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Status of the CKM matrix as of Summer 2009

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We review the current status of the Cabbibo-Kobayaski-Maskawa matrix of quark mixing in the standard model. We discuss the main ingredients of the global CKM analysis, with an emphasis on recent results and their impact. We assess the compatibility between various sources of information. We discuss the role of theoretical and experimental uncertainties. We use current data to analyse scenarios of potential deviations from the flavour sector in the standard model. We study the physics potential of future kaon experiments in light of current constraints and expected future performances.

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Introduction

Within the standard model (SM), quark mixing is described by the unitary Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix [1]. For three generations of quarks, the CKM matrix has 4 parameters, including an irreducible CP-odd phase. A non-vanishing value for this phase provides a mechanism for CP violation in the quark sector; therefore testing the CKM mechanism of quark mixing and CP violation provides an important test of the SM. An update on a global analysis of the CKM matrix is succintly described here.

The global CKM fit

The global fit to the parameters of the CKM matrix is based on a frequentist approach, including a specific *RFit* treatment to deal with theoretical uncertainties [2]. Only observables for which a good theoretical control is consensual are used. Details on the experimental and theoretical inputs, together with relevant references, can be found in the CKMfitter web page [3].

An exact Wolfenstein-like [4] parametrisation of the CKM matrix is used, in terms of four parameters $A, \lambda, \bar{\rho}, \bar{\eta}$ defined as

$$\lambda^2 = \frac{|V_{us}|^2}{|V_{us}|^2 + |V_{ud}|^2} \ , \ A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{us}|^2 + |V_{ud}|^2} \ , \ \bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}. \tag{1}$$

The first two parameters λ and A are unsensitive to CP violation; λ is determined with high accuracy from nuclear processes and semileptonic kaon decays, and A is extracted from the decay rate of charmed semileptonic B decays to a few percent accuracy. The remaining parameters $\bar{\rho}$ and $\bar{\eta}$ define the apex of the so-called unitarity triangle (UT). Information on the UT is extracted from measurements of observables related to its sides and angles.

Numerical inputs from several hadronic quantities are mandatory for the fits. These hadronic parameters limit the precision on the determination of the observables involving loop processes such as Δm_d, Δm_s, $|\varepsilon_K|$, and also the tree decay $B^+ \to \tau^+\nu$. We rely on lattice QCD (LQCD) simulations to estimate these quantities, for which we set up our own average [5].

Fig. 1 (Left) shows the global CKM fit results in the $(\bar{\rho}, \bar{\eta})$ plane. The fitted values of the CKM parameters are: $A = 0.8116^{+0.0097}_{-0.0241}$, $\lambda = 0.22521 \pm 0.00082$, $\bar{\rho} = 0.139^{+0.025}_{-0.027}$, and $\bar{\eta} = 0.341^{+0.016}_{-0.015}$. A good overall consistency at 95% confidence level (CL) is seen, providing strong evidence on the dominance of the CKM mechanism in quark mixing and CP violation.

$\mathbf{B}^+ \to \rho^+\rho^\mathbf{0}$ and the CKM angle α

As shown on Fig. 1 (Right), the CKM angle α is now determined to an accuracy of a few percent: $\alpha = 89.0^{+4.4}_{-4.2}$ degrees, and is in excellent agreement with the global CKM fit, for which a constraint excluding this measurement from the fit gives $\alpha = 95.6^{+3.3}_{-8.8}$ degrees. The increase in accuracy is essentially driven by the updated BABAR measurement of the $B^+ \to \rho^+\rho^0$ decay rate [6], whose new value enhances significantly the impact of the isospin analysis of $B \to \rho\rho$ modes and the extraction of α. As α provides now a stringent constraint on the CKM matrix (second only to $\sin 2\beta$ in importance), we checked that possible systematics from the assumption of isospin symmetry would yield a limited impact on the current determination of α.

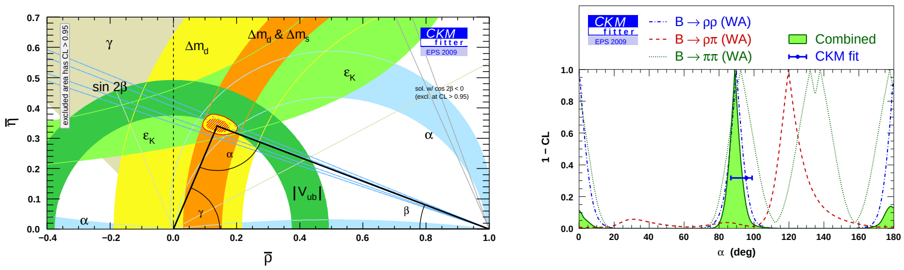

Figure 1: Left: Individual and global constraints, expressed as 95% CL, on the $(\bar{\rho},\bar{\eta})$ plane from the CKM fit. The red hashed region on the gobal fit corresponds to 68% CL. Right: CL profile of the CKM angle α with the present WA measurements. The blue dot is the indirect result on α from the global CKM fit.

$\mathbf{B^+ \to \tau^+\nu}$ versus $\sin 2\beta$

Looking at individual observables, the only significant discrepancies in the fit concern the measurement of $\sin 2\beta$ from charmonium B decays and the determination of $|V_{ub}|$ from the decay rate of $B^+ \to \tau^+\nu$. When removing each of these inputs from the global fit, the χ^2 value at minimum decreases by 2.3 and 2.4 units, respectively. The comparison of experimental and CKM fit values for these two observables is illustrated in Fig. 2 (Left). For $B^+ \to \tau^+\nu$, all the experimental measurements are consistent and their WA is $(1.73 \pm 0.35) \times 10^{-4}$, while the global CKM fit predicts a lower value of $\left(0.80^{+0.15}_{-0.09}\right) \times 10^{-4}$. Scenarios including non-SM contributions to the $B^+ \to \tau^+\nu$ decay (i.e. an additional term mediated by a charged Higgs) do not necessarily accomodate a larger value of the $B^+ \to \tau^+\nu$ BR [7]. While this hint of discrepancy does not qualify yet as an evidence for non-SM physics, it clearly motivates more precise meaurements.

Rare kaon decays: status and prospectives

We study the constraint from the measured BR of the $K^+ \to \pi^+\nu\bar{\nu}$ rare decay, for which a recent update from the E789 and E949 experiments yields 5 signal candidates, with negligible background [8]. The experimental measurement is $\left(1.73^{+1.15}_{-1.05}\right) \times 10^{-10}$, while the global fit using recent calculations [9] predicts a BR of $\left(0.811^{+0.027}_{-0.021}(\text{exp}) \pm 0.096(\text{theo})\right) \times 10^{-10}$. Still limited by statistics, the constraint already excludes at 95% CL a region around the $(1,0)$ vertex of the UT, as shown in Fig. 2 (Right). This illustrates the potential of a $\mathcal{O}(100)$ signal event experiment, such as the future NA62; additional strong constraints could be added by future experiments on $K_L \to \pi^0\nu\bar{\nu}$, such as KOTO [10]. While current experimental sensitivities to $K_L \to \pi^0\nu\bar{\nu}$ still lie orders of magnitude above the SM prediction, this measurement is essentialy free of theoretical errors and prospects for measurements could provide very a clean extraction of the $|\bar{\eta}|$ parameter of the CKM matrix. With expected future improvements in LQCD, a constraint on the UT exclusively from kaon physics will be accessible within a few years [11].

Conclusions

An ever-increasing number of results accumulated in recent years have shown that the CKM mechanism is dominant in the quark mixing sector and CP violation. The global fit to the CKM matrix shows an excellent overall consistency, with some few discrepancies within the present

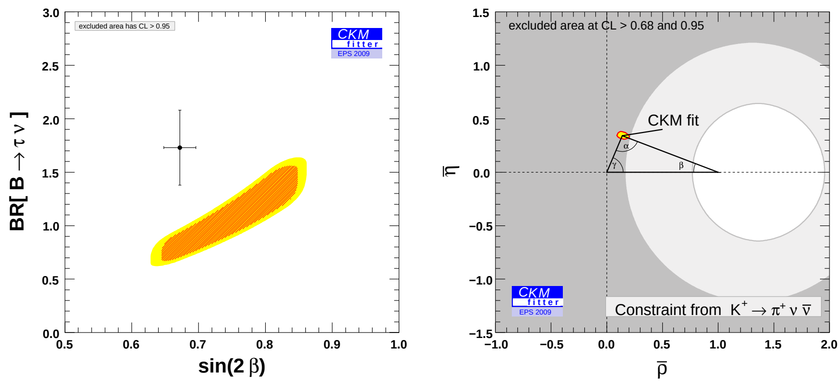

Figure 2: Left: Combined constraints on $\sin 2\beta$ and $B^+ \to \tau^+\nu$. The colour region is the result of the global CKM fit (excluding these two inputs), the superimposed black cross represents the WA of experimental measurements for these two observables. Right: Constraint on the $(\bar\rho, \bar\eta)$ plane from the BR measurement of $K^+ \to \pi^+\nu\bar\nu$ by E949.

result of our fit. In view of this situation, we are eagerly waiting for results based on the complete B factory datasets, for the next generation experiments at the LHC and at future super B factories, and dedicated future kaon experiments, all combined with improvements in the determinations of LQCD parameters.

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