NEW RESULTS FROM THE KAON PHYSICS PROGRAM AT FERMILAB

presented by

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ABSTRACT

The status of the Fermilab's (E731) search for direct CP violation through a precision measurement of $Re(\epsilon'/\epsilon)$ is presented. Recent results from the recent rare decay test run are also presented, as well as plans for the newly approved kaon physics initiative at Fermilab, KTeV.

1 Introduction

CP violation has been observed now for nearly thirty years. Since the original startling observation,[1] very little new information has become available to further probe the origins of CP violation. The following general observations and conclusions can however be made[2]:

1) All CP violation phenomena now observed in the kaon system are consistent will a small amount of mixing between the K^0 and $\bar{K}^0$ mass eigenstates. The observed states, K_L^0 and K_S^0, then are mixtures of the CP eigenstates:

$$K_L = (K_2 + \epsilon K_1)/\sqrt{1+|\epsilon^2|}$$
$$K_S = (K_1 + \epsilon K_2)/\sqrt{1+|\epsilon^2|}\ .$$

The observed decay $K_L \rightarrow \pi\pi$ has two components: the small ($\epsilon = 0.2\%$) indirect CP conserving amplitude $K_1 \rightarrow \pi\pi$, and the direct CP violating amplitude $K_2 \rightarrow \pi\pi$. At this point there is no conclusive evidence for a direct component, which is at most $2 \times 10^{-3} \cdot \epsilon$.

2) The formalism of the Standard Model can accommodate both indirect and direct CP violation. It was recognized[3] in 1973 that the charged weak coupling matrix, V_{ij}, (CKM matrix) has one remaining non-trivial phase after all unitarity constraints are imposed. CP violation in the context of the Standard Model is then simply enabled through complex V_{ij} couplings, *i.e.*, $V_{ij} \neq V_{ij}^*$. It should be emphasized that although this formalism can conveniently parameterize CP violation, no insight is gained to the origin within the theory.

3) CP violation in the Standard Model must have its ultimate origin in the Higgs sector of the model. This is clear from the observation that without the mechanism of spontaneous symmetry breaking the model is gauge invariant, and hence one can arbitrarily rotate the phase of complex gauge-field/fermion couplings so that all such couplings are real, leaving the fundamental interactions of the unbroken theory manifestly CP conserving. Of course the true origin of CP violation may lie even beyond the Higgs sector, in the breaking of an ultimately left-right symmetric model for example.[4]

The Fermilab kaon physics program endeavors to gain further insight into the mechanism of CP violation by searching for evidence of direct CP violation in kaon decays. This program is searching for evidence on two fronts; through the precision study of $K \to \pi\pi$ decays (E731), and by search for decays that are likely to have large CP violating components in the decay amplitude such as $K_L \to \pi^0 e^+ e^-$, $K_L \to \pi^0 \mu^+ \mu^-$ and $K_L \to \pi^0 \nu\bar{\nu}$, (E799).

2 E731: Search for Direct CP Violation in $K \to \pi\pi$

The E731 method searches for small differences between the K_S and K_L neutral and charged decay rates by measuring the following double ratio:

$$R = \frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}$$

where:

$$R = |\frac{\eta_{00}}{\eta_{+-}}|^2 \cong 1 + 6|\frac{\epsilon'}{\epsilon}| \quad .$$

If the magnitude of CP violation is independent of the decay amplitude and hence the final state, then $\eta_{+-} = \eta_{00} = \epsilon$, $R = 1$, and $|\epsilon'/\epsilon| = 0$. Any finite value of $|\epsilon'/\epsilon|$ then is evidence for direct CP violation in $K \to \pi\pi$ decays. Standard Model expectations[2] suggest that $|\epsilon'/\epsilon|$ is on the order of 10^{-3}, with a significant dependence on the top quark mass. E731's experimental challenge, then, is to measure the double ratio R with a sensitivity better than 0.6%. Such sensitivity requires large statistical samples of the four $K \to \pi\pi$ decay modes, and control of systematic uncertainties to R on the order of 0.1%. During the 1987–1988 fixed target run at Fermilab, E731 collected the following statistics on the four decay modes:

$$N(K_L \to \pi^+\pi^-) = 327{,}006 \text{ events.}$$
$$N(K_L \to \pi^0\pi^0) = 410{,}043 \text{ events.}$$
$$N(K_S \to \pi^+\pi^-) = 1{,}060{,}687 \text{ events.}$$
$$N(K_S \to \pi^0\pi^0) = 800{,}037 \text{ events.}$$

This level of statistics leads to a statistical error of 5×10^{-4} on $|\epsilon'/\epsilon|$. With this level of statistics in hand, the experimental challenge is driven by the requirement to control systematic errors on the double ratio at the 0.1% level. The experiment was designed to minimize biases between collection and subsequent analysis of the final four decay modes. Figure 1 shows an elevation view of the detector. Two K_L beams are produced by an upstream collimation system that views a beryllium target struck by an 800 GeV proton beam. The detector starts 120 meters from target, allowing most of the produced K_S component to decay away. A K_S component is coherently added to one of the incident K_L beams with an active regenerator composed of 2.0 interaction lengths of B_4C. Since the K_S component is added coherently, the K_L and K_S interfere in their decays to the same 2π final state. The decay rate distribution downstream of the regenerator is:

$$\frac{dN}{d\tau} \propto |\rho|^2 e^{-\Gamma_S \tau} + |\eta|^2 e^{-\Gamma_L \tau} + 2|\rho| \cdot |\eta| cos(\Delta m \tau + \phi_\rho - \phi_\eta) e^{-\frac{(\Gamma_S + \Gamma_L)}{2}\tau} \qquad (1)$$

where Γ_L and Γ_S are the K_L and K_S lifetimes, Δm is the $K_S - K_L$ mass difference, ρ is the regeneration amplitude, ϕ_ρ is the regeneration phase, ϕ_η is the phase of η, and τ is the proper time of the decay with respect to the regenerator. $K \to \pi^+\pi^-$ decays are measured with a spectrometer system downstream of the decay volume composed of four drift chambers and a 200 MeV/c momentum kick magnet. The spatial resolution of the drift chambers is better than 100 μm/plane. The energy and position of the four $K \to \pi^0\pi^0$ photons are measured with a lead-glass calorimeter where the absolute energy scale is known to better than 0.2%, and where the resolution is $\delta E/E = 1.5\% + 5.0\%/\sqrt{E}(\text{GeV})$. A typical $K \to \pi^0\pi^0 \to 4\gamma$ event is shown in Figure 2. The principal contributions to the systematic uncertainty on the double ratio are the following:

1) Acceptance corrections between the K_L and the K_S beams. Since the lifetimes of K_L and K_S differ by a factor of ×500, a precise relative acceptance correction is required. The total size of the correction to the double ratio is 4.5%, and this correction is known to an absolute accuracy of 0.05%. This

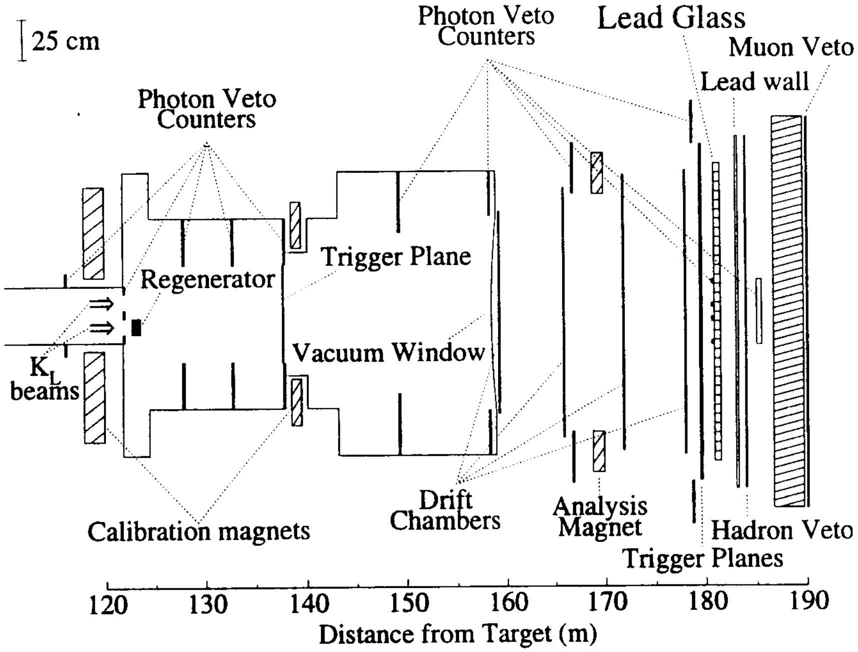


Figure 1. Elevation view of the E731 detector; note the different horizontal and vertical scales.

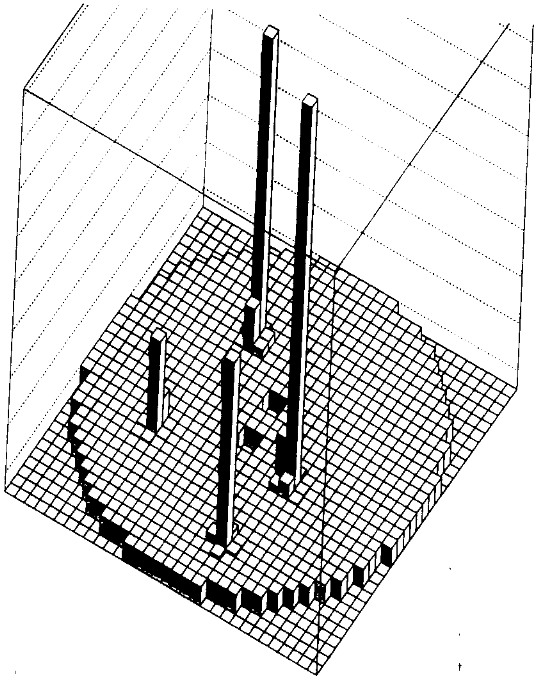


Figure 2. Distribution of photon clusters from a $K^0 \rightarrow 2\pi^0 \rightarrow 4\gamma$ event in the lead-glass electromagnetic calorimeter.

level of understanding is achieved by comparing Monte Carlo predictions to high statistics samples of CP conserving decays such as $K_L \rightarrow \pi^\pm e^\mp \nu$ and $K_L \rightarrow 3\pi^0$. Figure 3 demonstrates the agreement between the data and Monte Carlo for $K_L \rightarrow \pi^+\pi^-$, $K_L \rightarrow \pi^\pm e^\mp \nu$, and $K_L \rightarrow 3\pi^0$ decays. The residual uncertainty of acceptance understanding is extracted directly from the agreement between the Monte Carlo and the high statistics decay modes.

2) Differences in the background levels between the K_S and K_L beams. Although the background sources for each beam are small, at most 2–3%, their origins are completely different. The major background in the K_L beam is from $K_L \rightarrow 3\pi^0$ decay where two photons escape the detector or fuse together in the calorimeter. This background is kept below the 1.0% level by a hermetic photon veto system that surrounds the decay volume (see Figure 1). The other major source of background is from kaons that scatter into the K_L beam from the regenerator in the K_S beam. Due to the finite size of the beams, the transverse momentum of the parent kaon is not known in neutral mode decays, where only the center of energy is measured at the calorimeter. In contrast, the transverse momentum of charged decays can be measured, and is used to measure the amount of scattering at the regenerator. The size of this "crossover" background is 4.7%, and is known absolutely to the 0.1% level from charged decay measurements. Kaons incoherently scatter and stay in the regenerator beam as well, and the size of this background is 2.6% and is known absolutely at the 0.05% level. The center of energy distribution for neutral decays is shown in Figure 4.

3) Calibration and nonlinearities of the absolute energy scale. Any relative shift in the energy scale between neutral and charged decays corresponds to a systematic shift of $|\epsilon'/\epsilon|$. The neutral mode energy scale and nonlinearities can be measured by studying the agreement between the data and Monte Carlo reconstruction of the regenerator beam decay distribution. Figure 5 shows this comparison with and without an overall scale shift of 0.05%. From Figure 5 it is clear that the energy scale is understood to better than 0.05%.

Another powerful internal cross-check of the data and Monte Carlo is the extraction of the K_S lifetimes and mass difference from the decay distribution downstream of the regenerator (see Equation 1). Both Γ_S and Δm are extracted from charged and neutral decays separately, and together (see Figures 6 and 7). Extracted separately, Γ_S and Δm agree well between the neutral and charged data sets, and with the world averages.[5] Extracted together, Γ_S and Δm are determined better than the world average. These cross-checks and others allow excellent control over the systematic error in determining the double ratio.

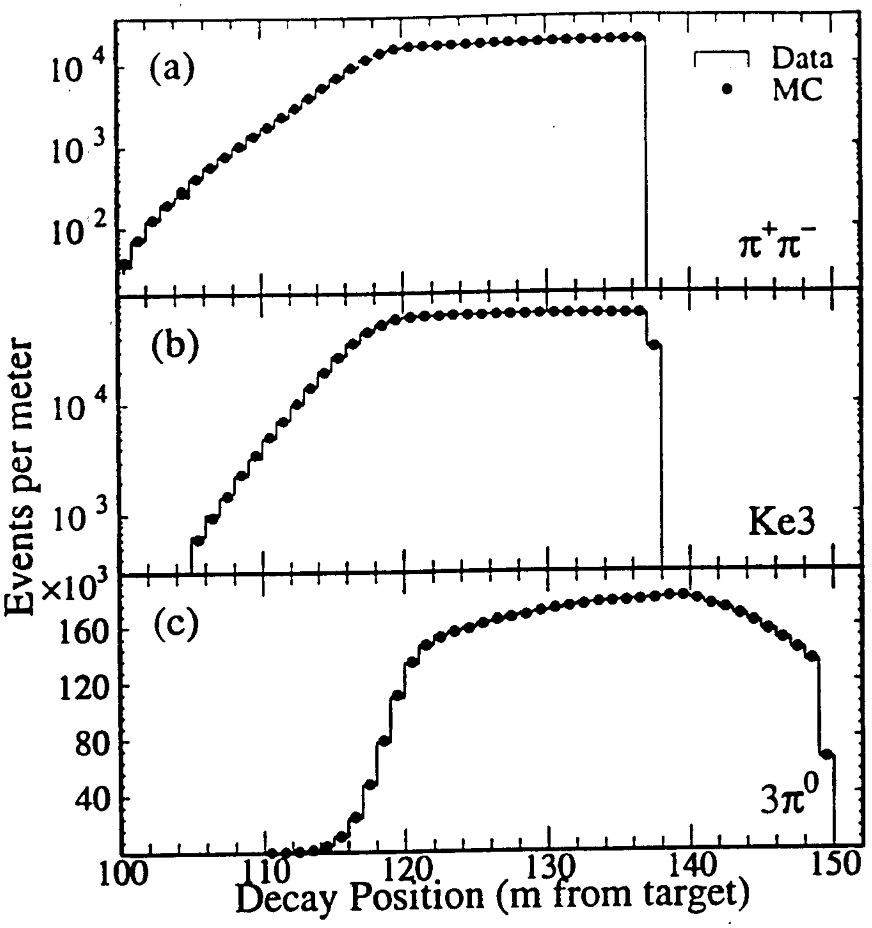


Figure 3. Decay vertex distributions of the (a) $K_L \rightarrow \pi^+\pi^-$, (b) $K_L \rightarrow \pi^\pm e^\mp \nu$, and (c) $K_L \rightarrow 3\pi^0$ data samples. Excellent agreement is seen between data and Monte Carlo for all three data sets.

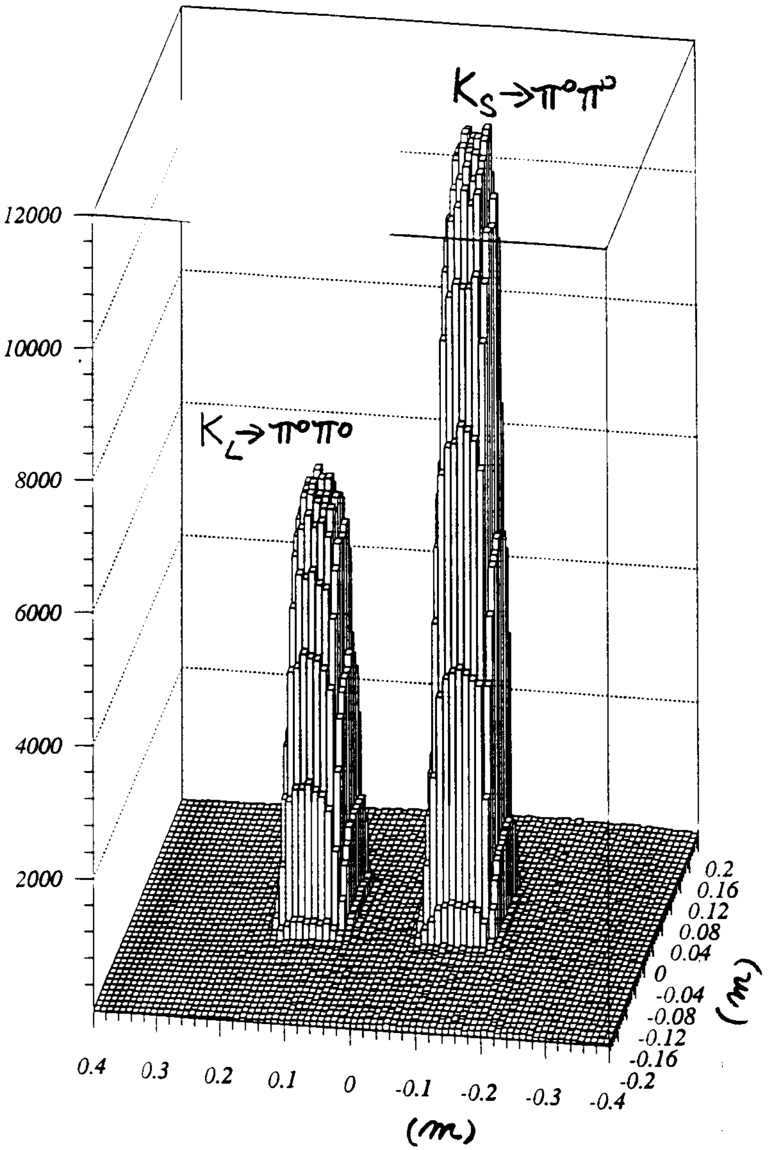
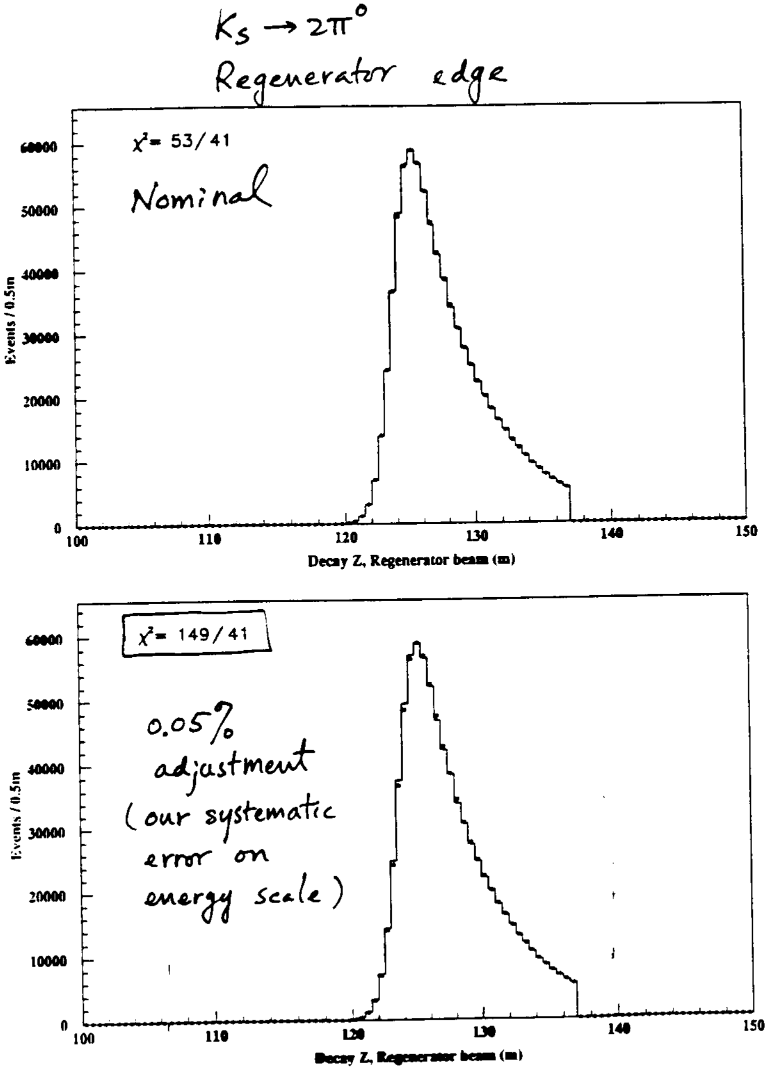


Figure 4. Reconstructed (x, y) position of $K^0 \to 2\pi^0$ decays projected to the regenerator z-plane.



$K_S \to 2\pi^0$
Regenerator edge

Nominal

0.05% adjustment (our systematic error on energy scale)

Figure 5. Reconstructed decay vertex position (Z) of $K_S^0 \to 2\pi^0 \to 4\gamma$ decays. The reconstructed position of the regenerator is a sensitive probe of the energy-scale understanding.

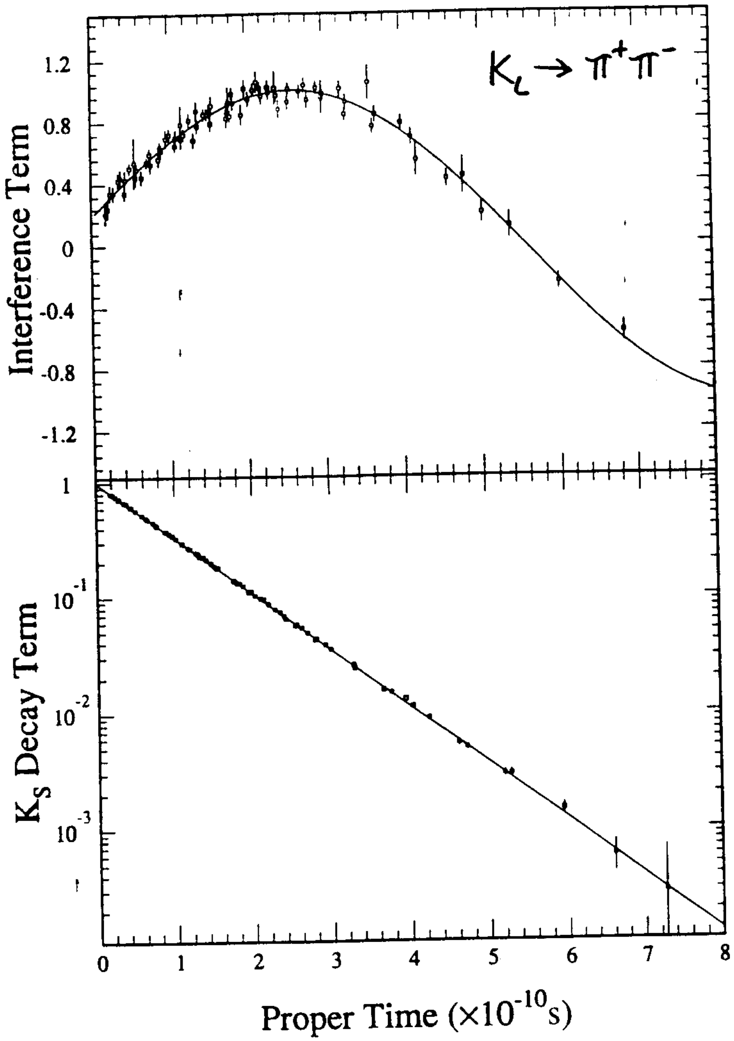


Figure 6. The $K_L - K_S$ interference and K_S components of $K^0 \to \pi^+\pi^-$ decay distribution downstream of the regenerator versus proper time.

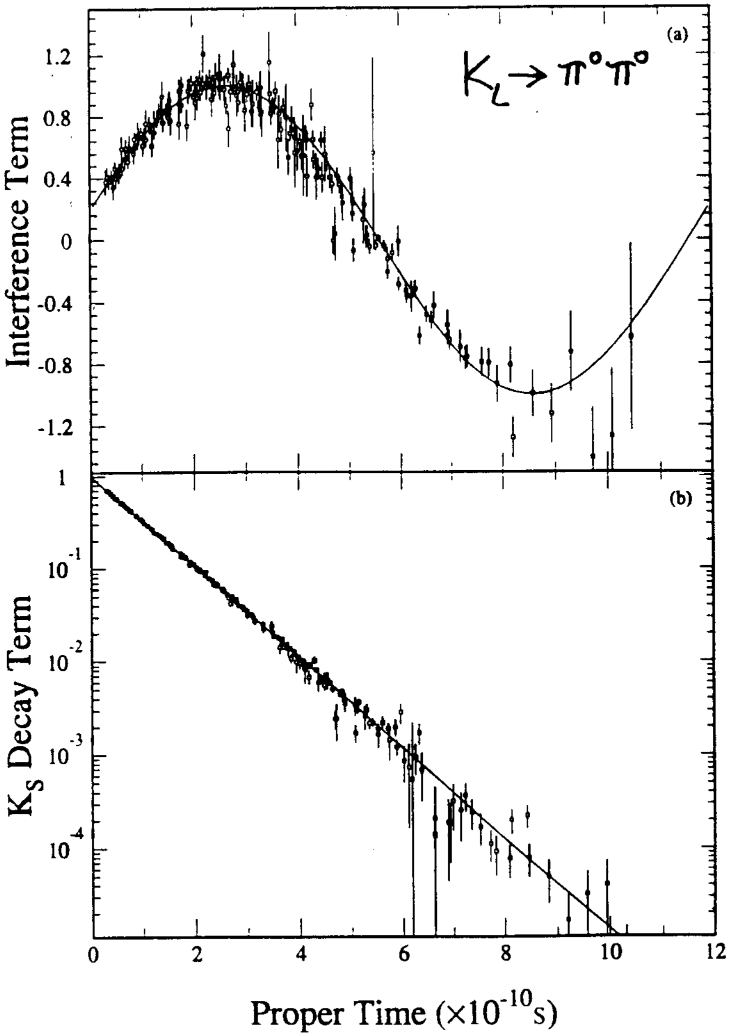


Figure 7. The $K_L - K_S$ interference and K_S components of $K^0 \to \pi^0\pi^0$ decay distribution downstream of the regenerator versus proper time.

Fitting for the double ratio and extracting $|\epsilon'/\epsilon|$, the E731 Collaboration reported the following *preliminary* measurement[6] at the 1991 Lepton Photon Conference in Geneva:

$$|\frac{\epsilon'}{\epsilon}| = (6.0 \pm 5.8(\text{Stat.}) \pm 3.2(\text{Sys.}) \pm 1.8(\text{Monte Carlo stat.})) \times 10^{-4}$$

which is consistent with *no direct CP violation.* The NA31 Collaboration reported[7] the following *preliminary* observation at the same conference:

$$|\frac{\epsilon'}{\epsilon}| = (23.0 \pm 7.0) \times 10^{-4}$$

which is a 3σ *observation of direct CP violation.*

Taken alone, each measurement leads to very different conclusions. Interpreted together, there is only a 2.1σ difference between the measurements, and there mean value is inconclusive in establishing an observation of direct CP violation in $K \rightarrow \pi\pi$ decays. Both collaborations expect to have finalized their analyses by the end of 1991. Both collaborations have proposed new experiments, each of which expect an order of magnitude increase in sensitivity. The new Fermilab effort,[8] KTeV, is proposed to run in the Fermilab 1995–1996 fixed target cycle, and the new CERN effort, NA48, is expected to start running late in 1994.

3 E799 Phase-I: Start of a New Rare Decay Program

The principal goal of the E799 experiment is to search for rare kaon decays that are likely[2] to have a large CP violating component in the decay amplitude. In contrast to $K_L \rightarrow \pi\pi$ decays where $|\epsilon'/\epsilon|$ is very small, decays such as $K_L \rightarrow \pi^0 e^+ e^-$ are expected[2] to have $|\epsilon'/\epsilon| \sim 1$. Unlike $K_L \rightarrow \pi\pi$ decays, the experimental challenge is to *find* examples of these decays, where the expected branching fraction is at the 10^{-11} level. The most recent measurements[9] limit this process to less than 5×10^{-9}. Phase-I of E799 will lower this limit into the 10^{-10} regime. Phase-II of E799 will push this limit near the range of the Standard Model expectations. Phase-II is part of the KTeV proposal, and will run in the 1995–1996 Fermilab fixed target running cycle.

Phase-I of E799 finished collecting data in January of 1992, and has finished the first pass data analysis. Detailed analyses are now underway. The E799 apparatus inherited a large acceptance for four-body modes, excellent charged tracking, and electromagnetic calorimetry from the proceeding E731 experiment. The detector was upgraded with a higher bandwidth data acquisition system and more flexible and powerful trigger system. The E799 experiment ran twelve physics triggers in parallel to address a broad range of rare kaon decay physics besides $K_L \rightarrow \pi^0 e^+ e^-$. In two months of physics running the E799 experiment collected 400 million physics triggers and wrote one Terabyte of data to tape. The rare decay physics that E799 can address by either measuring for the first time or setting significantly better limits now follows:

1) Decays that are likely to have a large CP violating component:

$$K_L^0 \rightarrow \pi^0 e^+ e^-$$

$$K_L^0 \rightarrow \pi^0 \mu^+ \mu^-$$

$$K_L^0 \rightarrow \pi^0 \nu\bar{\nu}\ ,\ (\pi^0 \rightarrow e^+ e^- \gamma)\ .$$

2) Rare π^0 decays through the copious CP conserving decay $K_L \rightarrow 3\pi^0$:

$$\pi^0 \rightarrow e^+ e^-\ ,\pi^0 \rightarrow e^+ e^- \gamma\ ,\pi^0 \rightarrow e^+ e^- \gamma\gamma\ ,\pi^0 \rightarrow e^+ e^- e^+ e^-\ .$$

3) Decays that probe the radiative structure of the kaon:

$$K_L^0 \rightarrow \gamma\gamma$$

$$K_L^0 \rightarrow \mu^+ \mu^- \gamma$$

$$K_L^0 \rightarrow e^+ e^- \mu^+ \mu^-$$

$$K_L^0 \rightarrow e^+ e^- e^+ e^-$$

$$K_L^0 \rightarrow \pi^+ \pi^- e^+ e^-\ .$$

4) Lepton number violating decays:

$$K_L^0 \rightarrow \pi^0 \mu^+ e^-$$

$$K_L^0 \rightarrow 3\pi^0 \; , \; \pi^0 \rightarrow \mu^+ e^- \; .$$

Examples of the physics reach of E799 Phase-I are shown in Figures 8 and 9. Figure 8 shows the first clear observation of the muonic Dalitz decay in the kaon system ($K_L \rightarrow \mu^+\mu^-\gamma$). This data shown represents 20% of the full data set. The only previous existing data on this mode is one candidate event.[10] Analysis of the full data set will allow a clean observation of the high-mass structure of the radiative K_L decay. Figure 9 shows a sample of approximately 800 π^0 double Dalitz decays ($\pi^0 \rightarrow e^+e^-e^+e^-$) which opens a new window to the radiative structure of the π^0. The previous world sample of double Dalitz decay is 116 events from bubble chamber photographs. This sample of π^0 double Dalitz decay requires the reconstruction of eight electromagnetic clusters in the lead-glass array, which contests to the high acceptance of E799 for many particle rare decay modes.

As the detailed analyses of E799 unfold, many rare decay modes will be measured for the first time, and it is possible that another clue to the CP violation enigma may be uncovered through the measurement of rare decay modes which are manifestly CP violating. The search for CP violation at Fermilab will be carried on at Fermilab through KTeV, which will increase the sensitivity to $|\epsilon'/\epsilon|$ by nearly an order of magnitude, and will increase the rare decay sensitivity by a factor of ×25. This increase in sensitivity will be achieved through:

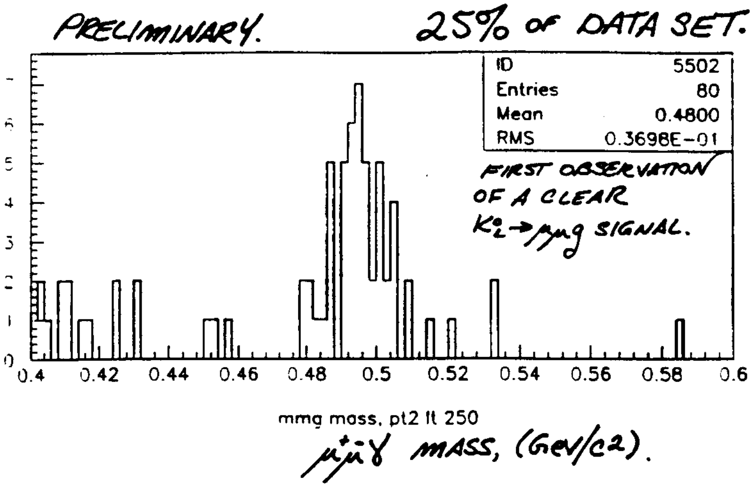
1) ×3.5 increase in proton intensity of target.

2) ×3.0 increase in running time.

3) ×1.4 increase in live time, 50% → 70%.

4) ×1.8 increase in acceptance through the use of CsI calorimetry and few accidental losses due to better secondary beam design.

Standard Model expectations[2] suggest that the KTeV will likely observe direct CP violation through the avenue of $|\epsilon'/\epsilon|$ measurements. In addition KTeV will complete the rare kaon decay program initiated through phase-I of E799.

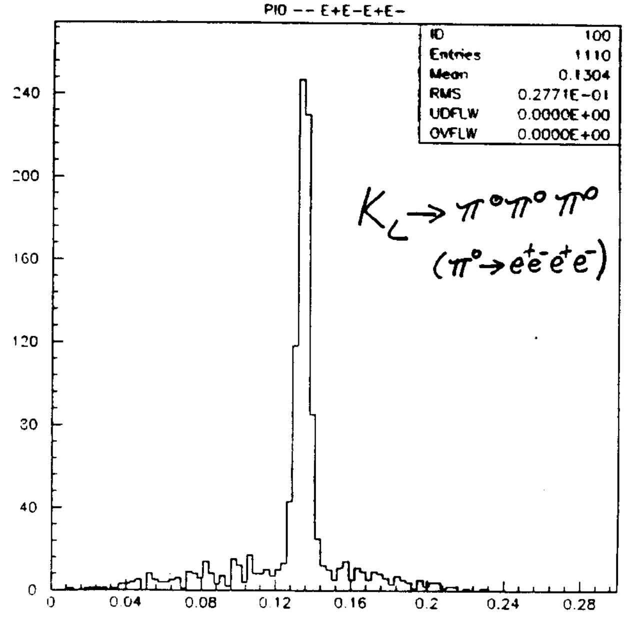

PRELIMINARY.

25% OF DATA SET.

FIRST OBSERVATION OF A CLEAR $K_L^0 \rightarrow \mu\mu g$ SIGNAL.

$\mu^+\mu^-\gamma$ MASS, (GeV/c2).

Figure 8. *Preliminary* mass distribution of $K_L \rightarrow \mu^+\mu^-\gamma$ candidates observed in 25% of the E799 data set.


$K_L \rightarrow \pi^0\pi^0\pi^0$

$(\pi^0 \rightarrow e^+e^-e^+e^-)$

Figure 9. *Preliminary* mass distribution of $K_L \rightarrow 3\pi^0, \pi^0 \rightarrow e^+e^-e^+e^-$ events observed in the full E799 data set.

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[7] See A. C. Schaffer (NA31 Collaboration), to appear in the *Proceedings of the APS Division of Particles and Fields Meeting, Vancouver, Canada, August 1991.*

[8] See Fermilab report FN-580 for a conceptual design of the KTeV experiment.

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