$V_{us}$ and CP violation from kaon decays with the KLOE detector

KLOE collaboration\(^1\) presented by Patrizia de Simone

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Abstract. The KLOE experiment has provided precise measurements of the branching ratio of the main neutral and charged kaon decay modes, of the $K_L$ and the $K^\pm$ lifetimes, and of the $K_L$ vector and scalar form factors. We present a description of the above measurements and an overall fit of all our data, with particular attention to correlations. These data provide the basis for the determination of the value of the CKM matrix element $V_{us}$ and a test of the unitarity of the quark mixing matrix. In addition our first measurement of the charge asymmetry in $K_S$ semileptonic decays, $A_S$, gives us the possibility to contribute to the knowledge of $\Re(\varepsilon)$ and testing the CPT symmetry through the Bell Steinberger relation.

1. The KLOE experiment at DAΦNE

DAΦNE, the Frascati φ factory [1], is an $e^+e^-$ collider working at a center of mass energy of $\sqrt{s} \simeq m_\phi \simeq 1020$ MeV. The φ production cross section is $\sim 3 \mu$b. The beams collide at the interaction point (IP) with a crossing angle $\theta_x \simeq 25$ mrad, therefore the φ’s are produced with a small momentum of $\sim 12.5$ MeV in the horizontal plane, and decay in almost collinear and monochromatic neutral (34%) and charged (49%) kaon pairs.

The KLOE detector consists of a large volume drift chamber surrounded by an electromagnetic calorimeter. A superconducting coil provides a 0.52 T solenoidal magnetic field.

The tracking detector is a cylindrical drift chamber [2] (DC) 4 m diameter and 3.3 m long, with a total of $\sim 52000$ wires, of which $\sim 12000$ are sense wires. In order to minimize the multiple scattering and the $K_L$ regeneration, and to maximize the detection efficiency of low energy γ’s, the DC works with an helium based gas mixture and its walls are made of light materials (mostly carbon fiber composites). The momentum resolution for tracks produced at large polar angle is $\sigma_{p\perp}/p\perp \leq 0.4\%$. Charged particle vertices are reconstructed with a spatial resolution of $\sim 3$ mm [3].

The fine sampling lead-scintillating fiber calorimeter [4] (EMC) consists of a barrel and two end-caps, and has solid angle coverage of 98%. Photon energies and arrival times are measured

1. F Ambrosino, A Antonelli, M Antonelli, F Archilli, P Beltrame, G Bencivenni, S Bertolucci, C Bini, C Bloise, S Bocchetta, F Bossi, P Branchini, G Capon, T Capussela, F Ceradini, P Ciambrone, F Crucianelli, E De Lucia, A De Santis, P de Simone, G De Zorzi, A Denig, A Di Domenico, C Di Donato, B Di Micco, M Dreucci, G Felici, S Fiore, P Franzini, C Gatti, P Gauzzi, S Giovannella, E Graziani, G Lanfranchi, J Lee-Franzini, D Leone, M Martini, P Massarotti, S Meola, S Miscetti, M Moulson, S Müller, F Murtaas, M Napolitano, F Nguyen, M Palutan, E Pasqualucci, A Passeri, V Patera, F Perfetto, P Santangelo, B Sciascia, T Spadaro, M Testa, L Tortora, P Valente, G Venanzoni, R Versaci, G Xu

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with resolutions \( \sigma_E/E = 5.7\%/\sqrt{E\text{(GeV)}} \) and \( \sigma_l = 57\text{ps}/\sqrt{E\text{(GeV)}} \pm 100\text{ps} \), respectively. Photon entry points are determined with an accuracy \( \sigma_z \sim 1 \text{ cm}/\sqrt{E\text{(GeV)}} \) along the fibers and \( \sigma_r \sim 1 \text{ cm} \) in the transverse direction.

The unique feature of a \( \phi - \text{factory} \) is the possibility of tagging. Specifically the detection of a \( K_L \) (\( K_S \)) guarantees the presence of a \( K_S \) (\( K_L \)) with known momentum and direction, the same holds for charged kaons pairs. The availability of tagged kaons enables the precision measurement of absolute BR’s.

The \( K_L \) beam is identified by the presence of a decay \( K_S \rightarrow \pi^+\pi^- \). The \( K_L \) momentum is given by the decay kinematics of \( \phi \rightarrow K_LK_S \) using the reconstructed \( K_S \) direction and the small velocity \( v_\phi \) of the \( \phi \) (\( v_\phi \) reconstructed run by run with the Bhabha events). The \( K_S \) beam is identified by a \( K_L \) interacting in the EMC called \( K_L \)-crash. A \( K_L \)-crash has a very clear signature consisting of a high energy (\( E \gtrsim 100 \text{ MeV} \)) deposit in the calorimeter not associated to tracks and with low velocity \( \beta_{K_L} \approx 0.22 \). Furthermore the momentum and the direction of the \( K_S \) is given by the kinematics of the \( \phi \) decay. The selection of the \( K^\pm \) beam is done reconstructing the 2 body decays \( K^\pm \rightarrow \pi^\pm\pi^0 \) and \( K^\pm \rightarrow \mu^\pm\bar{\nu}(\nu) \). These decays are identified from two clear peaks in the momentum of the charged secondary tracks in the kaon rest frame.

KLOE completed the data taking in March 2006 with a total integrated luminosity of \( \approx 2.5 \text{ fb}^{-1} \), corresponding to \( \approx 7.5 \times 10^9 \phi \)-mesons produced.

2. \( |V_{us}| \) measurement with kaons

In the Standard Model (SM) transition rates of semileptonic processes such as \( u \rightarrow d\bar{\nu}l \), with \( u \rightarrow (d) \) being a generic up (down) quark, can be computed in terms of the Fermi coupling \( G_F \) and the elements \( V_{ij} \) of the Cabibbo Kobayashi Maskawa (CKM) matrix [5] [6]. Measurements of the transition rates provide therefore precise determinations of the fundamental couplings of the SM.

Thanks to the smallness of \( |V_{ub}| \) (\( |V_{ub}|^2 \approx 1.5 \times 10^{-5} \) [20]) and the high-precision of \( |V_{ud}| \) [7], we can test at the per-mil level the unitarity relation

\[ |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \]  

(1)

if we measure \( |V_{us}| \) at the sub-percent level of accuracy. Beside testing the unitarity of the CKM matrix, which is naturally satisfied in the SM and in most of its extensions, the main interest hidden in relation 1 is a very stringent test of the universality of weak interactions. When extracting the \( V_{ij} \) from a given semileptonic process, the corresponding rate is normalized to \( G_F^{(\mu)} \), the Fermi coupling determined from the muon decay. As a result, testing the unitarity relation 1 is equivalent testing the universality of weak interactions between quarks and leptons.

Recently a significant large amount of data has been collected by several experiments: BNL-E865, KLOE, KTeV, ISTRA+ and NA48. Among these experiments KLOE is the only one that can at once measure the complete set of experimental inputs, branching ratios, lifetime and form factor parameters for the calculation of \( |V_{us}| \) from both charged kaons and \( K_L \)’s. In addition KLOE is the only experiment that can measure \( K_S \) branching ratios at the sub-percent level. The measurements on kaon decays published by KLOE before the 2007 are listed in Table 1.

In the following, the measurements related to \( |V_{us}| \) recently published by KLOE, are described with some detail.

2.1. \( K^\pm \) semileptonic decays

The measurement of the inclusive \( \text{BR}(K_S^{\pm}) \)'s uses four independent samples tagged by the decays: \( K_{\mu^2}, K_{\nu^2}, K_{\pi^2}^{\pm}, K_{\pi^0}^{\pm} \) (6 \( \times 10^7 \) events).

The signal selection asks for a decay vertex in the DC volume. Kinematical cuts are used to reject the non-semileptonic decays. To distinguish between \( K_{e3} \) and \( K_{\mu3} \) decays we evaluate
We have measured the $K^\pm K^{2.2.}$
by $K^{[13]}$: 

The importance to measure the absolute branching ratio of the $2.3. \ BR(K^\pm\pi^\pm\rho)$
given a statistical correlation of $T$ is:
are measured directly on data by means of the 

vertex reconstruction efficiency and the resolution functions 
are measured (we require the charged decay track to point to an energy deposit in EMC).

The BR is evaluated separately for each tag sample, and averaged accounting for correlations $[13]$: 

$$\begin{align*}
BR(K_{L3}^\pm) &= 0.4008(15) & 13 \times 10^6 & K_L \ \text{decays tagged by } K_S \to \pi^+\pi^-[8] \\
BR(K_{L3}^\pm) &= 0.2699(14) & \\
\tau_L &= 50.92(30) \ \text{ns} & 8.5 \times 10^6 & K_L \to 3\pi^0 \ \text{decays tagged by } K_S \to \pi^+\pi^-[9] \\
\lambda_L' \times 10^3 &= 25.5 \pm 1.8 & 2 \times 10^6 & K_{L3} \ \text{decays tagged by } K_S \to \pi^+\pi^-[10] \\
\lambda_L'' \times 10^3 &= 1.4 \pm 0.8 & \\
BR(K_{S3}) &= 7.046(91) \times 10^{-4} & 1.2 \times 10^8 & K_S \ \text{decays tagged by } K_L \ -\text{crashes}[11] \\
BR(K_{S2}^\pm) &= 0.6366(17) & 4.2 \times 10^6 & K^\pm \ \text{decays tagged by } K_{S2}^\pm[12] \\
\end{align*}$$

Table 1. KLOE measurements published before the 2007.

| Measurement | Result          | Sample                                      |
|------------|-----------------|---------------------------------------------|
| BR($K_{L3}^\pm$) | 0.4008(15)      | 13$ \times 10^6$ K_L decays tagged by $K_S \to \pi^+\pi^-$[8] |
| BR($K_{L3}^\pm$) | 0.2699(14)      |                                           |
| $\tau_L$    | 50.92(30) ns    | 8.5$ \times 10^6$ K_L $\to$ 3$\pi^0$ decays tagged by $K_S \to \pi^+\pi^-$[9] |
| $\lambda_L' \times 10^3$ | 25.5$ \pm 1.8$ | 2$ \times 10^6$ K_{L3} decays tagged by $K_S \to \pi^+\pi^-$[10] |
| $\lambda_L'' \times 10^3$ | 1.4$ \pm 0.8$ |                                           |
| BR($K_{S3}$) | 7.046(91)$ \times 10^{-4}$ | 1.2$ \times 10^8$ K_S decays tagged by $K_L$ -crashes[11] |
| BR($K_{S2}^\pm$) | 0.6366(17)      | 4.2$ \times 10^6$ K^\pm decays tagged by $K_{S2}^\pm$[12] |

the lepton mass, $m_{\text{lept}}^2$, from the velocity of the lepton, obtained with time-of-flight (ToF) measurements (we require the charged decay track to point to an energy deposit in EMC).

The number of $K_{S3}$ and $K_{S2}$ decays is then obtained by fitting the $m_{\text{lept}}^2$ distribution to a sum of MC distributions for the signals and residual background sources. The selection efficiency is evaluated from the MC, and corrections are applied to account for data-MC differences in tracking and clustering.

The BR is evaluated separately for each tag sample, and averaged accounting for correlations $[13]$: 

$$\begin{align*}
BR(K_{L3}^\pm) &= 0.4965 \pm 0.00038_{\text{stat}} \pm 0.00037_{\text{syst}} \\
BR(K_{S2}^\pm) &= 0.0323 \pm 0.00029_{\text{stat}} \pm 0.00026_{\text{syst}} \\
\end{align*}$$

2.2. K^\pm lifetime

We have measured the K^\pm lifetime using two different methods, both require a sample tagged by $K_{S2}$ decays and a charged decay vertex reconstructed in the DC ($15 \times 10^6$ events).

With the first method we measure the kaon proper time stepping along the kaon path, taking into account the energy losses. The vertex reconstruction efficiency and the resolution functions are measured directly on data by means of the $\pi^0$ vertex reconstruction using only calorimetric informations. The measured value is:

$$\tau(K^\pm) = 12.364 \pm 0.031_{\text{stat}} \pm 0.031_{\text{syst}} \ \text{ns.}$$

With the second method we measure the kaon decay time using a sample of kaon decays with a $\pi^0$ in the final state. From each ToF measurement of $\gamma$ we evaluate the kaon proper time (the time of the event $T_0$ has been evaluated following the decay paths of the tag decay). The result is:

$$\tau(K^\pm) = 12.337 \pm 0.030_{\text{stat}} \pm 0.020_{\text{syst}} \ \text{ns.}$$

Given a statistical correlation of $\rho=30.7\%$, the weighted mean is $[14]$: 

$$\tau(K^\pm) = 12.347 \pm 0.030 \ \text{ns}$$

2.3. BR($K^+ \to \pi^+\pi^0(\gamma)$)

The importance to measure the absolute branching ratio of the $K^+ \to \pi^+\pi^0(\gamma)$ decay ($K_{\pi2}$) is twofold: i) the most recent measurement, BR($K_{\pi2}$)$=0.2118\pm0.0028$, dates back to more than 30 years ago $[15]$, and ii) this BR is fundamental for BR($K_{\pi3}$) measurements normalized to BR($K_{\pi2}$) $[16]$, $[17]$ and used to measure the CKM matrix element $V_{us}$. The normalization sample used to measure the BR($K_{\pi2}$) is given by events tagged by $K^- \to \mu^-\nu$, and $K^- \to \pi^-\pi^0$ decays ($12 \times 10^6$ events).

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The signal count comes from the fit of the distribution of the momentum of the charged decay particle in the kaon rest frame, $p^*$, evaluated assuming the pion mass. The fit to the $p^*$ distribution is done using three contributions: $K_{\pi 2}$, $K_{\rho 2}$, and three bodies decays. The shapes of $K_{\pi 2}$ and $K_{\rho 2}$ components are obtained from data control samples selected using EMC information only. MC distribution is used for the three bodies decays. The reconstruction and selection efficiency has been evaluated on data from a control sample selected using EMC information only, to avoid correlation with the DC driven sample selection.

The weighted average, accounting for correlations, of the absolute branching ratios obtained using the samples tagged by $K_{\rho 2}$ and $K_{\pi 2}$ decays is a measurement with 4.6 per mil accuracy [18]:

$$BR(K_{\pi 2}^+) = 0.2065 \pm 0.0005_{\text{stat}} \pm 0.0008_{\text{syst}}.$$ 

The value reported is shifted by $-1.3\%$ ($\sim 2\sigma$) with respect to the PDG06 fit value [19], and has a 20% improvement in the fractional accuracy.

2.4. $K_{L\mu 3}$ form factor slopes

A data sample corresponding to $\sim 400\text{ pb}^{-1}$ has been analyzed. The $K_{L\mu 3}$ events are selected requiring a $K_L$ of known momentum and direction, tagged by $K_S \rightarrow \pi^+\pi^-\pi^0$ decay. In a fiducial volume extending to $\sim 0.4\lambda_L$, two-tracks decay vertices are selected around the $K_L$ line of flight. The background due to $K_L \rightarrow \pi e\nu$, $\pi^+\pi^-\pi^0$, and $\pi^+\pi^-$ is rejected by cutting on different combinations of $E_{\text{miss}}$ and $P_{\text{miss}}$ variables, where $E_{\text{miss}}$ is evaluated in different masses hypothesis for the secondary particles. The same variables are used to select the signal. A further reduction of the background at the level of $\sim 1.5\%$ is obtained using neural network and ToF techniques. The standard method to extract the scalar slope $\lambda_0$ is a fit to the $t$ spectrum, where $t$ is the momentum transfer. Because pure and efficient $\pi - \mu$ separation is difficult to achieve at low energies, we measure $\lambda_0$ through a fit of the neutrino energy $E_\nu$ distribution, which can be evaluated through a Lorentz transformation of the missing momentum $P_{\text{miss}}$ in the $K_L$ rest frame. We perform a combined fit of the neutrino energy spectrum with $K_{L\mu 3}$ results for the vector form factor slopes $\lambda'_+$, $\lambda''_+$ [10] to recover some loss of sensitivity. The results are [21]:

$$\lambda'_+ = (25.6 \pm 1.5_{\text{stat}} \pm 0.9_{\text{syst}}) \times 10^{-3}$$

$$\lambda''_+ = (1.5 \pm 0.7_{\text{stat}} \pm 0.4_{\text{syst}}) \times 10^{-3}$$

$$\lambda_0 = (15.4 \pm 1.8_{\text{stat}} \pm 1.3_{\text{syst}}) \times 10^{-3}$$

We did not measure simultaneously the linear $\lambda'_0$ and the quadratic $\lambda''_0$ terms of the scalar form factor because of their high correlation $\rho(\lambda'_0,\lambda''_0) = -99.96\%$ ($\rho(\lambda'_+,\lambda''_+) = -97.6\%$). However, use of the linear rather than the quadratic parametrization overestimates $\lambda_0$ by $\sim 20\%$. To clarify this situation, it is necessary a parametrization of the form factors with at least $t$ and $t^2$ terms but with only one parameter. A dispersive relation twice-subtracted at $t = 0$ and at $t = \Delta_{K\pi} = (m_K^2 - m_\pi^2)$ (known as the Callan-Treiman point), has been recently proposed [22]:

$$f_0(t) = \exp\left[\frac{t}{\Delta_{K\pi}}\log(C - G(t))\right]$$

such that $C = f_0(\Delta_{K\pi})$ and $f_0(0) = 1$. $G(t)$ is derived from $K\pi$ scattering data. The parameter $C$ is related to the form factor slopes, and we evaluate that fitting our $K_{L\mu 3}$ data with a $3^{rd}$ order expansion of the dispersive relation 2:

$$\lambda_+ = (25.7 \pm 0.6_{\text{stat+syst}}) \times 10^{-3}$$
\[ \lambda_0 = (14.0 \pm 2.1_{\text{stat+syst}}) \times 10^{-3} \]

Recently the measurement of the \( K_{L\mu3} \) form factor slopes has been updated using 1 fb\(^{-1} \) of the KLOE data set. The preliminary results are:

\[ \lambda_+ = (26.0 \pm 0.5_{\text{stat+syst}}) \times 10^{-3} \]
\[ \lambda_0 = (15.1 \pm 1.4_{\text{stat+syst}}) \times 10^{-3} \]

2.5. \( |V_{us}f_+(0)| \)

Semileptonic kaon decays offer a clean way to extract an accurate value of \( |V_{us}| \), the decay rates are given by:

\[ \Gamma_i(K \rightarrow \pi \nu(\gamma)) = \frac{G_F^2 M_K^5}{192\pi^3} C_i S_{EW} |V_{us}|^2 |f_+(0)|^2 I_i(\lambda) \left( 1 + \delta_{SU(2)}^i + \delta_{em}^i \right) \]  

(3)

where the index \( i \) runs over the 5 modes \((i = K_{L\mu3}, K_{L\mu3}^0, K_{S\tau3}, K_{e\tau3}, K_{\mu\tau3})\). \( I_i \) is the phase space integral that is a function of the vector and the scalar form factors. \( S_{EW} = 1.0232(3) \) is the universal short-distance radiative correction [23]. \( \delta_{em} \) and \( \delta_{SU(2)} \) are the long-distance electromagnetic and strong isospin-breaking corrections respectively. \( f_+(0) \equiv f_+^{K^0\pi^-}(0) \) is the vector form factor at zero momentum transfer which encodes the SU(3) breaking effects in the hadronic matrix element. Differences between the various semileptonic decay modes are due to isospin breaking effects, both of strong and electromagnetic origin. Finally the Fermi coupling constant \( G_F \) is related to the gauge coupling \( g \) by \( G_F = g^2/(4\sqrt{2} M_W^2) \), and assuming lepton universality, the muon decay rate provides the value \( G_F = 1.16637(1) \times 10^{-5} \text{ GeV}^{-2} \) [20].

To extract the value of \( |V_{us}| \) from eq.3 we need not only accurate experimental values for the \( \Gamma_i \) (evaluated from the \( \gamma \)-inclusive BR’s and from the kaon lifetimes) and the parameters describing the \( t \)-dependence of the vector and scalar form factors, but also the theoretical estimates of the \( \delta \)’s and \( f_+^{K^0\pi^-}(0) \).

| Mode       | \( |V_{us}f_+(0)| \) |
|------------|---------------------|
| \( K_{Le3} \) | 0.2155(7)          |
| \( K_{L\mu3} \) | 0.2167(9)          |
| \( K_{S\tau3} \) | 0.2152(14)        |
| \( K_{e\tau3}^\pm \) | 0.2152(13)       |
| \( K_{\mu\tau3}^\pm \) | 0.2132(15)       |
| **Average** | **0.2157(6)**      |

At KLOE we extract \( |V_{us}|f_+^{K^0\pi^-}(0) \) from both neutral and charged kaon modes, allowing for a consistency check between experiment and theory: the values are listed in Table 2. The five different determinations have been averaged, taking into account all known correlations[24]. We find \( |V_{us}f_+(0)| = 0.2157(6) \) with \( \chi^2/\text{ndf} = 7.0/4(13\%) \). The only external input to this analysis is the \( K_S \) lifetime.

The RBC and UKQCD collaborations have recently obtained \( f_+(0) = 0.961(5) \) from lattice calculations [25]; using this value our \( K_{L\mu3} \) results give \( |V_{us}| = 0.2237(13) \). A recent evaluation of \( |V_{ud}| \) from 0\(^+\)\(-\)0\(^+\) nuclear beta decays results is \( |V_{ud}| = 0.97418(26) \) [7], which combined with our result above, gives \( \Delta = 1 - |V_{ud}|^2 - |V_{us}|^2 = 0.0009(8) \), that verifies unitarity to \( \sim 0.1\% \).
2.6. $|V_{us}|/|V_{ud}|$ and sensitivity to charged Higgs from $K_{\mu 2}$ decay

Recent advances in lattice gauge techniques have allowed the evaluation of the ratio of the pseudoscalar decay constants $f_{\pi}$ and $f_K$. As a consequence, the $K_{\mu 2}$ partial decay rate provides an alternative method for the determination of $|V_{us}|$ via:

$$\frac{\Gamma(K \rightarrow \mu \nu(\gamma))}{\Gamma(\pi \rightarrow \mu \nu(\gamma))} \propto \frac{|V_{us}|^2 f_K^2}{|V_{ud}|^2 f_\pi^2}$$  \hspace{1cm} (4)

From our measurement of $BR(K^+ \rightarrow \mu^+ \bar{\nu}(\gamma))$ [12] and using the recent lattice determination of $\frac{f_K}{f_\pi}$ from the HPQCD/UKQCD collaboration $\frac{f_K}{f_\pi} = 1.189(7)$[26], we obtain $|V_{us}|/|V_{ud}| = 0.2321(13)$. This ratio can be used in a fit together with the values of $|V_{us}|$ from the KLOE $K_{\ell 3}$ results and $|V_{ud}|$ from Ref.[7] (see fig 1). The fit yields $|V_{us}|^2 = 0.0506(4)$ and $|V_{ud}|^2 = 0.9490(5)$ with a $\chi^2/\text{ndf}=2.3/1$ (13%). These values confirm the unitarity of the CKM quark mixing matrix as applied to the first row. We find $\Delta = 0.0004(7)$ which is compatible with unitarity at $\sim 0.6 \, \sigma$ level.

![Figure 1. KLOE results for $|V_{us}|^2$ and $|V_{us}|^2/|V_{ud}|^2$, together with $|V_{ud}|^2$ from $\beta$-decay measurements. The ellipse is the 1$\sigma$ contour from the fit. The unitarity constraint is illustrated by the dashed line.](image)

A particularly interesting test is the comparison between the values for $|V_{us}|$ obtained from helicity-suppressed $K_{\ell 2}$ decays and helicity-allowed $K_{\ell 3}$ decays. To reduce theoretical uncertainties and make use of the results discussed above, we exploit the ratio $BR(K_{\mu 2})/BR(\pi_{\mu 2})$ and study the quantity

$$R_{l23} = \frac{V_{us}(K_{\mu 2})}{V_{us}(K_{\ell 3})} \frac{V_{ud}(0^{+} \rightarrow 0^{+})}{V_{ud}(\pi_{\mu 2})}$$ \hspace{1cm} (5)

Within the SM, $R_{l23} = 1$, while deviations from 1 can be induced by non-vanishing scalar or right-handed currents. A scalar current due to a charged Higgs exchange is expected to lower the value of $R_{l23}$ [27], that becomes

$$R_{l23} = \left| 1 - \frac{m_{K^+}^2}{m_{H^+}^2} \left( 1 - \frac{m_{\pi^+}^2}{m_{K^+}^2} \right) \frac{\tan^2 \beta}{1 + \epsilon_0 \tan \beta} \right|$$ \hspace{1cm} (6)

where $\tan \beta$ is the ratio of the two Higgs vacuum expectation values in the Minimal Super Symmetric Model (MSSM), and $\epsilon_0 \sim 0.01$ [28]. Any effects of scalar currents on $0^+ \rightarrow 0^+$ nuclear transitions and $K_{\ell 3}$ decays are expected to be insignificant and $|V_{us}|$ and $|V_{ud}|$ as estimated from these modes are assumed to satisfy the unitarity condition, the only sizable effects are expected to come from the $K_{\mu 2}$ decays. To evaluate $R_{l23}$, we fit our data on $K_{\mu 2}$ and $K_{\ell 3}$ decays, using the lattice determinations of $f_+(0)$ and $f_K/f_\pi$ and the value of $|V_{ud}|$ discussed
above as input. We obtain $R_{l23} = 1.008(8)$. This measurement places bounds on the charged Higgs mass and $\tan\beta$.

The figure 2 shows the region (grey) in the $m_{H^+} - \tan\beta$ plane excluded at 95% CL by our result of $R_{l23}$. Measurements of BR($B\to\tau\nu$) [29] also set bounds (dashed region), as shown in figure 2.

2.7. Lepton universality in $K_{l3}$ decays

The values of $|V_{us}f_+(0)|$ obtained from our measurements on $K_{e3}$ and $K_{\mu3}$ decays can be used to test the universality of $e$ and $\mu$ couplings to the $W$ boson. From equation 3

$$r_{\mu e} = \frac{g_\mu^2}{g_e^2} = \frac{|V_{us}f_+(0)|^2_{\mu,\text{exp}}}{|V_{us}f_+(0)|^2_{e,\text{exp}}} = \frac{\Gamma_{\mu3} I_{\gamma3}(1 + \delta_{SU(2)} + \delta_{em})_e}{\Gamma_{e3} I_{\mu3}(1 + \delta_{SU(2)} + \delta_{em})_\mu}$$

where $g_l$ is the coupling strength at the $W\to l\nu$ vertex. In the SM, $r_{\mu e} = 1$. Averaging between charged and neutral modes, we find $r_{\mu e} = 1.000(8)$. The sensitivity of this result may be compared with that obtained for $\pi\to l\nu$ decays, $(r_{\mu e})_\pi = 1.0042(33)$ [30], and for leptonic $\tau$ decays, $(r_{\mu e})_\tau = 1.000(4)$ [20].

3. CP and CPT test from unitarity

The Bell-Steinberger relation [31] assumes the conservation of unitarity and provides a link between the $CP$ violation parameter $\text{Re}(\epsilon)$, the $CPT$ violating parameter $\text{Im}(\delta)$ and the physical kaon decay amplitudes:

$$\left(\frac{\Gamma_S + \Gamma_L}{\Gamma_S - \Gamma_L} + i \tan \phi_{SW}\right) \left(\frac{\text{Re}(\epsilon)}{1 + |\epsilon|^2} - i \text{Im}(\delta)\right) = \frac{1}{\Gamma_S - \Gamma_L} \sum_f A_L(f)A_S^*(f)$$

where $A_S(f)$ and $A_L(f)$ are the physical $K_S$ and $K_L$ decay amplitudes, and $\phi_{SW} = \arctan \left(2(m_L - m_S)/(\Gamma_S - \Gamma_L)\right)$. The advantage of the neutral kaon system is that only the $\pi\pi\pi$ and $\pi l\nu$ decay modes give significant contributions to the right-hand side of eq. 8.

Recently, we published improved results for $\text{Re}(\epsilon)$ and $\text{Im}(\delta)$ using eq. 8 and our measurements of neutral kaon decays [32]. Our analysis benefits in particular from three measurements: i) the branching ratio for $K_L \to \pi^+\pi^-$ [33], which is relevant for the
The determination of $\text{Re}(\epsilon)$; ii) the new upper limit on $\text{BR}(K_S \to 3\pi^0)$ [34], which is necessary to improve the accuracy on $\text{Im}(\delta)$; and iii) the measurement of the $K_S$ semileptonic charge asymmetry $A_S$ [11], which allows, for the first time, the complete determination of the direct contribution from semileptonic channels, without assuming unitarity.

Inserting all of the information in eq. 8 we finally obtain:

\[
\text{Re}(\epsilon) = (159.6 \pm 1.3) \times 10^{-5} \quad \text{Im}(\delta) = (0.4 \pm 2.1) \times 10^{-5}
\]  

The allowed region in the $\text{Re}(\epsilon)$, $\text{Im}(\delta)$ plane at 68% CL and 95% CL is shown in figure 3, left.

The limits on $\text{Im}(\delta)$ and $\text{Re}(\epsilon)$ can be used to constrain the mass and width difference between $K^0$ and $\bar{K}^0$ via

\[
\delta = \frac{i(m_{K^0} - m_{\bar{K}^0}) + \frac{1}{2}(\Gamma_{K^0} - \Gamma_{\bar{K}^0})}{\Gamma_S - \Gamma_L} \cos\phi_{SW} e^{i\phi_{SW}} [1 + \mathcal{O}(\epsilon)]
\]  

The allowed region in the $\Delta M = (m_{K^0} - m_{\bar{K}^0})$, $\Delta \Gamma = (\Gamma_{K^0} - \Gamma_{\bar{K}^0})$ plane is shown in figure 3, right. Since the total decay widths are dominated by long-distance dynamics, in models where $CPT$ invariance is a pure short-distance phenomenon, it is useful to consider the limit $\Gamma_{K^0} = \Gamma_{\bar{K}^0}$. In this limit, neglecting $CPT$–violating effects in the decay amplitudes, we obtain the following bound on the neutral kaon mass difference:

\[-5.3 \times 10^{-19} \text{ GeV} < m_{K^0} - m_{\bar{K}^0} < 6.3 \times 10^{-19} \text{ GeV} \quad \text{at 95% CL.}
\]

4. Conclusions

We have measured with very good accuracy all the main $K_S$, $K_L$, and $K^\pm$ BRs, the $K_L$ and $K^+$ lifetimes, and the form factor slopes for semileptonic $K_L$ decays. We obtain $|V_{us} f_+(0)| = 0.2157(6)$ from a weighted average of the determinations for the neutral and charged semileptonic kaon decay modes.

From our measurement of the $K_{\mu2}$ decay rate, we obtain $\frac{|V_{us}|^2}{|V_{ud}|^2} \times \frac{f_+}{f^-} = 0.7650 \pm 0.0033$.

Using recent lattice determination for the meson form factors, we obtain $|V_{us}| = 0.2237(13)$ and $|V_{us}|/|V_{ud}| = 0.2321(13)$. We perform a fit to combine these values with the most recent
evaluation of $|V_{ud}|$ from nuclear $\beta$ decay. The result satisfies the first-row CKM unitarity condition to within $0.6 \sigma$.

Using the values of $|V_{us}|$ obtained from data on $K_{\mu2}$ and $K_{l3}$ decays, we are able to exclude a large region in the $m_{H^+} - \tan \beta$ plane. The bounds from our measurements are complementary to those from results on $(B \rightarrow \tau \nu)$ decays.

We have also tested lepton universality in $K_{l3}$ decays, $r_{\mu e} = 1.000 \pm 0.008$.

The Bell-Steinberger relation is a very powerful tool to probe some of the basic principles of the fundamental interactions: CP and CPT symmetries. Using our measurements of neutral kaon decays, we obtained values for $\text{Re}(\epsilon)$ and $\text{Im}(\delta)$, improved by a factor of two with respect to previous best determinations.

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