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Current and future kaon experiments

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An overview of the recent past, present and future of flavour physics studies using kaon decays is presented.

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Dedicated to the memory of N. Cabibbo (1935-2010).

1 Mandatory introduction

Kaons have been a remarkably effective tool to provide insight for shaping the Standard Model (SM) as we know it. Besides originating the introduction of the very concept of flavour, the kaon system played the key role in the discovery of such phenomena as parity and CP violation, the GIM mechanism and the existence of charm, and was central in the investigation of lepton flavour and CPT symmetries. Besides historical reasons, this richness of results is partly due to this system being a rather simple one, while exhibiting all the subtleties linked to flavour physics.
Sixty-six years since the first published observation of a K meson in cosmic rays one might be excused for wondering whether the information which these particles can provide on Nature has been eventually exhausted. We anticipate that the answer is negative.

2 Glorious past

The copious amount of results on kaon decays obtained since the late '90s originates from the intense experimental effort aimed at the measurement of direct CP violation, which led to three experiments being built at CERN (NA48), Fermilab (KTeV) and Frascati (KLOE). As is well known, such experimental endeavour led to the proof of the existence of direct CP violation through the measurement of the ϵ'/ϵ parameter [1] [2], just shortly before B factories started measuring such phenomenon in B meson decays.

The importance of the ϵ'/ϵ measurement is qualitative, and lies in being the first verification of the CKM flavour picture of the Standard Model, proving that CP violation is indeed a ubiquitous property of weak interactions (as B factories impressively showed). Nevertheless, with the recent final analysis of KTeV data [2], ϵ'/ϵ is measured with rather good (12%) precision; unfortunately, so far, such precision could not be exploited quantitatively to constrain in a significative way the Standard Model through the "unitarity triangle", due to dire theoretical difficulties. A somewhat better situation exists for the oldest (indirect) CP violation parameter ϵ, which is now measured to a very good precision (below 0.5%), but whose potential in constraining the SM is also reduced by the theoretical difficulties related to low-energy hadron physics.
High hopes for theoretical improvements on these points lie in the steady progress of lattice QCD, which has the potential of transforming existing K physics measurements of CP violation in additional significant constraints on the closure of the unitarity triangle.

The legacy of CP-violation K experiments is however much larger than what was mentioned above. Besides leading to the development of state-of-the-art detectors and innovative detection and analysis techniques, many more physics results than initially anticipated were obtained as byproducts of the above investigations. Just to quote a couple among many: possible large CP violating effects driven by supersymmetry were excluded by NA48 with much improved limits on Dalitz plot asymmetries in $K^{\pm} \to 3\pi$ decays [3], and stringent limits on several flavour-violating decays were obtained by KTeV (e.g. [4]).

While NA48 and KTeV are hadron beam fixed-target experiments, KLOE, being a Kaon factory exploiting coherent pair production in e^+e^- resonant production, presents quite different strengths and weaknesses; in particular it has the capability of exploiting its absolute flux measurement for BR measurements, and is a unique facility for the production of tagged K_S particles [5]. Among the many results obtained, we highlight the recent study of semi-leptonic decays of K_S, with the first measurement of the (indirect) CP charge asymmetry in K_S [6]: while still well compatible with zero at present, such measurement is a first step towards a new CPT symmetry test by comparison with the corresponding K_L asymmetry, measured with 2% precision.

As another byproduct of the above experimental activities, much improved measurements of kaon Branching Ratios (BR) were obtained. The increased care in handling systematic issues, as required by the larger statistics available, led to an important shift in the value of most BRs, starting from the comprehensive set of relative measurements of K_L BRs by the KTeV experiment [7]. Further precise data obtained by NA48 [8] and KLOE [9] [10], also on $K^{\pm}$ and K_S (and also BNL E865 [11]), eventually led to the present state of kowledge, significantly different with respect to older PDG compilations. The single most significant issue responsible for the shifts was the proper handling of radiative corrections, quite important at the present level of statistical accuracy, and sometimes not correctly treated in older data.

3 Intriguing present

The campaign of neutral and charged kaon BR measurements was partly driven by the interest in checking some "tension" between the data and the unitarity constraint for the first row of the CKM matrix: flanking improved measurements of $|V_{ud}|$ from beta decays, the knowledge of the value of $|V_{us}|$ (Cabibbo angle) from semileptonic kaon decays $K \to \pi\ell\nu$ ($K_{\ell 3}$) was significantly improved. From the new set of BR measurements, and the critical re-examination of the older ones and their systematic error correlations, the experimental accuracy on the determination of $|V_{us}|$ is now close to 0.2%, with full statistical consistency between individual measurements. A detailed analysis of the above measurements can be found in [12].
Actually, $|V_{us}|$ cannot be extracted from the data without using theoretical input on the normalization of the $K \to \pi$ vector form factor at zero momentum transfer.

Such normalization is nowadays obtained from unquenched lattice QCD simulations [14] with about 0.5% precision and a consistency around 1%. Theoretical precision is thus approaching the experimental one, further improving the embarassingly good agreement of data with the SM. The comparison of $|V_{us}|$ measurements from different decay modes also allows a test of lepton universality, passed with flying colours at 0.5% precision [12].

Related measurements involve charged kaon leptonic decays $K \to \ell\nu$ ($K_{\ell 2}$). A renewed interest in such decays first arose from the observation [13] that improved Lattice QCD measurements of the ratio of kaon and pion decay constants (f_K/f_π) allow extracting $|V_{us}|$ from precise measurements of the $K_{\mu 2}$ BR. The lattice precision on f_K/f_π is now approaching the 1% level [14], while the experimental accuracy on the $K_{\mu 2}$ BR is below 0.3% [10].

It is also worth stressing that leptonic and semi-leptonic decays of pseudo-scalar mesons probe possible New Physics (NP) contributions with different chirality structures, so that the comparison of the two classes of decay modes (respectively helicity suppressed and allowed) allows placing bounds on some non-SM amplitudes in a given model: in the minimal supersymmetric extension of the SM such bounds relate to the value of the charged Higgs mass $m_{H^\pm}$ and the $\tan\beta$ parameter, excluding regions at low $m_{H^\pm}$ and large $\tan\beta$ [12].

It was also noted [15] that lepton-flavour violating terms, which appear in SUSY extensions of the SM, might affect the ratio of $K^\pm_{e2}$ to $K^\pm_{\mu 2}$ BRs (known in the SM to 0.04% precision) up to the percent level in some regions of parameter space. A recent measurement by KLOE [16] improved the experimental knowledge of the above ratio to 1.2%. A dedicated measurement of such universality in charged kaon leptonic decays was undertaken by the NA62 collaboration at CERN, using the NA48/2 apparatus. The main experimental difficulty in this measurement lies in the control of the background to K_{e2} from $K_{\mu 2}$ decays in which a muon radiates a very hard photon. The result from the analysis of 40% of the collected data [17] has 0.5% precision and is consistent with lepton universality and the SM.

4 Challenging future

As the great amount of flavour data collected in recent years shows, New Physics flavour effects cannot be large. After the general verification of the overall flavour structure of the SM, the trend towards finer and more stringent quantitative SM tests, looking for deviations in a search for NP, finds once more kaons in the first line.

It has been long known that a handful of ultra-rare kaon decay modes can act as very powerful probes of flavour physics [18], due to some unique features resulting in a few percent intrinsic precision in the theoretical BR prediction, an almost unique case in hadronic physics. Some features of these modes are summarized in table 1; the hard-GIM suppression in the SM allows potentially large NP contributions, and the extraction of the hadronic part of the amplitude from that of $K_{\ell 3}$, experimentally very well known, are the two key points to understand the relevance of these decays.

Mode	BR(SM)	BR(exp)
$K_L \to \pi^0 e^+ e^-$	10^{-11} ($3 \cdot 10^{-12}$ $\mathrm{CPV_{dir}}$)	$< 2.8 \cdot 10^{-10}$
$K_L \to \pi^0 \mu^+ \mu^-$	10^{-11} ($1 \cdot 10^{-12}$ $\mathrm{CPV_{dir}}$)	$< 3.8 \cdot 10^{-10}$
$K^+ \to \pi^+ \nu\overline{\nu}$	$(8.5 \pm 0.7) \cdot 10^{-11}$	$1.47^{+1.30}_{-0.89} \cdot 10^{-10}$
$K_L \to \pi^0 \nu\overline{\nu}$	$(2.6 \pm 0.4) \cdot 10^{-11}$	$< 2.6 \cdot 10^{-8}$

Table 1: Ultra-rare kaon decay modes. $\mathrm{CPV_{dir}}$ denotes the short-distance, direct-CP violating part of the BR.

The four decay modes of table 1 can probe different classes of NP; those with $\ell^+\ell^-$ in the final state are affected by irreducibile backgrounds, and their SM contributions include large-distance parts which are under worse theoretical control. The modes with neutrinos in the final state are cleaner, and represent the new "holy grail" of kaon physics. Precise measurement of these decays offers the potential to clarify the flavour structure of any NP directly observed in high-energy colliders, or to indirectly probe flavour effects in NP up to scales of order 100 TeV.

Experimental detection of $K \to \pi\nu\overline{\nu}$ decays presents formidable difficulties, due to the 10^{10} background/signal ratio coupled with non-closed kinematics due to undetected neutrinos. Seven $K^+ \to \pi^+\nu\overline{\nu}$ candidates were detected in the dedicated E787 and E949 BNL experiments [19] using low-energy kaon decays at rest. Only limits exist for $K_L \to \pi^0\nu\overline{\nu}$, some 3 orders of magnitude higher than the SM prediction [20]; see figure 1.

A program aimed at the measurement of $K_L \to \pi^0\nu\overline{\nu}$ is being pursued in Japan. The concept involves an intense thin "pencil" neutral beam entering a photon-hermetic vacuum decay region. The pilot project E391a at KEK took data in 2004 and 2005 with ~ 2 GeV/c K_L to test the experimental approach, and significantly improved the BR upper limit [21]. The first experiment aiming to a measurement is KOTO, presently in the commissioning phase at J-PARC [22]. The optimization of the new neutral beam line, and the better duty cycle and acceptance lead to an estimate of 2.7 SM events with 2.2 background events in 3 years, with a first run in 2011. A second phase is planned, involving a dedicated beam line and an improved detector, aiming at a O(100) event measurement.

Improvement on $K^+ \to \pi^+\nu\overline{\nu}$ is expected from the NA62 experiment at CERN [23]. This uses a new decay-in-flight approach with 75 GeV/c kaons in an unseparated beam and kinematic selection of slow pions which, combined with photon quasi-hermeticity and particle ID, lead to the expectation for 55 SM events per year with $\sim 20\%$ background. The experiment completed the R&D phase and started construction, aiming for a first test run in 2012.

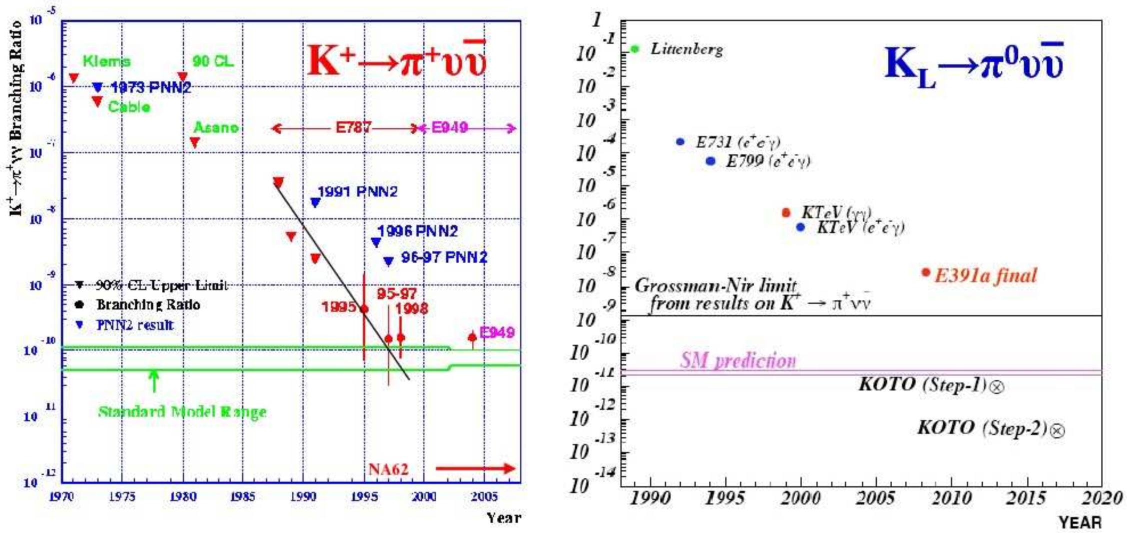

Figure 1: Experimental progress on the measurement of $K \to \pi\nu\overline{\nu}$ BRs.

5 Exciting times

A long-standing strong interest in $K \to \pi\nu\overline{\nu}$ materialized in the US as a number of interesting proposals which, unfortunately, could not be funded [28]. Fermilab's plans on high-intensity physics involve kaon decays as a central topic, and the physics goals of a proposed future 2 MW proton source ("Project X") [24] include "ultimate precision" rare kaon experiments, aiming for ~ 500 (200) $K^+ \to \pi^+\nu\overline{\nu}$ ($K_L \to \pi^0\nu\overline{\nu}$) decays per year with signal to background above 4. Such a facility would also allow an improved CPT test on $m(K^0) - m(\overline{K}^0)$, sensitive to effects at the Planck scale. Construction could start in 2015, with first physics in 2020.

Limited space precludes the description of many other interesting recent results from K decays, as well as a detailed discussion of ongoing programs such as the continuation of KLOE-2 [25], aiming at an eightfold increase in statistics. Finally, the TREK project in preparation at J-PARC [26] should be mentioned, aiming at a new search for non-SM T-violating transverse muon polarization in $K^+_{\mu 3}$ decays, with a tenfold improvement over the limit from the previous KEK experiment [27].

6 Bright conclusions

This brief review gives a bird's eye view of some of the fundamental physics which can be studied with kaons; detailed results can be found in other contributions to these proceedings and in the PDG compilation [20]. Kaons provided fundamental input to the building and the quantitative testing of the SM. They now enter as prime actors in the present era of precision tests, through challenging ultra-rare decay probes offering very powerful opportunities, pursued in many different laboratories. It is guaranteed that these "minimal" probes of flavour effects will play a prominent role also in future editions of the CKM conference.

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