RARE KAON DECAY PHYSICS

A. CECCUCCI
CERN, CH-1211 Geneva 23
E-mail: augusto.ceccucci@cern.ch

Recent progress in the field of rare kaon decays will be described. A brief summary of future experimental activities will also be given. Among the highlights, the improved upper limit on $K_{\rm L} \to \pi^0 e^+ e^-$, and the first observation of the $K_{\rm S} \to \pi^0 e^+ e^-$ are presented. A precise measurement of $K_{\rm S} \to \gamma\gamma$ and high statistics studies of the Dalitz kaon decays have recently been reported and will be briefly described.

1. Introduction

1.1. *Why Study Rare Kaon Decays?*

There are four main reasons to study rare kaon decays:

1. study of the explicit violation of the Standard Model (SM) like Lepton Flavor Violation;
2. probe of the flavor sector by means of Flavor Changing Neutral Currents (FCNC);
3. test of fundamental symmetries such as CP and CPT; and
4. study of the strong interaction at low energy in exclusive processes.

1.2. *Organization of the Paper*

This paper reviews the recent experimental progress in the field of rare kaon decays: in addition to $K_{\rm L}$ and K^+ rare decays that have been the subject of precise studies over many years, $K_{\rm S}$ rare decays have started to be studied to sensitivities below 10^{-8}. The paper is organized as follows: in Sec. 2 recent progress on $K_{\rm L,S} \to \pi^0 e^+ e^-$ and $K^+ \to \pi^+ \nu\overline{\nu}$ is reported: these decays, together with $K_{\rm L} \to \pi^0 \nu\overline{\nu}$ form the core of the program to challenge the Cabibbo–Kobayashi–Maskawa (CKM)[1,2] description of CP-violation and quark mixing using kaon decays. Tests of CP- and CPT-symmetry not strictly related to the CKM description are described in Sec. 3: they include the study of $K_{\rm S,L} \to \pi^+\pi^- e^+ e^-$, $K_{\rm S} \to 3\pi^0$ and the study of semileptonic $K_{\rm S}$ decays. Progress on the study of the kaon Dalitz decays is reported in Sec. 4 while new results on non-leptonic neutral kaon decays are reported in Sec. 5. The new initiatives that should lead to significant advances in this area of research by the end of the decade are briefly outlined in Sec. 6.

2. Tests of the Standard Model with Rare Kaon Decays

The $K \to \pi\nu\overline{\nu}$ and the $K_{\rm L} \to \pi^0 l^+ l^-$ decays allow the study of the coupling of the top quark by means of $s \to d$ virtual transitions which are very suppressed in the Standard Model. In the framework of the CKM description, CP-violation appears naturally from the presence of a complex irreducible phase in the mixing between the first and the third generation of quarks. Without a fourth generation, there is only one irreducible phase and, in the absence of new physics appearing in the virtual loops, the matrix must be unitary. The six unitarity relations can be displayed in the form of triangles on a complex plane. The triangles are all born equal in the sense that they have the same area which is the only *real* measure of CP-violation in the SM.[3] However, some relations look more *triangular* than others because all sides have similar length. For this reason it is common to display the

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \tag{1}$$

unitarity relation on the $\overline{\rho}$ and $\overline{\eta}$ complex plane following the Wolfenstein parametrization.[4] The kaon decay modes relevant to the study of the unitarity triangle are shown on Fig. 1. The area of the triangle is expressed by the Jarlskog invariant, which for kaons can be written as:

$$\begin{aligned} J_{CP} &= \Im V_{ud}V_{us}^* V_{td}V_{ts}^* \\ &= \sin\theta_C \cos\theta_C \Im V_{td}V_{ts}^* \\ &= \sin\theta_C \cos\theta_C \Im\lambda_t \ , \end{aligned} \tag{2}$$

where θ_C is the Cabibbo angle[1] and λ_t is a short-hand notation for $V_{td}V_{ts}^*$. It is useful to relate $\Im\lambda_t$

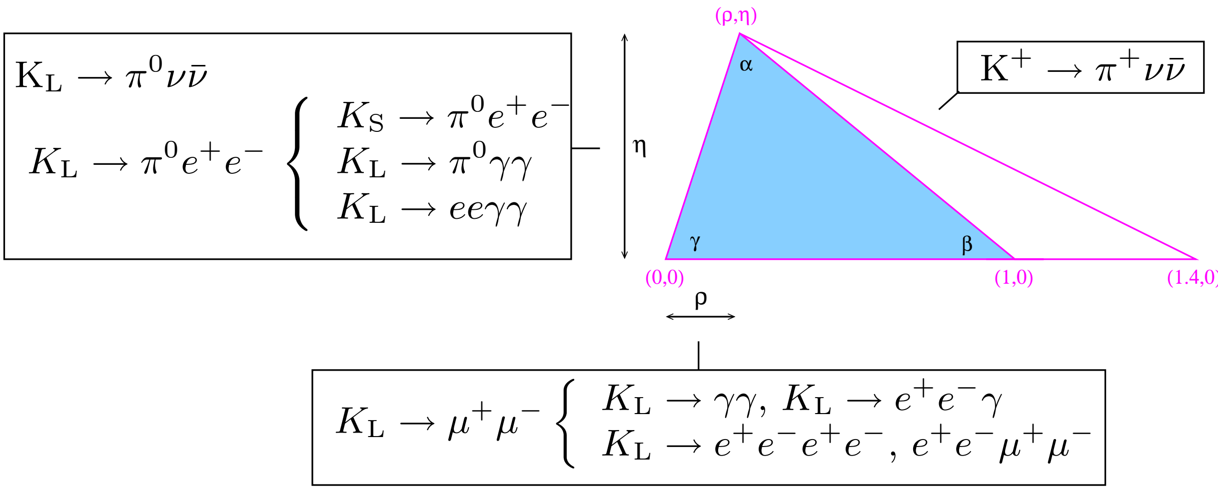

Figure 1. The rare kaon decays related to the study of the unitarity triangle.

and $\Re\lambda_t$ to the $\overline{\eta}$ and $\overline{\rho}$ quantities in the Wolfenstein parametrization:

$$\begin{aligned}\Im\lambda_t &= A^2\lambda^5\overline{\eta} \\ \Re\lambda_t &= A^2\lambda^5\overline{\rho}\ .\end{aligned} \qquad (3)$$

2.1. $K_L \to \pi^0\nu\overline{\nu}$

Even though no recent results have been reported on the subject at this conference, this article would not be complete without mentioning the status of the $K_L \to \pi^0\nu\overline{\nu}$ decay which is purely CP-violating[5] without long-distance contaminations. This decay has been dubbed the *holy grail* of kaon physics.[6] Measuring it is equivalent to a measurement of the height of the unitarity triangle and it can be predicted precisely to a few percent uncertainty because the hadronic matrix element can be taken from the well measured $Ke3$ decay. The current upper limit $< 5.9 \times 10^{-7}$ @ 90% CL[7] is more than one order of magnitude less sensitive than the model-independent limit[8] extracted from $K^+ \to \pi^+\nu\overline{\nu}$ which reads:

$$BR(K_L \to \pi^0\nu\overline{\nu}) < 1.7 \times 10^{-9} \quad 90\%\ \text{CL}\ . \qquad (4)$$

Prospects for further improving this channel are discussed in the last section.

2.2. $K_L \to \pi^0 e^+ e^-$

The physics interest is the same as $K_L \to \pi^0\nu\overline{\nu}$ but the experimental challenges, while very different, are still formidable. In addition, the interpretation of a possible observation is complicated by long-distance effects which require the study of additional reactions as depicted in Fig. 1. There has been a recent reanalysis of the decay by Buchalla, D'Ambrosio and Isidori,[9] motivated in part by a series of recent experimental results on the ancillary modes. The direct CP-violating short-distance contribution can be predicted taking $\Im\lambda_t$ from SM fits to the CKM unitarity triangle. For example taking[10]

$$\Im\lambda_t = 1.36 \times 10^{-4}, \qquad (5)$$

they find:

$$BR(K_L \to \pi^0 e^+ e^-)^{Direct}_{CPV} = (3.2 \pm 0.4) \times 10^{-12} \qquad (6)$$

which is indeed very small. In addition to the short-distance, there is another CP-violating contribution coming from the CP-even component of the K_L and proportional to $BR(K_S \to \pi^0 e^+ e^-)$. This component can be written as:

$$\begin{aligned}BR(K_L \to \pi^0 e^+ e^-)^{Indirect}_{CPV} &= \\ |\epsilon|^2 \tfrac{\tau_L}{\tau_S} BR(K_S \to \pi^0 e^+ e^-).\end{aligned} \qquad (7)$$

There are predictions of $BR(K_S \to \pi^0 e^+ e^-)$ spanning over one order of magnitude[11−13] and a measurement or a significant upper bound is necessary to fix this long-distance-dominated process.

The direct and the indirect CP-violating contributions can interfere, further complicating the extraction of $\Im\lambda_t$. However, if the indirect CP-violating component is large and if the interference term is constructive, the sensitivity to the short-distance physics is enhanced.

Last but not least, a CP-conserving amplitude has also to be taken into account. Information on this component can be extracted from the study of

Table 1. Limits on $K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \mu^+ \mu^-$ published by the KTeV Collaboration.

Mode	BR @ 90% CL	Ref.
$K_L \to \pi^0 e^+ e^-$	$< 5.1 \times 10^{-10}$	18
$K_L \to \pi^0 \mu^+ \mu^-$	$< 3.8 \times 10^{-10}$	19

$K_L \to \pi^0 \gamma\gamma$. It has been pointed out[14] that reliable estimates of this contribution must be performed in a model-independent way without imposing Vector Meson Dominance (VMD) a priori. This point of view has been followed[9]: determining the three counter-terms from $K_L \to \pi^0 \gamma\gamma$[15] and $K_S \to \gamma\gamma$[16] data, the CP-conserving contribution to $K_L \to \pi^0 e^+ e^-$ is found to be:

$$BR(K_L \to \pi^0 e^+ e^-)^{Conserving}_{CPC} < 3 \times 10^{-12}, \quad (8)$$

much smaller than the total CP-violating term. All the considerations presented in this section apply also to the study of $K_L \to \pi^0 \mu^+ \mu^-$ but the CP-conserving term in this case needs more attention. The best limits on $K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \mu^+ \mu^-$ are those obtained by the KTeV experiment at Fermilab. KTeV has two purposes: one experiment, E832, is devoted to the study of direct CP-violation in two-pion decays of the neutral kaon[17] (ϵ'/ϵ). The other, E799 II, is devoted to the study of rare kaon decays. E799 II used the extracted 800 GeV Tevatron proton beam and took data in 1997 and 1999 collecting about 7×10^{11} K_L decays in a relatively short running period. The experiment employs state-of-the-art CsI eletromagnetic calorimetry and a transition radiation detector to improve the pion/electron separation. The experimental difficulty resides in the presence of irreducible backgrounds from the radiative decay $K_L \to e^+ e^- \gamma\gamma$ which has a branching ratio of about $\approx 6 \times 10^{-7}$ and, to a lesser extent, $K_L \to \mu^+ \mu^- \gamma\gamma$. Only a very good two-photon mass resolution and kinematic cuts are available to suppress these backgrounds. As a consequence, in order to keep the backgrounds to the ≤ 1 event level, one is forced to reduce the acceptance quite significantly. Future searches will be background dominated and the progress will not be linear with the accumulated kaon flux. The published limits by KTeV are reported in Table 1. KTeV has also analyzed the data collected in 1999 to search

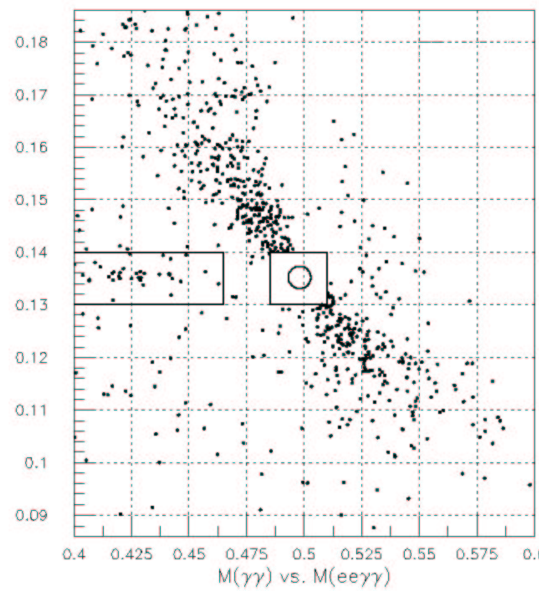

Figure 2. $M(\gamma\gamma)$ vs. $M(e^+e^-\gamma\gamma)$ scatter plot for the 1999 KTeV data. The signal (circle) and control (square) regions are masked.

for $K_L \to \pi^0 e^+ e^-$. Details on the analysis can be found in a preprint that has just become available.[20] In Fig. 2 the $M(\gamma\gamma)$ vs. $M(e^+e^-\gamma\gamma)$ scatter plot for the 1999 KTeV data is shown. In this figure the invariant mass of the four particles $M(e^+e^-\gamma\gamma)$ is plotted under the hypothesis that the two photons come from a π^0 decay. This improves the mass resolution but makes the radiative background appear as a diagonal swath in the scatter plot. Backgrounds not related to $e^+e^-\gamma\gamma$ are quite small. In particular, one notes that the excellent energy resolution of the detector allows the background $K_L \to \pi^0 e^+ e^- \gamma$ to be suppressed very efficiently. To further suppress the radiative background, one makes use of the different kinematics of the signal and of the background as studied by Greenlee.[21] The two useful variables are the minimum angle between any electron and any photon (θ_{min}), and the minimum angle of any photon with respect to the π^0 direction (θ_{π^0}) which, for a genuine π^0 decay, should be isotropically distributed but not for a radiative decay. The two distributions are shown in Fig. 3.

The values for the cuts on these kinematic variables were chosen to minimize the $BR(K_L \to \pi^0 e^+ e^-)$ upper limit in the absence of signal. After inspection of the signal box, one candidate event was found, which is consistent with the expected

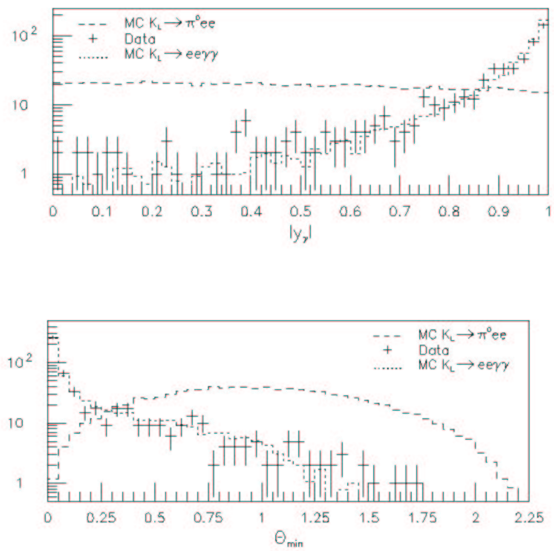

Figure 3. Comparison of $y_\gamma = \cos\theta_{\pi^0}$ (top) and θ_{min} (bottom) for $e^+e^-\gamma\gamma$ and $\pi^0e^+e^-$ final states.

background of 0.99 ± 0.35 events. The $M(\gamma\gamma)$ vs. $M(e^+e^-\gamma\gamma)$ scatter plot, with the unmasked signal region and after all cuts are applied, is shown in Fig. 4.

The KTeV result for the 1999 data is $BR(K_\mathrm{L} \to \pi^0e^+e^-) < 3.5 \times 10^{-10}$ @ 90% CL. Combining this result with the previous search leads to the final KTeV result:

$$BR(K_\mathrm{L} \to \pi^0e^+e^-) < 2.8 \times 10^{-10} \text{ @ 90\% CL.} \quad (9)$$

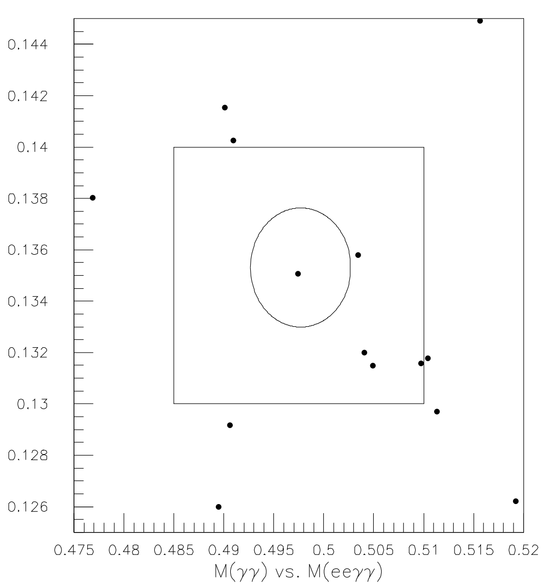

Figure 4. $M(\gamma\gamma)$ vs. $M(e^+e^-\gamma\gamma)$ scatter plot for the $K_\mathrm{L} \to \pi^0e^+e^-$ (1999 data).

2.3. *Observation of $K_\mathrm{S} \to \pi^0e^+e^-$*

As described in the previous section, in order to extract the short-distance information from $K_\mathrm{L} \to \pi^0l^+l^-$, one has to measure or at least bound to the appropriate level the $K_\mathrm{S} \to \pi^0l^+l^-$ reaction. The opportunity to study $K_\mathrm{S} \to \pi^0l^+l^-$ took place at CERN after the NA48 experiment completed the measurement of ϵ'/ϵ.[22,23] The NA48 detectors with upgraded readouts and a modified K_S beam line were used to collect data from an intense, short neutral beam. The neutral beam was produced by striking 400 GeV protons from the CERN SPS onto a Be target 40 cm long. The beam emerges from a 6 m long collimator and enters a 90 m long decay tank. The same number of K_L as K_S is produced in the target and the K_L decays have to be taken into account in the background subtraction. The mean energy of the kaons is about 100 GeV. During the year 2002 NA48/1 collected more than 3×10^{10} K_S decays in the fiducial volume. Previously, during the year 2000, NA48/1 collected data for final states consisting of only photons since the charged spectrometer was not available that year. Here we briefly describe the $K_\mathrm{S} \to \pi^0e^+e^-$ analysis based on the 2002 data. More details on the analysis can be found elsewhere.[24] Events with e^+e^- invariant mass ($M(ee)$) smaller than 0.165 GeV/c^2 are cut to reject $K_\mathrm{S} \to \pi^0\pi^0_D$ decays with a missing photon which could otherwise mimic the signal. In this notation, π^0_D is the shorthand for the $\pi^0 \to e^+e^-\gamma$ (Dalitz) decay. A comparison between the data and the Monte Carlo is shown in Fig. 5 for the events satisfying the relation: 0.09 GeV/c$^2 < M_{ee} < 0.165$ GeV/c^2. These events have the same topology as the signal but fall outside the masked search region and can be used to check the reconstruction procedure. The data is well reproduced by the simulation (the normalization is absolute) and confirms that $M_{ee} > 0.165$ GeV/c^2 to define the signal region is well justified. One can notice that the $\pi^0 \to e^+e^-$ ($BR \simeq 6 \times 10^{-8}$) contribution is quite visible and gives an idea of how small the residual backgrounds due to π^0 Dalitz decays and conversions are. This is due, to a large extent, to the very good energy resolution of the detector. No events reconstructed with two electrons of the same sign were found in the corresponding signal region. This demonstrates that $K_\mathrm{S} \to 2\pi^0$ events in which one pion undergoes a Dalitz decay

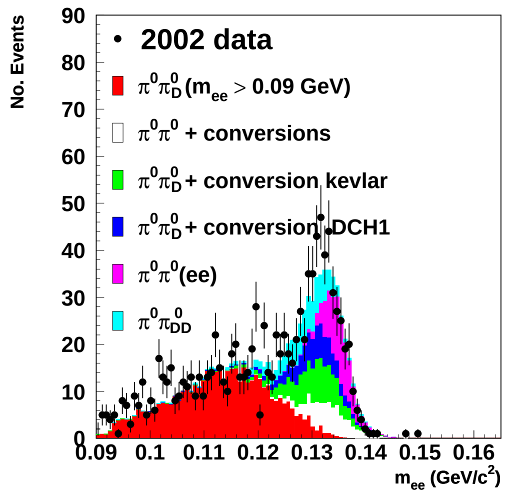

Figure 5. The M_{ee} invariant mass distributions for events that satisfy a $\pm 2.5\sigma$ cut on $M_{ee\gamma\gamma}$ around the kaon mass.

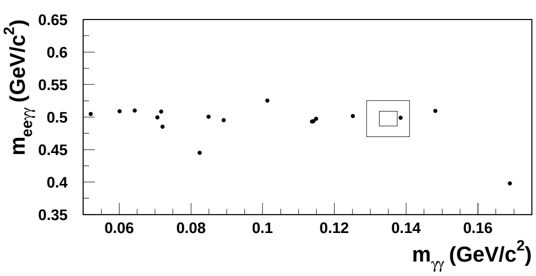

Figure 6. The $M(ee\gamma\gamma)$ vs. $M(\gamma\gamma)$ distribution for the $K_{\rm L}$ data collected in 2001. The sample contains about 10 times the expected number of $e^+e^-\gamma\gamma$ events expected in the 2002 sample and therefore it allows one to determine the radiative background precisely. The signal and background control boxes are indicated.

and a photon converts with subsequent loss of two charged particles of opposite sign are not of concern. The radiative background due to $K_{\rm L,S} \to e^+e^-\gamma\gamma$ was measured analyzing data collected by NA48 in 2001 from a pure $K_{\rm L}$ beam. The data set contains ten times more $K \to e^+e^-\gamma\gamma$ events than the 2002 sample and a precise measurement of the radiative background can therefore be made. The $M(e^+e^-\gamma\gamma)$ vs. $M(\gamma\gamma)$ distribution is shown in Fig. 6. $M(ee\gamma\gamma)$ is plotted by reconstructing the decay vertex with the charged tracks under the constraint that the kaon decay should lie on the straight line joining the target and the reconstructed kaon center-of-gravity. $M(\gamma\gamma)$ is reconstructed assuming the kaon mass. By plotting the data in this way, the two variables are not

Table 2. Sum of the backgrounds to $K_{\rm S} \to \pi^0 e^+e^-$

Source	Control region	Signal region
$K_{\rm S} \to \pi^0_D\pi^0_D$	0.03	< 0.01
$K \to e^+e^-\gamma\gamma$	0.11	0.08
Accidentals	0.19	0.07
Total	0.33	0.15

correlated. Background from the accidental overlap of different kaon decays has also to be taken into account. It typically originates from the time overlap of a $K_{\rm L} \to \pi e\nu$ decay where the pion is misidentified as an electron with a $K_{\rm S} \to \pi^0\pi^0$ decay in which one π^0 is lost outside the acceptance. Given the very good time resolution of the detectors and the wide readout window, this background is measured by counting the events that pass the analysis in the side-bands and extrapolating the result in the signal region. A rectangular signal region (2.5 standard deviations in $M(\gamma\gamma)$ and $M(e^+e^-\gamma\gamma)$ resolution) and a rectangular control region of 6 times 6 standard deviations, both centered around the kaon and π^0 mass, were kept masked until the background studies were completed in order to avoid any human bias. The summary of the expected backgrounds is reported in Table 2. Many other sources of background, for example those originating from neutral cascade decays, were investigated and found to be negligible. The inspection of the control box surrounding the signal region revealed no events, which is consistent with an expected background of 0.33 events. In the signal box seven candidate events were found. The candidates are displayed in Fig. 7. Given the background expectation of 0.15 events, the probability that all seven events are background is negligibly small ($\simeq 10^{-10}$). The events are therefore interpreted as the first observation of the $K_{\rm S} \to \pi^0 e^+e^-$ decay. The flux, measured by counting $\pi^0\pi^0_D$ events which are collected by the same trigger, amounts to 3.51×10^{10} $K_{\rm S}$ decays. After correcting for the acceptance and dividing by the flux, the measured branching ratio for $M(ee) > 0.165$ GeV/c^2 is found to be:

$$BR(K_{\rm S} \to \pi^0 e^+e^-, M(ee) > 0.165 \text{ GeV/c}^2) = (3.0^{+1.5}_{-1.2}(stat) \pm 0.2(syst)) \times 10^{-9}. \quad (10)$$

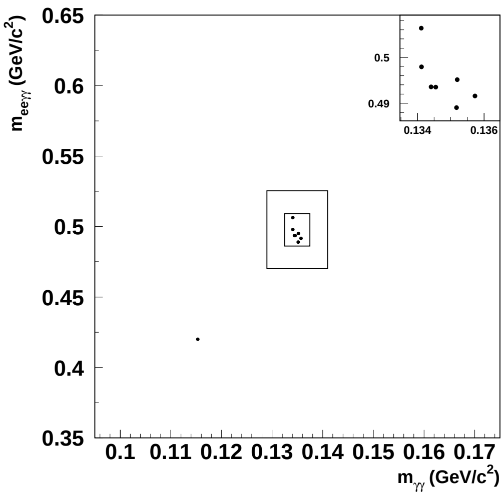

Figure 7. The $M(ee\gamma\gamma)$ vs. $M(\gamma\gamma)$ distribution for the seven candidate events. The same events are shown in the inset in more detail.

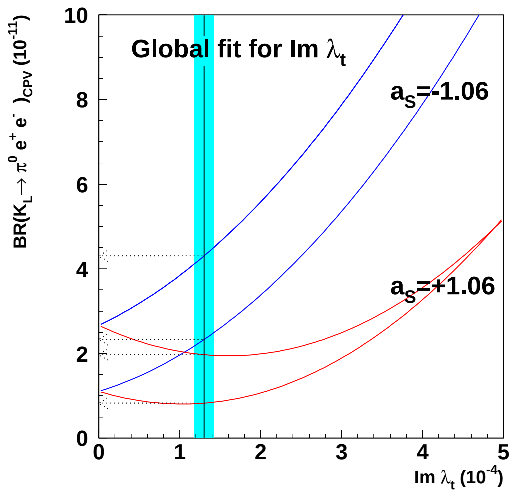

Figure 8. The sensitivity of the total CP-violating $K_\mathrm{L} \to \pi^0 e^+ e^-$ branching ratio as a function of $\Im\lambda_t$ for the two signs of the interference term.

Assuming a vector interaction and constant form factor, the result extrapolated to the full phase space becomes:

$$BR(K_\mathrm{S} \to \pi^0 e^+ e^-) = (5.8^{+2.8}_{-2.3}(stat) \pm 0.8(syst)) \times 10^{-9}, \quad (11)$$

where the systematic error is totally dominated by the form factor uncertainty. The result is in remarkable agreement with the prediction of L. Sehgal[11] which is 5.5×10^{-9}. In the notation of D'Ambrosio *et al.*,[25] this measurement can be related to a single parameter:

$$|a_\mathrm{S}| = 1.06^{+0.26}_{-0.21} \pm 0.07. \quad (12)$$

Unfortunately, the sign of a_S cannot be extracted from this experiment and the question whether the interference between the short- and long-distance CP-violation is constructive or destructive remains unanswered. Constructive interference is preferred theoretically. [9]

2.4. *Outlook for $K_\mathrm{L} \to \pi^0 e^+ e^-$ and $K_\mathrm{L} \to \pi^0 \mu^+ \mu^-$*

The sensitivity of the total CP-violating branching ratio as a function of $\Im\lambda_t$ is shown in Fig. 8 for the two signs of a_S. For constructive interference (i.e. a_S negative in this notation) the sensitivity to $\Im\lambda_t$ is enhanced. The KTeV Collaboration is analyzing the 1999 $K_\mathrm{L} \to \pi^0 \mu\mu$ data and the sensitivity on this mode will therefore be improved. The measurement of $K_\mathrm{S} \to \pi^0 \mu^+ \mu^-$ by NA48/1 is in progress. Further searches for $K_\mathrm{L} \to \pi^0 e^+ e^-$ and $K_\mathrm{L} \to \pi^0 \mu^+ \mu^-$ will be background dominated. It will be difficult to reduce the background from the radiative decays because KTeV and NA48 already have state-of-the-art calorimeters. The sensitivity to short-distance physics can be further enhanced if the interference between the short-distance and long-distance CP-violation turns out to be constructive. The signal-to-background ratio could be improved by collecting data from the time-dependent $K_\mathrm{L} - K_\mathrm{S}$ interference region.[26] Further progress relies on the availability of high energy, slowly extracted DC proton beams with intensity in excess of 10^{12} protons/s. *Factory mode* operation of the experiment over a few years has also to be envisaged. Compounding all these factors together one can explore the window of opportunity that spans from the current upper limit to the Standard Model prediction.

2.5. $K^+ \to \pi^+ \nu\overline{\nu}$

This decay is a very sensitive probe of the Standard Model because the hadronic matrix element can be extracted from the well measured $K^+ \to \pi^0 e\nu$ decay. There are no long-distance contributions to this mode and the QCD corrections have been calculated to NLO.[27,28] The theoretical error for the extraction

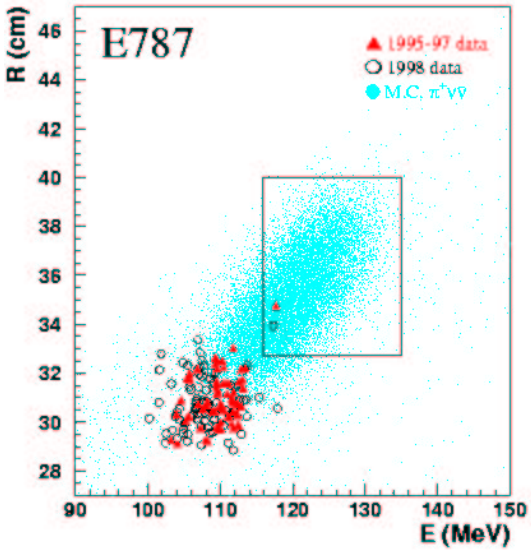

Figure 9. The range versus kinetic energy scatter plot. The analysis requires that the pion momentum is contained between 211 and 229 MeV/c. The circles are the 1998 data while the triangles are the 1995–1997 data. The group of events around $E = 108$ MeV corresponds to $K\pi 2$ decays. The simulated signal is represented by dots.

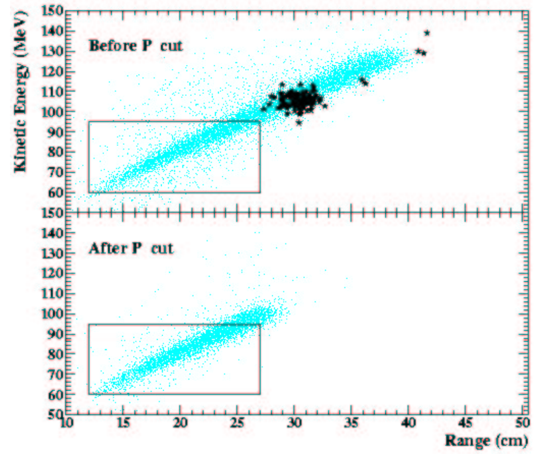

Figure 10. The kinetic energy vs. range scatter plot for the 1997 data in Region II before and after the momentum cut.

of $|\lambda_t|$ is limited to the knowledge of the charm quark contribution which translates into a small residual error on the decay amplitude. Other uncertainties are related to the poor knowledge of the CKM elements and will improve accordingly. One analysis,[29] using ϵ_K and $A_{\rm CP}(J\psi K_{\rm S})$ as inputs, predicts in the SM: $BR(K^+ \to \pi^+\nu\overline{\nu}) = (7.1 \pm 1.0) \times 10^{-10}$. To reach a 10^{-10} Single Event Sensitivity (SES), the analysis is usually restricted to the pion momentum region between the $K^+ \to \pi^+\pi^0$ ($K\pi 2$) and $K^+ \to \mu^+\nu$ ($K\mu 2$) peaks (Region I). Two events interpreted as a signal were published during the past years by the AGS-E787 experiment.[30] The range versus kinetic energy scatter plot containing the two signal events in the box is shown in Fig. 9. These two events provide a measurement of the branching ratio:

$$BR(K^+ \to \pi^+\nu\overline{\nu}) = (1.57^{+1.75}_{-0.83}) \times 10^{-10} \qquad (13)$$

which is on the high side of the SM prediction, albeit with very large errors. The analysis of the kinematic region with pion momentum above the $K^+ \to \pi^+\pi^0\pi^0$ endpoint and below the ($K\pi 2$) peak (Region II) relies greatly on the photon veto efficiency. There is one published analysis of Region II by AGS-E787,[31] which has been updated for this conference to include the data collected in 1997.[32]

The scatter plot of the kinetic energy versus range before and after the pion momentum cut is shown in Fig. 10 for the 1997 data. The combined 1996 and 1997 analysis yields the preliminary limit:

$$BR(K^+ \to \pi^+\nu\overline{\nu}) < 22 \times 10^{-10} \text{ @ } 90\% \text{ CL.} \qquad (14)$$

Even if the result is still an order of magnitude above the SM prediction, this result is quite important in my opinion because it opens the way to analyzing the decay in regions of larger acceptance, allowing one to test the dynamics of the $K^+ \to \pi^+\nu\overline{\nu}$ decay (to test, for example, the vector nature of the interaction). Many improvements were made to turn E787 into the successor experiment E949. In particular, the photon veto system was upgraded. E949 took data in 2002 for 12 weeks and results are expected soon. The experiment was originally approved to run for 60 weeks and therefore expects to take more data.

2.6. *Outlook*

A comparison between the constraint currently provided by K and B mesons on $\overline{\eta}$ and $\overline{\rho}$ was prepared by Gino Isidori and is shown in Fig. 11. Obviously, a large window of opportunity exists. Some of the observables to which rare kaon decays have access are well understood theoretically. We expect, within a reasonable time scale of about a decade, that a completely independent and competitive test of the CKM paradigm will be provided by rare kaon decay studies, notably $K \to \pi\nu\overline{\nu}$.

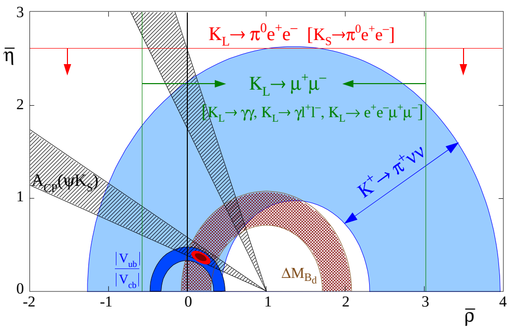

Figure 11. There is a window of opportunity to test the Standard Model with rare kaon decays.

3. Other Tests of CP- and CPT-Violation

3.1. $K_{L,S} \to \pi^+\pi^- e^+ e^-$

Large CP-violating effects are not confined to B decays. It was realized long ago that in the $K \to \pi^+\pi^-\gamma^* \to \pi^+\pi^- e^+ e^-$ decay, large effects due to CP-violation could be observed in the polarization of the photon. The decay has a branching ratio of $\simeq 3 \times 10^{-7}$ and its decay amplitude is dominated by two competing $K_L \to \pi^+\pi^-\gamma^*$ components: one from the CP-violating internal bremsstrahlung and the other from the CP-conserving direct emission associated with a magnetic dipole transition. Sehgal and Wanninger[33] and Heiliger and Sehgal[34] showed that the angular correlation of the e^+e^- and $\pi^+\pi^-$ planes contains an explicit CP-violating term arising from the interference of the two amplitudes. The CP-asymmetry in the distribution of the angle ϕ between the e^+e^- and $\pi^+\pi^-$ planes, in the kaon center-of-mass system is:

$$\mathcal{A}_\phi = \frac{\int_0^{\pi/2} \frac{d\Gamma}{d\phi} d\phi - \int_{\pi/2}^{\pi} \frac{d\Gamma}{d\phi} d\phi}{\int_0^{\pi/2} \frac{d\Gamma}{d\phi} d\phi + \int_{\pi/2}^{\pi} \frac{d\Gamma}{d\phi} d\phi}. \qquad (15)$$

This asymmetry, which originates mostly from $K^0\overline{K}^0$ mixing, is predicted to be as large as 14%. The asymmetry was first measured by KTeV.[35] The latest KTeV preliminary result was obtained combining the 1997 and 1999 statistics[36] and it is based on 5056 events. The asymmetry

$$\mathcal{A}_\phi = (13.3 \pm 1.4 \pm 1.0)\% \qquad (16)$$

is shown in Fig. 12 and is in good agreement with the theoretical prediction. The NA48 Collaboration has completed a thorough analysis of asymmetry and branching ratio for both K_L and K_S based on 1162 and 621 events, respectively.[37]

The K_L asymmetry measured by NA48 agrees with the expectation and with KTeV. No asymmetry is observed in K_S decays. This is expected because only one amplitude dominates the $K_S \to \pi^+\pi^- e^+ e^-$ decay. The K_S asymmetry measured by NA48 is shown in Fig. 13.

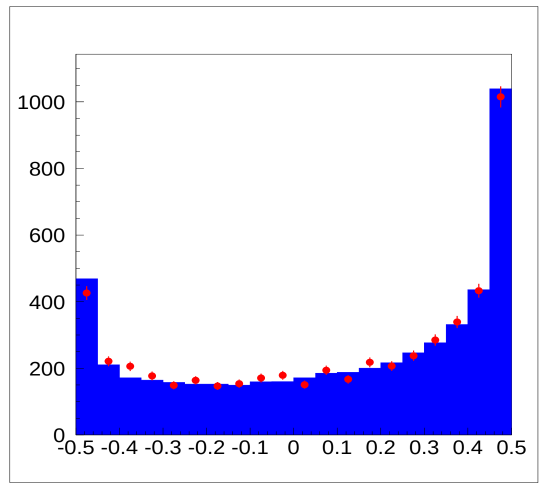

Figure 12. The $K_L \to \pi^+\pi^- e^+ e^-$ CP-violating asymmetry as measured by KTeV (data 1997+1999, preliminary).

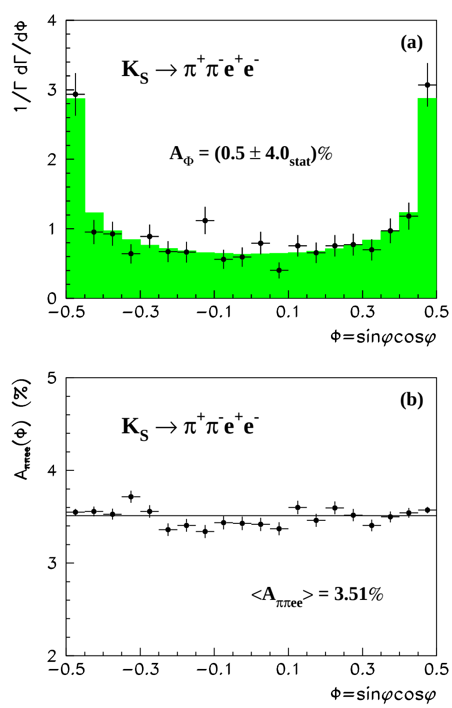

Figure 13. The $K_S \to \pi^+\pi^- e^+ e^-$ angular distribution as measured by NA48. In the bottom plot the acceptance is shown.

Table 3. Overview of current CP-violating results in $K_S \to 3\pi$ decays.

Experiment	Result
FNAL-E621[40]	$\Im\ \eta_{\pm 0} = (-1.5 \pm 1.7 \pm 2.5) \times 10^{-2}$
CPLEAR[41]	$\Re\ \eta_{\pm 0} = (-2 \pm 7^{+4}_{-1}) \times 10^{-3}$ $\Im\ \eta_{\pm 0} = (-2 \pm 9^{+2}_{-1}) \times 10^{-3}$
ITEP-761[42]	$\Re\ \eta_{000} = (-8 \pm 18) \times 10^{-2}$ $\Im\ \eta_{000} = (-5 \pm 27) \times 10^{-2}$
CPLEAR[43]	$\Re\ \eta_{000} = (18 \pm 14 \pm 6) \times 10^{-2}$ $\Im\ \eta_{000} = (15 \pm 20 \pm 3) \times 10^{-2}$
SND[44]	$BR(K_S \to 3\pi^0) < 1.4 \times 10^{-5}$ 90% CL

3.2. $K_S \to 3\pi^0$

CP-violation in $K^0 \to 2\pi$ decays is firmly established and the parameters which describe it ($\eta_\pm$, η_{00} and ϵ'/ϵ) are precisely measured.[38] CP-violation in $K_S \to 3\pi$ is equally allowed in the SM but has been investigated in much less detail owing to the difficulty of the measurements which involve rare kaon decays. A $\pi^+\pi^-\pi^0$ state is mainly CP-odd while a $3\pi^0$ state is purely CP-odd. The equivalent of η_{00} for $K_S \to 3\pi^0$ decays is $\eta_{000} = A(K_S \to 3\pi^0)/A(K_L \to 3\pi^0)$. In the SM $\eta_{000} = \epsilon + i\Im\ a_1/\Re\ a_1$, where a_1 is the isospin 1 amplitude for $K^0 \to \pi^0\pi^0\pi^0$ and $\epsilon = 2/3\eta_\pm + 1/3\eta_{00}$. The current experimental situation is summarized in Table 3. It is worth noticing that the test of CPT-conservation based on the comparison of the K^0 and $\overline{K}^0$ masses is currently limited by the poor knowledge of η_{000}.[39]

During the year 2000 NA48 did not have any drift chambers because they were damaged by the implosion of the carbon fiber beam pipe. So they exploited the excellent energy resolution of the liquid krypton calorimeter (LKr)[45] to collect $3\pi^0$ decays from a short neutral beam to improve the limits on η_{000}. The sensitivity to η_{000} comes from the $K_S - K_L$ interference that can be measured by studying the intensity of $3\pi^0$ decays in the short neutral beam as a function of the proper decay time of the kaon. In order to keep the acceptance correction small, the data were normalized using $3\pi^0$ decays collected from the long beam. The long beam is a pure K_L beam for all practical purposes and the $K_S - K_L$ interference expected in $3\pi^0$ decays is completely negligible.

Table 4. Systematic uncertainties.

	$\Re\ \eta_{000}$ (10^{-2})	$\Im\ \eta_{000}$ (10^{-2})
Accidentals	± 0.1	± 0.6
Energy scale	± 0.1	± 0.1
Dilution	± 0.3	± 0.4
Acceptance	± 0.3	± 0.8
Binning	± 0.1	± 0.2
Total	± 0.5	± 1.1

A Monte Carlo simulation was used to correct for the residual geometrical difference between the two beams. The decay energy spectra of kaons generated from the near and far beam are not identical. In order to take care of this difference, the analysis is done by fitting the data in 5 GeV wide energy bins according to the function:

$$f(E,t) = \frac{NEAR}{FAR} = A(E)[1 + |\eta_{000}|^2 e^{(\Gamma_L - \Gamma_S)t} + 2D(E)e^{\frac{1}{2}(\Gamma_L - \Gamma_S)t} \times (\Re\ \eta_{000} \cos\Delta mt - \Im\ \eta_{000} \sin\Delta mt)\ ]$$

where $A(E)$ are normalization constants and $D(E)$ is the so-called $K^0 - \overline{K}^0$ *dilution* describing the excess of K^0 over $\overline{K}^0$ in the incoherent mixture of neutral kaons produced by the 400 GeV protons in the Be target. $D(E)$ is a function of the energy and of the production angle. The dilution values were those measured by the NA31 experiment,[46] slightly adjusted to take into account the different production angle and proton energy.

There are about 5.6×10^6 $3\pi^0$ events from the near beam and in excess of 10^7 from the far beam. The near/far ratio corrected for the beam geometry is shown in Fig. 14 for three energy bins. The position of the collimator and the upstream and downstream boundaries of the fitting region are indicated on the figure. Systematic errors have been evaluated for accidentals, energy scale, K^0 dilution, acceptance, and binning and are reported in Table 4. NA48/1 has made two fits to Eq. (3.2).

1. The Real and the Imaginary part of η_{000} are fitted independently together with the normalization constants. The results are:

$$\Re\ \eta_{000} = -2.6 \pm 1.0(stat) \pm 0.5(syst) \times 10^{-2} \qquad (17)$$

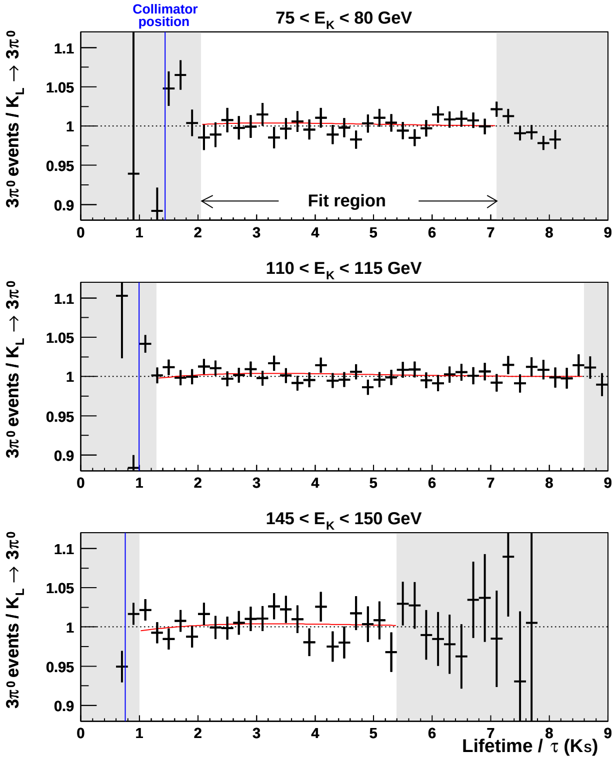

Figure 14. Near over far $3\pi^0$ data after the geometry correction. The position of the end of the collimator and the definition of the upstream and downstream limits of the fitting region are indicated. The upstream cuts were chosen to avoid resolution effects, and the downstream ones to insure good trigger efficiency.

$$\Im\ \eta_{000} = -3.4 \pm 1.0(stat) \pm 1.0(syst) \times 10^{-2}. \quad (18)$$

The χ^2/ndf is good (415/405) but the two parameters are strongly correlated. The fit is compatible with CP-conservation with a probability of a few percent.

2. To avoid the correlation of the parameters, they imposed CPT-conservation and fixed the Real part of η_{000} to the SM prediction:

$$\Re\ \eta_{000} = \Re\ \epsilon \simeq 1.6 \times 10^{-3}. \quad (19)$$

Fitting for $\Im\ \eta_{000}$ then yields:

$$\Im\ \eta_{000} = -1.2 \pm 0.7(stat) \pm 1.1(syst) \times 10^{-2} \quad (20)$$

which is compatible with CP-conservation within errors.

The result of the fits is shown in Fig. 15. The result given by Eq. (20) translates into the limit $BR(K_S \to \pi^0\pi^0\pi^0) < 3.0 \times 10^{-7}$ @ 90%CL which

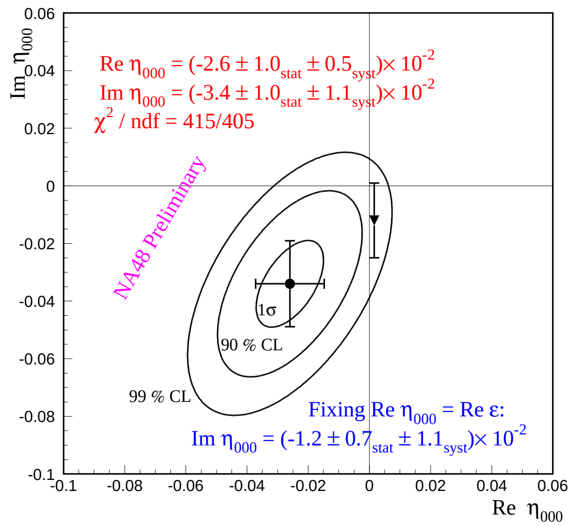

Figure 15. Results of the $3\pi^0$ fits.

improves the current limit by about 50 times and is compatible with the SM prediction of $\sim 1.9 \times 10^{-9}$. Results given by Eqs. (17) and (18) provide input to the Bell–Steinberger unitarity relation,[47] which constrains the CP- and CPT-violating parameter $\Im\ \delta$ under the hypothesis of conservation of probability:

$$(\Re\ \epsilon - i\Im\ \delta) \times (i2\Delta m + (\Gamma_S + \Gamma_L)) = \sum_f A(K_S \to f)^* A(K_L \to f). \quad (21)$$

Taking into account the NA48/1 result, we obtain:

$$\Im\ \delta = (-1.2 \pm 3.0) \times 10^{-5} \quad (22)$$

which represents an improvement of about 40% with respect to previous result:[48]

$$\Im\ \delta = (2.4 \pm 5.0) \times 10^{-5}. \quad (23)$$

Assuming CPT-conservation in the semileptonic K^0 decays, the phase of δ is fixed and the measurement translates into a new limit on the $K^0\overline{K}^0$ mass difference:

$$M(K^0) - M(\overline{K}^0) = (-1.7 \pm 4.2) \times 10^{-19}\ \text{GeV}. \quad (24)$$

3.3. *Semileptonic K_S Decays*

Semileptonic kaon decays are quite important for the study of fundamental parameters of the SM theory such as V_{us}.[49] Only K_S decays having branching ratios smaller than 10^{-3} can be considered relatively rare. Under the validity of the $\Delta S = \Delta Q$ rule

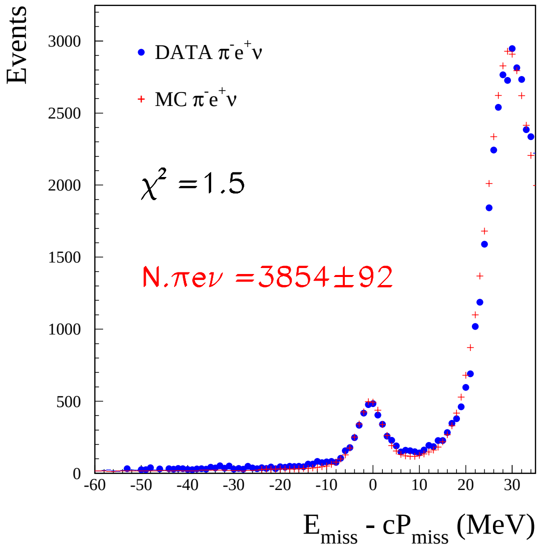

Figure 16. K_S semileptonic decays with positive charge measured by KLOE (2001 statistics, preliminary).

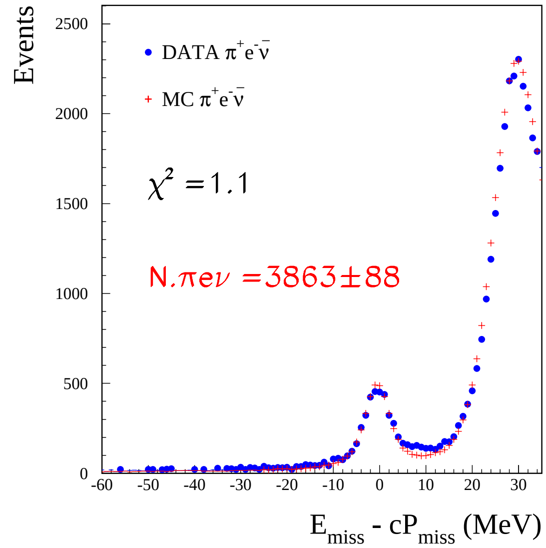

Figure 17. K_S semileptonic decays with negative charge measured by KLOE (2001 statistics, preliminary).

and CPT-conservation, the $K_S \to \pi e \nu$ rate can be derived from that of K_L semileptonic decays using known kaon parameters. The KLOE experiment, installed at the Frascati ϕ factory, can measure the $K_S \to \pi e \nu$ rate in a very straightforward way, using the $\phi \to K_S K_L$ decay. The ϕ decays at rest and therefore the kaons have practically fixed energy, enabling the K_S to be tagged by measuring the time of flight of the accompanying K_L which interacts in the electromagnetic calorimeter. KLOE has already published results on this mode.[50] Here we report the latest preliminary results[51] based on more statistics collected during 2001. A comparison of data and Monte Carlo is shown in Fig. 16 for positive leptons and in Fig. 17 for negative ones. The preliminary results are:

$$\begin{aligned} BR(K_S \to \pi^+ e^- \overline{\nu}) &= (3.44 \pm 0.09 \pm 0.06) \times 10^{-4} \\ BR(K_S \to \pi^- e^+ \nu) &= (3.31 \pm 0.08 \pm 0.05) \times 10^{-4} \\ BR(K_S \to \pi^\pm e^\mp \nu(\overline{\nu})) &= (6.76 \pm 0.12 \pm 0.10) \times 10^{-4} \end{aligned} \tag{25}$$

On the basis of these results, KLOE has made the first measurement of the CP charge asymmetry for $\mathcal{A}(K_S)$. Deviations of $\mathcal{A}(K_S)$ from the well measured[52] $\mathcal{A}(K_L) = (3.322 \pm 0.055) \times 10^{-3}$ would be a sign of CPT-violation. The preliminary value[51] is $\mathcal{A}(K_S) = (1.9 \pm 1.7 \pm 0.6) \times 10^{-2}$. Conversely, one can assume CPT-conservation and test the $\Delta S = \Delta Q$ rule. The KLOE statistics are improving and are now starting to be competitive with the results obtained by CPLEAR.[53]

4. Kaon Dalitz Decays

4.1. *Motivation*

Attempts to extract $\Re \lambda_t$ from the decay $K_L \to \mu^+ \mu^-$,[25,54] suffer from the lack of control of the long-distance part of the dispersive amplitude of the decay.[55] The study of the kaon Dalitz decays ($K_L \to \gamma^{(*)} \gamma^*$) allows one in principle to better constrain this long-distance contribution. Significant progress has been achieved on the Dalitz kaon decays as a byproduct of the ϵ'/ϵ experiments. Two models are available in the literature to parametrize the Dalitz form factors. In addition to the BMS model[56] where one parameter (α_K^*) is used to include vector contributions, a parametrization compatible with the chiral expansion to $\mathcal{O}(p^6)$ is available (DIP).[25] The two descriptions are related by the formula

$$\alpha(DIP) = -1 + (3.1 \pm 0.5) \alpha_K^*(BMS), \tag{26}$$

where the error is due to the different q^2 dependence of the two parametrizations.

4.2. $K_L \to e^+ e^- \gamma$ *and* $K_L \to e^+ e^- e^+ e^-$

The KTeV experiment has presented a preliminary analysis[57] of the data collected in 1997. The sample includes 93 383 $K_L \to e^+ e^- \gamma$ candidates. Background from $Ke3$ decays where a pion is misidentified as an electron are kept to less than 0.1% by the use of a transition radiation detector. It is very important to understand the tracking for close electron–positron pairs in order to determine the acceptance. The preliminary branching ratio

$$BR(K_{\rm L} \to e^+e^-\gamma) \times 10^6 = \\ 10.19 \pm 0.04(stat) \pm 0.07(syst) \pm 0.29(norm) \quad (27)$$

is in good agreement with the published NA48 value.[58] The decay rate is dominated by the QED radiative processes and the branching ratio is not very sensitive to the kaon structure. In order to extract the form factor, the q^2 distribution has to be studied. In Fig. 18 the KTeV data are compared with the simulation for different values of α_K^*. The data prefer a mildly negative value.

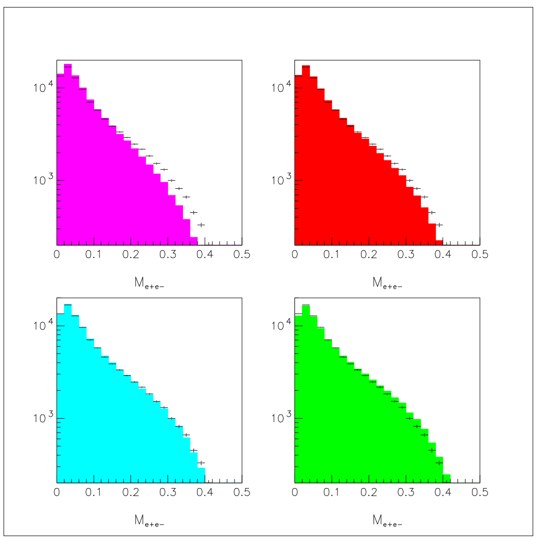

Figure 18. The $M(e^+e^-)$ distribution for $K_{\rm L} \to e^+e^-\gamma$ candidates as measured by KTeV (1997 statistics, preliminary), compared with several Monte Carlo simulations as a function of different form factors.

Fitting for α_K^* yields: $-0.186 \pm 0.011 \pm 0.09$. This very precise measurement (7% relative error!) is in good agreement with the value measured by KTeV[59] from $K_{\rm L} \to \mu^+\mu^-\gamma$ and disagrees with the NA48 $e^+e^-\gamma$ measurement, -0.36, at a level of about 2.6 standard deviations.

Extraction of the form factor from the $K_{\rm L} \to e^+e^-e^+e^-$ decay is complicated by the pairing ambiguity and by the small rate that prevents a precise determination. The branching ratio measurement is already limited by the knowledge of the normalization channel. The preliminary measurement of the branching ratio and of the form factor, based on 1100 (1997 + 1999 statistics) events was reported to be:[60]

$$BR(K_{\rm L} \to e^+e^-e^+e^-) = \\ (4.16 \pm 0.13 \pm 0.13 \pm 0.17) \times 10^{-8}, \quad (28)$$

$$\alpha_K^* = -0.03 \pm 0.13 \pm 0.04. \quad (29)$$

4.3. $K_{\rm L} \to e^+e^-\mu^+\mu^-$

This is one of the first results published by KTeV on the full 1997 and 1999 data.[61] It is a very clean measurement with 132 events. Details of the analysis can be found in the publication. Here we recall that the measured branching ratio is

$$BR(K_{\rm L} \to e^+e^-\mu^+\mu^-) = \\ (2.69 \pm 0.24 \pm 0.12) \times 10^{-9}. \quad (30)$$

A precise measurement of the form factor is prevented by the small statistics:

$$\alpha_K^*(\mu\mu ee) = -0.19 \pm 0.11. \quad (31)$$

Combining $K_{\rm L}$ decays in $\mu\mu\gamma$, $4e$, and $\mu\mu ee$, KTeV has given a first measurement of

$$\alpha(DIP) = -1.53 \pm 0.10. \quad (32)$$

4.4. *Outlook*

The current situation concerning the $K - \gamma^*\gamma^{(*)}$ form factor is summarized in Fig. 19. In the near future new results should become available from the NA48 experiment. They are analyzing $ee\gamma$ and $4e$ collected in 1998–1999 and 2001. Data still look quite scattered. The KTeV experiment has performed two precise measurements which agree between themselves suggesting a consistent description of the form factor. It will be interesting to see if the high statistics measurements from NA48 will finally confirm this picture.

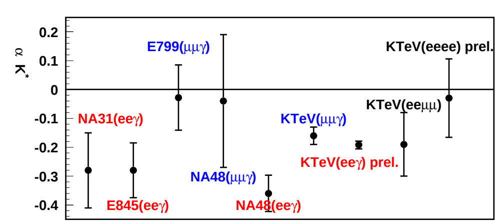

Figure 19. Measurements of the α_K^* form factor. Precise measurements by KTeV on $K_{\rm L} \to \mu^+\mu^-\gamma$ and from $K_{\rm L} \to e^+e^-\gamma$ seem to suggest a coherent picture of otherwise scattered data. Measurements from the full statistics of NA48 are eagerly awaited.

5. Nonleptonic Kaon Decays

5.1. $K_{L,S} \to \gamma\gamma$

The study of the decays $K_{S,L} \to \gamma\gamma$ and $K_{S,L} \to \pi^0\gamma\gamma$ is important for understanding the low-energy hadron dynamics of Chiral Perturbation Theory (χPT), since they are sensitive to higher order loop effects.[62] The K_L modes have already been studied precisely. The decay $K_L \to \pi^0\gamma\gamma$ is particularly interesting because it can be used to bound CP-conserving contributions to $K_L \to \pi^0 e^+ e^-$, as explained earlier in this article. Unfortunately the two most recent determinations do not quite agree[63,15] and, given the importance of the measurement, further experimental clarification would be welcome. Two measurements of the $K_L \to \gamma\gamma$ decay normalized to $K_L \to 3\pi^0$ have recently been published. The $K_L \to \gamma\gamma$ reaction is interesting because it provides the normalization to the absorptive amplitude of $K_L \to \mu^+\mu^-$. However, to fully exploit this good precision on $K_L \to \gamma\gamma$, the data should be normalized to $K_L \to \pi^0\pi^0$.

On the K_S side, significant progress has taken place and a precise measurement of $K_S \to \gamma\gamma$ and the first observation of the decay $K_S \to \pi^0\gamma\gamma$ were recently reported. The next sections briefly describe the measurement of $K_L \to \gamma\gamma$ done by KLOE, the precise measurement of $K_S \to \gamma\gamma$ and the first observation of $K_S \to \pi^0\gamma\gamma$ done by NA48/1.

5.2. $K_L \to \gamma\gamma$ *and* $K_S \to \gamma\gamma$

KLOE at the DAΦNE ϕ factory exploits K_S tagging to study K_L decays without having to subtract the K_S backgrounds. Based on 1.6×10^8 tagged K_L originating from from $10^9 \phi$ decays collected during the year 2000 and 2001, KLOE has selected 27 375 $K_L \to \gamma\gamma$ decays. The $\gamma\gamma$ invariant mass $M_{\gamma\gamma}$ is shown in Fig. 20. The background at low $M_{\gamma\gamma}$ is due to $K_L \to 2\pi^0$ and $K_L \to 3\pi^0$ decays. The result, normalized to $K_L \to 3\pi^0$ is:[64]

$$\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to \pi^0\pi^0\pi^0) = (2.79 \pm 0.02(stat) \pm 0.02(syst)) \times 10^{-3}. \quad (33)$$

In good agreement with the NA48/1 published result:[16]

$$\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to \pi^0\pi^0\pi^0) = (2.81 \pm 0.01(stat) \pm 0.02(syst)) \times 10^{-3}. \quad (34)$$

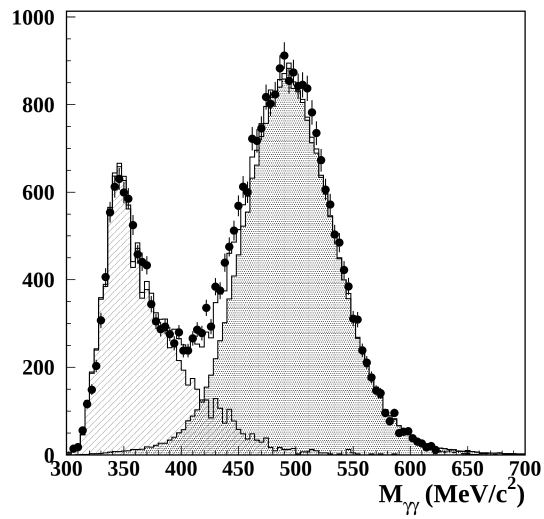

Figure 20. To cope with large backgrounds from $K_L \to 2\pi^0$ and $K_L \to 3\pi^0$ decays, KLOE is obliged to impose that $E_\gamma = M_K/2$ in the K_L rest frame. The energy of the photons can be boosted in the laboratory using the constraint: $\vec{p}(K_L) = \vec{p}(\phi) - \vec{p}(K_S)$.

The decay $K_S \to \gamma\gamma$ is especially interesting because χPT predicts unambiguously that the branching ratio is 2.25×10^{-6}, with an error of less than 10%. NA48/1 has performed a precise measurement of the $BR(K_S \to \gamma\gamma)$ from the data collected from a short neutral beam in the year 2000. The short neutral beam contains a $K_L \to \gamma\gamma$ component that can be precisely subtracted measuring the K_L flux from the number of reconstructed $3\pi^0$ decays and exploiting the precise $K_L \to \gamma\gamma$ to $K_L \to 3\pi^0$ ratio measured by the same experiment employing a long beam. The data is shown in Fig. 21. The NA48/1 $K_S \to \gamma\gamma$ result: [16]

$$BR(K_S \to \gamma\gamma) = (2.78 \pm 0.06(stat) \pm 0.03(syst) \pm 0.02(ext))10^{-6} \quad (35)$$

has an accuracy of about 3%. It differs by 30% from the $\mathcal{O}(p^4)$ prediction of χPT. Progress on this measurement and comparison with the theory is shown in Fig. 22. This measurement was used by Buchalla *et al.*[9] to extract one of the three counterterms that appear in χPT at $\mathcal{O}(p^6)$.

5.3. $K_S \to \pi^0\gamma\gamma$

The first observation of this decay was reported by NA48/1 from the analysis of the 2000 data.[65] In the decay $K_S \to \pi^0\gamma\gamma$, the photon pair production is

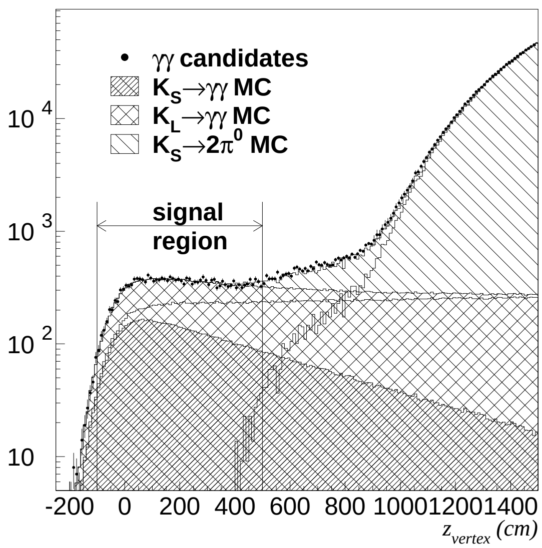

Figure 21. Decay vertex distribution for the $K\gamma\gamma$ candidates measured by NA48/1. Limiting the measurement to a few meter long decay region keeps the background from $K_{\rm S} \to 2\pi^0$ with missing photons in check. The irreducible component due to $K_{\rm L}$ can be precisely subtracted.

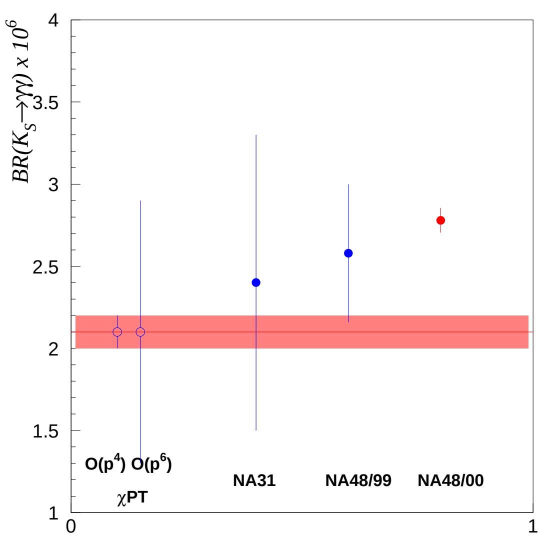

Figure 22. Comparison of the NA48/1 measurement of $BR(K_{\rm S} \to \gamma\gamma)$ with respect to previous measurements and the theoretical predictions.

described by an amplitude dominated by a pseudo-scalar meson pole. In χPT this pole is dominated by π^0 contribution, and the lowest order amplitude is non-vanishing, in contrast to the similar $K_{\rm L} \to \gamma\gamma$ decay. The theoretical prediction for the branching ratio is 3.8×10^{-8} with higher order corrections expected to be small[66] and is quoted in the kinematic region $z = m^2_{\gamma\gamma}/m^2_K > 0.2$ which is free from the overwhelming $K_{\rm S} \to \pi^0\pi^0$ background. A measurement of the branching ratio can provide information about the presence of extra non-pole contributions studied for example by Bijnens *et al.*.[67] In addition, the momentum dependence of the weak vertex which is predicted by χPT can be tested by the measured shape of the z spectrum. The lowest previously published limit on the branching ratio is $BR(K_{\rm S} \to \pi^0\gamma\gamma)_{z>0.2} < 3.3 \times 10^{-7}$ at the 90% confidence level.[68] The main difficulty in analyzing the NA48 data from 2000 was the lack of tracking chambers and the consequent difficulty to veto $\pi^0 \to e^+e^-\gamma$ decays with a missing particle. In Fig. 23 the data is shown with the sum of the background contributions and the excess due to $K_{\rm S} \to \pi^0\gamma\gamma$.

The result, for $z_q = q^2/M_k^2 > 0.2$ is:

$$BR(K_{\rm S} \to \pi^0\gamma\gamma) = (4.9 \pm 1.6(stat) \pm 0.9(syst)) \times 10^{-8} \quad (36)$$

in agreement with the theoretical prediction[66] of 3.8×10^{-8}.

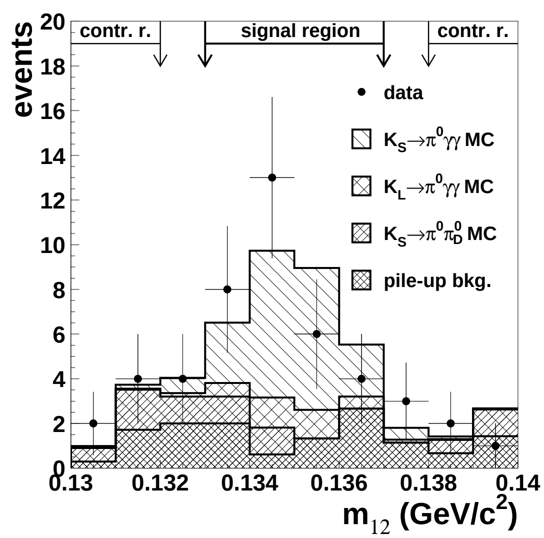

Figure 23. The invariant mass of the two photons forming a π^0. The data is compared with the sum of the predicted background and the $K_{\rm S} \to \pi^0\gamma\gamma$ excess.

6. The Future

New kaon experimental initiatives are planned and significant progress is expected soon. The NA48/2 experiment[69] at CERN is collecting simultaneous K^+ and K^- decays to search for direct CP-violation in the Dalitz plot slope asymmetry. They will also address the study of $\pi\pi$ s-wave scattering by studying a large sample of $Ke4$ decays. In doing so, several rare and medium-rare kaon decays will be thoroughly studied. Fig. 24 shows a sample of approximately 2800 $K^\pm \to \pi^\pm e^+ e^-$ collected by NA48/2 in just one month of data taking. Given that $BR(K^\pm \to \pi^\pm e^+ e^-) \simeq 3 \times 10^{-7}$, the figure clearly demonstrates the capabilities of the experiment.

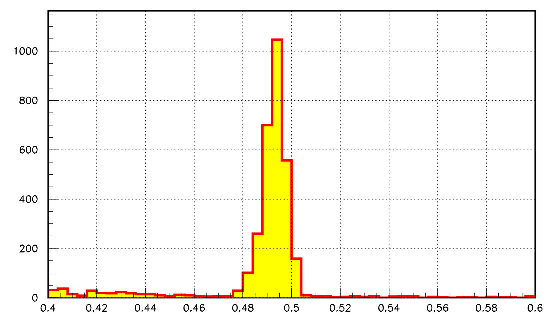

Figure 24. This $K^\pm \to \pi^\pm e^+ e^-$ sample (preliminary) was collected by NA48/2 in about one month. It corresponds to about 1/4 of the world statistics.

Similar sensitivities on charged kaon decays are expected by the OKA experiment at Protvino. CKM at FNAL has proposed[70] to collect 100 $K^+ \to \pi^+ \nu\overline{\nu}$ from decays in flight. The principle of the experiment is to make redundant measurements employing both magnetic spectrometers and tracking RICH's. The experiment is designed to work with a separated kaon beam of 22 GeV/c momentum. The beam design employs superconducting RF cavities of which a full prototype has already been built. Other challenges of CKM are the operation of straw tubes in vacuum and the capability to veto photons with very high efficiency. Both these detector aspects have been successfully prototyped by the Collaboration. The experimental situation on $K_{\rm L} \to \pi^0 \nu\overline{\nu}$ is poised to improve soon. In 2004 E391a[71] will be the first dedicated experiment to search for $K_{\rm L} \to \pi^0 \nu\overline{\nu}$. The experiment, which exploits a very well defined neutral pencil beam at the KEK PS and relies on the hermeticity of its veto system, aims to reach a SES of about 3×10^{-10}. It is a pilot experiment for further initiatives at J-PARC. KOPIO[72] at BNL aims to collect about 60 $K_{\rm L} \to \pi^0 \nu\overline{\nu}$ SM events with a signal-to-background ratio of about 2. The design is based on the principle of measuring as much as possible of the incoming $K_{\rm L}$ and the outgoing π^0. A micro-bunched proton beam from the AGS coupled with the use of low energy $K_{\rm L}$ determines the kaon energy by time of flight, allowing one to work in the rest frame of the kaon. Energy, impact position, and direction for each of the two photons from the π^0 decay will be measured.

I wish to conclude this article by stressing the complementarity between the direct searches performed at the energy frontier (at the Tevatron now and later at the LHC) and the precision measurements involving rare virtual processes. I believe that the interest for rare processes will remain or even increase once new phenomenology appears at the colliders. For example, the Minimal Supersymmetric Standard Model allows 43 CP-violating phases.[73] Limiting the parameter space by means of experimental information will remain fundamental. Interesting scenarios on the interplay between new physics and rare kaon decays are described by Grossman in these proceedings.[74]

Acknowledgments

I wish to thank the organizers of Lepton Photon 2003 for the opportunity to present this review at this excellent meeting. I also wish to thank the CERN DTP service for carefully editing the article. It is a pleasure to acknowledge the help of many colleagues who have contributed to this work: most of the credit goes to the members of the collaborations mentioned in this work. In particular, I owe a lot to my NA48 colleagues. Last but not least, a special mention goes to the phenomenologists who have kept my interest in kaon physics alive and kicking.

References

1. N. Cabibbo, *Phys. Rev. Lett.* **10**, 531 (1963).
2. M. Kobayashi and T. Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973).
3. C. Jarlskog, *Z. Phys.* C **29**, 491 (1985).
4. L. Wolfenstein, *Phys. Rev. Lett.* **51**, 1945 (1983).
5. L. S. Littenberg, *Phys. Rev.* D **39**, 3322 (1989).
6. L. Littenberg, arXiv:hep-ex/0010048.

7. A. Alavi-Harati *et al.* [The E799-II/KTeV Collaboration], *Phys. Rev.* D **61**, 072006 (2000) [arXiv:hep-ex/9907014].
8. Y. Grossman and Y. Nir, *Phys. Lett.* B **398**, 163 (1997) [arXiv:hep-ph/9701313].
9. G. Buchalla, G. D'Ambrosio and G. Isidori, arXiv:hep-ph/0308008.
10. M. Battaglia *et al.*, arXiv:hep-ph/0304132.
11. L. M. Sehgal, *Nucl. Phys.* B **19**, 445 (1970).
12. G. Ecker, A. Pich and E. de Rafael, *Nucl. Phys.* B **291**, 692 (1987).
13. C. Bruno and J. Prades, *Z. Phys.* C **57**, 585 (1993) [arXiv:hep-ph/9209231].
14. F. Gabbiani and G. Valencia, *Phys. Rev.* D **66**, 074006 (2002) [arXiv:hep-ph/0207189].
15. A. Lai *et al.* [NA48 Collaboration], *Phys. Lett.* B **536**, 229 (2002) [arXiv:hep-ex/0205010].
16. A. Lai *et al.*, *Phys. Lett.* B **551**, 7 (2003) [arXiv:hep-ex/0210053].
17. A. Alavi-Harati *et al.* [KTeV Collaboration], *Phys. Rev.* D **67**, 012005 (2003) [arXiv:hep-ex/0208007].
18. A. Alavi-Harati *et al.* [KTeV Collaboration], *Phys. Rev. Lett.* **86**, 397 (2001) [arXiv:hep-ex/0009030].
19. A. Alavi-Harati *et al.* [KTEV Collaboration], *Phys. Rev. Lett.* **84**, 5279 (2000) [arXiv:hep-ex/0001006].
20. A. Alavi-Harati *et al.* [KTeV Collaboration], arXiv:hep-ex/0309072.
21. H. B. Greenlee, *Phys. Rev.* D **42**, 3724 (1990).
22. A. Lai *et al.* [NA48 Collaboration], *Eur. Phys. J.* C **22**, 231 (2001) [arXiv:hep-ex/0110019].
23. J. R. Batley *et al.* [NA48 Collaboration], *Phys. Lett.* B **544**, 97 (2002) [arXiv:hep-ex/0208009].
24. J. R. Batley *et al.* [NA48/1 Collaboration], *Phys. Lett.* B **576**, 43 (2003) [arXiv:hep-ex/0309075].
25. G. D'Ambrosio, G. Isidori and J. Portoles, *Phys. Lett.* B **423**, 385 (1998) [arXiv:hep-ph/9708326].
26. A. Belyaev *et al.*, "Kaon physics with a high-intensity proton driver," arXiv:hep-ph/0107046.
27. G. Buchalla and A. J. Buras, *Nucl. Phys.* B **548**, 309 (1999) [arXiv:hep-ph/9901288].
28. M. Misiak and J. Urban, *Phys. Lett.* B **451**, 161 (1999) [arXiv:hep-ph/9901278].
29. S. H. Kettell, L. G. Landsberg and H. H. Nguyen, arXiv:hep-ph/0212321.
30. S. Adler *et al.* [E787 Collaboration], *Phys. Rev. Lett.* **88**, 041803 (2002) [arXiv:hep-ex/0111091].
31. S. Adler *et al.* [E787 Collaboration], *Phys. Lett.* B **537**, 211 (2002) [arXiv:hep-ex/0201037].
32. Bipul Bhuyan, BNL Particle Physics Seminar, July 24, 2003, `http://bnlku28.phy.bnl.gov/bhuyan/talk_bnl/html/talk_bnl.html`
33. L. M. Sehgal and M. Wanninger, *Phys. Rev.* D **46**, 1035 (1992) [Erratum ibid. D **46**, 5209 (1992)].
34. P. Heiliger and L. M. Sehgal, *Phys. Rev.* D **48**, 4146 (1993) [Erratum Phys. Rev. D **60**, 079902 (1999)].
35. A. Alav-Harati *et al.* [KTeV Collaboration], *Phys. Rev. Lett.* **84**, 408 (2000) [arXiv:hep-ex/9908020].
36. A. Golossanov,"CP Violation Measurement using $K_{\rm L} \to \pi + \pi^- e^+ e^-$ Events Observed by the KTeV (E799 II) Experiment at Fermilab", DPF2002 Meeting, `http://dpf2002.velopers.net/talks_pdf/172talk.pdf`
37. A. Lai *et al.* [NA48 Collaboration], *Eur. Phys.* J. C **30**, 33 (2003).
38. K. Hagiwara *et al.* [Particle Data Group Collaboration], *Phys. Rev.* D **66**, 010001 (2002).
39. I. I. Bigi and A. I. Sanda, *Phys. Lett.* B **466**, 33 (1999).
40. Y. Zou *et al.*, *Phys. Lett.* B **329**, 519 (1994).
41. R. Adler *et al.* [CPLEAR Collaboration], *Phys. Lett.* B **407**, 193 (1997).
42. V. V. Barmin *et al.*, *Phys. Lett.* B **128**, 129 (1983).
43. A. Angelopoulos *et al.* [CPLEAR Collaboration], *Phys. Lett.* B **425**, 391 (1998).
44. M. N. Achasov *et al.*, *Phys. Lett.* B **459**, 674 (1999) [arXiv:hep-ex/9907004].
45. A. Ceccucci, *Nucl. Instrum. Meth.* A **461**, 10 (2001).
46. R. Carosi *et al.* [NA31 Collaboration], *Phys. Lett.* B **237**, 303 (1990).
47. J. S. Bell and J. Steinberger, "Weak Interactions of Kaons,"Proc. Oxford International Conference on Elementary Particle Physics (RAL, Chilton, 1966), pp. 195–208 and 221.
48. A. Angelopoulos *et al.* [CPLEAR Collaboration], *Phys. Lett.* B **444**, 52 (1998).
49. Klaus Schubert, these proceedings.
50. A. Aloisio *et al.* [KLOE Collaboration], *Phys. Lett.* B **535**, 37 (2002) [arXiv:hep-ph/0203232].
51. L. Passalacqua, La Thuile 2003, "Recent results from KLOE", `http://www.pi.infn.it/lathuile/2003/talks/Passalacqua.pdf`
52. See for example, I. Mikulec, "CP violation and rare decays in K sector at NA48", `http://www.pi.infn.it/lathuile/2003/talks/Mikulec.pdf`
53. A. Angelopoulos *et al.* [CPLEAR Collaboration], *Phys. Rep.* **374**, 165 (2003).
54. D. Gomez Dumm and A. Pich, *Nucl. Phys. Proc. Suppl.* **74**, 186 (1999) [arXiv:hep-ph/9810523].
55. G. Valencia, *Nucl. Phys.* B **517**, 339 (1998) [arXiv:hep-ph/9711377].
56. L. Bergstrom, E. Masso and P. Singer, *Phys. Lett.* B **131**, 229 (1983).
57. J. LaDue, "Understanding Dalitz Decays of the $K_{\rm L}$, in particular the decays of $K_{\rm L} \to e^+e^-\gamma$ and $K_{\rm L} \to e^+e^-e^+e^-$", PhD thesis, University of Colorado - Boulder, May 2003.
58. V. Fanti *et al.* [NA48 Collaboration], *Z. Phys.* C **76**, 653 (1997).
59. A. Alavi-Harati *et al.* [KTeV Collaboration], *Phys. Rev. Lett.* **87**, 071801 (2001).
60. T. Barker, "Frontiers of Rarity, Searching for Unusual Kaon Decays at Fermilab", Fermilab seminar, 20 June 2003.
61. A. Alavi-Harati *et al.* [KTeV Collaboration], *Phys. Rev. Lett.* **90**, 141801 (2003) [arXiv:hep-

ex/0212002].
62. J. Kambor and B.R. Holstein, Phys. Rev. D **49**, 2346 (1994).
63. A. Alavi-Harati *et al.* [KTeV Collaboration], *Phys. Rev. Lett.* **83**, 917 (1999) [arXiv:hep-ex/9902029].
64. M. Adinolfi *et al.* [KLOE Collaboration], *Phys. Lett.* B **566**, 61 (2003) [arXiv:hep-ex/0305035].
65. A. Lai *et al.* [NA48 Collaboration], arXiv:hep-ex/0309022.
66. G. Ecker, A. Pich and E. de Rafael, *Phys. Lett.* B **189** 363 (1987).
67. J. Bijnens, E. Pallante and J. Prades, hep-ph/9801326
68. A. Lai *et al.*, *Phys. Lett.* B **556** 105 (2003).
69. R. Batley *et al.*, CERN-SPSC-2000-003.
70. P. S. Cooper [CKM Collaboration], *Nucl. Phys. Proc. Suppl.* **99B**, 121 (2001).
71. T. Inagaki *et al.*, KEK Internal Report 96-13, November 1996.
72. I-H. Chiang *et al.*, "KOPIO–a search for $K_{\rm L} \to \pi^0 \nu\overline{\nu}$", in RSVP proposal to NSF (October 1999).
73. J. R. Ellis, *Nucl. Phys. Proc. Suppl.* **99B**, 331 (2001) [arXiv:hep-ph/0011396].
74. Yuval Grossman, these proceedings.

DISCUSSION

Ikaros Bigi (University of Notre Dame):

There is a KEK experiment analyzing the muon transverse polarization in $K\mu3$ decays. What is the status of their analysis and what are their plans?

Augusto Ceccucci: Transverse muon polarization is a sensitive probe of non-standard CP-violation. I have not reviewed the KEK-E246 experiment because it is beyond the scope of a rare kaon decay talk. However, I am not aware of new results from that experiment since the KAON2001 meeting.

Robert Tschirhart (Fermilab): How is a limit placed on $\overline{\eta}$ from $K_{\mathrm{L}} \to \pi^0 e^+ e^-$ limit and $K_{\mathrm{S}} \to \pi^0 e^+ e^-$ measurement? What is assumed about the relative phase between K_{S} and K_{L}?

Augusto Ceccucci: Since the $K_{\mathrm{L}} \to \pi^0 e^+ e^-$ limit is much larger than the indirect CP-violation implied by the K_{S} measurement, the $K_{\mathrm{L}} \to \pi^0 e^+ e^-$ dominates the limit on $\overline{\eta}$. In the figure I presented, which was prepared by Gino Isidori, constructive interference is assumed.