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Precision study of $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ and $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ Dalitz plot distributions by NA48/2

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The NA48/2 experiment at the CERN SPS has collected an unprecedented sample of $K^{\pm} \to 3\pi$ decays. The high statistics and the good resolution of the detectors allow a unique investigation of the detailed phase space distributions of these decays. The effects of final state pion rescattering observed in the Dalitz plot distribution of the $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ decays turned out to be a powerful tool for extraction of the S-wave $\pi\pi$ scattering lengths. The large statistics also allowed a precise measurement of the Dalitz plot slope parameters for the $K^{\pm} \to 3\pi^{\pm}$ decays.

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Introduction

The primary goal of the NA48/2 experiment at the CERN SPS is the search for direct CP violation in $K^\pm \to 3\pi$ decays [1]. Data have been collected in 2003–04, providing samples of $\sim 4\times10^9$ fully reconstructed $K^\pm \to 3\pi^\pm$ and $\sim 10^8$ $K^\pm \to \pi^\pm\pi^0\pi^0$ decays. Surprisingly, a study of a partial sample of $K^\pm \to \pi^\pm\pi^0\pi^0$ decays corresponding to about 25% of the total sample revealed an anomaly in the $\pi^0\pi^0$ invariant mass (M_{00}) distribution in the region around $M_{00} = 2m_+$, where m_+ is the charged pion mass [2]. This anomaly, dubbed "cusp effect", never observed in previous experiments, was theoretically interpreted as an effect due mainly to the final state charge exchange scattering process $\pi^+\pi^- \to \pi^0\pi^0$ in $K^\pm \to 3\pi^\pm$ decay, and was shown to provide a precise determination of $a_0 - a_2$, the difference between the S-wave $\pi\pi$ scattering lengths in the isospin $I = 0$ and $I = 2$ states [3]. A number of theoretical approaches to describe this process are being developed; the original NA48/2 measurement of $a_0 - a_2$ was performed in the framework of the approach [4]. The current paper presents a new step of the analysis, namely a preliminary result of a measurement based on the full NA48/2 data sample within the same theoretical framework.

In addition, a measurement of the Dalitz plot slopes of the $K^\pm \to 3\pi^\pm$ decay based on a partial NA48/2 data sample is presented.

1. NA48/2 experimental setup

Two simultaneous K^+ and K^- beams are produced by 400 GeV protons impinging on a 40 cm long Be target. Particles with a central momentum of 60 GeV/c and a momentum band of $\pm3.8\%$ produced at zero angle are selected by a system of dipole magnets forming an "achromat" with null total deflection, focusing quadrupoles, muon sweepers and collimators. With 7×10^{11} protons per burst of 4.5 s duration incident on the target the positive (negative) beam flux at the entrance of the decay volume is 3.8×10^7 (2.5×10^7) particles per pulse, of which 5.7% (4.9%) are K^+ (K^-). The decay volume is a 114 m long vacuum tank.

Charged particles from $K^\pm$ decays are measured by a magnetic spectrometer consisting of four drift chambers and a large-aperture dipole magnet located between the second and third chamber. Each chamber has eight planes of sense wires: two horizontal, two vertical and two along each of two orthogonal 45° directions. The spectrometer is located in a tank filled with helium at atmospheric pressure and separated from the decay volume by a thin ($0.31\% X_0$) Kevlar window. A 16 cm diameter vacuum tube centered on the beam axis runs through the spectrometer and subsequent detectors. Charged particles are magnetically deflected in the horizontal plane by an angle corresponding to a transverse momentum kick of 120 MeV/c. The momentum resolution of the spectrometer is $\sigma(p)/p = 1.02\% \oplus 0.044\% p$ (p in GeV/c). The spectrometer is followed by a scintillator hodoscope consisting of two planes segmented into horizontal and vertical strips.

A liquid krypton calorimeter is used to reconstruct $K^\pm \to \pi^\pm\pi^0\pi^0$ decays. It is an almost homogeneous ionization chamber with an active volume of 7 m^3 of liquid krypton, segmented transversally into 13248 projective cells of 2×2 cm^2 by a system of Cu-Be ribbon electrodes, and with no longitudinal segmentation. The calorimeter is $27X_0$ thick and has an energy resolution $\sigma(E)/E = 0.032/\sqrt{E} \oplus 0.09/E \oplus 0.0042$ (E in GeV). Spatial resolution for a single electromagnetic shower is $\sigma_x = \sigma_y = 0.42\%/\sqrt{E} \oplus 0.06$ cm for each transverse coordinate x, y.

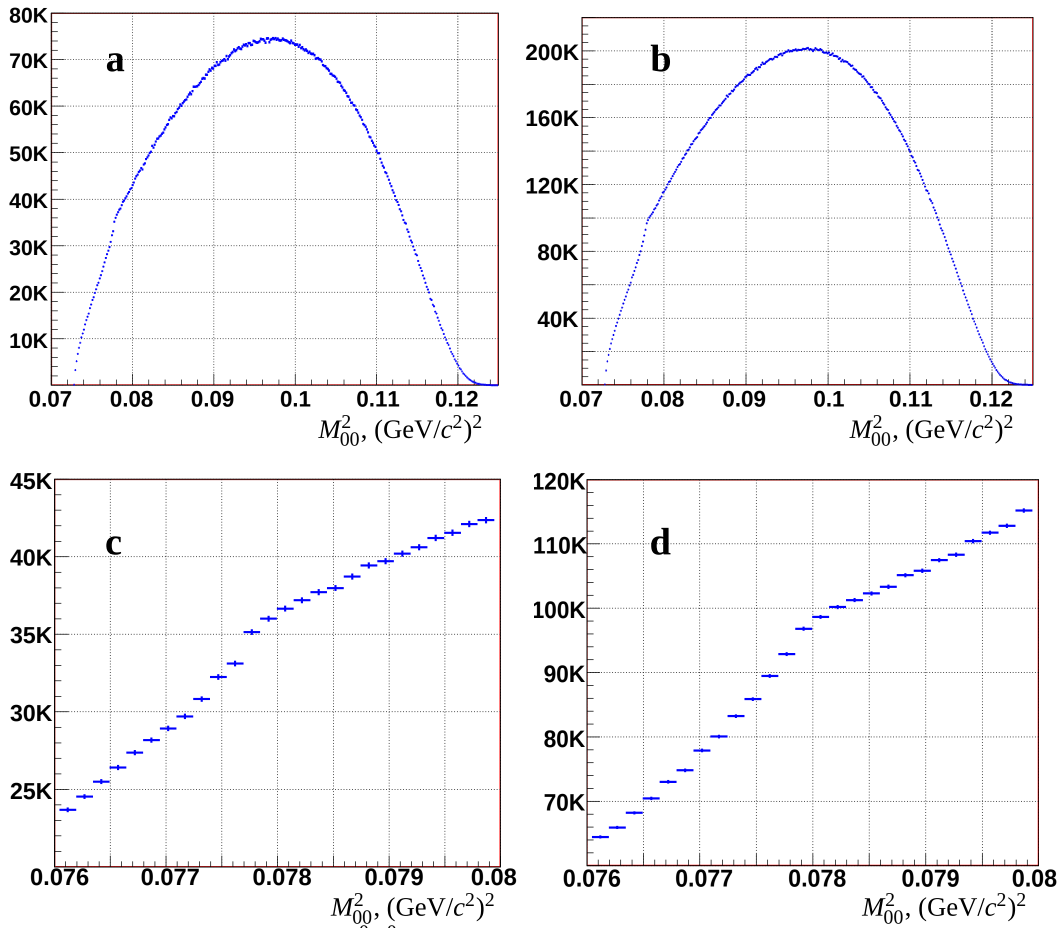

Figure 1: Reconstructed spectra of $\pi^0\pi^0$ invariant mass showing evidence for the cusp effect: the full kinematic range for (a) 2003 data (16.0×10^6 events), (b) 2004 data (43.6×10^6 events); zoomed threshold region for (c) 2003 data, (d) 2004 data. The 2003 plots correspond to the original discovery of the effect [2], while the 2004 plots correspond to the progress with respect to the original analysis.

A detailed description of the components of the NA48 detector can be found elsewhere [5].

2. Cusp effect and measurement of pion scattering lengths

The reconstructed spectra of $\pi^0\pi^0$ invariant mass M_{00} for 2003 and 2004 data samples (totally 59.6×10^9 events) are presented in Fig. 1. The change of slope at $\pi^+\pi^-$ threshold is clearly visible. For description of this effect the $K^\pm \to \pi^\pm\pi^0\pi^0$ amplitude is presented as a sum of two terms:

$$\mathcal{M} = \mathcal{M}_0 + \mathcal{M}_1, \tag{2.1}$$

where $\mathcal{M}_0$ is the "unperturbed" amplitude expressed as a polynomial expansion in terms of the kinematic variables $u = (s_3 - s_0)/m_+^2$ and $v = (s_1 - s_2)/m_+^2$, where $s_i = (P_K - P_i)^2$, $s_0 = (s_1 + s_2 + s_3)/3$, P_K and P_i are 4-momenta of kaon and pions, and $i = 1,2$ correspond to the two "even" (i.e. identical) pions:

$$\mathcal{M}_0(u,v) = \mathcal{M}_0(0,0)\cdot(1 + g_0u/2 + h'u^2/2 + k'v^2/2), \tag{2.2}$$

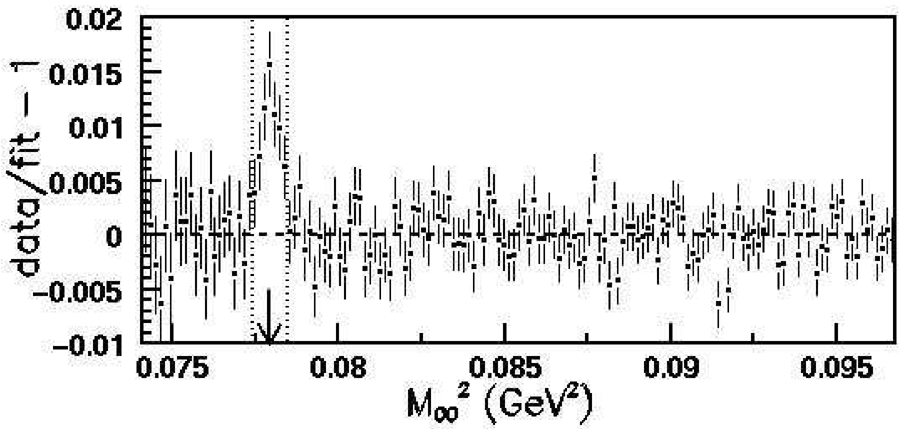

Figure 2: Deviation of the data spectrum from the fit result with statistical errors (combined 2003+2004 data set): $\Delta = Data/Fit - 1$. Good quality of the fit and an excess of events in the region of the threshold are demonstrated.

and $\mathscr{M}_1$ is a contribution from the $K^\pm \to 3\pi^\pm$ decay amplitude $\mathscr{M}_+$ through $\pi^+\pi^- \to \pi^0\pi^0$ charge exchange, which in particular simplest case of the original Cabibbo theory [3] is given by

$$\mathscr{M}_1 = -2a_x m_+ \mathscr{M}_+ \sqrt{1-(M_{00}/2m_+)^2}. \tag{2.3}$$

Here, in the limit of exact isospin symmetry, $a_x = (a_0 - a_2)/3$. The amplitude $\mathscr{M}_1$ changes from real to imaginary at the threshold $M_{00} = 2m_+$; as a consequence it interferes destructively with $\mathscr{M}_0$ below the threshold (leading to 13% integral depletion in this region), and adds quadratically above the threshold.

The model used for the present measurement is based on the formulation [4], which takes into account all rescattering precesses at the one-loop and two-loop level. In this approach the matrix element of the $K^\pm \to \pi^\pm\pi^0\pi^0$ decay includes a number of additional terms depending on five S-wave $\pi\pi$ scattering lengths (corresponding to the processes $\pi^+\pi^- \to \pi^0\pi^0$, $\pi^+\pi^+ \to \pi^+\pi^+$, $\pi^+\pi^- \to \pi^+\pi^-$, $\pi^+\pi^0 \to \pi^+\pi^0$ and $\pi^0\pi^0 \to \pi^0\pi^0$) expressed as linear combinations of a_0 and a_2. In addition to [4], isospin breaking effects are taken into account introducing a single parameter $\varepsilon = (m_+^2 - m_0^2)/m_+^2 = 0.065$ [6].

The fit to extract the scattering lengths and Dalitz plot slopes g_0, h' was performed in the M_{00} projection of the data using a full GEANT-based Monte Carlo simulation of the detector response. The used rescattering model does not include radiative corrections, which are particularly important at the threshold $M_{00} = 2m_+$, and contribute to formation of $\pi^+\pi^-$ atoms (pionium). Thus a group of seven bins near the threshold has been excluded from the fit. The quality of the fit ($\chi^2/\mathrm{NDF} = 164/139$ for 2003 analysis, and $\chi^2/\mathrm{NDF} = 119/139$ for 2004 analysis) illustrated in Fig. 2 shows an excess of events in this excluded region. This excess, being interpreted as due to pionium formation, yields the rate of pionium formation $R = \Gamma(K^\pm \to \pi^+ A_{2\pi})/\Gamma(K^\pm \to 3\pi^\pm) = (1.82 \pm 0.21) \times 10^{-5}$, somewhat higher than a theoretical prediction [7].

Measurement of the quadratic Dalitz plot slope k' was performed using the v projection of the data and fixing the values of a_0, a_2, g_0 and h' measured by the above method. Then the fit in M_{00} projection was re-iterated to account for the measured non-zero value of k'.

Systematic uncertainties due to fitting technique, trigger efficiency, description of geometric acceptance and resolution, calorimeter non-linearity, and simulation of showers in the calorimeter have been evaluated. External uncertainties due to limited experimental knowledge of $\mathscr{M}_+/\mathscr{M}_0$ at the $\pi^+\pi^-$ threshold have been also considered. Stability checks with respect to decay vertex position, particle separations in the calorimeter front plane, and kaon sign have been performed.

Results and conclusions

The original NA48/2 measurement of the of $\pi\pi$ scattering lengths [2] by exploring the cusp effect in the $K^\pm \to \pi^\pm\pi^0\pi^0$ decay spectrum has been improved: the full NA48/2 data sample has been used, and a more elaborate study of systematic effects performed. The model [4] with isospin breaking corrections has been used. The measured scattering lengths are:

$$\begin{aligned}(a_0 - a_2)m_+ &= 0.261 \pm 0.006_{\rm stat.} \pm 0.003_{\rm syst.} \pm 0.001_{\rm ext.}\\ a_2 m_+ &= -0.037 \pm 0.013_{\rm stat.} \pm 0.009_{\rm syst.} \pm 0.002_{\rm ext.}\end{aligned}$$

The external uncertainties are due to the limited knowledge of $\Gamma(K^\pm \to \pi^\pm\pi^0\pi^0)/\Gamma(K^\pm \to 3\pi^\pm)$. Moreover, an uncertainty $m_+\delta(a_0 - a_2) = 0.013$ has to be attributed to the result due to precision of the theoretical model. The Dalitz plot slopes corresponding to the used model are found to be

$$\begin{aligned}g_0 &= 0.649 \pm 0.003_{\rm stat.} \pm 0.004_{\rm syst.}\\ h' &= -0.047 \pm 0.007_{\rm stat.} \pm 0.005_{\rm syst.}\\ k' &= -0.0097 \pm 0.0003_{\rm stat.} \pm 0.0008_{\rm syst.}\end{aligned}$$

In addition, a measurement of the Dalitz plot slopes of the PDG parameterization [8] of the $K^\pm \to 3\pi^\pm$ decay with a sample of 4.71×10^8 fully reconstructed events yielded the following results:

$$\begin{aligned}g &= -0.21134 \pm 0.00013_{\rm stat.} \pm 0.00010_{\rm syst.}\\ h &= 0.01848 \pm 0.00022_{\rm stat.} \pm 0.00033_{\rm syst.}\\ k &= -0.00463 \pm 0.00007_{\rm stat.} \pm 0.00012_{\rm syst.}\end{aligned}$$

This measurement is described in detail in [9]. The results are compatible with the world average, and demonstrate the validity of the conventional parameterization at the new level of precision.

References

[1] J.R. Batley *et al.*, Phys. Lett. **B634** (2006) 474.
J.R. Batley *et al.*, Phys. Lett. **B638** (2006) 22.

[2] J.R. Batley *et al.*, Phys. Lett. **B633** (2006) 173.

[3] N. Cabibbo, Phys. Rev. Lett. **93** (2004) 121801.

[4] N. Cabibbo and G. Isidori, JHEP **0503** (2005) 021.

[5] V. Fanti *et al.* (NA48), Nucl. Instrum. Methods **A574** (2007) 433.

[6] K. Maltman and C.E. Wolfe, Phys. Lett. **B393** (1997) 19, erratum-ibid. **B424** (1998) 413.
K. Knecht and R. Urech, Nucl. Phys. **B519** (1998) 329.

[7] Z.K. Silagadze, JETP Lett. **60** (1994) 689.

[8] W.-M. Yao *et al.* (PDG), J. Phys. **G33** (2006) 1.

[9] J.R. Batley et al., Phys. Lett. **B649** (2007) 349.