FIRST RESULTS FROM NA48/2 EXPERIMENT AT CERN

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Abstract

The NA48/2 experiment at CERN is accomplishing high precision studies of charged kaon decays. An upgraded NA48 setup and simultaneous unseparated K^+/K^- beams are adopted.

The main goal is a search for direct CP-violation in the kaon decays into three pions with a sensitivity at a level of 10^{-4} on the asymmetry $A_g = (g_+ - g_-)/(g_+ + g_-)$ in Dalitz plot linear slope parameters g. The experimental procedure and the main systematic effects are discussed, based on the preliminary analysis of a fraction (less than 50%) of the data recorded. The statistical errors for $K^\pm \to \pi^+\pi^-\pi^\pm$ and $K^\pm \to \pi^0\pi^0\pi^\pm$ are $2.7 \cdot 10^{-4}$ and $5 \cdot 10^{-4}$, respectively. Large amount of charged kaon decays collected also allows precision measurements of several rare decay processes.

1 Introduction

Direct CP violation is expected to induce differerence in decay amplitudes: $|A(K^+ \to (3\pi)^+)| \neq |A(K^- \to (3\pi)^-)|$. The three body decay has a low Q value, which allows for the following parametrization in terms of the two Dalitz variables $u = (s_3 - s_0)/m_\pi^2$, $s_i = (P_K - P_\pi)^2$ (odd pion's coordinate) and $v = (s_1 - s_2)/m_\pi^2$ (even pion's coordinate): $|A(K \to (3\pi))| = a + b \cdot u + O(u^2, v^2)$, where a and b are two $\Delta I = 1/2$ interfering amplitudes. In case a and b have different weak and strong phases, the transitions to the two charge conjugate states $(3\pi)^\pm$ are unequally affected by the interference.

Different probability distributions of the final state momentum configuration for K^+ and K^- decays are then originated. Thus in the measurement of the observable matrix element, which is parametrized as $|M(u,v)|^2 \propto 1 + g \cdot u + O(u^2, v^2)$, the asymmetry

$$A_g = \frac{g^+ - g^-}{g^+ + g^-} \neq 0$$

of the slope parameter g would be signal of direct CP violation.

Theoretical predictions for asymmetry based on the Standard Model cover the range of $10^{-6} - 10^{-3}$ for A_g [1, 2], related to the "charged 3π channel" $K^\pm \rightarrow \pi^+\pi^-\pi^\pm$. The asymmetry $A_{g'}$, related to the "neutral 3π channel" $K^\pm \rightarrow \pi^0\pi^0\pi^\pm$ is expected to be of the same order of magnitude. Values of A_g at the level of $> 5 \cdot 10^{-5}$ would be very interesting for their implications on physics beyond standard model [3].

In the past no slope asymmetries were found down to a level of 10^{-3}. The experiment [4] at BNL studied A_g with a total amount of $3 \cdot 10^6$ decays and measured a slope asymmetry $A_g = (-7 \pm 5) \cdot 10^{-3}$ and a total decay rate asymmetry $\Delta\Gamma/2\Gamma = (5 \pm 7) \cdot 10^{-4}$. Recently HyperCP [5] at FNAL measured $A_g = (2.2 \pm 1.5 \pm 3.7) \cdot 10^{-3}$.

The experiment [6] at CERN-PS measured in the "neutral channel" a slope asymmetry at a level of $A_{g'} = (0.2 \pm 1.2) \cdot 10^{-2}$ and $\Delta\Gamma/2\Gamma = (4 \pm 3) \cdot 10^{-4}$. Recently the experiment ISTRA+ [7] at IHEP found $A_{g'} = (0.2 \pm 1.9) \cdot 10^{-3}$.

The aim of NA48/2 is to measure A_g and $A_{g'}$ with an accuracy of $\sim 10^{-4}$ (statistically dominated).

2 Experimental method and set up

NA48/2 exploits two simultaneous K^+ and K^- beams, overlapping both in space and time, with narrow momentum band.

The experimental method consists in detecting the asymmetries by considering slopes of ratios of normalized u distributions of K^+ and K^-: $R(u) = constant \cdot (N^+(u)/N^-(u))$, where $N^+(u)$ and $N^-(u)$ are the u spectra of $K^+ \rightarrow \pi^+\pi^+\pi^-$ and $K^- \rightarrow \pi^-\pi^-\pi^+$ decays respectively (and the *constant* provides the normalization of $R(0) = 1$).

If the acceptances for K^+ and K^- are properly equalized, for instance by frequently alternating the polarities of the relevant magnets along the particle paths during the data taking, then the ratio of the u distributions of K^+ and K^- would be independent of acceptances. A linear slope in the ratio:

$$R(u) = \frac{1 + g^+ u + O(u^2)}{1 + g^- u + O(u^2)} = 1 + (g^+ - g^-) \cdot u$$

would then be signal of direct CP violation.

2.1 Simultaneous, coaxial, focused $K^\pm$ beams

The novel design of the K12 beam line (fig. 1) allows to transport simultaneously positive and negative particles. Primary protons (400 GeV/c) from SPS impinge at 0 degree the Be target located $\sim$ 200m upstream from the central detector. The particles of opposite charge are split, selected in a narrow momentum band ($p_K = 60 \pm 3$ GeV/c) and recombined by passing through an achromatic device. A quadruplet of quadrupoles focuses the beams so that they overlap with accuracy better than 1 mm at the beginning of the central detector. A second "achromat" houses a collimator for absorbing neutrons, and two stations of Micromegas type TPC detector (KAon BEam Spectrometer). In combination with a third station, located downstream, the KABES chambers allow for tagging a single kaon and measuring its momentum. The particle rate at the KABES position is $\sim$ 40MHz. The final collimator, placed $\sim$ 100 m downstream from the target, is followed by a decay volume of $\sim$ 115 m length.

2.2 The NA48/2 central detector

The NA48 central detector described elsewhere [8] was used with new drift chambers readout, capable of standing high rates without introducing deadtime. The spectrometer magnet was operated in order to give $p_T = 120$ MeV/c kick, and the resolution in momentum (GeV/c) is $\sigma_p/p = 0.5\% + 0.015\% p$. The Liquid Kripton calorimeter provides a resolution in energy (GeV) of $\sigma_E/E = 3.2\%/E + 9\%/E + 0.42\%$.

Kaon masses from three pion decays are reconstructed with very good resolutions (1.7 MeV for the $K^\pm \to \pi^+\pi^-\pi^\pm$ decays and 1.2 MeV for $K^\pm \to \pi^0\pi^0\pi^\pm$ decays), which allows for precise calibration and monitoring of the minor instabilities of the spectrometer.

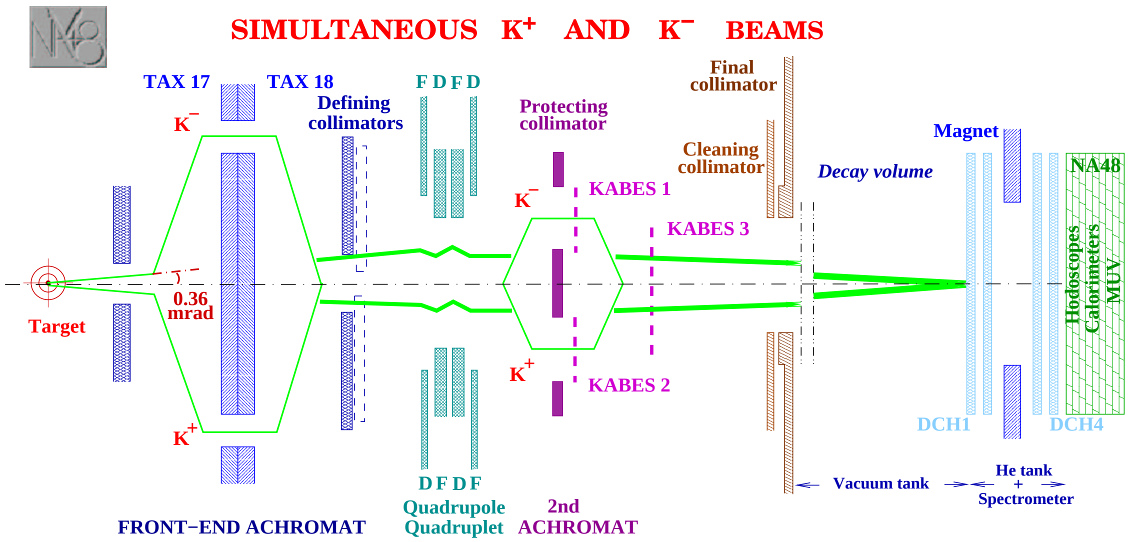

Figure 1: Schematic vertical section of the simultaneous K^+ and K^- beam line (not to scale).

2.3 Trigger

The trigger is based on a low level (L1) fast pre-selection (hodoscope multiplicity) and a high level (L2) selection (on-line processing of the information from calorimeter and drift chambers). From an input rate of 1 MHz, an output rate of 10 kHz triggers are readout with negligible dead time.

The full on-line kinematics reconstruction at L2 and the narrow range of beam momenta allow for triggering on both three tracks events and (two or) one track events (with some π^0 or photons in the LKr calorimeter) with adequate missing mass in order to reject the main background from $\pi^\pm\pi^0$.

2.4 Data Taking

Data were taken in years 2003 and 2004 for a total of more than 100 days of effective running. More than 2 billion of fully reconstructed $K^\pm \to \pi^+\pi^-\pi^\pm$, and more than 100 million of $K^\pm \to \pi^0\pi^0\pi^\pm$ were collected. The following analysis is performed on the last 28 days of data taking in 2003, where stable running conditions were reached.

3 Evaluation of the Direct CP violation asymmetry in the “charged mode”

The absence of relevant background in the $K^{\pm} \to \pi^+\pi^-\pi^{\pm}$ channel allows very simple on-line and off-line selections. Only information from the spectrometer and the hodoscope is involved, while calorimeters and muon veto will be used eventually to cross-check the systematics.

The analysis is arranged so that for K^+ and K^- decays the rate dependent inefficiencies and the accidental effects are the same. Special care is devoted to equalize the geometrical acceptance, as will be clarified by the following description of the experimental procedure.

(1) In the search for the CP-violating asymmetry A_g exclusively the slopes of ratios of normalized u-distributions are considered. In particular, the basic observables for the asymmetry measurement are defined by the comparison of normalized u distributions of K^+ with $B^{\uparrow}$ and K^- with $B^{\downarrow}$. They illuminate the detector in almost the same way (in particular downstream the spectrometer magnet) and the resulting asymmetry (A_R) is independent of the acceptance:

$$R_R = \frac{N(u, K^+, B^{\uparrow})}{N(u, K^-, B^{\downarrow})} = \frac{1 + g_+ u}{1 + g_- u} \sim 1 + 2g \cdot A_R \cdot u.$$

The analogous ratio (R_L) of u spectra of K^+ with $B^{\downarrow}$ and K^- with $B^{\uparrow}$ provides an independent measurement of the asymmetry (A_L). A deviation from zero in the average of these linear slopes $A = (A_R + A_L)/2$, which is the measurement of A_g, would be a signal of CP-violation, as long as both the detector set-up and the beams are either *stable in time* or *right-left symmetric.*

(2) In order to compensate for left-right asymmetries, the polarities of the relevant magnets along the beam line and the detector have been periodically inverted during the data taking. Every day: the spectrometer magnetic field sign (B) is reversed ($B^{\downarrow}$ /$B^{\uparrow}$), in order to cope with the difference in detector illumination by K^+ and K^- decay products. Every week: the achromat magnetic field signs (A) are reversed ($A^{\uparrow}$ /$A^{\downarrow}$) in order to cope with the difference in the flight paths followed by K^+ and K^-.

It is clear that in order to measure A_L and A_R it is necessary to collect data of K^+ (and K^-) with $B^{\uparrow}$ over a time interval and then compare u distributions with K^- (and respectively K^+) data collected with $B^{\downarrow}$ at a different time. During 2003 data taking the basic integration interval was

1 day, due to the spectrometer field B reversal periodicity. In 2004 the reversal periodicity was a few hours, in order to further reduce the effects of time instabilities.

Some magnetic fields along the beam lines can not be reversed (residual earth and stray magnetic fields; the transverse momentum kick due to those fields is $\sim 10^{-4}$ relative to the spectrometer momentum kick). They were accurately measured and considered in the reconstruction programs. The corresponding systematics on A_g estimated with Monte Carlo studies is below 10^{-5}.

(3) Concerning the variations in time of the detector response, two effects are found to be relevant:

i) time instabilities of detector geometry mainly due to variations of the transverse alignment of the chambers, which were measured to drift by small (below 70 μm) amounts;

ii) time instabilities of the spectrometer magnetic field: values cannot be reproduced after sign reversal with relative accuracy better than 10^{-3}.

The right-left accuracy of the relative transverse DCH alignment is obtained by adjusting properly the transverse position of the chambers or equivalently by imposing that K^+ and K^- three pion decays have the same reconstructed invariant mass, on average over periods of ~ 1 hour. The sensitivity of m_K is ~ 150 keV for 100μm displacement along the horizontal direction.

Time stability between periods with opposite direction of the spectrometer magnetic field is obtained by tuning the effective momentum scale so that the reconstructed invariant mass of $K^{pm} \to \pi^+\pi^-\pi^\pm$ decays equals the PDG value for the kaon mass (when averaged over periods of ~ 1 hour). The sensitivity of m_K to a perturbation of 10^{-3} to the magnitude of the magnetic field induces a change in mass of about 20 keV.

(4) Concerning variation in time of the two beam geometries, the most relevant effects are related to beam movements in short term (spill) and long term (hours) periods and to the non-perfect overlapping and coaxiality of the two beams.

Due to the presence of the beam pipe, pions with impact radius below 11 cm are lost, thus some radial selection is needed. In order to avoid systematics induced by a selection centered on the nominal beam axis, the real beam geometries are considered, so that events are rejected if any pion is intersecting the volume of a cylinder of appropriate radius and with axis centered on the momentum weighted barycenter of the positive (negative) kaon beam, as it is measured by the detector. Thus the radial acceptance selection is time-dependent (short and long term) in order to follow the movement of each beam.

In summary, the adopted experimental procedure ensures the highest immunity even to minor perturbations, and after the described kinematics' reconstruction and selection a number of 720 (400) millions K^+ (K^-) are used to estimate the final asymmetry, which is shown in fig. 2 as a function of time, i.e. the two consecutive day-pair. Offsets is applied, as the analysis is still blind.

Besides the above mentioned main systematics, other sources of error are being investigated.

i) residual acceptance affects (after symmetrisations), as well as resolution and non-linearity effects are studied by Monte Carlo;

ii) trigger inefficiency is preliminarly estimated to affect the asymmetry to a level below 10^{-4};

iii) accidental particles might affect the asymmetry only if asymmetrically correlated in space with K^+ and K^-;

iv) effects of interaction of pions with the detector material are investigated with complementary decay channels;

v) reconstruction efficiency, residual background and pion decays are studied with both complementary decay channels and Monte Carlo simulation.

In order to cross-check the effects from various systematics, some "fake asymmetries" are studied, which should be zero from first principles, but can be not null due to detector/beam effects. For instance the slope asymmetries extracted from the ratios $\frac{N(u,K^+,B^\uparrow)}{N(u,K^+,B^\downarrow)}$ and $\frac{N(u,K^-,B^\uparrow)}{N(u,K^-,B^\downarrow)}$ (fig. 2) are good indicators for the degree of left-right symmetry of the set-up after the above-mentioned procedure.

In addition an interesting control sample is provided by 3 pion events where only two are detected in the spectrometer. Due to the measurement of the kaon kinematics provided by KABES, the two pion events with completely measured kinematics give an useful handle to cross-check reconstruction efficiency, interaction of pions, accidentals effects and pion decays systematics.

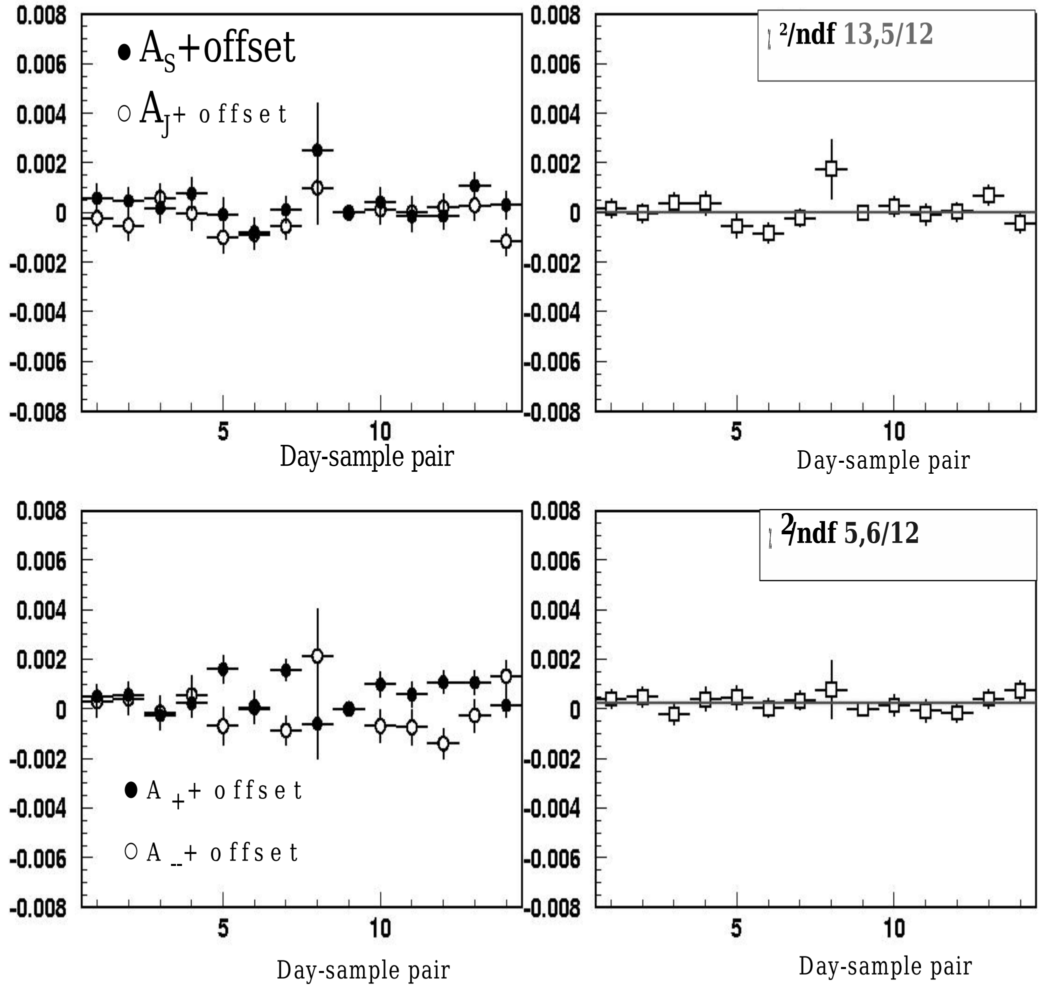

Figure 2: The measured asymmetries A_L, A_R and their average are shown as a function of the 14 day-pairs. An offset is applied because the analysis is still blind. There is no evidence of dependence on time. The "fake asymmetries" A_+ and A_- are also shown (below) as a function of time.

4 Study of the "neutral mode" decay

The interest in the decay $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$ has various reasons. First, despite it is statistically disfavoured with respect to $K^{\pm} \to \pi^+\pi^-\pi^{\pm}$, it is more sensitive to the CP violating linear slope differences, and the expected uncertainty is also at the level of 10^{-4}.

A second reason is that is allows precision studies of the $\pi\pi$ scattering lenghts. The charge exchange process $\pi^+\pi^- \rightarrow \pi^0\pi^0$ following a $K^\pm \rightarrow \pi^+\pi^-\pi^\pm$ decay is indeed not negligible under threshold and interferes destructively [9] with the direct emission $K^\pm \rightarrow \pi^0\pi^0\pi^\pm$. A high statistics and low systematics analysis of the shape of the $K^\pm \rightarrow \pi^0\pi^0\pi^\pm$ events as a function of the Dalitz variable u will then provide a precise (1%) measurement of the scattering lenghts a_0 and a_2.

Eventually, as byproduct of the same Dalitz plot analysis, and due to the excellent resolution of the LKr calorimeter in the Dalitz plot region of $m_{\pi^0\pi^0} = 2m_{\pi^\pm}$ ($\sim$ 350 keV in $m_{\pi^0\pi^0}$), the signal of the pionium atom can be extracted and its branching ratio can be precisely measured.

The event selection is based only on the spectrometer and the LKr calorimeter information. KABES provides useful information on the kaon kinematics. It is important to note that also this channel is background free.

The analyzed sample up to now consists in the 28 days sample discussed above. From this data after the kinematics' reconstruction and selection a number of 23 (13) million K^+ (K^-) are used to estimate the charge asymmetry. The resulting statistical error on $A_{g'}$ is $\sim 5 \cdot 10^{-4}$. The final sample (including 2003 and 2004 data taking) to be used for measuring the asymmetry and the dynamics parameters in the Dalitz plot will include more than 100 million events.

Different sources of systematics with respect to the "charged" mode are expected. For instance the role of inner radial acceptance selection is less critical than in the $K^\pm \rightarrow \pi^+\pi^-\pi^\pm$ case.

The u variable can be reconstructed either using the information of LKr calorimeter related to the $\pi^0\pi^0$ pair, independently of the spectrometer resolution, or using the spectrometer (charged π) and KABES information (kaon), independently of the calorimeter resolution. The former method provides very good resolution (especially at small $m_{\pi^0\pi^0}$ invariant mass), while the latter allows systematic studies of resolution and reconstruction effects (especially at high $m_{\pi^0\pi^0}$ masses).

5 Conclusions

The largest samples ever of $K^{\pm} \rightarrow \pi^{+}\pi^{-}\pi^{\pm}$ (more than $2{\cdot}10^{9}$), $K^{\pm} \rightarrow \pi^{0}\pi^{0}\pi^{\pm}$ (more than $0.1 \cdot 10^{9}$), and many rare kaon decays were recently recollected by NA48/2 and are being analyzed.

For the main channel $K^{\pm} \rightarrow \pi^{+}\pi^{-}\pi^{\pm}$, important sources of systematics in the study of the charge asymmetry are well identified and analyzed in detail. Up to now the uncertainty on the asymmetry ($< 3 \cdot 10^{-4}$) measured on a data sub-sample (less than half of the total), is still statistically dominated.

The $K^{\pm} \rightarrow \pi^{0}\pi^{0}\pi^{\pm}$ channel reveals to be very interesting, not only to measure the charge asymmetry, but also to determine with precision ($\sim 1\%$) important parameters of pion strong dynamics at low energy.

A precise ($\sim 1\%$) measurement of the $\pi\pi$ scattering length parameter a_0^0 will be obtained by the analysis of $\sim 10^6$ K_{e4} collected decays. This allows the measurement of the size of the $q\bar{q}$ QCD vacuum condensate postulated in χPT. In addition the following kaon rare decays: $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$, $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ and $K^{\pm} \rightarrow \pi^{\pm}l^{+}l^{-}$ will provide further tests of NLO predictions of χPT.

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