CP violation measurements in B mesons at Belle

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Abstract. We present recent measurements of time-dependent CP asymmetries in two neutral B decay modes: $B^0 \to \eta' K^0$ and $B^0 \to \omega K_S^0$. The measured values of mixing-induced ($\sin 2\phi_1^{\text{eff}}$) and direct CP violation parameters are: $\mathcal{S}_{\eta' K^0} = +0.68 \pm 0.07_{\text{stat}} \pm 0.03_{\text{syst}}$, $\mathcal{A}_{\eta' K^0} = +0.03 \pm 0.05_{\text{stat}} \pm 0.04_{\text{syst}}$ and $\mathcal{S}_{\omega K_S^0} = +0.91 \pm 0.32_{\text{stat}} \pm 0.05_{\text{syst}}$, $\mathcal{A}_{\omega K_S^0} = -0.36 \pm 0.19_{\text{stat}} \pm 0.05_{\text{syst}}$, respectively. These results are fully consistent with the current world average of $\sin 2\phi_1$ measured in $b \to c\bar{c}s$ transitions, and represent the most accurate measurements in these modes up-to-date. In addition, we present a new preliminary update on branching ratio measurement in $B^0 \to \pi^0\pi^0$ decay mode, the result of which: $\mathcal{B}(B^0 \to \pi^0\pi^0) = (0.90 \pm 0.12_{\text{stat}} \pm 0.10_{\text{syst}}) \times 10^{-6}$ represents an important ingredient in a $\pi\pi$ SU(2) isospin analysis, used to experimentally extract ϕ_2 angle from $B \to \pi\pi$ measurements. To obtain CP violation parameters ($\mathcal{B}(B^0 \to \pi^0\pi^0)$) the final data set of 772×10^6 (751.5×10^6) $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric e^+e^- collider in Japan (3.5×8.0 GeV) is used.

1. Introduction

Within the Standard Model (SM) the CP violation is established via charged weak currents and three generation Cabbibo-Kobayashi-Maskawa quark mixing matrix (CKM) [1], namely its single irreducible complex phase. Requirement on CKM unitarity gives rise to six triangles in the complex plane, one of which naturally describes the b-quark transitions and is characterized by three measurable quantities (angles): ϕ_1, ϕ_2 and ϕ_3. The B-factories with their experimental apparatuses, Belle [2] and BaBar, were designed to test the CKM mechanism. Particularly, one of the main tasks was an experimental determination of the angles together with the sides of the unitarity triangle. In the past decade, both Belle and BaBar clearly observed the CP violation in all statistically significant $b \to c\bar{c}s$ induced decays [3, 4]. The experimental outcome is a precise determination of $\sin 2\phi_1 = 0.667 \pm 0.023_{\text{stat}} \pm 0.012_{\text{syst}}$ (Belle result) [3] via time-dependent CP asymmetries in B^0 decays. Despite the fact that these measurements proved CKM predictions to be extremely successful, the matter-antimatter asymmetry (as incorporated in SM via CP violation) is well below what Universe observations require to solve the baryon asymmetry puzzle [5]. To search for new sources of CP violation, experimental effort has gradually focused on other quark transitions, e.g. $b \to q\bar{q}s$. They dominantly proceed via loop Feynman diagram, and thus can be regarded highly sensitive to a possible new heavy particle(s) contribution.

2. Recent ϕ_1 related Belle measurements

In B factories the B mesons are produced coherently from a $\Upsilon(4S)$ resonance. The $\Upsilon(4S)$ decays almost exclusively to a $B\bar{B}$ pair, where one B_{rec}^0 may be reconstructed in a studied decay mode while the other $\bar{B}_{\text{tag}}^0$ may reveal its flavour. Using a technique called time-dependent CP

analysis, one can extract CP violation parameters by measuring a CP asymmetry evolving in time. For a B decaying into a given CP final state f the CP asymmetry follows as:

$$a_{CP}(\Delta t) = \mathcal{A}_{\mathrm{f}} \cos(\Delta m_{\mathrm{d}} \Delta t) + \mathcal{S}_{\mathrm{f}} \sin(\Delta m_{\mathrm{d}} \Delta t), \tag{1}$$

where Δt stands for the proper time interval between B_{rec}^0 and $\bar{B}_{\mathrm{tag}}^0$, Δm_{d} ($\Delta \Gamma_{\mathrm{d}}$) is the difference between the masses (decay rates) of heavy and light B^0 mass eigenstates, and $\mathcal{A}_{\mathrm{f}}$ and $\mathcal{S}_{\mathrm{f}}$ represent direct and mixing-induced CP violation parameters, respectively. This relation assumes CPT invariance, perfect tagging and that $\Delta \Gamma_{\mathrm{d}} \sim 0$. For $b \to c\bar{c}s$ transitions, the SM predicts that $\mathcal{S}_{\mathrm{f}} = -\xi \sin 2\phi_1$ (with a very small theoretical uncertainty), where $\xi = -1(+1)$ for CP-odd (CP-even) final state. The ϕ_1 angle is related to the CKM elements as: $\phi_1 \equiv \arg[-V_{\mathrm{cd}} V_{\mathrm{cb}}^* / V_{\mathrm{td}} V_{\mathrm{tb}}^*]$.

In contrast to $c\bar{c}s$ transitions, $B^0 \to \eta' K^0$ and $B^0 \to \omega K_S^0$ represent physics decays induced by $b \to u\bar{u}s$ and $b \to d\bar{d}s$ transitions, where a penguin graph plays a dominant role. Nevertheless, a small pollution by CKM and colour-suppressed tree processes occurs and the CP violation parameters $\mathcal{S}_{\mathrm{f}}$ and $\mathcal{A}_{\mathrm{f}}$ may slightly deviate from the nominal values measured in $c\bar{c}s$ transitions. We expect $\mathcal{S}_{\mathrm{f}} \simeq -\xi \sin 2\phi_1$, $\mathcal{A}_{\mathrm{f}} \sim 0$. Therefore, observing a large deviation (further denoted as $\Delta\mathcal{S}_{\mathrm{f}}$) would be a clear sign for New Physics (NP). For the $B^0 \to \eta' K^0$ the SM predicts $\Delta\mathcal{S}_{\mathrm{f}}$ to be in the range: $[-0.05; +0.09]$ ($SU(3)_{\mathrm{F}}$ [6]) or $[-0.03; +0.03]$ (QCD factorization scheme [7]). For the $B^0 \to \omega K_S^0$ the SM predicts $\Delta\mathcal{S}_{\mathrm{f}}$ to be within $[+0.1; +0.2]$ (pQCD, QCD$_{\mathrm{F}}$, ... [8]).

2.1. Measurement of CP violation parameters in $B^0 \to \eta' K^0$
The overall reconstruction is performed separately in two CP eigenstates: $B^0 \to \eta' K_S^0$ ($CP = -1$) and $B^0 \to \eta' K_L^0$ ($CP = +1$) [9]. After a signal/background shape is determined, both channels are combined together and a common CP fit is performed. In order to increase the signal yield, several η' decay chains are used to reconstruct B^0 candidates: $\eta' \to \eta\pi^+\pi^-$ ($\eta \to \gamma\gamma$ or $\eta \to \pi^+\pi^-\pi^0$) and $\eta' \to \rho^0\gamma$ ($\rho^0 \to \pi^+\pi^-$). The last decay chain is not used in $B^0 \to \eta' K_L^0$ reconstruction due to its low signal-to-background ratio.
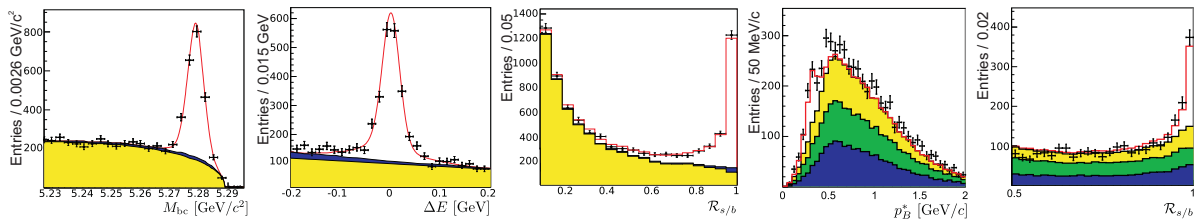
Figure 1. From left to right: Signal-enhanced M_{bc}, ΔE and $\mathcal{R}_{\mathrm{S/B}}$ distributions of $B^0 \to \eta' K_S^0$ candidates (red - total PDF, yellow - $q\bar{q}$ background, blue - $B\bar{B}$ background); signal-enhanced p_B^* and $\mathcal{R}_{\mathrm{S/B}}$ distributions of $B^0 \to \eta' K_L^0$ candidates (red - total PDF, blue, green and yellow - combinatorial background with fake η', real η' with fake K_L^0, and both real η' with real K_L^0, respectively). All analysed η' decay modes are combined in the plots.

In order to find the signal/background fraction, several event-distributions are simultaneously fitted (see Fig. 1). In $\eta' K_S^0$ analysis the following variables are used: a beam-constraint mass, $M_{\mathrm{bc}} = \sqrt{(E_{\mathrm{beam}}^{\mathrm{CMS}})^2 - (p_B^{\mathrm{CMS}})^2}$, difference between the B meson energy and beam energy, $\Delta E = E_B^{\mathrm{CMS}} - E_{\mathrm{beam}}^{\mathrm{CMS}}$, and $q\bar{q}$ (continuum) suppressing variable ($q = u, d, s, c$) - likelihood ratio, $\mathcal{R}_{\mathrm{S/B}}$. Similarly, in $\eta' K_L^0$ decay the yield is extracted by $\mathcal{R}_{\mathrm{S/B}}$ and the B^0 momentum in the CMS, $p*_B$, which is calculated using η' momentum and the K_L^0 flight direction, assuming $\Delta E = 0$. In total, $3541 \pm 90_{\mathrm{stat}}$ signal candidates are reconstructed. Afterwards, the values of $\sin 2\phi_1^{\mathrm{eff}}$ and

$\mathcal{A}_{\eta'K^0}$ are obtained by performing an unbinned, maximum-likelihood (uML) fit to the $(\Delta t; q)$ distributions of the signal region events (see Fig. 2). In the plots $q = +1$ and $q = -1$ stand for the B flavour on the tag side B^0 and $\bar{B}^0$, respectively. The new result, superseding previous Belle
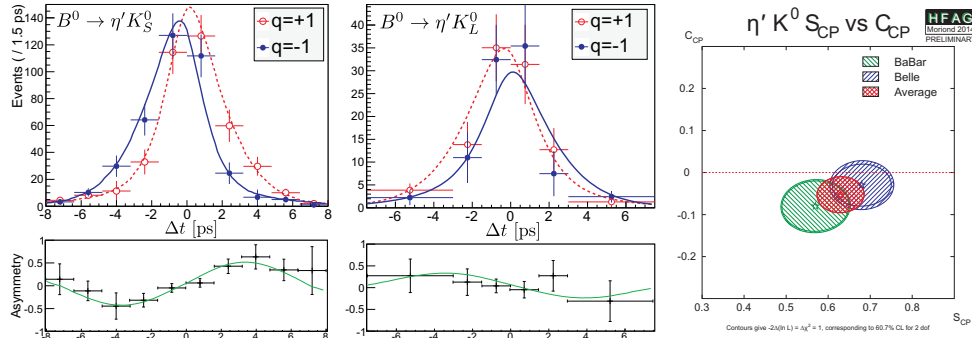
Figure 2. Data $(\Delta t; q)$ fit distributions for $\eta'K_S^0$ (left) and $\eta'K_L^0$ (middle). Plot combining results from Belle and BaBar by Heavy Flavour Averaging Group (HFAG) is on the right [10].

measurements [11], is: $\mathcal{S}_{\eta'K^0} = +0.68 \pm 0.07_{\text{stat}} \pm 0.03_{\text{syst}}$ and $\mathcal{A}_{\eta'K^0} = +0.03 \pm 0.05_{\text{stat}} \pm 0.04_{\text{syst}}$, which is fully consistent with the older Belle measurement [11], BaBar result [12] and the SM predictions, see the HFAG plot in Fig. 2.

2.2. Measurement of CP violation parameters in $B^0 \to \omega K_S^0$
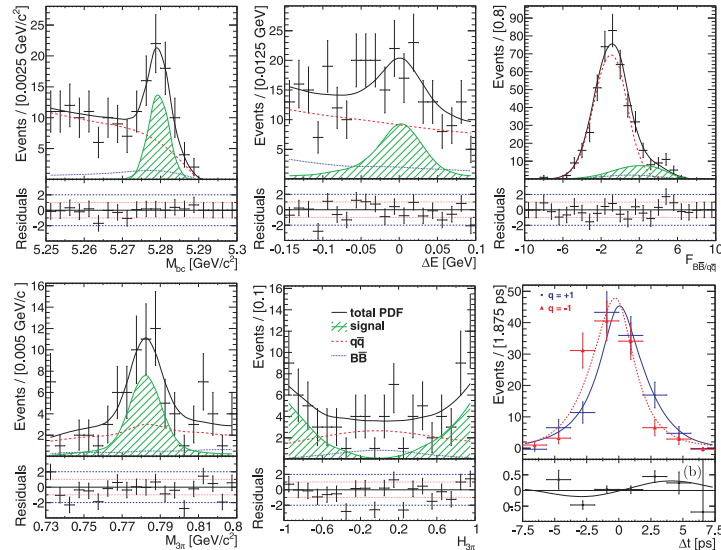
Figure 3. From left to right: Signal-enhanced fit projections in: M_{bc}, ΔE, Fisher ($F_{B\bar{B}/q\bar{q}}$), ω invariant mass ($M_{3\pi}$), ω helicity ($H_{3\pi}$) and $(\Delta t; q)$. The black curve corresponds to the total PDF, green to signal PDF, dashed red to $q\bar{q}$ background, blue dotted to $B\bar{B}$ background.

In $B^0 \to \omega K_S^0$, the CP parameters are directly obtained from a simultaneous seven-dimensional uML fit to signal/background distributions: M_{bc}, ΔE, invariant mass of $\omega \to \pi^+\pi^-\pi^0$, ω helicity angle, $\mathcal{H}_{3\pi}$, Fisher discriminant, $\mathcal{F}_{B\bar{B}/q\bar{q}}$ (used to suppress continuum), and fit to $(\Delta t; q)$ distribution (Fig. 3). In total, $234 \pm 22_{\text{stat}}$ signal candidates are reconstructed [13].
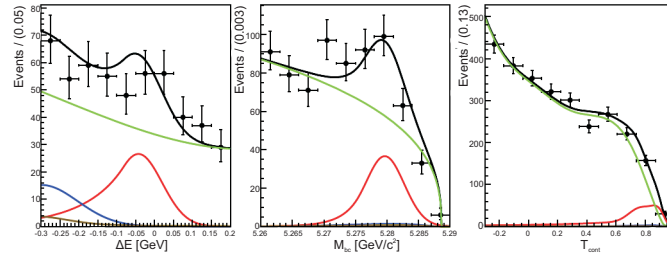
Figure 4. Signal-enhanced fit projections: ΔE (left), M_{bc} (middle), T_{cont} (right). Total PDF is displayed in black, signal in red, $q\bar{q}$ in green, rare B decays in brown and $B \to \rho\pi$ in blue.

The final result can be summarized as: $\mathcal{S}_{\omega K_S^0} = +0.91 \pm 0.32_{\text{stat}} \pm 0.05_{\text{syst}}$ and $\mathcal{A}_{\omega K_S^0} = -0.36 \pm 0.19_{\text{stat}} \pm 0.05_{\text{syst}}$. By performing a likelihood scan, a $\mathcal{S}_{\omega K_S^0}$ deviation of $3.1\,\sigma$ from the CP conservation hypothesis is found. That makes this result the first evidence of CP violation in this mode. In addition, the values are in a good agreement with previous Belle [14] and BaBar [12] results, so no evidence of NP is observed at the current level of exp. sensitivity.

3. New preliminary update on branching fraction measurement in $B^0 \to \pi^0\pi^0$

This measurement is a preliminary update on a previous Belle result: $\mathcal{B} = (2.3^{+0.4+0.2}_{-0.5-0.3}) \times 10^{-6}$ [15], and represents an important ingredient in a $\pi\pi$ SU(2) isospin analysis [16]. This analysis is applied to disentangle contribution of $\Delta\phi_2$ in $S_{\text{f}} \sim \sin(2\phi_2 + 2\Delta\phi_2)$ relation, and thus to experimentally extract ϕ_2 angle ($\phi_2 \equiv \arg[-V_{\text{td}}V_{\text{tb}}^*/V_{\text{ud}}V_{\text{ub}}^*]$) from $B \to \pi\pi$ measurements [17]. The theoretical prediction based on QCD factorization scheme is $\mathcal{B} < 1.0 \times 10^{-6}$ [18].

The analysis strategy consisted in a sequential reconstruction of four gammas, two neutral pions and B^0 candidates. The event-distributions used in a final uML fit are: M_{bc}, ΔE and a $q\bar{q}$ suppression variable, T_{cont}. T_{cont} is the output of a Fisher discriminant which combines event shape variables: $\cos\vartheta$ of the $\pi^0\pi^0$ system to the B^0-flight direction and $\cos\vartheta_{\text{thrust}}$ of the reconstructed B^0 compared to the thrust of the rest of the event. In the distributions (see Fig. 4) the continuum component forms the largest background contribution. The Belle new result is: $\mathcal{B}(B^0 \to \pi^0\pi^0) = (0.90 \pm 0.12_{\text{stat}} \pm 0.10_{\text{syst}}) \times 10^{-6}$, measured with $6.7\,\sigma$ significance.

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