Kaons - Recent Results and Future Plans

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Recent results and future plans of kaon physics are reviewed. Topics include CP violation, rare decays, light neutral-boson search, lepton flavor universality, and CPT and QM tests.

1 CP violation

This review article starts with the kaon-side story of CP violation. After the $K_L^0 \to \pi^+\pi^-$ decay was discovered [1] in 1964 and the CP asymmetry in the $K^0 - \overline{K^0}$ mixing was established [2], a long-standing problem has been its origin; the first question was whether it was due to the $\Delta S = 2$ *superweak* transition [3] or not. In 1973, Kobayashi and Maskawa [4] accommodated CP violation in the electroweak theory with six quarks (and single complex-phase). The Kobayashi-Maskawa theory [5], including the prediction of *direct* CP violation in the decay process from the CP-odd component (K_2) to the CP-even state ($\pi\pi$), was verified by the observations of Time-reversal non-invariance (CPLEAR [6] at CERN) and finite ϵ'/ϵ (NA48 at CERN and KTeV at FNAL) as well as the discoveries of top quark and CP-violating B decays.

The KTeV collaboration reported the final measurement of $Re(\epsilon'/\epsilon)$ with their entire data set: $(19.2 \pm 1.1(stat.) \pm 1.8(syst.)) \times 10^{-4}$ [7]. Combining all the measurements including the final result from NA48: $(14.7 \pm 2.2) \times 10^{-4}$ [8], the world average is $(16.8 \pm 1.4) \times 10^{-4}$ [9]; it clearly demonstrates the existence of direct CP violation. However, due to theoretical uncertainties in the hadronic matrix elements, to get information on the Standard Model and New Physics beyond it from $Re(\epsilon'/\epsilon)$ is difficult and remains to be a challenge to lattice QCD calculations [10].

In the modern classification [11] CP violation is grouped into three: in *mixing*, *decay*, and *interference between decays with and without mixing*. All of these have been extensively studied in the B Factory experiments, while the study of CP violation in the charged-kaon decay modes started recently. The NA48/2 experiment at CERN performed charge asymmetry measurements with the simultaneous $K^\pm$ beams of 60 ± 3 GeV/c in 2003 and 2004. The asymmetries of the linear slope parameter in the matrix element expansion of the $K^\pm \to \pi^\pm\pi^+\pi^-$ decay and the $K^\pm \to \pi^\pm\pi^0\pi^0$ decay were measured to be $(-1.5 \pm 2.2) \times 10^{-4}$ and $(1.8 \pm 1.8) \times 10^{-4}$ with the data sets of 4G and 0.1G events, respectively [12]. The Standard Model expectation is in $10^{-5} \sim 10^{-6}$, and no evidence for CP violation in *decay* was observed at the level of 2×10^{-4}. NA48/2 also measured the asymmetries of K^+ and K^- decay-widths in $K^\pm \to \pi^\pm e^+e^-$ and $K^\pm \to \pi^\pm\pi^0\gamma$ to be $(-2.2 \pm 1.5(stat.) \pm 0.6(syst.)) \times 10^{-2}$ [13] and $(0.0 \pm 1.0(stat.) \pm 0.6(syst.)) \times 10^{-3}$ [14] and set the upper limits of 2.1% and 0.15%, respectively.

The CP-violating processes in *mixing* and *decay* suffers from hadronic uncertainties. In contrast, the CP violation in *interference between decays with and without mixing* is theoretically clean, and the decay $K_L^0 \to \pi^0\nu\bar{\nu}$ [15] is known to be a golden mode in this category [16] because the branching ratio can be calculated with very small theoretical-uncertainties in the Standard

Model as well as in New Physics. Measurement of the branching ratios for $K^0 \to \pi^0 \nu\bar{\nu}$ and for the charged counterpart $K^+ \to \pi^+ \nu\bar{\nu}$ is the main issue in the near future plans of kaon physics, and is the topics of the next section.

2 Rare decays

The $K \to \pi\nu\bar{\nu}$ decay [17] is a Flavor-Changing Neutral Current (FCNC) process and is induced by the electroweak loop effects as Penguin and Box diagrams. The decay is suppressed in the Standard Model, and the branching ratios are predicted as $B(K_L^0 \to \pi^0\nu\bar{\nu}) = (2.76\pm0.40)\times10^{-11}$ and $B(K^+ \to \pi^+\nu\bar{\nu}(\gamma)) = (8.22\pm0.84)\times10^{-11}$ [18], in which the uncertainties are dominated by the allowed range of the quark-mixing matrix elements. Long-distance contributions are small, the hadronic matrix elements are extracted from the $K^+ \to \pi^0 e^+ \nu$ decay [19], and the next-to-next-to-leading order QCD corrections [20] and the QED and electroweak corrections [21] to the charm quark contribution to $K^+ \to \pi^+\nu\bar{\nu}$ have been calculated. New Physics could affect these branching ratios [22] and, by the measurement, the flavor structure in New Physics (operators and phases in the interactions of new particles) can be studied. The $K \to \pi\nu\bar{\nu}$ branching ratios beyond the Standard Model are presented in Fig. 1. A model-independent bound $B(K_L^0 \to \pi^0\nu\bar{\nu}) < 4.4 \times B(K^+ \to \pi^+\nu\bar{\nu})$ (Grossman-Nir bound [16]) can be extracted from their isospin relation.

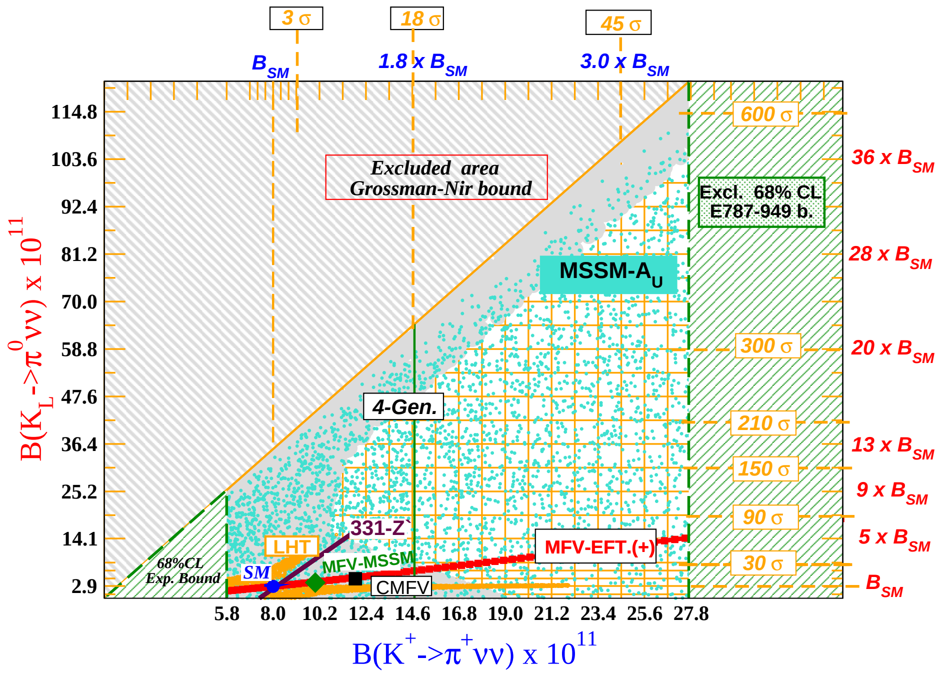

Figure 1: $K \to \pi\nu\bar{\nu}$ branching ratios beyond the Standard Model, by courtesy of F. Mescia and C. Smith [18].

The signature of $K \to \pi\nu\bar{\nu}$ is a kaon decay into *a pion plus nothing*. Background rejection is essential in these experiments, and *blind analysis* techniques have been developed and refined to achieve a high level of confidence in the background measurements. To verify *nothing*, hermetic extra-particle detection by photon and charged-particle detectors, called the *veto*, is imposed to the hits in coincidence with the pion time and with the energy threshold less than a few MeV. Tight veto requirements are indispensable in order to achieve a low detection-inefficiency $< 10^{-3} \sim 10^{-4}$; good timing resolution for low energy hits is therefore essential to avoid acceptance loss due to accidental hits.

The E391a experiment at KEK was the first dedicated search for the $K_L^0 \to \pi^0 \nu\bar{\nu}$ decay. A small-diameter neutral beam (called a *pencil* beam [23]) was developed and constructed. The K_L^0 beam whose momentum peaked at 2 GeV/c was produced by the 12-GeV proton synchrotron (KEK-PS). The energy and position of the two photons from π^0 decays were measured by a downstream calorimeter. The K_L^0-decay vertex position along the beam line was determined from the constraint of π^0 mass, and a π^0 with a large transverse momentum (≥ 0.12 GeV/c) was the signal. The remaining part of the calorimeter not hit by the two photons and the other detector subsystems that covered the decay region were used as a veto, which was crucial to suppress the major background from $K_L^0 \to \pi^0\pi^0$. The beam line and the collimation scheme were designed carefully to minimize the beam halo (mostly neutrons), which could interact with the counters near the beam and produce π^0's and η's.

Final results from E391a on $K_L^0 \to \pi^0 \nu\bar{\nu}$ were published recently [24]. Combining the data sets from February-April and October-December 2005, the single event sensitivity was 1.11×10^{-8} and no events were observed inside the signal region (Fig. 2, left). The upper limit on $B(K_L^0 \to \pi^0 \nu\bar{\nu})$ was set to be 2.6×10^{-8} at the 90% confidence level (C.L.). The E391a experiment has improved the limit from previous experiments by a factor of 20.

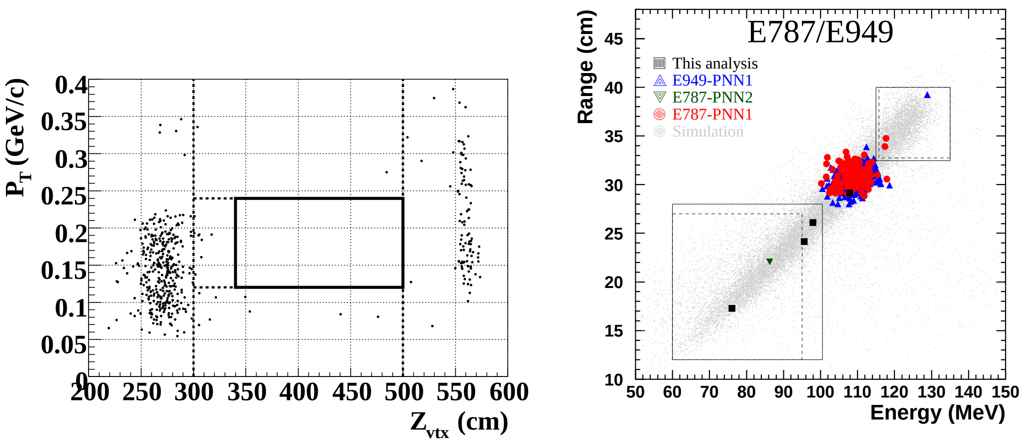

Figure 2: E391a result on $K_L^0 \to \pi^0 \nu\bar{\nu}$ [24] (left); E787/E949 result on $K^+ \to \pi^+ \nu\bar{\nu}$ [26] (right).

The E949 experiment at BNL measured the charged track emanating from $K^+ \to \pi^+ \nu\bar{\nu}$ decaying at rest in the stopping target. Charged-particle detectors for measurement of the π^+ properties were located in the central region of the detector and were surrounded by hermetic photon detectors. The π^+ momentum (P_{π^+}) from $K^+ \to \pi^+ \nu\bar{\nu}$ is less than 0.227 GeV/c, while the major background sources of $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu$ are two-body decays and have monochromatic momentum of 0.205 GeV/c and 0.236 GeV/c, respectively. The π^+ momentum regions above and below the peak from $K^+ \to \pi^+\pi^0$ were adopted. Redundant kinematic measurement and μ^+ rejection were employed; the latter was crucial because the $K^+ \to \mu^+\nu$ background had the same topology as the signal. Pion contamination to the incident K^+ beam (0.7 GeV/c) was reduced by two stages of electrostatic particle separation in the beam line to prevent the background due to scattered beam pions.

The E949 experiment observed one $K^+ \to \pi^+\nu\bar{\nu}$ event in the kinematic region $0.211 < P_{\pi^+} < 0.229$ GeV/c (PNN1) [25] and three events in the region $0.140 < P_{\pi^+} < 0.199$ GeV/c (PNN2) [26]. Combining the results with the observation of two events in PNN1 and one event in PNN2 by the predecessor experiment E787 gave $B(K^+ \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ (Fig. 2, right) [26], consistent with the Standard Model prediction.

The next generation of $K_L^0 \to \pi^0\nu\bar{\nu}$ is the E14 KOTO experiment [27] at the new high-intensity proton accelerator facility J-PARC (Japan Proton Accelerator Research Complex) [28]. The accelerators, consisting of a Linac, 3-GeV Rapid Cycle Synchrotron and Main Ring, succeeded in the acceleration to 30 GeV and slow and fast beam-extractions. The KOTO collaboration built the neutral beam line at the Hadron Hall of J-PARC and surveyed the beam in 2009. They started the detector construction in 2010 with the undoped CsI crystals used in the KTeV calorimeter. The next generation of $K^+ \to \pi^+\nu\bar{\nu}$ is the NA62 experiment [29] at CERN, which will use K^+ decays in flight from an un-separated beam of 75 GeV/c. The detector R&D with beam tests is close to the end, and the NA62 detector is being built. KOTO, as the first step in measuring $B(K_L^0 \to \pi^0\nu\bar{\nu})$ at J-PARC, aims at the observation of $K_L^0 \to \pi^0\nu\bar{\nu}$, and the goal of NA62 is to detect 100 $K^+ \to \pi^+\nu\bar{\nu}$ events. At FNAL, a new proposal [30] to measure $K^+ \to \pi^+\nu\bar{\nu}$ decays at rest has been submitted. Higher sensitivity kaon experiments based on a new high-intensity proton source at FNAL [31] are now under discussion.

At J-PARC, another new kaon experiment (E06 TREK) [32] is being prepared. In the $K^+ \to \pi^0\mu^+\nu$ decay, the transverse muon polarization (P_T) is a T-odd quantity and is a CP violation observable. New sources of CP violation may give rise to P_T as large as 10^{-3}. TREK is a successor to E246 at KEK-PS [33] and will measure the charged track and photons from the K^+ decay at rest with the E246 superconducting toroidal magnet, and aims at a P_T sensitivity of 10^{-4}. A low-momentum beam line is being built at the Hadron Hall.

3 Light neutral-boson search

Experimental searches for very light bosons have a long history, but a neutral boson whose mass is twice the muon mass has not yet been excluded. In 2005, the HyperCP collaboration at FNAL reported three events of the $\Sigma^+ \to p\mu^+\mu^-$ decay, and the dimuon mass may indicate a neutral intermediate state P^0 with a mass of 214.3 ± 0.5 MeV/c^2 [34]. Since the events were observed in an FCNC with a strange to down quark transition, P^0 should be confirmable with kaon decays. Dimuon masses in previous $K^+ \to \pi^+\mu^+\mu^-$ measurements were not observed in the narrow range around the P^0 mass; thus, P^0 should be a pseudo-scalar or axial-vector particle and be studied with the three-body decay $K \to \pi\pi P^0$.

The KTeV collaboration searched for the $K_L^0 \to \pi^0\pi^0\mu^+\mu^-$ decay for the first time [35] and set $B(K_L^0 \to \pi^0\pi^0\mu^+\mu^-) < 8.63 \times 10^{-11}$ and $B(K_L^0 \to \pi^0\pi^0 P^0 \to \pi^0\pi^0\mu^+\mu^-) < 9.44 \times 10^{-11}$ (90% C.L.). The E391a collaboration searched for the decay $K_L^0 \to \pi^0\pi^0 X$, $X \to \gamma\gamma$ in the mass range of X from 194.3 to 219.3 MeV/c^2, and set $B(K_L^0 \to \pi^0\pi^0 P^0 \to \pi^0\pi^0\gamma\gamma) < 2.4 \times 10^{-7}$

(90% C.L.) [36]. Both results almost ruled out the predictions when P^0 is a pseudo-scalar particle [37, 38].

The E787/E949 results on $K^+ \to \pi^+ \nu\bar{\nu}$ have also been interpreted in the two-body decay $K^+ \to \pi^+ X$, where X is a massive noninteracting particle either in stable or unstable, and in $K^+ \to \pi^+ P^0$, $P^0 \to \nu\bar{\nu}$. The limits are presented in [26].

4 Lepton flavor universality

Investigation of the lepton-flavor violating (LFV) processes involving both quarks and charged leptons ($K^0_L \to \mu^\pm e^\mp$ by E871 at BNL [39], $K^+ \to \pi^+\mu^+e^-$, $K^+ \to \pi^-\mu^+\mu^+$, and $K^+ \to \pi^-e^+e^+$ by E865 at BNL [40, 41], $K^0_L \to \pi^0\mu^\pm e^\mp$ and $K^0_L \to \pi^0\pi^0\mu^\pm e^\mp$ by KTeV [42]) has achieved stringent limits on the branching ratios in $10^{-9} \sim 10^{-12}$. Continual efforts are made to search for the $\mu^+ \to e^+\gamma$ decay and the $\mu^- N \to e^- N$ conversion with muons [43].

The LFV process in kaon decays is currently studied, intensively, in the context of high precision tests of Lepton Flavor universality. The ratio $R_K \equiv \Gamma(K^+ \to e^+\nu(\gamma))/\Gamma(K^+ \to \mu^+\nu(\gamma))$ is helicity suppressed in the Standard Model due to the V-A couplings and is predicted to be $R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$ [44], in which the radiative decay $K^+ \to e^+\nu\gamma$ ($K_{e2\gamma}$) via internal bremsstrahlung is included. Suppose a decay $K^+ \to e^+\nu_\tau$ exists due to the process of an intermediate charged-Higgs particle and a LFV Supersymmetric loop (Fig. 3) [45]. Since the neutrino flavor is undetermined experimentally, deviations of

$$R_K = \frac{\Sigma_i\, \Gamma(K^+ \to e^+\nu_i)}{\Sigma_i\, \Gamma(K^+ \to \mu^+\nu_i)} \simeq \frac{\Gamma_{SM}(K^+ \to e^+\nu_e) + \Gamma_{NP}(K^+ \to e^+\nu_\tau)}{\Gamma_{SM}(K^+ \to \mu^+\nu_\mu)}$$

from the Standard Model prediction, ΔR_K, in the relative size of $10^{-2} \sim 10^{-3}$ are suggested [46] as a function of the charged Higgs mass m_{H^+}, the ratio of the Higgs vacuum expectation values for the up- and down- quark masses (denoted as $\tan\beta$), and the effective $e-\tau$ coupling constant Δ_{13}:

$$\frac{\Delta R_K}{R_K^{SM}} = \frac{\Gamma_{NP}(K^+ \to e^+\nu_\tau)}{\Gamma_{SM}(K^+ \to e^+\nu_e)} = \left(\frac{m_{K^+}}{m_{H^+}}\right)^4 \left(\frac{m_\tau}{m_e}\right)^2 |\Delta_{13}|^2 \tan^6\beta$$

and can be experimentally studied. The same physics goal is pursued by the PIENU experiment [47] at TRIUMF and the PEN experiment [48] at PSI to measure $\Gamma(\pi^+ \to e^+\nu(\gamma))/\Gamma(\pi^+ \to \mu^+\nu(\gamma))$ precisely.

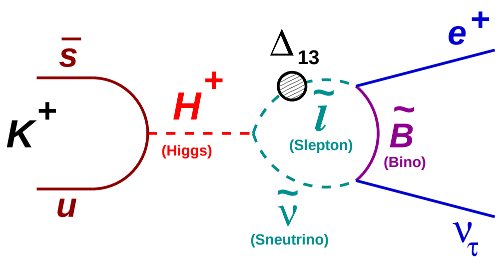

Figure 3: Diagram for the $K^+ \to e^+\nu_\tau$ decay.

The KLOE collaboration at DAΦNE, the Frascati ϕ factory, measured R_K with 3.3G of the K^+K^- pairs from ϕ mesons with an integrated luminosity of 2.2 fb^{-1} collected during 2001-2005 [49]. The $K^\pm \to \ell^\pm\nu$ decay in flight (~0.1 GeV/c) was reconstructed by the tracks of a kaon and a decay product with the same charge in the cylindrical drift chamber, and the squared mass m_ℓ^2 of the lepton for the decay was computed. To distinguish the $K^\pm \to e^\pm\nu$ events around $m_\ell^2 = 0$ from the tail of the $K^\pm \to \mu^\pm\nu$ peak, in addition to the track quality cuts, information about shower profile and total energy deposition in the electromagnetic calorimeter, combined with a neural network, and time-of-flight information were used for electron identification. The numbers of $K \to e\nu(\gamma)$ events were 7064±102 for K^+ and 6750±101 for K^-, respectively, 89.8% of which were $K \to e\nu$ events and the $K_{e2\gamma}$ events with $E_\gamma < 10$ MeV. The contribution from the $K_{e2\gamma}$ events with $E_\gamma > 10$ MeV, due to the direct-emission process, was studied [49, 50] by using a separate sample with photon detection requirement, and was subtracted. The numbers of $K \to \mu\nu(\gamma)$ events were 287.8M for K^+ and 274.2M for K^-, respectively. The difference between the K^+ and K^- counts was due to the larger cross section of K^- nuclear interaction in the material traversed. Finally, KLOE obtained $R_K = (2.493 \pm 0.025(stat.) \pm 0.019(syst.)) \times 10^{-5}$, in agreement with the Standard Model prediction. The regions excluded at 95% C.L. in the plane $M_{H^+} - \tan\beta$ are shown in Fig. 4, left, for different values of Δ_{13}.

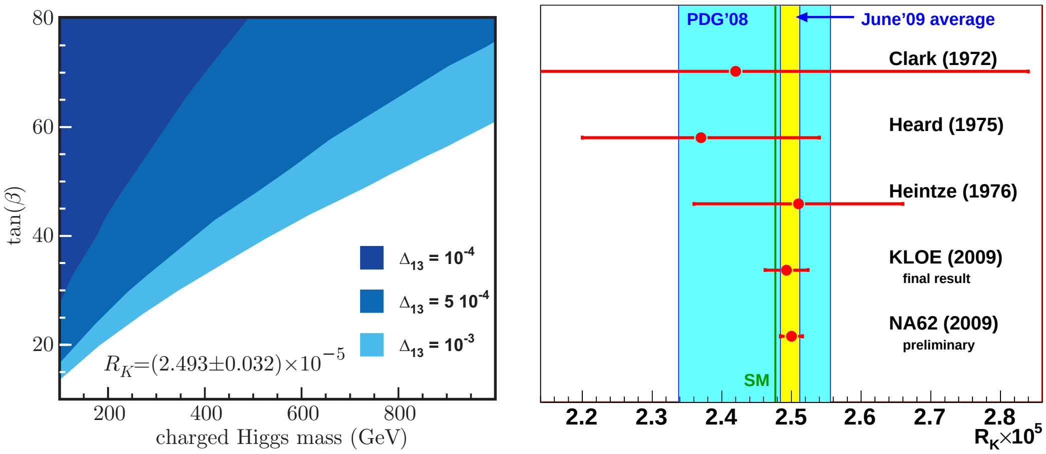

Figure 4: KLOE result on the excluded regions at 95% C.L. in the plane $m_{H^+} - \tan\beta$ for Δ_{13}=10^{-4}, 5×10^{-4} and 10^{-3} [49] (left); summary of the R_K measurements including the report from NA62 [51] (right).

The NA62 collaboration, as the first phase, collected data to measure R_K during four months in 2007, and collected special data samples to study systematic effects for two weeks in 2008. The beam line and detector apparatus of NA48/2 were used; 90% of the data were taken with the K^+ beam of 74.0 ± 1.6 GeV/c, because the muon sweeping system provided better suppression of the positrons produced by beam halo muons via $\mu \to e$ decay. Preliminary results based on the analysis of 40% of the 2007 data collected with the K^+ beam only were reported in [51]. The number of $K^+ \to e^+\nu$ candidate events was 51089, and the number of $K^+ \to \mu^+\nu$ candidate events was 15.56M. The source of the main background, (6.28 ± 0.17) %, was found to be the $K^+ \to \mu^+\nu$ decay with muon identification as positron due to *catastrophic* bremsstrahlung in or in front of the liquid-Krypton electromagnetic calorimeter (LKr). The probability of the mis-identification was studied with pure muon samples, without positron contamination due to $\mu^+ \to e^+$ decays in flight, selected from the tracks traversing a $9.2X_0$-thick lead wall installed in front of LKr. R_K was obtained to be $(2.500 \pm 0.012(stat.) \pm 0.011(syst.)) \times 10^{-5}$, consistent with the Standard Model prediction. Combining with other R_K measurements, the current world average is $(2.498 \pm 0.014) \times 10^{-5}$ as presented in Fig. 4, right. The final results from this 40% partial data will be available soon.

The R_K measurement will continue in the NA62 analysis of the full data sample as well as in the future KLOE-2 experiment, which is described in the next section.

5 CPT and QM tests

ϕ mesons decay into K^+K^- pairs with 49% and $K^0_L K^0_S$ pairs with 34%. In the latter, the initial state is a coherent (and entangled) quantum state:

$$|i\rangle \;=\; \frac{1}{\sqrt{2}}\,[\;|K^0\rangle|\overline{K^0}\rangle \;-\; |\overline{K^0}\rangle|K^0\rangle\;] \;=\; \frac{N}{\sqrt{2}}\,[\;|K^0_S\rangle|K^0_L\rangle \;-\; |K^0_L\rangle|K^0_S\rangle\;]$$

where $N \simeq 1$ is a normalization factor. In the KLOE experiment, by tagging K^0_L *crash* events in the calorimeter, a pure K^0_S beam was available and there has been a major improvement in K^0_S decay measurements [52]. With the results of various new measurements on neutral kaon decays, the Bell-Steinberger relation was used [53] to provide a constraint relating the unitarity of the sum of the decay amplitudes to the CPT observables. The latest limit on the mass difference between K^0 and $\overline{K^0}$ was 4.0×10^{-19} GeV at 95% C.L. [54].

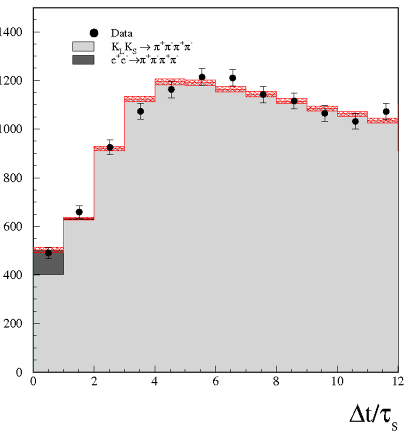

Figure 5: KLOE result on the fit to the measured $I(\Delta t)$ distribution of $\phi \to K^0_S K^0_L \to \pi^+\pi^-\pi^+\pi^-$ [56]. The black points with errors are data and the solid histogram is the fit result. The uncertainty arising from the efficiency correction is shown as the hatched area.

In the CP-violating process $\phi \to K^0_S K^0_L \to \pi^+\pi^-\pi^+\pi^-$, KLOE observed the quantum interference between two kaons for the first time [55]. The measured Δt distribution, with Δt the absolute value of the time difference of the two $\pi^+\pi^-$ decays, can be fitted with the distribution in the $K_S^0 - K_L^0$ basis:

$$
\begin{aligned}
I(\Delta t) &\propto e^{-\Gamma_L \Delta t} + e^{-\Gamma_S \Delta t} - 2(1-\zeta_{SL})\, e^{-\frac{(\Gamma_S+\Gamma_L)}{2}\Delta t} \cos(\Delta m \Delta t) \\
&\to 2\zeta_{SL}\left(1 - \frac{(\Gamma_S+\Gamma_L)}{2}\Delta t\right) \qquad \Delta t \to 0
\end{aligned}
$$

where Δm is the mass difference between K_L^0 and K_S^0. The interference term $e^{-\frac{(\Gamma_S+\Gamma_L)}{2}\Delta t} \cos(\Delta m \Delta t)$ is multiplied by a factor $(1-\zeta_{SL})$ with a *decoherence* parameter ζ_{SL}, which represents a loss of coherence during the time evolution of the states and should be zero in Quantum Mechanics (QM). Final results obtained from KLOE with 1.5 fb^{-1} in 2004-2005 were [56] $\zeta_{SL} = (0.3 \pm 1.8(stat.) \pm 0.6(syst.)) \times 10^{-2}$ (Fig. 5) and, to the fit with the distribution in the $K^0 - \overline{K^0}$ basis, $\zeta_{0\bar{0}} = (1.4 \pm 9.5(stat.) \pm 3.8(syst.)) \times 10^{-7}$; no deviation from QM was observed. Decoherence in the $K^0 - \overline{K^0}$ basis results in the CP-allowed $K_S^0 K_S^0 \to \pi^+\pi^-\pi^+\pi^-$ decays and thus the value for the decoherence parameter $\zeta_{0\bar{0}}$ is much smaller. Since the measurement of non-zero ζ_{SL} is sensitive to the distribution in the small Δt region, the decay vertex resolution due to charged-track extrapolation ($\sim 1\tau_S \simeq$ 6mm, to the vertex of a $K_S^0 \to \pi^+\pi^-$ decay close to the interaction point, in the KLOE detector) should be improved in future experiments. Other tests of CPT invariance and the basic principles of QM are discussed in [56, 57].

Kaon physics at the ϕ factory will continue with an upgraded KLOE detector, KLOE-2 [58], at an upgraded DAΦNE e^+e^- collider. During 2008 a new interaction scheme (*Crabbed Waist* collisions) was tested with the goal of reaching a peak luminosity of 5×10^{32} cm^{-2}s^{-1}, a factor of three larger than what previously obtained. In the first phase starting in 2010, the detector with minimal upgrade (two devices along the beam line to tag the scattered electrons/positrons from $\gamma\gamma$ collisions) restarts taking data for the integrated luminosity of 5 fb^{-1}. To the next phase, with the detector upgrades being planned for late 2011, an integrated luminosity of 20 fb^{-1} is expected. A cylindrical GEM detector [59] will be placed between the beam pipe and the inner wall of the drift chamber, as a new Inner Tracker, to improve the decay vertex resolution and to increase the acceptance for low transverse-momentum tracks.

6 Conclusions

The study of kaon physics continues to make great strides. The current program to study CP violation is being completed; the CP asymmetries in charged kaon decays have not been observed yet. The rare decays $K_L^0 \to \pi^0\nu\bar{\nu}$, $K^+ \to \pi^+\nu\bar{\nu}$ and the lepton flavor universality in $\Gamma(K^+ \to e^+\nu(\gamma))/\Gamma(K^+ \to \mu^+\nu(\gamma))$ will be measured with highly sophisticated detectors. A light neutral boson as a scalar/vector/pseudo-scalar particle was almost ruled out. CPT and QM tests will continue in a ϕ factory experiment. The kaon experiments, with ultra-high sensitivities and precisions, are essential and crucial as a probe of New Physics beyond the Standard Model.

Important topics of kaon physics: New Physics effects in ϵ_K and other meson-antimeson mixing observables [60, 61], V_{us} measurement with kaons and CKM unitarity test [62] (and the activities in the FlaviaNet Kaon Working Group [63, 64]), basic observables such as Δm, lifetimes, η_{+-}, and absolute branching ratios, radiative kaon decays, hadronic matrix elements and form factors, and $\pi\pi$ scattering (and the *cusp* effect) are not covered. The web site of the 2009 Kaon International Conference (KAON09) [65] and the Proceedings [66] would be considered as a companion to this review.

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Discussion

Cheng-Ju Lin (LBNL Berkeley): What is the plan to measure $K^+ \to \pi^+ \nu\bar{\nu}$ at J-PARC?
Answer: A Letter of Intent to measure $K^+ \to \pi^+ \nu\bar{\nu}$ with K^+ decay at rest, as in BNL E949/E787, has been submitted, but the proposal is not prepared yet. To do the measurement at J-PARC we need a low-momentum K^+ beam line with good electrostatic K^+/π^+ separation, but such a beam line is not ready.