Recent measurements of $\mathcal{CP}$ violation in the neutral kaon system

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During the last ten years the measurement of direct $\mathcal{CP}$ violation in the $K^0-\overline{K^0}$ system has been vigorously carried out by experiments NA48 at CERN and KTeV at Fermilab. The measurement of the parameter Re$(\varepsilon'/\varepsilon)$ has been achieved with an accuracy of 2×10^{-4}. We review some important results obtained by these two experiments among which the clear evidence of direct $\mathcal{CP}$ violation. The CPLEAR contribution to the precision determination of parameters in the kaon sector is briefly discussed.

1. INTRODUCTION

The decade after the discovery of the failure of $\mathcal{CP}$ symmetry [1] in the neutral kaon system was rich of experiments seeking the properties of the effect. The picture was well established in the mid 70's that the physical states of the neutral kaon system deviate slightly from pure CP eigenstates. The long-lived K_L and short-lived K_S result from the mixing of K_1^0 (CP=+1) and K_2^0 (CP=-1) where the size of the deviation from pure $\mathcal{CP}$ eigenstates is characterized by one complex parameter $\varepsilon\simeq 2.3\times10^{-3}\cdot e^{-i\frac{\pi}{4}}$. This gives rise to indirect $\mathcal{CP}$ violation effects among which $K_L\rightarrow 2\pi$ decays and $K_L\rightarrow \pi l\nu$ asymmetries have received extensive investigations [2]. The superweak force suggested by Wolfenstein [3] so that all observed $\mathcal{CP}$ violation comes from $K^0-\overline{K^0}$ transitions was challenged in 1973 by Kobayashi and Maskawa [4] when they proposed three generations of quarks with coupling between the different families. In this model $\mathcal{CP}$ violation is naturally accomodated by a non-trivial phase δ and arises *indirectly* from mixing through ε and *directly* from decay of the K_2^0. This $K_2^0\rightarrow 2\pi$ decay is parametrized by a second number ε' that reads:

$$\varepsilon'=\frac{\varepsilon}{\sqrt{2}}\left\{\frac{\langle\pi\pi_{I=2}|H|K_L\rangle}{\langle\pi\pi_{I=0}|H|K_L\rangle}-\frac{\langle\pi\pi_{I=2}|H|K_S\rangle}{\langle\pi\pi_{I=0}|H|K_S\rangle}\right\} \quad (1)$$

Because of the empirical $\Delta I=1/2$ selection rule one can infer from eq.(1) that Re$(\varepsilon'/\varepsilon)$ is expected in the 10^{-3} range. The parameters ε and ε' are related to each other through the amplitude ratios of the $\mathcal{CP}$ violating channel with respect to the $\mathcal{CP}$ conserving one. For the charged mode the ratio is given by:

$$\eta^{+-}\equiv\frac{A(K_L\rightarrow\pi^+\pi^-)}{A(K_S\rightarrow\pi^+\pi^-)}\simeq\varepsilon+\varepsilon'$$

and for the neutral mode by:

$$\eta^{00}\equiv\frac{A(K_L\rightarrow\pi^0\pi^0)}{A(K_S\rightarrow\pi^0\pi^0)}\simeq\varepsilon-2\,\varepsilon'$$

The ratio ε'/ε is a function of the coefficients of the 3x3 Cabibbo-Kobayashi-Maskawa (CKM) matrix V^{CKM}. A 'pedagogical' formula [5] describes it as:

$$\frac{\epsilon'}{\epsilon}\approx\frac{Im\lambda_t}{1.34}18\cdot\left(\frac{110MeV}{M_S(M_C)}\right)^2\left[0.75\cdot B_6-0.4\cdot B_8\left(\frac{M_T}{165GeV}\right)^{2.5}\right]\frac{\Lambda_{\overline{MS}}}{340MeV} \quad (2)$$

The Wolfenstein treatment of the CKM matrix is made with four parameters λ, A, ρ, η where each element of V^{CKM} is expanded as a power series in $\lambda=|V_{us}|=0.22$. In equation (2) $Im\lambda_t=|V_{ub}||V_{cb}|\sin\delta=\eta\lambda^5A^2$ and B_6 and

*Presented at the Siena Conference, The Legacy of LEP and SLC, October 8-11 2001, on behalf of the NA48 Collaboration : Cagliari, Cambridge, CERN, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Orsay, Perugia, Pisa, Saclay, Siegen, Torino, Warszawa, Wien.

B_8 are matrix elements corresponding to different penguins diagrams from the *electroweak* and *strong* sectors respectively. The theoretical uncertainties on B_6 and B_8 are still too large to allow a precise determination of $Im\lambda_t$ from the measurement of ε'/ε predicted in the range of up to 30×10^{-4} [6].

As shown if Fig. 1, the measurement from $K_L \to 2\pi$ decays combined with the theoretical formula for ε specify an hyperbola in the (ρ, η) plane. Since the analytical formula for ε'/ε is proportional to η the two parameters ε and ε' measured in the kaon system can be used for a determination of the unitarity triangle. The universality of this triangle will be tested further in the near future when precise measurements of $(\Delta M)_d/(\Delta M)_s$ and sin2β are available from $B^0_d \to \psi K_S$ and later when $K_L \to \pi^0\nu\overline{\nu}$ and $K^+ \to \pi^+\nu\overline{\nu}$ branching ratios will be known to about 15% [7].

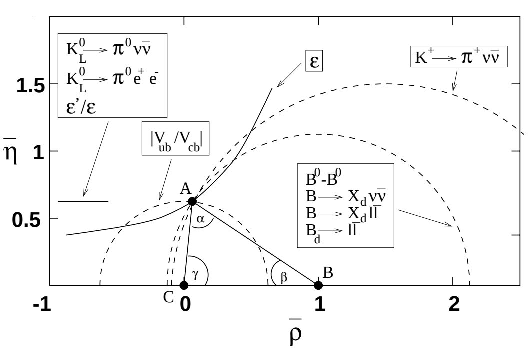

Figure 1. The constraints for the determination of the unitarity triangle (From Buras).

2. THE EXPERIMENTS

The first evidence for direct $\mathcal{CP}$ violation was made by CERN/NA31 in 1988, their final result published in 1993 being Re$(\varepsilon'/\varepsilon)$=$(23.0 \pm 6.5) \times 10^{-4}$ [8], whereas Fermilab/E731 was reporting $(7.4 \pm 5.9) \times 10^{-4}$ [9]. The Particle Data Group combined the two results to the inconclusive average of $(15 \pm 8) \times 10^{-4}$ and two new experiments, NA48 and KTeV, were designed to resolve the issue of direct $\mathcal{CP}$ violation in the $K_L \to 2\pi$ channel. The physical observables are the 2π rates in the four channels and they are used to calculate the double ratio R=$(\eta_{00}/\eta_{+-})^2$ = 1-6xRe$(\varepsilon'/\varepsilon)$. Several million $K_{L,S} \to 2\pi$ decays must be collected in order to measure Re$(\varepsilon'/\varepsilon)$ with an accuracy of 10^{-4}. Although both experiments are dedicated to the measurement of R they have also studied other neutral kaon decay channels. Another evidence of indirect $\mathcal{CP}$ violation is seen with the decay $K_L \to \pi^+\pi^-e^+e^-$. High resolution detectors are employed by both experiments to achieve excellent background rejection from high fluxes of kaons. Efficient data acquisition sytems using triggers with high rejection power and large bandwith and storage capacity are common features to NA48 and KTeV.

2.1. NA48 at CERN

NA48 uses two targets, located 126m and 6m upstream of the decay region, on which 450 GeV/c protons from the SPS with a cycle time of 14.4s produce kaons during an effective spill length of 1.7s. The observation of K_L decays is made from the upstream target and that from K_S decays from the downstream target and both charged and neutral modes are collected *simultaneously* to take advantage of fluxes cancellation and to be highly insensitive to dead-time effects. The K_S beam produced at the target in the decay volume 7.2cm above the K_L beam makes an angle such that the two beams converge at the center of the LKr calorimeter. Protons directed to the K_S target are identified by an upstream tagging station and by comparing this registred proton time to the event time in the detector the K_S decays are separated from the K_L ones. The method is used for $\pi^0\pi^0$ and for $\pi^+\pi^-$ and therefore R is only sensitive to the *difference* in misidentification probabilities between the two modes. This is kept at 10^{-4} level without any bias on R. The measurement uses a weighting technique such that R can be directly calculated with only a small acceptance correction. Each event vertex from $K_L \to 2\pi$ in the decay region is measured in

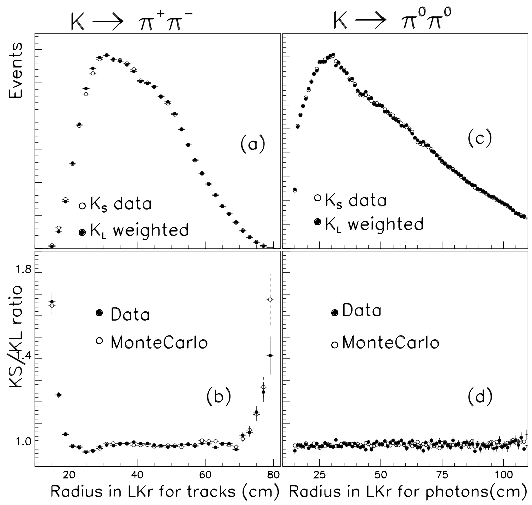

Figure 2. Illustration of the weighting method

units of K_S lifetime and the K_L distributions are weighted with

$$W(\tau) = \frac{I(\tau \text{ from } K_S \text{ target}) \to 2\pi}{I(\tau \text{ from } K_L \text{ target}) \to 2\pi}$$

which unfolds the K_L lifetime and folds in the K_S lifetime thus making the two distributions almost identical. This procedure would make the experiment "ideal" if both beams had the same divergence and geometry since the detector would see identical "sources" of K_L and K_S. The illumination of the detector by tracks and photons shown in Fig. 2 (a) and (c) is an example of the weighting procedure. The largest correction to R, while remaining small, comes from the second order difference in acceptances for $\pi^+\pi^-$ decays between K_S events and weighted K_L events as shown in Fig. 2 (b). It is estimated by Monte-Carlo to be $\Delta R = (+26.7 \pm 4.1(stat) \pm 4.0(syst)) \times 10^{-4}$. The measurement of $\mathrm{Re}(\varepsilon'/\varepsilon)$ was made with event statistics seven times larger than that used for the 1997 published result with sets of data taken during 1998 and 1999 as shown in Tab. 1.

2.2. KTeV at Fermilab

KTeV uses a single target on which 800 GeV/c protons from the Tevatron produce two side-by-side neutral beams arriving in the decay region after 90m. The short-lived particles have decayed away leaving almost pure K_L beams one of which strikes a regenerator converting K_L to coherent K_S. The four decay modes are collected *simultaneously* in the detector and the R measurement is made insensitive to beam intensity, deadtime effects and detector inefficiencies by alternating the regenerator sides beetween the accelerator cycles of about one minute. The charged-particle spectrometer provides momentum and vertex measurements of $\pi^+\pi^-$ events and the calorimeter uses CsI crystals to measure energies and positions of γ from $2\pi^0$ decays. The crucial requirement for measuring $\mathrm{Re}(\varepsilon'/\varepsilon)$ with this technique is the precise knowledge of the longitudinal dependance of the acceptance for each mode. It requires a detailed understanding of the detector response and many decay modes with high statistics are used for this. The quality of the agreement between data and Monte-Carlo simulation is shown in Fig. 3. The K_L beam impinging on the regenerator produces a *coherent* mixture of K_L and K_S whose common $\pi\pi$ decay channel creates the interference pattern shown in Fig. 4. The *diffractive* and *inelastic* components of the regenerator beam are identified by specific tails in the transverse momentum for the $\pi^+\pi^-$ decays and by their characteristic center of energy distributions for $\pi^0\pi^0$ decays. A first result was obtained and published with $K \to \pi^0\pi^0$ from 1996 and $K \to \pi^+\pi^-$ from 1997 and a new analysis was made with data sets from 1997 and combined with the published one as shown in Tab. 2.

Table 1
Number of selected events in millions (K_L weighted) and statistical precision on R for NA48.

	1998	1999	total
$K_L \to \pi^0\pi^0$	1.047	2.243	3.290
$K_S \to \pi^0\pi^0$	1.638	3.571	5.209
$K_L \to \pi^+\pi^-$	4.541	9.912	14.453
$K_S \to \pi^+\pi^-$	6.910	15.311	22.221
Stat. error (in 10^{-4})	18.0	12.2	10.1

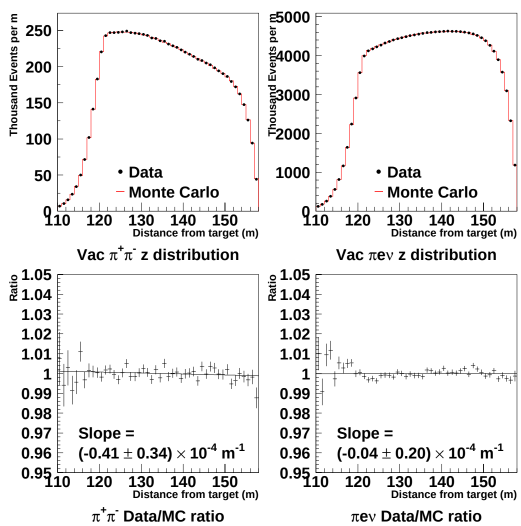

Figure 3. Data vs MC for charged decays in the K_L beam

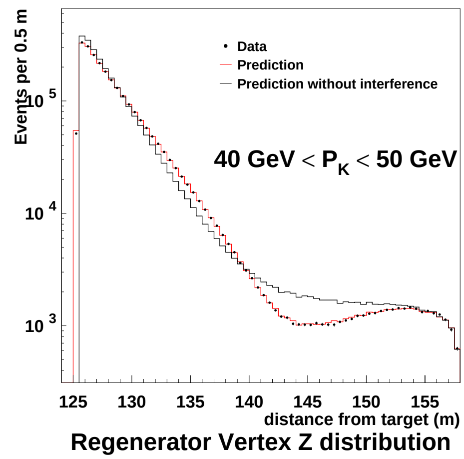

Figure 4. Interference behind KTeV regenerator.

2.3. Event reconstruction and background

After appropriate trigger selection both experiments are reconstructing their events with similar techniques. The $\pi^0\pi^0$ signal is extracted from energy and position measurement of photons in electro-magnetic calorimeters with high resolutions. The $\pi^+\pi^-$ signal are reconstructed with tracks recorded in drift chambers of magnetic spectrometers having similar performances. The background to the $\pi^0\pi^0$ signal comes uniquely from $K_L \to 3\pi^0$ for NA48. It is suppressed by the requirement that there is no additional shower within $(\pm 3)ns$ around the event time. In KTeV there is $K \to 2\pi$ scattering in the regenerator producing additional background in both beams. The background to the $\pi^+\pi^-$ mode are the semi-leptonic K_{e3} and $K_{\mu 3}$ decays for which either an electron or a muon fakes a pion. The typical background/signal ratios are well understood and are kept at the few per mille level or below. Finally there is a small contamination from $K \to 2\pi$ scattering from the final defining collimators in the K_L beam for KTeV and in both beams for NA48.

Table 2
Number of events in millions and statistical precision on R for KTeV.

	1996	1997	combined
$K_L \to \pi^0\pi^0$	0.9	2.5	3.4
$K_S \to \pi^0\pi^0$	1.4	4.2	5.6
$K_L \to \pi^+\pi^-$	2.6	8.6	11.2
$K_S \to \pi^+\pi^-$	4.5	14.9	19.4
Stat. error (in 10^{-4})	18.0	10.2	9.0

The corresponding corrections to R are all very small.

3. THE RESULTS

3.1. Direct $\mathcal{CP}$ violation

The NA48 analysis was made in bins of kaon energy from 70 to 170 GeV and for proper-time up to 3.5 τ_S from the beginning of the decay region. All corrections are applied to each bin separately, and then averaged using a statistically unbiased estimator. The stability of the result was tested against various conditions and the systematic checks are summarized in Fig. 5.

The KTeV result is obtained from the raw dou-

ble ratio after taking into account that the regenerator beam is not pure K_S and requires the precise determination of *average* acceptance. As part of their systematic studies they have also applied a reweighting method with a loss on the statistical error and both results are in good agreement. After all corrections have been applied the NA48 result for the 1997/98 data set is: $R = (0.99098 \pm 0.00101(stat) \pm 0.00126(syst))$ giving the measurement of the direct $\mathcal{CP}$ violation parameter $Re(\varepsilon'/\varepsilon) = (15.0 \pm 1.7(stat) \pm 2.1(syst) \times 10^{-4})$. Including the result from 1997 with correlated uncertainties taken into account the global NA48 result is:
$Re(\varepsilon'/\varepsilon) = (15.3 \pm 2.6) \times 10^{-4}$. CERN/NA48

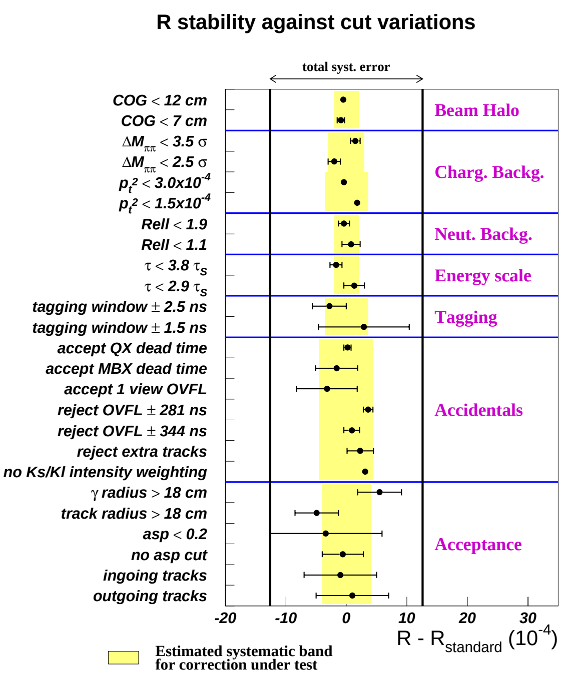

Figure 5. Systematic errors on $R - R_{standard}$ for experiment NA48.

The new measurement made by KTeV from the 1996/97 data set, statistically independent from their published result is $Re(\varepsilon'/\varepsilon) = (19.8 \pm 1.7(stat) \pm 2.3(syst) \pm 0.6(MC) \times 10^{-4})$. This has been combined with the reanalysis of the published result and gives:
$Re(\varepsilon'/\varepsilon) = (20.7 \pm 2.8) \times 10^{-4}$.

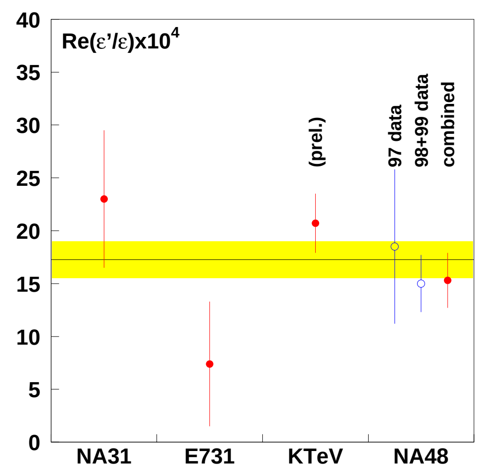

Figure 6. Recent results on ε'/ε.

The direct $\mathcal{CP}$ violation parameter $Re(\varepsilon'/\varepsilon)$ has therefore been measured with dramatic improvement by both experiments. These results from both sides of the Atlantic are in good agreement and the new averaged world value with PDG error scaling is now: $Re(\varepsilon'/\varepsilon) = (17.2 \pm 2.4) \times 10^{-4}$. The summary of the recent measurements of $Re(\varepsilon'/\varepsilon)$ is shown in Fig. 6 where it is worthwhile to appreciate that NA31 is 0.9σ above the world average value whereas E731 is 1.6σ above. They indeed belong to the legacy!

3.2. T violation from CPLEAR

The CPLEAR experiment at CERN has made extensive studies of the neutral kaon system with low energy antiprotons from the LEAR machine used as a source of tagged K^0 and $\overline{K^0}$ in $p\overline{p}$ annihilation at rest. The main components of the barrel-shaped detector are a central tracking system of wire chambers in solenoidal magnetic field, a threshold Cerenkov for particle identification and a lead-gas sampling electromagnetic calorimeter for photon detection. The strangeness produced at t=0 during the annihilation process, either $p\overline{p} \rightarrow K^+K^0\pi^-$ or $p\overline{p} \rightarrow K^-\overline{K^0}\pi^+$, is deciphered from the K^+ or K^- identification. This is made under the assumption that the $\Delta S = \Delta Q$ holds exactly and therefore the strangeness of the decaying neutral kaon is known through its K_{e3} signature. Thus the direct observation of the time evolution between K^0 and $\overline{K^0}$ can then be measured in optimum conditions. Out of the many studies that they have made [10], including test of quantum mechanics coherence, the asymmetry measurement A_T defined as:

$$\frac{N(\overline{K^0}_{t=0} \rightarrow \pi^- e^+ \nu_{t=\tau}) - N(K^0_{t=0} \rightarrow \pi^+ e^- \overline{\nu}_{t=\tau})}{N(\overline{K^0}_{t=0} \rightarrow \pi^- e^+ \nu_{t=\tau}) + N(K^0_{t=0} \rightarrow \pi^+ e^- \overline{\nu}_{t=\tau})}$$

has been made with very large stastistics of 6.4×10^5 events. As shown in Fig. 7 A_T is non zero and independent of time.

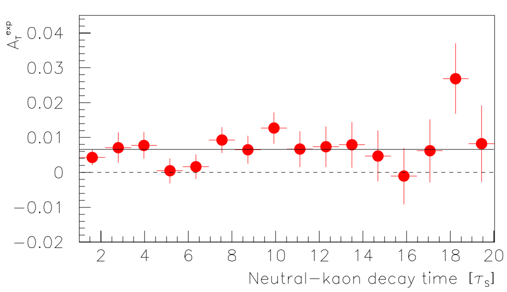

Figure 7. Time asymmetry from CPLEAR

The result:
$< A_T >= (6.6 \pm 1.3) \times 10^{-3}$ CERN/CPLEAR
gives the first observation of T violation from time conjugate processes. This *direct* measurement of time non-invariance translates into $Re(\varepsilon) = (1.65 \pm 0.35 \pm 0.25 \times 10^{-3})$ [11] in good agreement with the CPT theorem. With their general survey of the neutral kaon system CPLEAR has brought a significant amount of new and precise data to the field of fundamental symmetries in physics.

3.3. The indirect $\mathcal{CP}$ violating decay $K_L \rightarrow \pi^+\pi^-e^+e^-$

During data taking for ε'/ϵ NA48 made also parasitic recording of events with various trigger conditions to study hyperons and rare kaon decays. Among those the $K_L \rightarrow \pi^+\pi^-e^+e^-$ decay proceeding mainly through $\pi^+\pi^-\gamma^*$ intermediate state is related to indirect $\mathcal{CP}$-violation. The decay amplitude is dominated by two components: the indirect $\mathcal{CP}$-violating $K_L \rightarrow \pi^+\pi^-$ with inner bremsstrahlung, and the $\mathcal{CP}$-conserving photon M1 emission followed by internal conversion. The two amplitudes interfere with the results of $\mathcal{CP}$-violating circular polarization of the photon. The ϕ angle between the plane of the e^+e^- pair and the plane of the $\pi^+\pi^-$ pair is a T odd variable relevant for the study of this polarization. In the model of *Sehgal and Wanniger* [12], the unambiguous signature of $\mathcal{CP}$-violation is represented by the term Γ_3 of the angular distribution :

$$\frac{d\Gamma}{d\phi} = \Gamma_1 cos^2\phi + \Gamma_2 sin^2\phi + \Gamma_3 cos\phi sin\phi$$

The effect is studied experimentally through the asymmetry:

$$\mathcal{A}_\phi = \frac{N_{\cos\phi\sin\phi>0} - N_{\cos\phi\sin\phi<0}}{N_{\cos\phi\sin\phi>0} + N_{\cos\phi\sin\phi<0}}$$

which is predicted to be 14% by the theory [12]. The Monte-Carlo is used to calculate the acceptance correction, it includes a form factor F in the $M1$ direct emission term:

$$F = \tilde{g}_{M1}\left[1 + \frac{a_1/a_2}{(M_\rho^2 - M_K^2) + 2M_K E_\gamma^*}\right]$$

where the values $\tilde{g}_{M1} = 1.35^{+0.20}_{-0.17}$ and $a_1/a_2 = -0.720 \pm 0.029 GeV^2/c^2$ have been experimentally measured by $KTeV$ [13]. Using $K_L \rightarrow \pi^+\pi^-\pi^0_{\rm D}$ as normalization channel the preliminary branching ratio obtained is :

$$BR(K_L \rightarrow \pi^+\pi^-e^+e^-) = (3.1 \pm 0.1 \pm 0.2) \times 10^{-7}$$

which is in good agreement with the theoretical prediction of $\sim 3 \times 10^{-7}$ [12] and in fair agreement with the measurement from *KTeV* [14]. The

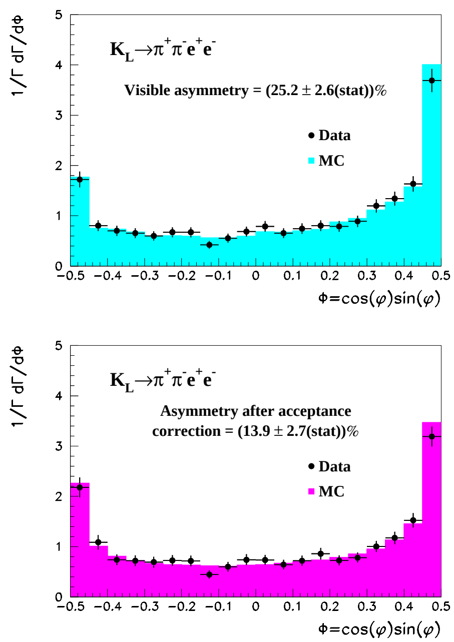

Figure 8. $\cos\phi \sin\phi$ distributions. *Top* : observed in the data, , *Bottom* : after acceptance unfolding.

$\mathcal{CP}$-violating asymmetry is maximum when the photon interference between the M1 direct emission and the inner bremsstrahlung is the largest. The experimentally observed asymmetry tends to be enhanced by the acceptance of the detector. With full simulation of the detector it has been shown that in the absence of interference the expected observed asymmetry is zero, and therefore no asymmetry is generated by apparatus effects. Fig. 8 shows the angular distribution of ϕ observed by NA48 and in comparison with the Monte-Carlo simulation before and after unfolding of the experimental acceptance. The asymmetry is measured to be:

$$\mathcal{A}_L = (13.9 \pm 2.7 \pm 2.0)\%$$

in agreement with the published value from *KTeV* [13] and with the theoretical prediction of [12].

A particular advantage of NA48 is the unique opportunity to work with an almost pure K_S beam coming from the near target. The $K_S \to \pi^+\pi^-e^+e^-$ channel was searched for, since in this decay the amplitude is dominated by the $\mathcal{CP}_{even}$ inner bremsstrahlung component and therefore the expected asymmetry of the ϕ angular distribution is $\mathcal{A}_S = 0$.

Using 105 fully reconstructed $K_L \to \pi^+\pi^-\pi^0_{\rm D}$ events originating from the K_S target as a normalisation sample the first observation of 56 events $K_S \to \pi^+\pi^-e^+e^-$ was made and published [15]. The analysis of this decay mode relies both on the good longitudinal and transverse vertex resolution allowing K_S/K_L identification and on the use of the tagging counter to provide the extra rejection power of 20 against the K_L beam background .

At the end of the 1999 $\mathrm{Re}(\varepsilon'/\varepsilon)$ data taking period, two days were devoted to a high intensity K_S test in order to estimate trigger rates for the future *NA48* programme. The proton beam intensity was increased by a factor ~ 200, giving a sensitivity equivalent to several years of operation with the standard $K_L + K_S$ beam setup. With this configuration 724 $K_S \to \pi^+\pi^-e^+e^-$ signal events were collected, adding up to 921 events when combined with 1998 and 1999 data. The branching ratio for this channel is measured to be:

$$BR(K_S \to \pi^+\pi^-e^+e^-) = (4.3 \pm 0.2 \pm 0.3) \times 10^{-5}$$

and it allows to calculate the inner bremstrahlung component part of $K_L \to \pi^+\pi^-e^+e^-$:
$BR(K_L^{IB} \to \pi^+\pi^-e^+e^-) = (1.3 \pm 0.1) \times 10^{-7}$
in good agreement with theoretical expectations. The ϕ angular asymmetry $\mathcal{A}_S$ of the $K_S \to \pi^+\pi^-e^+e^-$ decay has also been accurately measured :
$\mathcal{A}_S = (-0.2 \pm 3.4 \pm 1.4)\%$
It is compatible with zero, which confirms that the $\mathcal{CP}$ violating asymmetry $\mathcal{A}_L$ observed in

$K_L \to \pi^+\pi^-e^+e^-$ is real and does not result from artefact in the apparatus.

4. CONCLUSIONS

The search for $\mathcal{CP}$ violation made in the 70's was "punctuacted by some experiments of exceptional beauty" [16]. They contributed with theoretical work and new detector technologies to start a series of specific investigations looking for the direct decay of K_2^0. The efforts made at CERN and Fermilab during the last decade have indeed been very successful. The two experiments NA48 and KTeV have established the value of Re(ε'/ε) with great accuracy giving support to the Standard Model prediction and strong incentive to our theoretical collegues. There is hope that these difficult calculations are made more accurate in the near future to allow a determination of the unitarity triangle from ε and ε'. The kaon system has been a notorious source of discoveries and progress for 50 years and a promissing future still belongs to it with the rare decay channels $K \to \pi\nu\overline{\nu}$ for which theory [7] is making precise predictions. It will reveal the unitarity triangle from another viewpoint, complementary to the $B^0 - \overline{B^0}$ system, and perhaps will give hints to new physics beyond the Standard Model.

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