STATUS AND PROSPECTS ON MEASURING ϵ'/ϵ AT CERN AND FERMILAB

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We review the status of the NA48 and KTeV experiments. These experiments were constructed to measure $Re(\epsilon'/\epsilon)$, a parameter describing direct CP violation in the kaon system. Both experiments have successfully collected large samples of CP violating decays of $K_L \to \pi^0\pi^0$ and $K_L \to \pi^+\pi^-$. Combining these data with data from future runs, the experiments expect to achieve a combined statistical and systematic error on $Re(\epsilon'/\epsilon)$ on the order of $1 - 2 \times 10^{-4}$.

1 Introduction

Although CP violation through mixing was discovered in the neutral K meson system over 30 years ago, its origin and many details still remain a mystery. In particular, whether or not *direct* CP violation exists remains an open question. Within the context of the Standard Model, one expects direct CP violation, characterized by ϵ', to be small[1], on the order of 10^{-4} to 10^{-3}. On the other hand, the superweak model of Wolfenstein predicts that the fundamental interaction is a $\Delta S = 2$ coupling and therefore direct CP violation should be exactly zero. No conclusive experimental evidence exists for direct CP violation since the most recent measurements of $Re(\epsilon'/\epsilon)$ are in nominal disagreement [2,3]. The parameter ϵ measures indirect CP violation resulting from a small admixture of the wrong CP state. The Fermilab experiment measured, $\mathrm{Re}(\epsilon'/\epsilon) = (7.4 \pm 5.2 \pm 2.9) \times 10^{-4}$ while the CERN experiment measured, $\mathrm{Re}(\epsilon'/\epsilon) = (23.0 \pm 3.5 \pm 6.0) \times 10^{-4}$. Although this discrepancy is only about two sigma, the disagreement has warranted a new round of experiments, one at CERN (NA48) and another at Fermilab (KTeV).

The ratio of CP violating to CP conserving amplitudes can be related to ϵ and ϵ' through the relations,

$$\eta_{+-} \equiv \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \simeq \epsilon + \epsilon'. \tag{1}$$

$$\eta_{oo} \equiv \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} \simeq \epsilon - 2\epsilon'. \tag{2}$$

One can use these relationships to obtain an equation for the real part of ϵ'/ϵ.

$$\frac{|\eta_{+-}|^2}{|\eta_{oo}|^2} \simeq 1 + 6Re(\frac{\epsilon'}{\epsilon}). \tag{3}$$

From Eqs. (1-3) one sees that by measuring the double ratio of CP violating to CP conserving $K \rightarrow \pi\pi$ rates, one can obtain a value for $Re(\epsilon'/\epsilon)$. From an experimental point of view, many systematic effects cancel in measuring the double ratio. However since $Re(\epsilon'/\epsilon)$ is expected to be small, very large samples of CP violating decays need to be collected. In particular, the decay $K_L \rightarrow \pi^0\pi^0$ statistically limits the measurement of $Re(\epsilon'/\epsilon)$. The challenge for the experiments is to collect such large samples of kaon decays while carefully controlling the systematics and backgrounds.

Both the NA48 and KTeV experiments have chosen to collect all four decay modes simultaneously to reduce systematics due to time variations and accidental activity. However, the two experiments differ in a number of significant ways. One such difference lies in the production of the K_L and K_S beams. From Eq. 3 it is clear that the $Re(\epsilon'/\epsilon)$ measurement is very sensitive to the determination of whether a decay was a K_L or a K_S. In the case of the CERN experiment, the two beams are produced by different targets with the beams intersecting in the decay region. For the KTeV experiment, two K_L beams are produced with one beam striking a regenerator, thereby producing a component of K_S decays.

The two experiments have also chosen very different technologies for measuring neutral energy decays. Calorimetry is very important for the $Re(\epsilon'/\epsilon)$ measurement because the fully neutral decay, $K_L \rightarrow \pi^0\pi^0$, requires both good resolution to reduce backgrounds and good linearity for understanding systematic effects. In the case of the NA48 experiment, a liquid krypton calorimeter was chosen. This device has very finely spaced readout and is fairly immune to radiation damage. However, the large cryostat required to house the detector introduces material in front of the calorimeter. The KTeV experiment is using a pure CsI crystal calorimeter. This detector has somewhat less complexity than the NA48 detector and much less material in front of the calorimeter. However, it can suffer the effects of radiation. Both calorimeters have achieved an energy resolution below 1% in the region of interest.

2 The NA48 Experiment

The NA48 detector[4] is shown in Figure 1. The detector consists of four planar drift chambers, two on each side of an analyzing magnet, a set of photon vetoes, a liquid Krypton calorimeter and a muon system. The neutral beam is contained within an evacuated beam pipe that runs through the drift chambers and calorimeter into a beam dump. Each of the drift chambers consists of eight planes, with a view in X, Y and at 45° and -45°. A charged hodoscope downstream of the last drift chamber is used to define the event time for

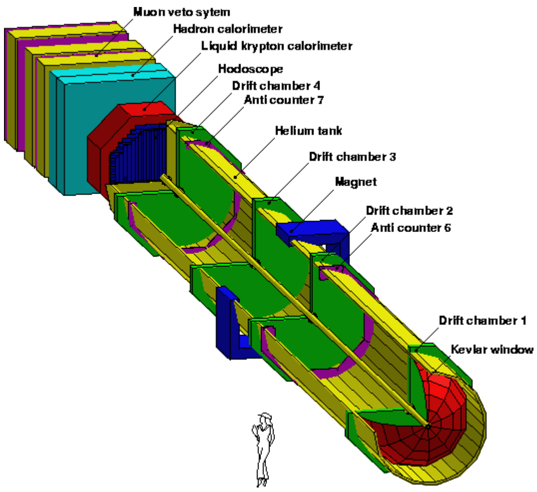

Figure 1: The NA48 detector.

charged events. The calorimeter consists of 13,500 cells, 1.25 m (27 X_0) long by (2 cm)^2. Located within the calorimeter is a plane of scintillating fibers, 9.5 X_0 deep, to measure the event time. There is approximately 0.85 X_0 of passive material in front of the calorimeter.

2.1 Beams

The NA48 experiment employs two separate targets to produce a K_L and a K_S beam. The K_L beam is produced by 450 GeV protons ($\sim 1.5 \times 10^{12}$ protons/pulse) hitting a beryllium target approximately 120m upstream of the detector. Protons that do not interact in the target are focused upon a bent crystal that channels a fraction ($\sim 3 \times 10^7$ protons/pulse) through a tagging counter, back along the neutral beam and onto another target just upstream of the detector. The targetting angles for the K_S target (4.2 mrad) and K_L targets (2.4 mrad) were chosen so that the two beams have similar momentum spectra. The K_S beam enters the detector 72mm above the K_L beam and at an angle of 0.6 mrad with respect to the K_L beam.

To distinguish whether a decay resulted from the K_L or the K_S target, the time difference between when a proton fires the tagging counter and the event time is studied. As seen in Figure 2, a time difference within 2ns of the event time results in a relatively pure K_S sample. The event time is defined by either

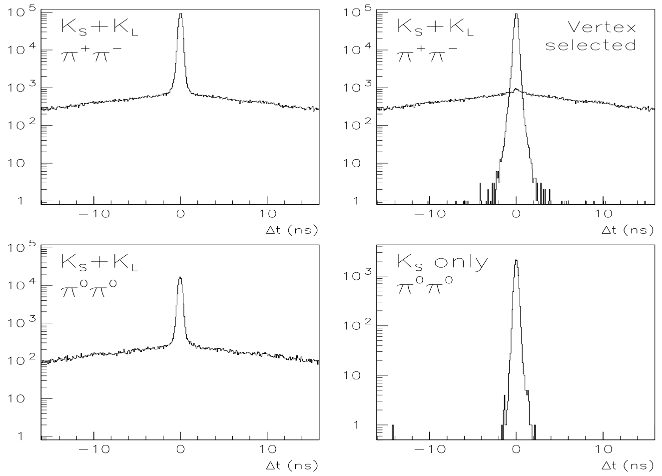

Figure 2: The time difference between the event time and the NA48 tagging counter. Events within 2ns of the event time are tagged as K_S decays. For charged decays, the two beams are separated using the vertex information. For neutral decays, the K_L beam was blocked and only K_S decays were allowed to examine the time difference. The mistag probability for K_S decays is 11.5% and is charged/neutral symmetric.

a scintillator hodoscope for charged decays or the LKr calorimeter for neutral decays. So, the timing characteristics of the hodoscope and the calorimeter need to be carefully monitored. The resolution of the charged hodoscope is approximately 200 ps while that of the calorimeter is 250 ps. Using the 2ns cut, the fraction of time that an event that is tagged as a K_S is actually a K_L is 11.5%. This number is well measured and charged/neutral symmetric, so one expects that the bias on $Re(\epsilon'/\epsilon)$ will be small.

2.2 Performance

The NA48 calorimeter is calibrated electronically and then a correction applied using semileptonic kaon decays, $K_L \rightarrow \pi e \nu$. The resolution achieved by the calorimeter is below 1% for energies above 25 GeV. In neutral kaon decays, the average photon energy is about 30 GeV. The calorimeter resolution for electrons is shown in Figure 3a. The position resolution for photons was measured to be less than 1mm in both the X and Y projections. During the 1997 run, a few problems with the calorimeter such as damaged capacitors and missing

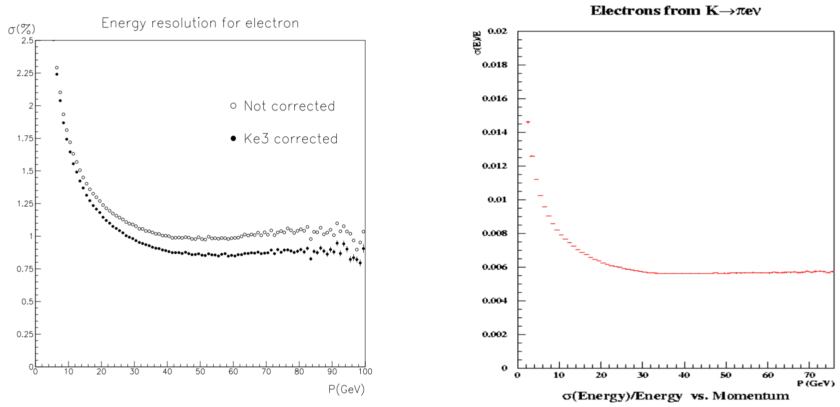

Figure 3: The a) NA48 LKr calorimeter energy resolution and the b) KTeV CsI calorimeter energy resolution.

channels arose. These problems have been fixed for the 1998 run.

The charged spectrometer for the NA48 experiment has worked well. Each plane achieves a resolution of about 120 μm. After offline cuts, the reconstructed $\pi^+\pi^-$ mass is shown in Figure 4a. As can be seen, the background for $K_S \to \pi^+\pi^-$ is low and the resolution, $\sigma_M = 2.6$ MeV/c^2, is quite good, a significant improvement over the previous NA31 experiment.

2.3 Status and Future

The NA48 experiment ran in 1997 and collected approximately 650,000 $K_L \to \pi^0\pi^0$ decays. This data sample is larger than the sample collected by the NA31 experiment. Using this data set, the NA48 experiment expects to produce a preliminary result with an error smaller than the previous NA31 result. The experiment is exploring two different methods for correcting for the K_S and K_L acceptances. Since the two decays have very different lifetimes, uncertainty in the acceptance can translate into a large systematic error. The NA48 experiment is investigating reweighting the K_L events to have a similar decay vertex spectrum as the K_S decays, thereby reducing the reliance upon Monte Carlo methods. Another option is to develop a sophisticated Monte Carlo simulation to understand the K_L and K_S decay vertex distribution. This is the KTeV experiment's technique and is also being pursued by the NA48 experiment.

The NA48 experiment is currently running and expects to collect nearly 2 million CP violating neutral decays during this runing period. Similar runs are

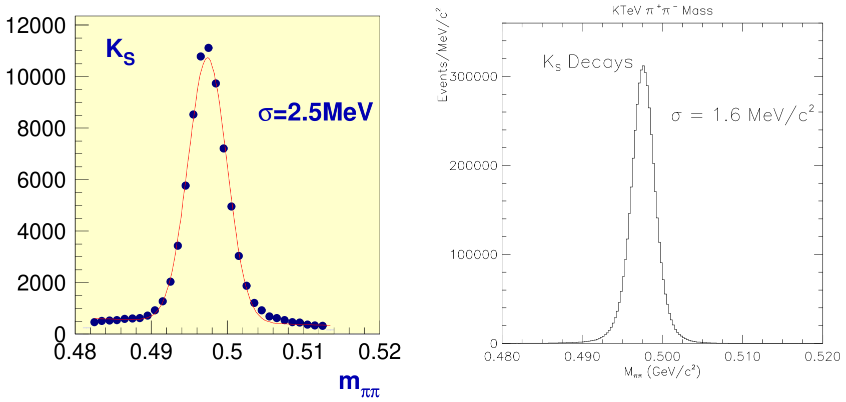

Figure 4: The reconstructed $\pi^+\pi^-$ mass distribution for the a) NA48 and b) KTeV experiments.

planned for both 1999 and 2000. By the end of these data collecting periods, the NA48 experiment plans to have a combined statistical and systematic error on $Re(\epsilon'/\epsilon)$ of less than 2×10^{-4}.

3 The KTeV Experiment

The KTeV detector is shown in Figure 5. Like the NA48 detector, the KTeV detector consists of a charged spectrometer for detecting $K_L \to \pi^+\pi^-$ decays and a calorimeter[5] for detecting $K_L \to \pi^0\pi^0$ decays. The muon system is primarily used to reject $K_L \to \pi\mu\nu$ events in the $Re(\epsilon'/\epsilon)$ measurement. The spectrometer has four drift chambers, two located upstream and two downstream of the spectrometer magnet. Each of the drift chambers contains two planes to measure the X position and two to measure the Y position. The KTeV calorimeter consists of 3100 pure CsI crystals that are 27 X_0 or 50 cm long. The crystals in the center of the calorimeter have a transverse cross section of (2.5 cm)^2 while the crystals around the outside of the calorimeter have a cross section of (5.0 cm)^2. To reduce backgrounds from events with missing photons, the KTeV detector contains a system of 11 photon vetoes with a coverage out to 100 mrad.

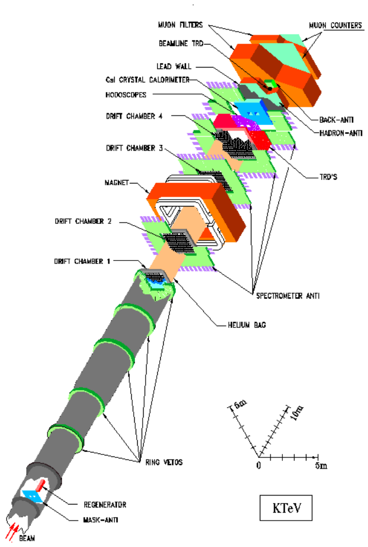

Figure 5: The KTeV detector.

3.1 Beams

In the KTeV experiment, two nearly identical K_L beams are produced in a target upstream of the decay volume. One of these beams is allowed to impinge upon a regenerator consisting of approximately 1.8 interaction lengths of scintillator. Once a minute the regenerator moves between the two neutral beams thereby reducing systematics due to detector and beam asymmetries. While the regeneration amplitude is only a few percent, the decays to two pions in the regenerator beam are almost completely due to K_S decays because a) the K_L decays are suppressed by ϵ and b) the K_S lifetime is over 500 times smaller than the K_L lifetime.

Because regeneration is a coherent process, the angular distribution of the K_S and K_L beams are identical and systematics due to differences in the K_S and K_L beam shapes are significantly reduced. In addition, since the regeneration amplitude has a $p^{-0.6}$ dependence, and the K_L spectrum has a p^{-1} dependence due the large K_L lifetime, the energy spectrum of K_S and K_L decays are relatively similar. A further advantage of regeneration is that the target for both beams is located well upstream of the detector, reducing backgrounds from particles produced in the target. One disadvantage of the regeneration technique is background produced by kaons scattering in

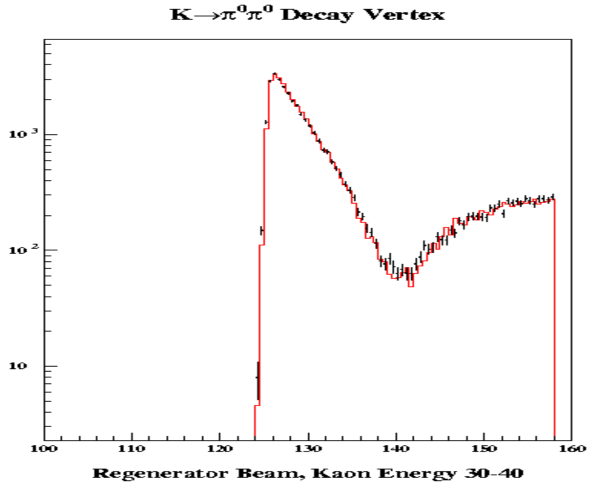

Figure 6: The decay vertex position for $K \to \pi^0\pi^0$ decays between 30 and 40 GeV.

the regenerator. This background can be reduced to approximately 0.3% by vetoing events that deposit energy in the regenerator scintillator.

The decay rate to two pions downstream of a regenerator is given by the following relation,

$$\begin{aligned} R \sim\ & |\rho|^2 e^{-\Gamma_S t} \\ & + |\eta|^2 e^{-\Gamma_L t} \\ & + 2|\rho||\eta| e^{-(\Gamma_S+\Gamma_L)t/2} \cos(\Delta m t + \Phi_\rho - \Phi_\eta) \end{aligned} \tag{4}$$

where ρ is the regeneration amplitude, Γ the K_L or K_S lifetime, Δm the K_L, K_S mass difference and Φ_ρ and Φ_η the phases of the regeneration amplitude and CP violating amplitudes, respectively. The distinctive shape of the intereference curve provides a powerful check of the consistency of the data used in the $Re(\epsilon'/\epsilon)$ measurement. Figure 6 shows the decay vertex for 2π decays in a restricted energy region. The interference between the K_S and K_L decays is clearly visible.

3.2 Performance

The KTeV experiment completed a data taking run in 1997. Both the calorimeter and charged spectrometer performed well during this period. The calorimeter achieved a resolution for electrons well below 1% as shown in Figure 3b.

The biggest problem encountered during the operation of the calorimeter was the failure of custom ASICs used in the CsI readout. Data taking was interrupted to replace these failures so that the calorimeter did not run with missing channels. The reconstructed $\pi^0\pi^0$ kaon mass resolution is 1.5 MeV/c^2. In the energy range, 3 to 60 GeV, the calorimeter is linear to 0.5%. During the run the center of the array received approximately 2.5 kRad and experienced a loss of light of approximately 0.5% per week.

The plane resolution of the charged spectrometer was approximately 100 μm. Some chamber degradation was encountered in the region of the chambers through which the beam passed. After nominal offline cuts, the reconstructed $\pi^+\pi^-$ mass is shown in Figure Figure 4b. The mass resolution for these events is approximately 1.6 MeV/c^2, and the background level from all sources, including scattered kaons, is approximately 0.1%.

To correct for the difference between the K_L and K_S acceptance, the KTeV experiment relies upon a detailed Monte Carlo. The main inputs to the Monte Carlo are the kaon momentum spectrum, the kaon transverse momentum spectrum and the apertures of the detector. Details of the Monte Carlo are checked using high statistic kaon decays such as $K_L \rightarrow \pi^0\pi^0\pi^0$ and $K_L \rightarrow \pi e \nu$. Figure 7 shows the decay vertex position for both $\pi^0\pi^0$ and $\pi^+\pi^-$ events. Note that the Monte Carlo simulation is overlaid on the data distribution and is nearly indistinguishable from the data. Differences between the two distributions results in a systematic error in the determination of $Re(\epsilon'/\epsilon)$.

3.3 Status and Future

The KTeV experiment collected approximately four million CP violating neutral decays between 1996 and 1997. Currently, the experiment plans to present a preliminary result based upon 25% of this data set. The errors from this analysis will be smaller than those of the E731 or the NA31 result.

The KTeV experiment is preparing to take data again in 1999. This run should increase the $Re(\epsilon'/\epsilon)$ data set by at least a factor of two. One expects that combining all of the data from the KTeV experiment that the combined statistical and systematic error should be on the order of 1×10^{-4}.

4 Conclusions

Both the NA48 and the KTeV experiment have successfully commissioned their detectors. Both detectors have performed well and have collected data sets that exceed in quality and quantity the data collected by their predecessors. Each experiment is planning on presenting a result in the near future that should be

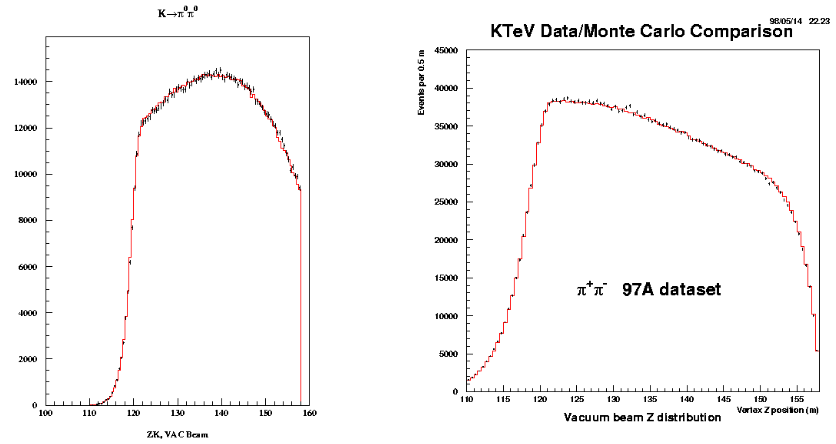

Figure 7: The decay vertex position for for the vacuum beam events for a) $\pi^0\pi^0$ and b) $\pi^+\pi^-$ events. The Monte Carlo (histogram) is overlaid on the data (crosses) for each mode.

an improvement on the previous results and, hopefully, will help to shed light on the current discrepancies on the measurement of $Re(\epsilon'/\epsilon)$. Future data will allow both experiments to approach the goal of a combined error on the order of 1×10^{-4}.

Acknowledgments

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