

ε'/ε Results from KTeV

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1 Introduction

Since the 1964 discovery of $K_L \rightarrow \pi^+\pi^-$ [1], understanding CP violation has been a major goal of particle physics. Subsequent experiments showed that the dominant mechanism of CP violation in neutral kaons (still the only particle system in which CP violation has been observed) is a small asymmetry between $K^0 \rightarrow \bar{K}^0$ and $\bar{K}^0 \rightarrow K^0$ mixing. This asymmetry, referred to as indirect CP violation, results in the K_L and K_S being states of mixed CP. The parameter ε , which is used to parameterize this effect, quantifies the CP impurity of the K_L and K_S states:

$$K_S \sim K_{\text{even}} + \varepsilon K_{\text{odd}} \quad (1)$$

$$K_L \sim K_{\text{odd}} + \varepsilon K_{\text{even}}, \quad (2)$$

where $|\varepsilon| = 2.28 \times 10^{-3}$, $CP|K_{\text{even}}\rangle = +1|K_{\text{even}}\rangle$, and $CP|K_{\text{odd}}\rangle = -1|K_{\text{odd}}\rangle$.

There has been considerable effort during the last 30 years to determine whether or not the CP symmetry is also violated in the decay amplitude (*i.e.*, $K_{\text{odd}} \rightarrow \pi\pi$). This effect is referred to as direct CP violation and is parameterized by ε' . The ratio ε'/ε can be determined from the double ratio of the 2-pion decay rates of K_L and K_S :

$$\text{Re}(\varepsilon'/\varepsilon) \simeq \frac{1}{6} \left[\frac{\Gamma(K_L \rightarrow \pi^+\pi^-)/\Gamma(K_S \rightarrow \pi^+\pi^-)}{\Gamma(K_L \rightarrow \pi^0\pi^0)/\Gamma(K_S \rightarrow \pi^0\pi^0)} - 1 \right]. \quad (3)$$

$\varepsilon'/\varepsilon \neq 0$ is an unambiguous indication of direct CP violation.

The Standard Model predicts both direct and indirect CP violation. Unfortunately, large hadronic uncertainties make precise calculations of $\text{Re}(\varepsilon'/\varepsilon)$ difficult. Most recent Standard Model predictions [2] are in the range $\text{Re}(\varepsilon'/\varepsilon) = (0 - 30) \times 10^{-4}$. Other models, such as the Superweak Model of Wolfenstein [3], predict no direct CP violating effects.

The two best previous measurements of ε'/ε come from E731 [4] at Fermilab and NA31 [5] at CERN:

$$\begin{aligned}\operatorname{Re}(\varepsilon'/\varepsilon) &= (7.4 \pm 5.9) \times 10^{-4} \text{ (E731)} \\ \operatorname{Re}(\varepsilon'/\varepsilon) &= (23 \pm 6.5) \times 10^{-4} \text{ (NA31)}.\end{aligned}$$

The CERN result is 3.5 standard deviations from zero, while the Fermilab result is just over 1 sigma from zero. To clarify this experimental situation and definitively resolve the question of whether or not direct CP violation occurs, new experiments were built at Fermilab (KTeV), CERN (NA48), and Frascati (KLOE) to attempt to measure ε'/ε at the $(1 - 2) \times 10^{-4}$ level. The KTeV and NA48 experiments are similar fixed-target experiments. They differ mainly in the method used to produce K_S , and in the technique used to correct for the difference in detector acceptance for K_S and K_L decays resulting from the large $K_S - K_L$ lifetime difference. The KLOE experiment at Frascati is trying a new technique using an $e^+e^- \rightarrow \phi$ collider.

The first measurement of ε'/ε from the KTeV experiment [6] is the subject of this paper. A more complete description of the KTeV measurement is given in [7]. The NA48 and KLOE experiments are described by Barr [8] and Bertolucci [9] in these proceedings.

2 The KTeV Detector

To achieve the required level of statistical and systematic uncertainty in ε'/ε , the KTeV experiment (Fig. 1) uses the same double-beam technique as E731 with a new detector and beamline. Following the primary target, collimators and sweeping magnets are used to form two almost parallel neutral beams. A fully active regenerator is placed in one of the beams 122 m from the production target, at the upstream end of the decay region, to provide a source of K_S for the experiment (this beam is referred to as the regenerator beam and the other as the vacuum beam). The regenerator (along with a movable absorber that attenuates the beam hitting the regenerator) is moved from one beam to the other each minute to eliminate many possible systematic errors in normalization and detector response. All four $K \rightarrow 2\pi$ decays are detected simultaneously. The detector consists of a large vacuum decay region instrumented with photon veto counters, a drift chamber spectrometer, and a CsI electromagnetic calorimeter. Compared to E731, KTeV also has an improved trigger and data acquisition system. The final stage of the trigger includes full event reconstruction and filtering before data are written to tape.

The performance of the calorimeter, made up of 3100 pure CsI crystals, is particularly important to the success of the experiment. The energy scale of

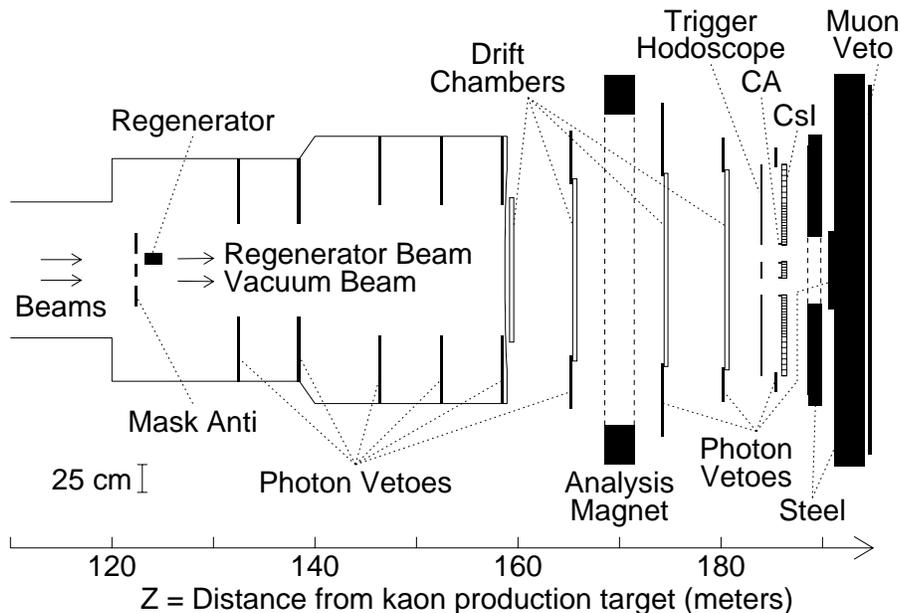


Figure 1: Diagram of the KTeV detector.

the calorimeter is directly related to the reconstructed decay position along the beam (z) direction for $K \rightarrow \pi^0\pi^0$ decays, and is therefore a critical part of understanding the detector's acceptance for neutral events. Figure 2 shows the energy resolution of the calorimeter as a function of momentum for electrons from $K \rightarrow \pi e \nu$ events. The average energy resolution for photons from $K \rightarrow \pi^0\pi^0$ events is 0.7%. The excellent energy resolution also reduces background for both the $\pi^+\pi^-$ and $\pi^0\pi^0$ decay modes.

3 $K \rightarrow \pi^+\pi^-$ and $K \rightarrow \pi^0\pi^0$ Analysis

The analysis presented here is based on $K \rightarrow \pi^0\pi^0$ data collected during 1996 and $K \rightarrow \pi^+\pi^-$ data collected during 1997 [10]. Using charged and neutral data from different running periods does not significantly increase the systematic error in ε'/ε because the two decay modes use essentially independent detector systems. It is critical, however, that the K_S/K_L flux ratio be the same in both years. This issue will be addressed in Section 4.

$K \rightarrow \pi^+\pi^-$ events are reconstructed in the charge spectrometer, consisting of four drift chambers, two on either side of a large dipole magnet providing a 0.41 GeV/c horizontal momentum kick. Important requirements for the $\pi^+\pi^-$ decay mode include:

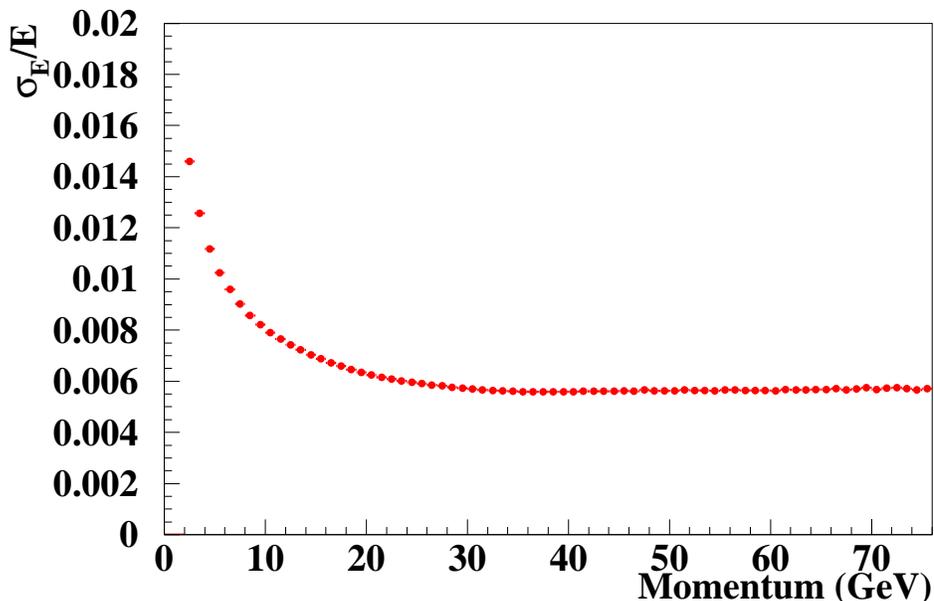


Figure 2: CsI energy resolution as a function of momentum measured with 200 million electrons from $K \rightarrow \pi e \nu$ decays.

- each track must have a momentum of at least 8 GeV/c and deposit less than 85% of its energy in the CsI calorimeter;
- there must not be any hits in the muon hodoscope located behind 4 m of steel;
- the square of the transverse momentum of the $\pi^+ \pi^-$ system relative to the initial kaon trajectory, p_t^2 , must be less than 250 MeV²/c².

The $K \rightarrow \pi^0 \pi^0$ reconstruction is based on the energies and positions of four photons measured in the CsI calorimeter. The events are reconstructed by selecting the photon pairing which is most consistent with both π^0 decays occurring at the same point. As an alternative to p_t^2 , which cannot be reconstructed in $\pi^0 \pi^0$ decays because the photon directions are not measured, we calculate a “ring number” based on the center-of-energy of the four photons at the calorimeter. The ring number is defined as the area (in cm²) of the smallest square that is centered on the beam and contains the center-of-energy. We require that the ring number be less than 110, which selects events with center-of-energy inside a square region of area 110 cm² centered on each beam.

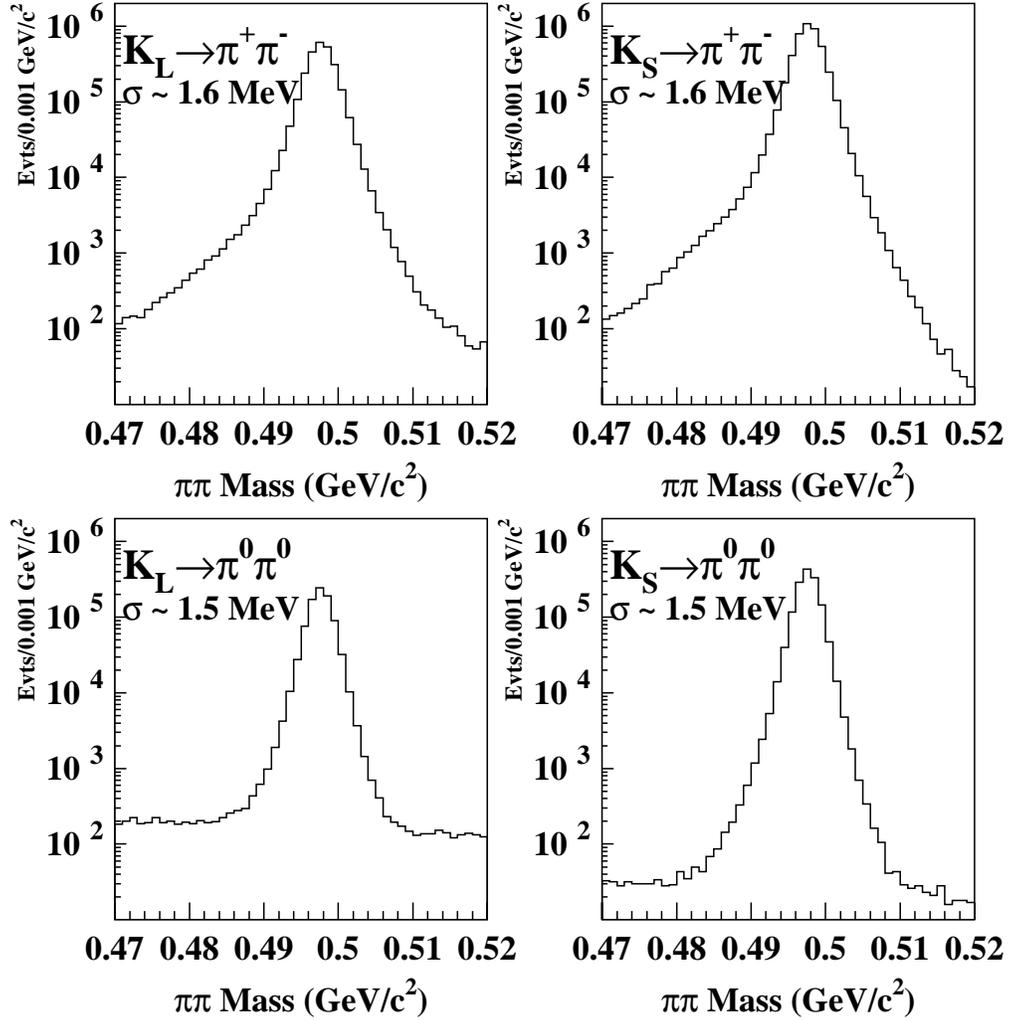


Figure 3: $K \rightarrow \pi\pi$ invariant-mass plots before background subtraction.

Invariant mass distributions for the $K \rightarrow 2\pi$ decay modes for events with $110 < z < 158 \text{ m}$ and $40 < E_K < 160 \text{ GeV}$ are shown in Fig. 3. The corresponding distributions of decay positions along the beam (z) direction are shown in Fig. 4.

There are two classes of background in these $K \rightarrow \pi\pi$ samples: misidentified kaon decays and real $K \rightarrow \pi\pi$ events that have scattered in the regenerator or final collimator. The total background levels for the four decay modes are shown in Fig. 5; Table 1 summarizes the different components of the background. For the $\pi^+\pi^-$ decay mode, backgrounds in both beams are less than 0.1%. In the

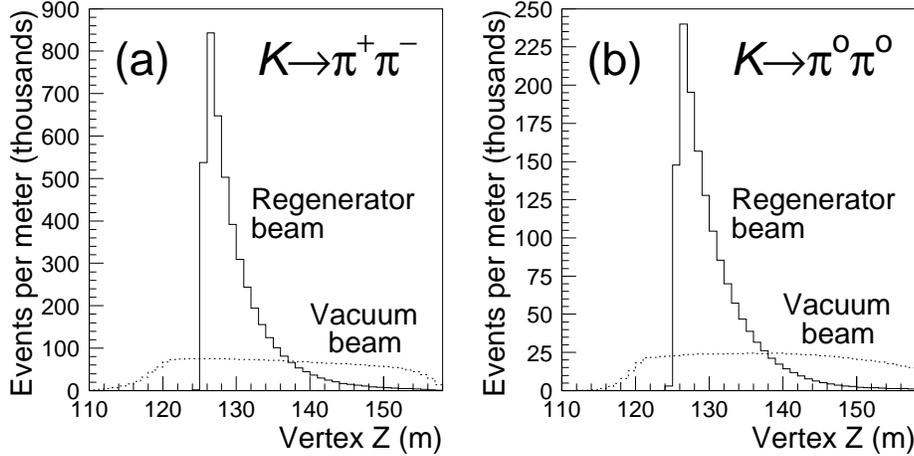


Figure 4: Decay vertex distributions for (a) $K \rightarrow \pi^+ \pi^-$ and (b) $K \rightarrow \pi^0 \pi^0$ decays, showing the difference between the “regenerator” (K_S) and “vacuum” (K_L) beams.

vacuum beam, the background comes mainly from misidentified semileptonic decays. In the regenerator beam, the main background is from kaons that scatter in the regenerator before decaying to $\pi^+ \pi^-$. The background levels are much higher for the $2\pi^0$ decay mode. As in the charged decay mode, kaons that scatter in the regenerator are the main background in the regenerator beam. Because the ring-number variable is not as effective as p_t^2 at identifying scattered kaons, however, the neutral-mode background from this source is 1.07% (more than an order of magnitude larger than in the charged decay mode). Kaons that scatter enough to be reconstructed in the wrong beam contribute a background of 0.3% to neutral decays in the vacuum beam. The vacuum beam also has a background of 0.27% from $K_L \rightarrow 3\pi^0$ decays with lost and/or overlapping photons. The numbers of $K \rightarrow 2\pi$ events after background subtraction are given in Table 2.

| | Vac. Beam $K_L \rightarrow \pi^+ \pi^-$ | Reg. Beam $K_S \rightarrow \pi^+ \pi^-$ | Vac. Beam $K_L \rightarrow \pi^0 \pi^0$ | Reg. Beam $K_S \rightarrow \pi^0 \pi^0$ |
|------------------------------|--|--|--|--|
| Misidentified K: | | | | |
| $K \rightarrow \pi \ell \nu$ | 0.069 | 0.003 | | |
| $K \rightarrow 3\pi^0$ | | | 0.27 | 0.01 |
| Scattered K: | | | | |
| regenerator | | 0.072 | 0.30 | 1.07 |
| collimator | 0.014 | 0.014 | 0.16 | 0.14 |
| Total | 0.083 | 0.089 | 0.73 | 1.22 |

Table 1: Background levels (in %) for $K \rightarrow \pi^+ \pi^-$ and $K \rightarrow \pi^0 \pi^0$

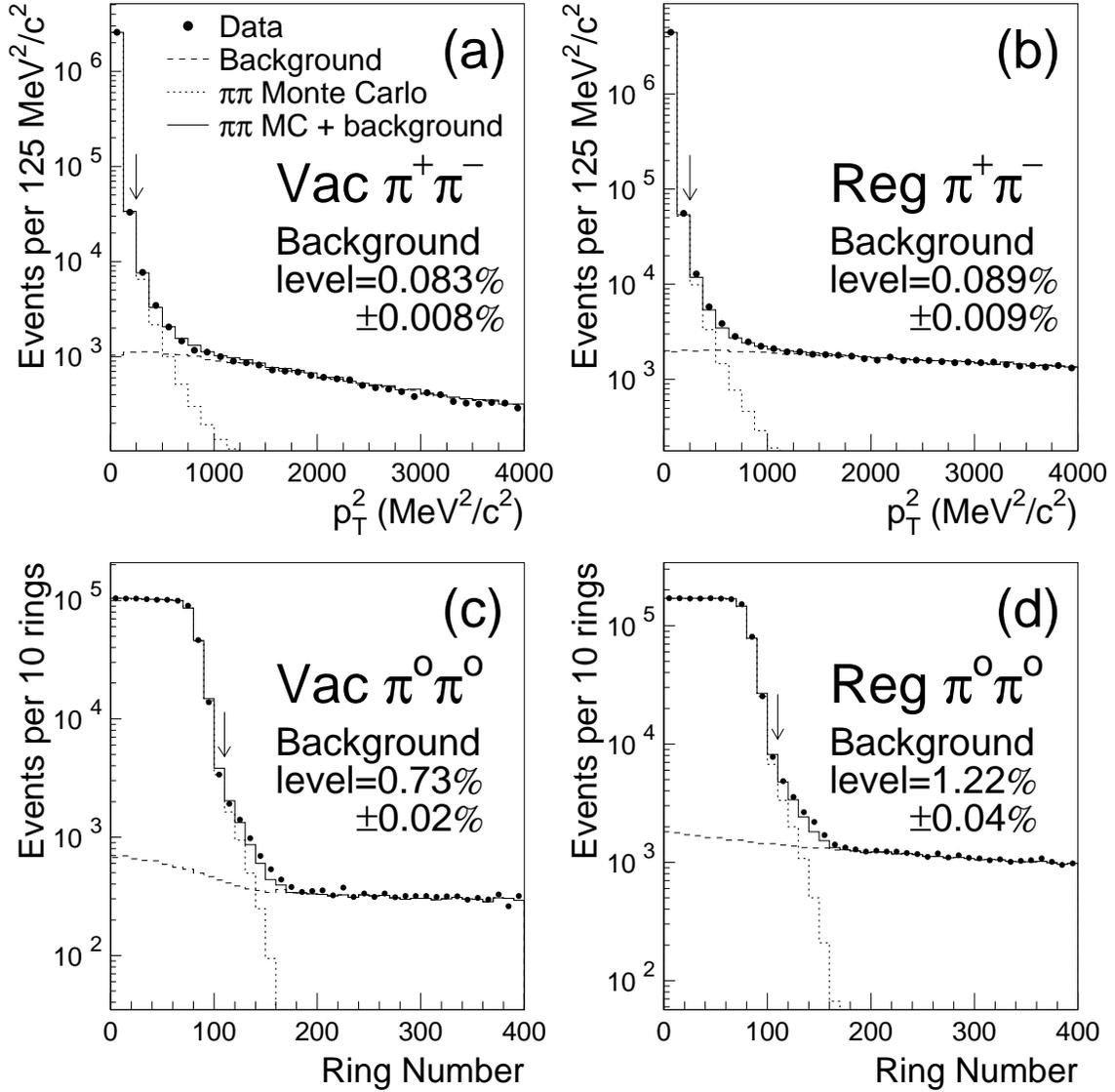


Figure 5: Distributions of p_T^2 for the $\pi^+\pi^-$ samples and ring number for the $\pi^0\pi^0$ samples. Total background levels and uncertainties are given for the samples passing the analysis requirements indicated with arrows.

As shown in Fig. 4, the difference between the K_L and K_S lifetimes results in very different decay vertex distributions for the K_L and K_S decays which must be compared to compute ε'/ε . Therefore, to extract a value for ε'/ε , the numbers in Table 2 must be corrected for the variation in detector acceptance as a function of z . We make this correction with a Monte Carlo (MC) simulation. The simulation models kaon production and regeneration to generate decays with the same

| | Vacuum Beam (K_L) | Regenerator Beam (K_S) |
|----------------------------|-----------------------|----------------------------|
| $K \rightarrow \pi^+\pi^-$ | 2,607,274 | 4,515,928 |
| $K \rightarrow \pi^0\pi^0$ | 862,254 | 1,433,923 |

Table 2: Numbers of events after background subtraction

energy and z distribution as the data. It also includes a detailed simulation of all detector elements.

The quality of the Monte Carlo simulation is studied using distributions from $K \rightarrow 2\pi$ decays, as well as higher statistics decay modes. Figure 6 shows a comparison of data and Monte Carlo vacuum beam z vertex distributions for the $\pi\pi$ signal modes, as well as for the much larger $\pi e\nu$ and $3\pi^0$ samples. Because the average decay positions for K_L and K_S decays differ by about 6 m, a relative slope of 10^{-4} per meter in the data/MC ratio would result in an error of 10^{-4} in ε'/ε . The only noticeable problem in Fig. 6 is the slope of $(-1.60 \pm 0.63) \times 10^{-4} \text{ m}^{-1}$ in the data/MC slope for $K \rightarrow \pi^+\pi^-$. Although this slope is only 2.5 sigma from zero and the slope in $K_L \rightarrow \pi e\nu$ is much smaller, we assign a systematic error of 1.6×10^{-4} on $\text{Re}(\varepsilon'/\varepsilon)$ based on the full size of the observed slope in $K_L \rightarrow \pi^+\pi^-$. The $\pi^0\pi^0$ and $3\pi^0$ data and Monte Carlo z distributions are consistent. Because the $3\pi^0$ decay mode is more sensitive to most acceptance problems, we use the slope in the data/MC ratio in $3\pi^0$ to place a limit of 0.7 ± 10^{-4} on the bias in $\text{Re}(\varepsilon'/\varepsilon)$ from the neutral-mode acceptance.

4 Systematic Errors

Table 3 summarizes the estimated systematic uncertainties in ε'/ε . The $\pi^+\pi^-$ and $\pi^0\pi^0$ columns list errors that are specific to the charged and neutral decay modes. The errors at the bottom of the table are common to both decay modes. Adding these errors in quadrature yields a total systematic error on ε'/ε of 2.8×10^{-4} . Only a few of these errors will be addressed here; additional details are given in [7].

The largest contribution to the systematic error comes from uncertainties in the z dependence of the acceptance, which are estimated from the comparison of z distributions for data and Monte Carlo discussed above. Other significant uncertainties result from the energy scale and background subtraction in neutral mode. To evaluate the uncertainty in the neutral energy scale, we compare the reconstructed z vertex of $\pi^0\pi^0$ events produced at the downstream edge of the regenerator with the reconstructed z vertex for π^0 pairs produced by hadronic interactions in the vacuum window at the downstream end of the decay region. The difference between these measurements is found to be 2 cm greater than the

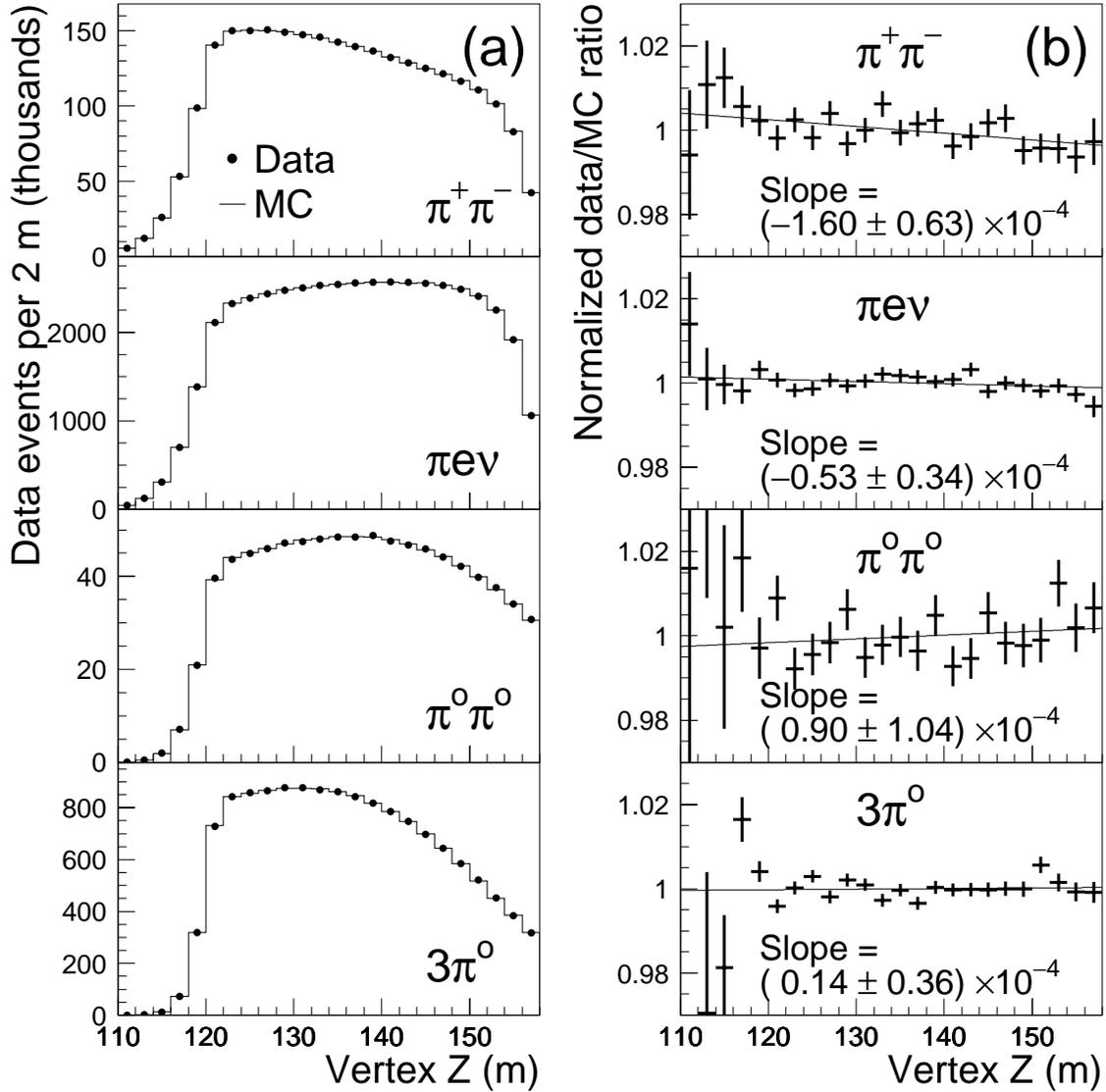


Figure 6: (a) Data vs. Monte Carlo comparisons of vacuum-beam z distributions for $\pi^+\pi^-$, $\pi e \nu$, $\pi^0\pi^0$, and $3\pi^0$ decays; (b) straight-line fits to the data/MC ratios.

| Source of uncertainty | Uncertainty ($\times 10^{-4}$) | |
|--|----------------------------------|-------------------|
| | from $\pi^+\pi^-$ | from $\pi^0\pi^0$ |
| Trigger (L1/L2/L3) | 0.5 | 0.3 |
| Energy scale | 0.1 | 0.7 |
| Calorimeter nonlinearity | — | 0.6 |
| Detector calibration, alignment | 0.3 | 0.4 |
| Analysis cut variations | 0.6 | 0.8 |
| Background subtraction | 0.2 | 0.8 |
| Limiting apertures | 0.3 | 0.5 |
| Detector resolution | 0.4 | 0.1 |
| Drift chamber simulation | 0.6 | — |
| Z dependence of acceptance | 1.6 | 0.7 |
| Monte Carlo statistics | 0.5 | 0.9 |
| K_S/K_L flux ratio: | | |
| 1996 versus 1997 | 0.2 | |
| Energy dependence | 0.2 | |
| Δm , τ_S , regeneration phase | 0.2 | |
| TOTAL | 2.8 | |

Table 3: Summary of systematic uncertainties in $\text{Re}(\varepsilon'/\varepsilon)$

actual distance between the regenerator edge and the vacuum window, resulting in a systematic error of 0.7×10^{-4} on $\text{Re}(\varepsilon'/\varepsilon)$. The neutral mode background uncertainty results largely from uncertainty in the acceptance for scattered $K \rightarrow \pi^+\pi^-$ decays, which are used to tune the Monte Carlo simulation for scattered events.

As mentioned earlier, in combining $\pi^+\pi^-$ and $\pi^0\pi^0$ data from different years, we must consider the possibility of a change in the K_S/K_L flux ratio between the two samples. Although the same regenerator and movable absorber were used for the two data samples, we assign a small uncertainty on $\text{Re}(\varepsilon'/\varepsilon)$ to account for the possible effect of a temperature difference between the two data collection periods, which would change the densities of the movable absorber and regenerator.

5 Results

The numbers of events and the relative acceptances (from the Monte Carlo simulation) for the four 2π decay modes can be used to calculate a simple estimate of ε'/ε using Eq. (1). This calculation [11] yields $\text{Re}(\varepsilon'/\varepsilon) = (26.5 \pm 3.0) \times 10^{-4}$, but it is not precisely correct because it assumes that there are only K_S decays

in the regenerator beam. As illustrated in Fig. 7, the regenerator beam contains a coherent mixture of K_S and K_L , which must be taken into account in the calculation of ε'/ε . The decay distribution in the regenerator beam also allows us to measure the K_S lifetime (τ_S), the $K_S - K_L$ mass difference (Δm), and the relative phases of the CP violating and CP conserving amplitudes (Φ_{00} for $K \rightarrow \pi^0\pi^0$ and Φ_{+-} for $K \rightarrow \pi^+\pi^-$):

$$\begin{aligned}\tau_S &= (0.8967 \pm 0.0007) \times 10^{-10} \text{ s} \\ \Delta m &= (0.5280 \pm 0.0013) \times 10^{-10} \text{ } \hbar \text{ s}^{-1} \\ \Delta\Phi &= \Phi_{00} - \Phi_{+-} = 0.09^\circ \pm 0.46^\circ.\end{aligned}$$

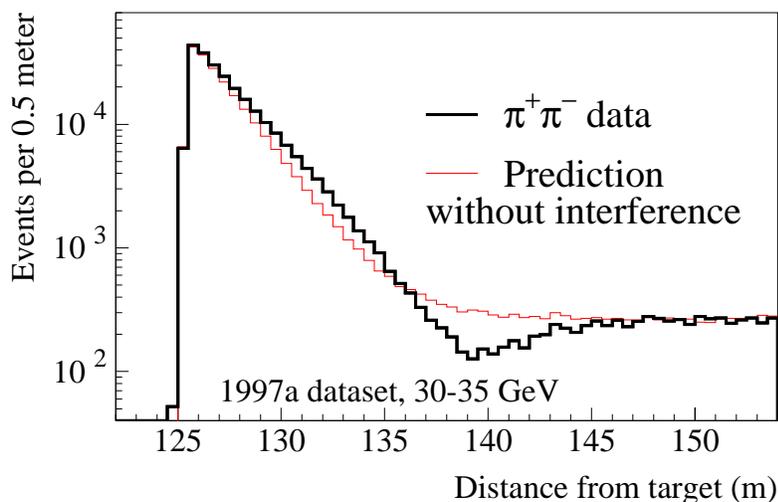


Figure 7: Decay vertex distribution from $K \rightarrow \pi^+\pi^-$ events with $30 < E_K < 35$ GeV downstream of the regenerator showing $K_S - K_L$ interference.

The final value of $\text{Re}(\varepsilon'/\varepsilon)$ is extracted from the background-subtracted and acceptance-corrected data with a fitting program that calculates decay vertex distributions, properly treating regeneration and $K_S - K_L$ interference downstream of the regenerator. Including the systematic error from Table 3, the result of the fit is

$$\begin{aligned}\text{Re}(\varepsilon'/\varepsilon) &= (28.0 \pm 3.0 \text{ (stat)} \pm 2.8 \text{ (syst)}) \times 10^{-4} \\ &= (28.0 \pm 4.1) \times 10^{-4}.\end{aligned}$$

We have performed several cross checks on this result. Consistent results are obtained at all kaon energies, beam intensities, periods during the run, magnet polarities, and for both regenerator positions. We also have done the analysis

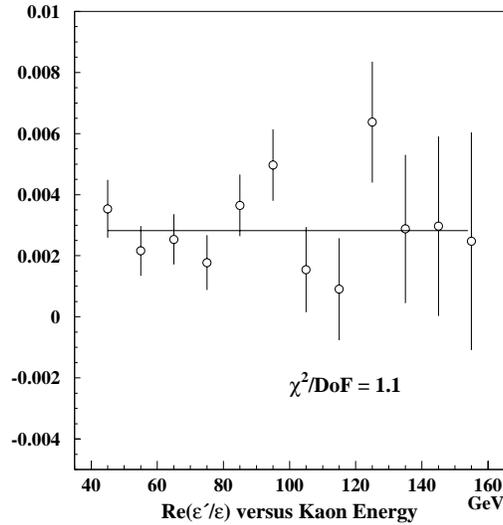


Figure 8: $\text{Re}(\varepsilon'/\varepsilon)$ as a function of kaon energy. The horizontal line represents the central value of $\text{Re}(\varepsilon'/\varepsilon) = 28.0 \times 10^{-4}$. Only statistical errors are shown.

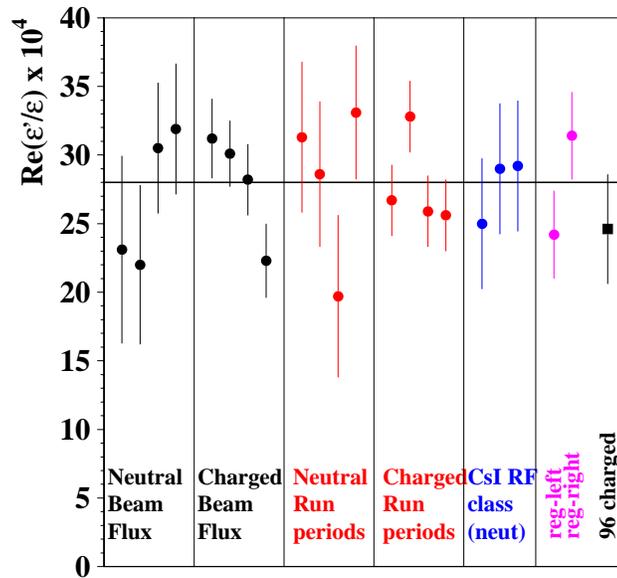


Figure 9: Cross checks on ε'/ε measurement. The horizontal line represents the central value of $\text{Re}(\varepsilon'/\varepsilon) = 28.0 \times 10^{-4}$. Within each category, only independent statistical errors are shown. The “96 charged” point also includes the additional systematic error described in [10].

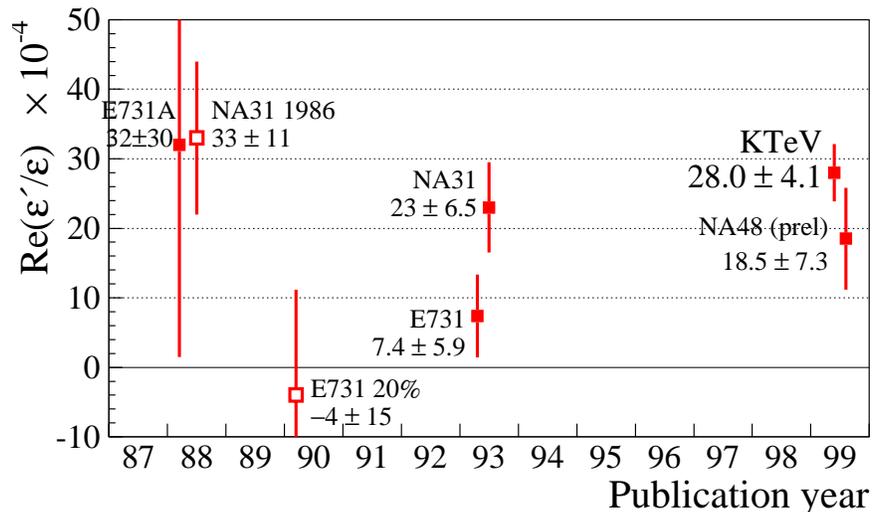


Figure 10: Recent measurements of ε'/ε . The solid points are statistically independent; the open points are included in other measurements.

using $\pi^+\pi^-$ data from 1996 (collected simultaneously with the $\pi^0\pi^0$ data) rather than $\pi^+\pi^-$ data from 1997. The result is consistent with that quoted above, but with a larger systematic error [10]. Some of these cross checks are summarized in Figs. 8 and 9. It is worth noting that the ε'/ε analysis was done “blind”: the value of ε'/ε was hidden with an unknown offset until after the analysis and evaluation of the systematic error were completed.

6 Conclusions

Based on about 1/4 of the data collected during the Fermilab 1996-1997 fixed-target run, KTeV has measured $\text{Re}(\varepsilon'/\varepsilon) = (28.0 \pm 3.0 \text{ (stat)} \pm 2.8 \text{ (syst)}) \times 10^{-4}$. This result establishes the existence of CP violation in a decay process at almost 7 sigma, and rules out the Superweak Model as the sole source of CP violation. Although the result is larger than most Standard Model calculations, it supports the Standard Model explanation of CP violation. Figure 10 shows a comparison of the KTeV measurement with previous results; the preliminary result of the NA48 experiment [8, 12] is shown also. The KTeV result is consistent with earlier evidence for direct CP violation from NA31 and differs from the E731 result by 2.9 sigma. Study of the E731 result has not revealed any error that would cause this discrepancy. A weighted average of all ε'/ε measurements gives $\text{Re}(\varepsilon'/\varepsilon) = (21.3 \pm 2.8) \times 10^{-4}$ with a confidence level of 7%.

The analysis of the remaining 3/4 of KTeV’s 1996-1997 data sample is in

progress. In 1999, we collected a new ε'/ε data set with statistics equal to the full 1996-1997 sample. Several small detector modifications were made to improve the systematic quality of the 1999 data. We also performed additional systematic studies during the 1999 run. The full data sample should allow us to reduce the statistical uncertainty on $\text{Re}(\varepsilon'/\varepsilon)$ to 1×10^{-4} . Significant work will be required to reduce the systematic error to a similar level.

Although the very existence of direct CP violation has been an issue until recently, the full data sets of KTeV, NA48, and KLOE may soon provide measurements of ε'/ε at the 5% level. Considerable improvement in theoretical calculations of ε'/ε will be required to take full advantage of this precision. There is some optimism, however, that the next rounds of calculations using lattice gauge theory may approach a 10% uncertainty in ε'/ε , making the precise measurements of ε'/ε equally precise tests of the Standard Model.

References

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- [6] The KTeV collaboration includes Arizona, UCLA, UCSD, Chicago, Colorado, Elmhurst, Fermilab, Osaka, Rice, Rutgers, Virginia, and Wisconsin.
- [7] A. Alavi-Harati *et al.* [KTeV Collaboration], Phys. Rev. Lett. **83**, 22 (1999) [hep-ex/9905060].
- [8] G. Barr, these proceedings.
- [9] S. Bertolucci, these proceedings.
- [10] We chose not to use $\pi^+\pi^-$ data from 1996 because the Level 3 trigger (full event reconstruction in software) had a 22% inefficiency resulting from an unanticipated drift chamber effect. Although the inefficiency was nearly the same in both beams, it would have led to an unacceptably large systematic error of $\sim 4 \times 10^{-4}$ on $\text{Re}(\varepsilon'/\varepsilon)$. The Level 3 software was modified for the

1997 run to allow for this chamber effect; the resulting inefficiency in 1997 was less than 0.1%.

[11] For this estimate, the z range for decays in the regenerator beam is restricted to the region just downstream of the regenerator ($124 < z < 132$ m) to reduce the importance of K_L decays in that beam.

[12] The NA48 result was published following this conference: V. Fanti *et al.* [NA48 Collaboration], Phys. Lett. **B465**, 335 (1999) [hep-ex/9909022].

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Discussion

Sherwood Parker (University of Hawaii): Did you make any changes to the apparatus to achieve the better results in the second run?

Blucher: There were no fundamental changes to the detector, but small modifications were made to improve data quality and datataking efficiency. For data quality, the most important changes involved the drift chamber system. The drift chamber electronics were improved to have higher gain and lower noise to reduce the chamber inefficiency. The two upstream drift chambers were also restrung because of damage sustained during the 1996-1997 run.

B. F. L. Ward (University of Tennessee): Is there any understanding of why there may have been a systematic bias in the earlier measurement that caused it to miss the higher value of $\text{Re}(\varepsilon'/\varepsilon)$?

Blucher: As mentioned earlier, we have studied the E731 analysis and have not found any evidence of a systematic problem. For example, comparisons of data and Monte Carlo z distributions for E731 [13], similar to those shown for KTeV in Fig. 6, do not show any sign of an acceptance problem.

Mario Calvetti (INFN, Florence): In your analysis, you rely on the Monte Carlo acceptance corrections to the first order. Why is this preferable to the method of NA48; that is, reweighting the events in order to have similar longitudinal vertex distribution?

Blucher: The NA48 procedure sacrifices statistics to reduce the required acceptance correction, while the KTeV procedure maximizes the statistical power of the data sample, but requires that the detector acceptance be understood. We

believe that we have a reliable procedure to estimate the systematic error associated with our acceptance correction. As a cross check, we have analyzed our data with an alternate technique that compares vacuum and regenerator beam z distributions directly, eliminating the need for a Monte Carlo acceptance correction. This analysis gives a consistent value of ϵ'/ϵ but with a significantly larger statistical error.