Measurements of CKM angles

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Measurements of Cabbibo-Kobayashi-Maskawa (CKM) CP violating angles as of 2009 are reviewed. The most precise CP violation parameter is the angle $\phi_1(\beta) = (21.1 \pm 0.9)^\circ$. The angle $\phi_2(\alpha)$ is obtained to be $(89.0 + 4.4/ - 4.2)^\circ$ and uncertainty of the angle $\phi_3(\gamma)$ is still $\approx 20^\circ$. The prospect to hunt New Physics beyond Kobayashi-Maskawa theory via CP violation measurement is also discussed.

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1. Introduction

During the first decade of the 21st century, two $B$-factory experiments, BaBar and Belle have carried out many $CP$ violation measurements to perform comprehensive test of Kobayashi-Maskawa (KM) theory [1]. As a result, 2008 Nobel Prize in Physics was given to Profs. Kobayashi and Maskawa, that is great pleasure for the experimentalists who contributed to the $B$-factory experiments. In this report, experimental constraints of three $CP$ violating angles, $\phi_1$, $\phi_2$ and $\phi_3$ (or $\beta$, $\alpha$ and $\gamma$) are reviewed. The possibility to hunt New Physics beyond the Standard Model (SM) is also discussed.

2. Time-dependent $CP$ violation and $B$-factory experiments

In $B$ meson system, the complex phase in the coupling $V_{td}$ which contributes to $B^0 - \bar{B}^0$ mixing cause the $CP$ violation phenomena in many cases, when the neutral $B$ meson decays into a $CP$ eigenstate $f_{CP}$ [2]. Therefore we have to measure the $CP$ asymmetry as a function of the proper time difference between the two $B$ meson decays produced by $\Upsilon(4S)$. Thus time-dependent $CP$ asymmetry is defined as

$$A_{CP}(\Delta t) = \frac{\Gamma(B^0(\Delta t) \rightarrow f_{CP}) - \Gamma(\bar{B}^0(\Delta t) \rightarrow f_{CP})}{\Gamma(B^0(\Delta t) \rightarrow f_{CP}) + \Gamma(\bar{B}^0(\Delta t) \rightarrow f_{CP})} = \mathcal{A}_{CP} \sin(\Delta m \Delta t) + \mathcal{S}_{CP} \cos(\Delta m \Delta t), \quad (2.1)$$

where $\Delta m$ is the mass difference between two mass eigenstates of neutral $B$ meson. The two $CP$ violation parameters, $\mathcal{A}_{CP}$ and $\mathcal{S}_{CP}$ are mixing-induced and direct $CP$ violation parameters, respectively$^1$.

In order to realize measurements of the time-dependent $CP$ violation, two $B$-factory experiments, Belle at KEK and BaBar at SLAC were built to collect huge number of $B$ meson pairs produced by KEKB and PEP-II energy-asymmetric $e^+e^-$ accelerators, respectively. So far, Belle has accumulated 780 $M\bar{B}\bar{B}$ pairs while BaBar has 470 $M\bar{B}\bar{B}$ data sample at $\Upsilon(4S)$. These numbers show remarkable success of the $B$-factories.

3. Measurements of $\sin 2\phi_1$

The $b \rightarrow c \bar{c} s$ mediated $B$ meson decays such as $B^0 \rightarrow J/\psi K^0$ is the most suitable process to measure the $CP$ violation angle $\phi_1$ via mixing-induced $CP$ violation because of the absence of complex phase in their decay amplitude, thus the direct relation, $\mathcal{A}_{CP} = -\xi_{CP} \sin 2\phi_1$ holds, where $\xi_{CP}$ is the $CP$ eigenvalue of the final state. Belle presented $\sin 2\phi_1 = 0.642 \pm 0.031 \pm 0.017$ [3] with 535 $M\bar{B}\bar{B}$ sample and BaBar obtained $\sin 2\phi_1 = 0.687 \pm 0.028 \pm 0.012$ [4] from 465 $M\bar{B}\bar{B}$ data, where the first error is statistical and second error is systematic. Both are consistent each other considering their errors and $\sin 2\phi_1$ has become a firm reference of the SM.

Recently, indirect determination of $\sin 2\phi_1$ using $V_{ub}$, $\Delta m_d$ and $\epsilon_K$ is found to be slightly higher than the direct measurement. $\mathcal{B}(B^+ \rightarrow \tau^+ \nu)$ is also higher than that obtained from the CKM global fit. Because of such a tension, Belle plans to revisit soon $\sin 2\phi_1$ measurement with its full $\Upsilon(4S)$ integrated luminosity corresponding to 780 $M\bar{B}\bar{B}$.

$^1$In some cases, $\xi_{CP} = -\mathcal{S}_{CP}$ is used to represent the direct $CP$ violation.
4. $\phi_2$ measurement

The interference between $b \to u$ mediated decays into proper $f_{CP}$ and $B^0 - \bar{B}^0$ mixing results in the $CP$ violation that can determine the angle $\phi_2$. There would be the $b \to d$ penguin contribution that cause a complexity to extract the angle $\phi_2$ from the observed $CP$ violation, however we can solve it by isospin analysis. As the $B$ decay final states to obtain $\phi_2$, there are three possibilities: $\pi \pi$, $\rho \rho$ and $\rho \pi$. From $\pi \pi$ [5] [6], $\rho \rho$ [7] [8] and $\rho \pi$ [7] [8] modes, $\phi_2$ is determined to be $(89.0^{+4.4}_{-4.2})^\circ$. In addition, BaBar collaboration performed measurements related to $a_1(\pi)$ decay mode [11] which can determine effective $\phi_2$.

5. $\phi_3$ measurement

The angle $\phi_3$ is determined by the $CP$ violation phenomena caused by the interference between $b \to c$ and $b \to u$ transitions. It takes place in the charged $B$ meson decays into a neutral $D$ meson and a charged Kaon, when the neutral $D$ meson decays into the final state where both $D^0$ and $\bar{D}^0$ can decay. Logically the most straight-forward approach is GLW method [12] to utilize the neutral $D$ meson decays into $CP$ eigenstates. The errors of $CP$ asymmetries of these decay modes are obtained to be $\sim 0.1$ [13] [14]. ADS method [15] suggests to use suppressed $D$ decay modes to obtain enhanced $CP$ asymmetry. Its sensitivity is still limited by statistics of the suppressed decay mode signal yield. [16] [17].

The measurement that can give the most stringent constraint on $\phi_3$ is the Dalitz analysis technique to use the neutral $D$ meson decay into $K^{0}_S \pi^+ \pi^-$ [18]. BaBar includes $D \to K^{0}_S K^+ K^-$ and tried $D \to \pi^+ \pi^- \pi^0$ mode [19]. While Belle recently added not only $D^{*} \to D \pi^0$ but also $D^{*} \to D \gamma$ [20] because these also can be used when $D \to K^{0}_S \pi^+ \pi^-$ occurs. Currently Dalitz model uncertainty is $9^\circ$ (Belle) or $5^\circ$ (BaBar), it can be reduced down to $2^\circ$ by an improved analysis technique using coherent $D\bar{D}$ production data at CLEO-c [21]. Among three $CP$ violation angles, constraint of $\phi_3$ has still the least precision of $\sim 20^\circ$.

6. $CP$ violation in penguin modes

The constraints on KM unitarity triangle have been obtained by the $B$ decays mediated by the tree diagrams where the SM predominantly contributes. On the other hand, the $B$ decays caused by the penguin diagrams are expected to be good at probing the new physics effects beyond the SM, because of their one loop nature. Especially in $SM$, $b \to s$ penguin mediated $B$ decays such as $B^0 \to \phi K^{0}$, $B^0 \to \eta^\prime K^{0}$, $B^0 \to K^{0}_S K^{0}_S K^{0}_S$ and so on are theoretically clean to have effective $\sin 2\phi_1$ ($\sin 2\phi_1^{eff}$) which is same as the $\sin 2\phi_1$ obtained by $b \to c\bar{s}s$ induced $B$ decay such as $B^0 \to J/\psi K^{0}$.

So far, there have been many two-body and quasi-two-body analyses. However, $\phi \to K^+ K^-$, $f_0 \to K^+ K^-$ and non-resonant contributions overlap (as do $\rho^0 \to \pi^+ \pi^-$ and $f_0 \to \pi^+ \pi^-$), therefore recently time-dependent Dalitz analyses have been performed in three-body decays such as $B^0 \to (K^+ K^-) K^{0}_S$ and $B^0 \to (\pi^+ \pi^-) K^{0}_S$ to resolve those overlapping contributions in amplitude level. The precision of $\sin 2\phi_1^{eff}$ of $b \to s$ mediated $B$ decays is still statistically limited, typically $0.1 \sim 0.2$ [22]. To obtain sensitivity in $\sin 2\phi_1^{eff}$ of $\theta^\circ (10^{-2})$, we need an integrated luminosity of $\theta^\circ (10ab^{-1})$, this fact requires a Super $B$-factory experiment.
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7. Summary

In summary, \( \sin^2 \phi_1 = 0.67 \pm 0.02 \) is gotten to be a firm SM reference. Constraint on \( \phi_2 \) is obtained to be \((89.0^{+4.4}_{-1.2})^\circ\). If the unitarity triangle is a right triangle, it indicates a miracle of nature. The precision of \( \phi_3 \) is still \( \sim 20^\circ \), it is just starting to be constrained. In order to hunt new physics effect via \( CP \) violation at \( b \to s \) mediated \( B \) decays by achieving \( \mathcal{O}(10^{-2}) \) sensitivity, we need \( \mathcal{O}(10 \text{ab}^{-1}) \) thus a Super \( B \)-factory experiment is awaited.

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References

[17] “Hadronic \( b \to c \) decays related to \( \gamma \) at BaBar”, talk given at EPS HEP 2009.
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