QCD Tests at the NA48/2 experiment at CERN

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Abstract

Very large statistics of charged kaon decays have been accumulated in 2003-2004 by the NA48/2 experiment at the CERN SPS. The analyses of $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$ ($K_{3\pi}$) and $K^{\pm} \to \pi^+\pi^- e^{\pm}\nu$ (K_{e4}) decays give complementary approaches to the study of low energy $\pi\pi$ scattering. From data samples of ∼60 millions $K_{3\pi}$ and ∼1 million K_{e4} decays, precise values of a_0 and a_2, the isospin 0 and 2 S-wave $\pi\pi$ scattering lengths, can be extracted with an unprecedented experimental precision of few percents, allowing accurate tests of Chiral Perturbation Theory predictions.

Key words: Ke4 decays, cusp, pi-pi scattering length, pi-pi rescattering, Chiral Perturbation Theory
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1. Introduction

In the past years, K_{e4} decays were traditionally the cleanest laboratory to study $\pi\pi$ scattering close to threshold and extract the values of the S-wave scattering lengths. Two experiments [1] collected sizable samples of such decays, the Geneva-Saclay collaboration at the CERN/PS (30000 K^+ decays) and the E865 collaboration at BNL (∼ 400000 K^+ decays). The NA48/2 collaboration at the CERN/SPS has collected more than one million decays in both charge modes in 2003-2004. Results from a partial sample have been published in [2]. From ∼23 millions decays collected in the $K_{3\pi}$ mode, the NA48/2 collaboration has shown experimental evidence of a cusp-like structure in the $\pi^0\pi^0$ mass distribution at the $\pi^+\pi^-$ threshold [3]. This effect was interpreted as mainly due to charge exchange rescattering of the $\pi^+\pi^-$ system to $\pi^0\pi^0$, allowing an independent measurement of the $\pi\pi$ S-wave scattering lengths. Both analyses triggered new developments in close collaboration between experiment and theory groups. Results based on the full

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data samples will be presented here. The form factors and $\pi\pi$ phase shift which characterize the K_{e4} decay are measured simultaneously and the S-wave $\pi\pi$ scattering lengths are then extracted with an improved precision using recent theoretical work [4] including isospin symmetry breaking mass effects. The slopes of the $K_{3\pi}$ Dalitz Plot are determined together with the S-wave $\pi\pi$ scattering lengths and rely also on refined theoretical calculations [5,6]. Both new results are compared to the precise predictions from Chiral Perturbation Theory (ChPT).

2. Analysis of K_{e4} decays

The 1.1 million event sample is distributed over a grid of (10 x 5 x 5 x 5 x 12) equal population boxes in the five-variable space which describes the decay kinematics: two invariant masses $M_{\pi\pi}$ and $M_{e\nu}$ and three angles θ_π, θ_e and Φ. Two axial (F, G) and one vector (H) complex form factors contribute to the transition amplitude and are further developed in partial waves identified to the phases of the $\pi\pi$ scattering [7]. The decay is then described by four real form factors (FF $= F_s,\ F_p,\ G_p,\ H_p$) and one phase shift ($\delta = \delta_s - \delta_p$) which are measured in the ten independent $M_{\pi\pi}$ bins and do not depend upon any particular model. Detailed numerical values of the Taylor expansion coefficients used to describe the FF variations with masses can be found in [8]. After subtraction of isospin mass effects, numerical solutions of Roy equations [9] are used to extract scattering lengths from the phase measurements in a 2-parameter fit:

$$a_0 = \quad 0.218 \quad \pm 0.013_{\rm stat} \pm 0.007_{\rm syst} \quad \pm 0.017_{\rm theo} \ ,$$

$$a_2 = -0.0457 \pm 0.0084_{\rm stat} \pm 0.0041_{\rm syst} \pm 0.030_{\rm theo} \ ,$$

as illustrated in Figure 1. Using the ChPT constraint [10] to relate a_2 and a_0, the value from the 1-parameter fit becomes: $a_0 = 0.220 \pm 0.005_{\rm stat} \pm 0.002_{\rm syst} \pm 0.006_{\rm theo}$.

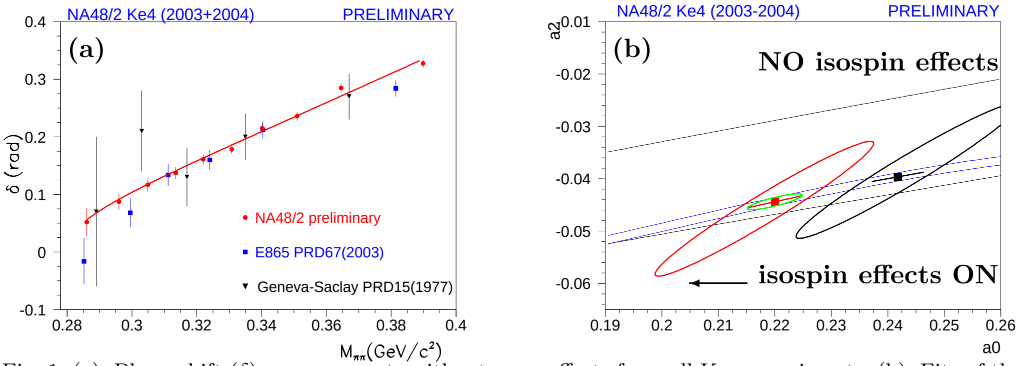

Fig. 1. (a): Phase shift (δ) measurements without mass effects from all K_{e4} experiments. (b): Fits of the NA48/2 K_{e4} data in the (a_0,a_2) plane without (black) and with (red) isospin mass effects. The symbols are the result of the one-parameter fit imposing the ChPT constraint. There is impressive agreement with the small (green) ellipse which corresponds to the most accurate prediction from ChPT.

3. Analysis of $K_{3\pi}$ decays

Two theoretical approaches have been developed using different formalisms and ingredients [5,6] to describe the decay amplitude together with one and two-loop rescattering effects. In both approaches, the M^2_{00} distribution is fitted, using the detector response matrix obtained from a large Monte-Carlo simulation, to extract the scattering lengths $a_0 - a_2$, a_2 and the Dalitz plot slopes g_0, h'_0 and k'_0 (details can be found in [8]). Using the ChPT relation [10], both models lead to consistent values from the constrained fit:

$$a_0 - a_2 = 0.267 \pm 0.003_{\rm stat} \pm 0.002_{\rm syst} \pm 0.001_{\rm ext} \pm 0.013_{\rm theo}.$$

The M^2_{00} distribution and the scattering length results are shown in Figure 2.

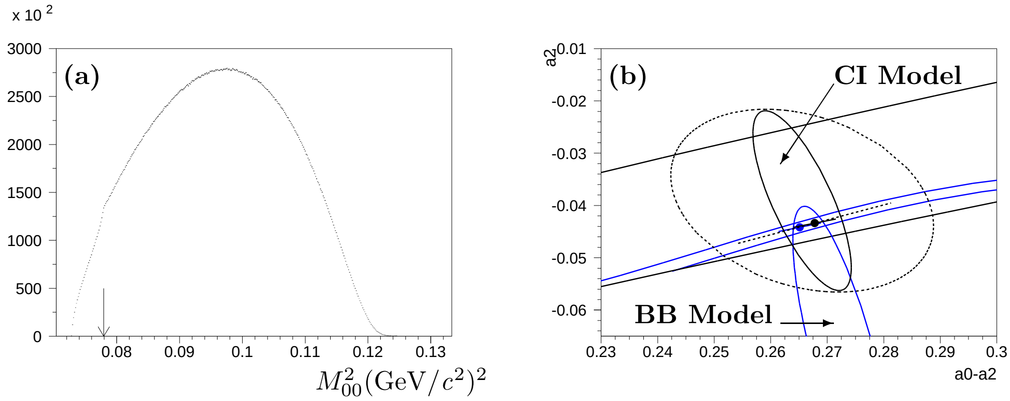

Fig. 2. (a): Invariant $\pi^0\pi^0$ mass squared. The arrow shows the cusp position. (b): $K_{3\pi}$ NA48/2 measurements in the (a_0-a_2, a_2) plane for the two models CI (Cabibbo-Isodori [5]) and BB (Bern-Bonn [6]). The symbols correspond to the constrained fit and the large ellipse to the conservative theory uncertainty.

4. Conclusion

The NA48/2 experiment has analyzed ∼one million K_{e4} decays and ∼60 millions $K_{3\pi}$ decays to extract the isospin 0 and 2 S-wave $\pi\pi$ scattering lengths with an experimental error of few percents, a factor three better than previous results [1]. With the help of dedicated calculations, developed in close collaboration between experiment and theory, precise results have been obtained: $a_0 = 0.220 \pm 0.005 \pm 0.006_{\rm theo}(K_{e4})$ and $a_0 - a_2 = 0.267 \pm 0.004 \pm 0.013_{\rm theo}(K_{3\pi})$, confirming the predictions of Chiral Perturbation Theory computed with similar precision: $a_0 = 0.220 \pm 0.005_{\rm theo}$, $a_0 - a_2 = 0.265 \pm 0.004_{\rm theo}$.

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