Results on Direct CP Violation in Charged Kaon Decays from the NA48/2 Experiment at CERN

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Abstract

The NA48/2 experiment at the CERN SPS collected a very high statistics of charged kaon decays, with the main purpose of searching for direct CP violation effects. Preliminary result on the direct CP-violating asymmetry parameter A_g in $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays is presented; using more than 1.6 $\times 10^9$ events A_g has been measured with an accuracy an order of magnitude better with respect to previous experiments.

Measurement of A_g^0 for the decay $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ is in progress, with an expected statistical precision similar to the one on A_g. In addition, in the decays of $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ a new interesting effect, namely an anomaly in the $\pi^0\pi^0$ mass spectrum, has been observed; this anomaly can be interpreted as an effect due to the final state exchange scattering process $\pi^+\pi^- \to \pi^0\pi^0$ and provides 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.

1 Introduction

CP violation remains one the most important tests of the Standard Model and of the way it can constrain the parameters of the CKM matrix; on the other hand, CP violation, and especially direct CP violation, can open a window to possible deviations from the Standard Model and to new physics beyond it.

Since its discovery in 1964 by Christenson et al.[1], in the decays of neutral kaons into two pions (indirect CP violation), the effect remained unrevealed for several decades. The existence of direct CP violation was definitively established by the NA48 [2] and KTeV [3] experiments, confirming the result obtained by NA31 [4] in the early 90's, by measuring the parameter ϵ' in the decays of neutral kaons into two pions. Recently, effects of CP violation have been observed in the decays of neutral B mesons by the BaBar and Belle Collaborations [5] that also reported evidence for direct CP violation [6].

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In kaons, complementary studies of CP violation can be carried out in the charged sector, by measuring the asymmetry between K^+ and K^- decays into three pions.

The $K^\pm \to \pi^\pm\pi^+\pi^-$ decay is usually described in terms of two Dalitz variables u and v:

$$u = \frac{s_3 - s_0}{m_\pi^2} \qquad\qquad v = \frac{s_2 - s_1}{m_\pi^2} \tag{1}$$

where $s_i = (p_K - p_{\pi i})^2$, p_K being the four-momentum of the decaying kaon, $p_{\pi i}$ those of the pions and $s_0 = \sum s_i/3$, $(i = 1, 2, 3)$ with index $i = 3$ for the odd pion (the one with different charge from the other two). The matrix element can be expressed as a polynomial expansion of u and v

$$|M(u, v)|^2 \propto 1 + gu + hu^2 + kv^2 + O(u^3, v^3) \tag{2}$$

where $|h|, |k| \ll |g|$ and [7]

$$g(\pi^\pm\pi^+\pi^-) = -0.2154 \pm 0.0035 \qquad\qquad g(\pi^\pm\pi^0\pi^0) = 0.652 \pm 0.031 \tag{3}$$

Since there is no mixing in decays of charged kaons, the difference in slope parameters g between K^+ and K^- is only due to direct CP violation. Other CP asymmetries, for instance the asymmetry of integrated decay rates A_Γ, are highly suppressed and, in addition, difficult to detect experimentally. The measurement of rate asymmetries would require a precise knowledge of the relative kaon fluxes for both charge sign; the measurement of A_g, describing the decay distributions, is independent on flux and can be performed just by comparing the Dalitz plot shapes. The corresponding asymmetry

$$A_g = \frac{g^+ - g^-}{g^+ + g^-} \tag{4}$$

is predicted in the SM to vary between few 10^{-6} to few 10^{-5} [8]. An analogous asymmetry, A_g^0, can be defined for the $K^\pm \to \pi^\pm\pi^0\pi^0$ dacay. Table 1 summarizes the present experimental information on A_g and A_g^0.

Asymmetry	Events	Experiment
$A_g = (-7 \pm 5) \times 10^{-3}$	3.2×10^6	BNL AGS (1970)[9]
$A_g^0 = (2 \pm 12) \times 10^{-3}$	115×10^3	CERN PS (1975)[10]
$A_g = (2.2 \pm 1.5 \pm 3.7) \times 10^{-3}$	54×10^6	HyperCP (2000)[11]
$A_g^0 = (0.2 \pm 1.9) \times 10^{-3}$	640×10^3	Protvino IHEP (2005)[12]

Table 1: Experimental measurements on direct CP violating slope asymmetries in $K^\pm$ dacays .

Models beyond the SM [13] predict a substantial enhancement of A_g that, while being out of reach for previous experiments with lower accuracy, are potentially accessible to NA48/2.

NA48/2 is an extension of the original NA48 experiment, devoted to the study of direct CP violation in neutral kaon decays, which culminated with the proof of direct CP violation [2]. After an experiment (NA48/1) dedicated to the study of rare K_S decays, the NA48 collaboration undertook charged kaon decay studies in order to look for further CP violation effects.

The primary aim of NA48/2 is to measure A_g with an accuracy of 2.2×10^{-4} and A_g^0 with an accuracy of the order of 3.5×10^{-4}. In order to achieve the design goal, a large amount of data need to be collected, which implies high intensity beams, large acceptance and data acquisition bandwidths; at the same time a careful control of the systematics is required. The experiment took data in two periods: in 50 days of run in 2003 and in 60 days in 2004 a total of 3.5×10^9 $K^\pm \to \pi^\pm\pi^+\pi^-$ events and 200×10^6 $K^\pm \to \pi^\pm\pi^0\pi^0$ were collected, corresponding to a total data volume of 200 TBytes. This article reports on the analysis and preliminary result relative to the data collected in 2003, about 1.6×10^9 of $K^\pm \to \pi^\pm\pi^+\pi^-$ decays.

2 The NA48/2 experiment

The NA48/2 largely exploits the existing NA48 detector, with some new components and a completely new beam line, that provides two simultaneous K^+ and K^- beams, overlapping both in space and time, with narrow momentum spectra (Fig. 1).

Primary 400 GeV/c protons from the SPS impinge at zero degrees on a beryllium target, which is 40 cm long and 2 mm in diameter and is located $\sim$ 200 m upstream from the central detector. The intensity of the beam is $\sim 7 \times 10^{11}$ protons per pulse of 4.8 s duration. The particles of opposite charge are split, selected in a narrow momentum band ($p_K = 60 \pm 3$ GeV/c) and recombined on the same axis by passing through an achromatic momentum selection stage. A set of quadrupoles focuses the beams before they are split again in the vertical plane and cleaned by a second achromatic set of magnetic dipoles, that, in association with the KABES detector, provides a 1% momentum measurement of the incoming beams. Both beams are then recombined, follow the same path, remaining superimposed within 1 mm, and, after passing the final collimator, traverse the entire $\sim$ 114 m decay volume, housed in a vacuum tank.

The main detector component used for the asymmetry measurement in $K^\pm \to \pi^\pm\pi^+\pi^-$ is the magnetic spectrometer composed of four large drift chambers [14] and a dipole magnet (horizontal momentum kick of 120 MeV/c) with a momentum resolution of $\sigma(p)/p = 1.0\% \oplus 0.044\%\ p$ (p in GeV/c). The $K^\pm \to \pi^\pm\pi^+\pi^-$ decays are selected by a two-level trigger. The first level (L1) is a multiplicity trigger that requires a fast coincidence of at least two hits in a scintillator hodoscope. The second level (L2) consists of a farm of fast processors [15] that reconstruct tracks from the drift chamber signals. The L2 requires at least two tracks being originated from the decay volume.

Events that were not selected by the above condition were also kept even if only one track, consistent with having originated in the decay volume, was reconstructed by L2. In this case it is required that the missing mass is incompatible with the kinematics of $\pi^\pm\pi^0$ decay.

The resulting trigger rate is about 10 kHz. A full description of the NA48 apparatus can be found elsewhere [2].

3 Measurement Method

The measurement of A_g is based on the comparison of the u distributions of K^+ and K^- decays. The density of $K^\pm$ events in the Dalitz plot is projected onto the u-

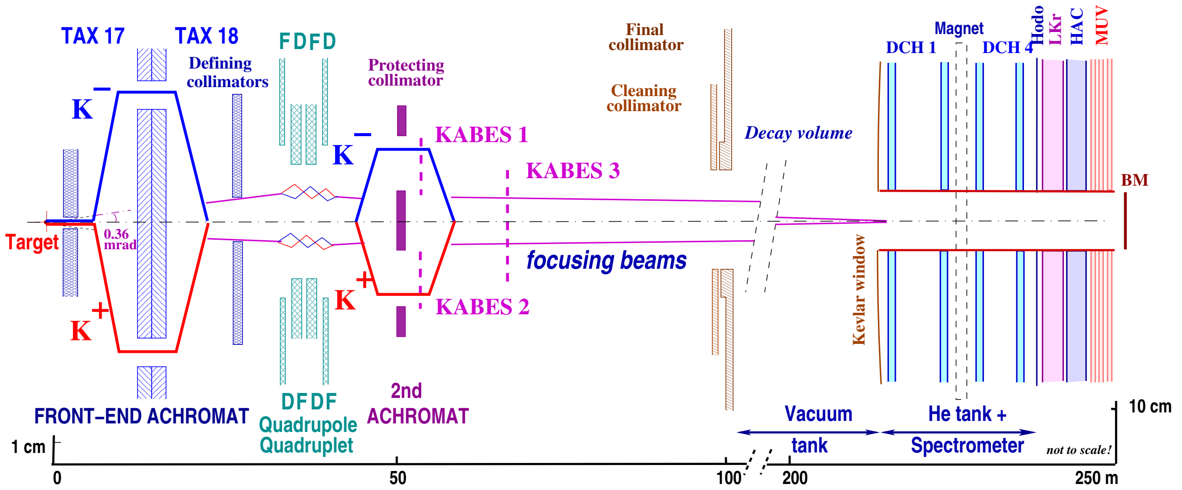

Figure 1: Schematic view of the NA48/2 beam and detector (not to scale).

axis to obtain one dimensional distributions $N^{\pm}(u)$. The ratio $R(u) = N^+(u)/N^-(u)$ is proportional with sufficient precision to $(1 + \Delta g \cdot u)$ and can be fit to a linear function to extract $\Delta g = g^+ - g^-$. The value of $A_g = \Delta g/2g$ is then computed.

Detector acceptance effects as well as variation in the response are cancelled by design, being the two charged beams superimposed in space and present at the same time. This results in a large cancellation of systematic effects in the asymmetry measurement. However, the magnetic fields of the beam line (achromats, focusing quadrupoles, etc.) and of the spectrometer (dipole) are intrinsic source of charge asymmetry in the detector. Any instrumental effect has to be both charge-asymmetric and u-dependent in order to potentially bias the measurement. In order to compensate for these asymmetries, the polarities of the relevant magnets along the beam line and the detector have been periodically reversed during the data taking, therefore effectively equalizing the time-averaged acceptance for K^+ and K^-. The achromat and quadrupoles of the beam line have been reversed on a weekly basis, in order to cope with the difference in the flight paths followed by K^+ and K^-; the spectrometer dipole every day in 2003 and every few hours in 2004, in order to cope with the difference in detector illumination by K^+ and K^- decay products. In two weeks an almost complete cycle, called super-sample, was completed, with a total of four super-samples in the year 2003. Each super-sample, treated as an independent unit in the analysis, contains four $K^+ \to \pi^+\pi^+\pi^-$ and $K^- \to \pi^-\pi^+\pi^-$ samples with different combinations of beam line and spectrometer magnet polarities. The ratio $N^+(u)/N^-(u)$ is obtained as a quadruple ratio of K^+/K^-

$$R(u) = R_{US}R_{UJ}R_{DS}R_{DJ} \approx \overline{R}(1 + 4\Delta g \cdot u) \qquad (5)$$

where the subscript $U(D)$ refers to a configuration in which K^+ beam runs through the upper (lower) beam path in the achromatic magnet sets while the subscript $S(J)$ refers to the spectrometer magnet polarity in which decay products having the same charge as the corresponding beam are deflected to the right (left) in the spectrometer (towards the Saleve (Jura) mountain respectively). A linear fit to Eq. 5 results in two parameters, normalisation $\overline{R}$ and Δg, from which A_g is extracted. The quadruple ratio technique in Eq. 5 is effective for hunting several systematic biases: beam line differences are cancelled by comparing K^+ and K^- travelling along the same path and local detector asymmetries by comparing K^+ and K^- illuminating the detector in the same way; global time-dependent effects cancel by the simultaneous detection of K^+ and K^- events. Using this technique, only asymmetries in the beam and in the detector with a variation in time shorter that the characteristic time scale of inversion of the polarity of magnets can affect the result. The strategy of the experiment is such that it is not required a Monte Carlo correction of the acceptance. Nevertheless, a detailed Monte Carlo program, based on GEANT and including the full detector simulation, is used to check the sensitivity of the result to various systematic effects.

4 Data Analysis

The main detector components used in the analysis of $K^\pm \to \pi^\pm\pi^+\pi^-$ are the magnetic spectrometer and the scintillator hodoscope; the chambers were aligned using data from special runs with the magnetic field switched off and with only muons illuminating the detector. Events are pre-selected requiring at least three tracks and one good reconstructed three-track vertex, with some acceptance and quality cuts. Hit information from the drift chambers and the measured magnetic field, scaled for the measured dipole magnet current and corrected for the small magnetic field due to the vacuum tank magnetization and the Earth's field, are combined together in order to reconstruct tracks, from which a three-track vertex is computed. Using measured momenta and track directions obtained at the vertex, the three-pion invariant mass is computed with a resolution of ~ 1.7 MeV/c^2.

Since the $K^\pm \to \pi^\pm\pi^+\pi^-$ is the dominant $K^\pm$ three-track decay, the selected sample is background free. Tails in the invariant mass distribution, due to muons from pions decaying in flight, have been shown to be symmetric for K^+ and K^-; no muon rejection is applied: this avoids introducing further potential instrumental asymmetries. The systematic uncertainty due to pion decay on the measured Δg is 0.4×10^{-4}, limited by statistical precision of the Monte Carlo sample.

The spectrometer internal alignment was continuously monitored by comparing the reconstructed $\pi\pi\pi$ invariant mass of K^+ and K^-, that must be equal by CPT. A difference in the measured masses can be induced by horizontal residual misalignment of the drift chambers. During the run, the relative position of the chambers was found to drift from few μm per day up to 200 μm. A shift of the last chamber of 1 μm, translates in a 1.5 KeV change in the invariant mass. The reconstructed momenta were corrected by $p' = p(1 + q\beta p)$ where p is the measured track momentum, q its charge sign and β a parameter related to the mass difference between K^+ and K^-; this reduces the effect to a negligible level.

The reproducibility of the magnetic field of the spectrometer can be controlled only to the level of $\sim 10^{-3}$, despite the degaussing procedure that precedes every inversion of the field. This effect is charge symmetric and cancels out in the ratio $N^+(u)/N^-(u)$. Residual adjustment is performed by a continuous momentum recalibration, which constrains the reconstructed three-pion invariant masses to the PDG kaon mass, with relative precision of $\sim 10^{-5}$.

The main acceptance limitation is due to the presence of the beam pipe traversing all the four drift chambers. The geometrical cut applied, intended to exclude insensitive areas, is done with respect to the beam centre rather than to the centre of the detector. In this way, time variations of the beam geometry, together with the dependence of the beam position on the kaon momentum are taken into account. The Monte Carlo is used to study the sensitivity to various acceptance definitions. A conservative limit on residual systematic effects related to acceptance is $\delta(\Delta g) = 0.5 \times 10^{-4}$.

The trigger is a potential source of systematic bias. Inefficiencies, which can be charge asymmetric, are studied and measured using control samples collected, along with the main trigger, with triggers uncorrelated with the one under study. The first level trigger inefficiency is small ($\sim 7 \times 10^{-4}$), constant in time, charge-symmetric and flat in u. No correction is applied and an uncertainty of $\delta(\Delta g) = 0.4 \times 10^{-4}$ is quoted, reflecting the limited statistics of the control sample. The second level inefficiencies are larger (0.2 to 1.8%) and vary in time. This inefficiency is related to local drift chambers' wire inefficiency, more important in the online reconstruction than in the offline. Each sample is corrected by the measured u-dependent trigger efficiency. Due to the limited statistics of the control sample, this is the largest systematic uncertainty at this stage of the analysis, although it could be reduced by further studies.

Other source of systematics were studied and evaluated: the dependance of the result on the u calculation was studied by changing the way the u-variable is computed from the measured track momenta. Additional studies were performed excluding various parts of the Dalitz plot. The sensitivity to the fitting interval ($-1 \leq u \leq +1$ for this result) has been checked as well as pile-up effects, track-charge misidentification, different way of π^+/π^- interaction in the chamber material.

All contributions to the systematic uncertainty are summarized in table 2.

Acceptance and beam geometry	0.5
Spectrometer alignment	0.1
Spectrometer magnet	0.1
Pion decay	0.4
u calculation and fitting	0.5
Pile-up	0.3
Total systematic uncertainty	0.9
Trigger efficiency - level 1	0.4
Trigger efficiency - level 2	0.8
Total trigger uncertainty	0.9
Total systematic error	1.3

Table 2: Preliminary limits on systematic uncertainties on Δg in units of 10^{-4}.

5 Preliminary result

The preliminary result, based on the full 2003 statistics, is obtained as the average of three independent analysis, all consistent with each other. After trigger efficiency corrections have been applied, the result is calculated separately from each super-sample and then averaged. The results from different super-samples are statistically consistent with each other with $\chi^2/ndf = 3.2/3$, as shown in the left part of Fig. 2. Systematic checks were performed by rearranging Eq. 5 in ratios of events of the same charge, such

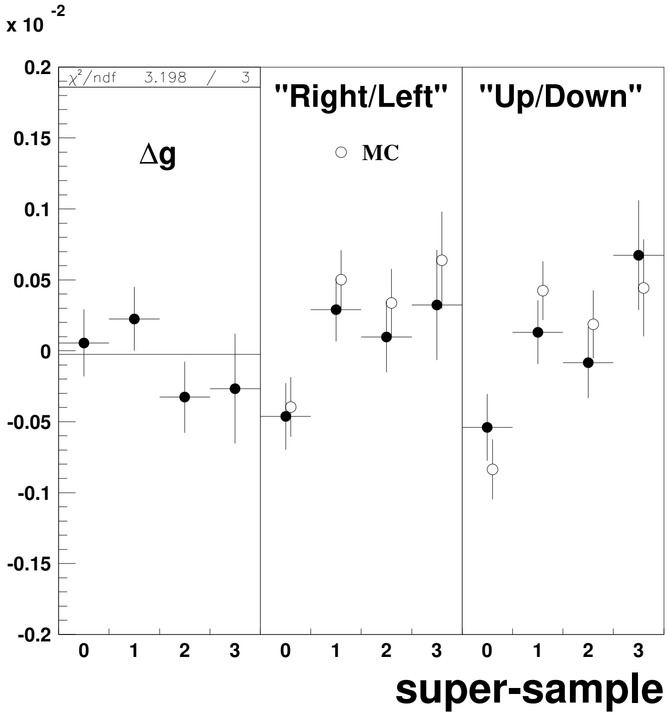

Figure 2: Measurement of Δg in four super-samples (left). Detector response (middle) and beam-line (right) asymmetries and their comparison to the Monte Carlo simulation.

that either they are deflected in opposite direction in the spectrometer magnet or they follow the upper or the lower path of the beam line. These control asymmetries are related to time-variation instrumental biases; they at the level of 10^{-4} and fully reproduced by Monte Carlo simulation, as shown in the middle and right parts of Fig. 2. Stability checks with respect to several variables, such as kaon energy and decay position, have been performed; no significant dependence has been found, as shown in Fig. 3.

The preliminary result from all four super-samples is

$$\Delta g = (-0.2 \pm 1.0_{stat} \pm 0.9_{stat(trig)} \pm 0.9_{syst}) \times 10^{-4} \tag{6}$$

Converted to the asymmetry using the PDG value of the Dalitz slope g [7]:

$$\begin{aligned} A_g &= (0.5 \pm 2.4_{stat} \pm 2.1_{stat(trig)} \pm 2.1_{syst}) \times 10^{-4} & (7)\\ &= (0.5 \pm 3.8) \times 10^{-4} & (8) \end{aligned}$$

This result is consistent with no CP violation and its precision is more than an order of magnitude better than previous measurements [9, 11]. The systematic uncertainty due to the trigger can be significantly improved by further studies of inefficiencies and other systematic effects can be reduced by using more data. The data collected in 2004 are being analysed and the extrapolated statistical uncertainty, using the full 2003 and 2004 statistics, is $\delta A_g = 1.6 \times 10^{-4}$. Also, smaller systematic effects in 2004 data are expected due to more frequent polarity alternation and better L2 performance.

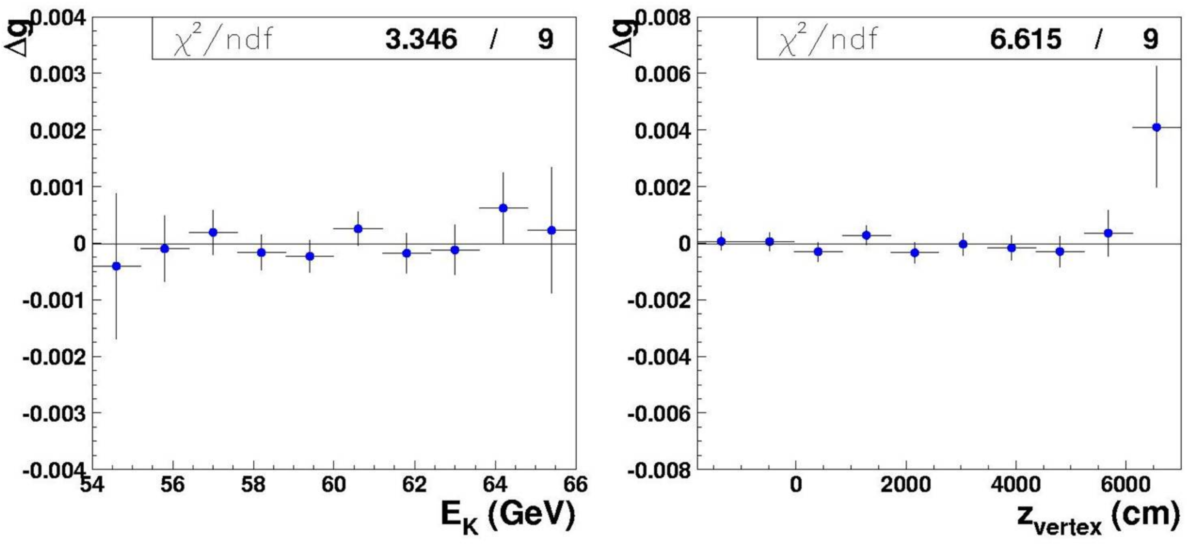

Figure 3: The linear slope difference Δg as a function of the kaon energy (left) and of the longitudinal decay vertex position (right).

6 Outlook for $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$

NA48/2 has collected a large sample (115×10^6) of $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ decays from which a linear slope asymmetry A_g^0, analogous to A_g, can be measured. Using the same strategy for the analysis, the u distribution for K^+ and K^- events is extracted from the Dalitz plot. This decay mode is statistically disfavoured, having a lower branching ratio ($N^0/N^{\pm} \sim 1/20$) and acceptance. This is almost completely compensated by a more favourable Dalitz plot distribution (1.5 gain factor) and by the ratio of slopes ($|g^0/g^{\pm}| \sim 3$), therefore the expected statistical uncertainty on A_g^0 is comparable to that on A_g. Only the electromagnetic calorimeter is used for the u-calculation, leading to totally different systematics and to a rather complementary CP-violation measurement. The analyzed sample up to now contains 50×10^6 reconstructed events, with a resulting statistical error on A_g^0 of $\sim 1.7 \times 10^{-4}$. The extrapolated statistical error for the full data set is $\delta A_g^0 = 1.1 \times 10^{-4}$. The slope asymmetries for the two $\pi\pi\pi$ decay modes are expected to be strongly correlated and the measurement of both would allow to constrain better the parameters.

7 The "cusp" effect

In the analysis of the $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ decay, the $\pi^0\pi^0$ invariant mass (M_{00}) distribution shows an anomaly in the in the region around $M_{00} = 2m_+$, where m_+ is the charged pion mass. This anomaly has been observed for the first time in this experiment, thanks to the large statistical sample and the excellent mass resolution. The sudden change in slope in the distribution suggests the presence of a threshold "cusp" effect from the decay $K^{\pm} \to \pi^{\pm}\pi^+\pi^-$ contributing to the $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ amplitude through the charge exchange reaction $\pi^+\pi^- \to \pi^0\pi^0$. It provides 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. Cabibbo has proposed a simple rescattering model [16] describing the $K^\pm \to \pi^\pm\pi^0\pi^0$ decay amplitude as the sum of two terms: the "unperturbed amplitude", namely the direct emission of $\pi^\pm\pi^0\pi^0$, and a contribution from $K^\pm \to \pi^\pm\pi^+\pi^-$ decay amplitude through the $\pi^+\pi^- \to \pi^0\pi^0$ charge exchange. Recently a more complete formulation of the model [17], which takes into account all rescattering processes at one-loop and two-loop level, has been proposed.

The preliminary result is based on a partial sample of 2.3×10^7 $K^\pm \to \pi^\pm\pi^0\pi^0$ dacays recorded in 2003. A best fit to the rescattering model [17], corrected for isospin symmetry breaking, gives the result

$$(a_0 - a_2)m_+ = 0.268 \pm 0.010(stat) \pm 0.004(syst) \pm 0.013(ext) \tag{9}$$

where the external error is an additional theoretical error of $\pm 5\%$ estimated in [17] as the result of neglecting higher order terms and radiative correction in the rescattering model. This result is in very good agreement with theoretical calculations performed in the framework of Chiral Perturbation Theory (ChPT), which predict $(a_0 - a_2)m_+ = 0.265 \pm 0.004$ [18].

8 Summary and conclusions

NA48/2 has collected an unprecedented statistics of charged kaon decays with the main purpose of looking for direct CP violation asymmetries. The principle of the experiment, two beams superimposed in space and time, and the technique used in the analysis, the quadruple ratio, allow high control of the systematics. The preliminary result on direct CP-violating charge asymmetry in $K^\pm \to \pi^\pm\pi^+\pi^-$ decays, based on 2003 data (1.6×10^9 events), $A_g = (0.5 \pm 2.4_{stat} \pm 2.1_{stat(trig)} \pm 2.1_{syst}) \times 10^{-4}$, has 10 times better precision than previous measurements. The systematic uncertainty due to the trigger can be improved by further studies of inefficiencies. The 2004 data contain $\sim 2 \times 10^9$ $K^\pm \to \pi^\pm\pi^+\pi^-$ events, possibly with higher quality; the extrapolated statistical uncertainty on the full data set is $\delta A_g = 1.6 \times 10^{-4}$, therefore the design goal is within reach.

The $K^\pm \to \pi^\pm\pi^0\pi^0$ channel reveals to be very interesting, not only to measure the charge asymmetry, but also to determine, with precision, important parameters of pion strong dynamics at low energy. The analysis of the complementary $K^\pm \to \pi^\pm\pi^0\pi^0$ dacay is under way; the statistical error on A_g^0, using a partial sample of 50×10^6 reconstructed events, is $\delta A_g^0 =\sim 1.7 \times 10^{-4}$ and the extrapolated statistical error on the full data set of 1.1×10^{-4}.

In $K^\pm \to \pi^\pm\pi^0\pi^0$ decays an anomaly in the $\pi^0\pi^0$ invariant mass distribution, at $M_{00} = 2m_+$, has been observed for the first time in this experiment. It can be described by a rescattering model [16, 17] dominated by the contribution of the $K^\pm \to \pi^\pm\pi^0\pi^0$ decay through the charge-exchange process $\pi^+\pi^- \to \pi^0\pi^0$. The difference $a_0 - a_2$ between the I=0 and I=2 S-wave $\pi\pi$ scattering lengths has been determined, leading to the result $(a_0 - a_2)m_+ = 0.268 \pm 0.010(stat) \pm 0.004(syst) \pm 0.014(ext)$ in very good agreement with the prediction of the Chiral Perturbation Theory.

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