SuperB and BelleII prospects on direct CP violation measurements

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1 Introduction

The CP violation observed in quark sector is explained by a irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix\(^1\) in the Standard Model. One of the unitarity constraints of the CKM matrix is given by the equation

\[
V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0
\]

which is represented by a triangle in the complex plane. The phase can be determined from measurements of the three angles and sides of the triangle. The angles are called as

\[
\alpha/\phi = \text{Arg} \left[ -(V_{td}V_{tb}^*)/(V_{ud}V_{ub}^*) \right],
\]

\[
\beta/\phi = \text{Arg} \left[ -(V_{cd}V_{cb}^*)/(V_{td}V_{tb}^*) \right],
\]

and

\[
\gamma/\phi = \text{Arg} \left[ -(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*) \right].
\]

The latest results of the measurements of sides and angles are shown in the Fig.1.

The angle \(\gamma/\phi\) is the least well determined among all angles. The measurement of \(\gamma/\phi\) had been proposed to use the process \(B \rightarrow D^{(*)}K^{(*)}\) involved with interference with \(b \rightarrow u\) and \(b \rightarrow c\) quark transition in the discussion of direct CP violation\(^2\). The measurement of \(\gamma/\phi\) is performed in a theoretically cleanly way since only the tree-dominated decays are involved. Some methods to extract \(\gamma/\phi\) had been suggested so far: GLW\(^3\), ADS\(^4\), Dalitz\(^5, 6\) analyses. The GLW analysis uses \(D^0\) and \(\overline{D}^0\) decay into CP eigenstates such as \(K^+K^-\) or \(K_S\pi^0\), etc. The observables of double ratio and asymmetry are defined as below:

\[
R_{CP} = \frac{2B(B^- \rightarrow D_{CP}^+K^-) + B(B^- \rightarrow D_{CP}^0K^-)}{B(B^- \rightarrow D^0K^-) + B(B^- \rightarrow \overline{D}^0K^-)}
\]

\[
= 1 + r_B^2 \pm 2r_B \cos \delta_B \cos \phi_3
\]

(1)

\[
A_{CP} = \frac{B(B^- \rightarrow D_{CP}^+K^-) - B(B^- \rightarrow D_{CP}^0K^-)}{B(B^- \rightarrow D_{CP}^0K^-) + B(B^- \rightarrow D_{CP}^+K^-)}
\]

\[
= \pm 2r_B \sin \delta_B \sin \phi_3/R_{CP}^2
\]

(2)

where the \(D_{CP}\) is the \(D\) meson reconstructed in the \(CP\)-even(+) or \(CP\)-odd(-) final state, \(r_B\) is the ratio of amplitudes between \(B^- \rightarrow \overline{D}^0K^-\) and \(B^- \rightarrow D^0K^-\) defined
Figure 1: The unitarity triangle.
as $r_B \equiv |A(B^+ \rightarrow D^0 K^-)|/|A(B^- \rightarrow D^0 K^-)|$, and $\delta_B$ is the difference of strong phase for these amplitudes.

The ADS analysis uses $B^- \rightarrow D^{(*)} K^{(*)-}$ decays followed by the Cabibbo-favored (CFD) and doubly Cabibbo-suppressed $D^0$ decays (DCSD), where the interfering amplitudes have comparable magnitude. The CFD (DCFD) decays of the $D$ meson that can be used for ADS are $D^0 \rightarrow K^- \pi^+$, $K^- \pi^+ \pi^0$ ($D^0 \rightarrow K^+ \pi^-$, $K^+ \pi^- \pi^0$), etc. The observables, double ratio and asymmetry, are defined as below.

$$R_{ADS} \equiv \frac{B(B^- \rightarrow [f]D K^-) + B(B^+ \rightarrow [\bar{f}]D K^+)}{B(B^- \rightarrow [\bar{f}]D K^-) + B(B^+ \rightarrow [f]D K^+)}$$

$$= r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D) \cos \phi_3$$

$$A_{ADS} \equiv \frac{B(B^- \rightarrow [f]D K^-) - B(B^+ \rightarrow [\bar{f}]D K^+)}{B(B^- \rightarrow [\bar{f}]D K^-) + B(B^+ \rightarrow [f]D K^+)}$$

$$= 2r_B r_D \sin(\delta_B + \delta_D) \sin \phi_3 / R_{ADS}$$

where $r_D = |A(D^0 \rightarrow f)|/|A(\overline{D}^0 \rightarrow f)|$ and $\delta_D$ is strong phase difference between $D^0 \rightarrow f$ and $D^0 \rightarrow \bar{f}$.

The Dalitz analysis with $D$ meson decay into the three-body decay $K_S h^+ h^-$ to extract the angle $\gamma / \phi_3$, where $h^\pm$ represents charged light hadrons such as pion and kaon. The model-dependent Dalitz analysis uses the isobar model [7] which assume that the three-body decay of the $D$ meson proceeds through the intermediate two-body resonances. The total amplitude over the Dalitz plot can be represented as the sum of two amplitudes for $D^0$ and $\overline{D}^0$ decays into the same final state $K_S h^+ h^-$ as below.

$$f_{D^+} = f_D(m^2_+, m^2_-) + r_B e^{\pm i\phi_3 + i\delta_B} f_D(m^2_-, m^2_+)$$

where $m^2_+ = m^2_{K_S h^+}$, $m^2_- = m^2_{K_S h^-}$. The $f_D(m^2_+, m^2_-)$ consists of the sum of intermediates two-body amplitudes and a single non-resonant amplitude as follows.

$$f_D(m^2_+, m^2_-) = \sum_{j=1}^{N} a_j e^{i\xi_j} A_j(m^2_+, m^2_-) + a_{NR} e^{i\xi_{NR}}$$

Where $a_j$ and $\xi_j$ are the amplitude and phase of the matrix element, $A_j$ is the matrix element of the $j$-th resonance, and $a_{NR}$ and $\xi_{NR}$ are the amplitude and phase of the non-resonant component. The $r_B e^{\pm i\phi_3 + i\delta_B}$ can be converted to the Cartesian parameters $x_\pm = r_\pm \cos(\pm \phi_3 + \delta)$ and $y_\pm = r_\pm \sin(\pm \phi_3 + \delta)$. The $x_\pm$ and $y_\pm$ are actual fitted parameters.

The precision of $\gamma / \phi_3$ measurement has progressed as the data accumulated at $B$-factories and new efficient physics methods and analysis techniques were developed.
Although current statistics of $e^+e^-$ colliders is over the 1.2 billion $B\overline{B}$ pairs, it is insufficient for reliable $\gamma/\phi_3$. The SuperB$^8$ and BelleII$^9$ projects are planned to accumulate the 50-75 times larger than at the $B$-factories with improved detectors in the next decade.

2 $\gamma/\phi_3$ determination

The current most precise determination of $\gamma/\phi_3$ have been performed with Dalitz method. The $\gamma/\phi_3$ results of an model-dependent unbinned Dalitz method by Belle and BaBar are $\gamma/\phi_3 = (78.4^{+10.8}_{-11.0} \pm 3.6 \pm 8.9)^\circ$ $^{10}$, $(68 \pm 14 \pm 4 \pm 3)^\circ$ $^{11}$ with modulo 180$^\circ$, respectively, where the 3rd error is the model uncertainty. The model-dependent measurement is likely to become dominated by the model uncertainty in the Super $B$-factories era. The new technique using model-independent binned Dalitz method$^{12, 13}$ is reported by Belle$^{14}$ is supposed to eliminate this uncertainty. The model-independent Dalitz plot is divided into $2N$ bins symmetrically under the exchange $m_2 \leftrightarrow m_2^\prime$. The bin index $i$ ranges from $-N$ to $N$ excluding 0. The expected number of events in bin $i$ of the Dalitz plot of the $D$ meson from $B^\pm \to DK^\pm$ is

$$N_i^\pm = h_B[K_{i+1} + r_{K_i}^2 K_{i+1} + 2\sqrt{K_i} K_{i-1} (x_{i+1} \pm c_i \pm y \pm s_i)]$$

(7)

where $h_B$ is a normalization constant and $K_i$ is the number of events in the $i$th bin of the $K_S^0 \pi^+ \pi^-$ Dalitz plot of the $D$ meson in a flavor eigenstate. $x$ and $y$ are the same parameters as the ones used in the model-dependent Dalitz analyses.

The Belle reported the first $\gamma/\phi_3$ measurement with the model-dependent Dalitz method, $\gamma/\phi_3 = (77.3^{+15.1}_{-14.6} \pm 4.1 \pm 4.3)^\circ(c_i, s_i))$. Here the 3rd error is the uncertainty of the strong phase determination in the Dalitz plane studied by CLEOc experiment based on 818 pb$^{-1}$ at $\Upsilon(3770)$$^{15}$. Now, the BESIII$$^{16}$ experiment had accumulated the 2.9 fb$^{-1}$. The uncertainty is expected to be less than 1 degree in the near future.

The GLW and ADS combined measurements have also comparable constraints and model-independent on the $\gamma/\phi_3$ determination in Fig.2. These measurements have an important role to determine the $\gamma/\phi_3$ in the SuperB and BelleII era. The expected precisions are shown in the Table$^{11}$

3 Direct $CP$ violation in charmless hadronic decay

The direct CP asymmetries has been observed in two-body decays such as $B^0 \to \pi\pi$ and $B^0 \to K\pi$ decays. The charmless 2-body $B$ meson decays could receive contribution from processes beyond the standard model. For example, the $B \to K\pi$ proceeds through the suppressed tree diagram and loop penguin diagram of similar
Figure 2: The correlation between the $\gamma/\phi_3$ and the ratio of interfering amplitudes $r_B$ of the decay $B \to DK$ from world average $D^{(*)}K^{(*)}$ decays (GLW+ADS) and Dalitz analyses.

| Observable                              | $B$ Factories (2ab$^{-1}$) | SuperB (75ab$^{-1}$) | BelleII (50ab$^{-1}$) |
|-----------------------------------------|----------------------------|----------------------|----------------------|
| $\gamma/\phi_3(B \to DK, GLW)$          | $\sim 15^\circ$            | 2.5$^\circ$          | } 5$^\circ$          |
| $\gamma/\phi_3(B \to DK, ADS)$          | $\sim 12^\circ$            | 2.0$^\circ$          |                      |
| $\gamma/\phi_3(B \to DK, Dalitz)$       | $\sim 9^\circ$             | 1.5$^\circ$          | 2$^\circ$            |
| $\gamma/\phi_3(B \to DK, combined)$     | $\sim 6^\circ$             | 1-2$^\circ$          | 1.5$^\circ$          |

Table 1: The expected precision of $\gamma/\phi_3$ determination at SuperB and BelleII. Both the statistical and systematic errors are assumed to scale with the integrated luminosity.
magnitude (Fig. 3). The interference of the two diagrams cause a direct CP asymmetry of 
\[ A_{CP}^f = \frac{\Gamma (B \rightarrow f) - \Gamma (B \rightarrow \bar{f})}{\Gamma (B \rightarrow f) + \Gamma (B \rightarrow \bar{f})} \].

Figure 3: Tree diagram and penguin diagram in $B \rightarrow hh$ decay.

The processes involved in the decays of neutral and charged $B$ decays to $K\pi$ are expected to be the same. Additional diagrams which can contribute to $B^+$ decays shown in Fig. 4 are expected to be much smaller than the contributions in Fig. 3, thus, the asymmetries $A_{CP}^{K^+\pi^0}$ in $B^\pm\pi^0$ decays and $A_{CP}^{K^+\pi^-}$ in $B^0(\bar{B}^0) \rightarrow K^\pm\pi^\mp$ decays are expected to be the same. The recent averages of $A_{CP}^{K^+\pi^0}$ and $A_{CP}^{K^+\pi^-}$ by HFAG\[17\] show significant (5σ) deviation of $\Delta A_{K\pi} = A_{CP}^{K^+\pi^0} - A_{CP}^{K^+\pi^-}$ from 0. This is known as $\Delta A_{K\pi}$ puzzle. A sum rule relation\[18\] in Equation (8) proposed to test the puzzle with various measured observables in $K\pi$ decays.

\[ A_{CP}^{K^+\pi^-} + A_{CP}^{K^0\pi^+} \frac{B(B^+ \rightarrow K^0\pi^+)}{B(B^+ \rightarrow K^+\pi^-)} \tau_{B^+} = A_{CP}^{K^+\pi^0} \frac{2B(B^+ \rightarrow K^+\pi^0)}{B(B^+ \rightarrow K^+\pi^-)} \tau_{B^+} + A_{CP}^{K^0\pi^0} \frac{2B(B^0 \rightarrow K^0\pi^0)}{B(B^0 \rightarrow K^0\pi^-)} \tau_{B^0} \] (8)

where $B(B \rightarrow f)$ denotes the corresponding branching fraction and $\tau_{B}(B^\pm)$ life time of neutral and charged $B$ mesons.

Figure 4: Color suppressed diagram and electroweak penguin diagram in $B^+ \rightarrow K^+\pi^0$ decay.
Using the current world average values for the corresponding observables\cite{17}, the sum rule can be represented as a dependence of the least precise asymmetry $A_{CP}^{K^0\pi^0}$ on the $A_{CP}^{K\pi^+}$ as shown in Fig.5. A violation of the sum rule would indicate new physics in $b \to 7q$ transition.

Figure 5: Current world-average constraints on $A_{CP}^{K^0\pi^0}$ vs $A_{CP}^{K\pi^+}$\cite{17} (left). Expected constraints with the same central values and scaled for the integrated luminosity of $L = 50 \text{ ab}^{-1}$ at the BelleII. Contribution of systematic error in the figure adapts the current systematic error without any scaling conservatively.

4 Conclusion

Current most precise determination of $\gamma/\phi_3$ is brought by the Dalitz analyses. Both the model-independent and improved model-dependent analysis pushed down the systematic limitation and open up the possibilities of much higher precision determination at super $B$ factories in near future. Furthermore, the combined ADS and GLW results have a competitive determination with the Dalitz analysis. Since the measurement of $\gamma/\phi_3$ is obtained theoretically cleanly from the tree-dominated decays, the precise measurement will still play an important role for the test of unitarity triangle in the super $B$ factories era.

The direct $CP$ violation in the charmless hadronic decay is suitable place to explore the new physics phenomena. A violation of the sum rule of $B \to K\pi$ would indicate new physics in $b \to 7q$ transition. The SuperB and BelleII also have good potential to search for the existence of new physics in this mode.
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