$\sin 2\phi_1$ with 45 Million $B\overline{B}$ Pairs at Belle

Masashi Hazumi
Institute of Particle and Nuclear Studies
High Energy Accelerator Research Organization (KEK)
1-1 Oho, Tsukuba-shi, Ibaraki-kun 305-0801, Japan

Abstract

We present an improved measurement of the standard model CP violation parameter $\sin 2\phi_1$ (also known as $\sin 2\beta$) based on a sample of 45×10^6 $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. One neutral B meson is reconstructed in a $J/\psi K_S^0$, $\psi(2S)K_S^0$, $\chi_{c1}K_S^0$, $\eta_c K_S^0$, $J/\psi K^{*0}$, or $J/\psi K_L^0$ CP-eigenstate decay channel and the flavor of accompanying B meson is identified from its decay products. From the asymmetry in the distribution of the time intervals between the two B meson decay points, we obtain $\sin 2\phi_1 = 0.82 \pm 0.12(\mathrm{stat}) \pm 0.05(\mathrm{syst})$.

In the Standard Model (SM), CP violation arises from an irreducible complex phase in the weak interaction quark-mixing matrix (CKM matrix) [1]. In particular, the SM predicts a CP-violating asymmetry in the time-dependent rates for B^0 and $\overline{B}^0$ decays to a common CP eigenstate, f_{CP}, with negligible corrections from strong interactions[2]:

$$A(t) \equiv \frac{\Gamma(\overline{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\overline{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})} = -\xi_f \sin 2\phi_1 \sin(\Delta m_d t), \quad (1)$$

where $\Gamma(B^0, \overline{B}^0 \to f_{CP})$ is the decay rate for a B^0 or $\overline{B}^0$ to f_{CP} dominated by a $b \to c\bar{c}s$ transition at a proper time t after production, ξ_f is the CP eigenvalue of f_{CP}, Δm_d is the mass difference between the two B^0 mass eigenstates, and ϕ_1 is one of the three interior angles of the CKM unitarity triangle, defined as $\phi_1 \equiv \pi - \arg(-V_{tb}^* V_{td} / - V_{cb}^* V_{cd})$. Non-zero values for $\sin 2\phi_1$ were reported by the Belle and BaBar groups[3, 4].

Belle's published measurement of $\sin 2\phi_1$ is based on a 29.1 fb^{-1} data sample containing 31.3×10^6 $B\overline{B}$ pairs produced at the $\Upsilon(4S)$ resonance. In this paper, we report an improved measurement that uses 45×10^6 $B\overline{B}$ pairs (42 fb^{-1}). The data were collected with the Belle detector [5] at the KEKB asymmetric collider [6], which collides 8.0 GeV e^- on 3.5 GeV e^+ at a small (± 11 mrad) crossing angle. We use events where one of the B mesons decays to f_{CP} at time t_{CP}, and the other decays to a self-tagging state, $f_{\rm tag}$, *i.e.*, a final state that distinguishes B^0 and $\overline{B}^0$, at time $t_{\rm tag}$. The CP violation manifests itself as an asymmetry $A(\Delta t)$, where Δt is the proper time interval between the two decays: $\Delta t \equiv t_{CP} - t_{\rm tag}$. At KEKB, the $\Upsilon(4S)$ resonance is produced with a boost of $\beta\gamma = 0.425$ nearly along the electron beam direction (z direction), and Δt can be determined as $\Delta t \simeq \Delta z/(\beta\gamma)c$, where Δz is the z distance between the f_{CP} and $f_{\rm tag}$ decay vertices, $\Delta z \equiv z_{CP} - z_{\rm tag}$. The Δz average value is approximately 200 μm.

The Belle detector [5] is a large-solid-angle spectrometer that consists of a silicon vertex detector (SVD), a central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM).

We reconstruct B^0 decays to the following CP eigenstates [1] $J/\psi K_S^0$, $\psi(2S)K_S^0$, $\chi_{c1}K_S^0$, $\eta_c K_S^0$ for $\xi_f = -1$ and $J/\psi K_L^0$ for $\xi_f = +1$. We also use $B^0 \to J/\psi K^{*0}$ decays where $K^{*0} \to K_S^0\pi^0$. Here the final state is a mixture of even and odd CP, depending on the relative orbital angular momentum of the J/ψ and K^{*0}. We find that the final state is primarily $\xi_f = +1$; the $\xi_f = -1$ fraction is $0.19 \pm 0.02(\rm stat) \pm 0.03(\rm syst)$[7]. For reconstructed $B \to f_{CP}$ candidates other than $J/\psi K_L^0$, we identify B decays using the energy difference $\Delta E \equiv E_B^{\rm cms} - E_{\rm beam}^{\rm cms}$ and the beam-energy constrained mass $M_{\rm bc} \equiv \sqrt{(E_{\rm beam}^{\rm cms})^2 - (p_B^{\rm cms})^2}$, where $E_{\rm beam}^{\rm cms}$ is the beam energy in the center-of-mass system (cms), and $E_B^{\rm cms}$ and $p_B^{\rm cms}$ are the cms energy and momentum of the reconstructed B candidate, respectively. Figure 1 (left) shows the $M_{\rm bc}$ distributions for all B^0 candidates except for $B^0 \to J/\psi K_L^0$ that have ΔE values in the signal region. Table 1 lists the numbers of observed candidates ($N_{\rm rec}$).

Candidate $B^0 \to J/\psi K_L^0$ decays are selected by requiring ECL and/or KLM hit patterns that are consistent with the presence of a shower induced by a neutral hadron. The centroid of the shower is required to be in a 45° cone centered on the K_L^0 direction that is inferred from two-body decay kinematics and the measured four-momentum of the J/ψ. Figure 1 (right) shows the $p_B^{\rm cms}$ distribution, calculated with the $B^0 \to J/\psi K_L^0$ two-body decay hypothesis. The histograms are the results of a fit to the signal and background distributions. There are 767 entries in total in the $0.20 \le p_B^{\rm cms} \le 0.45$ GeV/c signal region [2]; the fit indicates a signal purity of 60%. The reconstruction and selection criteria for all of f_{CP} channels used in the measurement

[1] Throughout this paper, when a decay mode is quoted, the inclusion of the charge conjugation mode is implied.

[2] When the K_L^0 is identified with the ECL only, the signal region is defined to be $0.20 \le p_B^{\rm cms} \le 0.40$ GeV/c.

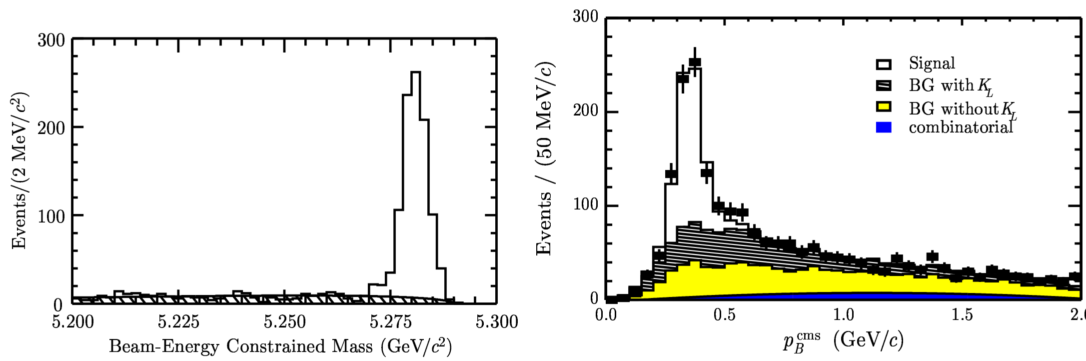

Figure 1: The beam-energy constrained mass distribution for all decay modes combined other than $J/\psi K_L^0$ (left). The $p_B^{\rm cms}$ distribution for $B^0 \to J/\psi K_L^0$ candidates with the results of the fit (right).

are described in more detail elsewhere [3].

Leptons, charged pions, kaons, and Λ baryons that are not associated with a reconstructed CP eigenstate decay are used to identify the b-flavor of the accompanying B meson: high momentum leptons from $b \to c\ell^-\overline{\nu}$; lower momentum leptons from $c \to s\ell^+\nu$; charged kaons and Λ baryons from $b \to c \to s$; fast pions from $B^0 \to D^{(*)-}(\pi^+, \rho^+, a_1^+$, etc.); and slow pions from $D^{*-} \to \overline{D}^0\pi^-$. Based on the measured properties of these tracks, two parameters, q and r, are assigned to an event. The first, q, has the discrete values $q = \pm 1$ that is $+1$ (-1) when $B_{\rm tag}$ is likely to be a B^0 ($\overline{B}^0$), and the parameter r is an event-by-event Monte-Carlo-determined flavor-tagging dilution factor that ranges from $r = 0$ for no flavor discrimination to $r = 1$ for an unambiguous flavor assignment. It is used only to sort data into six intervals of r, according to flavor purity; the wrong-tag probabilities, w_l $(l = 1, 6)$, that are used in the final fit are determined directly from data. Samples of B^0 decays to exclusively reconstructed self-tagged channels are utilized to obtain w_l using time-dependent B^0-$\overline{B}^0$ mixing oscillation: $(N_{\rm OF} - N_{\rm SF})/(N_{\rm OF} + N_{\rm SF}) = (1-2w_l)\cos(\Delta m_d \Delta t)$, where $N_{\rm OF}$ and $N_{\rm SF}$ are the numbers of opposite and same flavor events. The total effective tagging efficiency is determined to be $\sum_{l=1}^{6} f_l(1-2w_l)^2 = 0.270 \pm 0.008({\rm stat})^{+0.006}_{-0.009}({\rm syst})$, where f_l is the event fraction for each r interval.

The vertex position for the f_{CP} decay is reconstructed using leptons from J/ψ decays or kaons and pions from η_c and that for $f_{\rm tag}$ is obtained with well reconstructed tracks that are not assigned to f_{CP}. Tracks that are consistent with coming from a $K_S^0 \to \pi^+\pi^-$ decay are not used. Each vertex position is required to be consistent with a run-by-run-determined interaction region profile that is smeared in the r-ϕ plane by the B meson decay length. With these requirements, we are able to determine a vertex even with a single track; the fraction of single-track vertices is about 10%

for z_{CP} and 30% for $z_{\rm tag}$. The proper-time interval resolution function, $R_{\rm sig}(\Delta t)$, is formed by convolving four components: the detector resolutions for z_{CP} and $z_{\rm tag}$, the shift in the $z_{\rm tag}$ vertex position due to secondary tracks originating from charmed particle decays, and smearing due to the kinematic approximation used to convert Δz to Δt. A small component of broad outliers in the Δz distribution, caused by mis-reconstruction, is represented by a Gaussian function. We determine ten resolution parameters from the data from fits to the neutral and charged B meson lifetimes [8] and obtain an average Δt resolution of ~ 1.56 ps (rms). The width of the outlier component is determined to be (36^{+5}_{-4}) ps; the fractional areas are $(6^{+3}_{-2}) \times 10^{-4}$ and $(3.1 \pm 0.4) \times 10^{-2}$ for the multiple- and single-track cases, respectively.

After flavor tagging and vertexing, we find 766 events with $q = +1$ flavor tags and 784 events with $q = -1$. Figure 2 shows the observed Δt distributions for the $q\xi_f = +1$ (solid points) and $q\xi_f = -1$ (open points) event samples. The asymmetry between the two distributions demonstrates the violation of CP symmetry. We determine

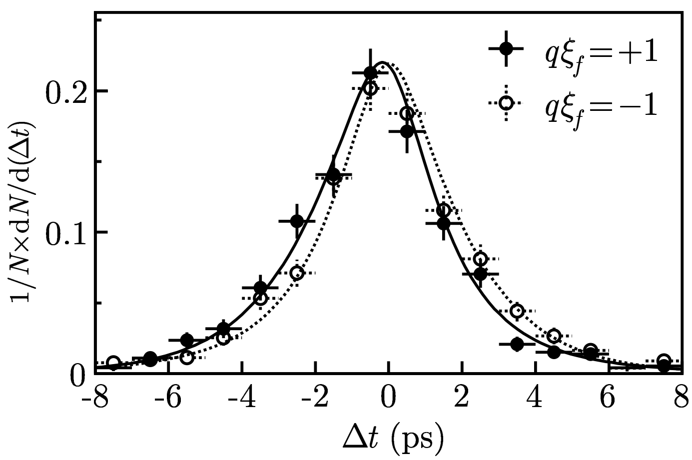

Figure 2: Δt distributions for the events with $q\xi_f = +1$ (solid points) and $q\xi_f = -1$ (open points). The results of the global fit with $\sin 2\phi_1 = 0.82$ are shown as solid and dashed curves, respectively.

$\sin 2\phi_1$ from an unbinned maximum-likelihood fit to the observed Δt distributions. The probability density function (pdf) expected for the signal distribution is given by

$$\mathcal{P}_{\rm sig}(\Delta t, q, w_l, \xi_f) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[1 - q\xi_f(1-2w_l)\sin 2\phi_1 \sin(\Delta m_d \Delta t)], \qquad (2)$$

where we fix the B^0 lifetime (τ_{B^0}) and mass difference at their world average values[9]. Each pdf is convolved with the appropriate $R_{\rm sig}(\Delta t)$ to determine the likelihood value for each event as a function of $\sin 2\phi_1$:

$$\begin{aligned} P_i &= (1-f_{\rm ol})\int\Big[f_{\rm sig}\mathcal{P}_{\rm sig}(\Delta t', q, w_l, \xi_f)R_{\rm sig}(\Delta t - \Delta t') \\ &\quad + (1-f_{\rm sig})\mathcal{P}_{\rm bkg}(\Delta t')R_{\rm bkg}(\Delta t - \Delta t')\Big]d\Delta t' + f_{\rm ol}P_{\rm ol}(\Delta t), \end{aligned} \tag{3}$$

where $f_{\rm sig}$ is the signal probability calculated as a function of $p_B^{\rm cms}$ for $J/\psi K_L^0$ and of ΔE and $M_{\rm bc}$ for other modes. $\mathcal{P}_{\rm bkg}(\Delta t)$ is the pdf for combinatorial background events, which is modeled as a sum of exponential and prompt components. It is convolved with a sum of two Gaussians, $R_{\rm bkg}$, which is regarded as a resolution function for the background. To account for a small number of events that give large Δt in both the signal and background, we introduce the pdf, $P_{\rm ol}$, and the fractional area, $f_{\rm ol}$, of the outlier component. The only free parameter in the final fit is $\sin 2\phi_1$, which is determined by maximizing the likelihood function $L = \prod_i P_i$, where the product is over all events. The result of the fit is

$$\sin 2\phi_1 = 0.82 \pm 0.12({\rm stat}) \pm 0.05({\rm syst}).$$

The sources of the systematic error are listed in Table 2. The systematic error is dominated by uncertainties in the vertex reconstruction. Other significant contributions come from uncertainties in the wrong tag fractions, the resolution function parameters and the $J/\psi K_L^0$ background fraction.

A number of checks on the measurement are performed. Table 3 lists the results obtained by applying the same analysis to various subsamples. All values are statistically consistent with each other. Figure 3(a), (b), and (c) show the raw asymmetries and the fit results for all modes combined, $(c\bar{c})K_S^0$, and $J/\psi K_L^0$, respectively. A fit to the non-CP eigenstate self-tagged modes $B^0 \to D^{(*)-}\pi^+$, $D^{*-}\rho^+$ and $J/\psi K^{*0}(K^+\pi^-)$, where no asymmetry is expected, yields 0.05 ± 0.04(stat). Figure 3(d) shows the raw asymmetry for these non-CP control samples.

Finally we comment on the possibility of direct CP violation. The signal pdf for a neutral B meson decaying into a CP eigenstate (Eq. (2)) can be expressed in a more general form as

$$\begin{aligned} \mathcal{P}_{\rm sig}(\Delta t, q, w_l, \xi_f) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\Big\{1 + q(1-2w_l)\Big[&\frac{2|\lambda|(-\xi_f)a_{CP}}{|\lambda|^2+1}\sin(\Delta m_d \Delta t) \\ &+\frac{|\lambda|^2-1}{|\lambda|^2+1}\cos(\Delta m_d \Delta t)\Big]\Big\}, \end{aligned} \tag{4}$$

where λ is a complex parameter that depends on both B^0-$\overline{B}^0$ mixing and on the amplitudes for B^0 and $\overline{B}^0$ decay to a CP eigenstate. The parameter a_{CP} in the coefficient of $\sin(\Delta m_d \Delta t)$ is given by $a_{CP} = -\xi_f Im\lambda/|\lambda|$ and is equal to $\sin 2\phi_1$ in the SM. The presence of the cosine term ($|\lambda| \neq 1$) would indicate direct CP violation;

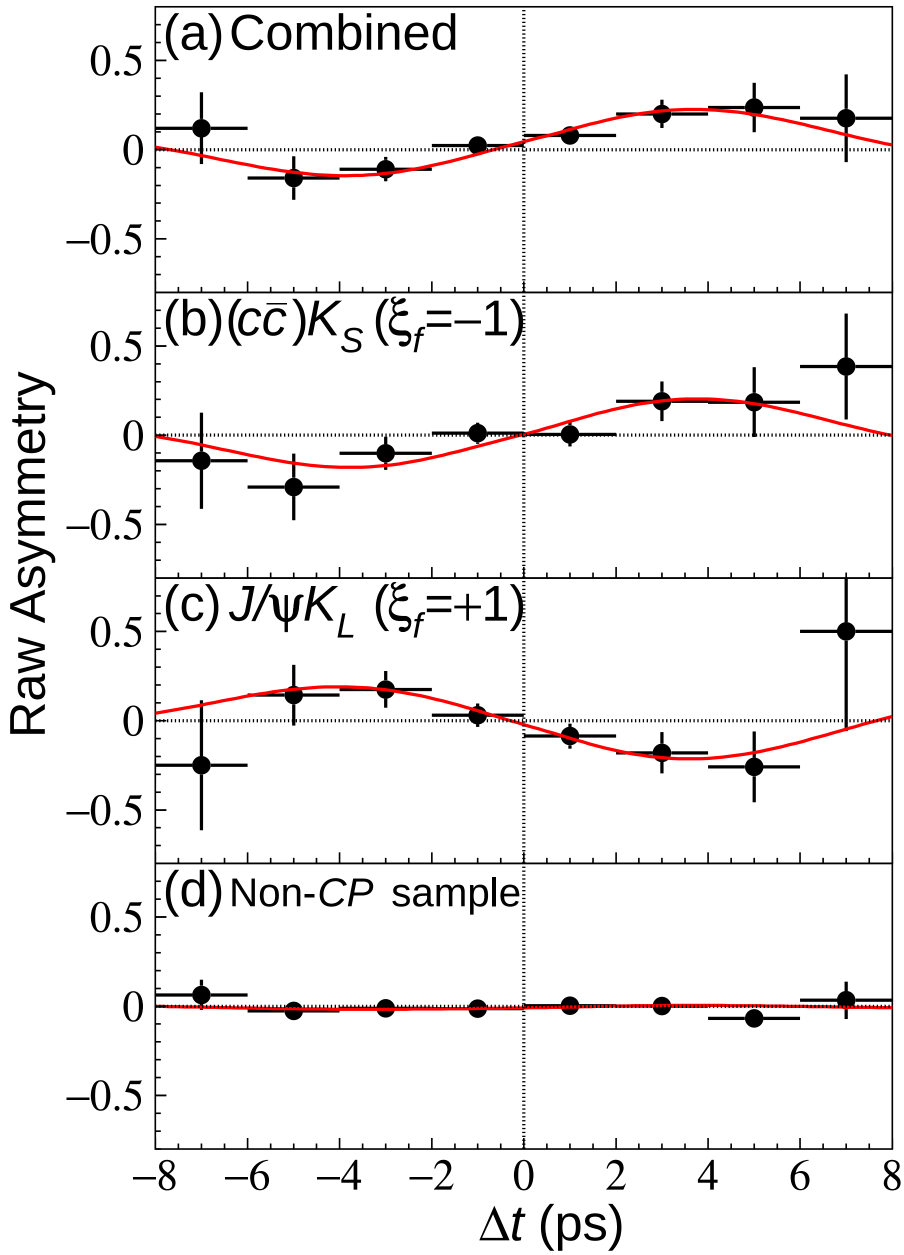

Figure 3: (a) The raw asymmetry for all modes combined. The asymmetry for $J/\psi K_L^0$ and $J/\psi K^{*0}$ is inverted to account for the opposite CP eigenvalue. The corresponding plots for (b) $(c\bar{c})K_S^0$, (c) $J/\psi K_L^0$, and (d) non-CP control samples are also shown. The curves are the results of the unbinned maximum likelihood fit applied separately to the individual data samples.

the value for $\sin 2\phi_1$ reported above is determined with the assumption $|\lambda| = 1$, as expected in the SM. In order to test this assumption, we also performed a fit using the above expression with a_{CP} and $|\lambda|$ as free parameters, keeping everything else the same. We obtain $|\lambda| = 1.01^{+0.08}_{-0.07}(\text{stat})$ and $a_{CP} = 0.82 \pm 0.12(\text{stat})$ for all CP modes combined. This result confirms the assumption used in our analysis.

We wish to thank the KEKB accelerator group for the excellent operation of the KEKB accelerator. We acknowledge support from the Ministry of Education, Culture, Sports, Science, and Technology of Japan and the Japan Society for the Promotion of Science; the Australian Research Council and the Australian Department of Industry, Science and Resources; the National Science Foundation of China under contract No. 10175071; the Department of Science and Technology of India; the BK21 program of the Ministry of Education of Korea and the CHEP SRC program of the Korea Science and Engineering Foundation; the Polish State Committee for Scientific Research under contract No. 2P03B 17017; the Ministry of Science and Technology of the Russian Federation; the Ministry of Education, Science and Sport of the Republic of Slovenia; the National Science Council and the Ministry of Education of Taiwan; and the U.S. Department of Energy.

References

[1] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

[2] A. B. Carter and A. I. Sanda, Phys. Rev. D **23**, 1567 (1981); I. I. Bigi and A. I. Sanda, Nucl. Phys. **B193**, 85 (1981).

[3] K. Abe *et al.* (Belle Collab.), Phys. Rev. Lett. **87**, 091802 (2001); K. Abe *et al.* (Belle Collab.), hep-ex/0202027, accepted for publication in Phys. Rev. D.

[4] B. Aubert *et al.* (BaBar Collab.), Phys. Rev. Lett. **87**, 091801 (2001); B. Aubert *et al.* (BaBar Collab.), hep-ex/0201020, submitted to Phys. Rev. D.

[5] A. Abashian *et al.* (Belle Collab.), Nucl. Instr. and Meth. A **479**, 117 (2002).

[6] E. Kikutani ed., KEK Preprint 2001-157 (2001), to appear in Nucl. Instr. and Meth. A.

[7] K. Abe *et al.* (Belle Collab.), Phys. Lett. B **538**, 11 (2002).

[8] K. Abe *et al.* (Belle Collab.), Phys. Rev. Lett. **88**, 171801 (2002).

[9] K. Hagiwara *et al.*, Particle Data Group, Phys. Rev. D **66**, 010001 (2002).

Mode	$N_{\rm rec}$	$N_{\rm bkg}$
$J/\psi(\ell^+\ell^-)K_S^0(\pi^+\pi^-)$	636	31.2
$J/\psi(\ell^+\ell^-)K_S^0(\pi^0\pi^0)$	102	20.8
$\psi(2S)(\ell^+\ell^-)K_S^0(\pi^+\pi^-)$	49	2.4
$\psi(2S)(J/\psi\pi^+\pi^-)K_S^0(\pi^+\pi^-)$	57	4.3
$\chi_{c1}(J/\psi\gamma)K_S^0(\pi^+\pi^-)$	34	2.3
$\eta_c(K^+K^-\pi^0)K_S^0(\pi^+\pi^-)$	39	11.1
$\eta_c(K_S^0K^-\pi^+)K_S^0(\pi^+\pi^-)$	33	8.9
$J/\psi(\ell^+\ell^-)K^{*0}(K_S^0\pi^0)$	55	6.0
$J/\psi(\ell^+\ell^-)K_L^0$	767	307

Table 1: The numbers of observed candidates ($N_{\rm rec}$) and the estimated background ($N_{\rm bkg}$) in the signal region for each f_{CP} mode.

source	+error	−error
vertex reconstruction	+0.030	−0.030
wrong tag fraction	+0.024	−0.026
resolution function	+0.022	−0.019
background fraction ($J/\psi K_L^0$)	+0.014	−0.015
background fraction (except for $J/\psi K_L^0$)	+0.007	−0.006
τ_{B^0} and Δm_d	+0.007	−0.006
total	+0.048	−0.048

Table 2: List of systematic errors on $\sin 2\phi_1$.

Sample	$\sin 2\phi_1$
$f_{\rm tag} = B^0$ ($q = +1$)	0.60 ± 0.19
$f_{\rm tag} = \overline{B}^0$ ($q = -1$)	0.99 ± 0.16
$J/\psi K_S^0(\pi^+\pi^-)$	0.67 ± 0.18
$(c\overline{c})K_S^0$ except $J/\psi K_S^0(\pi^+\pi^-)$	0.88 ± 0.31
$J/\psi K_L^0$	1.14 ± 0.23
$J/\psi K^{*0}(K_S^0\pi^0)$	1.62 ± 1.10
All	0.82 ± 0.12

Table 3: The values of $\sin 2\phi_1$ for various subsamples (statistical errors only).