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A New Gold Standard of the Weak Phase β Obtained by Combined BABAR+Belle CP Violation Measurements of $\bar{B}^0 \to D^{(*)}_{CP} h^0$ Decays

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The B factory experiments, BABAR at SLAC in the USA and Belle at KEK in Japan, established CP violation in the B meson system and contributed to a better understanding of the quark-flavor structure of the Standard Model. In this contribution to the FPCP 2016 proceedings the results of a new analysis campaign are summarized, which combines for the first time the large final data sets of both experiments in a single physics analysis. The measurement of the time-dependent CP violation in $\bar{B}^0 \to D^{(*)}_{CP} h^0$ decays and a first observation of CP violation governed by the weak phase β is reported. $\bar{B}^0 \to D^{(*)}_{CP} h^0$ decays will provide a very clean Standard Model reference for the new physics searches in penguin-dominated $b \to s$ transitions at the future high-luminosity B factory experiment Belle II.

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In the 2000s, the first generation B factory experiments, BABAR at SLAC in the USA and Belle at KEK in Japan, explored the quark flavor structure of the Standard Model in many independent measurements and achieved numerous scientific breakthroughs. Most importantly, the BABAR and Belle experiments established CP violation in the neutral and charged B meson system [1, 2, 3, 4]. Precision measurements of flavor observables related to the Unitarity Triangle of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [5] enable to test the Standard Model of electroweak interactions and to constrain the effects of potential new physics. The determination of the angles of the Unitarity Triangle is closely related to the measurements of CP violating effects. The most precise measured angle of the Unitarity Triangle is β, which is defined by the CKM matrix elements V_{ij} as $\arg\left[-V_{cd}V_{cb}^{*}/V_{td}V_{tb}^{*}\right]$. The current world average obtained by time-dependent CP violation measurements of the mixing-induced CP violation in $b \to c\bar{c}s$ transitions [6, 7] is $\sin(2\beta) = 0.69 \pm 0.02$ [8]. However, the interpretation of the results in terms of the weak phase β is associated with theoretical and possibly sizeable uncertainties related to possible penguins amplitudes contributing to $b \to c\bar{c}s$ transitions. A theoretical clean determination of β is important, because it can provide a Standard Model reference for the new physics searches in the quantum-loops of $b \to s$ penguin transitions [9].

Another approach to measure the weak phase β complementary to $b \to c\bar{c}s$ transitions is provided by $\bar{B}^0 \to D^{(*)}h^0$ decays, where h^0 denotes a light neutral hadron such as a π^0, η or ω meson. $\bar{B}^0 \to D^{(*)}h^0$ decays proceed only via tree-level amplitudes predominantly mediated by CKM-favored $b \to c\bar{u}d$ transitions. Therefore the measurements of the mixing-induced CP violation in $\bar{B}^0 \to D^{(*)}h^0$ decays enable to access the weak phase β in a theoretically clean way [10]. However, measurements of $\bar{B}^0 \to D^{(*)}h^0$ decays are experimentally challenging because of the low B and D meson branching fractions, the low reconstruction efficiencies due to the various involved neutral particles and radiative decays, and the presence of sizeable sources of background. The BABAR and Belle experiments previously carried out measurements of $\bar{B}^0 \to D^{(*)}h^0$ decays but were not sensitive enough to establish CP violation in these decays [11, 12, 13].

In a new analysis campaign, for the first time the large final data sets of the BABAR and Belle experiments are combined to perform a physics measurement using simultaneously the data of both experiments. The total combined integrated luminosity is $1.1\,\mathrm{ab}^{-1}$, which corresponds to about 1240×10^6 $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance. The joint BABAR+Belle approach significantly increases the experimental precision and enables for time-dependent CP violation measurements at unprecedented sensitivity. The first measurement carried out is a combined time-dependent CP violation measurement of $\bar{B}^0 \to D_{CP}^{(*)}h^0$ decays. The analysis is performed in a coherent analysis strategy. For example, due to the very similar performance of the detectors of both experiments almost the same selection requirements can be applied to the BABAR and Belle data samples.

In the measurement, the neutral D_{CP} mesons are reconstructed in the decays to the two-body CP eigenstates K^+K^-, $K_S^0\pi^0$ and $K_S^0\omega$. The light neutral hadrons h^0 are reconstructed in the decay modes $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$ and $\pi^+\pi^-\pi^0$, and $\omega \to \pi^+\pi^-\pi^0$. D^{*0} mesons are reconstructed in the decays to $D^0\pi^0$. In total, twelve final states are reconstructed from both BABAR and Belle

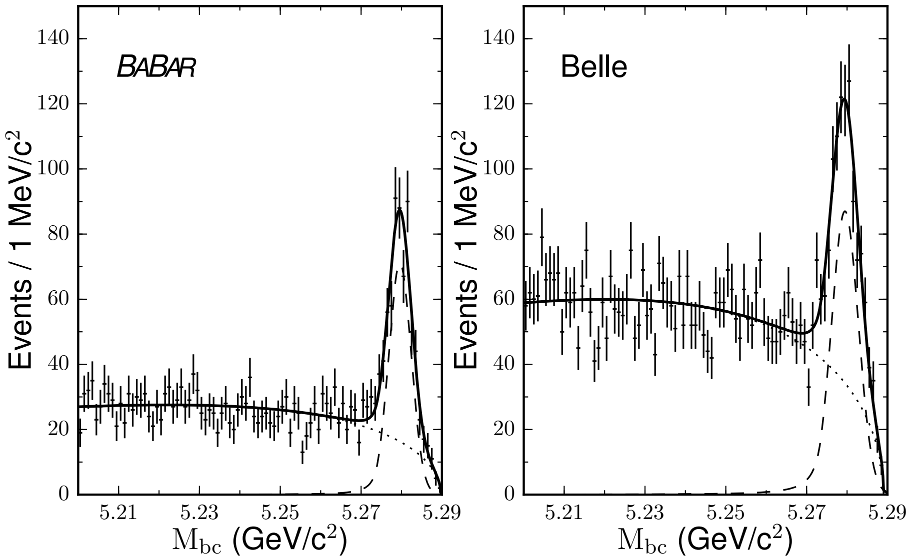

Figure 1: The $M_{\rm bc}$ distributions (data points with error bars) and fit projections (solid and dashed lines) of $\bar{B}^0 \to D_{CP}^{(*)} h^0$ decays for BABAR (left) and Belle (right).

data. Among them are seven *CP*-even and five *CP*-odd states. A major source of background in the measurement arises from $e^+e^- \to q\bar{q}$ $(q \in \{u,d,s,c\})$ events. This background is suppressed by multivariate classifiers provided by neural networks that are trained on variables that characterize the shape and topology of the events. The signal yields are estimated by time-integrated fits to the beam-constrained mass defined as $M_{\rm bc} = \sqrt{(E^*_{\rm beam}/c^2)^2 - (p^*_B/c)^2}$, where p^*_B denotes the momentum of the fully reconstructed B meson candidates and $E^*_{\rm beam}$ is the beam energy in the e^+e^- center-of-mass frame. The $M_{\rm bc}$ distributions for $\bar{B}^0 \to D_{CP}^{(*)} h^0$ decays reconstructed from BABAR and Belle data and projections of the fits are shown in Figure 1. For BABAR a yield of 508 ± 31 and for Belle a yield of 757 ± 44 $\bar{B}^0 \to D_{CP}^{(*)} h^0$ events are obtained.

The joint BABAR +Belle time-dependent *CP* violation measurement is performed by combining the flavor-tagged proper decay time distributions reconstructed from BABAR and Belle data on the likelihood level. The combined log-likelihood function to extract the *CP* violation parameters is defined as

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

where the indices i and j numerate events reconstructed from BABAR and Belle data, respectively. The probability density functions $\mathscr{P}$ for the time evolution of $\bar{B}^0 \to D_{CP}^{(*)} h^0$ decays are constructed by the convolution of the decay rate of neutral B mesons decaying to *CP* eigenstates, 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 empiric resolution functions that account for experiment specific finite resolution in the B meson vertex reconstruction and by further modifications that account for experiment specific flavor tagging algorithms. The background probability density functions are constructed from terms accounting for prompt decays and for non-prompt decays with effective lifetimes convoluted with

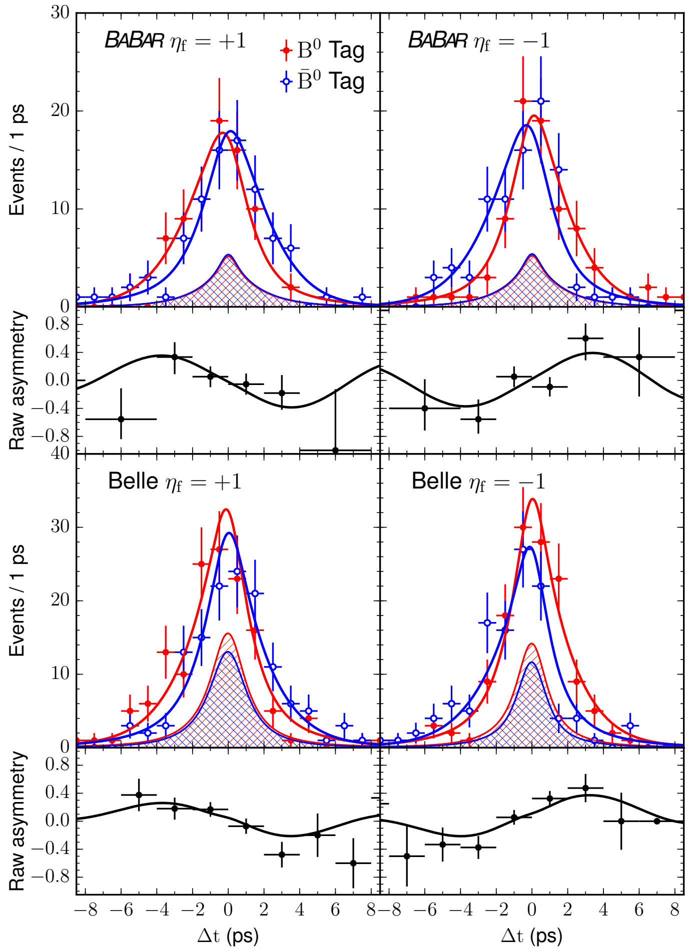

Figure 2: Experimental flavor-tagged proper decay time interval distributions of $\bar{B}^0 \to D_{CP}^{(*)} h^0$ decays (data points with error bars) and projections of the fit (solid lines) for *BABAR* (top) and Belle (bottom), and for the *CP*-even (left) and the *CP*-odd (right) final states.

effective resolution functions. The joint *BABAR* +Belle time-dependent *CP* violation measurement is performed by maximizing the log-likelihood function in Equation 1 with respect to the mixing-induced *CP* violation $\mathscr{S}$ and the direct *CP* violation $\mathscr{C}$. The result of the measurement including statistical and systematic uncertainties is:

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

The flavor-tagged proper decay time interval distributions for *BABAR* and Belle, and for the *CP*-even and the *CP*-odd final states and projections of the fit are shown in Figure 2. The measurement excludes the hypothesis of no mixing-induced *CP* violation in $\bar{B}^0 \to D_{CP}^{(*)} h^0$ decays with a significance of 5.4 standard deviations. The measurement establishes an observation of *CP* violation in $\bar{B}^0 \to D_{CP}^{(*)} h^0$ decays for the first time. The result agrees within 0.2 standard deviations with the more precise current world average of $\sin(2\beta) = 0.69 \pm 0.02$ [8] obtained by $b \to c\bar{c}s$ transitions [6, 7].

In summary, the first combined BABAR +Belle measurement performed on a data sample corresponding to 1240×10^6 $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance is reported. This first measurement performed on an integrated luminosity of more than one inverse attobarn establishes *CP* violation in $\bar{B}^0 \to D_{CP}^{(*)} h^0$ decays for the first time. The result is in very good agreement with the more precise measurements of $b \to c\bar{c}s$ transitions. The future high-luminosity *B* factory experiment Belle II is expected to further increase the precision of the weak phase β determined in $\bar{B}^0 \to D_{CP}^{(*)} h^0$ decays, which provides a new gold standard for the new physics searches in the mixing-induced *CP* violation of penguin-dominated $b \to s$ transitions. The results are published in Ref. [14].

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