New Physics and $CP$ Angles Measurement at $B$ Factory

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Abstract

We have analyzed how much the $CP$ angles to be measured at $B$ factories can deviate from the geometrical ones defined in unitarity triangle under the existence of new physics. The measurements are given in rephasing invariant form. If KM matrix is not a $3 \times 3$ and unitary matrix, $\hat{\phi}_1$ and $\hat{\phi}_3$ is affected, and the value of $\hat{\phi}_3$ depends on the decay mode. The deviation is constrained to be less than the experimental precision attained in the next decade by the available data of the magnitude of KM matrix elements. Deviation of the sum of three angles from $\pi$ cannot be detected unless new physics contributes significantly to $b$ decay or $D$ meson system.

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1. Introduction

In the three generation standard model the $CP$ violation phase appears in the quark mixing matrix at the coupling between quark charged current and $W$ boson as first pointed out by Kobayashi and Maskawa [1]. The quark mixing matrix, which we call KM matrix $V$ hereafter, is a $3 \times 3$ unitary matrix so that the following condition holds:

$$V_{ub}^*V_{ud} + V_{cb}^*V_{cd} + V_{tb}^*V_{td} = 0. \quad (1)$$

We have so-called unitarity triangle by expressing the above condition in complex plane. The still unfixed parameters in KM matrix can be determined through the measurements of the sides and the angles of this triangle. We can test the accuracy of the standard model by over-checking the consistency of the triangle. If the test fails, we can explore new physics beyond the standard model from the inconsistency [2]. This is one of the main aims of the $B$ factory projects which are now under way at several experimental facilities, KEK, SLAC and so on.

New physics can affect the determination of the unitarity triangle through (i) $B^0$-$\overline{B^0}$ mixing as in the case of SUSY standard models [3], (ii) $b$ decay as in $SU(2)_L \times SU(2)_R \times U(1)$ models [4] or (iii) deformation of KM matrix as in 4 generation models [5] or extra vector-like quark models [6]. It has once said that new physics can be explored by checking whether the sum of the three $CP$ angles becomes $\pi$ or not [2]. But this criterion is not necessarily effective [7]. When new physics affects $B^0$-$\overline{B^0}$ mixing alone (case (i)), the effects are cancelled in the sum of three angles. In the case of (ii) the sum in fact can deviate from $\pi$ [4]. The aim of this work is to study the case of case of (iii). It is shown under two reasonable assumptions that whether the sum becomes $\pi$ depends on what mode is used to measure the

![Figure 1: Unitarity triangle](image-url)
angle $\phi_3 (\gamma)$. The possible deviation from $\pi$ is also estimated and found to be less than the experimental precision to be attained in the next decade. Thus the sum of three CP angles will be measured to be consistent with $\pi$ even within the experimental precision even if KM matrix is not $3 \times 3$ nor unitary. The angles measurement alone is not sufficient to explore new physics unless new physics significantly affects $b$ decay or neutral $D$ meson system.

Below the effects of new physics on $CP$ angles are discussed with the following two assumptions;

Assumption I. Quark decay amplitude has the same phase as those given by the corresponding tree level $W$ boson exchange diagram up to minor corrections except for the $\Delta I = 1/2$ penguin type contribution.

Assumption II. Both $D^0$-$\bar{D}^0$ mixing and $CP$ violation are negligible in neutral $D$ meson system.

The second assumption is necessary since the $CP$ angle $\phi_3 (\gamma)$ is measured at $B$ factories by using the decay of $B$ mesons into a neutral $D$ meson and a $K$ meson.[9] If $D^0$-$\bar{D}^0$ mixing or $CP$ violation is significant in $D$ meson system, it obscures the determination of $\phi_3 (\gamma)$. Let us see if the above assumptions are satisfied taking the following models as examples:

**minimal SUSY standard model with no new $CP$ phase**: The quark decay is described by the standard $W$ boson processes and physical charged Higgs processes. The couplings among quarks and charged Higgs are given by KM matrix elements times real factors proportional to quark masses. Loop contribution by SUSY particles is suppressed due to SUSY GIM mechanism. Higgs loop is suppressed by at least one small Yukawa coupling. Therefore both assumptions are satisfied.

**multi-Higgs doublets model**: Both conditions are satisfied as far as flavor changing neutral current (FCNC) is suppressed by NFC [8] since the couplings among quarks and charged Higgs are KM matrix elements times real factors proportional to quark masses.

**4 or more generation model**: Although the KM matrix is no longer a $3 \times 3$ matrix, the assumptions are satisfied as far as the 4-th (or higher) generation quarks do not contribute significantly to $b \rightarrow s$ penguin process or $D$ meson physics.

**vector-like extra quark model**: The KM matrix is neither $3 \times 3$ nor unitary. But the assumptions are satisfied if FCNC is suppressed.

In the following arguments we examine what are measured as the $CP$ angles at $B$ factories under the influence of new physics without assuming that KM matrix is $3 \times 3$ and unitary. The measurements as CP angles are given in rephasing invariant form. They are compared
with the geometrical definitions of the angles in unitarity triangle, and we estimate the
differences between them.

2. New physics effects on angles

The angles of the unitarity triangle are geometrically defined as

\[ \phi_1 (\beta) \equiv \arg[V_{tb}^*V_{td}] - \arg[V_{tb}^*V_{td}] - \pi, \]
\[ \phi_2 (\alpha) \equiv \arg[V_{ub}^*V_{ud}] - \arg[V_{ub}^*V_{ud}] + \pi, \]
\[ \phi_3 (\gamma) \equiv \arg[V_{ub}^*V_{ud}] - \arg[V_{ub}^*V_{ud}] + \pi. \]

These angles do not necessarily agree with the CP angles to be measured in experiments.
Two of the CP angles corresponding to \( \phi_1 (\beta) \) and \( \phi_2 (\alpha) \), which we call \( \tilde{\phi}_1 \) and \( \tilde{\phi}_2 \), respectively, are measured through time dependent CP asymmetry of the neutral B meson decay into a CP eigenstate, \( f_{CP} \) [10]:

\[ \text{Asy}[f_{CP}] \equiv \frac{\Gamma[B^0 \to f_{CP}] - \Gamma[B^0 \to \overline{f}_{CP}]}{\Gamma[B^0 \to f_{CP}] + \Gamma[B^0 \to \overline{f}_{CP}]} \]
\[ = \frac{2}{2 + c_d} \left[ \text{Im} \left( \frac{q}{p} \rho \right) \sin(\Delta M_B t) - \frac{c_d}{2} \cos(\Delta M_B t) \right], \]

where

\[ \frac{q}{p} \equiv \left| \frac{M_{B^0}}{M_{B^0}} \right|, \quad M_{B^0}^2 \equiv \langle B^0 | \mathcal{H}^{A=B^0=2} | \overline{B^0} \rangle, \]
\[ \rho \equiv \frac{A[B^0 \to f_{CP}]}{A[B^0 \to \overline{f}_{CP}]} \quad |\rho|^2 \equiv 1 + c_d, \]

and we have neglected the absorptive part of \( \langle B^0 | \mathcal{H}^{A=B^0=2} | \overline{B^0} \rangle \), which is a good approximation in B meson system. The assumption I given before allows us to express \( \rho \) by KM matrix elements up to \( \Delta I = 1/2 \) penguin effect. The rest of the CP angle corresponding to \( \phi_3 (\gamma) \), which we call \( \tilde{\phi}_3 \), is measured via direct CP violation in \( B \to DK \) decays. Let us see in detail the differences between \( \phi_i \) and \( \tilde{\phi}_i \) \((i = 1, 2, 3)\).

The CP angle \( \tilde{\phi}_1 \) is measured in \( b(\bar{b}) \to c\bar{s}(\bar{s}) \) decay. A typical hadronic final state is \( J/\Psi K_S \). The weak phase of the decay amplitude is given by \( \arg[V_{cb}V_{cs}] \). There is no direct CP violation under the assumption I, i.e. \( |\rho| = 1 \), since no \( \Delta I = 1/2 \) process is involved. (There is a \( b \to s \) penguin contribution. But it has almost the same phase as that of the tree \( W \) boson contribution in the standard model. If 4-th quark or another new particle significantly contributes to \( b \to s \) penguin, the assumption I can be violated.) We have

\[ \text{Im} \left( \frac{q}{p} \rho \right) \bigg|_{J/\Psi K_S} = \text{Im} \left[ \left| \frac{M_{B^0}^2}{M_{B^0}^2} V_{cb}^*V_{cs} \right| \left( \frac{q_K}{p_K} \right)^* \right] \]
where
\[ \frac{q_K}{p_K} = \frac{[(M_{12}^K - (i/2)\Gamma_{12}^K)(M_{12}^{K*} - (i/2)\Gamma_{12}^{K*})]^{1/2}}{M_{12}^K - (i/2)\Gamma_{12}^K}, \]
with \( M_{12}^K - (i/2)\Gamma_{12}^K \equiv \langle K^0 | H^{S=-2} | \bar{K}^0 \rangle \). It is experimentally known that \( CP \) violation in \( K \) meson system is tiny, \( O(10^{-3}) \), so that we neglect it here. Then we can take \( M_{12}^K/\Gamma_{12}^K \) to be real, and
\[ \frac{q_K}{p_K} = \frac{\Gamma_{12}^K}{\Gamma_{12}^K} = \frac{V_{ud}V_{us}^*}{V_{ud}^*V_{us}}. \]

The phase of \( \Gamma_{12}^K \) is calculated from \( W \) boson exchange tree decay diagram since we neglected \( CP \) violation in \( K \) meson system. Let us define the phase discrepancy between the KM factors as
\[ \delta_1 \equiv \arg[V_{ud}V_{us}^*] - \arg[V_{cd}V_{cs}^*] + \pi, \]
where \( \delta_1 = O(10^{-3}) \) in the standard model. The phase of \( q_K/p_K \) is often taken to be \( V_{cd}V_{cs}^*/V_{ud}^*V_{us} \) in the literatures by assuming the dominance of charm quark contribution in the box diagram of of \( K^0\bar{K}^0 \) mixing as in the standard model. But \( \delta_1 \) may not be negligible if KM matrix is not 3\times3 and unitary. There is a possibility that the sum of charm quark contribution and new physics contributions cancel each other or happen to be almost the same phase with that of up quark contribution giving tiny \( CP \) violation in \( K \) system. So it is more appropriate to take \( q_K/p_K \) as in eq. (11).

We have
\[ \frac{A_{\text{asy}}[J/P K_s]}{\sin(\Delta M_{B^0})} = \text{Im} \left[ \frac{M_{12}^B}{M_{12}^B} \frac{V_{cb}V_{cs}^* V_{cd}^* V_{cs}^* e^{-2i\delta_1}}{V_{ud}V_{us}^*} \right] = -\sin(\phi_M + 2\phi_c + 2\delta_1), \]
where \( \phi_M \equiv \arg[M_{12}^B] \), \( \phi_c \equiv \arg[V_{cb}V_{cs}^*] \). In the case of the standard model \( \phi_M = -2\arg[V_{cb}V_{ud}] \), so that the righthand-side of eq.(13) becomes \( -\sin 2\phi_1 \) up to tiny correction of \( \delta_1 \). If a new physics affects \( \phi_M \) or \( \delta_1 \), then the \( CP \) angle to measure, \( \phi_2 = \phi_M/2 + \phi_c + \delta_1 - \pi \) (mod \( \pi \)), can deviate from the angle of the unitarity triangle, \( \phi_1 \).

The \( CP \) angle \( \phi_2 \) is measured in \( b(\bar{b}) \rightarrow u\bar{u}d(\bar{d}) \) decay. A typical hadronic final state is \( \pi\pi \). There is a \( \Delta I = 1/2 \) penguin contribution in this decay mode. But it can be removed by isospin analysis [11]. The weak phase of the resulting decay amplitude is controlled by KM matrix elements following the assumption I. The \( CP \) asymmetry is given by
\[ \text{Im}(\frac{q}{p})_{\pi\pi} = -\text{Im} \left[ \frac{M_{12}^B}{M_{12}^B} \frac{V_{ub}V_{ud}^*}{V_{ub}^*V_{ud}} \right] = \sin(\phi_M + 2\phi_u), \]
where \( \phi_u \equiv \arg[V_{ub}V_{ud}^*] \). In the case of the standard model the righthand-side of eq.(11) becomes \( \sin[2(\pi - \phi_2)] = -\sin 2\phi_2 \). With new physics effects on \( M_{12}^B \), the \( CP \) angle to measure, \( \phi_2 = -\phi_M/2 + \phi_u + \pi \) (mod \( \pi \)), can deviate from \( \phi_2 \).
The rest of the CP angles $\tilde{\phi}_3$ is obtained from the decays $B \to DK$, where $D$ is a neutral $D$ meson [9]. The involving quark processes are $b \to c\bar{u}s, u\bar{c}s$ and their CP conjugates. No penguin process is involved here, so that we can write down the amplitudes following the assumption I:

$$A(B^+ \to D^0K^+) \propto V_{ub}^* V_{cs}, \quad A(B^+ \to \overline{D}^0K^+) \propto V_{cb}^* V_{us}. \quad (15)$$

The neutral $D$ meson is identified by $CP$ eigenstates ($K_S\pi^0, K_S\omega, K_S\phi$ for $CP$ odd state and $K^+K^-$ for even state) or $CP$ non-eigenstates ($K^{\pm}\pi^{\mp}$ and so on) into which both $D^0$ and $\overline{D}^0$ can decay. The two amplitudes $A(B^+ \to D^0K^+)A(D^0 \to f)$ and $A(B^+ \to \overline{D}^0K^+)A(\overline{D}^0 \to f)$, where $f$ is a common final state of neutral $D$ mesons, interferes giving rise to $CP$ violation. When $f$ is taken to be $K^+K^-$, $K_S\pi^0$, $K_S\omega$ or $K_S\phi$, the interference term depends on

$$- \arg \frac{V_{cb}^* V_{us} V_{cd} V_{us}^*}{V_{ub}^* V_{cs} V_{cs}^* V_{us}} = - \arg [(V_{cb}^* V_{cd})(V_{ub} V_{ud}^*)(V_{us}^* V_{ud})(V_{cs} V_{cd}^*)]$$

$$= \phi_u - \phi_c - \delta_1 + \pi. \quad (16)$$

which becomes the $CP$ angle $\tilde{\phi}_3$ to measure. While if $f$ is taken to be $CP$ non-eigenstates, we get $\tilde{\phi}_3$ as

$$- \arg \frac{V_{cb}^* V_{us} V_{cd} V_{us}^*}{V_{ub}^* V_{cs} V_{cs}^* V_{ud}} = - \arg [(V_{cb}^* V_{cd})(V_{ub} V_{ud}^*)]$$

$$= \phi_u - \phi_c + \pi. \quad (17)$$

If $\pi\pi$ mode is available as $CP$ eigenstate, the measured angle $\tilde{\phi}_3$ is given as

$$- \arg \frac{V_{cb}^* V_{us} V_{cd} V_{ud}^*}{V_{ub}^* V_{cs} V_{cs}^* V_{ud}} = - \arg [(V_{cb}^* V_{cd})(V_{ub} V_{ud}^*)(V_{us} V_{ud}^*)(V_{cs}^* V_{cd})]$$

$$= \phi_c - \phi_u + \delta_1 + \pi. \quad (18)$$

There is a difference among the measured angle $\tilde{\phi}_3$ depending on which of the modes is used to identify neutral $D$ meson. If $\delta_1$ is larger than the experimental precision, the difference can be seen. But the limit on $\delta_1$ is severe as will be shown in the next section, so that we need high precision (at least below $10^6$) in $\tilde{\phi}_3$ measurement to observe the difference.

Now we have the formulae of the three $CP$ angles to measure:

$$\tilde{\phi}_1 = \phi_M/2 + \phi_c + \delta_1, \quad (19)$$

$$\tilde{\phi}_2 = -\phi_M/2 - \phi_u,$n

$$\tilde{\phi}_3 = \pi + \phi_u - \phi_c(\pm \delta_1).$$n

The sum of three angles becomes $\pi$ up to the correction $\delta_1$. The magnitudes of $\delta_1$ is negligible in the three generation standard model but might not be neglected when KM matrix is not
$3 \times 3$ and unitary. The limit on $\delta_1$ is discussed in the next section. The phase of $M_{12}$ cancels between $\phi_1$ and $\phi_2$, so that the sum does not change if new physics affects $B^0-\bar{B}^0$ mixing.

### 3. Constraints on $\delta_1$

Here we estimate how much the $\delta_1$ can be if KM matrix is not in the standard model form, i.e. $3 \times 3$ unitary. Let us investigate the constraints on $\delta_1$ from the present experimental values of KM matrix elements without assuming $V$ is $3 \times 3$ and unitary. With usual three generations of quarks and possible extra quarks the coupling among quark mass eigenstates and $W$ boson is given as

$$L_W = \frac{g_2}{\sqrt{2}} (\bar{u}_L \gamma^\mu V_{12} u_L + \bar{c}_L \gamma^\mu V_{13} c_L + \bar{t}_L \gamma^\mu V_{23} t_L + m_L) \mu^+ + (\text{h.c.}).$$

Here $V$ is not necessary unitary nor square, but it can be shown that it is at least a part of a larger unitary matrix [12]. Let us suppose there are $N_u$ $u$-type quark mass eigenstates, $U_L \equiv (u_L, c_L, t_L, \cdots, \psi_1, \psi_2, \cdots)^T$, which are related to weak eigenstates of $n_f$ ordinary $SU(2)_L$ doublet quarks, $U_L^0 \equiv (u^0_L, c^0_L, t^0_L, \cdots)^T$ and $k_u$ extra singlet quarks with charge $2/3$, $\Psi^0 \equiv (\psi^0_1, \psi^0_2, \cdots)^T$ as follows;

$$U_L = \left[ X_u \mid X^\dagger_u \right] \left( \frac{U^0_L}{\Psi^0} \right),$$

where $N_u \times n_f$ matrix $X_u$ and $N_u \times k_u$ matrix $X^\dagger_u$ are composing the unitary matrix. Similar relations hold in $d$-type quarks. The quark-$W$ coupling becomes as follows;

$$L_W = (g_2/\sqrt{2}) \bar{d}_L \gamma^\mu D^0_L W^+ + (\text{h.c.})$$

$$= (g_2/\sqrt{2}) \bar{u}_L \gamma^\mu (X_u X^\dagger_d) D_d W^+ + (\text{h.c.}).$$

The KM matrix $V$ is given by $(X_u X^\dagger_d)$ which is a $N_u \times N_d$ matrix. This KM matrix is not necessarily unitary but is a part of a larger unitary matrix;

$$\Omega \equiv \begin{pmatrix} (X_u X^\dagger_d) & X^u \\ X^d \end{pmatrix},$$

which can be shown by simply checking $\Omega^\dagger \Omega = 1$.

The KM matrix elements $V_{ij}$ ($i = 1, 2, j = 1 \sim 3$) are measured through semi-leptonic processes of hadrons. We assume that new physics effect is negligible in semi-leptonic processes in comparison with the standard model contributions. We can adopt the experimental
values of the KM matrix elements as the genuine ones with this assumption. This assumption is thought to be reasonable by the following reasons. Possible new physics effects on semi-leptonic processes is scalar boson exchange or another gauge boson exchange at the tree level. Physical charged Higgs scalars can contribute to semi-leptonic processes in multi-Higgs model. But the couplings among leptons and Higgs are suppressed due to the small masses of leptons. (No \( \tau \) lepton process is used in the determination of KM matrix elements.) So the contribution is negligible even if physical charged scalar is lighter than \( W \) boson considering its lower bound of mass \([13] \). \( W_R \) boson has a gauge coupling to leptons in \( SU(2)_L \times SU(2)_R \times U(1) \) models \([4] \). But the \( W_R \) couples to \( \nu_R \) which should be much heavier than \( b \) quarks for the see-saw mechanism to work \([14] \). Then \( W_R \) cannot contribute to the semi-leptonic processes in determining KM matrix elements. Loop effects of new physics is thought to be suppressed as most of the new particles will be heavier than \( W \) boson.

The present data on KM matrix elements are given as follows \([13] \):

\[
|V_{ud}| = 0.9736 \pm 0.0010, \quad |V_{us}| = 0.2205 \pm 0.0018, \\
|V_{cd}| = 0.224 \pm 0.016, \quad |V_{cs}| = 1.01 \pm 0.18.
\]

Since \( V \) is at least a part of unitary matrix \( \Omega \), we have the following inequalities:

\[
\sum_{i=3} |\Omega_{ai}|^2 = 1 - |V_{ud}|^2 - |V_{us}|^2 < 0.0056, \quad (24)
\]
\[
\sum_{i=3} |\Omega_{ci}|^2 = 1 - |V_{cd}|^2 - |V_{cs}|^2 < 0.293, \quad (25)
\]
\[
\sum_{i=3} |\Omega_{id}|^2 = 1 - |V_{ud}|^2 - |V_{cd}|^2 < 0.0094, \quad (26)
\]
\[
\sum_{i=3} |\Omega_{is}|^2 = 1 - |V_{us}|^2 - |V_{cs}|^2 < 0.295. \quad (27)
\]

With these data the following upper bounds are obtained by using Schwarz’s inequality:

\[
|\sum_{i=3} \Omega_{ai} \Omega_{ci}^*| \leq \sum_{i=3} |\Omega_{ai}| \Omega_{ci}^*| \leq \sqrt{\sum_{i=3} |\Omega_{ai}|^2 \sum_{j=3} |\Omega_{cj}|^2} < 0.040, \quad (28)
\]
\[
|\sum_{i=3} \Omega_{id} \Omega_{is}^*| \leq \sum_{i=3} |\Omega_{id}| \Omega_{is}^*| \leq \sqrt{\sum_{i=3} |\Omega_{id}|^2 \sum_{j=3} |\Omega_{js}|^2} < 0.053. \quad (29)
\]

Here for the discussion below we define

\[
\delta_3 = \arg[V_{cs}^* V_{us}] - \arg[V_{cd}^* V_{ud}] + \pi. \quad (30)
\]

The sum \( \delta_1 + \delta_3 \) becomes 0 (mod 2\( \pi \)) as shown below:

\[
\delta_1 + \delta_3 = \arg[V_{ud} V_{us}] - \arg[V_{cd} V_{cs}] + \pi + \arg[V_{cs}^* V_{us}] - \arg[V_{cd}^* V_{ud}] + \pi \quad (31)
\]
\[
= \arg[V_{ud} V_{us} V_{cs}^* V_{us}] - \arg[V_{cd} V_{cs}^* V_{ud}] + 2\pi
\]
\[
= 0 \text{ (mod } 2\pi\).
The unitarity conditions of $\Omega$,

\begin{align}
0 &= V_{ud}V_{us}^* + V_{cd}V_{cs}^* + \sum_{i=3}^{\Omega_{id}\Omega_{is}^*}, \\
0 &= V_{ud}V_{cd}^* + V_{us}V_{cs}^* + \sum_{i=3}^{\Omega_{ud}\Omega_{us}^*},
\end{align}

and the magnitudes of $V_{ud}$, $V_{us}$, $V_{cd}$ and $V_{cs}$ give

$$|\delta_1| < 0.25 \ (\simeq 14^\circ), \ |\delta_3| < 0.20 \ (\simeq 12^\circ).$$

The bound on $\delta_3$ should be applied also on $\delta_1$ because of the identity (31). It can be found from the above arguments and eq(20) that the deviation of the measured angle $\tilde{\phi}_3$ from the geometrical one is less than the experimental precision ($\pm 15^\circ$) by the simulation [15] as far as the two assumptions hold.

4. Summary

We have analyzed how the $CP$ angles ($\tilde{\phi}_{1-3}$) to be measured at B factories will deviate from the geometrical ones ($\phi_{1-3}$) defined in unitarity triangle under the existence of new physics. The new physics effect on $B^0-\bar{B}^0$ mixing can be significant on $\tilde{\phi}_1$ and $\tilde{\phi}_2$, but is cancelled in the sum of these two angles. If KM matrix from is not a $3 \times 3$ and unitary matrix, $\tilde{\phi}_1$ and $\tilde{\phi}_3$ is affected, and the value of $\tilde{\phi}_3$ depends on the decay mode used in the measurement. The deviation is constrained to be less than the experimental precision to be attained in the next decade by the available data of the magnitude of KM matrix elements. The criterion of new physics search to check the sum of the angles is not effective unless a new physics significantly affects $b$ decay itself at the tree level or through penguin process. If there exists significant contribution of a new physics to $D$ meson system, it can affects the determination of $\tilde{\phi}_3$ with $B \to DK$ process. The obtained value can differ from the $\tilde{\phi}_3$ got by another method like $B_s \to \rho K_S$ where no $D$ meson is involved. It is desirable to get fine (below 10%) precision and multiple ways of $CP$ angles measurements for finding a signature of new physics or constraining one.

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