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# CKM Fits: the Standard Model and the New Physics

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## Abstract.

An up-to-date profile of the Cabibbo-Kobayashi-Maskawa matrix is given, providing numerical and graphical constraints on the CKM parameters in the Standard Model. The constraints on additional parameters accounting for possible new physics contributions in a model-independent analysis are also reported.

## 1. Introduction

In the Standard Model (SM) of electroweak interactions, the CP violation arises from a single non-vanishing complex phase in the  $(3 \times 3)$  unitary Cabibbo-Kobayashi-Maskawa [1] matrix describing the quark flavour-mixing in charged currents interactions. Four fundamental constants are enough to parametrize this matrix. An exact, unitary to all orders and phase-convention independent parametrization [2] is used throughout this document, inspired from the one proposed by Wolfenstein et al.[4]:

$$\lambda = |V_{us}|/\sqrt{|V_{ud}|^2 + |V_{us}|^2}, A\lambda^2 = |V_{cb}|/\sqrt{|V_{ud}|^2 + |V_{us}|^2} \text{ and } \bar{\rho} + i\bar{\eta} = -V_{ud}V_{ub}^*/V_{cd}V_{cb}^*.$$

While  $\lambda$  and  $A$  are accurately determined ( $\lambda$  is measured from superallowed nuclear transitions ( $|V_{ud}|$ ) and semileptonic kaon decays ( $|V_{us}|$ ),  $A$  comes from the inclusive and exclusive semileptonic  $B$  decays), the parameters  $\bar{\rho}$  and  $\bar{\eta}$ , being the real and imaginary coordinates of the unitarity triangle (UT) apex, are much less constrained. The CP violation experiments are aiming at measuring both the sides and angles of the triangle, overconstraining the apex. The metrology of the apex parameters within the SM allows to measure the size of the CP violation through the Jarlskog invariant [3]. Yet, the main purpose of a global analysis of the sides and angles measurements is certainly to find inconsistencies, which would suggest new contributions above the Standard Model. Alternatively, it is worth to examine, in a generic way, which room is left to New Physics (NP) by the current  $B$  data. A relevant natural laboratory to study NP effects is the mixing of  $B$  mesons. Assuming NP contributions only in the short-distance part of the mixing process, it can be parametrized by two additional parameters:  $r_q^2 e^{2i\theta_q} = \langle \bar{B}_q^0 | M_{12}^{\text{SM+NP}} | B_q^0 \rangle / \langle \bar{B}_q^0 | M_{12}^{\text{SM}} | B_q^0 \rangle$  [5], where  $q$  stands for  $d$  or  $s$  quarks. It might be interesting to distinguish the NP amplitude, which leads to the following alternate parametrization:  $h_q e^{2i\sigma_q} = \langle \bar{B}_q^0 | M_{12}^{\text{NP}} | B_q^0 \rangle / \langle \bar{B}_q^0 | M_{12}^{\text{SM}} | B_q^0 \rangle$  [6, 7].

## 2. The Inputs

The inputs of the global fit we consider in the analyses reported in this document, performed within a frequentist statistical treatment, are the observables where the theoretical uncertainties

are quantitatively under control :

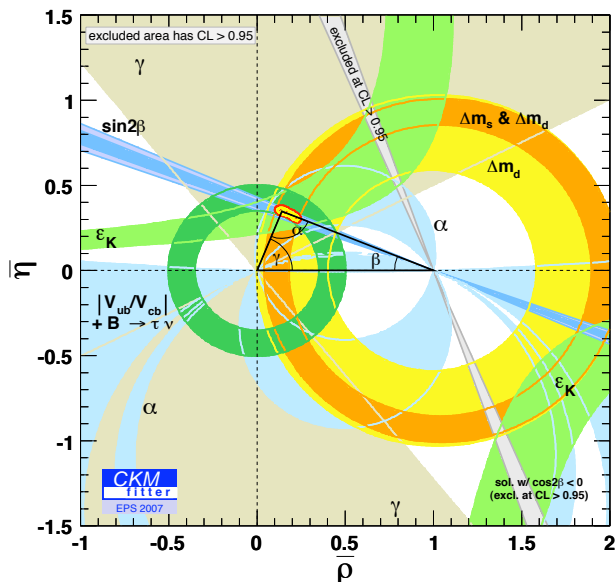
- $|V_{ud}|, |V_{us}|, |V_{cb}|$  determine the  $\lambda$  and  $A$  parameters and fix accordingly the length scale of the UT.
- $|V_{ub}|$  (including  $\mathcal{B}(B \rightarrow \tau\nu)$ ),  $\Delta m_d$  and  $\Delta m_s$  are CP-conserving observables (sensitive to  $\bar{\rho}$  and  $\bar{\eta}$ ) measuring the sides of the UT.
- $\alpha, \gamma, \sin 2\beta, \cos 2\beta$  are CP-violating observables measuring the UT angles and  $\varepsilon_K$  is the measure of CP-violation in the kaon mixing.

A complete review of the inputs used in this analysis can be found in [8].

In the presence of NP contributions, the observables transform as follows:  $\sin 2\beta \rightarrow \sin(2\beta + 2\theta_d)$ ,  $\alpha \rightarrow \pi - \gamma - \beta - \theta_d$  and  $\Delta m_q \rightarrow r_q^2 \cdot \Delta m_q^{SM}$ . Only few information on the phase  $2\theta_d$  can be obtained from the previous set of inputs ( $\alpha$  together with  $\sin 2\beta$  is actually a tree-level  $\gamma$  determination). As advocated for instance in [9], there are other observables, basically unuseful for the CKM metrology in the Standard Model, but emphasizing a double dependence to  $r_q$  and  $\theta_q$ : this is the case of  $A_{SL}^q$  or  $\Delta\Gamma_s$  for which the complete expressions can be found in [10] with NLO calculations.  $A_{SL}^d$  is of major importance to constrain the  $(r_d, \theta_d)$ .

### 3. The Global Fit

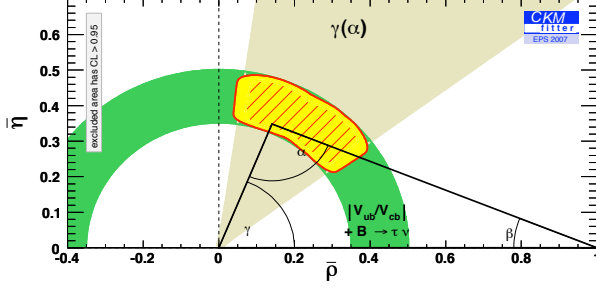
Figure 1 displays the result of the global fit together with the 95 % CL contours of the individual constraints.  $\alpha$  (together with  $\beta$ ),  $\gamma$  and  $|V_{ub}|$  determines  $\bar{\rho}$  and  $\bar{\eta}$  from tree-level processes in satisfactory agreement with the mixing loop-induced observables, as underlined in Figures 2 and 3. Table 1 gives a selection of the numerical values obtained from the global fit. The CKM paradigm is thus the dominant source of CP violation in  $B$  processes.



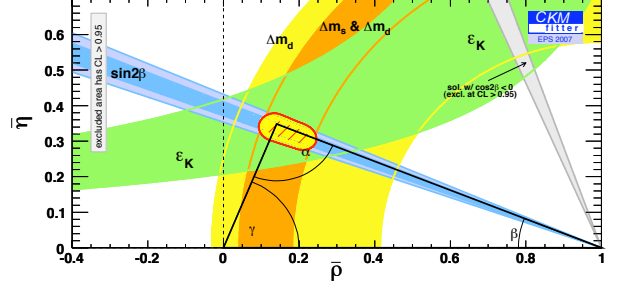
**Figure 1.** Individual constraints and the global fit result on the  $(\bar{\rho}, \bar{\eta})$  plane. Shaded areas have 95 % CL. The allowed region of coordinates at 95 % CL is shown in yellow with a red contour. The only differences in the inputs for this conference with respect to [8] are the  $\alpha$  and  $|V_{ub}|$  values, very slightly modified (see the web update in [2]). A nice overall agreement is observed between the individual constraints.

### 4. The New Physics in $B - \bar{B}$ Mixing

The global CKM fit provides so far a successful test of the SM hypothesis. It is not necessary to allow for supplementary CP-violation phases to describe the current data. Yet, it is useful to establish their constraints to the NP parameters in  $\Delta F = 2$  transitions. The inputs of the



**Figure 2.**  $(\bar{\rho}, \bar{\eta})$  constraints from tree-level observables only.

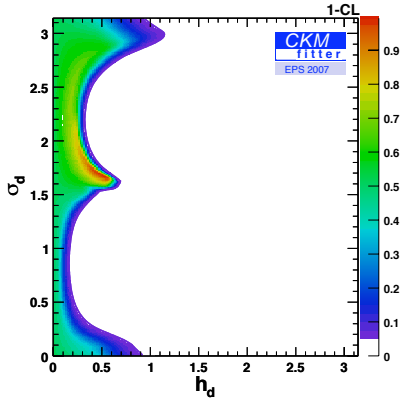


**Figure 3.**  $(\bar{\rho}, \bar{\eta})$  constraints from loop-induced observables only.

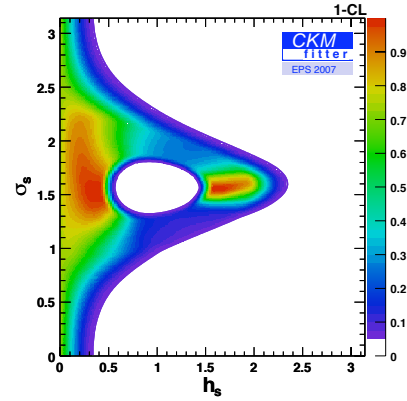
**Table 1.** Fit results: the CKM parameters within the framework of the Standard .

Parameter	Value and Uncertainties (95 % CL)
$\lambda$	$0.2258^{+0.0016}_{-0.0017}$
$A$	$0.817^{+0.030}_{-0.028}$
$\bar{\rho}$	$[0.108, 0.243]$
$\bar{\eta}$	$[0.288, 0.375]$
$J$	$(2.74^{+0.63}_{-0.22}) \times 10^{-5}$

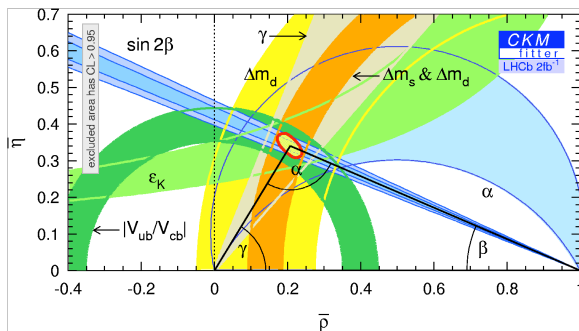
fit are those discussed in [8]. Figures 4 and 5 display the constraints on the  $(h_q, \sigma_q)$  planes, for the  $B_d$  and  $B_s$  systems, respectively. While the  $B_d$  system is tightly constrained (New CP-violating phases could only enter as a typical 30 % correction to the Standard Model), there are still large opportunities for NP contributions in the  $B_s$  mixing. Let us mention the remarkable interplay between the  $B$ -factories and the Tevatron measurements. Clearly, a measurement of the weak phase of the  $B_s$  mixing, denoted  $\beta_s$  and accurately predicted in the Standard Model, will constitute the real step forward on the subject. This is a first-year measurement of the LHCb experiment [11, 12, 13], which can rapidly exclude (or observe!) phase values receiving a large NP contribution.



**Figure 4.**  $(h_d, \sigma_d)$  constraints.



**Figure 5.**  $(h_s, \sigma_s)$  constraints.



**Figure 6.** Individual constraints and the global fit result on the  $(\bar{\rho}, \bar{\eta})$  plane as we could expect them from one nominal year of data taking from the LHCb experiment. The uncertainty on  $\Delta m_s$ ,  $\gamma$ ,  $\alpha$  et  $\sin 2\beta$  are 0.01 ps,  $10^\circ$ ,  $5^\circ$  and 0.02. Most of the improvement is due to the  $\gamma$  measurement. As in Figure 1, shaded areas have 95 % CL. The allowed region of coordinates at 95 % CL is shown in yellow and incrimed by the red contour.

## 5. Conclusions

The CKM mechanism is successful in describing the flavour dynamics of the present observables in  $B$  and  $K$  physics. It is now established that the CKM phase is the dominant source of CP violation in  $B$  systems and this is a major achievement of the  $B$  factories. The current limitations of the CKM consistency tests are of three origins: LQCD,  $\gamma$  and the  $B_s$  measurements. The near future is appealing : significant improvements can be expected in the lattice QCD predictions and the LHC start-up will bring precise measurements of the so far missing or badly measured observables as illustrated Figure 6. In flavour physics also, exciting times are in front of us.

## Acknowledgements

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