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Recent results on CPV and hadronic decays of B mesons at Belle

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Three recent studies on CP violation and related hadronic B meson decays by the Belle experiment, in particular on determination of the angle ϕ_1 of the Unitarity Triangle, are reported. The first joint analysis by Belle and BaBar focused on time-dependent CP asymmetry of $B \to D^{(*)}_{cp} h^0$, which is a combination of the tree-only $b \to c\bar{u}d$ and $b \to u\bar{c}d$ processes, and established CP asymmetry by 5σ. Using a similar process, $B \to D^{(*)} h^0$ with $D \to K^0_S \pi^+ \pi^-$, a time-dependent Dalitz plot analysis was performed and excluded the second ϕ_1 solution by 5σ. A new $b \to c\bar{c}d$ process, $B^0 \to \psi(2S)\pi^0$, was observed for the first time. All of these studies are relevant for the ultimate precision measurement of the Unitarity Triangle angle ϕ_1 at Belle II.

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1. Introduction

Violation of charge-parity (CP) symmetry in the Standard Model (SM) is the consequence of a non-vanishing complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark transition matrix. This was successfully demonstrated by the measurement of non-zero CP asymmetry in B meson decays at the two B-factories, Belle at KEK and BaBar at SLAC. The B-factories were designed and built to measure the CP violating parameter $\sin 2\phi_1$ through the time evolution of CP asymmetry between B^0 and $\overline{B}^0$ decaying into a common CP eigenstate, where ϕ_1 $(=\beta)$ is one of the angles of the Unitarity Triangle (UT), and it corresponds to the complex phase which appears in the box diagram of B^0-$\overline{B}^0$ mixing. To make this measurement possible, the following conditions were fulfilled at the B-factories: A large number of clean B meson pairs were produced from electron-positron collisions through the $\Upsilon(4S)$ resonance, in order to overcome the small $(O(10^{-5}))$ product branching fraction of the decay modes into a CP eigenstate; One of the B mesons is reconstructed in a CP eigenstate such as the "golden mode" $J/\psi K^0_S$ and hence it is unknown whether it originates from B^0 or $\overline{B}^0$, while flavor-specific information from the decay products of the other B meson is combined to put a flavor-tag whether it decayed as B^0 or $\overline{B}^0$ with an effective tagging efficiency of about 30%; The B^0-$\overline{B}^0$ system is produced in a boosted center-of-mass system with asymmetric beam energies to make the average decay length of about 200μm for Belle and 250μm for BaBar to measure the time evolution as a vertex displacement.

The decay $B \to J/\psi K^0_S$ dominantly proceeds through the tree diagram of the quark transition $b \to c\bar{c}s$ and has been considered to be theoretically clean, with only a tiny disturbing SM penguin contribution to the overall phase which has so far been neglected. Including similar $b \to c\bar{c}s$ modes, Belle measured $\sin 2\phi_1 = +0.667 \pm 0.023 \pm 0.013$ [1] and BaBar measured it to be $+0.687 \pm 0.028 \pm 0.012$ [2]. The world average of the angle ϕ_1 is now precisely measured to be $(21.9 \pm 0.7)^\circ$. The non-zero ϕ_1 value is the proof of the non-zero CP asymmetry presumably from the SM, while it is not enough to exclude additional contributions from physics beyond the SM to B^0-$\overline{B}^0$ mixing. A possible deviation from the SM has to be identified by measuring ϕ_1 without using the B^0-$\overline{B}^0$ mixing process, e.g., by constraining the other UT angles and sides. From available measurements of all three angles and three sides at the B-factories and other experiments, the UT triangle is now consistently overconstrained and hence the SM picture of CP violation is successfully demonstrated.

However, the overconstrained UT cannot yet preclude an O(10%) contribution from physics beyond the SM, and further improvement in precision for all the measurements is needed. Even for the most precisely measured parameter ϕ_1, precision is still statistically limited. In addition, the second solution of ϕ_1 from the precisely measured $\sin 2\phi_1$ has not yet been excluded at a high confidence level. In the next generation experiments, the ϕ_1 measurement becomes systematic error limited and it will eventually be important to limit the possible deviation due to the tiny penguin pollution in the $b \to c\bar{c}s$ modes.

Belle and BaBar data have been already extensively analyzed and it is not easy to improve the precision of CP asymmetry measurements. A number of new measurements have been recently made to improve our knowledge and hopefully set guidelines for the anticipated Belle II dataset. In particular, it is important to measure the angle ϕ_1 using the quark transitions other than $b \to c\bar{c}s$ as reported below.

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2. $\sin 2\phi_1$ from $B \to D_{cp}^{(*)} h^0$ with Belle + BaBar data

The final state of the decay $B \to D_{cp}^{(*)} h^0$ is a CP eigenstate, where h^0 is a neutral light meson (π^0, η or ω, CP=-1), D_{cp} is a D^0 or $\overline{D}^0$ meson decaying into a CP eigenstate such as $K_S^0\pi^0$, $K_S^0\omega$ (CP=-1) or K^+K^- (CP=$+1$), and D_{cp}^* is a D^* decaying into D_{cp} in $D_{cp}^* \to D_{cp}\pi^0$. Therefore a time-dependent CP asymmetry measurement is applicable in the same way as the golden mode $B \to J/\psi K_S^0$. The decay proceeds dominantly through the $b \to c\bar{u}d$ quark transition representing the favored $\overline{B}^0 \to D^0 h^0$ process, which contains no additional complex phase. Similarly to the $b \to c\bar{c}s$ processes, the measured CP asymmetry corresponds to $\sin 2\phi_1$ from the complex phase of B^0-$\overline{B}^0$ mixing.

There is a subdominant contribution through the $b \to c\bar{u}d$ quark transition representing the doubly-Cabibbo-suppressed $\overline{B}^0 \to \overline{D}^0 h^0$ process, which carries a non-zero complex phase. Unlike the $b \to c\bar{c}s$ processes, there is no contribution from a penguin loop process, and the relative contribution from the doubly-Cabibbo-suppressed decays is an order of magnitude smaller than that of the penguin pollution in the $b \to c\bar{c}s$ process and hence the measurement of $\sin 2\phi_1$ is theoretically cleaner [3]. Other possible ambiguity is from CP asymmetry in D^0 decays, which is an even smaller contribution and can be safely neglected.

The branching fraction of $B \to D_{cp}^{(*)} h^0$ is as small as O(10^{-6}), and due to the limited statistics, CP asymmetry has not been previously established. This motivated a joint analysis using the combined full dataset of Belle and BaBar [4]. Using a fit to the beam-energy constrained mass $M_{\rm bc} = \sqrt{(E^*_{\rm beam})^2 - (p^*_B)^2}$ where $E^*_{\rm beam}$ is the beam energy and p^*_B is the reconstructed B meson momentum in the center-of-mass system, 508 ± 31 signal events are found in the BaBar data of 431 million $B\overline{B}$ events, and 757 ± 44 signal events are found in the Belle data of 772 million $B\overline{B}$ events, as shown in Fig. 1. The main background is the continuum $e^+e^- \to q\bar{q}$ production, which is suppressed by using an event shape parameter based on a neural network.

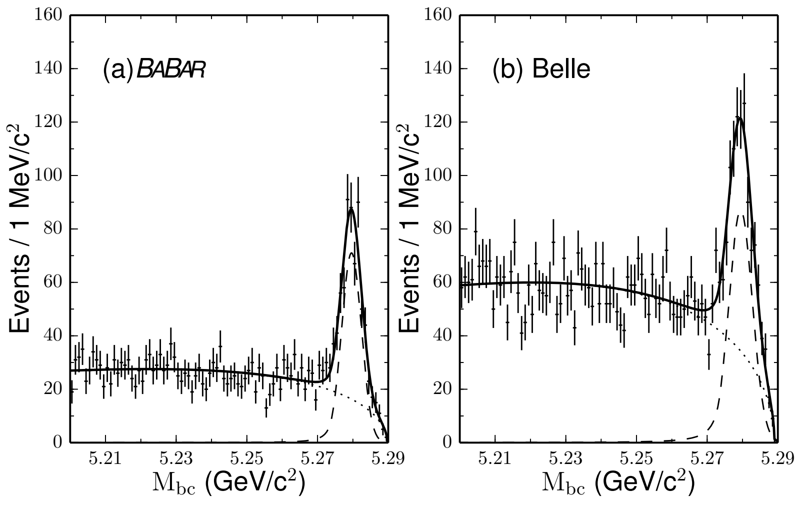

Figure 1: $M_{\rm bc}$ distribution of $B \to D_{cp}^{(*)} h^0$ events from the BaBar sample (left) and Belle (right).

Two experiments have developed similar but somewhat different analysis techniques to perform the time-dependent CP asymmetry measurement, for example on the event vertex resolution

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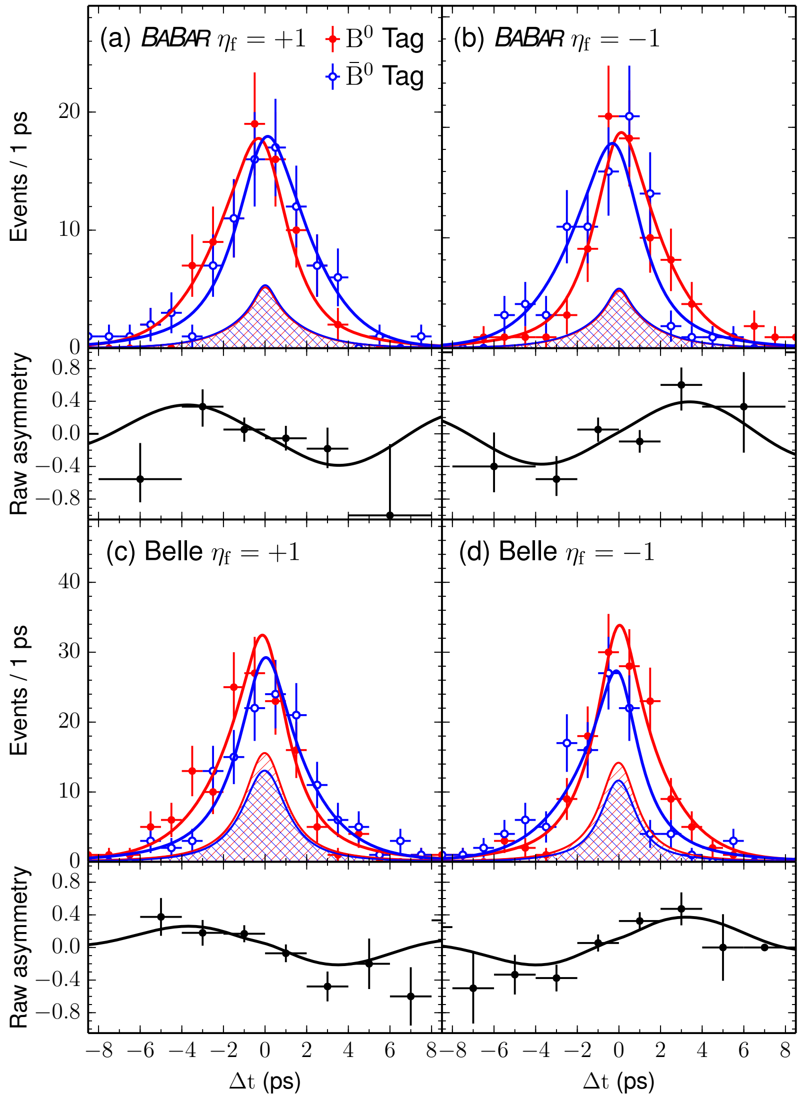

Figure 2: M_{bc} distribution of $B \to D_{cp}^{(*)} h^0$ events for the samples of the CP-even (right) and CP-odd (left) modes from BaBar (top) and Belle (bottom).

and tagging efficiency. Therefore, while the overall analysis procedure is kept common, the vertex resolution function and tagging quality for each event are applied according to the Belle or BaBar experiment. Combined analysis is performed by maximizing a joint log-likelihood function $\mathscr{L}$ on the time difference Δt from the vertex displacement Δz between the signal and tag B mesons,

$$\ln \mathscr{L} = \sum_i \ln \mathscr{P}_i^{\rm Belle} + \sum_j \ln \mathscr{P}_j^{\rm BaBar}. \tag{2.1}$$

Here, the probability density functions (PDFs) $\mathscr{P}^{\rm exp}$ (exp=Belle, BaBar) are defined as

$$\mathscr{P}^{\rm exp} = \sum_k f_k \int [P_k(\Delta t') R_k^{\rm exp}(\Delta t - \Delta t')]\, d\Delta t' \tag{2.2}$$

using experiment-dependent resolution functions $R_k^{\rm exp}$. The index k stands for the signal or background, and P_k is the signal or background model. While the background model is determined from the $M_{\rm bc}$ sideband and hence is experiment-dependent, the signal model,

$$P_{\rm sig}(\Delta t, q) = \frac{1}{4\tau_{B^0}} e^{\frac{-|\Delta t|}{\tau_{B^0}}} [1 + q(\mathscr{S} \sin(\Delta m \Delta t) - \mathscr{C} \cos(\Delta m \Delta t))], \tag{2.3}$$

is expressed with common parameters: the B^0 lifetime τ_{B^0}, the B^0-$\overline{B}^0$ mixing parameter Δm, coefficients $\mathscr{S}$ and $\mathscr{C}$ for the sine and cosine terms, with only one exception for the event and experiment-dependent flavor tagging quality parameter q. In the SM, $-\eta_f \mathscr{S} = \sin 2\phi_1$, where $\eta_f = \pm 1$ is the CP eigenvalue of the final state, and $\mathscr{C} = 0$.

The combined fit result is shown in Fig. 2. The fit gives

$$-\eta_f \mathscr{S} = +0.66 \pm 0.10 \pm 0.06, \quad \mathscr{C} = -0.02 \pm 0.07 \pm 0.03. \tag{2.4}$$

This is the first observation of non-zero CP asymmetry with statistical significance of 5.4σ. The results are in agreement with the ϕ_1 value from $b \to c\bar{c}s$, although the error is still large. It will be a competitive measurement with the full Belle II dataset, and it will be interesting to see if the ϕ_1 value differs from $b \to c\bar{c}s$.

3. $\cos 2\phi_1$ from $B \to D^{(*)} h^0$ with $D \to K_S^0 \pi^+ \pi^-$

The final state of the decay $B \to D^{(*)} h^0$, where h^0 is a neutral light meson and D decays into $K_S^0 \pi^+ \pi^-$, is not a CP eigenstate since the final state of $D^0 \to K_S^0 \pi^+ \pi^-$ is a mix of CP eigenstates such as $K_S^0 \rho^0$, flavor-specific final states such as $K^{*-}\pi^+$ and doubly-Cabibbo-suppressed states such as $K^{*+}\pi^-$, while the signs of charges of the flavor-specific states swap for the $\overline{D}^0 \to K_S^0 \pi^+ \pi^-$. Therefore, a simple repetition of the time-dependent CP asymmetry measurement does not work.

Many K resonances with different mass, width, spin and parity are involved, such as $K^*(892)$, $K_0^*(1430)$, $K_1(1270)$, $K_2^*(1430)$ and so on. Interference between resonances provides strong phase information at every Dalitz plot point of $K_S^0 \pi^+ \pi^-$. The signal is modeled as,

$$P_{\rm sig}(m_+^2, m_-^2, \Delta t) \propto e^{-\frac{|\Delta t|}{\tau_B}} \left[1 + q(\mathscr{A}(m_+^2, m_-^2) \cos(\Delta m \Delta t) + \mathscr{S}(m_+^2, m_-^2) \sin(\Delta m \Delta t))\right], \tag{3.1}$$

in analogy to Eq. 2.3 except $\mathscr{A} = -\mathscr{C}$ notation is used. The coefficient of the sine term is a function of ϕ_1,

$$\mathscr{S}(m_+^2, m_-^2) \propto {\rm Im}[f(m_-^2, m_+^2) f^*(m_+^2, m_-^2) e^{2\phi_1}]. \tag{3.2}$$

This can be used to disentangle the weak phase ϕ_1 itself, or in a form with both $\sin 2\phi_1$ and $\cos 2\phi_1$. Constraint on $\cos 2\phi_1$ can exclude the second ϕ_1 solution from the precisely measured $\sin 2\phi_1$ [5].

The final state can be modeled by the sum of known resonances, and the relative amplitude and phase can be obtained from an abundantly available sample of D^0 in inclusive $D^{*+} \to D^0 \pi^+$ for every Dalitz plot point. However, there are many controversial resonances which may or may not be included in the fit to the D^0 sample, and the choice of the included resonances introduces an unavoidable model error.

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In order to overcome this problem, a binned model-independent method has been proposed. In this method, the Dalitz plot is divided into bins, and in each bin, the average amplitude and phase in the bin are measured from data without prior knowledge of the resonant structure. While the amplitude can be measured from a clean sample such as $B^- \to D^0\pi^-$ by Belle, the phase measurement requires external information from coherent $\psi(3770) \to D^0\overline{D}^0$ events with both D^0 and $\overline{D}^0$ decaying into $K_S^0\pi^+\pi^-$ and events with $D \to K_S^0\pi^+\pi^-$ in one side and D decaying into a CP-eigenstate (CP-tagged) in the other side, which was provided by CLEO-c [6].

The time-dependent analysis is a complex analysis, but it is based on a combination of widely used techniques. Both of model-dependent and model-independent Dalitz plot analyses were developed to measure the UT angle ϕ_3 from $B \to DK$ decays, and a time-dependent Dalitz analysis has been used to measure the angle ϕ_1 in the $b \to s$ penguin decays such as $B \to K_S^0\pi^+\pi^-$. Model-dependent analysis on $B \to D^{(*)}h^0$ with $D \to K_S^0\pi^+\pi^-$ was previously performed by Belle with 386 million $B\overline{B}$ [7] and by BaBar with 383 million $B\overline{B}$ [8], excluding the second ϕ_1 solution at 98% and 86% confidence level, respectively.

A new analysis by Belle using the full dataset of 772 million $B\overline{B}$ events was performed with the binned model-independent approach [9]. In total, the following seven $D^{(*)}h^0$ modes are included: $D^0\pi^0$, $D^0\eta_{\gamma\gamma}$, $D^0\eta_{\pi^+\pi^-\pi^0}$, $D^0\omega$, $D^0\eta'$, $D^{*0}\pi^0$ and $D^{*0}\eta_{\gamma\gamma}$, where $\eta_{\gamma\gamma}$ and $\eta_{\pi^+\pi^-\pi^0}$ are the η meson reconstructed in the $\gamma\gamma$ and $\pi^+\pi^-\pi^0$ channels, respectively, and η' is reconstructed in the $\pi^+\pi^-\eta_{\gamma\gamma}$ channel. From a fit to $M_{\rm bc}$ and $\Delta E = E_B^* - E_{\rm beam}^*$ where E_B^* is the reconstructed B meson energy in the center-of-mass system, in total 962 ± 41 signal events are found, of which 464 ± 26 events of the $D^0\pi^0$ mode (Fig. 3) contributes with a signal fraction of (72 ± 4)% and 182 ± 18 events of the $D^0\omega$ mode with a fraction of (58 ± 8)%. The signal fraction of the other modes ranges between 44% and 70%.

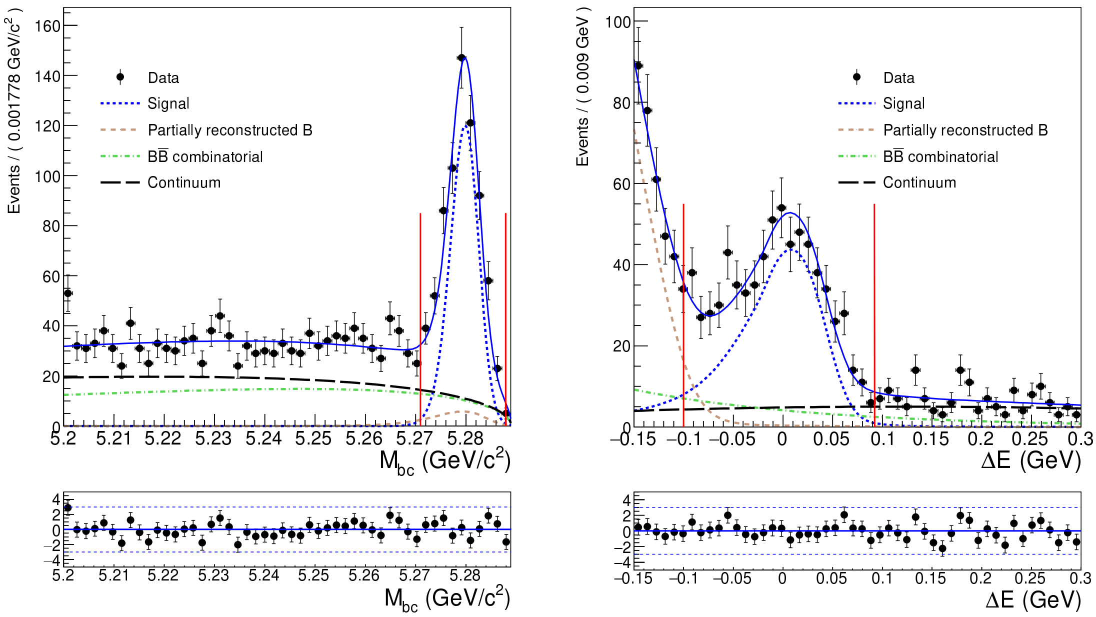

Figure 3: $M_{\rm bc}$ (left) and ΔE (right) distributions of $B \to D\pi^0$ events.

Events are divided into 8×2 bins on the Dalitz plot plane, where binning is chosen to minimize the variation of the amplitude and phase within the same bin based on a realistic resonant model, and for which CLEO-c data is available.

The number of events in bin i ($i = -8, \ldots, -1, +1, \ldots, +8$) is modeled as

$$N_i(\Delta t, \phi_1) = h e^{-\frac{|\Delta t|}{\tau_B}} \left[1 + q \frac{K_i - K_{-i}}{K_i + K_{-i}} \cos(\Delta m \Delta t) \right.$$
$$\left. + 2q\xi_{h^0}(-1)^l \frac{\sqrt{K_i K_{-i}}}{K_i + K_{-i}} \sin(\Delta m \Delta t)(S_i \cos 2\phi_1 + C_i \sin 2\phi_1) \right] \quad (3.3)$$

Here, h is a normalization constant, ξ_{h^0} is the CP eigenvalue of the h^0 meson, l is the angular momentum of the $D^{(*)0}h^0$ system, K_i is the integrated squared amplitude, and S_i and C_i represent the strong phase over the bin i integrated as

$$K_i = \int_i |\mathscr{A}_D(m_-^2, m_+^2)|^2 d\mathscr{D} \quad (3.4)$$

$$S_i = \frac{\int_i |\mathscr{A}_D||\overline{\mathscr{A}}_D| \sin \Delta\delta_D d\mathscr{D}}{\sqrt{K_i K_{-i}}}, \quad C_i = \frac{\int_i |\mathscr{A}_D||\overline{\mathscr{A}}_D| \cos \Delta\delta_D d\mathscr{D}}{\sqrt{K_i K_{-i}}} \quad (3.5)$$

from the amplitude $\mathscr{A}_D$ and phase δ_D over the Dalitz plot $\mathscr{D}$.

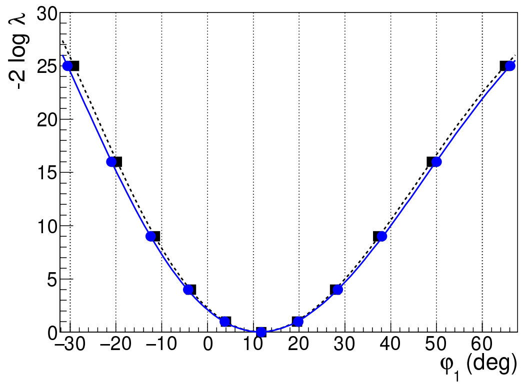

Figure 4: Likelihood curve for the ϕ_1 solution from the fit to the $B \to D^{(*)}h^0$ sample.

Table 1: Fit results of the time-dependent Dalitz plot fit to the $B \to D^{(*)}h^0$, $D \to K_S^0\pi^+\pi^-$, for the $D\pi^0$ mode, the $D\omega$ mode, the rest, and all combined.

Mode	$\sin 2\phi_1$	$\cos 2\phi_1$
$B^0 \to D\pi^0$	0.61 ± 0.37	$0.88^{+0.46}_{-0.52}$
$B^0 \to D\omega$	-0.12 ± 0.58	$1.28^{+0.62}_{-0.69}$
Others	0.44 ± 0.51	$0.89^{+0.49}_{-0.55}$
Combined	$0.43 \pm 0.27 \pm 0.08$	$1.06 \pm 0.33^{+0.21}_{-0.15}$

The fit results are summarized in Table 1. The angle ϕ_1 is extracted to be $11.7^\circ \pm 7.8^\circ \pm 2.1^\circ$ with no ambiguity for the second solution (Fig. 4). It is consistent by 1.3σ with the nominal $\phi_1 = 21.9^\circ$ solution from the $b \to c\bar{c}s$ process, while the second solution of $\phi_1 = 68.1^\circ$ is disfavored by 5.1σ.

The $\sin 2\phi_1$ result alone is not significant enough to establish another CP asymmetry, but it is consistent with other $\sin 2\phi_1$ measurements and can contribute to reduce the error of the tree-only measurement when combined with the $B \to D_{cp}^{(*)} h^0$ result.

4. Observation of $B^0 \to \psi(2S)\pi^0$

Another approach to verify the validity of the ϕ_1 measurement from $b \to c\bar{c}s$ is to use the $b \to c\bar{c}d$ process. The $b \to c\bar{c}d$ process is not free from the penguin diagram that affects the complex phase, but such a contribution is strongly suppressed and may provide useful information about the penguin pollution. Since the dominant $b \to c\bar{c}d$ tree diagram is also suppressed, $B \to J/\psi\pi^0$ is the only mode measured so far, providing $\sin 2\phi_1 = 0.65 \pm 0.21 \pm 0.05$ by Belle [10] which is consistent with $\sin 2\phi_1$ from $b \to c\bar{c}s$. The possible next mode, $B^0 \to \psi(2S)\pi^0$ was not previously observed.

Using the full dataset of Belle, the $B^0 \to \psi(2S)\pi^0$ mode was reconstructed in the decay chain of $\psi(2S) \to \ell^+\ell^-$ ($\ell = e, \mu$) or $\psi(2S) \to J/\psi\pi^+\pi^-$ [11]. Dominant background is from the misreconstructed other B decays into charmonium with the $b \to (c\bar{c})q$ processes ($q = d, s$), while continuum $e^+e^- \to q\bar{q}$ is not so problematic and is suppressed by the reduced Fox-Wolfram moment $R_2 < 0.5$. The signal is extracted from a fit to $M'_{\rm bc}$ and ΔE, where $M'_{\rm bc}$ is a modified beam-constrained mass to take into account the worse energy resolution of π^0 than rest of the particles.

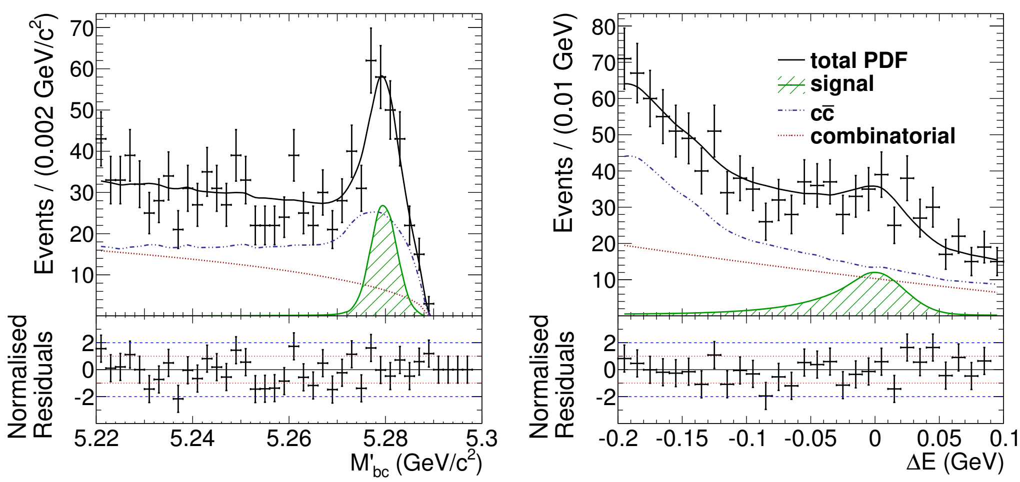

Figure 5: $M_{\rm bc}$ (left) and ΔE (right) distributions of $B^0 \to \psi(2S)\pi^0$ events.

The fit shown in Fig. 5 gives 85 ± 12 events, with statistical significance of 7.2σ. The measured branching fraction is

$$\mathscr{B}(B^0 \to \psi(2S)\pi^0) = (1.17 \pm 0.17 \pm 0.08) \times 10^{-5}, \tag{4.1}$$

which is comparable with $\mathscr{B}(B \to J/\psi\pi^0) = (1.76 \pm 0.16) \times 10^{-5}$. This is the first observation the mode, and it will contribute to the future time-dependent CP asymmetry measurement of the $b \to c\bar{c}d$ process.

5. Summary

The first observation of CP asymmetry in $B \to D_{cp}^{(*)} h^0$ from combined Belle and BaBar dataset was performed, which was not possible without a joint analysis. The result is consistent with the $\sin 2\phi_1$ measurement in the $b \to c\bar{c}s$ process, and with a reduced error from the Belle II dataset, this analysis is promising to constrain the penguin pollution in $\sin 2\phi_1$ in future. New results on $\cos 2\phi_1$ from a model-independent and time-dependent Dalitz analysis of $B \to D^{(*)}h^0$, $D \to K_S^0\pi^+\pi^-$ successfully excluded the second ϕ_1 solution by 5σ, to fill a possible hole in the successful B-factory measurements. Observation of $B^0 \to \psi(2S)\pi^0$ is a new $b \to c\bar{c}d$ mode to contribute to the future ϕ_1 measurements. Modes with h^0 will be more interesting with Belle II statistics, and may not be so easy for LHCb. But even before the Belle II data are available, Belle is still working on more analyses in preparation for ϕ_1, other CP asymmetry measurements and related hadronic B meson decays.

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