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The “wrong flavor” - topics on Kaon physics

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Kaon physics has played a key role in the shaping of the Standard Model, from the discovery of kaons until today and, even in the “B physics age”, it continues to be a good playground to investigate flavour dynamics and constrain physics beyond the Standard Model.

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Does the kaon really have the "wrong flavor" for this conference? Probably not. Kaon decays have played a key role in the shaping of the Standard Model (SM), from the discovery of kaons until today. Outstanding examples are the introduction of strangeness, the quark mixing, the discovery of *CP* violation, the suppression of flavour changing neutral currents and the GIM mechanism, etc.. Kaon decays continue nowadays to have an important impact on flavour dynamics to constrain physics beyond the SM. They involve an intricate interplay between weak, electromagnetic and strong interactions, and give rise to major theoretical challenges, given the intrinsically non perturbative nature of the strong interactions in kaon physics.

Recently, many good reviews of kaon physics have become available. Ref. [1] provides a theoretical comprehensive survey of kaon decays allowed in the SM, with branching fractions down to 10^{-11}, while from the experimental side, Ref. [2] is a rich source of information, to a large extent complementary to the present paper.

I will briefly present the new limit settled by KLOE on the branching fraction of the $K_S \to 3\pi^0$ decay, and the state-of-the-art of $R_K = \Gamma(K^{\pm}_{e2})/\Gamma(K^{\pm}_{\mu 2})$ by the KLOE, NA62, and TREK experiments. Then I will describe the long quest of the $K \to \pi\nu\bar{\nu}$ decay, both for the charged and the neutral modes, by the NA62, ORKA, and K0TO experiments, and I will conclude with a synthesis of the V_{us} determination, mainly from the outcome of Working Group I at the last CKM workshop.

In the SM, *CP* violation is described by the CKM mechanism. *CP* violation in the mixing (parameterized by the parameter ε) has been measured since the 60's, while direct *CP* violation (parameterized by ε') had to wait by the end of the 90's, when ε'/ε was measured owing to the efforts of the KTeV and NA48 experiments. Their legacy is the first confirmation of the CKM picture of *CP* violation, with ε'/ε and ε_K measured with good accuracy. Even if measurements in the kaon sector are reasonably precise, the impact of ε_K on unitarity triangle fits is not that impressive. In order to improve the situation, according to the lattice breakthrough claimed by the RBC and UKQCD collaborations [3] — "we anticipate that a complete calculation of *CP* violation in $K\pi\pi$ decay within the SM will be achieved before the fiftieth anniversary of its original discovery" — we have to wait until next year to know if kaons can really have a large impact on the knowledge of the unitarity triangle, before results from the search of the $K \to \pi\nu\bar{\nu}$ decays will become available.

Due to lack of statistics, the KLOE experiment at DAΦNE missed to measure ε'/ε. However, in addition to a large harvest of results in kaon and light meson physics, it succeeded in giving its contribution also to the study of *CP* violation in the kaon system. The $K_S \to 3\pi^0$ is pure $CP = -1$ state, and in the SM its branching fraction is expected to be 1.9×10^{-9}. The observation of K_S decaying into $3\pi^0$ is an unambiguous sign of *CP* violation in the mixing and/or in the decay. The existing upper limit on the branching ratio of this channel was dominated by KLOE itself, with a 1.2×10^{-7}. Recently, KLOE completed the analysis of its whole 2.5 fb^{-1} data sample, and published a new limit of 2.6×10^{-8} at 90% C.L. [4]. The observation of this decay should be feasibile in the near future at KLOE-2 (the successor of KLOE), assuming the validity of the SM prediction, owing to the new inner tracker and to the new forward calorimeters, with a better coverage around the interaction point.

Complementary to *CP* violation is the measurement of *T* violation, at the Japan Proton Accelerator Research Complex (J-PARC). Its hadron hall has three kaon lines, devoted to HEP experiments. J-PARC suffered for some damages from the 2011 earthquake, but they have been able to recover very quickly and the plans have been delayed of only about one year. One of the experiments planned at J-PARC to measure T violation is TREK (Time Reversal Experiment with Kaons, E06) [5]. This follows an original proposal by J. J. Sakuray [6]: in $K^+\mu 3$ decays, the transverse muon polarization (P_T) is null to first order, while higher order loop effects are at the 10^{-6} level. A non-zero P_T is a clear sign of T violation, but also an excellent probe for physics beyond the SM, with many existing models allowing for sizeable P_T. The data taking is foreseen to start in 2016, with a detector realized as an upgrade of the earlier E246 KEK experiment, which set the limit $P_T = -0.0017 \pm 0.0023_{\rm STAT} \pm 0.0017_{\rm SYST}$ [7]. The TREK experiment is aiming at a sensitivity of 10^{-4}.

Waiting for the measurement of T-violation, the TREK collaboration started a parallel effort to measure $R_K = \Gamma(K^{\pm}_{e2})/\Gamma(K^{\pm}_{\mu 2})$. In the last years this quantity received a lot of attention because of its 0.4 per mil accuracy in the SM prediction [8]. As in any very suppressed decay, non-SM physics can show up and lepton flavour violation could give rise to deviations from the SM at the percent level, depending on the effective $e\nu_\tau$ coupling [9]. Before the new measurements of R_K done in the last decade, the experimental accuracy was only at the 5% level.

The first experiment which completed, in 2009, a modern measurement of R_K was KLOE, analyzing its whole data sample. KLOE recorded about 14×10^3 K_{e2} events with 16% of background, and measured $R_K = 2.493 \pm 0.0025_{\rm STAT} \pm 0.0019_{\rm SYST} \times 10^{-5}$ [10]. The overall precision is 1.3%, dominated by the statistical contribution. Unfortunately, no more data have been collected from 2006 until now by KLOE.

The second actor of the modern R_K determination is the NA62 experiment. Even if with a long history behind — it has the legacy of the NA48 experiments — NA62 is to some extent a brand new collaboration, born in 2007. They aim at measuring the charged mode of the $K \to \pi\nu\bar{\nu}$ decay, but waiting for the construction and the installation of the new detector, they produced the most accurate measurement of R_K. Running at the SPS at CERN with a 75 GeV proton beam, they found 146×10^3 candidates, leading to a 3 per mil statistical and a similar systematic uncertainty $R_K = 2.488 \pm 0.0007_{\rm STAT} \pm 0.0007_{\rm SYST} \times 10^{-5}$ [11]. The present world average has a 0.4% precision, dominated by the NA62 measurement. It allows to exclude different regions (depending on the $e\nu_\tau$ coupling) in the $tg\beta$ Higgs-mass plane, with information complementary to that coming from other decays.

In the near future, R_K will be determined again by the TREK collaboration, owing to the E36 project, using a subset of the future TREK detector. They aim at a 2 per mil accuracy on both statistical and systematic uncertainties, and have a quite aggressive schedule with the final assembly in 2014 and the data taking lasting from fall 2014 until spring 2015, even if they "remain interested in executing E06 if the accelerator beam power will be growing faster" [12].

But the "holy grail" for the kaon physics today is the rare $K \to \pi\nu\bar{\nu}$ decay. The kaon system is theoretically very clean with few decay channels. The extreme hard-GIM and SM-suppressed FCNC decays give room for non-SM physics up to ten times the SM predictions. The $K \to \pi\nu\bar{\nu}$ has a unique sensitivity to flavor couplings on physics beyond the SM, at the scale of energy of the LHC, or even up to extremely high scales in the unfortunate case that no new effects show up at the LHC. A 10% precision in the measurement of the $K \to \pi\nu\bar{\nu}$ branching fraction can probe a new physics scale of 1000 TeV. For both the charged and the neutral modes, the $K \to \pi\nu\bar{\nu}$ SM prediction is quite accurate, to a large extent due to the fact that the hadronic matrix element for the decay can be obtained from the experimentally determined rate for K_{e3} decays BR($K^{\pm} \to \pi^{\pm}\nu\bar{\nu} =$

$(7.8 \pm 0.8) \times 10^{11}$) and BR($K_L \to \pi^0 \nu\bar{\nu} = (2.4 \pm 0.4) \times 10^{11}$) [13]. The achieved precisions are about 16% for the K_L and 10% for the $K^{\pm}$, both dominated by the V_{cb} contribution.

The values of the $K \to \pi\nu\bar{\nu}$ branching fractions, together with the ε_K value to solve the sign ambiguity, can completely determine the apex of the unitarity triangle. The present knowledge does not put any constraint in the apex, while a 10% determination of the charged mode plus a 15% determination of the neutral mode would start to provide interesting information, complementary to those from other decays. Moreover, new physics may affect branching ratios in a different way for different channels, and multiple measurements can discriminate among various scenarios. The long quest to observe the $K \to \pi\nu\bar{\nu}$ started in the 70's for the charged mode and in the 90's for the neutral mode. For the latter, the search still continues today, while for the charged mode a few $K^{\pm} \to \pi^{\pm}\nu\bar{\nu}$ events have been observed by the E787 and E949 [14, 15] experiments at BNL. Their combined data lead to a branching ratio that is compatible with the SM, but has still an error that is too large to provide a very stringent test of the model. In the near future, the NA62 and, probably, the ORKA experiments will dominate the scene. The signature for the $K^{\pm} \to \pi^{\pm}\nu\bar{\nu}$ decay mode is a K track in a π track out, with nothing more. NA62 at CERN aims at finding 100 signal events in order to measure the branching fraction with a 10% accuracy. The current status of the NA62 installation is summarized in [16]. The basic infrastructure of the NA62 experiment is inherited from NA48, including some of the beamline elements, most of the vacuum tanks, and most importantly, the LKr calorimeter, which will be used as a high-performance veto for the "harmful" forward photons. Most of the other detectors are either new or have been rebuilt. NA62 is expected to begin running in late 2014 (depending on SPS schedule) for two years. They use kaons in flight and plan to collect about 10^{13} kaons inside the fiducial volume. This large amount of data and the robust background rejection, together with a precise tracking system, great particle identification capabilities and hermetic photon vetoes, are the defining features of NA62.

In the $K^{\pm} \to \pi^{\pm}\nu\bar{\nu}$ determination, a new actor has recently entered the scene: the ORKA experiment (P966 FNAL proposal) [17]. They self dubbed ORKA as "the golden kaon experiment", aiming at a precision measurement of the $K^{\pm} \to \pi^{\pm}\nu\bar{\nu}$ branching fraction. To achieve its goal, ORKA will apply the method and the techniques that were demonstrated in the two BNL experiments, E878 and E949: kaons stopped in an active target plus a redundant pion identification via the reconstruction of the whole $\pi \to \mu \to e$ decay chain. It does not require better background rejection than E949 itself achieved. ORKA will use existing facilities at Fermilab and the entire detector will fit within the CDF tracking volume. The collaboration expects to begin construction in 2014 and to start collecting $K^{\pm} \to \pi^{\pm}\nu\bar{\nu}$ decays in 2017. First physics results should come in 2020, aiming at reducing the experimental error down to the size of theoretical uncertainty.

But the hardest job remains the observation of the $K_L \to \pi^0\nu\bar{\nu}$ decay, as to say nothing going to nothing. The K0TO experiment [18] (E14) plans to capture 100 events at the SM branching ratio, achieving a 5% measurement, using the 30 GeV beamline at J-PARC. K0TO is a large-acceptance detector with a small hole to allow the pencil K_L beam to pass through. It covers the decay region with hermetic and very efficient photon veto counters, profiting from and extending all the methods developed for KEK E391a [19]. They require events to have only two photons with π^0 invariant mass and large $p_T(\pi^0)$, corresponding to the momentum carried by the neutrinos. Projecting back from the photon hit positions towards the beam line, the K_L position in the decay region can be determined. For the rest, they have to "eliminate, eliminate, and eliminate" backgrounds and unwanted events.

To reach the SM level, the sensitivity of K0TO must be more than 1000 times better than that of E391a. But already with a 20-100 times improvement, K0TO could observe non-SM effects, if they exist. Having recovered quickly the earthquake damages, K0TO had a short physics run in March 2013, and in May the long physics run started with the goal of collecting enough data to reach the Grossman-Nir limit [20], i.e. the "experimental" upper bound set on the $K \to \pi\nu\bar{\nu}$ neutral mode by the measurement of the branching fraction of the charged mode. The final sensitivity is expected to reach the SM prediction (∼3 SM events). Further plans are now under discussion at KEK, for a K0TO-step2 phase [21] with a sensitivity goal of 10^{-13} (∼100 SM events).

The last part of this paper summarizes the kaon physics contribution to the knowledge of the CKM matrix, in particular its first row, from which the most stringent test of the CKM unitarity is obtained, using the relation $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \Delta_{CKM}$. The bounds on violations of the CKM unitarity translate into significant constraints on various new physics scenarios, and such tests may eventually turn up evidence of new physics. The actual limit of the unitarity condition is $\Delta_{CKM} = -0.0001(6)$, while in 2010 the same was $\Delta_{CKM,2010} = +0.0001(6)$. Despite the only difference of a sign, and with an absolute change of the value of one third of the accuracy, a lot of work has been done in the last two years to improve the knowledge of all the contributions to this stringent bound, and more is expected in the next years.

The best determination of $|V_{us}|$ arises from the study of $K_{\ell 3}$ and $K_{\ell 2}$ decays, see e.g. the accurate review prepared in 2010 by the FlaviaNet kaon working group [22]. During the last years there have been a few significant new measurements and some important theoretical developments. The experimental inputs for the determination of $|V_{us}|$ from $K_{\ell 3}$ decays are the rates and form factors for the decays of both charged and neutral kaons. There have been no new branching ratio measurements since the 2010 review. On the other hand, both the KLOE and KTeV collaborations have new measurements of the K_S lifetime [23, 24]. Finally, the NA48/2 experiment has recently obtained preliminary results for the form factors for charged kaon decays. The latter is important because it helps to resolve a controversy: the older measurements of the $K_{\mu 3}$ form factors for K_L decays from NA48 are in such strong disagreement with the other existing measurements, that they have been excluded from the FlaviaNet averages. The new NA48/2 measurements, on the other hand, are in good agreement with other measurements. For all of the above efforts, however, the value of and uncertainty on $|V_{us} f_+(0)|$ are essentially unchanged. This is because the new results are nicely consistent with the older averages, and neither the K_S lifetime nor the phase space integrals were significant contributors to the overall experimental uncertainty. The latter is dominated by the lifetime accuracy for the K_L and by the branching ratio for the K_S and $K^\pm$ determinations. Unfortunately, in the near future there are no kaon experiments planning new branching ratio or lifetime measurements. For the $K^\pm$, also the uncertainty on the theoretical isospin-breaking correction gives large contributions to the $|V_{us} f_+(0)|$ uncertainty. On a general ground, advances in algorithmic sophistication and computing power are leading to more and better lattice QCD estimates of the hadronic constants $f_+(0)$ and f_K/f_π, which enter the determination of $|V_{us}|$ from K_{l3} and $K_{\mu 2}$ decays, respectively. Due to their non-perturbative nature, the only way to improve their knowledge is by means of lattice QCD simulations. Since the ultimate goal is a test of the SM, any model-dependence should be avoided, and this is where progress in lattice simulations is currently being made. In addition, two groups working on the classification and averaging of results from lattice QCD have joined their efforts, constituting the newly formed Flavour Lattice Average Group (FLAG-2) to provide recommended values of these constants.

The current precision already allows us to put significant constraints on new physics. Through an effective field theory approach, and assuming flavor blind new physics interactions, it has been demonstrated [25] that Δ_{CKM} receives contributions from four short distance operators. Bounds on violations of CKM unitarity translate into significant constraints on various new physics scenarios. Such tests may eventually show up evidence of new physics. The present measurement of Δ_{CKM} provides strong constraints on all four operators, corresponding to an effective scale $\Lambda > 11$ TeV (at 90% C.L.). Depending on the operator, this constraint is at the same level or stronger than that generated by the electroweak observables.

In conclusion, all kaon measurements are currently in agreement with the SM, providing information complementary to the LHC. After 67 years of honorable service to physics, kaons are still active as ever in offering new ways to explore the mysteries of the flavour sector.

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