Measurements of the CKM angle ϕ_1/β from Belle and BaBar

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We report recent measurements of the CKM angle ϕ_1/β using large data samples collected by the Belle and BaBar experiments at the e^+e^- asymmetric-energy colliders.

I. INTRODUCTION

In the Standard Model (SM), the irreducible complex phase in the Cabbibo-Kobayashi-Maskawa (CKM) quark-mixing matrix gives rise to CP violation [1]. Measurements of the time-dependent CP-asymmetry amplitudes in final states accessible by both B^0 and $\overline{B}^0$ decays probe $\sin 2\phi_1$, where $\phi_1 = \beta = \arg[V_{cd}V_{cb}^*]/[V_{td}V_{tb}^*]$ is one of the unitary triangle angles. The phase difference $2\phi_1$ between decays with and without $B^0-\overline{B}^0$ mixing arises from box diagrams which mainly occur through a virtual top quark. An exclusive measurement of $\sin 2\phi_1$ is possible when no non-trivial relative weak phases appears in the decay mechanism.

In this article we report measurements obtained by the Belle and BaBar experiments at the asymmetric-energy e^+e^- B factories KEKB [2] and PEP-II [3]. Both accelerators operate at the $\Upsilon(4S)$ resonance, which is produced with a Lorentz boost of 0.43 at KEKB and 0.56 at PEP-II. At the time of writing Belle and BaBar collected more than $790\,\mathrm{fb}^{-1}$ and $550\,\mathrm{fb}^{-1}$ respectively, which corresponds to a total of approximately 1.4 billion $B\overline{B}$ events.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of Aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF) and an electromagnetic calorimeter (ECL) comprised of CsI (Ti) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). A detailed description of the Belle detector can be found elsewhere [4].

The momenta of charged particles are measured by the BaBar detector with a tracking system consisting of a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) surrounded by a 1.5 T solenoidal magnet. An electromagnetic calorimeter (EMC) comprising 6580 CsI(Tl) crystals is used to measure photon energies and positions. Charged hadrons are identified with a detector of internally reflected Cherenkov light (DIRC) and ionization measurements in the tracking detectors. The BaBar detector is described in detail elsewhere [5].

II. ANALYSIS TECHNIQUE

To measure time-dependent CP asymmetries we typically fully reconstruct a neutral B meson decaying into a CP eigenstate. From the remaining particles in the event, the vertex of the other B meson, $B_{\rm tag}$, is reconstructed and its flavor is identified (tagging). When assuming CP conservation in $B^0\overline{B}^0$ mixing and $\Delta\Gamma/\Gamma = 0$, the time-dependent decay rate of the neutral B meson to the CP eigenstate is given by:

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\Big\{1 + q\Big[\mathcal{S}\sin(\Delta m_d \Delta t) + \mathcal{A}\cos(\Delta m_d\Delta t)\Big]\Big\}, \quad (1)$$

where $q = +1(-1)$ when the other B meson in the event decay is a B^0 ($\overline{B}^0$), $\Delta t = t_{CP} - t_{\rm tag}$ is the proper time difference between the two decays. τ_{B^0} is the neutral B lifetime, Δm_d the mass difference between the two B^0 mass eigenstates and $\mathcal{S}$ and $\mathcal{A}$ are the CP-violating parameters

$$\mathcal{S} = \frac{2Im(\lambda)}{|\lambda|^2+1}, \quad \mathcal{A} = \frac{|\lambda|^2-1}{|\lambda|^2+1},$$

where λ is a complex parameter depending on the $B^0-\overline{B}^0$ mixing as well as on the decay amplitudes for both B^0 and $\overline{B}^0$ to the CP eigenstate. Note that in the BaBar convention $\mathcal{A} = -\mathcal{C}$.

When only one diagram contributes to the decay process and no other weak or strong phases appear in the process, the SM predicts $\mathcal{A} = 0$ and $\mathcal{S} = -\eta\sin 2\phi_1$ where η is the CP eigenvalue of the final state. A non-zero value for $\mathcal{A}$ would indicate a direct-CP violation. Any large measured deviation with respect to the prediction can be a sign of New Physics. However when other diagrams with different weak phases appear in the interaction, the experimental result of $\mathcal{S}$ will not necessarily be equal to $\sin 2\phi_1$. The decays presented in this paper are expected to only have a small deviation from $\sin 2\phi_1$ in the SM.

The measurements of $\sin 2\phi_1$ reported in this paper can be grouped according to their quark transitions:

- $\boldsymbol{b \to c\overline{u}d}$ **transitions** : $B^0 \to D^{(*)0}_{CP} h^0$;

- $\boldsymbol{b \to c\overline{c}s}$ **transitions** : $B^0 \to J/\psi K^0_{\rm S}$, $B^0 \to J/\psi K^0_{\rm L}$, $B^0 \to J/\psi K^{*0}$, $B^0 \to \psi(2S)K^0_{\rm S}$, $B^0 \to \eta_c K^0_{\rm S}$ and $B^0 \to \chi_{c1} K^0_{\rm S}$;

- **$b \to c\bar{c}d$ transitions**: $B^0 \to J/\psi\pi^0$ and $B^0 \to D^{*+}D^{*-}$.

The decays are grouped from top to bottom with decreasing tree amplitude or increasing sensitivity to New Physics. Finally we will also give an overview of recent measurements of $\cos 2\phi_1$ provided by $B^0 \to D_{CP}^{(*)0}h^0$ and $B^0 \to D^{*+}D^{*-}K_S^0$ decays.

III. $B^0 \to D_{CP}^{(*)0}h^0$ $(h^0 = \pi^0, \eta, \omega)$

The decay $B^0 \to D_{CP}^{(*)0}h^0(h^0 = \pi^0, \eta, \omega)$ is governed by a color-suppressed $b \to c\bar{u}d$ tree diagram. When the neutral D meson decays to a CP eigenstate Eq. 1 holds. The next-to-leading order diagram is a doubly Cabbibo and color-suppressed tree diagram with the same quark transitions as the main diagram. Therefore the SM corrections on $\sin 2\phi_1$ are expected to be only at the percent level [6]. However, R-parity-violating super-symmetric processes could enter at the tree level and lead to a deviation from the SM prediction.

BaBar reported a measurement of $\sin 2\phi_1$ [7] by reconstructing the following decay modes $D^{*0} \to D^0\pi^0$ and $D^0 \to K^+K^-$, $D^0 \to K_S^0\pi^0$ and $D^0 \to K_S^0\omega$. The analysis is performed on 383×10^6 $B\overline{B}$ pairs of which 340 ± 32 signal events are reconstructed. The measured CP-violating parameters,

$$\sin 2\phi_1 = 0.56 \pm 0.23\,(\text{stat}) \pm 0.05\,(\text{syst})$$
$$\mathcal{A} = 0.23 \pm 0.16\,(\text{stat}) \pm 0.04\,(\text{syst}),$$

are consistent with the SM expectations.

IV. $B^0 \to c\bar{c}K^0$ TRANSITIONS

The $b \to c\bar{c}K^0$ transitions are referred to as the golden modes due to their relatively large branching fractions $\mathcal{O}(10^{-4} - 10^{-5})$, low experimental background levels and high reconstruction efficiencies. Typically a signal purity of more than 95% is obtained for $B^0 \to J/\psi(\ell^+\ell^-)K_S^0(\pi^+\pi^-)$ decays. Furthermore the theoretical uncertainties are small [8]. These modes are dominated by a color-suppressed $b \to c\bar{c}s$ tree diagram and the dominant penguin diagram has the same weak phase. The highest order term with a different weak phase is a Cabibbo-suppressed penguin contribution. Therefore the prediction $\mathcal{S} = -\sin 2\phi_1$ and $\mathcal{A} = 0$ is valid to a good accuracy. Recent theoretical calculations suggest that the correction on $\mathcal{S}$ is of the order of 10^{-3}–10^{-4} [9]. Because of the high experimental precision and the low theoretical uncertainty these modes serve as a benchmark in the SM, which means that any other measurement of $\sin 2\phi_1$ that has a significant deviation, beyond the usual small SM corrections, indicates evidence for New Physics.

Both BaBar [10] and Belle [11] studied CP violation in these decays. Belle reconstructed around 7500 signal events in the $B^0 \to J/\psi K_S^0$ channel and 6500 signal events in the $B^0 \to J/\psi K_L^0$ channel using 535×10^6 $B\overline{B}$ pairs. BaBar reconstructed additional modes such as $J/\psi K^{*0}$, $\psi(2S)K_S^0$, $\eta_c K_S^0$ and $\chi_{c1}K_S^0$. Using a data sample of 383×10^6 $B\overline{B}$ pairs BaBar reconstructed approximately 6900 CP-odd signal events and 3700 CP-even signal events.

The results of the time-dependent CP analysis are shown in Table I including the BaBar result using only the $J/\psi K^0$ modes, to provide a direct comparison with Belle. The measurements of the two experiments agree well within the statistical uncertainties.

Belle recently reported also a measurement of the CP-violation parameters in the $B^0 \to \psi(2S)K_S^0$ channel [12]. Using a sample of 657×10^6 $B\overline{B}$ pairs, 1284 ± 38 signal events are reconstructed. The measured CP-violating parameters are included in Table I.

TABLE I: CP-violating parameters measured by Belle and BaBar with the golden modes, the errors are statistical only.

	$\sin 2\phi_1$	$\mathcal{A}$
BaBar $J/\psi K^0$	0.697 ± 0.035	-0.035 ± 0.025
BaBar all $c\bar{c}s$	0.714 ± 0.032	-0.049 ± 0.022
Belle $J/\psi K^0$	0.642 ± 0.031	0.018 ± 0.021
Belle $\psi(2S)K_S^0$	0.72 ± 0.09	0.04 ± 0.07

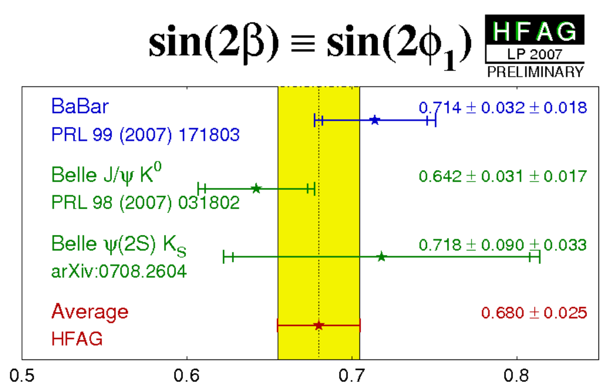

FIG. 1: Comparison between the Belle and BaBar measurements of $\sin 2\phi_1$ with $b \to c\bar{c}s$ decays. The bottom line shows the world average.

Figure 1 summarizes the results of $\sin 2\phi_1$ for $b \to c\bar{c}s$ decays from Belle and BaBar. A world average is calculated by the Heavy Flavor Averaging Group (HFAG) [13],

$$\sin 2\phi_1 = 0.680 \pm 0.025,$$

which reduces the total uncertainty on $\sin 2\phi_1$ to 3.7%.

BaBar also analyzed the CP-odd fraction of $b \to c\bar{c}s$ decays containing two vector particles. The CP eigenstate of these decays can be $+1$ or -1 depending on the total angular momentum. To disentangle the CP-odd fraction a three-dimensional angular analysis is performed on 232×10^6 $B\overline{B}$ events [14]. The extracted CP-odd fractions are shown in Table II. The result of $B \to J/\psi K^*$ is within two standard deviations consistent with CP-odd fraction measured at the Belle using 277×10^6 $B\overline{B}$ pairs The CP-odd fraction for the neutral B decay reads $0.195 \pm 0.012\,(\mathrm{stat}) \pm 0.008\,(\mathrm{syst})$ and for the charged B decays $0.180 \pm 0.014\,(\mathrm{stat}) \pm 0.010\,(\mathrm{syst})$ [15].

TABLE II: CP-odd fractions of three vector-vector $b \to c\bar{c}s$ decay modes, measured by BaBar. The first error mentioned is statistical, the second is systematic.

Decay	CP-odd fraction
$B \to J/\psi K^*$	$0.233 \pm 0.010 \pm 0.005$
$B \to \psi(2S)K^*$	$0.30 \pm 0.06 \pm 0.02$
$B \to \chi_{c1}K^*$	$0.03 \pm 0.04 \pm 0.02$

V. $B^0 \to J/\psi\pi^0$

The $B^0 \to J/\psi\pi^0$ decay takes place through a $b \to c\bar{c}d$ transition. The dominant tree diagram is Cabibbo suppressed but contrary to the golden modes, the dominant penguin diagram is of the same order as the tree diagram and has a different weak phase. Therefore, even within the SM, the deviation in $\sin 2\phi_1$ could be substantial.

Both Belle [16] and BaBar [17] have updated their CP-violation measurements in this decay. Belle performed an analysis on 535×10^6 $B\overline{B}$ pairs and obtained 290 events in the signal region, while BaBar used 466×10^6 $B\overline{B}$ pairs and obtained 184 signal events. The plots in Figure 2 show the proper time distribution and the raw asymmetry, defined as $(N_+ - N_-)/(N_+ + N_-)$, where $N_+(N_-)$ is the number of observed neutral B candidates with $q = +1(-1)$. Within the experimental uncertainties, the results are compatible with the SM prediction. The measured CP parameters are summarized in Table III. The BaBar result shows an evidence of CP violation, obtained with a 4σ significance.

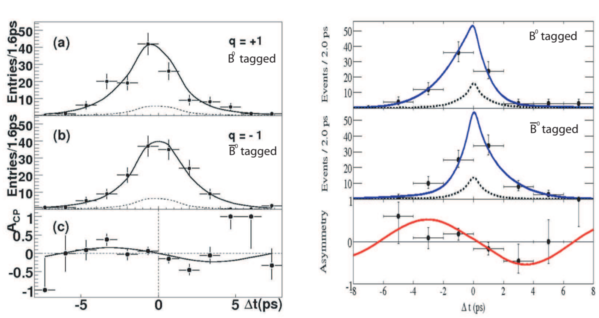

FIG. 2: The proper time distribution for tagged B^0 ($\overline{B}^0$) candidates and the raw asymmetry of $B^0 \to J/\psi\pi^0$ as a function of Δt measured by BaBar (right) and Belle (left). The lines represent the fit results.

TABLE III: CP-violating parameters in the $B^0 \to J/\psi\pi^0$ decay measured by Belle and BaBar. The first error mentioned is the statistical, the second is systematic.

	Belle	BaBar
$\sin 2\phi_1$	$0.65 \pm 0.21 \pm 0.05$	$1.23 \pm 0.21 \pm 0.04$
$\mathcal{A}$	$0.08 \pm 0.16 \pm 0.05$	$0.20 \pm 0.19 \pm 0.03$

VI. $B^0 \to D^{*+}D^{*-}$

The measurements of the double charm decay $B^0 \to D^{*+}D^{*-}$ are updated by both experiments [18] and the high statistics signals are shown in the left plots of Figure 3. The Belle analysis is performed on 657×10^6 $B\overline{B}$ pairs and has extracted 545 ± 29 signal events while the BaBar analysis found 638 ± 38 signal events in 383×10^6 $B\overline{B}$ pairs The tree amplitude is CKM-suppressed and the contribution of penguin diagrams in this decay is estimated to be at the percent level [19]. The CP eigenvalue of the

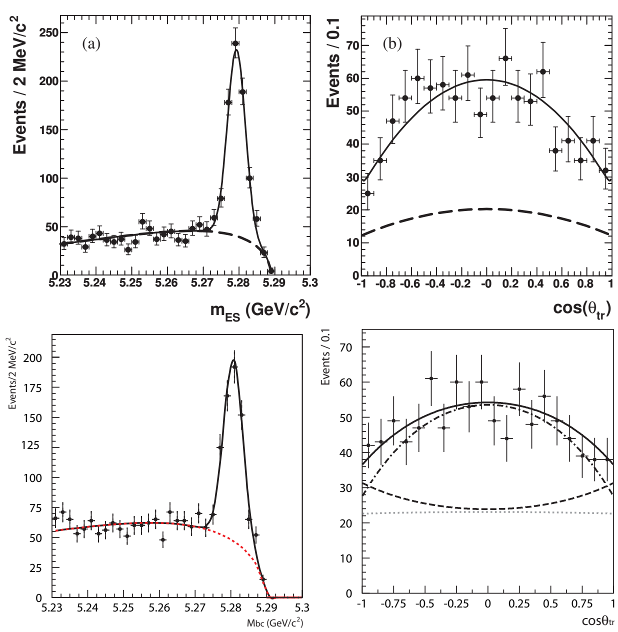

FIG. 3: The measured M_{bc} and $\cos\theta_{\mathrm{tr}}$ distributions in the signal region for BaBar (top) and Belle (bottom). The solid lines represent the projections of the fit results, the dotted lines are the background components.

$D^{*+}D^{*-}$ pair is $+1$ when it decays via a S and D wave or -1 for a P wave. A helicity study is performed to extract the CP-odd fraction, $R_{\rm odd}$, which dilutes the measurement of $\mathcal{S}$. The angular analysis is performed in the so-called transversity basis and the Belle and BaBar results are shown in the right plots of Figure 3. The extracted CP-odd fraction is $R_{\rm odd} = 0.143 \pm 0.034\,(\rm stat) \pm 0.008\,(\rm syst)$ for BaBar and $R_{\rm odd} = 0.116 \pm 0.042\,(\rm stat) \pm 0.004\,(\rm syst)$ for Belle, consistent with previous measurements.

Figure 4 shows the Δt distribution and the raw asymmetry for events with a good-quality tag. The fitted CP parameters are consistent with each other and the SM predictions. BaBar found $\mathcal{A} = 0.02 \pm 0.11\,(\rm stat) \pm 0.02\,(\rm syst)$ and $\sin 2\phi_1 = 0.66 \pm 0.19\,(\rm stat) \pm 0.04\,(\rm syst)$ while the Belle result is: $\mathcal{A} = 0.16 \pm 0.13\,(\rm stat) \pm 0.02\,(\rm syst)$ and $\sin 2\phi_1 = 0.93 \pm 0.24\,(\rm stat) \pm 0.15\,(\rm syst)$.

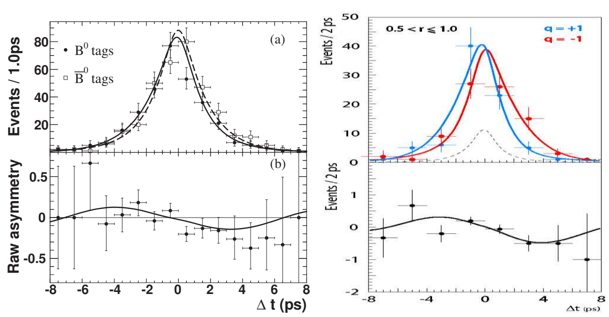

FIG. 4: Top: the Δt distributions of $B^0 \to D^{*+}D^{*-}$ events in the signal region for B^0 $(\overline{B}^0)$ tagged candidates. Bottom: the raw asymmetry as a function of Δt. The lines represent the fit result. The plots on the left show the BaBar result while the plots on the right are the Belle results.

VII. MEASUREMENT OF $\cos 2\phi_1$

The measurements of $\sin 2\phi_1$ leaves a 4-fold ambiguity in the value of ϕ_1 which can be partially resolved by measuring $\cos 2\phi_1$. We will show two analyzes in this section that measured the sign $\cos 2\phi_1$.

In the first analysis both B^0 and $\overline{B}^0$ mesons decay to the final state $D^{*+}D^{*-}K^0_{\rm S}$. A potential interference effect of the decay proceeding though an intermediate resonance can be measured by dividing the B-decay Dalitz plot into regions with $s^+ > (<)\, s^-$, where $s^\pm \equiv m^2(D^{*\pm}K^0_{\rm S})$ [20]. Belle performed a measurement on $449 \times 10^6\, B\overline{B}$ pairs which corresponds to $131.2^{+14.8}_{-14.1}$ extracted signal events and measured $2J_{s2}/J_0 \cos\phi_1 = -0.23^{+0.43}_{-0.41}\,(\rm stat) \pm 0.13\,(\rm syst)$ [21], where J_{s2} and J_0 are the integrals over the half-Dalitz space, $s^- > s^+$ of $|a|^2 - |\overline{a}|^2$ and the imaginary component, $Im(\overline{a}a^*)$ respectively, where $a(\overline{a})$ are the decay amplitudes of $B^0(\overline{B}^0) \to D^{*+}D^{*-}K_{S^0}$. Although the sign of the factor $2J_{s2}/J_0$ can be deduced from theory, a model-independent sign of $\cos 2\phi_1$ could not be obtained given the errors. A similar analysis is also performed by BaBar on $230 \times 10^6\, B\overline{B}$ pairs and concluded $\cos 2\phi_1 > 0$ with 94% confidence level [22].

A second technique to determine the sign of $\cos 2\phi_1$ utilizes the decay $B^0 \to D^*(\pi^+\pi^-K^0_{\rm S})h^0$, where $h^0 = \eta, \eta', \pi^0$ or ω. This decay can occur with and without $B^0\overline{B}^0$ mixing and interference effects are visible across the D^0 Dalitz plot. Belle performed this analysis on $386 \times 10^6\, B\overline{B}$ events [23] and the fit of the full Dalitz plot gives $\sin 2\phi_1 = 0.78 \pm 0.44\,(\rm stat) \pm 0.22(\rm syst + model)$ and $\cos 2\phi_1 = 1.87^{+0.40}_{-0.53}\,(\rm stat)^{+0.22}_{-0.32}\,(\rm syst + model)$, which gives a preferred positive sign of $\cos 2\phi_1$ at 96.8% confidence level. The result from BaBar [24] on $383 \times 10^6\, B\overline{B}$ events reads $\sin 2\phi_1 = 0.29 \pm 0.34\,(\rm stat) \pm 0.03\,\rm rm(syst) \pm 0.05\,(\rm model)$ and $\cos 2\phi_1 = 0.42 \pm 0.49\,(\rm stat) \pm 0.09\,(\rm syst) \pm 0.13\,(\rm model)$ leading to a preferred positive sign for $\cos 2\phi_1$ at 86% confidence level.

VIII. CONCLUSIONS

Various decay modes have been used by Belle and BaBar to measure $\sin 2\phi_1$ using high statistics $B\overline{B}$ samples. The two experiments have also performed measurements of the sign of $\cos 2\phi_1$, which is preferred to be positive. The measurements of the CP-violating parameters in the $b \to c\overline{c}s$ channels are the most precise results available and given the positive sign of $\cos 2\phi_1$, the world average gives $\phi_1 = 21.5^o \pm 1.0^o$ and $\phi_1 = 201.5^o \pm 1.0^o$, where the first is conform with the Standard Model. Finally, the new results of B decays to $D^{(*)0}_{CP}h^0$ $(h^0 = \pi^0, \eta, \omega)$, $J/\psi\pi^0$ and $D^{*+}D^{*-}$ are shown. The CP violating parameters are consistent with the Standard Model expectations within the uncertainties of the measurement.

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