A New Result on Direct CP Violation by NA48 at CERN

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The NA48 collaboration at CERN has measured the direct CP violation parameter $\mathrm{Re}(\epsilon'/\epsilon)$ from the decay rate of neutral kaons into two pions. During the 1998 and 1999 running periods, a result of $\mathrm{Re}(\epsilon'/\epsilon) = (15.0 \pm 2.7) \times 10^{-4}$ has been obtained. The principles of the experiment, the data analysis features and the systematic error evaluation will be described.

1 Introduction

Neutral kaons form a quantum system in which we can define the following eigenstates:

$$\begin{aligned}
\text{Strong}: &\quad \mathrm{K}^0\ (\bar{\mathrm{s}}\mathrm{d}), [S=+1]; &\quad \overline{\mathrm{K}^0}\ (\mathrm{s}\bar{\mathrm{d}}), [S=-1] \\
\text{CP}: &\quad \mathrm{K}_1 = \tfrac{1}{\sqrt{2}}(\mathrm{K}^0 + \overline{\mathrm{K}^0}), [CP=+1]; &\quad \mathrm{K}_2 = \frac{1}{\sqrt{2}}(\mathrm{K}^0 - \overline{\mathrm{K}^0}), [CP=-1] \\
\text{Lifetime}: &\quad \mathrm{K}_\mathrm{S} \simeq \mathrm{K}_1 + \varepsilon \mathrm{K}_2, [c\tau = 2.67\ \mathrm{cm}]; &\quad \mathrm{K}_\mathrm{L} \simeq \mathrm{K}_2 + \varepsilon \mathrm{K}_1, [c\tau = 15.5\ \mathrm{m}],
\end{aligned}$$

where $\varepsilon = (2.28 \pm 0.02) \times 10^{-3}$ [1] and S is the strangeness quantum number.

The K_L decays mainly into semileptonic channels and into 3 pion states with $CP = -1$; in few per mille of the cases it decays into 2 pion states with $CP = +1$. This so called *indirect* CP violation is due to the mixing of K^0 and $\overline{\mathrm{K}^0}$.

CP violation can also occur in the decay process itself, through the interference of final states with different isospins. This so called *direct* CP violation is represented by the parameter ϵ'.

Direct CP violation is expected to be $\sim$1/1000 of the indirect component. The ratio $\mathrm{Re}(\epsilon'/\epsilon)$ is only weakly bounded by theory to be between 0 and 30×10^{-4}. The measurable quantity $\mathrm{Re}(\epsilon'/\epsilon)$ is connected to the double ratio R of four decay rates as follows:

$$\mathrm{R} = \frac{\Gamma(\mathrm{K}_\mathrm{L} \to \pi^0\pi^0)}{\Gamma(\mathrm{K}_\mathrm{S} \to \pi^0\pi^0)} \Big/ \frac{\Gamma(\mathrm{K}_\mathrm{L} \to \pi^+\pi^-)}{\Gamma(\mathrm{K}_\mathrm{S} \to \pi^+\pi^-)} \approx 1 - 6 \times \mathrm{Re}(\epsilon'/\epsilon)\ .$$

2 The NA48 experiment

The double ratio of the decay widths reduces to the double ratio of number of decays if all the four modes are collected simultaneously (the fluxes cancel in the ratio) and in the same decay region (the fraction of accepted decays cancels in the ratio). To obtain the true double ratio R one has to correct the measured R_{exp} by a factor A_{corr} which would take into account of all the acceptance, trigger and analysis effects, such that $\mathrm{R}_{true} = \mathrm{R}_{exp} + \mathrm{A}_{corr}$.

In practice, measure accurately $\mathrm{Re}(\epsilon'/\epsilon)$ is equivalent to measure accurately the correction factor A_{corr}. All experimental efforts will concentrate to identify, minimize and precisely quantify all possible sources of biases.

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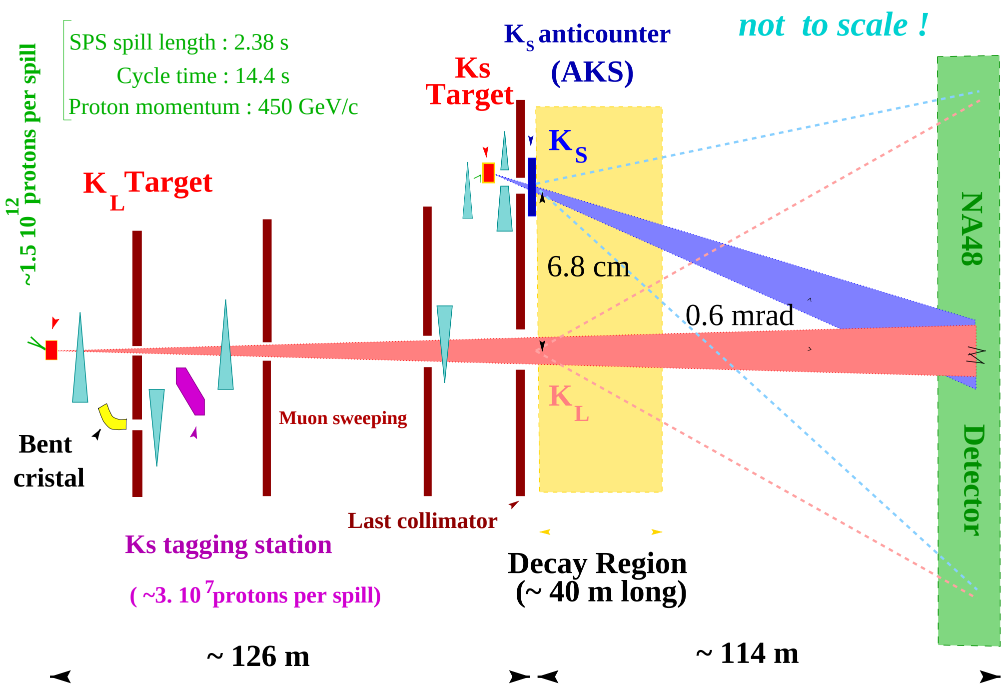

Fig. 1. The NA48 beam setup.

2.1 The NA48 beams

The NA48 experiment is installed at CERN and uses the 450 GeV/c proton beam delivered by the SPS accelerator. $\mathrm{K_L}$ and $\mathrm{K_S}$ beams are produced in different targets located 126 m and 6 m upstream of the decay fiducial region, respectively (see Fig. 1).

Protons not interacting in the $\mathrm{K_L}$ target reach a bent silicon crystal where a small fraction (about 10^{-5}) follows the bent crystal planes forming a secondary beam which impinges on the $\mathrm{K_S}$ target.

The two kaon beams share the same fiducial decay volume, they are separated by about 7 cm at the exit of the last collimator and converge at the position of the detectors, about 120 m downstream. In this way the four decay modes are collected simultaneously; long term variations on the $\mathrm{K_S}/\mathrm{K_L}$ ratio (with a RMS of about 9%) are taken into account by weighting $\mathrm{K_S}$ events to keep such a ratio constant[1].

2.2 The NA48 detector

The NA48 detector is designed to precisely identify and reject the CP conserving component of the $\mathrm{K_L}$ decays and to be able to register high rates for long periods in stable conditions (see Fig. 2).

$\mathrm{K_L}, \mathrm{K_S} \to \pi^+\pi^-$ decays are detected by a magnetic spectrometer made of 4 drift chambers and a dipole magnet providing 265 MeV p_T kick. The track momentum resolution, obtained from special electron runs is $\sigma(p)/p \simeq 0.48\% \oplus 0.009 \times p\%$, where p is in GeV/c.

The $\pi^+\pi^-$ trigger reduces in two stages the 500 KHz input to a 2 KHz output with an efficiency of $(97.896 \pm 0.024)\%$ (the error is of pure statistical nature due to the control sample used). The correction on R induced by the trigger inefficiency is $\Delta\mathrm{R} = (-3.6 \pm 5.2) \times 10^{-4}$.

[1] $\mathrm{K_S}$ reweighting is a small effect on R: about 3×10^{-4}.

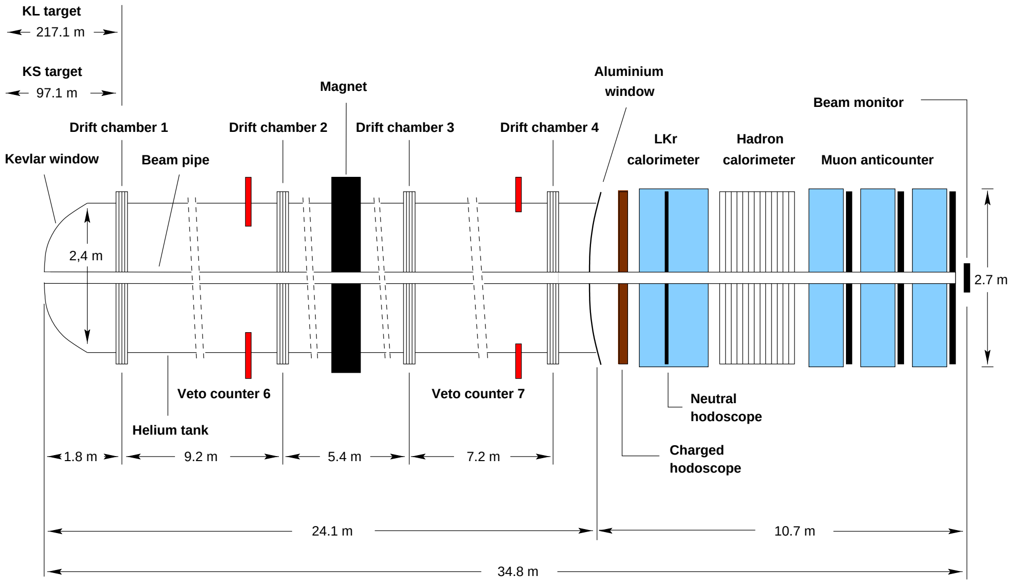

Fig. 2. The NA48 detector.

$K_L, K_S \to \pi^0\pi^0$ decays are detected by a Liquid Krypton electromagnetic calorimeter made of 13212 cells (2×2 cm$^2 \times 27\ X_0$, $X_0 = 4.7$ cm). The energy resolution is, with E in GeV:

$$\frac{\sigma(E)}{E} = \frac{(3.2 \pm 0.2)\%}{\sqrt{E}} \oplus \frac{(9 \pm 1)\%}{E} \oplus (0.42 \pm 0.05)\%.$$

The cells are made in projective geometry pointing to the middle of the decay region (about 114 m upstream).

A hadron calorimeter used for the total energy measurement, a muon veto system to identify the background from $K_L \to \pi\mu\nu$ ($K_{\mu 3}$) decays, an out-of-acceptance veto system and some intensity monitors complement the apparatus.

Dead time conditions are due mainly to the charged apparatus and include about 1.5% from the $\pi^+\pi^-$ trigger and about 20% from the drift chamber multiplicity limit. These conditions are recorded and applied offline to all the events (in particular to $\pi^0\pi^0$ events).

3 The analysis

The data analysis for the Re(ϵ'/ϵ) measurement is done in the following steps:

1. The decays into $\pi^+\pi^-$ and $\pi^0\pi^0$ are reconstructed.
2. These two samples are then identified as originated from the K_S or the K_L beam, using the tagging information.
3. The remaining 3-body background is subtracted from the K_L sample in both $\pi^+\pi^-$ and $\pi^0\pi^0$ modes.
4. Corrections are applied and the corresponding systematic uncertainties are evaluated.
5. The double ratio is computed and its stability with respect to several variables is checked.

3.1 Decay region definition

The beginning of the K_S decay region is sharply defined by a counter (AKS[2]) which rejects all the upstream decays both for $\pi^+\pi^-$ and for $\pi^0\pi^0$. The correction on R due to the AKS inefficiency is $\Delta R = (1.1 \pm 0.4) \times 10^{-4}$. The end of the K_S decay region as well as the beginning and the end of the K_L decay region are defined by the decay position reconstructed by the detectors. The decay position is measured w.r.t. the AKS position; the fiducial volume is defined by the proper time of the decay, measured in K_S lifetime units. The downstream cut has been chosen to be 3.5 K_S lifetimes, the K_L upstream cut is in the same position as the AKS.

The kaon energy range is 70 GeV $\leq E_K \leq$ 170 GeV where the K_L/K_S variation is smaller than 20%. Nevertheless R is measured in kaon energy bins (5 GeV wide) and then averaged, to be insensitive to $K_S - K_L$ energy spectrum differences.

The center of gravity R_{COG} is the kaon impact point extrapolated to the calorimeter. The cut $R_{COG} \leq 10$ cm is used to reject background decays and beam halo particles.

3.2 $\pi^+\pi^-$ reconstruction

The $\pi^+\pi^-$ invariant mass resolution is about 2.5 MeV (see Fig. 3) and the applied cut is at 3 σ's.

The background is due to K_L semileptonic decays in which an electron or a muon is identified as a pion. These backgrounds are suppressed by the E/p cut[3] and by the Muon veto counters. Further background suppression is achieved cutting on the kaon transverse momentum ($p_T^2 < 200$ (MeV/c)^2) to remove three-body decays with a missing neutrino and on the tracks momentum asymmetry to suppress Λ decays.

The kaon energy is calculated from the opening angle between the two tracks before the magnet and the ratio of two pions momenta. This method makes the measurement independent from energy scale uncertainties. Only the distance scale is sensitive to geometry differences between the first two chambers and also on their relative distance. This geometry can be checked reconstructing the position of the AKS anti counter for not vetoed decays into $\pi^+\pi^-$ ($\Delta z = 2$ cm). The correction on R due to this geometry is $\Delta R = (2.0 \pm 2.8) \times 10^{-4}$.

The background is estimated in two control regions of $M_{\pi\pi}$ and p_T^2, comparing the distributions of $K_L \to \pi^+\pi^-$ and of $K_L \to \pi e \nu$ (K_{e3}) and $K_{\mu 3}$ decays and then extrapolating to the signal region.

The first control region ($M_{\pi\pi} \gg M_K$) is dominated by K_{e3} decays, while the second one ($M_{\pi\pi} \ll M_K$) contains K_{e3} and $K_{\mu 3}$ decays in a similar amount. The $M_{\pi\pi}$ and p_T^2 tails of $K_L \to \pi^+\pi^-$ in the two control regions are estimated using K_S decays.

The background is measured to be $(16.9 \pm 3.0) \times 10^{-4}$, where the systematic error evaluation comes from a variation of control regions borders and by the modeling of the p_T^2 shape.

K_L beam scattering in the final collimator produce $\pi\pi$ events with high p_T which are removed in the $\pi^+\pi^-$ sample by the p_T cut, but are kept in the $\pi^0\pi^0$ sample, inducing a correction on R. K_S beam scattering are instead removed by the R_{COG} cut which is symmetric between $\pi^+\pi^-$ and $\pi^0\pi^0$.

The collimator background is estimated using $\pi^+\pi^-$ events with $p_T^2 > 200(MeV/c)^2$ with $M_{\pi\pi}$=M_K and it is cross-checked in $\pi^0\pi^0$ R_{COG} distribution. The beam scattering background gives a correction of $\Delta R = (-9.6 \pm 2.0) \times 10^{-4}$.

[2]The AKS is made by a photon converter (an iridium crystal 3 mm thick, corresponding to 1.79 X_0 at 0 angle), followed by a track veto (a scintillator counter).

[3]For each track a cluster in the calorimeter is associated; the E/p is the ratio of the cluster energy and the track momentum.

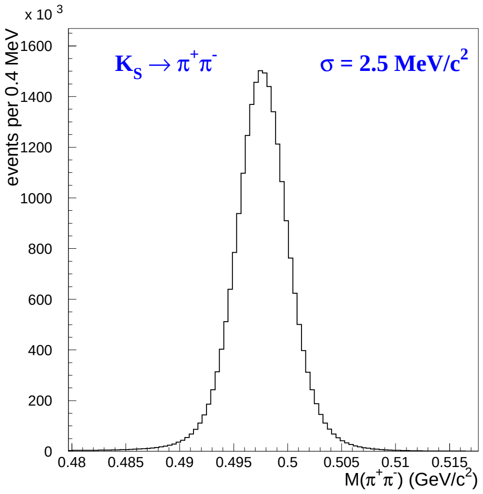

Fig. 3. Reconstructed $\pi^+\pi^-$ mass.

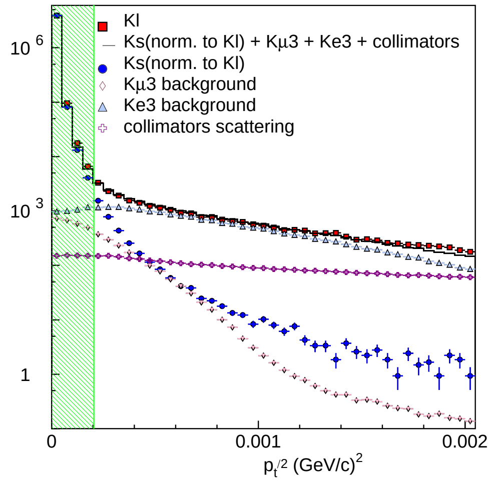

Fig. 4. Distribution of transverse momentum p_T^2 and comparison of the data with all known components.

3.3 $\pi^0\pi^0$ reconstruction

From the four detected photons in the calorimeter, the distance D of the decay from the calorimeter is given by $D = \sqrt{\sum E_i E_j \times (r_{ij})^2}/M_K$, where E_i are the photon energies and r_{ij} the distances between photons in the calorimeter. The two photons invariant mass is $m_{ij} = \sqrt{E_i E_j}\, r_{ij}/D$. The best combination of two photon couples which minimizes the χ^2 of the two photons invariant masses w.r.t. the π^0 mass is chosen and a cut on the χ^2 is applied to suppress decays into $3\pi^0$ with missing photons (see Fig. 5). Events with extra photons in time are rejected.

From the $K_S \to \pi^0\pi^0$ decay distribution the AKS position can be reconstructed: the calorimeter energy scale is adjusted to match the AKS nominal position. In this way the neutral energy knowledge is again converted into geometry (see Fig. 6).

The stability of the reconstructed AKS position is checked as a function of the kaon energy (non linearity check). In K_{e3} decays the electron energy measured by the calorimeter can be checked w.r.t. the momentum measured by the magnetic spectrometer: E/p is constant within $\approx 0.1\%$ from a few GeV to 100 GeV.

In special runs a π^- beam is directed onto two thin targets (one at the beginning of the kaon fiducial decay region, one at the end), producing π^0 and η with known decay position. $K_L \to \gamma\gamma$ decays are used to reconstruct the decay position assuming π^0 or η masses. The total uncertainty on R induced by the neutral energy scale is $\Delta R = \pm 5.8 \times 10^{-4}$.

The background in $\pi^0\pi^0$ events is due to $K_L \to 3\pi^0$ where two photons are outside the calorimeter acceptance or overlap with the other clusters. The background is estimated using a control region in χ^2 (the $3\pi^0$ background is almost flat because of its combinatorial nature) and using K_S events to evaluate resolution tails (see Fig. 7).

The systematic error evaluation of the background comes from the uncertainty in the background extrapolation from the control to the signal region. The extrapolation correction factor is calculated by a Monte Carlo simulation. Photon conversions and photon hadron-productions are also taken into account by the simulation. The correction is $\Delta R = (-5.9 \pm 2.0) \times 10^{-4}$.

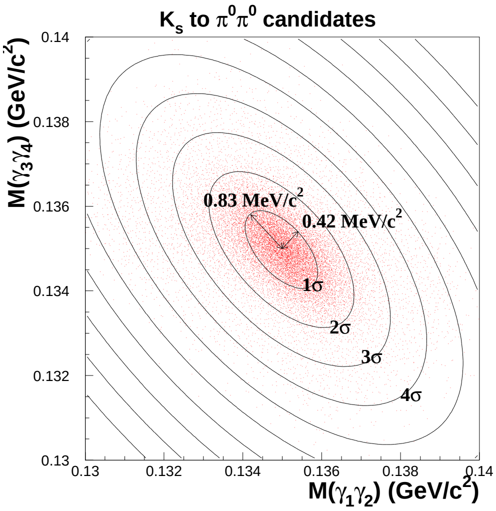

Fig. 5. Distribution of $K_S \to \pi^0\pi^0$ candidates in the space or two reconstructed $m_{\gamma\gamma}$ masses, m_1 and m_2.

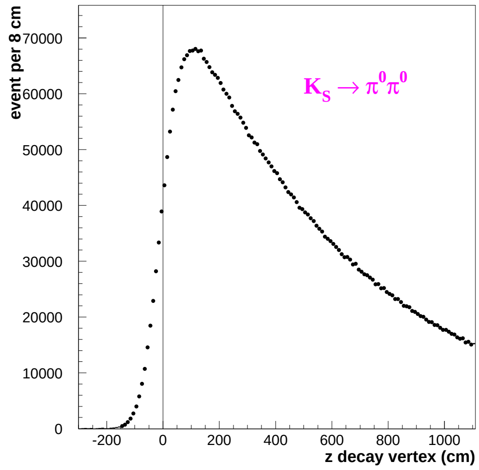

Fig. 6. Distribution of the reconstructed vertex position of $K_S \to \pi^0\pi^0$ candidates. The origin of the z_{vertex} axis is set to the nominal AKS position.

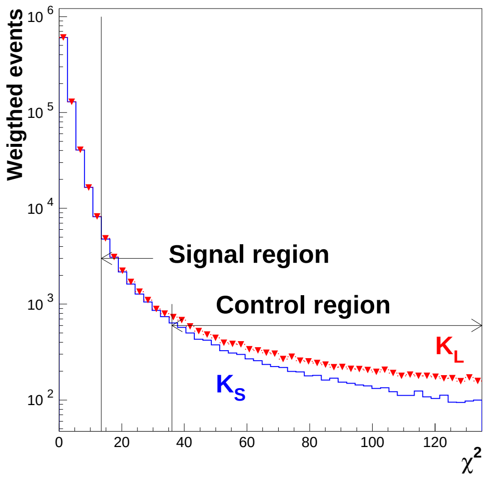

Fig. 7. Comparison of the χ^2 distributions for K_L and $K_S \to \pi^0\pi^0$ candidates showing the excess due to the $3\pi^0$ background in the K_L sample.

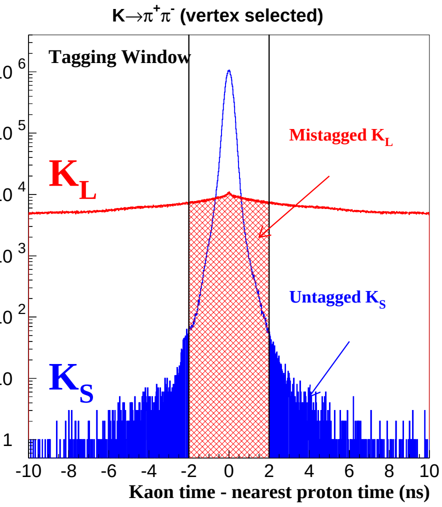

Fig. 8. Time coincidence for charged K_S and K_L events, identified by their reconstructed vertex.

3.4 Tagging

K_S and K_L are distinguished by a time of flight technique: all protons of the secondary beam cross a stack of scintillating counters (*tagger*) which measure their crossing time. A K_S decay will be in coincidence with a proton seen by the tagger. The coincidence window is 4 ns wide to minimize the probability that a K_S is out of coincidence because of tails in the time measurement and the probability that a K_L falls inside the coincidence because of the high proton rate (see Fig. 8).

The tagging inefficiency (α_{SL}) is the probability that a K_S is mistagged as a K_L due to a bad time measurement. In $\pi^+\pi^-$ mode it can be measured very precisely because K_S and K_L can also be separated by the vertex position. α_{SL}^{+-} is dominated by the tagger inefficiency, which is symmetric between decays into $\pi^+\pi^-$ and $\pi^0\pi^0$ and is measured to be $\alpha_{SL}^{+-} = (1.6 \pm 0.03) \times 10^{-4}$. $\Delta\alpha_{SL} = \alpha_{SL}^{00} - \alpha_{SL}^{+-}$ is due to differences in the tails between $\pi^+\pi^-$ and $\pi^0\pi^0$ event time measurements. We can compare directly charged and neutral measurements using events with γ's and e^+e^- from γ conversion which gives $\Delta\alpha_{SL} = (0 \pm 0.5) \times 10^{-4}$ which corresponds to an uncertainty on R of $\Delta R = (0 \pm 3.0) \times 10^{-4}$. The accidental tagging (α_{LS}) is the probability that a K_L is mistagged as a K_S because of an accidental proton coincidence. In $\pi^+\pi^-$, where K_S and K_L can be separated by the vertex position, it is measured to be $\alpha_{LS}^{+-} = (10.649 \pm 0.008)\%$.

The difference between $\pi^0\pi^0$ and $\pi^+\pi^-$ modes can be checked in events tagged as K_L looking at the proton intensity outside the coincidence window (proton sidebands). The extrapolation (W) from the sidebands to the tagging window is performed in $\pi^+\pi^-$ using pure K_L events selected by the vertex position, while $3\pi^0$ (which can come only from K_L decays) are used in the neutral case.

$$\begin{aligned}
\Delta\alpha_{LS}^{\text{sidebands}} &= (3.0 \pm 1.0) \times 10^{-4}, \\
\Delta W &= (1.3 \pm 1.1) \times 10^{-4}, \\
\Delta\alpha_{LS} &= (4.3 \pm 1.8) \times 10^{-4},
\end{aligned}$$

which[4] implies a correction on R of $\Delta R = (8.3 \pm 3.4) \times 10^{-4}$.

3.5 The Lifetime weighting principle and the acceptance correction

For a given decay position, the acceptances for K_S and K_L are the same. But K_S and K_L have very different decay lengths because $\tau_{K_L} \approx 600 \times \tau_{K_S}$, so the total acceptance for K_S and K_L is quite different and this would imply a large correction on R. To avoid this, K_L events are weighted w.r.t. their proper time on a event by event basis to make their decay distribution similar to the K_S one. The weight used is $\approx e^{-z/(\beta\gamma c)(1/\tau_{K_S} - 1/\tau_{K_L})}$. The acceptance correction almost cancels in the double ratio using the K_L lifetime weighting but in this way the statistical error on R increases by about 35%.

A small residual acceptance effect comes from the 0.6 mrad angle between the K_S and the K_L beam, especially in $\pi^+\pi^-$ events which at the first drift chamber are still separated by about 1 cm. The acceptance correction on R is estimated by a Monte Carlo simulation: $\Delta R = (26.7 \pm 4.1_{\text{MCstat}} \pm 4.0_{\text{syst}}) \times 10^{-4}$. The first error is due to Monte Carlo statistics and the systematic error comes from the knowledge of the beams geometry and by the comparison of two different Monte Carlos.

3.6 Accidental activity

The accidental activity from the beam can induce event losses. This effect cancels to first order in R but a residual correction on R can be due to $\Delta R \approx \Delta(\pi^+\pi^- - \pi^0\pi^0) \times \Delta(K_L - K_S)$ where

[4] 1×10^{-4} has been added to the error to take into account the variation w.r.t. the choice of the sidebands.

$\Delta(\pi^+\pi^- - \pi^0\pi^0)$ is the difference between neutral and charged losses; it is minimized by applying dead time conditions to all the modes and is estimated to be $(1.4\pm0.7)\%$. $\Delta(K_L - K_S)$ is the difference in the accidental activity seen by K_L and K_S events; it is small by the design of the experiment because the two beams are simultaneous and so K_L and K_S events see the same activity, within 1% (checked directly in data).

The intensity difference uncertainty corresponds to $\Delta R = (0 \pm 3) \times 10^{-4}$. The residual illumination difference uncertainty corresponds to $\Delta R = (0 \pm 3) \times 10^{-4}$ (estimated using random events overlayed to $\pi\pi$ Monte Carlo and data events). The total uncertainty is $\Delta R = (\pm 4.4) \times 10^{-4}$.

4 The result

The number of events (corrected for mistagging) collected in the years 1998 and 1999 are:

$$K_L \to \pi^0\pi^0 : \quad 3.29 \times 10^6, \quad K_S \to \pi^0\pi^0 : 5.21 \times 10^6,$$
$$K_L \to \pi^+\pi^- : \quad 14.45 \times 10^6, \quad K_S \to \pi^+\pi^- : 22.22 \times 10^6.$$

In Table 1 all corrections applied to the double ratio R_{exp} and their uncertainties are given. The double ratio is corrected by $A_{corr} = (+35.9\pm12.6)\times10^{-4}$, the biggest effects coming from acceptance, charged background, scattering and tagging. The quoted errors account for both statistical and systematic uncertainties and in some cases are statistically limited.

Table 1. Table of corrections applied to the double ratio with their uncertainties.

		in 10^{-4}	
$\pi^+\pi^-$ trigger inefficiency		-3.6	$\pm$ 5.2
AKS inefficiency		$+1.1$	$\pm$ 0.4
Reconstruction	of $\pi^0\pi^0$	—	$\pm$ 5.8
	of $\pi^+\pi^-$	$+2.0$	$\pm$ 2.8
Background	to $\pi^0\pi^0$	-5.9	$\pm$ 2.0
	to $\pi^+\pi^-$	$+16.9$	$\pm$ 3.0
Beam scattering		-9.6	$\pm$ 2.0
Accidental tagging		$+8.3$	$\pm$ 3.4
Tagging inefficiency		—	$\pm$ 3.0
Acceptance	statistical	$+26.7$	$\pm$ 4.1
	systematic		$\pm$ 4.0
Accidental activity		—	$\pm$ 4.4
Long term variations of K_S /K_L		—	$\pm$ 0.6
Total		$+35.9$	$\pm$ 12.6

All corrections are applied in 20 bins of kaon energy and the 20 values of R are averaged using an unbiased estimator. The result is

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

Fig. 10 shows the Double Ratio in bins of kaon energy after all the corrections.

A large number of systematic checks were devoted to verify the stability of the result with a change of the event selection. The output of the most important checks is shown in Fig. 9 where the deviation of the double ratio with respect to its standard value is shown for a series of modifications.

The corresponding $\mathrm{Re}(\epsilon'/\epsilon)$ value on 1998+99 data is obtained subtracting R from 1 and dividing by six:

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

which, combined with the published 1997 result [5] gives:

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

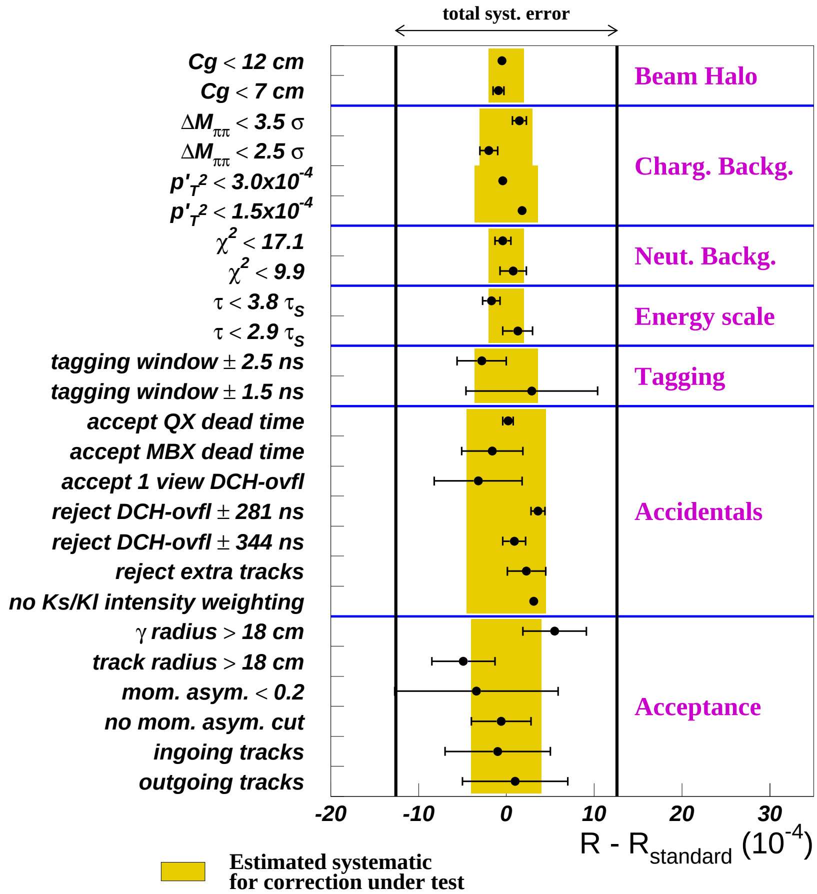

Fig. 9. Stability of the double ratio with variations of the selection cuts. The grey band shows the uncertainty related to the cut concerned.

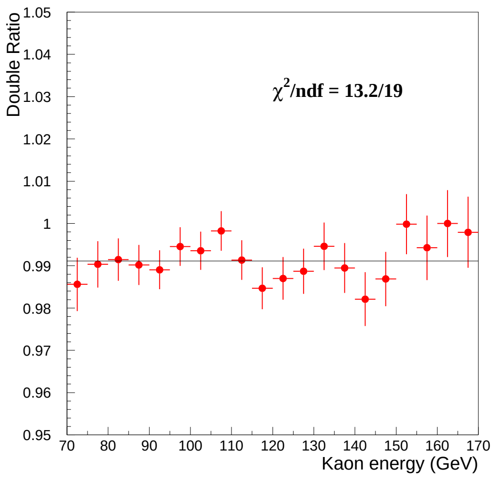

Fig. 10. Corrected double ratio as a function of kaon energy.

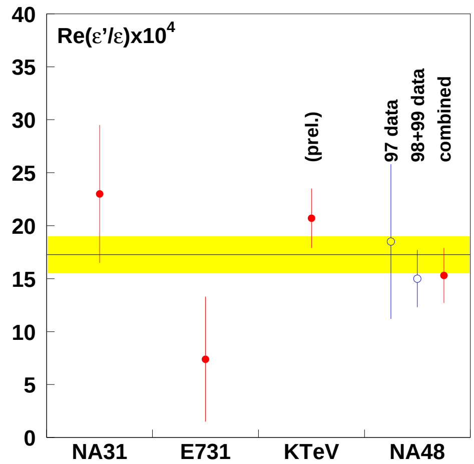

Fig. 11. Comparison of experimental results.

5 Experimental results comparison

The first generation of experiments published the following results ([2], [3]):

$$\begin{aligned} \text{NA31(CERN)}: \quad \mathrm{Re}(\tfrac{\epsilon'}{\epsilon}) &= \quad (23.0 \pm 6.5) \times 10^{-4}, \\ \text{E731(FNAL)}: \quad \mathrm{Re}(\tfrac{\epsilon'}{\epsilon}) &= \quad (7.4 \pm 5.9) \times 10^{-4}. \end{aligned}$$

The $\mathrm{Re}(\epsilon'/\epsilon)$ world average, including [2], [3], [4] is:

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

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

The direct CP violation in the neutral kaon system is now firmly established with a significance more than 9 σ's.

References

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