Measurement of the $CP$ Violation Parameter $\sin 2\phi_1$ in $B^0_d$ Meson Decays

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Abstract

We present a measurement of the Standard Model $CP$ violation parameter $\sin 2\phi_1$ (also known as $\sin 2\beta$) based on a 10.5 fb$^{-1}$ data sample collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric $e^+e^-$ collider. One neutral $B$ meson is reconstructed in the $J/\psi K_S$, $\psi(2S)K_S$, $\chi_{c1}K_S$, $\eta_c K_S$, $J/\psi K_L$ or $J/\psi \pi^0$ $CP$-eigenstate decay channel and the flavor of the accompanying $B$ meson is identified from its charged particle decay products. From the asymmetry in the distribution of the time interval between the two $B$-meson decay points, we determine $\sin 2\phi_1 = 0.58^{+0.32}_{-0.34}\text{(stat)}^{+0.09}_{-0.10}\text{(syst)}$.

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In the Standard Model (SM), $CP$ violation arises from a complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix $[1]$. In particular, the SM predicts a $CP$ violating asymmetry in the time-dependent rates for $B^0_d$ and $\bar{B}^0_d$ decays to a common $CP$ eigenstate, $f_{CP}$, without theoretical ambiguity due to strong interactions $[2]$: 

$$A(t) \equiv \frac{\Gamma(B^0_d \rightarrow f_{CP}) - \Gamma(B^0_d \rightarrow \bar{f}_{CP})}{\Gamma(B^0_d \rightarrow f_{CP}) + \Gamma(B^0_d \rightarrow \bar{f}_{CP})} = -\xi_f \sin 2\phi_1 \sin \Delta m_d t,$$

where $\Gamma(B^0_d \rightarrow f_{CP})$ is the decay rate for a $B^0_d$ to $f_{CP}$ at a proper time $t$ after production, $\xi_f$ is the $CP$-eigenvalue of $f_{CP}$, $\Delta m_d$ is the mass difference between the two $B^0_d$ mass eigenstates, and $\phi_1$ is one of the three internal angles of the CKM Unitarity Triangle, defined as $\phi_1 \equiv \pi - \arg \left( \frac{-V^*_{td}V_{ud}}{V^*_{td}V_{ud}} \right)$ $[3]$.

In this Letter, we report a measurement of $\sin 2\phi_1$ using $B^0_d \bar{B}^0_d$ meson pairs produced at the $\Upsilon(4S)$ resonance, where the two mesons remain in a coherent $p$-wave state until one of them decays. The decay of one of the $B$ mesons to a self-tagging state, $f_{tag}$, i.e. a final state that distinguishes between $B^0_d$ and $\bar{B}^0_d$, at time $t_{tag}$ projects the accompanying meson onto the opposite $b$-flavor at that time; this meson decays to $f_{CP}$ at time $t_{CP}$. The $CP$ violation manifests itself as an asymmetry $A(\Delta t)$, where $\Delta t$ is the proper time interval $\Delta t \equiv t_{CP} - t_{tag}$.

The data sample corresponds to an integrated luminosity of 10.5 fb$^{-1}$ collected with the Belle detector $[4]$ at the KEKB asymmetric $e^+e^-$ (3.5 on 8 GeV) collider $[5]$. At KEKB, the $\Upsilon(4S)$ is produced with a Lorentz boost of $\beta\gamma = 0.425$ along the electron beam direction ($z$ direction). Because the $B^0_d$ and $\bar{B}^0_d$ mesons are nearly at rest in the $\Upsilon(4S)$ center of mass system (cms), $\Delta t$ can be determined from the $z$ distance between the $f_{CP}$ and $f_{tag}$ decay vertices, $\Delta z \equiv z_{CP} - z_{tag}$, as $\Delta t \simeq \Delta z / \beta\gamma c$.

The Belle detector consists of a three-layer silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of 1188 aerogel Čerenkov counters (ACC), 128 time-of-flight (TOF) scintillation counters, and an electromagnetic calorimeter containing 8736 CsI(Tl) crystals (ECL) all located inside a 3.4-m-diameter superconducting solenoid that generates a 1.5 T magnetic field. The transverse momentum resolution for charged tracks is $(\sigma_{p_t}/p_t)^2 = (0.0019p_t)^2 + (0.0034)^2$, where $p_t$ is in GeV/$c$, and the impact parameter resolutions for $p = 1$ GeV/$c$ tracks at normal incidence are $\sigma_{r\phi} \simeq \sigma_z = 55 \mu m$. Specific ionization $(dE/dx)$ measurements in the CDC ($\sigma_{dE/dx} = 6.9\%$ for minimum ionizing pions), TOF flight-time measurements ($\sigma_{TOF} = 95$ ps), and the response of the ACC provide $K^\pm$ identification with an efficiency of $\sim 85\%$ and a charged pion fake rate of $\sim 10\%$ for all momenta up to 3.5 GeV/$c$. Photons are identified as ECL showers that have a minimum energy of 20 MeV and are not matched to a charged track. The photon energy resolution is $(\sigma_E/E)^2 = (0.013)^2 + (0.0007/E)^2 + (0.008/E^{1/4})^2$, where $E$ is in GeV. Electron identification is based on a combination of CDC $dE/dx$ information, the ACC response, and the position relative to the extrapolated track, shape and energy deposit of the associated ECL shower. The efficiency is greater than 90% and the hadron fake rate is $\sim 0.3\%$ for $p > 1$ GeV/$c$. An iron flux-return yoke outside the solenoid, comprised of 14 layers of 4.7-cm-thick iron plates interleaved with a system of resistive plate counters (KLM), provides muon identification with an efficiency greater than 90% and a hadron fake rate less than 2% for $p > 1$ GeV/$c$. The KLM is used in conjunction with the ECL to detect $K_L$ mesons; the angular resolution of the $K_L$ direction measurement ranges between 1.5$^\circ$ and 3$^\circ$.
We reconstruct $B_d^0$ decays to the following $CP$ eigenstates: $J/\psi K_S$, $\psi(2S)K_S$, $\chi_{c1}K_S$, $\eta_cK_S$ for $\xi_f = -1$ and $J/\psi \pi^0$, $J/\psi K_L$ for $\xi_f = +1$. The $J/\psi$ and $\psi(2S)$ mesons are reconstructed via their decays to $\ell^+\ell^-$ ($\ell = \mu, e$). The $\psi(2S)$ is also reconstructed via its $J/\psi \pi^+\pi^-$ decay, the $\chi_{c1}$ via its $J/\psi \gamma$ decay, and the $\eta_c$ via its $K^+K^-\pi^0$ and $K_S(\pi^+\pi^-)K^-\pi^+$ decays.

For $J/\psi$ and $\psi(2S) \rightarrow \ell^+\ell^-$ decays, we use oppositely charged track pairs where both tracks are positively identified as leptons. For the $B_d^0 \rightarrow J/\psi K_S(\pi^+\pi^-)$ mode, the requirement for one of the tracks is relaxed: a track with an ECL energy deposit consistent with a minimum ionizing particle is accepted as a muon and a track that satisfies either the $dE/dx$ or the ECL shower energy requirements as an electron. For $e^+e^-$ pairs, we include the four-momentum of every photon detected within 0.05 radians of the original $e^+$ or $e^-$ direction in the invariant mass calculation. Nevertheless a radiative tail remains and we accept pairs in the asymmetric invariant mass interval between $-12.5\sigma$ and $+3\sigma$ of $M_{J/\psi}$ or $M_{\psi(2S)}$, where $\sigma = 12$ MeV/c$^2$ is the mass resolution. The $\mu^+\mu^-$ radiative tail is smaller; we select pairs within $-5\sigma$ and $+3\sigma$ of $M_{J/\psi}$ or $M_{\psi(2S)}$. Candidate $K_S \rightarrow \pi^+\pi^-$ decays are oppositely charged track pairs that have an invariant mass within $\pm 4\sigma$ of the $K^0$ mass ($\sigma \simeq 4$ MeV/c$^2$). For the $J/\psi K_S$ final state, $K_S \rightarrow \pi^0\pi^0$ decays are also used. For $\pi^0\pi^0$ candidates, we try all combinations where there are two $\gamma\gamma$ pairs with an invariant mass between 80 and 150 MeV/c$^2$, assuming they originate from the center of the run-dependent average interaction point (IP). We minimize the sum of the $\chi^2$ values from constrained fits of each pair to the $\pi^0$ mass with $\gamma$ directions determined by varying the decay point along the $K_S$ flight path, which is taken as the line from the IP to the energy-weighted center of the four showers. We select combinations with a $\pi^0\pi^0$ invariant mass within $\sim \pm 3\sigma$ of $M_{K^0}$, where $\sigma \simeq 9.3$ MeV/c$^2$. For the $J/\psi \pi^0$ mode, we use a minimum $\gamma$ energy of 100 MeV and select $\gamma\gamma$ pairs with an invariant mass within $\pm 3\sigma$ of $M_{\gamma\gamma}$, where $\sigma \simeq 4.9$ MeV/c$^2$.

We isolate reconstructed $B$ meson decays using the energy difference $\Delta E \equiv E_{B}^{\text{cms}} - E_{\text{beam}}^{\text{cms}}$ and the beam-energy constrained mass $M_{bc} \equiv \sqrt{(E_{\text{beam}}^{\text{cms}})^2 - (p_{B}^{\text{cms}})^2}$, where $E_{\text{beam}}^{\text{cms}}$ is the cms beam energy, and $E_{B}^{\text{cms}}$ and $p_{B}^{\text{cms}}$ are the cms energy and momentum of the $B$ candidate. Figure 2 shows the $M_{bc}$ distribution for all channels combined (other than $J/\psi K_L$) after a $\Delta E$ selection that varies from $\pm 25$ MeV to $\pm 100$ MeV (corresponding to $\sim \pm 3\sigma$), depending on the mode. The $B$ meson signal region is defined as $5.270 < M_{bc} < 5.290$ GeV/c$^2$; the $M_{bc}$ resolution is 3.0 MeV/c$^2$. Table 1 lists the numbers of observed events ($N_{ev}$) and the background ($N_{bgd}$) determined by extrapolating the event rate in the non-signal $\Delta E$ vs. $M_{bc}$ region into the signal region.

Candidate $B_d^0 \rightarrow J/\psi K_L$ decays are selected by requiring the observed $K_L$ direction to be within 45° from the direction expected for a two-body decay (ignoring the $B_d^0$ cms motion). We reduce the background by means of a likelihood quantity that depends on the $J/\psi$ cms momentum, the angle between the $K_L$ and its nearest-neighbor charged track, the charged track multiplicity, and the kinematics that obtain when the event is reconstructed assuming a $B^+ \rightarrow J/\psi K^{*+}(K_L\pi^+)$ hypothesis. In addition, we remove events that are reconstructed as $B_d^0 \rightarrow J/\psi K_S$, $J/\psi K^{*0}(K^+\pi^-, K_S\pi^0)$, $B^+ \rightarrow J/\psi K^+$, or $J/\psi K^{*+}(K^+\pi^0 K_S\pi^+)$. Figure 2 shows the $p_{B}^{\text{cms}}$ distribution, calculated for a $B_d^0 \rightarrow J/\psi K_L$ two-body decay hypothesis, for the surviving events. The histograms in the figure are the results of a fit to the signal and background distributions, where the shapes are derived from Monte Carlo simulations (MC) [4], and the normalizations are allowed to vary. Among the total of
131 entries in the $0.2 < p_T^{\text{c.m.s.}} < 0.45$ GeV/c signal region, the fit finds 77 $J/\psi K_L$ events.

The leptons and charged pions and kaons among the tracks that are not associated with $f_{CP}$ are used to identify the flavor of the accompanying $B$ meson. Tracks are selected in several categories that distinguish the $b$-flavor by the track’s charge: high momentum leptons from $b \to c \ell^+ \nu$, lower momentum leptons from $c \to s \ell^+ \nu$, charged kaons from $b \to c \to s$, high momentum pions from decays of the type $B_d^0 \to D^{(*)} \pi^+$, and slow pions from $D^{(*)} \to D^{0} \pi^-$. For each track in one of these categories, we use the MC to determine the relative probability that it originates from a $B_d^0$ or $\bar{B}_d^0$ as a function of its charge, CMS momentum and polar angle, particle-identification probability, and other kinematic and event shape quantities. We combine the results from the different track categories (taking into account correlations for the case of multiple inputs) to determine a $b$-flavor $q$, where $q = +1$ when $f_{\text{tag}}$ is more likely to be a $B_d^0$ and $-1$ for a $\bar{B}_d^0$. We use the MC to evaluate an event-by-event flavor-tagging dilution factor, $r$, which ranges from $r = 0$ for no flavor discrimination to $r = 1$ for perfect flavor assignment. We only use $r$ to categorize the event.

For the $CP$ asymmetry analysis, we use the data to correct for wrong-flavor assignments.

The probabilities for an incorrect flavor assignment, $w_l$ ($l = 1, 6$), are measured directly from the data for six $r$ intervals using a sample of exclusively reconstructed, self-tagged $B_d^0 \to D^{(*)} \ell^+ \nu$, $D^{(*)} \pi^+$, and $D^{*} \rho^+$ decays. The $b$-flavor of the accompanying $B$ meson is assigned according to the above-described flavor-tagging algorithm, and values of $w_l$ are determined from the amplitudes of the time-dependent $B_d^0 - \bar{B}_d^0$ mixing oscillations [8]:

$$N_{\text{OF}} - N_{\text{SF}}(N_{\text{OF}} + N_{\text{SF}}) = (1 - 2w_l) \cos(\Delta m_d \Delta t).$$

Here $N_{\text{OF}}$ and $N_{\text{SF}}$ are the numbers of opposite and same flavor events. Table I lists the resulting $w_l$ values together with the fraction of the events ($f_l$) in each $r$ interval. All events in Table I fall in one of the six $r$ intervals. The total effective tagging efficiency is

$$\sum f_l (1 - 2w_l)^2 = 0.270_{-0.022}^{+0.021},$$

where the error includes both statistical and systematic uncertainties, in good agreement with the MC result of 0.274. We check for a possible bias in the flavor tagging by measuring the effective tagging efficiency for $B_d^0$ and $\bar{B}_d^0$ self-tagged samples separately, and for different $\Delta t$ intervals. We find no statistically significant difference.

The vertex positions for the $f_{CP}$ and $f_{\text{tag}}$ decays are reconstructed using tracks that have at least one 3-dimensional coordinate determined from associated $r\phi$ and $z$ hits in the same SVD layer plus one or more additional $z$ hits in other SVD layers. Each vertex position is required to be consistent with the IP profile smeared in the $r\phi$ plane by the $B$ meson decay length. (The IP size, determined run-by-run, is typically $\sigma_x \simeq 100$ $\mu$m, $\sigma_y \simeq 5$ $\mu$m and $\sigma_z \simeq 3$ mm.) The $f_{CP}$ vertex is determined using lepton tracks from the $J/\psi$ or $\psi(2S)$ decays, or prompt tracks from $\eta_c$ decays. The $f_{\text{tag}}$ vertex is determined from tracks not assigned to $f_{CP}$ with additional requirements of $\delta r < 0.5$ mm, $\delta z < 1.8$ mm and $\sigma_{\delta z} < 0.5$ mm, where $\delta r$ and $\delta z$ are the distances of the closest approach to the $f_{CP}$ vertex in the $r\phi$ plane and the $z$ direction, respectively, and $\sigma_{\delta z}$ is the calculated error of $\delta z$. Tracks that form a $K_S$ are removed. The MC indicates that the average $z_{CP}$ resolution is 75 $\mu$m (rms); the $z_{\text{tag}}$ resolution is worse (140 $\mu$m) because of the lower average momentum of the $f_{\text{tag}}$ decay products and the smearing caused by secondary tracks from charmed meson decays.

The resolution function $R(\Delta t)$ for the proper time interval is parameterized as a sum of two Gaussian components: a main component due to the SVD vertex resolution, charmed meson lifetimes and the effect of the CMS motion of the $B$ mesons, plus a tail component.
caused by poorly reconstructed tracks. The means ($\mu_{\text{main}}, \mu_{\text{tail}}$) and widths ($\sigma_{\text{main}}, \sigma_{\text{tail}}$) of the Gaussians are calculated event-by-event from the $f_{\text{CP}}$ and $f_{\text{tag}}$ vertex fit error matrices; average values are $\mu_{\text{main}} = -0.09$ ps, $\mu_{\text{tail}} = -0.78$ ps and $\sigma_{\text{main}} = 1.54$ ps, $\sigma_{\text{tail}} = 3.78$ ps. The negative values of the means are due to secondary tracks from charmed mesons. The relative fraction of the main Gaussian is determined to be 0.982 ± 0.007 from a study of $B_d^0 \rightarrow D^{*+} \ell^+ \nu$ events. The reliability of the $\Delta t$ determination and $R(\Delta t)$ parameterization is confirmed by lifetime measurements of the neutral and charged $B$ mesons [8] that use the same procedures and are in good agreement with the world average values [10].

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

$$P_{\text{sig}}(\Delta t, q, w_l, \xi_f) = \frac{e^{-|\Delta t|/\tau_{\text{bd}}}}{2 \tau_{\text{bd}}^{\xi_f}} \{1 - \xi_f q (1 - 2w_l) \sin 2\phi_1 \sin(\Delta m_d \Delta t)\},$$

where we fix the $B_d^0$ lifetime and mass difference at their world average values [10]. The pdf used for background events is $P_{\text{bkg}}(\Delta t) = f_{\tau} e^{-|\Delta t|/\tau_{\text{bkg}}} / 2 \tau_{\text{bkg}} + (1 - f_{\tau}) \delta(\Delta t)$, where $f_{\tau}$ is the fraction of the background component with an effective lifetime $\tau_{\text{bkg}}$ and $\delta(\Delta t)$ is the Dirac delta function. For all $f_{\text{CP}}$ modes except $J/\psi K_L$, we find $f_{\tau} = 0.10^{+0.11}_{-0.05}$ and $\tau_{\text{bkg}} = 1.75^{+1.15}_{-0.82}$ ps using events in background-dominated regions of $\Delta E$ vs. $M_{bc}$. The $J/\psi K_L$ background is dominated by $B \rightarrow J/\psi X$ decays, where some final states are $CP$ eigenstates and need special treatment. A MC study shows that the background contribution from the $\xi_f = -1$ sources $J/\psi K_S, \psi(2S)K_S$ and $\chi_{c1}K_S$ is 7.9%, while that from the $\xi_f = +1 \psi(2S)K_L$ and $\chi_{c1}K_L$ modes is 7.0%. Thus, the effects on the $CP$ asymmetry from these states nearly cancel. The remaining dominant $CP$ mode, $J/\psi K^*(K_L\pi^0)$, which accounts for 19% of the total background, is taken to be a 73/27 mixture of $\xi_f = -1$ and $+1$, respectively, based on our measurement of the $J/\psi$ polarization in the $B_d^0 \rightarrow J/\psi K^{*0}(K_S\pi^0)$ decay [11]. For the $J/\psi K^*(K_L\pi^0)$ background pdf we use $P_{\text{sig}}$ with effective $CP$ eigenvalue $\xi_f = -0.46^{+1.46}_{-0.54}$, where the error has been expanded to include all possible values. For the non-$CP$ background modes we use $P_{\text{bkg}}$ with $f_{\tau} = 1$ and $\tau_{\text{bkg}} = \tau_B$.

The pdfs are convolved with $R(\Delta t)$ to determine the likelihood value for each event as a function of $\sin 2\phi_1$:

$$L_i = \int \{f_{\text{sig}} P_{\text{sig}}(\Delta t', q, w_l, \xi_f) + (1 - f_{\text{sig}}) P_{\text{bkg}}(\Delta t')\} R(\Delta t - \Delta t') d\Delta t',$$

where $f_{\text{sig}}$ is the probability that the event is signal, calculated as a function of $p_B^{\text{rms}}$ for $J/\psi K_L$ and of $\Delta E$ and $M_{bc}$ for other modes. The most probable $\sin 2\phi_1$ is the value that maximizes the likelihood function $L = \prod_i L_i$, where the product is over all events. We performed a blind analysis: the fitting algorithms were developed and finalized using a flavor-tagging routine that does not divulge the sign of $q$. The sign of $q$ was then turned on and the application of the fit to all the events listed in Table 3 produces the result $\sin 2\phi_1 = 0.58^{+0.32}_{-0.34} \pm 0.09$, where the first error is statistical and the second systematic. The systematic errors are dominated by the uncertainties in $w_l$ ($\pm 0.05$) and the $J/\psi K_L$ background ($\pm 0.05$). Separate fits to the $\xi_f = -1$ and $\xi_f = +1$ event samples give $0.82^{+0.36}_{-0.41}$ and $0.10^{+0.57}_{-0.60}$, respectively [12]. Figure 3(a) shows $-2 \ln(L/L_{\text{max}})$ as a function of $\sin 2\phi_1$ for the $\xi_f = -1$ and $\xi_f = +1$ modes separately and for both modes combined. Figure 3(b) shows the
asymmetry obtained by performing the fit to events in $\Delta t$ bins separately, together with a curve that represents $\sin 2\phi_1 \sin(\Delta m_d \Delta t)$ for $\sin 2\phi_1 = 0.58$.

We check for a possible fit bias by applying the same fit to non-$CP$ eigenstate modes: $B^0_d \to D(*)^- \pi^+$, $D^{*-} \rho^+$, $J/\psi K^{*0}(K^+\pi^-)$, and $D^{*-} \ell^+\nu$, where “$\sin 2\phi_1$” should be zero, and the charged mode $B^+ \to J/\psi K^+$. For all the modes combined we find $0.065 \pm 0.075$, consistent with a null asymmetry.

We have presented a measurement of the Standard Model $CP$ violation parameter $\sin 2\phi_1$ based on a $10.5 \text{ fb}^{-1}$ data sample collected at the $\Upsilon(4S)$:

$$\sin 2\phi_1 = 0.58^{+0.32}_{-0.34}\text{(stat)}^{+0.09}_{-0.10}\text{(syst)}.$$

The probability of observing $\sin 2\phi_1 > 0.58$ if the true value is zero is 4.9%. Our measurement is more precise than the previous measurements [13] and consistent with SM constraints [14].

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TABLE I. The numbers of CP eigenstate events

| Mode | $N_{ev}$ | $N_{bkgd}$ |
|------|--------|-------|
| $J/\psi(\ell^+\ell^-)K_S(\pi^+\pi^-)$ | 123 | 3.7 |
| $J/\psi(\ell^+\ell^-)K_S(\pi^0\pi^0)$ | 19 | 2.5 |
| $\psi(2S)(\ell^+\ell^-)K_S(\pi^+\pi^-)$ | 13 | 0.3 |
| $\psi(2S)(J/\psi\pi^+\pi^-)K_S(\pi^+\pi^-)$ | 11 | 0.3 |
| $\chi_{c1}(\gamma J/\psi)K_S(\pi^+\pi^-)$ | 3 | 0.5 |
| $\eta_c(K^+K^-\pi^0)K_S(\pi^+\pi^-)$ | 10 | 2.4 |
| $\eta_c(K_SK^+\pi^-)K_S(\pi^+\pi^-)$ | 5 | 0.4 |
| $J/\psi(\ell^+\ell^-)\pi^0$ | 10 | 0.9 |
| Sub-total | 194 | 11 |
| $J/\psi(\ell^+\ell^-)K_L$ | 131 | 54 |

TABLE II. Experimentally determined event fractions ($f_l$) and incorrect flavor assignment probabilities ($w_l$) for each $r$ interval.

| $l$ | $r$ | $f_l$ | $w_l$ |
|-----|-----|------|-------|
| 1   | 0.000 – 0.250 | 0.393 ± 0.014 | 0.470 +0.037 -0.035 |
| 2   | 0.250 – 0.500 | 0.154 ± 0.007 | 0.336 +0.039 -0.042 |
| 3   | 0.500 – 0.625 | 0.092 ± 0.005 | 0.286 +0.037 -0.035 |
| 4   | 0.625 – 0.750 | 0.100 ± 0.005 | 0.210 +0.033 -0.031 |
| 5   | 0.750 – 0.875 | 0.121 ± 0.006 | 0.098 +0.028 -0.026 |
| 6   | 0.875 – 1.000 | 0.134 ± 0.006 | 0.020 +0.023 -0.019 |

FIG. 1. The beam-constrained mass distribution for all decay modes combined (other than $B_d^0 \rightarrow J/\psi K_L$). The shaded area is the estimated background. The dashed lines indicate the signal region.
FIG. 2. The $p_B^{\text{cms}}$ distribution for $B_d^0 \rightarrow J/\psi K_L$ candidates with the results of the fit. The solid line is the signal plus background; the shaded area is background only. The dashed lines indicate the signal region.
FIG. 3.  (a) Values of $-2\ln(L/L_{max})$ vs. $\sin 2\phi_1$ for the $\xi_f = -1$ and +1 modes separately and for both modes combined. (b) The asymmetry obtained from separate fits to each $\Delta t$ bin; the curve is the result of the global fit ($\sin 2\phi_1 = 0.58$).