Kaon Physics: Recent Results and Prospects

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Abstract

Selected recent results and future plans in kaon physics are reviewed. The discussed topics include CKM unitarity tests with semileptonic kaon decays, lepton flavour universality tests with purely leptonic kaon decays, and measurements of the ultra-rare $K\to\pi\nu\nu$ decays.

Introduction

Kaons, the lightest elementary particles containing the strange quark, have proved to be a copious source of information on fundamental interactions. They were essential in establishing the foundation of the Standard Model (SM); in particular the discovery of CP violation was made in the kaon system. At present, kaons provide an outstanding means of searching for new physics via precise measurements of their properties, including their rare decays. Historically manifestations of new phenomena have often been discovered at the "precision frontier" before their direct observation at the "energy frontier": a prominent example is the discovery of the third generation of quarks.

CKM unitarity tests with kaon decays

Within the SM, leptonic and semileptonic kaon decays can be used to obtain the most accurate determination of the magnitude of the Vus element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. A detailed analysis of these processes potentially also provides stringent constraints on new physics scenarios: while within the SM, all $d^i\to u^j l\nu$ transitions are ruled by the same CKM coupling V_{ji} (satisfying the unitarity condition $\Sigma_k|V_{jk}|^2=1$), and G_F is the same coupling that governs muon decay, this is not necessarily true beyond the SM. New bounds on violations of CKM unitarity and lepton universality translate into significant constraints on various new physics scenarios. Alternately, such tests may eventually provide evidence of new physics.

In the case of leptonic and semileptonic kaon decays, such tests are particularly significant given the large amounts of data collected recently by several experiments. Semileptonic decay modes are among the dominant ones for K_L and $K^\pm$; recent experiments have collected samples of $\sim10^5$ to $\sim10^7$ decays with low background contaminations of typically ~0.1%. However, K_S semileptonic decay modes are relatively rare ($BR\sim10^{-3}$), and the experimental precision is currently limited by the size of the available data samples. Importantly for the precision SM tests, substantial progress had recently been made in evaluating the corresponding hadronic matrix elements from lattice QCD, and the precise analytic calculations of radiative corrections.

The required experimental inputs for measurement of $|Vus|$ from semileptonic kaon decays are: (1) branching fractions (BR) of these decays; (2) kaon lifetimes; (3) phase space integrals computed on the basis of measurements of kinematic dependence of the form factors. There is a significant number of theoretical inputs, including (1) the form factor value at zero momentum transfer $f_+(0)$; (2) the short distance EW correction; (3) the channel-dependent isospin-breaking and long distance corrections.

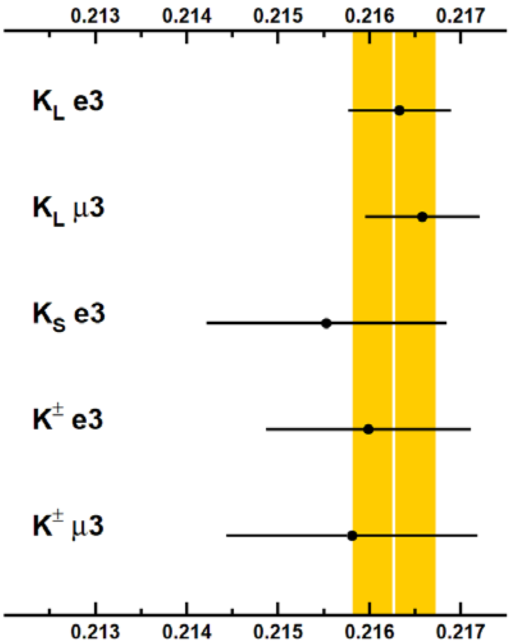

Fig. 1: *Comparison of values for* $|Vus|f_+(0)$ *measured from semileptonic kaon decay rates. The FlaviaNet average is indicated by a vertical band.*

The FlaviaNet kaon working group has recently updated a global analysis of kaon decay data [an10]. The experimental results are dominated by those from the CERN NA48, LNF KLOE, BNL E865, FNAL KTeV and IHEP ISTRA+ experiments. Fits to the world data for the dominant BRs (with the constraints $\Sigma BR_i=1$ for the sums of the major BRs) and lifetimes have been performed separately for the K_L, K_S and $K^\pm$. Combined fits to the form factor parameters have also been performed, leading to a ~0.1% precision of the phase space integrals. Special attention has been paid to treatment of the correlated errors of the results coming from the same experiment (the corresponding covariance matrices were provided by the experiments), treatment of radiative corrections, and the methods used by the experiments to estimate their systematic uncertainties.

A detailed description of the fit procedure is reported in [an10, an08]. The obtained values of BRs of the semileptonic decay modes are significantly different from those of PDG 2004, due to inclusion of many new measurements and elimination of several older results obtained neglecting radiative corrections or not reporting correlations. The values of $|Vus|f_+(0)$ extracted from each of the five measured decay modes are presented in Fig. 1. The precision of the K_L measurements is limited by the uncertainty of the K_L lifetime, while the K_S measurement is limited by the size of the data samples. For $K^\pm$, the isospin breaking corrections contribute significantly to the uncertainties. The average of the measurements in the five decay modes is $|Vus|f_+(0) = 0.2163(5)$.

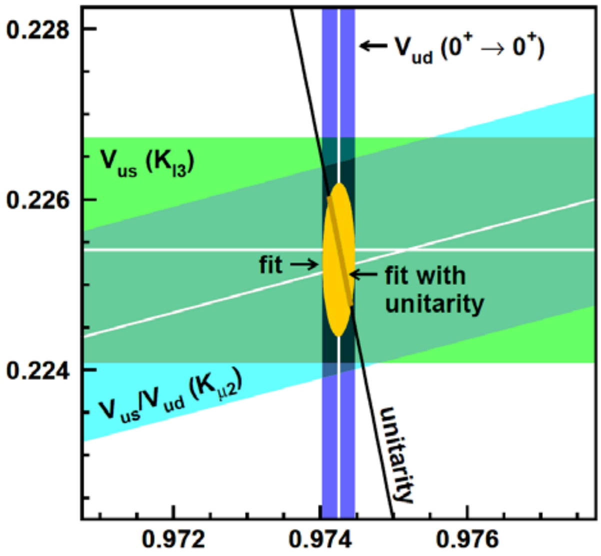

Fig. 2: *Result of FlaviaNet kaon working group fits to* $|Vus|$, $|Vud|$ *and* $|Vus|/|Vud|$.

An additional constraint on $|Vus|$ and $|Vud|$ comes from the measurements of the ratio of $K_{\mu 2}/\pi_{\mu 2}$ decay widths: $|Vus/Vud|f_K/f_\pi = 0.2758(5)$, where f_K and f_π are the pion and kaon decay constants. Finally, an independent measurement of $|Vud|$ comes from a combined analysis of superallowed $0^+\rightarrow 0^+$ nuclear beta decays [ha09]. A combined fit of all the above measurements using the values $f_+(0)=0.959(6)$, $f_K/f_\pi=1.193(6)$ obtained as averages of computations in the framework of lattice QCD leads to $|Vus|=0.2253(9)$, $|Vud| = 0.97425(22)$, as presented in Fig. 2. The quoted uncertainty on $|Vus|$ is limited mainly by the precision of the lattice QCD input.

With the above values, CKM first row unitarity holds to a level of $|Vud|^2+ |Vus|^2+|Vub|^2-1 = -0.0001(6)$, with a negligible contribution of $|Vub|$. This translates into 11 TeV upper limit for the energy scale of new physics at 90% CL [ci10].

Finally, a lepton universality test has been performed by comparison of the values of

$|V_{us}|f_+(0)$ measured separately in K_{e3} and $K_{\mu3}$ decays. The ratio of muon to electron couplings at the $W \to l\nu$ vertex has been measured to be $r_{\mu e} = 1.002(5)$, which is compatible to the SM prediction of $r_{\mu e} = 1$. The sensitivity of this test is similar to those obtained in pion and τ lepton decays.

Lepton universality tests with K_{l2} decays

The decays of pseudoscalar mesons to light leptons are suppressed in the SM by angular momentum conservation. In particular, the SM width of $P^\pm \to l^\pm\nu$ decays (with P = π, K, D_S, B) is

$$\Gamma^{SM}(P^\pm \to l^\pm\nu) = (G_F^2 M_P M_l^2/8\pi)(1-M_l^2/M_P^2)^2 f_P^2 |V_{qq'}|^2, \quad (1)$$

where G_F is the Fermi constant, M_P and M_l are the meson and lepton masses, f_P is the decay constant [ro10], and $V_{qq'}$ is the corresponding CKM matrix element.

Within the two Higgs doublet models (so called 2HDM of type II), including the minimal supersymmetric one, the charged Higgs boson ($H^\pm$) exchange induces a tree-level contribution to (semi)leptonic decays proportional to the Yukawa couplings of quarks and leptons [ho93]. In $P^\pm \to l^\pm\nu$, it can compete with the $W^\pm$ exchange due to the helicity suppression of the latter. At tree level, the $H^\pm$ exchange contribution is lepton flavour independent, and for P = π, K, B leads to [is06]

$$\Gamma(P^\pm \to l^\pm\nu)/\Gamma^{SM}(P^\pm \to l^\pm\nu) = [\,1-(M_P/M_H)^2 \tan^2\beta/(1+\varepsilon_0\tan\beta)\,]^2. \quad (2)$$

Here M_H is the $H^\pm$ mass, tanβ is the ratio of the two Higgs vacuum expectation values, and $\varepsilon_0 \approx 10^{-2}$ is an effective coupling. The contribution (2) is suppressed by approximately the quark mass ratios $(M_d/M_c) \approx 0.004$ and $(M_s/M_c) \approx 0.08$ for D and D_S mesons, respectively [ak09].

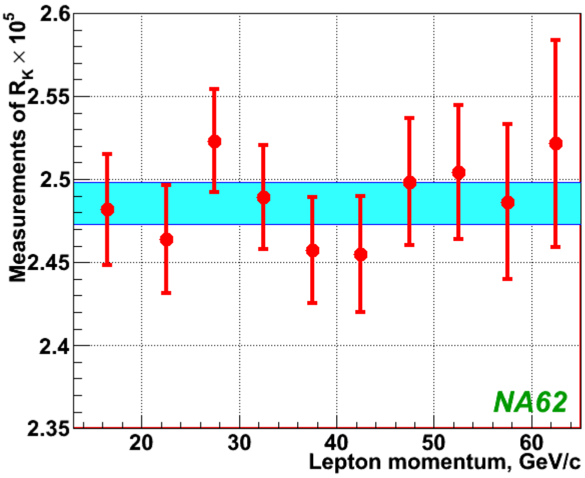

Fig. 3: *NA62 measurements of R_K in lepton momentum bins, and the averaged R_K (indicated by a band). The uncertainties in momentum bins are partially correlated, and include statistical and systematic contributions.*

A plausible choice of parameters (M_H=500 GeV/c^2, tanβ=40) leads to a ~30% relative suppression of the $B^+ \to l^+\nu$ decays, and ~0.3% suppression of the $K^+, D_S^+ \to l^+\nu$ decays with respect to their SM rates. However, searches for new physics in the decay rates are hindered by the uncertainties of their SM predictions. In particular, interpretation of the measurements of the ratio $\Gamma(K^+ \to \mu^+\nu)/\Gamma(K^+ \to \pi^0\mu^+\nu)$ of helicity suppressed to allowed decays in terms of constraints on (M_H, tanβ) phase space is currently limited by lattice QCD uncertainties [an10].

On the other hand, the ratio of kaon leptonic decay widths $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu2})$ is sensitive to lepton flavour violating (LFV) effects appearing at one-loop level via the $H^\pm$ exchange [ma06, ma08]. That provides a unique probe into mixing in the right-handed slepton sector [el09]. The dominant contribution due to the LFV coupling of the $H^\pm$ is

$$R_K^{LFV} = R_K^{SM}[1+(M_K/M_H)^4(M_\tau/M_e)^2|\Delta_{13}|^2\tan^6\beta],$$

where the mixing parameter between the superpartners of the right-handed leptons $|\Delta_{13}|$ can reach $\sim 10^{-3}$. This can enhance R_K by O(1%) relative without contradicting any presently known experimental constraints, including upper bounds on the LFV decays $\tau \to eX$ with X=η, γ, μμ.

Unlike the individual K_{l2} decay widths, the ratio $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$ is precisely predicted within the SM due to cancellation of the hadronic uncertainties [ci07]:

$$R_K^{SM} = (M_e/M_\mu)^2 (M_K^2 - M_e^2)^2/(M_K^2 + M_e^2)^2 (1 + \delta R_K^{QCD}) = (2.477 \pm 0.001) \times 10^{-5},$$

where $\delta R_K^{QCD} = (-3.79 \pm 0.04)\%$ is an electromagnetic correction due to the internal bremsstrahlung (IB) considered a part of the signal by definition. On the other hand, the structure-dependent (SD) $K^+ \to e^+ \nu\gamma$ decay is a background by definition of R_K, and is subtracted on the basis of independent measurements of its rate and form factor.

The sensitivity to LFV and the precision of the SM prediction mean that R_K, when measured to sub-percent precision, represents an excellent probe of lepton universality.

During the first phase of the NA62 experiment at CERN, a large minimum bias data sample of charged kaon ($K^\pm$) decays in flight at 74 GeV/c central momentum with 1.6 GeV/c RMS was collected in 2007, optimized for a precise R_K measurement in 2007. The NA48 experimental setup [fa07] was used. The results based on the analysis of about 40% of their data set were reported in [go10].

Almost 60k K_{e2} candidates (with the K^+ beam only) were collected with a background contamination of (8.8±0.3)%, and an excellent and well controlled positron identification efficiency of 99.3%. Lepton identification is based on the ratio E/p of energy deposition in the liquid krypton electromagnetic calorimeter, which is consistent to unity for positrons, and is

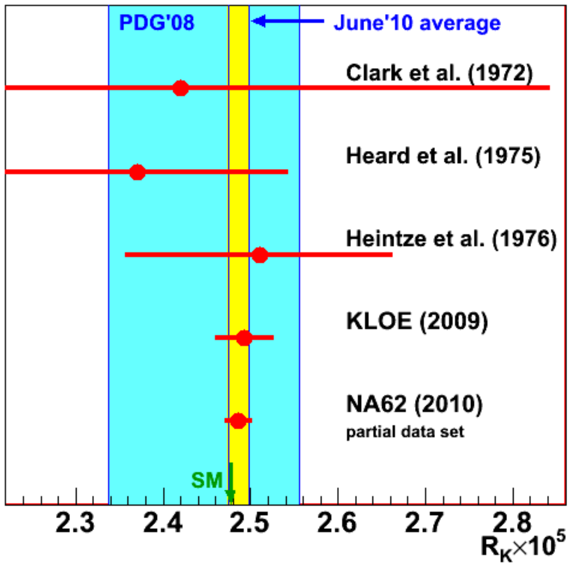

Fig. 4: *Summary of R_K measurements. The wide band represents the PDG 2008 average, while the narrow band corresponds to the 2010 average.*

much smaller (~0.1) for the muons. The principal background source in the K_{e2} sample (~6%) is the $K_{\mu 2}$ decay with the muon misidentified as a positron due to 'catastrophic bremsstrahlung', i.e. depositing over 95% of its energy in the calorimeter. The misidentification probability is $\sim 10^{-6}$, and momentum-dependent. It has been measured directly with a samples of pure muons (traversing a $9.2X_0$ thick lead bar, which suppresses the electron component), which allowed the systematic uncertainty due to $K_{\mu 2}$ background subtraction to be controlled to a 0.2% precision. Other large backgrounds (both at ~1% level) are: (1) due to the beam halo, measured with control data samples, and (2) due to the $K^+ \to e^+ \nu\gamma$ (SD) decay; a KLOE measurement [am09] has been used to subtract it. R_K was measured to a sub-percent precision for the first time: $R_K = (2.486 \pm 0.013) \times 10^{-5}$; the independent measurements in bins of lepton momentum and their average are presented in Fig. 3. The result is consistent to the SM prediction, putting constraints on the phase space of SM extension parameters.

A different, low-energy kaon approach to the R_K measurement has been pursued by the KLOE experiment at the DAFNE ϕ-factory in Frascati operating at 1.02 GeV e^+e^- energy [am09]. About 2.5 fb^{-1} of data were collected in

2001-05. Unlike NA62, a neural network with 12 input parameters is used for electron vs muon identification. About 13.8k K_{e2} candidates (of both kaon signs) were reconstructed. The background (mostly from $K_{\mu 2}$) amounted to 15%, and electron identification efficiency was ~90%. The KLOE result is $R_K = (2.493 \pm 0.031) \times 10^{-5}$, where the uncertainty is dominated by the statistical error.

A summary of the available R_K measurements is presented in Fig. 4. The recent NA62 and KLOE measurements have significantly improved the experimental precision, pushing it to the sub-percent level. The constraints on (M_H, tanβ) imposed by the world average R_K are shown in Fig. 5. The expected future improvements in R_K measurements include the analysis of the full NA62 data sample of 2007, precision measurements with the data sets to be collected by the KLOE-2 experiment at the upgraded DAFNE collider [ba10] starting in 2010, and the second phase of the NA62 experiment to be started in 2013.

Ultra-rare K→πνν decays

The K→πνν is a flavour-changing neutral current decay induced by electroweak loop effects (penguin and box diagrams). The decay is strongly suppressed in the SM and is dominated by top-quark contributions. The SM branching ratios are predicted to be $BR(K_L \to \pi^0 \nu\nu) = 2.57(37) \times 10^{-11}$ and $BR(K^+ \to \pi^+ \nu\nu) = 8.22(75) \times 10^{-11}$, where the quoted uncertainties are dominated by parametric ones, and the irreducible theoretical uncertainties are at a ~1% level [br10]. The hadronic matrix element required for the SM BR computation is extracted from the measurements of the K→πlν decays. The SM precision on these decays is exceptional, compared to other loop-induced meson decays. Theoretical cleanness and the very strong suppression of these decays mean that they play a central role in testing the SM and its extensions.

Experimentally, the existence of the two undetectable neutrinos in the final state and the extreme suppression of these decays mean

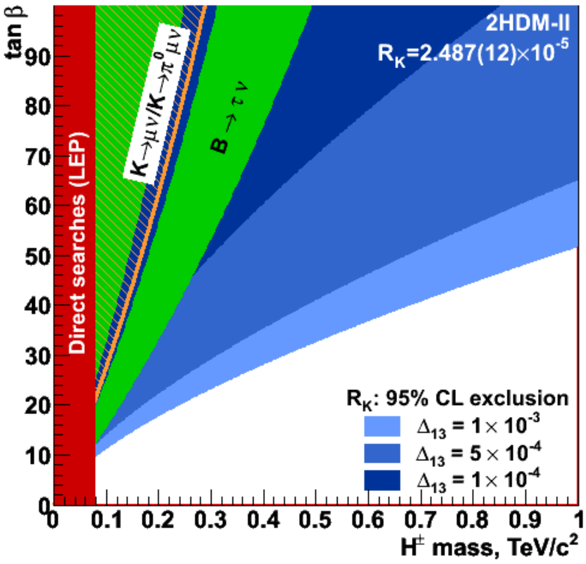

Fig. 5: *Exclusion limits in the (M_H, tanβ) parameter space derived from R_K (for various values of the mixing parameter Δ_{13}) and other measurements.*

background rejection by means of hermetic veto systems is essential.

The first observation of the $K^+ \to \pi^+ \nu\nu$ decay was performed by the Brookhaven National Laboratory E787 and E949 experiments using the stopped kaon technique [ad08, ar08, ar09]. A low energy (710 MeV/c) incident $K^\pm$ beam was slowed and stopped in a scintillating fiber target. The signal event signature consisted of an incoming $K^\pm$ and outgoing $\pi^\pm$ in the absence of any other coincident activity. The charged pion was identified by momentum, kinetic energy and range measurements in the drift chambers and range stack, and by observation of the π→μ→e decay sequence. Photons from $K^\pm \to \pi^\pm \pi^0$ and radiative kaon decays, as well as extra charged tracks, were detected by a hermetic veto system with 4π solid angle coverage. The signal region was divided into two parts in terms of π momentum, below and above the $K^+ \to \pi^+ \pi^0$ peak. Seven events were observed, with the expected background of 2.6 events, as shown in Fig. 6. The background primarily originates from the $K^\pm \to \pi^\pm \pi^0$ decays with the pion scattering in the target or the range stack, radiative $K^\pm \to \pi^\pm \pi^0 \gamma$ decays, and the K_{e4} decays. The final result is $BR = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ [ar09], which is consistent with the SM prediction. Its uncertainty is however much

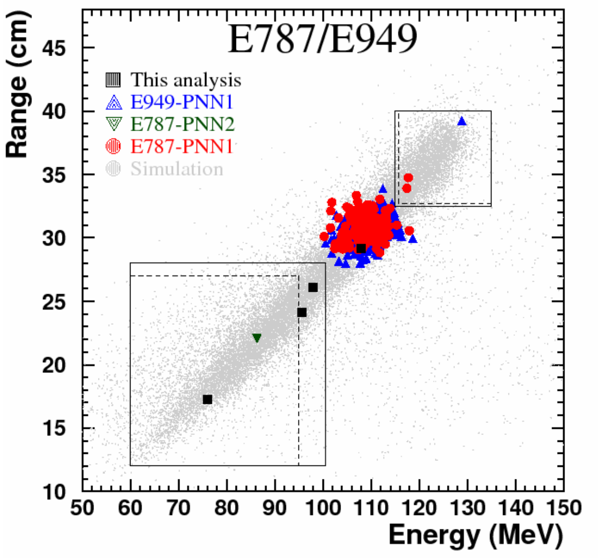

Fig. 6: *The $K^+\to\pi^+\nu\nu$ candidates collected by the BNL E787/E949 stopped kaon experiments.*

higher than that of the SM prediction. A possible future development of the stopped kaon technique is anticipated in the P996 proposal at the Fermi National Laboratory.

A forthcoming experiment aiming to measure the $K^+\to\pi^+\nu\nu$ decay rate to a ~10% relative precision by collecting ~100 decay candidates with ~10% background in two years of data taking, thus approaching the precision of the SM prediction, is the NA62 experiment at CERN [ru10] that will be housed in the North Area high intensity facility, and will be using the same SPS beam line as the preceding NA48 kaon experiments. The NA62 experiment is currently being constructed, and is expected to start physics data taking in 2013. It will use a novel decay-in-flight approach: 75 GeV/c kaons (K^+) derived from the 400 GeV/c CERN SPS protons will decay in a vacuum tank. To constrain the main backgrounds kinematically, the signal region will be divided into two by the $K^+\to\pi^+\pi^0$ peak, similarly to the BNL experiments. In order to achieve an excellent resolution on kinematical variables, pion and kaon momenta will be measured using a straw spectrometer operating in vacuum and a silicon pixel „gigatracker“ operating in a 800 MHz non-sepatared beam. The kinematic rejection power of the $K^+\to\pi^+\pi^0$ and $K^+\to\mu^+\nu$ decays will be at least 10^4, limited by non-Gaussian multiple scattering tails. Redundant particle identification (electromagnetic

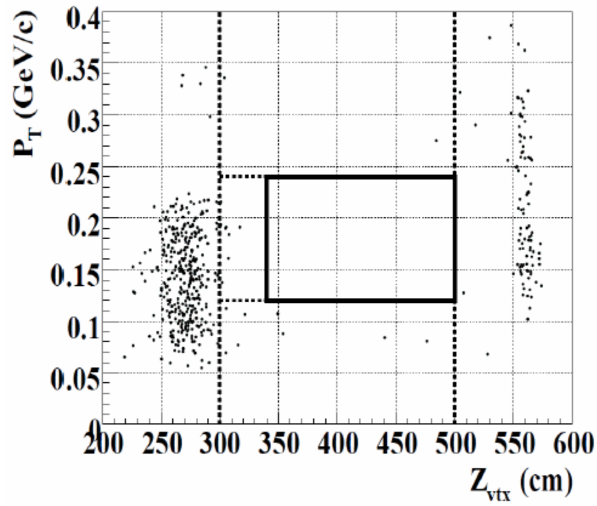

Fig. 7: *The KEK E391a final result: search for the $K_L\to\pi^0\nu\nu$ decay.*

calorimeter, RICH, muon counters) and hermetic photon veto systems will be employed.

The E391a experiment at KEK (Japan) was the first dedicated to search for the $K_L\to\pi^0\nu\nu$ decay. A „pencil“ (i.e. small cross-section) neutral beam with the energy peaking at 2 GeV was derived from the KEK-PS proton beam. The photons from the π^0 decays were measured by a calorimeter; the decay volume was surrounded by a veto counter system, which, together with the calorimeter, was crucial for suppression of the major $K_L\to\pi^0\pi^0$ background. The signal signature represented a single π^0 with a high transverse momentum (>120 MeV/c) originating from the fiducial decay volume. The beamline was optimised to suppress the neutron halo of the beam, which generated backgrounds through π^0 and η production by interaction with the detector elements. As demonstrated in Fig. 7, the final E391a upper limit based on the 2005 data set is $BR(K_L\to\pi^0\nu\nu) < 2.6\times10^{-8}$ at 90% CL, corresponding to zero observed events in the signal region with an expected background of (0.87 ± 0.41) events dominated by beam interactions [ah10]. While being a significant improvement over the previous measurements, this limit is still above the Grossman-Nir bound [gr97]. The E391a experiment is thus seen as preparation to the next stage of $BR(K_L\to\pi^0\nu\nu)$ measurements.

The next experiment aiming at BR($K_L \to \pi^0 \nu\nu$) is the E14 (KOTO) at J-PARC [na09]. It will use a new kaon beam derived from a high intensity proton accelerator facility. The beamline has been specifically designed for the suppression of the beam halo background (reaching a level of ~10^{-3} halo neutrons per K_L). The experimnent will use an upgraded E391a detector; in particular, a CsI calorimiter built using the KTeV crystals will be used. E14 is expected to improve the E391a single event sensitivity by a factor of ~3000, and aims at collecting 2.7 SM $K_L \to \pi^0 \nu\nu$ events with 2.1 expected background events in three years of data taking starting in 2011.

Conclusions

Kaon physics is continuing to make significant advances. Tremendous progress was achieved recently in measurements and interpretation of semileptonic kaon decays: CKM unitarity with $|Vud|^2+|Vus|^2$ has been tested to 0.06% precision, placing an O(10 TeV) bound on the scale of new physics. Precision measurements of the leptonic decays $K \to l\nu$ are placing non-trivial bounds on the 2HDM parameters. Finally, new experimental challenges are being addressed in the field of ultra-rare $K_L \to \pi^0 \nu\nu$ decay measurements. The upcoming high precision kaon experiments will be essential in probing new physics beyond the Standard Model.

This mini-review includes selected topics only. Several other aspects of kaon physics are not covered, including tests of the Chiral Perturbation Theory through radiative kaon decay rate measurements; measurement of pion scattering lengths in $K_{3\pi}$ and K_{e4} decays; future plans at FNAL and IHEP Protvino, KLOE-2 at Frascati and TREK at J-PARC.

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