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Review of NA48 CP violation measurements with neutral and charged kaons

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The main goal of the NA48 experiments at the CERN SPS has been the search for direct CP violation (CPV) in kaon decays. In this paper results from NA48 and NA48/2 are presented. The direct CPV parameter Re(ε′/ε) has been measured by NA48 from the decay rates of neutral kaons into two pions: combining the results from data collected in 1997, 98, 99 and 2001, an overall value of Re(ε′/ε) = $(14.7 \pm 2.2) \times 10^{-4}$ is obtained. Using a sample of 47000 $K_L \to \pi^+\pi^-$ and five million K_{e3} decays collected during a dedicated run in 1999 with a pure K_L beam, NA48 measured the ratio of the decay rates $\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_L \to \pi e\nu)$, from which the branching ratio of the CPV decay $K_L \to \pi^+\pi^-$, $BR(K_L \to \pi^+\pi^-) = (1.941 \pm 0.019) \times 10^{-3}$ and the CPV parameter $|\eta_{+-}| = (2.223 \pm 0.012) \times 10^{-3}$ were derived. In the charged kaon sector, NA48/2 has measured the asymmetry $A_g = (g^+ - g^-)/(g^+ + g^-)$ of the linear slope parameter g in the Dalitz plot of $K^\pm \to 3\pi$ decays from data collected in 2003 and 2004. Any non-zero value of A_g would be evidence for direct CPV. A new technique of asymmetry measurement, involving simultaneous K^+ and K^- beams and a large data sample allowed a result of unprecedented precision. The charge asymmetries were measured to be $A^c_g = (-1.5 \pm 2.2) \times 10^{-4}$ with 3.11×10^9 $K^\pm \to \pi^\pm \pi^+\pi^-$ decays and $A^n_g = (1.8 \pm 1.8) \times 10^{-4}$ with 9.13×10^7 $K^\pm \to \pi^\pm \pi^0\pi^0$ decays.

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1. Introduction

The investigation of CP violation is of major importance in particle physics as it addresses fundamental questions linked to the observed matter-antimatter asymmetry in the Universe. CP violation was discovered in $K^0 \to \pi\pi$ decays in 1964 [1]. Still, kaons remain a privileged observatory for flavour physics phenomena where all the features of flavour physics are present: kaons are a rather simple system of the lightest mesons containing a quark flavour of a generation beyond the first, they have rather long lifetimes, with a broad hierarchy between K_L and K_S, and they are produced in large quantity. While all three types of CP violation are observed in the neutral kaon system, only direct CP violation occurs in charged kaons since mixing is not allowed.

The NA48 Collaboration has carried out over the last decade an extensive experimental programme at CERN dedicated to the study of CP violation (and rare processes) in both neutral and charged kaon decays.

2. CP violation in Neutral Kaons

All three types of CP violation are observed in neutral kaons: the phenomena of neutral kaon mixing accounts for the indirect CP violation, measured with the parameter $Re(\varepsilon)$, where ε represents the asymmetric mixing of the CP eigenstates into the mass eigenstates occurring with $\Delta S=2$. Direct CP violation is due to an asymmetry in the amplitude of K^0 decays into two pion final states with different isospin values (I=0 or I=2). This effect is quantified by the measurement of the parameter $Re(\varepsilon')$. Taking into account direct CP violation, the ratios of CP-violating to CP-conserving amplitudes η_{+-} and η_{00}

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \qquad \eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)}$$

can be expressed as $\eta_{+-} \approx \varepsilon + \varepsilon'$ and $\eta_{00} \approx \varepsilon - 2\varepsilon'$. A non-zero value of ε' arises naturally in the SM from the complex phase of the CKM matrix.

Direct CP violation can be demonstrated measuring $\varepsilon' \neq 0$. Experimentally it is convenient to measure the double ratio R of decay widths, related to $Re(\varepsilon'/\varepsilon)$ by:

$$R = \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2 = \frac{\Gamma(K_L \to \pi^0\pi^0) \cdot \Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^0\pi^0) \cdot \Gamma(K_L \to \pi^+\pi^-)} \approx 1 - 6Re(\varepsilon'/\varepsilon)$$

The violation of CP symmetry takes also place in the interference between decays with and without mixing, where it is represented in terms of the parameters $Im(\varepsilon)$ and $Im(\varepsilon')$.

2.1 The NA48 experiment: beams and detector

NA48 was a fixed target experiment located at the CERN SPS complex. The NA48 experiment started data taking in 1997 using simultaneous K_L and K_S beams produced by the same primary 450 GeV/c proton beam (~1.5 × 10^{12} *ppp*). Given the different decay lengths of K_L and K_S, two different production targets are used, located 126 m and 6 m upstream of the beginning of the decay region. The non interacting protons are sent to a bent silicon crystal that deflects the proton beam back to the K_L beam direction by channelling and, at the same time, attenuates the beam impinging on the K_S target to ~3 × 10^7 *ppp*. To distinguish K_S and K_L decays the protons directed to the K_S target are detected by the tagging detector, an array of scintillator counters placed after the bent crystal: K_S decays are identified by comparing the time of flight between protons in the tagger and the kaon decay products in the detector.

A magnetic spectrometer consisting of four drift chambers and a central dipole magnet ($\sigma(p)/p \approx$ 1.02% + 0.044% p [GeV/*c*]) is used to detect $\pi^+\pi^-$ decays. The time of $\pi^+\pi^-$ events is measured by two scintillator hodoscope planes ($\sigma_t \approx$ 150 ps). A quasi-homogeneous Liquid Krypton electromagnetic calorimeter reconstructs $\pi^0\pi^0$ final states using the information on energy, position and time of the four photon clusters. The energy resolution is $\sigma(E)/E \approx 3.2\%/\sqrt{E} \oplus 0.09/E \oplus 0.42\%$ (E in GeV). The NA48 beams and detector [2] are schematically shown in Fig. 1.

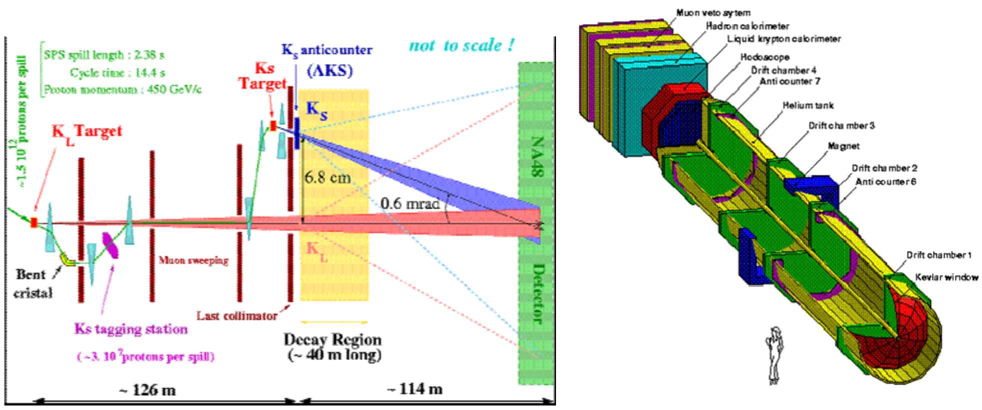

Figure 1: The layout of the NA48 neutral beams (left). The NA48 detector (right).

2.2 Measurement of Re(ε′/ε)

Re(ε′/ε) is derived from the double ratio R. The NA48 experiment is designed to exploit cancellations of systematic effects contributing symmetrically to different components of the double ratio. The four decay modes are collected simultaneously in the same decay region, minimising sensitivity to intensity variations, detection efficiency and accidental effects. K_L and K_S acceptances become similar and approximately cancel in the ratio, despite of the large lifetime disparity, by weighting K_L decays with a function of the proper time. Small differences between K_L and K_S beam intensity variations are eliminated by weighting K_S events by the

K_L/K_S intensity ratio. High resolution detectors are used to achieve an efficient background rejection: small remaining impurities due to the three body K_L decays are carefully subtracted. After applying all selection criteria the four $K\to\pi\pi$ decay modes are counted in a 70 to 170 GeV kaon energy interval, where K_L and K_S decay spectra are similar to within ±15%. To be insensitive to residual differences in the beam spectra, the analysis is performed in 20 bins of kaon energy. A detailed description of the analysis method and event selection can be found in [3,4,5].

The NA48 experiment collected data for the Re(ε′/ε) measurement in 1997 [3], 1988-1999 [4] and 2001 [5]. Data samples and results are summarized in Table 1. The comparison of results obtained in different periods of data taking is particularly significant since they were obtained from data taken at different average beam intensities. Taking into account the correlation of the systematic uncertainty between results, the combined final result on Re(ε′/ε) from NA48 [5] is Re(ε′/ε) = $(14.7 \pm 2.2) \times 10^{-4}$ showing a clean evidence of direct CP violation in the neutral kaon system.

Data Sample	$\mathbf{K_L\to\pi^0\pi^0}$	**Re(ε′/ε)**
1997	0.5 M	$(18.5 \pm 7.3) \times 10^{-4}$ [3]
1998 - 1999	3.0 M	$(15.0 \pm 2.7) \times 10^{-4}$ [4]
2001	1.5 M	$(13.7 \pm 3.1) \times 10^{-4}$ [5]

Table 1: Data sample and results for the Re(ε′/ε) measurement: results are stable along years.

2.3 The CP violation parameter $|\eta_{+-}|$

The observable η_{+-} is related to the parameters of indirect and direct CPV ($\eta_{+-} = \varepsilon + \varepsilon'$) and is defined as the amplitude ratio of CP violating to CP conserving neutral kaon decays into two charged pions: $|\eta_{+-}| = A(K_L\to\pi^+\pi^-)/A(K_S\to\pi^+\pi^-)$.

The NA48 measurement of $|\eta_{+-}|$ is based on data collected during a dedicated two-day minimum bias run in 1999 [6]. The basic measurement of this analysis is the ratio of decay rates $R = \Gamma(K_L\to\pi^+\pi^-)/\Gamma(K_L\to\pi e\nu)$, used to compute the branching ratio of the decay $K_L\to\pi^+\pi^-$

$$BR(K_L \to \pi^+\pi^-) = \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_L \to \pi e\nu)} \cdot BR(K_L \to \pi e\nu)$$

and the CP violation parameter $|\eta_{+-}|$

$$|\eta_{+-}| = \sqrt{\frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)}} = \sqrt{\frac{BR(K_L \to \pi^+\pi^-)}{BR(K_S \to \pi^+\pi^-)} \cdot \frac{\tau_{K_S}}{\tau_{K_L}}}$$

To obtain a clean signal of the CP violating decay $K_L\to\pi^+\pi^-$, the main K_L decay modes must be suppressed by several orders of magnitude. After selecting a sample of good 2-track events, the two decay channels are separated: electron vs pion identification is based on the ratio E/p of energy deposition in the electromagnetic calorimeter to track momentum measured by the spectrometer (Fig. 2 right). After all selections 47000 $K_L \rightarrow \pi^+\pi^-$ and 5×10^6 $K_L \rightarrow \pi e \nu$ decays are retained with about 5% background contamination in each sample. Fig. 2 left shows the distribution of the invariant $\pi^+\pi^-$ mass $m_{\pi\pi}$ after all requirements except the cut on $m_{\pi\pi}$ itself.

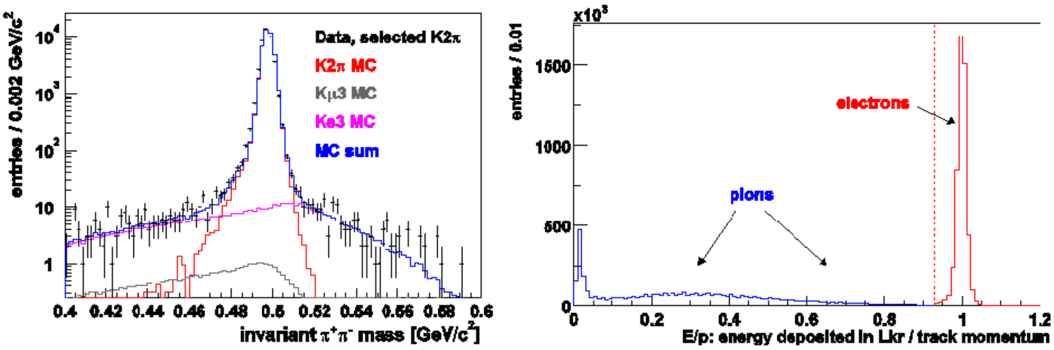

Figure 2: Distribution of the invariant $\pi^+\pi^-$ mass (left). E/p distribution for K_{e3} events (right).

Acceptance corrections and background subtraction are performed by Monte Carlo simulation, while trigger efficiencies are measured directly with the data and corrected for. The most relevant contribution to the systematic error is due to the uncertainty from the kaon energy spectrum. Details of the analysis can be found in [6].
The final result is:

$$\Gamma(K_L \rightarrow \pi^+\pi^-)/\Gamma(K_L \rightarrow \pi e \nu) = (4.835 \pm 0.022_{stat.} \pm 0.016_{syst.}) \times 10^{-3} = (4.835 \pm 0.027) \times 10^{-3}$$

The $K_L \rightarrow \pi^+\pi^-$ branching ratio is determined after subtraction of the contribution of the CP conserving direct emission process $K_L \rightarrow \pi^+\pi^-\gamma$ (DE) and including the CP violating inner bremsstrahlung component $K_L \rightarrow \pi^+\pi^-\gamma$ (IB):

$$BR(K_L \rightarrow \pi^+\pi^-) = (1.941 \pm 0.019) \times 10^{-3}$$

Using our result of the $BR(K_L \rightarrow \pi^+\pi^-)$, the CP violation parameter is finally determined

$$|\eta_{+-}| = \sqrt{\frac{BR(K_L \rightarrow \pi^+\pi^-)}{BR(K_S \rightarrow \pi^+\pi^-)} \cdot \frac{\tau_{K_S}}{\tau_{K_L}}} = (2.223 \pm 0.012) \times 10^{-3}$$

taking as input the most precise single measurementsof the K_L and K_S lifetimes τ_{KL} and τ_{KS} and branching fractions $BR(K_L \rightarrow \pi e \nu)$ and $BR(K_S \rightarrow \pi^+\pi^-)$. The result is in good agreement with recent measurement by KTeV [7] and KLOE[8], while contradicts the 2004 PDG value [9].

3. CP violation in Charged Kaons

In kaon physics, one of the most promising processes to search for direct CP violation is the charge asymmetry between K^+ and K^- decays into 3π. The matrix element for $K^\pm \rightarrow 3\pi^\pm$ can be parameterized as

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

where g,h,k are the so called linear and quadratic Dalitz plot parameters ($|h|$,$|k|$ « $|g|$), the two Lorentz invariant kinematic variables u and v are defined as

$$u = (s_3 - s_0)/m_\pi^2 \,, \quad v = (s_2 - s_1)/m_\pi^2 \,, \quad s_i = (P_K - P_i)^2 \quad i = 1,2,3 \;\; ; \quad s_0 = (s_1+s_2+s_3)/3$$

m_π is the charged pion mass, P_K and P_i are the kaon and pion four momenta, the indices i=1,2 correspond to the two pions of the same electrical charge (“even” pions) and i=3 to the pion of different charge (“odd” pion).

Direct CP violation can be measured through the asymmetry in the slope parameters g^+ and g^- describing respectively the linear dependence of the K^+ and K^- decays on the u variable of the Dalitz plot:

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

where Δg is the slope difference and g is the average linear slope.

The slope asymmetry is expected to be strongly enhanced with respect to the asymmetry of integrated decay rates. A recent full next-to-leading order ChPT calculation [10] predicts A_g to be of the order of 10^{-5} within the SM, while calculations involving processes beyond the SM [11,12] do not exclude enhancements up to few 10^{-4}.

3.1 The NA48/2 experimental set up

The primary goal of the NA48/2 experiment was the measurement of the slope charge asymmetries in both decay modes with a new level of precision achieved using a novel measurement technique based on simultaneous K^+ and K^- beams.

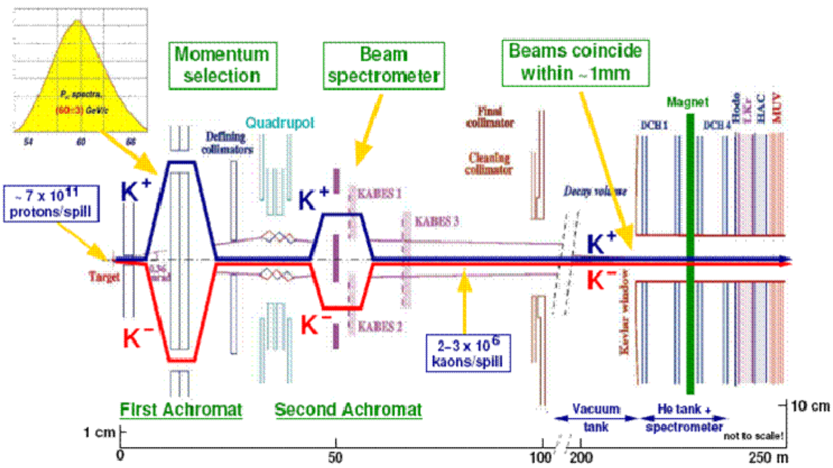

Figure 3: Schematic side view of the NA48/2 beam line.

The NA48/2 beam line (schematically shown in Fig. 3) is a key element of the experiment as it allows decays of K^+ and K^- to be recorded at the same time, leading to cancellation of several systematic uncertainties in the charge asymmetry measurement.

Two simultaneous K^+ and K^- beams are produced by 400 GeV/c protons on a beryllium target. Particles with a central momentum of (60±3) GeV/c are selected in a charge-symmetric way by a system of dipoles forming an achromat with zero total deflection, focusing quadrupoles, muon sweepers and collimators. With 7×10^{11} protons per burst 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% are K^+ and 4.9% are K^-.

Charged particles from $K^\pm$ decays are measured by the magnetic spectrometer and $K^\pm\rightarrow\pi^+\pi^-\pi^0$ decays are reconstructed by the Liquid Krypton electromagnetic calorimeter described in Section 2.1 and in [2].

3.2 The CP violation parameter A_g in $K^\pm \rightarrow 3\pi$ decays

The final measurement of A_g was performed using data collected in 2003 and 2004 [13] with selected data samples of 3.11×10^9 $K^\pm\rightarrow\pi^\pm\pi^+\pi^-$ and 9.13×10^7 $K^\pm\rightarrow\pi^+\pi^-\pi^0$ candidates. The measurement 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* axis to obtain one dimensional distributions $N^\pm(u)$. The reconstructed Dalitz plot distribution of selected $K^\pm\rightarrow\pi^+\pi^-\pi^0$ events and its projection on the *u* axis are shown in Fig. 4.

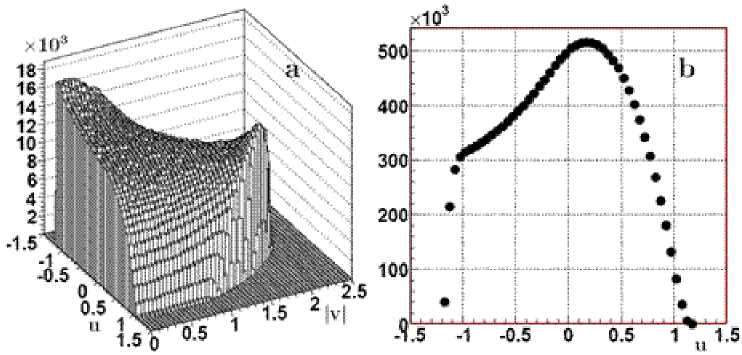

Figure 4: Reconstructed Dalitz plot distribution in the $u, |v|$ variables (left) and u spectrum for selected $K^\pm\rightarrow\pi^+\pi^-\pi^0$ events (right).

The ratio *R(u)* is computed as

$$R(u) = \frac{N^+(u)}{N^-(u)} \sim 1 + \frac{\Delta g \cdot u}{1 + gu + hu^2}$$

Any instrumental effect can induce a fake slope difference only if it is charge asymmetric and correlated with *u*. Detector acceptance and response variation effects cancel by design in NA48/2, being the two charged beams superimposed in space and present at the same time. Regular alternation of magnetic fields in all the beam line elements and in the spectrometer contributed to symmetrisation of left-right asymmetries. Data collected over a period which has all four possible combinations of magnet polarities represents a “supersample”, treated as an independent data set for the asymmetry measurement: for the $K^{\pm}\rightarrow\pi^{\pm}\pi^{+}\pi^{-}$ and $K^{\pm}\rightarrow\pi^{+}\pi^{-}\pi^{0}$ analysis nine and seven supersamples were collected respectively. The product of the four $K^{\pm}\rightarrow3\pi$ combinations of polarities in each supersample forms the quadruple ratio

$$R_4(u) = R_{US}(u) + R_{UJ}(u) + R_{DS}(u) + R_{DJ}(u)$$

where subscripts *U/D* refers to the configuration with the K^{+} passing along the upper/lower path in the achromats of the beam line and *S/J* refers to spectrometer magnet polarities corresponding to the even pions being deflected to the right/left direction in the spectrometer.
Δg is extracted from a fit to the quadruple ratio with a function of the form:

$$f(u) = n \cdot \left(1 + \frac{\Delta g \cdot u}{1 + gu + hu^2}\right)^4$$

and converted to the CP violating charge asymmetry Ag using the nominal values of the Dalitz plot slopes g recently measured by NA48/2 [14] for the charged mode and the PDG value for the neutral mode. The final results for the fits are shown in Fig. 5.

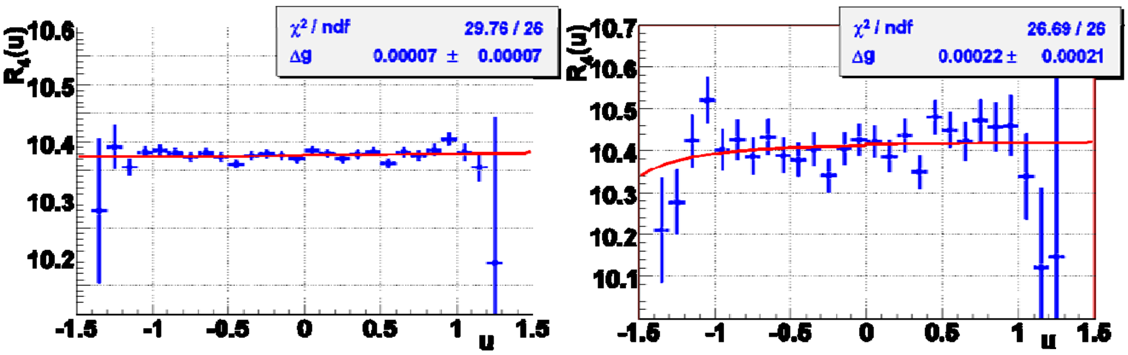

Figure 4: Quadruple ratio averaged by supersamples in bins of *u* for charged (left) and neutral (right) modes, with the result of the fit.

The results for the CP violating charge asymmetries for $K^{\pm}\rightarrow\pi^{\pm}\pi^{+}\pi^{-}$ and $K^{\pm}\rightarrow\pi^{+}\pi^{-}\pi^{0}$ decays are [13]:

$$A^{c}_{g} = (-1.5 \pm 1.5_{stat.} \pm 0.9_{trig.} \pm 1.3_{syst.}) \times 10^{-4} = (-1.5 \pm 2.2) \times 10^{-4}$$

$$A^{n}_{g} = (1.8 \pm 1.7_{stat.} \pm 1.7_{syst.}) \times 10^{-4} = (1.8 \pm 1.8) \times 10^{-4}$$

The achieved accuracy, mainly limited by the available statistics, improves by more than one order of magnitude that of previous measurements. The measured asymmetries are compatible with the SM predictions and do not show evidence for new physics beyond the SM; no evidence for direct CP violation at the order of 10^{-4} has been found. Due to the high precision achieved, the results can be used to constrain extensions of the SM predicting enhancements of the CP violating effects.

4. Conclusions

Over the past 10 years, the NA48 experiment at CERN SPS has carried out an extensive physics programme devoted to the study of CP violation. Final results from the NA48 and NA48/2 Collaborations with neutral and charged kaon decays respectively have been presented.

References

[1] J. H. Christenson et al., *Phys. Rev. Lett*. **13** , 138 (1964).

[2] V. Fanti *et al.*, *Nucl. Inst. Methods A* **574** (2007) 433.

[3] V. Fanti *et al.*, Phys. Lett. B **465** (1999) 465.

[4] A. Lai *et al.*, *Eur. Phys. J. C* **22** (2001) 231.

[5] J.R. Batley *et al.*, *Phys. Lett. B* **544** (2002) 97.

[6] A.Lai *et al.*, *Phys. Lett. B* **645** (2007) 26.

[7] T. Alexopoulos *et al.*, KTeV Coll., *Phys. Rev. D* **70:092006** (2004).

[8] F. Ambrosino *et al.*, KLOE Coll., *Phys .Lett. B* **638** (2004) 140.

[9] S. Eidelman *et al.,* Particle Data Group, *Phys .Lett. B* **592** (2004) 1.

[10] E. Gámiz *et al*, *JHEP* **10** (2003) 42.

[11] E.P. Shabalin, *ITEP preprint* **8-9**8 (1998).

[12] G. D'Ambrosio *Phys. Lett. B* **480** (2000) 164.

[13] J.R. Batley *et al.*, *Eur. Phys. J. C* **52** (2007) 875.

[14] J.R. Batley *et al.*, *Phys. Lett. B* **649** (2007) 349.