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MEASUREMENT OF DIRECT CP VIOLATION IN $K \to \pi\pi$ DECAYS* **

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The NA48 experiment at CERN performed a measurement of direct CP violation in decays of $K_{\rm L}$ and $K_{\rm S}$ into $\pi^+\pi^-$ and $\pi^0\pi^0$. Preliminary results based on data taken in 1998 are presented. The new data, combined with published NA48 data from 1997, give the CP violating parameter $\mathrm{Re}(\varepsilon'/\varepsilon) = (14.0 \pm 4.3) \times 10^{-4}$.

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The dominant component of CP violation in decays of neutral kaons is the mixing between strangeness eigenstates K^0 and $\bar{K}^0$, described by the parameter ε. Direct CP violation can occur when the CP eigenstate K_2 of CP$= -1$ decays into two-pion final state which has CP$= +1$. This leads to interference of amplitudes with different isospins and can be parametrized by ε'.

In the Standard Model, the CP violation parameters are related to the CKM matrix. Constraints given to ε' by theory and by experimental data from other processes are weak. Precision of theoretical predictions for ε' is mainly limited by poorly known cancellation of weak and electromagnetic penguin diagrams of kaon decays and by hard to calculate strong radiative corrections and final state interactions [1].

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The ε'/ε can be related to the combination of decay frequencies

$$R = \frac{\Gamma(K_{\rm L} \to \pi^0\pi^0)/\Gamma(K_{\rm S} \to \pi^0\pi^0)}{\Gamma(K_{\rm L} \to \pi^+\pi^-)/\Gamma(K_{\rm S} \to \pi^+\pi^-)} = 1 - 6 \cdot {\rm Re}(\varepsilon'/\varepsilon)\,.$$

This double ratio technique was used to determine ${\rm Re}(\varepsilon'/\varepsilon)$ by the NA31 [2], E731 [3], KTeV [4] and NA48 [5] experiments. The first two experiments gave no clear answer and were marginally consistent with each other, whereas refs [4,5] positively evidence for direct CP violation.

The first NA48 result [5] was based on data taken in 1997. In 1998 new data were taken in the same experimental conditions.

In order to count events simultaneously in four decay modes, the NA48 designed two collinear kaon beams with similar momentum spectra and detects all decays in the same time. Kaon production targets on those beams are separated by 120 m but the fiducial volume for decays is the same. Due to the different decay lengths for $K_{\rm L}$ (3400 m) and $K_{\rm S}$ (5.9 m) only the $K_{\rm L}$ component from the more distant target survives to the decay volume. Decays from the nearby target are predominantly $K_{\rm S}$. To distinguish $K_{\rm L}$ from $K_{\rm S}$, proton tagging counter was located on the $K_{\rm S}$ beam. The 90 m long decay region extends after the $K_{\rm S}$ target and is contained in a vacuum tank.

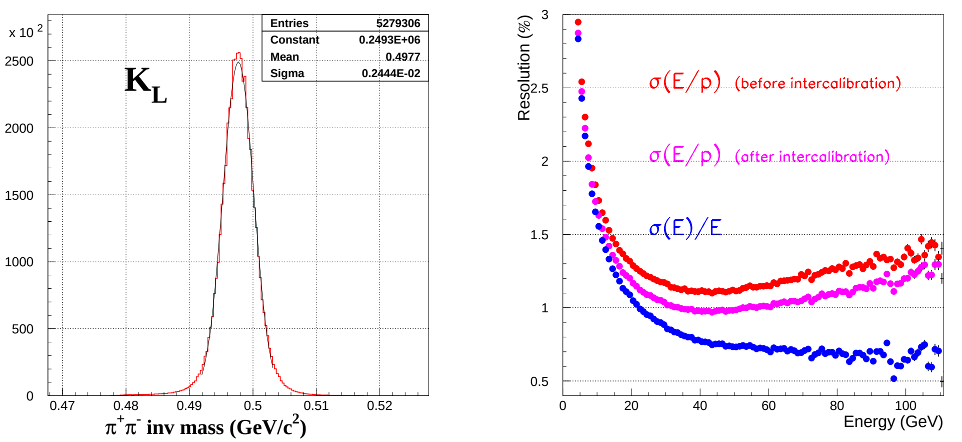

Fig. 1. (a) Effective mass of $\pi^+\pi^-$ from the decay of $K_{\rm L}$ measured in the magnetic spectrometr, (b) Energy resolution in the electromagnetic calorimeter.

Kaons decaying into charged pions are measured in magnetic spectrometer, consisting of the bending magnet and four drift chambers. Reconstructed $\pi^+\pi^-$ effective mass is shown in Fig. 1(a). Two scintillator hodoscope planes, horizontal and vertical, are placed after the magnetic spectrometer and provide the signal for the $\pi^+\pi^-$ trigger. The hodoscope time resolution is 200 ps per track.

Neutral decays $K \to \pi^0\pi^0$ are measured by detecting photons from pion decays in the electromagnetic calorimeter filled with liquid crypton. The showers are readout by 13212 cells $2 \times 2 \times 127$ cm^3 with projective geometry with time resolution better than 300 ps for 20 GeV photons. Energy resolution in the calorimeter is shown in Fig. 1(b).

A two level $\pi^+\pi^-$ trigger was used. At the first level the hodoscope signals from opposite quadrants were required in coincidence with a total energy in the calorimeter larger than 35 GeV. At the second level, in addition, the two-track, the vertex and the mass requirements were added. The 2nd level trigger rate was 2 kHz.

The $\pi^0\pi^0$ trigger used cell information to compute the energy peaks in x and y projections (no more than 5 in each), the event center of gravity (less than 15 cm) and total energy (larger than 50 GeV). The trigger rate was about 2 kHz.

Charged tracks were reconstructed from the hits and drift times in the spectrometer and a vertex was defined at the point of closest approach (< 3 cm) of tracks. Vertex resolution was 50 cm along the beam and 2 mm in transverse direction. In order to reject background from Λ decays, the symmetry between opposite-charge momenta was required. To reject background from semileptonic $Ke3$ decays the $E/p < 0.8$ had to be satisfied for both tracks. For good $\pi^+\pi^-$ events the mass had to agree within $\pm 3\sigma$ with kaon mass. Further reduction of the $Ke3$ background was obtained by cut on kaon transverse momentum.

Neutral decays were selected by requiring four clusters in the fiducial volume of the calorimeter, with energies 3–100 GeV, all in time within ± 5 ns of the avarage. Longitudinal position of the vertex was reconstructed from cluster energies and impact coordinates, assuming kaon mass. For all photon combinations the invariant masses of pairs were computed and compared to the nominal π^0 mass and the best fitting combination was chosen.

For the $\pi^+\pi^-$ decays, the $K_{\rm L}$ and $K_{\rm S}$ were cleanly distinguished by vertical coordinate of decay vertex. For the $\pi^0\pi^0$ mode, the event was classified as $K_{\rm S}$ if there is a proton signal from the tagging counter within a ± 2 ns coincidence with the event time. Accidental coincidence between the tagging signal and a $K_{\rm L}$ event may be wrongly classified as a $K_{\rm S}$ decay. Such mistagging for charged decays was measured using vertex y coordinate and for neutral decays from proton coincidences at times offset from the actual

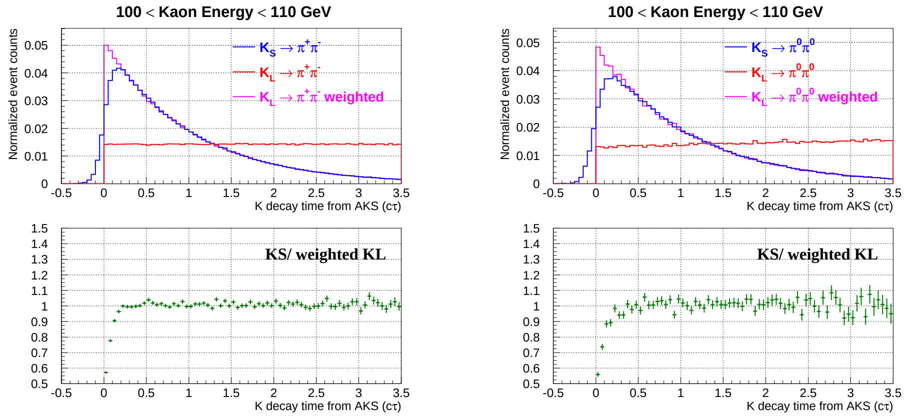

Fig. 2. Distribution of decay vertex time, in units of τ_S, for K_S, K_L and $K_L^{(\text{weighted})}$ events. The ratio $K_S/K_L^{(\text{weighted})}$ is also shown. The left figures are for $\pi^+\pi^-$ and the right are for $\pi^0\pi^0$ decays.

event. Tagging inefficiencies also arose from inefficient proton reconstruction and errors in time reconstruction.

The K_L and K_S acceptances were made the same by weighting K_L events according to their decay time and using nominal lifetimes. Distributions of vertex decay times, for all decay modes and for weighted and unweighted events, are shown in Figs 2. Small differenes in acceptances were studied and corrected for by using Monte Carlo simulation.

Event statistics from 1998 data, after removing background and correcting for mistagging, amounts to 1.14, 1.80, 4.87 and 7.46 millions events for $K_L \to \pi^0\pi^0$, $K_S \to \pi^0\pi^0$, $K_L \to \pi^+\pi^-$ and $K_S \to \pi^+\pi^-$, respectively, about 3 times the 1997 statistics [5]. The raw value was found $R_{\text{raw}} = 0.98899 \pm 0.00173$. After correcting for tagging, trigger efficiencies, acceptance and background the values $R = 0.99267 \pm 0.00173(\text{stat}) \pm 0.00238$ (syst) and $\text{Re}(\varepsilon'/\varepsilon) = [12.2 \pm 2.9\ (\text{stat}) \pm 4.0\ (\text{syst})] \times 10^{-4}$ were determined. Combined preliminary data from 1998 and final 1997 [5] give

$$\text{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = (14.0 \pm 4.3) \times 10^{-4},$$

where all errors were added in quadratures. Averaged world data for $\text{Re}(\varepsilon'/\varepsilon)$, *cf.* Fig. 3, is

$$\text{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = (19.3 \pm 2.4) \times 10^{-4}, \qquad \frac{\chi^2}{\text{ndf}} = 11.1/5\,.$$

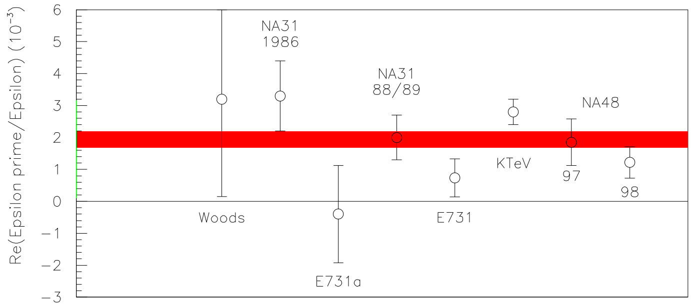

Fig. 3. World data on $\mathrm{Re}(\varepsilon'/\varepsilon)$. The world average, represented by the grey belt, is $(19.3 \pm 2.4) \pm 10^{-4}$ with $\chi^2 = 11.1/5$.

In conclusion, the NA48 data alone and world data altogether, evidence for the direct CP violation in neutral kaon decays.

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