TOPICAL CONFERENCE

TALKS

RARE KAON DECAYS

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Abstract

Recent experiments on rare kaon decays are described, with emphasis on the program at the Brookhaven National Laboratory Alternating Gradient Synchrotron. New limits on the modes $K_L \to \mu e$ and $K_L \to ee$ and a preliminary new measurement of the $K_L \to \mu\mu$ branching ratio are presented from AGS Experiment 791. Other modes, including $K^+ \to \pi^+\mu^+e^-$, $K^+ \to \pi^+ + nothing$, and $K_L \to \pi^\circ e^+e^-$, which have been the focus of other AGS experiments, are also discussed.

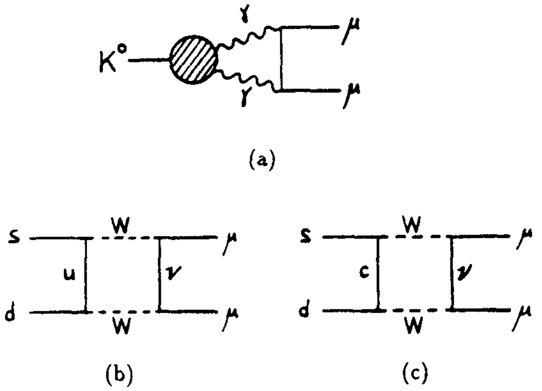
1 Introduction

The study of kaon decays has contributed much to our present understanding of particle physics. In the early 1970 s, however, there was something of a hiatus in these studies, which lasted for roughly a decade. Recently, renewed interest led to a series of very ambitious experiments, utilizing state-of-the-art detector technology, to achieve previously unattainable sensitivities. Work on these new experiments began about five years ago and the first round of these experiments is coming to an end. Even more ambitious experiments are being planned for the future.

The historically "rare" decays $K_L \to \pi\pi$ and $K_L \to \mu\mu$ will be discussed first, both to illustrate the importance of such studies in the evolution of our present day thinking and also to set the stage for considering recent work.

The decay $K_L \to \pi^+\pi^-$ was first observed[1] in 1964 and with it the first violation of the hypothesis that the combined operation of parity and charge conjugation (CP) was a conserved quantity. The branching ratio for $K_L \to \pi^+\pi^-$ is 2×10^{-3}. Once considered to be a rare decay, this is copious by the standards which apply today. In some of the modern experiments discussed below, this decay serves primarily as a calibration.

The common decay $K^\pm \to \mu^\pm\nu$ occurs via a strangeness changing charged current interaction through the exchange of the $W^\pm$ boson. In a gauge theory based on $SU(2)$, a strangeness changing neutral current interaction should also exist. Experimentally, however, it has long been known that the decay $K_L \to \mu\mu$ is extremely rare. Since the early 1970 s it has been clear that the decay rate for $K_L \to \mu\mu$ is approximately saturated by the process $K_L \to \gamma\gamma \to \mu\mu$, shown in Figure 1(a), and that the branching ratio was at the level of 10^{-8} or somewhat smaller[2, 3, 4, 5]. The solution to this dilemma was proposed by Glashow, Illiopoulos, and Maiani[6]. By introducing a fourth quark (charm) in a weak isospin doublet with the strange quark, they showed that there was a cancellation between tree level flavor changing terms. Second order weak contributions to $K_L \to \mu\mu$ were still possible from the box diagrams shown in Figure 1(b) and (c), but enter with opposite sign, so that as long as the charm quark mass was below about 3 GeV, this contribution was within the experimentally allowed range.



(a)

(b) (c)

Figure 1: Contributions to $K_L \to \mu\mu$: (a) the 2-photon process, (b) and (c) the box diagrams involving the up and charm quarks, respectively. These latter two contributions substantially cancel.

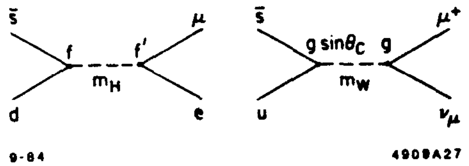


Figure 2: Diagrams for the decays $K_L \to \mu e$ (left) and $K^+ \to \mu^+\nu$ (right).

Prior to 1988, the world's sample of $K_L \to \mu\mu$ decays was 25 events[3, 4, 5]. One experiment, Expt. 791 at the Brookhaven National Laboratory (BNL), has recently collected a data sample consisting of about 700 such decays.

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AGS Expt. 791[7] has primarily focused on the forbidden decay $K_L \to \mu e$, but also has sensitivity for the strangeness changing neutral current decays $K_L \to \mu\mu$ and $K_L \to ee$. The conservation of separate lepton number (e.g., muon number) is a feature of the Standard Model, but is not expected to hold in most of the popular extensions (such as technicolor, supersymmetry, etc.). Observation of the decay $K_L \to \mu e$ would be a signal of new physics. Unfortunately, there is no particular prediction for the branching ratio which provides a clear experimental target. Nonetheless, the power of a search for a small branching ratio decay to probe for very high mass scale interactions makes this an attractive avenue of research. The conventional argument is to compare the ratio of decay rates of the processes shown in Figure 2. The diagram on the left shows $K_L \to \mu e$, mediated by some heavy particle H with mass M. The diagram on the right show the familiar decay $K^+ \to \mu^+\nu$. To a good approximation, phase space and helicity factors cancel in the ratio, so that

$$\frac{\Gamma(K_L \to \mu e)}{\Gamma(K^+ \to \mu^+\nu)} \simeq \left|\frac{ff'/M_H^2}{g^2 sin\theta_c/M_W^2}\right|^{1/2},$$

where g is the electroweak coupling, θ_c the Cabibbo angle, and M_W the mass of the W boson. Substituting known quantities and rearranging the equation leads to

$$M_H \simeq 20\ TeV\left(\frac{1\times 10^{-8}}{Br(K_L \to \mu e)}\right)^{1/4}\left|\frac{ff'}{g^2}\right|^{1/2}.$$

Assuming couplings similar to the electroweak coupling, a branching ratio of 10^{-11} corresponds to a mass around 110 TeV. No presently forseeable accelerator can reach such energies.

The decay rate for $K_L \to \mu\mu$ is dominated by the 2-photon intermediate state, as seen from the fact that the branching ratio is consistent with the absorptive (imaginary) amplitude ($K_L \to \gamma\gamma \to \mu\mu$) alone, a value usually referred to as the unitarity bound. The standard value of the unitarity bound[8] is given by

$$\Gamma(K_L \to \mu\mu)_{abs} = 1.2\times 10^{-5}\Gamma(K_L \to \gamma\gamma).$$

The Particle Data Group[9] lists $(5.70 \pm 0.23)\times 10^{-4}$ as the branching ratio for $K_L \to \gamma\gamma$. Therefore, the unitarity bound is about 6.8×10^{-9}. [There is a theoretical uncertainty at the 10 to 20% level, on top of the experimental uncertainty of $Br(K_L \to \gamma\gamma)$, so this is not a rigid bound.] Recent measurements of $K_L \to \mu\mu$, which are dominated by E791, are close to this value, so that the dispersive amplitude is evidently small.

Interpretation of the $K_L \to \mu\mu$ branching ratio is made difficult by the long-distance nature of the dominant 2-photon contribution. Short-distance contributions to $K_L \to \mu\mu$ have been evaluated[10] and the general consequence of a small dispersive amplitude for $K_L \to \mu\mu$ is to limit the magnitude of the real part of the CKM product $V_{ts}^*V_{td}$ as a function of the top quark mass. Some recent theoretical analyses[11] use the recent results from CERN[12] and BNL[13] on the $K_L \to ee\gamma$ form factor in estimating the long distance part of the $K_L \to \mu\mu$ dispersive amplitude. They then derive constraints on the short distance part, using the $K_L \to \mu\mu$ branching ratio, which in turn constrains CKM parameters. One conclusion of this analysis is that the branching ratio for $K^+ \to \pi^+\nu\bar{\nu}$ is probably smaller than previously expected.

The decay $K_L \to ee$ also receives a contribution from the 2-photon process that dominates $K_L \to \mu\mu$. However, this contribution is helicity suppressed, so that the expected branching ratio is much smaller than $K_L \to \mu\mu$. The suppression, however, is not simply a factor of m_e^2/m_μ^2, which would reduce it to the 2×10^{-13} level. Instead, there is a logarithmic singularity as $m_\ell \to 0$ in the total electrodynamic cross section for $\gamma\gamma \to \ell^+\ell^-$ which modifies the naive factor by more than an order of magnitude. Consequently, it is expected[8] that $K_L \to ee$ occurs at a branching ratio of about 3×10^{-12}. The range between this value and the $K_L \to \mu\mu$ level is a window for observing a new flavor-changing neutral current interaction.

Before discussing the experiment, it is useful to discuss the sources of background. The most important potential background to $K_L \to \mu e$ comes from the decay $K_L \to \pi e\nu$, followed by $\pi \to \mu\nu$ in flight (or alternatively, simple misidentification of the π as a μ). If the energy of the ν in the K_{e3} decay is close to zero, the event can be confused with $K_L \to \mu e$. Rejection of this background depends on the invariant mass distribution of the background process having an end-point 8.4 MeV below the mass of the K_L. Therefore, precise event reconstruction is essential. The next most important potential background is the decay $K_L \to \pi e \nu$ in which the π is misidentified as an e and the e is misidentified as a μ. If this occurs, then in the case where the misidentified π has large momentum compared to the electron, the event can reconstruct with invariant mass equal to (or above) the K_L mass. Good particle identification is required to reject this background. An additional potential background is the overlap of two K_L decays ($K_L \to \pi e \nu$ and $K_L \to \pi \mu \nu$), with the pions being missed. Calculations indicate this background should not be a problem above the 10^{-12} level, which is not approached by the present generation of experiments.

E791 was performed in the B5 neutral beam at the AGS. Figure 3 shows the E791 detector layout. About 4-5 $\times 10^{12}$ protons per spill with 24 GeV in energy were incident on a one interaction length copper target. A neutral beam was defined by a series of collimators centered at a 2.75 degree angle from the incident proton beam direction. Two dipole sweeping magnets removed charged particles from the beam. The "decay volume" was a region extending from roughly 10 meters from the target to the most upstream drift chamber at 18 meters from the target. Most of the collimation channel and the entire decay volume were under vacuum. The beam volume within the spectrometer was filled with helium.

Tracking was performed by five drift chamber modules (each module makes two x and two y measurements). The regions between drift chambers were filled with helium to reduce multiple scattering and particle interactions. Each of the two dipole magnets provided $\Delta p_T \simeq 300$ MeV, but with opposite sign. Downstream of the final drift chamber, a finely segmented scintillator hodoscope, a gas threshold Čerenkov counter, another hodoscope and a large lead glass array followed in sequence. The scintillation counter hodoscopes provided the signals used in the lowest level (fast logic) trigger. The Čerenkov counter also provided a fast signal, corresponding to the presence of an electron, which was used in the low level trigger. The lead glass gave an electromagnet energy measurement which was used for offline $\pi : e$ discrimination. A meter of steel followed the lead glass to stop all particles except muons.

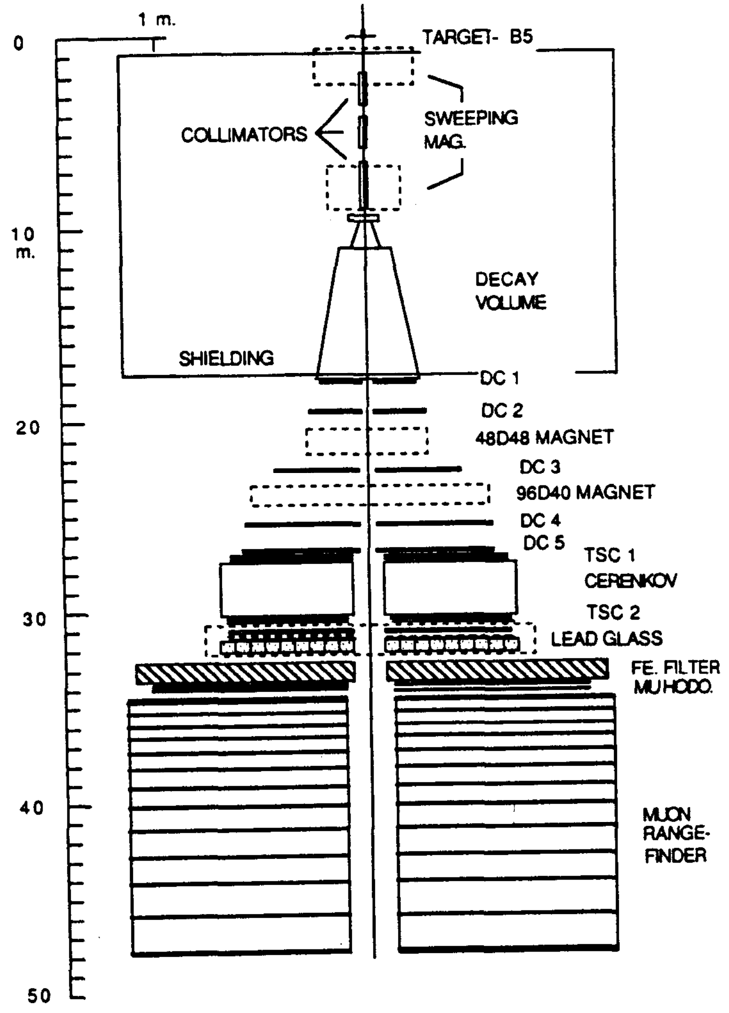

Figure 3: Plan view of the E791 detector.

Behind the steel, a segmented scintillation hodoscope provided a fast muon signal for the low level trigger. Finally, muons were stopped in a segmented absorber stack with large proportional wire chambers spaced throughout the stack. This "rangefinder"[14] provided a muon range measurement which corresponds to a 10% measurement of momentum and was important in the offline muon identification.

High rate capability was achieved with a system of fully-custom high speed front-end electronics[15, 16], a massively parallel readout architecture[17], and a multi-level trigger system. Trigger decisions were made in two stages. A low level fast logic trigger was based on the scintillation counter hodoscopes, the Čerenkov counter, the muon hodoscopes, and meantimer signals from the upstream drift chambers. A high level trigger was based on rudimentary event reconstruction using drift chamber hits. This was carried out in a farm of eight SLAC 3081/E processors.[18]

The event analysis consisted of basically four steps: (1) pattern recognition using drift chamber hits to identify tracks in the spectrometer; (2) fitting the event to obtain the best tracking and momentum information; (3) imposition of particle identification criteria from the Čerenkov counter, lead glass, muon hodoscope and muon rangefinder to classify the event; and (4) imposition of final fiducial-type cuts to insure events were fully contained within the detector volume and that the kinematic measurements were of high quality.

The decay $K_L \to \pi^+\pi^-$ has the same topology as $K_L \to \mu e$, is copious by modern standards, and its branching ratio is well known. It is useful as an indicator of detector performance and a heavily prescaled sample is used as the branching ratio normalization. A useful quantity, denoted by Θ_K, and referred to as the collinearity angle, is the angle the reconstructed K_L makes with respect to the line from the target to the decay vertex. This quantity will be zero (within measurement resolution) for decays with no missing particles, but will usually be much larger in cases where there is missing transverse momentum due to missed neutrinos. Figure 4(a) shows Θ_K^2 versus $\pi\pi$ invariant mass for a sample of $K_L \to \pi^+\pi^-$ events. A gaussian fit to the mass distribution after a cut requiring $\Theta_K < 1$ mrad, shown in Figure 4(b), yields a mass resolution of 1.4 MeV.

E791 has completed three data taking runs, in 1988, 1989, and 1990. The

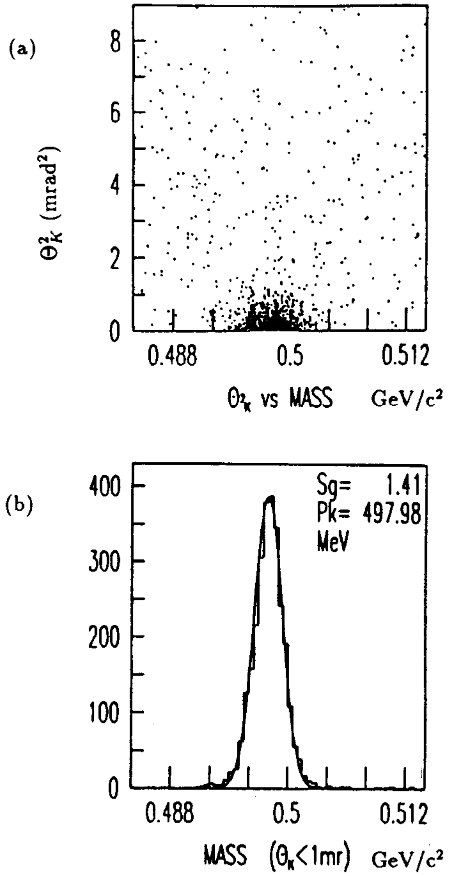

Figure 4: (a) Scatter plot of the square of the angle, Θ_K, between the parent K_L direction and the direction of the reconstructed K_L versus invariant mass for (a) $K_L \to \pi^+\pi^-$ events and (b) the projection onto the mass axis after requiring $\Theta_K < 1$ mrad.

best published limits[19] on $K_L \to \mu e$ and $K_L \to ee$ and the highest statistics $K_L \to \mu\mu$ branching ratio measurement[20] are from the 1988 run of E791. The analysis of data taken during 1989 is now almost completed. No $K_L \to \mu e$ or $K_L \to ee$ candidates have been found. The $K_L \to \mu\mu$ signal is 284 ± 19 events. Candidate events for the modes $K_L \to \mu\mu$ and $K_L \to \mu e$ are shown in Figure 5. The preliminary new results are:

$$Br(K_L \to \mu e) < 8.4 \times 10^{-11} \qquad \text{(90\% confidence level)}$$

$$Br(K_L \to ee) < 1.1 \times 10^{-10} \qquad \text{(90\% confidence level)}$$

$$Br(K_L \to \mu\mu) = (7.6 \pm 0.5(\text{stat.}) \pm 0.4(\text{syst.})) \times 10^{-9}.$$

The 1990 data will be combined with the 1988 and 1989 samples in the future. Figure 6 shows the combined $K_L \to \mu\mu$ sample in a single histogram. More than 700 events are in the peak.

Two other experiments, E780 at BNL and E137 at KEK, have produced results on the modes $K_L \to \mu e$, $K_L \to ee$, and $K_L \to \mu\mu$ recently. Tables 1, 2, and 3 summarize the history of experimental results on these modes.

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A related process to $K_L \to \mu e$ is $K^+ \to \pi^+ \mu e$, which also would violate separate lepton number conservation. A comparison of $K^+ \to \pi^+ \mu e$ to $K_L \to \pi^o \mu\nu$, following along the lines of the earlier argument for $K_L \to \mu e$, can be used to show that

$$M_H \simeq 8\ TeV \left(\frac{1 \times 10^{-8}}{Br(K^+ \to \pi^+ \mu e)} \right)^{1/4} \left| \frac{ff'}{g^2} \right|^{1/2}.$$

Therefore, $K^+ \to \pi^+ \mu e$ is somewhat less sensitive to high mass scales than $K_L \to \mu e$ for a $V - A$ interaction. However, this process probes the scaler or vector part of a new interaction, while $K_L \to \mu e$ is sensitive to the pseudoscaler or axial vector part. It is important therefore to do both experiments.

E777[24] is shown in Figure 7. The beam contained about 2×10^8 positively charged 6 GeV particles per spill, of which about 5% were K^+'s. The detector consisted of two spectrometer magnets, multiwire proportional chambers for

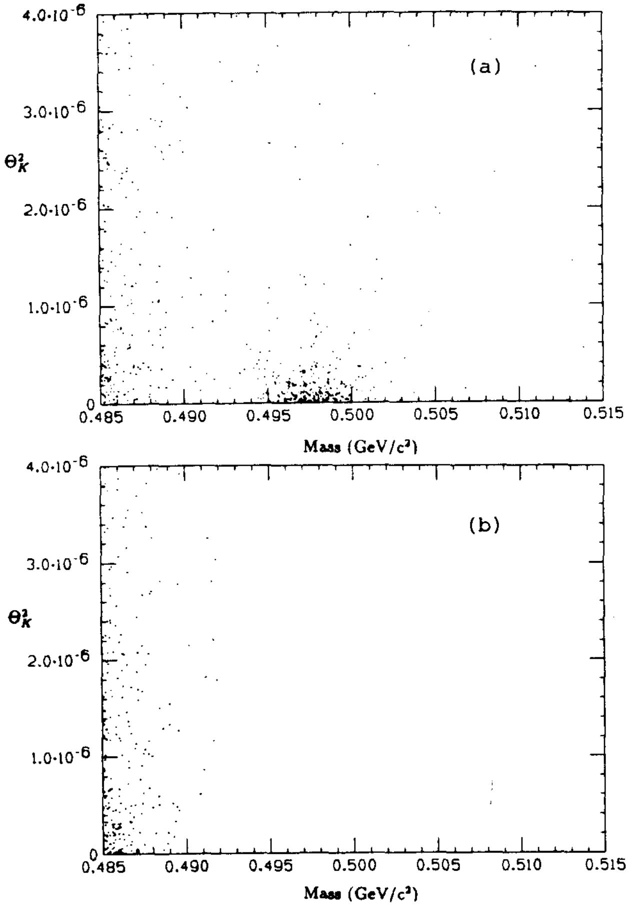

Figure 5: Scatter plots of the square of the angle, Θ_K, between the parent K_L direction and the direction of the reconstructed K_L versus invariant mass, for (a) $K_L \to \mu\mu$ and (b) $K_L \to \mu e$.

Source	90% C.L. Limit
1986 Particle Data Book	6×10^{-6}
BNL E780[21]	1.9×10^{-9}
KEK E137[22]	4.3×10^{-10}
BNL E791[19] (1988 data only)	2.2×10^{-10}
KEK E137[23] (unpublished)	2.1×10^{-10}
BNL E791 (new — 1989 data only — preliminary)	8.4×10^{-11}

Table 1: Results from recent $K_L \to \mu e$ searches.

Source	90% C.L. Limit
1986 Particle Data Book	2×10^{-7}
BNL E780[21]	1.2×10^{-9}
KEK E137[22]	5.6×10^{-10}
BNL E791[19] (1988 data only)	3.2×10^{-10}
KEK E137[23] (unpublished)	2.7×10^{-10}
BNL E791 (new — 1989 data only — preliminary)	1.1×10^{-10}

Table 2: Results from recent $K_L \to ee$ searches.

Source	Year	Events	BR ($\times 10^{-9}$)
Clark et al.[2]	1971	0	< 1.8
Carithers et al.[3]	1973	6	14^{+13}_{-7}
Fukushima et al.[4]	1976	3	$8.8^{+10.7}_{-5.5}$
Shochet et al.[5]	1977	16	$8.1^{+2.8}_{-1.8}$
KEK E137[22]	1989	54	8.4 ± 1.1
BNL E791[19] (1988 data only)	1989	87	$5.8 \pm 0.6 \pm 0.4$
BNL E791 (1989 data only — prelim.)	1990	284	$7.6 \pm 0.5 \pm 0.4$
Unitarity bound	—	—	$\simeq 6.8$

Table 3: Summary of $K_L \to \mu\mu$ branching ratio measurements.

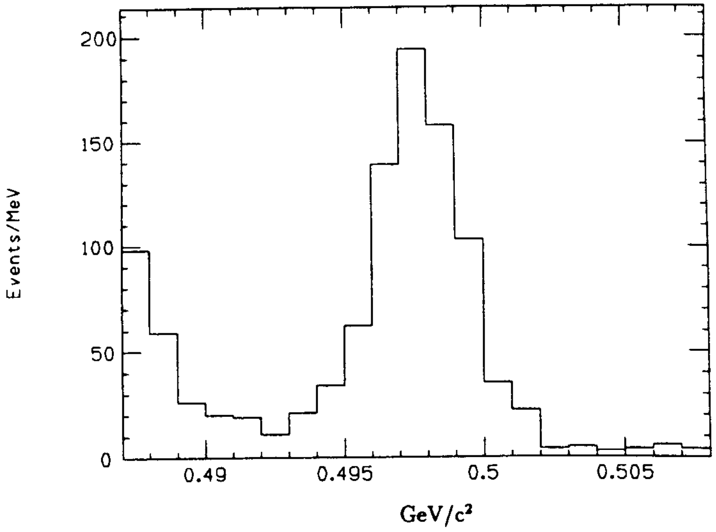

Figure 6: $K_L \to \mu^+\mu^-$ events from the full E791 data sample.

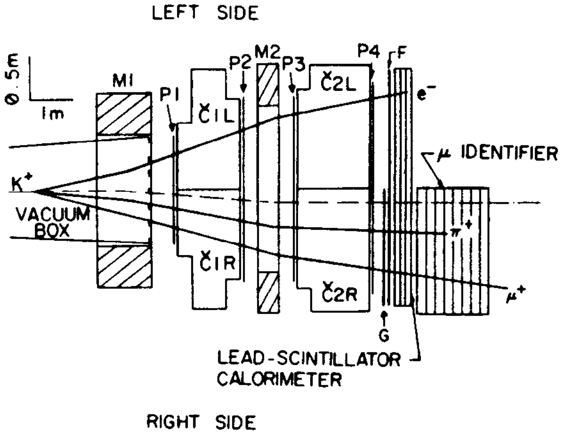

Figure 7: Plan view of the E777 detector.

tracking, sequential Čerenkov counters to obtain high quality particle identification, a lead-scintillator shower counter, and a muon detector consisting of steel plates alternating with planes of proportional tubes. The decay mode $K^+ \rightarrow \pi^+\pi^+\pi^-$ was used as a normalization in this experiment. Figure 8(a) shows $K^+ \rightarrow \pi^+\pi^+\pi^-$ events on a scatter plot of rms distance of closest approach of three track combinations to a common vertex (S) versus invariant mass. Figure 8(b) shows $K^+ \rightarrow \pi^+\mu^+e^-$ candidates on a similar plot. No candidates fall within the box. From these data, E777 has published[25] a 90% confidence level upper limit on $K^+ \rightarrow \pi^+\mu^+e^-$ of 2.1×10^{-10}. The best limit on the other sign process, $K^+ \rightarrow \pi^+\mu^-e^+$, is 6.9×10^{-9} from an experiment performed several years ago at the CERN PS.[26]

E777 was also sensitive to $K^+ \rightarrow \pi^+e^+e^-$ and has collected a sample of roughly 2000 such decays. This has already lead to limits[27] on the process $K^+ \rightarrow \pi^+A^\circ$, followed by $A^\circ \rightarrow e^+e^-$, where A° is an axion-like particle or possibly a light Higgs. Ultimately, the analysis of $K^+ \rightarrow \pi^+e^+e^-$ events should result in improved measurements on the branching ratio and structure of this decay and a new measurement of the branching ratio for $\pi^\circ \rightarrow e^+e^-$.

4 AGS Expt. 787

In the decay $K^+ \rightarrow \pi^+ + \textit{nothing}$, the *nothing* refers to one or more neutral very weakly interacting particles, which are not observed in the detector. Several candidates have been proposed which could provide the *nothing*; examples include the familon, two light photinos, and a host of others. But the process can also occur in the Standard Model through the second order weak diagrams shown in Figure 9, in which case the decay is $K^+ \rightarrow \pi^+\nu\bar{\nu}$. These diagrams have been calculated by a number of authors[28] and until recently it was expected the branching ratio was in the range $1\text{-}8\times10^{-10}$. It should be particularly sensitive to the V_{td} element of the Kobayashi-Maskawa matrix, and given a knowledge of the top quark mass, a measurement of this branching ratio will probably provide the best measure of V_{td}. However, as noted earlier, the recent measurements of the $K_L \rightarrow \mu\mu$ branching ratio provide additional information on Standard Model parameters which tends to rule out[11] the upper half of the allowed range.

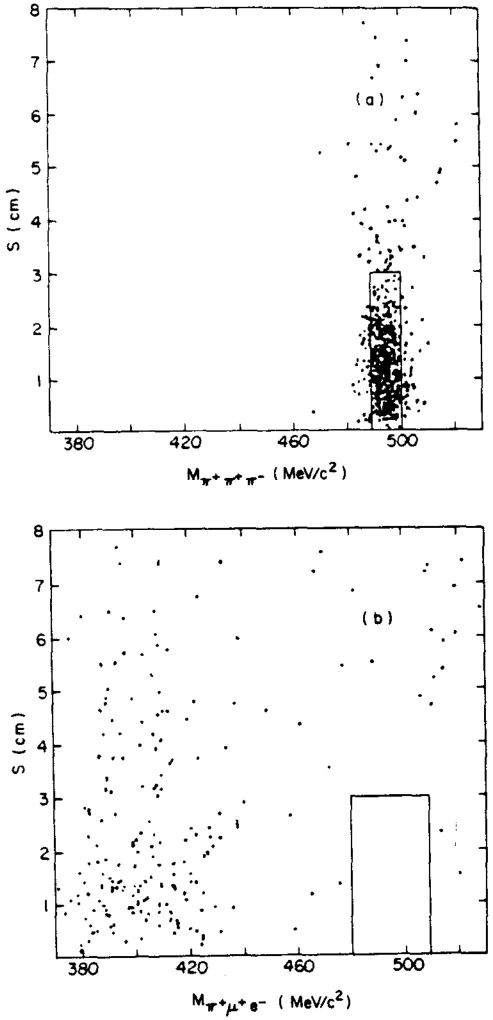

Figure 8: Scatter plots of the quantity S versus invariant mass, for (a) $K^+ \rightarrow \pi^+\pi^+\pi^-$ and (b) $K^+ \rightarrow \pi^+\mu^+e^-$ from E777.

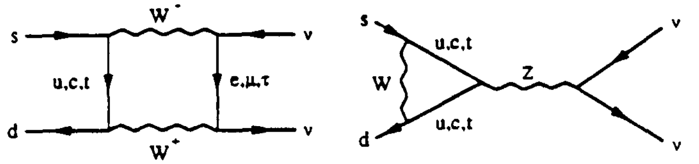

Figure 9: Diagrams responsible for $K^+ \to \pi^+\nu\overline{\nu}$ in the Standard Model.

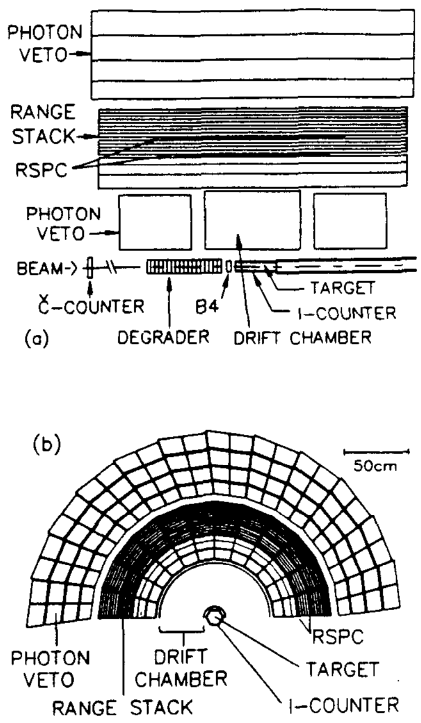

Figure 10: Schematic (a) side and (b) end views showing the upper half of the E787 detector.

Expt. 787[29] at BNL is searching for this decay and has the goal of reaching the Standard Model level. The experiment stops K^+'s in an active scintillating fiber target. The K^+ decay products are then observed in a large, virtually hermetic, 4π detector which is shown in Figure 10. The scintillating fiber target is surrounded by a cylindrical drift chamber. A plastic scintillator range stack surrounds the central drift chamber. Finally, a lead-scintillator photon veto system surrounds the range stack. A field of 1 Tesla is applied by a solenoidal magnet.

The major backgrounds for $K^+ \to \pi^+\nu\overline{\nu}$ are the familiar decays $K^+ \to \pi^+\pi^\circ$ and $K^+ \to \mu^+\nu$. Both of these decays create a π^+ with a specific momentum, while the $K^+ \to \pi^+\nu\bar{\nu}$ creates a π^+ with a momentum distributed from 0 to 227 MeV, so that some rejection comes from simply avoiding these peaks. Additional rejection of the $K^+ \to \pi^+\pi^\circ$ comes from vetoing the photons from the π°, which is done so efficiently that only about 2 in 10^6 π°'s are missed. Additional rejection against $K^+ \to \mu^+\nu$ is obtained by observing the full π^+ decay chain ($\pi \to \mu \to e$). This is accomplished by digitizing the photomultiplier signals from the range stack with 500 MHz 8-bit transcient digitizers over a period of 10 μsec for each event.

E787 took data during 1988, 1989, and 1990 at the AGS. Results from the 1988 data include:

- an upper limit[30] (90% confidence level) of 1.5×10^{-7} on the branching ratio of the decay $K^+ \to \pi^+H$, followed by $H \to \mu^+\mu^-$, for a Higgs boson in the mass interval $220 < m_H < 320$ MeV/c^2;
- upper limits[30] on the branching ratios of the decays $K^+ \to \pi^+\mu^+\mu^-$ and $K^+ \to \mu^+\nu\mu^+\mu^-$ of 2.3×10^{-7} and 4.1×10^{-7}, respectively;
- an upper limit[31] of 3.4×10^{-8} for $K^+ \to \pi^+\nu\overline{\nu}$; and
- an upper limit[31] of 6.4×10^{-9} for decays of the form $K^+ \to \pi^+X^\circ$, where X° is any massless, weakly interacting particle.

Figure 11 shows a scatter plot of range versus kinetic energy for pions in E787. $K^+ \to \pi^+\nu\overline{\nu}$ decays would appear inside the box. The events which are seen are consistent with the interpretation of $K^+ \to \pi^+\pi^\circ$ decays where both photons escape detection.

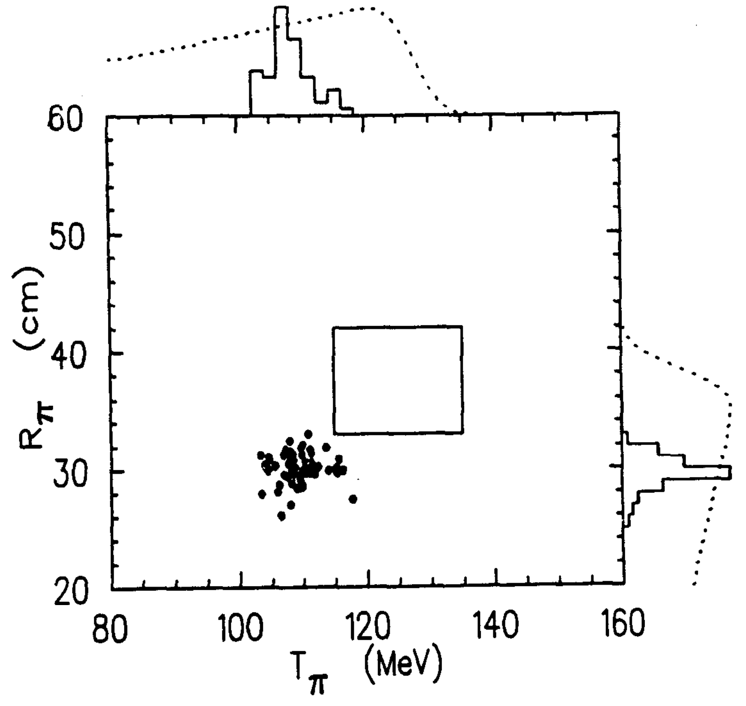

Figure 11: Range versus kinetic energy of pions in events satisfying all selection criteria for $K^+ \rightarrow \pi^+\nu\bar{\nu}$ from E787. The dotted curves on the projection axes show the expected Standard Model $K^+ \rightarrow \pi^+\nu\bar{\nu}$ spectrum folded with the detector resolution.

Results are not yet available from the 1989 and 1990 data samples of E787. It is expected that the combined sensitivity of these new data will approach or perhaps go below the $1 \times 10-9$ level for $K^+ \rightarrow \pi^+\nu\bar{\nu}$. Future upgrades to the beam and the detector are planned which will ultimately result in E787 reaching the Standard Model prediction for $K^+ \rightarrow \pi^+\nu\bar{\nu}$. The hope, of course, is to see $K^+ \rightarrow \pi^+$+*nothing* above that level, since it would signal new physics.

5 AGS Expt. 845

The decay $K_L \rightarrow \pi^\circ e^+e^-$ is expected[32] to occur within the Standard Model with a branching ratio in the neighborhood of 10^{-11}. Its observation at a significantly higher level would signal a new flavor changing neutral current interaction. However, most of the recent interest in this process has been motivated by its sensitivity to direct CP violation in the Standard Model, which refers to the "direct" decay of the CP-odd eigenstate K_2 to a state of even CP, rather than to the decay of the small admixture (characterized by the familiar parameter ϵ) of the CP-even state K_1 in the K_L. Three amplitudes are expected to contribute to the rate for this decay: a direct CP violating part, a CP violating part due to mass mixing, and a CP conserving part due to the 2-photon exchange process $K_L \rightarrow \pi^\circ\gamma^*\gamma^* \rightarrow \pi^\circ e^+e^-$. The presence of the three contributions complicates both the theoretical discussion of this decay and the experimental program necessary to explore it. The hope has been that the direct CP violation in this decay will be the dominant part, so that a measurement of the branching ratio will provide a good constraint on the CP violating KM product $s_2s_3s_\delta$, subject to knowledge of the top quark mass.

Three experiments have published limits on $K_L \rightarrow \pi^\circ e^+e^-$. These are listed in Table 4. The lowest is from BNL E845[33]. The E845 detector is shown in Figure 12. It is a compact detector, to obtain large 4-body acceptance, with a dipole spectrometer magnet, drift chambers, a hydrogen Čerenkov counter, and a lead glass array. Figure 13 shows $K_L \rightarrow \pi^\circ e^+e^-$ candidates. While no events appear inside the signal box, it is clear that there are background events nearby.

The E845 collaboration has explained this background as coming from the

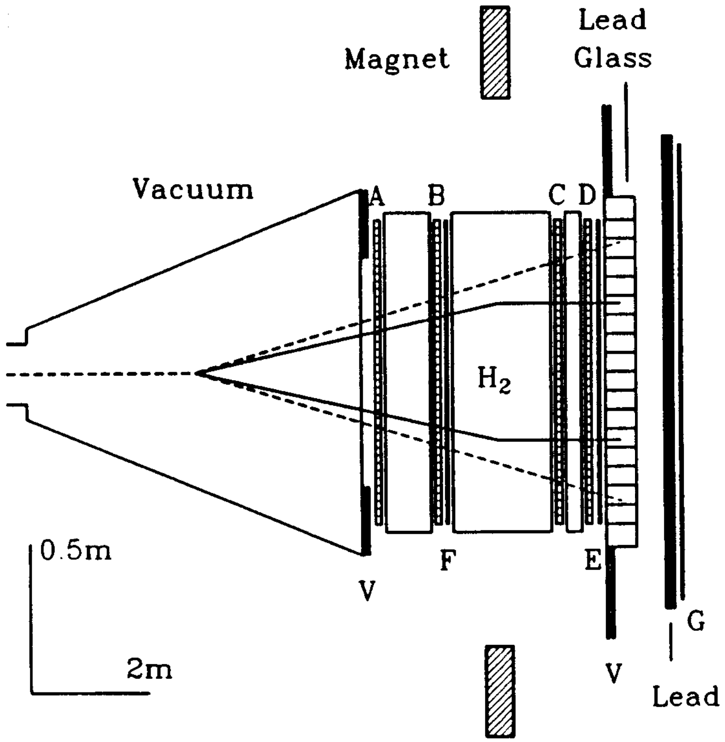

Figure 12: Plan view of the E845 detector.

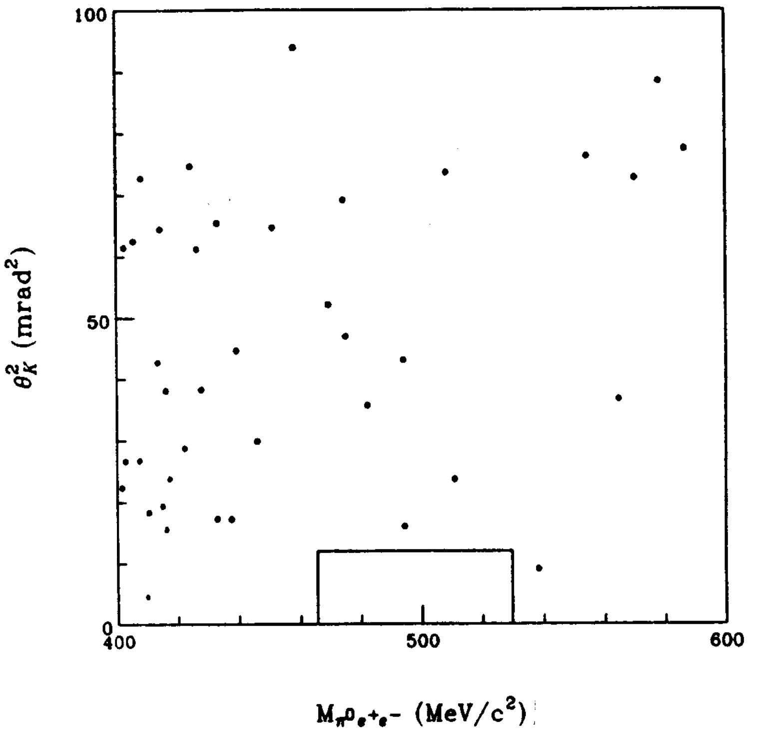

Figure 13: Scatter plots of the square of the collinearity angle versus invariant mass $K_L \to \pi^\circ e^+ e^-$ from E845.

Source	90% C.L. Limit
CERN NA31[34]	4×10^{-8}
FNAL E731[35]	7.5×10^{-9}
BNL E845[36]	5.5×10^{-9}

Table 4: Results from recent $K_L \rightarrow \pi^\circ e^+ e^-$ searches.

direct $K_L \rightarrow e^+e^-\gamma\gamma$ decay. It occurs through internal bremsstrahlung of a photon from one of the e's in the decay $K_L \rightarrow e^+e^-\gamma$. A calculation by Greenlee[37] (a member of the E845 collaboration) has shown that the direct $K_L \rightarrow e^+e^-\gamma\gamma$ decay constitutes a serious, probably fatal background to the experimental study of the $K_L \rightarrow \pi^\circ e^+e^-$ decay mode. The calculated branching ratio for $K_L \rightarrow e^+e^-\gamma\gamma$ is 2.8×10^{-9}. While considerable suppression of the background process can be obtained through kinematic cuts, ultimately the suppression is inadequate provided the $K_L \rightarrow \pi^\circ e^+e^-$ branching ratio is at or below about 1×10^{-10}. This can be seen from Figure 14. The figure shows the branching ratio at which the background appears as a function of the efficiency of cuts on the signal process, $K_L \rightarrow \pi^\circ e^+e^-$. This calculation assumes the requirement $|m_{\gamma\gamma} - m_{\pi^\circ}| < 5$ MeV.

An independent calculation by Dicus[38] reproduces the Greenlee result (within a factor of two). The results of this calculation are shown in Figure 15. Here, the effective branching ratio of the background process (after cuts requiring $m_{ee} > m_{\pi^\circ}$ and $|m_{\gamma\gamma} - m_{\pi^\circ}| < 5$ MeV) is plotted along with that for the signal, as a function of a cut on $\theta_{e\gamma}$. The angle $\theta_{e\gamma}$ is defined as the smallest angle between any electron and any photon in the decay, calculated in the center of mass frame. This angle is a natural variable to cut on since the radiated photon in the $K_L \rightarrow e^+e^-\gamma\gamma$ decay will tend to be along the direction of the radiating electron. In the figure, the branching ratio for $K_L \rightarrow \pi^\circ e^+e^-$ has been taken as 1×10^{-11}.

E845 also observed 919 events of the type $K_L \rightarrow e^+e^-\gamma$, leading to a new measurement[13]of the branching ratio and form factor for that decay. These results are in excellent agreement with an earlier measurement by NA31[12] at CERN.

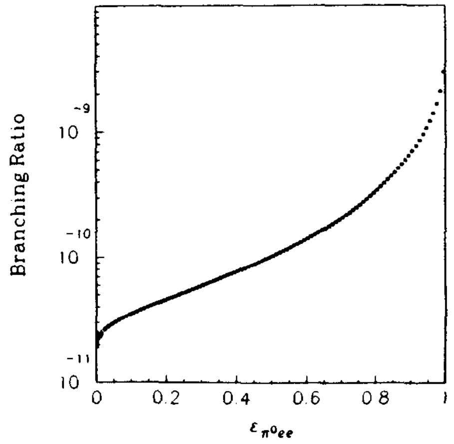

Figure 14: Predicted effective branching ratio at which the background process $K_L \rightarrow e^+e^-\gamma\gamma$ appears as a function of the efficiency of kinematic cuts on $K_L \rightarrow \pi^\circ e^+e^-$, from reference 37.

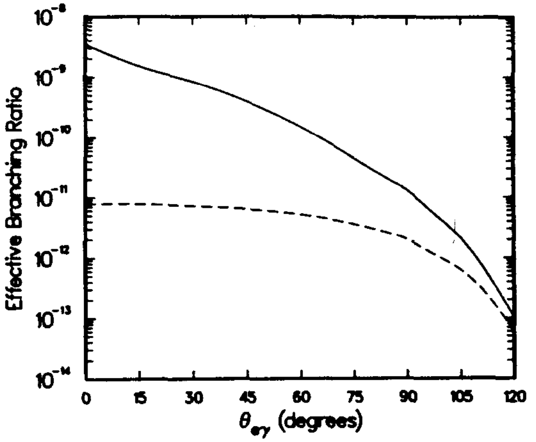

Figure 15: Predicted effective branching ratio of $K_L \rightarrow e^+e^-\gamma\gamma$ (solid line) and $K_L \rightarrow \pi^\circ e^+e^-$(dashed line) versus the minumum center of mass angle between any $e\gamma$ pair.

6 Conclusion

Three of the four AGS experiments which have been discussed, E791, E777 and E845, have completed data taking. Final results from E791 on the modes $K_L \to \mu e$, $K_L \to ee$, and $K_L \to \mu\mu$ can be expected within the next six to nine months. Additional results from E777 on $K^+ \to \pi^+ e^+ e^-$ should be available soon. New proposals have been submitted to BNL for experiments to push both $K_L \to \mu e$ and $K^+ \to \pi^+ \mu^+ e^-$ to the 10^{-12} level. No future work at BNL is contemplated on the $K_L \to \pi^\circ e^+ e^-$ mode. The approved experiments at KEK (E162) and FNAL (E799) will probably be background limited. E787 will have new results from 1989 and 1990 data sets soon. E787 has a plan for a series of beamline and detector upgrades which will ultimately result in a sensitivity for $K^+ \to \pi^+ \nu\bar{\nu}$ at the Standard Model level.

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CP- Violation in K^0 – decays at CERN

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ABSTRACT

Two experiments will be discussed, NA31 and CP-LEAR. The main results of NA31 on CP- and CPT- violation will be reviewed . A recent measurement of the decay $K_L \to \pi^0\gamma\gamma$, which has some relevance for CP-violation in the decay $K_L \to \pi^0 e^+ e^-$,will be presented in some detail, and a new proposal for a more precise measurement of ϵ'/ϵ will be outlined. For CP-LEAR the aims of the experiment and a brief status report will be given.

1. CP– and CPT– violation parameters

There are two distinct possibilities of CP– violation in K^0 decay: by state mixing and in the decay matrix. Mixing between K^0 and $\bar{K}^0$ occurs because K^0 and $\bar{K}^0$ couple to the same intermediate states via the weak interaction. The eigenstates K_L and K_S with definite masses and lifetimes are not necessarily identical with the eigenstates K_1 and K_2 of the CP- operator. In general one has

$$K_L = \frac{1}{\sqrt{2(1+|\epsilon_L|^2)}}(K_2 + \epsilon_L K_1) \tag{1}$$

$$K_S = \frac{1}{\sqrt{2(1+|\epsilon_S|^2)}}(K_1 + \epsilon_S K_2) \tag{2}$$

and $\epsilon_L = \epsilon_S = \epsilon$, if CPT is conserved. If the time evolution of the K^0 and $\bar{K}^0$ states is parametrized by the mass matrix M and the decay matrix Γ, viz.

$$i\partial\Psi/\partial t = (M - i\Gamma)\Psi \qquad ,\Psi = \begin{pmatrix} K^0 \\ \bar{K}^0 \end{pmatrix}, \tag{3}$$

the parameter ϵ is related to the matrix elements by

$$\epsilon = \frac{\epsilon_S + \epsilon_L}{2} = \frac{\Gamma_{12} - \Gamma_{12}^* + i(M_{12} - M_{12}^*)}{\gamma_S - \gamma_L - 2i(m_L - m_S)}. \tag{4}$$

In the traditional phase convention (A_0= real, see below) Γ_{12} is practically real and the phase of ϵ is determined by the phase of the denominator of (4), with

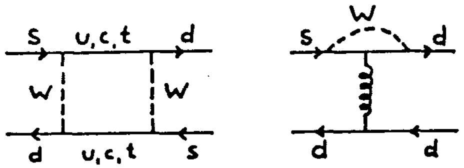

*Fig.1.*a) Box diagram b) Penguin diagram

the numerical value $\phi_\epsilon = (43.7 \pm 0.2)^0$. With this admixture of ϵK_1 in its wave function, the K_L-state can now decay to $\pi^+\pi^-$ or $\pi^0\pi^0$, which are even under CP because of Bose- statistics. Since $< 2\pi|K_L >= \epsilon < 2\pi|K_S >$, the ratio of decay rates into charged and neutral pions is the same for K_L and K_S, if state mixing is the only source of CP- violation, as for example in the superweak model[1]. With quark diagrams the mixing is described by the famous box graph (Fig.1a). The real part of the amplitude is related to $\Delta m = m_L - m_S$, the imaginary part to ϵ. As first noticed by Kobayashi and Maskawa[2], with three generations of quarks it is possible to have a unitary quark mixing matrix with complex phase factors that cannot be absorbed in the definition of quark states. The smallness of CP- violation is then due to the smallness of the product of the three generation- mixing angles. If these angles were large, CP-violation would be a prominent effect.

A second possibility is that CP is violated in the transition itself (*direct CP- violation*). This happens if the matrix elements A_0 and A_2 between K^0 and the two possible I=0 and I=2 eigenstates of two pions do not have the same phase. Denoting the strong interaction phase shifts with δ_I , the transition amplitudes are given by

$$< 2\pi|_I|T|K^0 >= A_I \exp(i\delta_I) \tag{5}$$

$$< 2\pi|_I|T|\bar{K}^0 >= \bar{A}_I \exp(i\delta_I). \tag{6}$$

One phase is free; in the usual convention , A_0 is taken to be real. Direct CP- violation is then linked to a nonzero value of

$$\epsilon' = \frac{i}{\sqrt{2}} \frac{Im A_2}{A_0} \exp(i(\delta_2 - \delta_0)). \tag{7}$$

Note that the phase of ϵ' is given by the strong interaction phase shifts [3]

$$\phi_{\epsilon'} = \frac{\pi}{2} + \delta_2 - \delta_0 \approx (45 \pm 15)^0 \quad . \tag{8}$$

In the standard model, ϵ' can be calculated, in principle, from Penguin- diagrams (Fig.1b). These involve exchange of gluons. More recently, exchanges of photon and Z_0 were also computed [4], with the effect of decreasing ϵ'/ϵ for higher masses of the top quark.

Quite independent of the details of these calculations it is worthwhile to find out experimentally whether there is CP- violation in a Δ S = 1 transition. If there is, it seems indeed plausible that CP- violation is related to quark mixing. Even though ϵ' is a small number, in fact suppressed by a factor $A_0/A_2 \approx 20$,the highest chance to establish direct CP- violation anywhere is still in $K \to 2\pi$ decay .

Assuming CPT -conservation, the measurable CP-violation amplitudes

$$\eta_{+-} = \frac{< \pi^+\pi^-|T|K_L >}{< \pi^+\pi^-|T|K_S >} \tag{9}$$

$$\eta_{00} = \frac{< \pi^0\pi^0|T|K_L >}{< \pi^0\pi^0|T|K_S >} \tag{10}$$

are related to the parameters ϵ and ϵ' by

$$\eta_{+-} = \epsilon + \epsilon' \tag{11}$$

$$\eta_{00} = \epsilon - 2\epsilon'. \tag{12}$$

The experimental values as of two years ago are graphically represented in Fig.2. Within the given framework, and with the phases of ϵ and ϵ' as quoted, it is however impossible to have ϕ_{00} and ϕ_{+-} different by more than a degree, as suggested by these data. If the data are right, CPT cannot be conserved.

Allowing for CPT- violation, there are again two effects: CPT- violation in the state mixing, and CPT- violation in the transition. If in the state mixing $\epsilon_S \neq \epsilon_L$, then

$$\delta = \frac{\epsilon_S - \epsilon_L}{2} = \frac{(\Gamma_{11} - \Gamma_{22}) + i(M_{11} - M_{22})}{\gamma_S - \gamma_L - 2i(m_L - m_S)} \tag{13}$$

is a measure of CPT- violation.

If in the transition amplitudes $\bar{A}_I \neq A_I^*$ for I=0 or I=2, there is CPT-violation. Defining for convenience the CPT- violating amplitudes as

$$\alpha_0 = \frac{A_0^* - \bar{A}_0}{A_0 + \bar{A}_0} \qquad \alpha_2 = \frac{1}{\sqrt{2}} \frac{A_2^* - \bar{A}_2}{A_0 + \bar{A}_0} \exp(i(\delta_2 - \delta_0)), \tag{14}$$

the measurable amplitudes η_{+-} and η_{00} become

$$\eta_{+-} = \epsilon + \epsilon' - \delta + \alpha_0 + \alpha_2 \tag{15}$$

$$\eta_{00} = \epsilon - 2\epsilon' - \delta + \alpha_0 - 2\alpha_2 \tag{16}$$

$$\eta_{00} - \eta_{+-} = 3(\epsilon' + \alpha_2). \tag{17}$$

A nonzero phase difference $\phi_{00} - \phi_{+-}$ requires then a nonzero value ofα_2. In the case $\alpha_2 = \alpha_0 = 0$ the mass difference $M_{11} - M_{22}$, that is $M_{K^0} - M_{\bar{K}^0}$, can be measured by looking at the projection $\delta_\perp$ of δ perpendicular to ϵ,

$$\delta = \epsilon - (\frac{2}{3}\eta_{+-} + \frac{1}{3}\eta_{00}) \tag{18}$$

$$\delta_\perp \approx |\eta|(\frac{2}{3}\phi_{+-} + \frac{1}{3}\phi_{00} - \phi_\epsilon) \tag{19}$$

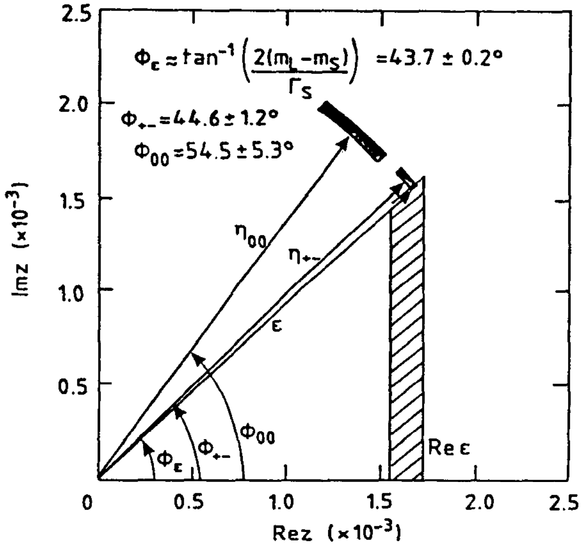

Fig.2. Status of CP-violation parameters as of 1988.

2. Measurements of ε'/ε by NA31

The NA31 experiment has been presented at many occasions[5] since the publication of the first result. More data were taken in 1988 and 1989 ; they will triple the original statistics and improve on the systematic error. Yet, there is no result so far.In the following discussion I will summarize the main points and indicate why and how a new experiment may be done.

Direct CP-violation is most conveniently measured as a deviation of the double ratio

$$R = \frac{\dfrac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)}}{\dfrac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)}} = 1 - 6Re(\varepsilon'/\varepsilon) \qquad (20)$$

from unity. Experimentally, it is necessary to measure at least two of the four rates $K_S \to \pi^0\pi^0, K_S \to \pi^+\pi^-, K_L \to \pi^0\pi^0, K_L \to \pi^+\pi^-$ at the same time. The NA31 group has chosen to detect charged and neutral decays concurrently, and to switch in regular intervals from a K_L to a K_S beam. Neutral beams were derived at (3.5 ± 0.5) mrad from targets hit by 450 GeV protons. In K_S running the target station was close to the decay fiducial volume, and moveable along the beam to cover a 50m decay length almost uniformly with K_S decays (seeFig.3). Geometrical acceptances cancel therefore in the double ratio (20) of K_S and K_L decays. The beams are contained in vacuum throughout the apparatus to avoid background from neutron and photon interactions.

The detector[6] includes two wire chambers and an iron scintillator calorimeter for the measurement of decays into charged pions, and a fine grain liquid argon calorimeter segmented laterally in 1 cm wide strips and longitudinally in two groups of 40 cells, for the measurement of photons. Four rings of veto counters surrounding the decay volume detect large angle photons from $3\pi^0$ decays. $K_{\mu 3}$ decays are suppressed by two planes of muon counters behind 1.5m and 2.3m of iron equivalent, K_{e3} decays are suppressed in the trigger and also offline by the longitudinal pattern of energy deposition in the liquid argon counter. $K \to \pi^+\pi^-\pi^0$ decays are identified, if at least one photon is visible.

The main problem for all CP- violation experiments in $K \to 2\pi$ decays is the suppression of $K_L \to 3\pi^0$ decays. For events in which two photons escape the detector and the veto system, the kinematical constraints of the π^0 and K^0 masses and the direction of the reconstructed K^0 momentum vector are the only tools to separate signal and background. To maintain a high rate the decay point is not measured — one would have to convert at least two photons — but is reconstructed using the K^0 mass as constraint. The reconstruction is therefore sensitive to the photon energy scale. This in turn provides a method to calibrate the photon detector : the upstream end of the decay region in the K_S mode is defined by an anticounter preceeded by 8mm of Pb. The reconstructed position of this counter is used to determine the scales of neutral and charged energies with an accuracy of 0.1 %. Background from $3\pi^0$ decays in which two photons miss the detector is uniformly distributed in the space of two-photon invariant masses (Figs.4a,b). It culminates at large distance from the collimator(Fig.4c), since the kinematic constraint shifts the decay point downstream, compensating the energy lost in the missing photons by an increase of the opening angle for the visible photons.

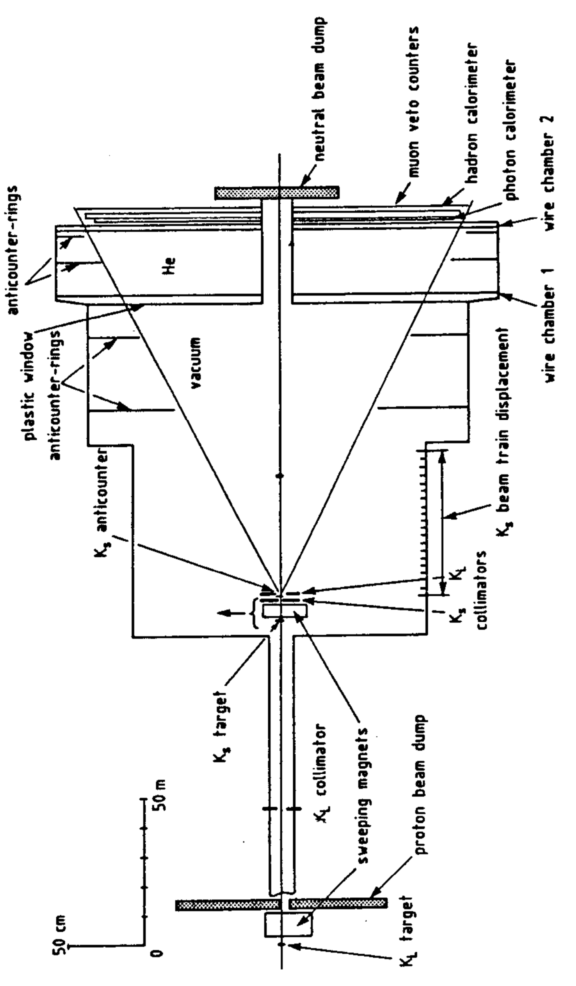

Fig.3. Layout of the NA31 experiment.

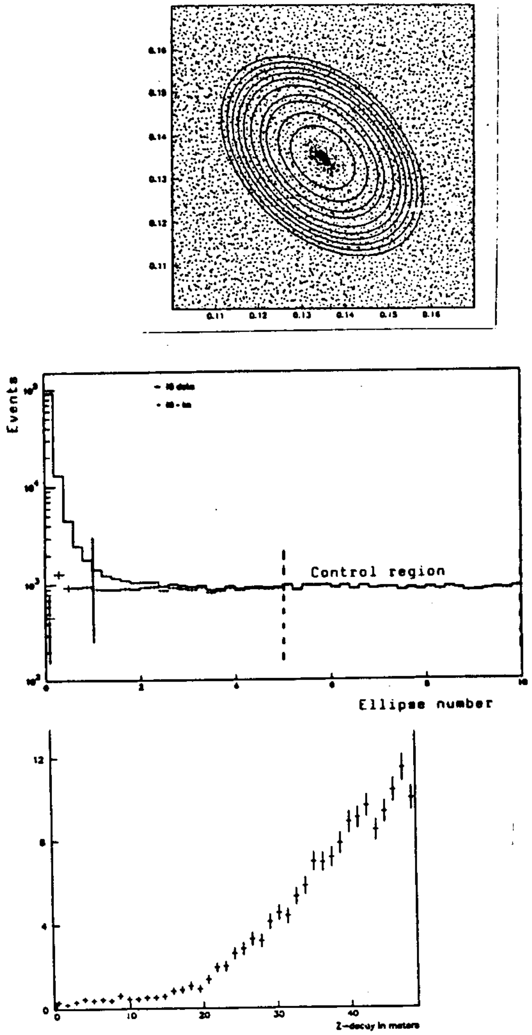

Fig.4. a) Invariant masses of best photon pairs in $K_L \rightarrow \pi^0\pi^0$.
b) events in rings of equal area of Fig.3a.
c) z- distribution of neutral background.

In $K^0 \rightarrow \pi^+\pi^-$ candidates the background from three-body decays can be suppressed by measuring the distance d_t between target and decay plane. The resolution in d_t is measured with K_S decays; the remaining background, visible at large d_t, consists mainly of K_{e3} events and can be safely extrapolated into the signal region using Monte Carlo or data (Fig.5) . The published result[7] of NA31, based on 109 000 $K_L \rightarrow \pi^0\pi^0$ events, is

$$Re(\epsilon'/\epsilon) = (3.3 \pm 1.1)10^{-3}$$

with about equal contributions from statistical ($0.67 \cdot 10^{-3}$) and systematic ($0.83 \cdot 10^{-3}$) errors. A breakdown of the systematic errors is given in Tab.1. Among the larger items are the difference of charged and neutral energy scales and the background subtraction in $K_L \rightarrow \pi^+\pi^-$ decays. Both of these errors should be reduced in the data taking of 1988 and 1989; the former, because the K_S and K_L spectra were more equalized by choosing a larger target angle and a lower proton energy (360 GeV) for K_S running ; the latter, because a transition radiation detector[8] was inserted to identify electrons in K_{e3} decays, the most important background.

In the meantime a null result[9] from the FNAL experiment E731,

$$Re(\epsilon'/\epsilon) = (-0.4 \pm 1.4(\text{stat.}) \pm 0.6(\text{syst.})) \cdot 10^{-3}$$

made it likely, that the true value of ϵ'/ϵ is rather on the lower than on the higher side of the NA31 value — the average of the two results is $(2.1 \pm 1.0) \cdot 10^{-3}$— and therefore a new attempt may be necessary to establish CP–violation with sufficient (say 5 standard deviations) confidence.

The theoretical value of ϵ'/ϵ has been decreasing over the years. Figure 6 shows some older calculations with indication of theoretical uncertainties, and a more recent evaluation of a most likely value, as a function of the unknown mass of the top quark. The theoretical uncertainties are a subject of sometimes controversial statements — so they are still large. A discussion is given, for example , in Ref.10.

A proposal to measure ϵ'/ϵ with systematic and statistical errors of $2 \cdot 10^{-4}$ was recently submitted [11] by a collaboration involving members of the NA31 team. The proposed experiment differs from NA31 in many respects; apart from running at about ten times higher K_L intensity there are various conceptional changes:

- K_S and K_L beams run at the same time. A small fraction of the primary proton beam is deflected by a bent crystal and transported to the K_S target.
- The decay volume is kept short and proportional to the Lorentz factor of Kaons. The K_S target is in a fixed position.
- The affiliation of an event to the K_S or K_L beam is done by timing. The primary protons in the K_S beam can be recorded individually at an intensity of 10^7 /spill by a thin counter in the beam. If an event is a K_S decay, it must be correlated in time with a primary proton.

Further changes in the design are a magnetic spectrometer for the measurement of charged decays and the suggestion to use a liquid Xenon calorimeter for the detection of neutrals. The proposed layout of the experiment is shown in Fig.7 .

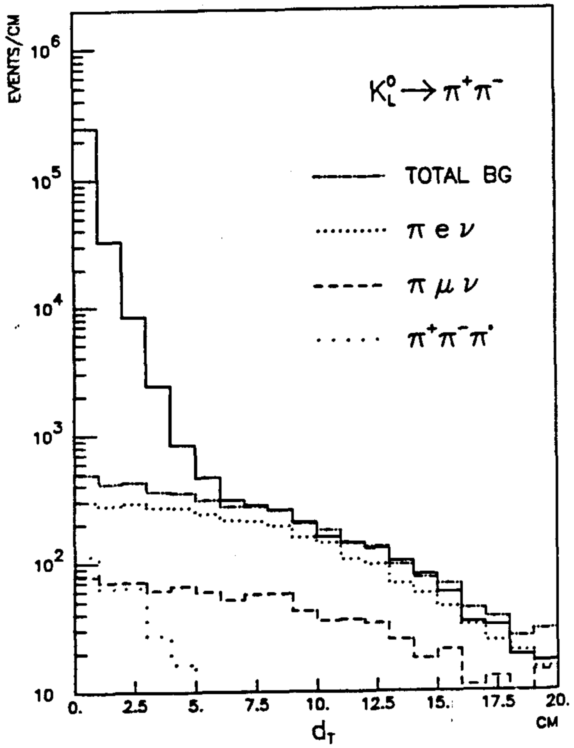

Fig.5. Acoplanarity in charged decays .
The composition of the background is indicated.

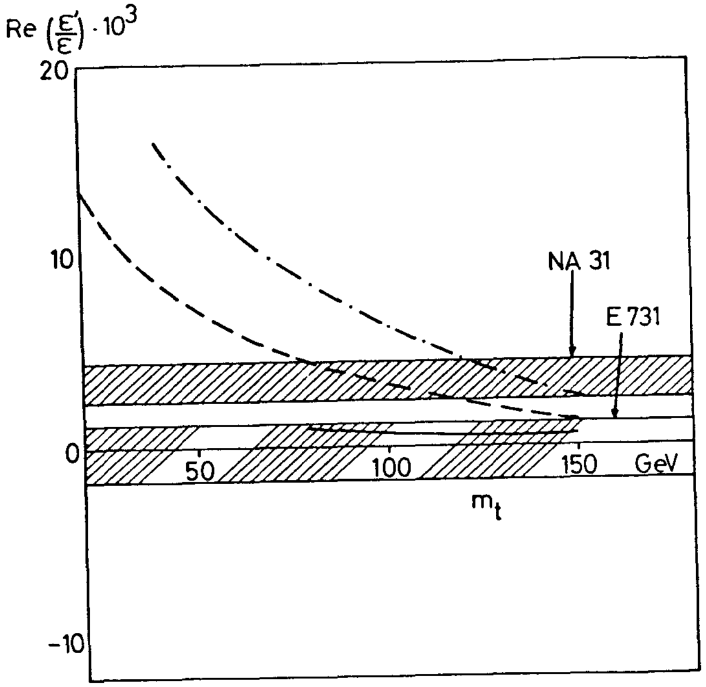

Fig.6 Theoretical predictions for ϵ'/ϵ as a function of the top quark mass . Solid line Ref.4,dotted (dash-dotted) line Ref.11 with B= 2/3 (1/3).

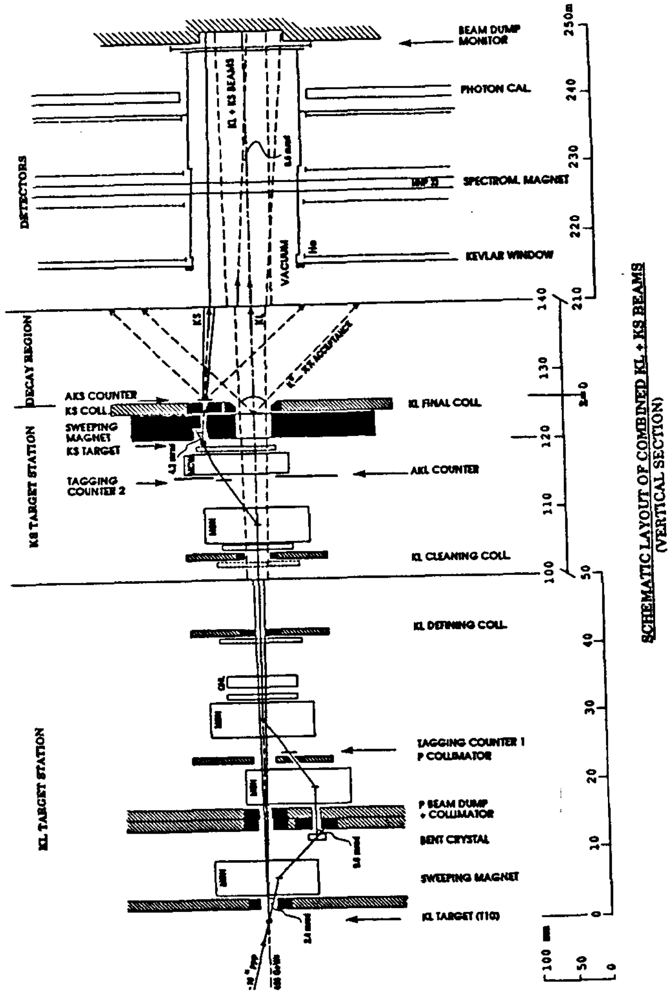

Fig.7 Layout of a proposed SPS -experiment for a measurement of ϵ'/ϵ .

Tab.1 Systematic uncertainties on the double ratio (in %)

background subtraction for $K_L \to 2\pi^0$	0.2
background subtraction for $K_L \to \pi^+\pi^-$	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%

3. Measurement of ϕ_{00} and $\phi_{+-}$by NA31

An initial K^0 particle decays to two pions with a rate proportional to

$$\exp(-\Gamma_S t) + 2|\eta|\exp(-\Gamma_S/2\,t)\cos(\Delta m t - \phi) + |\eta|^2\exp(-\Gamma_L t), \qquad (21)$$

because of the different time evolution of K_S and K_L in the initial wave function. The sign of the interference term changes for a $\bar{K}^0$ initial state. The phase ϕ_{00} (or ϕ_{+-}) can be extracted from the observed interference pattern behind a proton target, in which K^0 and $\bar{K}^0$ are produced incoherently with different rates. The NA31 group measured[13] the individual phases, ϕ_{00} and ϕ_{+-}, and the phase difference $\phi_{00} - \phi_{+-}$, from the interference behind a target. To be independent of Monte Carlo detection efficiency calculations, data were taken with two different target positions (L=48m and L=33m in front of the collimator) corresponding to an average phase difference of $\pi/2$. Frequent changes, about once per day, between Near and Far runs assure approximately the same running conditions. For each decay point there are two sets of data. For a given K^0 momentum the ratio of Near and Far data can be calculated directly from ( ) , independent of acceptance. Figure 8 shows this ratio, as a function of the decay point position , for three different momenta. The ratio approaches the value $\exp(-\Delta L/\gamma\beta\tau_S)$ at early life times, and unity at late times. The data show a clear interference pattern, from which the cos term can be isolated (Fig.9).The results are summarized, together with a recent measurement[14] of the E731 group, in Tab.2. The phase difference is compatible with zero; there is no evidence for CPT- violation in the decay amplitude A_2.

There is , however, in the NA31 experiment, a 1.5 standard deviation discrepancy between ϕ_{+-} and ϕ_ϵ, which relates to a possible CPT- violation in the state. Since ϕ_{+-} and Δm are strongly correlated in this experiment, the correlation is explicitely shown in Fig.10. A similar discrepancy was observed in the most precise previous experiment [15] on ϕ_{+-}. It is desirable to clarify this point by more precise determinations of ϕ_{+-} and Δm.

Meanwhile, the NA31 result on ϕ_{+-} and ϕ_{00} can be used [13] to give an upper limit

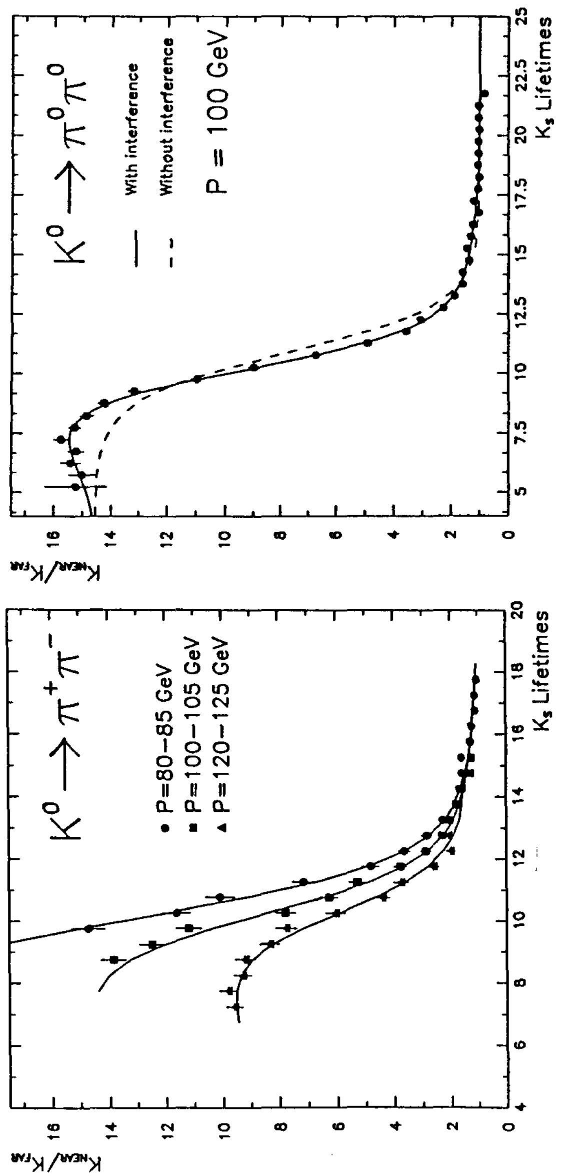

Fig.8 Ratio of Near and Far data as a function of proper time, calculated from a fixed point between the two targets. In b) the data are normalized to a momentum of 100 GeV.

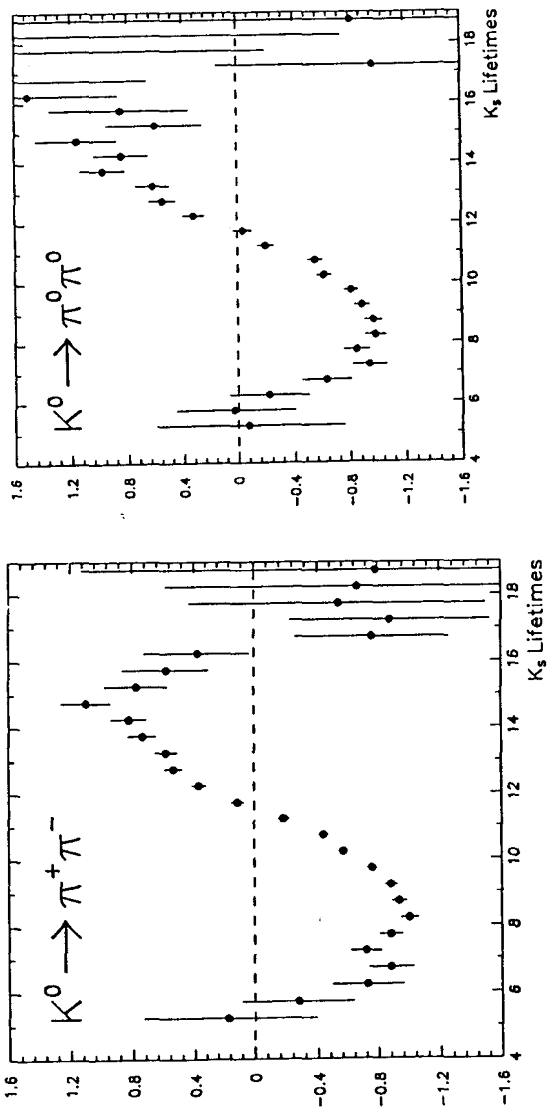

Fig.9 $K_L - K_S$ interference terms in neutral and charged decay modes.

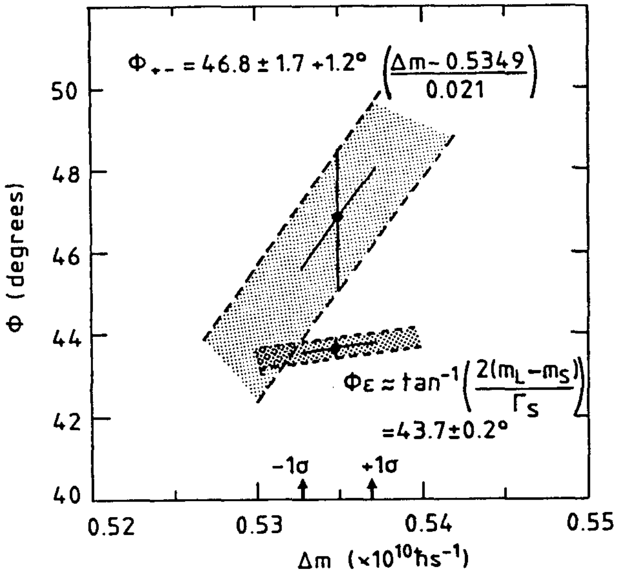

Fig.10 Correlation between ϕ_{+-} and Δm from NA31.

Tab.2 Phase measurements

	NA31	E731
ϕ_{+-}	$(46.8 \pm 1.4 \pm 0.7)^0$	$(47.7 \pm 2.0 \pm \cdots)^0$
ϕ_{00}	$(47.1 \pm 2.1 \pm 1.0)^0$	$(47.4 \pm 1.4 \pm \cdots)^0$
$\phi_{00} - \phi_{+-}$	$(0.3 \pm 2.6 \pm 1.0)^0$	$(-0.3 \pm 2.4 \pm 1.2)^0$

The errors are the statistical (1^{st}) and the systematic (2^{nd}) error

for CPT- violation in the state. The value

$$\delta_\perp = (1.3 \pm 0.8) \cdot 10^{-4} \tag{22}$$

$$\delta_\perp < 2.6 \cdot 10^{-4} \text{ at } 90\% \text{ C.L.} \tag{23}$$

$$\text{implies} \quad \left| \frac{M_{K^0} - M_{\bar{K}^0}}{M_{K^0}} \right| < 5 \cdot 10^{-18}\,. \tag{24}$$

4. The decays $K_L^0 \rightarrow \pi^0 e^+ e^-$ and $K_L \rightarrow \pi^0 \gamma\gamma$

As a possible way to observe CP- violation, both direct and indirect, in another channel, the decay $K_L^0 \rightarrow \pi^0 e^+ e^-$ has been much discussed [16]. If the intermediate state to which e^+ and e^- couple, is a one photon state, the decay is forbidden by CP conservation (the decay $K_S \rightarrow \pi^0 e^+ e^-$ is allowed). With a two-photon intermediate state, however, the decay is allowed by CP. If the two photons are in a state with total angular momentum J=0, the coupling to e^+e^- vanishes in the limit of zero lepton mass, and is negligiable (BR≈ 10^{-14}) for electrons. There is however the possibility[17] that a two-photon intermediate state with nonzero angular momentum can be formed by " vector-dominance"- diagrams, in which case the CP- conserving contribution to $K_L \rightarrow \pi^0 e^+ e^-$ could be substantial.

A first measurement[18] of $K_L \rightarrow \pi^0 \gamma\gamma$ by the NA31 group excludes that possibility, by giving an upper limit to the vector - dominance type coupling.

To isolate the decay from a large background of $K_L \rightarrow 3\pi^0$, in which one of the photons misses the detector and the other overlaps in space with another photon, the fiducial decay region was limited to the first 20m behind the collimator. Decays with the correct signature are mostly compatible with estimated background from $K_L \rightarrow 3\pi^0$ decays upstream of the collimator with a photon lost in the collimator. This background , which peaks at the downstream end of the decay region, can be removed by requiring that no two photons in the observed event are kinematically compatible with a π^0 from a decay in the interval between 7m upstream of the reconstructed vertex and 15m upstream of the end of the collimator. To include the cases in which two photons from two different π^0's overlap, the overlap is undone, sharing the energy such that two π^0's from a common vertex can be formed. All 12 possibilities of such a configuration are tested. Only a third of the geometrically accepted $K_L \rightarrow \pi^0 \gamma\gamma$ decays are expected to survive this cut, but the background is almost completely removed (Fig.11).

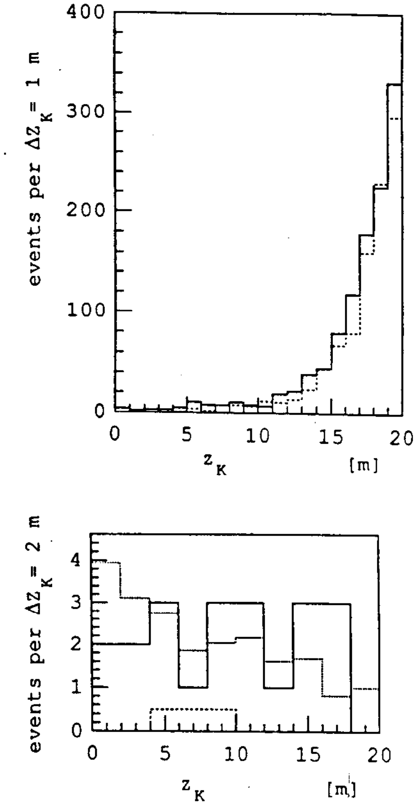

Fig.11 a) Vertex of $K_L \rightarrow \pi^0 \gamma\gamma$ candidates with expected background (dashed line) b) same as a) after cuts (see text). The dotted line is the expected signal distribution.

Evidence for a signal comes from the $\gamma_1\gamma_2$ invariant mass distribution(Fig.12). The invariant masses of the other two photons, γ_3 and γ_4, peak at the highest allowed values, in agreement with expectation from chiral perturbation theory [19]. The experimental branching ratio for $K_L \rightarrow \pi^0\gamma\gamma$ into final states with $m_{\gamma\gamma} > 280$ MeV is $((2.1\pm0.6)\cdot10^{-6}$, not incompatible with the theoretical prediction[19] $0.67\cdot10^{-6}$.In contrast to a model, which includes also a vector-dominance term, no signal is observed at low $\gamma_3\gamma_4$ masses, limiting the vector coupling constant to $-0.3 < a_V < 0.5$. Since the branching ratio for the $K_L \rightarrow \pi^0e^+e^-$ decay is given by BR $=4.4\cdot10^{-12}|a_V|^2$, this result corresponds to a BR$< 1.1\cdot10^{-12}$, an order of magnitude below the expected contributions from direct or indirect CP-violation.

The best experimental upper limit [20] is BR$(K_L \rightarrow \pi^0e^+e^-) < 5.5\cdot10^{-9}$. A serious background to the decay is from radiative Dalitz decays ($K_L \rightarrow e^+e^-\gamma\gamma$ with BR $\approx 6\cdot10^{-7}$), as discussed recently in Ref.21. This background makes an experiment on $K_L \rightarrow \pi^0e^+e^-$ indeed very difficult.

5. CP - LEAR

A new method of production of neutral Kaons with known strangeness was proposed [22] by the CP–LEAR collaboration. The method is to stop antiprotons in a thin hydrogen gas target and measure the reactions

$$p\bar{p} \rightarrow \bar{K}^0K^+\pi^-$$

$$p\bar{p} \rightarrow K^0K^-\pi^+ \ ,$$

which have a branching ratio of $\approx 10^{-3}$. This is sufficiently large for CP- violation studies, if $2\cdot10^6$ stopping $\bar{p}$/sec from LEAR are available. The strangeness of the initial K^0 is tagged by the strangeness of the charged K. The asymmetry between K^0 and $\bar{K}^0$, proportional to the interference term in (21), can be used to measure the CP - violation parameters. The asymmetry

$$A_{+-} = \frac{R(K^0 \rightarrow \pi^+\pi^-) - R(\bar{K}^0 \rightarrow \pi^+\pi^-)}{R(K^0 \rightarrow \pi^+\pi^-) + R(\bar{K}^0 \rightarrow \pi^+\pi^-)} \qquad (25)$$

$$= 2\frac{|\eta_{+-}|\exp(-\gamma_S/2t)\cos(\Delta mt - \phi_{+-}}{\exp(-\gamma_S t) + |\eta_{+-}|^2\exp(-\gamma_L t)} - 2Re\,\epsilon \qquad (26)$$

shown in Fig.13 ,can be used to measure η_{+-},ϕ_{+-} and Δm. The corresponding asymmetry A_{00} is measured with somewhat larger errors ($0.5\tau_S$) on the vertex. A direct comparison of the fitted values of η_{+-} and η_{00} may therefore be limited by systematic errors. These can be avoided if one compares instead the time integrated rates. With

$$R = \int_0^T R(t)dt, \qquad T \approx 20\tau_S \qquad (27)$$

one obtains for the time integrated asymmetries:

$$I_{00} = 4Re\,\eta_{00} - 2Re\,\epsilon \qquad (28)$$

$$I_{+-} = 4Re\,\eta_{+-} - 2Re\,\epsilon \qquad (29)$$

$$\frac{I_{00}}{I_{+-}} = 1 - 6Re\,(\epsilon'/\epsilon). \qquad (30)$$

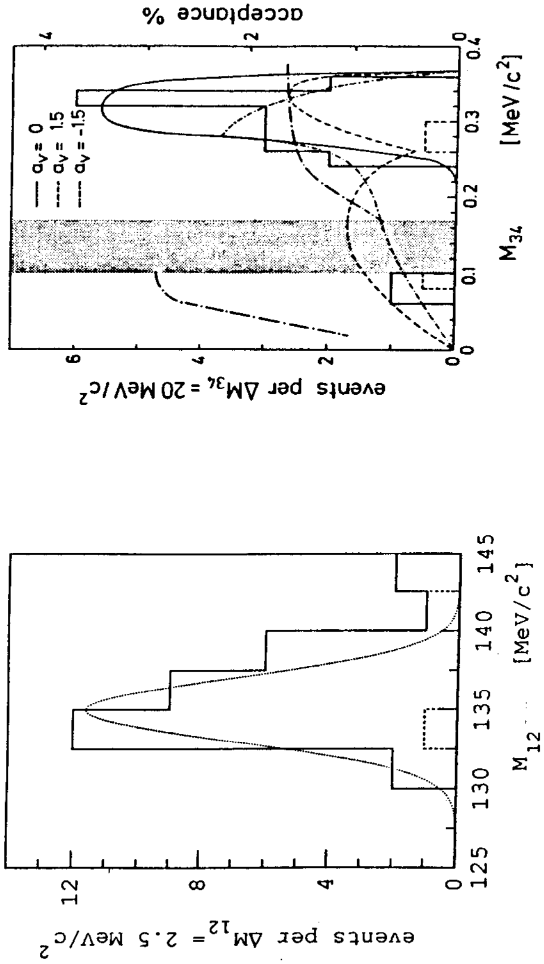

Fig.12 a) Invariant $m_{\gamma\gamma}$ distribution of π^0 candidates in $K_L \rightarrow \pi^0\gamma\gamma$.
b) Invariant mass of 3^{rd} and $4^{th}\gamma$ in $K_L \rightarrow \pi^0\gamma\gamma$ compared with various models. The acceptance is given by the wide dash- dotted line.

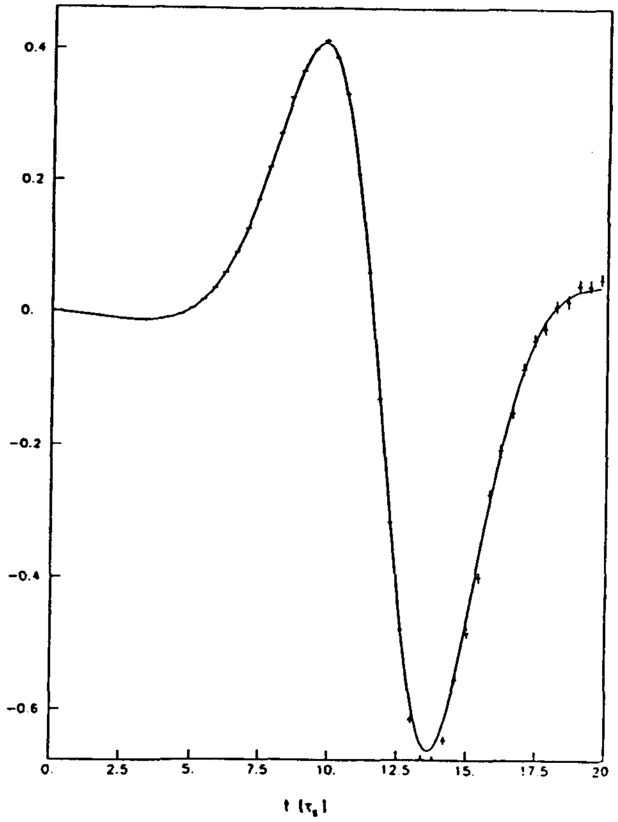

Fig.13 Expected asymmetry of $K \rightarrow \pi^+\pi^-$ decays in the CP -LEAR experiment.

Tab.3 Expected errors in CP- LEAR

	error	present value
η_{+-}	$3.5 \cdot 10^{-6}$	$(2.27 \pm 0.02) \cdot 10^{-3}$
η_{00}	$5 \cdot 10^{-6}$	$(2.26 \pm 0.02) \cdot 10^{-3}$
ϵ'/ϵ	$1.5 \cdot 10^{-3}$	$(2.1 \pm 1.0) \cdot 10^{-3}$
ϕ_{+-}	0.1^0	$(46.0 \pm 1.3)^0$
ϕ_{00}	0.17^0	$(47.5 \pm 2.2)^0$
Δm	$0.001 \cdot 10^{10}\hbar/s$	$(0.535 \pm 0.0022) \cdot 10^{10}\hbar/s$
η_{+-0}	$< 0.6 \cdot 10^{-3}$	< 0.12

In a cylindrical detector (see Figs.14 and 15) around the gas target charged particles are measured by tracking with drift chambers and identified by means of time of flight and liquid Cerenkov counters; photons are detected in a calorimeter made of lead plates interleaved with streamer tubes. The apparatus will be complete in the fall of 1990. A first look at the charged decays reveals a nice K^0 signal (Fig.16), with some background, which undoubtedly will be better understood as the analysis progresses.

The experiment should be ideally suited to look for the CPT- violating effect mentioned earlier, which implies a measurement of ϕ_{+-} and Δm. It will also be sensitive enough to observe CP- violation in the K_S system, by looking at $K_S \rightarrow \pi^+\pi^-\pi^0$. The expected statistical accuracies for a total exposure of $2 \cdot 10^{13}$ $\bar{p}$ are compared with the present values of the parameters in Tab.3.

Acknowledgements

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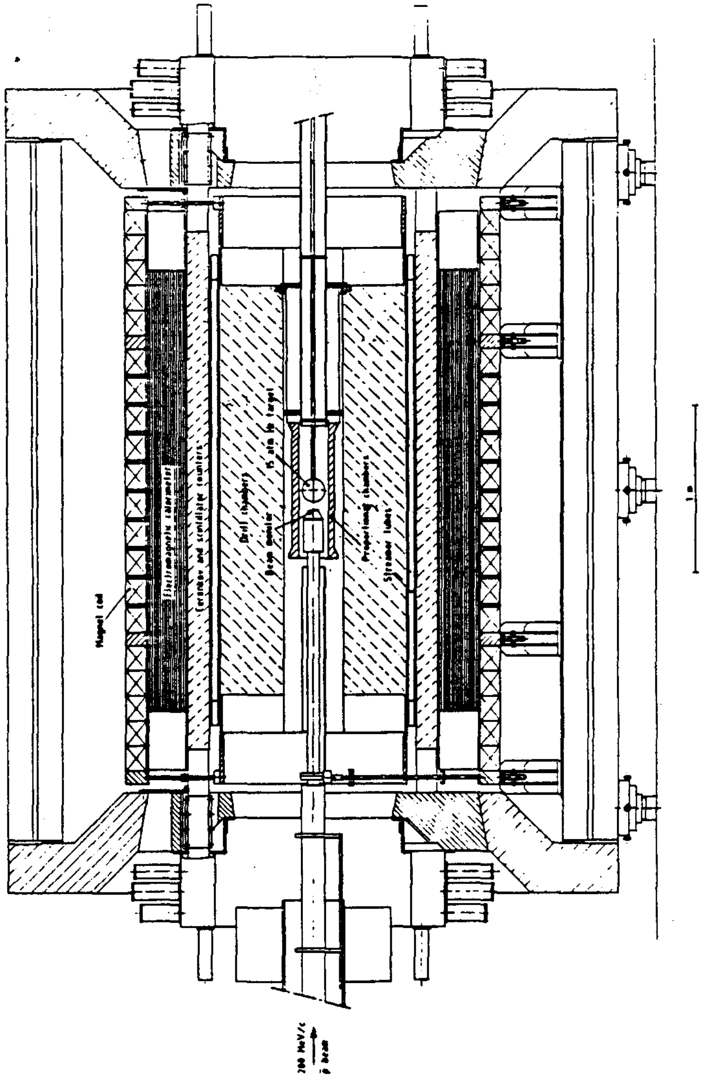

Fig.14 Side view of the CP-LEAR detector.

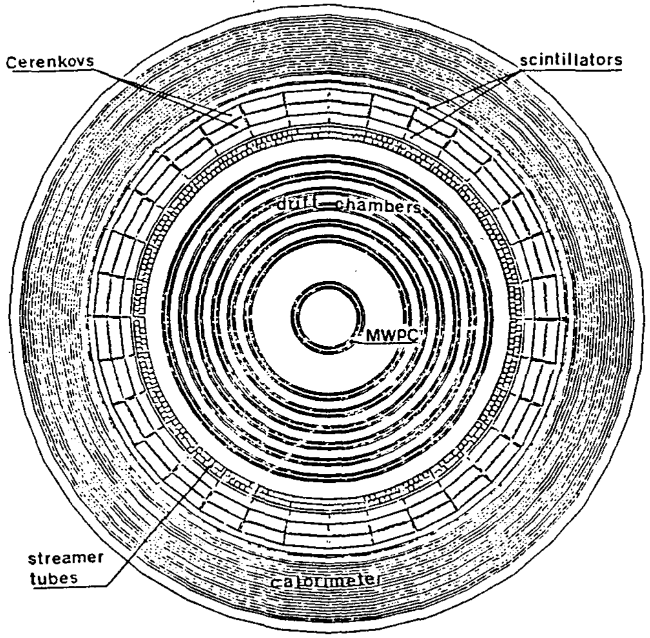

Fig.15 End view of the CP-LEAR detector.

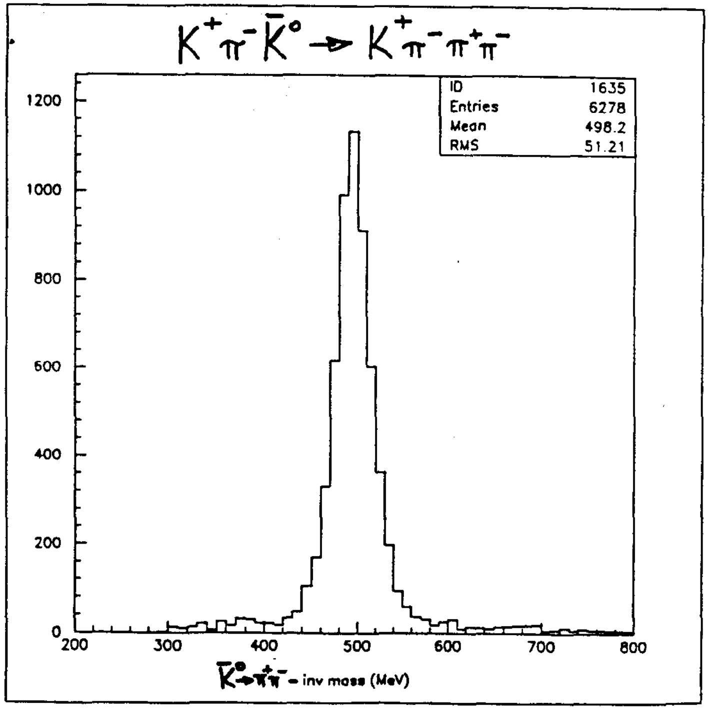

Fig.16 First signal of $K \to \pi^+\pi^-$ decays in CP-LEAR.

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