Observation of large CP violation in the B-meson system

Nobu Katayama*[a]

[a]Institute of Particle and Nuclear Studies
High Energy Accelerator Research Organization
Oho 1–1, Tsukuba-shi, 305–0801, Japan

Representing the Belle Collaboration

We report a measurement of the CP violation parameter $\sin 2\phi_1$ based on a 29.1 fb^{-1} data sample recorded at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric e^+e^- collider. One neutral B meson is fully reconstructed as a $J/\psi K_S$, $\psi(2S)K_S$, $\chi_{c1}K_S$, $\eta_c K_S$, $J/\psi K_L$ or $J/\psi K^{*0}$ decay and the flavor of the 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 determine $\sin 2\phi_1 = 0.99 \pm 0.14(stat) \pm 0.06(sys)$ and conclude that CP symmetry is violated in the neutral B meson system.

1. Introduction

The CP violating effects have been observed in K_L decay [1]. Kobayashi and Maskawa proposed an elegant explanation of these effects in the three-generation Standard Model [2]. In their model, CP violation is a consequence of the complex phases in the quark mixing matrix,

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

The nontrivial complex phases are conventionally assigned to the furthest off-diagonal elements V_{ub} and V_{td}. In 1981, Sanda, Bigi and Carter [3] pointed out that the KM model predicted large CP violation in certain decays of B mesons for a range of quark mixing parameters.

The model predicts a CP violating asymmetry in the time-dependent rates for initial B^0 and $\overline{B}^0$ decays to a common CP eigenstate, f_{CP} [3]. In the case where $f_{CP} = (c\overline{c})K_{S,L}$, the asymmetry is given by

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

where $\Gamma(\overline{B}^0\ (B^0) \to f_{CP})$ is the decay rate for $\overline{B}^0(B^0)$ to f_{CP} 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 internal angles of the Unitarity Triangle, defined as $\phi_1 \equiv \pi - \arg\left(\frac{-V_{tb}^* V_{td}}{-V_{cb}^* V_{cd}}\right)$ [4]. For the $(c\overline{c})K_{S,L}$ decays, both the ambiguity due to strong interactions and the contribution from direct CP violation are expected to be small [4].

We report a new measurement of $\sin 2\phi_1$ [5] that uses improved reconstruction algorithms and incorporates data taken by July 2001 to achieve a four-fold increase in the size of the event sample. The result reported here includes the earlier data and supersedes the previous value [6]. All data samples have been analyzed and reconstructed with the same consistent procedure.

We use a 29.1 fb^{-1} data sample, which contains 31.3 million $B\overline{B}$ pairs, collected with the Belle detector at the KEKB asymmetric-energy e^+e^- (3.5 on 8 GeV) collider [8]. KEKB operates at the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58$ GeV) with a peak luminosity that exceeds 4×10^{33} cm^{-2}s^{-1}. The Belle detector [9] is a large-solid-angle magnetic spectrometer that consists of a three-layer silicon vertex detector (SVD), a 50-layer central

*E-mail address:nobu.katayama@kek.jp

drift chamber (CDC), a mosaic of aerogel threshold Čerenkov counters (ACC), time-of-flight scintillation counters (TOF), and an array 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 mesons and to identify muons (KLM).

We measure $\sin 2\phi_1$ using $B^0\overline{B}^0$ meson pairs produced at the $\Upsilon(4S)$ resonance. The two mesons remain in a coherent p-wave state until one of them decays. The decay of one of the B mesons at time $t_{\rm tag}$ to a final state, $f_{\rm tag}$, which distinguishes between B^0 and $\overline{B}^0$, projects the accompanying B meson onto the opposite b-flavor at $t_{\rm tag}$; this meson decays to f_{CP} at time t_{CP}. CP violation manifests itself as an asymmetry $A(\Delta t)$, where Δt is the proper time interval $\Delta t \equiv t_{CP} - t_{\rm tag}$. At KEKB, the $\Upsilon(4S)$ is produced with a Lorentz boost of $\beta\gamma = 0.425$ nearly along the electron beam line (z). Since the B^0 and $\overline{B}^0$ mesons are nearly at rest in the $\Upsilon(4S)$ center of mass system (cms), Δt can be determined from the displacement in z between the f_{CP} and $f_{\rm tag}$ decay vertices—*i.e.* $\Delta t \simeq (z_{CP} - z_{\rm tag})/\beta\gamma c \equiv \Delta z/\beta\gamma c$.

The measurement requires the reconstruction of $B^0 \to f_{CP}$ decays, the determination of the b-flavor of the accompanying (tagging) B meson, the measurement of Δt, and a fit of the expected Δt distribution to the measured distribution using a likelihood method.

2. Selection of $B^0 \to CP$ eigenstates

We reconstruct B^0 decays to the following CP eigenstates [10]: $J/\psi K_S$, $\psi(2S)K_S$, $\chi_{c1}K_S$, $\eta_c K_S$ for $\xi_f = -1$ and $J/\psi K_L$ for $\xi_f = +1$. We also use $B^0 \to J/\psi K^{*0}$ decays where $K^{*0} \to K_S\pi^0$. 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}. The CP content is determined from a fit to the full angular distribution of all $J/\psi K^*$ decay modes other than $K^{*0} \to K_S\pi^0$. We find that the final state is primarily $\xi_f = +1$; the $\xi_f = -1$ fraction is $0.19 \pm 0.04(\mathrm{stat}) \pm 0.04(\mathrm{syst})$ [11].

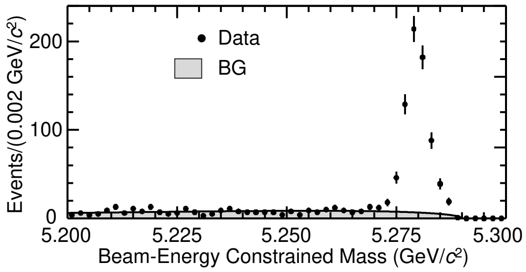

Figure 1. The beam-energy constrained mass distribution for all decay modes combined other than $J/\psi K_L$. The shaded area is the estimated background. The signal region is the range $5.27 - 5.29$ GeV/c^2.

2.1. $B^0 \to (c\bar{c})K_S$ decays

J/ψ and $\psi(2S)$ mesons are reconstructed via their decays to $\ell^+\ell^-$ ($\ell = \mu, e$). The $\psi(2S)$ is also reconstructed via $J/\psi\pi^+\pi^-$, and the χ_{c1} via $J/\psi\gamma$. The η_c is detected in the $K^+K^-\pi^0$ and $K_SK^-\pi^+$ modes. For the $J/\psi K_S$ mode, we use $K_S \to \pi^+\pi^-$ and $\pi^0\pi^0$ decays; for other modes we only use $K_S \to \pi^+\pi^-$.

The J/ψ, $\psi(2S)$ and K_S selection has been described elsewhere [6]. For $\chi_{c1}K_S$ decays, we select $\chi_{c1} \to J/\psi\gamma$ decays, rejecting γ's that are consistent with $\pi^0 \to \gamma\gamma$ decays, and use the requirement $385 < M_{\gamma\ell\ell} - M_{\ell\ell} < 430.5$ MeV/c^2. Candidate $\eta_c \to K^+K^-\pi^0$ ($K_SK^-\pi^+$) decays are selected with a $KK\pi$ mass requirement that takes into account the natural width of the η_c. For $J/\psi K^{*0}(K_S\pi^0)$ decays, we use $K_S\pi^0$ combinations that have an invariant mass within 75 MeV/c^2 of the nominal K^* mass. We reduce background from low-momentum π^0's by requiring $\cos\theta_{K^*} < 0.8$, where θ_{K^*} is the angle between the K_S momentum vector and the K^{*0} flight direction calculated in the K^{*0} rest frame.

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 cms beam energy, and $E_B^{\rm cms}$ and $p_B^{\rm cms}$ are the cms energy and momentum of

Table 1
The numbers of observed events (N_{ev}) and the estimated background (N_{bkgd}) in the signal region for each f_{CP} mode.

Mode	N_{ev}	N_{bkgd}
$J/\psi(\ell^+\ell^-)K_S(\pi^+\pi^-)$	457	11.9
$J/\psi(\ell^+\ell^-)K_S(\pi^0\pi^0)$	76	9.4
$\psi(2S)(\ell^+\ell^-)K_S(\pi^+\pi^-)$	39	1.2
$\psi(2S)(J/\psi\pi^+\pi^-)K_S(\pi^+\pi^-)$	46	2.1
$\chi_{c1}(J/\psi\gamma)K_S(\pi^+\pi^-)$	24	2.4
$\eta_c(K^+K^-\pi^0)K_S(\pi^+\pi^-)$	23	11.3
$\eta_c(K_SK^-\pi^+)K_S(\pi^+\pi^-)$	41	13.6
$J/\psi K^{*0}(K_S\pi^0)$	41	6.7
Sub-total	747	58.6
$J/\psi(\ell^+\ell^-)K_L$	569	223

the B candidate.

Figure 1 shows the combined M_{bc} distribution for all channels other than $J/\psi K_L$ after a mode-dependent requirement on ΔE. Table 1 lists the numbers of observed candidates (N_{ev}) and the background (N_{bkgd}) determined by extrapolating the rate in the non-signal ΔE *vs.* M_{bc} region into the signal region.

2.2. $B^0 \to (c\bar{c})K_L$ decays

Candidate $B^0 \to J/\psi K_L$ decays are selected by requiring ECL and/or KLM hit patterns. The centroid of the hit is required to be in a 45° cone centered on the K_L direction that is inferred from two-body decay kinematics and the measured four-momentum of the J/ψ. We reduce the background by means of a likelihood ratio that depends on the J/ψ cms momentum, the angle between the K_L and its nearest-neighbor charged track, the charged track multiplicity of the event, etc. In addition, we remove events that are reconstructed as $B^0 \to J/\psi K_S$, $J/\psi K^{*0}(K^+\pi^-, K_S\pi^0)$, $B^+ \to J/\psi K^+$, or $J/\psi K^{*+}(K^+\pi^0, K_S\pi^+)$ decays. Finally, K_L clusters with positions that match photons from reconstructed π^0's are also rejected.

Figure 2 shows the p_B^{cms} distribution, calculated with the $B^0 \to J/\psi K_L$ two-body decay hypothesis. The shapes of the background distributions are derived from Monte Carlo simulations (MC) and the normalization and peak position of the signal are allowed to vary. The fit finds a total of 346 ± 29 $J/\psi K_L$ signal events, and a signal purity of 61%.

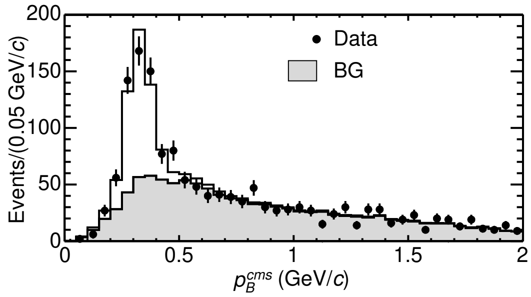

Figure 2. The p_B^{cms} distribution for $B^0 \to J/\psi K_L$ candidates with the results of the fit. The solid line is the signal plus background; the shaded area is background only. The signal region for KLM (ECL-only) clusters is $0.2 \le p_B^{\mathrm{cms}} \le 0.45(0.40)$ GeV/c.

3. Flavor tagging

Leptons, charged pions, and kaons that are not associated with a reconstructed CP eigenstate decay are used to identify the flavor of the accompanying B meson. Initially, the b-flavor determination is performed at the track level. Several categories of well measured tracks that distinguish the b-flavor by the track's charge are selected: 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 $b \to c \to s$, high momentum pions that originate from decays of the type $B^0 \to D^{(*)-}(\pi^+, \rho^+, a_1^+, \text{etc.})$, and slow pions from $D^{*-} \to \overline{D}^0\pi^-$. We use the MC to determine a category-dependent variable that indicates whether a track originates from a B^0 or $\overline{B}^0$. The values of this variable depend on the tagging particle's charge, cms momentum, polar angle and particle-identification probability, as well as other kinematic and event shape quantities. The results from the separate track categories are then combined to take into account correlations

Table 2
The event fractions (f_l) and incorrect flavor assignment probabilities (w_l) for each r interval. The errors include both statistical and systematic uncertainties.

l	r	f_l	w_l
1	$0.000 - 0.250$	0.405	$0.465^{+0.010}_{-0.009}$
2	$0.250 - 0.500$	0.149	$0.352^{+0.015}_{-0.014}$
3	$0.500 - 0.625$	0.081	$0.243^{+0.021}_{-0.030}$
4	$0.625 - 0.750$	0.099	$0.176^{+0.022}_{-0.017}$
5	$0.750 - 0.875$	0.123	$0.110^{+0.022}_{-0.014}$
6	$0.875 - 1.000$	0.140	$0.041^{+0.011}_{-0.010}$

in the case of multiple track-level tags. This stage determines two event-level parameters, q and r. The first, q, has the discrete values $q = +1$ when the tag-side B meson is more likely to be a B^0 and -1 when it is more likely to be a $\overline{B}^0$. The parameter r is an event-by-event flavor-tagging dilution factor which ranges from $r = 0$ for no flavor discrimination to $r = 1$ for unambiguous flavor assignment. It is used only to sort data into six intervals of r, according to flavor purity; the wrong-tag probabilities for the final fit are determined from data.

The probabilities of an incorrect flavor assignment, w_l $(l = 1,6)$, are determined directly from the data for the six r intervals using exclusively reconstructed, self-tagged $B^0 \to D^{*-}\ell^+\nu$, $D^{(*)-}\pi^+$, $D^{*-}\rho^+$ and $J/\psi K^{*0}(K^+\pi^-)$ decays. The b-flavor of the accompanying B meson is assigned according to the flavor-tagging algorithm described above. The values of w_l are obtained from the amplitudes of the time-dependent $B^0\overline{B}^0$ mixing oscillations: $(N_{\rm OF} - N_{\rm SF})/(N_{\rm OF} + N_{\rm SF}) = (1-2w_l)\cos(\Delta m_d \Delta t)$. Here $N_{\rm OF}$ and $N_{\rm SF}$ are the numbers of opposite and same flavor events. We fix Δm_d at the world average value [12]. Table 2 lists the resulting w_l values together with the fraction of the events (f_l) in each r interval. The total effective tagging efficiency is $\sum_l f_l(1-2w_l)^2 = 0.270 \pm 0.008({\rm stat})^{+0.006}_{-0.009}({\rm syst})$.

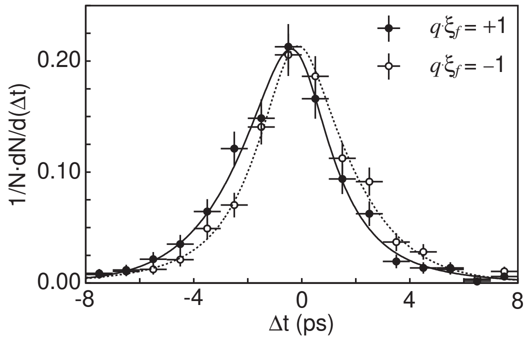

Figure 3. Δt distributions for the events with $q\xi_f = +1$ (solid points) and $q\xi_f = -1$ (open points). The results of the global fit (with $\sin 2\phi_1 = 0.99$) are shown as solid and dashed curves, respectively.

4. Vertexing

The vertex positions for the f_{CP} and $f_{\rm tag}$ decays are reconstructed using tracks that have at least one three-dimensional coordinate in an SVD layer along with one or more additional z hits in the other layers. Each vertex position is required to be consistent with the interaction point profile smeared in the r-ϕ plane by the B meson decay length. The f_{CP} vertex is determined using lepton tracks from J/ψ or $\psi(2S)$ decays, or prompt tracks from η_c decays. The $f_{\rm tag}$ vertex is determined from well reconstructed tracks not assigned to f_{CP}. Tracks that form a K_S are not used. The MC indicates that the typical vertex-finding efficiency and vertex resolution (rms) for z_{CP} ($z_{\rm tag}$) are 92 (91)% and 75 (140) μm, respectively.

The proper-time interval resolution for the signal, $R_{sig}(\Delta t)$, is obtained by convolving a sum of two Gaussians (a *main* component due to the SVD vertex resolution and charmed meson lifetimes, plus a *tail* component caused by poorly reconstructed tracks) with a function that takes into account the cms motion of the B mesons. The fraction in the main Gaussian is determined to be 0.97 ± 0.02 from a study of $B^0 \to D^{*-}\pi^+$, $D^{*-}\rho^+$, $D^-\pi^+$, $J/\psi K^{*0}$, $J/\psi K_S$ and $B^+ \to$

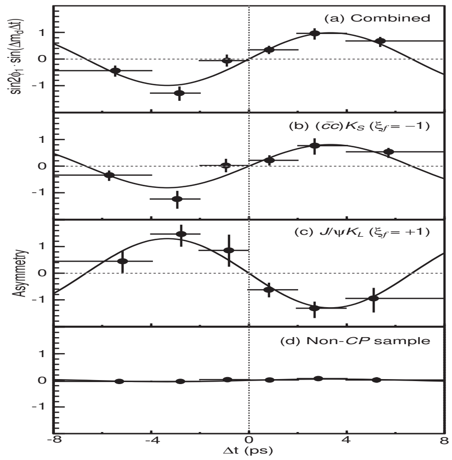

Figure 4. (a) The asymmetry obtained from separate fits to each Δt bin for the full data sample; the curve is the result of the fit. The corresponding plots for the (b) $(c\bar{c})K_S$ ($\xi_f = -1$), (c) $J/\psi K_L$ ($\xi_f = +1$), and (d) B^0 control samples are also shown.

$\overline{D}^0\pi^+$, $J/\psi K^+$ events. The means ($\mu_{\rm main}$, $\mu_{\rm tail}$) and widths ($\sigma_{\rm main}$, $\sigma_{\rm tail}$) of the Gaussians are calculated event-by-event from the f_{CP} and $f_{\rm tag}$ vertex fit error matrices and the χ^2 values of the fit; typical values are $\mu_{\rm main(tail)} = -0.24(0.18)$ ps and $\sigma_{\rm main(tail)} = 1.49(3.85)$ ps. The background resolution $R_{bkg}(\Delta t)$ has the same functional form but the parameters are obtained from a sideband region in M_{bc} and ΔE. We obtain lifetimes for the neutral and charged B mesons using the same procedure; the results [13] agree well with the world average values.

After vertexing we find 560(577) events with $q = +1(-1)$ flavor tags. Figure 3 shows the observed Δt distributions for the $q\xi_f = +1$ (solid points) and $q\xi_f = -1$ (open points) event samples. There is a clear asymmetry between the two distributions; this demonstrates that CP symmetry is violated.

5. $\sin 2\phi$ fitting

We determine $\sin 2\phi_1$ by performing an unbinned maximum-likelihood fit of a CP violating probability density function (pdf) to the observed Δt distributions. For modes other than $J/\psi K^{*0}$ the pdf expected for the signal is

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

where we fix τ_{B^0} and Δm_d at their world average values [12]. The pdf used for the background distribution is $\mathcal{P}_{\rm bkg}(\Delta t) = f_\tau e^{-|\Delta t|/\tau_{\rm bkg}}/2\tau_{\rm bkg} + (1-f_\tau)\delta(\Delta t)$, where f_τ is the fraction of the background component with an effective lifetime $\tau_{\rm bkg}$ and δ is the Dirac delta function. For all f_{CP} modes other than $J/\psi K_L$, a study using events in background-dominated regions of ΔE *vs.* $M_{\rm bc}$ shows that f_τ is negligibly small. For these modes, $\mathcal{P}_{\rm bkg}(\Delta t) = \delta(\Delta t)$.

The $J/\psi K_L$ background is dominated by $B \to J/\psi X$ decays where some final states are CP eigenstates. We estimate the fractions of the background components with and without a true K_L cluster by fitting the $p_B^{\rm cms}$ distribution to the expected shapes determined from the MC. We also use the MC to determine the fraction of events with definite CP content within each component.

For the $J/\psi K^*$ mode, we use the ξ_f content determined from the full angular analysis.

Each pdf is convolved with the appropriate $R(\Delta t)$ to determine the likelihood value for each event as a function of $\sin 2\phi_1$:

$$\begin{aligned} P_i \;=\; & \int \{ f_{\rm sig}\mathcal{P}_{\rm sig}(\Delta t', q, w_l, \xi_f) R_{\rm sig}(\Delta t - \Delta t') \\ & + (1-f_{\rm sig})\mathcal{P}_{\rm bkg}(\Delta t') R_{\rm bkg}(\Delta t - \Delta t')\} d\Delta t', \end{aligned}$$

where $f_{\rm sig}$ is the probability that the event is signal, calculated as a function of $p_B^{\rm cms}$ for $J/\psi K_L$ and of ΔE and $M_{\rm bc}$ for other modes. The only free parameter 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

$$\sin 2\phi_1 = 0.99 \pm 0.14({\rm stat}) \pm 0.06({\rm syst}).$$

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

Sample	$\sin 2\phi_1$
$f_{\rm tag} = B^0$ $(q=+1)$	0.84 ± 0.21
$f_{\rm tag} = \overline{B}^0$ $(q=-1)$	1.11 ± 0.17
$J/\psi K_S(\pi^+\pi^-)$	0.81 ± 0.20
$(c\bar{c})K_S$ except $J/\psi K_S(\pi^+\pi^-)$	1.00 ± 0.40
$J/\psi K_L$	1.31 ± 0.23
$J/\psi K^{*0}(K_S\pi^0)$	0.85 ± 1.45
All	0.99 ± 0.14

In Fig. 4(a) we show the asymmetries for the combined data sample that are obtained by applying the fit to the events in each Δt bin separately. The smooth curve is the result of the global unbinned fit. Figures 4(b) and (c) show the corresponding asymmetries for the $(c\bar{c})K_S$ $(\xi_f = -1)$ and the $J/\psi K_L$ $(\xi_f = +1)$ modes separately. The observed asymmetries for the different CP states are opposite, as expected. The curves are the results of unbinned fits applied separately to the two samples; the resultant $\sin 2\phi_1$ values are 0.84 ± 0.17(stat) and 1.31 ± 0.23(stat), respectively.

6. Systematic checks

The systematic error is dominated by uncertainties due to effects of the tails of the vertex distributions, which contribute 0.04. Other significant contributions come from uncertainties (a) in w_l (0.03); (b) in the resolution function parameters (0.02); and (c) in the $J/\psi K_L$ background fraction (0.02). The errors introduced by uncertainties in Δm_d and τ_{B^0} are 0.01 or less.

We performed a number of checks on the measurement. Table 3 lists the results obtained by applying the same analysis to various subsamples. All values are statistically consistent with each other. Fitting to the non-CP eigenstate self-tagged modes $B^0 \to D^{(*)-}\pi^+$, $D^{*-}\rho^+$, $J/\psi K^{*0}(K^+\pi^-)$ and $D^{*-}\ell^+\nu$, where no asymmetry is expected, yields 0.05 ± 0.04. The asymmetry distribution for this control sample is shown in Fig. 4(d).

7. Conclusion

We conclude that there is large CP violation in the neutral B meson system. A zero value for $\sin 2\phi_1$ is ruled out at a level greater than 6σ. Our result is consistent with the higher range of values allowed by the constraints of the KM model as well as with our previous measurement.

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