

FIRST EVIDENCE FOR DIRECT CP VIOLATION

CERN–Dortmund–Edinburgh–Mainz–Orsay–Pisa–Siegen Collaboration

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The double ratio R of the relative decay rates of the short- and long-lived neutral kaons into two charged and two neutral pions was measured to be $0.980 \pm 0.004 \pm 0.005$. The deviation of R from unity implies CP violation in the transition of the CP -odd K_2 into two pions with $\epsilon'/\epsilon = (3.3 \pm 1.1) \times 10^{-3}$.

Since its first observation in the decay of the long-lived neutral kaon into two pions [1], CP violation remains one of the enigmas in particle physics. While CP violation is manifest in neutral kaon decays, the search for CP -violating effects elsewhere has been unsuccessful. In the phenomenology of CP violation in the neutral kaon system [2] it is convenient to define the CP eigenstates $K_1 = (K^0 + \bar{K}^0)/\sqrt{2}$ and $K_2 = (K^0 - \bar{K}^0)/\sqrt{2}$ with $K_1 = +CP K_1$ and $K_2 = -CP K_2$. The short- and long-lived K^0 are the mass eigenstates which can be written as $K_S \approx K_1 + \epsilon K_2$ and $K_L \approx K_2 + \epsilon K_1$. The parameter ϵ describes CP violation induced by kaon state mixing. Direct CP violation may also occur in the decay of the K_2 into two pions with a relative amplitude of [2]

$$\epsilon' = i/\sqrt{2} \operatorname{Im}(A_2/A_0) \exp[i(\delta_2 - \delta_0)],$$

where A_0 and A_2 are the amplitudes for the decay into isospin 0 and 2 two-pion states; δ_0 and δ_2 are the corresponding $\pi\pi$ scattering phase shifts at the mass of the K^0 . With these definitions the ratios of K_L and K_S decay amplitudes into $2\pi^0$ and $\pi^+\pi^-$ respectively are

$$\eta_{00} \equiv \langle 2\pi^0 | T | K_L \rangle / \langle 2\pi^0 | T | K_S \rangle$$

$$\equiv |\eta_{00}| \exp(i\Phi_{00}) = \epsilon - 2\epsilon'$$

and

$$\eta_{+-} \equiv \langle \pi^+\pi^- | T | K_L \rangle / \langle \pi^+\pi^- | T | K_S \rangle$$

$$\equiv |\eta_{+-}| \exp(i\Phi_{+-}) = \epsilon + \epsilon'$$

The relevant experimental measurements are the magnitudes and phases of these two parameters, and the real part of ϵ determined from the charge asymmetry in semileptonic K_L decays: $|\eta_{+-}| = (2.27 \pm 0.02) \times 10^{-3}$ [3]; $\Phi_{+-} = 44.6^\circ \pm 1.2^\circ$ [4]; $|\eta_{00}/\eta_{+-}| = 1.00 \pm 0.01$ [5]; $\Phi_{00} = 55^\circ \pm 5^\circ$ [6]; and $\operatorname{Re} \epsilon = (1.62 \pm 0.09) \times 10^{-3}$ [7]. All experimental results are compatible with $\epsilon = 2.27 \times 10^{-3} \exp(i43.7^\circ)$ and the superweak model [8] in which state mixing is the only source of CP violation and $\epsilon' = 0$ #1.

#1 We disregard here the two-standard-deviation discrepancy in Φ_{00} . A considerably more sensitive measurement of $\Phi_{00} - \Phi_{+-}$ is being carried out by this group.

In the theory of six weakly interacting quarks [9], direct CP violation as well as state mixing are introduced by transitions via heavy-quark intermediate states. Based on this, a small but non-zero value of ϵ'' is predicted [10]. From $\pi\pi$ scattering, its phase is determined to be $61^\circ \pm 3^\circ$ [11]. This angle is close to the phase of ϵ , so that to a good approximation $\operatorname{Re} \epsilon'/\epsilon = 1/6(1 - |\eta_{00}/\eta_{+-}|^2)$. This relation is used to determine ϵ'/ϵ from the double ratio of K_S and K_L decay rates into charged and neutral pions:

$$R = \left| \frac{\eta_{00}}{\eta_{+-}} \right|^2 = \frac{\Gamma(K_L \rightarrow 2\pi^0)/\Gamma(K_L \rightarrow \pi^+\pi^-)}{\Gamma(K_S \rightarrow 2\pi^0)/\Gamma(K_S \rightarrow \pi^+\pi^-)}.$$

This experiment has been performed at the CERN Super Proton Synchrotron. It is based on the concurrent detection of $2\pi^0$ and $\pi^+\pi^-$ decays. Collinear K_S and K_L beams are employed alternately, changing frequently from one to the other to reduce time-dependent effects. Details of the apparatus and beams have been given elsewhere [12]. Kaons with energies around 100 GeV are produced by 450 GeV protons incident upon one of two targets at an angle of 3.6 mrad with respect to the kaon beam line. The K_L are derived from $\sim 10^{11}$ protons per pulse and are selected by two-stage collimation at distances of 48 m and 120 m, respectively, from the first production target. Alternatively, $\sim 10^7$ protons per pulse are brought onto the second target, from which the K_S are selected by collimation after 7 m. The retractable K_S target station, sweeping magnet and collimator system are mounted on a train which can be moved through 48 m of the K_L decay region. The K_S data are taken with the beam train displaced in 1.2 m steps so that both the K_S and K_L decay distributions become effectively uniform in the fiducial region (the average K_S decay length is 6 m).

The detector is based on calorimetry and is designed for good stability and high efficiency, large acceptance and fast data-acquisition. A schematic layout of the apparatus is shown in fig. 1. The principal features are summarized as follows:

- both K_S and K_L beams are transported in vacuum;
- an anticounter in the K_S beam, preceded by a 7 mm

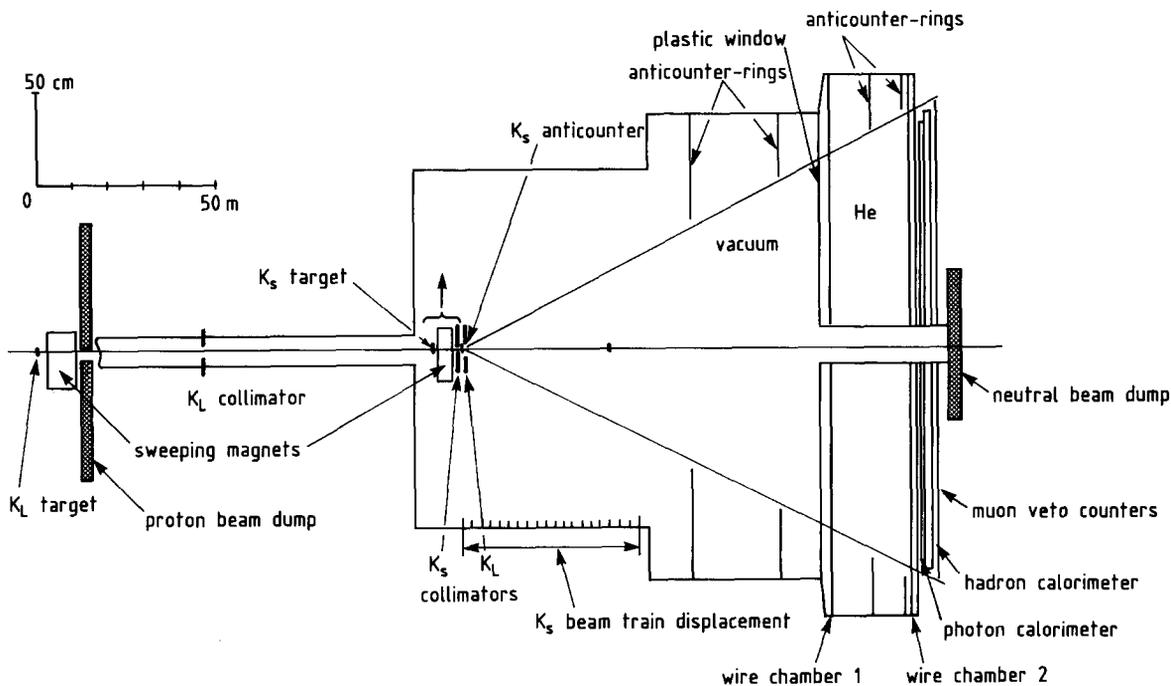


Fig. 1. Schematic layout of apparatus and beams.

lead converter, vetos decays in the collimator, defines the upstream edge of the decay region, and permits the relative calibration of the $2\pi^0$ and $\pi^+\pi^-$ energy scales to a precision better than $\pm 10^{-3}$;

- four ring-shaped anticounters surrounding the decay region detect large-angle photons and thus reduce unwanted three-body decays;
- two wire chambers spaced 25 m apart, with ± 0.5 mm resolution in each projection, track charged pions;
- a hodoscope of scintillation counters triggers on $\pi^+\pi^-$ decays by a coincidence of hits in opposite quadrants;
- a liquid-argon/lead sandwich calorimeter with strip readout measures photons with ± 0.5 mm position and $\pm 7.5\%/\sqrt{E}$ (GeV) energy resolution;
- a plane of scintillation counters, installed in the liquid argon after 13 radiation lengths of material, triggers on $2\pi^0$ decays;
- an iron/scintillator sandwich calorimeter measures, in conjunction with the liquid-argon calorimeter, the energy of charged pions with $\pm 65\%/\sqrt{E}$ (GeV) resolution;

- two planes of scintillators, after a total of 3 m of iron equivalent, reject $K^0 \rightarrow \pi\mu\nu$ decays.

The decay region is evacuated and the volume between the chambers is filled with helium. A thin composite Kevlar window of 3×10^{-3} radiation length separates the decay region from the wire chamber section. A tube of 20 cm diameter, through the centre of the window and the detectors, allows the neutral beam to continue in vacuum as far as the final beam dump.

Single counting rates are typically 10^5 Hz, originating predominantly from K^0 decays and beam-associated muons. The trigger on two-body K^0 decays is done in three steps. A pretrigger signal is generated from a coincidence of hits in opposite quadrants of the scintillator hodoscope, or from a left-right coincidence of the liquid-argon scintillators, with a veto from the ring and muon anticounters. A trigger signal is accepted, subject to further conditions on calorimeter energies, the number of hits in the first chamber, and the number of peaks in the liquid-argon calorimeter. After digitization of pulse heights and chamber information, three-body decays are rejected using on-line processors. The pretrigger rate is about 10 kHz,

and typically 1000 events are recorded per burst in the K_L beam.

The $K^0 \rightarrow 2\pi^0 \rightarrow 4\gamma$ decays are reconstructed from the measured positions and energies of the photons. Details of the reconstruction method may be found in ref. [13]. Events with extra photons of more than 2.5 GeV are rejected. For accepted events, the photon energies have to be above 5 GeV with at least 5 cm separation between shower centres, and the centre of gravity of the energies of all photons has to lie within the beam region. The K^0 energy is measured with typically 1% accuracy. The distance of the decay vertex from the calorimeter is calculated, using the K^0 mass as a constraint, with similar precision. Constraints on the masses of two-photon pairs are used to reduce the background, which is primarily due to $K_L \rightarrow 3\pi^0 \rightarrow 6\gamma$ decays with undetected photons. This background is uniformly distributed in a two-dimensional scatter plot of photon-pair masses. The π^0 mass resolution is ~ 2 MeV. Signal and background events are counted in equal-area χ^2 contours around the region defined for accepted events (see fig. 2). The sig-

nal region is taken as $\chi^2 < 9$. Background is subtracted by linear extrapolation into the signal region. It is about 4% in the K_L beam but depends strongly on the longitudinal vertex position because of the apparent vertex shift due to the missing energy in $3\pi^0$ decays with undetected photons. It is negligible in the K_S beam.

The $K^0 \rightarrow \pi^+\pi^-$ decays are reconstructed from space points defined by at least three hits out of the four planes in each of the two wire chambers. Events with extra space points in the first chamber are rejected for both charged and neutral decays. The longitudinal vertex resolution is better than 1 m. The K^0 energy is calculated with 1% precision from the kaon mass, the opening angle between the two tracks, and the ratio of track energies as measured in the calorimeter. This ratio is limited to a maximum of 2.5, in order to achieve this resolution and also to reduce the contribution of $\Lambda \rightarrow p\pi$ decays to a negligible level. Events with isolated photons, such as $K^0 \rightarrow \pi^+\pi^-\pi^0$ decays and events with accidental photons, are rejected. The $K^0 \rightarrow \pi\pi\pi$ events are identified and re-

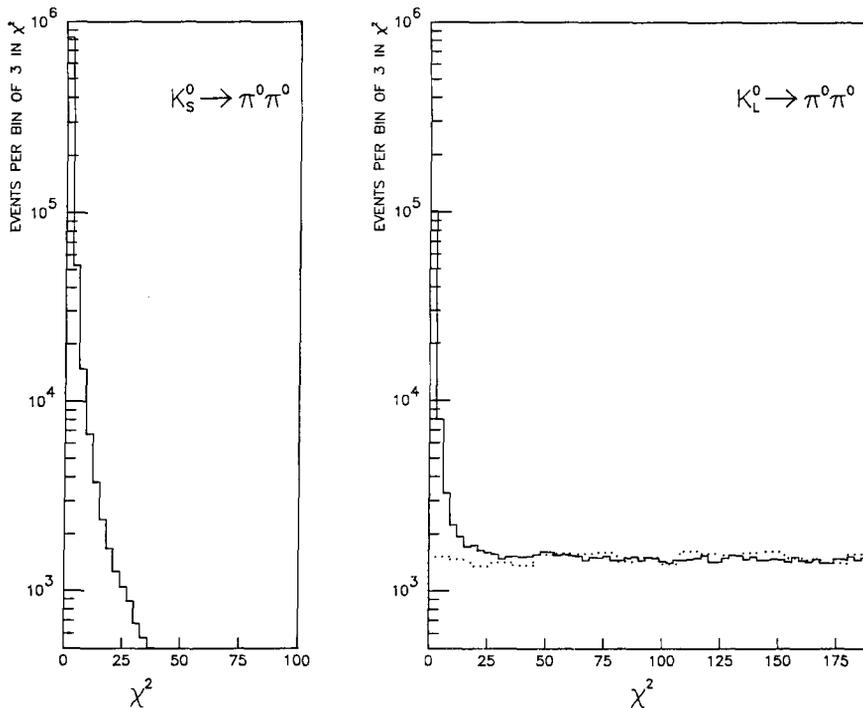


Fig. 2. Number of accepted 4γ events as a function of χ^2 , for $K_S \rightarrow 2\pi^0$ and $K_L \rightarrow 2\pi^0$ data, and a Monte Carlo calculation for background originating from $K_L \rightarrow 3\pi^0$ decays. The signal region is taken as $\chi^2 < 9$.

jected by comparing, for each track, the energy deposited in the front half of the photon calorimeter with the energy deposited in the hadron calorimeter. About half of the detected $\pi^+\pi^-$ events are lost equally from K_S and K_L because of all these requirements. Possible variations of the rejection rate due to systematic changes in detector response are monitored by the observed $\pi^+\pi^-$ mass. The response of the hadron calorimeter is evaluated to be constant within $\pm 0.5\%$, leading to an uncertainty ($< 0.1\%$) in the measured ratio of $K_S \rightarrow \pi^+\pi^-$ and $K_L \rightarrow \pi^+\pi^-$ event rates. After cuts on the $\pi^+\pi^-$ mass and on the reconstructed centre of gravity with respect to the beam axis, a residual background of the three-body decays must be subtracted.

In a two-body decay the decay plane should contain the production target, but because of measurement errors and multiple scattering, a certain distribution of the perpendicular distance d_T of this plane to the target is expected, and can be measured with $K_S \rightarrow \pi^+\pi^-$ decays. In the three-body decays of K_L , because of the non-coplanarity of the decay, a much broader d_T distribution is expected. This is il-

lustrated in fig. 3, where the d_T distributions of accepted two-track events in the K_S and K_L beams are shown separately. The d_T distribution in K_S decays is scaled geometrically in order to compare directly with K_L .

The signal region is taken to be $d_T < 5$ cm, and the control region for the background extrapolation is taken as $7 \text{ cm} < d_T < 12 \text{ cm}$. The fraction of events in the background region is $(3.6 \pm 0.1) \times 10^{-3}$ of the signal. This background consists mainly of $K_L \rightarrow \pi e \nu$ decays and has contributions from $K \rightarrow \pi \mu \nu$ where the muon loses its energy by bremsstrahlung in the hadron calorimeter, from $K \rightarrow \pi^+\pi^-\pi^0$ where one photon overlaps the shower of one of the charged pions, and a small amount of K_S production in the final K_L collimator. The $K^0 \rightarrow \pi^+\pi^-\pi^0$ background is subtracted directly by counting events with identified photons as a function of the distance between the photon and the nearest track. The remaining $K^0 \rightarrow \pi e \nu$ candidates are identified by the well-defined electron shower width in the photon calorimeter and longitudinal energy deposition, and the $K^0 \rightarrow \pi \mu \nu$ candidates by the shower width in the hadron calorimeter for events in

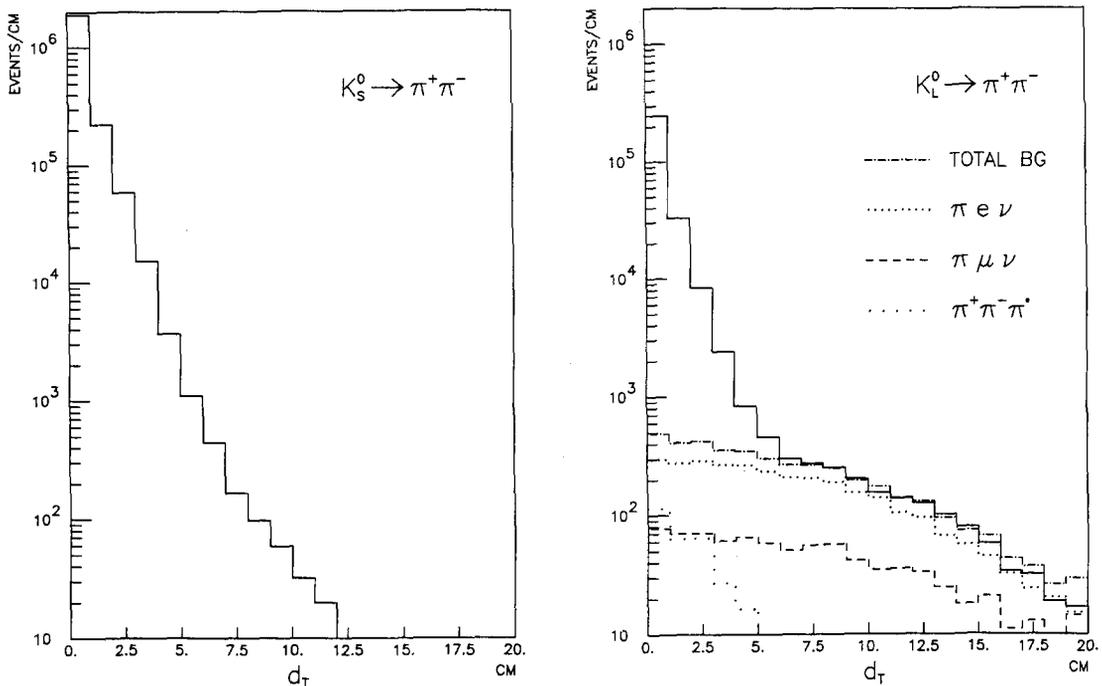


Fig. 3. Event distribution for charged decays as a function of distance d_T between the decay plane and the production target, for K_S and K_L decays and for various background components.

Table 1
Background composition for $K_L \rightarrow \pi^+ \pi^-$ decays.

Background	Control region	Signal region
$K^0 \rightarrow \pi^+ \pi^- \pi^0$	$(0.1 \pm 0.1) \times 10^{-3}$	$(1.0 \pm 1.0) \times 10^{-3}$
$K^0 \rightarrow \pi \nu$	$(2.8 \pm 0.2) \times 10^{-3}$	$(4.4 \pm 0.3) \times 10^{-3}$
$K^0 \rightarrow \pi \mu \nu$	$(0.5 \pm 0.2) \times 10^{-3}$	$(0.7 \pm 0.3) \times 10^{-3}$
regenerated K_S	$(0.2 \pm 0.1) \times 10^{-3}$	$(0.4 \pm 0.2) \times 10^{-3}$
total	$(3.6 \pm 0.1) \times 10^{-3}$	$(6.5 \pm 2.0) \times 10^{-3}$

which both charged particles deposit less than 5 GeV in the photon calorimeter. The shape of the d_T distributions for the background events is determined from data samples for $K^0 \rightarrow \pi \nu$ and residual $K^0 \rightarrow \pi^+ \pi^- \pi^0$ decays, and by Monte Carlo for $K^0 \rightarrow \pi \mu \nu$ decays. The inelastic K_S regeneration on the K_L beam collimator has been determined from events with the vertex close to the collimator. The average background subtracted by extrapolation in d_T is $(6.5 \pm 2.0) \times 10^{-3}$, including systematic uncertainties (see table 1). In the case of K_S the background is negligible.

The total available statistics is $\sim 10^6$ K_L and $\sim 10^7$ K_S two-pion decays. The energy spectra of accepted $2\pi^0$ and $\pi^+ \pi^-$ events are shown in fig. 4. After recon-

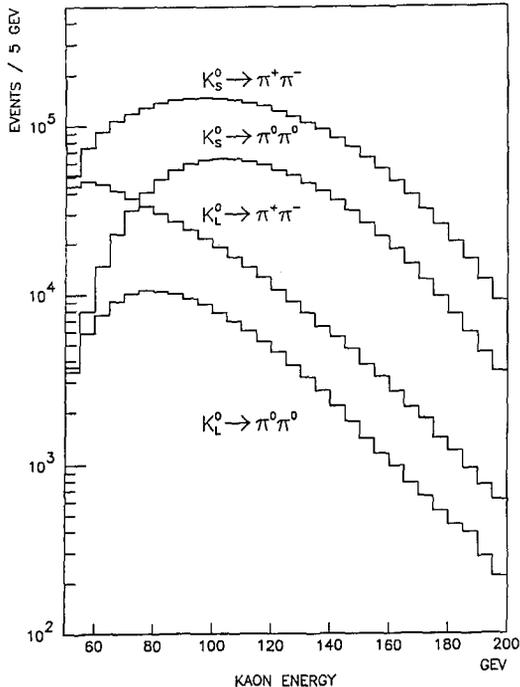


Fig. 4. Energy spectra for K_S and K_L decays into two pions.

struction, the relative energy scales of neutral and charged decays are adjusted to be the same within $\pm 10^{-3}$ by fits of the vertex distributions to the position of the anticounter in the K_S beam (see fig. 5). In this analysis, the data were selected in the energy range 70–170 GeV and with vertices between 10.5 and 48.9 m from the position of the final K_L beam collimator. A breakdown of event statistics is given in table 2 second column. The double ratio is evaluated in 10×32 bins in energy and vertex position, for each of 16 self-contained data sets of K_S and K_L . The weighted average, corrected for acceptance and resolution, is $R = 0.977 \pm 0.004$ (statistical error). In principle, the detection efficiencies for the two decay modes cancel. A Monte Carlo calculation has been used to determine the acceptance ratio. It includes the effect of the known difference in K_S and K_L beam divergences (0.7%) and the scattering of the K_S beam in the anticounter and collimator (0.3%, as measured from events without centre-of-gravity and d_T cuts, see table 2, fourth column), and the effects due to finite bin size and to energy and vertex resolution. The net total Monte Carlo correction amounts to 0.3% on R for the weighted average of all bins.

The trigger system and analysis procedures are designed such that no significant bias should result in the events retained for analysis. Event losses due to inefficiencies of the pretrigger hodoscope counters and of the trigger system itself are measured using a sample of events with relaxed trigger conditions. Since those results are consistent with the expectation of no bias (see table 2, fifth and sixth columns), no correction has been applied. Gains and losses of good events due to accidentals are measured by overlaying a sample of events with events taken with a random trigger, at a rate proportional to the neutral beam intensity. These are primarily due to the cuts on extra space points in the first wire chamber on the number of photons. An asymmetry between charged and neutral decays is observed (table 2, last column), and a correction is applied ($0.34 \pm 0.1\%$). This asymmetry is mainly due to a loss of charged decays in the K_S beam caused by additional background in the first chamber. Another correction of 0.06% accounts for the difference in efficiency, for charged and neutral decays, of the anticounter in the K_S beam.

The various systematic uncertainties are listed in table 3. Of these, the dominant ones are due to a pos-

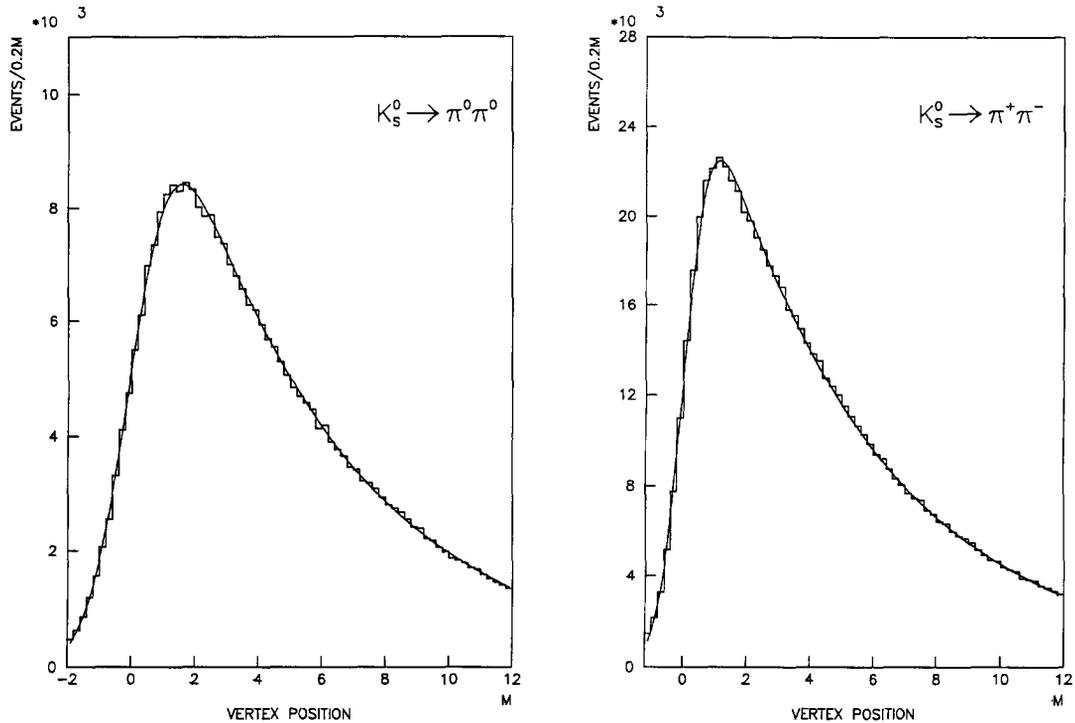


Fig. 5. $K_S \rightarrow 2\pi^0$ and $K_S \rightarrow 2\pi^+\pi^-$ event distributions as a function of distance from the anticounter in the K_S beam. The continuous lines show the best fits to the data.

sible energy scale difference between charged and neutral decays, the subtraction of backgrounds in the K_L beam, and the net losses of good events by accidentals. After all corrections we obtain the final result, $R = 0.980 \pm 0.004 \pm 0.005$, with statistical and systematic uncertainties given separately. With combined errors this corresponds to $\text{Re } \epsilon' / \epsilon = (3.3 \pm 1.1) \times 10^{-3}$. This is the first time that evidence of CP -violating effects is seen in the decay of the CP -odd K_2

into two pions, as implied by a non-zero value of ϵ' . It is at the level predicted recently by several evaluations of the standard model for a t -quark mass in the range 50–100 GeV [14] and does not agree with the superweak model [8].

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Table 2
Event statistics and corrections.

	Signal events ($\times 1000$)	Background (%)	Scattering (%)	Inefficiencies		Accidental losses (%)
				pretrigger (%)	trigger (%)	
$K_L \rightarrow 2\pi^0$	109	4.0		0.06 ± 0.06	0.20 ± 0.10	2.6 ± 0.07
$K_L \rightarrow \pi^+\pi^-$	295	0.6	< 0.1	0.37 ± 0.07	0.05 ± 0.06	2.6 ± 0.05
$K_S \rightarrow 2\pi^0$	932	< 0.1		0.04 ± 0.02	0.12 ± 0.03	2.5 ± 0.05
$K_S \rightarrow \pi^+\pi^-$	2300	< 0.1	0.3	0.48 ± 0.03	0.01 ± 0.01	2.8 ± 0.05
effect on R			0.3	-0.12 ± 0.10	-0.03 ± 0.12	-0.34 ± 0.10

Table 3

Systematic uncertainties on the double ratio R (in %).

background subtraction for $K_L \rightarrow 2\pi^0$	0.2
background subtraction for $K_L \rightarrow \pi^+ \pi^-$	0.2
$2\pi^0/\pi^+ \pi^-$ difference in energy scale	0.3
regeneration in the K_L beam	<0.1
scattering in the K_S beam	0.1
K_S anticounter inefficiency	<0.1
difference in K_S/K_L beam divergence	0.1
calorimeter instability	<0.1
Monte Carlo acceptance	0.1
gains and losses by accidentals	0.2
pretrigger and trigger inefficiency	0.1
total systematic uncertainty	$\pm 0.5\%$

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