Strange Quark Physics at Sixty-Four

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1 Introduction

At a point in time, sixty-four years after the first observation of strange particle by Le Prince Ringuet in the decay of a charged kaon in a cloud chamber [1], strange quark physics is still remarkably robust. The high statistics and precision measurements that are now possible lend themselves to searches for new physics.

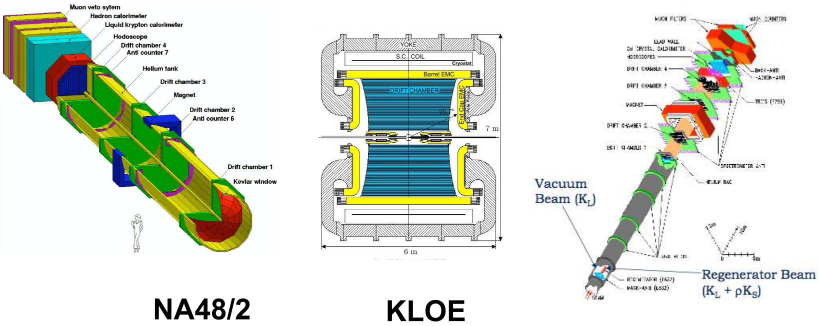
There are too many new results in the recent past to cover all the new measurements that deserve attention in this paper. New results in the following areas that have been recently reported and are included in this paper:

- CP violation.
- searches for lepton flavor violation in neutral kaon decays.
- e,μ universality and new physics in kaon decays.
- V_{us} measurements.

Due to lack of space, beautiful results on quantum coherence and CUSP measurements in kaon decay will not be covered. Lack of space also precludes inclusion of many excellent results bearing on chiral perturbation theory.

The majority of the new results are due to three experiments, KTeV, NA48/2, and KLOE, diagrams of which are shown in Fig. 1. In addition, we are just beginning to see the first results from E391a shown in Fig. 2 (soon to upgraded to experiment E14 at J-PARC). This is the first dedicated experiment designed to search for $K_L \to \pi^0 \nu \bar{\nu}$. The NA48/2 experiment is expected to be followed by NA62 and the KLOE experiment by KLOE II in the future. The future for kaon physics in the US is much more problematic, given the status and priority of the Project X kaon initiative at Fermilab.

With the large statistics and precision measurements of the present generation of experiments, we can ask the question of whether there are any hints of new physics of any kind and if not, do we have a problem developing from the lack of any such evidence at this time. While each high sensitivity search or measurement must be judged on its own merits, as compared with theoretical expectations for new physics levels, a problem with the non-appearance of new physics may be developing.

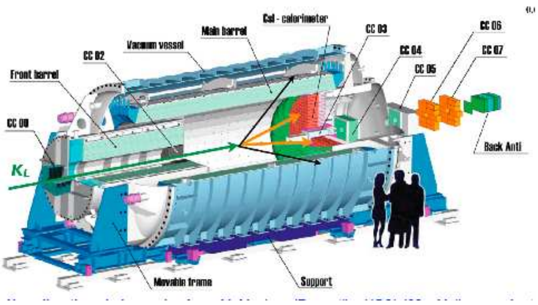


NA48/2
Future NA62

KLOE
Future KLOE II

KTeV

Figure 1: KTeV, NA48/2, and KLOE Experiments.



Future E14 at J-PARC

Figure 2: E391a Experiment (to become E14 at J-PARC).

2 Direct CP Violation Measurements and Searches in $K_{L,S}$ Decays

2.1 Direct CP Detection in $K_{L,S}$ Decays into Di-pions

We have recently seen the completion of the epsilon prime analysis from the entire KTeV data set from 1996, ‘97 and ‘98 and the report of a final answer for epsilon prime. Epsilon prime, the parameter whose non-zero value indicates that the weak interaction is direct CP violating, is obtained from the comparison of the charged and neutral two pion decay modes of the K_L and K_S mesons. The real part of the ratio of epsilon prime to epsilon (the amplitude for the indirect CP violating decay of the neutral kaons) can be shown to be related to these decays via the expression

$$Re(\frac{\epsilon'}{\epsilon})\approx \frac{1}{6}[\frac{\Gamma(K_L\to\pi^+\pi^-)\Gamma(K_S\to\pi^+\pi^-)}{\Gamma(K_L\to\pi^0\pi^0)\Gamma(K_S\to\pi^0\pi^0)} - 1].$$

In order to obtain adequate two body decay statistics for both K_S and K_L decays, the KTeV experiment was designed to take data simultaneously using two neutral beams, one of which was a “vacuum” neutral beam composed of a mixture of K_L's and neutrons (and a small number of hyperons) beam and a similar beam in which a regenerator was placed to produce a $K_{L,S}$ mixture. These two beams passed into an approximately 90 meter decay region where the kaons decayed. The decay products were then detected and measured by a spectrometer just downstream of the decay region. The spectrometer consisted of a drift chamber and large aperture magnet to measure the charge and momentum of the charged pions followed by a CsI calorimeter to identify and measure the energy of the electrons and photons and a muon detector to identify μ's.

The statistics for each of the four two-body decay modes are shown in Table 1. As can be seen from the table, the most difficult mode to obtain statistics for was the $K_L \to \pi^0\pi^0$ accumlated in vacuum beam operation and is, therefore, the largest contributor to the statistical error.

Decay mode	K_L Vacuum Beam	$''K_S''$ Regenerator Beam
$K \to \pi^+\pi^-$	25,107,242	43,674,208
$K \to \pi^0\pi^0$	5,968,198	10,180,175

Table 1: Two Body $K_{L,S} \to$ di-pion decay mode statistics.

Many systematics were studied for the $\pi^+\pi^-$ and $\pi^0\pi^0$ modes. The largest contribution to the $Re(\frac{\epsilon'}{\epsilon})$ from the $\pi^+\pi^-$ mode is due to an acceptance uncertainty of 0.57×10^{-4} out of a total uncertainty from all systematics from the $\pi^+\pi^-$ mode of 0.81×10^{-4}. The largest contribution to the uncertainty in the $Re(\frac{\epsilon'}{\epsilon})$ from the $\pi^0\pi^0$ mode was due to uncertainties in the CSI cluster reconstruction and contributed 0.75×10^{-4} to a total uncertainty of 1.55×10^{-4} from the $\pi^0\pi^0$ mode. The combined uncertainties from the $\pi^+\pi^-$ and $\pi^0\pi^0$ modes is 1.78×10^{-4}. The final answer for $Re(\frac{\epsilon'}{\epsilon})$ is

$$Re(\frac{\epsilon'}{\epsilon})=[19.2 \pm 1.1(stat) \pm 1.8(syst)] \times 10^{-4}$$

In addition to the determination of $Re(\frac{\epsilon'}{\epsilon})$, the KTeV experiment has fit for the $Im(\frac{\epsilon'}{\epsilon})$ and several other important neutral kaon parameters. Fig. 3 shows the result of the fit for $Im(\frac{\epsilon'}{\epsilon})$ and Table 2 gives a summary of the neutral kaon parameters extracted from the full data set.

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \varepsilon + \varepsilon'$$

$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \varepsilon - 2\varepsilon'$$

$$\phi_{SW} = \tan^{-1}\left(\frac{2\Delta m}{\Delta\Gamma}\right)$$

$$\phi_{+-} \approx \phi_\varepsilon + \mathrm{Im}(\varepsilon'/\varepsilon)$$

$$\phi_{00} \approx \phi_\varepsilon - 2\,\mathrm{Im}(\varepsilon'/\varepsilon)$$

$$\Delta\phi \equiv \phi_{00} - \phi_{+-} \approx -3\,\mathrm{Im}(\varepsilon'/\varepsilon)$$

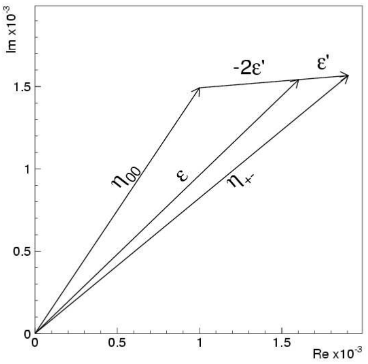


Figure 3: $Re(\frac{\epsilon'}{\epsilon})$ vs.$Im(\frac{\epsilon'}{\epsilon})$.

Neutral Kaon parameter	
$Re(\frac{\epsilon'}{\epsilon})$	$19.2 \pm 1.1(stat) \pm 1.8(syst)] \times 10^{-4}$
Δm	$(5269.9 \pm 12.3) \times 10^6 \hbar s^{-1}$
τ_S	$(89.623 \pm 0.047) \times 10^{-12} s$
ϕ_ϵ	$(43.86 \pm 0.63)^o$ no CPT constraint
ϕ_ϵ-ϕ_{SW}	$(0.40 \pm 0.56)^o$ no CPT constraint
$\Delta\phi$	$(0.30 \pm 0.35)^o$ no CPT constraint
$\frac{Rate(K^0 \to \pi^+\pi^-) - Rate(\overline{K}^0 \to \pi^+\pi^-)}{Rate(K^0 \to \pi^+\pi^-) + Rate(\overline{K}^0 \to \pi^+\pi^-)}$	$(5.5 \pm 0.5) \times 10^{-5}$

Table 2: Parameters of Neutral Kaon Decays.

2.2 Searches for the $K_L \to \pi^0\nu\overline{\nu}$ Decay

The $K_L \to \pi^0\nu\overline{\nu}$ decay is a "golden" mode in the sense that this mode is almost 100% direct CP violating with no long distance contributions to the decay amplitude and with hadronic matrix elements that can be determined from kaon modes with larger branching ratios. A measurement of its branching ratio is a measurement of η, the CP violating phase of the CKM matrix. The detection of this mode is very difficult since its signature is essentially two γ's plus "nothing" and the Standard Model branching ratio is expected to be of order $2.76 \pm 0.40 \times 10^{-11}$ [3].

The E391a experiment at KEK that will move to J-PARC and be upgraded to E14 is the first dedicated experiment to attempt to detect and measure the branching ratio for the $K_L \to \pi^0\nu\overline{\nu}$. In the E-14 experiment a beam of neutrons and K_L's is injected into the experiment where the $K_L \to \pi^0\nu\overline{\nu}$ decays take place in a decay volume surrounded by vetos to eliminate all other decay modes. The main backgrounds are neutron+residual gas $\to \pi^0$ and $K_L \to \pi^0\pi^0$ decays where two photons are undetected.

The signal consists of two photons detected in the electromagnetic calorimeter (part of which will be constructed using the KTeV CsI elements). The two photons are required to form a π^0 mass and point toward the neutral beam which has small transverse dimensions.

The first results from the E391a version of the experiment have been reported. They improve the existing limits by an order of magnitude. Table 3 lists the new result from E391a and compares it to previous results from KTeV.

Experiment	BR(($K_L \to \pi^0 \nu\overline{\nu}$) Limit
E391a [5]	$< 6.7 \times 10^{-8}$
KTeVII [6]	$< 5.9 \times 10^{-7}$
KTeVI [7]	$< 1.6 \times 10^{-6}$

Table 3: Branching ratio limit for $K_L \to \pi^0 \nu\overline{\nu}$. Note that the KTeVII result was achieved requiring that one of the photons to convert to a Dalitz pair.

3 Search for Lepton Flavor Violation in Neutral Kaon decays

The KTeV experiment has also searched for Lepton Flavor violation in three decay channels, $K_L \to \pi^0 \mu e$, $K_L \to \pi^0\pi^0 \mu e$, and $\pi^0 \to \mu e$ [2]. The major backgrounds for all three LFV modes were $Ke3$ or $Ke4$ decays where a pion decayed or faked a muon. The signal region after physics cuts for the $K_L \to \pi^0 \mu e$ is shown in Fig. 4. As can be seen, no events were found in the signal region. The same was true for the other two decays, leading to the upper limits for the three decays given in Table 4

mode	upper limit (90% CL)
BR($K_L \to \pi^0 \mu e$)	$< 7.56 \times 10^{-11}$
BR($K_L \to \pi^0\pi^0 \mu e$)	$< 1.7 \times 10^{-10}$
BR($\pi^0 \to \mu e$)	$< 3.59 \times 10^{-10}$

Table 4: Upper limits for LFV in $K_L \to \pi^0 \mu e$, $K_L \to \pi^0\pi^0 \mu e$, and $\pi^0 \to \mu e$.

The result for BR($K_L \to \pi^0 \mu e$) is 83 times lower than previously obtained. The result for BR($K_L \to \pi^0\pi^0 \mu e$) is the first upper limit for this mode. Finally, the result for BR($\pi^0 \to \mu e$ is a factor of 20 lower than obtained in previous experiments. To see where these searches rank relative to previous LFV searches made using other modes, we show in Fig. 5 a composite of all such searches with these KTeV limits included.

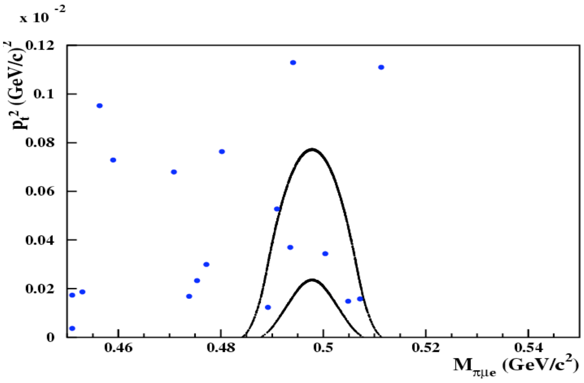


Figure 4: Signal Region for $K_L \to \pi^0 \mu e$.

4 Searches for New Physics and e,μ Universality Violation

The muon and electron differ by only their mass and coupling to the Higgs particle as far as we know at this time. New physics might well be expected to show up in the deviations from predictions in processes whose only difference is in whether an electron or μ is involved and are otherwise well determined in the Standard Model. The following three ratios present opportunities to detect such deviations:

- Test of lepton universality for weak vector currents
  $$R_{e\mu} = \frac{\Gamma(K_{e3})}{\Gamma(K_{\mu 3})} \to \frac{G_F^e}{G_F^\mu}$$
- Test of H^+ (scalar)exchange or presence of right handed currents
  $$R_{K\pi} = \frac{\Gamma(K \to \mu\nu)}{\Gamma(\pi \to \mu\nu)}$$
- Test for LFV due to pseudoscalar weak currents
  $$R_K = \frac{\Gamma(K \to e\nu)}{\Gamma(K \to \mu\nu)}$$

4.1 $R_{e\mu} = \frac{\Gamma(K_{e3})}{\Gamma(K_{\mu 3})}$

Using K_{l3} branching ratios obtained by KLOE, NA48, KTeV, and ISTRA+, the FlaviA kaon working group has made new determinations of

$$\frac{g_\mu^2}{g_e^2} = \frac{\Gamma_{\mu 3} I_{e3}(1+\delta_{e3})}{\Gamma_{e3} I_{\mu 3}(1+\delta_{\mu 3})} = \frac{[|V_{us}|f_+(0)]^2_{\mu 3,obs}}{[|V_{us}|f_+(0)]^2_{e3,obs}}$$

Here the I's are kaon structure functions and the δ's are SU(3) and EM theoretical corrections. The results are

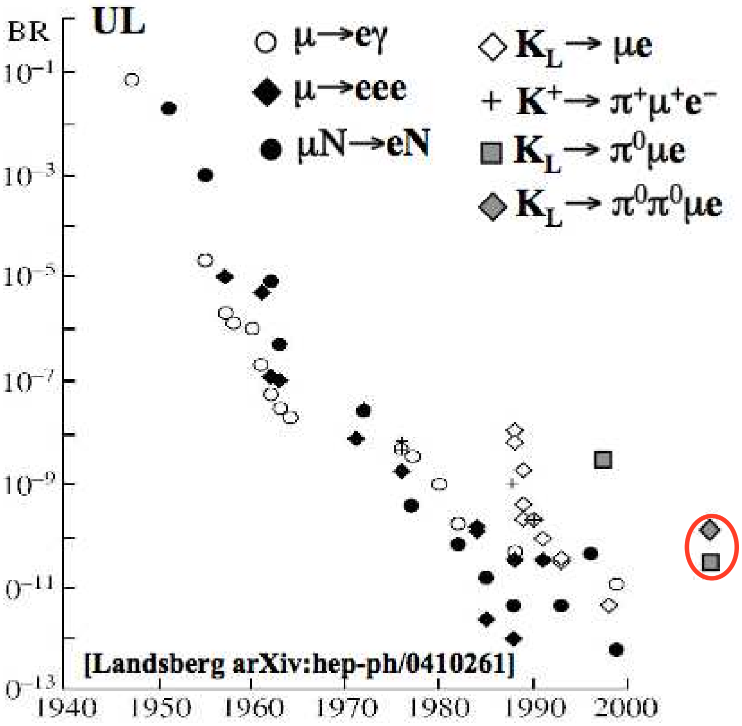


Figure 5: LFV Violation searches over the years [4]

$$\begin{array}{ll} K_L & \frac{g_\mu^2}{g_e^2} = 1.0049(61) \\ K^+ & \frac{g_\mu^2}{g_e^2} = 1.0029(86) \\ \text{AVG} & \frac{g_\mu^2}{g_e^2} = 1.0043(52) \end{array}$$

this can be compared with the result $\frac{g_\mu^2}{g_e^2} = 0.9998(40)$ extracted from $\tau \longrightarrow l\nu\nu$ decays (PDG07). Thus, we have no evidence for new physics from $\frac{g_\mu^2}{g_e^2}$ measurements.

4.2 $R_{K\pi} = \frac{\Gamma(K\to\mu\nu)}{\Gamma(\pi\to\mu\nu)}$

In the two Higgs doublet models and MSSM, exchanges of H^+ can provide and extra scalar current which could make contributions [8] to $\Gamma(K \longrightarrow l\nu)$ beyond the Standard Model of the form

$$\frac{\Gamma(K\to l\nu)}{\Gamma_{SM}(K\to l\nu)} \simeq \mid 1 - \frac{m_K^2}{M_{H+}^2}(1 - \frac{m_d}{m_s})\frac{tan^2\beta}{1+\epsilon_0 tan\beta} \mid$$

This contribution is supposedly suppressed in $\pi l2$ compared to $Kl2$ decays and, thus, could show up as a deviation from the Standard Model expectation for the ratio $\frac{Kl2}{\pi l2}$ shown below:

$$\frac{\Gamma(Kl2)}{\Gamma(\pi l2)} = \mid \frac{V_{us}}{V_{ud}} \mid^2 \frac{f_K^2 m_K}{f_\pi^2 m_\pi} \left(\frac{1-\frac{m_l^2}{m_K^2}}{1-\frac{m_l^2}{m_\pi^2}}\right)^2 \times (1+\delta_e m)$$

In the Standard model the quantity

$$\mid \frac{V_{us}(K_{l2})}{V_{ud}(\pi_{l2})} \times \frac{V_{ud}(0^+ \to 0^+)}{V_{us}(K_{l3})} \mid$$

is supposed to be equal to one and in the two Higgs doublet (or MSSM) model equal to

$$\mid 1 - \frac{m_K^2}{M_{H^+}^2}(1-\frac{m_d}{m_s})\frac{tan^2\beta}{1+\epsilon_0 tan\beta} \mid$$

The present value of this quantity as determined by the FlaviA kaon working group is 1.0018(57), completely consistent with the SM.

4.3 $R_K = \frac{\Gamma(K\to e\nu)}{\Gamma(K\to\mu\nu)}$

A search for new physics has been done using $R_K = \frac{\Gamma(K_{e2})}{\Gamma(K_{\mu 2})}$. In the SM this ratio should equal $2.477(1) \times 10^{-5}$ to an accuracy of 0.04% [9]. Deviations from the SM can be enhanced by helicity supression [10] and in R-parity violating MSSM, lepton flavor violation can give 1% deviations from the SM. At present, no experiment reaches this level of precision. Current measurements are

$$\begin{array}{cl} \text{KLOE} & R_K = 2.55(5)_{stat}(5)_{sys} \times 10^{-5} \\ \text{NA48(2003 data)} & R_K = 2.416(43)_{stat}(24)_{sys} \times 10^{-5} \\ \text{NA48(2004 data)} & R_K = 2.455(45)_{stat}(41)_{sys} \times 10^{-5} \end{array}$$

once again, perfectly consistent with the SM. NA62 has collected 100,000 Ke2 events and can possibly achieve a 0.5% precision. The world average of $R_K = 2.457(32) \times 10^{-5}$ puts significant restrictions on the $tan\beta - M_H$ plane according to the FlaviA kaon working group calculations.

5 The Status of V_{us}

In the recent past, checks of "first row" unitarity of the CKM matrix consistently found unitarity to be significantly violated, Then it was realized by the KTeV experiment that the use of PDG averages for branching ratios for kaon decay modes needed to determine V_{us} was flawed, and that most major branching ratios needed to be remeasured. This remeasurement has proceeded using the high statistics available from the KTeV, KLOE, and NA48 experiments. Determination of $|V_{us}| \times f_+(0)$ has been performed by doing global fits and averages of the dominant K_L, K_S, and $K^{\pm}$ using branching ratios, lifetimes, and various parameterizations of the $K \to \pi$ hadronic form factors.

5.1 Determination of $|V_{us}|$ using $KL3$ Decays

V_{us} can be determined using the $K_{l3_\gamma})$ modes (inclusive of radiative effects). The dependence of the partial width for the $K_{l3_\gamma})$ on $|V_{us}| \times f_+(0)$ is given by

$$\Gamma(K_{l3_\gamma}) = \frac{C_K^2 G_F^2 M_K^2}{192\pi^3} S_{EW} |V_{us}|^2 |f_+(0)|^2 I_{Kl}(\lambda_{+,0})(1 + \delta^K_{SU(2)} + \delta^{Kl}_{em})^2$$

In this expression, K can indicate K^+ or K^0 and l either e or μ. Determination of V_{us} requires many inputs as listed in Table 5 below:

Inputs from Theory	Inputs from Experiment
$S_{EW} \equiv$ Short Distance EW Correction	$\Gamma(K_{l3_\gamma}) \equiv$ Branching Ratio
$\delta^K_{SU(2} \equiv$ Form factor correction SU(2) breaking	$I_{Kl}(\lambda) \equiv$ Phase space integral
$\delta^{Kl}_{em} \equiv$ Long distance EM effects	$\lambda \equiv$form factor dependence on t
$f_+(0) \equiv$Form factor at t=0	C_K^2=1/2 for K^+, 1 for K^0

Table 5: Inputs for determination of $|V_{us}| \times f_+(0)$.

The $K(e3)$ branching ratios come mainly from the KTeV, Na48, KLOE and ISTRA+ experiments and are in good agreement. The $K(\mu 3)$ data are not completely consistent from these experiments since the new NA48 λ_0 form factor is hard to accommodate considering results from other experiments. The form factors (for neutral $K(l3)$ decays) are defined by

$$< \pi^-(k)|\bar{s}\gamma^\mu u|K^0(p) >= (p+k)^\mu f_+(t) + (p-k)^\mu f_-(t)$$

$$\text{where } f_-(t) = \frac{m_K^2 - m_\pi^2}{t}(f_0(t) - f_+(t))$$

and are less well determined at this point. There are three parameterizations of the $K \rightarrow \pi$ hadronic matrix elements $f_{+,0}$ commonly used (the f_- form factor is negligible for K_{e3}). The Taylor expansion and the Pole parameterization have the forms given below;

Taylor Expansion: $f_{+,0}(t) = f_{+,0}(0)(1 + \lambda'_{+,0}\frac{t}{m_\pi^2} + \frac{1}{2}\lambda^{``}_{+,0}(\frac{t}{m_\pi^2})^2 + ...)$
Pole parameterization: $f_{+,0}(t) = f_{+,0}(0)(\frac{M_{V,S}^2}{M_{V,S}^2 - t})$

The third approach to obtaining a description of the hadronic matrix element involves a dispersive approach plus $K\pi$ scattering data to determine both $f_+(t)$ and $f_0(t)$.

Using the branching ratios and the form factors from KTeV,NA48, KLOE and ISTRA+, the FlaviA kaon working group has performed a global fit for $|V_{us}|f_+(0)$ the result of which is shown in Fig. 6 below.

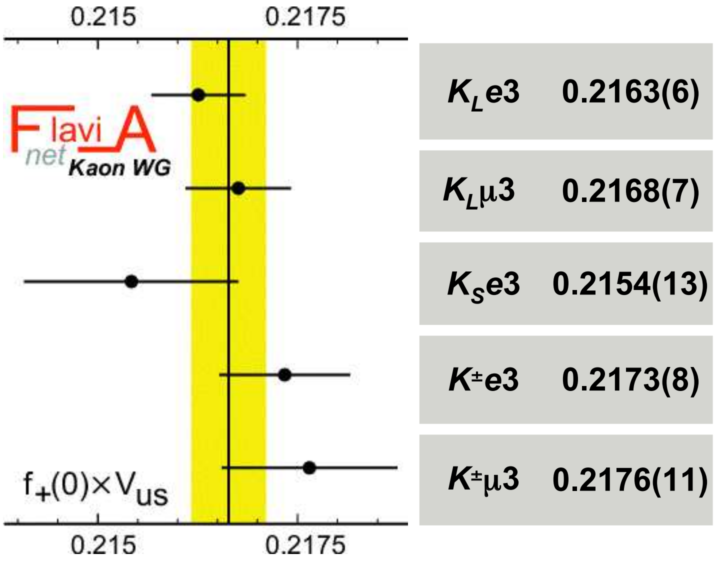


Figure 6: Determination by the FlaviA kaon working group of $|V_{us}|f_+(0)$.

The average of the results from each mode is

$$|V_{us}|f_+(0){=}0.2166(5)$$

The ultimate extraction of V_{us} depends on the theoretical estimates of the the intercept of $f_+(t)$ at t=0. There are many attempts to theoretically determine $f_+(0)$ including the Leutwyler and Roos estimate of $f_+(0)$=0.961(8). Lattice evaluations agree well with this value. Using the RBC-UKQCD07 lattice estimate of $f_+(0)$=0.964(5), the result $|V_{us}|$=0.2246(12) is obtained.

5.2 Determination of the Ratio $\frac{|V_{us}|^2}{|V_{ud}|^2}$ from $\frac{\Gamma(K_{\mu 2(\gamma)})}{\Gamma(\pi_{\mu 2(\gamma)})}$

The ratio $\frac{V_{us}}{V_{ud}}$ can be obtained from the ratio of $K(\mu 2)$ $\pi(\mu 2)$ decays, thereby giving another constraint on $|V_{us}|$. The dependence of the ratio of the K and π $\mu 2$ decays on $\frac{V_{us}}{V_{ud}}$ is given by

$$\frac{\Gamma(K_{\mu 2(\gamma)})}{\Gamma(\pi_{\mu 2(\gamma)})} = \frac{|V_{us}|}{|V_{ud}|} \times \frac{f_K}{f_\pi} \times \frac{M_K(1-\frac{m_\mu^2}{M_K^2})^2}{m_\pi(1-\frac{m_\mu^2}{m_\pi^2})^2} \times (1 + \alpha(C_K - C_\pi))$$

In this expression $C_{K,\pi}$ contains EW radiative corrections. Using the HPQCD-UKQCD07 lattice gauge calculation of $\frac{f_K}{f_\pi}$ of 1.189(7), the result $\frac{|V_{us}|}{|V_{ud}|}$=0.2321(15) is obtained.

5.3 Determination of V_{us} from Global Fit

The FlaviA kaon working group has taken into account all information in a global fit for V_{us}. Fig. 7 shows the fit using $|Vus|$=0.2246(12),$\frac{|V_{us}|}{|V_{ud}|}$=0.2321(15), and V_{ud}=0.97418(26) [11] with and without a CKM unitarity constraint. The results of the fit with no unitarity constraint are V_{us}=0.2253(9), V_{ud}=0.97417(26), and 1-V_{us}^2-V_{ud}^2=0.0002(6). Applying the unitarity constraint gives V_{us}=0.2255(7).

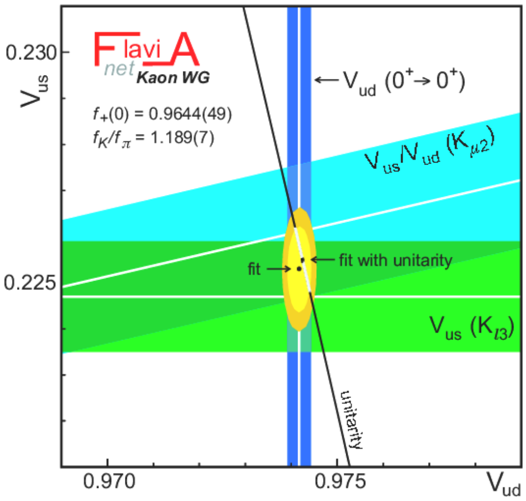


Figure 7: FlaviA kaon working group global fit for V_{us}

6 Conclusions

Examining the span of new experimental results, we are forced to conclude that there is no evidence for new physics. There is not yet any hint of CPT violation has been detected or any evidence for lepton flavor violation or violations or μ-e universality. However, progress has been made in driving down the limits for LFV to the 10^{-11} level. In addition, KTeV has produced the final result for $Re\frac{\epsilon'}{\epsilon}$ along with more precise measurements of many other neutral kaon parameters. Improvements in the precision determination of V_{us} have been achieved using new data from KTeV, NA48/2, KLOE, and ISTRA+ and global fits by the FlaviA kaon working group. Finally, we can expect to see more data in the future from KLOE II, NA62, and E391a.

7 Acknowledgements

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