CP Violation and Rare Decays

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Experimental studies of rare and CP violating kaon decays are described. Searches for CP violation in other particle systems are discussed briefly.

I. INTRODUCTION

The origin of CP violation is one of the fundamental questions of particle physics. Currently, we know of only two distinct examples of CP violation: the matter-antimatter asymmetry in the universe and CP violation in the neutral kaon system. Although there are several manifestations of CP violation in the neutral kaon system, all of them (with the possible exception of the measurements of ϵ'/ϵ which will be discussed below) can be explained by asymmetric $K_0 - \overline{K_0}$ mixing. This mixing results in the K_L and K_S being states of mixed CP, and is referred to as indirect CP violation. The parameter ϵ, which is used to parameterize this effect, quantifies the CP impurity of the K_L and K_S states:

$$K_S \sim K_{\rm even} + \epsilon K_{\rm odd}$$
$$K_L \sim K_{\rm odd} + \epsilon K_{even},$$

where $|\epsilon| = 2.28 \times 10^{-3}$, $CP|K_{\rm even}>= +1|K_{\rm even}>$, and $CP|K_{\rm odd}>= -1|K_{\rm odd}>$.

In the Standard Model, all CP violation comes from a single complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1], which in the Wolfenstein approximation [2] may be written as

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}.$$

In addition to the indirect CP violation described above, the Standard Model predicts "direct" CP violation, in which CP is violated in the decay amplitude (*e.g.*, $K_{\rm odd} \to \pi\pi$). Other models, such as the Superweak Model of Wolfenstein [3], predict no direct CP violating effects. The Standard Model also predicts CP violation in other particle systems. In particular, the B system is predicted to have large CP violating effects.

Our current understanding of CP violation leaves several unresolved questions:

- Is CP violation unique to the K meson system?
- Does direct CP violation occur?
- Is the Standard (CKM) Model the correct description of CP violation?
- What is the connection (if any) between CP violation in elementary particles and the matter-antimatter asymmetry in the universe?

The first three of these questions are the focus of several current and future experiments. These questions and some related topics will be discussed in the following sections. The last question, while probably the most intriguing, will not be addressed in this paper.

II. DIRECT CP VIOLATION IN $K \to \pi\pi$: ϵ'/ϵ

Since the discovery of CP violation in the $K_{\rm L} \to \pi^+\pi^-$ decay mode [4], searches for direct CP violation have been performed using $K \to 2\pi$ decays. The ratio ϵ'/ϵ can be determined from the double ratio of the 2-pion decay rates of

K_L and K_S:

$$1 + 6\mathrm{Re}(\epsilon'/\epsilon) \sim \frac{,\ (K_L \to \pi^+\pi^-)/,\ (K_S \to \pi^+\pi^-)}{,\ (K_L \to \pi^0\pi^0)/,\ (K_S \to \pi^0\pi^0)}.$$

$\epsilon'/\epsilon \neq 0$ is an unambiguous indication of direct CP violation. As mentioned above, direct CP violation occurs in the Standard Model. Unfortunately, calculations of $Re(\epsilon'/\epsilon)$ depend sensitively on input parameters and on the method used to calculate hadronic matrix elements, resulting in a large uncertainty in the predicted value of ϵ'/ϵ. Most recent Standard Model predictions are in the range $Re(\epsilon'/\epsilon) = (0 - 20) \times 10^{-4}$ [7].

The two best previous measurements of ϵ'/ϵ come from E731 at Fermilab [5] and NA31 at CERN [6]:

$$\mathrm{Re}(\epsilon'/\epsilon) = (7.4 \pm 5.9) \times 10^{-4} \text{ (E731)}$$
$$\mathrm{Re}(\epsilon'/\epsilon) = (23 \pm 6.5) \times 10^{-4} \text{ (NA31)}.$$

The CERN result is 3.5 standard deviations from zero, while the Fermilab result is only 1 sigma from zero.

To clarify the current experimental situation and definitively resolve the question of whether or not direct CP violation occurs, three groups are attempting to measure ϵ'/ϵ at the $1 - 2 \times 10^{-4}$ level. The Fermilab and CERN groups have built new detectors and beamlines (called KTeV and NA48, respectively) designed to improve significantly on their previous experiments. An experiment called KLOE at Frascati is trying a completely new technique using an $e^+e^- \to \phi$ collider.

The KTeV (Fig. 1) and NA48 (Fig. 2) experiments are quite similar. Both experiments collect all 4 decay modes simultaneously using two beams – one for K_{L} decays and one for K_{S} decays. Each detector includes a long, evacuated decay region, followed by a charged spectrometer and a very precise electromagnetic calorimeter. The KTeV calorimeter uses pure CsI crystals and NA48 uses liquid krypton. Both calorimeters have excellent energy and position resolution; the average energy resolution is better than 1% and the average position resolution is about 1mm for both experiments. The performance of these calorimeters is crucial to the success of the experiments because the reconstructed position of decays along the beamline depends directly on the energy scale of the calorimeter. The excellent energy resolution also reduces background for both the $\pi^+\pi^-$ and $\pi^0\pi^0$ decay modes.

The principal difference between KTeV and NA48 is the method used to produce K_{S} decays. KTeV, like E731, uses a thick regenerator in one of the two beams to produce a K_{S} component through coherent regeneration. The KTeV regenerator is fully active to reduce the background from inelastic interactions. NA48 transports a small part of the primary proton beam past the primary (K_{L}) target to a secondary (K_{S}) target close to the experiment. A time coincidence between the detector (*e.g.*, the calorimeter for the $K \to 2\pi^0$ decay mode) and a counter placed in the proton beam upstream of the K_{S} target is used to identify K_{S} decays.

The difference between the K_{L} and K_{S} lifetimes means that the distribution of decay positions along the beam (z) direction will be very different for the K_{L} and K_{S} decays which must be compared to extract ϵ'/ϵ. Figure 3 shows z distributions from KTeV for the 4 decay modes. KTeV corrects for the variation in detector acceptance as a function of z with a Monte Carlo simulation. The quality of the simulation is studied using distributions from both the 2π decays, as well as higher statistics $K_{\mathrm{L}} \to 3\pi^0$, $K_{\mathrm{L}} \to \pi^+\pi^-\pi^0$, and $K_{\mathrm{L}} \to \pi e \nu$ decays. NA48 greatly reduces the necessary acceptance correction by reweighting K_{L} decays to have the same z distribution as K_{S} decays (see Fig. 4). The drawback of the reweighting procedure is that it increases the statistical uncertainty in the result by about a factor of 2.

Both KTeV and NA48 already have collected substantial data sets and are in the final stages of analyzing the first parts of those data sets. KTeV plans to present results of the analysis of the first quarter of their data sample during the next few months. Figure 5 shows invariant mass plots for the $K \to \pi\pi$ decay modes from this sample. NA48 also plans to present an ϵ'/ϵ result based on their 1997 data sample during the next few months. The expected statistical errors for these analyses are given in Table I.

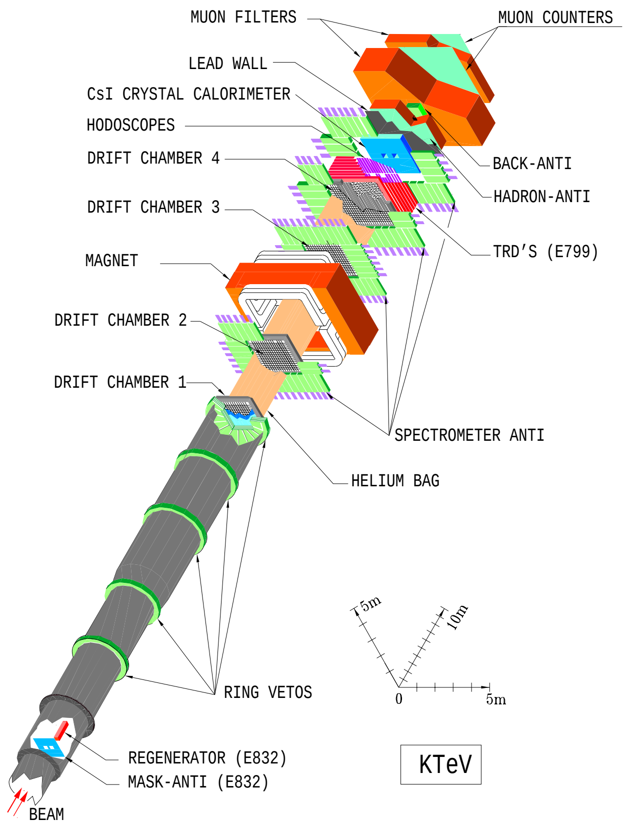

FIG. 1. Diagram of the KTeV detector.

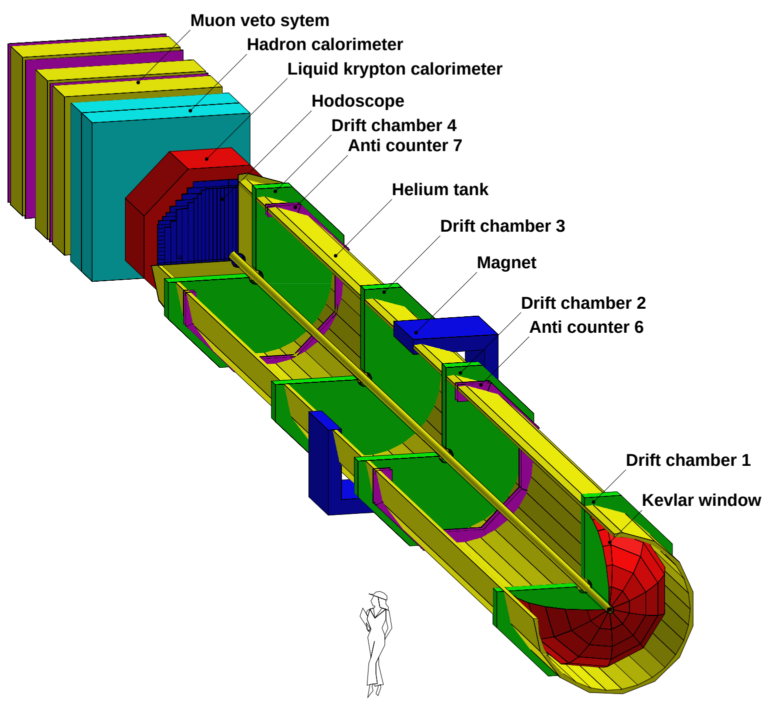

FIG. 2. Diagram of the NA48 detector.

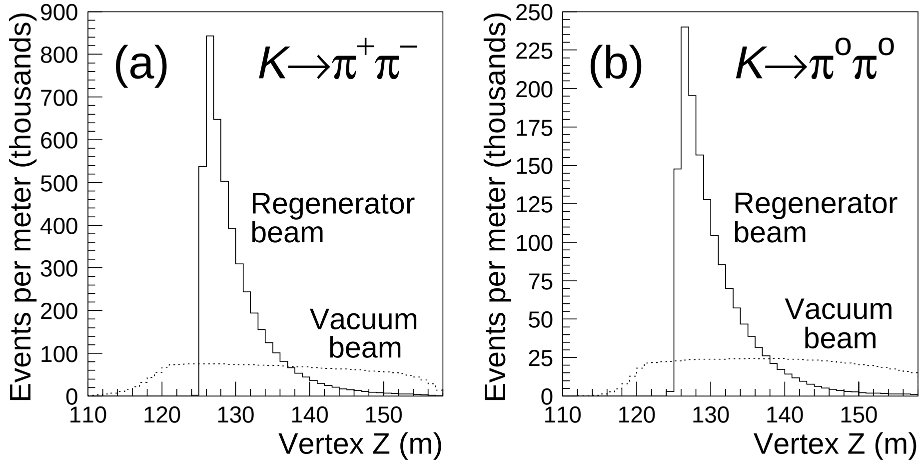

FIG. 3. Decay vertex distributions from KTeV for (a) $K \to \pi^+\pi^-$ and (b) $K \to \pi^0\pi^0$ decays, showing the difference between the "regenerator" (K_S) and "vacuum" (K_L) beams.

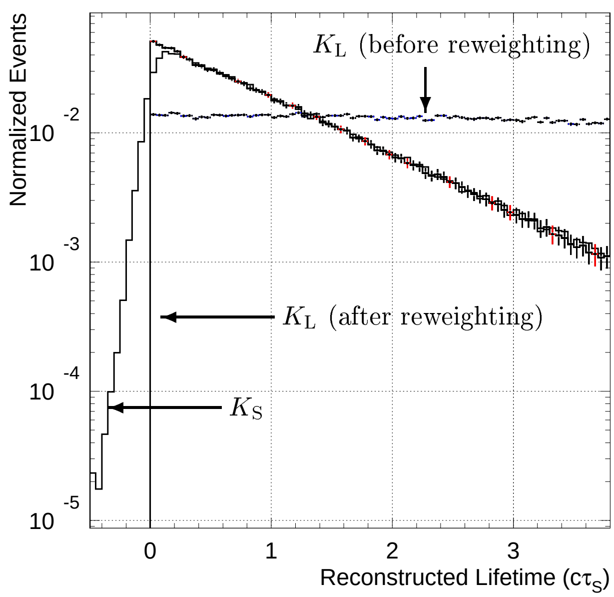

FIG. 4. Decay vertex distributions from NA48 for $K \to \pi\pi$ before and after lifetime reweighting.

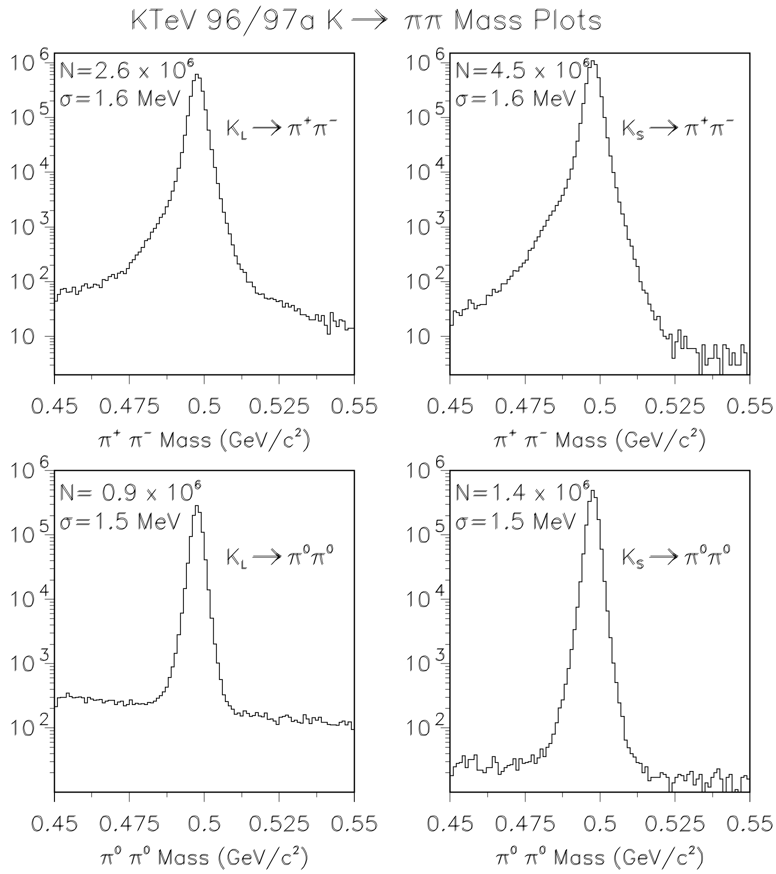

FIG. 5. $K \to \pi\pi$ invariant-mass plots from the first quarter of KTeV's 1996-1997 data sample.

The KLOE experiment at Frascati will use an e^+e^- collider (DAΦNE) at the ϕ resonance to produce large numbers of $K_{\rm L}K_{\rm S}$ pairs. At a luminosity of $5 \times 10^{32}{\rm cm}^{-2}{\rm s}^{-1}$, the large cross section of $\sigma(e^+e^- \to \phi) = 4.4$ μbarn results in $\sim 0.75 \times 10^{10}$ $K_{\rm L}K_{\rm S}$ pairs per year. KLOE is a 4π detector with a very large radius (*e.g.*, the central drift chamber has a radius of 2m) to achieve good efficiency for $K_{\rm L}$ and $K_{\rm S}$ decays. The experiment tags $K_{\rm S}$ and $K_{\rm L}$ using the dominant decay modes and can then study decays of the other kaon in the event. In addition to measuring ϵ'/ϵ, the KLOE program includes many unique CPT tests and $K_{\rm S}$ physics.

The KLOE experiment currently is installed on the beam line and expects to be ready for beam at the end of February 1999. They plan several months of operation during 1999 at about 10% of the design luminosity.

Table I summarizes the projected statistical errors on ϵ'/ϵ from the three groups for the next few years.

TABLE I. Projected statistical errors on ϵ'/ϵ in units of 10^{-4}

	KTeV	NA48	KLOE
Results planned for Winter/Spring 99	3	4-5	–
Using all current data	1.4	2.3	–
Using all data expected by 1/00	0.9	1.6[a]	10

III. DIRECT CP VIOLATION IN RARE K DECAYS

A. $K_{\rm L} \to \pi^0 \nu \overline{\nu}$

The same electroweak penguin diagrams that interfere destructively with gluonic penguin diagrams to make ϵ' so small also contribute to rare decays, providing another possibility of detecting direct CP violation. The clearest of these decay modes is $K_L \to \pi^0 \nu \overline{\nu}$, which is essentially pure direct CP violation. In the Standard Model, the branching ratio is

$$B(K_L \to \pi^0 \nu \overline{\nu}) = 8 \times 10^{-11} (\frac{m_t}{m_W})^{2.2} A^4 \eta^2 \sim 3 \times 10^{-11}.$$

The theoretical uncertainty in extracting η (the phase of the CKM matrix in the Wolfenstein parameterization [2]) from the branching ratio is at the 1% level [8].

Unfortunately, this decay mode is extremely difficult to isolate experimentally. The signature is a single π^0 with transverse momentum. The backgrounds include $K_{\rm L} \to \pi^0 \pi^0$ or $K_{\rm L} \to \pi^0 \pi^0 \pi^0$ where the photons from all but one π^0 escape detection, $\Lambda \to n \pi^0$, where the n is not detected, and neutron interactions in detector material.

KTeV has searched for this decay mode using both the $\pi^0 \to \gamma\gamma$ and $\pi^0 \to e^+ e^- \gamma$ decay modes. The Dalitz decay ($\pi^0 \to e^+ e^- \gamma$) allows a better reconstruction of the final state but suffers from a low branching ratio. The $\pi^0 \to \gamma\gamma$ analysis is based on 12 hours of data taken with a single, narrow beam, while the $\pi^0 \to e^+ e^- \gamma$ analysis uses all of the data from the experiment's rare decay running (E799). KTeV sets the following limits at 90% confidence level:

$$B(K_{\rm L} \to \pi^0 \nu \overline{\nu}) < 1.6 \times 10^{-6} \text{ using } \pi^0 \to \gamma\gamma \text{ [9]}$$
$$B(K_{\rm L} \to \pi^0 \nu \overline{\nu}) < 5.9 \times 10^{-7} \text{ using } \pi^0 \to e^+ e^- \gamma \text{ [10]}$$

The best limit on this decay mode is still more than 4 orders of magnitude from the Standard Model prediction.[1] In spite of the obvious difficulty/challenge in detecting $K_{\rm L} \to \pi^0 \nu \overline{\nu}$, three groups have submitted letters of intent or proposals to measure this decay mode: E926 at Brookhaven [12], KAMI at Fermilab [13], and E391 at KEK [14].

B. $K_{\rm L} \to \pi^0 e^+ e^-$

Since the $K_{\rm L} \to \pi^0 \nu \nu$ experimental signature is so challenging (at least with current detectors), another approach is to consider decays with two electrons (or muons) instead of neutrinos. Although the experimental signature is clearer, there are other problems. In addition to a new background ($K_L \to ee\gamma\gamma$), this mode is no longer pure direct CP violation. In addition to the direct CP violating contribution, which is expected to be about 5×10^{-12} [15], there is an indirect CP violating contribution and a CP conserving contribution. The indirect CP violating contribution can be determined by measuring $K_S \to \pi^0 e^+ e^-$. This mode has not yet been observed, but should be measured by KLOE. The expected indirect CP violating branching ratio of $K_L \to \pi^0 e^+ e^-$ is $1 - 5 \times 10^{-12}$ [16]. The CP conserving contribution, which proceeds via a two photon intermediate state, can be estimated from measurements of $K_L \to \pi^0 \gamma\gamma$. KTeV's recent measurement of this mode (see Fig. 6) corresponds to a CP conserving $K_L \to \pi^0 e^+ e^-$ branching ratio of $1 - 2 \times 10^{-12}$ [17].

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[1] Grossman and Nir [11] have pointed out that isospin relations may be used to place a more restrictive upper limit on this decay mode based on the $K^+ \to \pi^+ \nu \overline{\nu}$ decay:

$$B(K_L \to \pi^0 \nu \overline{\nu}) < \frac{\tau(K_L)}{\tau(K^+)} B(K^+ \to \pi^+ \nu \overline{\nu}) < 7 \times 10^{-9}.$$

The best current limit on $K_L \to \pi^0 e^+ e^-$ comes from E799I [18], the predecessor to KTeV: $B(K_L \to \pi^0 e^+ e^-) < 4.3 \times 10^{-9}$. Including data from 1997 and the upcoming 1999 run, KTeV expects to have a single event sensitivity of $\sim 2.5 \times 10^{-11}$ for this decay.

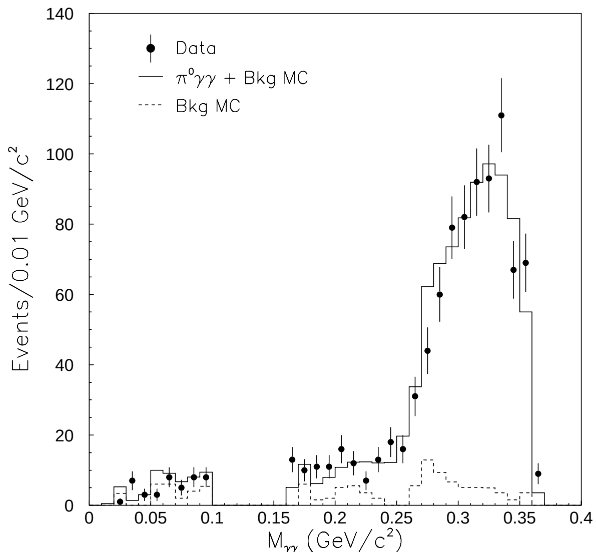

FIG. 6. $\gamma\gamma$ invariant mass plot for $K_L \to \pi^0\gamma\gamma$ candidates from KTeV. The corresponding branching ratio is $B(K_L \to \pi^0\gamma\gamma) = (1.76 \pm 0.06 \pm 0.08) \times 10^{-6}$ [17].

IV. CP/T VIOLATION

KTeV recently has presented evidence for a new manifestation of indirect CP violation in the decay $K_L \to \pi^+\pi^- e^+ e^-$. This decay proceeds via an intermediate $\pi^+\pi^-\gamma^*$ state with two significant amplitudes: an inner Bremsstrahlung amplitude which is CP violating and a direct emission amplitude which is CP conserving. KTeV presented a new study of the $K_L \to \pi^+\pi^-\gamma$ decay at this conference [19]. Figure 7 shows the photon energy in the center of mass for $K_L \to \pi^+\pi^-\gamma$ events; the inner Bremsstrahlung and direct emission components of the spectrum are indicated. The interference between these two amplitudes leads to a CP violating polarization in the photon. This polarization can be detected in $K_L \to \pi^+\pi^- e^+ e^-$ decays, where the γ has converted internally to e^+e^- pair. Defining ϕ as the angle between the normals to the $\pi^+\pi^-$ and e^+e^- planes measured in the K_L center of mass frame,

$$\frac{d,}{d\phi} = ,_1 \cos^2\phi + ,_2 \sin^2\phi + ,_3 \sin\phi\cos\phi.$$

The last term is odd under both CP and T.

Figure 8 shows the invariant-mass spectrum for $K_L \to \pi^+\pi^- e^+ e^-$ candidates. KTeV has measured a branching ratio of $B(K_L \to \pi^+\pi^- e^+ e^-) = (3.32 \pm 0.14 \pm 0.28) \times 10^{-7}$ [20]. Figure 9 shows the distribution of the angle between the e^+e^- and $\pi^+\pi^-$ planes. The measured asymmetry is

$$A = \frac{N(\sin\phi\cos\phi > 0) - N(\sin\phi\cos\phi < 0)}{N(\sin\phi\cos\phi > 0) + N(\sin\phi\cos\phi < 0)} = (14.6 \pm 2.3 \pm 1.1)\%.$$

This asymmetry is explicitly CP violating. There has been some debate about whether or not an asymmetry in this T-odd variable also constitutes direct observation of T violation. The issues that have been raised include:

- Final state interactions. $\sin\phi\cos\phi$ is odd under T and CP. Since final state interactions cannot cause an asymmetry which is CP odd, the observed asymmetry in $\sin\phi\cos\phi$ cannot be the result of final state interactions.

- Exchange of initial and final states. Since the initial and final states are not exchanged in the $K_L \to \pi^+\pi^- e^+ e^-$ analysis, it has been argued that additional assumptions are required to identify this effect as T violation unambiguously [21].

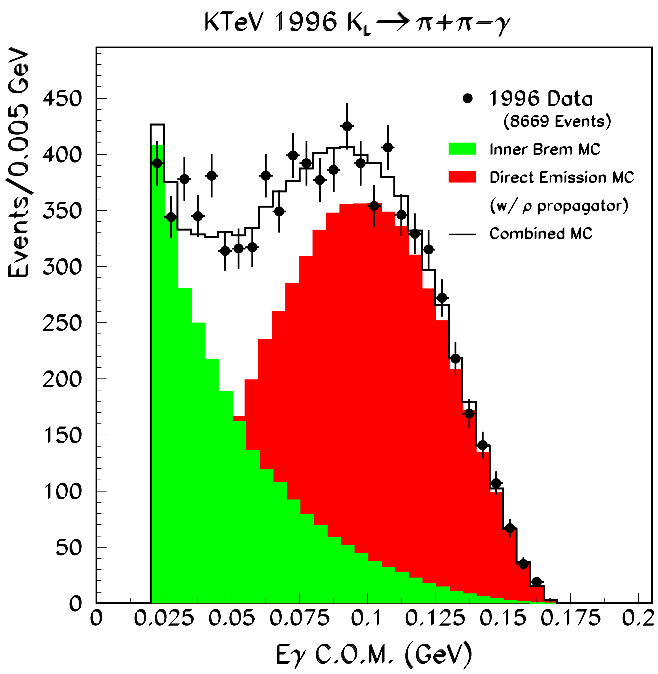

FIG. 7. Gamma energy in center-of mass frame in $K_{\rm L} \rightarrow \pi^+\pi^-\gamma$ events from KTeV. The contributions from the CP conserving direct emission amplitude and from the CP violating inner Bremsstrahlung amplitude are shown.

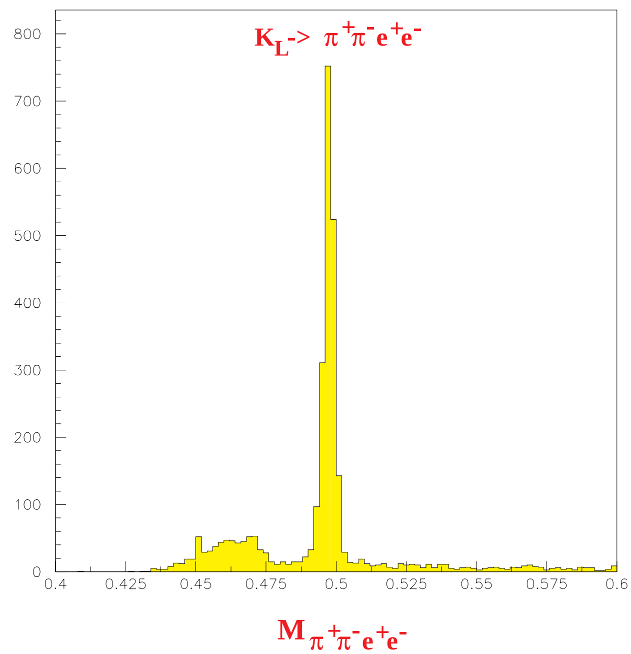

FIG. 8. $\pi^+\pi^-e^+e^-$ mass for $K_{\rm L} \rightarrow \pi^+\pi^-e^+e^-$ candidates from KTeV.

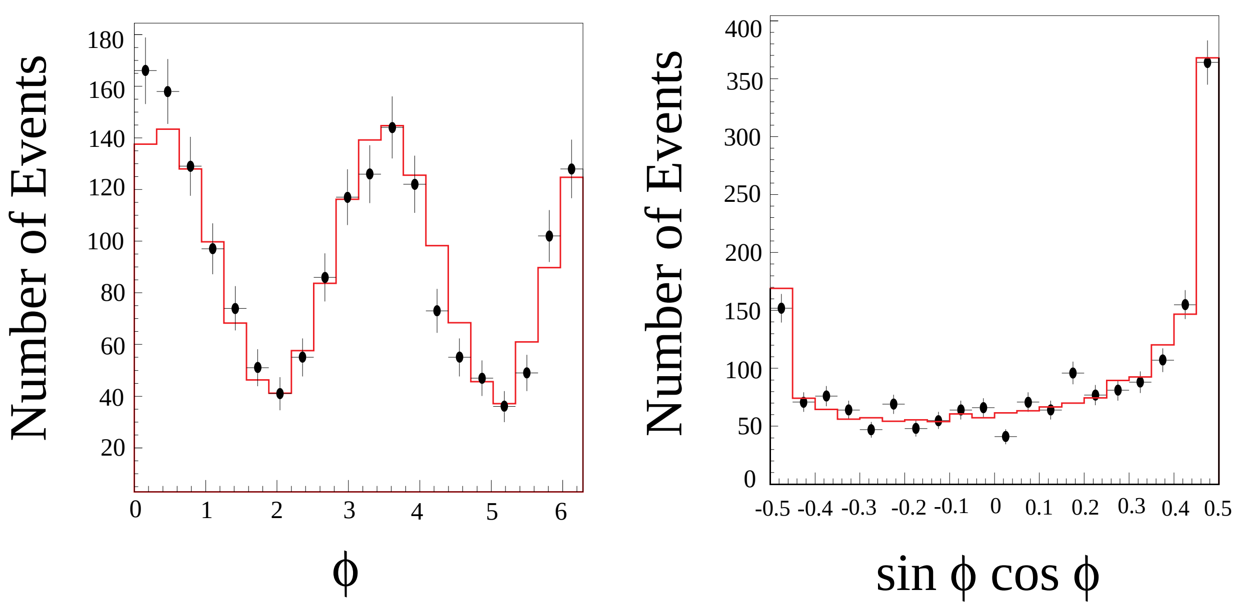

FIG. 9. Observed ϕ (left) and $\sin\phi\cos\phi$ (right) distributions from KTeV. The data are shown as dots and the theoretical prediction (using a Monte Carlo simulation) as a histogram.

CPLEAR recently performed a search for T violation in which the initial and final states are exchanged [22]. They perform the so-called Kabir test of T violation by comparing $K^0 \to \overline{K}^0$ with $\overline{K}^0 \to K^0$. CPLEAR studies neutral kaons with the reaction $p\overline{p} \to K^-\pi^+K^0$ or $K^+\pi^-\overline{K}^0$; the charged kaon is used to tag the strangeness of the neutral kaon at production (t=0). Semileptonic decays are then used to determine the strangeness of the neutral kaon at the moment it decays ($t = t'$). They measure the following rate asymmetry as a function of decay time:

$$A = \frac{R(K^0(t=0) \to \overline{K}^0(t=t')) - R(\overline{K}^0(t=0) \to K^0(t=t'))}{R(K^0(t=0) \to \overline{K}^0(t=t')) + R(\overline{K}^0(t=0) \to K^0(t=t'))}.$$

This asymmetry is plotted in Fig. 10. The average decay rate asymmetry is $A = (6.6 \pm 1.3 \pm 1.0) \times 10^{-3}$, indicating T violation.

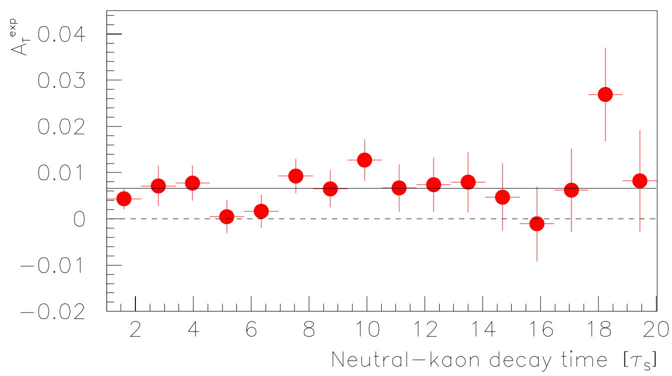

FIG. 10. $K^0 \to \overline{K}^0$ – $\overline{K}^0 \to K^0$ asymmetry as a function of decay time from CPLEAR.

V. OTHER CKM CONSTRAINTS FROM RARE K DECAYS

CP conserving rare K decays also can be used to provide important constraints on parameters of the CKM matrix. Two of these decay modes will be discussed here: $K^+ \to \pi^+\nu\overline{\nu}$ and $K_L \to \mu^+\mu^-$.

A. $K^+ \to \pi^+\nu\overline{\nu}$

The branching ratio of the decay $K^+ \to \pi^+\nu\overline{\nu}$ provides a clean determination of $|V_{td}|$; the theoretical uncertainty in extracting $|V_{td}|$ from the branching ratio is about 7% [23]. Based on the current knowledge of Standard Model parameters, the branching ratio is expected to be in the range $B(K^+ \to \pi^+\nu\overline{\nu}) \sim 0.6 - 1.5 \times 10^{-10}$ [24].

Using data collected during 1995, BNL E787 [25] has reported the observation of a single $K^+ \to \pi^+\nu\overline{\nu}$ event with an estimated background of 0.08 ± 0.03 events. Figure 11 shows a plot of range (in equivalent cm of scintillator) versus energy for data and a Monte Carlo simulation of the signal. Assuming that the observed event is signal, they quote a branching ratio of $B(K^+ \to \pi^+\nu\overline{\nu}) = 4.2^{+9.7}_{-3.5} \times 10^{-10}$, and a corresponding estimate of $0.006 < |V_{td}| < 0.06$. The central value of this branching ratio is about 4 times the Standard Model estimate.

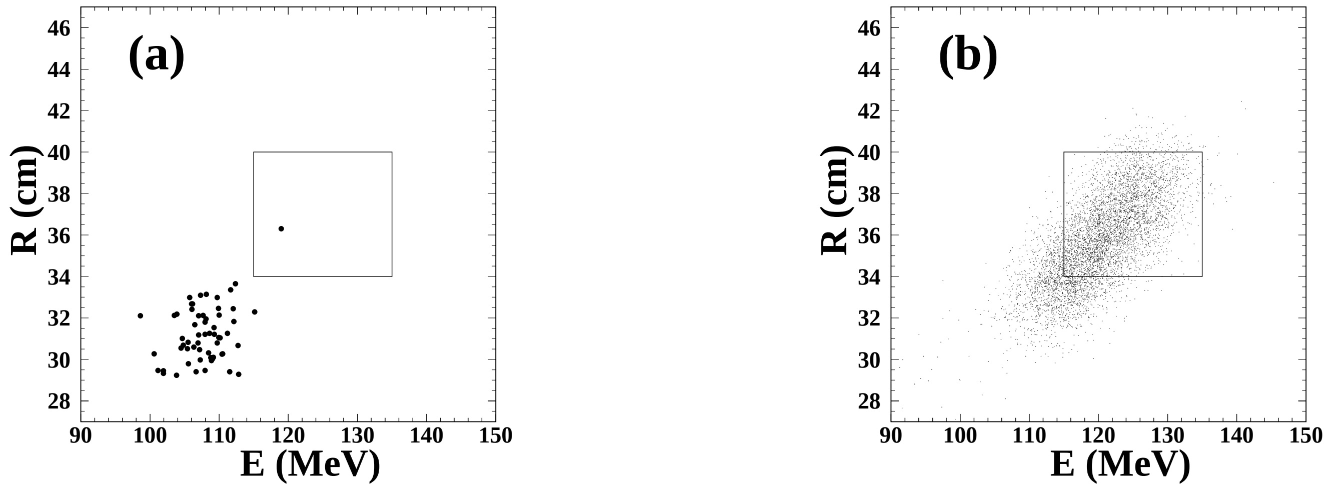

FIG. 11. BNL E787 measurement of $K^+ \to \pi^+\nu\overline{\nu}$. Range vs. energy with other analysis requirements applied for (a) data and (b) Monte Carlo simulation of $K^+ \to \pi^+\nu\overline{\nu}$.

E787 continued to collect data from 1995 through 1998. Without any improvements to the analysis, the full data sample is expected to have a sensitivity 4.4 times greater than that of the 1995 data alone. New results including additional data are expected soon. E787 has received approval for additional running with an upgraded detector (E949) to reach a sensitivity of $\sim 1 \times 10^{-11}$ for $K^+ \to \pi^+\nu\overline{\nu}$ [26]. The CKM collaboration at Fermilab has submitted a letter of intent for a new experiment at Fermilab's Main Injector with a sensitivity of $\sim 1 \times 10^{-12}$ for this decay mode [27].

B. $K_{\rm L} \to \mu^+\mu^-$

The decay $K_{\rm L} \to \mu^+\mu^-$ is sensitive to ρ in the Wolfenstein parameterization of the CKM matrix through diagrams like the one in Fig. 12(a), but most of the rate comes from $K_{\rm L} \to \gamma\gamma$, $\gamma\gamma^*$, $\gamma^*\gamma^*$ diagrams (Fig 12(b)). Therefore, these long distance contributions must be subtracted to extract the interesting short distance physics.

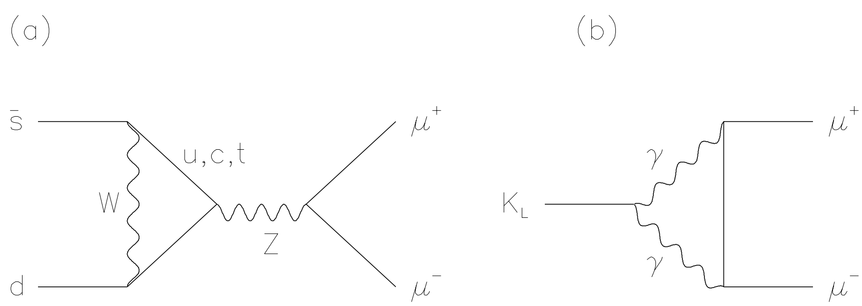

FIG. 12. Examples of (a) short distance and (b) long distance diagrams contributing to $K_{\rm L} \to \mu^+\mu^-$.

Unlike most of the rare decays discussed so far, $K_{\rm L} \to \mu^+\mu^-$ is well measured. BNL E871 [28] has reported a preliminary branching ratio of

$$B(K_{\rm L} \to \mu^+\mu^-) = (7.23 \pm 0.22) \times 10^{-9}.$$

Figure 13 shows distributions of $\mu^+\mu^-$ invariant mass and transverse momentum from the E871 analysis. At present, the long-distance contributions cannot be calculated accurately enough to allow a useful measurement of ρ from this decay mode. This situation should improve, however, as a result of the large KTeV and NA48 data sets. These groups should make greatly improved measurements of $K_L \to e^+e^-\gamma$, $\mu^+\mu^-\gamma$, $e^+e^-\mu^+\mu^-$, $e^+e^-e^+e^-$ which provide important constraints on the $\gamma^*\gamma^*$ and $\gamma\gamma^*$ contributions. For example, KTeV presented a plot of 38 $K_L \to e^+e^-\mu^-\mu^-$ events at this conference [29]; the previous world sample was 1 event [30].

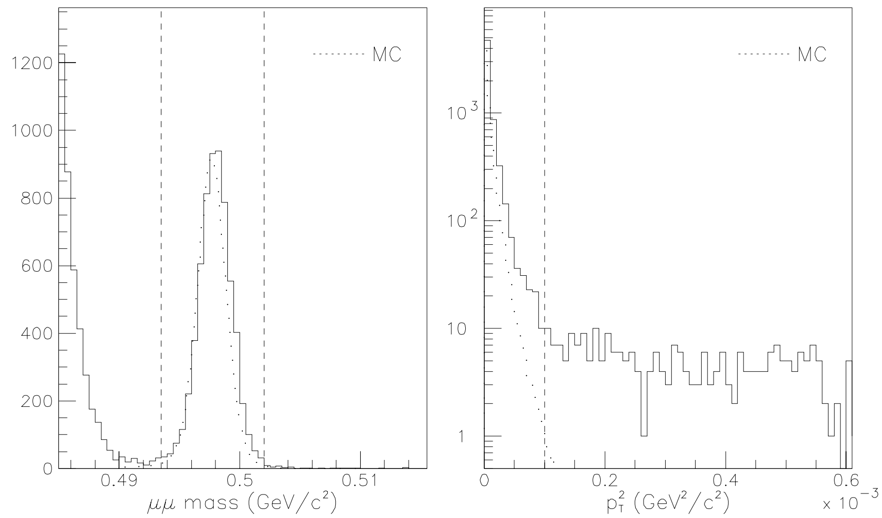

FIG. 13. BNL E871 measurement of $K_L \to \mu^+\mu^-$.

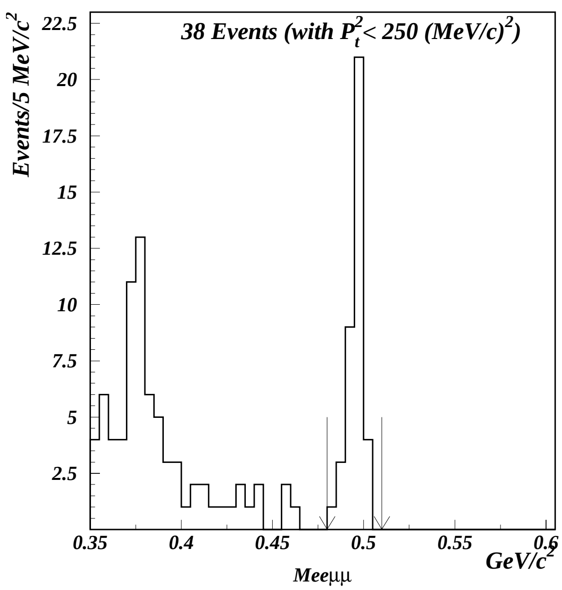

FIG. 14. $K_L \to \mu^+\mu^-e^+e^-$ candidates from KTeV.

VI. RARE K DECAYS AND PHYSICS BEYOND THE STANDARD MODEL

Rare decays also provide a unique window to physics beyond the Standard Model. During the last year, Colangelo and Isidori [31] suggested that the $K \to \pi\nu\overline{\nu}$ and $K \to \pi\ell^+\ell^-$ decays may be extremely sensitive to low energy SUSY. Table II summarizes the current limits/measurements for three of these decay modes, along with the Standard Model predictions, and the maximum possible branching ratios with SUSY from Colangelo and Isadori. Buras and Silvestrini recently investigated the effect of SUSY on these decay modes and found significantly smaller enhancements [32].

SUSY, as well as several other models of physics beyond the Standard Model, also can include lepton flavor violation. The most senstive tests for many of these models are performed in the kaon system. Table III summarizes current and expected limits for lepton flavor violation in K decays. Figure 15 shows data from the BNL E865 search for $K^+ \to \pi^+ \mu^+ e^-$.

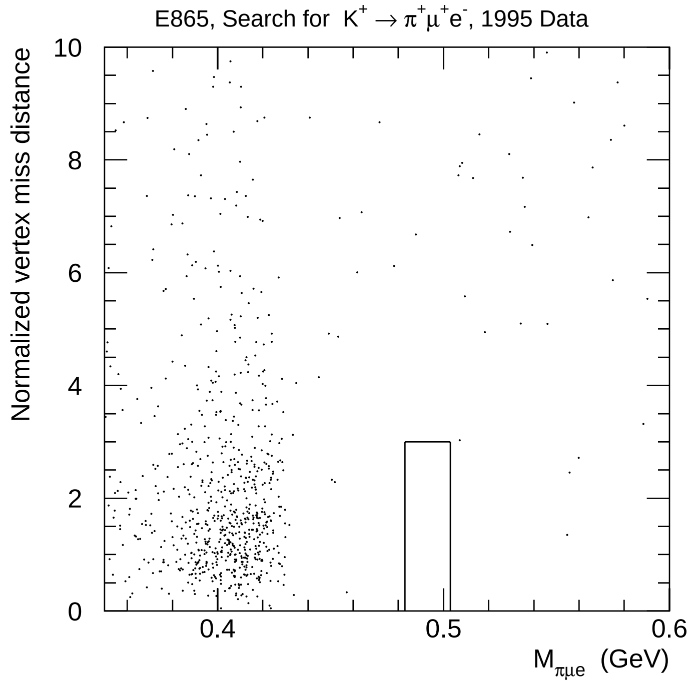

FIG. 15. Quality of fit to a common vertex versus invariant mass for $K^+ \to \pi^+ \mu^+ e^-$ from BNL E865.

TABLE II. SUSY implications for rare K decay branching ratios

Decay Mode	Max. SUSY BR [a]	Standard Model BR	Current result/limit
$K^+ \to \pi^+ \nu\overline{\nu}$	$(40-100) \times 10^{-11}$	$(9.1 \pm 3.8) \times 10^{-11}$	$(4.2^{+9.7}_{-3.5}) \times 10^{-10}$ (BNL E787)
$K_{\mathrm{L}} \to \pi^0 \nu\overline{\nu}$	$(60-400) \times 10^{-11}$	$(2.8 \pm 1.7) \times 10^{-11}$	$< 5.9 \times 10^{-7}$ (KTeV)
$K_{\mathrm{L}} \to \pi^0 e^+ e^-$	$(10-60) \times 10^{-11}$	$(5 \pm 2) \times 10^{-11}$	$< 4.3 \times 10^{-9}$ (FNAL E799I)

[a] Maximum predicted branching ratio for $m_{\mathrm{SUSY}} \sim 0.6 - 1$ TeV.

TABLE III. Lepton flavor violation searches with kaon decays

Decay Mode	Current limit (90% c.l.)	Expected limit with current data
$K_{\mathrm{L}} \to e^{\pm} \mu^{\mp}$	5.1×10^{-12} (BNL E871)	experiment complete
$K^+ \to \pi^+ \mu^+ e^-$	2.1×10^{-10} (BNL E865)	$\sim 1 \times 10^{-11}$ (E865)
$K_{\mathrm{L}} \to \pi^0 e^{\pm} \mu^{\mp}$	3.2×10^{-9} (FNAL E799I)	$\sim 2.5 \times 10^{-10}$ (KTeV)

VII. CP VIOLATION IN OTHER PARTICLE SYSTEMS

Searches for CP violation are underway using several other particle systems, including hyperons, D mesons, and B mesons. Most attention has focussed on the B system where the Standard Model predicts large CP violating effects.

CP violation in the B mesons usually is discussed in terms of the unitarity triangle shown in Fig. 16. In principle, the B system can be used to measure the angles of this triangle, labelled α, β, and γ, as well as the magnitudes of the sides. Methods for measuring these different parameters are described in detail elsewhere in these proceedings [33,34]. During the next few years, several different experiments (BaBar, Belle, CDF, HeraB) should make precise measurements of $\sin 2\beta$ using $B \to J\psi K_S$, as well as several additional modes. The first observations of some of these modes were reported at this conference [34]. The angles α and γ appear far more challenging both experimentally and theoretically. The data samples needed to measure these two angles may require new experiments at hadron colliders such as LHCB and BTeV.

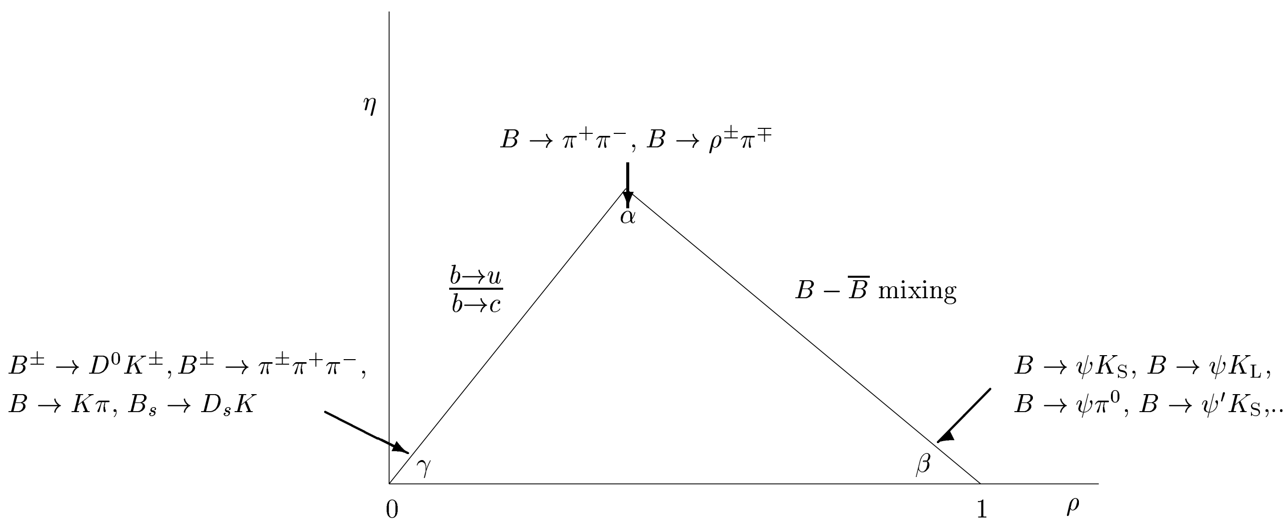

FIG. 16. Unitary triangle with B decays relevant to measurements of different parameters.

Initial searches for CP violation in B mesons have concentrated on the decay $B \to J/\psi K_S$. OPAL [35] and CDF [36] have published first measurements of the rate difference between $B \to J/\psi K_S$ and $\overline{B} \to J/K_S$, which provides a theoretically clean measurement of $\sin 2\beta$:

$$A(t) = \frac{B^0(t) - \overline{B}^0(t)}{B^0(t) - \overline{B}^0(t)} = -\sin(2\beta)\sin(\Delta m_d t),$$

where $B^0(t)$ ($\overline{B}^0(t)$) is the rate of produced B^0 ($\overline{B}^0$) mesons decaying to $J/\psi K_S$ at proper time t, and Δm_d is the mass difference between the two B^0 mass eigenstates. The flavor of the B at the time of production is determined either from tagging the flavor of the other B in an event, or from correlations between the B flavor and the charge of nearby particles. Their results are:

$$\sin 2\beta = (3.2^{+1.8}_{-2.0} \pm 0.5) \quad \text{(OPAL)}$$
$$\sin 2\beta = (1.8 \pm 1.1 \pm 0.3) \quad \text{(CDF)}.$$

Figure 17 shows the invariant-mass plot for $B \to J/\psi K_S$ candidates used in the CDF analysis. A new CDF analysis using more flavor tags and accepting tracks that miss the silicon vertex detector is almost complete, and is expected to have a factor of 2 smaller error than their published result.

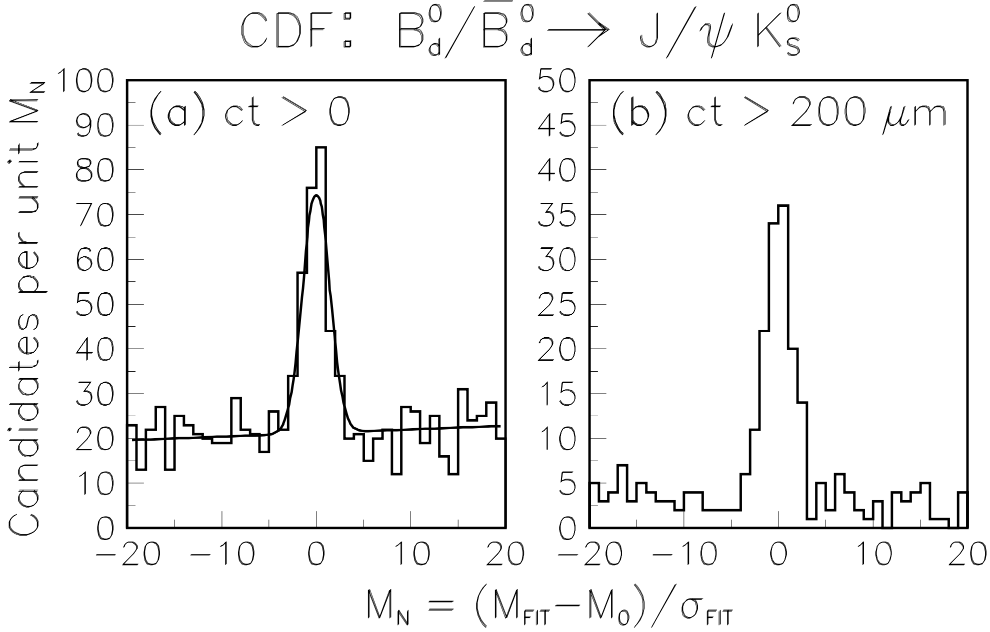

FIG. 17. Normalized mass distribution for $B \to J\psi K_S$ candidates with (a) $ct > 0$ and (b) $ct > 200$ μm from CDF. Normalized mass is defined as M_N = (measured mass - nominal B mass) / uncertainty in measured mass.

VIII. CONCLUSIONS

After a 35 year wait, there may soon be some fundamentally new information on CP violation. The following results are expected during the next several months:

- the first ϵ'/ϵ results from KTeV and NA48;[2]
- an improved $\sin(2\beta)$ analysis from CDF;[3]
- a new $K^+ \to \pi^+\nu\overline{\nu}$ result from E787.

The experimental goals for the next couple of years include:

- the first results from B factories;
- measurements of ϵ'/ϵ at the 10^{-4} level;
- many new rare decay results.

If CP violation is observed in the B system, it will be important to make a detailed comparison of CP violation in K and B mesons. In particular, measurements of η from $K_L \to \pi^0\nu\overline{\nu}$, $|V_{td}|$ from $K^+ \to \pi^+\nu\overline{\nu}$, and $\sin 2\beta$ from $B \to J/\psi K_S$ will allow a comparison of CP violation in K and B mesons with very little theoretical uncertainty.

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[2]Following this conference, KTeV announced a preliminary measurement of ϵ'/ϵ based on $\sim$ 20% of their data sample: $Re(\epsilon'/\epsilon) = (28.0 \pm 3.0\ \text{(stat)} \pm 2.8\ \text{(syst)}) \times 10^{-4}$. This result establishes the existence of direct CP violation at almost 7 sigma, and is consistent with earlier evidence for direct CP violation from NA31. It rules out the Superweak Model as the sole source of CP violation.

[3]Following this conference, CDF presented the preliminary results of this improved analysis. They find $\sin 2\beta = 0.79^{+0.41}_{-0.44}$.

IX. ACKNOWLEDGEMENTS

I wish to thank A. Ceccucci, C. Dukes, P. Franzini, S. Kettel, J. Kroll, R. Hawkings, R. Lee, K-B. Luk, P. Sheldon, F. Wuerthwein, M. Zeller, and my colleagues on KTeV for providing preliminary results of their experiments. Also, I benefited from discussions with R. Briere, G. Isidori, J.R. Patterson, J. Rosner, S. Stone, R. Tschirhart, Y. Wah, and B. Winstein.

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