PROCEEDINGS OF SCIENCE

Probing non perturbative QCD with K_{e4} and $K^{\pm} \to \pi^{\pm}\gamma\gamma$ decays from the NA48/2 and NA62 experiments

Dmitry MADIGOZHIN[*†]
(JINR, Dubna)
E-mail: `Dmitri.Madigojine@cern.ch`

The NA48/2 collaboration has analyzed 1.1 million charged kaon decays $K^{\pm} \to \pi^{+}\pi^{-}e^{\pm}\nu$ leading to an improved determination of the branching fraction at percent level precision and detailed form factor studies. The collaboration also has accumulated 45000 semi-leptonic charged kaon decays $K_{e4}(00)$ to $\pi^0\pi^0 e\nu$, increasing the world available statistics by several orders of magnitude. Background contamination at the one percent level and very good π^0 reconstruction allow the first accurate measurement of the branching fraction and decay form factor. A sample of about 300 $K^{\pm} \to \pi^{\pm}\gamma\gamma$ rare decays with a background contamination below 10% has been collected by the NA48/2 and NA62 experiments at CERN during low intensity runs with minimum bias trigger configuration. The measurements of the rate and decay properties are presented.

XXI International Workshop on Deep-Inelastic Scattering and Related Subjects
22-26 April, 2013
Marseilles, France

[*] Speaker.

[†] for the NA48/2 and NA62 Collaborations: F. Ambrosino, A. Antonelli, G. Anzivino, R. Arcidiacono, W. Baldini, S. Balev, J.R. Batley, M. Behler, S. Bifani, C. Biino, A. Bizzeti, B. Bloch-Devaux, G. Bocquet, V. Bolotov, F. Bucci, N. Cabibbo, M. Calvetti, N. Cartiglia, A. Ceccucci, P. Cenci, C. Cerri, C. Cheshkov, J.B. Chèze, M. Clemencic, G. Collazuol, F. Costantini, A. Cotta Ramusino, D. Coward, D. Cundy, A. Dabrowski, G. D'Agostini, P. Dalpiaz, C. Damiani, H. Danielsson, M. De Beer, G. Dellacasa, J. Derré, H. Dibon, D. Di Filippo, L. DiLella, N. Doble, V. Duk, J. Engelfried, K. Eppard, V. Falaleev, R. Fantechi, M. Fidecaro, L. Fiorini, M. Fiorini, T. Fonseca Martin, P.L. Frabetti, A. Fucci, S. Gallorini, L. Gatignon, E. Gersabeck, A. Gianoli, S. Giudici, A. Gonidec, E. Goudzovski, S. Goy Lopez, E. Gushchin, B. Hallgren, M. Hita-Hochgesand, M. Holder, P. Hristov, E. Iacopini, E. Imbergamo, M. Jeitler, G. Kalmus, V. Kekelidze, K. Kleinknecht, V. Kozhuharov, W. Kubischta, V. Kurshetsov, G. Lamanna, C. Lazzeroni, M. Lenti, E. Leonardi, L. Litov, D. Madigozhin, A. Maier, I. Mannelli, F. Marchetto, G. Marel, M. Markytan, P. Marouelli, M. Martini, L. Masetti, P. Massarotti, E. Mazzucato, A. Michetti, I. Mikulec, M. Misheva, N. Molokanova, E. Monnier, U. Moosbrugger, C. Morales Morales, M. Moulson, S. Movchan, D.J. Munday, M. Napolitano, A. Nappi, G. Neuhofer, A. Norton, T. Numao, V. Obraztsov, V. Palladino, M. Patel, M. Pepe, A. Peters, F. Petrucci, M.C. Petrucci, B. Peyaud, R. Piandani, M. Piccini, G. Pierazzini, I. Polenkevich, I. Popov, Yu. Potrebenikov, M. Raggi, B. Renk, F. Retière, P. Riedler, A. Romano, P. Rubin, G. Ruggiero, A. Salamon, G. Saracino, M. Savrié, M. Scarpa, V. Semenov, A. Sergi, M. Serra, M. Shieh, S. Shkarovskiy, M.W. Slater, M. Sozzi, T. Spadaro, S. Stoynev, E. Swallow, M. Szleper, M. Valdata-Nappi, P. Valente, B. Vallage, M. Velasco, M. Veltri, S. Venditti, M. Wache, H. Wahl, A. Walker, R. Wanke, L. Widhalm, A. Winhart, R. Winston, M.D. Wood, S.A. Wotton, O. Yushchenko, A. Zinchenko, M. Ziolkowski.

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1. Introduction

The study of both K_{e4} and $K^{\pm} \to \pi^{\pm}\gamma\gamma$ decays can provide valuable inputs to test Chiral Perturbation Theory (ChPT). NA48/2 experiment, devoted to the search for CP-violating asymmetry in $K^{\pm} \to 3\pi^{\pm}$ decays [1], has also provided large samples of rare kaon decays in 2003-2004. In 2007-2008, the NA62 experiment [2] (R_K phase) collected a large data sample with the same detector but a modified beam line. A detailed description of the NA48/2 detector elements is available in [3].

Two simultaneous K^+ and K^- beams are 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*) are selected by two systems of dipole magnets, focusing quadrupoles, muon sweepers and collimators. Charged particles from $K^{\pm}$ decays are measured by a magnetic spectrometer consisting of four drift chambers (DCH1–DCH4) and a dipole magnet located between DCH2 and DCH3. The magnetic spectrometer is followed by a scintillator hodoscope. A liquid Krypton calorimeter (LKr) measures the energy of electrons and photons.

The kinematics of the $K^{\pm} \to \pi^+\pi^-e^{\pm}\nu$ (K_{e4}^{+-}) decay is described by five variables [4]: the dipion squared invariant mass S_π, the dilepton squared invariant mass S_e, the angle θ_π of the $\pi^{\pm}$ in the dipion rest frame with respect to the flight direction of dipion in the kaon rest frame, the angle θ_e of the $e^{\pm}$ in the dilepton rest frame with respect to the flight direction of dilepton in the kaon rest frame, and the angle ϕ between the dipion and dilepton planes in the kaon rest frame. The decay amplitude is the product of the leptonic weak current and (V-A) hadronic current.The hadronic current is described in terms of three (F,G,R) axial-vector and one (H) vector complex form factors.

These form factors are developed in a partial wave expansion, limited to S- and P-waves and considering a unique phase δ_p for all P-wave contributions (in absence of CP violating weak phases): $F = F_s e^{i\delta_{fs}} + F_p e^{i\delta_{fp}} cos\theta_\pi$, $G = G_p e^{i\delta_{gp}}$, $H = H_p e^{i\delta_{hp}}$

The decay probability depends only on the form factor magnitudes F_s, F_p, G_p, H_p, a single phase $\delta = \delta_s - \delta_p$ 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 measured 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.

For the $K^{\pm} \to \pi^0\pi^0e^{\pm}\nu$ (K_{e4}^{00}) decay mode, the matrix element doesn't depend on θ_π and ϕ angles. It includes the only form factor F_s with a possible variation with S_π and S_e.

2. K_{e4}^{+-} results

The hadronic form factors in the S- and P-wave and their variation with energy have been obtained concurrently with the phase difference between the S- and P-wave states of the $\pi\pi$ system, leading earlier to the precise determination of a_0^0 and a_2^0, the I=0 and I=2 S-wave $\pi\pi$ scattering lengths [6].

A high precision measurement of K_{e4}^{+-} normalized (divided by f_s) form factor parameters has been published by NA48/2 in [7]. Their absolute values can be obtained from the branching ratio measurement. Details of this new K_{e4}^{+-} branching ratio measurement by NA48/2 can be found in [8].

The K_{e4}^{+-} rate is measured relative to the $K^{\pm} \to \pi^{+}\pi^{-}\pi^{\pm}$ ($K_{3\pi}^{+-}$) normalization channel.The K_{e4} and $K_{3\pi}$ candidates are reconstructed from three charged tracks consistent with the same decay vertex. Kinematic separation from signal and normalization is obtained by requiring (or not) missing mass and missing transverse momentum in the 3π decay hypothesis. Electron identification criteria require track momentum larger than 2.75 GeV/c , $0.9 < E(LKr)/p(DCH) < 1.1$ and associated LKr shower properties consistent with the electron hypothesis. Pion identification criteria require track momentum larger than 5 GeV/c and $E(LKr)/p(DCH) < 0.8$.

A total sample of about 1.1 million K_{e4}^{00} candidates (one electron track $e^{\pm}$ and two opposite sign pions) and about 19 millions of prescaled $K_{3\pi}$ candidates (three charged pions with total charge ±1) were selected from data recorded in 2003-2004.

There are two main background sources: $K^{\pm} \to \pi^{+}\pi^{-}\pi^{\pm}$ 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. The total background contribution is below 1% of the signal.

A detailed GEANT3-based [10] Monte Carlo simulation was used to compute acceptances, taking into account full detector geometry, DCH alignment, local inefficiencies and beam properties. The resulting K_{e4}^{+-} branching fraction is found to be $BR(K_{e4}^{+-}) = (4.257 \pm 0.004_{stat} \pm 0.016_{syst} \pm 0.031_{ext})10^{-5}$, three times more precise than the current PDG value [9]. The external error, from the uncertainty of the normalization channel branching ratio, dominates the total error of the measurement.

The measured branching fraction has been used to extract f_s normalization form factor and all the absolute values of hadronic form factor parameterization coefficients.

3. K_{e4}^{00} decay studies

The K_{e4}^{00} rate is measured relative to $K^{\pm} \to \pi^{0}\pi^{0}\pi^{\pm}$ ($K_{3\pi}^{00}$) normalization channel. These two samples are collected with the same trigger logics, highly efficient for this event topology. A common event selection was considered as far as possible.

Events with at least four γ, detected by LKr, and at least one track, reconstructed from spectrometer data, were regarded as K_{e4}^{00} or $K_{3\pi}^{00}$ candidates. Every combination of two γ pairs, detected by LKr, was considered as a pair of π^{0}. Reconstructed longitudinal positions of both $\pi^{0} \to 2\gamma$ decay candidates were required to coincide within 500 cm, and their average position Z_n was in the fiducial volume.

Decay longitudinal position Z_{ch}, assigned to every 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, was required to have the difference between these two measured longitudinal positions $|Z_n - Z_{ch}|$ less than 800 cm.

Pion and electron identification was the same as in K_{e4}^{+-} case (see Section 2). K_{e4}^{00} and $K_{3\pi}^{00}$ 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 $K_{3\pi}^{0}$ hypothesis, and p_t is the transversal momentum.

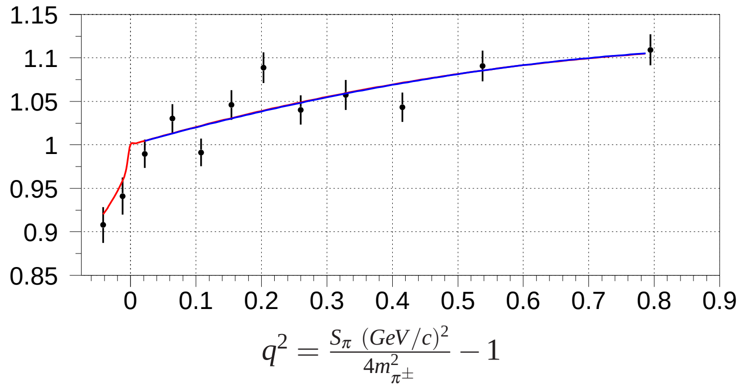

Figure 1: K^{00}_{e4} normalized form factor squared F^2_S/f^2_s. Below $S_\pi = (2m_{\pi^\pm})^2$ the curve takes into account the lowest order $\pi\pi$ rescattering contribution from [11].

Elliptic cut separates about 70 million $K^{00}_{3\pi}$ normalization events from 45000 K^{00}_{e4} candidates. Residual fake-electron background is about 1.3% of K^{00}_{e4} signal. Background from $K^{00}_{3\pi}$ with the subsequent $\pi^{\pm} \to e^{\pm}\nu$ is 0.1% of the signal, that is a small fraction of total background.

The preliminary result has been obtained: $Br(K^{00}_{e4}) = (2.595 \pm 0.012_{stat} \pm 0.024_{syst} \pm 0.032_{ext})10^{-5}$. This measurement is 10 times more precise, than the current PDG corresponding value [9]. Systematic error includes the contributions from background uncertainty, simulation statistical error, sensitivity to form factor, radiation correction simulation effect, trigger efficiency and beam geometry uncertainties. External error comes from PDG 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 (Fig. 1). It is very 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), investigated by NA48/2 experiment recently [6] on the basis of advanced ChPT formulations.

4. $K^{\pm} \to \pi^{\pm}\gamma\gamma$ results

Measurements of radiative non-leptonic kaon decays provide stringent tests of ChPT. In this framework, the $K^{\pm} \to \pi^{\pm}\gamma\gamma$ decay receives two non-interfering contributions at lowest non-trivial order $\mathscr{O}(p^4)$: the pion and kaon *loop amplitude* depending on an unknown $\mathscr{O}(1)$ 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 with 60 GeV/c $K^{\pm}$ beams, and a 3-month NA62 run in 2007 with 74 GeV/c $K^{\pm}$ beams. Signal events are selected in the region $z = (m_{\gamma\gamma}/m_K)^2 > 0.2$ to reject the $K^{\pm} \to \pi^{\pm}\pi^0$ background peaking at $z = 0.075$. 147 (175) decays candidates are observed in the 2004 (2007) data set, with backgrounds contaminations of 12% (7%) from $K^{\pm} \to \pi^{\pm}\pi^0(\pi^0)(\gamma)$ decays with merged photon clusters in the electromagnetic calorimeter.

The characteristic z distributions are displayed in Figure 2. The values of the $\hat{c}$ parameter in the framework of the ChPT $\mathscr{O}(p^4)$ and $\mathscr{O}(p^6)$ parameterizations according to [13] have been measured by performing likelihood fits to the data. The preliminary combined results of the fits based on 2004 and 2007 runs data are in agreement with the earlier BNL E787 (31 events, [14])

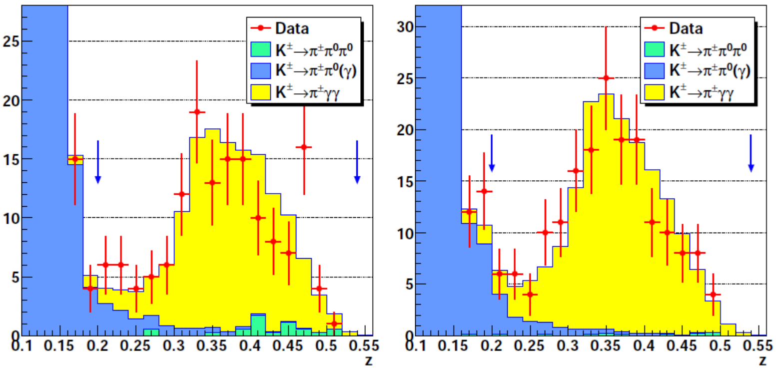

Figure 2: Characteristic z distributions with MC expectations for signal and backgrounds: 2004 data (left) and 2007 data (right). The signal region is indicated with arrows.

ones: $\hat{c}$ for $\mathscr{O}(p^4)$ fit = 1.56 ± 0.23; $\hat{c}$ for $\mathscr{O}(p^6)$ fit = 2.00 ± 0.26; branching fraction for $\mathscr{O}(p^6)$ fit = $(1.01 \pm 0.06) \times 10^{-6}$.

5. Conclusion and future prospects

New measurements of the K_{e4}^{+-} and K_{e4}^{00} branching ratios have been obtained at improved precision by the NA48/2 experiment. First results on F_S form factor of K_{e4}^{00} are consistent with the K_{e4}^{+-} corresponding measurement within the current statistics. The branching ratio and form factor parameter of the $K^{\pm} \to \pi^{\pm}\gamma\gamma$ decay are obtained at improved precision.

Future prospects include the observation of several thousand decays in similar muonic modes $K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$ (never observed) and $K^{\pm} \to \pi^+\pi^-\mu^{\pm}\nu$ (7 events observed).

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