Indirect Determination of the Vertex and Angles of the Unitarity Triangle

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The values of the elements of the Cabibbo-Kobayashi-Maskawa matrix are constrained by direct and indirect measurements. A fit to experimental data and theory calculations allows the indirect determination of the vertex and angles of the unitarity triangle as:

\[ \rho = 0.18 \pm 0.07 \quad \eta = 0.35 \pm 0.05 \]

\[ \sin 2\alpha = 0.14^{+0.25}_{-0.38} \quad \sin 2\beta = 0.73 \pm 0.07 \quad \gamma = 63^{+8}_{-11} \text{ degrees.} \]

Information is derived on the presence of CP violation in the matrix, on non-perturbative QCD parameters and on the \( B^0 \) oscillation frequency.

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1 Introduction

In the Standard Model of the electroweak interactions \([1,2,3]\), a \(3 \times 3\) unitary matrix describes the mixing of the quark mass eigenstates into the weak interaction ones. This matrix is known as the Cabibbo-Kobayashi-Maskawa (CKM) matrix \([4,5]\), and can be written in terms of just four real parameters \([6]\):

\[
V_{\text{CKM}} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} \approx \begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}.
\]

\(A, \rho\) and \(\eta\) are of order unity and \(\lambda\) is the sine of the Cabibbo angle. The parameter \(\eta\) is the complex phase of the matrix, directly related to the violation of the CP symmetry in the weak interactions. The measurement of the parameters of the CKM matrix is of fundamental importance for both the description of the weak interaction of quarks and to shed light on the mechanism of CP violation.

The parameters \(A\) and \(\lambda\) are known with an accuracy of a few percent and this work concentrates on the indirect determination of \(\rho\) and \(\eta\). This is also described as the study of the vertex or the angles of a triangle in the \(\rho - \eta\) plane, whose other two vertices are located in \((0,0)\) and \((1,0)\). This triangle, called the unitarity triangle, is depicted in Figure 1. This study follows the same procedure as a previous publication \([7]\) with an update of the input parameters, as described in the following.

A large number of physical processes are parametrised in terms of the values of the elements of the CKM matrix. Among them, four present the largest sensitivity to \(\rho\) and \(\eta\), given the knowledge of the involved theoretical and experimental quantities. These processes are discussed in the following and then used in a fit to derive \(\rho\) and \(\eta\). Conclusions are then drawn from the results of this fit.

![Figure 1: The unitarity triangle.](image)

2 Constraints

2.1 \(\lambda\) and \(A\)

The value of the sine of the Cabibbo angle is measured as \([8]\):

\[
\lambda = 0.2196 \pm 0.0023.
\]
The study of inclusive semileptonic B decays by the CLEO [9] and the LEP [10] experiments yields information on the value of $|V_{cb}|$. Further constraints are derived from the study of the $B^0 \rightarrow D^{*+}\ell\nu$ decay, both at the Υ(4S) [11] and at the Z pole [10]. From these measurements, a value $|V_{cb}| = (40.9 \pm 1.9) \times 10^{-3}$ is extracted, which yields:

$$A = \frac{|V_{cb}|}{\lambda^2} = 0.83 \pm 0.04.$$

### 2.2 CP Violation for Neutral Kaons

The mass eigenstates of the neutral kaons can be written as $|K_S\rangle = p|K^0\rangle + q|\bar{K}^0\rangle$ and $|K_L\rangle = p|K^0\rangle - q|\bar{K}^0\rangle$. The relation $p \neq q$ implies the violation of the CP symmetry that, in the Wu-Yang phase convention [12], is described by the parameter $\epsilon_K$ defined as:

$$\frac{p}{q} = \frac{1 + \epsilon_K}{1 - \epsilon_K}.$$  

The precise measurements of the $K_S \rightarrow \pi^+\pi^-$ and $K_L \rightarrow \pi^+\pi^-$ decay rates imply [8]:

$$|\epsilon_K| = (2.280 \pm 0.019) \times 10^{-3}.$$  

The relation of $|\epsilon_K|$ to the CKM matrix parameters is [13,14]:

$$|\epsilon_K| = \frac{G_F f_K^2 m_K m_W^2}{6\sqrt{2}\pi^2 \Delta m_K} B_K \left( A^2 \lambda^6 \eta \right)$$

$$\times \left[ y_c (\eta_{ct} f_3(y_c, y_t) - \eta_{cc}) + \eta_{tt} y_t f_2(y_t) A^2 \lambda^4 (1 - \rho) \right].$$

The functions $f_3$ and $f_2$ of the variables $y_t = m_t^2/m_W^2$ and $y_c = m_c^2/m_W^2$ are given in Reference [15]. The measured value of the top quark mass, $174.3 \pm 5.1$ GeV [8], is scaled as proposed in Reference [16], giving:

$$m_t(m_t) = 167.3 \pm 5.2 \text{ GeV},$$

while the mass of the charm quark is chosen as [8]:

$$m_c(m_c) = 1.25 \pm 0.10 \text{ GeV}.$$  

The calculated QCD corrections in Equation (2) are described by the consistent set of parameters [16,17,18,19]:

$$\eta_{cc} = 1.38 \pm 0.53, \quad \eta_{tt} = 0.574 \pm 0.004, \quad \eta_{ct} = 0.47 \pm 0.04.$$  

Non-perturbative QCD contributions to this process are affected by a large uncertainty and are summarised by the “bag” parameter $B_K$, chosen as [20]:

$$B_K = 0.87 \pm 0.14.$$
The other physical constants appearing in Equation (2) are reported in Table 1. The measurement of $|\epsilon_K|$ constrains the vertex of the unitarity triangle onto an hyperbola in the the $\rho - \eta$ plane.

Recent measurements of direct CP violation in the neutral kaon sector from the KTEV [21] and NA48 [22] experiments confirm the previous NA31 result [23]. These measurements could result in a lower bound to $\eta$. Nonetheless they are not used to constrain the CKM matrix owing to the large uncertainties that affect the corresponding theoretical calculations [24,25].

2.3 Oscillations of $B^0_d$ Mesons

The behaviour of neutral mesons containing a $b$ quark depends on the the mass difference between the heavy and light mass eigenstates, $B_H$ and $B_L$. These are different from the CP eigenstates $B^0_d$ and $\bar{B}^0_d$. The mass difference, $\Delta m_d = m_{B_H} - m_{B_L}$, is measured [26] at LEP, the $\Upsilon(4S)$ and the TEVATRON by means of the study of the oscillations of one CP eigenstate into the other. A recent average is:

$$\Delta m_d = 0.487 \pm 0.014 \text{ps}^{-1}.$$ 

Recent results from the Babar [27] and Belle [28] collaborations are not yet included in this average with which they are statistically comparable. The value of $\Delta m_d$ is related to the CKM parameters as:

$$\Delta m_d = \frac{G_F^2 m_W^2 m_B}{6\pi^2} \left( f_{B_d} \sqrt{B_{B_d}} \right)^2 \eta_B y_f f_2(y_f) A^2 \lambda^6 \left[ (1 - \rho)^2 + \eta^2 \right]. \quad (3)$$

The calculated QCD correction $\eta_B$ amounts to [16,17,18,19]:

$$\eta_B = 0.55 \pm 0.01,$$

while non-perturbative QCD contributions are summarised by [29]:

$$f_{B_d} \sqrt{B_{B_d}} = 0.206 \pm 0.029 \text{ GeV}.$$

The vertex of the unitarity triangle is constrained by $\Delta m_d$ onto a circle in the $\rho - \eta$ plane, with centre in $(1, 0)$.

2.4 Oscillations of $B^0_s$ Mesons

The $B^0_s$ mesons are predicted to mix like the $B^0_d$ mesons, but their larger mass difference, $\Delta m_s$, results into faster oscillations. These have eluded direct observation and the current 95% Confidence Level (CL) lower limit on $\Delta m_s$ from the LEP, SLD and CDF collaborations is [26]:

$$\Delta m_s > 14.9 \text{ps}^{-1} \text{ (95\% CL)}.$$
The experiments, once combined, are sensitive to values of $\Delta m_s$ up to $17.9 \text{ ps}^{-1}$ and a 2.5 $\sigma$ indication for the observation of $B_s^0$ oscillations is observed around $\Delta m_s = 17.7 \text{ ps}^{-1}$.

The expression for $\Delta m_s$ as a function of the CKM parameters is similar to that for $\Delta m_d$, and taking their ratio, it follows:

$$\Delta m_s = \Delta m_d \frac{1}{\lambda^2} \frac{m_{B_s} \xi^2}{m_{B_d}} \frac{1}{(1 - \rho)^2 + \eta^2}. \quad (4)$$

All the theoretical parameters and their uncertainties are included in the quantity $\xi$, known as [29]:

$$\xi = \frac{f_{B_d} \sqrt{B_{B_d}}}{f_{B_s} \sqrt{B_{B_s}}} = 1.16 \pm 0.07.$$

The lower limit on $\Delta m_s$ constrains the vertex of the unitarity triangle in a circle in the $\rho - \eta$ plane with centre in (1,0).

### 2.5 Charmless Semileptonic b Decays

The constraints described so far suffer from the uncertainties in non-perturbative QCD quantities entering their expressions. The determination of either $|V_{ub}|$ or the ratio $|V_{ub}|/|V_{cb}|$ constitutes a constraint free from these uncertainties as:

$$|V_{ub}|/|V_{cb}| = \lambda \sqrt{\rho^2 + \eta^2}. \quad (5)$$

The CLEO collaboration has measured this ratio by means of the endpoint of inclusive charmless semileptonic B decays as: $|V_{ub}|/|V_{cb}| = 0.08 \pm 0.02$. The ALEPH [31], DELPHI [32] and L3 [33] collaborations have measured at LEP the inclusive charmless semileptonic branching fraction of beauty hadrons; these are averaged [10] as:

$$|V_{ub}| = (4.13^{+0.63}_{-0.75}) \times 10^{-3}.$$

Using the quoted value of $|V_{cb}|$, a combination with the CLEO measurement yields:

$$|V_{ub}|/|V_{cb}| = 0.089 \pm 0.010.$$

This constraint is represented by a circle in the $\rho - \eta$ plane with centre in (0,0), shown in Figure 2, that also presents all the other constraints described so far.

### 3 The fit

The $\rho$ and $\eta$ parameters are determined from a fit to the constraints described above. The experimental and theoretical quantities appearing in the formulae (2), (3),
Figure 2: Constraints in the $\rho - \eta$ plane. $B^0_s$ oscillations are reported as a 95% CL limit, while the other constraints represent a $\pm 1\sigma$ variation of the experimental and theoretical parameters entering in the formulae in the text. Central values are indicated by the dashed lines. A darker area shows the overlap among the constraints.

Table 1: Physical constants and parameters of the fit. The values not discussed in the text follow from Reference [8].

| Parameter | Value |
|-----------|-------|
| $\lambda$ | $0.2196(23)$ |
| $G_F$ | $1.16639(1) \times 10^{-5}$ GeV$^{-2}$ |
| $f_K$ | $0.1598(15)$ GeV |
| $\Delta m_K$ | $0.5304(14) \times 10^{-2}$ ps$^{-1}$ |
| $m_K$ | $0.497672(31)$ GeV |
| $m_W$ | $80.419(38)$ GeV |
| $m_{B_d}$ | $5.2792(18)$ GeV |
| $m_{B_s}$ | $5.3692(20)$ GeV |
| $m_B$ | $5.290(2)$ GeV |
| $\eta_B$ | $0.55(1)$ |
| $\eta_{lu}$ | $0.574(4)$ |
| $A$ | $0.83(4)$ |
| $\eta_{ct}$ | $0.47(4)$ |
| $\eta_{cc}$ | $1.38(53)$ |
| $\bar{m}_c(m_c)$ | $1.25(10)$ GeV |
| $\bar{m}_t(m_t)$ | $167.3(5.2)$ GeV |
| $f_{B_d}\sqrt{B_{B_d}}$ | $0.206(29)$ GeV |
| $B_K$ | $0.87(14)$ |
| $\xi$ | $1.16(7)$ |
| $|\epsilon_K|$ | $2.280(19) \times 10^{-3}$ |
| $\Delta m_d$ | $0.487(14)$ ps$^{-1}$ |
| $|V_{ub}|/|V_{cb}|$ | $0.089(10)$ |

([4] and [5]) are divided into two classes. Those whose uncertainties are below 2% are fixed to their central value as listed in the left half of Table 1. The quantities affected by a larger uncertainty and $|\epsilon_K|$ are considered as additional parameters of the fit, constraining their values to the estimates summarised in the right half of Table 1.
The following expression is then minimised:

\[
\chi^2 = \frac{(\hat{A} - A)^2}{\sigma_A^2} + \frac{(\hat{m}_e - m_e)^2}{\sigma_{me}^2} + \frac{(\hat{m}_t - m_t)^2}{\sigma_{mt}^2} + \frac{(\hat{B}_K - B_K)^2}{\sigma_{B_K}^2} + \frac{(\hat{\eta}_{cc} - \eta_{cc})^2}{\sigma_{\eta_{cc}}^2} + \\
\frac{(\hat{\eta}_{et} - \eta_{et})^2}{\sigma_{\eta_{et}}^2} + \frac{(f_{B_d} \sqrt{B_{B_d}} - f_{B_d} \sqrt{B_{B_d}})^2}{\sigma_{f_{B_d} \sqrt{B_{B_d}}}^2} + \frac{(\hat{\xi} - \xi)^2}{\sigma_{\xi}^2} + \frac{(\hat{V}_{ub}/\hat{V}_{cb} - |V_{ub}|/|V_{cb}|)^2}{\sigma_{|V_{ub}|/|V_{cb}|}^2} + \\
\frac{|\hat{\epsilon}_K - |\epsilon_K|)^2}{\sigma_{|\epsilon_K|}^2} + \frac{(\Delta m_d - \Delta m_d)^2}{\sigma_{\Delta m_d}^2} + \chi^2 (A (\Delta m_s), \sigma_A (\Delta m_s)).
\]

The symbols with a hat represent the reference values and the corresponding \( \sigma \) denote their uncertainties. The free parameters of the fit are \( \rho, \eta, A, m_e, m_t, B_K, \eta_{et}, \eta_{cc}, f_{B_d} \sqrt{B_{B_d}} \) and \( \xi \), used to calculate the values of \( |\epsilon_K|, \Delta m_d, \Delta m_s \) and \( |V_{ub}|/|V_{cb}| \) by means of the formulae (2), (3), (4) and (5).

As \( \Delta m_s \) is not yet measured, its experimental information has to be included in the \( \chi^2 \) following a different approach \( 6 \). The results of the search for \( B^0_s \) oscillations are combined \( 24 \) in terms of the oscillation amplitude \( A \) \( 22 \), a parameter that is zero in the absence of any signal and compatible with one otherwise, as expressed by the oscillation probability \( P \):

\[
P \left[ B^0_s \rightarrow (B^0_s, B^0_s) \right] = \frac{1}{2\tau_s} e^{-t/\tau_s} (1 \pm A \cos \Delta m_s).
\]

The results of different experiments are combined in terms of \( A (\Delta m_s) \) and of its uncertainty \( \sigma_A (\Delta m_s) \). The 95% CL limit on \( \Delta m_s \) is the value for which the area above one of the Gaussian distribution with mean \( A (\Delta m_s) \) and variance \( \sigma_A^2 (\Delta m_s) \) equals 5% of its total area. In the fit, each value taken by the parameters \( \rho, \eta \) and \( \xi \) is converted into a value of \( \Delta m_s \) by means of formula \( 6 \). A value of the CL for the oscillation hypothesis is then calculated by integrating the Gaussian distribution with mean \( A (\Delta m_s) \) and variance \( \sigma_A^2 (\Delta m_s) \). The value \( \chi^2 (A (\Delta m_s), \sigma_A (\Delta m_s)) \) of a \( \chi^2 \) distribution with one degree of freedom corresponding to this CL is then calculated and finally added to the \( \chi^2 \) of the fit.

The fit indicates the following values for the \( \rho \) and \( \eta \) parameters:

\[
\rho = 0.18 \pm 0.07 \quad \eta = 0.35 \pm 0.05
\]

\[
0.05 < \rho < 0.30 \quad 0.26 < \eta < 0.44 \quad (95\% \text{CL}).
\]

No large change in these results is observed if the theory contribution constraints are removed from the \( \chi^2 \) and a flat distribution within the uncertainties is used in their
place. Figure 3 presents the confidence regions for the vertex of the unitarity triangle. The value of the angles of the unitarity triangle are determined as:

\[
\sin 2\alpha = 0.14^{+0.25}_{-0.38} \quad \sin 2\beta = 0.73 \pm 0.07 \quad \gamma = 63^{\pm 8}\text{ degrees.}
\]

\[-0.77 < \sin 2\alpha < 0.50 \quad 0.59 < \sin 2\beta < 0.87 \quad 44^\circ < \gamma < 82^\circ \quad (95\%\text{CL})\]

The angles \(\alpha\) and \(\beta\) are reported in terms of the functions \(\sin 2\alpha\) and \(\sin 2\beta\), to which the studies of the CP symmetry usually refer.

\[\begin{array}{cccc}
\rho & \eta & 68\% \text{ CL} & 95\% \text{ CL} \quad 99\% \text{ CL} \\
\hline
\Delta m_s & \\
\Delta m_d & \\
|V_{ub}|/|V_{cb}| & \\
|\varepsilon_K| & \\
\end{array}\]

Figure 3: The favoured unitarity triangle and the confidence regions for its vertex; the \(\Delta m_s\) limit and the central values of the other constraints are also shown.

Several direct measurements of \(\sin 2\beta\) were recently reported, as listed in Table 2. Their average, \(\sin 2\beta^{\text{exp.}} = 0.48 \pm 0.16\), is lower but in agreement with the present estimate, that does not make use of this direct information.

4 Consequences of the fit

A strong experimental evidence for CP violation in the CKM matrix, described by values of its complex phase, \(\eta\), different from zero, comes from the neutral kaon system. It is of interest to investigate whether processes other than kaon physics predict a value of \(\eta\) compatible with zero or not. Figure 4 presents the results of a fit from which the information from the kaon system is removed. The presence of a CP violating phase in the matrix, i.e. its complex nature is strongly favoured.
Table 2: Measurements of \( \sin 2\beta \) and their average, compared with the fit result.

|       | Aleph  | BaBar   | Belle   | CDF     | Average | This fit |
|-------|--------|---------|---------|---------|---------|----------|
| \( \sin 2\beta \) | 0.93\(^{+0.64}_{-0.88}\) \(\pm 0.36\) | 0.34 \(\pm 0.20\) \(\pm 0.05\) | 0.58\(^{+0.32}_{-0.34}\) \(\pm 0.09\) | 0.79\(^{+0.41}_{-0.44}\) | 0.48 \(\pm 0.16\) | 0.73 \(\pm 0.07\) |

The values of the parameters \( B_K \) and \( f_{B_d} \sqrt{B_{B_d}} \) that describe non-perturbative QCD effects can be estimated by removing their constraint from the fit. This procedure yields:

\[
\rho = 0.17 \pm 0.07 \quad \eta = 0.38^{+0.05}_{-0.06} \quad B_K = 0.76^{+0.21}_{-0.15}
\]

in the first case and in the second:

\[
\rho = 0.21^{+0.07}_{-0.08} \quad \eta = 0.34 \pm 0.05 \quad f_{B_d} \sqrt{B_{B_d}} = 0.227^{+0.019}_{-0.015} \text{ GeV}.
\]

The fit indicates a value of \( B_K \) with an uncertainty larger than the input one, yet

Figure 4: The favoured unitarity triangle and the confidence regions for its vertex, no information from the kaon system is used in the fit. The experimental measurements of CP violation in the neutral kaon and neutral \( b \) meson systems are superimposed.
of similar magnitude. The value of $f_{B_d}\sqrt{B_{B_d}}$ is found to be well in agreement with the predicted one with a smaller uncertainty, this implies that the high experimental precision of the $\Delta m_d$ constraint is not fully exploited by the fit, limited by the uncertainty on the $f_{B_d}\sqrt{B_{B_d}}$ parameter.

The $\Delta m_s$ constraint heavily affects the $\rho$ uncertainty. Indeed, a fit that does not make use of the $\Delta m_s$ information results in:

$$\rho = 0.09^{+0.10}_{-0.15} \quad \eta = 0.40 \pm 0.05.$$  

This fit is used to estimate the favoured values of $\Delta m_s$ as:

$$\Delta m_s = 14.0^{+3.4}_{-3.3} \text{ps}^{-1}$$

$$7.4 \text{ps}^{-1} < \Delta m_s < 21.0 \text{ps}^{-1} \quad (95\% \text{CL}).$$

5 Conclusions

The measurements of $|\epsilon_K|$, $\Delta m_d$ and $|V_{ub}|$, together with the lower limit on $\Delta m_s$, effectively constrain the CKM matrix: from a fit to the experimental results and theory parameters, the vertex and the angles of the unitarity triangle are determined as:

$$\rho = 0.18 \pm 0.07 \quad \eta = 0.35 \pm 0.05$$

$$\sin 2\alpha = 0.14^{+0.25}_{-0.38} \quad \sin 2\beta = 0.73 \pm 0.07 \quad \gamma = 63^{+8}_{-11} \text{ degrees}.$$  

These results are in agreement with those of recent similar analyses [40,41,42,43,44].

A coherent picture of the current understanding of the CKM matrix is presented by a fit that does not use any constraint from the kaon system. Its results are displayed in Figure 4. The favoured region for the vertex of the unitarity triangle corresponds to that experimentally indicated by the measurement of the CP violation in the neutral kaon system and overlaps with the one indicated by the recent measurements of $\sin 2\beta$.

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