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# First Observation of CP Violation in $\bar{B}^0 \rightarrow D^{(*)}CP h^0$ Decays by a Combined Time-Dependent Analysis of BABAR and Belle Data

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# First Observation of $CP$ Violation in $\bar{B}^0 \rightarrow D_{CP}^{(*)}h^0$ Decays by a Combined Time-Dependent Analysis of $BABAR$ and Belle Data

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We report a measurement of the time-dependent  $CP$  asymmetry of  $\bar{B}^0 \rightarrow D_{CP}^{(*)} h^0$  decays, where the light neutral hadron  $h^0$  is a  $\pi^0$ ,  $\eta$  or  $\omega$  meson, and the neutral  $D$  meson is reconstructed in the  $CP$  eigenstates  $K^+ K^-$ ,  $K_S^0 \pi^0$  or  $K_L^0 \omega$ . The measurement is performed combining the final data

samples collected at the  $\Upsilon(4S)$  resonance by the *BABAR* and Belle experiments at the asymmetric-energy  $B$  factories PEP-II at SLAC and KEKB at KEK, respectively. The data samples contain  $(471 \pm 3) \times 10^6 B\bar{B}$  pairs recorded by the *BABAR* detector and  $(772 \pm 11) \times 10^6 B\bar{B}$  pairs recorded by the Belle detector. We measure the  $CP$  asymmetry parameters  $-\eta_f \mathcal{S} = +0.66 \pm 0.10$  (stat.)  $\pm 0.06$  (syst.) and  $\mathcal{C} = -0.02 \pm 0.07$  (stat.)  $\pm 0.03$  (syst.). These results correspond to the first observation of  $CP$  violation in  $\bar{B}^0 \rightarrow D_{CP}^{(*)} h^0$  decays. The hypothesis of no mixing-induced  $CP$  violation is excluded in these decays at the level of 5.4 standard deviations.

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In the standard model (SM) of electroweak interactions,  $CP$  violation arises from an irreducible complex phase in the three-family Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. The *BABAR* and Belle experiments have established  $CP$  violating effects in the  $B$  meson system [2–5]. Both experiments use their measurements of the mixing-induced  $CP$  violation in  $b \rightarrow c\bar{c}s$  transitions [6, 7] to determine precisely the parameter  $\sin(2\beta) \equiv \sin(2\phi_1)$  [*BABAR* uses  $\beta$  and Belle uses  $\phi_1$ , hereinafter  $\beta$  is used]. The angle  $\beta$  is defined as  $\arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$ , where  $V_{ij}$  is the CKM matrix element of quarks  $i, j$ .

A complementary and theoretically clean approach to access  $\beta$  is provided by  $\bar{B}^0 \rightarrow D^{(*)0} h^0$  decays, where  $h^0 \in \{\pi^0, \eta, \omega\}$  denotes a light neutral hadron. These decays are dominated by CKM-favored  $b \rightarrow c\bar{u}d$  tree amplitudes. CKM-disfavored  $b \rightarrow u\bar{c}d$  amplitudes carrying different weak phases contribute also to the decays, but are suppressed by  $V_{ub}V_{cd}^*/V_{cb}V_{ud}^* \approx 0.02$  relative to the leading amplitudes. An interference between the decay amplitudes without and with  $B^0\text{-}\bar{B}^0$  mixing emerges if the neutral  $D$  meson decays to a  $CP$  eigenstate  $D_{CP}$ . Neglecting the suppressed amplitudes, the time evolution of  $\bar{B}^0 \rightarrow D_{CP}^{(*)} h^0$  decays is governed by  $\beta$  [8]. Because only tree-level amplitudes contribute to  $\bar{B}^0 \rightarrow D^{(*)0} h^0$  decays, these decays are not sensitive to most models of physics beyond the standard model (BSM). However, the measurement of the time-dependent  $CP$  violation enables testing of the measurements of  $b \rightarrow c\bar{c}s$  transitions [6, 7] and provides a SM reference for the BSM searches in the mixing-induced  $CP$  violation of  $b \rightarrow s$  penguin-mediated  $B$  meson decays [9–12]. Any sizable deviation in the  $CP$  asymmetry of  $\bar{B}^0 \rightarrow D_{CP}^{(*)} h^0$  decays from processes involving  $b \rightarrow c\bar{c}s$  or penguin-mediated  $b \rightarrow s$  transitions would point to BSM. Such deviations could for example be caused by unobserved heavy particles contributing to loop diagrams in  $b \rightarrow c\bar{c}s$  or  $b \rightarrow s$  penguin transitions [13].

An experimental difficulty in the use of  $\bar{B}^0 \rightarrow D_{CP}^{(*)} h^0$  decays arises from low  $B$  and  $D$  meson branching fractions [ $\mathcal{O}(10^{-4})$  and  $\mathcal{O}(\leq 10^{-2})$ , respectively] and low reconstruction efficiencies. Previous measurements performed separately by the *BABAR* and Belle collaborations were not able to establish  $CP$  violation in these or related decays [14–16].

In this Letter, we present a measurement of the time-

dependent  $CP$  violation in  $\bar{B}^0 \rightarrow D_{CP}^{(*)} h^0$  decays. For the first time, we combine the large final data samples collected by the *BABAR* and Belle experiments. This new approach enables time-dependent  $CP$  violation measurements in the neutral  $B$  meson system with unprecedented sensitivity.

The time-dependent rate of a neutral  $B$  meson decaying to a  $CP$  eigenstate is given by

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

where  $q = +1$  ( $-1$ ) represents the  $b$ -flavor content when the accompanying  $B$  meson is tagged as a  $B^0$  ( $\bar{B}^0$ ) and  $\Delta t$  denotes the proper time interval between the decays of the two  $B$  mesons produced in an  $\Upsilon(4S)$  decay. The neutral  $B$  meson lifetime is represented by  $\tau_{B^0}$ , and the  $B^0\text{-}\bar{B}^0$  mixing frequency by  $\Delta m_d$ . Neglecting the CKM-disfavored decay amplitudes in  $\bar{B}^0 \rightarrow D_{CP}^{(*)} h^0$  decays, the SM predicts  $\mathcal{S} = -\eta_f \sin(2\beta)$  and  $\mathcal{C} = 0$ , where  $\eta_f$  is the  $CP$  eigenvalue of the final state, and  $\mathcal{S}$  and  $\mathcal{C}$ , respectively, quantify mixing-induced and direct  $CP$  violation [17].

This analysis is based on data samples collected at the  $\Upsilon(4S)$  resonance containing  $(471 \pm 3) \times 10^6 B\bar{B}$  pairs recorded with the *BABAR* detector at the PEP-II asymmetric-energy  $e^+e^-$  (3.1 on 9 GeV) collider [18] and  $(772 \pm 11) \times 10^6 B\bar{B}$  pairs recorded with the Belle detector at the KEKB asymmetric-energy  $e^+e^-$  (3.5 on 8 GeV) collider [19]. At *BABAR* (Belle) the  $\Upsilon(4S)$  is produced with a Lorentz boost of  $\beta\gamma = 0.560$  (0.425), allowing the measurement of  $\Delta t$  from the displacement of the decay vertices of the two  $B$  mesons. The *BABAR* and Belle detectors are described in Refs. [20, 21].

Reconstructed tracks of charged particles are considered as kaon and pion candidates. Kaons are identified using the particle identification techniques described in Refs. [20, 21]. Photons are reconstructed from energy deposits in the electromagnetic calorimeters, and the energy of photon candidates is required to be at least 30 MeV. Combinations of two photons are considered as  $\pi^0$  meson candidates if the reconstructed invariant mass is between 115 and 150 MeV/ $c^2$ . Candidate  $\eta$  mesons are reconstructed in the decay modes  $\eta \rightarrow \gamma\gamma$  and  $\pi^+\pi^-\pi^0$ . The invariant mass is required to be within 20 MeV/ $c^2$  of the nominal mass [22] for  $\eta \rightarrow \gamma\gamma$  candidates, and within

10 MeV/c<sup>2</sup> for  $\eta \rightarrow \pi^+\pi^-\pi^0$  candidates. For each photon in the  $\eta \rightarrow \gamma\gamma$  decay mode a minimal energy of 50 MeV is required.

For  $\omega$  mesons the decay mode  $\omega \rightarrow \pi^+\pi^-\pi^0$  is reconstructed with invariant mass required to be within 15 MeV/c<sup>2</sup> of the nominal mass [22]. Neutral kaons are reconstructed in the decay mode  $K_S^0 \rightarrow \pi^+\pi^-$ , with invariant mass required to be within 15 MeV/c<sup>2</sup> of the nominal mass [22]. The requirements exploiting the  $K_S^0$  decay vertex displacement from the interaction point (IP) described in Refs. [15, 23] are applied. Neutral  $D$  mesons are reconstructed in the decay modes to  $CP$  eigenstates  $D_{CP} \rightarrow K^+K^-$ ,  $K_S^0\pi^0$  and  $K_S^0\omega$ . The invariant mass is required to be within 12 MeV/c<sup>2</sup> of the nominal mass [22] for  $D_{CP} \rightarrow K^+K^-$  candidates, within 25 MeV/c<sup>2</sup> for  $D_{CP} \rightarrow K_S^0\pi^0$  candidates, and within 20 MeV/c<sup>2</sup> for  $D_{CP} \rightarrow K_S^0\omega$  candidates. We reconstruct  $D^{*0}$  mesons in the decay mode  $D^{*0} \rightarrow D^0\pi^0$ , and the invariant mass must be within 3 MeV/c<sup>2</sup> of the nominal mass [22].

Neutral  $B$  mesons are reconstructed in the  $CP$ -even ( $\eta_f = +1$ ) final states  $\bar{B}^0 \rightarrow D_{CP}\pi^0$  and  $D_{CP}\eta$  (with  $D_{CP} \rightarrow K_S^0\pi^0$ ,  $K_S^0\omega$ ),  $\bar{B}^0 \rightarrow D_{CP}\omega$  (with  $D_{CP} \rightarrow K_S^0\pi^0$ ),  $\bar{B}^0 \rightarrow D_{CP}^*\pi^0$  and  $D_{CP}^*\eta$  (with  $D_{CP} \rightarrow K^+K^-$ ), and in the  $CP$ -odd ( $\eta_f = -1$ ) final states  $\bar{B}^0 \rightarrow D_{CP}\pi^0$ ,  $D_{CP}\eta$ ,  $D_{CP}\omega$  (with  $D_{CP} \rightarrow K^+K^-$ ), and  $\bar{B}^0 \rightarrow D_{CP}^*\pi^0$  and  $D_{CP}^*\eta$  (with  $D_{CP} \rightarrow K_S^0\pi^0$ ) [24].

Neutral  $B$  mesons are selected by the beam-energy-constrained mass  $M_{bc} \equiv m_{ES} = \sqrt{(E_{beam}^*/c^2)^2 - (p_B^*/c)^2}$  [BABAR uses  $m_{ES}$  and Belle uses  $M_{bc}$ , hereinafter  $M_{bc}$  is used] and by the energy difference  $\Delta E = E_B^* - E_{beam}^*$ , where  $E_{beam}^*$  denotes the energy of the beam, and  $p_B^*$  and  $E_B^*$  are the momentum and energy of the  $B$  meson candidates, evaluated in the  $e^+e^-$  center-of-mass (c.m.) frame. The selected regions are  $5.2 \text{ GeV}/c^2 < M_{bc} < 5.3 \text{ GeV}/c^2$  and  $-100 \text{ MeV} < \Delta E < 100 \text{ MeV}$ , except for  $\bar{B}^0 \rightarrow D_{CP}^*\pi^0$  decays, where  $-75 \text{ MeV} < \Delta E < 100 \text{ MeV}$  is required to exclude tails from partially reconstructed  $B^- \rightarrow D^{(*)0}\rho^-$  decays peaking at  $\Delta E \approx -250 \text{ MeV}$ .

In  $\bar{B}^0 \rightarrow D^0\omega$  and in  $D^0 \rightarrow K_S^0\omega$  decays, the  $\omega$  vector mesons are polarized. The angular distribution of  $\omega \rightarrow \pi^+\pi^-\pi^0$  decays is exploited to discriminate against background. The quantity  $\cos\theta_N$  is defined as the cosine of the angle between the neutral  $B$  meson direction and the normal to the  $\pi^+\pi^-\pi^0$  plane in the  $\omega$  meson rest frame. A requirement of  $|\cos\theta_N| > 0.3$  is applied.

After applying the above selection requirements, the average multiplicity of reconstructed  $\bar{B}^0 \rightarrow D_{CP}^*h^0$  candidates in an event is 1.3. In case of multiple  $B$  meson candidates in an event, one candidate is selected using a criterion based on the deviations of the reconstructed  $D^{(*)}$  and  $h^0$  meson masses from the nominal values. The probability for this method to select the correct signal is 82% (81%) for BABAR (Belle).

In  $\bar{B}^0 \rightarrow D_{CP}^*h^0$  decays, the dominant source of back-

ground originates from  $e^+e^- \rightarrow q\bar{q}$  ( $q \in \{u, d, s, c\}$ ) continuum events. This background is suppressed by using neural network (NN) multivariate classifiers that combine information characterizing the shape of an event [25]. The observables included in the NNs are the ratio  $R_2$  of the second to the zeroth order Fox-Wolfram moment, a combination of 16 modified Fox-Wolfram moments [26], the sphericity of the event [27], and  $\cos\theta_B^*$ , where  $\theta_B^*$  is the angle between the direction of the reconstructed  $B$  meson and the beam direction in the c.m. frame. The NN selection reduces the background by 89.3% (91.8%) and has a signal efficiency of 75.5% (74.3%) for BABAR (Belle).

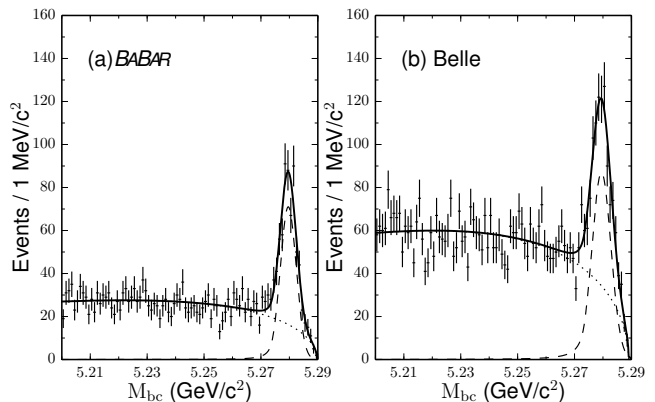


FIG. 1. The  $M_{bc}$  distributions (data points with error bars and fit projections (solid line) of  $\bar{B}^0 \rightarrow D_{CP}^*h^0$  decays for (a) BABAR and (b) Belle. The dashed (dotted) lines represent projections of the signal (background) fit components.

The signal yields are determined by unbinned maximum likelihood fits to the  $M_{bc}$  distributions. In the fits, the signal component is parametrized by a Crystal Ball function [28] and the background component is modeled by an ARGUS function [29]. The experimental  $M_{bc}$  distributions and fit projections are shown in Fig. 1. The signal yields are summarized in Table I.

TABLE I. Summary of  $\bar{B}^0 \rightarrow D_{CP}^*h^0$  signal yields.

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

The time-dependent  $CP$  violation measurement is performed using established BABAR and Belle techniques for the vertex reconstruction, the flavor-tagging, and the modeling of  $\Delta t$  resolution effects (see Refs. [6, 7, 30–33]) and is briefly summarized below. The proper time interval  $\Delta t$  is given as  $\frac{\Delta z}{c\beta\gamma}$ , where  $\Delta z$  is the distance between

the decay vertices of the signal  $B$  meson and of the accompanying  $B$  meson. The  $\bar{B}^0 \rightarrow D_{CP}^{(*)}h^0$  signal decay vertex is reconstructed by a kinematic fit including information about the IP position. For Belle, an iterative hierarchical vertex reconstruction algorithm following a bottom-up approach starting with the final state particles is applied, while for *BABAR* the vertex reconstruction includes simultaneously the complete  $B$  meson decay tree including all secondary decays. In the kinematic fits, the invariant masses of  $\pi^0$ ,  $\eta$ ,  $\omega$ , and  $D_{CP}$  candidates are constrained to their nominal values [22]. The decay vertex and the  $b$ -flavor content of the accompanying  $B$  meson are estimated from reconstructed decay products not assigned to the signal  $B$  meson. The  $b$ -flavor content is inferred by flavor-tagging procedures described in Refs. [6, 32]. The applied algorithms account for different signatures such as the presence and properties of prompt leptons, charged kaons and pions originating from the decay of the accompanying  $B$  meson, and assign a flavor and an associated probability. Selection requirements on the quality of the reconstructed decay vertices and the  $\Delta t$  measurements are applied.

The  $CP$  violation measurement is performed by maximizing the log-likelihood function

$$\ln \mathcal{L} = \sum_i \ln \mathcal{P}_i^{\text{BABAR}} + \sum_j \ln \mathcal{P}_j^{\text{Belle}}, \quad (2)$$

where the indices  $i$  and  $j$  denote the events reconstructed from *BABAR* and Belle data, respectively. The probability density function (p.d.f.) describing the  $\Delta t$  distribution for *BABAR* is defined by

$$\mathcal{P}^{\text{BABAR}} = \sum_k f_k \int [P_k(\Delta t') R_k(\Delta t - \Delta t')] d(\Delta t'), \quad (3)$$

and for Belle by

$$\begin{aligned} \mathcal{P}^{\text{Belle}} = & (1 - f_{\text{ol}}) \sum_k f_k \int [P_k(\Delta t') R_k(\Delta t - \Delta t')] d(\Delta t') \\ & + f_{\text{ol}} P_{\text{ol}}(\Delta t), \end{aligned} \quad (4)$$

where the index  $k$  represents the signal and background p.d.f. components. The symbol  $P_k$  denotes the p.d.f. describing the proper time interval of the particular physical process, and  $R_k$  refers to the corresponding resolution function. The fractions  $f_k$  are evaluated on an event-by-event basis as a function of  $M_{\text{bc}}$ . Belle treats outlier events with large  $\Delta t$  using a broad Gaussian function in the p.d.f. component  $P_{\text{ol}}$  with a small fraction of  $f_{\text{ol}} \approx 2 \times 10^{-4}$ , while *BABAR* includes outlier effects in the resolution function. The signal p.d.f. is constructed from the decay rate in Eq. (1), including the effect of incorrect flavor assignments and convolution with resolution functions to account for the finite vertex resolution. The models of the  $\Delta t$  resolution effects at *BABAR* and Belle follow different empirical approaches and are described in detail

in Refs. [6, 31]. The background p.d.f.s for *BABAR* and Belle are composed of the sum of a Dirac delta function to model prompt background decays and an exponential p.d.f. for decays with effective lifetimes. The background p.d.f. is convolved with a resolution function modeled as the sum of two Gaussian functions. The background parameters are fixed to values obtained by fits to the events in the  $M_{\text{bc}} < 5.26 \text{ GeV}/c^2$  sidebands.

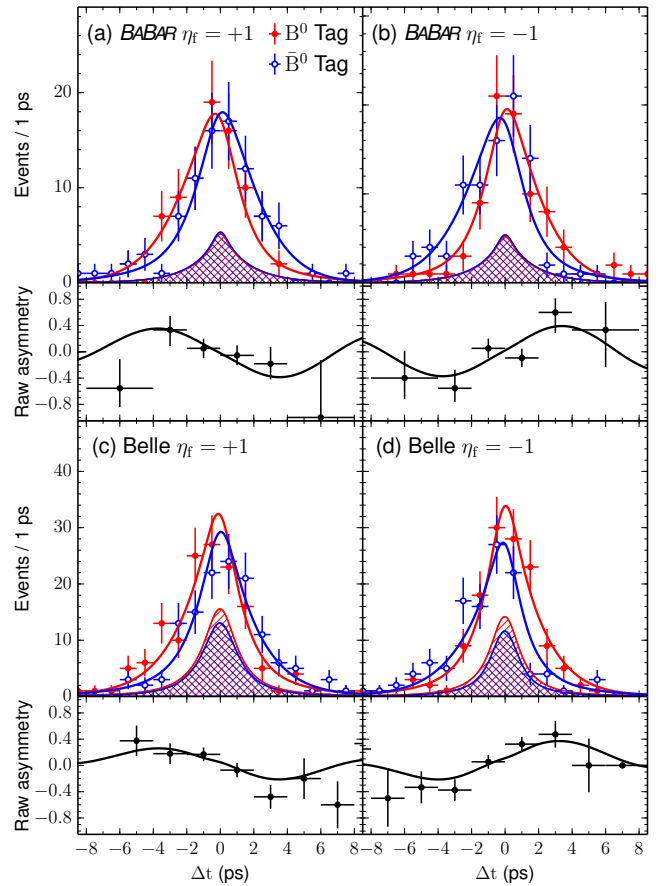


FIG. 2. (color online). The proper time interval distributions (data points with error bars) for  $B^0$  tags (red) and  $\bar{B}^0$  tags (blue) and the  $CP$  asymmetries of  $\bar{B}^0 \rightarrow D_{CP}^{(*)}h^0$  decays for (a)-(b) *BABAR* and (c)-(d) Belle for candidates associated with high quality flavor tags. The solid lines show projections of the sum of signal and background components in the fit, while the hatched areas show only the background components.

The combined *BABAR* and Belle measurement is performed by maximizing Eq. (2) for events in the  $5.27 \text{ GeV}/c^2 < M_{\text{bc}} < 5.29 \text{ GeV}/c^2$  signal region. The values of  $\tau_{B^0}$  and  $\Delta m_d$  are fixed to the world averages [22]. The free parameters in the fit are  $\mathcal{S}$  and  $\mathcal{C}$ . The result is

$$\begin{aligned} -\eta_f \mathcal{S} &= +0.66 \pm 0.10 \text{ (stat.)} \pm 0.06 \text{ (syst.)}, \\ \mathcal{C} &= -0.02 \pm 0.07 \text{ (stat.)} \pm 0.03 \text{ (syst.)}. \end{aligned} \quad (5)$$

The linear correlation between  $-\eta_f \mathcal{S}$  and  $\mathcal{C}$  is  $-4.9\%$ . Through comparison of the log-likelihood of the fit to the



distribution from an ensemble test performed with input from the data distributions, a  $p$ -value of 0.46 is obtained. The flavor-tagged proper time interval distributions and projections of the fit are shown in Fig. 2.

The evaluation of the systematic uncertainties in the  $CP$  violation parameters follows standard approaches of the *BABAR* and Belle experiments described in detail in Refs. [6, 7, 33]; the results are summarized in Table II. For the vertex reconstruction, the sources of systematic uncertainties include the applied constraints and selection requirements on the vertex fits of the signal  $B$  meson and the accompanying  $B$  meson, and on the  $\Delta t$  fit range. These contributions are estimated by variations of the constraints and selection requirements. The systematic uncertainties due to the misalignment of the silicon vertex detectors are estimated by Monte Carlo (MC) simulations. For *BABAR*, the uncertainty of the  $z$  scale is estimated by variations of the  $z$  scale and corresponding uncertainties. For Belle, a possible  $\Delta t$  bias is estimated using MC simulations. The systematic uncertainties due to the  $\Delta t$  resolution functions, the parameterization of the  $\Delta t$  background p.d.f., the calculation of the signal purity, the flavor-tagging, and the physics parameters  $\tau_{B^0}$  and  $\Delta m_d$  are estimated by variation of the fixed parameters within their uncertainties. Fit biases are estimated using large samples of MC-simulated signal decays. The contribution of backgrounds that have the same final states as the reconstructed  $\bar{B}^0 \rightarrow D_{CP}^{(*)}h^0$  decay modes and that can peak in the  $M_{bc}$  signal region is estimated using  $D$  meson mass sidebands on data and using generic  $B\bar{B}$  MC samples. These backgrounds account for less than 8% of the signal and consist mainly of flavor-specific decays such as partially reconstructed  $B^- \rightarrow D^{(*)0}\rho^-$  decays. The systematic uncertainty due to this peaking background is estimated using MC simulations in which the peaking background is modeled, and the nominal fit procedure, which neglects this peaking background, is applied. The effect of interference between  $b \rightarrow c\bar{u}d$  and  $\bar{b} \rightarrow \bar{u}c\bar{d}$  decay amplitudes of the accompanying  $B$  meson is estimated using MC simulations that account for possible deviations from the time evolution described by Eq. (1) [34]. Possible correlations between *BABAR* and Belle are accounted for in the evaluation of the contributions due to the physics parameters, the peaking background, and the tag-side interference. In the MC studies described above, the largest deviations are assigned as systematic uncertainties. The total systematic uncertainty is the quadratic sum of all contributions.

The statistical significance of the results is estimated using a likelihood-ratio approach by computing the change in  $2\ln\mathcal{L}$  when the  $CP$  violation parameters are fixed to zero. The effect of systematic uncertainties is included by convolution of the likelihood distributions. No significant direct  $CP$  violation is observed. The measurement excludes the hypothesis of no mixing-induced

TABLE II. Summary of systematic uncertainties for the time-dependent  $CP$  violation measurement in  $\bar{B}^0 \rightarrow D_{CP}^{(*)}h^0$  decays (in units of  $10^{-2}$ ).

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

$CP$  violation in  $\bar{B}^0 \rightarrow D_{CP}^{(*)}h^0$  decays at a confidence level of  $1 - 6.6 \times 10^{-8}$ , corresponding to a significance of 5.4 standard deviations.

The analysis is validated by a variety of cross-checks. The same measurement is performed for  $\bar{B}^0 \rightarrow D^{(*)0}h^0$  decays with the CKM-favored  $D^0 \rightarrow K^-\pi^+$  decay mode. These decays provide a kinematically similar, high statistics control sample. The result agrees with the assumption of negligible  $CP$  violation for these decays. Measurements of the neutral  $B$  meson lifetime using the control sample and  $\bar{B}^0 \rightarrow D_{CP}^{(*)}h^0$  decays yield  $\tau_{B^0} = 1.518 \pm 0.026$  (stat.) ps and  $\tau_{B^0} = 1.520 \pm 0.064$  (stat.) ps, respectively, in agreement with the world average  $\tau_{B^0} = 1.519 \pm 0.005$  ps [22]. All measurements for the control sample and for  $\bar{B}^0 \rightarrow D_{CP}^{(*)}h^0$  decays have also been performed for data separated by experiment and by decay mode, and yield consistent results. The results for  $\bar{B}^0 \rightarrow D_{CP}^{(*)}h^0$  decays separated by experiment are  $\sin(2\beta) = 0.52 \pm 0.15$  (stat.) for *BABAR* and  $0.83 \pm 0.15$  (stat.) for Belle, and the results separated by the  $CP$  content of the final states are  $\sin(2\beta) = 0.52 \pm 0.15$  (stat.) for  $CP$ -even and  $0.80 \pm 0.15$  (stat.) for  $CP$ -odd.

In summary, we combine the final *BABAR* and Belle data samples, totaling more than  $1 \text{ ab}^{-1}$  collected at the  $\Upsilon(4S)$  resonance [19, 36], and perform a simultaneous analysis of the data collected by both experiments. We observe for the first time  $CP$  violation in  $\bar{B}^0 \rightarrow D_{CP}^{(*)}h^0$  decays driven by mixing-induced  $CP$  violation. We measure  $\sin(2\beta) = 0.66 \pm 0.10$  (stat.)  $\pm 0.06$  (syst.). This result agrees within 0.2 standard deviations with the world average of  $\sin(2\beta) = 0.68 \pm 0.02$  [35] measured from  $b \rightarrow c\bar{c}s$  transitions, and is consistent with the measurements of  $b \rightarrow s$  penguin-mediated  $B$  meson decays [9–12] at current precision. The presented measurement supersedes the previous *BABAR* result for  $\bar{B}^0 \rightarrow D_{CP}^{(*)}h^0$  decays [15].

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