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Mixing-induced CP violation in B_d decays

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The mixing-induced *CP* violation in B_d decays is an essential phenomena to test the Kobayashi-Maskawa scheme which has been established as the right description of the flavor mixing as well as *CP* violation in the quark sector. In addition to the measurements performed by the *B*-factory experiments of BaBar and Belle, the LHCb experiment has started to provide interesting results. Recent measurements are reviewed to see the attempts to test how the *CP* violation angle $\phi_1 (= \beta)$ determination is firm as the anchor-point of the Standard Model (SM).

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1. Introduction

Measurements of the mixing induced *CP* violation play the crucial role to test Kobayashi-Maskawa theory [1]. The quark-mixing matrix, KM-matrix, may contain an irreducible complex phase that gives rise to *CP*-violating asymmetries in the time-dependent rates of B_d and $\overline{B}_d$ decays into a common *CP* eigenstate [2]. Since the $B_d - \overline{B}_d$ mixing involves the V_{td} which contains an irreducible complex phase denoted as $\bar{\eta}$ in the Wolfenstein parameterization, the quantum interference with proper B_d meson decay amplitudes provides rich variety of time-dependent *CP* violation phenomena. The B_d decays governed by $b \to c$ quark level transitions into a *CP* eigenstate are the suitable process to measure the time-dependent *CP* violation parameters to get $\phi_1 = \beta \equiv \arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$. Toward SuperKEKB/Belle II and LHCb Run2 era, where precise measurements of time-dependent *CP* violation in various $b \to s$ and $b \to d$ induced rare decays are aimed to hunt new *CP* violating phase in the New Physics (NP) beyond the Standard Model (SM), the precise arguments for $\phi_1 = \beta$ determination is becoming important as the firm SM reference. In this context, The BaBar, Belle and LHCb recent measurements are reviewed and future prospect is discussed.

2. Experimental challenges to perform time-dependent *CP* violation in *B* meson decays at *B*-factories and LHCb.

In order to carry out time-dependent *CP* violation in *B* meson decays, following conditions are necessary to be satisfied; (i) producing enough number of *B* mesons and recording their decays, (ii) reconstruction of the B_d decays into the *CP* eigenstate f_{CP}, (iii) tagging its *b*-flavor and (iv) measuring the time evolution from the *B* decay vertices. For (i), apparently an excellent performance accelerator is required. With taking branching fractions of B_d meson to the f_{CP} into account, 10^{34} cm^{-2}s^{-1} should be achieved in the e^+e^- colliding beam experiment at the $\Upsilon(4S)$. At the same time, in order to make measurements of the time evolution on B_d system possible, energy-asymmetric collision is indispensable feature of the accelerator. These requirements have been satisfied at *B*-factory experiments, BaBar at PEP-II and Belle at KEKB. In the *p*-*p* collision at the LHC accelerator, making measurements competitive with the *B*-factories requires 10^{32} cm^{-2}s^{-1}. In LHCb experiment, the luminosity leveling operation combined with the proper detector system have been exploited to realize the data accumulation to satisfy such a condition. For the requirements of (ii), (iii) and (iv), each experiment has own approaches.

At the asymmetric-energy e^+e^- colliders operated at the $\Upsilon(4S)$ resonance, the trigger and data acquisition systems are designed and operated to have very high efficiency for the *B* meson pair production events, nearly 100%. Since only a *B* meson pair is produced, the $B_d - \overline{B}_d$ mesons are in the coherent oscillation until one of them decays. In the event of interest, one of B_d mesons decays into a *CP* eigenstate, f_{CP}, at the time t_{CP} while the accompanying *B* meson decays into the *b*-flavor specific final state, $f_{\rm tag}$ at the time $t_{\rm tag}$, and the time evolution is to be measured as a function of the proper time difference, $\Delta t \equiv t_{CP} - t_{\rm tag}$. The time-dependent *CP* asymmetry is expressed as

$$A_{CP}(\Delta t) = \frac{\Gamma(\overline{B}_d(\Delta t) \to f_{CP}) - \Gamma(B_d(\Delta t) \to f_{CP})}{\Gamma(\overline{B}_d(\Delta t) \to f_{CP}) + \Gamma(B_d(\Delta t) \to f_{CP})} = \mathscr{S}_{f_{CP}} \sin(\Delta m_d \Delta t) + \mathscr{A}_{f_{CP}} \cos(\Delta m_d \Delta t), \quad (2.1)$$

where $\Gamma(\overline{B}_d(\Delta t) \to f_{CP})$ ($\Gamma(B_d(\Delta t) \to f_{CP})$), Δm_d, $\mathscr{S}_{fCP}$ and $\mathscr{A}_{fCP}$ ($\mathscr{C}_{fCP} = -\mathscr{A}_{fCP}$ is also used in some literature) denote the corresponding time-dependent $\overline{B}_d$ (B_d) decay rate, $B_d - \overline{B}_d$ mixing frequency, mixing induced *CP* and direct *CP* asymmetries, respectively. In $b \to c$ transition induced B_d decays to a f_{CP}, if only the SM leading term contributes, $\mathscr{S}_{fCP} = -\eta_f \sin 2\phi_1 (= -\eta_f \sin 2\beta)$ and $\mathscr{A}_{fCP} = 0$ are predicted, where η_f is the *CP* eigenvalue of the final state f_{CP}. Since the B_d mesons are almost at rest with respect to the $\Upsilon(4S)$, the Δt can be reconstructed by the displacement between the two B meson decay in the z-direction, Δz, where z-axis is anti-parallel to the positron beam, by the relation of $\Delta z = \beta\gamma c \Delta t$. The boost factor $\beta\gamma = 0.425$ at KEKB and $\beta\gamma = 0.56$ at PEP-II colliders, provided by their energy-asymmetric e^+e^- collisions, the Δt resolution is about one third of the B lifetime, thus determination and validation of the Δt resolution is the most delicate treatment in the B-factory measurements. On the other hand, the e^+e^- environment's advantage is the high flavor tagging efficiency (ε) and small wrong tag fraction (w) to realize the large effective flavor tagging efficiency reaching 30%.

At the LHCb experiment, the b-hadrons produced in forward direction in p-p collisions are detected by the single-arm spectrometer. In the ideal cases, 1000 or 2000 times more the proper B decay signal yield for the unit integrated luminosity (i.e. per fb^{-1}) can be obtained. Here one can notice that actual B meson signal yields depend on the decay modes because of the trigger and reconstruction efficiencies. Because not only the b-hadron of interest but also many particles are produced in the same event in a p-p collision, the B_d oscillation is incoherent. Thus the time evolution is measured as a function of not Δt but t, the proper time from the production point. It means that the Δt in the time-dependent *CP* violation formula of eq. (2.1) is replaced by the t. The b-flavor is tagged by the opposite side b-hadron decay daughters (opposite side tag) as well as the pion charge which is kinematically closest to the $B_d \to f_{CP}$ (same side tag). Because of the higher wrong tag fraction, w, the effective flavor tagging efficiency is approximately 3%. It is one order of magnitude lower than the B-factory experiments and is compensated by the large B meson production rate.

BaBar and Belle accumulated 433 fb^{-1} and 711 fb^{-1}, respectively. On the other hand, LHCb accumulated 3 fb^{-1}. As discussed in the following sections, with these integrated luminosities, these experiments are bringing the measurements being competitive each other in proper B_d decay modes.

3. Measurement of $\sin 2\phi_1 = \sin 2\beta$.

Since the leading term of $b \to c\bar{c}s$ induced B_d decay does not contain the complex phase in Wolfenstein parameterization of the KM-matrix, the *CP* violation arises only from the phase in $B_d - \overline{B}_d$ mixing. Experimentally, the proper decay processes appear as $B_d \to$ charmonium K^0. The tree diagram of the decay amplitude is the Cabbibo-favored, therefore the relatively large branching fraction allows us a precision measurement of the *CP* violation. LHCb experiment has performed the time-dependent *CP* violation in $B_d \to J/\psi K^0_S$ decays reconstructed in the $J/\psi \to \mu^+\mu^-$ and $K^0_S \to \pi^+\pi^-$ final states. The reconstructed B_d candidates and time evolution of the asymmetry for the tagged net $B_d \to J/\psi K^0_S$ signal are shown in Figure 1. The resultant *CP* violation parameters are found to be $\mathscr{S}_{fCP} = 0.731 \pm 0.035 \pm 0.020$ and $\mathscr{A}_{fCP} = -\mathscr{C}_{fCP} = 0.038 \pm 0.032 \pm 0.005$, where the first and second errors are statistical and systematic errors, respectively [3].

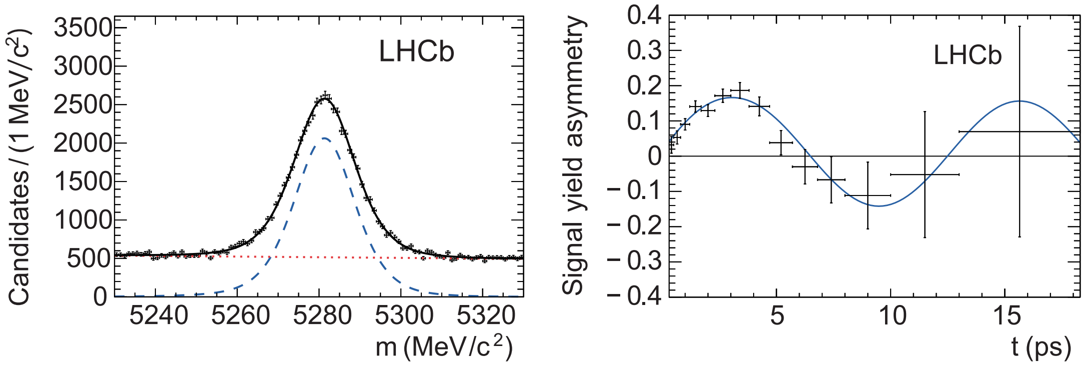

Figure 1: Distribution of the reconstructed mass (left) and time evolution of the asymmetry (right) in tagged $B_d \to J/\psi K^0_S$ candidates [3].

Now the world average is given to be $\sin 2\phi_1 = 0.69 \pm 0.02$ by combining with the last measurements brought by BaBar [4] and Belle [5] collaborations, $\sin 2\phi_1 = 0.687 \pm 0.028 \pm 0.012$ and $\sin 2\phi_1 = 0.668 \pm 0.023 \pm 0.013$, respectively. Now the LHCb experiment's capability has been demonstrated by bringing competitive results with the ones in B-factory experiments.

4. Penguin free decay process, $B_d \to D^{(*)0}_{CP} h^0$.

The leading term of the $b \to c\bar{c}s$ transition is the tree diagram, while the sub-leading term is the $b \to s$ penguin. Since the additional $c\bar{c}$ pair formation is the OZI-suppressed diagram and the SM $b \to s$ penguin contains no additional complex phase, the theoretical uncertainty in the time-dependent CP violation is regarded to be small. However, because of the one-loop transition nature, the effect coming from the NP might not be zero, therefore how we can constrain or avoid the possible penguin contribution would be an important issue.

One of the possible approach is to use "Penguin free" B_d decays to a f_{CP}. The $b \to c\bar{u}d$ transition's leading term has no complex phase and it results in the $B_d \to D^{(*)0}h^0$ mode, where h^0 represents a light neutral hadron. The sub-leading term of the $B_d \to D^{(*)0}h^0$ decay is the doubly Cabbibo-suppressed tree diagram, therefore this B_d decay mode is regarded to be "Penguin free". The sub-leading contribution has the V_{ub} which contains the complex phase, but it is the tree diagram thus theoretically under control within the SM.

However, only when the neutral $D^{(*)}$ meson decays to a CP eigenstate it becomes possible to perform the time-dependent CP violation to extract $\phi_1 = \beta$ in this decay mode. Therefore, sensitivity is limited by the low $D^{(*)}$ meson's branching fractions to CP eigenstates. In order to overcome it, the joint analysis using BaBar and Belle data has been performed. Hereafter, D^0_{CP} denotes the neutral D meson decaying to the CP eigenstates such as K^+K^-, $K^0_S\pi^0$ or $K^0_S\omega$ modes and D^{*0}_{CP} represents the neutral D^{*0} mesons reconstructed by the $D^0_{CP}\pi^0$ final state and thus $D^{(*)0}_{CP}$ is a general term for D^0_{CP} and D^{*0}_{CP}. As the h^0, π^0, η or ω are reconstructed. Using the data samples contain 471 M (BaBar) plus 772 M (Belle) $B\bar{B}$ pairs, $B_d \to D^{(*)0}_{CP}h^0$ decay signal yields are obtained to be 508 ± 31 events (BaBar) plus 757 ± 44 events (Belle) as shown in Figure 2.

Thanks to the best statistics available today, the time-dependent CP violation parameters are obtained to be $-\eta_f \mathscr{S}_{f_{CP}} = +0.66 \pm 0.10 \pm 0.06$ and $\mathscr{C}_{f_{CP}} = -\mathscr{A}_{f_{CP}} = -0.02 \pm 0.07 \pm 0.03$ where

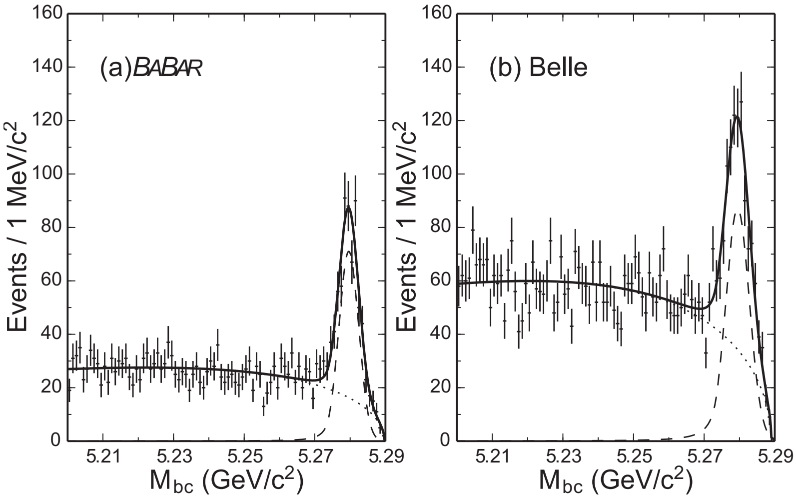

Figure 2: Distribution of the $M_{\rm bc}$ distributions for the reconstructed $B_d \to D^{(*)0}_{CP} h^0$ candidates in BaBar (left) and Belle (right) data [6].

first and second errors are statistical and systematic uncertainties. The Δt distributions as well as time-dependent asymmetries for the $B_d \to D^{(*)}_{CP} h^0$ candidates found in BaBar and Belle data are shown in Figure 3. This result corresponds to the observation of the CP violation at the level of 5.4σ and is found to be consistent with the $\sin 2\phi_1 = \sin 2\beta$ determination in $B_d \to$ charmonium K^0 decays. Scaling this result to the full statistics of Belle II experiment at SuperKEKB, 50 ab^{-1}, the uncertainty is thought to decrease down to $\sim \pm 0.015$ that is the same level as the current $\sin 2\phi_1$ determination. Therefore the time-dependent CP violation in $B_d \to D^{(*)0}_{CP} h^0$ would give a new additional standard to determine $\phi_1 = \beta$ in the Belle II era.

5. Consideration about constraint on the potential penguin contribution

Among $b \to c$ transition induced B decays, the $b \to c\bar{c}d$ transition induced B decays play very interesting role to constrain the possible penguin effect to the CP violation in the $b \to c\bar{c}s$ oriented B decays. Since the sub-leading term of $b \to c\bar{c}d$ transition is the $b \to d$ penguin amplitude, it is sensitive to the penguin contribution because of the complex phase contained in V_{td} even within the SM. Exploiting a plausible assumption by the SU(3) flavor symmetry, the CP violation in the $b \to c\bar{c}d$ decays can put a stringent constraint on the penguin effect to the neutral B meson mixing phase. The $B_d \to J/\psi\pi^0$ mode has been studied by BaBar and Belle collaborations and the effect to constrain the penguin contribution in ϕ_1 determination is discussed in Ref. [7]. Recently, LHCb reported the study of $B_d \to J/\psi\pi^+\pi^-$ decays [8]. The $\pi^+\pi^-$ decays are mostly coming from ρ^0 meson, thus based on the SU(3) symmetry among light vector mesons, the resultant CP violation puts a stringent constraint on the potential penguin contribution to the determination of $B_s - \overline{B}_s$ mixing phase, ϕ_s.

Here, thanks to the large b-hadron production rate, the $B_d \to J/\psi\pi^+\pi^-$ decay signal yield is one order of magnitude larger than that for each B-factory experiment. This means LHCb data is good at resolving possible contributions as the di-pion source, in addition to ρ^0, ω, f_2, non-resonant and so on. Large B_d signal yield has also advantage to determine the polarization of

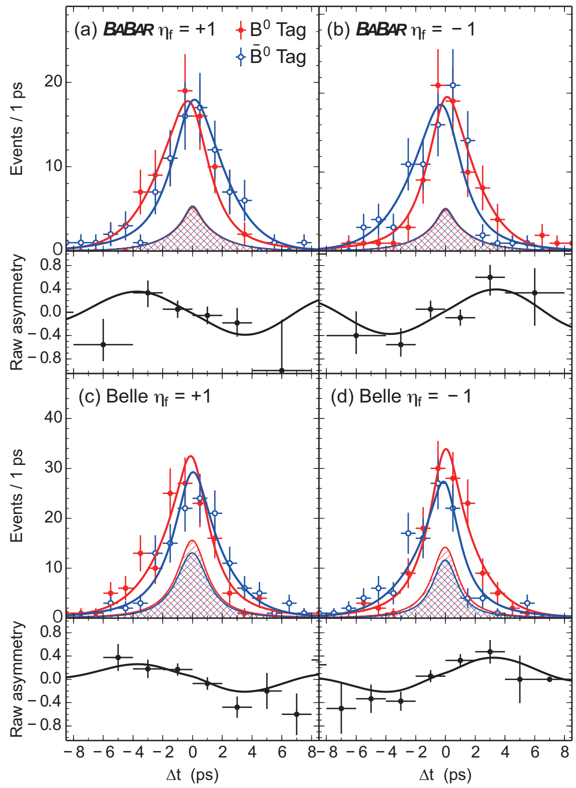

Figure 3: Distribution of the Δt distributions for B_d tags (red) and $\overline{B}_d$ tags (blue) and time evolution of the CP asymmetries of $B_d \to D_{CP}^{(*)0} h^0$ decays for (a)-(b) BaBar and (c)-(d) Belle [6].

the $B_d \to J/\psi\rho^0$ decays for which CP-even and CP-odd fraction has to be disentangled because it is an admixture state in general. Since the effective flavor tagging efficiency is much higher in e^+e^- collider-based B-factories than the LHCb environment, it may be worth to think about performing the time-dependent CP violation measurement on $B_d \to J/\psi\pi^+\pi^-$ mode using the LHCb information for resolving composition of the di-pion mass spectrum as well as the $J/\psi\rho^0$ polarization to attempt to maximize the sensitivity for the CP violation measurement. Note that it requires more precise estimation to show the possible improvement in a quantitative manner.

6. Summary

As an inevitable step toward hunting New Physics in much higher sensitivities for the time-dependent CP violation in $b \to s$ and $b \to d$ governed B meson decays with higher statistics data to be made available by LHCb Run2 as well as Belle II experiments, the $b \to c$ transision induced B_d decays are being very carefully visited to establish the firm Standard Model reference. In the flagship mesurement, determination of $\sin 2\phi_1 = \sin 2\beta$ with $B_d \to J/\psi K_S^0$ mode, LHCb has brought a competitive result with B-factory experiments.

Making possible penguin contribution to the determination of the CP violation angle $\phi_1 = \beta$ under control is an important issue to define the firm SM reference. The "Penguin free" $B_d \to D_{CP}^{(*)} h^0$ mode has been analyzed by the joint analysis effort between BaBar and Belle collaborations.

The resultant *CP* violation is found to be consistent with the current $\phi_1 = \beta$ determination and is revealed to become an additional reference with the Belle II statistics. Exploiting the *CP* violation in the $b \to c\bar{c}d$ induced B_d modes and the plausible SU(3) flavor relation to constrain the possible penguin contribution to the golden mode is also found to be promising. All those attempts are important steps for further precision measurements in the coming Belle II and LHCb Run2 era.

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