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Kaon physics

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Summary. — Kaon physics can test new-physics effects in leptonic or semileptonic decays. A unitarity test of the first row of the CKM mixing matrix is obtained from the precision measurements of $K_{\ell 3}$ widths for $K^{\pm}$, K_L, and K_S. The measurement of $R_K = \Gamma(K^+ \to e^+\nu)/\Gamma(K^+ \to \mu^+\nu)$ with an accuracy at the % level, aims at finding evidence of deviations from the SM prediction induced by lepton-flavor violation new-physics effects.

PACS `13.20.Eb` – Decays of K mesons.
PACS `12.15.Hh` – Determination of Cabibbo-Kobayashi & Maskawa (CKM) matrix elements.

1. – Introduction

Purely leptonic and semileptonic decays of K mesons ($K \to \ell\nu, K \to \pi\ell\nu$, $\ell = e, \mu$) are mediated in the Standard Model (SM) by tree-level W-boson exchange. Gauge coupling universality and three-generation quark mixing imply that semileptonic processes such as $d^i \to u^j \ell\nu$ are governed by the effective Fermi constant $G_{ij} = G_\mu V_{ij}$, where G_μ is the muon decay constant and V_{ij} are the elements of the unitary Cabibbo-Kobayashi Maskawa (CKM) matrix. This fact has simple but deep consequences, that go under the name of universality relations. In the SM the effective semileptonic constant G_{ij} does not depend on the lepton flavor. If one extracts V_{ij} from different semileptonic transitions assuming quark-lepton gauge universality (*i.e.* normalizing the decay rates with G_μ), the CKM unitarity condition $\sum_j |V_{ij}|^2 = 1$ should be verified.

Beyond the SM, these universality relations can be violated by new contributions to the low-energy $V - A$ four-fermion operators, as well as new non $V - A$ structures. Therefore, precision tests of the universality relations probe physics beyond the SM and are sensitive to several SM extensions [1-4].

2. – Measurement of V_{us}

Large amount of data has been collected on the semileptonic modes $K \to \pi\ell\nu$ by several experiments, BNL-E865, KLOE, KTeV, ISTRA+, and NA48, in the last few years. These data have stimulated a substantial progress on the theoretical inputs, so that most of the theory-dominated errors associated to radiative corrections and hadronic form factors have been reduced below 1%. Presently, the unitarity test $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2 =$

TABLE I. – *Values of* $|V_{us}|f_+(0)$ *extracted from* $K_{\ell 3}$ *decay rates.*

K_Le3	$K_L\mu3$	K_Se3	$K^{\pm}e3$	$K^{\pm}\mu3$
0.2163(6)	0.2166(6)	0.2155(13)	0.2160(11)	0.2158(14)

$1+\Delta_{\text{CKM}}$ implies that Δ_{CKM} is consistent with zero at the level of 6×10^{-4}. V_{us} from $K\to\pi\ell\nu$ decays contributes about half of this uncertainty, mostly coming from the hadronic matrix element. Both experimental and theoretical progress in $K_{\ell 3}$ decays will be needed in order to improve the accuracy on Δ_{CKM} in the future. It has been shown [4] that presently semileptonic processes and the related universality tests provide constraints on NP that cannot be obtained from other electroweak precision tests and/or direct measurements at the colliders.

In the last years, many efforts have been dedicated to the correct averaging of the rich harvest of recent results in kaon physics. The FlaviaNet kaon working group has published a comprehensive review [5] in 2008 where a detailed description of the averaging procedure can be found. However, the significant progress on both the experimental and theoretical sides, has motivated the same group to publish an updated analysis [6]. All the V_{us}-related results presented refer to the FlaviaNet working group outcomes. Many experiments have been performed to precisely measure many K decay parameters. Branching ratios for main, subdominant and rare decays, lifetimes, parameters of decay densities and charge asymmetries have been measured with unprecedented accuracy for K_S, K_L and $K^{\pm}$. Different techniques have been used, often allowing careful checks of the results from experiments with independent sources of systematic errors. The values of $|V_{us}|f_+(0)$ obtained from the world average of K semileptonic measurements [6] are shown in table I.

The five decay modes agree well within the errors and average to $|V_{us}|f_+(0) = 0.2163(5)$, with $\chi^2/\text{ndf} = 0.77/4$ (Prob = 94%). Significant lepton-universality tests are provided by the comparison of the results from different leptonic channels. Defining the ratio $r_{\mu e} = |V_{us}|f_+(0)^2_{\mu3}/|V_{us}|f_+(0)^2_{e3}$ we have $r_{\mu e} = g^2_\mu/g^2_e$, with g_ℓ the coupling strength at the $W\to\ell\nu$ vertex. Lepton universality can be then tested comparing the measured value of $r_{\mu e}$ with the SM prediction $r^{SM}_{\mu e}=1$. Averaging charged- and neutral-kaon modes, we obtain $r_{\mu e} = 1.002(5)$, to be compared with the results from leptonic pion decays, $(r_{\mu e})_\pi = 1.0042(33)$ [7], and from leptonic τ decays $(r_{\mu e})_\tau = 1.000(4)$ [8].

Using the determination of $|V_{us}|f_+(0)$ from $K_{\ell 3}$ decays and the value $f_+(0) = 0.959(5)$ (see ref. [6] for a detailed discussion on this choice), we get $|V_{us}| = 0.2254(13)$. Furthermore, a measurement of $|V_{us}|/|V_{ud}|$ can be obtained from the comparison of the radiation-inclusive decay rates of $K^{\pm}\to\mu^{\pm}\nu(\gamma)$ and $\pi^{\pm}\to\mu^{\pm}\nu(\gamma)$, combined with lattice calculation of f_K/f_π [9]. Using the BR($K^{\pm}\to\mu^{\pm}\nu$) average value (dominated by KLOE result [10]) and the lattice result $f_K/f_\pi = 1.193(6)$ (again see ref. [6] for a detailed discussion on this choice), we get $|V_{us}|/|V_{ud}| = 0.2312(13)$. This value can be used in a fit together with the measurements of $|V_{us}|$ from $K_{\ell 3}$ decays and $|V_{ud}| = 0.97425(22)$ [11] from superallowed nuclear β decays. The result of this fit is $|V_{ud}| = 0.97425(22)$ and $|V_{us}| = 0.2253(9)$, with $\chi^2/\text{ndf} = 0.014/1$ (Prob = 91%), from which we get $1-(|V_{ud}|^2+|V_{us}|^2+|V_{\text{ub}}|^2) = -0.0001(6)$ which is in striking agreement with the unitarity hypothesis. Using these results, we evaluate $G_{\text{CKM}} = G_\mu\sqrt{|V_{ud}|^2+|V_{us}|^2+|V_{\text{ub}}|^2} = 1.16633(35)\times10^{-5}\,\text{GeV}^{-2}$, with $G_\mu = 1.166371(6)\times10^{-5}\,\text{GeV}^{-2}$. At present, the sensitivity of the quark-lepton universality test through the G_{CKM} measurement is competitive and even better than the measurements from τ decays and the electroweak precision tests [12]. Thus unitarity can also be interpreted as a test of the universality of lepton and quark weak couplings to the W-boson, allowing bounds to be set on extensions of the SM leading to some kind of universality breaking. For instance, the existence of additional Z' gauge bosons, giving different loop-contributions to muon and semileptonic decays, can break gauge universality [1]. The measurement of G_{CKM} can set constraints on the Z' mass which are competitive with direct search at the colliders. When considering supersymmetric extensions, differences between muon and semileptonic decays can arise in the loop contributions from SUSY particles [2, 3]. The slepton-squark mass difference could be investigated improving present accuracy on the unitarity relation by a factor of ∼ 2–3.

3. – Measurement of $R_K = \Gamma(Ke2)/\Gamma(K\mu 2)$

The SM prediction of R_K benefits from cancellation of hadronic uncertainties to a large extent and therefore can be calculated with high precision. Including radiative corrections, the total uncertainty is less than 0.5 per mil [1, 13]: $R_K = (2.477 \pm 0.001) \times 10^{-5}$. Since the electronic channel is helicity-suppressed by the $V - A$ structure of the charged weak current, R_K can receive contributions from physics beyond the SM, for example from multi-Higgs effects inducing an effective pseudoscalar interaction. It has been shown in ref. [14] that deviations from the SM of up to few percent on R_K are quite possible in minimal supersymmetric extensions of the SM and in particular should be dominated by lepton-flavor–violating contributions with tauonic neutrinos emitted in the electron channel:

$$R_K = R_K^{SM} \times \left[1 + \frac{m_K^4}{m_H^4}\frac{m_\tau^2}{m_e^2}|\Delta_R^{31}|^2 \tan^6\beta\right], \tag{1}$$

where M_H is the charged Higgs mass, Δ_R^{31} is the effective e-τ coupling constant depending on MSSM parameters, and $\tan\beta$ is the ratio of the two vacuum expectation values. Note that the pseudoscalar constant f_K cancels in R_K^{SM}. In order to compare with the SM prediction at this level of accuracy, one has to treat carefully the effect of radiative corrections, which contribute to nearly half the $K_{e2\gamma}$ width. In particular, the SM prediction is made considering all photons emitted by the process of internal bremsstrahlung (IB) while ignoring any contribution from structure-dependent direct emission (DE). Of course both processes contribute, so in the analysis DE is considered as a background which can be distinguished from the IB width by means of a different photon energy spectrum.

The NA48 Collaboration presented two preliminary results for R_K (2003 and 2004 data samples): the fractional statistical error due to Ke2 counts is 1.85%, while the systematic error due to background subtraction is 1.59%. For these reasons, the NA48 experimental setup has been optimized by the NA62 Collaboration for the purpose of a new dedicated data taking during 2007. The data taking lasted for 4 months, and allowed NA62 to acquire the largest Ke2 sample in the world, amounting to more than 10^5 events. The preliminary result [15] of the analysis of a partial data sample of 51089 $K^+ \to e^+\nu$ candidates, is $R_K = (2.500 \pm 0.016) \times 10^{-5}$ consistent with the SM expectation.

Using the present KLOE dataset collected at the ϕ peak, and corresponding to ∼ 3.6 billion K^+K^- pairs, a measurement of R_K with an accuracy of about 1% has been

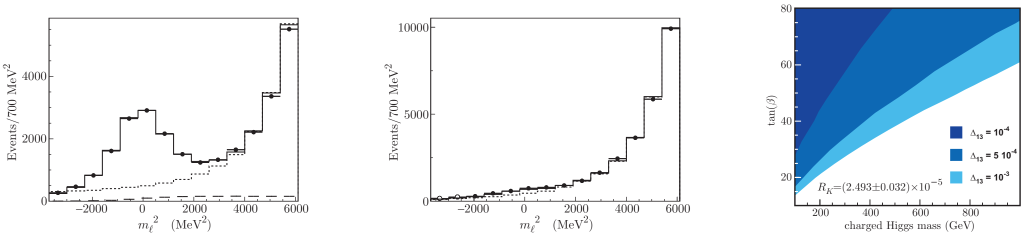

Fig. 1. – Fit projections onto the m_ℓ^2 axis for $NN > 0.98$ (left) and $NN < 0.98$ (center), for data (black dots), MC fit (solid line), and $K_{\mu 2}$ background (dotted line). The contribution from K_{e2} events with $E_\gamma > 10\,\text{MeV}$ is visible in the left panel (dashed line). Right: Excluded regions at 95% CL in the plane M_H–$\tan\beta$ for $\Delta_R^{31} = 10^{-4}, 5 \times 10^{-3}, 10^{-3}$.

performed. ϕ-mesons are produced, essentially at rest and decay into K^+K^- pairs with a BR of $\sim 49\%$. Kaons get a momentum of $\sim 100\,\text{MeV}$ which translates into a low speed, $\beta_K \sim 0.2$. Since the wanted observable is a ratio of BRs for two channels with similar topology and kinematics, one expects to benefit from some cancellation of the uncertainties on tracking, vertexing, and kinematic identification efficiencies. Small deviations in the efficiency due to the different masses of e's and μ's have been evaluated using MC. A powerful kinematic variable used to distinguish $K \to e\nu$ and $K \to \mu\nu$ decays from the background is calculated from the track momenta of the kaon and the secondary particle: assuming $m_\nu = 0$, the squared mass of the secondary particle (m_ℓ^2) is evaluated. The selection applied is enough for clean identification of a $K \to \mu\nu$ sample, while further rejection is needed in order to identify $K \to e\nu$ events: the background, which is dominated by badly reconstructed $K \to \mu\nu$ events, is ∼10 times more frequent than the signal in the region around m_e^2. Information from the e.m. calorimeter is used to improve background rejection, training a neural network (NN) on $K_L \to \pi l \nu$ data. Additional separation has been obtained using time of flight information. The number of $K \to e\nu(\gamma)$ is determined with a binned likelihood fit to the two-dimensional NN *vs.* m_ℓ^2 distribution. In the fit region, a small fraction of $K \to e\nu(\gamma)$ events is due to the direct-emission structure-dependent component (DE): the value of this contamination, f_{DE}, is fixed in the fit to the expectation from simulation. This assumption has been evaluated by performing a dedicated measurement of DE, which yielded as a by-product a determination of f_{DE} with a 4% accuracy [16]. This implies a systematic error on Ke2 counts of 0.2%, as obtained by repeating the fit with values of f_{DE} varied within its uncertainty. In the fit region, KLOE counts 7064 ± 102 $K^+ \to e^+\nu(\gamma)$ and 6750 ± 101 $K^- \to e^-\nu(\gamma)$ events. Figure 1 shows the sum of fit results for K^+ and K^- projected onto the m_ℓ^2 axis in a signal ($NN > 0.98$) and a background ($NN < 0.98$) enhanced region.

The KLOE final result is $R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$ [16]. The 1.1% fractional statistical error has contributions from signal count fluctuation (0.85%) and background subtraction. The 0.8% systematic error has a relevant contribution (0.6%) from the statistics of the control samples used to evaluate corrections to the MC. Including the new KLOE result, the world average reaches an accuracy at the % level: $R_K = 2.468(25) \times 10^{-5}$. In the framework of MSSM with LFV couplings, the R_K value can be used to set constraints in the space of relevant parameters (see eq. (1)). The regions excluded at 95% CL in the plane $\tan\beta$-charged-Higgs mass are shown in the right panel of fig. 1 for different values of the effective LFV coupling Δ_R^{31}.

4. – Conclusions

The experimental precision in leptonic and semileptonic kaon decays is nicely matched below the percent level by theoretical precision, allowing to perform very precise measurements of SM parameters and to set stringent bounds on physics beyond the SM. R_K present world average allows severe constraints to be set on new-physics contributions in the MSSM with lepton flavor violating couplings.

Future experiments aim to perform precise measurements of rare kaon decays, in particular there are experimental programs designed to gain new insight on the Unitarity Triangle and on the CKM mechanism by observing $K \to \pi\nu\bar{\nu}$ events. This rare process, BR $\sim 10^{10}$, is computed with very small theoretical errors, providing one of the cleanest tests of the SM and, possibly, it could give some hints on the flavour structure of new physics. For the neutral mode, the E391a experiment at KEK published recently the upper limit $\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) < 2.6\times10^{-8}$. A future project is the KOTO experiment [17] under construction at JPARC, which aims at the observation of the $K_L \to \pi^0\nu\bar{\nu}$ process. For charged mode, the E494 experiment at BNL observed 4 events, which combined with the previuos E787 result, give $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} \times 10^{-10}$, consistent with the SM expectation. The NA62 [18] experiment under construction at CERN aims at observing an hundred of events of the $K^+ \to \pi^+\nu\bar{\nu}$ decay. A target accuracy of order 10% should be reached, thus making experiments in this field very challenging projects, expecially with respect to backgrounds suppression, particle identification capabilities and detector efficiency.

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