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Combined CP Violation Measurements of $\bar{B}^0 \to D^{(*)}h^0$ Decays by the *BABAR* and Belle Collaborations

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Measurements of the time-dependent CP violation of $\bar{B}^0 \to D^{(*)}h^0$ decays are presented which are sensitive to the angle β of the CKM Unitarity Triangle. The measurements make for the first time simultaneous use of the $(471 \pm 3) \times 10^6$ $B\bar{B}$ pairs collected by the BABAR experiment and the $(772 \pm 11) \times 10^6$ $B\bar{B}$ pairs collected by the Belle experiment in single physics analyses. We report combined BABAR+Belle results for the time-dependent CP violation 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 decays to the two-body CP eigenstates K^+K^-, $K^0_S\pi^0$ or $K^0_S\omega$. In this first measurement performed on a data sample of more than 1 ab^{-1}, 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 obtained. We measure the CP asymmetry parameters $-\eta_f \mathscr{S} = +0.66 \pm 0.10\,(\text{stat.}) \pm 0.06\,(\text{syst.})$ and $\mathscr{C} = -0.02 \pm 0.07\,(\text{stat.}) \pm 0.03\,(\text{syst.})$. In addition, we report preliminary results of a second ongoing combined BABAR+Belle measurement which will extract the not well-known value of $\cos(2\beta)$ from a time-dependent Dalitz analysis of $\bar{B}^0 \to D^{(*)}h^0$ decays with $D \to K^0_S\pi^+\pi^-$ decays.

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1. Introduction

Precise knowledge of flavor observables such as the angles of the Cabibbo-Kobayashi-Maskawa (CKM) Unitarity Triangle enables for stringent tests of the Standard Model (SM) of particle physics and to put tight constraints on potential new effects of physics beyond. In the SM, the irreducible complex phase in the three-family CKM quark-mixing matrix is the only source of *CP* violation [1]. In general, the determination of the angles of the CKM Unitarity Triangle is closely related to the measurements of *CP* violating phenomena. The best known 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 BABAR, Belle and LHCb experiments have precisely determined the angle β by time-dependent *CP* violation measurements of $b \to c\bar{c}s$ transitions including the gold-plated decay mode $B^0 \to J/\psi K_S^0$ [2]. The current world average obtained from the measurements of $b \to c\bar{c}s$ transitions is $\sin(2\beta) = 0.691 \pm 0.017$ [3]. However, these results are associated with theoretical uncertainties due to possible quantum-loop (penguin) contributions to $b \to c\bar{c}s$ transitions that could be sizable in the presence of both, not understood hadronic effects and new physics, which could lead to a systematic shift on the measured parameter of $\sin(2\beta)$ [4].

A complementary and theoretically clean probe for β is provided by $\bar{B}^0 \to D^{(*)}h^0$ decays where $h^0 \in \{\pi^0, \eta, \omega\}$ denotes a light neutral hadron. $\bar{B}^0 \to D^{(*)}h^0$ decays are mediated only by tree-level amplitudes, in good approximation only by CKM-favored $b \to c\bar{u}d$ transitions, and thus enable to extract β without any uncertainties originating from higher-order SM or new physics corrections [5]. Measurements of β using $\bar{B}^0 \to D^{(*)}h^0$ decays can be used to test the precision measurements of $b \to c\bar{c}s$ transitions and can provide a SM anchor point for the new physics searches in the time-dependent *CP* violation of hadronic *B* meson decays predominantly mediated by $b \to s$ penguin amplitudes. However, measurements of $\bar{B}^0 \to D^{(*)}h^0$ decays are experimentally challenging because of low *B* and *D* meson branching fractions, and low reconstruction efficiencies and sizable background levels due to the many neutral particles in the final states. The BABAR and Belle experiments previously reported measurements of $\bar{B}^0 \to D^{(*)}h^0$ decays using *D* meson decays to two-body *CP* eigenstates and to self-conjugated three-body final states, but neither experiment alone was sensitive enough to establish *CP* violation in $\bar{B}^0 \to D^{(*)}h^0$ decays [6].

We report the results from a new analysis campaign, which for the first time makes use of the large data sets collected by the BABAR and Belle experiments of together more than $1\,\text{ab}^{-1}$ in single physics measurements. This novel approach enables for an unprecedented sensitivity in time-dependent *CP* violation measurements of neutral *B* meson decays. A time-dependent *CP* violation measurement of $\sin(2\beta)$ in $\bar{B}^0 \to D_{CP}^{(*)}h^0$ decays with D_{CP} decaying to two-body *CP* eigenstates is presented, which uses simultaneously the $(471 \pm 3) \times 10^6\, B\bar{B}$ pairs collected by the BABAR experiment and the $(772 \pm 11) \times 10^6\, B\bar{B}$ pairs collected by the Belle experiment. In addition, preliminary results of an on-going second combined BABAR+Belle measurement are reported which aims to measure the experimentally not well-known cosine of the angle β by a time-dependent Dalitz analysis of $\bar{B}^0 \to D^{(*)}h^0$ decays with $D \to K_S^0\pi^+\pi^-$ decays.

2. Combined BABAR+Belle Measurement of $\sin(2\beta)$ in $\bar{B}^0 \to D_{CP}^{(*)}h^0$ decays

In the decays of neutral *B* mesons to *CP* eigenstates such as in $\bar{B}^0 \to D_{CP}^{(*)}h^0$ decays, an inter-

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ference between the decay without B^0-$\bar{B}^0$ oscillations and the decay following B^0-$\bar{B}^0$ oscillations emerges. In this case, the time-dependent decay rate of the B meson decay is given by the following expression:

$$g(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left\{1 + q\left[\mathscr{S}\sin(\Delta m_d \Delta t) - \mathscr{C}\cos(\Delta m_d \Delta t)\right]\right\}, \tag{2.1}$$

The Δt is the proper time interval between the decays of the two B mesons in an $\Upsilon(4S)$ event, and $q = +1\,(-1)$ denotes the production flavor of the B meson decaying to the *CP* eigenstate that is inferred by tagging the accompanying B meson as a B^0 ($\bar{B}^0$). The τ_{B^0} and Δm_d are the neutral B meson lifetime and the B^0-$\bar{B}^0$ oscillation frequency, respectively. The parameters $\mathscr{S}$ and $\mathscr{C}$ quantify the mixing-induced and the direct *CP* violation in the B meson decay. For $\bar{B}^0 \to D_{CP}^{(*)}h^0$ decays neglecting the CKM-disfavored decay amplitudes the SM predicts $\mathscr{S} = -\eta_f \sin(2\beta)$ and $\mathscr{C} = 0$, where the *CP* eigenvalue of the final state is represented by $\eta_f = \pm 1$.

In the combined BABAR+Belle measurement of $\bar{B}^0 \to D_{CP}^{(*)}h^0$ decays, the neutral D_{CP} meson is reconstructed in the two-body *CP* eigenstates K^+K^-, $K_S^0\pi^0$ and $K_S^0\omega$, and the light neutral hadron h^0 is either a π^0, η or ω meson. D^{*0} mesons are reconstructed in the decay to $D_{CP}\pi^0$. In total, the measurement reconstructs twelve final states, among them are seven (five) *CP*-even (*CP*-odd) final states. In the analysis, the dominant source of background arises from e^+e^- annihilations into light quark pairs. This $e^+e^- \to q\bar{q}$ ($q \in \{u,d,s,c\}$) continuum background is reduced by usage of neural networks trained on event shape variables.

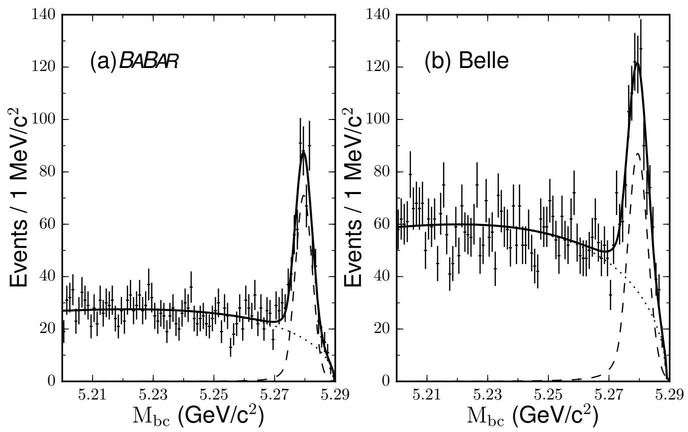

Figure 1: The M_{bc} distributions (data points with error bars) of $\bar{B}^0 \to D_{CP}^{(*)}h^0$ decays reconstructed from (a) BABAR and (b) Belle data and projections of the fits (solid line). The dashed and dotted lines represent projections of the signal and background components of the fits, respectively.

Figure 1 shows the time-integrated distributions for BABAR and Belle of the beam-constrained mass defined as $M_{bc} = \sqrt{(E^*_{beam}/c^2)^2 - (p^*_B/c)^2}$, where E^*_{beam} is the energy of the beam and p^*_B is the momentum of the reconstructed B meson candidate in the e^+e^- center-of-mass frame. A total yield of 508 ± 31 (757 ± 44) $\bar{B}^0 \to D_{CP}^{(*)}h^0$ signal events is obtained for BABAR (Belle) by fits to the M_{bc} distributions.

The simultaneous BABAR+Belle time-dependent *CP* violation measurement is performed by combining the flavor-tagged proper time interval distributions of each experiment on the likelihood level. The combined log-likelihood function is given by

$$\ln \mathscr{L} = \sum_i \ln \mathscr{P}_i^{BABAR} + \sum_j \ln \mathscr{P}_j^{\text{Belle}}, \tag{2.2}$$

where the indices i and j denote events reconstructed from *BABAR* and Belle data, respectively, and the $\mathscr{P}_i$ and $\mathscr{P}_j$ are probability density functions (p.d.f.s) describing the corresponding proper decay time interval distributions. The signal p.d.f.s are constructed by convolution of the decay rate of the neutral B meson decay to a *CP* eigenstate given by Equation 2.1 with experiment specific resolution functions accounting for the finite resolution in the B meson vertex reconstruction and by accounting for effects of incorrect flavor assignments. The background p.d.f.s account for prompt decays and for non-prompt decays with effective lifetimes convoluted with effective resolution functions. The free parameters in the fit are $\mathscr{S}$ and $\mathscr{C}$. The flavor-tagged proper decay time interval distributions and projections of the fit separated by experiments and *CP* eigenvalues are shown in Figure 2.

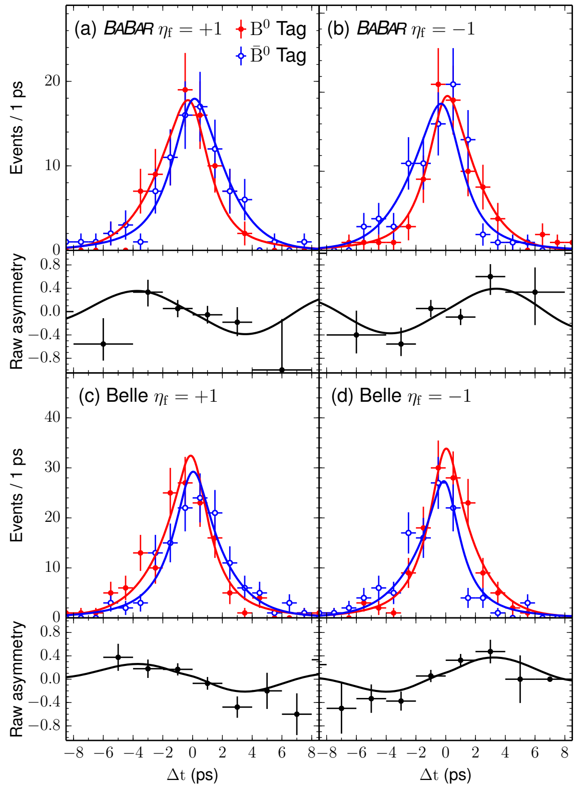

Figure 2: Experimental flavor-tagged proper decay time interval distributions (data points with error bars) of $\bar{B}^0 \to D_{CP}^{(*)} h^0$ decays for *BABAR* (top) and Belle (bottom) and for *CP*-even (left) and *CP*-odd (right) final states. The solid lines are projections of the fit. The bottom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

The result of the measurement including statistical and systematic uncertainties is:

$$\begin{aligned} -\eta_{f_{CP}} \mathscr{S} &= +0.66 \pm 0.10\,(\text{stat.}) \pm 0.06\,(\text{syst.}) \\ \mathscr{C} &= -0.02 \pm 0.07\,(\text{stat.}) \pm 0.03\,(\text{syst.}) \end{aligned} \tag{2.3}$$

The result shows *CP* violation in $\bar{B}^0 \to D^{(*)}_{CP}h^0$ decays driven by mixing-induced *CP* violation according to $\sin(2\beta)$, and no significant direct *CP* violation is observed. The result agrees well with the SM prediction and is compatible at the level of 0.2 standard deviations with the current world average of $\sin(2\beta) = 0.691 \pm 0.017$ [3] obtained by the precision measurements of $b \to c\bar{c}s$ transitions. The measurement excludes the no mixing-induced *CP* violation hypothesis with a significance of 5.4 standard deviations including the effects of systematic uncertainties. The measurement establishes an observation of *CP* violation in $\bar{B}^0 \to D^{(*)}_{CP}h^0$ decays for the first time. The results are published in Ref. [7].

3. Combined *BABAR*+Belle measurement of $\cos(2\beta)$ by a time-dependent Dalitz analysis of $\bar{B}^0 \to D^{(*)}h^0$ decays with $D \to K^0_S\pi^+\pi^-$ decays

The determination of the angle β of the CKM Unitarity Triangle from measurements of $\sin(2\beta)$ has a two-fold ambiguity of 2β and $\pi - 2\beta$. Analyses of $\bar{B}^0 \to D^{(*)}h^0$ decays with the D mesons decaying to the $K^0_S\pi^+\pi^-$ multi-body final state can resolve this ambiguity. The interference between D^0 and $\bar{D}^0$ decays and the variation of the relative strong phases over the Dalitz phasespace enable to extract not only $\sin(2\beta)$ but also $\cos(2\beta)$ by a time-dependent Dalitz analysis [8].

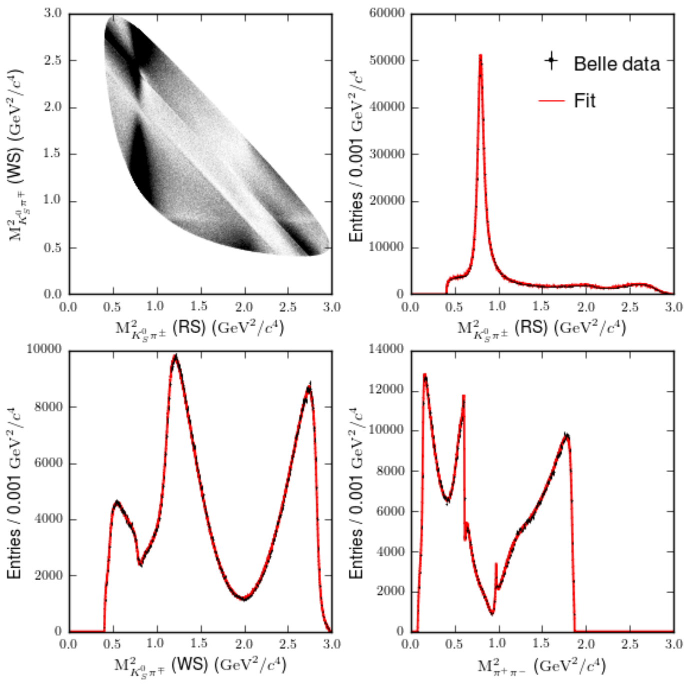

Figure 3: Preliminary result of a Dalitz fit to a high-statistics flavor-tagged sample of $D \to K^0_S\pi^+\pi^-$ decays reconstructed from $e^+e^- \to c\bar{c}$ events collected by Belle. The $D \to K^0_S\pi^+\pi^-$ Dalitz model used in the fit accounts for 14 intermediate two-body resonances. The $\pi\pi$ and $K\pi$ S-wave contributions are modeled by the K-matrix and LASS approaches, respectively.

The second ongoing combined *BABAR*+Belle measurement will extract the experimentally not well-known value of $\cos(2\beta)$. In this measurement, the $D \to K^0_S\pi^+\pi^-$ Dalitz model required for the analysis of the B meson decay is directly obtained from high-statistics flavor-tagged samples of $D \to K_S^0\pi^+\pi^-$ decays provided by $e^+e^- \to c\bar{c}$ data. The developed Dalitz model accounts for 14 intermediate two-body resonances and parameterizes the complex $\pi\pi$ and $K\pi$ S-wave dynamics by the K-matrix and LASS approaches, respectively. The preliminary result of the $D \to K_S^0\pi^+\pi^-$ Dalitz fit to events reconstructed from Belle $e^+e^- \to c\bar{c}$ data is shown in Figure 3.

The obtained $D \to K_S^0\pi^+\pi^-$ Dalitz model will be used in the subsequent time-dependent analysis of $\bar{B}^0 \to D^{(*)}h^0$ decays to extract $\cos(2\beta)$ combining BABAR and Belle data. The measurement aims to provide the world's most precise measurement of $\cos(2\beta)$ to potentially exclude multi-fold solutions of the CKM Unitarity Triangle.

4. Summary

The combined usage of the large BABAR and Belle data sets in single physics measurements enables for an unprecedented sensitivity in time-dependent *CP* violation measurements of neutral B meson decays. The first combined BABAR+Belle measurement has been presented, which is also the first measurement which uses a data sample of more than $1\,\mathrm{ab}^{-1}$. The measurement establishes an observation of *CP* violation in $\bar{B}^0 \to D_{CP}^{(*)}h^0$ decays governed by $\sin(2\beta)$ for the first time and agrees well with the more precise measurements of $b \to c\bar{c}s$ transitions. At the future high-luminosity B factory experiment Belle II, the results of $\bar{B}^0 \to D_{CP}^{(*)}h^0$ decays will provide a new SM reference for the new physics in the time-dependent *CP* violation of hadronic B meson decays that are predominantly mediated by $b \to s$ penguin amplitudes. In addition, preliminary results of the second combined BABAR+Belle measurement have been reported which will extract the not well-known value of $\cos(2\beta)$ by a time-dependent Dalitz analysis of $\bar{B}^0 \to D^{(*)}h^0$ decays with $D \to K_S^0\pi^+\pi^-$ decays.

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