MEASUREMENT OF DIRECT CP VIOLATION BY NA48

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The NA48 experiment at the CERN SPS aims to search for direct CP violation in the K^0 system through the measurement of $\mathrm{Re}(\varepsilon'/\varepsilon)$ with high accuracy. In 1999 the NA48 collaboration has published its first measurement based on 1997 data. A new result, based on 1998 and 1999 data, is presented in this article. The result, combined with 1997 data, $\mathrm{Re}(\varepsilon'/\varepsilon) = (15.3 \pm 2.6) \times 10^{-4}$, contributes to the precise determination of the size of direct CP violation.

1 Introduction

In the neutral kaon system the CP eigenstates are linear combinations of the strangeness eigenstates, K^0 and $\overline{K^0}$. If the mass eigenstates, K_S and K_L, were pure CP eigenstates, K_L would decay only into CP=–1 and K_S only into CP=+1 final states. The two decay modes in $\pi^+\pi^-$ and $\pi^0\pi^0$ have CP=+1, so K_S are allowed to decay into pion pairs, but not K_L. Then, in the neutral kaon system CP violation manifests in the observation of the CP-forbidden $K_L \to \pi\pi$ decays. First evidence of CP violation was observed in 1964 by Christenson, Cronin, Fitch and Turlay[?].

In the Standard Model, CP violation is related to the existence of three generations of quarks and to a complex phase in the CKM matrix. Two different mechanisms contribute: *indirect* CP violation, due to the mixing of the K^0 and $\overline{K^0}$ states, represented by the parameter ε, and *direct* CP violation, due to the decay process itself, through the interference of final states with different isospins, and represented by the parameter ε'.

The parameters ε and ε' are related to the amplitude ratios

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \simeq \varepsilon + \varepsilon' \qquad \eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} \simeq \varepsilon - 2\varepsilon'$$

which represent the strength of the CP violating amplitudes with respect to the CP conserving ones, in each mode. ε' is small compared to ε and it is convenient to measure $\mathrm{Re}(\varepsilon'/\varepsilon)$. The experimental observable, the double ratio R, is related to the decay widths and to $\mathrm{Re}(\varepsilon'/\varepsilon)$ through

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

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The first generation of experiments, NA31 at CERN and E731 at Fermilab, gave inconclusive results: while NA31[?] reported evidence for direct CP violation, indicating a 3.5σ effect, the result of E731[?] was compatible with no effect. Two new experiments were setup to clarify the situation.

In 1999 first results were reported and both experiments confirmed the existence of direct CP violation: KTeV at Fermilab measured $\mathrm{Re}(\varepsilon'/\varepsilon) = ((28.0 \pm 4.1) \times 10^{-4})$[?] and NA48 at CERN $\mathrm{Re}(\varepsilon'/\varepsilon) = ((18.5 \pm 7.3) \times 10^{-4})$[?]. Before June 2001, the four most precise results [?,?,?,?] gave a world average of $(19.2 \pm 2.5) \times 10^{-4}$, with a $\chi^2/\mathrm{ndf} = 10.4/3$, that indicates poor constincency between the data. In order to establish the size of direct CP violation, new results form the two experiment, with substantially smaller uncertainties, were expected. Current theoretical predictions are in the range $(1 \div 30 \times 10^{-4})$[?].

This paper describes a new result from NA48, based on the analysis of data collected during the 1998 and 1999 runs; the statistics, is seven times larger ($\sim 3.3 \times 10^6\, K_L \to \pi^0\pi^0$) than that used for the published 1997 result[?].

2 The NA48 method

NA48 aims to measure $\mathrm{Re}(\varepsilon'/\varepsilon)$ with an accuracy of 2×10^{-4} using the double ratio technique and nearly collinear simultaneous K_S and K_L beams. The required statistical error is reached by collecting several millions of $K_L \to \pi^0\pi^0$ (the statistically limiting decay mode); data are collected using fast and efficient data acquisition system, triggers with high rejection power and high capacity data storage systems.

The basic principle of the experiment is to make the systematic biases symmetric between either the $\pi^+\pi^-$ and $\pi^0\pi^0$ decays or the K_L and K_S beams. 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 *simultaneously*; this cancels out effects due to beam fluxes, inefficiencies in K_S, K_L identification, trigger and event selection, as well as dead time and accidental losses. In order to minimise acceptance corrections, the four decay modes are collected from a *common decay region* and with two *quasi collinear beams*, so that the decay products illuminate the detector in a similar way. However, due to the very different lifetimes of the K_S and K_L particles, the vertex distributions vary a lot along the beam direction. In order to obtain almost identical decay distributions for K_L and K_S, K_L decays are *weighted* with a function of the proper time. The backgound, that cannot be reduced by cancellation, is suppressed using *high resolution detectors*. The remaining K_S-K_L difference in energy spectra are reduced by performing the analysis in *energy bins* (20 bins, between 70 and 170 GeV).

3 Experimental set-up

The NA48 beam line[?] and detector[?] are designed to fulfill these requirements. A primary 450 GeV proton beam ($\sim 1.5 \times 10^{12}\,ppp$) at the SPS accelerator produces the K_L beam on a beryllium target. The non-interacting protons are sent to a bent silicon crystal[?]; only a small fraction of protons satisfy the conditions for channelling and an attenuated proton beam ($\sim 3 \times 10^7\,ppp$) impinges on the K_S target. In the way to the target, the protons pass through a tagging station, that tag protons that are going to produce the K_S beam.

The decays in $\pi^+\pi^-$ are reconstructed using a magnetic spectrometer composed of four large drift chambers and a dipole magnet. The momentum resolution is $\sigma(p)/p \simeq 0.5\% \oplus 0.009p[GeV/c]\%$ ($\sim 1\%$ for 100 GeV/c track momentum). The time of $\pi^+\pi^-$ events is measured by a scintillator hodoscope ($\sigma_t \approx 200\,ps$). The trigger for $\pi^+\pi^-$ decays consists of a fast pretrigger and a processor farm[?] that computes the decay vertex position and the invariant mass from the drift chamber signals. This trigger has an inefficiency of $\sim 2.2\%$ and a dead time of $\sim 1.1\%$.

The decays in $\pi^0\pi^0$ are reconstructed from the informations on energy, position and time of the four clusters given by the Liquid Krypton electromagnetic calorimeter. 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). The time resolution is $\sim 250\,ps$. The neutral trigger[?] uses the calorimeter informations and look-up tables to make a fast decision. The inefficiency is $\sim 0.1\%$ with almost no dead time.

The reconstructed decay products have to be assigned to a parent particle (either K_L or K_S); the identification is done using the tagging station. The time of flight between the detector and the tagger is measured: events with a time coincidence inside a $\pm 2ns$ window are assigned to K_S parent particle, events outside this window are identified as K_L.

4 Data analysis

The data collected during the 1998 run amount to 1.1 millions of $K_L \to \pi^0\pi^0$ in 135 days of data taking. In 1999, an upgrade of the trigger and event builder PC farm, as well as a better stability of the detectors and electronics, resulted in high data taking efficiency and the experiment collected, in 128 days, 2.2 millions of $K_L \to \pi^0\pi^0$.

4.1 Event selection

The analysis is based on the principle of minimising the corrections to be applied to the double ratio of the decay counts. The key points of the analysis can be summarized as follows:

- 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). An anti-counter (AKS), placed in the K_S beam, determines the beginning of the K_S decay region.
- Dead time in the trigger or read out is applied to all four modes, in order to equalise intensity conditions and to preserve the principle of symmetrization.
- In $\pi^+\pi^-$ decays K_S and K_L can also be identified by extrapolating the vertical decay vertex position. To keep the symmetry principle, the tagging is used for K_S -K_L identification both for $\pi^0\pi^0$ and $\pi^+\pi^-$ decays; in this way the measurement is sensitive only to differences between neutral and charged mistagging probabilities.
- To cancel the contribution from the different K_L and K_S lifetimes to the acceptance, each K_L candidate is weighted with a function of the proper time to match the decay vertex distribution of K_S (Fig. 1).

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 K_S/K_L spectra. The result is obtained by averaging the twenty double ratios.

4.2 K_S-K_L misidentification

In the tagging procedure, there are two possible sources of misidentification: 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 the differences between the mistagging probabilities, $\Delta\alpha_{SL} = \alpha^{00}_{SL} - \alpha^{+-}_{SL}$ and $\Delta\alpha_{LS} = \alpha^{00}_{LS} - \alpha^{+-}_{LS}$. The tagging inefficiency measured in $\pi^+\pi^-$ 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 with $\pi^+\pi^-$ decays, is $\alpha^{+-}_{LS} = (10.649 \pm 0.008)$; the value of $\Delta\alpha_{LS}$ is estimated using sidebands away from the coincidence peak in the time difference distribution: $\Delta\alpha_{LS} = (4.3 \pm 1.8) \times 10^{-4}$ (Fig. ??).

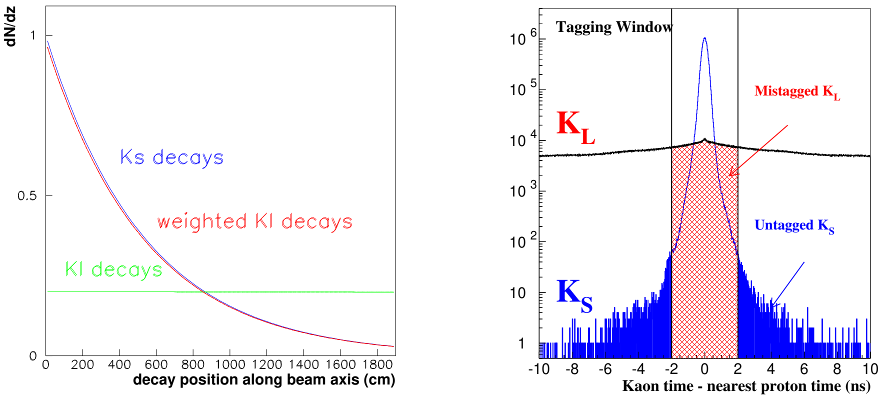

Figure 1. left: Reconstructed lifetime distribution for $K_L \to \pi\pi$ before and after weighting; right: The time difference between a $K \to \pi\pi$ candidate and the nearest proton time in the tagger. The K_S and K_L contributions are identified by vertical vertex separation.

4.3 Charged and Neutral Background

In both decay modes, K_S has no significant background. The main source of background in $\pi^+\pi^-$ decays are semileptonic 3-body decays $K_L \to \pi e \nu$ and $K_L \to \pi \mu \nu$. The K_{e3} is rejected by measuring the energy of the electrons in the calorimeter and their momentum in the spectrometer and then by requiring $E/p < 0.8$. For the $K_{\mu 3}$ case, 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.

In $\pi^0\pi^0$ decays, the dominant background is $K_L \to \pi^0\pi^0\pi^0$. This background is rejected by requiring no extra showers in time. Furthermore an invariant mass cut in the space of the two π^0 invariant mass 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. **??**).

4.4 Other systematics

Other sources of systematics have been carefully studied. The *accidental activity* effects are evaluated by overlaying random events to real good events and by studying the beam correlation at small and large time scales. In the

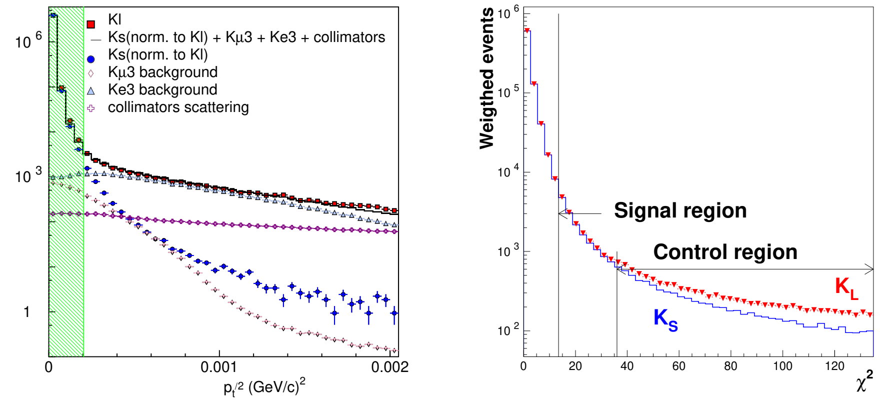

Figure 2. left: Distribution of charged signal and background components in the $p_T'^{\,2}$; right: Distribution of neutral signal and background excess in K_L in the χ^2 variable.

$\pi^0\pi^0$ decays the distance scale is directly related to the *energy scale*. The latter is constrained by reconstructing the well known position of a detector: in our case it is the AKS position, which determines the beginning of the decay region. The *acceptance correction* is reduced to a very small level due to the symmetric detector illumination, consequence of the K_L weighting procedure. The small residual effect, due to the small angle between the two beams, is estimated using Monte Carlo. Table **??** 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 The result

The result, obtained from the data collected in years 1998 and 1999 (statistics shown in Table **??**), is

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

which corresponds to

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

Combining this result with the published result (1997 data)[?], we obtain

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

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

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.

6 Conclusion and outlook

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

Recently the KTeV collaboration has anounced a new result[?] based on data from the 1997 run and a revised analysis of their published result[?] (part of the 1996 statistics): $\mathrm{Re}(\varepsilon'/\varepsilon) = (20.7 \pm 2.8) \times 10^{-4}$.

Taking into account the results from previous generation expriments [?,?], the KTeV updated result[?] and the NA48 combined result, presented in this paper, we obtain a world average (see Fig. 3) of

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

with $\chi^2/\mathrm{ndf} = 5.5/3$ (14 % probability).

This definitely establishes direct CP violation.

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

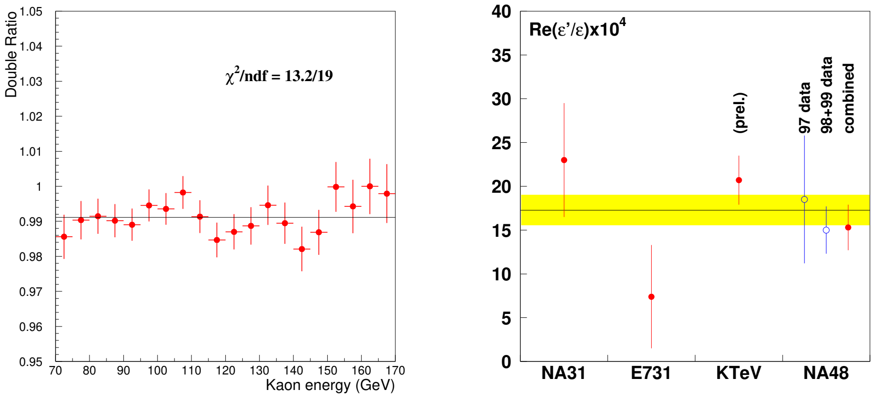

Figure 3. left: Stability of the double ratio with kaon energy; right: Experimental results comparison; full points are used in the average.

$\sim$ 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 (spill), we will check the result under different conditions.

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