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## CP and Rare Decays

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### Abstract

*CP* violation experiments, new measurements of the parameters of the neutral *K* system and searches for rare decays are summarized. Perspectives for the near future are presented.

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## 1. Introduction

The study of  $K$  mesons, begun more than 50 years ago, has been central to the development of the standard model.  $CP$  violation was discovered in '64,<sup>[1]</sup> through the observation of the unexpected decay  $K_L \rightarrow \pi^+ \pi^-$ . Since then, experiments searching for a difference in  $\eta_{+-}$  and  $\eta_{00}$  have been going on. The complex amplitude ratios are defined in the standard notation as:<sup>[2]</sup>

$$\frac{A(K_L \rightarrow \pi^+ \pi^-)}{A(K_S \rightarrow \pi^+ \pi^-)} = |\eta_{+-}| e^{i\phi_{+-}} = \epsilon + \epsilon'$$

$$\frac{A(K_L \rightarrow \pi^0 \pi^0)}{A(K_S \rightarrow \pi^0 \pi^0)} = |\eta_{00}| e^{i\phi_{00}} = \epsilon - 2\epsilon'$$

The classical measurable quantity  $\mathcal{R}$ , the so called double ratio of the four rates for  $K_{L,S} \rightarrow \pi^0 \pi^0, \pi^+ \pi^-$  as defined below, is related to  $\epsilon, \epsilon'$  by

$$\mathcal{R} = \left| \frac{\eta_{00}}{\eta_{+-}} \right|^2 = 1 - 6\Re(\epsilon'/\epsilon).$$

Observation of  $\Re(\epsilon'/\epsilon) \neq 0$  is proof of "direct"  $CP$  violation, *i.e.* that the amplitude for  $|\Delta S|=1$ ,  $CP$  violating transitions  $A(K_2 \rightarrow 2\pi) \neq 0$ .

All observations of  $CP$  violation,  $\mathcal{CR}$  for short, *i.e.* the decays  $K_L \rightarrow 2\pi, \pi^+ \pi^- \gamma$  and the charge asymmetries in  $K_{\ell 3}$  decays are examples of so called "indirect" violation, due to  $|\Delta S|=2$   $K^0 \leftrightarrow \bar{K}^0$  transitions introducing a small  $CP$  impurity in the mass eigenstates

$$K_S \sim (K_1 + \epsilon K_2)/\sqrt{2}, \quad K_L \sim (K_2 + \epsilon K_1)/\sqrt{2}$$

where  $K_1$  and  $K_2$  are the  $CP$  even and odd superposition of  $K^0, \bar{K}^0$  and  $\epsilon \sim 2 \times 10^{-3}$ .

There is no new information on direct  $\mathcal{CR}$  and we are still confronted with a slightly unsatisfactory experimental situation:<sup>[3]</sup>

$$\Re(\epsilon'/\epsilon) = (7.4 \pm 5.9) \times 10^{-4}$$

$$\Re(\epsilon'/\epsilon) = (23 \pm 6.5) \times 10^{-4}$$

Taking the Particle Data Group's<sup>[4]</sup> (PDG94) average at face value, we could say

that the confidence level that  $0 < \Re(\epsilon'/\epsilon) < 3 \times 10^{-3}$  is 94%. I will come back to the future prospects in this field.

A fundamental task of experimental physics today is the determination of the four parameters of the CKM mixing matrix, including the phase which results in  $\mathcal{CP}$ . A knowledge of all parameters is required to confront experiments. Rather, many experiments are necessary to complete our knowledge of the parameters and prove the uniqueness of the model or maybe finally break beyond it. As it happens rare  $K$  decays can be crucial to this task. I will therefore discuss the following topics: new measurements of  $K_S$ ,  $K_L$  parameters and searches for symmetry violations; new rare  $K$  decay results; other searches for  $\mathcal{CP}$  and  $\mathcal{T}$ . I will also briefly describe perspectives for developments in the near future.

## 2. New Measurements of the Neutral Kaon Properties

### 2.1. CPLEAR

The CPLEAR experiment<sup>[5]</sup> studies neutral  $K$  mesons produced in equal numbers in proton-antiproton annihilations at rest:

$$\begin{aligned} p\bar{p} &\rightarrow K^- \pi^+ K^0 \quad \text{BR } 2 \times 10^{-3} \\ &\rightarrow K^+ \pi^- \bar{K}^0 \quad \text{BR } 2 \times 10^{-3} \end{aligned}$$

The charge of  $K^\pm(\pi^\pm)$  tags the strangeness  $S$  of the neutral  $K$  at  $t=0$ . They have recently presented several new results<sup>[6,7]</sup> from studying  $\pi^+\pi^-$ ,  $\pi^+\pi^-\pi^0$  and  $\pi^\pm \ell^\mp \bar{\nu}(\nu)$  final states. Their measurement of the  $K_L-K_S$  mass difference  $\Delta m$  is independent of the value of  $\phi_{+-}$ , unlike in most other experiments. They have improved limits on the possible violation of the  $\Delta S = \Delta Q$  rule, quantified by the amplitude's ratio  $x = A(\Delta S = -\Delta Q)/A(\Delta S = \Delta Q)$ , without assuming  $CPT$  invariance. A direct test of  $CPT$  invariance has also been obtained. The data require small corrections for background asymmetry  $\sim 1\%$ , differences in tagging efficiency,  $\varepsilon(K^+\pi^-) - \varepsilon(K^-\pi^+) \sim 10^{-3}$  and in detection,  $\varepsilon(\pi^+e^-) - \varepsilon(\pi^-e^+) \sim 3 \times 10^{-3}$ . They also correct for some regeneration in the detector.

#### 2.1.1 $K^0(\bar{K}^0) \rightarrow e^+(e^-)$

Of particular interest are the study of the decays  $K^0(\bar{K}^0) \rightarrow e^+(e^-)$ . One can define the four decay intensities:

$$\left. \begin{array}{l} I^+(t) \text{ for } K^0 \rightarrow e^+ \\ \bar{I}^-(t) \text{ for } \bar{K}^0 \rightarrow e^- \end{array} \right\} \Delta S = 0 \quad \left. \begin{array}{l} \bar{I}^+(t) \text{ for } \bar{K}^0 \rightarrow e^+ \\ I^-(t) \text{ for } K^0 \rightarrow e^- \end{array} \right\} |\Delta S| = 2$$

where  $\Delta S = 0, 2$  mean that the strangeness of the decaying  $K$  is the same as it was at  $t=0$  or has changed from  $K^0$ - $\bar{K}^0$  mixing. One can then define four asymmetries:

$$\begin{aligned} A_1(t) &= \frac{I^+(t) + \bar{I}^-(t) - (\bar{I}^+(t) + I^-(t))}{I^+(t) + \bar{I}^-(t) + \bar{I}^+(t) + I^-(t)} \\ A_2(t) &= \frac{\bar{I}^-(t) + \bar{I}^+(t) - (I^+(t) + I^-(t))}{\bar{I}^-(t) + \bar{I}^+(t) + I^+(t) + I^-(t)} \end{aligned}$$

$$A_T(t) = \frac{\bar{I}^+(t) - I^-(t)}{\bar{I}^+(t) + I^-(t)}, \quad a_{CPT}(t) = \frac{\bar{I}^-(t) - I^+(t)}{\bar{I}^-(t) + I^+(t)}$$

From the time dependence of  $A_1$  they obtain:  $\Delta m = (0.5274 \pm 0.0029 \pm 0.0005) \times 10^{10} \text{ s}^{-1}$ , a result which is independent of  $\phi_{+-}$  and  $\Re x = (12.4 \pm 11.9 \pm 6.9) \times 10^{-3}$ , without assuming  $CPT$ . From  $A_2$  and assuming  $CPT$  they obtain  $\Im x = (4.8 \pm 4.3) \times 10^{-3}$ , a result  $\sim 5$  times more stringent than the PDG94 world average.  $A_T$  gives a direct measurement of  $T$  violation. Assuming  $CPT$ , the expected value for  $A_T$  is  $6.52 \times 10^{-3}$ . The CPLEAR result is  $A_T = (6.3 \pm 2.1 \pm 1.8) \times 10^{-3}$ . From a study of the  $CPT$  violating asymmetry,  $A_{CPT}(t)$ , they obtain  $\Re \delta_{CPT} = (0.07 \pm 0.53 \pm 0.45) \times 10^{-3}$ . We will come back later to the definition of  $\delta_{CPT}$ .

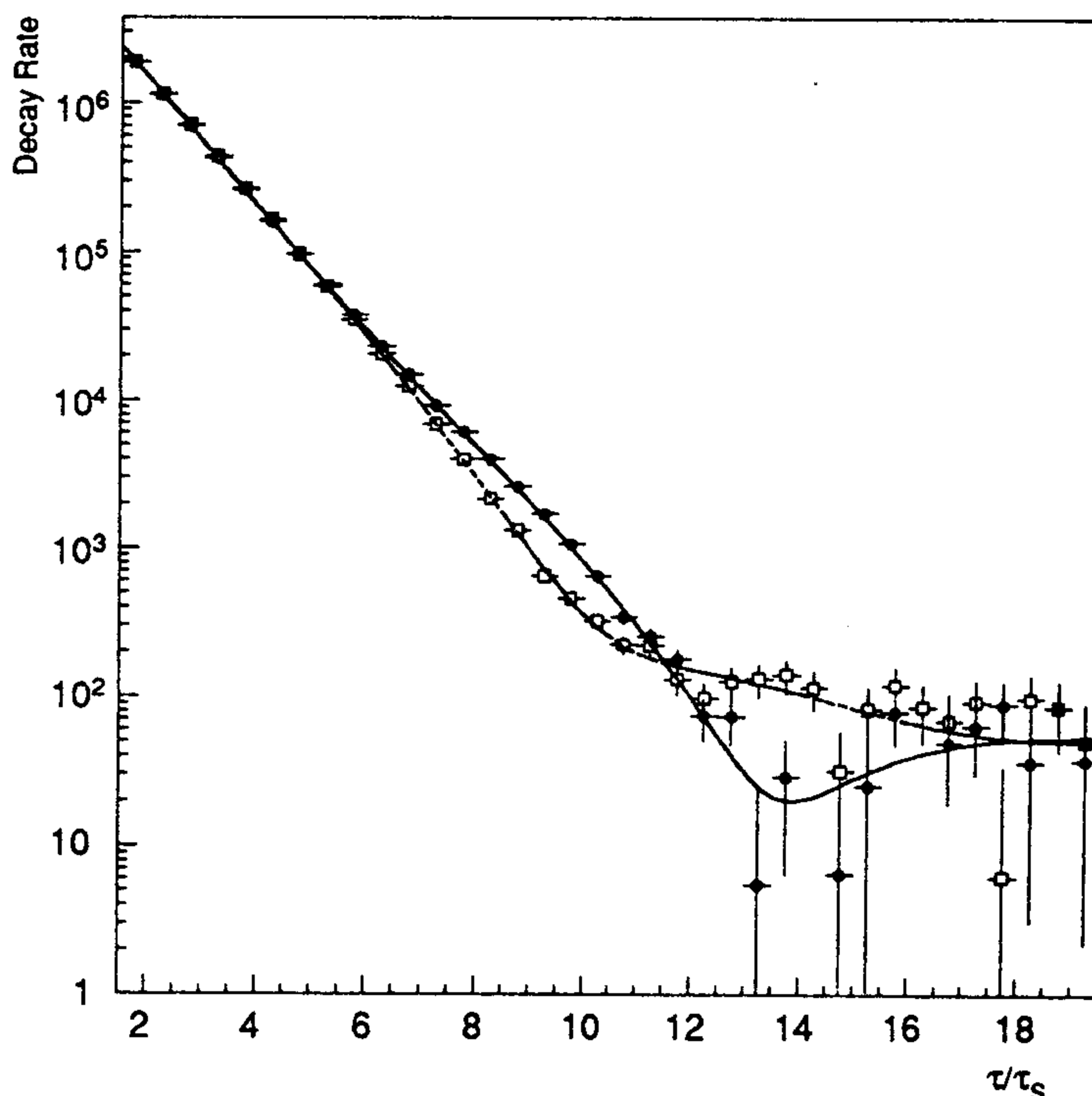


Fig. 2.1. Decay distributions for  $K^0$  and  $\bar{K}^0$ .

### 2.1.2 $\pi^+\pi^-\pi^0$ Final States

Studies of  $K^0-\bar{K}^0 \rightarrow \pi^+\pi^-\pi^0$  decays give the results  $\Re \eta_{+-0} = (-4 \pm 17 \pm 3) \times 10^{-3}$  and  $\Im \eta_{+-0} = (-16 \pm 20 \pm 8) \times 10^{-3}$ , where  $\eta_{+-0} = A(K_L \rightarrow \pi^+\pi^-\pi^0)/A(K_S \rightarrow \pi^+\pi^-\pi^0)$ . By setting  $\Re \eta_{+-0} = \Re \eta_{+-}$  they obtain  $\Im(\eta_{+-0}) = (-11 \pm 14 \pm 8) \times 10^{-3}$ . These results are significantly more precise than any previous ones.

### 2.1.3 $\pi^+\pi^-$ Final State

Finally from an analysis of  $1.6 \times 10^7$   $\pi^+\pi^-$  decays of  $K^0$  and  $\bar{K}^0$  they determine  $|\eta_{+-}| = (2.312 \pm 0.043 \pm 0.03 \pm 0.011_{\tau_S}) \times 10^{-3}$  and  $\phi_{+-} = 42.6^\circ \pm 0.9^\circ \pm 0.6^\circ \pm 0.9^\circ_{\Delta m}$ . The errors in the values quoted reflect uncertainties in the knowledge of the  $K_S$  lifetime and the  $K_S-K_L$  mass difference, respectively. Fig. 2.1 shows the decay intensities of  $K^0$  and  $\bar{K}^0$ , while fig. 2.2 is a plot of the time dependent asymmetry

$A_{+-} = (I(\bar{K}^0 \rightarrow \pi^+\pi^-) - \alpha I(K^0 \rightarrow \pi^+\pi^-)) / (I(\bar{K}^0 \rightarrow \pi^+\pi^-) + \alpha I(K^0 \rightarrow \pi^+\pi^-))$ .  
 Most systematics cancel in the ratio and the residual difference in efficiencies for  $K^0$  and  $\bar{K}^0$  decays is determined from a fit to the same data:  $\alpha = 0.9989 \pm 0.0006$ .

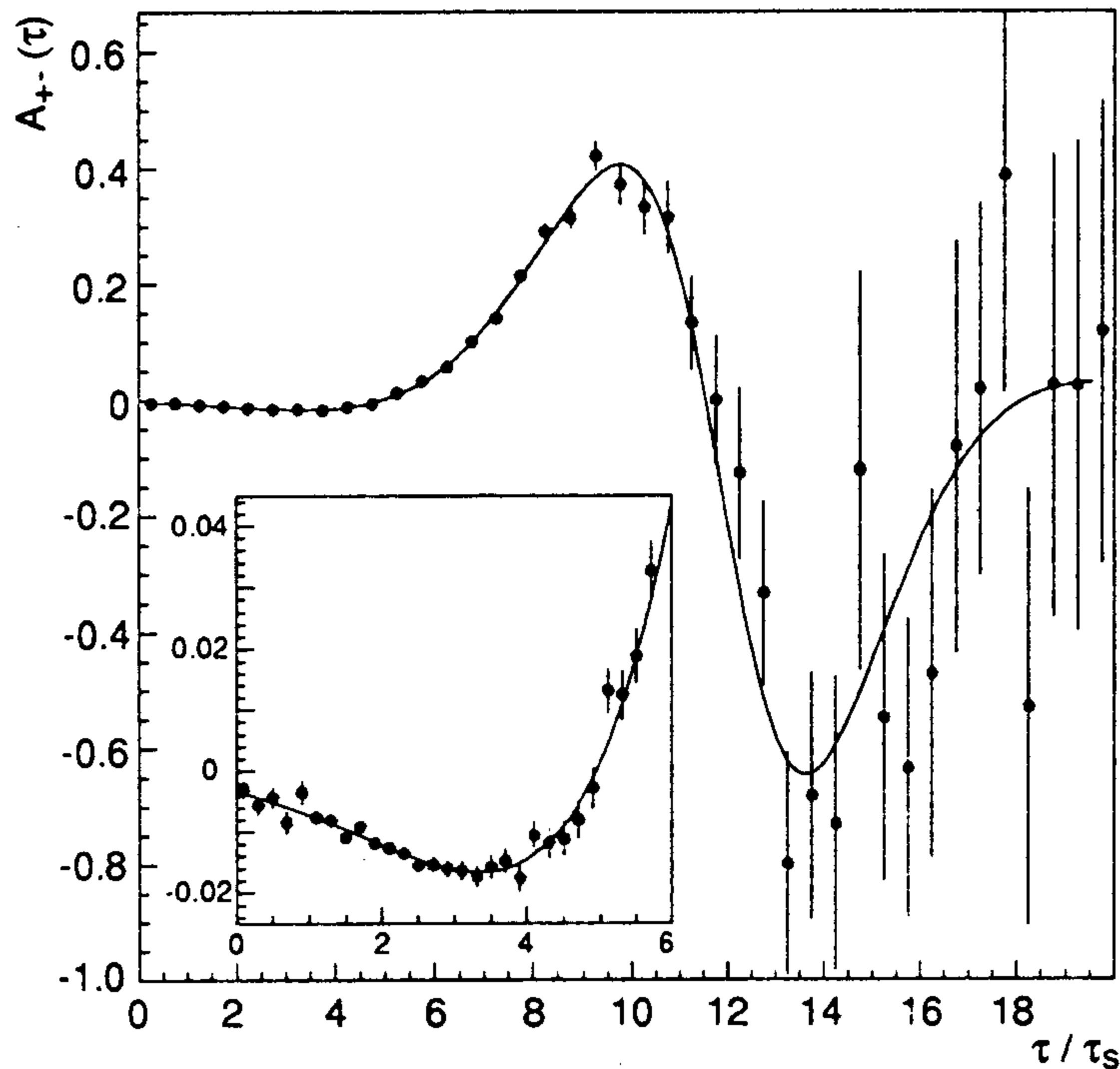


Fig. 2.2. Difference of decay distributions for  $K^0$  and  $\bar{K}^0$ .

## 2.2. E621 at FNAL

For completeness the following new results for  $K \rightarrow \pi^+\pi^-\pi^0$  must be mentioned.<sup>[8]</sup> In this experiment the  $CP$  conserving amplitude  $A(K_S \rightarrow \pi^+\pi^-\pi^0)$  is measured, obtaining

$$|\rho_{\pi^+\pi^-\pi^0}| = \left| \frac{A(K_S \rightarrow \pi^+\pi^-\pi^0, I=2)}{A(K_L \rightarrow \pi^+\pi^-\pi^0)} \right| = 0.035_{-0.011}^{+0.019} \pm 0.004$$

$$\phi_\rho = -59^\circ \pm 48^\circ$$

$$\text{BR}(K_S \rightarrow \pi^+\pi^-\pi^0) = (3.9_{-1.8}^{+0.54+0.8}) \times 10^{-7}$$

$$\Im(\eta_{+-0}) = -0.015 \pm 0.017 \pm 0.025, \quad \text{assuming } \Re(\eta_{+-0}) = \Re(\epsilon).$$

## 2.3. E773 at FNAL

E773 is essentially the old E731 setup, with minor improvements. New results have been obtained on  $\Delta m$ ,  $\tau_S$ ,  $\phi_{00} - \phi_{+-}$  and  $\phi_{+-}$  from a study of  $K \rightarrow \pi^+\pi^-$ ,  $\pi^0\pi^0$  decays.<sup>[9]</sup> From a study of  $\pi^+\pi^-\gamma$  final states,  $|\eta_{+-\gamma}|$  and  $\phi_{+-\gamma}$  are obtained.<sup>[10]</sup>

### 2.3.4 Two Pion Final States

This study of  $K \rightarrow \pi\pi$  is a classic experiment where one beats the amplitude  $A(K_L \rightarrow \pi\pi)_i = \eta_i A(K_S \rightarrow \pi\pi)$  with the coherently regenerated  $K_S \rightarrow \pi\pi$  amplitude

$\rho A(K_S \rightarrow \pi\pi)$ , resulting in the decay intensity

$$I(t) = |\rho|^2 e^{-\Gamma_S t} + |\eta|^2 e^{-\Gamma_L t} + 2|\rho||\eta| e^{-\Gamma t} \cos(\Delta m t + \phi_\rho - \phi_{+-})$$

Measurements of the time dependence of  $I$  for the  $\pi^+\pi^-$  final state yields  $\Gamma_S$ ,  $\Gamma_L$ ,  $\Delta m$  and  $\phi_{+-}$ . They give the following results:  $\tau_S = (0.8941 \pm 0.0014 \pm 0.009) \times 10^{-10}$  s setting  $\phi_{+-} = \phi_{SW} = \tan^{-1} 2\Delta m/\Delta\Gamma$  and floating  $\Delta m$ ;  $\Delta m = (0.5297 \pm 0.0030 \pm 0.0022) \times 10^{10} \text{ s}^{-1}$  using for  $\tau_S$  the PDG94 value, leaving  $\phi_{+-}$  free in the fit;  $\phi_{+-} = 43.53^\circ \pm 0.58^\circ \pm 0.40^\circ$ , using for  $\tau_S$  the PDG94 value and for the mass difference the combined values of E731 and E773,  $\Delta m = (0.5282 \pm 0.0030) \times 10^{10} \text{ s}^{-1}$ . Including the uncertainties on  $\Delta m$  and  $\tau_S$  and the correlations in their measurements they finally quote  $\phi_{+-} = 43.53^\circ \pm 0.97^\circ$ .

From a simultaneous fit to the  $\pi^+\pi^-$  and  $\pi^0\pi^0$  data they obtain  $\Delta\phi = \phi_{00} - \phi_{+-} = 0.62^\circ \pm 0.71^\circ \pm 0.75^\circ$ , which combined with the E731 result gives  $\Delta\phi = -0.3^\circ \pm 0.88^\circ$ .

### 2.3.5 Estimating the error on $\phi_{+-}$

The E773 estimate of the  $\phi_{+-}$  error has been criticized by Kleinknecht and Luitz (K-L in the following).<sup>[11]</sup> They quite correctly point out that the results of an experiment of this kind should be given as

$$\phi_\rho - \phi_{+-} = \phi_{\text{meas}} \pm \delta\phi_{\text{meas}}$$

followed by a statement that  $\phi_\rho$  is estimated as

$$\phi_\rho = \phi_{\text{Est.}} \pm \delta\phi_{\text{Est.}}$$

E773 cannot in fact present their results in such a fashion because of the analysis method used. Essentially they use analyticity and the assumption that  $|f - \bar{f}| \propto p^\beta$ , from which it follows that  $\phi_f = -(1 + \beta)\pi/2$ .

They then perform grand fits to the data, which span the range  $40 < p < 160$  GeV/c, floating not only the  $K$  parameters of interest but also the exponent of the power law and the value of  $|f - \bar{f}|$  at 70 GeV/c.

They justify this procedure on the basis of

1. A fit done in this way properly takes in account all correlations, assuming of course that  $|f - \bar{f}| \propto p^\beta$ ,  $\phi_f = -(1 + \beta)\pi/2$  is correct.
2. They argue that for a large class of functions with small deviations from a single power law, fitting to a single parameter  $\beta_{\text{eff}}$ , does in fact give a correct answer for the effective (and properly weighted) value of  $\phi_{+-}$ .
3. They perform a calculation of the  $f - \bar{f}$  regeneration amplitude in carbon,<sup>[12]</sup> using Glauber screening and  $K - N$  data and find excellent agreement with data at 3-10 GeV/c<sup>[13]</sup> and 40-160 GeV/c.<sup>[9]</sup> The total shift between a single power law and the fit using this procedure is  $-0.04^\circ$  and they estimate that the ultimate error on the phase in this type of measurement could be as low as  $\pm 0.35^\circ$ .

Since they do give the result from the fit for the power,  $\beta = -0.571 \pm 0.007$ , one can reconstruct  $\phi_f$  and especially the error,  $\delta\phi_{\text{Est.}} = 90^\circ \times 0.009 = 0.63^\circ$ . K-L use the complete dispersion relation which I rewrite as

$$\phi_f(p_0) = -\frac{\pi}{2} - \int_0^\infty \frac{\beta}{\pi p} \frac{d}{d} \log \coth|u|^2, \quad u = \log\left(\frac{p}{p_0}\right).$$

If  $\beta$  varies slowly with  $p$  then

$$\phi_f(p_0) = -\frac{\pi}{2} - \sum \beta_i \int_{p_i}^{p_{i+1}} \dots = -\frac{\pi}{2} - \sum \beta_i I_i$$

and

$$\delta\phi_{\text{Est.}} = \sum \delta\beta_i \times I_i.$$

A comparison between the error estimates of K-L and E773 is given in table 1, for  $p_0 = 70$  GeV

Table 1.

$p$ Interval	Integral	K-L		E773	
		$\delta\beta$	$\delta\phi$	$\delta\beta$	$\delta\phi$
0-10	0.0912	0.025	0.002	0.007	
10-30	0.1876	0.025	0.005	0.007	
30-130	0.9368	0.020	0.019	0.007	
130- $\infty$	0.3551	0.050	0.018	0.007	
SUM	$\pi/2$		0.044		0.011
Error			$2.5^\circ$		$0.63^\circ$

By inspection of the data on  $|f - \bar{f}|$ , a more reasonable estimate of the error, in my opinion, is as given in table 2.

Table 2.

Momentum Interval	Integral	$\delta\beta$	$\delta\phi$
0-10	0.0912	0.020	0.0018
10-40	0.2877	0.010	0.0029
40-160	0.9071	0.007	0.0063
160-300	0.1354	0.014	0.0019
300- $\infty$	0.14938	0.03	0.0045
			0.0174
		Error	$1.0^\circ$

The error on the phase gets larger for high and low momenta, which are more sensitive to the larger error on  $\beta$ . The actual momentum spectrum of the data should therefore be used. Using the error in table 2 gives  $\phi_{+-} = 43.53^\circ \pm \sim 1.4^\circ$ .

#### 2.4. Combined Results from Different Experiments

Because of the error estimate uncertainties mentioned earlier, the correlations between parameters, as well as between *past and new* measurements, it is not wise for me to try to combine results and get better limits. Better measurements will come soon, certainly by LP99.

The CPLEAR collaboration<sup>[14]</sup> has performed an analysis for obtaining the best value for  $\Delta m$  and  $\phi_{+-}$ , taking properly into account the fact that different experiments have different correlations between the two variables. The data<sup>[6,7,9,15-21]</sup> with their correlations are shown in fig. 2.3.

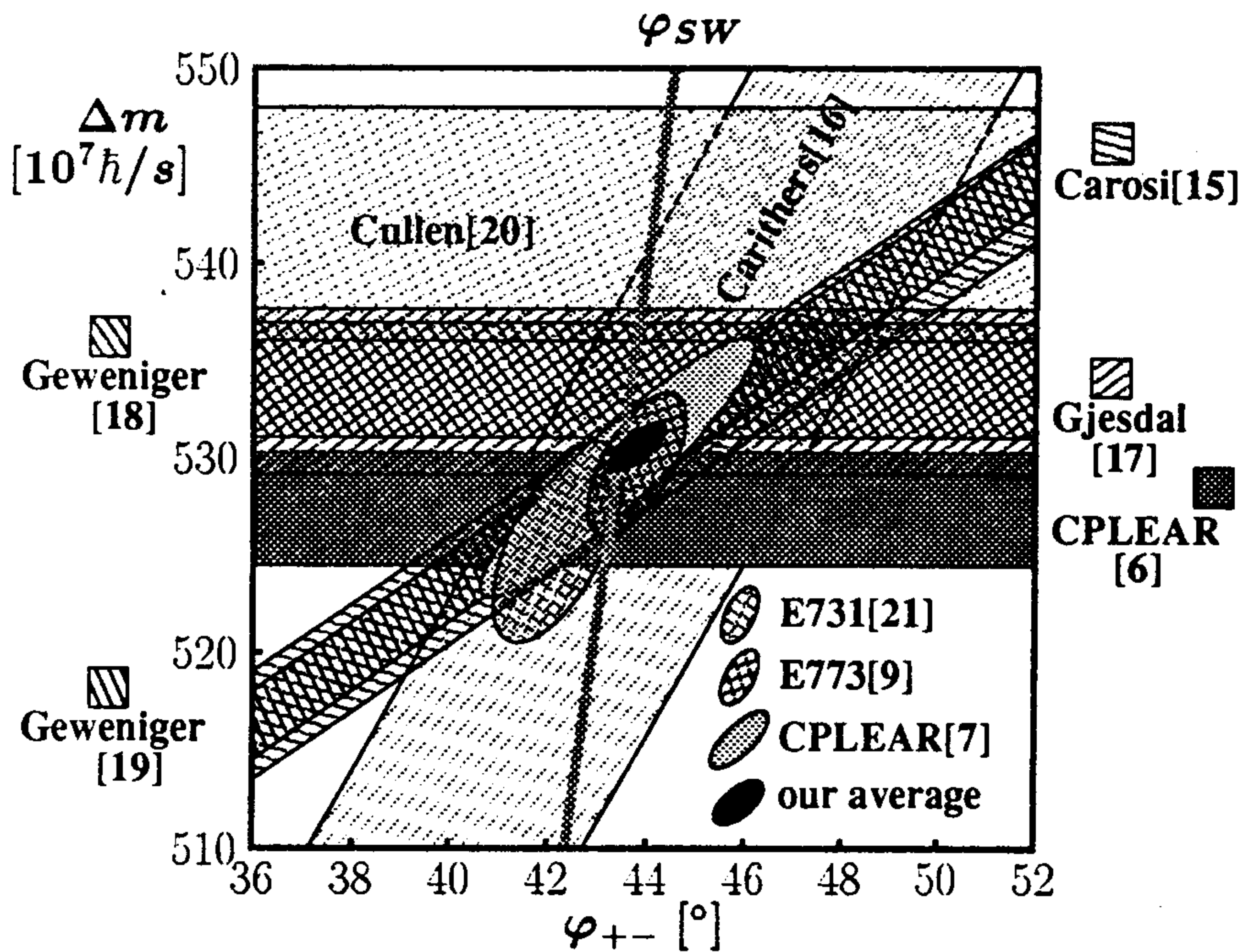


Fig. 2.3.  $\Delta m$  and  $\phi_{SW}$  from ref. 14.

A maximum likelihood analysis of all data gives  $\Delta m = (530.6 \pm 1.3) \times 10^7 \text{ s}^{-1}$  and  $\phi_{+-} = 43.75^\circ \pm 0.6^\circ$ .  $\phi_{+-}$  is very close to the *superweak phase*  $\phi_{SW} = 43.44^\circ \pm 0.09^\circ$ .

#### 2.4.6 $K \rightarrow \pi^+ \pi^- \gamma$

The time dependence of this decay, like that for two pion case, allows extraction of the corresponding parameters:<sup>[10]</sup>  $|\eta_{+-\gamma}| = (2.362 \pm 0.064 \pm 0.04) \times 10^{-3}$  and  $\phi_{+-\gamma} = 43.6^\circ \pm 3.4^\circ \pm 1.9^\circ$ . Comparison with  $|\eta_{+-}| \sim |\epsilon| \sim 2.3$ ,  $\phi_{+-} \sim 43^\circ$  gives excellent agreement. This implies that the decay is dominated by radiative contribution and that all one sees is the *CP* impurity of the *K* states.

In fact there is an elegant point to this measurement. Because interference is observed (which vanishes between orthogonal states) one truly measures the ratio

$$\eta_{+-\gamma} = \frac{A(K_L \rightarrow \pi^+ \pi^- \gamma, \mathcal{CP})}{A(K_S \rightarrow \pi^+ \pi^- \gamma, \mathcal{CP} \text{ OK})}$$

which is dominated by E1, inner bremsstrahlung transitions. Thus again one is mea-



asuring the  $CP$  impurity of  $K_L$ . Direct  $CP$  could contribute via E1, direct photon emission  $K_L$  decays, but it has not been observed, within the sensitivity of the measurement.

### 3. Tests of $CPT$ Invariance

The measured parameters in neutral  $K$  decays can be combined to put limits on possible  $CPT$  violation in the  $K$  system. In the following I present a recent analysis of Maiani,<sup>[22]</sup> based on PDG94 data, and also give the limits obtained by CPLEAR and E773.

One problem with the neutral  $K$  system is that before arriving to the answer one has to go through the definition of 21 parameters. Maiani defines the  $K_S$  and  $K_L$  states as

$$K_S \equiv N_S(|K_1\rangle + \epsilon_S|K_2\rangle), \quad K_L \equiv N_L(|K_2\rangle + \epsilon_L|K_1\rangle), \quad \epsilon_{S,L} \equiv \epsilon_M \pm \Delta$$

where  $\Delta \equiv \delta_{CPT}$  mentioned earlier and the two pion amplitudes and  $N_S, N_L$  are the appropriate state normalization coefficients:

$$A(K^0 \rightarrow 2\pi, I) \equiv \sqrt{\frac{2}{3}}(A_I + B_I)e^{i\delta_I}$$

$$A(\bar{K}^0 \rightarrow 2\pi, I) \equiv \sqrt{\frac{2}{3}}(A_I^* - B_I^*)e^{i\delta_I}$$

where, for each value of the two pion isospin,  $I=0$  and  $2$ ,  $A$  and  $B$  have the symmetries

	$\Re A$	$\Im A$	$\Re B$	$\Im B$
$CP$	+	-	-	+
$T$	+	-	+	+
$CPT$	+	+	-	-

The Wu and Yang convention is used, which requires  $A_0$  real and positive. Then:

$$\eta_{+-} = \epsilon_L + \frac{A(K_2 \rightarrow \pi^+\pi^-)}{A(K_1 \rightarrow \pi^+\pi^-)} = \epsilon + \epsilon'$$

$$\eta_{00} = \epsilon_L + \frac{A(K_2 \rightarrow \pi^0\pi^0)}{A(K_1 \rightarrow \pi^0\pi^0)} = \epsilon - 2\epsilon'$$

$$\epsilon = \epsilon_M - \left(\Delta - \frac{\Re B_0}{A_0}\right), \quad \epsilon' = ie^{i(\delta_2 - \delta_0)} \frac{\omega}{\sqrt{2}} \left[ \frac{\Im A_2}{A_2} - 1 \left( \frac{\Re B_2}{A_2} - \frac{\Re B_0}{A_0} \right) \right],$$

with  $\omega = A_2/A_0=0.045$ , from  $K_S$  and  $K^+$  decays. Four more complex variables need be added for describing the semileptonic decays, allowing both for  $\mathcal{CP}$  and  $\Delta S = -\Delta Q$ . Additional parameters are required for three pion decays. The relations

above are illustrated in the complex plane in fig. 3.1.

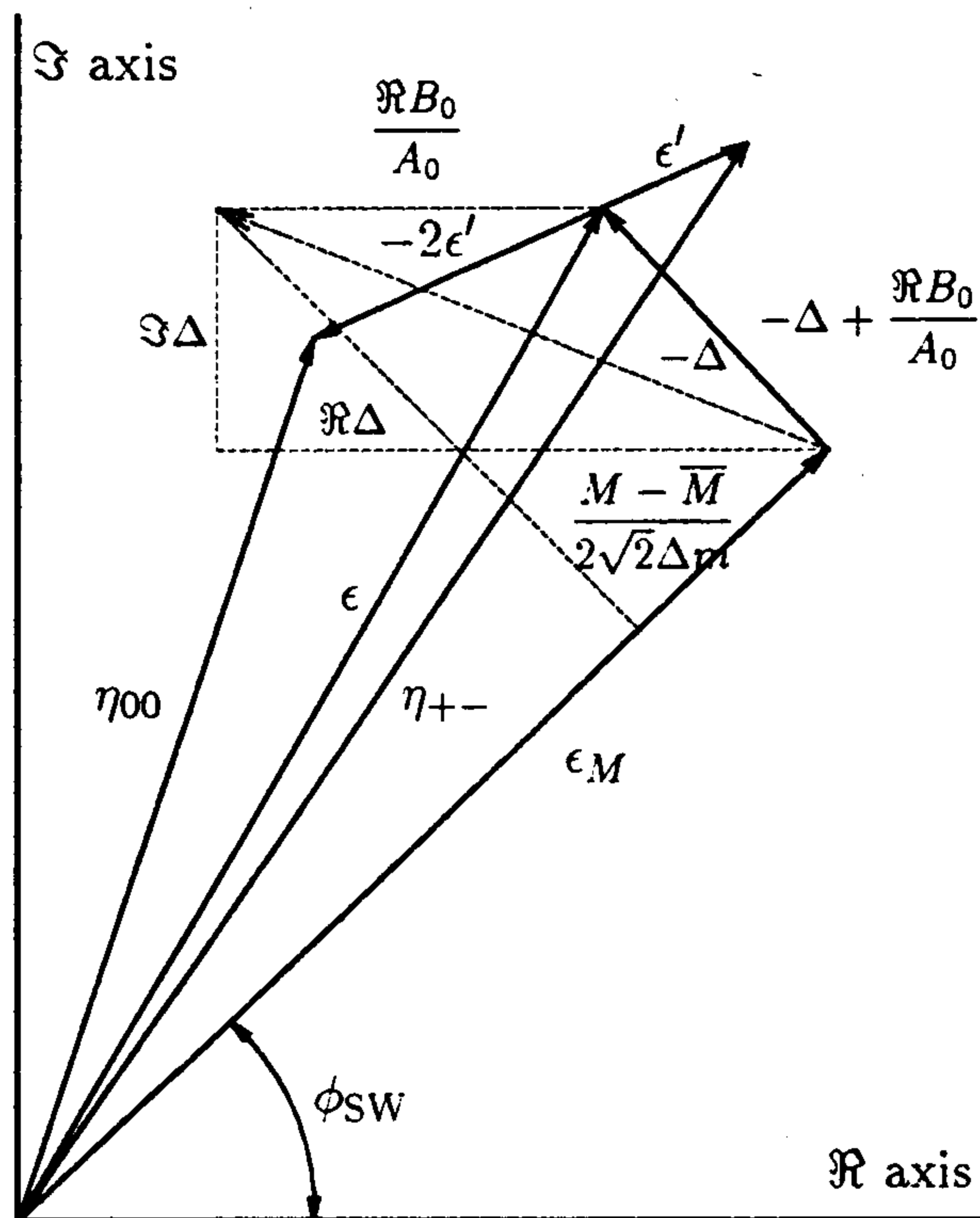


Fig. 3.1 Complex plane representation of the  $\epsilon$  and  $\eta$  parameters, not to scale.

### 3.1. An Analysis Based on Data from PDG94

The following data are used by Maiani:

$$\phi_{\text{SW}} \equiv \tan^{-1} \frac{2\Delta m}{\Delta\Gamma} = 43.73^\circ \pm 0.15^\circ$$

$$|\eta_{+-}| = (2.269 \pm 0.023) \times 10^{-3}$$

$$|\eta_{00}/\eta_{+-}| = (0.9955 \pm 0.0023) \times 10^{-3}$$

$$\phi_{+-} = 44.3^\circ \pm 0.8^\circ$$

$$\phi_{+-} - \phi_{00} = -1.0^\circ \pm 1.0^\circ$$

$$A_L = (3.27 \pm 0.12) \times 10^{-3}$$

from which, since  $\epsilon'/\epsilon$  is so small,

$$|\epsilon| = \left| \frac{2\eta_{+-} + \eta_{00}}{3} \right| = (2.266 \pm 0.03) \times 10^{-10}$$

$$\arg(\epsilon) = \phi_{+-} + \frac{\phi_{00} - \phi_{+-}}{3} = 44.0^\circ \pm 1.0^\circ$$

and  $\arg(\epsilon) - \phi_{\text{SW}} = 0.3^\circ \pm 1.0^\circ$ , which implies no *CPT* violation.

From the leptonic asymmetry,  $A_L$ , Maiani obtains

$$\frac{\Re B_0}{A_0} = (-0.1 \pm 0.6) \times 10^{-4}$$

$$\Delta = [(0.0 \pm 0.6) - i(0.1 \pm 0.2)] \times 10^{-4}$$

and a limit on the  $\mathcal{CR}\mathcal{T}$  mass difference

$$\frac{M_{11} - M_{22}}{m_K} = (0.0 \pm 0.9) \times 10^{-18}$$

Note that the result above for  $\Delta$  is considerably more stringent than the direct measurement from CPLEAR,  $\Re\Delta = (0.7 \pm 5.3 \pm 4.5) \times 10^{-4}$ , which however is a direct experimental observation.<sup>[23]</sup>

### 3.1.7 Other determinations of the $K^0$ - $\bar{K}^0$ mass difference

E773, using their values for  $\phi_{\text{SW}}$ ,  $\phi_{+-}$  and  $\Delta\phi$  obtain the limit

$$\frac{|m_{K^0} - m_{\bar{K}^0}|}{m_{K^0}} \sim \frac{2\Delta m}{m_{K^0}} \frac{|\eta_{+-}|}{\sin \phi_{\text{SW}}} \times$$

$$|\phi_{+-} - \phi_{\text{SW}} + \Delta\phi/3| < 1.3 \times 10^{-18}$$

The CPLEAR limit for the mass difference, does not assume  $\Delta S = \Delta Q$  and uses their own new limits on  $\Im x$  and  $\Im\eta_{+-0}$ . The limit on  $\mathcal{CR}\mathcal{T}$  is only slightly weaker:<sup>[23]</sup>

$$\frac{|m_{K^0} - m_{\bar{K}^0}|}{m_{K^0}} < 2.2 \times 10^{-18}$$

## 4. Rare $K$ Decays

Rare  $K$  decays offer several interesting possibilities, which could ultimately open a window beyond the standard model. They allow the determination of the CKM matrix parameters, as for instance from the  $\mathcal{CR}$  decay  $K_L \rightarrow \pi^0 \nu \bar{\nu}$ , as well as from the  $CP$  conserving one  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ . They also permit the verification of conservation laws which are not strictly required in the standard model, for instance by searching for  $K^0 \rightarrow \mu e$  decays.

The connection between measurements of neutral  $K$  properties and branching ratios and the  $\rho$  and  $\eta$  parameters of the Wolfenstein parameterization of the CKM matrix, ( $V_{td} \propto 1 - \eta - i\rho$ ) is shown *schematically* in fig. 4.1.

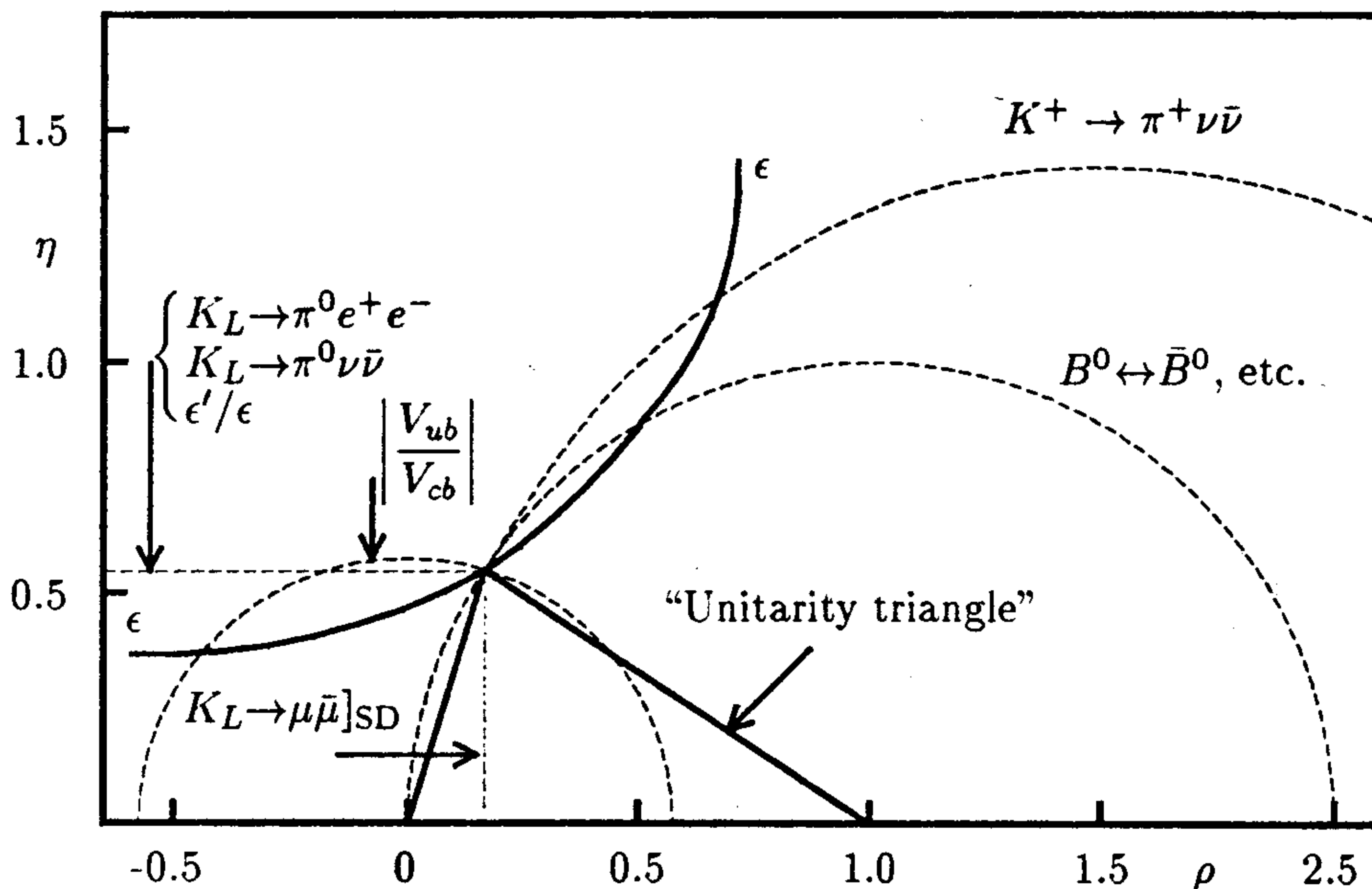


Fig. 4.1. Constraints on  $\eta$  and  $\rho$  from physical measurements.

In general the situation valid for the more abundant  $K$  decays, *i.e.* that the  $\mathcal{CR}|_{\text{direct}}$  decays have much smaller rates than the  $\mathcal{CR}|_{\text{indirect}}$  ones, can be reversed for very rare decays. In addition while the evaluation of  $\epsilon'$  is particularly unsatisfactory because of the uncertainties in the calculation of the hadronic matrix elements, it is not the case for some rare decays. A classification of measurable quantities according to increasing uncertainties in the calculation of the hadronic matrix elements is given by Buras<sup>[24]</sup> as: 1.  $BR(K_L \rightarrow \pi^0 \nu \bar{\nu})$ , 2.  $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ , 3.  $BR(K_L \rightarrow \pi^0 e^+ e^-)$ ,  $\epsilon_K$ , and 4.  $\epsilon'_K$ ,  $BR(K_L \rightarrow \mu \bar{\mu}]_{\text{SD}}$ , where SD stands for *short distance* contributions. A similar situation holds for the  $B$  meson system. The observation  $\epsilon' \neq 0$  remains a unique proof of direct  $\mathcal{CR}$ . Measurements of 1 through 3, plus present knowledge, over determine the CKM matrix. So do measurements in the  $B$ -system. It would be better to have them both. Rare  $K$  decay experiments are not easy however, just like measuring  $\Re(\epsilon'/\epsilon)$  has not turned out to be. Typical expectations for some of the interesting decays are:

$$\begin{aligned} BR(K_L \rightarrow \pi^0 e^+ e^-, \mathcal{CR}]_{\text{dir}}) &\sim (5 \pm 2) \times 10^{-12} \\ BR(K_L \rightarrow \pi^0 \nu \bar{\nu}) &\sim (3 \pm 1.2) \times 10^{-11} \\ BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) &\sim (1 \pm .4) \times 10^{-10} \end{aligned}$$

The most extensive program in this field has been ongoing for a long time at BNL and I have learned that large statistics have been collected this year and are under analysis. Sensitivities of the order of  $10^{-11}$  will be reached, although  $10^{-(12 \text{ or } 13)}$  is really necessary. Experiments with high energy kaon beams have been making excellent progress toward observing rare decays.

I will discuss new results from E799-I<sup>[25-31]</sup> (E731 without regenerators) and

NA31.<sup>[32-37]</sup> The results obtained by the two experiments are summarized in the tables below.

Table 3. E799-I Rare  $K$ -decays Results.

Reaction	Events	$BR$ or limit	Ref.
$K_L \rightarrow \pi^0 \nu \bar{\nu}$		$< 5.8 \times 10^{-5}$	25
$K_L \rightarrow e^+ e^- e^+ e^-$	27	$(4.0 \pm 0.8 \pm 0.3) \times 10^{-8}$	26
$K_L \rightarrow \pi^0 \pi^0 \gamma$		$< 2.3 \times 10^{-4}$	27
$K_L \rightarrow e^+ e^- \gamma \gamma, E_\gamma > 5 \text{ MeV}$		$(6.5 \pm 1.2 \pm 0.6) \times 10^{-7}$	28
$K_L \rightarrow \mu^+ \mu^- \gamma$	207	$(3.23 \pm 0.23 \pm 0.19) \times 10^{-7}$	29
$K_L \rightarrow \pi^0 \mu^\pm e^\mp$		$< 6.4 \times 10^{-9}$	30
$K_L \rightarrow e^+ e^- \mu^+ \mu^-$	1	$(2.9_{-2.4}^{+6.7}) \times 10^{-9}$	31

Table 4. NA31 Rare  $K$ -decays Results.

Reaction	Events	$BR$ or limit	Ref.
$K_S \rightarrow \pi^0 e^+ e^-$	0	$< 1.1 \times 10^{-6}$	32
$K_L \rightarrow \pi^0 \pi^0 \gamma$	3	$< 5.6 \times 10^{-6}$	33
$K_L \rightarrow e^+ e^- e^+ e^-$	8	$(10.4 \pm 3.7 \pm 1.1) \times 10^{-8}$	34
$K_L \rightarrow \pi^0 \pi^0 \pi^0$		$0.211 \pm 0.003$	35
		$\Gamma(K_L \rightarrow 3\pi^0) / \Gamma(K_L \rightarrow \pi^+ \pi^- \pi^0) = 1.611 \pm 0.037$	35
		$\Gamma(K_L \rightarrow 3\pi^0) / \Gamma(K_L \rightarrow \pi e \nu) = 0.545 \pm 0.01$	35
$K_L \rightarrow \pi^0 \gamma \gamma$	57	$(1.7 \pm 0.3) \times 10^{-6}$	36
$K_L \rightarrow e^+ e^- \gamma$	2000	$(9.1 \pm 0.3 \pm 0.5) \times 10^{-6}$	36
$K_L \rightarrow 3\gamma$		$< 2.8 \times 10^{-7}$	36
$K_S \rightarrow \gamma \gamma$	16	$(2.4 \pm 0.9) \times 10^{-6}$	37

The new results above do not yet determine  $\rho$  and  $\eta$ . They do however confirm the feasibility of such program.

#### 4.1. Search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

This decay,  $CP$  allowed, is best for determining  $V_{td}$ . At present there is no information, other than the E787-BNL's limit  $BR < 7.5 \times 10^{-9}$ .<sup>[38]</sup> The new E787<sup>[39]</sup> detector, which in an engineering run found 12 events of  $K \rightarrow \pi \mu^+ \mu^-$ ,  $BR \sim 10^{-8}$ , has collected data for a total of 7500 double density 8 mm tapes. This corresponds to about one  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  event. At least 100 are necessary for a first  $V_{td}$  measurements.

#### 4.2. $K \rightarrow \gamma \gamma$

Direct  $\mathcal{CR}$  is possible in this channel. Defining the two photon states, where  $L$

and  $R$  refer to the photon polarizations,

$$|+\rangle = (|LL\rangle + |RR\rangle)/\sqrt{2}$$

$$|-\rangle = (|LL\rangle - |RR\rangle)/\sqrt{2}$$

we have four possibilities for  $K_L, K_S \rightarrow \gamma\gamma$ , given below, with the expected  $BR$ 's:

	$ +\rangle$	$ -\rangle$
$K_L$	$7 \times 10^9, \mathcal{CP}$	$6 \times 10^{-4}$
$K_S$	$2 \times 10^{-6}$	$5 \times 10^{-12}, \mathcal{CP}$

The  $\mathcal{CP}$  channels can be isolated by measuring the  $\gamma$  polarization, using Dalitz conversion. The present results confirm expectations on the  $CP$  conserving channels. Both E799-I and NA31 have detected  $K_L \rightarrow e^+e^-e^+e^-$  decays, 27 and 8 events respectively, finding  $BR = (3.9 \pm 0.8, 10 \pm 4) \times 10^{-8}$  to be compared with the expectation  $(3.4 \pm 0.2) \times 10^{-8}$ . They also have determined that  $CP|K_2\rangle = -|K_2\rangle$ . NA31 has also observed 69  $K \rightarrow \gamma\gamma$  events, of which 52 are from  $K_L$  and one is background. From this they derive  $BR(K_S \rightarrow \gamma\gamma) = (2.4 \pm 0.9) \times 10^{-6}$ . These results are in agreement with expectations, still one needs sensitivities of  $10^{-12}$ .

#### 4.3. $K \rightarrow \mu^+\mu^-$

Second order weak amplitudes give contributions which depend on  $\rho$ , with  $BR|_{SD} \sim 10^{-9}$ . Measurements of the muon polarization are necessary. One however needs to confirm the calculations for  $K \rightarrow \gamma\gamma \rightarrow \mu^+\mu^-$ , which can confuse the signal. The following results are relevant

1. NA31 with 2000  $K_L \rightarrow e^+e^-\gamma$  events finds  $BR = (9.1 \pm 0.3 \pm 0.5) \times 10^{-6}$ . The  $BR$  depends on the  $K\gamma^*\gamma$  form factor, with contribution from vector meson dominance and the  $KK^*\gamma$  coupling,  $f(q^2) = f_{VMD} + \alpha_{K^*} f_{KK^*\gamma}$ . The measured  $BR$  corresponds to  $\alpha_{K^*} = -0.27 \pm 0.1$ .
2. E799-I observes 207  $K_L \rightarrow \mu^+\mu^-\gamma$  events, giving  $BR = (3.23 \pm 0.23 \pm 0.19) \times 10^{-7}$  and  $\alpha_{K^*} = 0.13^{+0.21}_{-0.35}$
3. E799-I has found one  $K_L \rightarrow e^+e^-\mu^+\mu^-$  event,<sup>[31]</sup> on the basis of which they estimate the branching ratio as  $BR = (2.9^{+6.7}_{-2.4}) \times 10^{-9}$ . Expectations are  $2.3 \times 10^{-9}$ , from VMD and  $8 \times 10^{-10}$  for  $f(q^2) = \text{const}$ . Previous limits were  $BR < 4.9 \times 10^{-6}$ .

At BNL the experiment E871<sup>[40]</sup> should have  $10^4$   $K \rightarrow \mu^+\mu^-$  events recorded and, according to the results above, might extract a first significant value for  $\rho$ .

#### 4.4. $K_L \rightarrow \pi^0 e^+e^-$

The direct  $\mathcal{CP}$   $BR$  is expected to be  $\sim 5 \times 10^{-12}$ . There are however three contributions to the rate plus a potentially dangerous background.

1.  $K_2 \rightarrow \pi^0 \gamma\gamma \rightarrow \pi^0 e^+e^-$ , a  $CP$  allowed transition.
2.  $K_L \rightarrow \pi^0 e^+e^-$ , from the  $K_L$   $CP$  impurity ( $\epsilon|K_1\rangle$ ).

3. Direct  $\mathcal{CR}$  from short distance, second order weak contributions, via  $s \rightarrow d + Z$ , the signal of interest.
4. Background from  $K_L \rightarrow \gamma\gamma^* \rightarrow e^+e^- \gamma \rightarrow e^+e^- \gamma\gamma$ , with a photon from final state radiation.

The relevant experimental results are:

1. NA31: 57  $K_L \rightarrow \pi^0 \gamma\gamma$ ,  $BR = (1.6 \pm 0.3) \times 10^{-6}$ , equivalent to  $BR(K_L \rightarrow \pi^0 e^+ e^-) = 5 \times 10^{-13}$
2. NA31 finds no  $K_S \rightarrow \pi^0 e^+ e^-$  events or  $BR < 1.1 \times 10^{-6}$ , from which  $BR(K_L \rightarrow \pi^0 e^+ e^-) \sim |\epsilon|^2 (\Gamma_S / \Gamma_L) BR(K_S) < 3.2 \times 10^{-9}$ , which is not quite good enough yet.
3. 799-I finds 58  $K_L \rightarrow e^+ e^- \gamma\gamma$  events,  $BR = (6.5 \pm 1.2 \pm 0.6) \times 10^{-7}$ .

The background from point 3 above will not be dangerous for the new proposed experiments (KTEV and NA48), because of the superior resolution of their new electromagnetic calorimeter. The observation of direct  $\mathcal{CR}$  contributions to  $K_L \rightarrow \pi^0 e^+ e^-$  should be convincing when the necessary sensitivity is reached.

#### 4.5. $K_L \rightarrow \pi^0 \nu \bar{\nu}$

This process is a pure direct  $\mathcal{CR}$  signal. The present limits are far from the goal. The sensitivities claimed for E799-II and at KEK are around  $10^{-9}$ . Another factor of 100 improvement is necessary.

### 5. Other $\mathcal{CR}$ Searches

Upper limits on the weak  $\tau$  electric dipole form factor  $\tilde{d}_W$  have been placed by the LEP experiments. ALEPH<sup>[41]</sup> finds  $|\tilde{d}_W| < 1.5 \times 10^{-17}$ , DELPHI<sup>[42]</sup> gives  $|\tilde{d}_W| < 2.1 \times 10^{-17}$  and OPAL<sup>[43]</sup> places limits on both the real and imaginary parts of  $\tilde{d}_W$ ,  $|\Re \tilde{d}_W| < 7.8 \times 10^{-18}$ ,  $|\Im \tilde{d}_W| < 4.5 \times 10^{-17}$ . Observation of a non zero value for  $\tilde{d}_W$  is proof of direct  $\mathcal{CR}$ . KEK experiment 246 is approved for a measurement of the muon polarization in  $K^+ \rightarrow \pi^0 \mu^+ \nu$ , which allows searching for  $\tilde{\kappa}$ .<sup>[44]</sup> Experiment E871<sup>[45]</sup> at FNAL will run next spring searching for  $\mathcal{CR}$  in hyperon decay. They will measure the  $\mathcal{C}$  asymmetry parameter  $\alpha$  for  $\Lambda$ ,  $\bar{\Lambda}$ ,  $\Xi^-$  and  $\bar{\Xi}^+$  in the decays  $\Xi \rightarrow \Lambda \pi$ ,  $\Lambda \rightarrow p \pi$  to a sensitivity of  $(\alpha - \bar{\alpha}) < 10^{-4}$ . A non vanishing value of  $\alpha - \bar{\alpha}$  is unambiguous proof of direct  $\mathcal{CR}$ . The expected signal is  $5 \times 10^{-4}$ .

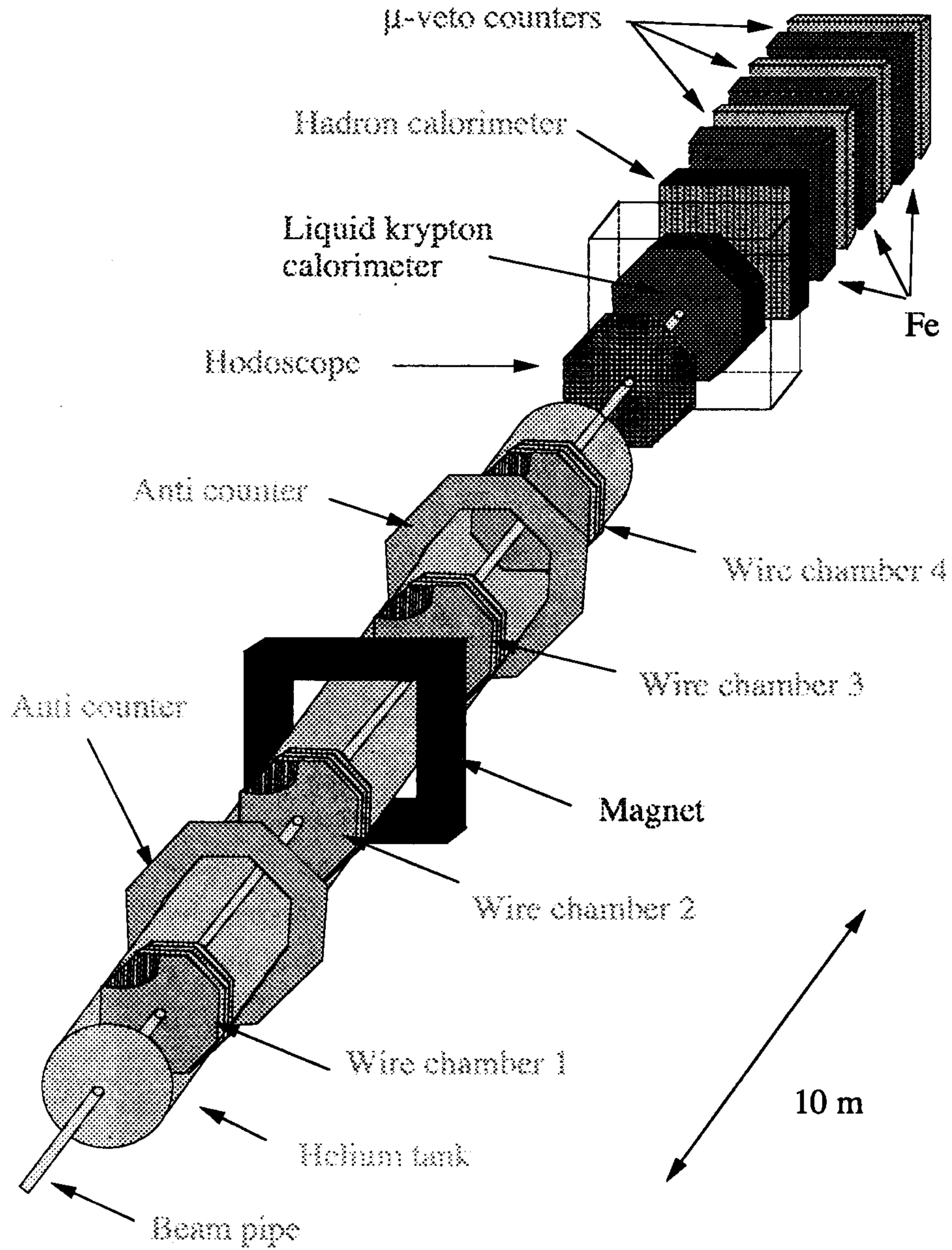
### 6. Future

Three new experiments: NA48<sup>[46]</sup> in CERN, KTEV<sup>[47]</sup> at FNAL and KLOE<sup>[48]</sup> at LNF, are under construction and will begin taking data in '96 - '97, with the primary aim to reach an ultimate error in  $\Re(\epsilon'/\epsilon)$  of  $\mathcal{O}(10^{-4})$ . The sophistication of these experiments takes advantage of our experience of two decades of fixed target and  $e^+e^-$  collider physics. Fundamental in KLOE is the possibility of continuous

self-calibration while running, via processes like Bhabha scattering and charged  $K$  decays.

### 6.1. NA48

## The NA48 Detector



**Fig. 6.1.** The NA48 experiment at CERN.

A new feature of NA48, with respect to its predecessor NA31, is that  $K_L$  and  $K_S$  beams simultaneously illuminated the detector, by the very clever use of a bent crystal



to deflect a portion of the incident proton beam. This deflected beam is brought to a  $K_S$  production target located close to the detector, reducing systematic errors due to different dead times when detecting  $\pi^+\pi^-$  or  $\pi^0\pi^0$   $K$  decays. The superior resolution of the liquid krypton calorimeter further improves the definition of the fiducial regions and improves rejection of  $3\pi^0$ 's decays. A magnetic spectrometer has also been added. Fig. 6.1 gives is view of the NA48 setup.

### 6.2. KTEV

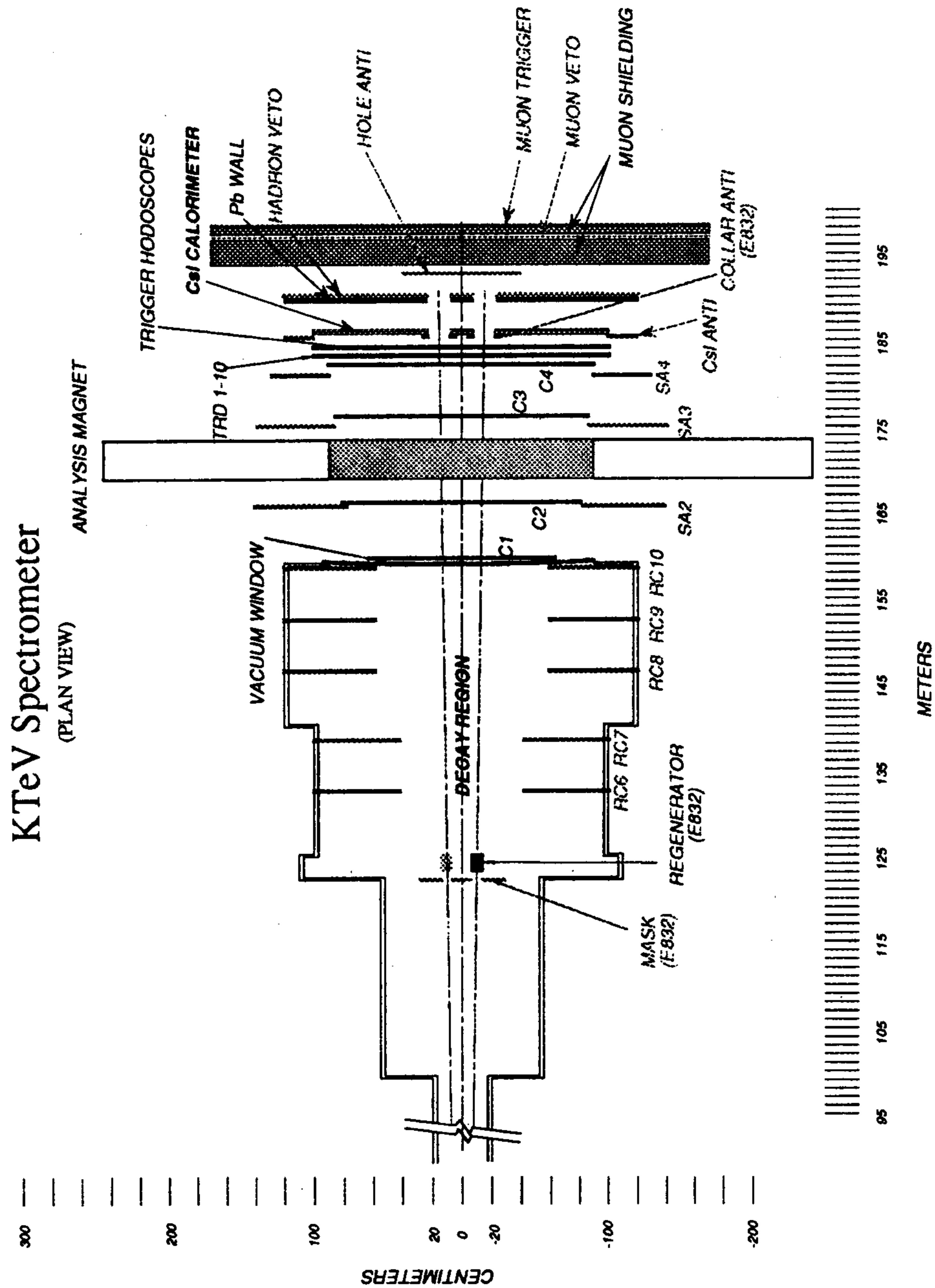


Fig. 6.2. Plan view of the KTeV experiment at FNAL.

The KTEV experiment retains the basic principle of E731, with several significant improvements, the most important being the use of CsI crystals for the electromagnetic calorimeter. This results in better energy resolution which is important for background rejection in the  $\pi^0\pi^0$  channel as well as in the search for rare  $K$  decays. A plan view of KTEV is shown in fig. 6.2.

### 6.3. KLOE

The KLOE detector looks very much like a collider detector and will be in fact operated at the DAΦNE collider under construction at the Laboratori Nazionali di Frascati, LNF. A cross section of KLOE is shown in fig. 6.3. At DAΦNE  $K$ -mesons are produced in pairs at rest in the laboratory, via the reaction  $e^+e^- \rightarrow \phi \rightarrow 2K$ .  $\sim 5000$   $\phi$  mesons are produced per second at a total energy of  $W=1020$  MeV and full DAΦNE luminosity.

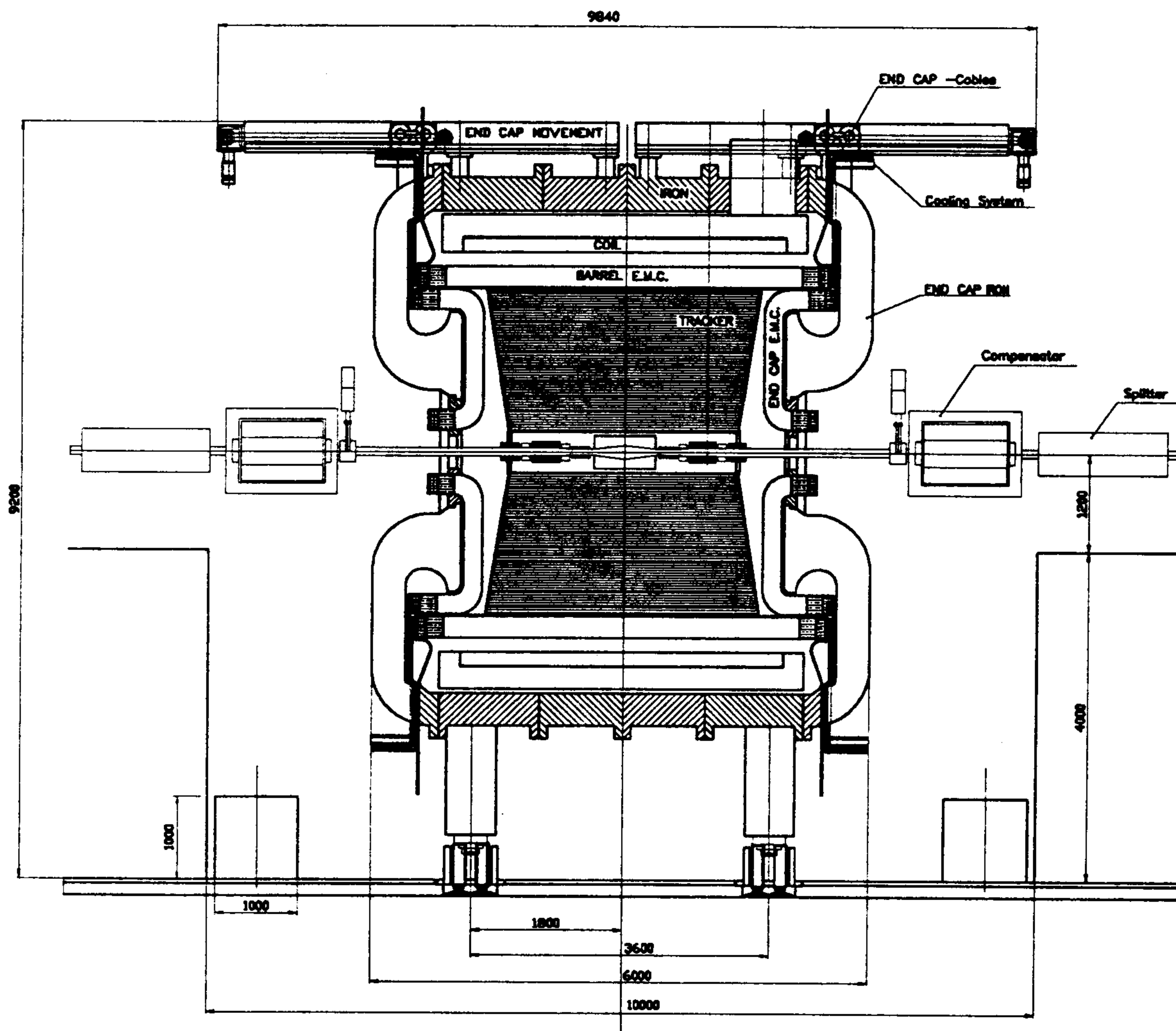


Fig. 6.3. Section of KLOE at DAΦNE.

The two neutral kaons are produced in a pure  $C$ -odd quantum state. This implies

that, to a very high level of accuracy, the final state is always  $K_S K_L - K_L K_S$  or  $K^0 \bar{K}^0 - \bar{K}^0 K^0$ . Tagging of  $K_S$ ,  $K_L$ ,  $K^0$ ,  $\bar{K}^0$  is therefore possible. A pure  $K_S$  beam of about  $10^{10}$  per year is a unique possibility at DAΦNE at full luminosity. The produced kaons are monochromatic, with  $\beta \sim 0.2$ . This allows measurement of the flight path of neutral  $K$ 's by time of flight.

Finally because of the well defined quantum state, spectacular interference effects are observable,<sup>[49,50]</sup> allowing a totally different way of measuring  $\Re(\epsilon'/\epsilon)$ , in addition to the classical method of the double ratio  $\mathcal{R}$ . This experiment is however more difficult, because no first order cancellations of many systematic errors are possible.

#### 6.4. Conclusions

Ultimately three independent measurements performed with very different techniques should be able to determine whether  $\Re(\epsilon'/\epsilon) \neq 0$ , as long as  $\Re(\epsilon'/\epsilon) \sim \text{few} \times 10^{-4}$ .

Each experiment has additional by-products of interest in kaon physics. From KTEV and NA48, more precise values of  $\phi_{+-}$  and  $\Delta\phi$  will be obtained. KTEV expects to reach an error of  $0.5^\circ$  in the experimental determination of  $\phi_f$  or  $\phi_\rho$  using semileptonic decays. NA48 can measure  $\phi_{+-}$  by oscillations of the decay rate behind their production targets, if  $n(K^0) \neq n(\bar{K}^0)$ . The strong correlation between  $\Delta m$  and  $\phi_{+-}$  does not change. However all errors will be smaller. Likewise other parameters relevant to testing  $CPT$  invariance will be measured to higher accuracy, e.g. the charge asymmetry  $A_L$  in semileptonic decays. In this respect the uniqueness of DAΦNE is that of providing a tagged, pure  $K_S$  beam which allows KLOE to measure the charge asymmetry  $A_S$  in leptonic decays of  $K_S$ -mesons to an accuracy  $\delta A_S \sim \text{few} \times 10^{-4}$ . The value of  $\Gamma_L$  is becoming relevant in the analysis of the  $K^0 - \bar{K}^0$ ,  $K_S - K_L$  system. This is a measurement which KLOE can perform, improving the accuracy by  $\sim \times 15$ .

Concerning rare decays the number of events collected by KTEV and NA48 should increase by a factor of 100, corresponding to putting limits of  $\text{few} \times 10^{-11}$  on unobserved decays and an improvement of a factor ten in the measurable rates. The statistics available at DAΦNE for  $K_L$  decays cannot compete with that of KTEV and NA48. However the tagged  $K_S$  beam will allow us to improve the measurements of rare  $K_S$  decays by three orders of magnitude.

One last open question is a better test of the  $\Delta S = \Delta Q$  rule. This is not possible with the  $K^0 - \bar{K}^0$  state produced at DAΦNE (without invoking  $CPT$ ) nor with high energy  $K$  beams.  $K$ 's tagged via strong interactions are required to test the rule. The copious  $K^+ K^-$  production at DAΦNE provides tagged  $K^+(K^-)$  beams which, via charge exchange, results in strangeness tagged  $K^0(\bar{K}^0)$ 's, much in the same way it is done in CPLEAR. CPLEAR has collected tens of million events, KLOE can do at least a factor of ten better.

A little farther in time, a strong  $K$  program at the main injector at FNAL, KAMI, if approved, could by the beginning of the next millennium, be quite competitive with and complementary to the  $B$ -factories in determining the CKM matrix parameters (or finding something wrong with the standard model).

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