ϕ_1/β from $B \to charmonium/charm$ Modes

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The asymmetric B-factories have provided valuable information on CP violation so far. In particular, one of the angles of the Unitarity Triangle, $\phi_1(=\beta)$, has been measured by several approaches. Since FPCP2004, some measurements have been updated and improved. In this Letter, the latest status of ϕ_1 measurements, performed at BaBar and Belle experiments using $B \to charm/charmonium$ decays, are reported.

1. Introduction

CP violation in the Standard Model (SM) stems from an irreducible complex phase in the weak interaction 3×3 quark-mixing (CKM) matrix [1]. Applying the unitarity constraint, especially between the first and third generation, an equation $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$, which can be depicted as an Unitarity Triangle in a complex plane, is required to be satisfied. The key objective of B-factories [2, 3] is to determine three angles or sides of this triangle.

At the B-factories, it is predicted that a CP violating asymmetry lies in the time-dependent rates for B^0 and $\bar{B}^0$ decays to a common CP eigenstate "f_{CP}", which is generally written as:

$$A(t) \equiv \frac{\Gamma(\bar{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\bar{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})} = S_{f_{cp}} \sin\Delta m_d t + A_{f_{cp}} \cos\Delta m_d t$$

$$S_{f_{cp}} = \frac{2Im\lambda}{|\lambda|^2+1} \quad \text{and} \quad A_{f_{cp}} = \frac{|\lambda|^2-1}{|\lambda|^2+1}$$

where $\Gamma(\bar{B}^0\ (B^0) \to f_{CP})$ is the decay rate for a $\bar{B}^0(B^0)$ to f_{CP} at a proper time t after production, Δm_d is the mass difference between the two B^0 mass eigenstates, $A_{f_{cp}}$ [1] and $S_{f_{cp}}$ are expressed with a complex parameter, λ, that depends both on $\bar{B}^0 - B^0$ mixing and on the amplitudes for $\bar{B}^0(B^0)$ decay to CP eigenstates. In the SM, $|\lambda|$ is equal to the absolute value of the ratio of the $\bar{B}^0$ to B^0 decay amplitude to a good approximation.

In this Letter, the latest status of ϕ_1 measurements are reported, here ϕ_1 is the one of the angles of the Unitarity Triangle, performed at BaBar and Belle experiments using $B \to charm/charmonium$ [2] decays.

[1]sometimes, $A_{f_{cp}}$ is expressed as $-C_{f_{cp}}$.
[2]Unless explicitly stated, charge conjugate decay modes are assumed throughout this letter.

2. $b \to c\bar{c}s$ Decay Modes

The determination of ϕ_1 from $b \to c\bar{c}s$ decay modes, as typified by $B^0 \to J/\psi K^0$, provides the stringent constraint on the Unitarity Triangle at this stage. For these decay modes, the CP violation parameters are rather precisely expressed as $S_{b\to c\bar{c}s} = -\xi_f \sin 2\phi_1$ and $A_{b\to c\bar{c}s} = 0$, where ξ_f is -1 for $(c\bar{c})K_S$ and $+1$ for $(c\bar{c})K_L$ final state. Using $B^0 \to J/\psi K^0$ decays recorded in 386M $B\bar{B}$ events, Belle has updated the results [4]. Figure 1a(c) and b(d) show the observed proper time distribution for $B^0 \to J/\psi K_S (J/\psi K_L)$ and corresponding raw asymmetry. The CP violation parameters are determined by performing an unbinned maximum-likelihood fit to the proper time distributions. The K_S and K_L samples are combined with taking into account the CP eigenstates. The fit results are $S_{b\to c\bar{c}s}(=\sin 2\phi_1) = 0.652 \pm 0.039(\text{stat}) \pm 0.020(\text{syst})$ and $A_{b\to c\bar{c}s} = 0.010 \pm 0.026 \pm 0.036$. BaBar has also measured these parameters with considering not only $J/\psi K^0$ but also $\psi(2S)K_S$, $\chi_{c1}K_S$ and $\eta_c K_S$ decays observed in 227M $B\bar{B}$ events [5] and determined to be, $\sin 2\phi_1 = 0.722 \pm 0.040 \pm 0.023$ and $A_{b\to c\bar{c}s} = -0.051 \pm 0.033 \pm 0.014$.

The combined results from B-factories [6] (summarized in Fig. 2) are

$$S_{b\to c\bar{c}s} = \sin 2\phi_1 = 0.685 \pm 0.032(0.028\text{stat.only})$$
$$A_{b\to c\bar{c}s} = -0.026 \pm 0.041(0.020\text{stat.only})$$

and show a good agreement with the SM expectations. The relative error for $\sin 2\phi_1$ has reached less than 5% level. This fact allows us to test a new physics effect which would manifests itself in a loop-diagram such as $b \to s$ penguin [4, 7, 8].

3. $\cos 2\phi_1$ Measurements

The analyses for $b \to c\bar{c}s$ decay modes impose constraints on $\sin 2\phi_1$ only and then lead to a four-fold ambiguity in the determination of ϕ_1. The next natural step is to reduce this ambiguity from four-fold to two-fold by measuring the sign of $\cos 2\phi_1$. For this purpose, the following two methods have been performed.

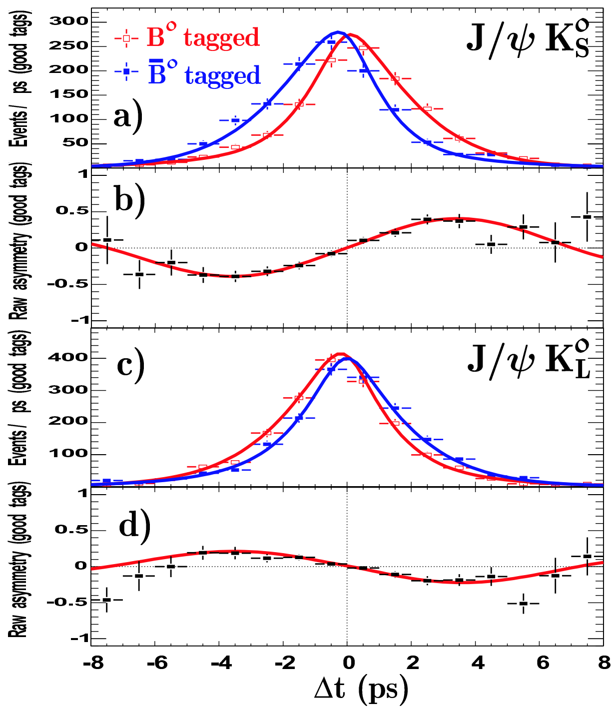

Figure 1: a(c) shows the observed proper time distribution for $B^0 \to J/\psi K_S (J/\psi K_L)$ at Belle. Open(closed) squares represent events tagged as $B^0 (\bar{B}^0)$. b(d) shows the corresponding raw asymmetry together with an unbinned maximum-likelihood fit result.

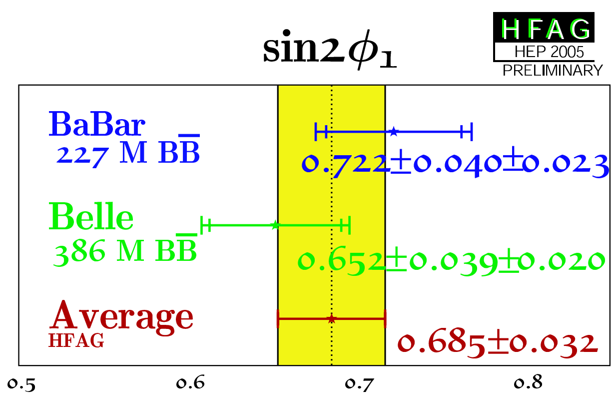

Figure 2: $\sin 2\phi_1$ from B-factories.

3.1. $B^0 \to J/\psi K^{*0}$ Decay

Because the $B^0 \to J/\psi K^{*0}$ mode is a pseudoscalar decay to two vector particles, interference between three helicity states with different CP eigenstates contributes to the CP violation parameters $\sin 2\phi_1$ and $\cos 2\phi_1$ [9–12]. To extract these, the complex transversity amplitudes of three helicity states and strong phase differences are necessary to be measured in advance. BaBar [13] and Belle [14] have performed this analysis. In particular, BaBar has measured these through a time-integrated angular analysis of flavor specific decays, such as $B^+ \to J/\psi K^{*+} (K^{*+} \to K_S \pi^+$ and $K^+\pi^0)$ and $J/\psi K^{*0} (K^{*0} \to K^+\pi^-)$ modes recorded in 88M $B\bar{B}$ events, considering the interference between S-wave and P-wave $K\pi$ final states [13]. Using these values, then an unbinned maximum likelihood fit has been applied to the time-dependent angular distribution of the CP decay mode $B^0 \to J/\psi K^{*0} (K^{*0} \to K^0_S \pi^0)$. The extracted $\sin 2\phi_1$ and $\cos 2\phi_1$ from this fit are;

$$\sin 2\phi_1 = -0.10 \pm 0.57 \pm 0.14$$
$$\cos 2\phi_1 = 3.32^{+0.76}_{-0.96} \pm 0.27$$

When $\sin 2\phi_1$ is fixed to 0.731 (this was the world average as of this analysis), the resultant $\cos 2\phi_1 = 2.72^{+0.50}_{-0.79} \pm 0.27$ is obtained and the sign of $\cos 2\phi_1$ is found to be positive at the 86% C.L.

3.2. $B^0 \to D[K^0_S \pi^+\pi^-]h^0$ Decay

Another technique of reducing ϕ_1 ambiguity is based on the analysis of $B^0 \to D_{CP} h^0$ governed by the CKM favored $b \to c\bar{u}d$ transitions [15]. Here h^0 means light neutral mesons. Though the CKM suppressed $b \to u\bar{c}d$ decays contribute to these modes, the effect is small and can be taken into account. When D_{CP} decays to $K^0_S \pi^+\pi^-$, a time dependent Dalitz plot analysis of the neutral D decay allows to determine ϕ_1 directly.

Belle has performed an analysis for the decays $B \to D\pi^0$, $D\eta$, $D\omega$ and also for the $B \to D^*\pi^0$, $D^*\eta$ ($D^* \to D\pi^0$ and $D \to K^0_S \pi^0 \pi^-$) collected in 386M $B\bar{B}$ events [16]. Totally 309 ± 31 events were observed. An unbinned maximum likelihood fit has been applied to the observed time-dependent Dalitz plot. The results are given in Table I for each of the three final states separately. Then the result of the simultaneous fit over all these modes is;

$$\phi_1 = 16 \pm 21 \pm 11^\circ$$

The first error is statistical and the second is systematic. The 95% C.L. region including systematic uncertainty is $-30^\circ < \phi_1 < 62^\circ$.

Table I Fit results of ϕ_1 for the three final states. The errors are statistical only.

Final state	$\phi_1 [^\circ]$
$D\pi^0$	11 ± 26
$D\omega$, $D\eta$	28 ± 32
$D^*\pi^0, D^*\eta$	25 ± 35

Taking into account both the angular analysis of $B \to J/\psi K^{*0}$ and the time-dependent Dalitz plot analysis of $B \to D_{CP} h^0$, the solutions with negative

$\cos 2\phi_1$ can be considered to be ruled out at $\sim 3\sigma$ [6]. The resultant constraint to the $\sin 2\phi_1$ obtained by these ϕ_1 measurements is shown in Fig. 3.

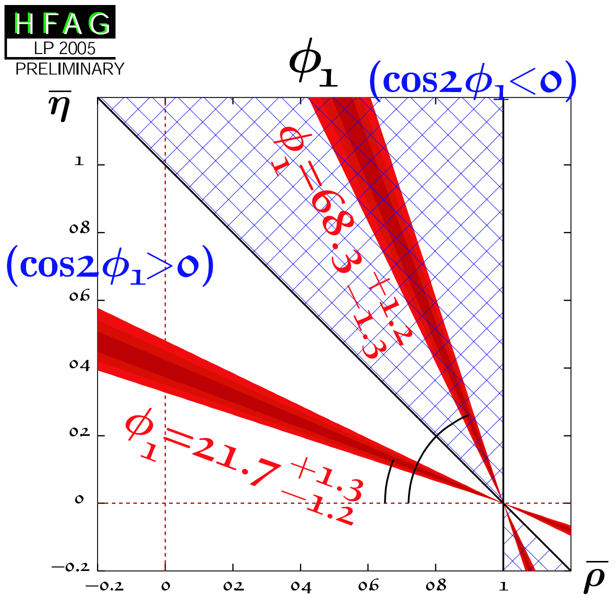

Figure 3: Constraint for ϕ_1 on the $(\bar{\rho}, \bar{\eta})$ plane, obtained from the analysis of $b \to c\bar{c}s$ decays, the angular analysis of $B \to J/\psi K^{*0}$ and the time-dependent Dalitz plot analysis of $B \to D_{CP}h^0$. The hatched area, corresponding to the solutions with negative $\cos 2\phi_1$, is ruled out at $\sim 3\sigma$.

4. $b \to c\bar{c}d$ Decay Modes

The comparison $\sin 2\phi_1$ derived from $b \to c\bar{c}s$ modes with that from different quark transition is an important test to check the SM. Because a sizable CP asymmetry deviated from the SM expectation might be observed, if new physics beyond the SM exists. The decays dominated by the $b \to c\bar{c}d$ transition, such as $B^0 \to J/\psi\pi^0$ and $D^{(*)+}D^{(*)-}$, are suitable for this check [17–22].

Since the FPCP2004, BaBar has updated the results for these decay modes. Recently, the improved measurement for $B^0 \to J/\psi\pi^0$ mode observed in 232M $B\bar{B}$ events has been reported [17]. The 109 ± 12 signal events are observed and CP violation parameters are determined to be,

$$
\begin{aligned}
S_{J/\psi\pi^0} &= 0.68 \pm 0.30 \pm 0.04 \\
C_{J/\psi\pi^0}(= -A_{J/\psi\pi^0}) &= -0.21 \pm 0.26 \pm 0.06
\end{aligned}
$$

These are consistent both with previous measurements from B-factories [18] and with the SM expectations.

Other improved measurements for the $B^0 \to D^{(*)+}D^-$ decays have been also reported. In particular, BaBar has performed a first measurement of CP asymmetries in the $B^0 \to D^+D^-$ decay [19]. The measured values are

$$
\begin{aligned}
S_{D^+D^-} &= -0.29 \pm 0.63 \pm 0.06 \\
C_{D^+D^-} &= -0.11 \pm 0.35 \pm 0.06
\end{aligned}
$$

and consistent again with the SM expectations within the currently large statistical uncertainty, that will be more precise in the future.

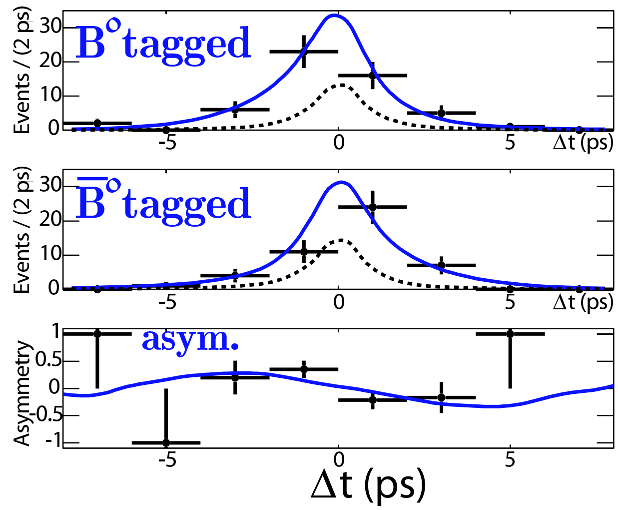

Figure 4: The proper time distribution for $B \to J/\psi\pi^0$ tagged as B^0 (top) and $\bar{B}^0$ (middle) observed at BaBar. The solid lines are the sum of signal and backgrounds and the dotted lines show the background components. The time-dependent CP asymmetry is shown (bottom) with an unbinned maximum-likelihood fit result.

5. Summary

One of the angles of the Unitarity Triangle, $\phi_1 (= \beta)$, has been measured by several approaches at B-factories, BaBar and Belle experiments. The analyses for $b \to c\bar{c}s$ decay modes impose the stringent constraint on $\sin 2\phi_1$ with a precision of $\sim 5\%$.

Then the four-fold ambiguity of ϕ_1, which are allowed in $[0, 2\pi]$ mathematically, are reduced by the time-dependent angular analysis of $B^0 \to J/\psi K^{*0}$ and the time-dependent Dalitz plot analysis of D_{CP} in $B^0 \to D_{CP}h^0$ decays, the solutions with negative $\cos 2\phi_1$ can be considered to be ruled out at $\sim 3\sigma$.

The comparisons $\sin 2\phi_1$ derived from $b \to c\bar{c}s$ modes with that from different quark transition, $b \to c\bar{c}s$, also have been done, because a sizable CP asymmetry deviated from the SM expectation might be observed, if new physics beyond the SM exists. Though these measurements are dominated by statistical uncertainties, more significant measurements will be anticipated in the future.

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