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ϵ'/ϵ and Rare K_L Decays From KTeV Experiment

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We update the current status for the measurement of the direct-CP violation parameters ϵ'/ϵ in the KTeV experiment at Fermilab. Substaintial statistics have been accumulated during the 1996-7 run and 1999 run for both ϵ'/ϵ and rare K_L decay searches. The first KTeV result on ϵ'/ϵ published last year was $\mathrm{Re}(\epsilon'/\epsilon) = (28.0 \pm 4.1) \times 10^{-4}$ based on the 23% data from 1996-7 run. Combining with the previous E731, NA31 and the recent preliminary NA48 results, the grand average is $\mathrm{Re}(\epsilon'/\epsilon) = (19.3 \pm 3.6) \times 10^{-4}$ (with $S = 1.49$), more than 5σ above zero. More data from both KTeV and NA48 after completing the analysis will further improve the precision of this measurement in the near future and hopefully further improve the agreement. New results on the braching ratio and form factor measurements of $K_L \to \mu^+\mu^-\gamma$ using 1997 data are also presented. We find that $BR(K_L \to \mu^+\mu^-\gamma) = (3.66 \pm 0.04_{stat} \pm 0.07_{syst}) \times 10^{-7}$. The form factor parameter α_{K^*} is measured to be $\alpha_{K^*} = -0.157^{+0.025}_{-0.027}$. We make the first measurement of the parameter α from the D'Ambrosio, Isidori, and Portolés form factor, finding $\alpha = -1.53 \pm 0.09$. This measurement of α limits the CKM parameter $\rho > -0.2$.

1. Introduction

KTeV (Kaon at TeVatron) experiment was designed to use the high energy neutral kaons, produced from the Fermilab Tevatron beam striking a fixed target, to study the CP-violation – so called matter and anti-matter asymmetry and other important rare decay phenomena.

The "origin" of CP violation is a long lasting piece of puzzle in physics. The CP violation was originally discovered by Cronin and Fitch [1] in $K_L \to \pi^+\pi^-$ decays in 1964. The dominant effect is due to a small asymmetry of the $K^0 - \bar{K}^0$ mixing or an admixture of wrong CP states in the K_S and K_L neutral kaons before the decay, parametrized by ϵ, ~ 0.0023.

However, the question is whether or not the CP violation occurs in the $K \to \pi\pi$ decay process itself, or whether the CP-odd component of neutral kaon decays directly into the CP-even final state. An effect referred to as "direct-CP violation" [2], parametrized by ϵ' which contributes differently to the rates of $K_L \to \pi^+\pi^-$versus $K_L \to \pi^0\pi^0$ decays (relative to the corresponding K_S decays), and would be observed as a nonzero value in the ratio of $\mathrm{Re}(\epsilon'/\epsilon)$.

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To extract the ϵ', we measure the double ratio R experimentally,

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

For more than 35 years, the small CP violation has only been observed in weak decays and so far only in the neutral kaon system, e.g. charge asymmetry δ_l in K_{e3} and $K_{\mu 3}$ decays; η_{+-}, η_{00} and $\eta_{+-\gamma}$ in $K_L \to 2\pi$ and $K_L \to \pi^+\pi^-\gamma$ decays [3]; as well as the recent CP-odd and T-odd angular asymmetry in $K_L \to \pi^+\pi^-e^+e^-$ [4].

While CP violation can be accommodated within the Standard Model with three generations of quark families [5] with a complex phase, we still do not fully understand the *origin* of this violation and do not know whether the Standard Model provides the *sole* source of CP violation or not. The search for a more complete understanding of CP violation has been the driving force behind a variety of recent kaon experiments, such as KTeV, NA48 and KLOE, as well as B-factory experiments, such as Belle and Babar. Besides a small amount of unequal mixture can give such tiny indirect CP-violation effect, ϵ; there are also other decay processes [6] in the Standard Model

Table 1
Experimental measurments on $\mathrm{Re}(\epsilon'/\epsilon)$ since 1986.

Experiments	Year Published	$\mathrm{Re}(\epsilon'/\epsilon)(\times 10^{-4})$
E731A [7]	1988	(32 ± 30)
NA31 ('86) [8]	1988	(33 ± 11)
E731B (20%) [9]	1990	(-4 ± 15)
E731B (final) [10]	1993	(7.4 ± 5.9)
NA31 (final) [11]	1993	(23.0 ± 6.5)
KTeV (23% '96-'97) [12]	1999	(28.0 ± 4.1)
NA48 ('97) [13]	1999	(18.5 ± 7.3)
NA48 ('98 prelim.) [14]	2000	(12.2 ± 4.9)
Grand Average ($S = 1.49$)		(19.3 ± 3.6)

which can give a new kind of *CP*-violation directly, the ϵ', smaller than ϵ. The effect of non-zero direct *CP*-violation has only been established recently by NA31 [11] and KTeV [12]. Table 1 lists the $\mathrm{Re}(\epsilon'/\epsilon)$ measurements since 1986 including the most recent results from KTeV and NA48 [15].

The standard Cabbibo-Kobayashi-Maskawa (CKM) model accomodates *CP* violation with a complex phase in the quark mixing matrix. However, the theoretical calculations of $\mathrm{Re}(\epsilon'/\epsilon)$ are still uncertain depending on several input parameters and on the method used to estimate the hadronic matrix elements [16], though the recent estimates had favored non-zero values around 10^{-3}. Alternatively, a "superweak" interaction [17] could also produce the observed *CP*-violating mixing effect (ϵ) but would give $\mathrm{Re}(\epsilon'/\epsilon) = 0$. Therefore, a non-zero measurement of $\mathrm{Re}(\epsilon'/\epsilon)$ rules out the superweak interaction is the sole source of *CP* violation, and would establish the "direct" *CP*-violation phenomenon from the decay process itself.

If the direct *CP* violation exists, not only we would observe a non-zero value for $\mathrm{Re}(\epsilon'/\epsilon)$, but also we should observe very rare direct *CP*-violating kaon decay modes, such as $K_L \to \pi^0 e^+ e^-$, $K_L \to \pi^0 \mu^+ \mu^-$and $K_L \to \pi^0 \nu \bar{\nu}$. The probability of observing such rare decays is quite small, less than 10^{-10} to 10^{-11}. Current experiments are barely reaching this sensitivity in KTeV [18] and the search is still on-going.

2. KTeV Detector

The KTeV experiment (shown in Fig. 1) was designed to improve on the previous experiments and ultimately to have the sensitivity to establish "direct" *CP*-violation if $\mathrm{Re}(\epsilon'/\epsilon)$ is on the order of 10^{-3} with a sensitivity of 10^{-4}. The experimental technique was essentially the same as in E731 [19] with many improvements in beam and detector performance. Double kaon beams from a BeO target (produced from an 800 GeV/c proton beam striking at 4.8 $mrad$ angle with an intensity of 4.5×10^{12} per pulse) was used to enable the simultaneous collection of K_L and K_S decays to minimize the systematics due to time variation of beam flux and detector inefficiencies. A precision magnetic spectrometer (with 412 MeV/c p_T kick in KTeV but 200 MeV/c for E731) was used to minimize backgrounds in the $\pi^+\pi^-$ samples and to allow *in situ* calibration of the calorimeter with electrons. A high precision EM calorimeter, 3100-crystal Cesium Iodide (CsI) array, was used in KTeV instead of the lead-glass calorimeter in E731 for $\pi^0\pi^0$ reconstruction and better background suppression. Superb mass resolutions (1.5 MeV/c^2 for $\pi^0\pi^0$ and 1.6 MeV/c^2 for $\pi^+\pi^-$) and photon energy resolution (better than 0.7% above 20 GeV/c^2) were achieved. Nearly hermetic photon vetoes were employed for further background reduction for the $\pi^0\pi^0$ mode. A new beamline was constructed for KTeV with cleaner beam collimation and improved muon sweeping.

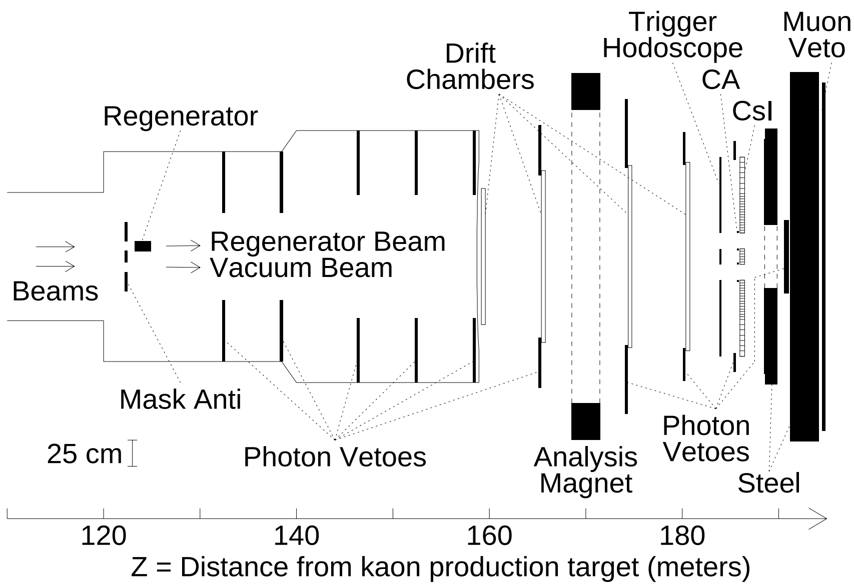

Figure 1. Plan view of the KTeV apparatus with double kaon beam as configured to measure $\mathrm{Re}(\epsilon'/\epsilon)$. The evacuated decay volume ends with a thin vacuum window at $Z = 159\ m$, followed by magnetic spectrometer for $\pi^+\pi^-$. The label "CsI" indicates the electromagnetic calorimeter for $\pi^0\pi^0$ detection.

While the method of producing a K_S beam (by passing a K_L beam through a "regenerator") was also the same as E731, the KTeV regenerator was made of scintillator and was fully active to reduce the scattered background to the coherently regenerated K_S. Unlike E731, both $\pi^+\pi^-$ and $\pi^0\pi^0$ data were taken simultaneously in KTeV.

3. The Status of ϵ'/ϵ Measurements

High statistics 2π data was taken by KTeV in two running periods, 1996-1997 and 1999 fixed target runs at Fermilab. The 1996-1997 data sample gives about 4 million CP-violating $K_L \to \pi^0\pi^0$ (the limiting statistics mode) and for the 1999 run about 4.5 million $K_L \to \pi^0\pi^0$ decays.

First result of $\mathrm{Re}(\epsilon'/\epsilon)$ based on a sub-sample from 23% of 1996-1997 data sample of KTeV was published in 1999 [12] with the statistics after background subtraction of 2.607M $\pi^+\pi^-$ events in the vacuum beam, 4.516M $\pi^+\pi^-$ in the regenerator beam, 862K $\pi^0\pi^0$ in the vacuum beam and 1.434M $\pi^0\pi^0$ in the regenerator beam.

The $\mathrm{Re}(\epsilon'/\epsilon)$ was extracted from the background-subtracted data using a fitting program which analytically calculates regeneration and decay distributions accounting for $K_S - K_L$ interference. After the acceptance correction, the resulting prediction for each decay mode is integrated over Z and compared to data in 10 GeV bins of kaon energy. CPT symmetry is assumed, and the values of $K_S - K_L$ mass difference (Δm) and K_S lifetime (τ_S) are fixed to PDG values [20]. The regeneration amplitude is allowed to float in the fit, but constrained to have a power law dependence on kaon energy, with the phase determined by analyticity [21].

Fitting was done "blind", by hiding the central value of $\mathrm{Re}(\epsilon'/\epsilon)$ with an unknown random offset between η_{+-} and η_{00}, until after the analysis and systematic error evaluation were finalized. The final fit gave $\mathrm{Re}(\epsilon'/\epsilon) = (28.0 \pm 3.0) \times 10^{-4}$, where the error is statistical only with a χ^2 of 30 for 21 degrees of freedom. Table 2 summarize the studies of various systematics where the details can be found in reference [12]. The to-

Table 2
Systematic uncertainties on $\mathrm{Re}(\epsilon'/\epsilon)$.

Source of Uncertainty	Uncertainty ($\times 10^{-4}$) $\pi^+\pi^-$	$\pi^0\pi^0$
Trigger and Level 3	0.5	0.3
Energy nonlinearity	0.1	0.9
Calibration/alignment	0.3	0.4
Cut variations	0.6	0.8
Background	0.2	0.8
Detector resolution	0.5	0.5
Chamber simulation	0.6	-
Acceptance	1.6	0.7
Monte-carlo statistics	0.5	0.9
Flux and physics parameters	0.35	
TOTAL	2.8	

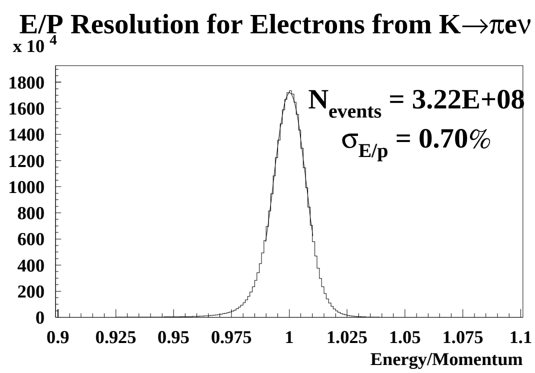

Figure 2. E/p resolution of CsI calorimeter for calibration $e^{\pm}$ from $Ke3$ decays of 1997 data.

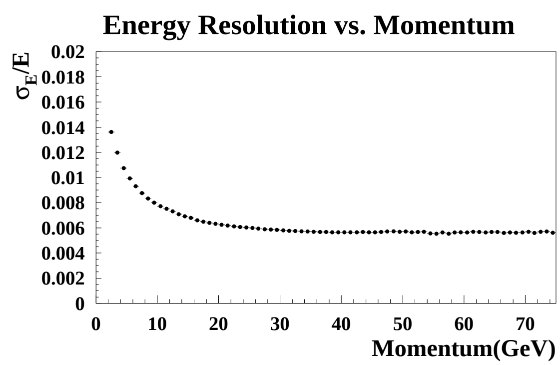

Figure 3. Intrinsic energy resolution versus momentum of an electron or photon for the CsI calorimeter from 1997 data.

tal systematic error is 2.8×10^{-4} with the largest one from the uncertainties of acceptance corrections and CsI calorimeter energy scale and nonlinearity. Effects due to accidental activities were taken into account in the monte-carlo acceptance simulation by overlaying the random accidental triggers taken during the run, on top of monte-carlo events. Several cross-checks on this $\mathrm{Re}(\epsilon'/\epsilon)$ result have been performed in this analysis. Consistent values were obtained at all kaon energies, and there was no significant variation as a function of time or beam intensity.

The rest of data from 1997 KTeV run are currently being analyzed with improved calibration and resolution for CsI and drift chamber system to reduce both statistical and systematic uncertainties. The E/p resolution for the calibration $e^{\pm}$ collected *in situ* from 322 million $Ke3$ decays is 0.70%, as shown in Fig. 2. The intrinsic energy resolution versus momentum for an electron or photon is shown in Fig 3. We expect a factor of 2 improvement in statistics for $\mathrm{Re}(\epsilon'/\epsilon)$ with 1997 data comparing with the published result based on first 23% data sample. Same "blind" analysis procedure will be used to hide

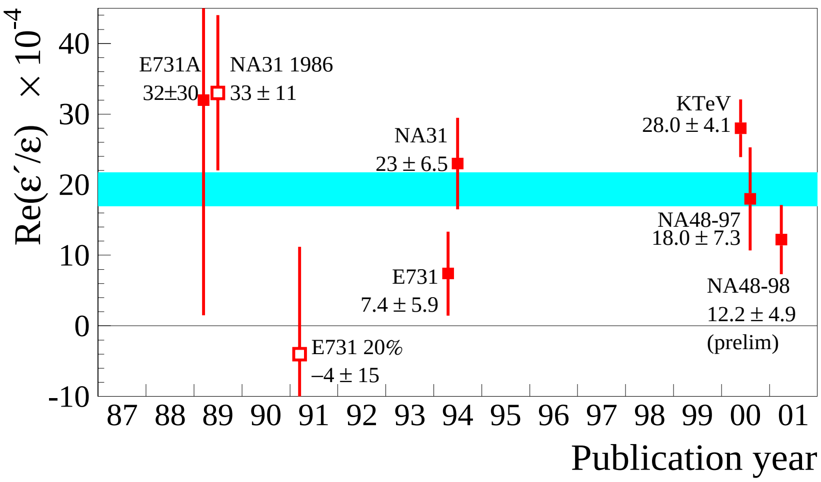

Figure 4. Comparison of the recent $\mathrm{Re}(\epsilon'/\epsilon)$ measurements since 1986.

the central value until the systematics uncertainties are understood. Data taken in 1999 run has doubled the statistics again with much improved detector performance and additional systematic checks, such as improved drift chamber efficiency in the neutral-beam region, reliable CsI readout electronics and better on-line calibration, various intensity studies and short regenerator studies. We expect KTeV will reduce the $\mathrm{Re}(\epsilon'/\epsilon)$ statistical uncertainty to $\sim 1 \times 10^{-4}$ and lower the systematics to a similar level.

The grand average so far for the measurements from KTeV, NA48, NA31 and E731 is $\mathrm{Re}(\epsilon'/\epsilon) = (19.3 \pm 2.4) \times 10^{-4}$ with a poor $\chi^2/ndf = 11.1/5$. Using the error treatment of Particle Data Group to increase the uncertainty based on the χ^2/ndf, $S = 1.49$, we get $\mathrm{Re}(\epsilon'/\epsilon) = (19.3 \pm 3.6) \times 10^{-4}$, more than 5σ above zero, which shows that a superweak interaction cannot be the explanation of CP violation in the K meson system. While this result is at the high end of standard-model predictions supports the notion of a nonzero phase in the CKM matrix, further theoretical and experimental advances are needed before one can say whether or not there are other sources of CP violation contributions beyond the standard model. So far the spread of the theoretical calculation on ϵ'/ϵ remains large (see the article [16] summarizing the theoretical status). Figure 4 shows the trend of recent experimental results on $\mathrm{Re}(\epsilon'/\epsilon)$ since 1986. In next few years we expect $\mathrm{Re}(\epsilon'/\epsilon)$ to be precisely measured by experiments (such as KTeV, NA48 and KLOE) to 5-10% of itself, which would challenge the theorists to further refine their calculations to understand the origin of direct CP violation.

4. Braching Ratio and Form Factor of $K_L \to \mu^+\mu^-\gamma$

The $K_L \to \mu^+\mu^-\gamma$ decay is a probe into the long distance physics associated with the intermediate $K_L \to \gamma^*\gamma$ vertex. Long distance processes involve low-energy electromagnetic interactions typically described by pseudoscalar meson pole models. These models are defined by the particular construction of a form factor in the differential decay rate which is a function of the off-shell photon invariant mass. Two such parameterizations come from Bergström, Massó, and Singer (BMS) [22]:

$$f(x) = \frac{1}{1-0.418x} + \frac{2.3\alpha_{K^*}}{1-0.308x}\left(\frac{4}{3} - \frac{1}{1-0.418x} - \frac{1}{9}\frac{1}{1-0.405x} - \frac{2}{9}\frac{1}{1-0.238x}\right), \qquad (2)$$

and from D'Ambrosio, Isidori, and Portolés (DIP) [23]:

$$f(x) = 1 + \alpha \left(\frac{x}{x - 2.40} \right), \quad (3)$$

where $x = (m_{\mu\mu}/m_{K_L})^2$. These form factors are used to calculate the long distance contributions to $BR(K_L \to \mu^+\mu^-)$, and a limit on the CKM parameter ρ can be extracted from the remaining short distance portion of the $K_L \to \mu^+\mu^-$ rate.

High intensity double K_L beam was employed in KTeV by removing the regenerator and Mask Anti counter from the beam in Fig. 1. KTeV collected $K_L \to \mu^+\mu^-\gamma$ signal and $K_L \to \pi^+\pi^-\pi^0$ normalization data with triggers requiring hits in trigger hodoscopes and drift chambers consistent with two tracks that point to clusters in the CsI calorimeter and that originate from a common vertex. The major difference in the signal trigger was an additional requirement that each of two muon trigger scintillator planes (located behind a 1 m shielding steel downstream of the muon veto hodoscope) have at least two hits. This necessitates a very good understanding of the absolute muon detection efficiency, which has been measured to $< 0.5\%$ of itself. Details of the measurement are found elsewhere [24].

All of the backgrounds to $K_L \to \mu^+\mu^-\gamma$ are kaon decays with one or more charged pions misidentified as muons. The dominant background mode is $K_L \to \pi^\pm\mu^\mp\nu$ with the pion misidentified and additional calorimeter energy accidentally coincident with the kaon decay. Because all backgrounds are characterized by missing or extra momentum, the most powerful rejection cut was that the reconstructed transverse momentum relative to the kaon flight direction be less than 10 MeV/c.

The final reconstructed $m_{\mu^+\mu^-\gamma}$ distribution is shown in Fig. 5a. There are 9327 events in the mass window 490 MeV/c^2 $< m_{\mu^+\mu^-\gamma} <$ 506 MeV/c^2. A factor of 40 increase in statistics over the current world sample. The normalized Monte Carlo predicts 221.9 ± 14.9 background events under the signal mass peak (2.4% background). Uncertainty in muon acceptances is the largest contribution to the combined 1.1% internal systematic error. However, this is dominated by the 1.6% uncertainty on $BR(K_L \to \pi^+\pi^-\pi^0)$ [3]. These errors are reflected in the final result $BR(K_L \to \mu^+\mu^-\gamma) = (3.66 \pm 0.04_{stat} \pm 0.07_{syst}) \times 10^{-7}$, which represents more than a factor of three improvement in precision over previous measurements.

Fig. 5b shows a model-independent measurement of the form factor as a function of x. The parameters, α_{K^*} and α were measured from the x distribution shape by making an unbinned likelihood comparison with Monte Carlo generated with various parameter values. Measurements were also made by integrating the differential decay rate using Eq. (2) or (3) to find $BR(K_L \to \mu^+\mu^-\gamma)$ as a function of α_{K^*} or α. The shape and branching ratio results were combined to give $\alpha_{K^*} = -0.157^{+0.025}_{-0.027}$ and $\alpha = -1.53 \pm 0.09$. The α_{K^*} measurements [25] from $K_L \to e^+e^-\gamma$ and $K_L \to \mu^+\mu^-\gamma$ are also shown in Fig. 6. Our new measurement establishes the α_{K^*} difference between electron and muon modes at the 3σ level. New high statistics measurement of $K_L \to e^+e^-\gamma$ from KTeV will likely shed light on such difference between electron mode and muon mode.

Extraction of a ρ limit begins with the decomposition $BR(K_L \to \mu^+\mu^-) = |\mathrm{Re}A|^2 + |\mathrm{Im}A|^2$. The experimental value $BR(K_L \to \mu^+\mu^-) = (7.15 \pm 0.16) \times 10^{-9}$ is almost completely saturated by the long distance unitarity bound, where $|\mathrm{Im}A|^2 = (7.00 \pm 0.18) \times 10^{-9}$ [3][26]. Short distance and $K_L \to \gamma^*\gamma^*$ contributions make up $\mathrm{Re}A = \mathrm{Re}A_{SD} + \mathrm{Re}A_{LD}$, which is limited to $|\mathrm{Re}A_{exp}|^2 < 4.0 \times 10^{-10}$(90%C.L.) by subtracting $|\mathrm{Im}A|^2$ from $BR(K_L \to \mu^+\mu^-)$ [27]. The $\mathrm{Re}A_{LD}$ can be calculated using the form factor measured from $K_L \to \mu^+\mu^-\gamma$ along and $\overline{\rho} = \rho(1 - \lambda^2/2)$ is limited with the expression

$$\overline{\rho} \; > \; 1.2 - \max \left[\frac{|\mathrm{Re}A_{exp}| + |\mathrm{Re}A_{LD}|}{3 \times 10^{-5}} \times \left(\frac{\overline{m}_t(m_t)}{170 \text{ GeV}} \right)^{-1.55} \left(\frac{|V_{cb}|}{0.040} \right)^{-2} \right]. \quad (4)$$

Using the measured form factor parameters, the limits on $\mathrm{Re}A_{LD}$ derived with the two models are $|\mathrm{Re}A_{LD}|_{BMS} < 3.6 \times 10^{-5}$ and $|\mathrm{Re}A_{LD}|_{DIP} < 2.07 \times 10^{-5}$. The $|\mathrm{Re}A_{LD}|_{BMS}$ limit is then combined with that on $|\mathrm{Re}A_{exp}|$

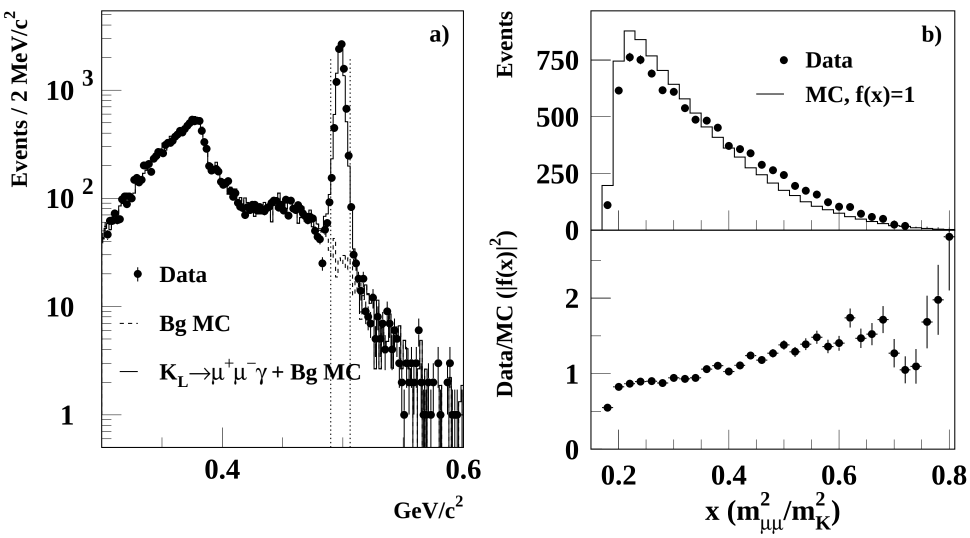

Figure 5. a) The reconstructed $m_{\mu^+\mu^-\gamma}$ distribution after final cuts. b) The dimuon mass distributions for data and for Monte Carlo with no form factor (top). The data/Monte Carlo ratio is a direct measurement of the form factor (bottom).

to obtain $\rho > -1.0$, which is not a useful result [28] However, using the $|\mathrm{Re}A_{LD}|_{DIP}$ limit yields $\rho > -0.2$. This result is quite close to the combined limit of $\rho > 0$ bsed on $|V_{ub}|$, B mixing, and ϵ [29]. The ρ limits from this channel are now dominated by theoretical uncertainties and the remaining experimental benifit would be an α measurement from $K_L \to e^+e^-\gamma$ to provide a consistency check of the DIP model.

5. Future Prospects

In a few years we expect $\mathrm{Re}(\epsilon'/\epsilon)$ can be precisely measured by experiments such as KTeV, NA48 and KLOE to 5-10% of itself, which would challenge the theorists to refine their calculations for the origin of direct-CP violation. This may well be the most precise measurement in search for "direct" CP violation in the next 5 to 10 years before upcoming B-physics experiments and the next generation $K_L \to \pi^0\nu\bar{\nu}$ experiments, such as KAMI, BNL-926 and KEK-PS-391 [30]. The $K_L \to \pi^0\nu\bar{\nu}$ decay though very challenging experimentally, is essentially pure direct CP violation and can be calculated theoretically very precisely and cleanly [31]. Its branching ratio depends directly on the CP-violating phase of the Standard CKM Model with little theoretical uncertainty. Therefore, an observation of $K_L \to \pi^0\nu\bar{\nu}$ signal events in the predicted range would measure directly the magnitude of CP-violating phase in CKM matrix elements. An observation of $K_L \to \pi^0\nu\bar{\nu}$ outside the range predicted by standard model would indicate new physics [32].

At the end of data taking for KTeV 1999 run we have devoted a few extra weeks beam time to study the neutral beam flux, momentum spectra of K_L and neutron in the neutral beam as well as the n/K_L ratio with 150 GeV Main Injector beam for the preparation of the future KAMI $K_L \to \pi^0\nu\bar{\nu}$ experiment.

6. Questions and Comments

Hsiang-nan Li (National Cheng-Kung Univ., Taiwan):
"The constraint on the determination of the CKM matrix element from the data of ϵ'/ϵ is in fact weaker than those from other modes."

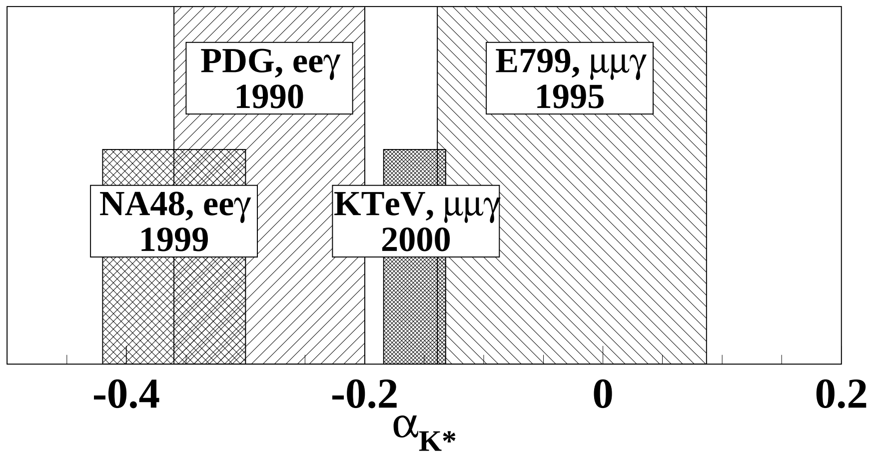

Figure 6. Comparison of the α_{K^*} measurement with previous experiments.

Yee Bob Hsiung's answer:
"Yes, the current spread of the theoretical calculation on ϵ'/ϵ is still much larger than the uncertainties from the grand averge of the experimental measuremnts. I am hoping in the near future, say from Lattice QCD calculation, we can reduce the uncertainties to the level of experiment for us to use ϵ'/ϵ as a constraint to determine the unitarity triangle of the CKM matrix elements."

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