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Measurements of the CKM angle ϕ_1/β at the B Factories

Himansu Sahoo on behalf of the Belle and BaBar Collaborations

Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii, 96848, USA, himansu@phys.hawaii.edu

Abstract

In this proceeding, we report the recent measurements of the CKM angle ϕ_1/β using large data samples collected by the Belle and BaBar experiments. The experiments have collected more than 1 billion $B\overline{B}$ pairs of data sample at the $\Upsilon(4S)$ resonance using the facilities of the asymmetric-energy e^+e^- colliders KEKB and PEP-II.

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SLAC National Accelerator Laboratory, Menlo Park, CA 94025

1 Introduction

In the standard model (SM), CP violation in B^0 meson decays originates from an irreducible complex phase in the 3×3 Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix [1]. The unitarity condition of the CKM matrix gives rise to a relation $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$, which can be represented by a triangle in the complex plane, known as the Unitarity Triangle (UT). The main objective of the B-factories is to test the SM picture of the origin of CP violation by measuring the angles (denoted by ϕ_1, ϕ_2 and ϕ_3)* and sides of the UT using different B decays. In this paper, we report the recent measurements concerning the angle ϕ_1 ($\equiv \pi - \arg(V_{tb}^* V_{td}/V_{cb}^* V_{cd})$).

2 Experimental Apparatus

The measurements discussed in this paper have been obtained by the Belle and BaBar experiments, located at the KEKB and PEP-II asymmetry-energy e^+e^- B factories. The accelerators operate at the $\Upsilon(4S)$ resonance, which is produced with a Lorentz boost of 0.43 at KEKB (3.5 on 8.0 GeV) [2] and 0.56 at PEP-II (3.1 on 9.0 GeV) [3]. The KEKB accelerator of the B factory in Japan achieved the current world record with a peak luminosity of 2.1×10^{34} cm^{-2}s^{-1}. Both the experiments have already stopped data dating. BaBar stopped operation in April 2008 and collected more than 430 fb^{-1} of data at $\Upsilon(4S)$ resonance. Belle stopped operation in June 2010 and collected more than 710 fb^{-1} of data. After a decade of successful operation, the B factories have a data sample of nearly 1200×10^6 $B\overline{B}$ pairs. The Belle and BaBar detectors are described in detail elsewhere [4, 5].

3 Measurements of ϕ_1/β

Measurements of time-dependent CP asymmetries in B^0 meson decays that proceed via the dominant CKM favored $b \to c\bar{c}s$ tree amplitude, such as $B^0 \to J/\psi K^0$, have provided a precise measurement of the angle ϕ_1, thus providing a crucial test of the mechanism of CP violation in the SM. For such decays the interference between the tree amplitude and the amplitude from $B^0 - \overline{B}^0$ mixing is dominated by the single phase ϕ_1. Other decay modes, which allow the measurements of ϕ_1 are $b \to c\bar{c}d$ transitions like $B^0 \to J/\psi\pi^0$, $B^0 \to D^{(*)+}D^{(*)-}$, $B^0 \to D^+D^-$. These modes are dominated by tree diagram, but loop may contribute. We can also measure ϕ_1 from pure penguin decays like ϕK_S^0, $f_0 K_S^0$, $K^+K^-K^0$, $K_S^0\pi^0$, $\eta' K_S^0$ and ωK_S^0. In these decays sensitivity to new physics (NP) increases.

The $\sin 2\phi_1$ measurement from the B factories is one of the main constraints in the global fit by CKM fitter Collaboration. Recently CKM fitter reported a tension

*BaBar uses an alternative notation β, α and γ corresponding to ϕ_1, ϕ_2 and ϕ_3.

($\sim 2.8\sigma$) between the measurement of $\mathcal{B}(B \to \tau\nu)$ and the value predicted from other observables excluding this measurement. So further measurements of $\sin 2\phi_1$ will help to clarify this tension.

4 Analysis Technique

In the B meson system, the CP violating asymmetry lies in the time-dependent decay rates of the B^0 and $\overline{B}^0$ decays to a common CP-eigenstate (f_{CP}). The asymmetry can be written as:

$$\begin{aligned}\mathcal{A}_{CP}(t) &= \frac{\Gamma[\overline{B}^0(t) \to f_{CP}] - \Gamma[B^0(t) \to f_{CP}]}{\Gamma[\overline{B}^0(t) \to f_{CP}] + \Gamma[B^0(t) \to f_{CP}]} \\ &= \mathcal{S}\sin(\Delta m_d t) + \mathcal{A}\cos(\Delta m_d t)\end{aligned}$$

where

$$\mathcal{S} = \frac{2\,\mathrm{Im}\lambda}{|\lambda|^2+1} \qquad\qquad \mathcal{A} = \frac{|\lambda|^2-1}{|\lambda|^2+1}. \tag{1}$$

Here $\Gamma(B^0(\overline{B}^0) \to f_{CP})$ is the decay rate of a $B^0(\overline{B}^0)$ meson decays to f_{CP} at a proper time t after the production, Δm_d is the mass difference between the two neutral B mass eigenstates, λ is a complex parameter depending on the $B^0 - \overline{B}^0$ mixing as well as the decay amplitudes of the B meson decays to the CP eigenstate. The parameter $\mathcal{S}$ is the measure of mixing-induced CP violation, whereas $\mathcal{A}$ is the measure of direct CP violation†.

In the B factories, in order to measure the time-dependent CP violation parameters, we fully reconstruct one neutral B meson into a CP eigenstate. From the remaining particles in the event, the vertex of the other B meson is reconstructed and its flavor is identified. In the decay chain $\Upsilon(4S) \to B^0\overline{B}^0 \to f_{CP}f_{\rm tag}$, where one of the B mesons decays at time t_{CP} to a CP eigenstate f_{CP}, which is our signal mode, and the other decays at time $t_{\rm tag}$ to a final state $f_{\rm tag}$ that distinguishes between B^0 and $\overline{B}^0$, the decay rate has a time dependence given by [6]

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\Big\{1 \;\; + \;\; q\cdot\Big[\mathcal{S}\sin(\Delta m_d\Delta t) + \mathcal{A}\cos(\Delta m_d\Delta t)\Big]\Big\}. \tag{2}$$

Here τ_{B^0} is the neutral B lifetime, $\Delta t = t_{CP} - t_{\rm tag}$, and the b-flavor charge q equals $+1$ (-1) when the tagging B meson is identified as B^0 ($\overline{B}^0$). Since the B^0 and $\overline{B}^0$ are approximately at rest in the $\Upsilon(4S)$ center-of-mass system, Δt can be determined from the displacement in z between the f_{CP} and $f_{\rm tag}$ decay vertices: $\Delta t \simeq \Delta z/(\beta\gamma c)$, where c is the speed of light. The vertex position of the f_{CP} decay is reconstructed using charged tracks (for example, lepton tracks from J/ψ in $B^0 \to J/\psi K_S^0$ decays) and

†Note that BaBar uses the convention $\mathcal{C} = -\mathcal{A}$.

that of the $f_{\rm tag}$ decay from well-reconstructed tracks that are not assigned to f_{CP} [7]. The Δz is approximately 200 μm in Belle and 250 μm in BaBar. We also consider the effect of detector resolution and mis-identification of the flavor [8]. Finally, the CP violation parameters are obtained from an unbinned maximum likelihood fit to the Δt distribution.

5 $b \to c\overline{c}s$ Decay Modes

The $b \to c\overline{c}s$ decays are known as the golden modes for CP violation measurements. They have clean experimental signatures: many accessible modes with relatively large branching fractions $\mathcal{O}(10^{-4})$, low experimental background levels and high reconstruction efficiencies. These modes are dominated by a color-suppressed $b \to c\overline{c}s$ tree diagram and the dominant penguin diagram has the same weak phase. The CP violation comes from the V_{td} element in the mixing box diagram, which contains the phase. For f_{CP} final states resulting from a $b \to c\overline{c}s$ transition, the SM predicts $\mathcal{S} = -\xi_{CP} \sin 2\phi_1$ and $\mathcal{A} = 0$, where ξ_{CP} is known as the CP eigenvalue and have values $+1(-1)$ for CP-even (CP-odd) final states. The asymmetry is given as

$$\mathcal{A}_{CP} = \xi_{CP} \sin(2\phi_1) \sin(\Delta m \Delta t). \quad (3)$$

We can verify this experimentally by measuring the number of $B^0(\overline{B}^0)$ decays to CP eigenstate. Because of the high experimental precision and low theoretical uncertainty these modes provide a reference point in the SM. A non-zero value of $\mathcal{A}$ or any measurement of $\sin 2\phi_1$ that has a significant deviation indicates an evidence for NP.

Belle recently reported new measurements with its full data sample ($772 \times 10^6 B\overline{B}$ pairs) using the modes $B^0 \to J/\psi K^0$, $B^0 \to \psi' K_S^0$ and $B^0 \to \chi_{c1} K_S^0$. The J/ψ candidates are reconstructed from their decays to e^+e^- and $\mu^+\mu^-$, with the K_S^0 reconstructed from $\pi^+\pi^-$. The ψ' candidates are reconstructed from e^+e^-, $\mu^+\mu^-$ as well as $J/\psi\pi^+\pi^-$ decays. The χ_{c1} is reconstructed from its decays to $J/\psi\gamma$. Belle reported nearly 15600 CP-odd signal events with a purity of 96% and nearly 10000 CP-even signal events with a purity of 63%. Belle observed CP violation in all charmonium modes and the results are summarized in Table 1.

Figure 1 shows the background-subtracted Δt distributions for good-tagged events only (all charmonium modes are combined). We define the raw asymmetry in each Δt bin as $(N_+ - N_-)/(N_+ + N_-)$, where N_+ (N_-) is the number of observed candidates with $q = +1$ (-1). The systematic uncertainties are significantly improved compared to the previous Belle measurements [9, 10] due to a better model for the resolution function (decay mode independent). Combining all charmonium modes, Belle reported the world's most precise measurements:

$$\begin{aligned} \sin 2\phi_1 &= 0.668 \pm 0.023(\text{stat}) \pm 0.013(\text{syst}), \\ \mathcal{A} &= 0.007 \pm 0.016(\text{stat}) \pm 0.013(\text{syst}). \end{aligned} \quad (4)$$

Decay Mode	$\mathcal{S}$	$\mathcal{A}$
$B^0 \to J/\psi K^0_S$	0.671 ± 0.029	-0.014 ± 0.021
$B^0 \to J/\psi K^0_L$	-0.641 ± 0.047	0.019 ± 0.026
$B^0 \to \psi' K^0_S$	0.739 ± 0.079	0.103 ± 0.055
$B^0 \to \chi_{c1} K^0_S$	0.636 ± 0.117	-0.023 ± 0.083

Table 1: The CP-violating parameters measured by Belle with golden modes using a data sample of $772 \times 10^6 B\overline{B}$ pairs (the errors are statistical only). Belle observed CP violation in all charmonium modes.

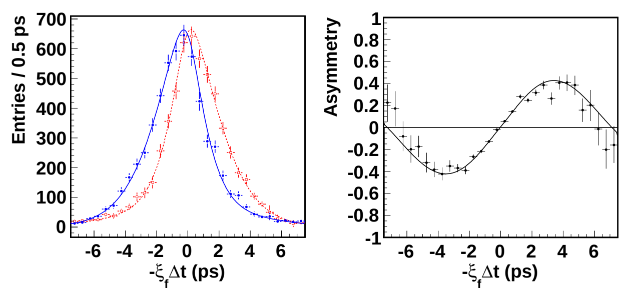

Figure 1: The left plot shows the Δt distribution for $q = +1$ (red) and $q = -1$ (blue) and right plot is the raw asymmetry. These are background-subtracted and for good-tagged events only.

BaBar reconstructed the decay modes $B^0 \to J/\psi K^0$, $B^0 \to \psi' K^0_S$, $B^0 \to \chi_{c1} K^0_S$, $B^0 \to \eta_c K^0_S$ and $B^0 \to J/\psi K^{*0}$. Using a data sample of $465 \times 10^6 B\overline{B}$ pairs, BaBar reported nearly 8400 CP-odd signal events with a purity of 93% and nearly 5800 CP-even signal events with a purity of 56%. Combing all charmonium modes BaBar measured $\sin 2\phi_1 = 0.687 \pm 0.028 \pm 0.012$ and $\mathcal{C} = 0.024 \pm 0.020 \pm 0.016$ [11].

Combining the measurements from Belle and BaBar, the new world average calculated by the Heavy Flavor Averaging Group (HFAG) is [12]

$$\begin{aligned} \sin 2\phi_1(b \to c\bar{c}s) &= 0.678 \pm 0.020, \\ \mathcal{A}(b \to c\bar{c}s) &= -0.013 \pm 0.017. \end{aligned} \tag{5}$$

Figure 2 summarizes the results of $\sin 2\phi_1$ for $b \to c\bar{c}s$ decays from Belle and BaBar. The measurements of the two experiments agree very well within the statistical uncertainties. The experimental uncertainty on $\sin 2\phi_1$ is reduced to 3% and thus serves as a firm reference point for the SM. The value of $\mathcal{A}$ is consistent with zero. The new results will definitely provide a better constraint on the allowed region in the CKM fitter. The measurement of $\sin 2\phi_1$ leaves a two-fold ambiguity in the value of ϕ_1. Both Belle and BaBar measured the sign of $\cos 2\beta$ to be positive at 98.3% and 86%

confidence levels, respectively. This favors the smaller value of ϕ_1 solution. The new measurements give the value [12]

$$\phi_1(\beta) = (21.4 \pm 0.8)^\circ, \tag{6}$$

which is the most precise measurement with $< 1^\circ$ error.

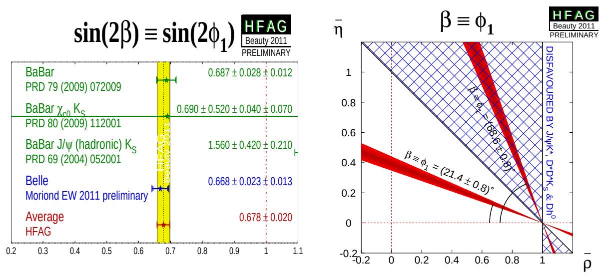

Figure 2: The left plot shows the comparison between the Belle and BaBar measurements of $\sin 2\phi_1$ with $b \to c\bar{c}s$ decays and constraints on ϕ_1 on the $(\overline{\rho}, \overline{\eta})$ plane is shown in the right plot. The hatched area is excluded corresponding to the negative $\cos(2\phi_1)$ solution.

6 $b \to c\bar{c}d$ Decay Modes

The $B^0 \to J/\psi\pi^0$ decay takes place through a $b \to c\bar{c}d$ transition. The dominant tree diagram is Cabibbo-suppressed. However, there is a penguin diagram of the same order that has a different weak phase. So, small deviation in $\sin 2\phi_1$ from golden modes is expected in the SM. The BaBar result provides an evidence of CP violation at 4σ level [13], while the value for Belle result is 2.4σ [14]. The decay $B^0 \to D^{*+}D^{*-}$ also goes through the $b \to c\bar{c}d$ transition. This mode requires an angular analysis to separate CP-even and CP-odd events. Belle reports a statistical significance of 3.2σ for direct CP violation in the $B^0 \to D^+D^-$ mode [15].

7 $b \to sq\bar{q}$ Decay Modes

An alternative way to measure the angle ϕ_1 is to measure the time-dependent CP asymmetries in charmless hadronic final states. These are $b \to s$ penguin dominated decays. Any non-SM particles, like Higgs or SUSY particles can enter the loop. So, these are sensitive to NP. The value of $\mathcal{S}$ is expected to be $\sin 2\phi_1$ for a pure penguin amplitude, but can be different if there is an extra CP phase from NP. As a consequence, an effective $\sin 2\phi_1$ value is measured. Significant deviation from $\sin 2\phi_1$ in golden modes would indicate NP. The deviations have been estimated in several theoretical models and are expected to be positive. These estimates are mode and model dependent.

Belle and BaBar have recently performed time-dependent Dalitz analyses in the $B^0 \to K^+K^-K^0_S$ [16] final state using $657 \times 10^6 B\overline{B}$ [17] and $465 \times 10^6 B\overline{B}$ pairs, respectively. This gives directly the value of ϕ_1 (we do not need to worry about the two-fold ambiguity here). The results are consistent with the SM expectation from $b \to c\bar{c}s$ decays. The $\sin 2\phi_1^{\rm eff}$ in various $b \to s$ penguin modes is summarized in Fig. 3. The results are consistent between Belle and BaBar and also consistent with the SM expectation within the statistical uncertainties. It is fair to say that we need more data to see a sensitivity comparable with theoretical uncertainties.

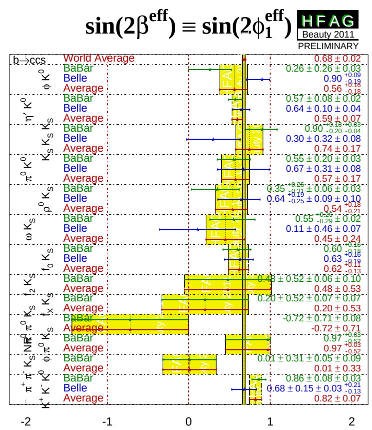

Figure 3: The summary of effective $\sin 2\phi_1$ measurements in $b \to s$ penguin decay modes.

8 Conclusion

In this review, we have presented the recent measurements of the CKM angle ϕ_1/β by Belle and BaBar. Thanks to the excellent performance of the two B factories, which collected large data sample at the $\Upsilon(4S)$ resonance; the angle ϕ_1 has been measured with $< 1^\circ$ precision. The CP violating parameters in $b \to c\bar{c}s$ decays are the most precise measurements and provides a reference point for new physics searches. The time-dependent CP asymmetry in penguin dominated decays is consistent with standard model expectations within the uncertainties of the measurement.

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