

# Measurements of the CKM Angle $\beta/\phi_1$ at $B$ Factories

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We present a review of the measurements of the CKM angle  $\beta$  ( $\phi_1$ ) by the *BABAR* and Belle experiments at the asymmetric-energy  $e^+e^-$   $B$  Factories PEP-II and KEKB. The angle  $\beta$  ( $\phi_1$ ) is measured by time-dependent  $CP$  analyses of neutral  $B$  meson decays in a  $\Upsilon(4S) \rightarrow B\bar{B}$  system, where one  $B$  meson is fully reconstructed in a final state that can be accessed to by both  $B^0$  and  $\bar{B}^0$ , usually a  $CP$  eigenstate. This angle has been measured at a high precision through  $B^0 \rightarrow (c\bar{c})K^0$  channels. We also review another tree-dominated decay  $B^0 \rightarrow D^{(*)0}h^0$  ( $h^0 = \pi^0, \eta^{(\prime)}, \omega$ ); tree decays with penguin pollutions,  $B^0 \rightarrow D^{(*)\pm}D^\mp$  and  $J/\psi\pi^0$ ; and penguin dominated modes,  $B^0 \rightarrow \eta'K^0, K^+K^-K^0$ , and  $K_S^0K_S^0K_S^0$ . A hint of  $\sin 2\beta$  ( $\sin 2\phi_1$ ) in charmless modes less than  $(c\bar{c})K^0$  modes still persists, which may be an indication of possible new physics entering the loop in the penguin diagram.

## 1. Introduction

Measurements of time-dependent  $CP$  asymmetries in  $B^0$  meson decays, through the interference between decays with and without  $B^0$ - $\bar{B}^0$  mixing, have provided stringent tests on the mechanism of  $CP$  violation in the standard model (SM). The time-dependent  $CP$  asymmetry amplitude equals to  $\sin 2\beta$ <sup>1</sup> in the SM if the  $B$  meson decays to a final states that can be accessed to by both  $B^0$  and  $\bar{B}^0$  without non-trivial relative weak phase. The angle  $\beta = \arg(V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$  is a phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. The phase difference,  $2\beta$ , between decays with and without  $B^0$ - $\bar{B}^0$  mixing, arises through the box diagrams in  $B^0$ - $\bar{B}^0$  mixing, which are dominated by the diagrams with virtual top quark.

In this paper we present a review of recent measurements of  $\beta$  at *BABAR* and Belle experiments at the asymmetric-energy  $e^+e^-$   $B$  Factories PEP-II and KEKB, including precision measurements using  $B^0 \rightarrow (c\bar{c})K^0$  decays, new decay modes with tree diagram,  $B^0 \rightarrow D^{(*)0}h^0$  ( $h^0 = \pi^0, \eta^{(\prime)}, \omega$ ), tree decays with penguin pollutions,  $B^0 \rightarrow D^{(*)\pm}D^\mp$  and  $J/\psi\pi^0$ , and penguin dominated modes,  $B^0 \rightarrow \eta'K^0, K^+K^-K^0$ , and  $K_S^0K_S^0K_S^0$ . We also present the measurements that resolve the two-fold ambiguity in  $2\beta$ . Finally we present the comparison between the latest  $\sin 2\beta$  measurements of  $(c\bar{c})K^0$  modes and charmless modes.

At the time of the writing of this paper, Belle and *BABAR* have collected more than  $700 \text{ fb}^{-1}$  and  $400 \text{ fb}^{-1}$  of data, respectively, which correspond to more than 1.1 billion  $\Upsilon(4S) \rightarrow B\bar{B}$  decays. Most results shown here are based on  $535 \times 10^6$  ( $383 \times 10^6$ )  $B\bar{B}$  pairs of data for Belle (*BABAR*) experiment.

<sup>1</sup>*BABAR* and Belle collaborations use different conventions to label the three CKM angles. Here we adopt the *BABAR* convention of  $\beta, \alpha$  and  $\gamma$ , rather than Belle's  $\phi_1 = \beta, \phi_2 = \alpha$ , and  $\phi_3 = \gamma$ .

## 2. Time-Dependent $CP$ Asymmetry

To measure time-dependent  $CP$  asymmetries, we typically fully reconstruct a neutral  $B$  meson decaying into a  $CP$  eigenstate. From the remaining particles in the event, the vertex of the other  $B$  meson,  $B_{\text{tag}}$ , is reconstructed and its flavor is identified (tagged). The proper decay time difference  $\Delta t = t_{CP} - t_{\text{tag}}$ , between the signal  $B$  ( $t_{CP}$ ) and  $B_{\text{tag}}$  ( $t_{\text{tag}}$ ) is determined from the measured distance between the two  $B$  decay vertices projected onto the boost axis and the boost ( $\beta\gamma = 0.56$  at PEP-II and  $0.43$  at KEKB) of the center-of-mass (c.m.) system. The  $\Delta t$  distribution, assuming  $CP$  conservation in  $B^0$ - $\bar{B}^0$  mixing and  $\Delta\Gamma/\Gamma = 0$ , is given by:

$$F_{\pm}(\Delta t) = \frac{\Gamma e^{-\Gamma|\Delta t|}}{4} [1 \mp \Delta w \pm (1 - 2w)(\eta_f \mathcal{S} \sin(\Delta m \Delta t) - \mathcal{C} \cos(\Delta m \Delta t))], \quad (1)$$

where the upper (lower) sign is for events with  $B_{\text{tag}}$  being identified as a  $B^0$  ( $\bar{B}^0$ ),  $\eta_f$  is the  $CP$  eigenvalue of the final state,  $\Delta m$  is the  $B^0$ - $\bar{B}^0$  mixing frequency,  $\Gamma$  is the mean decay rate of the neutral  $B$  meson, the mistag parameter  $w$  is the probability of incorrectly identifying the flavor of  $B_{\text{tag}}$ , and  $\Delta w$  is the difference of  $w$  for  $B^0$  and  $\bar{B}^0$ . In the SM, the parameters  $\mathcal{S} = \text{Im}\lambda/(1 + |\lambda|)$  and  $\mathcal{C} = (1 - |\lambda|)/(1 + |\lambda|)$ , where  $\lambda = \frac{q}{p} \frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f}$ , and  $\mathcal{A}_f$  ( $\bar{\mathcal{A}}_f$ ) is the amplitude of  $B^0$  ( $\bar{B}^0$ ) decaying to the  $CP$  final state  $f$ . In the SM, if only one diagram contributes to the decay process,  $\mathcal{S} = -\sin 2\beta$  and  $\mathcal{C} = 0$ . A non-zero value of  $\mathcal{C}$  would indicate direct  $CP$  violation.

Because there can be other diagrams with a different weak phase, the experimental result of  $\mathcal{S}$  does not necessarily equal to  $-\sin 2\beta$ . To separate the measured value from the standard model  $\sin 2\beta$ , we denote the measured one  $\sin 2\beta_{\text{eff}}$ .

### 3. $B^0 \rightarrow (c\bar{c})K^0$

The  $CP$  violation in neutral  $B$  meson system was first established experimentally by *BABAR* and Belle in 2001 using  $B$  decays to a charmonium ( $c\bar{c}$ ) and a neutral  $K$  meson [2]. These modes are dominated by a color-suppressed  $b \rightarrow c\bar{c}s$  tree diagram. The dominant penguin diagram has the same weak phase. The term that has a different weak phase is a penguin contribution that is Cabibbo suppressed by  $\mathcal{O}(\sin^2 \theta_{Cabibbo})$ . Therefore, to a good accuracy, the parameters  $\mathcal{S} = -\sin 2\beta$  and  $\mathcal{C} = 0$ . Recent theoretical calculations suggest that the correction on  $\mathcal{S}$  is in the order of  $10^{-3}$ – $10^{-4}$  [3].

These modes have relatively large ( $\mathcal{O}(10^{-4}$ – $10^{-5})$ ), branching fractions and have low experimental backgrounds and high reconstruction efficiencies. For the mode  $B^0 \rightarrow J/\psi(\ell^+\ell^-)K_S^0(\pi^+\pi^-)$ , the signal purity is typically greater than 95%.

From  $535 \times 10^6 B\bar{B}$  pairs, Belle reconstructs approximately 7500  $B^0 \rightarrow J/\psi K_S^0$  and 6500  $J/\psi K_L^0$  signal events, with  $J/\psi \rightarrow \ell^+\ell^-$  ( $\ell = e, \mu$ ) and  $K_S^0 \rightarrow \pi^+\pi^-$  or  $\pi^0\pi^0$ , and measures  $\sin 2\beta_{\text{eff}} = +0.642 \pm 0.031 \pm 0.017$  and  $\mathcal{C} = -0.018 \pm 0.021 \pm 0.014$  [4].

*BABAR* uses many other modes in addition to  $J/\psi K_S^0$  and  $J/\psi K_L^0$ , including  $\psi(2S)K_S^0$ ,  $\chi_{c1}K_S^0$ ,  $\eta_c K_S^0$  and  $J/\psi K^{*0}(K_S^0\pi^0)$ . *BABAR* reconstructs approximately 6900  $CP$ -odd signal events and 3700  $CP$ -even signal events from  $383 \times 10^6 B\bar{B}$  pairs, and obtains  $\sin 2\beta_{\text{eff}} = +0.714 \pm 0.032 \pm 0.018$  and  $\mathcal{C} = +0.049 \pm 0.022 \pm 0.017$  [5]. In addition, *BABAR* also performs measurements, including systematic uncertainties, using individual mode, because the theoretical corrections could in principle be different among those modes. *BABAR* also reports the result using the same decay modes as used by Belle in order to provide a direct comparison. The two experiments agree well within the uncertainty.

The averages, calculated by the Heavy Flavor Averaging Group (HFAG) [6], are  $\sin 2\beta_{\text{eff}} = +0.678 \pm 0.026$  and  $\mathcal{C} = +0.012 \pm 0.020$ . The uncertainty on  $\sin 2\beta_{\text{eff}}$  is 4%, or approximately  $1^\circ$  on  $\beta$ . Because of the high experimental precision and low theoretical uncertainty, the result from these modes serves as a benchmark in the SM; any other measurements of  $\sin 2\beta$  that have a significant deviation from it, beyond the usually small SM corrections, would indicate evidence for new physics.

### 4. $B^0 \rightarrow D^{(*)\pm}D^{(*)\mp}$

The decay  $B^0 \rightarrow D^{(*)\pm}D^{(*)\mp}$  is dominated by a color-allowed Cabibbo-suppressed  $b \rightarrow c\bar{c}d$  tree diagram. The penguin diagram in the SM has a different weak phase and is expected to contribute few percent correction [7] to  $CP$  asymmetry. A large deviation in  $\sin 2\beta_{\text{eff}}$  from that in  $B^0 \rightarrow (c\bar{c})K^0$  would indicate

possible new physics contribution to the loop in the penguin diagram.

The final state  $D^+D^-$  is a  $CP$  eigenstate so  $\mathcal{S} = -\sin 2\beta$  and  $\mathcal{C} = 0$  in the SM when neglecting the penguin contribution. The final state  $D^{*\pm}D^{*\mp}$  is a mixture of  $CP$  even and  $CP$  odd states. An angular analysis is needed to disentangle the contributions from different  $CP$  states. The final state  $D^{*\pm}D^\mp$  is not a  $CP$  eigenstate. The decay amplitudes can have a strong phase difference  $\delta$ , i.e.,  $\mathcal{A}(B^0 \rightarrow D^{*+}D^-)/\mathcal{A}(B^0 \rightarrow D^{*-}D^+) = Re^{i\delta}$ . As a result, the  $\mathcal{S}$  and  $\mathcal{C}$  parameters, (+ for  $D^{*+}D^-$  and – for  $D^{*-}D^+$ ) are  $\mathcal{S}_\pm = 2R \sin(2\beta_{\text{eff}} \pm \delta)/(1 + R^2)$ , and  $\mathcal{C}_\pm = \pm(R^2 - 1)/(R^2 + 1)$ , assuming there is no direct  $CP$  violation.

Belle collaboration recently reports evidence for a large direct  $CP$  violation in  $D^+D^-$  channel using a data sample of  $535 \times 10^6 B\bar{B}$  pairs. They measure  $\mathcal{S} = -1.13 \pm 0.37 \pm 0.09$  and  $\mathcal{C} = -0.91 \pm 0.23 \pm 0.06$  [8]. The  $CP$  conservation,  $\mathcal{S} = \mathcal{C} = 0$ , is excluded at  $4.1\sigma$  level and  $\mathcal{C} = 0$  is excluded at  $3.2\sigma$ . However, such a large direct  $CP$  violation has not been observed in previous measurements with  $B^0 \rightarrow D^{(*)\pm}D^{(*)\mp}$  decays, involving the same quark-level weak decay [9–12]. *BABAR* also uses the same decay modes and measures  $\mathcal{S} = -0.54 \pm 0.34 \pm 0.06$  and  $\mathcal{C} = 0.11 \pm 0.22 \pm 0.07$  [13], which is consistent with the SM with small penguin contributions. Figure 1 shows the  $\Delta t$  distributions for  $B^0$ -tagged and  $\bar{B}^0$ -tagged events separately. For the result from Belle, the plots show clear difference between the yields of  $B^0$ -tagged and  $\bar{B}^0$ -tagged events. The consistency of these two results are quite low ( $\chi^2/\text{dof} = 12/2$ , or C.L.=0.003, corresponding to  $3\sigma$ ). Figure 2 shows the comparison by HFAG.

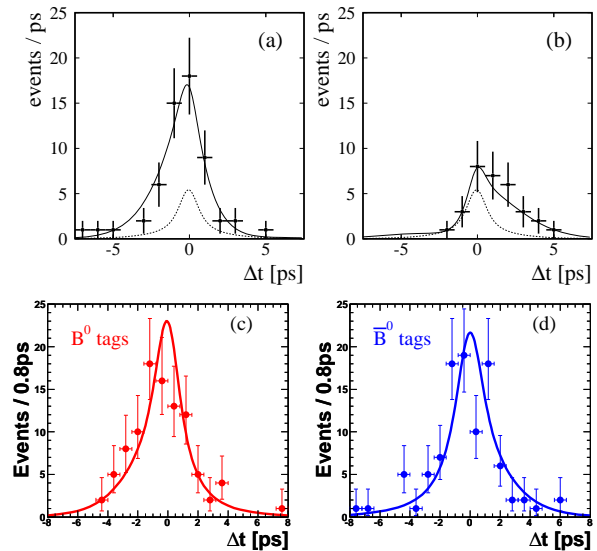


Figure 1:  $\Delta t$  distributions of  $B^0 \rightarrow D^+D^-$  from (a,b) Belle experiment and (c,d) *BABAR* experiment. Plots (a) and (c) are for  $B^0$ -tagged events and (b) and (d) are for  $\bar{B}^0$ -tagged events.

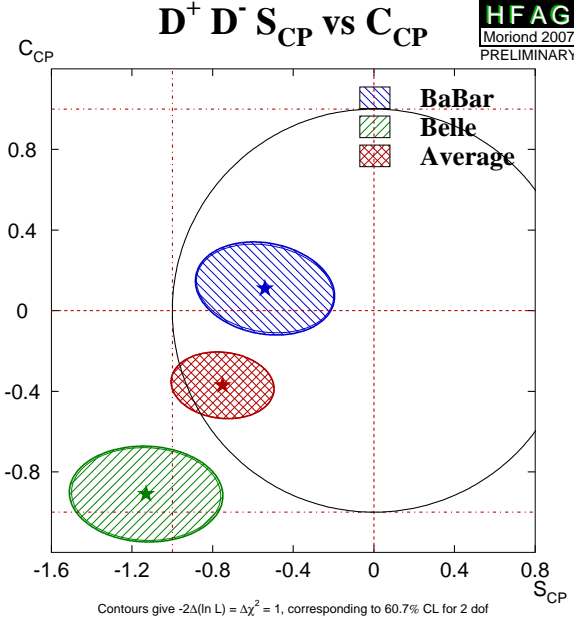


Figure 2: The comparison between Belle's and BABAR's  $B^0 \rightarrow D^+ D^-$  results.

BABAR also reports an updated measurement of  $B^0 \rightarrow D^{*\pm} D^\mp$  [13]. The result is  $\mathcal{C}_{D^{*+}D^-} = 0.18 \pm 0.15 \pm 0.04$ ,  $\mathcal{S}_{D^{*+}D^-} = -0.79 \pm 0.21 \pm 0.06$ ,  $\mathcal{C}_{D^{*-}D^+} = 0.23 \pm 0.15 \pm 0.04$ , and  $\mathcal{S}_{D^{*-}D^+} = -0.44 \pm 0.22 \pm 0.06$ . It is also illustrative to express the parameters  $\mathcal{C}$  and  $\mathcal{S}$  in a slightly different parameterization [14]:  $\mathcal{C}_{D^*D} = (\mathcal{C}_{D^{*+}D^-} + \mathcal{C}_{D^{*-}D^+})/2$ ,  $\Delta\mathcal{C}_{D^*D} = (\mathcal{C}_{D^{*+}D^-} - \mathcal{C}_{D^{*-}D^+})/2$ ,  $\mathcal{S}_{D^*D} = (\mathcal{S}_{D^{*+}D^-} + \mathcal{S}_{D^{*-}D^+})/2$  and  $\Delta\mathcal{S}_{D^*D} = (\mathcal{S}_{D^{*+}D^-} - \mathcal{S}_{D^{*-}D^+})/2$ . The quantities  $\mathcal{C}_{D^*D}$  and  $\mathcal{S}_{D^*D}$  parameterize flavor-dependent direct  $CP$  violation, and mixing-induced  $CP$  violation related to the angle  $\beta$ , respectively. The parameters  $\Delta\mathcal{C}_{D^*D}$  and  $\Delta\mathcal{S}_{D^*D}$  are insensitive to  $CP$  violation.  $\Delta\mathcal{C}_{D^*D}$  describes the asymmetry between the rates  $\Gamma(B^0 \rightarrow D^{*+}D^-) + \Gamma(\bar{B}^0 \rightarrow D^{*-}D^+)$  and  $\Gamma(B^0 \rightarrow D^{*-}D^+) + \Gamma(\bar{B}^0 \rightarrow D^{*+}D^-)$ , while  $\Delta\mathcal{S}_{D^*D}$  is related to the strong phase difference,  $\delta$ . BABAR reports

$$\begin{aligned} \mathcal{C}_{D^*D} &= 0.21 \pm 0.11 \pm 0.03 \\ \mathcal{S}_{D^*D} &= -0.62 \pm 0.15 \pm 0.04 \\ \Delta\mathcal{C}_{D^*D} &= -0.02 \pm 0.11 \pm 0.03 \\ \Delta\mathcal{S}_{D^*D} &= -0.17 \pm 0.15 \pm 0.04. \end{aligned} \quad (2)$$

The parameter  $\mathcal{S}_{D^*D} = \frac{2R}{1+R^2} \cos \delta \sin 2\beta_{\text{eff}}$  in the SM. BABAR finds that it is non-zero at approximately  $4\sigma$  level, which indicates  $\sin 2\beta_{\text{eff}} \neq 0$  at the same significance in these modes.

## 5. $B^0 \rightarrow J/\psi\pi^0$

The  $B^0 \rightarrow J/\psi\pi^0$  decay has the same quark level diagrams as  $J/\psi K^0$  except that the  $s$  quark in  $b \rightarrow c\bar{c}s$  is substituted by a  $d$  quark. Therefore, the dominant tree diagram is Cabibbo suppressed compared to that of  $J/\psi K^0$ . However, unlike  $J/\psi K^0$ , the dominant penguin diagram in  $J/\psi\pi^0$ , whose CKM element factor is in the same order as the tree, has a different weak phase from the tree. Therefore the deviation in  $\sin 2\beta_{\text{eff}}$  from that of  $J/\psi K^0$  could be substantial. This mode is also useful to constrain the penguin pollution in  $B^0 \rightarrow (c\bar{c})K^0$  mode in a more model-independent way (assuming SU(3) symmetry) [15].

Neither BABAR nor Belle updated their results since 2005. The current results are  $\sin 2\beta_{\text{eff}} = -0.72 \pm 0.42 \pm 0.09$  and  $\mathcal{C} = 0.01 \pm 0.29 \pm 0.03$  using  $152 \times 10^6 B\bar{B}$  pairs in Belle [16] and  $\sin 2\beta_{\text{eff}} = -0.68 \pm 0.30 \pm 0.04$  and  $\mathcal{C} = -0.21 \pm 0.26 \pm 0.06$  using  $232 \times 10^6 B\bar{B}$  pairs in BABAR [17].

## 6. $B^0 \rightarrow D^{(*)0}h^0$ ( $h^0 = \pi^0, \eta^{(\prime)}, \omega$ )

### 6.1. $\sin 2\beta_{\text{eff}}$ measurement using $D^0$ decays to $CP$ eigenstates

The decay  $B^0 \rightarrow D^{(*)0}h^0$  ( $h^0 = \pi^0, \eta^{(\prime)}, \omega$ ) is dominated by a color-suppressed  $b \rightarrow c\bar{u}d$  tree diagram. The final state is a  $CP$  eigenstate if the neutral  $D$  meson also decays to a  $CP$  eigenstate, and therefore Eq. 1 applies. This mode is free of penguin diagrams. The next diagram is also a color-suppressed tree diagram,  $b \rightarrow u\bar{c}d$ , which is doubly Cabibbo suppressed. The SM correction on  $\sin 2\beta_{\text{eff}}$  is believed to be a few percent [18]. Because it has no penguin contributions, the “usual” new physics that only enters the loops through unobserved heavy virtual particles would not affect these decays, other than that they can still affect the box diagrams in  $B^0$ - $\bar{B}^0$  mixing. However, more exotic new physics models such as  $R$ -parity-violating supersymmetry [18] could enter at tree level in these decays (Fig. 3).

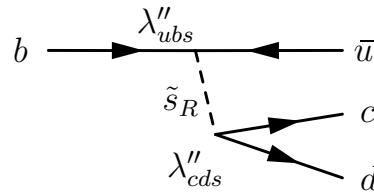


Figure 3:  $R$ -parity-violating supersymmetry diagram that could contribute to  $B^0 \rightarrow D^{(*)0}h^0$  decays.

BABAR recently reports a measurement of  $\sin 2\beta_{\text{eff}}$  using  $D^{(*)0}\pi^0$  with  $D^0 \rightarrow K^+K^-$ ,  $K_s^0\omega$ , and

$D^{(*)0}\eta$  with  $D^0 \rightarrow K^+K^-$ , and  $D^0\omega$  with  $D^0 \rightarrow K^+K^-, K_S^0\omega, K_S^0\pi^0$ . The  $D^{*0}$  is reconstructed from  $D^{*0} \rightarrow D^0\pi^0$ , when applicable. *BABAR* uses  $383 \times 10^6$   $B\bar{B}$  pairs and obtains  $\sin 2\beta_{\text{eff}} = 0.56 \pm 0.23 \pm 0.05$  and  $\mathcal{C} = -0.23 \pm 0.16 \pm 0.04$  [19]. This result is 2.3 $\sigma$  away from  $CP$  conservation.

## 6.2. Resolve ambiguity using

$$D^0 \rightarrow K_S^0\pi^+\pi^-$$

The  $B^0$  mixing phase  $2\beta$  has a two-fold ambiguity from  $\sin 2\beta$  measurement,  $2\beta$  and  $\pi - 2\beta$  (or equivalently  $\beta$  has a four-fold ambiguity,  $\beta, \pi/2 - \beta, \pi + \beta$ , and  $3\pi/2 - \beta$ ). The ambiguity can be resolved by studying decay modes that involve multi-body final states, where the known variation of the strong phase differences across the phase space allows one to access  $\cos 2\beta$  in addition to  $\sin 2\beta$ . To resolve the ambiguity, one only need to know the sign of  $\cos 2\beta$ .

Both Belle and *BABAR* have performed a time-dependent  $D \rightarrow K_S^0\pi^+\pi^-$  Dalitz plot analysis in the decay  $B^0 \rightarrow D^{(*)}[K_S^0\pi^+\pi^-]h^0$  [20] to measure  $\cos 2\beta$  (and  $\sin 2\beta$ ). The decay rate of the  $B$  meson, accompanied by a  $B^0$  (+ sign) or  $\bar{B}^0$  (- sign) is proportional to

$$\begin{aligned} \mathcal{P}_{\pm} &= \frac{e^{-\Gamma\Delta t}}{2} |\mathcal{A}_B|^2 \cdot \left[ (|\mathcal{A}_{\bar{D}}|^2 + |\lambda|^2 |\mathcal{A}_D|^2) \right. \\ &\quad \mp (|\mathcal{A}_{\bar{D}}|^2 - |\lambda|^2 |\mathcal{A}_D|^2) \cos(\Delta m\Delta t) \\ &\quad \left. \pm 2|\lambda|\xi_{h^0}(-1)^L \text{Im}(e^{-2i\beta} \mathcal{A}_D \mathcal{A}_{\bar{D}}^*) \sin(\Delta m\Delta t) \right], \end{aligned} \quad (3)$$

where  $\mathcal{A}_B$  is the  $B$  decay amplitude, and  $\mathcal{A}_D$  ( $\mathcal{A}_{\bar{D}}$ ) is the decay amplitude of  $D^0$  ( $\bar{D}^0$ ) and is a function of the Dalitz plot variables ( $m_{K_S^0\pi^+}^2, m_{K_S^0\pi^-}^2$ ), which is determined from large data samples of  $e^+e^- \rightarrow XD^{*+}, D^{*+} \rightarrow D^0\pi^+$  events. The factor  $\xi_{h^0}$  is the  $CP$  eigenvalue of  $h^0$ , and  $(-1)^L$  is the angular momentum factor. In the last term of Eq. 3 we can rewrite

$$\begin{aligned} \text{Im}(e^{-2i\beta} \mathcal{A}_D \mathcal{A}_{\bar{D}}^*) &= \text{Im}(\mathcal{A}_D \mathcal{A}_{\bar{D}}^*) \cos 2\beta \\ &\quad - \text{Re}(\mathcal{A}_D \mathcal{A}_{\bar{D}}^*) \sin 2\beta, \end{aligned} \quad (4)$$

and treat  $\cos 2\beta$  and  $\sin 2\beta$  as independent parameters in the analyses.

Belle obtains  $\cos 2\beta = 1.87_{-0.53-0.32}^{+0.40+0.22}$  and  $\sin 2\beta = 0.78 \pm 0.44 \pm 0.22$ , and determines  $\cos 2\beta > 0$  at 98.3% confidence level [21]. *BABAR* measures  $\cos 2\beta = 0.54 \pm 0.54 \pm 0.08 \pm 0.18$  and  $\sin 2\beta = 0.45 \pm 0.36 \pm 0.05 \pm 0.07$ , where the last errors are due to Dalitz model uncertainty, and determines  $\cos 2\beta > 0$  at 87% confidence [22]. Another mode ( $B^0 \rightarrow K^+K^-K^0$ ) can also be used to resolve this ambiguity. We will discuss it later in Sec. 7.2.

## 7. $\sin 2\beta_{\text{eff}}$ in $b \rightarrow s$ penguin dominated modes

In the measurement of  $\sin 2\beta$ , different charmless modes have different standard model corrections and uncertainties coming from, e.g., Cabibbo-suppressed trees, final state interaction long distance effect, etc. Several theoretical calculations predict the corrections and uncertainties are in the order of 1 to 10 percent [23–25].

These charmless  $b \rightarrow sq\bar{q}$  penguin modes are more sensitive to new physics that enters the loops because the new physics does not have to compete with the SM tree processes. In this section we present several notable  $\sin 2\beta$  measurements in charmless  $B$  decays and compare the current results with the high precision  $B \rightarrow (c\bar{c})K^0$  mode.

### 7.1. $B^0 \rightarrow \eta' K^0$

This mode is the most precisely measured penguin mode in the  $B$  Factories. It also has one of the smallest theoretical corrections and uncertainties. Therefore it is arguably the best penguin mode for searches of new physics that could affect  $\sin 2\beta$ . Both *BABAR* and Belle published their observations of  $CP$  asymmetry in this mode this year with more than  $5\sigma$  significance. This is the first time  $CP$  violation is observed in penguin modes with such a large significance. *BABAR* uses  $383 \times 10^6$   $B\bar{B}$  pairs ( $\sim 1050$   $\eta'K_S^0$  and  $\sim 250$   $\eta'K_L^0$  signal events) and measure  $\sin 2\beta_{\text{eff}} = 0.58 \pm 0.10 \pm 0.03$  and  $\mathcal{C} = -0.16 \pm 0.07 \pm 0.03$  [26]. Belle uses  $535 \times 10^6$   $B\bar{B}$  pairs ( $\sim 1420$   $\eta'K_S^0$  and  $\sim 450$   $\eta'K_L^0$  signal events) and measure  $\sin 2\beta_{\text{eff}} = 0.64 \pm 0.10 \pm 0.04$  and  $\mathcal{C} = 0.01 \pm 0.07 \pm 0.05$  [4]. The  $\Delta t$  distributions and asymmetries are shown in Fig. 4.

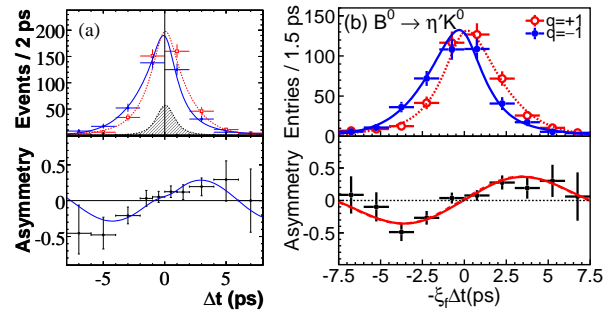


Figure 4: The  $\Delta t$  distributions and asymmetries in  $\eta'K^0$  mode for (a) *BABAR* (only  $\eta'K_S^0$  is shown) and (b) Belle.

### 7.2. $B^0 \rightarrow K^+K^-K^0$ and $\phi K^0$

The total branching fraction of the three-body  $B^0 \rightarrow K^+K^-K^0$  decay is relatively large, about six times the dominant resonance  $\phi(\rightarrow K^+K^-)K^0$ .

The final state is a mixture of  $CP$  even and  $CP$  odd states, depending on the spins of the resonances. *BABAR* [27] reconstructs about 1000  $K^+K^-K_S^0$  and 500  $K^+K^-K_L^0$  signal events from  $347 \times 10^6 B\bar{B}$  pairs, and performs a time-dependent Dalitz plot analysis to extract the  $CP$  asymmetry parameter and Dalitz plot model parameters simultaneously. The probability function of the  $B$  meson decay rate is similar to Eq. 3. Here *BABAR* chooses to extract  $\beta$  directly, rather than to fit for  $\cos 2\beta$  and  $\sin 2\beta$ . *BABAR*'s Dalitz model includes  $\phi(1020)$ ,  $f_0(980)$ ,  $X_0(1500)$  [28],  $\chi_{c0}$ , and non-resonance terms. Using the whole phase space, *BABAR* obtains  $\beta_{\text{eff}} = 0.361 \pm 0.079 \pm 0.037$ , which corresponds to  $\sin 2\beta_{\text{eff}} = 0.66 \pm 0.12 \pm 0.05$ . *BABAR* also fits for the region with  $m_{K^+K^-} < 1.1 \text{ GeV}/c^2$  and obtains  $\beta_{\text{eff}}(\phi K^0) = 0.06 \pm 0.16 \pm 0.05$ , and  $\beta_{\text{eff}}(f_0 K^0) = 0.18 \pm 0.19 \pm 0.04$ , which correspond to  $\sin 2\beta_{\text{eff}}(\phi K^0) = 0.12 \pm 0.31 \pm 0.10$  and  $\sin 2\beta_{\text{eff}}(f_0 K^0) = 0.35 \pm 0.35 \pm 0.08$ .

Since the angle  $\beta_{\text{eff}}$  is extracted directly, the  $(2\beta, \pi - 2\beta)$  ambiguity can be resolved. *BABAR* scans the angle  $\beta_{\text{eff}}$  and finds the change in the log likelihood from the best solution (near  $21^\circ$ ) to the second solution (near  $69^\circ$ ) corresponds to  $4.5\sigma$  statistical significance, and thus rules out the second solution.

Belle does not perform the time-dependent Dalitz analysis. It uses a quasi-two-body approach for  $\phi K^0$ , and combines all resonances in  $K^+K^-K^0$ , excluding  $\phi K^0$ . Using  $535 \times 10^6 B\bar{B}$  pairs, Belle obtains 420  $\phi K^0$  signal events, and  $\sin 2\beta_{\text{eff}} = 0.50 \pm 0.21 \pm 0.06$  and  $C = -0.07 \pm 0.15 \pm 0.05$  [4]. For  $B^0 \rightarrow K^+K^-K^0$ , Belle reconstructs 840 signal events and measures  $\sin 2\beta_{\text{eff}} = 0.68 \pm 0.15 \pm 0.03_{-0.13}^{+0.21}$  and  $C = 0.09 \pm 0.10 \pm 0.05$  [29]. The last uncertainty in  $\sin 2\beta_{\text{eff}}$  is due to the limited knowledge of the  $CP$  content in  $B^0 \rightarrow K^+K^-K^0$ , which are determined from the branching fractions of  $B^+ \rightarrow K^+K_S^0K_S^0$  and  $B^0 \rightarrow K^+K^-K^0$  using isospin relations. This uncertainty does not exist in *BABAR*'s measurement because of the full Dalitz analysis.

### 7.3. $B^0 \rightarrow K_S^0 K_S^0 K_S^0$

The decay  $B^0 \rightarrow K_S^0 K_S^0 K_S^0$  is a pure  $CP$ -even state [30], therefore a Dalitz analysis is not necessary. Belle uses  $535 \times 10^6 B\bar{B}$  pairs and obtains  $\sin 2\beta_{\text{eff}} = 0.30 \pm 0.32 \pm 0.08$  and  $C = -0.31 \pm 0.20 \pm 0.07$  [4]. *BABAR* uses  $383 \times 10^6 B\bar{B}$  pairs and determines  $\sin 2\beta_{\text{eff}} = 0.71 \pm 0.24 \pm 0.04$  and  $C = 0.02 \pm 0.21 \pm 0.05$  [31].

## 8. Conclusion

The measurement of  $\sin 2\beta$  is a rich program at the  $B$  Factories. A total of more than 900 million  $\Upsilon(4S) \rightarrow B\bar{B}$  pairs have been analyzed and the  $B$  Factories have achieved a precision of 4%

in  $\sin 2\beta$  measurement,  $\sin 2\beta = 0.678 \pm 0.026$ , using  $B^0 \rightarrow (c\bar{c})K^0$  decays. By studying the time-dependent evolution in multibody final states, such as  $B^0 \rightarrow D^0[K_S^0\pi^+\pi^-]h^0$  and  $B^0 \rightarrow K^+K^-K^0$  (and  $B^0 \rightarrow J/\psi K^{*0}(K_S^0\pi^0)$  [32, 33], not discussed here), the ambiguity in  $\beta$  is resolved and we are confident that  $\beta = (21.3 \pm 1.0)^\circ$  (in  $[0, \pi]$ ), rather than  $(68.7 \pm 1.0)^\circ$ .

Belle observes evidence for large direct  $CP$  asymmetry in  $B^0 \rightarrow D^+D^-$  channel. However, it is not confirmed by *BABAR*, and none of the other  $D^{(*)\pm}D^{(*)\mp}$  modes, which have the same quark-level weak decays, show large direct  $CP$  violation. More data are needed to resolve this discrepancy.

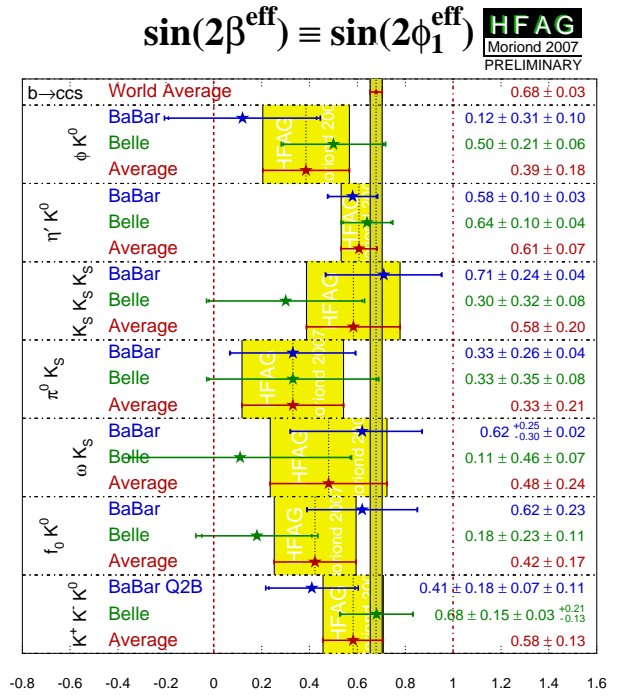


Figure 5: Results of  $\sin 2\beta_{\text{eff}}$  from selected  $b \rightarrow s$  penguin modes, compared to the world average, dominated by  $B^0 \rightarrow (c\bar{c})K^0$  mode.

Penguin dominated modes are great channels for probing physics beyond the standard model. Both  $B$  Factories have observed a clear  $CP$  asymmetry in  $B^0 \rightarrow \eta' K^0$  decays, and a great progress has been made in many other penguin modes. Currently the central values of  $\sin 2\beta_{\text{eff}}$  in most of the penguin modes are smaller than that in  $(c\bar{c})K^0$  mode. See Fig. 5. The naive average of penguin modes, ignoring the theoretical corrections and uncertainties, and the experimental correlations among systematic uncertainties, is approximately 2.5 standard deviations away from  $(c\bar{c})K^0$  mode. This is a tantalizing hint of possible new physics effect. However, it should not be taken too seriously because of the aforementioned details we

have ignored.

Both  $B$  Factories are expected to record more than double the analyzed datasets before they finish the data taking in the next year or two. We will be able to constrain the standard model and physics beyond the standard model much better, but it is unlikely we will have a clear answer to whether new physics has a significant effect in the  $CP$  asymmetry in the  $B$  decays.

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