PROCEEDINGS OF SCIENCE

CPV & CKM in kaon and light flavour: status and prospects

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Abstract. V_{us} and V_{ud} are the most accurately known elements of the CKM matrix. The status of CKM first-row unitarity shows a discrepancy of $\sim 3\sigma$ with respect to the Standard Model prediction. In this proceeding the current state and the future prospects of the experimental measurements that contribute to the determination of V_{us} and V_{ud} are summarized.

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1. Introduction

In the Standard Model of fundamental interactions (SM), the Cabibbo-Kobayashi-Maskawa (CKM) matrix is a 3×3 unitary matrix that describes the three-generations quark mixing transformation [1] [2]. To better address the unitarity, it is convenient to adopt the Wolfestein parametrization [3]:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4) \quad (1)$$

in which the parameter $\lambda = \sin(\theta_C)$ (where θ_C is the Cabibbo angle) plays a central role.

Although CKM unitarity can be tested using unitarity triangles, a different class of precision tests involves only the moduli of the CKM matrix elements, $|V_{ij}|$. The first-row elements are constrained by

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \quad (2)$$

that, at the current level of precision, can be approximated to $|V_{ud}|^2 + |V_{us}|^2 = 1$.

Since $|V_{us}|$ and $|V_{ud}|$ are the most accurately known elements of the CKM matrix, Eq. (2) is the most stringent test of CKM unitarity.

2. V_{us} from kaon semiletptonic decays

$|V_{us}|$ can be extracted from the kaon semileptonic decays $K \to \pi\ell\nu$ ($K\ell 3$) [4]

$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5 C_K^2}{192\pi^3} |V_{us}|^2 S_{EW} \; |f_+^{K\pi}(0)|^2 \; I_{K\ell}^{(0)} \left(1 + \delta_{EM}^{K\ell} + \delta_{SU(2)}\right) \quad (3)$$

where $K \in \{K^\pm, K_{L,S}\}$, ℓ refers to either e or μ, G_F is the Fermi constant, M_K is the kaon mass, C_K^2 is 1 (1/2) for neutral (charged) kaon decays, S_{EW} is the short-distance radiative correction and $\delta_{SU(2)}$ is the deviation from one of the ratio of $f_+(0)$ for the charged to neutral kaon decay. In Eq. (3), the theoretical inputs consist of the mode-dependent long-distance radiative correction, $\delta_{EM}^{K\ell}$, and the form factor at zero momentum transfer $f_+(0)$ for the $\ell\nu$ system. The decay rates $\Gamma(K \to \pi\ell\nu(\gamma))$ are experimentally determined, measuring the BRs and the lifetimes, and the phase-space integral $I_{K\ell}$ is obtained from a fit to the measured decay spectra.

The KLOE-2 collaboration recently reported the measurement of the ratio $\mathcal{R} = \Gamma(K_S \to \pi\ell\nu)/\Gamma(K_S \to \pi^+\pi^-)$ [5, 6], contributing to the determination of $|V_{us}|$. From these measurements, it is possible to extract the branching ratios of the $K_S\ell 3$ decay modes

$$Br(K_S \to \pi\mu\nu) = (4.56 \pm 0.11_{\text{stat}} \pm 0.17_{\text{syst}}) \times 10^{-4}$$
$$Br(K_S \to \pi e\nu) = (7.153 \pm 0.037_{\text{stat}} \pm 0.044_{\text{syst}}) \times 10^{-4}$$

together with the product $|V_{us}|f_+(0)$.

The product $|V_{us}|f_+(0)$ from the six kaon semileptonic decay modes can be averaged according to the prescriptions in [7]

$$|V_{us}|f_+(0) = 0.21656(35) \quad (4)$$

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Using the form factor average $f_+(0) = 0.9698 \pm 0.0017$ [8], the following result is obtained [9]

$$|V_{us}|_{(K\ell 3)} = 0.22330(35)_{\rm exp}(39)_{\rm LAT}(8)_{\rm RC+IB}(53)_{\rm TOT} \tag{5}$$

where the errors refer to experiment, lattice input for the matrix elements, isospin-breaking and radiative corrections.

3. $|V_{us}|/|V_{ud}|$ with kaon and pion leptonic decays

The measurement of the kaon and pion leptonic radiative inclusive decays is an alternative to the semileptonic kaon decays in the extraction of the CKM first-row elements. The ratio of these decay rates depends on $|V_{us}|/|V_{ud}|$, according to the relation [9] [10]

$$\frac{|V_{us}|\, f_{K^+}}{|V_{ud}|\, f_{\pi^+}} = \left[\frac{\Gamma(K \to \mu\nu(\gamma))\ M_{\pi^+}}{\Gamma(\pi \to \mu\nu(\gamma))\ M_{K^+}}\right]^{1/2} \frac{1 - m_\mu^2/M_{\pi^+}^2}{1 - m_\mu^2/M_{K^+}^2}\,(1 - \delta_{EM}/2 - \delta_{SU(2)}/2) \tag{6}$$

Combining f_{K^+}/f_{π^+} from lattice gauge theory calculations [8] and the experimental measurements of the rates $\Gamma(\pi \to \mu\nu(\gamma))$ and $\Gamma(K \to \mu\nu(\gamma))$, the ratio $|V_{us}|/|V_{ud}|$ can be precisely determined [9]

$$\frac{|V_{us}|}{|V_{ud}|}_{(K\mu 2)} = 0.23108(23)_{\rm exp}(42)_{\rm LAT}(16)_{\rm RC+IB}(51)_{\rm TOT} \tag{7}$$

4. V_{ud} evaluation

The most precise determination of $|V_{ud}|$ is provided by the analysis of a set of fifteen superallowed nuclear β-decays ($0^+ \to 0^+$ transitions). Using the most precise determination of $|V_{ud}|$ from each transition [9]

$$|V_{ud}|_{(\beta)} = 0.97367(11)_{\rm exp}(13)_{\Delta_R^V}\,(27)_{\rm NS}\ (32)_{\rm TOT} \tag{8}$$

$|V_{ud}|$ can be extract from the neutron decay, measuring the neutron lifetime τ_n and the ratio between the axial and the vector coupling $\lambda = G_A/G_V$. Using τ_n from [11] and λ from [12]

$$|V_{ud}|_{(n,best)} = 0.97413(13)_{\Delta_R}(35)_{\lambda}(20)_{\tau_n} \tag{9}$$

5. The Cabibbo angle anomaly and physics beyond the SM

The first-row CKM unitarity status is illustrated in Fig. 1 [9]. The tension between the global fit and the CKM unitarity constraint is 2.8σ (Cabibbo angle anomaly).

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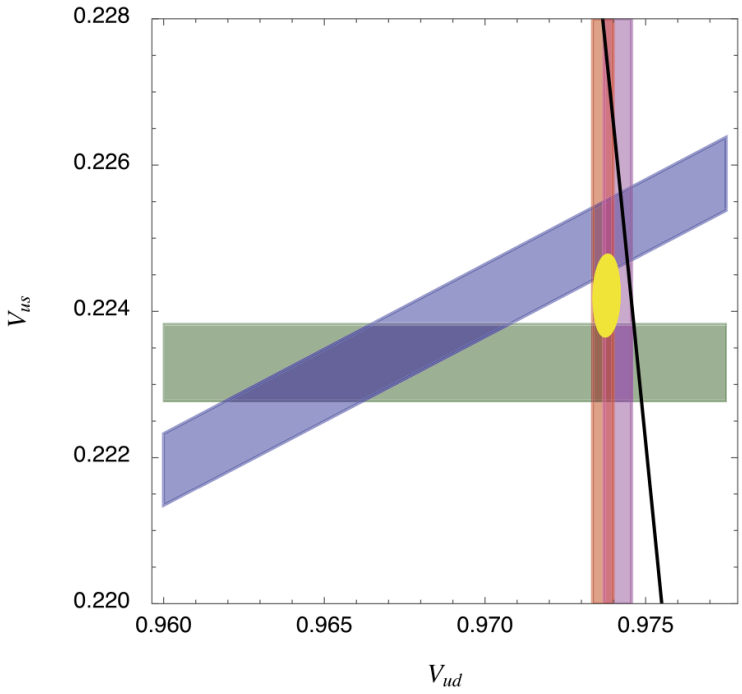

Figure 1: The two vertical bands are the limits on V_{ud} set by neutron decay (violet) and from β superallowed transitions (red). The diagonal band represents the limits from the ratio V_{us}/V_{ud} while the green horizontal band corresponds to V_{us} form kaon semileptonic decays. The black solid line shows the unitarity constraint and and the yellow ellipse illustrate the fit at 68% confidence to all the four bands.

The results of the previous sections can be combined in three variables

$$\Delta^{(1)}_{CKM} = |V_{ud}|^2_{\beta} + |V_{us}|^2_{K_{\ell 3}} - 1 = -0.00176(56)$$

$$\Delta^{(2)}_{CKM} = |V_{ud}|^2_{\beta}\left(\frac{1}{|V_{us}/V_{ud}|^2_{K_{\mu 2}}} + 1\right) - 1 = -0.00098(58) \tag{10}$$

$$\Delta^{(3)}_{CKM} = |V_{us}|^2_{K_{\ell 3}}\left(\frac{1}{|V_{us}/V_{ud}|^2_{K_{\mu 2}}} + 1\right) - 1 = -0.0164(63)$$

each showing a discrepancy with respect to the SM expectation.

The current tension with the CKM unitarity constraint can be explained in terms of physics beyond the SM (BSM), including right-handed currents both in the strange and non-strange sector. In this scenario, the Eqs (10) can be rewritten in terms of two parameters ϵ_R and $\Delta\epsilon_R$, which quantify right-handed currents in the non-strange and strange sectors, respectively

$$\Delta^{(1)}_{CKM} = 2\epsilon_R + 2\Delta\epsilon_R|V_{us}|^2$$

$$\Delta^{(2)}_{CKM} = 2\epsilon_R - 2\Delta\epsilon_R|V_{us}|^2 \tag{11}$$

$$\Delta^{(3)}_{CKM} = 2\epsilon_R + 2\Delta\epsilon_R(2 - |V_{us}|^2)$$

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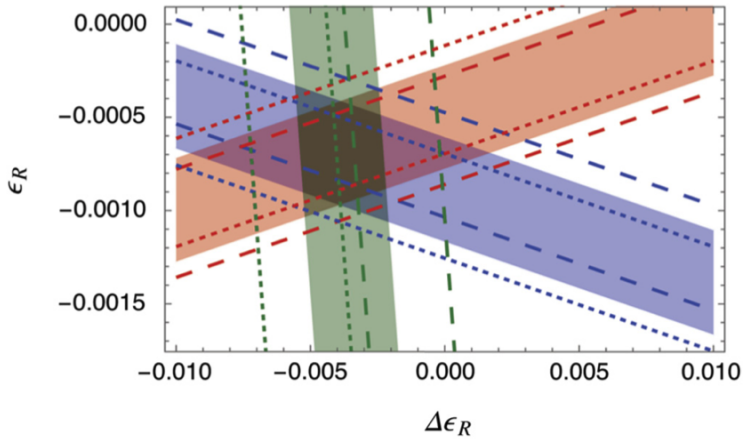

Figure 2: Constraints in the ϵ_R - $\Delta\epsilon_R$ plane. In green the band corresponding to $\Delta^{(3)}_{CKM}$, the blue solid band corresponds to $\Delta^{(1)}_{CKM}$ and the red band with the positive slope corresponds to the limit on $\Delta^{(2)}_{CKM}$. The current situation is represented in the filled bands, while the long-dashed bands are the $+2\sigma$ scenario and the short-dashed bands are the -2σ scenario.

The corresponding constraints on ϵ_R and $\Delta\epsilon_R$ are shown in Fig. 2 (filled bands). Using the values in Eq (5), (7) and (8)

$$\begin{aligned} \epsilon_R &= -0.69(27) \times 10^{-3} \\ \Delta\epsilon_R &= -3.9(1.6) \times 10^{-3} \end{aligned} \tag{12}$$

the right handed currents scenario is excluded with a significance of 3.1σ.

6. CKM prospect in kaon/pion panorama

The current disagreement with the unitarity constraint in Eq (2) has triggered numerous BSM explanations. However, it is clear that the role played by experiments is crucial. This section presents two possible measurements that could provide a significant contribution to the experimental inputs used in the determination of the CKM first-row elements.

In Fig. 2 the impact on the constraint on ϵ_R and $\Delta\epsilon_R$ of a projected measurement of the $K \to \pi\mu\nu$/ $K \to \mu\nu$ ($K_{\mu 3}/K_{\mu 2}$) branching ratio at 0.2% level at 2σ above and below the current measurement is shown in the dashed lines. The NA62 experiment at CERN is a suitable environment for such a measurement [13].

NA62 at CERN is a fixed-target experiment designed to measure the $K^+ \to \pi^+\nu\bar{\nu}$ branching fraction with a good control of the systematic effects [14]. The versatility of the NA62 experimental setup, combined with the multiple trigger chains available [15], allows the study of a variety of K^+ meson decays [16–20]. One week of low-intensity data with a dedicated minimum bias trigger set-up was collected during the 2024 run and an additional week is planned in 2025. With these data, NA62 can perform a suite of measurements of common kaon decays selecting single positively charged tracks events, exploiting the clean environment and high statistics provided by low-intensity run.

On the other hand, a precise measurement of the pion beta decay branching ratio would enable a determination of V_{ud} that is competitive with those in the nuclear sector.

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The PIBETA experiment at PSI measured the very small branching ratio for $\pi^+ \to \pi^0 e^+ \nu_e$ with a precision of $\pm 0.6\%$ [21]. The measurement yields

$$|V_{ud}|_{(\pi\beta)} = 0.97386(281)_{\mathrm{BR}}(9)_{\tau_\pi}(14)_{\mathrm{RC}}(28)_{I_\pi}\,[283]_{\mathrm{total}} \tag{13}$$

The role of theoretical uncertainties in this decay is marginal, and the gap between the precision achieved in the nuclear sector and that from pion beta decay must be filled by future experiments.

PIONEER is a next-generation rare pion decay experiment that plans to measure the $\pi^+ \to \pi^0 e^+ \nu_e$ branching ratio during the Phase II and III of its physics program, while focusing on lepton flavor universality in the ratio $R_{e/\mu} = \Gamma(\pi^+ \to e^+ \nu e(\gamma))/\Gamma(\pi^+ \to \mu^+ \nu \mu(\gamma))$ in Phase I [22]. The goal for Phase II of PIONEER is to improve the branching ratio by a factor 3, while aiming for the ultimate precision of 3×10^{-4} in Phase III.

7. Conclusions

V_{us} and V_{ud} are the most accurately known elements of the CKM matrix and the Cabibbo universality test is a precision tool to explore what may lie beyond the SM. Precision measurements from kaon semileptonic and leptonic decays together with nuclear measurements are used to put constraints in the V_{us}-V_{ud} plane. The current status of the CKM first-row unitarity test shows a discrepancy of $2.8\,\sigma$ with respect to the SM expectation. Both experimental and theoretical investigations are essential and progress is expected on multiple fronts. The measurement of the $K_{\mu 3}/K_{\mu 2}$ branching ratio will tell the last word on the right-handed currents scenario, while the measurement of the $\pi^+ \to \pi^0 e^+ \nu$ branching ratio, with an improvement by up to a factor 6 in precision, will play a competitive role in the determination of V_{ud}.

References

[1] N. Cabibbo, *Phys. Rev. Lett.* **10** (1963) 531.

[2] M. Kobayashi, T. Maskawa, *Prog. of Theor. Phys.* **49** (1973) 652.

[3] L. Wolfenstein, *Phys. Rev. Lett.* **51** (1983) 1945.

[4] S. Navas et al. (Particle Data Group), *Phys. Rev. D,* **110** (2024) 030001.

[5] KLOE-2 collaboration, *JHEP* **02**, (2023) 098.

[6] KLOE-2 collaboration, *Phys. Lett. B* **804** (2020) 135378.

[7] M. Antonelli et al. (FlaviaNet Working Group on Kaon Decays), *Eur. Phys. J. C* **69** (2010) 399.

[8] Flavour Lattice Averaging Group (FLAG), *arXiv:411.04268v2* [hep-lat] (2024).

[9] V. Cirigliano, A. Crivellin, M. Hoferichter and M. Moulson, *Phys. Lett. B* **838** (2023) 137748.

[10] W.J. Marciano, *Phys. Rev. Lett.* **93** (2004) 231803.

[11] F.M. Gonzalez, et al., *Phys. Rev. Lett.* **127** (2021) 162501.

[12] B. Märkisch, et al., , *Phys. Rev. Lett.* **122** (2019) 242501.

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[13] E. Cortina Gil et al. (NA62 collaboration), *JINST* **12** (2017) P05025.

[14] E. Cortina Gil et al. (NA62 collaboration), *JHEP* **02** (2025) 191.

[15] E. Cortina Gil et al. (NA62 collaboration), *JHEP* **03** (2023) 122.

[16] E. Cortina Gil et al. (NA62 collaboration), *JHEP* **11** (2022) 011.

[17] E. Cortina Gil et al. (NA62 collaboration), *JHEP* **09** (2023) 040.

[18] E. Cortina Gil et al. (NA62 collaboration), *Phys. Lett. B* **850** (2024) 138513.

[19] E. Cortina Gil et al. (NA62 collaboration), *Phys. Lett. B* **846** (2023) 138193.

[20] E. Cortina Gil et al. (NA62 collaboration), *Phys. Lett. B* **859** (2024) 139122.

[21] D. Počanić et al., *Phys. Rev. Lett.* **93** (2004) 181803.

[22] W. Altmannshofer et al., *arXiv:2203.01981* [hep-ex] (2022).

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