DIRECT CP VIOLATION RESULTS IN $K^{\pm} \rightarrow 3\pi^{\pm}$ DECAYS FROM NA48/2 EXPERIMENT AT CERN

C. BIINO

Istituto Nazionale di Fisica Nucleare,
via Pietro Giuria 1,
Torino, 10125, Italy
E-mail: cristina.biino@cern.ch

After firmly establishing direct CP Violation in two pions decays of neutral kaons, the NA48 experiment, during the 2003 run at CERN-SPS, has collected more than 1.6 billion of charged kaon decays into three charged pions, using a unique double beam technique which allows a high level of control on systematic effects. The measurement of the direct CP violation Dalitz plot linear slope asymmetry parameter A_g is reported. This result corresponds to more than an order of magnitude improvement in precision with respect to previous experiments and is limited by the statistics of the data sample.

1. Introduction

Forty years after its discovery, CP violation (CPV) still plays a central role in the experimental programs of high energy physics. CP violation in the neutral kaon system and in the neutral B mesons system can occur either in the mixing of two eigenstates or manifest as an asymmetry in two CP conjugate decay amplitudes (direct CP violation).

Direct CP violation is the most straightforward CP effect but it is difficult to detect experimentally and to connect to the parameters of the underlying fundamental theory, but it is a crucial window into physics beyond the Standard Model (SM).

It took more than thirty years since the discovery of CP violation in mixing of neutral kaon states in 1964 [1] to establish direct CP violation in the kaon system [2], [3]. The new world average value of :

$$Re(\epsilon'/\epsilon) = (16.7 \pm 2.6) \times 10^{-4}$$

is higher than most predictions and could be an indication of errors in the calculation of the matrix element of the decay, or might be a hint of failure of the SM. Therefore a measurement of direct CPV in other processes is quite relevant. In kaons, besides the already mentioned parameter ϵ' in $K_L \rightarrow \pi\pi$ decays, the most promising complementary observables are decay rates of GIM suppressed rare kaon decays proceeding through flavor-changing neutral currents, and the asymmetry between K^+ and K^- decays into three pions.

The usual phenomenological description of $K^\pm \rightarrow 3\pi$ decays is made in terms of the bi-dimensional Dalitz plot parameters u and v [4], related respectively to the energy sharing to the odd pion (charge opposite with respect to the other two) and among the two even pions. The matrix element is usually described in a polynomial expansion of the two Dalitz variables u and v and parametrized in terms of slopes:

$$|M(u,v)|^2 \sim 1 + gu + hu^2 + kv^2$$

where $g(\pi^\pm\pi^+\pi^-) = -0.2154 \pm 0.0035$ and $g(\pi^\pm\pi^0\pi^0) = -0.652 \pm 0.031$. Since the phase space is small, the expansion converges rapidly. The linear slope $|g|$ dominates over $|h|$ and $|k|$. The slope g can differ between K^+ and K^- only due to DCPV and the measured quantity is :

$$A_g = (g_+ - g_-)/(g_+ + g_-) = \Delta g/2g$$

The measurement of differences among the above parameters describing the decay distributions is independent on fluxes and can be performed just by comparing the Dalitz plot shapes.

Several experiments have searched for the asymmetry A_g. The precision reached so far is at the level of few 10^{-3} [5]. SM predictions vary between few 10^{-6} to few 10^{-5}. Models beyond the SM allow a wider range of A_g predicting substantial enhancements [6].

After a successful program of investigations with neutral kaons which culminated with the establishment and accurate measurement of direct CP violation in the decays of neutral kaons into two pions [3], the NA48 collaboration is now devoted [7] to measure the parameter A_g in $\pi^\pm\pi^+\pi^-$ and $\pi^\pm\pi^0\pi^0$ modes to a precision $\sim 2 - 4 \times 10^{-4}$. The above figure requires collecting very large samples and therefore intense beams, large acceptance and data acquisition bandwidth. These have to be matched with a careful control of systematics.

NA48/2 has a great potential for closing the gap between experimental and theoretical results, reaching the interesting region in which one can start to detect enhancements due to physics behind the SM.

In this paper the analysis and results based on about 1.6 billions of $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays taken in the first data taking period are presented.

2. Beams and Detector

NA48/2 uses the original detector [3] and a completely novel beam line system, designed and built to transport simultaneously positive and negative kaon beams, superimposed in space, focused and with narrow momentum spectra. The beam design plays an important role in enforcing large cancellations of detector acceptance effects.

The beams of charged particles are produced by 400 GeV/c primary protons from the SPS imping at zero degree angle on a beryllium target of 2 mm diameter and 40 cm length at a chosen nominal intensity of $7 \times 10^{11} ppp$ (with 16.8 s cycle time and 4.8 s flat-top). A schematic vertical section of the simultaneous K^+ and K^- beam line is shown in Fig. 1 The two beams have an acceptance opening angle of ± 0.36 mm in both planes, defined by a common collimator.

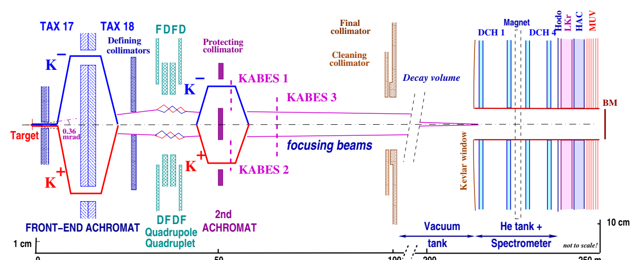

Figure 1. Lateral view of the NA48/2 beam and detector. The vertical scale is strongly enhanced. The two beams are superimposed to within $\sim 1mm$ all along the decay region.

Upstream of this the central momentum of 60 GeV and the momentum bite of ±3 GeV is selected symmetrically for K^+ and K^- in the front end achromat unit, consisting of 4 dipole magnets which splits the two beams in the vertical plane and recombines them on the same axis. The two beams, containing about 6.4×10^7 particles per pulse (12 times more pions than kaons), with a kaon charge ratio $K^+/K^- \sim 1.8$ (the analysis is independent of this ratio) pass through magnetic focusing and muon sweeping stages. A system of four quadrupoles is designed to focus particles of each sign similarly in both planes to small spot sizes ($\sim$ 5 mm r.m.s.) at the spectrometer position. The two beams, after passing the cleaning and the final collimators, remain superimposed to within 1 mm while traveling through the ~ 114 m long vacuum decay region. This superposition symmetrizes the acceptance and contributes to the reduction of systematic biases. The two beams are again split and cleaned in the second achromat, that together with the KABES detector could serve also as a beam spectrometer allowing a 1% momentum measurement of the incoming kaons. Any structure remaining inside the beam spots is naturally exchanged between K^+ and K^- by regular inversions of all beam magnets fields.

The decay region is contained in a vacuum tank. Note that the decay products from charged pions in the beam, due to the limited transverse momentum available, are mostly confined to remain within such pipe, without illuminating the detector itself.

The main part of the NA48 detector used for the measurement of the CP violating asymmetry in $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays is the magnetic spectrometer, composed of four drift chambers and a dipole magnet (120 MeV/c horizontal kick) enclosed in a helium filled tank. The drift chambers have an octagonal shape with an area of about 4.5 m^2. Each is made of four sets of two staggered planes of sense wires oriented along four 45^0 directions. The momentum resolution is $\sigma(p)/p = 1.0\,\% \oplus 0.044\,p\,\%$ (p in GeV/c).

The interesting decays are triggered with a two-level trigger system. At the first level the rate is reduced to few hundred KHz by requiring at least two hits in a scintillator hodoscope placed behind the magnetic spectrometer. The second level trigger consists of hardware coordinates builders and a farm of asynchronous microprocessors that reconstructs tracks using data from the drift chambers. At least two tracks are required to converge within 5 cm in the decay volume.

3. Measurement Method

The measurement is based on comparing u plots of K^+ and K^- decays by projecting events in the u-v Dalitz plot on the u axis to obtain one dimensional distributions $N^{\pm}(u)$. In case of the $\pi^{\pm}\pi^{+}\pi^{-}$ final state the ratio $R(u) = N^{+}(u)/N^{-}(u)$ is proportional with sufficient precision to $(1+\Delta g u)$. $A_g = \Delta g/2g$ is extracted from a linear fit to the ratio R(u). Clearly any imperfection has to be both charge-asymmetric and non-flat in u, in order to potentially bias the measure. Charge related beam and detector differences can induce asymmetric effects, the most obvious being that due to imperfect left-right detector symmetry when coupled with the lateral deflecting effect of the spectrometer magnet. While the beam is carefully aligned along the detector axis, any local imperfection of the spectrometer can introduce an acceptance asymmetry. This effect is canceled to first order by periodically reverse the magnetic spectrometer field (once per day), therefore equalizing the time-average acceptance for K^+ and K^-. Any residual difference between "upper" and "lower" beam paths in the achromats are canceled by periodically (once per week) reversing all magnetic fields along the beam lines, so that $K^\pm$ paths are exchanged.

The $\sim$ two week cycle represents a supersample which is treated in the analysis as an independent data unit. In the 2003 period we collected four supersamples. Each one contains four $K^+ \to \pi^+\pi^+\pi^-$ and four $K^- \to \pi^-\pi^-\pi^+$ samples with different combination of magnet polarities. The actual ratio R(u) is obtained as a quadruple ratio of K^+/K^- samples:

$$R(u) = R_{US}R_{UJ}R_{DS}R_{DJ} \simeq \bar{R}(1 + 4\Delta g u)$$

where the subscripts U (D) refer to the beam line magnets polarities (a sample where K^+ travel along the upper/lower beam path in the achromats), while S (J) represent the spectrometer magnet polarity in which decay products having the same charge as the corresponding beam are deflected to the right with respect to the direction of the beam, toward Saleve mountain (to the left, toward Jura mountains). A linear fit of the above ratio results in the normalization $\bar{R}$ and Δg from which A_g is extracted. The quadrupole ratio exploits several cancellations of systematic biases:

(i) beam line differences - by comparing K^+ and K^- traveling along the same paths
(ii) detector asymmetries - by comparing K^+ and K^- illuminating the detector in the same way
(iii) global time-dependent effects - by the simultaneous detection of K^+ and K^- events

The only residual effects which can affect the asymmetry measurement are time variation of asymmetries in experimental conditions on a time scale of about one subsample. This method is independent on the relative size of the samples with different magnet configuration. The statistical uncertainty depends on the statistics of the smallest sample involved.

While, due to the superposition of the two beams, the measurement doesn't require a MonteCarlo simulation, nevertheless a GEANT-based MonteCarlo program with detailed detector simulation, including time-varying local drift chamber inefficiency and alignment maps and beam line geometry variations, has been developed to check the sensitivity of the result to various systematic effects.

4. Data Analysis

NA48/2 took data in two periods. About 4 billions of $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ and about 200 millions of $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ decays have been collected during the 50 day period in year 2003 and the 60 day period in 2004 . The total recorded data volume amounts to about 200 TB.

Several stages of compactification and filtering of data, requiring at least three reconstructed tracks in the magnetic spectrometer and loose acceptance and quality cuts as well as at least one good reconstructed three tracks vertex, were necessary in order to reduce the data to a size suitable for the final analysis.

The measurement of the pion momenta is based on the knowledge of the magnetic field in the spectrometer magnet and on the tracking information from the drift chambers. Track reconstruction combines hits from all four drift chambers using measured magnetic field map rescaled to the recorded current in the spectrometer analyzing magnet and correcting for the small magnetic field due to the vacuum tank magnetization and the Earth's field, which were measured before the run. This stray-field correction reduces the azimuthal variation of the reconstructed invariant mass of $\sim 1MeV/c^2$ by an order of magnitude. The three tracks vertex is reconstructed using track segments from the first half of the spectrometer and the vertex constrained track parameters are used to compute the three pion invariant mass, with resolution $\simeq 1.7MeV/c$. Small non-Gaussian invariant mass tails arise from kink tracks in which a charged pion decayed. To avoid introducing instrumental asymmetries, no muon rejection is applied, which is possible since the sample is practically background free. The Monte-Carlo simulation shows that those tails are highly symmetric between K^+ and K^-. Only far tails are rejected by the cut $|m_{\pi\pi\pi} - m_K| < 9\, MeV/c^2$, where m_K is the PDG value. The systematic uncertainty due to pion decay, limited by the precision of generated MonteCarlo, is $\delta(\Delta g) = 0.4 \times 10^{-4}$.

The spectrometer internal alignment was calibrated using data from special runs in which muons were recorded with magnetic spectrometer off.

A fine control of the spectrometer internal alignment is obtained by continuously monitoring the difference in the reconstructed three pion invariant masses for K^+ and K^-, which can be induced by a residual horizontal misalignment between chambers before and after the spectrometer magnet, at the level of $\sim 1.5\, KeV/\mu m$. Tiny relative drifts of chambers positions (as small as a few μm per day up to 200 μm) were detected in this way and the reconstructed momenta corrected accordingly to $p' = p(1+q\beta p)$, where q is the sign of the charge, p is the track momentum (in GeV/c) and β a parameter of order $10^{-5} GeV^{-1}$ related to the measured mass difference for positive and negative events.

Each spectrometer magnetic field reversal was preceded by a full degaussing procedure, but the reproducibility of the absolute magnitude of the field integral, and its equality for both polarities, can be controlled on-line only to within $\sim 5 \times 10^{-4}$. Smaller variations are continuously corrected offline by forcing the mean reconstructed three-pion invariant mass to the nominal PDG kaon mass with $\sim 10^{-5}$ precision. This is done by scaling the measured track momenta symmetrically for positively and negatively charged tracks. This effect is charge symmetric and by collecting simultaneously K^+ and K^- it cancels in the ratio R(u).

Other small effects are canceled by the fact that geometric acceptance cuts were defined with respect to the average beam positions (both before and after magnetic spectrometer).

The beam tube traversing the center of the detector is determining the acceptance. The largest instrumental effect on the event density in the Dalitz plot occurs at large u values, where there is a steep drop in acceptance due to the "odd" pion being lost into the central beam pipe hole while similar "cuts" at large $(u \pm v)/2$ values, where one of the even pions is lost, are mapped onto a wide u region, after projection. To avoid inducing a u asymmetry in the way the acceptance-defining central hole is seen by the two beams, software acceptance cuts are applied which are centered on the effective beam axis, independently for K^+ and K^-. All three tracks are required to traverse the first drift chambers at least 11.5 cm from the beam center and the last drift chambers at least 13.5 cm (the latter cut takes into account the ~ 2 cm lateral beam displacement due to the spectrometer magnet). These cuts are related to the beam center rather then the detector axis, the reason is that the beam optics can control on-line the beam position to only $\pm$ 1 mm. The actual beam position is continuously monitored to a better precision by calculating the momentum weighted center of gravity of the three pions, independently for K^+ and K^-. In addition to the time variation of the beam position, also the dependence from the kaon momentum variation is taken into account ($\sim \pm 1$ mm both in horizontal and vertical direction). In doing this K^+ and K^- acceptance variations cancel completely and no MonteCarlo correction is needed. A conservative limit on residual systematic uncertainty, $\delta(\Delta g) = 0.3 \times 10^{-4}$ was determined by studying the sensitivity to various acceptance definitions.

The trigger is a potential source of systematic bias and is studied by using downscaled control samples from low bias triggers collected along with the main triggers. Since the beams are simultaneous, rate-dependent inefficiencies are charge symmetric. The inefficiency of the first level trigger was small, 9×10^{-4}, and stable in time. No correction is applied and an uncertainty of $\delta(\Delta g) = 0.4 \times 10^{-4}$, limited by the statistic of the control sample, is estimated. For the second level trigger inefficiencies are larger (0.4 to 1.5%) and change in time, being related to local drift chamber inefficiencies which are more important in the trigger than in the reconstruction due to reduced redundancy. No significant charge asymmetry or u dependence was observed but, since the size of the control sample is not sufficient to completely exclude such effects, a conservative approach is adopted by correcting each sample by the measured u-dependent trigger efficiency and therefore introducing a significant statistical error due to the statistical power of the control sample.

Table 1. Summary of limits on systematic and trigger uncertainties on $\Delta g = A_g/2g$, in units of 10^{-4}.

Acceptance, beam geometry	0.3
Spectrometer alignment	0.1
Spectrometer magnet	0.1
Pion decay	0.4
u computation and fitting	0.2
Accidental activity	0.2
Total systematic uncertainty	0.6
Trigger efficiency: level 1	0.4
Trigger efficiency: level 2	0.5

Other possible sources of systematic effects were studied and evaluated such as the dependence on the way the u variable is calculated or the fitting limits, effects due to uncertainty on the knowledge of the stray magnetic fields, pile-up effects, inhomogeneities in the spectrometer alignment, accuracy of time-tracking for various changes in the beam geometry and to charge asymmetric pion interactions. Additional studies were performed excluding various border parts of the Dalitz plot. This result is obtained from the fit restricted in the interval $-1 < u < 1$. Values of systematic uncertainties are shown in Table 1.

5. Result and Conclusions

The result presented is obtained as the average of three independent analysis, all of them giving consistent results within uncorrelated uncertainties. The result is calculated for each of the four supersamples of 2003 data taking and then combined, after trigger efficiency corrections, taking into account correlated systematic uncertainties.

The results from the four supersamples are statistically consistent with each other ($\chi^2/ndf = 0.4/3$). The measurement stability as a function of the supersample is shown in the left part of Fig. 2.

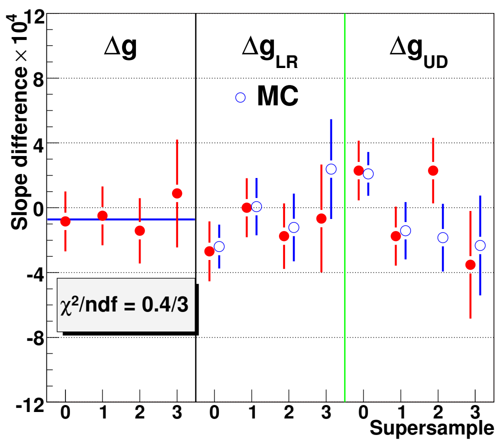

Figure 2. Left plot: stability of the preliminary result as a function of supersample. Two plots on the right side: stability of "null" asymmetries and their comparison to MonteCarlo simulation.

The result stability was checked with respect to several variables such as kaon energy and decay position, without finding any significant dependence. As a systematic check, "null" ratios were computed by building ratios of events of the same charge, deflected in opposite directions in the spectrometer magnet or distinguished only by the upper or lower path of kaons along the beam line. In this case the result is expected to be equal to zero and any asymmetry in such ratios reflects instrumental biases coupled to time variations. Such effects are at the 10^{-4} level and therefore second order effects are negligible. Moreover these results are fully reproduced by the MonteCarlo simulation as due to time variation of the detector inefficiencies and beam optics.

The difference in the linear slope parameter of the Dalitz plot for $3\pi^{\pm}$

decays of $K^{\pm}$, measured with the 2003 data sample, is found to be :

$$\Delta g = g^{+} - g^{-} = (-0.7 \pm 0.9_{stat} \pm 0.6_{stat(trig)} \pm 0.6_{syst}) \times 10^{-4}$$

Converted to the direct CP violation charge asymmetry in $K^{\pm} \rightarrow 3\pi^{\pm}$ decays using the PDG value of the Dalitz plot slope $g = -0.2154 \pm 0.0035$, this leads to

$$A_g = (1.7 \pm 2.1_{stat} \pm 1.4_{stat(trig)} \pm 1.4_{syst}) \times 10^{-4} = (1.7 \pm 2.9) \times 10^{-4}$$

The precision obtained is limited mainly by the available statistics. This result is consistent with no CP violation and its precision is one order of magnitude better than earlier measurements.

Na48/2 has also collected about 200 millions of $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$ decays from which a measurement of the corresponding slope asymmetry is extracted. This decay mode is disfavored statistically due to the lower branching ratio and acceptance but its more favorable Dalitz plot population leads to expected statistical uncertainty on A_g comparable to that of the charged decay mode. Systematic uncertainties are different in this case, but it is interesting to notice that for this decay the asymmetry is extracted using only information from the electromagnetic calorimeter, therefore leading to a rather complementary CP-violation measurement.

The preliminary result, presented in November 2005, is:

$$A_g^0 = (1.7 \pm 1.7_{stat} \pm 1.2_{stat(trig)} \pm 1.3_{syst} \pm 0.2_{ext}) \times 10^{-4} = (1.7 \pm 2.4) \times 10^{-4}$$

References

1. J. H. Christenson et al.,*Phys. Rev. Lett.* **13**, 138 (1964).
2. G. Barr et al., *Physics Letters* B **317**, 233 (1993); A. Alavi-Harati et al., *Phys. Rev. Lett.* **83**, 22 (1999); A. Alavi-Harati et al., *Phys. Rev.* D **67**, 012005 (2003); Erratum: *Phys. Rev.* D **70**, 079904 (2004).
3. V. Fanti et al., *Phys. Lett.* B **465**, 335 (1999); A. Lai et al., *Eur.Phys.J.* C **22**, 231 (2001); J.R. Batley et al., *Physics Letters* B **544**, 97 (2002).
4. S. Eidelman et al., (PDG), *Physics Letters* B **592** (2004).
5. W. T. Ford et al., *Phys. Rev. Lett.* **25**,1370 (1970); K. M. Smith et al., *Nucl. Phys.* B **91**, 45 (1975); W-S. Choong, Ph.D. thesis, Berkeley (2000) LBNL-47014; G. A. Akopdzhanov et al., *Eur. Phys. J.* C **40**, 343 (2005).
6. L. Maiani et al., The Second DAΦNE Physics Handbook, Vol.I, 51 (1995); A. A. Bel'kov et al., hep-ph/0311209; G. D'Ambrosio et al., *Int. J Mod. Phys.* A **13**, 1 (1998); E. P. Shabalin, *Phys. Atom. Nucl.* **68**, 88 (2005); E. Gamiz et al., *JHEP* **0310**, 042 (2003). E. P. Shabalin, ITEP preprint 8-98 (1998); G. D'Ambrosio et al., *Phys. Lett.* B **480**, 164 (2000);
7. R. Batley et al., Addendum III to Proposal P253, CERN/SPSC 2000-03, CERN, January 2000.