Fermi National Accelerator Laboratory

FERMILAB-Conf-94/214-E

E731

CP Violation Measurements in Neutral Kaon System at Fermilab

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July 1994

Talk given at *XXIXth Rencontres de Moriond, Electroweak session*, Meribel, France, March 12-19, 1994.

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

CP VIOLATION MEASUREMENTS IN NEUTRAL KAON SYSTEM AT FERMILAB

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Current results on the *direct* CP-violation measurements ε'/ε in neutral kaon system at Fermilab (E731) in US are reviewed. The method used also allowed precise determinations of several other kaon decay parameters, Δm, $\Delta\Phi$ and Φ_{+-} for stringent test on CPT invariance. New results of rare kaon decays from E799-I for $K_L \to \pi^0 e^+e^-$, $\pi^0\mu^+\mu^-$, $\pi^0\nu\bar{\nu}$ and $e^+e^-e^+e^-$ are also presented here. We then discuss the current status of the new KTeV experiment and the future prospects of the possible kaon experiments at Fermilab Main Injector.

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Introduction

CP-violation was first discovered in K_L decays in 1964. Since then, all manifestations of *CP*-violation are consistent with time-asymmetric oscillations (parametrized by ε) between K^0 and $\bar{K}^0$. The standard Cabbibo-Kobayashi-Maskawa (CKM) model[1] can naturally accommodate *CP*-violation, but it also predicts *direct CP*-violation where a particle of one *CP* eigenstate can *decay directly* to a final state of opposite *CP*. The alternative theories, such as the "superweak" model[2] which hypothesizes a new ΔS=2 interaction, predicts a mixing between K^0 and $\bar{K}^0$, but no *direct* *CP*-violation in the decay amplitude. Therefore it is important to search for the *direct CP*-violation.

The presence of *direct CP*-violation, parametrized by ε', would shift the ratio of *CP*-violating to *CP*-conserving $\pi\pi$ decay amplitudes, η, of $\pi^+\pi^-$ (charged) to $\pi^0\pi^0$ (neutral) final state. Thus the following double ratio R of $\pi\pi$ rates would differ from unity:

$$R = \frac{|\eta_{+-}|^2}{|\eta_{00}|^2} = \frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)} \cong 1 + 6\, Re(\varepsilon'/\varepsilon) \quad (1)$$

In the CKM model, the expected level for Re(ε'/ε) is of order 0.001.[3]

The *direct CP*-violation could also appear in the rare K_L decays, such as $\pi^0 e^+e^-$, $\pi^0\mu^+\mu^-$ or $\pi^0\nu\bar{\nu}$, but with very small branching ratio in the CKM model, in the range between 10^{-12} to 10^{-11} (depend on the top quark mass).[3] The possible contributions to these modes result from *CP*-conserving, indirect *CP*-violating, and *direct CP*-violating processes. The relative contributions from each process vary for different final state leptons. For example, in the decay $K_L \to \pi^0\nu\bar{\nu}$ the *direct CP*-violating process is the only significant contribution to the branching ratio and would therefore be theoretically the cleanest signal for *direct CP*-violation. There are other theories, probing physics beyond the standard model, could enhance those rare decays by an order of magnitude. Therefore it is important to study those rare K_L decays to understand the *origin* of the *CP*-violation.

It is interesting to probe *CPT* symmetry in addition to *CP*-violation. While it is difficult to build a realistic local quantum field theory that does not satisfy *CPT* symmetry, it is possible that the topology of string theories could lead to a violation of *CPT* symmetry. In the neutral kaon system, *CPT* symmetry coupled with Unitarity implies that the K_S and K_L lifetimes and the K_S-K_L mass difference Δm should be related to the phases of η_{+-} and η_{00} via

$$\Phi_{+-} \approx \Phi_{00} \approx tan^{-1}\frac{2\Delta m}{\Gamma_S - \Gamma_L} \quad (2)$$

where $\Gamma_{S(L)}$ is the $K_{S(L)}$ decay rate and $\Phi_{+-(00)} = arg(\eta_{+-(00)})$. The righthand expression is commonly known as the superweak phase Φ_{SW}. Accurate measurements of Δm and τ_S are necessary not only for the verification of (2), but also for accurate determination of the phases Φ_{+-} and Φ_{00}. One can also directly compare the charged and neutral phases, which are expected to be equal to within a fraction of a degree, *i.e.*, $\Delta\Phi = \Phi_{+-} - \Phi_{00} \approx 0$, if *CPT* is invariant.[4]

Results from E731 on ε'/ε, Δm, $\Delta\Phi$ and Φ_{+-}.

The primary goal of the Fermilab E731 experiment has been a precise measurement of the *CP*-violating parameter $Re(\varepsilon'/\varepsilon)$. The final results and detailed descriptions of the detector, reconstruction technique, background determination and systematics can be found in the publications.[5] The results will be summarized here following a brief description of the measurement technique.

To minimize systematics in the measurement of double ratio in (1), $K \to \pi\pi$ decays to either the neutral or charged final state were collected simultaneously. The experiment used two parallel K_L beams, and K_S were produced in one of them by coherent regeneration. This gave K_L and K_S with identical spatial and similar momentum distributions. The regenerator alternated between the two beams to make any biases from asymmetries in the beams and detector negligible. Because the decays from the two beams are collected simultaneously, the ratio of rates in the two beams is largely insensitive to accidental activity and to changes in detector or accelerator performance on any time scale during the run. However, the difference in the K_L and K_S lifetimes requires that the detector acceptance as a function of decay vertex be well understood. Millions decay to the Ke3 and $3\pi^0$ final states were collected to aid the acceptance determination. A detailed Monte Carlo (MC) simulation was used for the acceptance determination as well as for simulation of some of the backgrounds. The agreement between MC and data distributions in the $2\pi^0$ and $\pi^+\pi^-$ decay modes, as well as in the copious $3\pi^0$ and Ke3 modes are all excellent. It is important that the event trigger, reconstruction and selection criteria were independent of the beam from which the kaon decayed.

The final result for $Re(\varepsilon'/\varepsilon)$ was obtained[5] by fitting the $2\pi^0$ and $\pi^+\pi^-$ data simultaneously in momentum bins between 40-160 GeV, which is

$$Re(\varepsilon'/\varepsilon) = (7.4 \pm 5.2_{stat.} \pm 2.9_{syst.}) \times 10^{-4}.$$

The value is consistent with zero. The combined uncertainty is 5.9×10^{-4}. It implies $Re(\varepsilon'/\varepsilon) < 17 \times 10^{-4}$ (95% confidence).

While evidence for *direct CP*-violation in the $\pi\pi$ decays of the neutral kaon was given in 1988 by the CERN NA31 experiment,[6] E731 collaboration reported the final result in 1993, which favors no *direct CP*-violation!

The same E731 data set was used to determine several other parameters of the neutral kaon by fitting the decay rate distribution at a distance z downstream of the regenerator for a kaon momentum p:

$$\frac{dN}{dpdz} \propto F(p)|\rho(p)e^{-z(\Gamma_S/2+i\Delta m)/\gamma c} + \eta e^{-z\Gamma_L/2\gamma c}|^2, \qquad (3)$$

where c is the speed of light and γ is the kaon Lorentz boost. The incident flux of kaon $F(p)$ is identical to that in the vacuum beam. The regeneration amplitude $\rho(p)$ is expected to have the form $\rho(p) \propto p^{\alpha} exp(-i\pi(2+\alpha)/2)$, where the phase $\Phi_\rho = \pi(2+\alpha)/2$ follows from analyticity. In all the fits, the regeneration was constrained to have this momentum dependence with the regeneration amplitude and the power α. The charged and neutral modes were fitted separately. *CPT* was assumed explicitly in these fits through the use of (2). Our trigger and fiducial z cuts let us probe out to proper times of $7\tau_S$ in $\pi^+\pi^-$ mode, while the extended fiducial volume in the $2\pi^0$ mode lets us probe out to almost $11\tau_S$, as shown in Figure 1a and 1b. Combining the charged and neutral fits gave[5)]

$$\tau_S = (0.8929 \pm 0.0016) \times 10^{-10} s,$$
$$\Delta m = (0.5286 \pm 0.0028) \times 10^{10} \hbar /s.$$

τ_S agrees well with the current Particle Data Group[7)] (PDG) average, while Δm is about 2 standard deviations lower than the PDG average of $(0.5351 \pm 0.0024) \times 10^{10} \hbar /s$.

For the $\Delta\Phi$ measurement, a simultaneous fit to the charged and neutral mode data is done by floating $\mathrm{Re}(\varepsilon'/\varepsilon)$, Φ_{+-} and $\Delta\Phi$ and used the above τ_S and Δm from our data. The fit gives $\Delta\Phi = -1.6° \pm 1.0° \pm 0.7°$ with the combined error $\pm 1.2°$. This is more precise than the PDG average of $-0.1° \pm 2.0°$. To extract Φ_{+-}, we performed a similar fit with Δm floating. We obtained $\Phi_{+-} = 42.2° \pm 1.4°$, and a consistent value for Δm (with about twice the error). Our results are in good agreement with the expectations of (2).

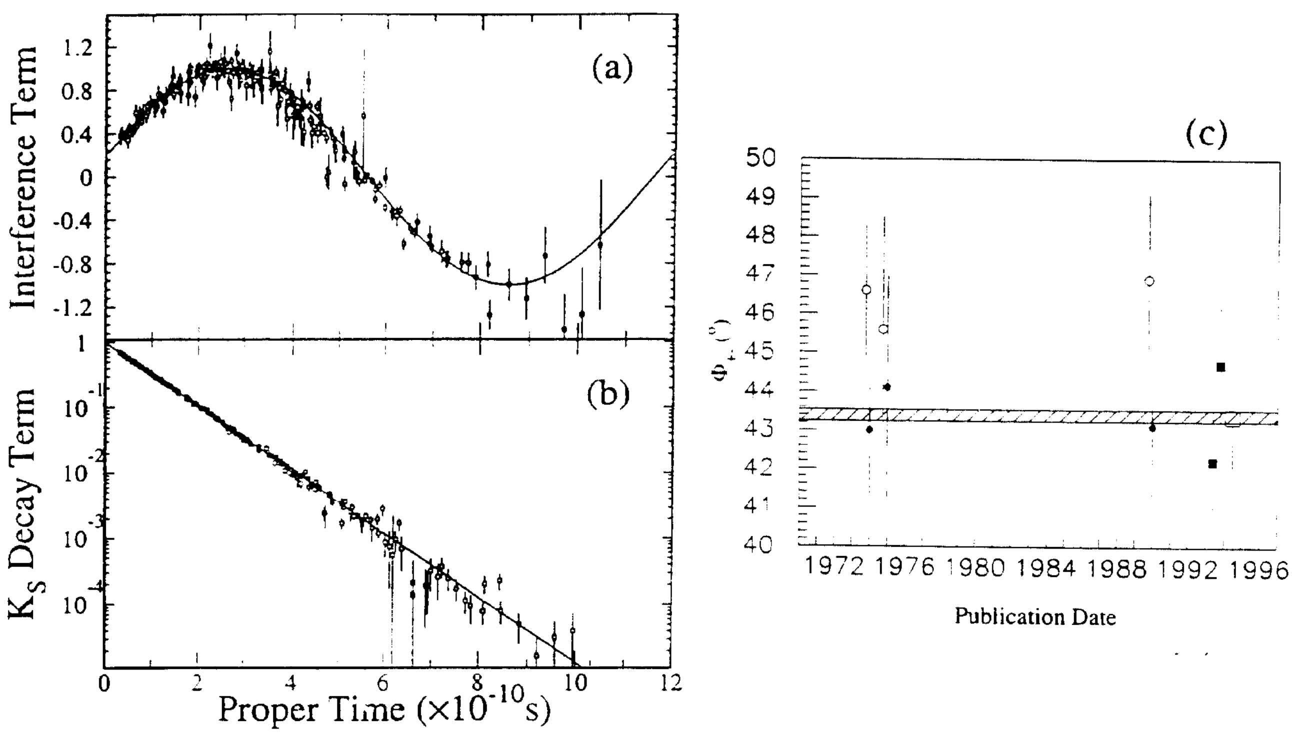

FIGURE 1: (a) The interference term of the distribution in proper time for $2\pi^0$ decays; (b) the exponential decay term for $K_S \to 2\pi^0$; (c) the recent measurements of Φ_{+-}, the open circles are the results used to determine PDG average and the solid points are the same measurements corrected using E731 Δm and more recent results. The references to the results are in time order 8), 5), 9).

Furthermore, taking the quoted sensitivities to Δm and our new Δm result to correct previous measurements of Φ_{+-},[8] in Figure 1c, gives an average of $\Phi_{+-} = 42.8° \pm 1.1°$, in good agreement with our measurement and (2). The preliminary Δm measurement from CPLEAR[9] and E773 data have confirmed the preferred lower E731 value than PDG average. The results from E773 on Φ_{+-} and $\Delta\Phi$ will be ready soon in the next few months after almost two years detailed data analysis.

Rare decay results from E799-I

E799-I is an experiment with the principal focus on how to improve the search of *CP*-violating rare K_L decay modes, $\pi^0 e^+e^-$, $\pi^0\mu^+\mu^-$ or $\pi^0\nu\bar{\nu}$. The experiment collected many different rare decay modes from October 1991 to January 1992 which corresponded to about 26 billion K_L decays from the various prescaled normalization modes. New limits on these modes from the data collected have recently been published. These new results will be summarized below.

For the decay $K_L \to \pi^0\mu^+\mu^-$, the best previous limit is 1.2×10^{-6} at 90% confidence level.[7] About 60 million 2μ triggers were collected in E799-I run which requires mainly two hits in non-adjacent counters in muon trigger plane, at least 6 GeV deposited in the EM calorimeter, and there be hits in the drift chambers consistent with two tracks. The event selection first looked for two tracks in the drift chambers originated from a common vertex with good muon identification, additionally two photon candidates formed a good π^0 mass as well as the invariant mass of $\pi^0\mu^+\mu^-$ within 15 MeV/c^2 of the K_L mass (3σ cut) and p_t^2 (transverse momentum square) less than 500 (MeV/c)^2 (3σ cut). Figure 2a shows the p_t^2 versus total invariant mass for all the remaining $K_L \to \pi^0\mu^+\mu^-$ candidates. There are no candidate events in the signal region. The events at low mass are consistent with being from $K_L \to \pi^0\pi^+\pi^-$ events. The sensitivity for this decay mode was determined from $K_L \to \pi^0\pi^+\pi^-$ events in the prescaled (3600) minimum bias two track triggers. The acceptance for $K_L \to \pi^0\mu^+\mu^-$ is $1.4 \pm 0.1\%$ and for $K_L \to \pi^0\pi^+\pi^-$ is 4.26%. There were 50352 candidate $K_L \to \pi^0\pi^+\pi^-$ events in the minimum bias sample which gives the single event sensitivity for $K_L \to \pi^0\mu^+\mu^-$ to be $(2.2 \pm 0.01_{stat} \pm 0.2_{syst}) \times 10^{-9}$. The limit on branching ratio is[10]

$$B(K_L \to \pi^0\mu^+\mu^-) < 5.1 \times 10^{-9} \quad \text{(90\% confidence)}.$$

This measurement represents an improvement in $K_L \to \pi^0\mu^+\mu^-$ sensitivity of over a factor of 200. Since this measurement is relatively background free, future experiment should be able to achieve still higher sensitivities.

For the decay $K_L \to \pi^0 e^+e^-$, the best previous limits on the branching ratio are 5.5×10^{-9} from BNL E845 and 7.5×10^{-9} from E731.[7] The new upper limit from E799-I using the decay $K_L \to e^+e^-\gamma$ events for normalization and the result is[10]

$$B(K_L \to \pi^0 e^+e^-) < 4.3 \times 10^{-9} \quad \text{(90\% confidence)}.$$

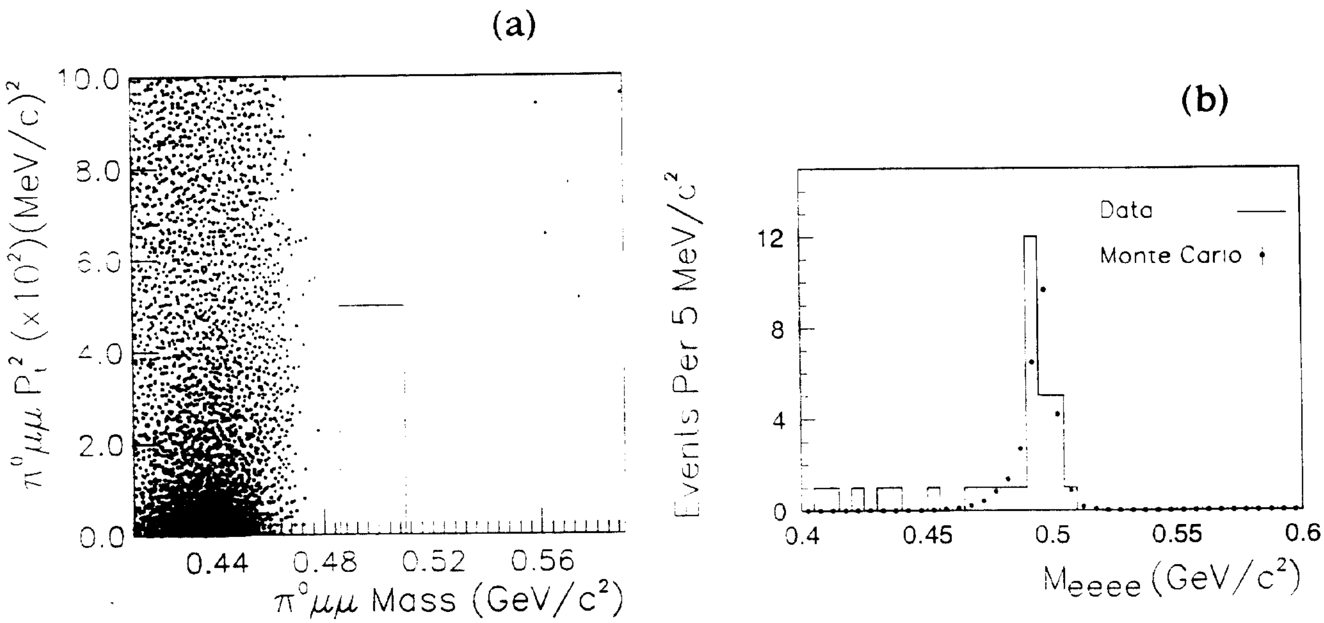

FIGURE 2: (a) $\pi^0\mu\mu$ invariant mass vs p_t^2 distribution, no event in signal region; (b) $K_L \rightarrow e^+e^-e^+e^-$ mass distribution. There are 27 4*e* events in the signal region.

This is a 20% improvement on the previous limit. By combining the three most sensitive limits, the "world limit" is then $B(K_L \rightarrow \pi^0 e^+e^-)_{world} < 1.8 \times 10^{-9}$. This is a two order of magnitude higher than the Standard Model predictions, so there is still room for new physics to be discovered in this mode.

The search for $K_L \rightarrow \pi^0 \nu\bar{\nu}$ was tagged by π^0 Dalitz decays ($\pi^0 \rightarrow e^+e^-\gamma$) and normalized to $K_L \rightarrow e^+e^-\gamma$ events. No events was seen in the signal region, results the limit[11)] on the branching ratio to be $B(K_L \rightarrow \pi^0\nu\bar{\nu}) < 5.7 \times 10^{-5}$.

Finally, a search for the rare decay of $K_L \rightarrow e^+e^-e^+e^-$ has been carried out in the E799-I analysis.[12)] There are 27 clean 4*e* events in the reconstructed invariant mass region, as shown in Figure 2b. The branching ratio was normalized to the 1540 fully reconstructed $3\pi^0$ events with two π^0s Dalitz decay . The branching ratio after correcting the loss due to radiative correction is

$$B(K_L \rightarrow e^+e^-e^+e^-) = (3.96 \pm 0.78 \pm 0.32) \times 10^{-8}.$$

Status of New KTeV experiments

The goal of KTeV is to perform the same measurements as E731 and E799-I with a fully optimized detector and beam, making major inroads upon all of the problems encountered with the last detector. A much cleaner and more intense neutral beam is under construction.

ε'/ε can be measured to a precision of 10^{-4} (E832), and a large variety of rare decay modes of the neutral kaon can be studied at the 10^{-11} level (E799-II). The latest Standard Model calculations by two groups (Buras *et al.*[13]) and Martinelli *et al.*[14])) favor a non-zero value of ε'/ε around 7×10^{-4}, weakly dependent upon the top quark mass. Thus with this sensitivity, there is an excellent chance of observing the *direct* CP-violation.

The detector consists of a large pure CsI electromagnetic calorimeter, a drift chamber spectrometer with a new large aperture magnet, an extensive veto system, a TRD system, a muon system and an elaborate trigger and data acquisition system. For E832, the same technique as in E731 (2 simultaneous beams with a regenerator in one) is employed. For E799, both beams will be K_L. The detector is now under construction (about 50% completion). The building will be completed in May of 1995 and the date for first beam is January 1996.

Future Prospect - Kaon At Main Injector (KAMI)

KTeV is designed to determine ε'/ε with a precision of 10^{-4} and study a variety of interesting rare kaon decays at the 10^{-11} level. However, to make substantial further progress, a new higher intensity source of kaons is needed. The Main Injector will provide that source with 3×10^{13} protons per 2.9 sec at 120 GeV.

Measurements of ε'/ε, $K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ together with a measurement of $B^0 \to \psi K_S$ can in fact over-constrain the CP-violating unitarity triangle shown in Figure 3. A 10% measurement of the $K_L \to \pi^0 \nu\bar{\nu}$ branching ratio constrains the Wolfenstein η parameter to the 5% level with very little theoretical uncertainty.[15]) In addition, a 10% measurement of the $K^+ \to \pi^+ \nu\bar{\nu}$ branching ratio cleanly constrains the magnitude of V_{td}, thereby constraining $\sqrt{(\rho\text{-}1.0)^2 + \eta^2}$ as shown in Figure 3. Current constraints on the magnitude of V_{td} are extracted from measurements of B^0-$\bar{B}^0$ mixing, and this extraction suffers from significant theoretical uncertainties. In contrast, extracting V_{td} from the $K^+ \to \pi^+ \nu\bar{\nu}$ branching ratio is theoretically robust.

One of the first goals of a high intensity B physics program will be a good measurement of the $B^0 \to \psi K_S$ decay mode which in turn determines the angle β in Figure 3. A comprehensive B physics program aims to constrain the unitary triangle by measuring each of the three angles. Measuring the other two angles, α and γ, is significantly more difficult than measuring β at either Fermilab collider or the B-factory. A $\pm 5°$ measurement of 2β should be possible at the collider in the Main Injector era, which together with measurements of the ε'/ε and rare K decays can over-constrain the unitarity triangle toward the understanding of the CP-violation. Hence measurements at KAMI have the potential to critically test the CP-violating unitarity triangle possibly years before a B-factory can do the same.

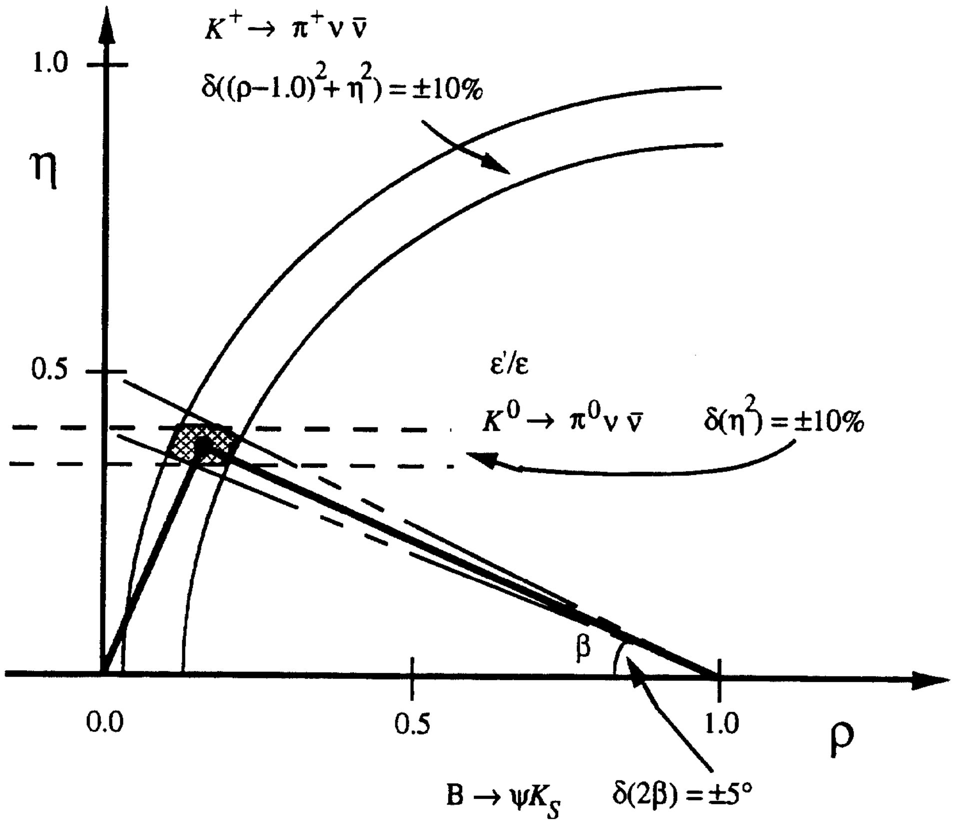

FIGURE 3: Determination of the CP-violating unitarity triangle assuming that 10% measurements on branching ratios of $K_L \to \pi^0 \nu \bar{\nu}$ and $K^+ \to \pi^+ \nu \bar{\nu}$ at KAMI together with a ±5° measurement on 2β of $B^0 \to \psi K_S$ from the Fermilab Collider in the Main Injector era.

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