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Kaon physics: status and perspectives

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The current status of SM tests with kaons is briefly reviewed, and perspectives for ongoing experiments are presented.

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1. Introduction

There's beauty in kaons, too.

The study of K mesons, being the entrance gate to the world of flavour physics, was an unrivaled contribution to the understanding of nature and the shaping of the standard model (SM) as we know it. One of the aims of this talk is to show that these mesons still hold a large potential for probing the validity of the edifice built by generations of physicists, and hopefully to uncover the evidence of its awaited downfall.

Most of the current research program on kaons stems in one way or another from the legacy of one of the most daring experimental endeavors of the past twenty years, namely the fixed-target high-energy experiments which led to the proof of existence of direct CP violation, namely NA48 [2] (and its predecessor NA31 [1]) at CERN and KTeV [3] at Fermilab. The outcome of these experiments was the first confirmation of the CKM picture of CP violation. Besides a rather precise determination of the elusive ε'/ε direct CP violation parameter, such experiments - with their innovative techniques and state-of-the art electromagnetic calorimeters - spawned a significant and large set of additional measurements.

The downside of such investigations, including subsequent attacks on other manifestations of CP violation [4], is that theoretical computations within the low-energy kaon systems are affected by huge technical difficulties, so that the final quantitative impact on the determination of the unitarity triangle (UT) is limited by the theoretical shortcomings in relating rather accurate measurements to equally significant determinations of the underlying SM parameters, an unfortunate situation which is avoided for some measurements among those available in the study of B meson decays. The best example of this state of affairs is truly the ε'/ε direct CP violation parameter: while the relevance of the above experimental results is completely independent from the actual numerical value of the measured parameter, being rather given by its 9 standard deviation non-zero value, we are talking of a tiny O(10^{-6}) decay asymmetry [5] which is known to be consistent with the SM but cannot be predicted yet to a significant precision. It goes to the merit of our theoretical colleagues that the corresponding 35-year effort in taming the theoretical difficulties in this prediction goes on unrelentedly, having risen to the level of a figure of merit of the quality of computations [6].

The state of the more mundane indirect-CP violating parameter ε is better: now measured to 0.5% accuracy, after a "branching ratio revolution" resulting in an update of several measurements, mostly due to a careful treatment of radiative corrections, its constraint on the apex of the UT is significant, if not impressive compared to other experimental data. Steady theoretical progress, not anymore limited to lattice QCD, is raising the numerical significance of the ε parameter in the UT fits: the theoretical error is now of the order of 7% [7], with the normalization factor B_K computed on the lattice to better than 2% precision with NNLO corrections [8], and improving measurements on other CKM parameters such as $|V_{cb}|$ would lead to a further improvement of the situation. In this respect the legacy of the KLOE experiment at Frascati must be also mentioned, in particular for its unique strength on absolute K_S branching ratio measurements; recent results include the first measurement of indirect CP violation in semileptonic K_S decays [9] and the best limit on that in $3\pi^0$ decays [10]. The physics program at KLOE2 is continuing, with emphasis on spectroscopy and tests of quantum mechanics and CPT in the kaon system.

PoS(Beauty2014)040

Decay mode	BR limit (90% CL)
$K_L \to e^{\pm}\mu^{\mp}$	$4.7 \cdot 10^{-12}$ (BNL E871) [15]
$K_L \to e^{\pm}e^{\pm}\mu^{\mp}\mu^{\mp}$	$4.12 \cdot 10^{-11}$ (FNAL KTeV) [16]
$K_L \to \pi^0\mu^{\pm}e^{\mp}$	$7.6 \cdot 10^{-11}$ (FNAL KTeV) [17]
$K_L \to \pi^0\pi^0\mu^{\pm}e^{\mp}$	$1.7 \cdot 10^{-10}$ (FNAL KTeV) [17]
$K^+ \to \pi^+\mu^+e^-$	$1.3 \cdot 10^{-11}$ (BNL E777/865) [18]
$K^+ \to \pi^+\mu^-e^+$	$5.2 \cdot 10^{-10}$ (BNL E865) [19]
$K^+ \to \pi^-\mu^+e^+$	$5.0 \cdot 10^{-10}$ (BNL E865) [19]
$K^+ \to \pi^-e^+e^+$	$6.4 \cdot 10^{-10}$ (BNL E865) [19]
$K^+ \to \pi^-\mu^+\mu^+$	$1.1 \cdot 10^{-9}$ (CERN NA48/2) [23]
$K^+ \to \mu^-\nu e^+e^+$	$2 \cdot 10^{-8}$ (CERN Geneva-Saclay) [20]

Table 1: BR limits for some lepton-flavour violating K decays.

2. More flavour and LFV

Other kaon measurements recently confronted the SM, and one of the unique contributions from such a system is the measurement of the Cabibbo angle, or $|V_{us}|$, from the branching ratio (BR) of semileptonic K decays. The FlaviaNet global fit [11] reports the experimental result as $|V_{us}|f_+(0) = 0.2163 \pm 0.0005$, and with the dominant 0.6% theoretical error on the form factor normalization $f_+(0)$ this corresponds to $|V_{us}| = 0.2253 \pm 0.0014$, which shows no hint of violations of unitarity in the first row of the CKM matrix. The above measurement also results in a significant lepton universality test through the comparison of $K_{\mu 3}$ and K_{e3} branching ratios, and the allowed parameter space of several beyond-SM models can also be eroded.

The precision measurement of the BR of time-honored helicity-suppressed leptonic decays K_{e2} and $K_{\mu 2}$ holds a potential for probing scalar densities of right-handed current contributions, with O(10^{-2}) deviations being allowed [21] from the SM value, known to $4 \cdot 10^{-4}$ precision [22]. An experimental campaign for improved measurements of the above ratio was performed [13] [14], resulting in a tenfold precision increase in the measurement to $4 \cdot 10^{-3}$: $R_K = BR(K^+ \to e\overline{\nu})/BR(K^+ \to \mu\overline{\nu}) = (2.488 \pm 0.009) \cdot 10^{-5}$, fully compatible with the SM prediction. Potential for new physics is still open, and prospects for experimental improvements are present: the goal of the first phase of the TREK experiment [12], in preparation at J-PARC, is indeed pushing the experimental precision on R_K to the 2.5 per mille level using stopped kaon decays.

The study of lepton flavour violation (LFV) in K decays has a very long history, and it is said that kaons shattered more theoretical models in this field than any other particle. Some of the reasons are the availability of high-statistics, clean signatures and controllable backgrounds. Limits reach now the 10^{-10} to 10^{-11} region, offering sensitivities to contributions from unknown particles of masses up to O(100 TeV) for couplings comparable to those of weak interactions (see Table 1).

As a recent example, the limit for $K^+ \to \pi^-\mu^+\mu^+$ decays, possibly mediated by Majorana neutrino exchange, was recently updated as a byproduct of the NA48/2 experiment at CERN [23], and the new NA62 experiment in preparation at CERN has a large potential for improving this and other limits on LFV K^+ decays.

3. Other physics

Measurements of kaon decay BRs and properties contribute to the knowledge of the parameters of the systematic expansion in momenta p which is at the basis of chiral perturbation theory (ChPT), the effective approach which allows predictions in the low-energy QCD regime, instrumental to allow probing fundamental parameters of the theory. One example is the continuous improvement in the measurement of the $K^+ \to \pi^+\gamma\gamma$ decay, with a 10^{-6} BR computed to $O(p^6)$ in ChPT, represented by the recent NA62 measurement $BR(K^+ \to \pi^+\gamma\gamma) = (1.00 \pm 0.07) \cdot 10^{-6}$ [24]. Unfortunately, the combination of ChPT parameters uniquely probed by this decay mostly relates to a suppressed region of the $\gamma\gamma$ spectrum, so that the effect of the highest-order terms in the expansion cannot be discriminated yet.

An old-fashioned measurement which recently came back to the stage is the determination of $\pi\pi$ scattering lengths, arguably one of the most basic parameters of QCD. Kaon decays recently contributed to a much improved determination of such quantities, both through a high-statistics (1.1 M decays) study of the "classic" partial-wave spectra of kinematic variables in $K^\pm \to \pi^\pm\pi^\mp e^\pm\nu$ ($K^\pm_{e4}$) decays [25], as well as through the study of final-state interactions by the analysis of kinematic thresholds in $K^\pm \to \pi^\pm\pi^0\pi^0$ [26] in NA48/2. The combination of these measurements resulted in the most precise determination of the isospin 0 and 2 S-wave $\pi\pi$ scattering lengths.

$$\begin{aligned} a_0^0 &= 0.2210 \pm 0.0047_{stat} \pm 0.0040_{syst} \\ a_0^2 &= -0.0429 \pm 0.0044_{stat} \pm 0.0028_{syst} \\ a_0^0 - a_0^2 &= 0.2639 \pm 0.0020_{stat} \pm 0.0015_{syst} \end{aligned}$$

where the errors are further reduced if additional theoretical constraints from ChPT are included. This sensitive test confirms the predictions of ChPT and the underlying assumption of a large quark condensate contributing to the pion mass.

A unique experimental campaign with a 40-year tradition in K physics is the search for time-reversal violation through the measurement of muon polarization P_T transverse to the decay plane in $K \to \pi\mu\nu$ decays; in these semileptonic processes CP violation is not dynamically suppressed, and the tiny SM contribution, expected to be $O(10^{-7})$, is entirely negligible, so that the limit of the approach is given by the spurious effect due to final-state interactions at $O(10^{-5})$. The most recent measurement by the KEK E246 experiment [29] is

$$P_T = -0.0017 \pm 0.0023_{stat} \pm 0.0011_{syst}$$

or $P_T < 5 \cdot 10^{-3}$ at 90% CL, showing no sign of time reversal violation. The measurement is still statistically limited, and a further experimental step to reach 10^{-4} precision in 1 year of data-taking was proposed at J-PARC (TREK) [12], exploiting a higher beam intensity combined with an active polarimeter and several other improvements in the detector. This part of the experimental program is currently waiting for higher beam power to be available from the J-PARC complex.

4. Golden modes

In several kaon decay modes the contribution from short-distance physics, which is reliably computed within the SM and can provide sensitivity to yet undiscovered particles, is hidden by

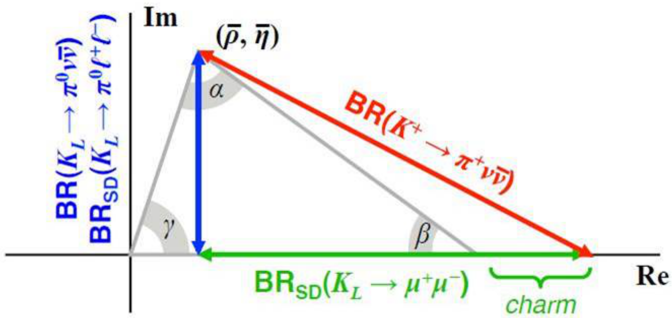

Figure 1: Determination of the unitarity triangle from $K \to \pi\ell\ell$ decays.

long-distance contributions whose theoretical determinations are marred by serious difficulties. One example is $K_S \to \mu^+\mu^-$, less attractive than its corresponding B meson decay for challenging the SM; nevertheless, a great improvement in the knowledge of the BR of this decay was recently obtained by the CERN LHCb experiment, which also produces a large amount of K_S (10^{13}/fb^{-1}), about 40% of which decay within the VELO detector allowing a sensible measurement: $BR(K_S \to \mu^+\mu^-) < 9 \cdot 10^{-9}$ (at 90% CL) [28].

Conversely, there exist a few “golden modes” in kaon decays which offer a unique theoretically clean environment to probe the SM, thanks to the very small intrinsic theoretical errors (at the percent level) and the strong sensisitvity to many new physics models and heavy-particle contributions. Since we now know through many experimental results that the flavour structure of any possible “TeV-scale” new physics is not too weird, probes of this kind become more and more relevant, and undoubtedly represent the central focus of current experimental projects using kaons.

These decays are semileptonic modes with lepton pairs in the final state, namely the K_L decays into $\pi^0 e^+e^-$, $\pi^0\mu^+\mu^-$ and $\pi^0\nu\bar{\nu}$ and the charged $K^\pm$ decay into $\pi^\pm\nu\bar{\nu}$. The theoretical cleanliness of such decays stems from a very strong GIM suppression within the SM, and from the fact that the hadronic part of the amplitude can be extracted from the precise experimental knowledge of the semileptonic $K \to \pi\ell\nu$ decays using isospin simmetry with tiny uncertainties, thus completely avoiding the difficulties related to QCD corrections. Furthermore, the final states with neutrinos are also almost free from long-distance contributions, and represent the most promising modes for new physics searches; an intense theoretical activity was devoted to these decay modes [30]. A feeling of the sensitivities is provided by the fact that a 10% BR measurement can probe up to a 1000 TeV scale for SM-like couplings; the measurement of the $\pi\nu\bar{\nu}$ decay modes for both K_L and $K^\pm$ can determine the unitarity triangle in a completely independent way with respect to heavy meson data (see Fig. 1). Furthermore, the correlation pattern of the BR measurements for the two $\pi\nu\bar{\nu}$ modes offers a strong discriminating power towards different new physics models [31].

Similar information can be obtained from the decay modes with charged leptons in the final state, provided the long-distance and indirect-CP-violating contributions are subtracted first, which in turn requires ancillary precision measurements of other K decay modes; since the experimental challenges to detect these decay modes are not significantly smaller than for neutrino-pair modes, no dedicated experimental project is being pursued for the time being, although proposals were

Decay mode	BR $\cdot 10^{11}$ (SM)	Theory error	Γ_{SD}/Γ	BR $\cdot 10^{11}$ (experiment)
$K_L \to \pi^0 e^+ e^-$	35 ± 10	10%	0.4	< 28 (FNAL KTeV) [32]
$K_L \to \pi^0 \mu^+ \mu^-$	14 ± 3	15 %	0.3	< 38 (FNAL KTeV) [33]
$K_L \to \pi^0 \nu\overline{\nu}$	2.4 ± 0.4	2%	0.9	< 26000 (KEK E391a) [36]
$K^\pm \to \pi^\pm \nu\overline{\nu}$	7.8 ± 0.8	4%	0.99	17 ± 12 (BNL E787/E949) [34]

Table 2: Expected (SM) and measured values for $K \to \pi\ell\ell$ decay branching ratios. The theory error column indicates the approximate theoretical precision (excluding parametric uncertainties) on the short-distance part of the BR (which represents a fraction of the total indicated in the next column).

put forward in the past and experimental limits were obtained as spin-off results of other kaon experiments. Table 2 summarizes the theoretical and experimental status for the four decay modes being discussed.

Focusing on the $\pi\nu\overline{\nu}$ modes, it is a well known fact in high-energy physics that the processes which are easy for theory are quite nightmarish for experiment and vice versa, and these decays are emblematic in this sense, requiring identification of a decay mode with a single measurable particle in the final state and non-closed kinematics, in a background 10^{10} times larger. Physicists like difficult challenges, and a quite long search was undertaken, with dedicated experiments E787 and E949 at Brookhaven eventually resulting in the actual detection of a handful of $K^+ \to \pi^+\nu\overline{\nu}$ events [34] (7 candidates with 2.6 expected background) corresponding to the BR value reported in Table 2, clearly consistent with the SM prediction but with a (statistical) error which does not allow precise conclusions. These experiments exploited low-energy K^+ decaying at rest, and relied on the detection of the full $\pi \to \mu \to e$ decay chain for particle identification and background suppression.

Several experiments were proposed for accurate measurements of the $K \to \pi\nu\overline{\nu}$ decay modes, and while many of those could not reach the approval stage [35], two projects are actually underway: NA62 at CERN for the K^+ mode and KOTO at J-PARC for the K_L one. The key issues for these decay in-flight experiments are high kaon fluxes, a high vacuum with hermetic detectors and high-resolution redundant measurements of all kinematic variables.

The NA62 experiment at CERN [37] uses a high energy (75 GeV/c) unseparated (6% K^+) positive hadron beam to search for $\pi^+\nu\overline{\nu}$ decays of K^+ in flight in a 40 m long evacuated decay region (Fig. 2). Multiple redundant measurements of the incoming kaon (particle identification, momentum and angle) are performed with Čerenkov and silicon tracking detectors on the full-intensity 800 MHz beam, which is then deflected to remain in an evacuated beam pipe crossing all downstream detectors, where charged particles are tracked in straw chambers in vacuum and identified with a large Čerenkov detector; several high-performance photon veto detectors and muon detectors are instrumental in reducing the huge backgrounds. The experiment is currently performing its commissioning run, with 2015 being the first of three foreseen physics data-taking years to reach the expected goal of measuring O(100) SM events with 10% background.

The J-PARC K_L experiment represents a step forward with respect to the pilot experiment E391a performed at KEK [36], which set the current limit for the $K_L \to \pi^0\nu\overline{\nu}$ decay using a small-angle pencil neutral beam from a high-intensity ($2 \cdot 10^{12}$ ppp) 12 GeV/c proton beam, into a com-

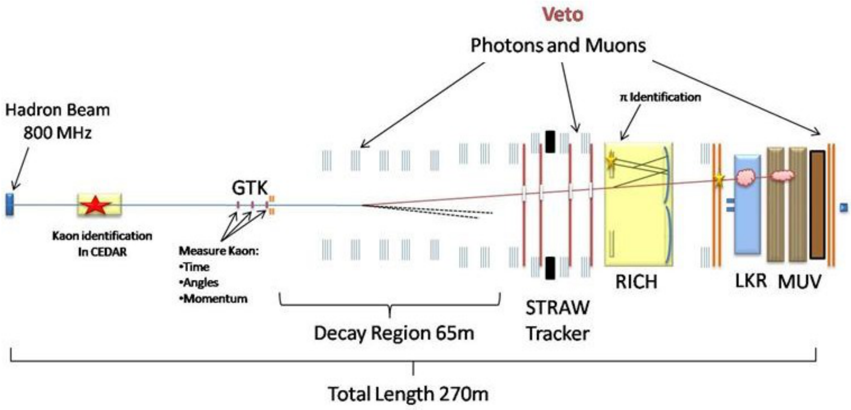

Figure 2: Sketch of the CERN NA62 experiment for the measurement of $K^+ \to \pi^+ \nu\overline{\nu}$ decays.

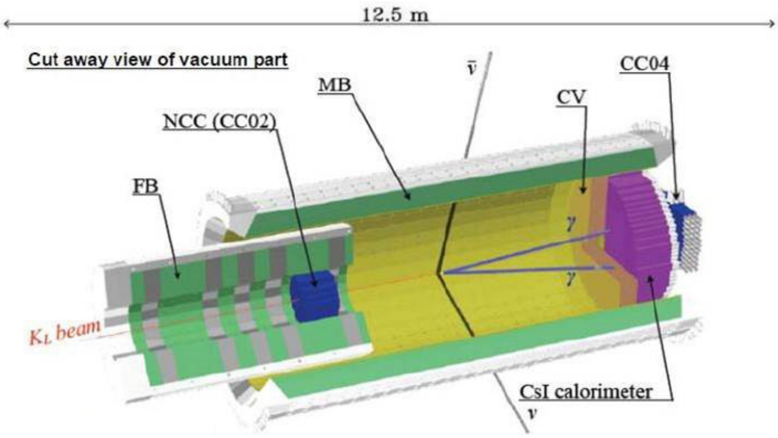

Figure 3: Sketch of the J-PARC KOTO experiment for the measurement of $K_L \to \pi^0 \nu\overline{\nu}$ decays.

pact, hermetic detector with a pure CsI electromagnetic calorimeter. In one year of data taking in 2004-2005, with 1% acceptance, the experiment detected no signal events with 0.85 expected background, resulting in the BR value reported in Table 2.

The KOTO experiment [38] improves on the E391a experience and detector, exploiting the more intense J-PARC 30 GeV/c proton beam, aiming at a sensitivity of 2.7 SM events with 2.2 background in 3 years. The detector (Fig. 3) includes a longer and higher-granularity, 2700-CsI-crystal electromagnetic calorimeter (inherited from KTeV), a new backside charged veto detector and a new beam-hole lead-aerogel photon veto. After some engineering runs and unexpected accidents, the experiment is scheduled to start data taking early in 2015 with the goal to go below the Grossman-Nir BR limit (derived from the measured K^+ BR) in a few months.

5. Conclusions

The study of kaon decays was instrumental in building the SM, and now reached sensitivities to BRs in the 10^{-12} range, constantly constraining many new physics models along the way. Existing precision measurements might already exhibit discrepancies with respect to the SM, but more progress on the precision of theoretical predictions is required to assess this. While allowing many interesting and important physics studies, kaons are now moving from discovery tools to quantitative probes, thanks to a bunch of high-sensitivity, theoretically clean decay modes. Such progress goes along with the required increase in beam power, from 10s to 100s of kW, in a flourishing of ultra-challenging experimental enterprises.

It really looks like some of the beauty of the "minimal flavour laboratory" represented by kaons is still waiting to blossom.

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PoS(Beauty2014)040