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Observation of CP Violation in $\bar{B}^0 \to D^{(*)}_{CP} h^0$ Decays in a Combined Analysis using BABAR and Belle Data

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We report a time-dependent CP violation measurement of $\bar{B}^0 \to D^{(*)}_{CP} h^0$ decays, where the light neutral hadron h^0 is a π^0, η or ω meson, and the neutral D meson is reconstructed in decays to two-body CP eigenstates K^+K^-, $K^0_S\pi^0$ or $K^0_S\omega$. The measurement is performed by combining the final data samples of $(471 \pm 3) \times 10^6\, B\bar{B}$ pairs collected by the BABAR experiment and $(772 \pm 11) \times 10^6\, B\bar{B}$ pairs by the Belle experiment. A first observation of CP violation in $\bar{B}^0 \to D^{(*)}_{CP} h^0$ decays governed by mixing-induced CP violation according to $\sin(2\beta)$ is presented.

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The precise measurements of observables related to the CKM [1] Unitarity Triangle provide strong tests on the Standard Model of electroweak interactions, and enable to constrain potential effects of physics beyond the Standard Model. The *BABAR* and Belle experiments established *CP* violation in the B meson system [2, 3, 4, 5]. By time-dependent measurements of the mixing-induced *CP* violation in $b \to c\bar{c}s$ transitions, both experiments precisely determined the angle β, which is defined by CKM matrix elements V_{ij} as $\arg\left[-V_{cd}V^*_{cb}/V_{td}V^*_{tb}\right]$. The current world average obtained from measurements of $b \to c\bar{c}s$ transitions [6, 7] is $\sin(2\beta) = 0.68 \pm 0.02$ [8]. The results obtained in $b \to c\bar{c}s$ transitions are associated with theoretical uncertainties related to possible penguin contributions, which could be sizeable in the presence of new physics effects and could lead to a systematic shift on the parameter $\sin(2\beta)$ [9].

A complementary approach to measure the weak phase β is provided by $\bar{B}^0 \to D^{(*)}h^0$ decays, where $h^0 \in \{\pi^0, \eta, \omega\}$ is a light neutral hadron. $\bar{B}^0 \to D^{(*)}h^0$ decays are mediated only by tree-level amplitudes, dominated by CKM-favored $b \to c\bar{u}d$ transitions, and enable for a theoretically clean way to access β [10]. The measurements of $\bar{B}^0 \to D^{(*)}h^0$ decays can provide a Standard Model reference for the new physics searches in the mixing-induced *CP* violation of $b \to s$ penguin transitions. However, there are experimental difficulties in the measurements of $\bar{B}^0 \to D^{(*)}h^0$ caused by the low involved B and D meson branching fractions, low reconstruction efficiencies and the presence of sizeable background. Earlier measurements carried out separately by the *BABAR* and Belle experiments were not sensitive enough to significantly establish *CP* violation in $\bar{B}^0 \to D^{(*)}h^0$ decays [11, 12, 13].

To increase the achievable experimental sensitivity, a time-dependent *CP* violation measurement of $\bar{B}^0 \to D^{(*)}_{CP}h^0$ is performed, that makes for the first time simultaneous use of the large data sets collected by the *BABAR* and Belle experiments, totaling more than $1\,\mathrm{ab}^{-1}$ collected at the $\Upsilon(4S)$ resonance corresponding to about $1240 \times 10^6\, B\bar{B}$ pairs. The very similar performance of the detectors of both experiments enable for a coherent analysis strategy, which for example enables to apply almost the same selection requirements to the *BABAR* and Belle data samples.

In the measurement, the light neutral hadron h^0 is reconstructed as a π^0, η or ω meson. 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 total, twelve final states are reconstructed, among them seven (five) in *CP*-even (*CP*-odd) states. The dominant background originates from $e^+e^- \to q\bar{q}$ ($q \in \{u,d,s,c\}$) continuum events. This background is suppressed by selection requirements on neutral network multivariate classifiers trained on event shape variables. The signal yields are estimated by fits to the beam-constrained mass defined by $M_{\mathrm{bc}} = \sqrt{(E^*_{\mathrm{beam}}/c^2)^2 - (p^*_B/c)^2}$, where p^*_B is the momentum of reconstructed B meson candidates and E^*_{beam} is the energy of the beam in the e^+e^- center-of-mass (c.m.) frame. For *BABAR* (Belle) a yield of 508 ± 31 (757 ± 44) signal events is obtained.

The time-dependent measurement is performed by combining the flavor-tagged proper decay time distributions reconstructed from *BABAR* and Belle data on the likelihood level. The combined

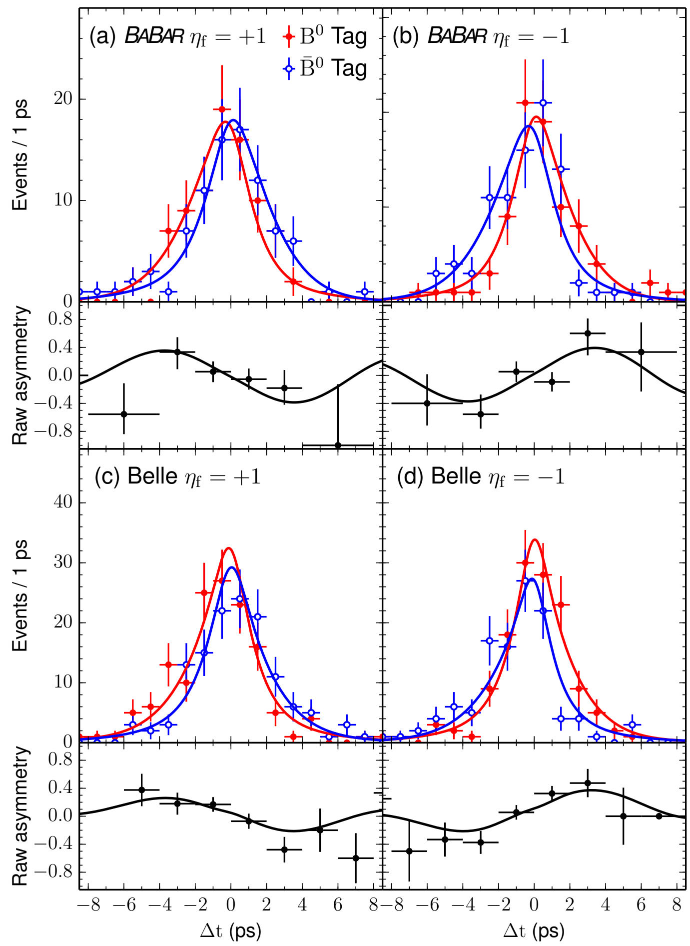

Figure 1: Projections of the fit (solid lines) and experimental flavor-tagged proper decay time distributions (data points with error bars) for *BABAR* (top) and Belle (bottom) separated for *CP*-even (left) and *CP*-odd (right) final states.

log-likelihood function is defined as

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

where the indices i and j numerate events reconstructed from *BABAR* and Belle data, respectively. The signal probability density functions are constructed from the convolution of the decay rate of a neutral B meson decaying to a *CP* eigenstate, defined as

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

with experiment specific resolution functions to account for the finite vertex resolution and with modifications to account for the effects of incorrect flavor assignments. The background probability density functions account for prompt decays and for non-prompt decays with effective lifetimes convoluted with effective resolution functions. The measurement is carried out by minimizing the combined log-likelihood function in Eq. 1 with respect to the *CP* violation parameters $\mathscr{S}$ and

$\mathscr{C}$, which measure mixing-induced and direct *CP* violation, respectively. The experimental flavor-tagged proper decay time distributions for *BABAR* and Belle and for *CP*-even and *CP*-odd final states are shown together with projections of the fit in Fig. 1.

Including statistical and systematic uncertainties, the result of the measurement is:

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

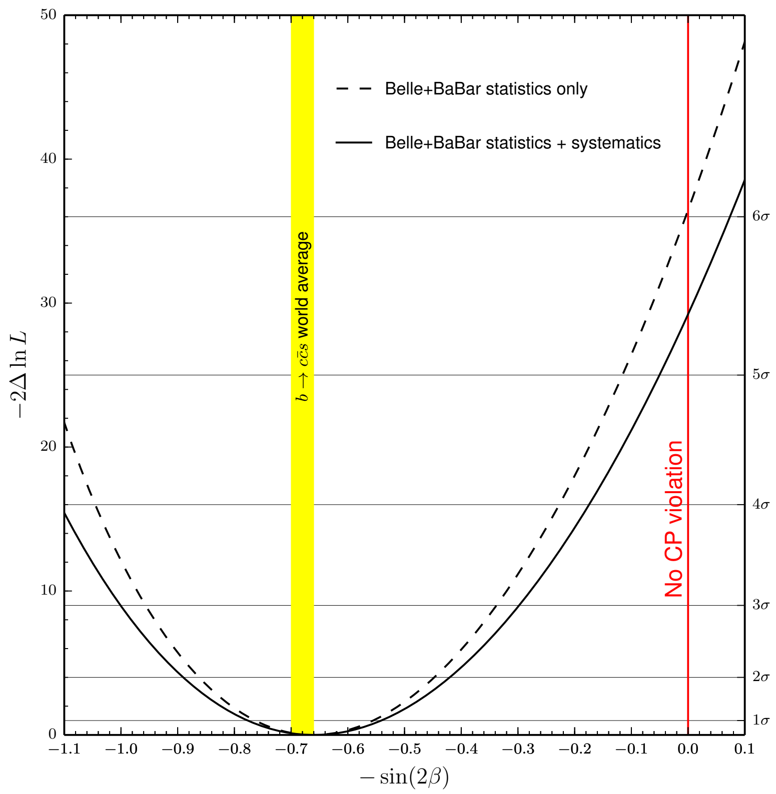

Figure 2: $-2\Delta\ln\mathscr{L}$ distributions for the combined *BABAR* +Belle measurement with respect to the mixing-induced *CP* violation in $\bar{B}^0 \to D^{(*)}_{CP} h^0$. The solid (dashed) line accounts for the statistical+systematic uncertainties (statistical uncertainties only). The yellow band represents the current world average of $\sin(2\beta)$ obtained from measurements of $b \to c\bar{c}s$ transitions [8]. The red line shows the no mixing-induced *CP* violation hypothesis.

The statistical significance of the obtained results is determined by a likelihood-ratio approach, and the results with respect to the mixing-induced *CP* violation are shown in Fig. 2. Including the effects of systematic uncertainties, the no mixing-induced *CP* violation hypothesis is excluded with 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 with the current world average of $\sin(2\beta) = 0.68 \pm 0.02$ [8] within 0.2 standard deviations. No significant direct *CP* violation is observed.

In summary, for the first time the large final data samples of the *BABAR* and Belle experiments including $1240 \times 10^6 \, B\bar{B}$ pairs collected on the $\Upsilon(4S)$ resonance are combined to perform a simultaneous time-dependent *CP* violation measurement in the neutral B^0 system. The measurement provides the first observation of *CP* violation in $\bar{B}^0 \to D^{(*)}_{CP} h^0$ decays driven by mixing-induced *CP* violation according to $\sin(2\beta)$. The result is in very good agreement with the precision measurements in $b \to c\bar{c}s$ transitions [6, 7]. The results are published in Ref. [14]

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