the radiative photon is soft, its energy spectrum is different from the one emitted in the SD modes, and this background is reduced to a negligible amount using kinematic and geometrical cuts. Thus, the study of these decays allows to fulfill the precise check of the ChPT predictions at high orders.

The presented analysis is based on the data sample collected in 2007 (NA62 R_K-phase), acquired with a minimum bias trigger.

About 10k candidates are selected using the criteria achieving a signal acceptance of $\sim 7\%$ (see Fig.3(right)). The main source of background to the $K_{e2\gamma}$ decay coming from the K_{e3} and $K_{2\pi}$ channels is estimated as $\sim 5\%$ with the MC simulation. Background channels with muons in the final state, such as the $K_{\mu 3}$ were found to be negligible. The kaon flux is evaluated using the K_{e3} (followed by $\pi^0 \to \gamma\gamma$) decay as a normalization channel. The analysis is in progress that will allow a precision measurement of decay rate and an estimation of the form factor parameters.

6. The precision measurement of $K^+ \to \pi^+ \nu\overline{\nu}$ decay

Among the flavour changing neutral current K and B decays, the $K^+ \to \pi^+ \nu\overline{\nu}$ decay plays a key role in the search for new physics through the underlying mechanisms of flavour mixing. This decay is strongly suppressed in the SM (highest CKM suppression), and is dominated by top-quark loop contributions. The SM branching ratios have been computed to an exceptionally high precision with respect to other loop-induced meson decays, the uncertainties are dominated by parametric ones, and the irreducible theoretical uncertainties are at $\sim 1\%$ level [15]. The extreme theoretical cleanness of this decay remains also in a certain new physics scenarios. Experimentally, the $K^+ \to \pi^+ \nu\overline{\nu}$ decay has been observed by the BNL E787/E949 experiments, and the measured branching ratio is $(1.73^{+1.15}_{-1.05}) \times 10^{-10}$. The achieved precision is inferior to that of the SM expectation ($Br = (7.81 \pm 0.80) \cdot 10^{-11}$ [15]).

The main goal of the NA62 experiment at CERN is the measurement of the $K^+ \to \pi^+ \nu\overline{\nu}$ decay rate at the 10% precision level, which would constitute a significant test of the SM [16]. The experiment is expected to collect about 100 signal events in two years of data taking, keeping the systematic uncertainties and backgrounds low. Assuming $\sim 10\%$ signal acceptance and the SM

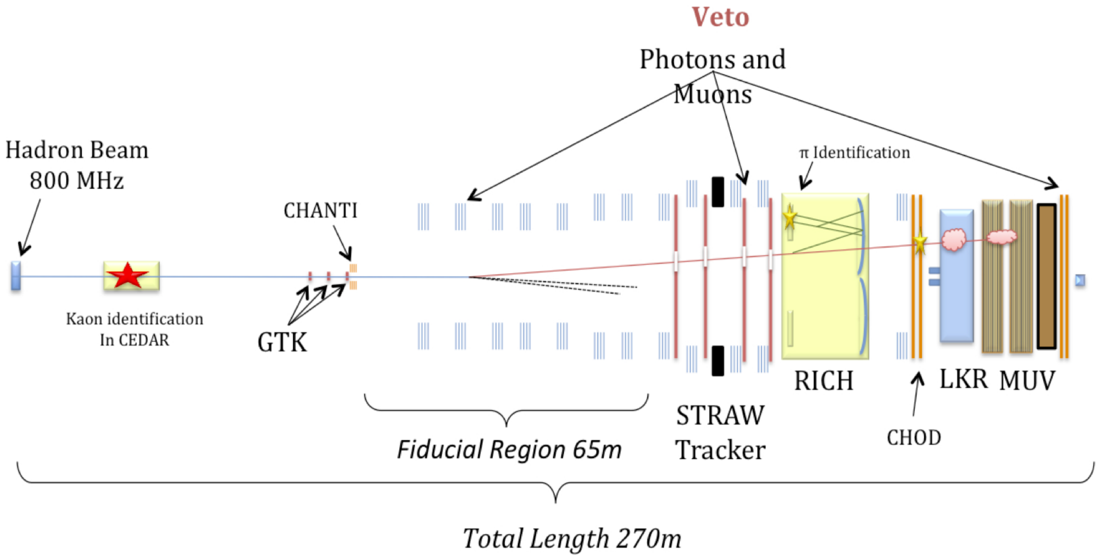

Figure 4: The NA62 apparatus for the measurement of very rare charged kaon decays.

decay rate, the kaon flux should correspond to at least 10^{13} K^+ decays in the fiducial volume. In order to achieve a small systematic uncertainty, a rejection factor for generic kaon decays of the order of 10^{12} is required, and the background suppression factors need to be measured directly from the data.

The CERN SPS 400 GeV/c primary protons produce 75 GeV/c unseparated monochromatic $\delta p/p \sim 1\%$) beam of charged hadrons: p, π and K. The 750 MHz intensity beam provides 50 MHz kaon rate (6%) with the 6 MHz rate decays. In total 4.8×10^{12} kaon decays per year will be recorded. The main NA62 subdetectors are (Fig.4): a differential Cherenkov counter (CEDAR) on the beam line to identify the beam K^+; a silicon pixel beam tracker; guard-ring counters surrounding the beam tracker to veto catastrophic interactions of particles; a downstream spectrometer composed of 4 straw chambers operating in vacuum; a Ring Imaging Cherenkov (RICH) detector to distinguish pions and muons; a scintillator hodoscope; a muon veto detector. The photon veto detectors will include a series of annular lead glass calorimeters surrounding the decay and detector volume, the NA48 LKr calorimeter, and two small angle calorimeters to provide hermetic coverage for photons emitted at close to zero angle to the beam. The experiment is under preparation, and the first technical run is scheduled for October - December 2012.

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