NEW MEASUREMENT OF DIRECT CP VIOLATION BY THE NA48 EXPERIMENT AT CERN

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The NA48 experiment at the CERN SPS aims to measure $\mathrm{Re}(\varepsilon'/\varepsilon)$, the direct CP violation parameter in the K^0 system, with high accuracy. In 1999 the NA48 collaboration has published its first measurement based on 1997 data. The presented result is based on data collected in 1998 and 1999. The combination with the 1997 result is $\mathrm{Re}(\varepsilon'/\varepsilon) = (15.3 \pm 2.6) \times 10^{-4}$.

1 Introduction

First evidence of CP violation in the neutral kaon system was observed in 1964 by Christenson, Cronin, Fitch and Turlay[1]. Until then the mass eigenstates K_S and K_L were considered pure CP eigenstates: K_L decaying only into CP=–1 and K_S only into CP=+1 final states. The observation of the CP-forbidden $K_L \to \pi\pi$ decays indicates violation of CP-symmetry.

CP violation can occurr via two different mechanisms: *indirect* CP violation, due to the mixing of the K^0 and $\overline{K^0}$ states, described by the parameter ε, and *direct* CP violation, due to the decay process itself through the interference of final states with different isospins, described by the parameter ε'.

The experimental determination of $\mathrm{Re}(\varepsilon'/\varepsilon)$ is done through the double ratio R:

$$\mathrm{R} = \frac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)} \Big/ \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)} \simeq 1 - 6\ \mathrm{Re}(\varepsilon'/\varepsilon) \qquad (1)$$

First experiments on direct CP violation, NA31 at CERN and E731 at Fermilab, gave inconsistent results: while NA31[2] reported evidence for direct CP violation, the result of E731[3] was compatible with no effect. In 1999 new results were announced by two new generation experiments that confirmed the existence of direct CP violation: KTeV[4] measured $\mathrm{Re}(\varepsilon'/\varepsilon) = (28.0 \pm 4.1) \times 10^{-4}$ and NA48[5] published $\mathrm{Re}(\varepsilon'/\varepsilon) = (18.5 \pm 7.3) \times 10^{-4}$.

*on behalf of the NA48 Collaboration: Cagliari, Cambridge, CERN, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Orsay, Perugia, Pisa, Saclay, Siegen, Torino, Warszawa, Wien.

This paper describes a new result from NA48, based on the analysis of data collected during the 1998 and 1999 runs, which statistics is seven times larger than the one used for the published 1997 result[5].

2 The NA48 method

The aim of NA48 is to measure $\mathrm{Re}(\varepsilon'/\varepsilon)$ with an accuracy of few 10^{-4}: several millions of $K_L \to \pi^0\pi^0$ decays, which is the statistically limiting decay mode, are needed to achieve the aimed precision. This requires a high intensity beam with a powerful trigger and data acquisition systems, as well as a high capacity data storage and data processing farm.

The basic principle of the experiment is to make the systematic biases symmetric between two of the four components of the double ratio. In this way most of the systematic effects cancel to first order and only the differences between two components need to be considered in detail in the analysis.

In order to fully exploit the double ratio technique, the four decay modes are collected at the same time in the same decay region using simultaneous and nearly collinear K_S and K_L beams, so that the decay products illuminate the detector in a similar way. Since due to the large lifetime disparity the K_S and K_L populate the decay volume in different ways, K_L decays are weighted with a function of the proper time: in this way the K_S and the K_L acceptances become similar and approximately cancel in the double ratio. The residual background after the event selection is suppressed to a sufficiently low level using high resolution detectors. The remaining K_S-K_L difference in energy spectra is reduced by performing the analysis in 20 energy bins.

3 Experimental set-up

The NA48 beams and detector are shown in Fig. 1. K_L and K_S beams are produced by the primary 450 GeV proton beam ($\sim\ 1.5 \times 10^{12} ppp$) delivered by the SPS accelerator. The non-interacting protons are sent to a bent silicon crystal[6] 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 $\sim 3 \times 10^7 ppp$. To distinguish K_S and K_L decays the protons directed to the K_S target are detected by the tagging detector[7]. A magnetic spectrometer consisting of four drift chambers and a dipole magnet ($\sigma(p)/p \simeq 0.5\% \oplus 0.009p[GeV/c]\%$, $\sim 1\%$ for 100 GeV/c track momentum) is used to detect $\pi^+\pi^-$ decays. The time of $\pi^+\pi^-$ events is measured by a scintillator hodoscope ($\sigma_t \approx 200\,ps$).

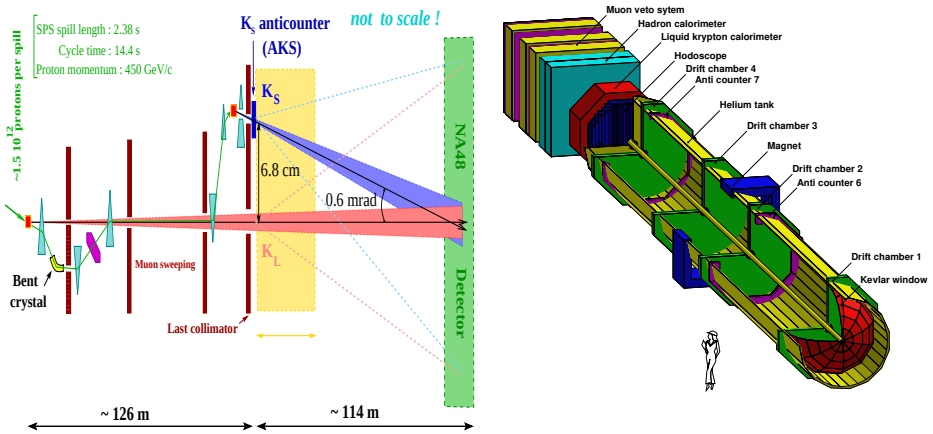

Figure 1. *Schematics layout of the NA48 beams and the detector.*

A quasi-homogeneus Liquid Krypton electromagnetic calorimeter reconstructs $\pi^0\pi^0$ decays using the information on energy, position and time of the four photon clusters. The energy resolution is $\sigma(E)/E \simeq 3.2\%/\sqrt{E} \oplus 0.09/E \oplus 0.42\%$ (E in GeV, better than 1% for 25 GeV photons) and the time resolution is $\sim 250\,ps$.

The trigger for $\pi^+\pi^-$ decays consists of a fast pretrigger and a processor farm[8] that computes the decay vertex position and the invariant mass from the drift chamber signals with an inefficiency of $\sim 2.2\%$ and a dead time of $\sim 1.1\%$. The neutral trigger[9] uses horizontal and vertical projections of the energy deposits in the calorimeter to compute the total energy, the decay vertex and the number of showers to reduce the $\sim$1 MHz particle rate to a $\sim$2 kHz trigger rate with negligible dead time and an inefficiency of $\sim 0.1\%$

The reconstructed decay products are assigned to a parent K_L or K_S using the tagging station. The time of flight between the detector and the tagger is measured: events with a proton in time coincidence with the decay are assigned to K_S otherwise they are identified as K_L.

4 Data analysis

The NA48 experiment collected 1.0 millions of $K_L \to \pi^0\pi^0$ during the 1998 run, while in 1999 an upgrade of the trigger and event builder PC farm, as well as a better stability of the detectors and electronics, allowed to collect 2.2 millions of $K_L \to \pi^0\pi^0$.

The analysis strategy consists in minimising the corrections to be applied to the double ratio of the decay counts. The smallness of the corrections follows from the symmetry in the four decay counting.

4.1 Event selection and Background subtraction

The four decay modes are counted in the same kaon energy interval ($70\,GeV < E_K < 170\,GeV$), and decay volume ($0 < \tau_S < 3.5$ in units of K_S lifetime). Events are counted in each sample, and corrections are applied in twenty bins of kaon energy, each 5 GeV wide, in order to reduce the influence of residual difference in the K_S/K_L spectra and the result is obtained by averaging the twenty double ratios.

In both decay modes K_S has no significant background. The main source of background in $\pi^+\pi^-$ decays are K_L semileptonic 3-body decays. The $K_L \to \pi e \nu$ is rejected by comparing the energy of the electrons in the calorimeter and their momentum in the spectrometer and requiring $E/p < 0.8$. To reject $K_L \to \pi\mu\nu$ no associated hit in the muon veto is required. In addition a cut on the kaon invariant mass is applied. The remaining background is subtracted using two control regions in the invariant mass-rescaled transverse momentum squared plane ($p_T^{'\,2}$). The background under the signal region is estimated using cleanly identified K_{e3} and $K_{\mu 3}$ events (Fig. 2 Left).

The dominant background in $\pi^0\pi^0$ events are $K_L \to \pi^0\pi^0\pi^0$decays, that are rejected by requiring no extra showers in time. An invariant mass cut in the space of the two π^0 invariant masses is applied, using a χ^2-like variable. The residual backgroung under the signal is estimated from the control region in the χ^2 distribution (Fig. 2 Right).

4.2 K_S-K_L misidentification

Two possible sources of mistagging must be considered: K_S can be identified as K_L (α_{SL}) due to tagging inefficiencies, and K_L can be identified as K_S (α_{LS}) due to accidental coincidences between protons in the tagger and K_L decays. The double ratio is sensitive only to differences between the charged and neutral mistagging probabilities, $\Delta\alpha_{SL} = \alpha_{SL}^{00} - \alpha_{SL}^{+-}$ and $\Delta\alpha_{LS} = \alpha_{LS}^{00} - \alpha_{LS}^{+-}$. The tagging inefficiency measured in charged decays is $\alpha_{SL}^{+-} = (1.63 \pm 0.03) \times 10^{-4}$; the differential effect is evaluated using $2\pi^0$ and $3\pi^0$ events with one photon conversion: $\Delta\alpha_{SL} = (0 \pm 0.5) \times 10^{-4}$. The accidental tagging probability, measured in $\pi^+\pi^-$events, is $\alpha_{LS}^{+-} = (10.649 \pm 0.008)$; the value of $\Delta\alpha_{LS}$ estimated using sidebands away from the coincidence peak in the time difference distribution is $\Delta\alpha_{LS} = (4.3 \pm 1.8) \times 10^{-4}$.

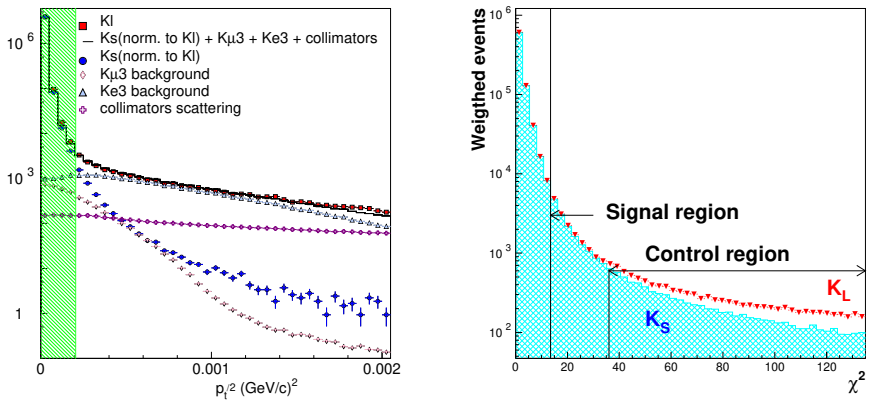

Figure 2. *Left: Charged signal and background components in the* $p_T'^2$ *distributions; Right: Neutral signal and background excess in the* χ^2 *variable distributions.*

4.3 Corrections and systematic uncertainties

Accidental activity effects are evaluated by overlaying random events to good events and by studying the beam correlation at small and large time scales. In the $\pi^0\pi^0$ decays, one of the main sources of systematics is the uncertainty on the distance scale that enters the measurement through the definition of the decay region, and that is related to the energy scale. The latter is constrained by reconstructing the well known position of the AKS detector which determines the beginning of the decay region. The acceptance correction is reduced to a very small level due to the symmetric detector illumination after the K_L weighting procedure: residual effects, due to the small angle between the two beams, are estimated using Monte Carlo. Table 1 shows a list of all corrections and systematic uncertainties applied to the raw double ratio; the effect on $\mathrm{Re}(\varepsilon'/\varepsilon)$ is obtained dividing the numbers by a factor of 6.

5 Result

The statistics collected in years 1998 and 1999 is shown in Table 2.
After applying all corrections to the raw double ratio the result is

$$\mathrm{R} = 0.99098 \pm 0.00101_{stat} \pm 0.00126_{syst} \tag{2}$$

which corresponds to

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (15.0 \pm 2.7) \times 10^{-4} \tag{3}$$

Source	$\Delta(R)$ (in 10^{-4} units)	
$\pi^+\pi^-$ background	16.9	± 3.0
$\pi^0\pi^0$ background	-5.9	± 2.0
beam scattering background	-9.6	± 2.0
Tagging inefficiency		± 3.0
Accidental tagging	8.3	± 3.4 (part. stat)
$\pi^+\pi^-$ scale	2.0	± 2.8
$\pi^0\pi^0$ scale		± 5.8
AKS inefficiency	1.1	± 0.4
Acceptance correction	26.7	± 4.1 (MC stat)
		± 4.0 (syst)
$\pi^+\pi^-$ trigger	-3.6	± 5.2 (stat)
Accidental event losses		± 4.4 (part. stat)
Total	35.9	± 12.6

Table 1. *Corrections and systematic uncertainties on R.*

$K_L \to \pi^0\pi^0$	3.29×10^6	$K_S \to \pi^0\pi^0$	5.21×10^6
$K_L \to \pi^+\pi^-$	14.45×10^6	$K_S \to \pi^+\pi^-$	22.22×10^6

Table 2. *Number of selected events after accounting for mistagging.*

Combining this result with the published 1997 result[5], we obtain

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (15.3 \pm 2.6) \times 10^{-4} \tag{4}$$

The stability of the corrected double ratio with applied cuts and changes in beam and detector conditions has been extensively checked. In Fig. 3 the stability with kaon energy is shown.

6 Conclusions

The NA48 result confirms the existence of direct CP violation, with a positive value of ε', 5.9 standard deviations away from zero.

Taking into account previous generation expriments results[2,3], the KTeV updated result[10] ($\mathrm{Re}(\varepsilon'/\varepsilon) = (20.7 \pm 2.8) \times 10^{-4}$) and the NA48 combined result presented in this paper, we obtain a world average (see Fig. 3) of

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (17.2 \pm 1.8) \times 10^{-4} \tag{5}$$

with $\chi^2/\mathrm{ndf} = 5.5/3$ (14 % probability) that definitely establishes direct CP violation.

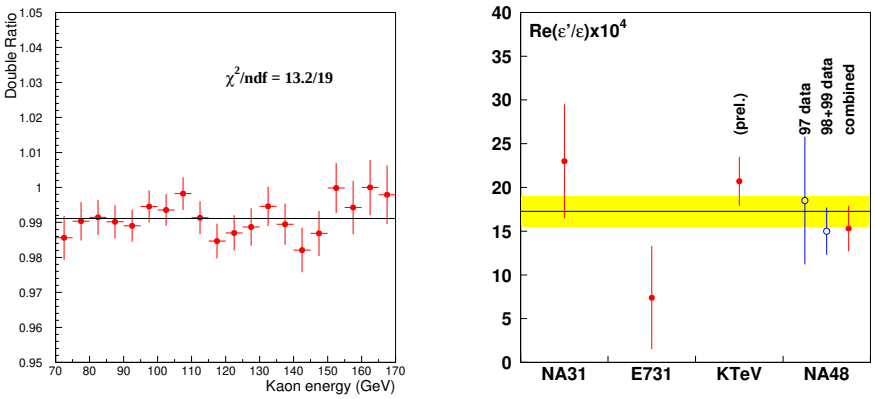

Figure 3. *Left: Stability of the double ratio with kaon energy; Right: Experimental results comparison; full points are used in the average.*

In the year 2000, NA48 collected data without the spectrometer, due to an implosion of the beam pipe that damaged all the four drift chambers; these data were used for systematic checks for the neutral decays.

The year 2001 is the last year of data taking and we expect to collect ~ 1.5 millions of $K_L \to \pi^0\pi^0$. We will complete the statistics and, with the new spectrometer and different beam conditions, we will check the result under different conditions.

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