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|Vud| and |Vus|

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In the first part this review presents a very accurate determination od |V$_{us}$| from nuclear superallowed $0^+ \rightarrow 0^+$ transition, as described in [1].
In the second part, the analysis of leptonic and semileptonic kaon decays data done by the FlaviaNet Kaon Working group, as described in [2], are presented. Data include all recent results by BNL-E865, KLOE, KTeV, ISTRA+, and NA48. Experimental results are critically reviewed and combined, taking into account theoretical (both analytical and numerical) constraints on the semileptonic kaon form factors. We report on a very accurate determination of V_{ud} and V_{us} and tests ot the CKM Unitarity from the top row

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†WWW access at www.lnf.infn.it/wg/vus/; for sake of completeness and brevity for all references we refer to the Note written by the FlaviaNet Kaon WG [2].

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1. Introduction

In the Standard Model, SM, transition rates of semileptonic processes such as $d^i \to u^j \ell \nu$, with d^i (u^j) being a generic down (up) quark, can be computed with high accuracy in terms of the Fermi coupling G_F and the elements V_{ji} of the Cabibbo-Kobayashi Maskawa (CKM) matrix. Measurements of the transition rates provide therefore precise determinations of the fundamental SM couplings.

A detailed analysis of semileptonic decays offers also the possibility to set stringent constraints on new physics scenarios. While within the SM all $d^i \to u^j \ell \nu$ transitions are ruled by the same CKM coupling V_{ji} (satisfying the unitarity condition $\sum_k |V_{ik}|^2 = 1$) and G_F is the same coupling appearing in the muon decay, this is not necessarily true beyond the SM. Setting bounds on the violations of CKM unitarity, violations of lepton universality, and deviations from the $V - A$ structure, allows us to put significant constraints on various new-physics scenarios (or eventually find evidences of new physics). In the case of leptonic and semileptonic kaon decays these tests are particularly significant given the large amount of data recently collected by several experiments: BNL-E865, KLOE, KTeV, ISTRA+, and NA48. The analysis of these data provides precise determination of fundamental SM couplings, sets stringent SM test almost free from hadronic uncertainties, and finally can discriminate between new physics scenarios. The high statistical precision of measurements and the detailed information on kinematical distributions have provided substantial progress on the theory side, in particular the theoretical error on hadronic form factors has been reduced at the 1% level.

The paper is organized as follows. First in Sec. 2 we present the $|V_{ud}|$ estimation from superallowed $0^+ \to 0^+$decay. In Sec. 3 we present fits to world data on the leading branching ratios and lifetimes, for K_L, K_S, and $K^\pm$ mesons. Sec. 4 summarizes the status of the knowledge of form factor slopes from $K_{\ell 3}$ decays. The physics results obtained are described in Sec. 5, in particular the measurement of $|V_{us} f_+(0)|$.

2. |V$_{ud}$| determination.

The evaluation of the V$_{ud}$ can be obtained from the study of the superallowed nuclear-beta decay, from the neutron-beta decay, from the beta-decay transition between I=1/2 isospin doublets in mirror nuclei and from the pion beta decay. Precise measurements of the β-decay between nuclear states with (J^P, I) = (0^+, 1) provide the most precise determination for V$_{ud}$. Only the vector current is involved in these transitions. Thus, according to the conserved vector current (CVC) hypothesis, the experimental ft-value, phasespace integral times the partial half-life, for each of these superallowed transitions should be related directly to a vector coupling constant, G$_V$. This is the same for all of them and is related to the fundamental weak-interaction coupling constant, G$_F$, via the relation

$$G_V = G_F g_V V_u d = G_F V_u d \tag{2.1}$$

since g$_V$ = 1 according to CVC. |V$_{ud}$|^2 can be obtained from:

$$|V_{ud}|^2 = \frac{K}{2G_F^2(1+\Delta_R^V)Ft} \tag{2.2}$$

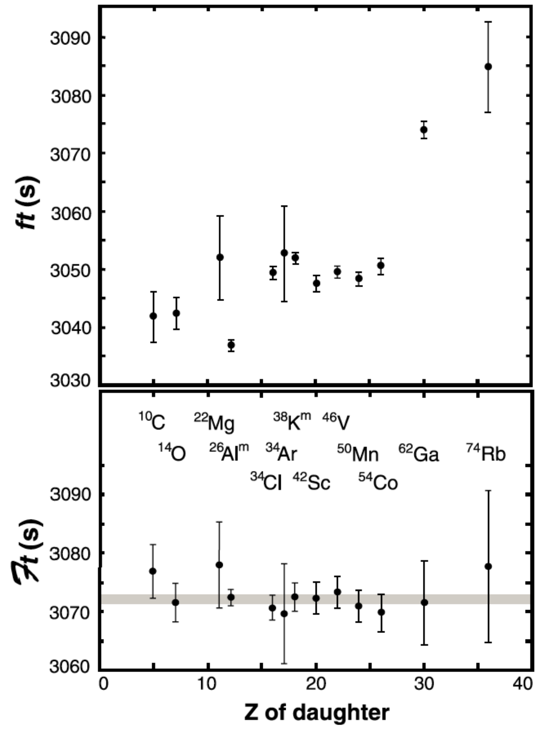

Figure 1: Display of ft (top) and *Ft* (bottom) as a function of the Z of the daughter nucleus.

where $K/(\hbar c)^6 = 2\pi^3\hbar \ln 2/(m_e c^2)^5 = 8120.2787(11)\times 10^{10}$ GeV^4 s and Δ_R^V is the transition-independent part of the radiative correction. The *Ft* value is defined in order to include several corrections to the ft-value of a superallowed transition. These corrections account for the isospin symmetrybreaking and the radiative effects:

$$Ft = ft(1+\delta_R^{'})(1+\delta_{NS}\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)} \tag{2.3}$$

where δ_C is the isospin-symmetry-breaking correction, δ_R and δ_{NS} comprise the transitiondependent part of the radiative correction. The first is a function only of the electron's energy and of the Z of the daughter nucleus, while the second, like δ_C, depends in its evaluation on the details of the nuclear structure of the parent and daughter states. All these correction terms are small, of order 1%, so equation (2.3) provides an experimental method for determining G_V, and thus V_{ud}. In a recent survey of world data [1], the ft values of thirteen superallowed transitions were obtained with high precision. Taking into accont all the correctons one obtain, see fig 1:

$$Ft = 3071.81 \pm 0.79_{stat} \pm 0.27_{syst} \text{ s.} \tag{2.4}$$

From equation (2.2)

$$|V_{ud}|^2 = 0.94916 \pm 0.00044 \tag{2.5}$$

$$|V_{ud}| = 0.97425 \pm 0.00022 \quad [\text{nuclear superallowed}] \tag{2.6}$$

Table 1: Results of fit to K_L BRs and lifetime. S is the scale factor applied to the error in order to obtain chi^2 = ndf.

Parameter	Value	S
BR(K_{e3})	0.4056(9)	1.3
BR($K_{\mu3}$)	0.2704(10)	1.5
BR($3\pi^0$)	0.1952(9)	1.2
BR($\pi^+\pi^-\pi^0$)	0.1254(6)	1.3
BR($\pi^+\pi^-$)	1.967(7) $\times 10^{-3}$	1.1
BR($\pi^+\pi^-\gamma$)	4.15(9) $\times 10^{-3}$	1.6
BR($\pi^+\pi^-\gamma_{DE}$)	2.84(8) $\times 10^{-5}$	1.3
BR($2\pi^0$)	8.65(4) $\times 10^{-4}$	1.4
BR($\gamma\gamma$)	5.47(4) $\times 10^{-4}$	1.1
τ_L	51.16(21) ns	1.1

Table 2: Results of fit to $K^\pm$ BRs and lifetime.

Parameter	Value	S
BR($K_{\mu2}$)	63.47(18)%	1.3
BR($\pi\pi^0$)	20.61(8)%	1.1
BR($\pi\pi\pi$)	5.73(16)%	1.2
BR(K_{e3})	5.078(31)%	1.2
BR($K_{\mu3}$)	3.359(32)%	1.9
BR($\pi\pi^0\pi^0$)	1.757(24)%	1.0
$\tau_\pm$	12.384(15) ns	1.2

3. Experimental data: BRs and lifetime

Numerous measurements of the principal kaon BRs, or of various ratios of these BRs, have been published recently. For the purposes of evaluating $|V_{us} f_+(0)|$, these data can be used in a PDG-like fit to the BRs and lifetime. A detailed description to the fit procedure and the references of all experimental input used can be found in Ref. [2].
For K_L the results are given in table 1, while table 2 gives the results for $K^\pm$.

For the K_S, the fit is dominated by the KLOE measurements of $BR(K_S \to \pi e\nu)$ and of $BR(\pi^+\pi^-)/BR(\pi^0\pi^0)$. These, together with the constraint that the K_S BRs must add to unity, and the assumption of universal lepton couplings, completely determine the K_S leading BRs. In particular, $\mathrm{BR}(K_S \to \pi e\nu) = 7.05(8)\times 10^{-4}$. For τ_{K_S} we use 8.959(6) $\times 10^{-11}$ s, where this is the non-*CPT* constrained fit value from the PDG, [3].

The fit takes into account the correlation between these values, as well as their dependence on the $K^\pm$ lifetime. The world average value for $\tau_\pm$ is nominally quite precise; the 2010 PDG quotes $\tau_\pm = 12.385(25)$ ns. However, the error is scaled by 2.1; the confidence level for the average is 0.17%. The two new measurements from KLOE [4] agree with the PDG average, and give

Table 3: Averages of quadratic fit results for K_{e3} and $K_{\mu 3}$ slopes.

	K_L and K^-
$\lambda'_+ \times 10^3$	25.02 ± 1.12
$\lambda''_+ \times 10^3$	1.57 ± 0.48
$\lambda_0 \times 10^3$	13.34 ± 1.41
$\rho(\lambda'_+, \lambda''_+)$	-0.95
$\rho(\lambda'_+, \lambda_0)$	$+0.376$
$\rho(\lambda''_+, \lambda_0)$	-0.573
$I(K^0_{e3})$	0.15457(20)
$I(K^\pm_{e3})$	0.15894(21)
$I(K^0_{\mu 3})$	0.10266(20)
$I(K^\pm_{\mu 3})$	0.10564(20)
$\rho(I_{e3}, I_{\mu 3})$	$+0.56$

a smaller scale factor to the $\tau_\pm$ value. The fit doesn't use the result from Lobkowicz. It's also important to stress that the fit doesn't use the BRs from Chiang.

4. Experimental data: $K_{\ell 3}$ form factors

The hadronic $K \to \pi$ matrix element of the vector current is described by two form factors (FFs), $f_+(t)$ and $f_0(t)$, defined by $\langle \pi^-(k)|\bar{s}\gamma^\mu u|K^0(p)\rangle = (p+k)^\mu f_+(t) + (p-k)^\mu f_-(t)$ and $f_-(t) = \frac{m_K^2 - m_\pi^2}{t}\left(f_0(t) - f_+(t)\right)$ where $t = (p-k)^2$.
By construction, $f_0(0) = f_+(0)$. In order to compute the phase space integrals we need experimental or theoretical inputs to determinate the t-dependence of FF. In principle, Chiral Perturbation Theory (ChPT) and Lattice QCD are useful tools to set theoretical constraints. However, in practice the t-dependence of the FFs at present is better determined by measurements and by combining measurements and dispersion relations. Many approaches have been used, and all have been described in detail in [2]. For K_{e3} decays, recent measurements of the quadratic slope parameters of the vector form factor $(\lambda'_+, \lambda''_+)$ are available from KTeV, KLOE, ISTRA+, and NA48.
The same collaborations recentely measured also the slope parameters $(\lambda'_+, \lambda''_+, \lambda_0)$ for $K_{\mu 3}$ decays Here we list only the averages of quadratic-lineal fit results for K_{l3} slopes (4) used to determine $|V_{us}| f_+(0)$. It is important to stress that the significance of the quadratic term in the vector form factor is strong for both K_{e3} (4.2σ) and $K_{\mu 3}$ (3.5σ) fit to all data.

5. Physics results

5.1 Determination of $|V_{us}| f_+(0)$ and $|V_{us}|/|V_{ud}| f_K/f_\pi$

The value of $|V_{us}| f_+(0)$ has been determined from the decay rate of kaon semileptonic decays:

$$\Gamma(K_{\ell 3(\gamma)}) = \frac{G_\mu^2 M_K^5}{192\pi^3} C_K S_{\rm ew} |V_{us}|^2 f_+(0)^2 \times \quad (5.1)$$

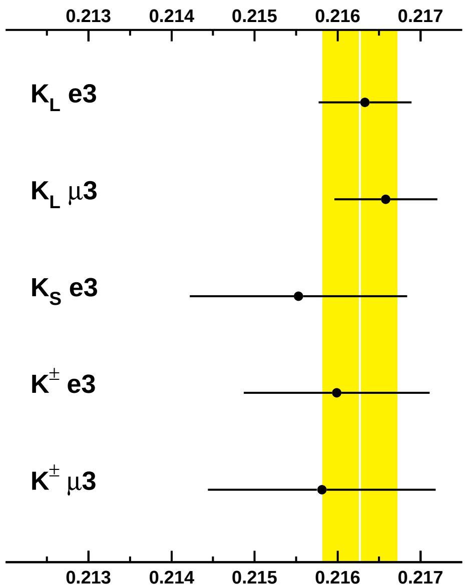

Figure 2: Display of $|V_{us}|f_+(0)$ for all channels.

mode	$\lvert V_{us}\rvert f_+(0)$	% err	BR	τ	Δ	Int
$K_L \to \pi e \nu$	0.2163(6)	0.26	0.09	0.20	0.11	0.06
$K_L \to \pi \mu \nu$	0.2168(7)	0.29	0.15	0.18	0.11	0.08
$K_S \to \pi e \nu$	0.2154(13)	0.61	0.60	0.03	0.11	0.06
$K^\pm \to \pi e \nu$	0.2173(8)	0.52	0.31	0.09	0.40	0.06
$K^\pm \to \pi \mu \nu$	0.2176(11)	0.63	0.47	0.08	0.39	0.08
average	0.2163(5)					

Table 4: Summary of $|V_{us}|f_+(0)$ determination from all channels.

$$I_K^\ell(\lambda_{+,0})\left(1+\delta^K_{SU(2)}+\delta^{K\ell}_{\rm em}\right)^2$$

using the world average values reported in previous sections for lifetimes, branching ratios and phase space integrals and the radiative and $SU(2)$ breaking corrections discussed in [2]. The results are shown in figure 2 and given in Table 4, for $K_L \to \pi e \nu$, $K_L \to \pi \mu \nu$, $K_S \to \pi e \nu$, $K^\pm \to \pi e \nu$, $K^\pm \to \pi \mu \nu$, and for the combination. The average, $|V_{us}|f_+(0) = 0.2163(5)$, has an uncertainty of about of 0.2%. The results from the five modes are in good agreement, the fit probability is 94%. In particular, comparing the values of $|V_{us}|f_+(0)$ obtained from $K^0_{\ell 3}$ and $K^\pm_{\ell 3}$ we obtain a value of the SU(2) breaking correction $\delta^K_{SU(2)_{exp.}} = 2.7(4)\%$ in agreement with the CHPT calculation $\delta^K_{SU(2)} = 2.9(4)\%$.

The test of Lepton Flavor Universality (LFU) between K_{e3} and $K_{\mu 3}$ modes constraints a possible anomalous lepton-flavor dependence in the leading weak vector current. It can therefore be compared to similar tests in τ decays, but is different from the LFU tests in the helicity-suppressed modes π_{l2} and K_{l2}. The results on the parameter $r_{\mu e} = R^{\rm Exp}_{K_{\mu 3}/K_{e3}}/R^{\rm SM}_{K_{\mu 3}/K_{e3}}$ is $r_{\mu e} = 1.002 \pm 0.005$, in excellent agreement with lepton universality. With a precision of 0.5% the test in K_{l3} decays has now reached the sensitivity of other determinations: $r_{\mu e}(\tau) = 1.000 \pm 0.004$ and $r_{\mu e}(\pi) =$

1.0042 ± 0.0033 [3]
An independent determination of V_{us} is obtained from $K_{\ell 2}$ decays. The most important mode is $K^+ \to \mu^+ \nu$, which has been recently updated by KLOE reaching a relative uncertainty of about 0.3%. Hadronic uncertainties are minimized considering the ratio $\Gamma(K^+ \to \mu^+ \nu)/\Gamma(\pi^+ \to \mu^+ \nu)$:

$$\frac{\Gamma(K^{\pm}_{\ell 2(\gamma)})}{\Gamma(\pi^{\pm}_{\ell 2(\gamma)})} = \left|\frac{V_{us}}{V_{ud}}\right|^2 \frac{f_K^2 m_K}{f_\pi^2 m_\pi} \left(\frac{1 - m_\ell^2/m_K^2}{1 - m_\ell^2/m_\pi^2}\right)^2 \times (1 + \delta_{\rm em})$$

Using the world average values of BR($K^{\pm} \to \mu^{\pm} \nu$) and of $\tau^{\pm}$ given in Section 3 and the value of $\Gamma(\pi^{\pm} \to \mu^{\pm} \nu) = 38.408(7)\ \mu s^{-1}$ from [3] we obtain: $|V_{us}|/|V_{ud}|\, f_K/f_\pi = 0.2758 \pm 0.0005$.

5.2 Theoretical estimates of $f_+(0)$ and f_K/f_π

The main obstacle in transforming these highly precise determinations of $|V_{us}|\, f_+(0)$ and $|V_{us}|/|V_{ud}|\, f_K/f_\pi$ into a determination of $|V_{us}|$ at the precision of 0.1%, are the theoretical uncertainties on the hadronic parameters $f_+(0)$ and f_K/f_π. By construction, $f_+(0)$ is defined in the absence of isospin-breaking effects of both electromagnetic and quark-mass origin. More explicitly $f_+(0)$ is defined by the $K^0 \to \pi^+$ matrix element of the vector current in the limit $m_u = m_d$ and $\alpha_{\rm em} \to 0$, keeping kaon and pion masses to their physical values. This hadronic quantity cannot be computed in perturbative QCD, but it is highly constrained by $SU(3)$ and chiral symmetry. In the chiral limit and, more generally, in the $SU(3)$ limit ($m_u = m_d = m_s$) the conservation of the vector current implies $f_+(0)$=1. Expanding around the chiral limit in powers of light quark masses we can write $f_+(0) = 1 + f_2 + f_4 + \ldots$ where f_2 and f_4 are the NLO and NNLO corrections in ChPT. The Ademollo-Gatto theorem implies that $(f_+(0) - 1)$ is at least of second order in the breaking of $SU(3)$ This in turn implies that f_2 is free from the uncertainties of the $\mathscr{O}(p^4)$ counter-terms in ChPT, and it can be computed with high accuracy: $f_2 = -0.023$. The difficulties in estimating $f_+(0)$ begin with f_4 or at $\mathscr{O}(p^6)$ in the chiral expansion. Several analytical approaches to determine f_4 have been attempted over the years, essentially confirming the original estimate by Leutwyler and Roos. The benefit of these new results, obtained using more sophisticated techniques, lies in the fact that a better control over the systematic uncertainties of the calculation has been obtained. However, the size of the error is still around or above 1%, which is not comparable to the 0.2% accuracy which has been reached for $|V_{us}|\, f_+(0)$.
Recent progress in lattice QCD gives us more optimism in the reduction of the error on $f_+(0)$ below the 1% level. Most of the currently available lattice QCD results have been obtained with relatively heavy pions and the chiral extrapolation represents the dominant source of uncertainty. There is a general trend of lattice QCD results to be slightly lower than analytical approaches. An important step in the reduction of the error associated to the chiral extrapolation has been recently made by the UKQCD-RBC10 collaboration. Their preliminary result $f_+(0) = 0.959(5)$ is obtained from the unquenched study with $N_F = 2 + 1$ flavors, with an action that has good chiral properties on the lattice even at finite lattice spacing (domain-wall quarks). They also reached pions masses (≥ 330 MeV) much lighter than that used in previous studies of $f_+(0)$. The overall error is estimated to be 0.5%, which is very encouraging.
In contrast to the semileptonic vector form factor, the pseudoscalar decay constants are not protected by the Ademollo-Gatto theorem and receive corrections linear in the quark masses. Expanding f_K/f_π in power of quark masses, in analogy to $f_+(0)$, $f_K/f_\pi = 1 + r_2 + \ldots$ one finds that

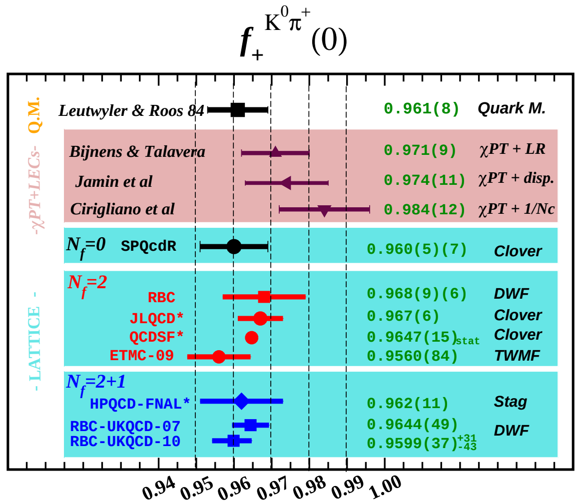

Figure 3: Some different ttheoretical estimate of $f_+(0)$ are shown.

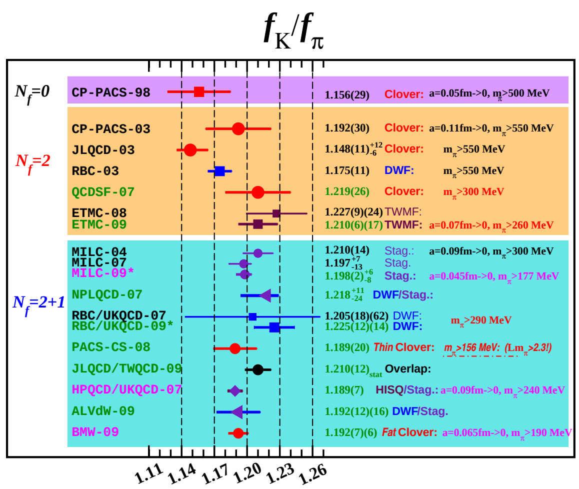

Figure 4: Some different ttheoretical estimate of f_K/f_π are shown.

the $\mathscr{O}(p^4)$ contribution r_2 is already affected by local contributions and cannot be unambiguously predicted in ChPT. As a result, in the determination of f_K/f_π lattice QCD has essentially no competition from purely analytical approaches. The present overall accuracy is about 1%. The novelty are the new lattice results with $N_F = 2+1$ dynamical quarks and pions as light as 280 MeV, obtained by using the so-called staggered quarks. These analyzes cover a broad range of lattice spacings (i.e. a=0.06 and 0.15 fm) and are performed on sufficiently large physical volumes ($m_\pi L \geq 5.0$). It should be stressed, however, that the sensitivity of f_K/f_π to lighter pions is larger than in the computation of $f_+(0)$ and that chiral extrapolations are far more demanding in this case. In the following analysis we will use as reference value average from the results of the analyses from BMW, MILC09 and the HPQCD/UKQCD result $f_K/f_\pi = 1.193(6)$.

5.3 Test of CKM unitarity

To determine $|V_{us}|$ and $|V_{ud}|$ we use the value $|V_{us}|f_+(0) = 0.2163(5)$, the result $|V_{us}|/|V_{ud}|f_K/f_\pi =$

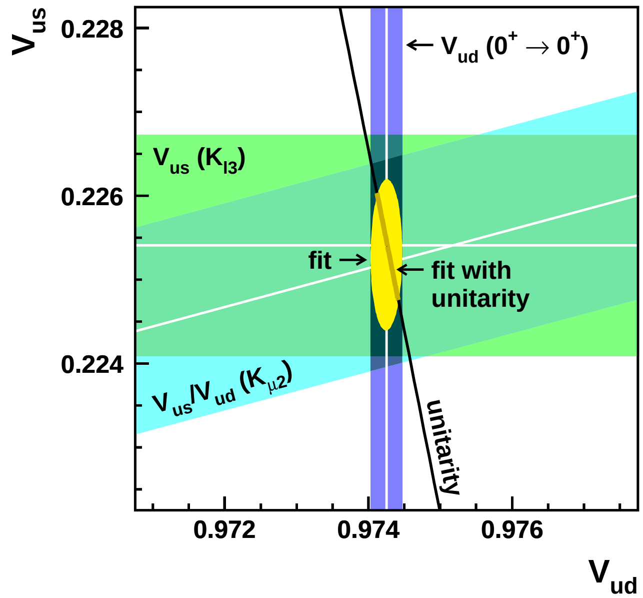

Figure 5: Results of fits to $|V_{ud}|$, $|V_{ux}|$, and $|V_{us}|/|V_{ud}|$.

$0.2758(5)$, $f_+(0) = 0.959(5)$, and $f_K/f_\pi = 1.193(6)$. From the above we find: $|V_{us}| = 0.2254 \pm 0.0013$ from $K_{\ell 3}$ only, and $|V_{us}|/|V_{ud}| = 0.2321 \pm 0.0013$ from $K_{\ell 2}$ only. These determinations can be used in a fit together with the the recent evaluation of V_{ud} from $0^+ \to 0^+$ nuclear beta decays: $|V_{ud}|$=0.97425±0.00022. This global fit gives $V_{ud} = 0.97425(22)$ and $V_{us} = 0.2253(9)$, with $\chi^2/\mathrm{ndf} = 0.014/1$ (91%). This result does not make use of CKM unitarity. If the unitarity constraint is included, the fit gives $V_{us} = 0.2254(6)$ and $\chi^2/\mathrm{ndf} = 0.024/2$ (99%). Both results are illustrated in Figure 5. The test of CKM unitarity can be also interpreted as a test of universality of the lepton and quark gauge couplings. Using the results of the fit (without imposing unitarity) we obtain: $G_{\mathrm{CKM}} \equiv G_\mu \left[|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2\right]^{1/2} = (1.16633 \pm 0.00035) \times 10^{-5}$ GeV^{-2}, in perfect agreement with the value obtained from the measurement of the muon lifetime: $G_\mu = (1.166371 \pm 0.000006) \times 10^{-5}$ GeV^{-2}. The current accuracy of the lepton-quark universality sets important constraints on model building beyond the SM. For example, the presence of a Z' would affect the relation between G_{CKM} and G_μ. In case of a Z' from $SO(10)$ grand unification theories we obtain $m_{Z'} > 700$ GeV at 95% CL, to be compared with the $m_{Z'} > 720$ GeV bound set through the direct collider searches [3]. In a similar way, the unitarity constraint also provides useful bounds in various supersymmetry-breaking scenarios.

5.4 $K_{\ell 2}$ sensitivity to new physics

A particularly interesting test is the comparison of the $|V_{us}|$ value extracted from the helicity-suppressed $K_{\ell 2}$ decays with respect to the value extracted from the helicity-allowed $K_{\ell 3}$ modes. To reduce theoretical uncertainties from f_K and electromagnetic corrections in $K_{\ell 2}$, we exploit the ratio $BR(K_{\ell 2})/BR(\pi_{\ell 2})$ and we study the quantity

$$R_{l23} = \left| \frac{V_{us}(K_{\ell 2})}{V_{us}(K_{\ell 3})} \frac{V_{ud}(0^+ \to 0^+)}{V_{ud}(\pi_{\ell 2})} \right| .$$

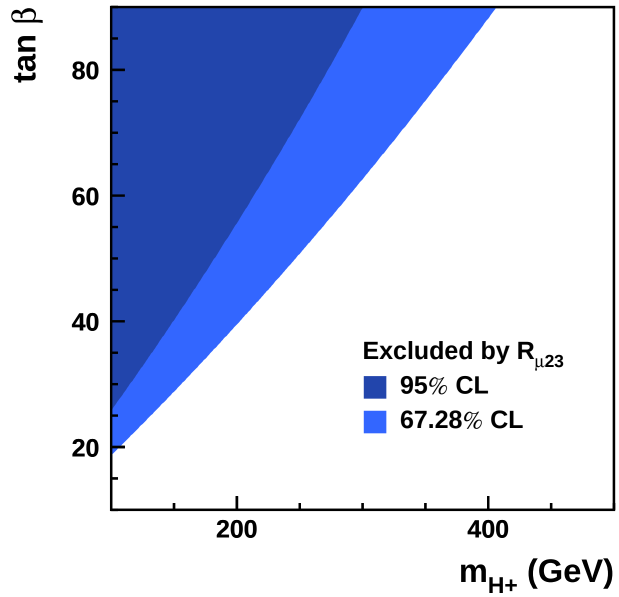

Figure 6: Excluded region in the charged Higgs mass-tan β plane. The region excluded by $B \to \tau\nu$ is also indicated.

Within the SM, $R_{l23} = 1$, while deviation from 1 can be induced by non-vanishing scalar- or right-handed currents. Notice that in R_{l23} the hadronic uncertainties enter through $(f_K/f_\pi)/f_+(0)$. In the case of effect of scalar currents due to a charged Higgs, the unitarity relation between $|V_{ud}|$ extracted from $0^+ \to 0^+$ nuclear beta decays and $|V_{us}|$ extracted from $K_{\ell 3}$ remains valid as soon as form factors are experimentally determined. This constrain together with the experimental information of $\log C^{MSSM}$ can be used in the global fit to improve the accuracy of the determination of R_{l23}, which in this scenario turns to be $R_{l23}|^{\rm exp}_{\rm scalar} = 0.999 \pm 0.007$. Here $(f_K/f_\pi)/f_+(0)$ has been fixed from lattice. This ratio is the key quantity to be improved in order to reduce present uncertainty on R_{l23}. This measurement of R_{l23} can be used to set bounds on the charged Higgs mass and $\tan\beta$. Figure 6 shows the excluded region at 95% CL in the M_H–$\tan\beta$ plane. The measurement of BR($B \to \tau\nu$) can be also used to set a similar bound in the M_H–$\tan\beta$ plane. While $B \to \tau\nu$ can exclude quite an extensive region of this plane, there is an uncovered region in the exclusion corresponding to a destructive interference between the charged-Higgs and the SM amplitude. This region is fully covered by the $K \to \mu\nu$ result.

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