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RECENT RESULTS ON KAON PHYSICS*

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A review of recent results on kaon physics is presented. Firstly, results on kaon semileptonic decays are summarised and a value for the CKM matrix element V_{us} is extracted, compatible at 1σ with that expected from CKM unitarity. Then precision data on K_{l3} and K_{l2} decay rates are presented and tests for new physics searches are discussed. Finally, preliminary results on the K_{e4} decay $K^{\pm} \to \pi^+\pi^- e^{\pm}\nu$ are summarised. The $\pi\pi$ scattering lengths a_0^0 and a_0^2 is extracted from the K_{e4} phase shift and from the slope change in the M_{00}^2 distribution of $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$ decays.

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1. Kaon semileptonic decays and V_{us}

The K_{l3} decay rate, including possible photon from internal bremsstrahlung, is given by

$$\Gamma(K_{l3}) = \left(\frac{C_K^2 G_F^2 M_K^5}{192\pi^3}\right)\left(S_{\rm EW}|V_{us}|^2|f_+(0)|I_K^l(\lambda)\right)(1 + 2\Delta_{\rm SU(2)} + 2\Delta_{\rm EW})\,.$$

The decay width $\Gamma(K_{l3})$ is experimentally determined by measuring the kaon lifetime and the semileptonic BRs. Here $f_+(0)$ is the form factor at $q^2 = 0$, $S_{\rm EW} = 1.0232$ is a short-distance electro-weak correction, I_K^l is the phase space integral which depends on the form factors, and V_{us} is the CKM matrix element. The factor C_K^2 is 1 for K^0 and 1/2 for $K^{\pm}$. The correction $(1+\Delta_K^l)^2 \approx 1+2\Delta_{\rm SU(2)}^l+2\Delta_{\rm EW}^l$ takes into account SU(2) symmetry breaking and long-distance electro-magnetic interactions. The hadronic matrix element, which determines the form factor, is parameterised in terms of its value at zero momentum transfer for neutral $K \to \pi$ decays: $f_+(0) = f_+^{K^0\pi^-}(0)$. The form factor dependence on the momentum is described by one or more

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slope parameters λ, which are measured from the decay spectra, and is integrated over the decay phase space, giving rise to the I^l_K integral.

At present, the constraint $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2$ from the first row of the CKM matrix offers the most precise test of its unitarity. At the time of the PDG 2004 edition, there was a 2.3σ indication of unitarity violation. Recently, many new measurements of branching ratios, lifetimes, and form factor slopes were made by KLOE, KTev, NA48 and ISTRA, all based on much higher statistics and with radiative corrections applied consistently.

Results presented here focus on charged kaon semileptonic decays. The NA48 experiment has published precise measurements of $\Gamma(K^{\pm}_{l3})/\Gamma(K^{\pm} \to \pi^{\pm}\pi^0)$ obtained with simultaneous K^+K^- beams. The sample amounts to 30–50 $\times$ 10^3 events for K^- and K^+, respectively, and the final accuracy is limited by statistics [1]: $\Gamma(K^{\pm}_{e3})/\Gamma(K^{\pm} \to \pi^{\pm}\pi^0) = 0.2470(9)(4)$ and $\Gamma(K^{\pm}_{\mu3})/\Gamma(K^{\pm} \to \pi^{\pm}\pi^0) = 0.1637(6)(3)$, where the first error is statistical and the second is due to systematic effects. The K_{e3} ratio has been measured also by the ISTRA Collaboration, using a sample of 2.2×10^6 K^-_{e3} decays [2]: $\Gamma(K^-_{e3})/\Gamma(K^- \to \pi^-\pi^0) = 0.2449(4)(14)$, in good agreement with the NA48 one. The KLOE experiment recently presented the absolute measurement of the semileptonic branching ratios, from $\phi \to K^+K^-$ events in which one of the two kaons decays to $\mu^{\pm}\nu$ or $\pi^{\pm}\pi^0$ [3]: BR $(K^{\pm}_{e3}) = 0.04965(53)$ and BR $(K^{\pm}_{\mu3}) = 0.03233(39)$.

Using all the experimental [4] and theoretical [5] inputs available, a value for $|V_{us}|f_+(0)$ has been extracted for $K_{\rm L}$, $K_{\rm S}$ and $K^{\pm}$ modes (Table I).

TABLE I

Values of $|V_{us}|f_+(0)$ extracted from K_{le} decays. Sources contributing to the total fractional error are reported separately in percent.

Mode	$\lvert V_{us}\rvert f_+(0)$	% error	BR(%)	τ(%)	Δ(%)	$I(\lambda)$(%)
$K_{\rm L}(e3)$	0.21627(60)	0.28	0.09	0.19	0.15	0.09
$K_{\rm L}(\mu3)$	0.21678(67)	0.31	0.10	0.18	0.15	0.15
$K_{\rm S}(e3)$	0.21544(144)	0.67	0.65	0.03	0.15	0.10
$K^{\pm}(e3)$	0.21725(89)	0.41	0.29	0.09	0.26	0.10
$K^{\pm}(\mu3)$	0.21800(114)	0.52	0.42	0.09	0.26	0.15

The five decay modes agree well within errors, and average to $|V_{us}|f_+(0)$ $= 0.21663(47)$ with $\chi^2/ndf = 2.62/4$ (Prob = 62%). The separate averages of the neutral and charged modes agree within 1.1σ. This gives confidence on the reliability of the SU(2) breaking correction. Alternatively an experimental estimate of $\Delta_{\rm SU(2)}$ is obtained by comparing the neutral result with the charged one evaluated without correcting for the breaking. A value of $\Delta_{\mathrm{SU}(2)} = 2.84(40)$ is obtained, in good agreement with the value estimated from theory.

Assuming the standard value [6] for $f_+(0) = 0.961(8)$, a value for $|V_{us}| = 0.2254(19)$ is obtained. To test the CKM unitarity, using $|V_{ud}| = 0.97372(26)$ [7] from an average of nuclear beta decays, a result for $V_{ud}^2 + V_{us}^2 - 1 = -0.0011(10)$ is derived, which is consistent with unitarity to about 1σ.

2. Lepton universality tests with kaons

Contrary to lepton flavour violation which has recently been discovered in the neutrino sector, lepton universality in meson decays is strictly required in the Standard Model. Violation of lepton universality would be an immediate indication of new physics and most theories of beyond the Standard Model predict lepton flavour violating transitions (LFV).

Search for LFV in the semileptonic decays K_{l3} is a test of the vector current of the weak interactions. Currently, the best test comes from the comparison of the $\tau \to e\nu_e\nu_\tau$ and $\tau \to \mu\nu_\mu\nu_\tau$ decay rates, from which the ratio of coupling constants is determined $g_\mu^2/g_e^2 = 0.9998 \pm 0.0040$. With the current precision, the tests in K_{l3} decays have reached the sensitivity of τ decays.

Lepton flavour independent factors cancel in the ratio of the semileptonic decay rates $\Gamma(K_{\mu3})/\Gamma(K_{e3})$. Using phase space integrals and form factors from the global fit of the Flavianet group [4], a Standard Model expectation is derived for $R(K_{l3})$: $R^{\mathrm{SM}}(K_{l3}) = \Gamma(K_{\mu3})/\Gamma(K_{e3}) = 0.6657(31)$ for K_{L} and 0.6591(31) for $K^\pm$. Five recent and precise direct measurements of $R(K_{l3})$ ([1,3,8–10]) are summarised in Table II, all in agreement with the Standard Model expectation. More information are used when performing a global fit to all available kaon data [11]: $r_{\mu e} = R^{\mathrm{exp}}_{K\mu3/Ke3}/R^{\mathrm{SM}}_{K\mu3/Ke3} = 1.0059(87)$ for $K^\pm$ and 1.0039(56) for K^0. The experimental uncertainties

TABLE II

Recent direct measurements of $R(K_{l3}) = \Gamma(K_{\mu3})/\Gamma(K_{e3})$.

Experiment	Channel	$R(K_{l3})$
KTeV (2004)	K_{L}	0.6640 ± 0.0026
KLOE (2006)	K_{L}	0.6734 ± 0.0059
KEK–E246 (2001)	K^+	0.671 ± 0.011
NA48/2 (2007)	$K^\pm$	0.663 ± 0.003
KLOE (2007)	$K^\pm$	0.6511 ± 0.0087

dominate in the $K^{\pm}$ case, while experimental and theoretical uncertainties contribute in similar magnitude in the K^0 case. Combining both results gives $r_{\mu e} = 1.0042(50)$ in good agreement with lepton universality.

The ratio $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$ is precisely calculated in the Standard Model as $R_K = m_e^2/m_\mu^2(m_K^2 - m_e^2)^2/(m_K^2 - m_\mu^2)^2 = (2.472 \pm 0.001) \times 10^{-5}$, where radiative corrections are taken into account. Given the very high accuracy of the SM prediction, any significant experimental deviation would immediately be evidence for new physics that violate lepton universality. Recent works point out that sizable violations of lepton universality can be expected in K_{l2} decays [12]: at tree level, lepton flavour violating terms are forbidden in the MSSM, but loop diagrams could induce lepton flavour violating Yukawa couplings $H^+ \to l\nu_\tau$ to the charged Higgs boson H^+. For moderately large $\tan\beta$ and Higgs mass, SUSY contributions may enhance R_K by up to a few percent.

Three new preliminary measurements were reported by NA48/2 and KLOE. The first NA48/2 preliminary result is based on 4000 K_{e2} from 2003 data set: $R_K = 2.416 \pm 0.043 \pm 0.024$ [13]. The second preliminary result is based on 4000 events from 2004 data set: $R_K = 2.455 \pm 0.045 \pm 0.041$ [14]. Both statistics and systematics uncertainties are independent, since the systematics is either of statistical nature or determined independently. The larger systematic uncertainty in the second measurements is explained by a different method of background rejection, which relies only on data statistics. An improvement by a factor 3 in precision is the goal of the P326 Collaboration at CERN which had a dedicated run period in 2007 to measure R_K. The KLOE preliminary result is based on 8000 K_{e2} decays: $R_K = 2.55 \pm 0.05 \pm 0.05$ [15]. The statistical uncertainty is dominated by MC statistics and the estimate of the systematic uncertainty is conservative. Adding all the available statistics and generally improving on present limitations should reduce the uncertainty to 1%. Both collaborations measure the R_K ratio inclusive of radiative corrections.

A combination of the three results above with the current PDG value yields a new world average of $R_K = (2.457 \pm 0.032) \times 10^{-5}$, in very good agreement with SM expectations. This represents a factor 3 improvement in precision with respect to the previous average. In the SUSY framework discussed above, this result gives strong constraints for $\tan\beta$ and $M_{H^\pm}$: for a moderate value of $\Delta_{13} \approx 5 \times 10^{-4}$, $\tan\beta > 50$ is excluded for charged Higgs masses up to 1000 GeV/c^2 at 95% CL (see figure 1(left)). In general this limit is stronger than that obtained from $B \to \tau\nu_\tau$ decays; however, no assumption on Δ_{13} is needed for the B decays. Prospects for the exclusion plot with an uncertainty on R_K of 0.3% are shown in figure 1(right).

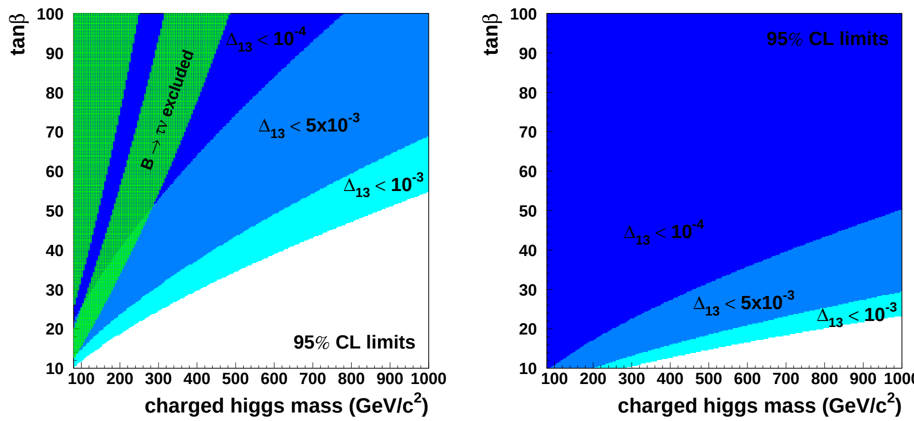

Fig. 1. Left: Exclusion limits from $K_{e2}/K_{\mu 2}$ for different values of Δ_{13}, and from $B \to \tau\nu_\tau$ decays. Right: Prospects with an uncertainty of 0.3% from $K_{e2}/K_{\mu 2}$ decays.

3. K_{e4} decays and $\pi\pi$ scattering lengths

Charged K_{e4} data give access to the $\pi\pi$ phase shift $\delta = \delta_0^0 - \delta_1^1$. The variation of the phase shift with the invariant mass $M_{\pi\pi}$ near threshold can be related to the $\pi\pi$ s-wave scattering lengths for isospin states 0 (a_0^0) and 2 (a_0^2), if dispersion relations and data at different energies [16–19] are used. The change in slope (cusp) observed in the $M_{\pi^0\pi^0}$ distribution of $K^\pm \to \pi^0\pi^0\pi^\pm$ decays at $M_{00} = 2m_{\pi^+}$ can be explained by $\pi^+\pi^-$ rescattering terms and provides another measurement of the a_0^0 and a_0^2 scattering lengths.

More than 670000 charged K_{e4} decays were collected in 2003 by the CERN/SPS experiment NA48 [20], with a ratio of background to signal of $\sim 0.5\%$. K_{e4} decays are described by the five kinematic Cabibbo–Maksymowicz variables: $M_{\pi\pi}$ and $M_{e\nu}$ invariant masses; angle Φ between the dipion plane and the dilepton plane in the kaon rest frame; θ_e and θ_π angles between the positive pion or lepton and the direction of the total dipion or dilepton momentum in the kaon rest frame. The axial form factors F, G, R and the vector form factor H contribute to the transition amplitude and can be expanded in terms of s, p, d waves:

$$F = F_s e^{i\delta_s} + F_p e^{i\delta_p} \cos\theta_\pi + \dots\,, \quad G = G_p e^{i\delta_g} + \dots\,, \quad H = H_p e^{i\delta_h}\,.$$

The form factor R is suppressed by a factor $m_e^2/M_{e\nu}^2$ and cannot be measured here. Neglecting d wave terms and assuming the same phase for F_p, G_p, H_p, only one phase $\delta(q^2) = \delta_s - \delta_p$ and four form factors are left, which are expanded further in terms of $q^2 = (M_{\pi\pi}^2/4m_\pi^2) - 1$:

$$F_s = f_s \left(1 + \frac{f_s'}{f_s q^2} + \frac{f_s''}{f_s q^4} + \dots\right), \qquad F_p = (f_p + \dots),$$
$$G_p = (g_p + g_p' q^2 + \dots), \qquad H_p = (h_p + \dots).$$

From the data sample, equi-populated bins are defined in the five-parameter space. Independent four-parameter fits are performed, in bins of $M_{\pi\pi}$. The set of form factors and the phase shift are used to minimise the differences between data events and predicted events from a detailed simulation. Polynomial expressions, function of the dimensionless variable q^2, are used to fit the form factor variations. The Universal Band central line constraint is used to deduce a value for the scattering length a_0^0. The numerical results, including a 2-parameter fit where both scattering lengths are free, are shown in Table III. The axial and vector form factors have been measured with a precision of a few percent and evidence for a non-zero f_p term of $\sim 5\%$ has been established.

TABLE III

Values obtained for the form factors. For the scattering lengths, both 1 and 2 parameter fit results are shown.

Parameter	Value
f_s'/f_s	$0.172 \pm 0.009_{\rm stat} \pm 0.006_{\rm sys}$
f_e'/f_s	$0.081 \pm 0.008_{\rm stat} \pm 0.008_{\rm sys}$
g_p/f_s	$0.873 \pm 0.013_{\rm stat} \pm 0.012_{\rm sys}$
h_p/f_s	$-0.411 \pm 0.019_{\rm stat} \pm 0.007_{\rm sys}$
f_s''/f_s	$-0.090 \pm 0.009_{\rm stat} \pm 0.007_{\rm sys}$
f_p/f_s	$-0.048 \pm 0.004_{\rm stat} \pm 0.004_{\rm sys}$
g_p'/f_s	$0.081 \pm 0.022_{\rm stat} \pm 0.014_{\rm sys}$
$a_0^0(1p)$	$0.256 \pm 0.006_{\rm stat} \pm 0.005_{\rm sys}$
$a_0^0(2p)$	$0.233 \pm 0.016_{\rm stat} \pm 0.007_{\rm sys}$
$a_0^2(2p)$	$-0.047 \pm 0.011_{\rm stat} \pm 0.004_{\rm sys}$

The phase shift δ has been extracted in a model-independent way [21]. The NA48 phase shift measurements and those from previous experiments are shown in figure 2 with the Universal Band predictions for two values of a_0^0. The data are in good agreement and favour large values of a_0^0.

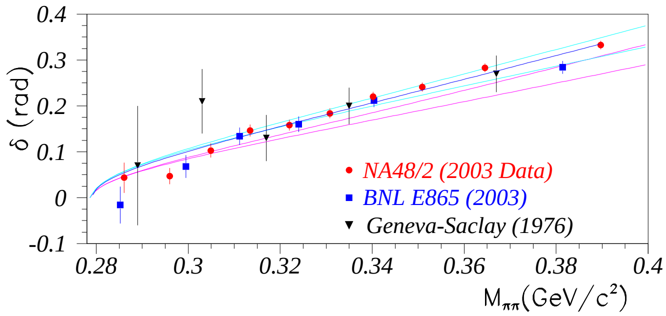

Fig. 2. Phase shift measurements from NA48, E865 and Geneva–Saclay experiments. Top and bottom bands correspond to the predictions of the Roy equations for $a_0^0 = 0.26$ and 0.22, respectively.

The sudden change of slope observed by NA48 in the $M_{\pi^0\pi^0}$ distribution of a sample of $\sim 60\times 10^6$ fully reconstructed $K^\pm \to \pi^0\pi^0\pi^\pm$ decays at $M_{00} = 2m_{\pi^+}$ can be explained by $\pi^+\pi^-$ rescattering terms [22, 23], and provides another measurement of the a_0^0 and a_0^2 scattering lengths. A fit of the single mass distribution allows the determination of the scattering lengths: $a_0^2 = -0.041 \pm 0.022_{\rm stat} \pm 0.014_{\rm sys}$, $a_0^0 - a_0^2 = 0.268 \pm 0.010_{\rm stat} \pm 0.004_{\rm sys} \pm 0.013_{\rm ext}$. The external error corresponds to an estimate of the effect of the missing higher order terms and radiative corrections in the rescattering model.

The extraction of the $\pi\pi$ scattering lengths a_0^0 and a_0^2 is subjected to theoretical external inputs where uncertainties of the same order as the NA48 experimental precision are present. To investigate the compatibility of the

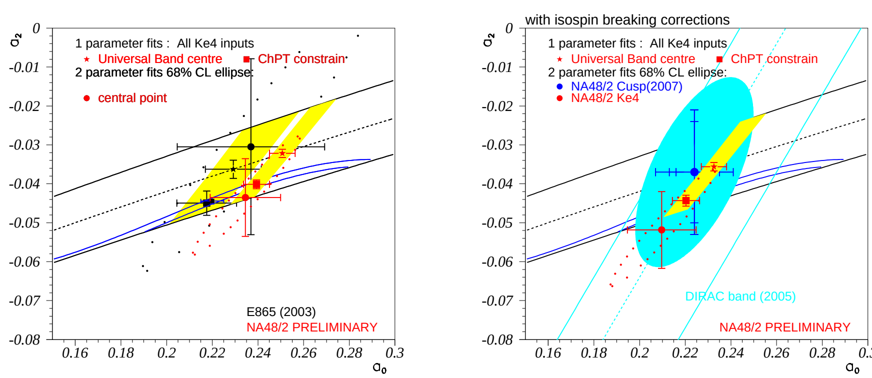

Fig. 3. Left: Comparison of NA48 and E865 results in the scattering length plane. Right: Comparison including isospin breaking corrections.

two high statistics experiments, the results of the 1- and 2-parameter fits are presented in the plane (a_0^0, a_0^2) where they show marginal consistency (see figure 3 left). Recent theoretical developments [24] suggest that isospin breaking effects, neglected so far, should be considered when extracting $\pi\pi$ scattering lengths from phase measurements. Under this assumption, measurements of the same scattering lengths in the $K^\pm \to \pi^0\pi^0\pi^\pm$ decays [22] show very consistent results (see figure 3 right), in good agreement with the predictions of Chiral Perturbation Theory [17].

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