Combined CP Violation Measurements by the *BABAR* and Belle Collaborations

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Summary. — We present a measurement of the time-dependent CP violation of $\overline{B}^0 \to D_{CP}^{(*)} h^0$ decays, where the light neutral hadron h^0 is a π^0, η or ω meson, and the neutral D meson decays to the two-body CP eigenstates K^+K^-, $K_S^0\pi^0$ or $K_S^0\omega$. The measurement is performed by combining the final data sets of $(471 \pm 3) \times 10^6$ $B\overline{B}$ pairs collected by the *BABAR* experiment and $(772 \pm 11) \times 10^6$ $B\overline{B}$ pairs by the Belle experiment in a single physics analysis. In this first measurement performed on a data sample of more than $1\,\mathrm{ab}^{-1}$, we report a first observation of CP violation in $\overline{B}^0 \to D_{CP}^{(*)} h^0$ decays governed by mixing-induced CP violation according to the weak phase β. We measure the CP asymmetry parameters $-\eta_f \mathcal{S} = +0.66 \pm 0.10\,(\mathrm{stat.}) \pm 0.06\,(\mathrm{syst.})$ and $\mathcal{C} = -0.02 \pm 0.07\,(\mathrm{stat.}) \pm 0.03\,(\mathrm{syst.})$.

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PACS `13.25` – Hw.

In the Standard Model, the only source of CP violation is an irreducible complex phase in the three-family Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1, 2]. The B factory experiments *BABAR* at SLAC in the US and Belle at KEK in Japan established CP violation in the neutral and charged B meson system [3, 4, 5, 6]. Both experiments precisely measured the angle β of the Unitarity Triangle, defined by the CKM matrix elements V_{ij} as $\arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$, using the time-dependent CP violation in $b \to c\bar{c}s$ transitions [7, 8]. The current world average is $\sin(2\beta) = 0.68 \pm 0.02$ [9]. The time-dependent CP violation of $b \to c\bar{c}s$ transitions is associated with theoretical uncertainties due to possible penguin contributions.

A complementary and theoretically clean probe for β is provided by $\overline{B}^0 \to D^{(*)}h^0$ decays, where $h^0 \in \{\pi^0, \eta, \omega\}$ denotes a light neutral hadron. These decays are mediated only by tree-level amplitudes that are dominated by CKM-favored $b \to c\bar{u}d$ transitions. In $\overline{B}^0 \to D^{(*)}h^0$ decays, an interference between the decay amplitudes with and without B^0-$\overline{B}^0$ oscillations emerges if the neutral D meson decays to a CP eigenstate D_{CP}. In

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this case, the time evolution of $\overline{B}^0 \to D^{(*)}_{CP}h^0$ decays is governed only by the weak phase β [10]. The measurement of the time-dependent *CP* violation of $\overline{B}^0 \to D^{(*)}_{CP}h^0$ decays allows for a determination of β that is theoretically more clean than using $b \to c\bar{c}s$ transitions, and can provide a new gold standard reference for the new physics searches in the mixing-induced *CP* violation of $b \to s$ penguin-mediated B meson decays. Any sizable deviation in the *CP* violation of $\overline{B}^0 \to D^{(*)}_{CP}h^0$ decays from $b \to s$ penguin transitions would point to physics beyond the Standard Model which could be caused, for example, by unobserved heavy particles or additional *CP* violating phases contributing to loop diagrams in $b \to s$ penguin transitions [11].

However, the measurements of $\overline{B}^0 \to D^{(*)}h^0$ decays are experimentally challenging because of low B and D meson branching fractions ($\mathcal{O}(10^{-4})$ and $\mathcal{O}(\leq 10^{-2})$, respectively), low reconstruction efficiencies, and large backgrounds. Previous measurements carried out separately by the BABAR and Belle collaborations using two-body [12] and three-body D meson decays [13, 14] were not sensitive enough to establish *CP* violation in $\overline{B}^0 \to D^{(*)}h^0$ decays.

In this article, we present a time-dependent *CP* violation measurement of $\overline{B}^0 \to D^{(*)}_{CP}h^0$ decays. In this measurement, we combine for the first time the large final data sets of $(471\pm3)\times10^6$ $B\overline{B}$ pairs collected by the BABAR experiment and $(772\pm11)\times10^6$ $B\overline{B}$ pairs by the Belle experiment in a single physics analysis. The novel approach increases the achievable experimental precision and enables time-dependent *CP* violation measurements in the neutral B meson system with unprecedented sensitivity.

TABLE I. – *Summary of $\overline{B}^0 \to D^{(*)}_{CP}h^0$ signal yields.*

Decay mode	BABAR	Belle
$\overline{B}^0 \to D_{CP}\pi^0$	241 ± 22	345 ± 25
$\overline{B}^0 \to D_{CP}\eta$	106 ± 14	148 ± 18
$\overline{B}^0 \to D_{CP}\omega$	66 ± 10	151 ± 17
$\overline{B}^0 \to D^*_{CP}\pi^0$	72 ± 12	80 ± 14
$\overline{B}^0 \to D^*_{CP}\eta$	39 ± 8	39 ± 10
$\overline{B}^0 \to D^{(*)}_{CP}h^0$ total	508 ± 31	757 ± 44

In $\overline{B}^0 \to D^{(*)}_{CP}h^0$ decays, the light neutral hadron h^0 is reconstructed as a π^0, η or ω meson and the neutral D meson is reconstructed in the decays to two-body *CP* eigenstates K^+K^-, $K^0_S\pi^0$ and $K^0_S\omega$. D^{*0} mesons are reconstructed in the decays to $D^0\pi^0$. In the measurement, twelve final states are reconstructed in total, among them seven (five) *CP*-even (*CP*-odd) states. Continuum $e^+e^- \to q\overline{q}$ ($q \in \{u, d, s, c\}$) events are the dominant source of background. This background is reduced by selection requirements on multivariate classifiers provided by neural networks trained on variables characterizing the event shapes. The $\overline{B}^0 \to D^{(*)}_{CP}h^0$ signal yields are estimated by unbinned maximum likelihood fits to the beam-constrained mass defined as $M_{\rm bc} \equiv \sqrt{(E^*_{\rm beam}/c^2)^2 - (p^*_B/c)^2}$, where $E^*_{\rm beam}$ is the energy of the beam and p^*_B is the momentum of reconstructed B

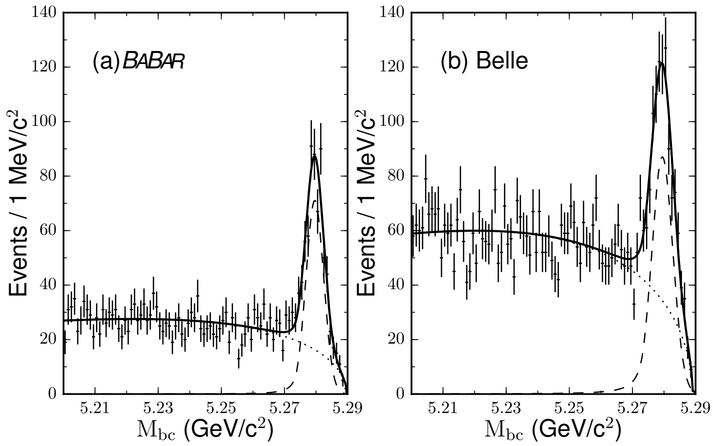

Fig. 1. – The M_{bc} data distributions (data points with error bars) and projections of the fits (solid line) of $\overline{B}^0 \to D_{CP}^{(*)} h^0$ decays for (a) BABAR and (b) Belle. The dashed and dotted lines represent projections of the signal and background components of the fits, respectively.

meson candidates in the e^+e^- center-of-mass frame. A signal yield of 508 ± 31 (757 ± 44) events is obtained for BABAR (Belle). The signal yields split into decay modes and experiments are summarized in Table I. The M_{bc} data distributions and projections of the fits are shown in Figure 1.

The time-dependent *CP* violation analysis is performed by combining the BABAR and Belle flavor-tagged proper decay time distributions on the likelihood level. In the measurement, the following log-likelihood function is maximized:

$$\ln \mathcal{L} = \sum_i \ln \mathcal{P}_i^{\mathrm{BABAR}} + \sum_j \ln \mathcal{P}_j^{\mathrm{Belle}} \tag{1}$$

The indices i and j denote events reconstructed from BABAR and Belle data, respectively. The probability density functions for signal are constructed from the convolution of experiment-specific resolution functions accounting for the finite B meson vertex resolution with the decay rate of a neutral B meson decaying to a *CP* eigenstate, defined as

$$g(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \{1 + q[\mathcal{S} \sin(\Delta m_d \Delta t) - \mathcal{C} \cos(\Delta m_d \Delta t)]\}, \tag{2}$$

where Δt is the the proper time interval between the decays of the two B mesons produced in an $\Upsilon(4S)$ decay, and $\mathcal{S}$ and $\mathcal{C}$, respectively, measure mixing-induced and direct *CP* violation. The $q = +1\,(-1)$ denotes the b-flavor content when the accompanying B meson is tagged as a B^0 ($\overline{B}^0$) meson. The neutral B meson lifetime is represented by τ_{B^0}, and the B^0-$\overline{B}^0$ mixing frequency by Δm_d. The experimental flavor-tagged proper decay time distributions for BABAR and Belle for the *CP*-even and *CP*-odd final states and projections of the fit are shown in Fig. 2.

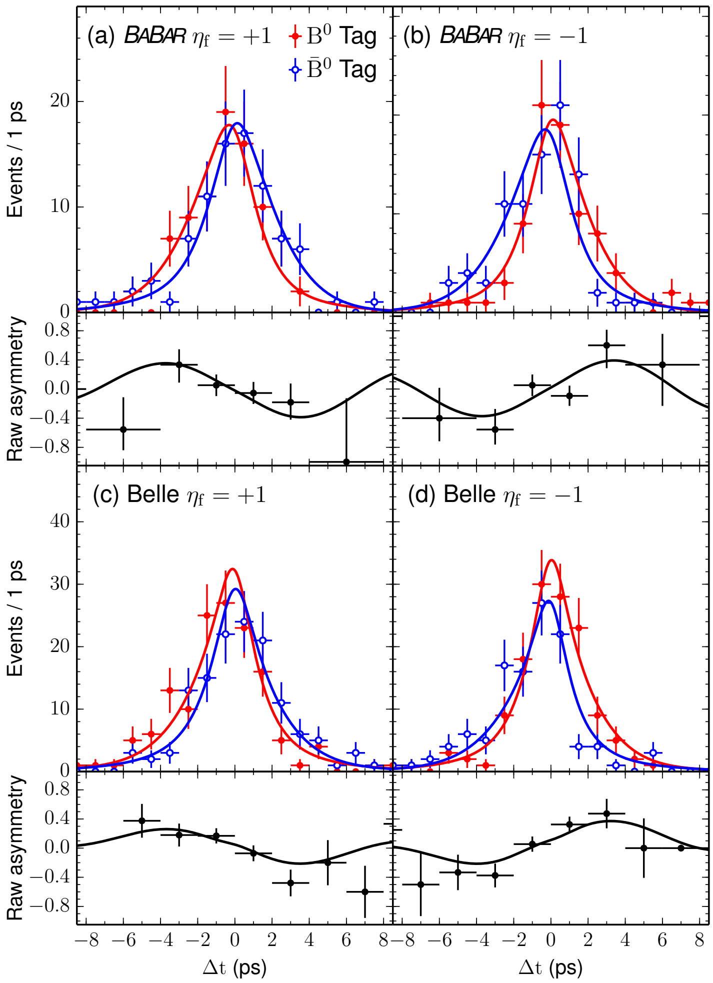

Fig. 2. – The proper time interval distributions of $\overline{B}^0 \to D^{(*)}_{CP} h^0$ decays (data points with error bars) for B^0 tags (red) and $\overline{B}^0$ tags (blue) and the corresponding CP violating asymmetries for (a)-(b) BABAR and (c)-(d) Belle for candidates associated with high quality flavor tags.

The result of the measurement including statistical and systematic uncertainties is

$$\begin{aligned} -\eta_{f_{CP}} \mathcal{S} &= +0.66 \pm 0.10\,(\text{stat.}) \pm 0.06\,(\text{syst.}) \\ \mathcal{C} &= -0.02 \pm 0.07\,(\text{stat.}) \pm 0.03\,(\text{syst.}), \end{aligned} \tag{3}$$

where $\eta_{f_{CP}}$ is the CP eigenvalue of the final state. The individual sources contributing to the systematic uncertainties are summarized in Table II.

The statistical significance of the result is estimated by a likelihood-ratio approach. Including systematic uncertainties, the measurement excludes the hypothesis of no mixing-induced CP violation in $\overline{B}^0 \to D^{(*)}_{CP} h^0$ decays at a confidence level of $1 - 6.6 \times 10^{-8}$. This

TABLE II. – *Systematic uncertainties of the measured time-dependent CP violation parameters of* $\bar{B}^0 \to D^{(*)}_{CP} h^0$ *decays (in units of* 10^{-2}*).*

Source	$\mathcal{S}$	$\mathcal{C}$
Background Δt PDFs	0.4	0.1
Δt resolution functions	2.0	0.4
Flavor-tagging	0.3	0.3
Peaking background	4.9	0.9
Physics parameters	0.2	< 0.1
Possible fit bias	0.6	0.8
Signal purity	0.6	0.3
Tag-side interference	0.1	1.4
Vertex reconstruction	1.5	1.4
Total	5.6	2.5

corresponds to a significance of 5.4 standard deviations, establishing an observation of *CP* violation in $\bar{B}^0 \to D^{(*)}_{CP} h^0$ decays for the first time. The result agrees well with the Standard Model prediction of $\mathcal{S} = -\eta_{f_{CP}} \sin(2\beta)$ and $\mathcal{C} = 0$. The measured mixing-induced *CP* violation is compatible with the current world average of $\sin(2\beta) = 0.68 \pm 0.02$ [9] within 0.2 standard deviations.

In summary, we combine for the first time the final data sets of the BaBar and Belle experiments in a single physics analysis to measure the time-dependent *CP* violation of $\bar{B}^0 \to D^{(*)}_{CP} h^0$ decays. In this first measurement performed on a data sample of more than $1\,\mathrm{ab}^{-1}$, we observe for the first time *CP* violation in $\bar{B}^0 \to D^{(*)}_{CP} h^0$ decays driven by mixing-induced *CP* violation, and we measure $\sin(2\beta) = 0.66 \pm 0.10\,(\mathrm{stat.}) \pm 0.06\,(\mathrm{syst.})$. The result is consistent within 0.2 standard deviations with the more precise world average of $\sin(2\beta) = 0.68 \pm 0.02$ [9] measured from $b \to c\bar{c}s$ transitions. At the expected precision of the upcoming high-luminosity B factory experiment Belle II, $\bar{B}^0 \to D^{(*)}_{CP} h^0$ decays will provide a new new gold standard reference for the new physics searches in the mixing-induced *CP* violation of $b \to s$ penguin-mediated B meson decays.

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