TESTS OF CHIRAL PERTURBATION THEORY WITH K_{e4} DECAYS AT NA48/2*

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The experiment NA48/2 at CERN SPS performed high precision measurement of the form factors of $K^{\pm} \to \pi^+\pi^- e^{\pm}\nu$ decays and s-wave $\pi\pi$ scattering lengths a_0 and a_2 for isospin 0 and 2, respectively. The preliminary result on the full available statistics of more than 1 million K_{e4}^{+-} decays achieves a precision similar to the theoretical one and provides excellent test of Chiral Perturbation Theory.

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1. Introduction

In Chiral Perturbation Theory (ChPT), the quark condensate $\langle \bar{q}q \rangle_0$ determines the relative size of mass and momentum terms in the perturbative expansion. The value of this fundamental parameter must be determined experimentally. ChPT relates the quark condensate to s-wave $\pi\pi$-scattering lengths in isospin states $I = 0$ and $I = 2$, a_0 and a_2, which are predicted with 2% precision [1]. The decays $K^{\pm} \to \pi^+\pi^- e^{\pm}\nu$ (K_{e4}^{+-}) provide a clean access to a_0 and a_2, since the two pions are the only hadrons and they are produced close to threshold. In 1977 the Geneva–Saclay Collaboration at CERN/PS performed such a measurement based on $\sim 30000 K_{e4}^{+}$ decays [2], and more recently the E865 Collaboration at BNL measured a_0 and a_2 on $\sim 400\,000 K_{e4}^{+}$ decays [3].

The experiment NA48/2 at CERN/SPS collected very large sample of simultaneously recorded K^+ and K^- decays, allowing to study many interesting processes in kaon physics. In this experiment the $\pi\pi$ scattering lengths were measured in two ways: *(i)* by studying the "cusp"-like structure in the spectrum of the $\pi^0\pi^0$ invariant mass around $M_{00}^2 = 4m_{\pi^+}^2$ in

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$K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ decays, observed for the first time by NA48/2; *(ii)* by studying the phase shift in K_{e4}^{+-} decays. The results on part of the statistics have been published for both measurements [4, 5].

2. Beam and experimental setup

The beam line of NA48/2 experiment is designed to deliver simultaneously K^+ and K^-, produced on a beryllium target from SPS primary protons[1]. The beams of $60 \pm 3\,\mathrm{GeV}/c$ momentum are selected by a system of magnetic elements. After final cleaning and collimation the two beams enter 114 m long decay volume, where they coincide within 1 mm. The decay products are then identified and measured in the detector of the experiment [7]. The momenta of charged particles are measured by magnetic spectrometer consisting of four drift chambers and a dipole magnet. The resolution of the spectrometer is $\sigma(p)/p = 1.0\% \oplus 0.044\%\, p$ (p in GeV/c), which provides very good mass resolution for charged particle final states (for example $\sigma(M_{\pi^{\pm}\pi^{+}\pi^{-}}) = 1.7\ \mathrm{MeV}/c^2$). A scintillator hodoscope, located after the spectrometer, sends fast trigger signals from charged particles and measures their time with a resolution of 150 ps. The electromagnetic energy of particles is measured by a liquid krypton calorimeter, a quasi-homogeneous ionisation chamber with an active volume of $10\,\mathrm{m}^3$. The energy resolution is $\sigma(E)/E = 0.032/\sqrt{E} \oplus 0.09/E \oplus 0.0042$ and the spatial resolution in the transverse coordinates x and y for a single electromagnetic shower $\sigma_x = \sigma_y = 0.42/\sqrt{E} \oplus 0.06\,\mathrm{cm}$ (E in GeV). A muon detector is also used in the analysis as a veto system against $\pi \to \mu\nu$ decays. The trigger system of NA48/2 is organised in two levels: the first level requires specific signals from the detectors, while the second one performs on-line processing of the information from the spectrometer and basic reconstruction of the decay, after which the decision whether or not to keep the event is taken.

The experiment took data in 2003 and 2004 for 110 days in total. The ratio of K^+ and K^- fluxes is ~ 1.8.

3. K_{e4}^{+-} selection and background

The selection of K_{e4}^{+-} topologies requires three charged tracks forming a common vertex. Only one of them should be consistent with the electron hypothesis, *i.e.* an associated energy deposit in the calorimeter consistent with the measured track momentum. The other two tracks should have opposite signs and are considered pions (unless they give signal in muon detector). Specific cuts are adopted to enhance the efficiency of electron–pion separation and to keep the background at low level. The main source of

[1] More detailed description and schematic of the beam line can be found in [6].

background is $K^\pm \to \pi^\pm\pi^+\pi^-$ with $\pi \to e\nu$ decays or pion misidentified as an electron. The suppression of these decays is achieved by requiring the event to be outside an ellipse in the $(p_\mathrm{t}, M_{3\pi})$ plane (where p_t and $M_{3\pi}$ are the transverse momentum and the invariant mass of the three charged particles under the 3π hypothesis) centred at $(0,M_K)$, with semi-axes ± 35 MeV$/c$ and ± 20 MeV$/c^2$. $K^\pm \to \pi^\pm\pi^0(\pi^0)$ also can fake the signal in case of subsequent Dalitz decay of a π^0, a lost photon and one electron misidentified as pion. The decays $K^\pm \to \pi^+\pi^- e^\mp\nu$ (called "wrong sign" events (WS)) are highly suppressed by the $\Delta S = \Delta Q$ rule. They can be used to evaluate the background contribution. According to the relative misidentification probability the amount of background is $2\times$ WS if coming from $K^\pm \to \pi^\pm\pi^+\pi^-$ and $1\times$ WS if coming from $K^\pm \to \pi^\pm\pi^0(\pi^0)$ decays. The relative level of background obtained with WS events to the signal is $\sim 0.5\%$, which has been crosschecked with Monte Carlo simulation of the contributing decays.

The total amount of selected K_{e4}^{+-} decays is 1.15 million.

4. K_{e4}^{+-} analysis and results

The form factors of K_{e4}^{+-} decay can be parameterized as a function of five kinematic variables [8]: the invariant masses $M_{\pi\pi}$ and $M_{e\nu}$, and the angles θ_π, θ_e and ϕ (see Fig. 1). The hadronic part of the matrix element can be

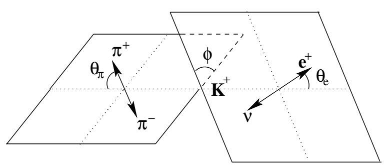


Fig. 1. Definition of the angular kinematic variables which describe the K_{e4} decays.

described in terms of two axial[2] (F and G) and one vector (H) complex form factors [9]. Their expansions into partial s and p waves (neglecting d waves and assuming isospin symmetry) are further developed in Taylor series in $q^2 = M_{\pi\pi}^2/4m_{\pi^\pm}^2 - 1$ and $M_{e\nu}^2/4m_\pi^2$. This allows to determine the form factor parameters from the experimental data [10, 11]:

$$F = F_s e^{i\delta_s} + F_p \cos\theta_\pi e^{i\delta_p}\,, \qquad G = G_p e^{i\delta_g}\,, \qquad H = H_p e^{i\delta_h},$$

where $$F_s = f_s + f_s' q^2 + f_s'' q^4 + f_e' M_{e\nu}^2/4m_\pi^2\,, \qquad F_p = f_p + f_p' q^2 + \ldots\,,$$

$$G_p = g_p + g_p' q^2 + \ldots\,, \qquad H_p = h_p + h_p' q^2 + \ldots\,.$$

[2] The third axial form factor R is not accessible with $Ke4$, being suppressed by $m_e^2/M_{e\nu}^2$.

Since in this analysis the branching fraction of K_{e4}^{+-} is not measured, only relative form factors with respect to f_s are accessible.

The following method is used to extract the form factor parameters: In a first step, $10 \times 5 \times 5 \times 5 \times 12$ iso-populated bins are defined in ($M_{\pi\pi}$, $M_{e\nu}$, $\cos\theta_\pi$, $\cos\theta_e$, ϕ) space. With 739 000 K_{e4}^{+} and 411 000 K_{e4}^{-} selected candidates each box is filled with 49 K_{e4}^{+} and 27 K_{e4}^{-} events. For each bin in $M_{\pi\pi}$, comparing data and Monte Carlo simulation, ten independent five-parameter ($F_s, F_p, G_p, H_p, \delta = \delta_s - \delta_p$) fits are performed. In the second step, the variation of each fitted parameter with $M_{\pi\pi}$ is used to extract the form factor parameters using the above relations[3].

The Monte Carlo sample contains 25 times larger statistics than the data sample. The simulation is based on GEANT3 and takes into account geometrical acceptance of the detectors, resolution effects and time-dependent imperfections. Coulomb corrections are considered in the simulation as well as the emission of real radiative photons, as described by the PHOTOS package [12].

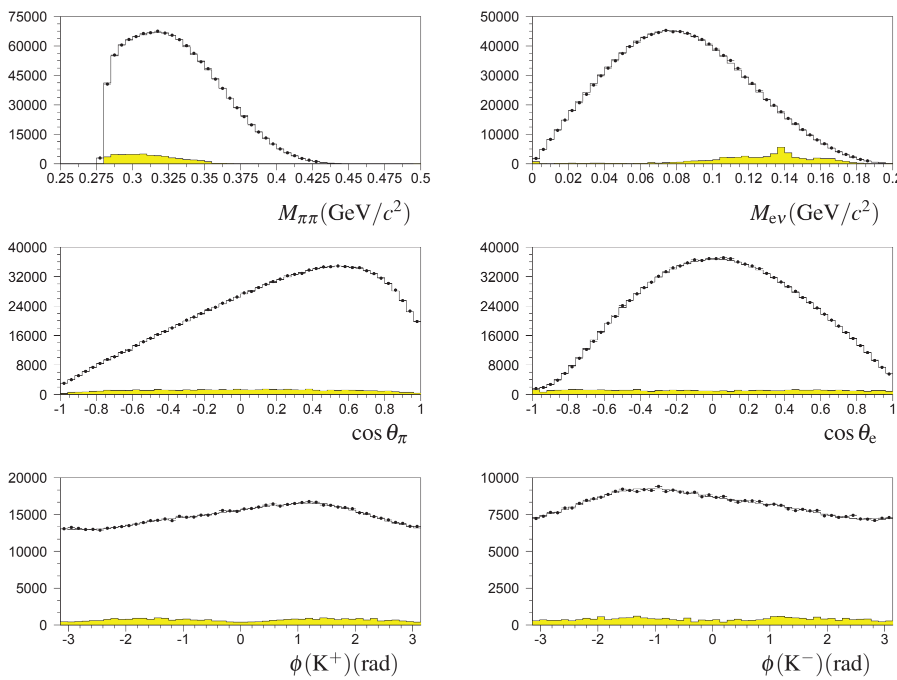


Fig. 2. Comparison between data after background subtraction (dots) and simulation (histogram) for the best form factor fit. The shaded area corresponds to the background contribution multiplied by 10.

[3] For the F_p and H_p a constant term is sufficient for a good fit.

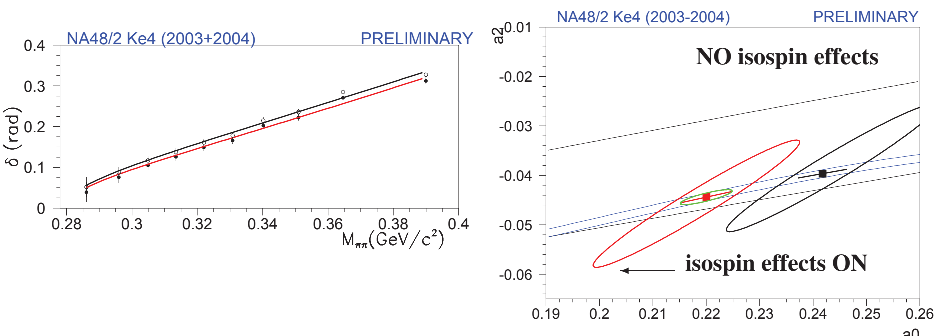
The comparison between data and Monte Carlo simulation for the best fits is shown in Fig. 2.

The following preliminary results are obtained:

$$\begin{aligned}
f'_s/f_s &= 0.158 \pm 0.007_{\rm stat} \pm 0.006_{\rm syst}\,, \\
f''_s/f_s &= -0.078 \pm 0.007_{\rm stat} \pm 0.007_{\rm syst}\,, \\
f'_e/f_s &= 0.067 \pm 0.006_{\rm stat} \pm 0.009_{\rm syst}\,, \\
f_p/f_s &= -0.049 \pm 0.003_{\rm stat} \pm 0.004_{\rm syst}\,, \\
g_p/f_s &= 0.869 \pm 0.010_{\rm stat} \pm 0.012_{\rm syst}\,, \\
g'_p/f_s &= 0.087 \pm 0.017_{\rm stat} \pm 0.015_{\rm syst}\,, \\
h_p/f_s &= -0.402 \pm 0.014_{\rm stat} \pm 0.008_{\rm syst}\,.
\end{aligned}$$

The systematic errors are conservatively taken from the published results on 2003 data sample [4] and are mostly statistically limited.

Scattering lengths are extracted from the q^2 dependence of $\delta = \delta_s - \delta_p$ by using numerical solutions of Roy equations [13, 14]. The unprecedented precision of NA48/2 result on part of the statistics triggered theoretical work on determination of the effect of isospin symmetry breaking on phase shift [15]. The size of the correction on δ is ~10 mrad (Fig. 3(a)) and the resulting change of a_0 and a_2 is ~2 standard deviations (Fig. 3(b)).



(a) (b)

Fig. 3. (a) Phase shift variation with q^2 without (upper curve and open circles) and with (lower curve and full dots) isospin correction. The lines correspond to a two-parameter fit; (b) corresponding scattering lengths in (a_0,a_2) plane. The symbols show the one-parameter fit result. The smallest ellipse corresponds to the best ChPT prediction, which is in remarkable agreement with the experimental result with isospin effects taken into account.

Using a fit with both a_0 and a_2 as free parameters, the results are:

$$\begin{aligned}
a_0 &= 0.218 \pm 0.013_{\rm stat} \pm 0.007_{\rm syst} \pm 0.004_{\rm theo}\,, \\
a_2 &= -0.0457 \pm 0.0084_{\rm stat} \pm 0.0041_{\rm syst} \pm 0.028_{\rm theo}\,,
\end{aligned}$$

with a correlation of 96.7%. Using the ChPT constraint ($a_2 + 0.0444 = 0.236(a_0 - 0.22) - 0.61(a_0 - 0.22)^2 - 9.9(a_0 - 0.22)^2 \pm 0.0008$) leads to the following result for the only free parameter a_0:

$$a_0 = 0.220 \pm 0.005_{\rm stat} \pm 0.002_{\rm syst} \pm 0.006_{\rm theo} \,.$$

The theoretical error comes from the control of isospin corrections and inputs to the Roy equations. The above results are in excellent agreement with the prediction of ChPT [16]: $a_0 = 0.220 \pm 0.005$ and $a_2 = -0.0444 \pm 0.0010$.

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