RECENT NA48/2 AND NA62 RESULTS

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The NA48/2 Collaboration at CERN has accumulated and analysed unprecedented statistics of rare kaon decays in the K_{e4} modes: $K_{e4}(+-)$ ($K^{\pm} \to \pi^+\pi^- e^{\pm}\nu$) and $K_{e4}(00)$ ($K^{\pm} \to \pi^0\pi^0 e^{\pm}\nu$) with nearly one percent background contamination. It leads to the improved measurement of branching fractions and detailed form factor studies. New final results from the analysis of 381 $K^{\pm} \to \pi^{\pm}\gamma\gamma$ rare decay candidates collected by the NA48/2 and NA62 experiments at CERN are presented. The results include a decay rate measurement and fits to Chiral Perturbation Theory (ChPT) description.

1 Introduction

The main goal of NA48/2 experiment was the search for CP-violating asymmetry in $K^{\pm} \to 3\pi^{\pm}$ decays [1]. Also it has provided in 2003-2004 a large data sample for charged kaon rare decay studies. In 2007-2008, the NA62 experiment [2] (R_K phase) has collected a large data sample with the same detector [3] but modified beam line. Two simultaneous K^+ and K^- beams were produced by 400 GeV/c protons on a beryllium target. Particles of opposite charge with a central momentum of 60 GeV/c and a momentum band of $\pm 3.8\%$ (rms) (74 GeV/c $\pm 1.9\%$ for NA62 R_K phase) were selected by the system of magnets and collimators. Charged products of $K^{\pm}$ decays were measured by the magnetic spectrometer consisting of four drift chambers (DCH1–DCH4) and a dipole magnet located between DCH2 and DCH3. The spectrometer was

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followed by a scintillator hodoscope. A Liquid Krypton calorimeter (LKr) was used to measure the energy of electrons and photons.

2 K_{e4}^{+-} decay

Kinematics of the $K^{\pm} \to \pi^+\pi^- e^{\pm}\nu$ (K_{e4}^{+-}) decay is defined by five variables [4]: the squared invariant masses of dipion (S_π) and dilepton (S_e), the angle θ_π of $\pi^{\pm}$ in dipion rest frame with respect to the flight direction of dipion in the kaon center of mass system, the similar angle θ_e of $e^{\pm}$ in dilepton rest frame, and the angle ϕ between dipion and dilepton planes.

K_{e4} decay amplitude is a product of the leptonic weak current and (V-A) hadronic current, described in terms of three (F,G,R) axial-vector and one (H) vector complex form factors. Sensitivity of K_{e4} decay matrix element to R form factor is negligible due to the small mass of electron. Form-factors may be developed in a partial wave expansion:

$$\begin{aligned} F &= F_s e^{i\delta_{fs}} + F_p e^{i\delta_{fp}} cos\theta_\pi + F_d e^{i\delta_{fd}} cos^2\theta_\pi + ... \\ G &= G_p e^{i\delta_{gp}} + G_d e^{i\delta_{gd}} cos\theta_\pi + ... \\ H &= H_p e^{i\delta_{hp}} + H_d e^{i\delta_{hd}} cos\theta_\pi + ... \end{aligned} \quad (1)$$

Limiting the expansion to S- and P-waves and considering a unique phase δ_p for all P-wave form factors in absence of CP violating weak phases, one will obtain the decay probability, that depends only on the real form factor magnitudes F_s, F_p, G_p, H_p, a single phase shift $\delta = \delta_s - \delta_p$ and kinematic variables. The form factors can be developed in a series expansion of the dimensionless invariants $q^2 = (S_\pi/4m_\pi^2) - 1$ and $S_e/4m_\pi^2$ [5]. Two slope and one curvature terms are sufficient to describe the F_s form factor variation within the available statistics ($F_s/f_s = 1 + (f_s'/f_s)q^2 + (f_s''/f_s)q^4 + (f_e'/f_s)S_e/4m_\pi^2$), while two terms are enough to describe the G_p form factor ($G_p/f_s = g_p/f_s + (g_p'/f_s)q^2$), and two constants – to describe the F_p and H_p form factors.

Hadronic form factors for the S- and P-waves have been obtained by NA48/2 concurrently with the phase difference between the S- and P-wave states of $\pi\pi$ system, leading to the precise determination of a_0^0 and a_2^0, the I=0 and I=2 S-wave $\pi\pi$ scattering lengths [7].

A high precision measurement of K_{e4}^{+-} form factors and branching fraction has been published by NA48/2 few years later [8,9]. K_{e4}^{+-} decay rate was measured relative to $K^{\pm} \to \pi^+\pi^-\pi^{\pm}$ ($K_{3\pi}^{+-}$) normalization channel. A track of charged particle with a momentum $p > 2.75$ GeV and $0.9 < E/p < 1.1$ was identified as $e^{\pm}$, while the track with $p > 5$ GeV and $E/p < 0.8$ was regarded as $\pi^{\pm}$. A dedicated linear discriminant variable based on shower properties has been applied to reject events with one misidentified pion. To suppress $K_{3\pi}^{+-}$ background, the vertex invariant mass $M_{3\pi}$ in the $\pi^+\pi^-\pi^{\pm}$ hypothesis and its transverse momentum p_t were required to be outside an ellipse centered at PDG kaon mass [10] and zero transversal momentum, with semi-axes of 20 MeV/c^2 and 35 MeV/c, respectively.

The squared missing mass was required to be > 0.04 $(Gev/c^2)^2$ to reject $\pi^{\pm}\pi^0$ decays with a subsequent $\pi^0 \to e^+e^-\gamma$ process. The invariant mass of e^+e^- system was required to be > 0.03 GeV/c^2 in order to reject photon conversions.

For the normalization channel $K_{3\pi}^{+-}$ the $M_{3\pi}$ and p_t were inside a smaller ellipse with semi-axes 12 MeV/c^2 and 25 MeV/c, respectively. A sample of about 1.11 million K_{e4}^{+-} candidates and about 19 millions of prescaled $K_{3\pi}$ candidates were selected from data recorded in 2003-2004.

Two main background sources are known: $K^{\pm} \to \pi^+\pi^-\pi^{\pm}$ decays with subsequent $\pi \to e\nu$ decay or a pion mis-identified as an electron; and $K^{\pm} \to \pi^0(\pi^0)\pi^{\pm}$ with subsequent $\pi^0 \to e^+e^-\gamma$ decay with undetected photons and an electron mis-identified as a pion. Their admixture in the signal events is estimated to be below 1%.

A detailed GEANT3-based [11] Monte Carlo simulation was used to take into account full detector geometry, DCH alignment, local inefficiencies and beam properties.

The resulting K^{+-}_{e4} branching fraction[9] $BR(K^{+-}_{e4}) = (4.257\pm0.004_{stat}\pm0.016_{syst}\pm0.031_{ext})10^{-5}$ is 3 times more precise than available PDG value[10] . It has been used to extract the common normalization form factor f_s[9].

3 K^{00}_{e4} decay

The K^{00}_{e4} rate is measured relative to the $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$ ($K^{00}_{3\pi}$) normalization channel. These two modes are collected using the same trigger and with a similar event selections. The separation between them occurs only at a later stage.

Events with at least four γ, detected by LKr, and at least one track, reconstructed from spectrometer data, were regarded as K^{00}_{e4} or $K^{00}_{3\pi}$ candidates. Every combination of 4 reconstructed γ with energies $E > 3$ GeV was considered as a possible pair of π^0 decays. Reconstructed longitudinal positions Z_1 and Z_2 of both $\pi^0 \to 2\gamma$ decay candidates were required to coincide within 500 cm, with their average position $Z_n = (Z_1 + Z_2)/2$ inside the fiducial volume 106 m long.

Decay longitudinal position Z_{ch}, assigned to the track, was defined by the closest distance approach between the track and the beam axis. Combined vertex, composed of four LKr clusters and one charged track with momentum $p > 5GeV$, was required to have the difference $|Z_n - Z_{ch}|$ less than 800 cm. If several combinations satisfy the vertex criteria, the case of minimum $(\frac{Z_1-Z_2}{\sigma_n})^2 + (\frac{Z_n-Z_{ch}}{\sigma_c})^2$ has been chosen, where σ_n and σ_c are the Z_n-dependent widths of corresponding distributions.

A track was preliminarily identified as $e^{\pm}$, if it has an associated LKr cluster with E/p between 0.9 and 1.1, otherwise $\pi^{\pm}$ was assumed at the first stage. Further suppression of pions mis-identified as electrons is obtained by means of discriminant variable which is a linear combination of E/p, shower width and energy weighted track-to-cluster distance at LKr front face.

K^{00}_{e4} and $K^{00}_{3\pi}$ decays were discriminated by means of elliptic cuts in the $(M_{\pi^0\pi^0\pi^{\pm}}, p_t)$ plane, where $M_{\pi^0\pi^0\pi^{\pm}}$ is the invariant mass of combined vertex in the $K^0_{3\pi}$ hypothesis, and p_t is the transversal momentum. Elliptic cut separates about 94 million $K^{00}_{3\pi}$ normalization events from about 65000 K^{00}_{e4} candidates. Residual fake-electron background is about 0.65% of K^{00}_{e4} amount. Background from $K^{00}_{3\pi}$ with the subsequent $\pi^{\pm} \to e^{\pm}\nu$ is 0.12% of the signal, and the accidental-related background is about 0.23%. It gives in total 1% of background admixture.

For the case of $K^{\pm} \to \pi^0\pi^0 e^{\pm}\nu$ (K^{00}_{e4}) decay, due to restrictions of symmetry, matrix element doesn't depend on θ_π and ϕ angles. It is parametrized in terms of the only formfactor F_s, that may depend on S_π and S_e. Form factor F_s was extracted from the fit of events distribution on (S_e, S_π) plane, taking into account the acceptance, calculated from MC simulation. The following empirical parameterization has been used: $F_s/f_s = 1 + (f'_s/f_s)q^2 + (f''_s/f_s)q^4 + (f'_e/f_s)S_e/4m^2_\pi$ for $q^2 > 0$ and $F_s/f_s = 1 + d\sqrt{|q^2/(1+q^2)|} + (f'_e/f_s)S_e/4m^2_\pi$ for $q^2 < 0$.

The results are in agreement with NA48/2 K^{+-}_{e4} analysis described above: $f'_s/f_s = 0.149 \pm 0.033_{stat} \pm 0.014_{syst}$, $f''_s/f_s = -0.070 \pm 0.039_{stat} \pm 0.013_{syst}$, $f'_e/f_s = 0.113 \pm 0.022_{stat} \pm 0.007_{syst}$, $d = -0.256 \pm 0.049 \pm 0.016_{syst}$.

The obtained form factor was used to obtain the final result of branching fraction measurement: $Br(K^{00}_{e4}) = (2.552 \pm 0.010_{stat} \pm 0.010_{syst} \pm 0.032_{ext})10^{-5}$. It is 10 times more precise, than PDG corresponding value[10]. Systematic error includes the contributions from background, simulation statistical error, sensitivity to form factor, radiation correction, trigger efficiency and beam geometry. External error comes from uncertainty of normalization channel $K^{00}_{3\pi}$ branching fraction.

Below the threshold of $S_\pi = (2m_{\pi^{\pm}})^2$ the measured K^{00}_{e4} decay form factor shows a deficit of events, that is well described by the present empirical parameterization (Fig. 1). It is similar to the effect of $\pi^+\pi^- \to \pi^0\pi^0$ rescattering in $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$ decay (cusp effect[6]), investigated by NA48/2 collaboration earlier[7] on the basis of ChPT formulations.

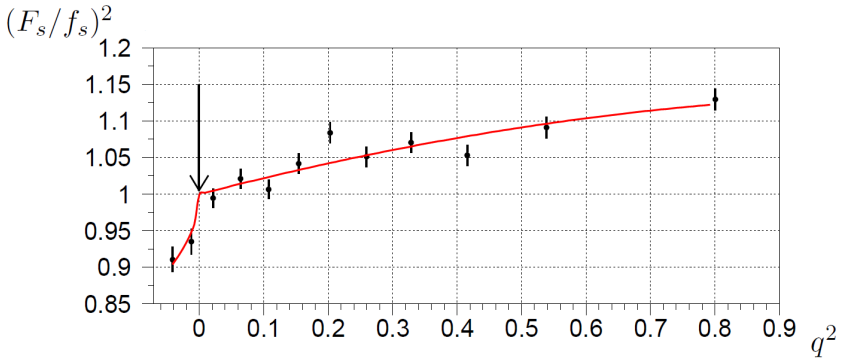

Figure 1 – K^{00}_{e4} normalized form factor squared as a function of q^2. The line corresponds to the adopted empirical fit. The arrow points to the $2m_\pi$ threshold.

4 $K^\pm \to \pi^\pm\gamma\gamma$ decay

In the ChPT framework, the $K^\pm \to \pi^\pm\gamma\gamma$ decay receives two non-interfering contributions at lowest non-trivial order $\mathcal{O}(p^4)$: the pion and kaon *loop amplitude* depending on an unknown $\mathcal{O}(1)$ constant $\hat{c}$ representing the total contribution of the counterterms, and the *pole amplitude* [12].

New measurements of this decay have been performed using data collected during a 3-day special NA48/2 run in 2004 and a 3-month NA62 run in 2007. Signal events are selected in the region of $z = (m_{\gamma\gamma}/m_K)^2 > 0.2$ to reject the $K^\pm \to \pi^\pm\pi^0$ background peaking at $z = 0.075$. 149 (232) decays candidates are observed in the 2004 (2007) data set, with backgrounds contaminations of 10.4% (7.5%) from $K^\pm \to \pi^\pm\pi^0(\pi^0)(\gamma)$ decays with merged photon clusters in the electromagnetic calorimeter.

The values of $\hat{c}$ in the frameworks of the ChPT $\mathcal{O}(p^4)$ and $\mathcal{O}(p^6)$ parameterizations [13] as well as branching ratio have been measured using likelihood fits to the data. The main systematic effect is due to the background uncertainty. Uncertainties related to trigger, particle identification, acceptance and accidental effects found to be negligible. The final combined results based on 2004 and 2007 runs data [14,15] are: $\hat{c}$ for $\mathcal{O}(p^4)$ fit $= 1.72 \pm 0.20_{stat} \pm 0.06_{syst}$; $\hat{c}$ for $\mathcal{O}(p^6)$ fit $= 1.86 \pm 0.23_{stat} \pm 0.11_{syst}$; branching fraction $Br(K_{\pi\gamma\gamma})$ for $\mathcal{O}(p^6)$ fit $= (1.003 \pm 0.056) \times 10^{-6}$. The model-independent branching ratio for $z > 0.2$ is equal to $(0.965 \pm 0.063) \times 10^{-6}$. New results are in agreement with the earlier (based on 31 events) BNL E787 [16] ones.

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