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# Flavour physics and CP violation

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**Abstract.** It is well known that the study of flavour physics and CP violation is very important to critically test the Standard Model and to look for possible signature of new physics beyond it. The observation of CP violation in kaon system in 1964 has ignited a lot of experimental and theoretical efforts to understand its origin and to look for CP violation effects in other systems besides the neutral kaons. The two $B$-factories BABAR and BELLE, along with other experiments, in the last decade or so made studies in flavour physics and CP violation a very interesting one. In this article we discuss the status and prospectives of the flavour physics associated with the strange, charm and bottom sectors of the Standard Model. The important results in kaon sector will be briefly discussed. Recently, mixing in the charm system has been observed, which was being pursued for quite some time without any success. The smallness of the mixing parameters in the charm system is due to the hierarchical structure of the CKM matrix. Interestingly, so far we have not found CP violation in the charm system but in the future, with more dedicated experiments at charm threshold, the situation could change. Many interesting observations have been made in the case of bottom mesons and some of them show some kind of deviations from that of the Standard Model expectations which are mainly associated with the $b \to s$ flavour changing neutral current transitions. It is long believed that the $B_s$ system could be the harbinger of new physics since it is a system in which both bottom and strange quarks are the constituents. Recently, D0 and CDF announced their result for the $B_s$ mixing which is claimed to be the first possible new physics signature in the flavour sector. We plan to touch upon all important issues pointing out both theoretical and experimental developments and future prospects in this review article.

**Keywords.** CP violation; kaon decays; charm decays; $B$ physics.

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## 1. Introduction

The study of flavour physics and CP violation has been so interesting that huge machines have been built for the experiments relating to it and a lot of theoretical developments have occurred in recent times. There is no need to mention that flavour physics and CP (the combined operation of charge conjugation (C) and parity (P)) violation studies in the past have led to many novel discoveries. It is one of the areas in physics where the theoretical developments and the experimental activities are closely interrelated and at present it is dominated by huge experimental activities (mainly due to electron–positron asymmetric $B$-factories). With the onset of the Large Hadron Collider at CERN, the flavour physics is poised for another golden period in particle physics where it is said that the LHC data might redefine the future of particle physics. So the flavour sector is believed to provide us with the flavour of physics beyond the Standard Model which might be just around the corner.

The Large Hadron Collider (LHC) at the European laboratory for high energy physics (popularly known as CERN) in Geneva, Switzerland is ready for experiments from this summer. The LHC is termed as the mother of all experiments, which was in fact the centre of media attraction in last September during the test run, for all the hype and also unfortunately for some wrong reasons. The fact is that this will be the experiment with highest energy till date which will be nearer to the energy scale believed to have occurred during the early stages of the evolution of the Universe. Therefore, it is expected that the experiments at the LHC will shed some light on the prevailing state of affairs during the early Universe and possibly many more (wanted/unwanted) surprises. The bottom line is that the LHC for sure is going to change/dictate the future course of action/direction in high energy physics.

The Standard Model (SM) of electroweak interactions [1] has been extremely successful in explaining almost all the data observed so far, except the neutrino sector, upto an energy scale of about 100 GeV. But still there are many reasons to believe that it is not the ultimate theory of nature, rather the low energy limit of a more fundamental theory, the true nature of which is not yet known. For example, some of the problems which could not be answered by the SM are the gauge hierarchy problem, the matter–antimatter asymmetry of the Universe, the observed nonzero neutrino mass to name a few. Therefore, intensive search for physics beyond the SM is now being performed in almost all areas of high energy physics. Let us remind all the readers that the all important particle of the SM, the so-called Higgs particle (also called the God particle) [2] is not yet discovered. But it is widely believed that the Higgs discovery is around the corner (Higgs mass up to 114 GeV has already been ruled out) [3] and the SM Higgs is almost impossible to escape the LHC detection if it indeed exists. Otherwise the SM framework where the masses of all the massive fermions and gauge bosons are generated through the Higgs mechanism will be in great danger. Without any doubt we hope that plenty of Higgs will be detected at the LHC (not just the SM Higgs ones) and in a lighter vein one can provide a nickname for the LHC (Liberal Higgs Café). Apart from the important task of discovering Higgs, the LHC is believed to provide us clues to the physics beyond the SM (physics that exists above the electroweak scale and may be well upto the Planck energy). Suffice it to mention that there are many beyond the SM scenarios that have been discussed in the literature to describe physics above the electroweak scale. These viable ideas, which are theoretically very exciting, will be tested at the LHC and possibly at least some of them will be completely ruled out. The String theorists are also looking at the LHC for some favour and there are many interesting ideas here too.

Major experiments at the LHC are the ALICE, ATLAS, CMS and LHCb. The ALICE is an ion collider experiment whereas part of the goals of ATLAS and CMS are associated with the flavour sector. The LHCb is a dedicated $B$-physics experiment like the $B$-factories, where apart from the usual $B$-mesons a large number of other hadrons containing a bottom quark (like $B_s$, $B_c$ and $\Lambda_b$) will be studied. Needless to mention that the $B_s$- and $B_c$-mesons are expected to provide valuable and clean experimental signals in some cases. Therefore, these studies might corroborate our previous findings from other experiments and/or predictions or else might reveal something completely unexpected.

Standard Model weak interactions are long known to violate parity and charge conjugation symmetries, in most cases even maximally. However, the combined operation CP was believed to be a good quantum number but in 1964 Christenson *et al* [4] discovered the violation of CP symmetry in the kaon system. Actually the violation was observed once in about 500 events. In 1967, Sakharov [5] pointed out that in order to explain the observed baryon asymmetry of the Universe, CP violation is essential along with some other requirements (baryon number violation and thermal non-equilibrium). In 1973, Kobayashi and Maskawa [6] proposed that there should be at least three family of quarks (or six quarks) to explain the observed CP violation. The 2008 Physics Nobel prize was awarded to Kobayashi and Maskawa [7] for their pioneering work on CP violation along with Y Nambu. The immensely successful Standard Model of electroweak theory in fact has three generations of quarks and Kobayashi–Maskawa mechanism is an integral part of it.

It is well known that flavour physics contributed significantly to the development of the SM, e.g., (i) the $K^0 - \bar{K}^0$ mixing led to a successful prediction of the charm mass before it was discovered, (ii) CP violation in kaon system indicated that there should be three generations before any third generation fermion was discovered and (iii) the large $B^0 - \bar{B}^0$ mixing led to the possibility of a very large top quark mass. So one can expect that history will be repeated again and it would probably be the flavour physics which will give us the first indication of new physics (NP) beyond the existing SM.

The article is organized as follows. In §2 we briefly discuss about the CP violation effect in the Standard Model. Section 3 covers the important developments in the kaon sector. In §4 we present the evidences of mixing in the $D$-meson system. Section 5 is devoted to the bottom ($B$) meson where we will discuss various rare decays and CP violation parameters which are important from experimental point of view. Section 6 will be about the bottom-strange system. New physics signals from $B$-factory data are discussed in §7 and the conclusions and future prospects are outlined in §8.

## 2. CP violation in the Standard Model

The Standard Model of electroweak interactions is based on the gauge group $SU(2)_L \times U(1)_Y$ [1] and it contains three families of quarks and leptons. In this model the left-handed quarks (i.e., quarks with negative helicity) are transformed as doublets under $SU(2)_L$ group as

$$Q^I_{Li} = \begin{pmatrix} u^I_{Li} \\ d^I_{Li} \end{pmatrix}, \tag{1}$$

while the corresponding right-handed quarks (with positive helicity) transform as singlets under $SU(2)_L$ denoted by $u^I_{Ri}$ and $d^I_{Ri}$. In our notation the superscript $I$ is for the interaction eigenstates and the subscript $i = 1, 2, 3$ is the generation index. The charged and neutral current interactions of the quarks with the $SU(2)_L$ gauge bosons ($W^\pm$ and $Z$) are given by

$$\mathcal{L}_W = \frac{g}{\sqrt{2}}(W^+_\mu \bar{u}^I_{Li}\gamma_\mu d^I_{Li} + W^-_\mu \bar{d}^I_{Li}\gamma_\mu u^I_{Li}) \tag{2}$$

and

$$\mathcal{L}_Z = \frac{g}{2\cos\theta_W} Z_\mu(\bar{u}^I_{Li}\gamma_\mu u^I_{Li} - \bar{d}^I_{Li}\gamma_\mu d^I_{Li} - 2\sin^2\theta_W J^\mu_{em}) , \tag{3}$$

where

$$J^\mu_{em} = \frac{2}{3}(\bar{u}^I_{Li}\gamma_\mu u^I_{Li} + \bar{u}^I_R\gamma_\mu u^I_R) - \frac{1}{3}(\bar{d}^I_{Li}\gamma_\mu d^I_{Li} + \bar{d}^I_{Ri}\gamma_\mu d^I_{Ri}) , \tag{4}$$

is the electromagnetic current and $g$ is the weak coupling constant.

The $SU(2)_L \times U(1)_Y$ Yukawa couplings involving the left-handed doublets of quarks, right-handed singlets and the Higgs doublet are given as

$$\begin{aligned}\mathcal{L}_Y &= \Big( - Y^d_{ij}\bar{Q}^I_{Li}\phi d^I_{Rj} - Y^u_{ij}\bar{Q}^I_{Li}\tilde{\phi} u^I_{Rj}\Big) + \text{h.c.} \\ &= -\left[(\bar{u}^I_{Li}\bar{d}^I_{Li})Y^d_{ij}\begin{pmatrix}\phi^+ \\ \phi^0\end{pmatrix} d^I_{Rj} + (\bar{u}^I_{Li}\bar{d}^I_{Li})Y^u_{ij}\begin{pmatrix}\phi^{0\dagger} \\ -\phi^-\end{pmatrix} u^I_{Rj}\right] + \text{h.c.},\end{aligned} \tag{5}$$

where $Y^{(u,d)}$s are the $3\times 3$ complex matrices and $\phi$ is the Higgs field. This part of the Lagrangian is in general CP violating and the CP violation effect is related to the complex Yukawa couplings. This can be understood as follows. The hermiticity of the Lagrangian implies that $\mathcal{L}_Y$ contains terms which come in pairs of the form

$$Y_{ij}\bar{\psi}_{Li}\phi\psi_{Rj} + Y^*_{ij}\bar{\psi}_{Rj}\phi^\dagger\psi_{Li}. \tag{6}$$

Under CP transformation the operators are interchanged as

$$\bar{\psi}_{Li}\phi\psi_{Rj} \leftrightarrow \bar{\psi}_{Rj}\phi^\dagger\psi_{Li} \tag{7}$$

but the Yukawa couplings $Y_{ij}$ and $Y^*_{ij}$ remain unchanged. This implies that CP is a symmetry of $\mathcal{L}_Y$ if $Y_{ij} = Y^*_{ij}$.

Now let us show that quark mixing is the only source of CP violation in the SM. When the Higgs field $\phi$ acquires a vacuum expectation value (VEV), it triggers spontaneous symmetry breaking (SSB) of the original gauge group as $SU(2)_L \times U(1)_Y \to U(1)_{\rm QED}$. On substituting $\phi^0$ by its VEV, $v/\sqrt{2}$, the mass terms are obtained as

$$\mathcal{L}_{\rm mass} = -\bar{d}^I_{Li}(M^{d^I})_{ij} d^I_{Rj} - \bar{u}^I_{Li}(M^{u^I})_{ij} u^I_{Rj} + \text{h.c.}, \tag{8}$$

where $M^{d^I} = Y^d v/\sqrt{2}$ and $M^{u^I} = Y^u v/\sqrt{2}$.

On transforming from the weak interaction eigenstate basis to the physical mass eigenstate basis (mass basis corresponds to diagonal mass matrices), one can always find unitary matrices $U^u_{L(R)}, U^d_{L(R)}$ such that

$$U_L^{u\dagger} M^{u^I} U_R^u = M^u = \text{diag}(m_u, m_c, m_t),$$
$$U_L^{d\dagger} M^{d^I} U_R^d = M^d = \text{diag}(m_d, m_s, m_b), \tag{9}$$

where the matrices $U$ are unitary, $M^u$ and $M^d$ are diagonals. Thus, the mass eigenstates $u_{L(R)i}$ and $d_{L(R)i}$ are related to the corresponding weak eigenstates by the following unitary transformations:

$$u^I_{L(R)i} = U^u_{L(R)i} u_{L(R)i}, \quad d^I_{L(R)i} = U^d_{L(R)i} d_{L(R)i}. \tag{10}$$

The charged current interaction in eq. (2) in terms of the quark mass eigenstates is given by

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} (W^+_\mu \bar{u}_{Li} \gamma^\mu V_{ij} d_{Lj} + W^-_\mu \bar{d}_{Li} \gamma^\mu V^\dagger_{ij} u_{Lj}), \tag{11}$$

where

$$V = U_L^{u\dagger} U_L^d, \tag{12}$$

is the Cabibbo–Kobayashi–Maskawa (CKM) [6,8] matrix given as

$$V \equiv V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}.$$

This means that the charged current couplings in the mass eigenstate basis will be modified as seen from eq. (11). However, the neutral current Lagrangian in the mass basis remains unchanged, i.e., there are no flavour changing neutral currents (FCNCs) at the tree level in the SM. One can interpret this mixing phenomenon in a more general way as the down-type quark interaction eigenstates $(d^I, s^I, b^I)$ result from the mixing of the corresponding mass eigenstates $(d, s, b)$ and they are related to each other through the unitary CKM matrix $V_{\text{CKM}}$ as

$$\begin{pmatrix} d^I \\ s^I \\ b^I \end{pmatrix} = V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \tag{13}$$

Let us now find out the number of independent parameters required to parametrize the CKM matrix. In general, an $N \times N$ complex matrix contains $2N^2$ real parameters; the unitarity constraints reduce it to $N^2$ real parameters. Since the phases of the quark fields are not observable, $(2N-1)$ phases can be rotated away. Thus we have $(N-1)^2$ independent physical parameters. Since an $N \times N$ orthogonal matrix has $N(N-1)/2$ angles, we conclude that $N \times N$ unitary matrix contains $N(N-1)/2$ rotation angles and $(N-1)^2 - N(N-1)/2 = (N-1)(N-2)/2$ physical phases. Thus, the $3 \times 3$ CKM matrix contains three Cabibbo-type angles and one physical phase. This phase is responsible for CP violation in the Standard Model.

There are many ways to express the elements of $V_{\rm CKM}$ in terms of three rotation angles and one phase. Thus, many different parametrizations for the CKM matrix have been proposed in literature. The standard parametrization used by the particle data group (PDG) is [9]

$$V_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}{\rm e}^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}{\rm e}^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}{\rm e}^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}{\rm e}^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}{\rm e}^{i\delta} & c_{23}c_{13} \end{pmatrix},$$

where $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$ $(i,j = 1,2,3)$ ($\theta_{ij}$ are the rotation angles) and the complex phase $\delta$ is responsible for CP violation in the SM.

One of the most important and popular parametrizations is the Wolfenstein parametrization [10] which has the following change of variables:

$$s_{12} \equiv \lambda, \quad s_{23} \equiv A\lambda^2, \quad s_{13}{\rm e}^{-i\delta} \equiv A\lambda^3(\rho - i\eta), \tag{14}$$

where $\lambda$, $A$ and $\rho$ are known as the Wolfenstein parameters. The CKM matrix thus becomes

$$V_{\rm CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\bar\rho - i\bar\eta) & -A\lambda^2 & 1 \end{pmatrix},$$

where $\eta \neq 0$ is responsible for CP violation in the SM and $\bar\rho$ and $\bar\eta$ are given by

$$\bar\rho = \rho\left(1 - \frac{\lambda^2}{2}\right), \quad \bar\eta = \eta\left(1 - \frac{\lambda^2}{2}\right). \tag{15}$$

It was first emphasized by Jarlskog that CP violation can be described via a rephasing quantity $J$ known as Jarlskog invariant [11] which is independent of the parametrization and defined as

$$\text{Im}(V_{ij}V_{kl}V_{il}^*V_{kj}^*) = J\sum_{m,n=1}^{3} \varepsilon_{\rm ikm}\varepsilon_{jln}, \tag{16}$$

where the $V$'s are the elements of the CKM matrix and $i,j,k,l = 1,2,3$. In terms of the standard parametrization

$$J = c_{12}c_{23}c_{13}^2 s_{12}s_{23}s_{13}\sin\delta. \tag{17}$$

Thus, in order to have an observable CP violation effect in the SM, the mixing angles $\theta_{ij}$ should not be zero or $\pi/2$ and the phase $\delta$ should not be zero or $\pi$.

The Yukawa Lagrangian in eq. (5) is, in general, CP violating. More precisely, CP is violated if and only if [11]

$$\text{Im}(\det[Y^d Y^{d\dagger}, Y^u Y^{u\dagger}]) \neq 0. \tag{18}$$

In the mass basis, the condition (18) translates to a necessary and sufficient condition for CP violation in the quark sector of the SM as

$$(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_t^2 - m_u^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_b^2 - m_d^2)J \neq 0. \tag{19}$$

Thus, in order that CP be violated in the SM, the following requirements must be met:

(a) The quarks of the same given charge should not be degenerate in mass.
(b) None of the three mixing angles should be zero or $\pi/2$.
(c) The phase $\delta$ of the CKM matrix should be neither zero nor $\pi$.

It is thus found that the nonzero complex phase is the origin of CP violation in the SM. Concerning the test of CKM picture of CPV the central target is the unitarity triangle. The unitarity of CKM matrix, i.e., $V_{\mathrm{CKM}}^\dagger V_{\mathrm{CKM}} = V_{\mathrm{CKM}} V_{\mathrm{CKM}}^\dagger = 1$, gives 12 equations (six normalization and six orthogonal relations). The orthogonality conditions can be represented by six triangles in the complex plane, which are known as unitarity triangles. The important feature of these triangles is that all these triangles have the same area and the area is related to the measure of CP violation $J$ through

$$J = 2 \cdot A, \tag{20}$$

where $A$ denotes the area of the triangle.

The triangle which can be best explored by $B$-decays is the graphical representation of the relation

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0. \tag{21}$$

The important feature of this traingle is that all the sides are of the same order (e.g., in the Wolfenstein representation they are of order $\lambda^3$) and hence the unitarity triangle is almost like an equilateral triangle, which naturally provides us a chance to measure its angles. Had it been quashed as in the case of other triangles, then we would not have been successful to determine the angles. One can normalize the above equation by dividing it by $V_{cd}V_{cb}^*$ and choose the base to be of unit length and the corresponding triangle is shown in figure 1. The angles of this triangle are termed as: $\alpha$, $\beta$ and $\gamma$ (or $\phi_1$, $\phi_2$ and $\phi_3$) which are defined as

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right), \quad \alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \quad \beta = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right). \tag{22}$$

The angles $\beta$ and $\gamma$ are directly related to the complex phases of the CKM elements $V_{td}$ and $V_{ub}$, respectively as

$$V_{td} = |V_{td}|\mathrm{e}^{-i\beta}, \quad V_{ub} = |V_{ub}|\mathrm{e}^{-i\gamma}. \tag{23}$$

The angle $\alpha$ can be obtained through the relation

$$\alpha + \beta + \gamma = 180^\circ. \tag{24}$$

It can be seen that a nonzero value of $\beta$ or $\gamma$ implies that $\eta$ is nonzero and thus CP violation cannot be ruled out. It is, therefore, imperative that the three angles of

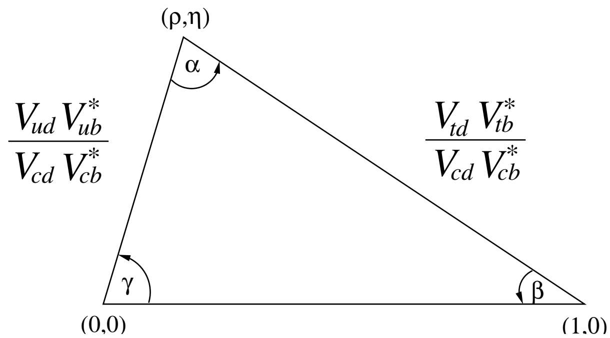


**Figure 1.** The rescaled unitarity triangle

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the triangle be measured independently to get decisive information on the origin of CP violation.

After having an idea of CP violation in the Standard Model, we would now like to discuss the implications of this theory for the phenomenology of CP violation in meson decays. Although our main focus will be on $B$-meson decays, first we would like to present the important results of kaon and charm sectors.

## 3. CP violation in the kaon system

We now briefly discuss the manifestation of CP violation in neutral $K$ system. The two neutral kaons $K^0$ and $\bar{K}^0$ can decay to pions via the weak interaction $|\Delta S| = 1$. Thus, mixing can occur via (virtual) intermediate pion states. These transitions are $|\Delta S| = 2$ transitions and are thus second-order weak transitions. Thus, if at time $t = 0$, we have a pure $K^0$ state, then at any later time $t$, we can have a superposition of both $K^0$ and $\bar{K}^0$. Therefore, we can form the linear combination (CP eigenstates)

$$K_{L,S} = \frac{K^0 \pm \bar{K}^0}{\sqrt{2}}, \tag{25}$$

where $K_S$ and $K_L$ are the particles associated with the short-lived and long-lived $K$-mesons which can decay to $2\pi$ (CP even) and $3\pi$ (CP odd) states, respectively. A diagram called the box diagram as shown in figure 2 depicts the $K^0 - \bar{K}^0$ mixing.

With the discovery of the decay $K_L \to 2\pi$ in 1964, it was established that $K_L$ and $K_S$ are not CP eigenstates anymore but the new CP eigenstates are $K_1$ and $K_2$ defined as

$$\begin{aligned} K_1 &= \frac{1}{\sqrt{2}}(K^0 - \bar{K}^0), \quad \mathrm{CP}|K_1\rangle = K_1, \\ K_2 &= \frac{1}{\sqrt{2}}(K^0 + \bar{K}^0), \quad \mathrm{CP}|K_2\rangle = -K_2, \end{aligned} \tag{26}$$

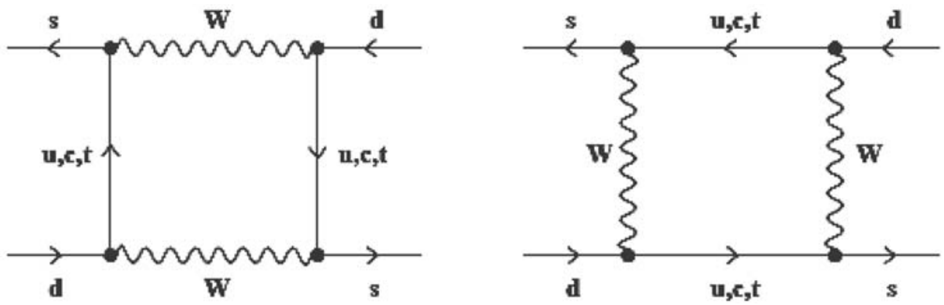


**Figure 2.** Box diagrams depicting $K^0 - \bar{K}^0$ mixing.

and are related to the mass eigenstates $K_S$ and $K_L$ by

$$K_S = \frac{K_1 + \bar{\varepsilon} K_2}{\sqrt{(1+|\bar{\varepsilon}|^2)}}, \quad K_L = \frac{K_2 + \bar{\varepsilon} K_1}{\sqrt{(1+|\bar{\varepsilon}|^2)}}\ , \tag{27}$$

where $\bar{\varepsilon}$ parametrizes the deviation from the CP conserving limit. This violation is called indirect CP violation as it arises from the fact that the weakly decaying eigenstates of definite lifetimes, $K_S$ and $K_L$, are each an admixture of the wrong CP to a degree $\bar{\varepsilon}$. The measure for this type of CP violation is defined as

$$\varepsilon \equiv \frac{A(K_L \to (\pi\pi)_{I=0})}{A(K_S \to (\pi\pi)_{I=0})}, \tag{28}$$

where $\varepsilon = \bar{\varepsilon} + i\xi$ and $\xi = \mathrm{Im} A_0 / \mathrm{Re}\, A_0$.

CP violation can also be direct and is realized via a direct transition of a CP odd to a CP even state: $K_2 \to \pi\pi$. A measure of such a violation is given by the complex parameter

$$\varepsilon' = \frac{1}{\sqrt{2}} \mathrm{Im}\left(\frac{A_2}{A_0}\right) \exp(i\phi_{\varepsilon'}), \tag{29}$$

where $A_I$ is the amplitude for $K^0$ to decay into a two-pion final state with isospin $I$, with the strong phase $\phi_{\varepsilon'}$ factored out. Experimentally, the two parameters $\varepsilon$ and $\varepsilon'$ can be determined by measuring the ratios

$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)}, \quad \eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \tag{30}$$

or

$$\eta_{00} = \varepsilon - 2\varepsilon', \quad \eta_{+-} = \varepsilon + \varepsilon'. \tag{31}$$

The observed CP violation parameters in $K_L \to \pi\pi$ decays are summarized below [3].

$$|\eta_{00}| = (2.222 \pm 0.012) \times 10^{-3}, \quad |\eta_{+-}| = (2.233 \pm 0.012) \times 10^{-3}, \tag{32}$$

$$|\varepsilon| = (2.229 \pm 0.012) \times 10^{-3}, \quad \mathrm{Re}(\varepsilon'/\varepsilon) = (1.65 \pm 0.26) \times 10^{-3}. \qquad (33)$$

As can be seen from the expressions (32) and (33), the CP violation parameters $\varepsilon$ and $\varepsilon'$ in the $K$ systems show small effects and since the kaons are light, too many decay modes are not available. Therefore, it is difficult to relate these CP violation effects to CKM parameters. However, it came to the realization that CP violation may not be restricted to neutral kaon systems but may also be present in the neutral mesons containing charm and bottom quarks. Investigations have shown that CP violation in charmed $D$ systems may not be observable or is small in the SM. It is expected that in $B$-mesons, the effects will be larger and so it will be easy to relate them to SM parameters.

### 3.1 *Results from rare kaon sector*

The rare decays $K \to \pi\nu\bar{\nu}$, being theoretically very clean and extremely suppressed in the SM are known to be one of the best probes of new physics in the flavour sector. The SM predictions obtained in the NNLO level is

$$\begin{aligned} &\mathrm{Br}(K_L \to \pi^0\nu\bar{\nu})_{\mathrm{SM}} = (2.76 \pm 0.40) \times 10^{-11}, \quad [12] \\ &\mathrm{Br}(K^+ \to \pi^+\nu\bar{\nu})_{\mathrm{SM}} = (8.5 \pm 0.7) \times 10^{-11}. \quad [13] \end{aligned} \qquad (34)$$

Recently, the BNL experiment (E949) [14] observed three $K^+ \to \pi^+\nu\nu$ events and the branching ratio was found to be $\mathrm{Br}(K^+ \to \pi^+\nu\nu) = 1.73^{+1.15}_{-1.05} \times 10^{-10}$, however with large uncertainties. Regarding the $K_L$, we have only the upper bound for $\mathrm{Br}(K_L \to \pi^0\nu\bar{\nu}) < 6.7 \times 10^{-8}$ [15], as this decay is experimentally very challenging. We have plenty of data in the kaon sector from KTeV, KLOE, NA48 experiments. It is believed that at J-PARC (E-14) Japan and NA62 (P326) CERN experiments, hopefully, it will be possible to identify the new physics in the rare decay mode $K_L \to \pi^0\nu\bar{\nu}$ (which is a golden mode in the kaon sector as far as new physics is concerned).

Another important parameter is the determination of $|V_{us}|$ from the leptonic and semileptonic kaon decays. In fact using $K_{l3}$ ($K \to \pi l\nu$) decays, where $l = e, \mu$, the Gobal Flavianet fit [16] to all kaon data obtained the value of $V_{us}$ to be $|V_{us}| = 0.2246 \pm 0.0012$. New physics (say, from charged Higgs) effect in $K_{l2}$ (new results expected from KLOE, NA62) can be compared with that of $B \to \tau\nu$ to constrain the parameter space. Search for direct CP violation in $K \to 3\pi$ decays has obtained null result and no direct CPV in $K \to 3\pi$ observed at the level of $O(10^{-4})$.

## 4. Mixing in the charm sector

Let us now turn our attention to the charm sector. First, let us go into a bit of history: discovery of charm quark was made in 1974. In 1980s the theory of $D$-mixing for both short distance (SD) and long distance (LD) contributions, within the framework of the SM, was developed. We had experimental results from E687, E791 and FOCUS Collaborations in 1990s. In 2000s the CLEO, BELLE and BABAR experiments contributed to the data in the charm sector and finally after a long wait in 2007, $D^0-\bar{D}^0$ mixing (interestingly by all the experiments, i.e., BELLE, BABAR, CLEO, CDF) [17–19] was observed. Since this is an important result, we will discuss a bit on this in the following. The heavy flavour averaging group (HFAG) (charm subgroup) [20] obtained the mixing parameters in the $D^0$ system (2007) as

$$x_D = \frac{\Delta m}{\bar{\Gamma}} = \left(8.4^{+3.2}_{-3.4}\right)\times 10^{-3}, \quad y_D = \frac{\Delta\Gamma}{2\bar{\Gamma}} = (6.9\pm 2.1)\times 10^{-3}. \quad (35)$$

Now we discuss the formalism and notations used here. In order to study the $D^0-\bar{D}^0$ mixing, the time evolution of the mass eigenstates are defined as

$$|D_1(t)\rangle = |D_1\rangle \mathrm{e}^{-(\frac{\Gamma_1}{2}+im_1)t}, \quad |D_2(t)\rangle = |D_2\rangle \mathrm{e}^{-(\frac{\Gamma_2}{2}+im_2)t}. \quad (36)$$

The weak states are related to the mass eigenstates as

$$|D^0\rangle = \frac{1}{2p}(|D_1\rangle + |D_2\rangle) \quad \text{and} \quad |\bar{D}^0\rangle = \frac{1}{2q}(|D_1\rangle - |D_2\rangle), \quad (37)$$

where $p$ and $q$ are the mixing parameters. Similarly, the time evolution of the weak eigenstates is given by

$$\begin{aligned} |D^0(t)\rangle &= \mathrm{e}^{-(\frac{\bar{\Gamma}}{2}+i\bar{m})t}\left\{\cosh[(\cdots)t]|D^0\rangle + \frac{q}{p}\sinh[(\cdots)t]|\bar{D}^0\rangle\right\}, \\ |\bar{D}^0(t)\rangle &= \mathrm{e}^{-(\frac{\bar{\Gamma}}{2}+i\bar{m})t}\left\{\frac{p}{q}\sinh[(\cdots)t]|D^0\rangle + \cosh[(\cdots)t]|\bar{D}^0\rangle\right\}. \end{aligned} \quad (38)$$

In the above expressions we have used $(\cdots) = (\frac{\Delta\Gamma}{4} + i\frac{\Delta m}{2})$, $\bar{m} = (m_1+m_2)/2$; $\bar{\Gamma} = (\Gamma_1+\Gamma_2)/2$, $\Delta m = m_2 - m_1$; $\Delta\Gamma = (\Gamma_2 - \Gamma_1)$.

For $\Delta m t \ll 1$ and $\Delta\Gamma t \ll 1$, one can write $|\langle f|H|D^0(t)\rangle|^2$ for a process $D^0(t)\to f$, in a simple form which is

$$\begin{aligned} |\langle f|H|D^0(t)\rangle|^2 \propto \mathrm{e}^{-\bar{\Gamma}t}\Big\{&1 + [y\,\mathrm{Re}(\lambda) - x\,\mathrm{Im}(\lambda)](\bar{\Gamma}t) \\ &+ |\lambda|^2\frac{x^2+y^2}{4}(\bar{\Gamma}t)^2\Big\}, \end{aligned} \quad (39)$$

where we have introduced the notation $x = \Delta m/\bar{\Gamma}$, $y = \Delta\Gamma/2\bar{\Gamma}$ and $\lambda = (q/p)(\mathcal{A}(\bar{D}^0\to f))/(\mathcal{A}(D^0\to f))$. To elaborate the formalism, now we will consider a specific example. So we discuss the $D^0$ mixing using the lifetime difference with $D^0\to K^-\pi^+$. There are two possibilities: (i) $D^0(t)\to K^+\pi^-$ which is doubly Cabibbo suppressed (DCS), (ii) $D^0\to\bar{D}^0\to K^+\pi^-$, where $D^0$ goes over to $\bar{D}^0$ and then decays to $K^-\pi^+$ (which is Cabibbo favoured (CF)). We can thus write eq. (39) as

$$\begin{aligned} |\langle f|H|D^0(t)\rangle|^2 \propto \mathrm{e}^{-\bar{\Gamma}t}\Bigg\{&R_D + \left|\frac{q}{p}\right|\sqrt{R_D}[y\cos(\phi+\delta) - x\sin(\phi+\delta)] \\ &\times(\bar{\Gamma}t) + \left|\frac{q}{p}\right|^2\frac{x^2+y^2}{4}(\bar{\Gamma}t)^2\Bigg\}. \end{aligned} \quad (40)$$

Here $f$ is $K^+\pi^-$ and

$$\lambda = \frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f} = \left|\frac{q}{p}\right| R_D^{-1/2} \mathrm{e}^{i(\phi+\delta)}. \tag{41}$$

In the above expression we have explicitly introduced the strong and weak phases in the decay process. $\delta$ is the strong phase between the DCS and CF amplitudes and $\phi$ is the corresponding weak phase. $R_D^{1/2}$ is the ratio of DCS to the CF amplitude, $R_D^{1/2} = |A(D^0 \to K^+\pi^-)/A(\bar{D}^0 \to K^+\pi^-)|$. The expression can be further simplified as

$$|\langle f|H|D^0(t)\rangle|^2 \propto \mathrm{e}^{-\bar{\Gamma}t} \left\{ R_D + \left|\frac{q}{p}\right| \sqrt{R_D}[y'\cos\phi - x'\sin\phi](\bar{\Gamma}t) + \left|\frac{q}{p}\right|^2 \frac{x'^2+y'^2}{4}(\bar{\Gamma}t)^2 \right\}, \tag{42}$$

where $x'$ and $y'$ are related to $x$ and $y$ through

$$x' = x\cos\delta + y\sin\delta, \quad y' = y\cos\delta - x\sin\delta. \tag{43}$$

It should be noted here that $|q/p| = 1$, $\phi = 0$ correspond to no CP violation.

There have been studies using three-body $K$ decays using the Dalitz plot techniques to measure various CP asymmetry parameters which we are not quoting here and can be found in the literature [21]. Before concluding this section we note that CLEO-c and BES-III are two experiments which will continue to explore the physics in the charm sector.

The two-dimensional contour plots between different mixing parameters [20] are shown in figure 3. One can see from the top panel of figure 3 that no CPV point ($|q/p| = 1$, $\phi = 0$) is within the 1-$\sigma$ range, and therefore no CP violation has been established so far in the $D^0$ system, whereas if one looks at the bottom panel of figure 3, the no-mixing point ($x$, $y$ =0) is excluded by more than 6-$\sigma$ and this is the evidence of mixing in the $D^0$ system, which is now firmly established by all the existing experiments.

The ratio $R$ of $D^0 \to K^+\pi^-$ to $D^0 \to K^-\pi^+$ decay rates can be approximated as simple quadratic function of $t/\tau$ [18,22], where $t$ is the proper time and $\tau$ is the mean $D^0$ lifetime,

$$R(t/\tau) = R_D + \sqrt{R}_D y'(t/\tau) + \frac{x'^2+y'^2}{4}(t/\tau)^2. \tag{44}$$

In the absence of mixing $x' = y' = 0$ and $R(t/\tau) = R_D$. In the left panel of figure 4 (taken from [18]) again it is shown that no-mixing is excluded. In the right panel, the value $R$ with and without mixing [18] is shown which clearly establishes the mixing in charm system.

## 5. CP violation in $B$-meson system

Now we will discuss the physics related to $B$-system (for a review, one can refer [23]). The subject has received much attention in recent times because of the fact

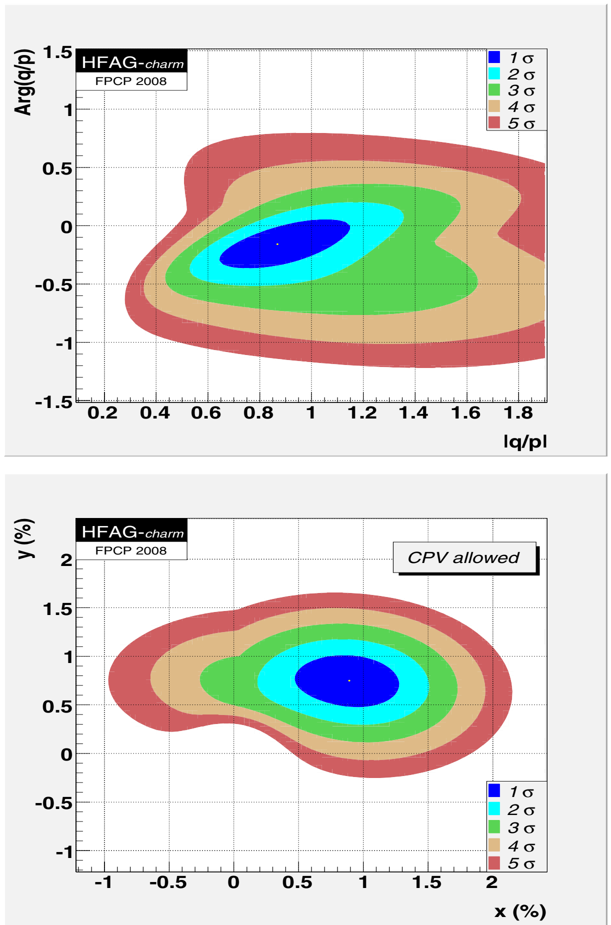


**Figure 3.** Two-dimensional contour plot between $|q/p|$ and the weak phase $\phi$ (top panel) and between $x$ and $y$ (bottom panel). The experimental ranges are depicted by various colours as indicated in the figure.

that two dedicated giant $B$-factories were constructed, named BABAR (SLAC, USA) and BELLE (KEK, Japan) which were designed to perform $B$-related studies and hopefully to uncover the signal of new physics apart from verifying the SM predictions. The data taking at BABAR is already over whereas the BELLE will stop taking data in a year's time. The BELLE will be upgraded to what is called Super-KEKB and BABAR will be replaced by Super-$B$ at Frascati, Italy. These are the two upcoming facilities which are known in the literature as the Super-$B$ factories which will continue to take data in the $B$-sector. The objectives will be the precision measurements of various parameters and looking for signals of physics beyond the SM. It should be emphasized here that there is another dedicated $B$ experiment which is going to start taking data soon at the Large Hadron Collider (LHC) and is known as LHC-b experiment. There is no need to mention that

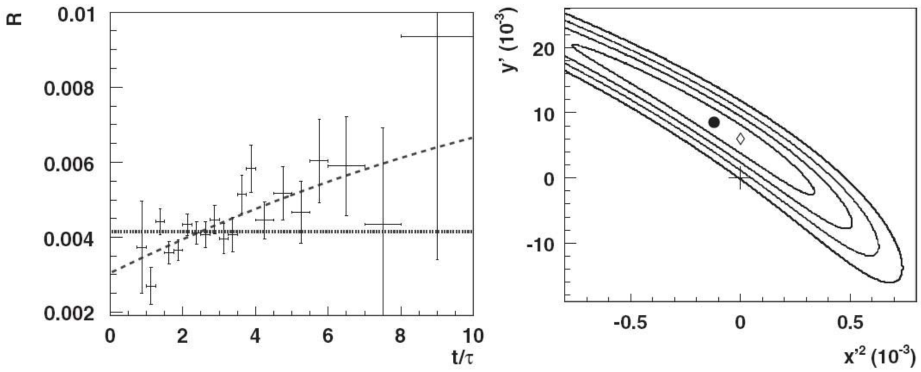


**Figure 4.** In the left panel of the plot, $R$ vs. normalized proper decay time $t/\tau$ is plotted and the horizontal line corresponds to no mixing and the dotted line to that of mixing. In the right side we have shown a plot of $y'$ vs. $x'^2$ where the blob corresponds to the central value as obtained from the D0 data and the + corresponds to the no-mixing point.

Tevatron II is taking data and so CDF and D0 are expected to play important roles in this sector and to provide important clues for the upcoming LHC-b experiment.

Analogous to $K^0 - \bar{K}^0$ mixing, the neutral $B$-mesons ($B_q^0$ $(q = d, s)$) experience the particle–antiparticle mixing phenomena. Due to the mixing the mass eigenstates denoted as $B_H$ and $B_L$, where $H(L)$ stands for Heavy(Light), differ from the corresponding flavour eigenstates $B_q^0$ and $\bar{B}_q^0$ and this mixing is responsible for the CP violation in $B$-system within the SM. Here we very briefly describe the oscillation phenomenon in the neutral $B$-meson system. It is a second-order weak transition and is induced via a box diagram as in the kaon system (figure 2) with $s$ replaced by $b$ and $d$ by $q = (d, s)$ for $B_q - \bar{B}_q^0$ mixing. The flavour eigenstates in the $B_{d,s}^0 - \bar{B}_{d,s}^0$ mixing are given by

$$B_d^0 = (\bar{b}d), \quad \bar{B}_d^0 = (b\bar{d}), \quad B_s^0 = (\bar{b}s), \quad \bar{B}_s^0 = (b\bar{s}). \tag{45}$$

Due to the flavour mixing, the time evolution of the $B_q^0 - \bar{B}_q^0$ system is described by

$$i\frac{\mathrm{d}\psi(t)}{\mathrm{d}t} = \hat{H}\psi(t), \quad \text{with} \quad \psi(t) = \begin{pmatrix} |B_q^0(t)\rangle \\ |\bar{B}_q^0(t)\rangle \end{pmatrix}, \tag{46}$$

where

$$\hat{H} = \hat{M} - i\frac{\hat{\Gamma}}{2} = \begin{pmatrix} M_{11} - i\frac{\Gamma_{11}}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{21} - i\frac{\Gamma_{21}}{2} & M_{22} - i\frac{\Gamma_{22}}{2} \end{pmatrix} \tag{47}$$

with $\hat{M}$ and $\hat{\Gamma}$ being the mass matrix and decay width matrix, respectively and they are Hermitian. Due to hermiticity of the $M$ and $\Gamma$ matrices, $M_{21} = M_{12}^*$, $\Gamma_{21} = \Gamma_{12}^*$ and due to CPT invariance, $M_{11} = M_{22} \equiv M$, $\Gamma_{11} = \Gamma_{22} \equiv \Gamma$. The Hamiltonian thus becomes

$$\hat{H} = \begin{pmatrix} M - i\frac{\Gamma}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{12}^* - i\frac{\Gamma_{21}^*}{2} & M - i\frac{\Gamma}{2} \end{pmatrix}. \tag{48}$$

Now onwards we will concentrate only on $B_d^0 - \bar{B}_d^0$ system, but analogous relations will hold for $B_s$-system as well. With the diagonalization of the Hamiltonian matrix, one obtains two physically observed mass eigenstates given by

$$B_H = pB^0 + q\bar{B}^0, \quad B_L = pB^0 - q\bar{B}^0, \tag{49}$$

where

$$p = \frac{1 + \bar{\varepsilon}_B}{\sqrt{2(1 + |\bar{\varepsilon}_B|^2)}}, \quad q = \frac{1 - \bar{\varepsilon}_B}{\sqrt{2(1 + |\bar{\varepsilon}_B|^2)}} \tag{50}$$

and $\bar{\varepsilon}_B$ corresponds to $\bar{\varepsilon}$ in the kaon system and $H$ and $L$ indicate heavy and light, respectively. In the $B^0 - \bar{B}^0$ system, the lifetime difference $\Delta\Gamma = \Gamma_H - \Gamma_L$ is much smaller as compared to the mass difference $\Delta M = M_H - M_L$, i.e., $\Delta\Gamma \ll \Delta M$. Therefore, the mass eigenstates $B_H$ and $B_L$ are usually distinguished by their masses and not by their lifetimes. The mixing parameters $p$ and $q$ are related to the off-diagonal elements of the mass matrix which are given as

$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}, \tag{51}$$

which in the limit $\Gamma_{12} \ll M_{12}$ reduces to

$$\frac{q}{p} \approx \sqrt{\frac{M_{12}^*}{M_{12}}}. \tag{52}$$

The mass difference $\Delta M_d$ can be expressed in terms of the off-diagonal elements in the $B^0$-meson mass matrix

$$\Delta M_d = 2|M_{12}^{(d)}|. \tag{53}$$

In the SM, the effective Hamiltonian describing the $\Delta B = 2$ transition, induced by the box diagram, is given by [24]

$$\hat{H} = \frac{G_{\mathrm{F}}^2}{16\pi^2} \lambda_t^2 M_W^2 S_0(x_t) \eta_t (\bar{d}b)_{V-A} (\bar{d}b)_{V-A}, \tag{54}$$

where $\lambda_t = V_{tb} V_{td}^*$, $\eta_t$ is the QCD correction factor and $S_0(x_t)$ is the loop function

$$S_0(x_t) = \frac{4x_t - 11x_t^2 + x_t^3}{4(1 - x_t)^2} - \frac{3}{2} \frac{\log x_t x_t^3}{(1 - x_t)^3}, \tag{55}$$

with $x_t = m_t^2/M_W^2$. Evaluation of the box diagrams gives the element $M_{12}$ as

$$(M_{12})_d = \frac{1}{2m_{B_d}} \langle \bar{B}_d | \hat{H} | B_d \rangle = \frac{G_{\mathrm{F}}^2}{12\pi^2} f_{B_d}^2 \hat{B}_{B_d} m_{B_d} M_W^2 (V_{td}^* V_{tb})^2 S_0(x_t) \eta_t, \tag{56}$$

where we have used the vacuum insertion method to evaluate the matrix elements of the four quark current operators which is given as

$$\langle \bar{B}_d|\bar{d}\gamma^\mu(1-\gamma_5)b\bar{d}\gamma_\mu(1-\gamma_5)b|B_d\rangle = \frac{8}{3}f_{B_d}^2\hat{B}_{B_d}m_{B_d}^2, \tag{57}$$

where $f_{B_d}$ is the $B_d$-meson decay constant and $\hat{B}_{B_d}$ is the bag parameter. Thus, we have

$$(M_{12}^*)_d \propto (V_{td}V_{tb}^*)^2, \quad (M_{12}^*)_s \propto (V_{ts}V_{tb}^*)^2. \tag{58}$$

As the CKM elements $V_{td}$ and $V_{ts}$ are expressed in terms of the angle $\beta_{(s)}$ of the unitarity triangle as

$$V_{td} = |V_{td}|\mathrm{e}^{-i\beta}, \quad V_{ts} = |V_{ts}|\mathrm{e}^{-i\beta_s}, \tag{59}$$

one can obtain

$$\left(\frac{q}{p}\right)_{d,s} = \exp(-2i\phi_M^{d,s}), \quad \phi_M^d = \beta, \quad \phi_M^d = \beta_s. \tag{60}$$

Now let us see the effect of mixing in the time development of a pure flavour eigenstate. Due to mixing, the proper time evolution of states that are pure $B^0$ or $\bar{B}^0$ at time $t=0$ is given by

$$|B^0(t)\rangle = g_+(t)|B^0\rangle + \frac{q}{p}g_-(t)|\bar{B}^0\rangle,$$

$$|\bar{B}^0(t)\rangle = \frac{p}{q}g_-(t)|B^0\rangle + g_+(t)|\bar{B}^0\rangle, \tag{61}$$

where

$$g_+(t) = \exp(-\Gamma t/2)\exp(-iMt)\cos(\Delta M t/2),$$

$$g_-(t) = \exp(-\Gamma t/2)\exp(-iMt)i\sin(\Delta M t/2). \tag{62}$$

Now let us consider the decay of initial $B^0(\bar{B}^0)$ into a common final CP eigenstate $f_{\mathrm{CP}}$. Defining the amplitudes for these processes as

$$A = \langle f_{\mathrm{CP}}|\hat{H}|B^0\rangle, \quad \bar{A} = \langle f_{\mathrm{CP}}|\hat{H}|\bar{B}^0\rangle, \tag{63}$$

and their ratio

$$\lambda = \frac{q}{p}\frac{\bar{A}}{A}, \tag{64}$$

the time-dependent rates for initially pure $B^0$ or $\bar{B}^0$ states to decay into the final CP eigenstate at time $t$ is given by

$$\Gamma(B^0(t) \to f_{\rm CP}) = |A|^2 {\rm e}^{-\Gamma t}\left(\frac{1+|\lambda|^2}{2} + \frac{1-|\lambda|^2}{2}\cos\Delta M t - {\rm Im}\,\lambda \sin\Delta M t\right),$$
$$\Gamma(\bar{B}^0(t) \to f_{\rm CP}) = |A|^2 {\rm e}^{-\Gamma t}\left(\frac{1+|\lambda|^2}{2} - \frac{1-|\lambda|^2}{2}\cos\Delta M t + {\rm Im}\,\lambda \sin\Delta M t\right). \quad (65)$$

As these two decay rates are not identical, they would signal CP violation in the corresponding decay processes.

In general, CP violation effects in $B$-system are classified into three categories which are basically known as (i) CP violation in mixing, (ii) CP violation in decay and (iii) CP violation in the interference of mixing and decay. We now briefly elaborate these things in a concise way.

(i) *CP violation in mixing*

This type of CP violation is due to the fact that the mass eigenstates are different from the CP eigenstates and is defined by $\mathrm{Re}(\varepsilon) \neq 0$ or $|q/p| \neq 1$. The effect can be observed in semileptonic decays of $B$ and $K$ where the final states contain 'wrong charge' leptons and can be attained only through $B^0 - \bar{B}^0$ mixing. The asymmetry is defined as

$$a_{SL}(B) = \frac{\Gamma(\bar{B}^0(t) \to l^+\nu X) - \Gamma(B^0(t) \to l^-\bar{\nu} X)}{\Gamma(\bar{B}^0(t) \to l^+\nu X) + \Gamma(B^0(t) \to l^-\bar{\nu} X)} = \frac{1-|q/p|^4}{1+|q/p|^4}, \quad (66)$$

where $B^0(0) = B^0$, $\bar{B}^0(0) = \bar{B}^0$ and the time evolution of these states are given by eqs (61) and (62). The asymmetry becomes nonzero as the phases in the transitions $B^0 \to \bar{B}^0$ and $\bar{B}^0 \to B^0$ differ from each other.

(ii) *CP violation in decay*

This type of CP violation is also known as direct CP violation and is best described in charged $B$ and $K$ decays. It can also be measured in the neutral modes. Defining

$$\mathcal{A}_{f^+} = \langle f^+|\mathcal{H}^{\rm weak}|B^+\rangle, \quad \bar{\mathcal{A}}_{f^-} = \langle f^-|\mathcal{H}^{\rm weak}|B^-\rangle, \quad (67)$$

the asymmetry is given as

$$\mathcal{A}_{\rm CP}^{\rm dir}(B^\pm \to f^\pm) = \frac{\Gamma(B^+ \to f^+) - \Gamma(B^- \to f^-)}{\Gamma(B^+ \to f^+) + \Gamma(B^- \to f^-)} = \frac{1-|\bar{A}_{f^-}/A_{f^+}|^2}{1+|\bar{A}_{f^-}/A_{f^+}|^2}. \quad (68)$$

For direct CP violation, one requires at least two different interfering contributions to the decay amplitude having different weak ($\phi_i$) and strong ($\delta_i$) phases. For example, they can be two tree diagrams, two penguin diagrams or one tree and one penguin diagram. In this way, we can write the decay amplitude $A_{f^+}$ and its CP conjugate $\bar{A}_{f^-}$ as

$$A_{f^+} = \sum_{i=1,2} A_i e^{i(\delta_i+\phi_i)}, \quad \bar{A}_{f^-} = \sum_{i=1,2} A_i e^{i(\delta_i-\phi_i)}. \tag{69}$$

It should be noted that the weak phases $\phi_i$ in the CP conjugate amplitudes have opposite signs, whereas the strong phases $\delta_i$ have the same sign as CP is conserved in strong interactions. Thus, we can have $|\bar{A}_{f^-}/A_{f^+}| \neq 1$ and the direct CP asymmetry is, therefore, nonzero and is given as

$$\mathcal{A}_{\rm CP}^{\rm dir}(B^\pm \to f^\pm) = \frac{-2A_1A_2\sin(\delta_1-\delta_2)\sin(\phi_1-\phi_2)}{A_1^2+A_2^2+2A_1A_2\cos(\delta_1-\delta_2)\cos(\phi_1-\phi_2)}. \tag{70}$$

(iii) *CP violation in the interference of mixing and decay*

This type of CP violation occurs in neutral $B$-decays only where the final states are common to both $B^0$ and $\bar{B}^0$. The effect can be observed by comparing the time-dependent decays into final CP eigenstates. From eq. (65), one can obtain the time-dependent CP asymmetry defined as

$$\begin{aligned} A_{\rm CP}(t) &= \frac{\Gamma(B^0(t)\to f_{\rm CP}) - \Gamma(\bar{B}^0(t)\to f_{\rm CP})}{\Gamma(B^0(t)\to f_{\rm CP}) + \Gamma(\bar{B}^0(t)\to f_{\rm CP})} \\ &= \mathcal{A}_{\rm CP}^{\rm dir}(f_{\rm CP})\cos(\Delta M t) + \mathcal{A}_{\rm CP}^{\rm mix}(f_{\rm CP})\sin(\Delta M t), \end{aligned} \tag{71}$$

where $\mathcal{A}_{\rm CP}^{\rm dir}$ is the direct CP violating parameter and $\mathcal{A}_{\rm CP}^{\rm mix}$ is the contribution describing CP violation in the interference of mixing and decay which is also usually called mixing-induced CP violation. In terms of $\lambda$, they are defined as

$$\mathcal{A}_{\rm CP}^{\rm dir}(f) = \frac{1-|\lambda|^2}{1+|\lambda|^2} \equiv C_f, \quad \mathcal{A}_{\rm CP}^{\rm mix}(f) = \frac{-2\,{\rm Im}\,\lambda}{1+|\lambda|^2} \equiv S_f. \tag{72}$$

The CKM weak phases can be determined by measuring the mixing-induced CP asymmetry parameters. If there is only one contribution to the decay amplitude or if the different contributions to the decay amplitude have the same weak phases, then the hadronic matrix elements and the strong phases drop out and one obtains

$$\frac{A(\bar{B}^0\to f)}{A(B^0\to f)} = \eta_f e^{-2i\phi_D}, \tag{73}$$

with $\eta_f = \pm 1$ being the CP parity of the final state and $\phi_D$ is the weak phase in the decay amplitude $A(B^0 \to f)$. Hence,

$$\lambda_f = \eta_f \exp(2i\phi_M)\exp(-2i\phi_D), \quad |\lambda_f|^2 = 1 \tag{74}$$

and

$$\mathcal{A}_{\rm CP}^{\rm dir}(f) = C_f = 0, \tag{75}$$

$$\mathcal{A}_{\rm CP}^{\rm mix}(f) = -{\rm Im}\,\lambda_f = \eta_f\sin(2\phi_D - 2\phi_M) = S_f. \tag{76}$$

Consequently, the asymmetry is given as

$$A_{\rm CP}(t) = S_f \sin(\Delta M t). \tag{77}$$

In general we can write

$$A = \sum_i A_i \exp(i\delta_i)\exp(i\phi_i), \quad \bar{A} = \sum_i A_i \exp(i\delta_i)\exp(-i\phi_i), \tag{78}$$

where $A_i$ are real, $\phi_i$ are weak CKM phases and $\delta_i$ are strong phases. Thus, $\bar{A} = A$ if all amplitudes that contribute to the direct decay have the same CKM phase, which we denote by $\phi_D$ and one can have $\bar{A}/A = \exp(-2i\phi_D)$.

Let us briefly discuss the measurement of $\sin 2\beta$ in $B \to \psi K_s$ mode. The mixing phase in the $B_d$ system is given in eq. (60). The decay phase in the quark subprocess $b \to c\bar{c}s$ is $\bar{A}/A = (V_{cb}V_{cs}^*)/(V_{cb}^*V_{cs})$. Thus

$$\lambda(B \to \psi K_s) = \left(\frac{V_{tb}^* V_{td}}{V_{tb}V_{td}^*}\right)\left(\frac{V_{cs}^* V_{cb}}{V_{cs}V_{cb}^*}\right) \tag{79}$$

which gives $\operatorname{Im}\lambda = \sin(2\beta)$.

In addition, there is small penguin contribution to $b \to c\bar{c}s$. However, it depends on the CKM combinations $V_{tb}V_{ts}^*$ which has to a very good approximation the same phase (modulo $\pi$) as the tree diagram $V_{cb}V_{cs}^*$. Hence only a single weak phase contributes to the decay.

This method was first suggested by Bigi and Sanda [25] and $\beta$ has been cleanly determined from this golden mode $B \to J/\psi K_s$ by both the $B$-factories with value

$$\sin 2\beta = 0.673 \pm 0.023 \; . \qquad [20] \tag{80}$$

The same angle $\beta$ can also be obtained from $B \to \phi K_s, \eta K_s$ etc. but with some uncertainties. CKM angle $\alpha$ is affected by the penguin pollution (which is because we do not understand how to effectively calculate the penguin contribution) and can be determined from $B \to \pi\pi, \rho\rho$ etc. The best method to do so is the Gronau and London method [26]. Now we are left with the final angle; the CKM angle $\gamma$. $\gamma$ can be obtained from the modes such as $B \to DK$, $B_s \to D_s K$ etc. The Gronau–London–Wyler (GLW) [26] and the Atwood–Dunietz–Soni (ADS) [27] are two useful methods in which $\gamma$ could be determined but because of experimental difficulties actually this was not possible. In fact, it was thought that $\gamma$ cannot be determined in the $B$-factories and we have to wait until the hadronic machines for its determination. In 2003, one interesting method known as Giri–Grossman–Soffer–Zupan (GGSZ) [28] was proposed (which is also known as Dalitz method in the literature) for the determination of the same using multi-body $D$-decays. And for the first time in 2003, the CKM angle $\gamma$ was determined using this method at BELLE [29] and the next year at BABAR [30]. In this method, the modes used are $B^- \to D^0 K^-$ followed by $D^0$ decaying to a multibody final state. For the determination of $\gamma$, interference of amplitudes containing the CKM elements $V_{ub}$ (which contains the weak phase $\gamma$) and $V_{cb}$ (which is real in the SM) are considered. Let $A_1 = B^- \to D^0 K^-(\bar{u}b \to \bar{u}c\bar{u}s)$ and $A_2 = B^- \to \bar{D}^0 K^-(\bar{u}b \to \bar{u}u\bar{c}s)$. These amplitudes contain the CKM elements as $A_1 \sim V_{cb}V_{us}^*$; $A_2 \sim V_{ub}V_{cs}^*$ and they interfere with each other if both $D^0$ and $\bar{D}^0$ can decay into the same final state. These two amplitudes contain the phases $\theta = -\gamma + \delta$ and $\bar{\theta} = \gamma + \delta$, where $\delta$ is the

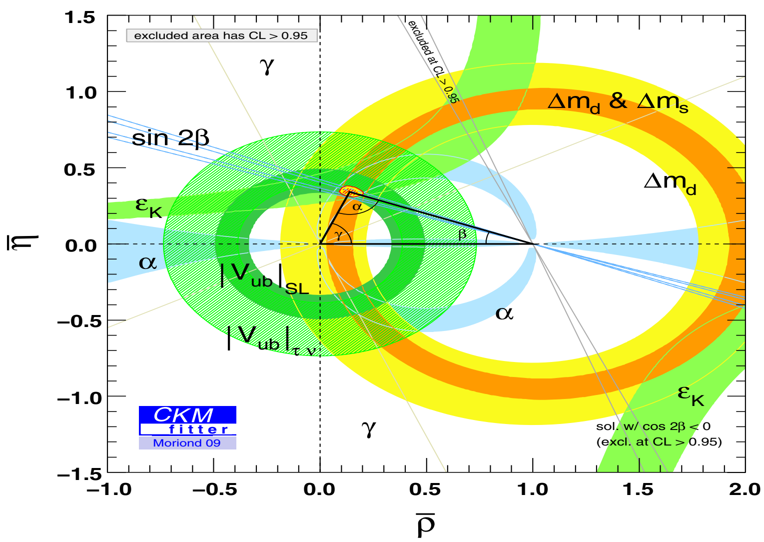


**Figure 5.** The CKM-fitter unitarity triangle in the ($\bar{\rho}$, $\bar{\eta}$) plane constructed using all the available data.

strong phase in $B^+ \to DK^+$ process and the ratio of the amplitudes is parametrized as $r_B = |A(B^- \to \bar{D}^0 K^-)/A(B^- \to D^0 K^-)|$. For these modes $r_B \sim 0.1$, and therefore the sensitivity of $\gamma \sim 1/r_B$ is around 10%. The present global fit of the CKM unitarity triangle by the CKM fitter group [31] is shown in figure 5.

From the above discussions one can notice that nonleptonic decays play key role in the studies of CKM phenomenon. Therefore, here we briefly describe how to deal with such processes. The effective $\Delta B = 1$ Hamiltonian [32], describing the weak hadronic decays of $B$-mesons is given as

$$\mathcal{H}_{\rm eff}(\Delta B = 1) = \frac{G_{\rm F}}{\sqrt{2}} \left\{ \sum_{p=u,c} V_{pb} V_{pq}^* (c_1(\mu) O_1^p(\mu) + c_2(\mu) O_2^p(\mu)) \right. \left. - V_{tb} V_{tq}^* \sum_{i=3}^{10} c_i(\mu) O_i(\mu) \right\}, \tag{81}$$

where $G_{\rm F}$ is the Fermi constant, $q = d, s$ and $c_i(\mu)$ are the Wilson coefficients evaluated at the renormalization scale $\mu$. $O_i$ are the current–current four-fermion operators given as

$$O_1^p = (\bar{p}b)_{V-A} (\bar{q}p)_{V-A},$$
$$O_2^p = (\bar{p}_\alpha b_\beta)_{V-A} (\bar{q}_\beta p_\alpha)_{V-A},$$
$$O_{3(5)} = (\bar{q}b)_{V-A} \sum_{q'} (\bar{q}' q')_{V-A(V+A)},$$
$$O_{4(6)} = (\bar{q}_\alpha b_\beta)_{V-A} \sum_{q'} (\bar{q}'_\beta q'_\alpha)_{V-A},$$

$$O_{7(9)} = \frac{3}{2}(\bar{q}b)_{V-A}\sum_{q'} e_{q'}(\bar{q}'q')_{V+A(V-A)},$$
$$O_{8(10)} = \frac{3}{2}(\bar{q}_\alpha b_\beta)_{V-A}\sum_{q'} e_{q'}(\bar{q}'_\beta q'_\alpha)_{V+A(V-A)}, \quad (82)$$

where $O_{1(2)}$ denotes the colour allowed (suppressed) tree, $O_{3-6}$ the QCD penguins and $O_{7-10}$ the electroweak penguin operators. $\alpha$ and $\beta$ are colour indices and $(\bar{q}_i q_2)_{V\pm A} = \bar{q}_1\gamma_\mu(1\pm\gamma_5)q_2$. In the sums, the quark $q'$ runs over the quark fields that are active at the scale $\mu = \mathcal{O}(m_b)$, i.e., $q' \in u, d, c, s$. The Wilson coefficients $c_i(\mu)$ (short distance part) are basically perturbative whereas the long distance parts are the hadronic matrix elements $\langle O_i(\mu)\rangle$ and nonperturbative.

The hadronic matrix elements $\langle O_i\rangle$ are conventionally evaluated by assuming the factorization hypothesis [33]. This consists of the decay amplitudes being factorized into products of two current matrix elements by inserting the vacuum. This approximation amounts to evaluating the matrix elements of the four-quark operators, given in (82), between the decaying $B$-meson and the final hadronic states $f_1 f_2$ as the product of two matrix elements of the type $\langle f_1|\bar{q}b|B\rangle$ which mediates the $B \to f_1$ transition and $\langle f_2|\bar{q}'q'|0\rangle$ which describes vacuum $\to f_2$ transition. The resulting matrix elements are parametrized in terms of form factors and decay constants. The form factors are usually calculated using a model and therefore the results are model-dependent. Therefore, the exploration of CPV is not an easy task. The decay constants and form factors for $B \to P, V$ transitions are defined as

$$\langle 0|A_\mu|P(q)\rangle = if_P q_\mu, \quad \langle 0|V_\mu|V(p,\varepsilon)\rangle = f_V m_V \varepsilon_\mu,$$
$$\langle P'(p')|V_\mu|P(p)\rangle = \left(p_\mu + p'_\mu - \frac{m_P^2 - m_{P'}^2}{q^2}q_\mu\right)F_1(q^2) + F_0(q^2)\frac{m_P^2 - m_{P'}^2}{q^2}q_\mu,$$
$$\langle V(p',\varepsilon)|V_\mu|P(p)\rangle = \frac{2}{m_P + m_V}\varepsilon_{\mu\nu\alpha\beta}\varepsilon^{*\nu}p^\alpha p'^\beta V(q^2),$$
$$\langle V(p',\varepsilon)|A_\mu|P(p)\rangle = i\Bigg[(m_P + m_V)\varepsilon^*_\mu A_1(q^2) - \frac{\varepsilon^*\cdot p}{m_P + m_V}(p+p')_\mu A_2(q^2) - 2m_V\frac{\varepsilon^*\cdot p}{q^2}q_\mu[A_3(q^2) - A_0(q^2)]\Bigg], \quad (83)$$

where $P$ and $V$ denote pseudoscalar and vector mesons, $V_\mu$ and $A_\mu$ the vector and axial-vector currents, $\varepsilon$ is the polarization vector of $V$ and $q = p - p'$. The decay constants are given by $f_P$, $f_V$ and the form factors by $F_1(q^2)$, $F_0(q^2)$, $V(q^2)$, $A_1(q^2)$, $A_2(q^2)$, $A_3(q^2)$. Various models, for example quark models [33,34], light-cone sum rule approach [35,36], etc. can be employed to evaluate these form factors.

The results of generalized factorization method can be improved by including the nonperturbative corrections. There are various methods that are available in the market like QCD factorization [37], perturbative QCD [38] and soft colinear effective theory (SCET) [39] to evaluate the hadronic matrix elements but all of them have their own problems and lots of work need to be done to understand the dynamics.

## 6. $B_s$-system and new physics

Let us now discuss a bit about the beauty-strange ($B_s$) system. As a matter of curiosity the question arises as to what is so important about this system and why should we pay much attention to this. There are at least three important reasons. The first reason is that the studies of $B_s$-system is complimentary to the studies in $\Upsilon(4S)$ involving $B_d$-mesons. Also there exist several alternative methods to measure the CKM angle $\gamma$ using $B_s$-decay modes. These include $B_s \to D_s^{\pm} K^{\mp}$ [40], $B_s \to D^0(\bar{D}^0)\phi$ [41], $B_s \to K\pi$ [42], $B_s \to K^+K^-$ [43] etc.

The second reason is that from the $B$-factories data we have noticed some kind of deviations in $b \to s$ penguin-mediated transitions. Therefore, $B_s$-system can be used as a complementary probe to suppliment the results obtained from $B_d$-system. Recently, Fleischer and Gronau [44] proposed a method based on flavour $SU(3)$ for identifying and extracting new physics amplitudes in charmless $B_s$ decays using the time-dependent CP asymmetries.

The third reason is that the bottom-strange system has large mass difference which makes the system very interesting. The CDF Collaboration [45] recently reported new results on $B_s - \bar{B}_s$ mass difference

$$\Delta M_{B_s} = (17.77 \pm 0.10 \pm 0.07)\ \text{ps}^{-1}. \tag{84}$$

Although the experimental result appears to be consistent with the SM predictions [46]

$$(\Delta M_{B_s})^{\text{SM}}|_{(\text{HP+JL})\text{QCD}} = (23.4 \pm 3.8)\ \text{ps}^{-1}, \tag{85}$$

it does not completely exclude the possibility of new physics effects in $B_s - \bar{B}_s$ mixing phenomena.

The important difference of $B_s$-system with respect to $B_d - \bar{B}_d$ system is that the value of the width difference $\Delta\Gamma_s$ is predicted to be significantly nonzero, allowing information on $\phi_s$, the CP violating phase related to $B_s - \bar{B}_s$ mixing, to be extracted without tagging the flavour of the $B_s$-meson. Within the SM, due to the hierarchical nature of the CKM matrix elements, $\phi_s$ is predicted to be small, i.e., $\phi_s = 2\beta_s = 2\arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \simeq 0.04$. This can be easily visualized by looking into the CKM matrix in the Wolfenstein parametrization and keeping terms upto $\mathcal{O}(\lambda^5)$

$$V = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + \frac{1}{2}A^2\lambda^5[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4(1 + 4A^2) & A\lambda^2 \\ A\lambda^3[1 - (1 - \frac{1}{2}\lambda^2)(\rho + i\eta)] & -A\lambda^2 + \frac{1}{2}A\lambda^4[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}A^2\lambda^4 \end{pmatrix}$$
$$+\mathcal{O}(\lambda^6), \tag{86}$$

where $\lambda \simeq 0.22$. However, the measured values of the phase by CDF [47] and D0 [48] are found to be large

$$\phi_s(\text{CDF}) \in [0.24, 1.36] \quad (68\% \text{ C.L.})$$
$$\phi_s(\text{D0}) = 0.57^{+0.30}_{-0.24}(\text{stat.})^{+0.02}_{-0.07}(\text{syst.}). \tag{87}$$

Combined data anlyses including the semileptonic asymmetry in the $B_s$ decay indicate that the CP violating phase deviates about $3\sigma$ from the SM predictions [49]. If this large phase still persists in the upcoming results from Fermilab, it would be the first clear signal of new physics beyond the Standard Model.

Let us concentrate on the topic where new physics signature has been claimed in the literature. Decays of $B_s$-meson via $b \to c\bar{c}s$ transition, e.g., $B_s \to J/\psi\phi$ can probe $\phi_s$. However, the vector final state $J/\psi\phi$ contains mixture of polarization amplitudes: CP odd $A_\perp$ and CP even $A_0$ and $A_\parallel$. This can be understood as follows. While the $B_s$-meson has spin 0, the final states $J/\psi$ and $\phi$ have spin 1. Consequently, the total angular momentum of the final state can be either 0, 1 or 2. States with angular momentum 0 and 2 are CP even while the state with angular momentum 1 is CP odd. These terms need to be disentangled using the angular analysis [50] in order to extract $\phi_s$. Recently, CDF Collaboration has carried out a flavour tagged time-dependent analysis of $B_s \to J/\psi\phi$ using 2.8 fb$^{-1}$ of data and observed a very large CP asymmetry $S_{J/\psi\phi} \in [0.24, 1.36]$ [47]. Within the SM, this asymmetry is expected to be vanishingly small which comes basically from $B_s - \bar{B}_s$ mixing phase. Since this mode receives dominant contribution from $b \to c\bar{c}s$ tree-level transition, the new physics contribution to its decay amplitude is expected to be negligible. Therefore, the observed large CP asymmetry is believed to be originating from the new CP violating phase in $B_s - \bar{B}_s$ mixing.

Let us consider the mass and width differences in the $B_s$ system which are given as

$$\Delta M_s = M_s^H - M_s^L \approx 2|M_{12}|, \quad \Delta\Gamma_s = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos(\phi_s). \tag{88}$$

Therefore, the width difference between the mass eigenstates is also sensitive to the same new physics phase. The confidence region in the two-dimensional space of $2\beta_s = \phi_s$ and $\Delta\Gamma$ is reported in [51] and the corresponding correlation plot is shown in the top panel of figure 6. Assuming the SM predicted value of $2\beta_s = 0.04$ and $\Delta\Gamma = 0.096$ ps$^{-1}$, the probability of deviation is around 15% which corresponds to 1.5 G standard deviation [47]. In future with the reduced error bars we can say whether actually we have seen the signature of new physics [52] or not. Also the results from LHC will be very crucial to confirm or rule out the claim.

A conventional way to parametrize the new physics in a model-independent way is [53]

$$\frac{\langle B_s|H_{\text{eff}}^{\text{full}}|\bar{B}_s\rangle}{\langle B_s|H_{\text{eff}}^{\text{SM}}|\bar{B}_s\rangle} = C_{B_s} \mathrm{e}^{2i\phi_{B_s}}, \tag{89}$$

where $H_{\text{eff}}^{\text{full}}$ is the effective Hamiltonian generated by both SM and new physics, while $H_{\text{eff}}^{\text{SM}}$ contains only the SM contribution. $C_{B_s} = 1$ and $\phi_{B_s} = 0$ correspond to the SM expectation and deviation from these would signal the existence of physics beyond the SM. Using various experimental inputs of $B_s$-meson decays the UTfit Collaboration [52] obtained the bounds on NP parameters as shown in figure 6 (bottom panel) and found that the deviation of the phase $\phi_{B_s}$ from zero is at $3.7\sigma$ level.

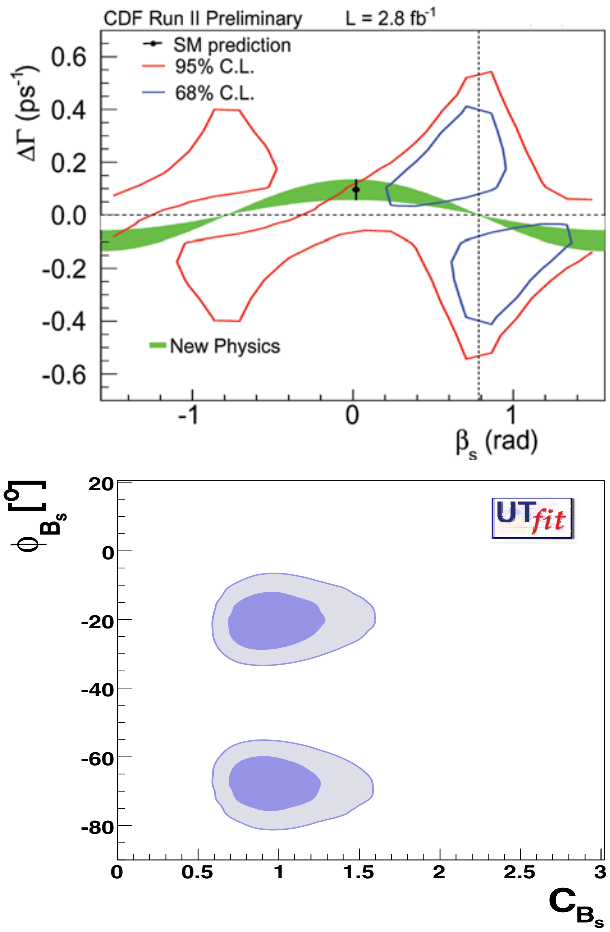


**Figure 6.** Correlation plots between $\Delta\Gamma_s$ and $\beta_s$ with CDF Run II 2.8 fb$^{-1}$ data (top) and the probability region in $\phi_{B_s}$–$C_{B_s}$ plane where the dark (light) regions correspond to 68% (95%) C.L. (bottom panel).

## 7. New physics signals from $B$-factory data

Although the results of the currently running two asymmetric $B$-factories are almost in the line of SM expectations and there is no clear indication of new physics so far, there are some interesting deviations from SM expectations which could provide us an indirect signal of new physics. Here we are presenting the list of few such deviations which are associated with the CP violation parameters of flavour changing neutral current (FCNC) mediated $b \to s$ transitions. Some modes with apparent difficulty are $B \to K\pi$, $B \to \phi K_s$, $B \to \phi K^*$, $B_s \to K\pi$ etc.

• Let us first concentrate on the decay modes $B \to K\pi$, where the direct CP violation in the $B$-system was first observed and which subsequently ruled out the superweak CP violation scenario [54] forever. There appears to be some disagreement between the direct CP asymmetry parameters of $B^- \to \pi^0 K^-$ and that of $\bar{B}^0 \to \pi^+ K^-$. $\Delta A_{\rm CP}(K\pi)$, which is the difference of these two parameters, is found to be around 15% [20], whereas the SM expectation is vanishingly small. This constitutes what is called $\Delta A_{\rm CP}(K\pi)$ puzzle in the literature and is believed to be an indication of the existence of new physics.

• Next we consider the decay mode $\bar{B}^0 \to \phi K^0$. In the SM, it proceeds through the quark level transition $b \to s\bar{s}s$ and hence the mixing-induced CP asymmetry in this mode ($S_{\phi K}$) is expected to give the same value as that of $B \to J/\psi K_s$ with an uncertainty of around 5% [55]. However, the present world average of this parameter is $S_{\phi K} = 0.39 \pm 0.17$ [20], which has nearly $2.4\sigma$ deviation from the corresponding $S_{\psi K_s}$, with $S_{\phi K_s} < S_{\psi K_s}$.

• Recently, a very largish CP asymmetry has been measured by the CDF Collaboration [47] in the tagged analysis of $B_s \to J/\psi \phi$ with value $S_{\psi\phi} \in [0.24, 1.36]$. Within the SM this asymmetry is expected to be vanishingly small, which comes basically from $B_s - \bar{B}_s$ mixing phase. Since this mode receives dominant contribution from $b \to c\bar{c}s$ tree-level transition, the NP contribution to its decay amplitude is naively expected to be negligible. Therefore, the observed large CP asymmetry is believed to be originating from the new CP violating phase in $B_s - \bar{B}_s$ mixing.

• $B_s \to \mu^+\mu^-$ problem has been widely discussed in the literature. This process is very clean and the only non-perturbative part involved here is the decay constant of $B_s$-meson. Therefore, it is a good hunting ground to look for new physics. The SM value of its branching ratio is quite small (${\rm Br}(B_s \to \mu^+\mu^-) = (3.35 \pm 0.32) \times 10^{-9}$) [56] which is well below the present experimental upper limit [20] (${\rm Br}(B_s \to \mu^+\mu^-) < 4.7 \times 10^{-8}$). So if there were a signal of new physics elsewhere in $b \to s$ transitions, it could also be found in this mode. Therefore, $B_s \to \mu^+\mu^-$ is a golden mode to detect new physics.

All the above-mentioned deviations may be considered as the smoking gun signal of new physics. It is then natural to ask what type of new physics could be responsible for all such deviations. The first step to answer such questions was discussed in [57], where the effects of a variety of new physics models on the CP asymmetries in $B$-decays were studied. However, here we are not focussing on various types of the new physics models, rather we have limited ourselves to the much broader and general interpretation of the new physics scenario, the minimal flavour violation (MFV) scenario [58]. In the minimal flavour violation models, the general structure of FCNC process present in the SM is preserved. In particular all flavour violating and CP violating transitions are governed by the CKM matrix, with the CKM phase being the only source of CP violation. In particular there are no FCNC transitions at the tree-level. The only relevant operators in the effective Hamiltonian below the weak scale are the ones that are relevant in the SM. Various extended Higgs models [59,60], supersymmetric models [61,62], the SM with one universal extra dimension [63] and under certain assumptions the warped extra dimension models [64] belong to this class. At present most experimental data that we have at our disposal, are consistent with MFV but this information is still rather limited. On the other hand, there are at least two pieces of data that could point towards the importance of new operators, new sources of flavour violation and in particular of CP violation. These are the $\Delta A_{\rm CP}(K\pi)$ problem and $S_{\psi\phi}$ problem. To elaborate a bit on this issue, let us consider the case of $S_{\psi\phi}$. To explain the result obtained for $\phi_s$, new sources of CP violation beyond the CKM phase are required, which strongly disfavour the MFV hypothesis. These new phases will in general produce correlated effects in $\Delta B = 2$ processes and $b \to s$ decays. These correlations cannot be studied in a model-independent way, but it will be interesting to analyse them in specific extensions of the SM. In this respect, improving the results on CP violation in $b \to s$ penguins at the present and future experimental facilities is of utmost importance.

## 8. Conclusions

To conclude, we have outlined the recent results in the kaon sector and pointed out the future experiments where dedicated kaon experiments are to be taken up. We discussed briefly the observation of mixing in the charm system with some examples and emphasized that understanding the charm sector is very much crucial. There are some dedicated experiments in the charm sector which will enrich our understanding. Then we discussed the $B$-sector results and outlined the stages leading to the confirmation of the CKM phenomenon of CP violation. Finally, we discussed the interesting result relating to the $B_s$-system where new physics signature can show up. With many experiments and thus with huge data, the flavour and CP sector will certainly guide us to a better understanding of the high energy physics and to decipher the signals of new physics.

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## References

[1] S L Glashow, *Nucl. Phys.* **22**, 579 (1961)
S Weinberg, *Phys. Rev. Lett.* **19**, 1264 (1967)
A Salam, in: *Elementary particle theory* edited by N Svartholm (Almqvist and Wiksell, Stockholm, 1968)
[2] P W Higgs, *Phys. Rev. Lett.* **13**, 508 (1964)
F Englert and R Brout, *Phys. Rev. Lett.* **13**, 321 (1964)
[3] Particle Data Group: C Amsler *et al*, *Phys. Lett.* **B667**, 1 (2008)
[4] J H Christenson *et al*, *Phys. Rev. Lett.* **13**, 138 (1964)
[5] A D Sakharov, *JETP Lett.* **5**, 24 (1967)
[6] M Kobayashi and T Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973)

[7] http://nobelprize.org/nobel_prizes/physics/laureates/2008/
[8] N Cabibbo, *Phys. Rev. Lett.* **10**, 531 (1963)
[9] L-L Chau and W-Y Keung, *Phys. Rev. Lett.* **53**, 1802 (1984)
[10] L Wolfenstein, *Phys. Rev. Lett.* **51**, 1945 (1983)
[11] C Jarlskog, *Phys. Rev. Lett.* **55**, 1039 (1985); *Z. Phys.* **C29**, 491 (1985)
[12] A J Buras, M Garbahn, U Haisch and U Nierste, *Phys. Rev. Lett.* **95**, 261805 (2005); *J. High Energy Phys.* **11**, 002 (2006)
[13] J Brod and M Garbahn, *Phys. Rev.* **D78**, 034006 (2008)
[14] E949 Collaboration: A V Artamonov *et al*, *Phys. Rev. Lett.* **101**, 191802 (2008)
[15] E391 Collaboration: J K Ahn *et al*, *Phys. Rev. Lett.* **100**, 201802 (2008)
[16] Flavianet Working Group: M Antonelli *et al*, arXiv:0801.1817 [hep-ph]
[17] Babar Collaboration: B Aubert *et al*, *Phys. Rev. Lett.* **98**, 211802 (2007)
[18] CDF Collaboration: T Altonen *et al*, *Phys. Rev. Lett.* **100**, 121802 (2008)
[19] Belle Collaboration: U Bitenc *et al*, *Phys. Rev.* **D77**, 112003 (2008)
[20] Heavy Flavor Averaging Group, http://www.slac.stanford.edu/xorg/hfag
[21] Belle Collaboration: L M Zhang *et al*, *Phys. Rev. Lett.* **99**, 131803 (2007)
Babar Collaboration: B Aubert *et al*, arXiv:0807.4544 (hep-ex)
[22] G Blaylock *et al*, *Phys. Lett.* **B355**, 555 (1995)
CLEO Collaboration: R Godang *et al*, *Phys. Rev. Lett.* **84**, 5038 (2000)
[23] I I Bigi and A I Sanda, *CP violation* (Cambridge, 2000)
G C Branco, L Lavoura and J P Silva, *CP violation* (Oxford University Press, 1999)
[24] T Inami and C S Lim, *Prog. Theor. Phys.* **65**, 297 (1981); **65**, 1772E (1981)
[25] I I Bigi and A I Sanda, *Nucl. Phys.* **B193**, 85 (1981)
[26] M Gronau and D London, *Phys. Lett.* **B253**, 483 (1991)
M Gronau and D Wyler, *Phys. Lett.* **B265**, 172 (1991)
[27] D Atwood, I Dunietz and A Soni, *Phys. Rev. Lett.* **78**, 3257 (1997); *Phys. Rev.* **D63**, 036005 (2001)
[28] A Giri, Y Grossman, A Soffer and J Zupan, *Phys. Rev.* **D68**, 054018 (2003)
[29] Belle Collaboration: K Abe *et al*, *BELLE-CONF-0343*, arXiv:hep-ex/0308043 (1-25) (2003)
Belle Collaboration: A Poluektov *et al*, *Phys. Rev.* **D70**, 072003 (2004)
[30] Babar Collaboration: B Aubert *et al*, *Phys. Rev. Lett.* **95**, 121802 (2005)
[31] CKM fitter: J Charles *et al*, *Euro, Phys. J.* **C41**, 1 (2005), hep-ph/0406181; updates at http://ckmfitter.in2p2.fr
[32] G Buchalla, A J Buras and M Lactenbacher, *Rev. Mod. Phys.* **68**, 1125 (1996)
[33] M Bauer, B Stech and M Wirbel, *Z. Phys.* **C29**, 637 (1985); *ibid.* **34**, 103 (1987)
[34] N Isgur, D Scora, B Grinstein and M B Wise, *Phys. Rev.* **D39**, 799 (1989)
D Scora and N Isgur, *Phys. Rev.* **D52**, 2783 (1995)
[35] P Ball and V M Braun, *Phys. Rev.* **D58**, 094016 (1998)
P Ball, *J. High Energy Phys.* **9809**, 005 (1998)
[36] P Ball and R Zwicky, *Phys. Rev.* **D71**, 014015 (2005); *ibid.* **71**, 014029 (2005)
[37] M Beneke, G Buchalla, M Neubert and C T Sachradja, *Phys. Rev. Lett.* **83**, 1914 (1999); *Nucl. Phys.* **B591**, 313 (2000); *ibid.* **606**, 245 (2001)
M Beneke and M Neubert, *Nucl. Phys.* **B651**, 225 (2003); *ibid.* **675**, 333 (2003)
[38] H N Li, hep-ph/9903323
Y Y Keum and H N Li, *Phys. Rev.* **D63**, 074006 (2001)
Y Y Keum, H N Li and A I Sanda, *Phys. Lett.* **B504**, 6 (2001); *Phys. Rev.* **D63**, 054008 (2001)

[39] C W Bauer, S Fleming and M E Luke, *Phys. Rev.* **D63**, 014006 (2001)
C W Bauer, S Fleming, D Pirjol and I W Stewart, *Phys. Rev.* **D63**, 114020 (2001)
C W Bauer and I W Stewart, *Phys. Lett.* **B526**, 134 (2001)
C W Bauer, D Pirjol and I W Stewart, *Phys. Rev.* **D65**, 054022 (2002)
[40] R Aleksan, I Dunietz and B Kayser, *Z. Phys.* **C54**, 653 (1992)
[41] M Gronau and D London, *Phys. Lett.* **B253**, 483 (1991)
A K Giri, R Mohanta and M P Khanna, *Phys. Rev.* **D65**, 056015 (2002)
[42] M Gronau and J Rosner, *Phys. Lett.* **B482**, 71 (2000)
M Gronau and D Pirjol, *Phys. Lett.* **B449**, 321 (1999)
[43] M Gronau and J Rosner, *Phys. Rev.* **D65**, 113008 (2002)
[44] R Fleischer and M Gronau, *Phys. Lett.* **B660**, 212 (2008)
[45] CDF Collaboration: A Abulencia *et al*, *Phys. Rev. Lett.* **97**, 242003 (2006)
[46] JLQCD Collaboration: S Aioki *et al*, *Phys. Rev. Lett.* **91**, 212001 (2003)
HPQCD Collaboration: A Gray *et al*, *Phys. Rev. Lett.* **95**, 212001 (2005)
[47] CDF Collaboration: T Aaltonen *et al*, *Phys. Rev. Lett.* **100**, 161802 (2008)
[48] D0 Collaboration: V M Abazov *et al*, *Phys. Rev. Lett.* **101**, 241801 (2008)
[49] A Lenz and U Nierste, *J. High Energy Phys.* **0706**, 072 (2007)
Heavy Flavour Averaging Group: E Barberio *et al*, arXiv:0808.1297 (hep-ph)
[50] A Dighe, I Dunietz, H Lipkin and J Rosner, *Phys. Lett.* **B369**, 144 (1996)
A Dighe, I Dunietz and R Fleischer, *Euro. Phys. J.* **C6**, 647 (1999)
[51] http://www-cdf.fnal.gov/physics/new/bottom/080724.blessed-tagged_BsJPsiPhi_update_prelim/
[52] UTfit Collboration: M Bona *et al*, arXiv:0803.0659 (hep-ph); arXiv:0906.0953 (hep-ph)
[53] J M Soares and L Wolfenstein, *Phys. Rev.* **D47**, 1021 (1993)
N G Deshpande, B Dutta and S Oh, *Phys. Rev. Lett.* **77**, 4499 (1996)
J P Silva and L Wolfenstein, *Phys. Rev.* **D55**, 5331 (1997)
Y Grossman, Y Nir and M O Worah, *Phys. Lett.* **B407**, 307 (1997)
[54] L Wolfenstein, *Phys. Rev. Lett.* **13**, 180 (1964)
[55] Y Grossman and M P Worah, *Phys. Lett.* **B395**, 241 (1997)
D London and A Soni, *Phys. Lett.* **B407**, 61 (1997)
Y Grossman, G Isidori and M P Worah, *Phys. Rev.* **D58**, 057504 (1997)
[56] M Blanke, A J Buras, D Guadagnli and C Tarantino, *J. High Energy Phys.* **10**, 003 (2006)
[57] C O Dib, D London and Y Nir, *Int. J. Mod. Phys.* **A6**, 1253 (1991)
Y Nir and D Silverman, *Nucl. Phys.* **B345**, 301 (1990)
M Gronau and D London, *Phys. Rev.* **D55**, 2845 (1997)
Y Grossman, Y Nir and R Rattazi, in: *Heavy flavours II* edited by A J Buras and M Lindner (World Scientific, Singapore, 1998) p. 755
[58] A J Buras, P Gambino, M Garbahn, S Jager and L Silverstrini, *Phys. Lett.* **B500**, 161 (2001)
G D'Ambrosio, G F Giudice, G Isidori and A Strumia, *Nucl. Phys.* **B645**, 155 (2002)
A J Buras, hep-ph/0310208
[59] L J Hall and L Randall, *Phys. Rev. Lett.* **65**, 2939 (1990)
R S Chivukula and H Georgi, *Phys. Lett.* **B188**, 99 (1987)
A Ali and D London, *Euro. Phys.* **C9**, 687 (1999)
E Gabrielli and G F Giudice, *Nucl. Phys.* **B433**, 3 (1995); Erratum, *ibid.* **B507**, 549 (1997)

[60] B Grinstein, M J Savage and M B Wise, *Nucl. Phys.* **B319**, 271 (1989)
W S Hou and R S Willey, *Phys. Lett.* **B202**, 591 (1988)
S L Glashow and S Weinberg, *Phys. Rev.* **D15**, 1958 (1977)
G G Athanasiu and F J Gilman, *Phys. Lett.* **B153**, 274 (1985)
[61] M Dine, A E Nelson and Y Shriman, *Phys. Rev.* **D51**, 1362 (1995)
M Dine, A E Nelson, Y Nir and Y Shriman, *Phys. Rev.* **D53**, 2658 (1996)
[62] L Randall and R Sundrum, *Nucl. Phys.* **B557**, 79 (1999)
G F Giudice, M A Luty, H Murayama and R Rattazzi, *J. High Energy Phys.* **9812**, 027 (1998)
[63] T Appelquist, H-C Cheng and B A Dpbrescu, *Phys. Rev.* **D64**, 035002 (2001)
[64] A L Fitzpatrick, L Randall and G Perez, *Phys. Rev. Lett.* **100**, 171604 (2008)
G Perez and L Randall, *J. High Energy Phys.* **0901**, 077 (2009)
R Rattazzi and A Zaffaroni, *J. High Eenergy Phys.* **0104**, 021 (2001)
G Cacciapaglia *et al*, *J. High Energy Phys.* **0804**, 006 (2008)