MEASUREMENT OF DIRECT CP VIOLATION PARAMETER $Re(\epsilon'/\epsilon)$ IN THE NEUTRAL KAON SYSTEM

A GLAZOV
On behalf of the KTeV Collaboration
DESY, Notkestrasse 85, Hamburg, 22607, Germany

The final measurement of the direct CP violation parameter $Re(\epsilon'/\epsilon)$ performed by the KTeV collaboration is presented. The new result, $Re(\epsilon'/\epsilon) = [19.2 \pm 1.1_{\rm stat} \pm 1.8_{\rm syst}]$, improves precision of the previous measurement[1] and is consistent with it. Along with the measurement of $Re(\epsilon'/\epsilon)$, new measurements of the $K_L - K_S$ mass difference, Δm, the K_S lifetime, τ_S, the phase $\phi_\epsilon = \arg(\epsilon)$ and the phase difference $\Delta\phi$ are performed. The data are consistent with CPT symmetry, the value of $Re(\epsilon'/\epsilon)$ is consistent with the NA48 result[2].

1 Introduction

Violation of CP symmetry in weak interactions was first discovered in 1964 when the decay $K_L \to \pi^+\pi^-$ was observed. It was realized in the following experiments that the main reason for the effect is a small difference between $K^0 \to \bar{K}^0$ and $\bar{K}^0 \to K^0$ transition rates, which is termed as indirect CP violation. CP can be also violated directly in a decay amplitude, a search for this process has been performed by experiments at CERN[3,2] and Fermilab[4,1]. In this letter, the final measurement of direct CP violation by the KTeV experiment at Fermilab is reported.

Direct CP violation manifests itself as a difference in the level of CP violation for different decay modes. For neutral kaons, $K \to \pi^+\pi^-$ and $K \to \pi^0\pi^0$ decay amplitudes can be compared:

$$\begin{aligned} \eta_{+-} &= \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \epsilon + \epsilon' \\ \eta_{00} &= \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \epsilon - 2\epsilon'. \end{aligned} \tag{1}$$

Here ϵ quantifies common indirect CP violation while ϵ' parameterizes a difference between the two modes and thus is a direct CP violation parameter.

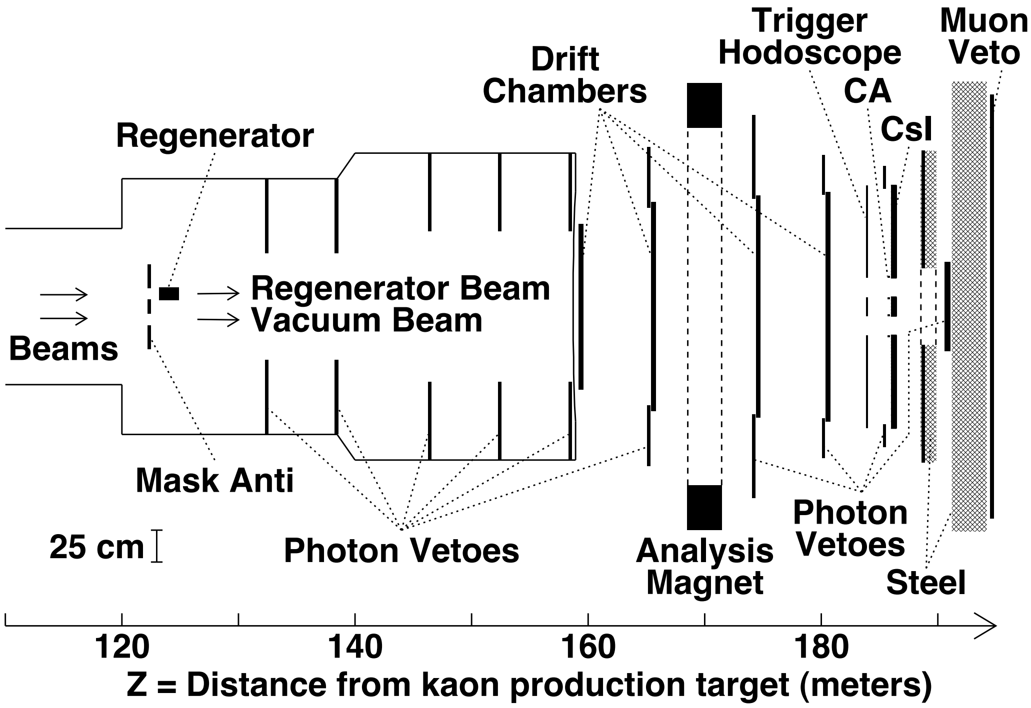

Figure 1: Schematic view of the KTeV detector

CPT invariance imposes additional constraints on the complex parameters ϵ and ϵ'. In particular phase of ϵ must be equal to the "superweak" phase, $\phi_\epsilon = \phi_{SW} \equiv \arctan(2\Delta m/\Delta\Gamma)$, where $\Delta m \equiv m_L - m_S$ is the $K_L - K_S$ mass difference and $\Delta\Gamma \equiv \Gamma_S - \Gamma_L$ is the difference in the decay widths. CPT invariance together with measurements of the strong phase shifts[5] also requires that $\phi_\epsilon \approx \phi_{\epsilon'}$. Therefore, $Re(\epsilon'/\epsilon)$ is a measure of direct CP violation while $Im(\epsilon'/\epsilon)$ is a measure of CPT violation. Experimentally, $Re(\epsilon'/\epsilon)$ is determined using double ratio of the decay rates:

$$\frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)} = \left|\frac{\eta_{+-}}{\eta_{00}}\right|^2 \approx 1 + 6Re(\epsilon'/\epsilon), \tag{2}$$

while $Im(\epsilon'/\epsilon)$ can be determined from the phase difference of the decay amplitudes:

$$\Delta\phi \equiv \phi_{00} - \phi_{+-} \approx -3Im(\epsilon'/\epsilon). \tag{3}$$

Previous measurements of $Re(\epsilon'/\epsilon)$ have established that it has small non-zero value. This letter presents the final KTeV measurement of $Re(\epsilon'/\epsilon)$ which is based on complete data sample, including new 1999 data period that about doubles the statistics of the previous KTeV publication[1], and significantly improved experimental procedure.

2 KTeV Detector and Data Analysis

The KTeV apparatus (see Fig. 1) uses double beam technique to simultaneously collect the four decay modes $K_{L,S} \to \pi^+\pi^-(\pi^0\pi^0)$. The two neutral beams are formed from secondary particles produced by 800 GeV/c protons colliding on a beryllium oxide target using a system of collimators, absorbers and sweeping magnets. The neutral kaon decays are detected in $110 - 158$ m range from the production target (for the KTeV coordinate system this corresponds to a positive Z direction). The kaon energies used in this analysis are in $40 - 160$ GeV range. At

125 m from the production target one of the beams passes through a plastic regenerator which produces coherent mixture of K_L and K_S states, for $K \to \pi\pi$ decays the K_S state dominates. The regenerator alternates between the two neutral beams during the periods with no proton collisions on target, at about once per minute rate, in order to reduce systematic differences between K_L and K_S decays. The kaon beam with the regenerator is termed in the following as the regenerator beam while the other beam is termed as the vacuum beam.

The charged decay products are detected in a drift chamber spectrometer. The spectrometer is equipped with two chambers before and two after an analyzing magnet. Each chamber measures charged particle tracks in horizontal and vertical views. The neutral decay products are measured in a CsI crystal calorimeter, located after the spectrometer at 186 m from the production target. The crystals of the calorimeter have transverse dimensions of 2.5×2.5 cm^2 for the central region surrounded by 5×5 cm crystals in the outer range, there are 3100 crystals in total.

An extensive veto system rejects background events coming from interactions in the regenerator, semileptonic and $K_L \to \pi^0\pi^0\pi^0$ decays. The background levels, which include non-$K \to \pi\pi$ decays as well as $K \to \pi\pi$ decays in which the kaon scatters in the regenerator, after all selection cuts do not exceed 0.1% for the $\pi^+\pi^-$ ("charged") and 1.2% for the $\pi^0\pi^0$ ("neutral") mode.

The reconstruction of $K \to \pi^+\pi^-$ mode starts from selecting events with two track measured in the spectrometer. Each track is matched to a cluster in CsI calorimeter and $E/p < 0.85$ is required to reject $K \to \pi^\pm e^\mp \nu$ events. No signal is allowed in the muon veto system, located behind the CsI calorimeter, to reject $K \to \pi^\pm \mu^\mp \nu$ events. A high efficiency of the muon system is ensured by imposing $p > 8$ GeV/c condition for momentum of each track. The invariant mass of the two tracks, assuming the tracks are charged pions, is selected in 488 MeV/c^2 $< m_{\pi^+\pi^-} <$ 508 MeV/c^2 range. The transverse momentum squared of the kaon is required to be $p_T^2 < 250$ MeV^2/c^2 in order to reject events in which the kaon undergoes scattering in the regenerator or in an upstream collimator.

To measure $K \to \pi^0\pi^0$ decays four photon clusters of energy are detected in the CsI calorimeter. The clusters are paired together to reconstruct $\pi^0 \to \gamma\gamma$ decays. For each pairing the Z coordinate of the decay point with respect to the calorimeter surface is calculated as $Z_{12} = r_{12}\sqrt{E_1 E_2}/m_{\pi^0}$, where $E_{1,2}$ are the photon energies, r_{12} is the distance between the photons and m_{π^0} is the nominal π^0 mass. All six pairings are considered and the one which leads to the most consistent Z_{12} determination is used. The decay Z vertex position is estimated using an error weighted average of Z_{12}. The kaon transverse vertex position is reconstructed by using a center of energy of the clusters, it is required to be situated inside the beam profile in order to reduce scattering background. The kaon energy is measured as a sum of the cluster energies. A cut on total invariant mass is imposed 488 MeV/c^2 $< m_{\pi^0\pi^0} <$ 508 MeV/c^2 which rejects $K \to \pi^0\pi^0\pi^0$ events.

Distributions of the Z coordinate of $K_S \to \pi\pi$ and $K_L \to \pi\pi$ decay vertices have very different shape because of the difference in the lifetimes. To take this into account, KTeV uses a detailed Monte Carlo simulation (MC). Quality of this simulation can be tested by comparing the Z vertex distribution in the vacuum beam, see Fig 2. A linear slope in the ratio of the data to MC distributions can be directly translated into uncertainty of $Re(\epsilon'/\epsilon)$ using a difference of an average Z position of the decay vertex for K_S and K_L decays. The systematic uncertainty is derived based on $K_L \to \pi^+\pi^-$ decays for the charged and $K_L \to \pi^0\pi^0\pi^0$ decays for the neutral mode.

Compared to the previous KTeV publication[1], several significant improvements of the measurement procedure were introduced. These include improvements for the 1999 data taking (i.e. better duty cycle for the proton extraction and repaired electrons of CsI calorimeter), for the data analysis (i.e. better model for drift chamber resolution which lead to $\sim 15\%$ increase of $m_{\pi^+\pi^-}$ resolution), while the main improvements were made for the detector simulation. The

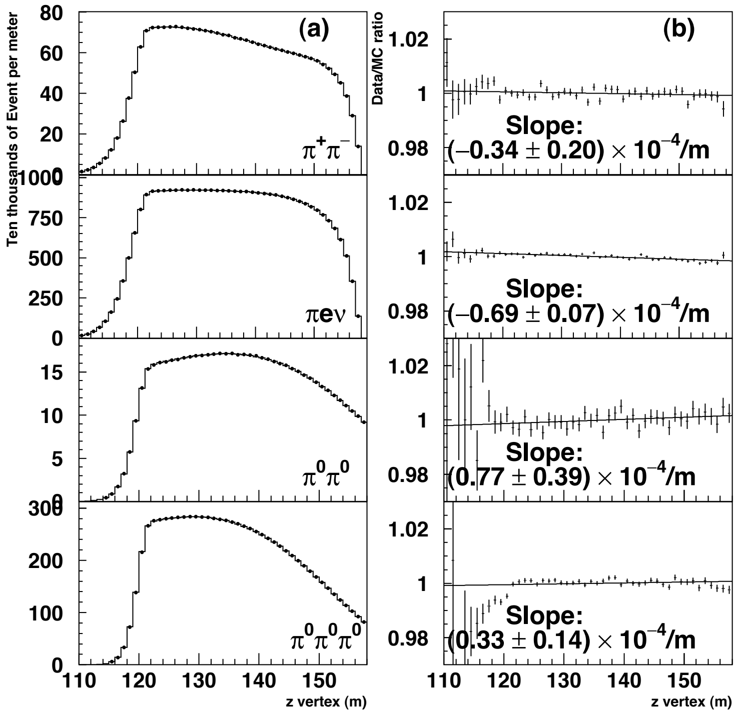

Figure 2: Z coordinate of the kaon decay point in the vacuum beam for data (dots) and MC (histogram), (a), and the ratio of data to MC distributions, (b), for (from top to bottom) $K_L \to \pi^+\pi^-$, $K_L \to \pi^\pm e^\mp \nu$, $K_L \to \pi^0\pi^0$ and $K_L \to \pi^0\pi^0\pi^0$ decays.

updates in MC include new charged particle tracing in the detector, which were also used for the KTeV measurement of the parameter V_{us}[6] and better description of the photon showers, using a new GEANT-based[7] shower library. The new simulation of the photon showers leads to significant reduction of the energy scale uncertainty, which is the main source of the error for $Re(\epsilon'/\epsilon)$, this error is reduced from 1.3×10^{-4} to 0.65×10^{-4}.

3 Results

For the full combined dataset, the result of the analysis is

$$Re(\epsilon'/\epsilon) = [19.2 \pm 1.1_{\text{stat}} \pm 1.8_{\text{syst}}] \times 10^{-4} = [19.2 \pm 2.1] \times 10^{-4}. \tag{4}$$

The result is in a good agreement with the previous KTeV publication[1] : $Re(\epsilon'/\epsilon) = [20.7 \pm 1.5_{\text{stat}} \pm 2.4_{\text{syst}}] \times 10^{-4}$. A comparison of the KTeV measurement with other experiments is presented in Fig. 3. A good agreement between different results is observed; the world average, $Re(\epsilon'/\epsilon) = [16.8 \pm 1.4] \times 10^{-4}$, corresponds to a measurement of the direct CP violation parameter with 8% precision.

Decays in the regenerator beam are sensitive to $K_L - K_S$ interference and thus allow to measure Δm, ϕ_ϵ and $Im(\epsilon'/\epsilon)$. Measurements of Δm and ϕ_ϵ depend strongly on the properties of the kaon regeneration and transmission in the regenerator beam. The transmission in the regenerator beam has been re-measured using a high statistics sample of $K \to \pi^+\pi^-\pi^0$ events collected in 1999. A dedicated study of the screening corrections allowed to significantly reduce uncertainty arising from the kaon regeneration. As a result, the measurement of ϕ_ϵ is significantly improved compared to previous KTeV publication[1] providing a better CPT symmetry test. For

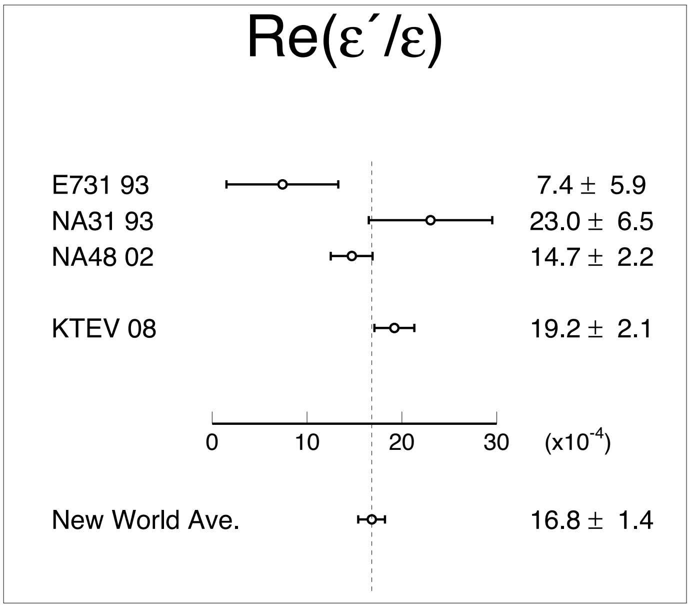

Figure 3: $Re(\epsilon'/\epsilon)$ measured by E731[4], NA31[3], NA48[2] and KTeV[1] collaborations together with an average of these four measurements labeled as "New World Ave.".

an analysis without CPT constraints, KTeV obtains:

$$\begin{array}{lcl} \tau_S & = & [89.589 \pm 0.070] \times 10^{-12}\ \mathrm{s}, \\ \Delta m & = & [5279.7 \pm 19.5] \times 10^6\ \hbar/\mathrm{s}, \\ \phi_\epsilon & = & [43.86 \pm 0.63]^\circ, \\ Im(\epsilon'/\epsilon) & = & [-17.20 \pm 20.20] \times 10^{-4}. \end{array} \tag{5}$$

The measured $Im(\epsilon'/\epsilon)$ corresponds to $\Delta\phi = [0.30 \pm 0.35]^\circ$. The data are consistent with CPT symmetry: $Im(\epsilon'/\epsilon)$ and $\delta\phi = \phi_\epsilon - \phi_{SW} = [0.40 \pm 0.56]^\circ$ are consistent with zero. Imposing the CPT conservation as an additional constraint allows to reduce uncertainties on τ_S and Δm. This is illustrated in Fig. 4 which shows correlations of $\tau_S, \Delta m$ and ϕ_ϵ together with a band derived from $\delta\phi = 0$ condition. The resulting τ_S and Δm are:

$$\begin{array}{lcl} \tau_S & = & [89.623 \pm 0.047] \times 10^{-12}\ \mathrm{s}, \\ \Delta m & = & [5269.9 \pm 12.3] \times 10^6\ \hbar/\mathrm{s}. \end{array} \tag{6}$$

Using these values KTeV determines $\phi_{SW}|_{cpt} = [43.419 \pm 0.058]^\circ$.

4 Conclusions

The final measurement of $Re(\epsilon'/\epsilon)$ and other kaon system parameters by the KTeV collaboration based on complete dataset is presented. Increase of the data sample and improvements of the analysis techniques allow to reduce the total uncertainties compared to the previous publication[1]. The world measurements of $Re(\epsilon'/\epsilon)$ are consistent with each other and establish firmly the presence of direct CP violation in the kaon decays. With improved precision, the data do not show any indication of CPT symmetry violation.

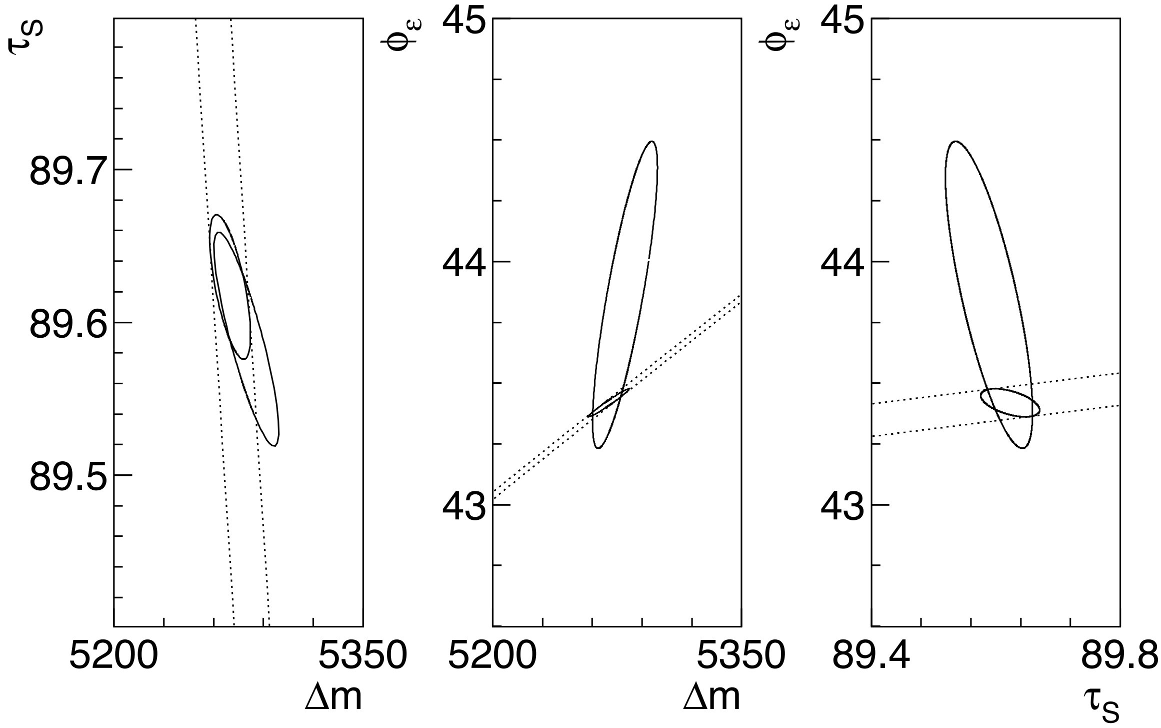

Figure 4: $\delta\chi^2 = 1$ contours of total uncertainty for (a) Δm and τ_S, (b) ϕ_e and Δm, (c) τ_S and ϕ_e. Dashed lines show $\phi_\epsilon = \phi_{SW}$ CPT constraint. Larger (smaller) ellipses correspond to results without (with) assumption of CPT symmetry conservation.

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