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Measurements of CKM angles at Belle

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In this review recent studies on *CP* violation and related hadronic *B* decays by the Belle experiment, in particular measurements of CKM angles ϕ_1 and ϕ_2 are reported.

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1. Introduction

In the standard model (SM) of electroweak interaction, charge-parity (CP) violation arises from an irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. The Belle and BaBar experiments have established CP violating effects in the B meson system. Both experiments use their measurements of the mixing-induced CP violation in $b \to c\bar{c}s$ transitions to precisely determine the parameter $\sin(2\phi_1)$, where ϕ_1 is defined as $\arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$, with V_{ij} is the CKM matrix element of quarks $i,\ j$. In this proceeding an overview of recent measurements of the CKM angles ϕ_1 and ϕ_2 $\left(\arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*]\right)$ is presented. Unless stated otherwise, all measurements presented here are based on Belle's final dataset of 772×10^6 $B\bar{B}$ pairs.

2. First observation of CP violation in $\bar{B}^0 \to D_{CP}^{(*)}h^0$ decays with Belle + BaBar data

The decay $\bar{B}^0 \to D^{(*)}h^0$, where h^0 is a light, unflavored neutral meson ($h^0 \in \pi^0,\ \eta,\ \omega$), is dominated by a $b \to c\bar{u}d$ color-suppressed tree diagram in the SM. The final state $D^{(*)}h^0$ is a CP eigenstate if the neutral D meson decays to a CP eigenstate as well (*i.e.*, $D_{CP}^0 \to K_S^0\pi^0$, $D_{CP}^0 \to K_S^0\omega$ ($CP = -1$) or $D_{CP}^0 \to K^+K^-$ ($CP = +1$) and $D_{CP}^* \to D_{CP}^0\pi^0$). Therefore, a time-dependent CP asymmetry measurement is applicable in the same way as used in the $b \to c\bar{c}s$ decays, but with a small correction from the $b \to u\bar{c}d$ process. This $b \to u\bar{c}d$ amplitude is suppressed by $V_{ub}V_{cd}^*/V_{cb}V_{ud}^* \approx 0.02$ relative to the leading amplitude. Neglecting the suppressed amplitude, the time evolution of $\bar{B}^0 \to D_{CP}^{(*)}h^0$ decays is governed by ϕ_1[2].

Due to the limited available statistics, previous measurements performed separately by the BaBar and Belle collaborations were not able to establish CP violation in these or related decays [3]. This motivated a joint analysis using the combined full dataset of Belle and BaBar experiments [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, we extract 508 ± 31 signal events in the BaBar data of 431 million $B\bar{B}$ events and 757 ± 44 signal events in the Belle data of 772 million $B\bar{B}$ events, as shown in Fig. 1. The dominant source of background originates from $e^+e^- \to p\bar{q}$ ($q \in u,\ d,\ s,\ c$) continuum events. To suppress this background, we use a multivariate analyzer based on a neural network. The neural network uses the so-called event shape variables to discriminate continuum events, which tend to be jetlike, from spherical $B\bar{B}$ events.

The time-dependent CP violation measurement is performed using established Belle and BaBar techniques for the vertex reconstruction, the flavor-tagging, and the modeling of Δt resolution effects, where Δt is the proper time interval between the decays of the two B mesons produced in an $\Upsilon(4S)$ decay. Combined analysis is performed by maximizing a joint log-likelihood function

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

The experiment-dependent probality density function (PDF) $\mathscr{P}^{\rm Exp}$ is defined as

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

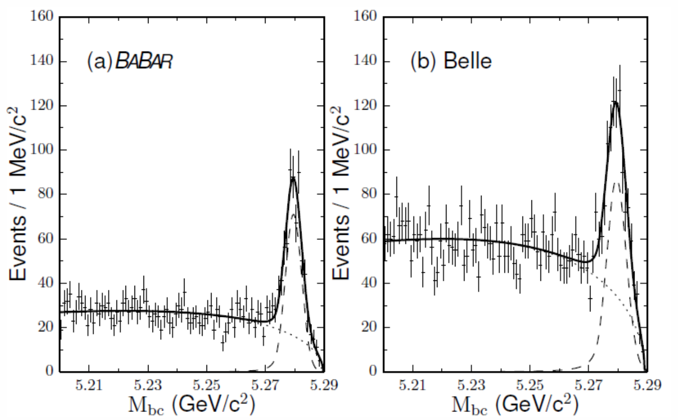

Figure 1: M_{bc} distributions (data points with error bars) and fit projections (solid lines) of $\bar{B}^0 \to D^{(*)}_{CP} h^0$ decays for (a) BaBar and (b) Belle. The dashed (dotted) lines represent projections of the signal (background) fit components.

where the index k represents the signal and background PDF components. The symbol P_k denotes the PDF describing the proper time interval of the particular physical process and R_k^{Exp} refers to the corresponding resolution function. The fractions f_k are evaluated on an event-by-event basis as a function of M_{bc}. While the background model is determined from the M_{bc} sideband and hence is experiment-dependent, the signal model is expressed as

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

where the B^0 meson lifetime is represented by τ_{B^0}, $B^0 - \bar{B}^0$ mixing frequency by Δm and q is event- and experiment-dependent tagging quality parameter. In the SM, the coefficients, $S = -\eta_f \sin(2\phi_1)$ and $A = 0$, where η_f is the CP eigenvalue of the final state. S and A quantify mixing-induced and direct CP violation, respectively. The combined fit gives

$$-\eta_f S = +0.66 \pm 0.10\,(\text{stat.}) \pm 0.06\,(\text{syst.}), \;\; A = -0.02 \pm 0.07\,(\text{stat.}) \pm 0.03\,(\text{syst.}). \tag{2.4}$$

These results correspond to the first observation of CP violation in $\bar{B}^0 \to D^{(*)}_{CP} h^0$ decays with a significance of 5.4 standard deviations and are in agreement with the value of ϕ_1 measured from $b \to c\bar{c}s$ transitions.

3. Measurement of ϕ_1 in $B^0 \to \bar{D}^{(*)0} h^0$ with time-dependent binned Dalitz plot analysis

In this analysis, we present a model-independent measurement of the angle ϕ_1 in $b \to c\bar{u}d$ transitions governing $B^0 \to \bar{D}^{(*)0} h^0$ decays, with subsequent decay $\bar{D}^0 \to K_S^0 \pi^+ \pi^-$ is not a CP eigenstate [5]. From a fit to M_{bc} and $\Delta E = E_B - E_{\text{beam}}$, where E_B is the reconstructed B mesons energy in the center-of-mass system, we extract total 962 ± 41 signal events, of which 464 ± 26 events are from $B^0 \to \bar{D}^0 \pi^0$ mode (Fig. 2), with a signal fraction $(72.1 \pm 4.1)\%$ and 182 ± 18 events from $B^0 \to \bar{D}^0 \omega$ with a fraction of $(58.4 \pm 5.7)\%$. The signal fraction of other decay modes ranges between 44% and 70%.

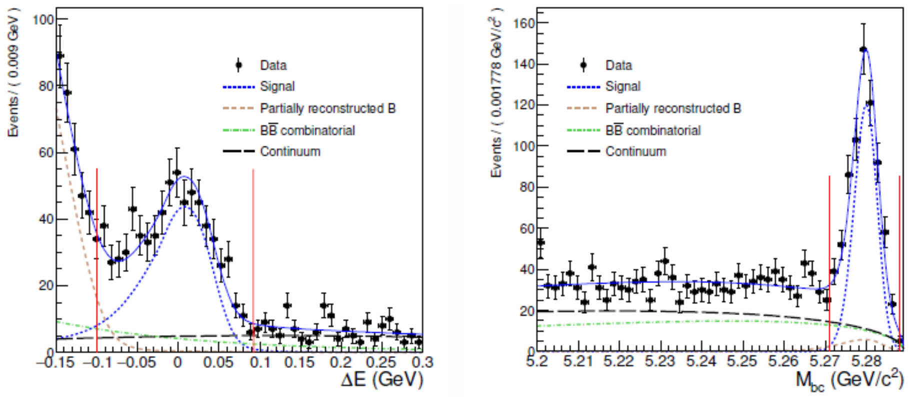

Figure 2: $M_{\rm bc}$ and ΔE distributions of $B^0 \to \bar{D}^0\pi^0$ decays.

Our measurement of ϕ_1 is based on the binned Dalitz distribution approach. This idea was proposed in Ref. [6] to measure the angle ϕ_3. Events are divided into 16 bins on the Dalitz plot plane and the number of events in bin i ($i = -8,\ldots,-1,+1,\ldots,+8$) is modeled as

$$P_i(\Delta t,\phi_1) = he^{-\frac{|\Delta t|}{\tau_B}}\Big[1+q\frac{K_i-K_{-i}}{K_i+K_{-i}}\cos(\Delta m\Delta t) + 2q\xi_{h^0}(-1)^L\frac{\sqrt{K_iK_{-i}}}{K_i+K_{-i}}\sin(\Delta m\Delta t)\big(S_i\cos(2\phi_1)+C_i\sin(2\phi_1)\big)\Big], \quad (3.1)$$

where h is the normalization constant, ξ_{h^0} is the CP eigenvalue of h^0 meson, L is the relative angular momentum in the $D^{(*)0}h^0$ system, K_i is the integrated squared amplitude, and S_i and C_i represent the weighted averages of the sine and cosine of the phase difference between $\bar{D}^0$ and D^0 decay amplitudes over the ith Dalitz plot bin. The parameters K_i can be measured with a set of flavor-tagged neutral D mesons such as $D^{*+}\to D^0\pi^+$ or $B^+\to\bar{D}^0\pi^+$ decays, by measuring signal yield in each Dalitz plot bin. The measurement of the phase parameters S_i and C_i is more complicated and can be done with coherent decays of $D^0\bar{D}^0$ pairs [7]. We obtain

$$\begin{aligned}\sin(2\phi_1) &= 0.43\pm0.27\,(\text{stat.})\pm0.08\,(\text{syst.})\\ \cos(2\phi_1) &= 1.06\pm0.33\,(\text{stat.})^{+0.21}_{-0.15}\,(\text{syst.})\\ \phi_1 &= 11.7^\circ\pm7.8^\circ\,(\text{stat.})\pm2.1^\circ\,(\text{syst.}).\end{aligned} \quad (3.2)$$

The value $\sin(2\phi_1) = 0.691\pm0.017$ measured in $b\to c\bar{c}s$ transitions determines the absolute value of $\cos(2\phi_1)$, leading two possible solutions in the $0^\circ \le \phi_1 \le 180^\circ$ range. Our measurement is inconsistent with the negative solution, corresponding to the value $\phi_1 = 68.1^\circ$ at the level of 5.1 standard deviations, but in agreement with the positive solution, corresponding to the value $\phi_1 = 21.9^\circ$ at 1.3 standard deviations.

4. First observation of the decay $B^0 \to \psi(2S)\pi^0$

Although decays mediated via $b\to c\bar{c}s$ transitions allow us to access the ϕ_1 at first order (tree), its value is prone to distortion from suppressed higher-order loop-induced (penguin) amplitudes containing different weak phases. The related $b\to c\bar{c}d$ induced decays can be used to quantify the shift in ϕ_1 caused by these loop contributions and may provide useful information about the penguin pollution [8]. Since the dominant $b \to c\bar{c}d$ tree amplitude is also suppressed, $B^0 \to J/\psi\pi^0$ is the only mode measured so far, providing $\sin(2\phi_1) = 0.65 \pm 0.21$ (stat.) ± 0.05 (syst.) by Belle [9], 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 observed previously.

The decay mode $B^0 \to \psi(2S)\pi^0$ is reconstructed with $\psi(2S) \to \ell^+\ell^-$ ($\ell = e, \mu$) or $\psi(2S) \to J/\psi(\to \ell^+\ell^-)\pi^+\pi^-$ [10]. The major background contribution originates from $b \to c\bar{c}q$ decays other than the signal. The background arises from $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) continuum events is not so problematic and is suppressed by applying a loose requirement on the ratio of second- to zeroth-order Fox-Wolfram moments. The signal is extracted from a fit to $M'_{\rm bc}$ and ΔE, where $M'_{\rm bc}$ is the modified beam-constrained mass to take into account the worse energy resolution of π^0 than rest of the particles. The fit gives 85 ± 12 signal events with a significance of 7.2 standard deviations. The branching fraction is measured to be

$$\mathscr{B}(B^0 \to \psi(2S)\pi^0) = [1.17 \pm 0.17\ (\text{stat.}) \pm 0.08\ (\text{syst.})] \times 10^{-5}. \quad (4.1)$$

This measurement constitutes the first observation of this decay and it will contribute to the future time-dependent CP asymmetry measurement of the $b \to c\bar{c}d$ process.

5. Study of $B^0 \to \rho^+\rho^-$ decays

In order to access ϕ_2, charmless decay modes that are mediated via $b \to u\bar{u}d$ transitions are necessary. Examples are the decays $B \to \pi\pi$, $\rho\pi$, $\rho\rho$. At tree level, one expects $A = 0$ and $S = \sin(2\phi_2)$. Possible penguin contributions can give rise of direct CP violation, $A \neq 0$ and also pollute the measurement of ϕ_2, $S = \sqrt{1-A^2}\sin(2\phi_2^{\rm eff})$, where the observed $\phi_2^{\rm eff} = \phi_2 - \Delta\phi_2$ is shifted by $\Delta\phi_2$ due to different weak and strong phases from additional non-leading contributions. This inconvience can be overcome by estimating $\Delta\phi_2$ using either an isospin analysis [11] or $SU(3)$ flavor symmetry [12]. In this analysis, we present a measurement of the branching fraction and the longitudinal polarization fraction of $B^0 \to \rho^+\rho^-$ decays, as well as the time-dependent CP violating parameters [13].

In addition to combinatorial background, the presence of multiple background components with the same four-pion final state as $B^0 \to \rho^+\rho^-$ make this decay quite difficult to isolate and interferences between the various four-pion modes need to be considered. A multi-dimensional maximum likelihood fit is performed. The fit uses the variables ΔE, $M_{\rm bc}$, the masses and helicity angles (angle between one of the daughter of $\rho^\pm$ meson and the B flight direction in the corresponding rest frame of the $\rho^\pm$.) of the two reconstructed $\rho^\pm$ mesons to separate longitudinally polarized states from transversely polarized states, a fisher discriminant to separate the jet-like continuum events from the spherical $B\bar{B}$ decays and the Δt distribution for the two flavors of $B_{\rm tag}$. We obtain the branching fraction

$$\mathscr{B}(B^0 \to \rho^+\rho^-) = [28.3 \pm 1.5\ (\text{stat.}) \pm 1.5\ (\text{syst.})] \times 10^{-6}, \quad (5.1)$$

the fraction of longitudinal polarization

$$f_L = 0.988 \pm 0.012\ (\text{stat.}) \pm 0.023\ (\text{syst.}), \quad (5.2)$$

and the *CP* violating parameters

$$S = -0.13 \pm 0.15\,(\text{stat.}) \pm 0.05\,(\text{syst.}), \;\; A = 0.00 \pm 0.10\,(\text{stat.}) \pm 0.06\,(\text{syst.}). \quad (5.3)$$

These results together with the other Belle measurements [14] are used to perform an isospin analysis to constrain the CKM angle ϕ_2 and obtain two solutions with $\phi_2 = (93.7 \pm 10.6)^\circ$ being most compatible with other SM based fits to the data. The size of the penguin pollution is consistent with zero: $\Delta\phi_2 = (0.0 \pm 9.6)^\circ$. Figure 3 shows the ϕ_2 can from the isospin analysis.

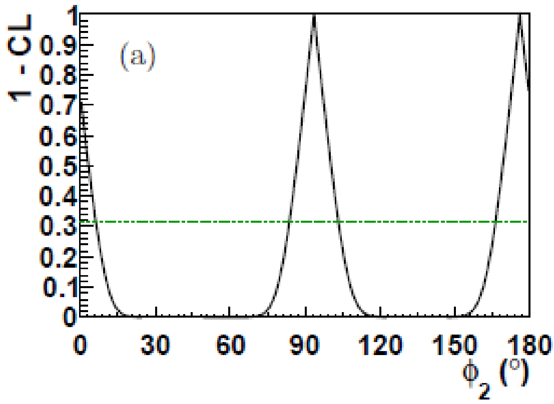

Figure 3: Probability scan of ϕ_2 in the $B \to \rho\rho$ system. The horizontal line shows the 68% confidence level.

6. Summary

The first observation of *CP* violation in $\bar{B}^0 \to D^{(*)}_{CP} h^0$ decays from a combined analysis of Belle and BaBar dataset is presented. The result is consistent with the value of $\sin(2\phi_1)$ measured in the $b \to c\bar{c}s$ process. Using a similar process, $B^0 \to \bar{D}^{(*)0} h^0$ with $\bar{D}^0 \to K^0_S \pi^+\pi^-$, a model-independent time-dependent Dalitz plot analysis is performed and excludes the second ϕ_1 solution by 5.1 standard deviations. Observation of $B^0 \to \psi(2S)\pi^0$ is presented, which will contribute to the ϕ_1 measurement in future. And finally ϕ_2 measurement from $B \to \rho\rho$ decays is presented.

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