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Improved measurement of mixing-induced *CP* violation in the neutral *B* meson system

K. Abe,[8] K. Abe,[41] T. Abe,[42] I. Adachi,[8] H. Aihara,[43] M. Akatsu,[21] Y. Asano,[48] T. Aso,[47] V. Aulchenko,[2] T. Aushev,[12] A. M. Bakich,[38] E. Banas,[26] A. Bay,[17] P. K. Behera,[49] I. Bizjak,[13] A. Bondar,[2] A. Bozek,[26] M. Bračko,[19,13] J. Brodzicka,[26] T. E. Browder,[7] B. C. K. Casey,[7] P. Chang,[25] Y. Chao,[25] K.-F. Chen,[25] B. G. Cheon,[37] R. Chistov,[12] Y. Choi,[37] Y. K. Choi,[37] M. Danilov,[12] L. Y. Dong,[10] A. Drutskoy,[12] S. Eidelman,[2] V. Eiges,[12] Y. Enari,[21] C. W. Everton,[20] F. Fang,[7] H. Fujii,[8] C. Fukunaga,[45] N. Gabyshev,[8] A. Garmash,[2,8] T. Gershon,[8] B. Golob,[18,13] K. Gotow,[50] R. Guo,[23] J. Haba,[8] K. Hanagaki,[32] F. Handa,[42] K. Hara,[30] T. Hara,[30] Y. Harada,[28] N. C. Hastings,[20] H. Hayashii,[22] M. Hazumi,[8] E. M. Heenan,[20] I. Higuchi,[42] T. Higuchi,[8] L. Hinz,[17] T. Hojo,[30] T. Hokuue,[21] Y. Hoshi,[41] W.-S. Hou,[25] H.-C. Huang,[25] T. Igaki,[21] Y. Igarashi,[8] T. Iijima,[21] K. Inami,[21] A. Ishikawa,[21] H. Ishino,[44] R. Itoh,[8] H. Iwasaki,[8] Y. Iwasaki,[8] H. K. Jang,[36] H. Kakuno,[44] J. Kaneko,[44] J. H. Kang,[52] J. S. Kang,[14] N. Katayama,[8] H. Kawai,[3] H. Kawai,[43] Y. Kawakami,[21] N. Kawamura,[1] T. Kawasaki,[28] H. Kichimi,[8] D. W. Kim,[37] Heejong Kim,[52] H. J. Kim,[52] H. O. Kim,[37] Hyunwoo Kim,[14] K. Kinoshita,[5] S. Kobayashi,[34] K. Korotushenko,[32] S. Korpar,[19,13] P. Križan,[18,13] P. Krokovny,[2] S. Kumar,[31] A. Kuzmin,[2] Y.-J. Kwon,[52] J. S. Lange,[6,33] G. Leder,[11] S. H. Lee,[36] J. Li,[35] A. Limosani,[20] J. MacNaughton,[11] G. Majumder,[39] F. Mandl,[11] D. Marlow,[32] S. Matsumoto,[4] T. Matsumoto,[45] W. Mitaroff,[11] K. Miyabayashi,[22] Y. Miyabayashi,[21] H. Miyake,[30] G. R. Moloney,[20] T. Mori,[4] A. Murakami,[34] T. Nagamine,[42] Y. Nagasaka,[9] T. Nakadaira,[43] E. Nakano,[29] M. Nakao,[8] H. Nakazawa,[4] J. W. Nam,[37] Z. Natkaniec,[26] K. Neichi,[41] S. Nishida,[15] O. Nitoh,[46] S. Noguchi,[22] T. Nozaki,[8] S. Ogawa,[40] T. Ohshima,[21] T. Okabe,[21] S. L. Olsen,[7] Y. Onuki,[28] W. Ostrowicz,[26] H. Ozaki,[8] P. Pakhlov,[12] H. Palka,[26] C. W. Park,[14] H. Park,[16] K. S. Park,[37] J.-P. Perroud,[17] L. E. Piilonen,[50] F. J. Ronga,[17] N. Root,[2] M. Rozanska,[26] K. Rybicki,[26] H. Sagawa,[8] S. Saitoh,[8] Y. Sakai,[8] H. Sakamoto,[15] M. Satapathy,[49] A. Satpathy,[8,5] O. Schneider,[17] S. Schrenk,[5] C. Schwanda,[8,11] S. Semenov,[12] K. Senyo,[21] R. Seuster,[7] H. Shibuya,[40] B. Shwartz,[2] V. Sidorov,[2] J. B. Singh,[31] N. Soni,[31] S. Stanič,[48,*] A. Sugi,[21] A. Sugiyama,[21] K. Sumisawa,[8] T. Sumiyoshi,[45] K. Suzuki,[8] S. Suzuki,[51] S. Y. Suzuki,[8] H. Tajima,[43] T. Takahashi,[29] F. Takasaki,[8] K. Tamai,[8] N. Tamura,[28] J. Tanaka,[43] M. Tanaka,[8] G. N. Taylor,[20] Y. Teramoto,[29] S. Tokuda,[21] T. Tomura,[43] K. Trabelsi,[7] W. Trischuk,[32,†] T. Tsuboyama,[8] T. Tsukamoto,[8] S. Uehara,[8] K. Ueno,[25] Y. Unno,[3] S. Uno,[8] N. Uozaki,[43] Y. Ushiroda,[8] S. E. Vahsen,[32] G. Varner,[7] K. E. Varvell,[38] C. C. Wang,[25] C. H. Wang,[24] J. G. Wang,[50] M.-Z. Wang,[25] Y. Watanabe,[44] E. Won,[14] B. D. Yabsley,[50] Y. Yamada,[8] A. Yamaguchi,[42] H. Yamamoto,[42] Y. Yamashita,[43] Y. Yamashita,[27] M. Yamauchi,[8] H. Yanai,[28] J. Yashima,[8] P. Yeh,[25] M. Yokoyama,[43] Y. Yuan,[10] Y. Yusa,[42] H. Yuta,[1] C. C. Zhang,[10] J. Zhang,[48] Z. P. Zhang,[35] V. Zhilich,[2] and D. Žontar[48]

(Belle Collaboration)

[1]*Aomori University, Aomori*
[2]*Budker Institute of Nuclear Physics, Novosibirsk*
[3]*Chiba University, Chiba*
[4]*Chuo University, Tokyo*
[5]*University of Cincinnati, Cincinnati, Ohio*
[6]*University of Frankfurt, Frankfurt*
[7]*University of Hawaii, Honolulu, Hawaii*
[8]*High Energy Accelerator Research Organization (KEK), Tsukuba*
[9]*Hiroshima Institute of Technology, Hiroshima*
[10]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing*
[11]*Institute of High Energy Physics, Vienna*
[12]*Institute for Theoretical and Experimental Physics, Moscow*
[13]*J. Stefan Institute, Ljubljana*
[14]*Korea University, Seoul*
[15]*Kyoto University, Kyoto*
[16]*Kyungpook National University, Taegu*
[17]*Institut de Physique des Hautes Énergies, Université de Lausanne, Lausanne*
[18]*University of Ljubljana, Ljubljana*
[19]*University of Maribor, Maribor*
[20]*University of Melbourne, Victoria*
[21]*Nagoya University, Nagoya*
[22]*Nara Women's University, Nara*
[23]*National Kaohsiung Normal University, Kaohsiung*
[24]*National Lien-Ho Institute of Technology, Miao Li*
[25]*National Taiwan University, Taipei*

*On leave from Nova Gorica Polytechnic, Nova Gorica.
†On leave from University of Toronto, Toronto, Ontario.

[26]*H. Niewodniczanski Institute of Nuclear Physics, Krakow*
[27]*Nihon Dental College, Niigata*
[28]*Niigata University, Niigata*
[29]*Osaka City University, Osaka*
[30]*Osaka University, Osaka*
[31]*Panjab University, Chandigarh*
[32]*Princeton University, Princeton, New Jersey*
[33]*RIKEN BNL Research Center, Brookhaven, New York*
[34]*Saga University, Saga*
[35]*University of Science and Technology of China, Hefei*
[36]*Seoul National University, Seoul*
[37]*Sungkyunkwan University, Suwon*
[38]*University of Sydney, Sydney NSW*
[39]*Tata Institute of Fundamental Research, Bombay*
[40]*Toho University, Funabashi*
[41]*Tohoku Gakuin University, Tagajo*
[42]*Tohoku University, Sendai*
[43]*University of Tokyo, Tokyo*
[44]*Tokyo Institute of Technology, Tokyo*
[45]*Tokyo Metropolitan University, Tokyo*
[46]*Tokyo University of Agriculture and Technology, Tokyo*
[47]*Toyama National College of Maritime Technology, Toyama*
[48]*University of Tsukuba, Tsukuba*
[49]*Utkal University, Bhubaneswer*
[50]*Virginia Polytechnic Institute and State University, Blacksburg, Virginia*
[51]*Yokkaichi University, Yokkaichi*
[52]*Yonsei University, Seoul*

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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 85×10^6 $B\overline{B}$ 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 the accompanying B meson is identified from its decay products. From the asymmetry in the distribution of the time interval between the two B meson decay points, we obtain $\sin 2\phi_1 = 0.719 \pm 0.074(\mathrm{stat}) \pm 0.035(\mathrm{syst})$.

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In the standard model (SM), *CP* violation arises from an irreducible complex phase in the weak interaction quark-mixing matrix [Cabibbo-Kobayashi-Maskawa (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}, where the transition is dominated by the $b \to c\overline{c}s$ process, 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 rate for B^0 or $\overline{B}^0$ 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 interior angles of the CKM unitarity triangle, defined as $\phi_1 \equiv \pi - \arg(V_{tb}^* V_{td} / V_{cb}^* V_{cd})$. Nonzero values for $\sin 2\phi_1$ have been 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 85×10^6 $B\overline{B}$ pairs (78 fb^{-1}). Two important changes exist in the analysis with respect to the published result [3]; we apply a new track reconstruction algorithm that provides better performance and a new proper-time interval resolution function [5] that reduces systematic uncertainties in $\sin 2\phi_1$. The data were collected with the Belle detector [6] at the KEKB asymmetric collider [7], 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_{tag}, which distinguishes B^0 from $\overline{B}^0$, at time t_{tag}. The *CP* violation manifests itself as an asymmetry $A(\Delta t)$, where Δt is the proper time interval between the two decays: $\Delta t \equiv t_{CP} - t_{\mathrm{tag}}$. At KEKB, the $\Upsilon(4S)$ resonance is produced with a boost of $\beta\gamma = 0.425$ nearly along the z axis defined as antiparallel to the positron beam 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_{tag} decay

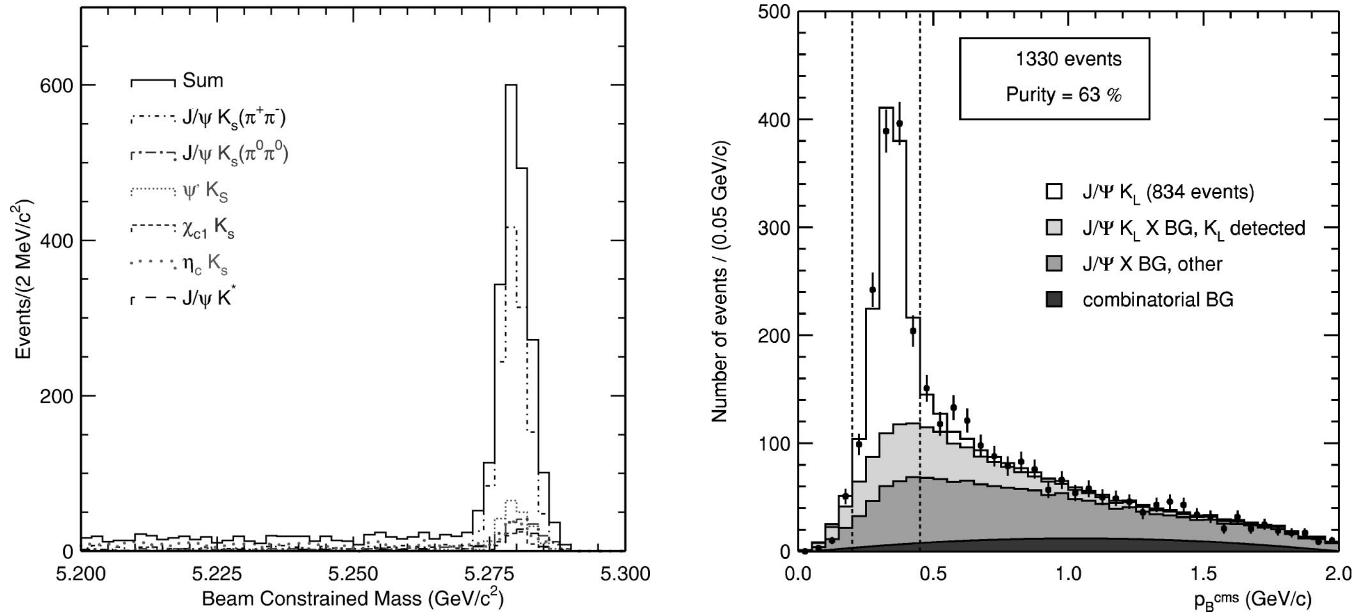

FIG. 1. The beam-energy constrained mass distribution for all decay modes other than $J/\psi K_L^0$ (left). The $p_B^{\rm cms}$ distribution for $B^0 \to J/\psi K_L^0$ candidates with the results of the fit (right).

vertices, $\Delta z \equiv z_{CP} - z_{\rm tag}$. The average value of Δz is approximately 200 μm.

The Belle detector [6] is a large-solid-angle spectrometer that includes a silicon vertex detector (SVD), a central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), time-of-flight (TOF) scintillation counters, 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 [8]: $J/\psi K_S^0$, $\psi(2S)K_S^0$, $\chi_{c1}K_S^0$, $\eta_c K_S^0$ 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 $0.19 \pm 0.02(\text{stat}) \pm 0.03(\text{syst})$ [9]. 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 $K_S^0 K^-\pi^+$, $K^+K^-\pi^0$, and $p\overline{p}$ modes. For the $J/\psi K_S^0$ mode, we use $K_S^0 \to \pi^+\pi^-$ and $\pi^0\pi^0$ decays; for other modes we only use $K_S^0 \to \pi^+\pi^-$. 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) of the $\Upsilon(4S)$ resonance, 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 I 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 K_L^0 meson. The centroid of the shower is required to be within a 45° cone centered on the K_L^0 direction 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 1330 entries in total in the $0.20 \leqslant p_B^{\rm cms} \leqslant 0.45$ GeV/c signal region; the fit indicates a signal purity of 63%. The reconstruction and selection criteria for all f_{CP} channels used in the measurement are described in more detail elsewhere [3].

Charged leptons, 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. Based on the measured properties of these tracks, two parameters, q and r, are assigned to an event. The first, q, has the discrete value $+1$ (-1) when the tag-side B meson 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 estimated 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-tagging 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 event fractions and wrong tag fractions are summarized in Table II. The total effective tagging efficiency is determined to be $\epsilon_{\rm eff} \equiv \Sigma_{l=1}^{6} \epsilon_l (1 - 2w_l)^2 = 0.288 \pm 0.006$,

TABLE I. The numbers of reconstructed $B \to f_{CP}$ candidates before flavor tagging and vertex reconstruction, $N_{\rm rec}$, the numbers of events used for the $\sin 2\phi_1$ determination, $N_{\rm ev}$, and the estimated signal purity in the signal region for each f_{CP} mode.

Mode	ξ_f	$N_{\rm rec}$	$N_{\rm ev}$	Purity
$J/\psi(\ell^+\ell^-)K_S^0(\pi^+\pi^-)$	-1	1285	1116	0.976 ± 0.001
$J/\psi(\ell^+\ell^-)K_S^0(\pi^0\pi^0)$	-1	188	162	0.82 ± 0.02
$\psi(2S)(\ell^+\ell^-)K_S^0(\pi^+\pi^-)$	-1	91	76	0.96 ± 0.01
$\psi(2S)(J/\psi\pi^+\pi^-)K_S^0(\pi^+\pi^-)$	-1	112	96	0.91 ± 0.01
$\chi_{c1}(J/\psi\gamma)K_S^0(\pi^+\pi^-)$	-1	77	67	0.96 ± 0.01
$\eta_c(K_S^0K^-\pi^+)K_S^0(\pi^+\pi^-)$	-1	72	63	0.65 ± 0.04
$\eta_c(K^+K^-\pi^0)K_S^0(\pi^+\pi^-)$	-1	49	44	0.72 ± 0.04
$\eta_c(p\overline{p})K_S^0(\pi^+\pi^-)$	-1	21	15	0.94 ± 0.02
All with $\xi_f = -1$	-1	1895	1639	0.936 ± 0.003
$J/\psi(\ell^+\ell^-)K^{*0}(K_S^0\pi^0)$	$-1(19\%)/+1(81\%)$	101	89	0.92 ± 0.01
$J/\psi(\ell^+\ell^-)K_L^0$	$+1$	1330	1230	0.63 ± 0.04
All		3326	2958	0.81 ± 0.01

where ϵ_l is the event fraction for each r interval. The error includes both statistical and systematic uncertainties. Improvements in the Monte Carlo simulation [10] and in the track reconstruction yield $\epsilon_{\rm eff}$ that is higher by 6.7% (relative) than the value in Ref. [3].

The vertex position for the f_{CP} decay is reconstructed using leptons from J/ψ decays or charged hadrons from η_c decays, 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 the interaction region profile, determined run-by-run, smeared in the r-ϕ plane to account for 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 22% 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 the kinematic approximation that the B mesons are at rest in the cms [5]. A small component of broad outliers in the Δz distribution, caused by mis-reconstruction, is represented by a Gaussian function. We determine twelve resolution parameters from fits of data to the neutral and charged B meson lifetimes [5] and obtain an average Δt resolution of $\sim$1.43 ps (rms). The width of the outlier component is determined to be 42^{+5}_{-4} ps; the fractions of the outlier components are $(2 \pm 1) \times 10^{-4}$ for events with both vertices reconstructed with more than one track, and $(2.7 \pm 0.2) \times 10^{-2}$ for events with at least one single-track vertex.

After flavor tagging and vertexing, we find 1465 events with $q = +1$ flavor tags and 1493 events with $q = -1$. Table I lists the numbers of candidates used for the $\sin 2\phi_1$ determination, $N_{\rm ev}$, and the estimated signal purity in the signal region for each f_{CP} mode. 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 $\sin 2\phi_1$ from an unbinned maximum-likelihood fit to the observed Δt distributions. The probabil-

TABLE II. The event fractions ϵ_l, wrong tag fractions w_l, and effective tagging efficiencies $\epsilon_{\rm eff}^l = \epsilon_l(1-2w_l)^2$ for each r interval. The errors include both statistical and systematic uncertainties. The event fractions are obtained from the $J/\psi K_S^0$ simulation.

l	r interval	ϵ_l	w_l	$\epsilon_{\rm eff}^l$
1	0.000–0.250	0.398	0.458 ± 0.006	0.003 ± 0.001
2	0.250–0.500	0.146	0.336 ± 0.009	0.016 ± 0.002
3	0.500–0.625	0.104	0.228 ± 0.010	0.031 ± 0.002
4	0.625–0.750	0.122	$0.160^{+0.009}_{-0.008}$	0.056 ± 0.003
5	0.750–0.875	0.094	0.112 ± 0.009	0.056 ± 0.003
6	0.875–1.000	0.136	0.020 ± 0.006	$0.126^{+0.003}_{-0.004}$

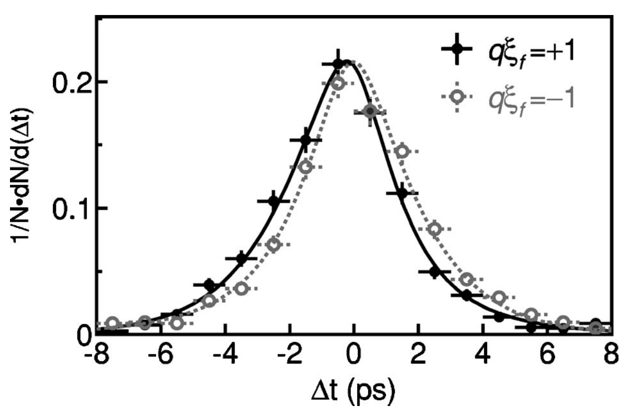

FIG. 2. The Δt distributions for the events with $q\xi_f = +1$ (solid points) and $q\xi_f = -1$ (open points). The results of the global fit with $\sin 2\phi_1 = 0.719$ are shown as solid and dashed curves, respectively.

TABLE III. The numbers of candidate events, $N_{\rm ev}$, and values of $\sin 2\phi_1$ for various subsamples (statistical errors only).

Sample	$N_{\rm ev}$	$\sin 2\phi_1$
$J/\psi K_S^0(\pi^+\pi^-)$	1116	0.73 ± 0.10
$(c\bar{c})K_S^0$ except $J/\psi K_S^0(\pi^+\pi^-)$	523	0.67 ± 0.17
$J/\psi K_L^0$	1230	0.78 ± 0.17
$J/\psi K^{*0}(K_S^0\pi^0)$	89	0.04 ± 0.63
$f_{\rm tag}=B^0$ $(q=+1)$	1465	0.65 ± 0.12
$f_{\rm tag}=\overline{B}^0$ $(q=-1)$	1493	0.77 ± 0.09
$0<r\leqslant0.5$	1600	1.27 ± 0.36
$0.5<r\leqslant0.75$	658	0.62 ± 0.15
$0.75<r\leqslant1$	700	0.72 ± 0.09
data before 2002	1587	0.78 ± 0.10
data in 2002	1371	0.65 ± 0.11
All	2958	0.72 ± 0.07

ity density function (PDF) expected for the signal distribution is given by

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

where we fix the B^0 lifetime τ_{B^0} and mass difference at their world average values [11]. Each PDF is convolved with the appropriate $R_{\rm sig}(\Delta t)$ to determine the likelihood value for each event as a function of $\sin 2\phi_1$:

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

where $f_{\rm sig}$ is the signal fraction 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 of the outlier component, $P_{\rm ol}$, and its fraction $f_{\rm ol}$. The only free parameter in the final fit is $\sin 2\phi_1$, which is determined by maximizing the likelihood function $L=\Pi_i P_i$, where the product is over all events. The result of the fit is

$$\sin 2\phi_1=0.719\pm0.074({\rm stat})\pm0.035({\rm syst}).$$

The systematic error is dominated by uncertainties in the vertex reconstruction (0.022). Other significant contributions come from uncertainties in w_l (0.015), the resolution function parameters (0.014), a possible bias in the $\sin 2\phi_1$ fit (0.011), and the $J/\psi K_L^0$ background fraction (0.010). The errors introduced by uncertainties in Δm_d and τ_{B^0} are less than 0.010.

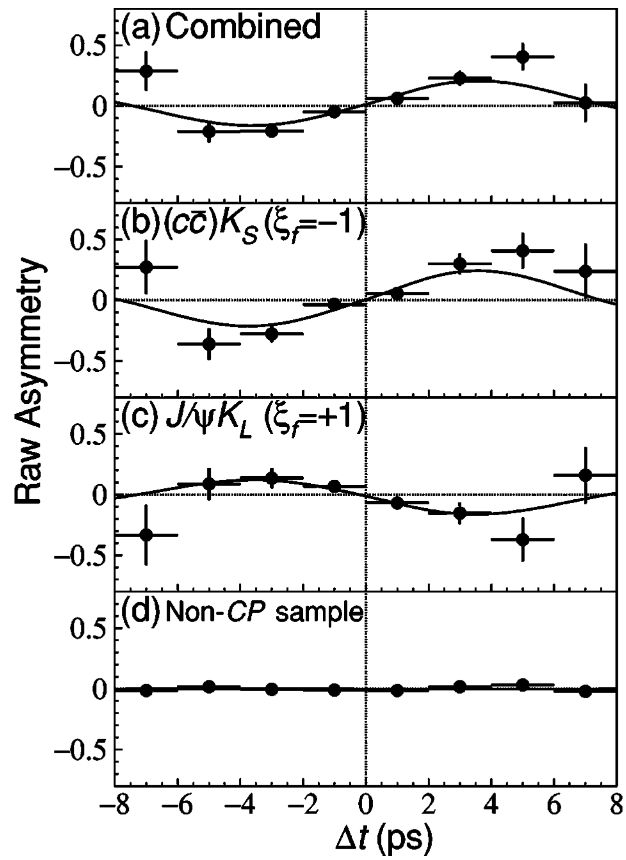

FIG. 3. (a) The raw asymmetry for all modes combined. The asymmetry for $J/\psi K_L^0$ and $J/\psi K^{*0}$ is inverted to account for the opposite *CP* eigenvalue. The corresponding plots for (b) $(c\bar{c})K_S^0$, (c) $J/\psi K_L^0$, and (d) non-*CP* control samples are also shown. The curves are the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

Several checks on the measurement are performed. Table III lists the results obtained by applying the same analysis to various subsamples. All values are statistically consistent with each other. Figures 3(a)–3(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 modes $B^0\to D^{(*)-}\pi^+$, $D^{*-}\rho^+$, $J/\psi K^{*0}(K^+\pi^-)$, and $D^{*-}\ell^+\nu$, where no asymmetry is expected, yields $0.005\pm0.015({\rm stat})$. Figure 3(d) shows the raw asymmetry for these non-*CP* control samples.

The signal PDF for a neutral B meson decaying into a *CP* eigenstate [Eq. (2)] can be expressed in a more general form as

$$\mathcal{P}_{\rm sig}(\Delta t,q,w_l)=\frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left\{1+q(1-2w_l)\left[\frac{2\,{\rm Im}\,\lambda}{|\lambda|^2+1}\times\sin(\Delta m_d\Delta t)+\frac{|\lambda|^2-1}{|\lambda|^2+1}\cos(\Delta m_d\Delta t)\right]\right\}, \qquad (4)$$

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 presence of the cosine term ($|\lambda|\neq 1$) would indicate direct *CP* violation; the value for $\sin 2\phi_1$ reported above is determined with the assumption $|\lambda|=1$, as $|\lambda|$ is expected to be very close to 1 in the SM. In order to test this assumption, we also performed a fit using the above expression with $a_{CP}=-\xi_f \operatorname{Im}\lambda/|\lambda|$ and $|\lambda|$ as free parameters, keeping everything else the same. We obtain

$$|\lambda| = 0.950 \pm 0.049(\mathrm{stat}) \pm 0.025(\mathrm{syst})$$

and $a_{CP}=0.720\pm 0.074(\mathrm{stat})$ for all *CP* modes combined, where the sources of the systematic error for $|\lambda|$ are the same as those for $\sin 2\phi_1$. This result is consistent with the assumption used in our analysis.

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