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KAON PHYSICS

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ABSTRACT

The most recent progress and future prospects in kaon physics are reviewed. Main results are the first observation of the rare decays $K_S \to \pi^0 e^+ e^-$ and $K_S \to \pi^0 \mu^+ \mu^-$ by NA48, new $K^+ \to \pi^+ \nu \overline{\nu}$ event observed by E949 and new precision measurements of $K_{S,L} \to \pi e \nu$ decays by KTeV, KLOE and NA48 made in an effort to resolve the slight deviation from the unitarity in the CKM matrix, involving the $|V_{us}|$ coupling.

1 Introduction

The observation and understanding of kaon decays has been crucial for the progress in the theory of particle physics, especially for the Standard Model (SM). The first observation of the decay $K_L \to \pi^+\pi^-$ by Christenson, Cronin, Fitch and Turlay 40 years ago [1] has shown for the first time that the CP symmetry is violated in nature and guided Kobayashi and Maskawa, a decade later, to introduce a third quark family into their quark mixing scheme [2]. Low decay rates observed in the decay $K_L \to \mu^+\mu^-$, lead to the discovery of the GIM mechanism [3] and to the prediction of the charm quark. A few years ago, the direct violation of the CP symmetry in the decay amplitude, predicted by the Standard Model and first observed by NA31 with 3σ evidence [4], has been firmly established by NA48 [5, 6] and KTeV [7]. At present, the field of kaon physics still provides exciting results.

In this paper, the subject is divided into three parts. In the first part, the recent progress in the understanding of the rare decays involving flavor-changing neutral currents (FCNC) is described. The second part is devoted to semileptonic kaon decays especially to the decay $K_{S,L} \to \pi e\nu$ or K_{e3}, the best probe for the measurement of the CKM matrix element $|V_{us}|$. In the third part, recent studies of CP violation in kaon decays are reviewed.

2 Rare Decays

In the quest to find New Physics (NP) beyond SM, the searches for SM-forbidden kaon decays, in particular those which violate the lepton flavor, are ceding territory to measurements in the quark flavor sector. GIM-suppressed one-loop FCNC processes are very sensitive to additional flavor structure with up to an order of magnitude enhancements with respect to SM decay rates predicted by various NP models [8, 9, 10].

There are two classes of these decays (Fig. 1):

- Pure FCNC decays: $K_L \to \pi^0\nu\overline{\nu}$ and $K^+ \to \pi^+\nu\overline{\nu}$. These decays are fully dominated by short-distance dynamics which can be calculated perturbatively and the hadronic matrix element can be obtained from the well measured $K^+ \to \pi^0 e^+\nu$ decay. This leads to an extremely precise (to few %) relation between decay rates and the combination of CKM matrix elements $\lambda_t = V^*_{ts}V_{td}$. This level of theoretical cleanness in constraints to the CKM unitarity triangle is only matched by the CP asymmetry in $B \to J/\psi K_S$. Unfortunately, from the experimental point of view these decays are very challenging.

- Decays with both short-distance and long-distance contribution: $K_L \to \pi^0 l^+ l^-$ $(l = e, \mu)$ and $K_{L,S} \to \mu^+\mu^-$. Here, the long-distance amplitudes must be determined to a sufficient precision in order to access the short-distance physics. The determination of the long-distance contributions is done in the framework of Chiral Perturbation Theory (χPT) which is an effective field theory of SM describing the low energy (at kaon mass) hadron dynamics. As χPT is an effective theory, many parameters have to be determined experimentally with the help of other rare kaon decays.

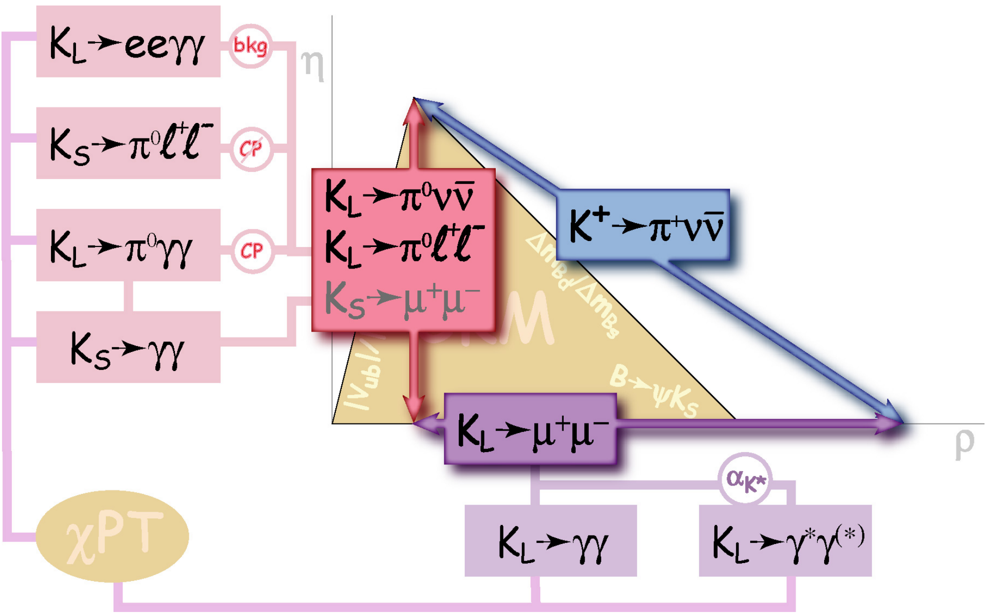

Figure 1: *Rare kaon FCNC reactions can fully determine the CKM unitarity triangle. Long-distance contributions to some of these processes are calculated in the framework of χPT with the help of other, related kaon rare decays.*

2.1 $K_L \to \pi^0 l^+ l^-$

The decay amplitude of $K_L \to \pi^0 \nu\overline{\nu}$, entirely due to direct CP violation [11], is proportional to $Im\lambda_t$ and determines the height of the CKM unitarity triangle usually denoted by the Wolfenstein parameter η [12]. The present experimental limit [13] is many orders of magnitude above the SM expectation [9, 14].

While the experimental state of the art is slowly reaching the level of being capable to seriously search for this challenging decay, an alternative decay accessing the same physics is under study. This is the decay $K_L \to \pi^0 l^+ l^-$. The advantage of this decay is that all the decay products can be detected, though the presence of radiative background can become a significant obstacle.

The short-distance direct CP-violating (DCPV) contribution to the decay $K_L \to \pi^0 e^+ e^-$ calculated by Buchalla, D'Ambrosio and Isidori [15] is

$$BR(K_L \to \pi^0 e^+ e^-)_{DCPV} \approx 4.4 \times 10^{-12} \tag{1}$$

and to the decay $K_L \to \pi^0 \mu^+ \mu^-$ obtained by Isidori, Smith and Unterdorfer [16] is

$$BR(K_L \to \pi^0 \mu^+ \mu^-)_{DCPV} \approx 1.8 \times 10^{-12} \tag{2}$$

in both cases using the latest SM CKM fit result $Im\lambda_t = 1.36 \times 10^{-4}$ [17].

Unlike $K_L \to \pi^0 \nu\overline{\nu}$, these decays receive also two long-distance contributions. The CP-conserving (CPC) contribution proceeds through two virtual photons and has been recently determined by a precise study of the decay $K_L \to \pi^0\gamma\gamma$ [18] in the low invariant $\gamma\gamma$ mass region. The $BR(K_L \to \pi^0 e^+ e^-)_{CPC}$ is negligible [15] while in the muon channel the CP-conserving contribution is

$$BR(K_L \to \pi^0 \mu^+ \mu^-)_{CPC} \approx 5.2 \times 10^{-12} \tag{3}$$

which is few times larger than the DCPV part [16].

The CP-conserving decay $K_1 \to \pi^0 l^+ l^-$, through $K^0 - \overline{K^0}$ mixing, provides an extra long-distance indirect CP-violating (ICPV) contribution to the $K_L \to \pi^0 l^+ l^-$. In addition, DCPV and ICPV components interfere with each other. Clearly, in order to determine this long-distance component the knowledge of $BR(K_S \to \pi^0 l^+ l^-)$ is necessary. The theoretical predictions, scattered over an order of magnitude around few 10^{-9}, do not provide a sufficient unambiguity [19].

The search for $K_S \to \pi^0 e^+ e^-$ and $K_S \to \pi^0 \mu^+ \mu^-$ decays was the primary goal of the NA48/1 extension [20] of the scientific program of the NA48 experiment at CERN, taking place in the year 2002. This experiment, after successfully finishing the precise measurement of $Re\ \varepsilon'/\varepsilon$ in 2001, took the opportunity to use the well functioning apparatus to study rare K_S decays. For this purpose the original beam setup, consisting of simultaneous high-intensity far-target and low-intensity near-target beams from SPS, was modified to run only the near-target beam line but at much higher intensity. This setup has been successfully tested and employed during the year 2000, in a period in which the spectrometer was in repair, leading to a series of results on K_S decays with purely photons in final state: $K_S \to \gamma\gamma$ [21], $K_S \to \pi^0\gamma\gamma$ [22], $K_S \to \pi^0\pi^0\pi^0$ [23].

Both $K_S \to \pi^0 e^+ e^-$ and $K_S \to \pi^0 \mu^+ \mu^-$ decays were successfully found by NA48/1. In the $K_S \to \pi^0 e^+ e^-$ mode, 7 events with background expectation of

$0.15^{+0.10}_{-0.04}$ events were found [24], while in the $K_S \to \pi^0\mu^+\mu^-$ mode, 6 events with $0.22^{+0.19}_{-0.12}$ of expected background were observed [25]. In the electron channel, in order to obtain a low background level a cut on ee invariant mass, $m_{ee} > 0.165$ GeV/c^2, had to be applied. This cut eliminates $K_S \to \pi^0\pi^0$ decays with successive π^0 decays in the Dalitz mode ($\pi^0 \to ee\gamma$) or with a $\gamma \to ee$ conversion in the material, but reduces the signal acceptance by about a factor of two. The main task of these searches, to control the background to a sufficient precision, has been performed with minimal help of Monte Carlo simulations. The main background in both modes, accidental coincidences due to high intensity of the beam, could be estimated to a level much lower than one event due to the availability of a large (> 200 ns) readout window. This allows one to have more than an order of magnitude larger control region with respect to the coincidence signal window of 3 ns. The contribution of $K_L \to e^+e^-\gamma\gamma$ background to the $K_S \to \pi^0e^+e^-$ channel was estimated using 2001 data containing ten times larger K_L flux than the near-target data of 2002.

From the observed events, following branching fractions have been extracted:

$$BR(K_S \to \pi^0e^+e^-) = (5.8^{+2.8}_{-2.3}{}_{stat} \pm 0.8_{syst}) \times 10^{-9} \tag{4}$$
$$BR(K_S \to \pi^0\mu^+\mu^-) = (2.8^{+1.5}_{-1.2}{}_{stat} \pm 0.2_{syst}) \times 10^{-9} \tag{5}$$

In the case of $K_S \to \pi^0e^+e^-$ the extrapolation to the full m_{ee} kinematic region has been done assuming no form factor and the uncertainty connected to this has been taken into account. In principle, having measured both decays, the form factor, parametrised as $W_S \sim a_S + b_S(m_{ll}/m_K)^2$, should be fully determined, at least up to a sign ambiguity. Due to low statistics, however, only $|a_S|$ can be calculated using the the vector-meson-dominance (VMD) model ansatz $b_S/a_S = 0.4$. Averaging both decay modes one obtains $|a_S|_{ll} = 1.21^{+0.22}_{-0.18}$. The ratio

$$\frac{BR(K_S \to \pi^0\mu^+\mu^-)}{BR(K_S \to \pi^0e^+e^-)} = 0.50 \pm 0.33 \tag{6}$$

is consistent with the prediction of the VMD model: 0.23 [26].

With these measurements, the last missing component in the effort to predict the branching fraction of decays $K_L \to \pi^0l^+l^-$ has been determined. Following the theoretical analyses [15, 16] the expected BR's using SM fits are:

$$BR(K_L \to \pi^0e^+e^-)_{SM} \approx (17_{ICPV} \pm 9_{INTF} + 4_{DCPV}) \times 10^{-12} \tag{7}$$
$$BR(K_L \to \pi^0\mu^+\mu^-)_{SM} \approx (8_{ICPV} \pm 3_{INTF} + 2_{DCPV} + 5_{CPC}) \times 10^{-12} \tag{8}$$

where the uncertainties on the individual contributions are at the level of 20-30%. The sign of the interference term (INTF) depends on the unknown sign of the a_S parameter. A constructive interference is favoured now by two theoretical groups [15, 27]. This means that despite of dominance of the long-distance indirect CP-violating contribution relatively good sensitivity to the $Im\lambda_t$ is retained through the interference term.

The best present limits on the BR's of $K_L \rightarrow \pi^0 l^+ l^-$ decays are provided by the KTeV collaboration:

$$BR(K_L \rightarrow \pi^0 e^+ e^-) < 2.8 \times 10^{-10} (90\% CL)[28] \tag{9}$$

$$BR(K_L \rightarrow \pi^0 \mu^+ \mu^-)) < 3.8 \times 10^{-10} (90\% CL)[29] \tag{10}$$

These limits are still far from SM predictions, however, many NP scenarios foresee strong enhancements in the decay rates of these processes [8]. In particular, a rather recent model of enhanced electroweak penguins predicts an order of magnitude enhancement of the direct CP-violating component in both decays [10]. Therefore, even slight improvement of these limits can have selective power on models beyond SM. Although currently no experiment plans to search for $K_L \rightarrow \pi^0 l^+ l^-$ decays, possibilities to reach SM sensitivity have been studied and proposed [30].

2.2 $K^+ \rightarrow \pi^+ \nu\overline{\nu}$

The decay $K^+ \rightarrow \pi^+ \nu\overline{\nu}$ is fully dominated by short-distance processes. The decay amplitude depends on both $Re\lambda_t$ and $Im\lambda_t$. This, combined with one of other FCNC kaon decays, offers a possibility of fully determining the CKM unitarity triangle using exclusively rare kaon decays. A non-negligible charm admixture in the loop contributes to slightly higher theoretical uncertainty compared to the decay $K_L \rightarrow \pi^0 \nu\overline{\nu}$. The SM prediction for the branching fraction is

$$BR(K^+ \rightarrow \pi^+ \nu\overline{\nu})_{SM} = (7.8 \pm 1.2) \times 10^{-11} [9,\ 10,\ 14] \tag{11}$$

The experiment E787 using the AGS at BNL searched for the decay $K^+ \rightarrow \pi^+ \nu\overline{\nu}$ between years 1995 and 1999. It used a separated K^+ beam stopped in an active target. The signal signature included identification of the K^+ in a Cherenkov counter, measurement of the energy, momentum and range of the charged track and the absence of any other signals in coincidence with the examined event. In the kinematic region $211 < P_\pi < 229$ MeV/c (Region I), where P_π is the π^+ momentum, two events have been found with 0.14 ± 0.05 events background expectation. The background determination was based entirely on data [31].

The successor of the E787 experiment, E949, started to operate in the year 2002. This experiment uses the same apparatus and technique as E787 with upgraded photon veto system and range stack. The upgrades allowed the experiment to run at higher instantaneous intensity, with smaller dead time and should improve the sensitivity in the less clean kinematic region $P_\pi < 195$ MeV/c (Region II) [32]. First results from the 2002 run has been announced recently. One more event was found with the background expectation of 0.30 ± 0.03 events [33]. This new event has significantly lower signal to background ratio compared to two E787 events. The combined experimental branching ratio is

$$BR(K^+ \to \pi^+ \nu\overline{\nu}) = (14.7^{+13.0}_{-8.9}) \times 10^{-11} \tag{12}$$

This result is compatible with SM prediction. However, the fact that the central value is about factor two above the expectation and the uncertainties are large, leaves an exciting window for NP models [14]. The experiment E949 may take more data in the future and improve the present uncertainty by a factor two or three.

2.3 $K_L \to \mu^+\mu^-$

The decay $K_L \to \mu^+\mu^-$ is the best measured among the rare kaon FCNC processes with $BR(K_L \to \mu^+\mu^-) = (7.18 \pm 0.17) \times 10^{-9}$ [34]. The short-distance process depends on $Re\lambda_t$ (or ρ in the Wolfenstein parametrisation) and, within SM, is estimated to contribute with a $BR(K_L \to \mu^+\mu^-)^{SD}_{SM} = (0.8 \pm 0.3) \times 10^{-9}$ [10]. Here the difficulty resides in determination of the dominant long-distance contribution which proceeds through two photon exchange.

The absorptive part of the long-distance contribution can be determined with the help of the $K_L \to \gamma\gamma$ decay. Recently, two new results were published:

$$\frac{\Gamma(K_L \to \gamma\gamma)}{\Gamma(K_L \to \pi^0\pi^0\pi^0)} = (2.81 \pm 0.01_{stat} \pm 0.02_{syst}) \times 10^{-3} \text{ by NA48 [21]} \tag{13}$$

$$\frac{\Gamma(K_L \to \gamma\gamma)}{\Gamma(K_L \to \pi^0\pi^0\pi^0)} = (2.79 \pm 0.02_{stat} \pm 0.02_{syst}) \times 10^{-3} \text{ by KLOE [35]} \tag{14}$$

Both results agree well with each other.

More problematic is the small dispersive part of the long-distance amplitude which interferes with the short-distance process. This part can be related to the form factor in two photon decays, $K_L \to \gamma^*\gamma$ and $K_L \to \gamma^*\gamma^*$, with one or both photons off shell. In an earlier theoretical analysis this form factor was parametrised by a single parameter α_{K^*} [36]. Later, refined analysis, introduced a pair of parameters α, β [37]. The latest results from the KTeV collaboration, with notably a very precise measurement of the $K_L \to e^+e^-\gamma$ decay [38], provide a new precision step in the determination of this contribution. In the formalism of [36] the result is $\alpha_{K^*} = -0.186 \pm 0.014$ which can be translated to $\alpha = -1.611 \pm 0.044$ in terms of [37]. The statistics available in $K_L \to \gamma^*\gamma^*$ modes, like $K_L \to e^+e^-\mu^+\mu^-$ and $K_L \to e^+e^-e^+e^-$ is not yet sufficient to extract the parameter β. The $K_L \to e^+e^-\gamma$ result by KTeV agrees well with their earlier result on $K_L \to \mu^+\mu^-\gamma$ [39] while it is in a 2.6 σ discrepancy with the published NA48 result based on a small part of the total data sample [40]. New result by NA48 with significantly higher statistics is expected very soon[1].

2.4 Summary and Prospects

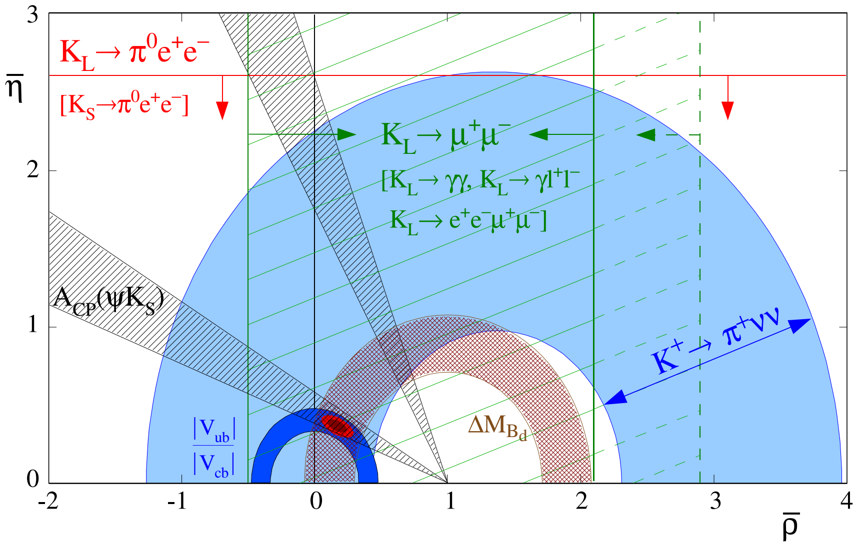

Figure 2: *Comparison of present constraints on $\overline{\rho}$ and $\overline{\eta}$ from rare kaon decays and B-decays [42].*

A comparison of constraints imposed by the latest rare kaon decay results and constraints provided by B-physics is shown in the Fig. 2 [42]. The impact of the latest E949 $K^+ \to \pi^+\nu\overline{\nu}$ event is not shown but the change, due to small weight of this event is small. The smaller $\overline{\rho}$ interval from $K_L \to \mu^+\mu^-$ corresponds to the case of negative interference between short- and long-distance contributions. The kaon constraints are still about an order of magnitude away from SM expectations. On the

[1]Shortly after this conference NA48 presented a preliminary result using full statistics [41] which is in agreement with KTeV results.

other hand, as mentioned before, many NP models predict substantial enhancements of FCNC amplitudes. Therefore any improvement of these limits can already have selective power among NP models.

Even in the absence of a large NP signal, currently pursued experimental projects provide a very good potential to reach the SM level in the coming decade. The first experiment dedicated to the search for $K_L \to \pi^0 \nu\overline{\nu}$ decay, the experiment E391a at KEK PS in Japan, took first data this year and might double the statistics next year. The technique is based on a low-energy pencil beam with highly efficient photon veto system. The aim is to reach a single event sensitivity of about 4×10^{-10} [43] which is very close to some NP predictions [10]. This experiment is a pilot experiment for a much more ambitious project at the future J-PARC facility which plans to collect more than 100 "SM" events.

Another experiment dedicated to the $K_L \to \pi^0 \nu\overline{\nu}$ search, KOPIO, is under development at BNL with an approved budget for the year 2005. The experiment plans to use micro-bunched proton beam from AGS extracting low-energy K_L at a large angle from the target. The kaon energy is measured by time of flight and the event reconstruction relies on high redundancy of measured quantities [44]. The expected sensitivity is similar to the Japanese project at J-PARC.

New projects to measure the $K^+ \to \pi^+ \nu\overline{\nu}$ decay are also under way. In addition to the experiment E949 at BNL, high statistics experiments are being developed and proposed at Fermilab and CERN. The Fermilab CKM project aims to collect about 100 "SM" events [45]. Unfortunately, at present the experiment is not supported by Fermilab. At CERN, a working group within the NA48 collaboration has studied the possibility to use part of the NA48 equipment for a future $K^+ \to \pi^+ \nu\overline{\nu}$ experiment under the working name NA48/3. An Expression of Interest has been submitted a few months ago [46] and a Letter of Intent will be submitted soon.

3 Semileptonic Decays

The 2002 edition of PDG has revealed a slight deviation from the unitarity in the first row of the CKM matrix [49]. The expression $|V_{us}|^2 + |V_{ud}|^2 + |V_{ub}|^2$, where the V_{ub} is negligible, deviated from unity by 2.2 standard deviations. Both V_{us} and V_{ud} contribute with similar uncertainties.

This apparent discrepancy triggered an avalanche of experimental and theoretical results, especially concerning V_{us}. The most precise way of extracting the coupling V_{us} is by measuring the decay rate of the semileptonic kaon decay decay

Table 1: *KTeV measurements of main K_L decay widths. The first uncertainty is statistical and the second systematic.*

Decay Modes	Partial Width Ratio
$\Gamma(K_L \to \pi\mu\nu)/\Gamma(K_L \to \pi e\nu)$	$0.6640 \pm 0.0014 \pm 0.0022$
$\Gamma(K_L \to \pi^0\pi^0\pi^0)/\Gamma(K_L \to \pi e\nu)$	$0.4782 \pm 0.0014 \pm 0.0053$
$\Gamma(K_L \to \pi^+\pi^-\pi^0)/\Gamma(K_L \to \pi e\nu)$	$0.3078 \pm 0.0005 \pm 0.0017$
$\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_L \to \pi e\nu)$	$(4.856 \pm 0.017 \pm 0.023) \times 10^{-3}$
$\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_L \to \pi^0\pi^0\pi^0)$	$(4.446 \pm 0.016 \pm 0.019) \times 10^{-3}$

$K \to \pi l\nu$ (K_{l3}) and using the relation:

$$\Gamma(K_{l3}) \sim |V_{us}|^2 f_+^2(0) I_K^l (1 + \delta_{rad}^l) \quad (15)$$

where $f_+(0)$ is the form factor normalisation, I_K^l is the phase space integral and δ_{rad}^l represents the radiative corrections. More explicit formulae can be found elsewhere [49, 47, 48]. $\Gamma(K_{l3})$ and I_K^l are measured experimentally, while $f_+(0)$ and δ_{rad}^l are calculated by theorists. New development in all four components have been made recently.

The experiment KTeV at Fermilab, which was designed to measure precisely the direct CP-violation parameter $Re\ \varepsilon'/\varepsilon$ and to search for rare K_L decays, has published recently a set of measurements of all the main K_L decay modes [50]. Measurements of five ratios of decay rates are summarised in the Tab.1. The ratios are chosen such that a large part of the systematic effects, like e.g. trigger or detector efficiencies, cancel. Also, in $K_L \to \pi\mu\nu$ the information from the muon system is not used and in $K_L \to \pi^+\pi^-\pi^0$ the π^0 is not reconstructed to minimise systematic biases. Main systematic uncertainties originate from detector imperfections difficult to simulate, in particular the reconstruction efficiencies and material simulation. Clearly, the most difficult ratio $\Gamma(K_L \to \pi^0\pi^0\pi^0)/\Gamma(K_L \to \pi e\nu)$, where information from different detectors has to be combined, suffers from the largest uncertainty. Using the five ratios all main six K_L branching ratios can be extracted.

All ratios involving the $K_L \to \pi e\nu$ (K_{e3}) decay disagree by several standard deviations from the present world averages [51]. Therefore, new measurements of these decay widths are highly desirable and both KLOE and NA48 are in a process of analysing these decays.

Together with the K_{l3} decay widths, KTeV measured also the form factor shapes extracting for the first time the quadratic term λ''_+ [52]. Combining both $K_L \to \pi e\nu$ and $K_L \to \pi\mu\nu$ results and using an in-house calculation of radiative corrections [48] they obtain [53]:

$$|V_{us}|f_+(0) = 0.2165 \pm 0.0012 \tag{16}$$

Another interesting result addressing the V_{us} determination has been recently presented by the KLOE collaboration. This unique experiment collects $\phi \to K_S K_L$ data at the Frascati ϕ-factory DAPHNE. By tagging the opposite K_L this experiment can access K_S decay modes which, in fixed target experiments, would be flooded by K_L background. The $K_S \to \pi^+\pi^-(\gamma)$ background is rejected by requiring $m_{\pi\pi} < 490$ MeV/c^2. The remaining background is separated by testing for the presence of neutrino comparing the missing energy and missing momentum, where the original direction of K_S is determined from the position of the opposite K_L. The branching fraction is $BR(K_S \to \pi e\nu) = (7.09 \pm 0.07_{stat} \pm 0.08_{syst}) \times 10^{-4}$ [54]. Using the CKM working group recipe [17] they obtain

$$|V_{us}|f_+(0) = 0.2157 \pm 0.0018 \tag{17}$$

New measurement of the $K_L \to \pi e\nu$ decay rate and form factor has been presented by NA48 at [55]. This measurement is normalised to an inclusive 2-track decay rate:

$$R = \frac{\Gamma(K_L \to \pi e\nu)}{\Gamma(K_L \to 2track)} = 0.497 \pm 0.004 \tag{18}$$

To extract the branching fraction $BR(K_L \to 2track)$ is calculated by subtracting from unity all major neutral decay modes. Here the dominant contribution comes from $K_L \to \pi^0\pi^0\pi^0$ decay. At present, the new KTeV result on $BR(K_L \to \pi^0\pi^0\pi^0)$ [50] disagrees by six standard deviations from the PDG value [51]. A new measurement of $BR(K_L \to \pi^0\pi^0\pi^0)$ is needed to resolve this situation[2].

In the last months, several new theoretical calculations of $f_+(0)$ have been published. A new lattice calculation [57] agrees with the original χPT calculation at $O(p^4)$ [58] while χPT calculations at $O(p^6)$ obtain slightly higher value [47, 59]. A summary of the present experimental and theoretical situation is shown in the Fig. 3. In general the experimental results from semileptonic decays of neutral kaons are consistent with each other and with the earlier measurement of $K^+ \to \pi^0 e^+\nu$ by E865 [60]. However, the situation, especially from the theoretical side, is not completely satisfactory.

[2]Shortly after this conference a new preliminary result has been presented by NA48 [41, 56] which confirms the KTeV measurement of $BR(K_L \to \pi^0\pi^0\pi^0)$.

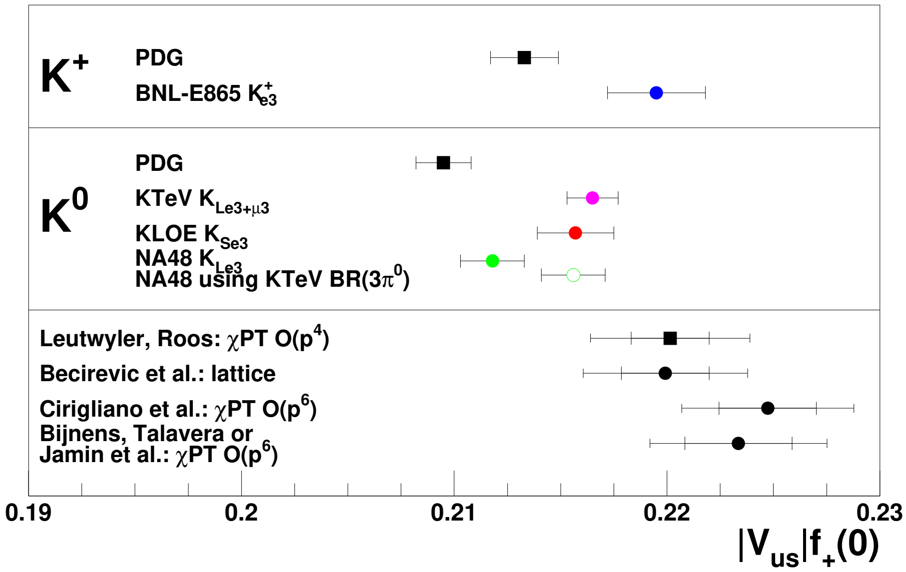

Figure 3: *Comparison of old (squares) and new (circles) results on V_{us}. K^+ results are corrected by the ratio of $f_+(0)$ for neutral and charged kaons. The theoretical results correspond to $f_+(0)(1-|V_{ud}|^2)^{1/2}$ where the larger error bar includes the uncertainty on V_{ud}.*

Two other new results falling into the category of semileptonic decays have been published by NA48. The decay $K_L \to \pi^0 \pi e \nu$, interesting e.g. for the study of the $\pi\pi$ scattering, has been measured with an improved precision [61]:

$$BR(K_L \to \pi^0 \pi e \nu) = (5.21 \pm 0.07_{stat} \pm 0.09_{syst}) \times 10^{-5} \tag{19}$$

A set of form factors was fitted using distributions of five Cabibbo-Maksymowicz variables. The result agrees with previous measurements and with theoretical predictions [62].

The second result is the measurement of the radiative $K_L \to \pi e \nu \gamma$ decay. Here, the analysis is complicated by the fact that the acceptance calculation can depend on the theoretical model inserted into the Monte Carlo event generator. NA48 has performed a model-independent analysis by re-weighting the Monte Carlo events according to kinematic distributions obtained from data. The result [63]

$$\frac{\Gamma(K_L \to \pi e \nu \gamma)}{\Gamma(K_L \to \pi e \nu)} = (9.60 \pm 0.07_{stat}\ {}^{+0.12}_{-0.11 syst}) \times 10^{-3} \tag{20}$$

agrees with theoretical predictions based on χPT [64] but disagrees with a published result from KTeV which has similar statistical precision [65].

4 CP Violation

The decay $K_S \to \pi^0\pi^0\pi^0$ is purely CP-violating and is, up to now, unobserved. The CP-violation parameter $\eta_{000} \equiv A(K_S \to \pi^0\pi^0\pi^0)/A(K_L \to \pi^0\pi^0\pi^0)$ is proportional to the expression $\varepsilon + iImA_1/ReA_1$, where ε is the parameter of indirect CP violation in the kaon system and A_1 is the isospin 1 decay amplitude. The imaginary part of η_{000} is in principle sensitive to direct CP violation [51]. In addition, the poor knowledge of η_{000}, limits at present the CPT tests in the K system.

In a recently published paper, NA48 searches for the decay $K_S \to \pi^0\pi^0\pi^0$ by exploring the interference between K_S and K_L and fitting the decay distribution of the data taken during the special near-target run in the year 2000. The result [23]

$$Re\eta_{000} = -0.002 \pm 0.011_{stat} \pm 0.015_{syst} \tag{21}$$

$$Im\eta_{000} = -0.003 \pm 0.013_{stat} \pm 0.017_{syst} \tag{22}$$

represents an order of magnitude improvement with respect to previous results and leads to a limit $|\eta_{000}| < 0.045$ at 90% CL level. This can be translated to $BR(K_S \to \pi^0\pi^0\pi^0) < 7.4 \times 10^{-7}$ which is more than an order of magnitude better than the currently published limit but still two orders of magnitude above the SM expectation. Using the Bell-Steinberger [66] relation and other measured kaon CP-violating decay amplitudes one can extract a significantly improved limit on the CPT-violating parameter δ: $Im\delta = (-0.2 \pm 2.0) \times 10^{-5}$. Assuming that CPT is conserved in the decay leads to a measurement of $K^0\overline{K^0}$ mass difference $m_{K^0} - m_{\overline{K^0}} = (-0.2 \pm 2.8) \times 10^{-19}$ GeV/c^2. By imposing full CPT invariance the limit on branching fraction becomes $BR(K_S \to \pi^0\pi^0\pi^0) < 2.3 \times 10^{-7}$.

Similar results have been recently presented by the KLOE collaboration however, obtained by completely different technique. KLOE experiment is capable to search for the decay $K_S \to \pi^0\pi^0\pi^0$ directly by tagging the K_S decays with an opposite K_L as described in the section 3. They observe 4 events in the signal region with 3.2 ± 1.4 background events expected. This leads to a limit $BR(K_S \to \pi^0\pi^0\pi^0) < 2.1 \times 10^{-7}$ at 90% CL or $|\eta_{000}| < 0.024$ [67]. New data from KLOE promise steady improvements of these limits in the future.

Using their newly measured branching fractions of all main K_L decays, KTeV collaboration obtained also a more precise measurement of the CP-violating parameter $|\eta_{+-}|$. With the help of the expression

$$|\eta_{+-}|^2 = \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)} = \frac{\tau_S}{\tau_L}\frac{BR(K_L \to \pi^+\pi^-) + BR(K_L \to \pi^0\pi^0)(1 + 6Re\ \varepsilon'/\varepsilon)}{1 - BR(K_S \to \pi e\nu)} \tag{23}$$

where the normalisation is done under the assumption $\Gamma(K_S \to \pi e\nu) = \Gamma(K_L \to \pi e\nu)$, KTeV obtains [50]:

$$|\eta_{+-}| = (2.228 \pm 0.005_{KTeV} \pm 0.009_{\tau_{KL}}) \times 10^{-3} \tag{24}$$

The main uncertainty comes from the poor knowledge of the K_L lifetime, which may be measured more precisely soon by KLOE [68]. This result differs by more than three standard deviations from the current world average [51]. This is another indication of the inconsistencies in our understanding of the main K_L branching ratios, which will hopefully be resolved soon by new results from KLOE and NA48.

Finally, new searches for direct CP-violation are under way in the decays of charged kaons. The second extension of the NA48 experiment, NA48/2 [69], uses simultaneous K^+ and K^- beams to measure the asymmetry in the Dalitz plot slope parameter g

$$A_g \equiv \frac{g(K^+ \to \pi\pi\pi) - g(K^- \to \pi\pi\pi)}{g(K^+ \to \pi\pi\pi) + g(K^- \to \pi\pi\pi)} \tag{25}$$

More than 2 billion $K^\pm \to \pi^\pm\pi^+\pi^-$ and few hundred millions of $K^\pm \to \pi^\pm\pi^0\pi^0$ have been collected in years 2003 and 2004 [70]. This will allow to access A_g to the level better than 2×10^{-4} which is better than an order of magnitude with respect to previous experiments. The theoretical predictions within SM vary between -5×10^{-5} and 5×10^{-5} [71] while enhancements to the level of 10^{-4} are predicted by models beyond SM [72]. Similar sensitivity is expected from the experiment OKA in Protvino.

5 Conclusions

Most recent developments in the experimental kaon physics have been reviewed. The amount of presented results, despite of the fact that this review is necessarily selective and incomplete, documents the unfading activity in this field. New results in rare decays have shed more light on the FCNC processes which seem to be one of the best windows to the New Physics in the future. Especially the golden modes $K \to \pi\nu\overline{\nu}$ are the targets of new projects in kaon physics. They promise an exciting interplay together with B-factories and Tevatron or LHC experiments, in the coming years in the quest for physics beyond Standard Model.

The situation around the unitarity test in the first row of the CKM mixing matrix seems to improve. The new experimental results are consistent with each other. On the other hand various theoretical calculations lead to different conclusions. The question “Is the unitarity in CKM matrix conserved?” is not completely answered yet.

In the intermediate term, many new results are expected from experiments at Frascati, Brookhaven, CERN and KEK. The luminosity of the DAPHNE machine is improving and promises new interesting results from the powerful experiment KLOE. The huge sample of charged kaon decays accumulated by NA48/2 will yield not only new results on direct CP violation but also on a full palette of rare decays of charged kaons. Of course, a continuing support from the theorists is essential to keep kaon physics attractive.

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