Improved Measurement of CP Violation in Neutral B Decays to $c\bar{c}$

B. Aubert, M. Bona, D. Boutigny, Y. Karyotakis, J. P. Lees, V. Poireau, X. Prudent, V. Tisserand, A. Zghiche, J. Garra Tico, E. Grauges, L. Lopez, A. Palano, G. Eigen, I. Ofei, B. Stugu, L. Sun, G. S. Abrams, M. Battaglia, D. N. Brown, J. Button-Shafer, R. N. Cahn, Y. Gsovsky, R. G. Jacobsen, J. A. Kadyk, L. T. Kerth, Yu. G. Kolomensky, G. Kukartsev, D. Lopes Pegna, G. Lynch, L. M. Mir, T. J. Orimoto, M. Pripstein, N. A. Roe, M. T. Roman, K. Tackmann, W. A. Wenzel, P. del Amo Sanchez, C. M. Hawkes, A. T. Watson, T. Held, H. Koch, B. Lewandowski, M. Pelizza, T. Schroeder, M. Steinke, W. N. Cottingham, D. Walker, D. J. Asgeirsson, T. Cuhadar-Donszelmann, B. G. Fulsom, C. Hearty, N. S. Knecht, T. S. Mattsson, J. A. McKenna, A. Khan, M. Saleem, T. Teodorescu, V. E. Blinov, A. D. Bukin, V. P. Druzhinin, V. B. Golubev, A. P. Onuchin, S. L. Serednyakov, Yu. I. Skovpen, E. P. Solodov, K. Y. Tadyshkev, M. Bondioli, S. Curry, I. Eschrich, D. Kirkby, A. J. Lankford, P. Lund, M. Mandelkern, E. C. Martin, D. P. Stoker, S. Abachi, C. Buchanan, S. D. Foulkes, J. W. Gary, F. Liu, O. Long, B. C. Shen, L. Zhang, H. P. Paar, S. Rahatlou, V. Sharma, J. W. Berryhill, C. Campagnari, A. Cuna, B. Dahmes, T. M. Hong, D. Kovalskyi, J. D. Richman, T. W. Beck, A. M. Eisner, C. J. Flacco, C. A. Heusch, J. Kroseberg, W. S. Lockman, T. Schalk, B. A. Schumm, A. Seiden, M. C. Wilson, L. O. Winstrom, E. Chen, C. H. Cheng, A. Dvoretzki, F. Fang, D. G. Hitlin, I. Narsky, T. Pietaken, F. C. Porter, G. Mancinielli, B. T. Meadows, K. Mishra, M. D. Sokoloff, F. Blanco, P. C. Bloom, S. Chen, W. T. Ford, F. J. Hirschauer, A. Kreisell, M. Nagel, U. Nauenberg, A. Olias, J. G. Smith, K. A. Ulmer, S. R. Wagner, J. Zhang, A. M. Gaburean, A. Sofer, W. H. Toki, R. J. Wilson, F. Winklmeier, Q. Zeng, D. D. Altenburg, E. Feltresi, A. Hauke, H. Jasper, J. Merkle, A. Petzold, B. Spaan, K. Wacker, T. Brandt, V. Klose, H. M. Lacker, W. F. Mader, R. Nagowski, J. Schubert, K. R. Schubert, R. Schwierz, J. E. Sundermann, A. Volk, D. Bernard, G. R. Bonneau, E. Latour, V. Lombardo, Ch. Thiebaux, M. Verden, P. J. Clark, W. Gradl, F. Muheim, S. Playfer, A. I. Robertson, Y. Xie, M. Andreotti, D. Bettoni, C. Bozzi, R. Calabrese, A. Cecchi, G. Cibinetto, P. Franchini, E. Luppi, M. Negrini, A. Petrella, L. Piemontese, E. Prencipe, V. Santoro, F. Anulli, R. Baldini-Ferroli, A. Calcabrera, R. de Sangro, G. Finocchiaro, S. Pacetti, P. Patrignani, M. Piccolo, M. R. Monge, S. Passaggio, C. Patrignani, E. Robutti, A. Santroni, S. Tosi, K. S. Chaisanguanthum, M. Morii, J. Wu, R. S. Dubitzky, J. Marks, S. Schenk, U. Uwer, D. J. Bard, P. D. Dauncey, R. L. Flack, J. A. Nash, M. B. Nikolich, W. Panduro Vazquez, P. K. Behera, X. Chai, M. J. Charles, U. Mallick, N. T. Meyer, V. Ziegler, J. Cochran, H. B. Crawford, V. Egyes, W. T. Meyer, S. Prell, E. I. Rosenberg, A. E. Rubin, A. V. Gritsan, Z. J. Guo, C. K. Lae, A. G. Denig, M. Fritsch, G. Schott, N. Arnaud, J. Béquilleux, M. Davier, G. Grosdidier, A. Höcker, V. Lepeltier, F. Le Diberder, A. M. Gabareen, S. Pruvot, S. Rodier, P. Roudeau, M. H. Schune, J. v. Sordini, A. Stocchi, W. F. Wang, G. Wormser, D. J. Lange, D. M. Wright, C. A. Chavez, I. J. Forster, J. R. Fry, E. Gabathuler, R. Gamet, D. E. Hutchcroft, D. J. Payne, K. C. Schofield, C. Touramanis, A. J. Bevan, K. A. George, F. Di Lodovico, W. Menges, R. Saccò, G. Cowan, H. U. Flaecher, D. A. Hopkins, P. S. Jackson, T. R. McMahan, F. Salvatore, A. C. Wren, D. N. Brown, C. L. Davis, J. Allison, R. N. Barlow, R. J. Barlow, Y. M. Chia, C. L. Edgar, G. D. Lafferty, T. J. West, J. I. Yi, J. H. Hugon, C. Chen, A. Jawahery, D. A. Roberts, G. Simi, J. M. Tuggle, G. Blaylock, C. Dallapiccola, S. H. Shtab, X. Li, T. B. Moore, E. Salvati, S. Saremi, R. Cowan, P. H. Fisher, G. Sciolla, J. S. Sekula, M. Spitznagel, F. Taylor, R. K. Yamamoto, S. E. Melachlin, P. M. Patel, S. H. Robertson, A. Lazzara, F. Palombo, J. M. Bauer, L. Cremaldi, V. Eschenburg, R. Godang, R. Kroeger, D. A. Sanders, D. J. Summers, H. W. Zhao, S. Brunet, C. Côté, M. Simard, P. Taras, F. B. Viala, H. Nichols, G. De Nardo, F. Fabozzi, L. Lista, D. Monorchio, C. Sciaccia, M. A. Baik, G. Raven, H. L. Snoek, C. P. Jessop, J. M. LoSecco, G. Benelli, L. A. Corwin, K. K. Gan, K. Honscheid, D. Hufnagel, H. Kagan, R. Kass, J. P. Morris, A. M. Rahimi, J. J. Regensburger, R. Ter-Antonyan, Q. K. Wong, N. L. Blount, J. Brau, R. Frey, O. Ignonkina, J. A. Kolb, M. Lu, R. Rahmat, N. B. Sinev, D. Strom, J. Strube, E. Torrence, N. Gagliardi, A. Gaz, M. Margoni, M. Morandin, A. Pomplii, M. Posocco, M. Rotondo, F. Simonetto, R. Stroili, C. Voci, E. Ben-Haim, H. Briand, J. Chauveau, P. David, Del Buono, Ch. de la Vaissière, O. Hamon, B. L. Hartfiel, Ph. Leruste, J. Malelles, J. Ocariz, 0031-9007 (2007) PHYSICAL REVIEW LETTERS week ending 26 OCTOBER 2007 171803-1 © 2007 The American Physical Society
A. Perez,57 L. Gladney,58 M. Biasini,59 R. Covarelli,59 E. Manoni,59 C. Angelini,60 G. Batignani,60 S. Bettarini,60 G. Calderini,60 M. Carpinelli,60 R. Cenci,60 A. Cervelli,60 F. Forti,60 M. A. Giorgi,60 A. Lusiani,60 G. Marchiori,60 M. A. Mazur,60 M. Morganti,60 N. Neri,60 E. Paoloni,60 G. Rizzo,60 J. J. Walsh,60 M. Haire,61 J. Biesiada,62 P. Elmer,62 Y. P. Lau,62 C. Lu,62 J. Olsen,62 A. J. S. Smith,62 A. V. Telnov,62 E. Baracchini,63 F. Bellini,63 G. Cavoto,63 A. D’Orazio,63 D. del Re,63 E. Di Marco,63 R. Faccini,63 F. Ferrarotto,63 F. Ferroni,63 M. Gaspero,63 P. D. Jackson,63 L. Li Gioi,63 M. A. Mazzoni,63 S. Morganti,63 G. Piredda,63 F. Polci,63 F. Renga,63 C. Voe na,63 M. Ebert,64 H. Schro¨der,64 R. Waldi,64 T. Adye,65 G. Castelli,65 B. Franek,65 E. O. Olaiya,65 W. Roethel,65 M. A. Mazur,66 M. Haire,66 J. Biesiada,66 P. Elmer,66 Y. P. Lau,66 C. Lu,66 J. Olsen,66 A. J. S. Smith,66 A. V. Telnov,66 E. Baracchini,67 F. Bellini,67 G. Cavoto,67 A. D’Orazio,67 D. del Re,67 E. Di Marco,67 R. Faccini,67 F. Ferrarotto,67 F. Ferroni,67 M. Gaspero,67 P. D. Jackson,67 L. Li Gioi,67 M. A. Mazzoni,67 S. Morganti,67 G. Piredda,67 F. Polci,67 F. Renga,67 C. Voe na,67 M. Ebert,68 H. Schro¨der,68 R. Waldi,68 T. Adye,69 G. Castelli,69 B. Franek,69 E. O. Olaiya,69 W. Roethel,69 M. A. Mazur,69 M. Haire,69 J. Biesiada,69 P. Elmer,69 Y. P. Lau,69 C. Lu,69 J. Olsen,69 A. J. S. Smith,69 A. V. Telnov,69 E. Baracchini,70 F. Bellini,70 G. Cavoto,70 A. D’Orazio,70 D. del Re,70 E. Di Marco,70 R. Faccini,70 F. Ferrarotto,70 F. Ferroni,70 M. Gaspero,70 P. D. Jackson,70 L. Li Gioi,70 M. A. Mazzoni,70 S. Morganti,70 G. Piredda,70 F. Polci,70 F. Renga,70 C. Voe na,70 M. Ebert,71 H. Schro¨der,71 R. Waldi,71 T. Adye,72 G. Castelli,72 B. Franek,72 E. O. Olaiya,72 W. Roethel,72 M. A. Mazur,72 M. Haire,72 J. Biesiada,72 P. Elmer,72 Y. P. Lau,72 C. Lu,72 J. Olsen,72 A. J. S. Smith,72 A. V. Telnov,72 E. Baracchini,73 F. Bellini,73 G. Cavoto,73 A. D’Orazio,73 D. del Re,73 E. Di Marco,73 R. Faccini,73 F. Ferrarotto,73 F. Ferroni,73 M. Gaspero,73 P. D. Jackson,73 L. Li Gioi,73 M. A. Mazzoni,73 S. Morganti,73 G. Piredda,73 F. Polci,73 F. Renga,73 C. Voe na,73 M. Ebert,74 H. Schro¨der,74 R. Waldi,74 T. Adye,75 G. Castelli,75 B. Franek,75 E. O. Olaiya,75 W. Roethel,75 M. A. Mazur,75 M. Haire,75 J. Biesiada,75 P. Elmer,75 Y. P. Lau,75 C. Lu,75 J. Olsen,75 A. J. S. Smith,75 A. V. Telnov,75 E. Baracchini,76 F. Bellini,76 G. Cavoto,76 A. D’Orazio,76 D. del Re,76 E. Di Marco,76 R. Faccini,76 F. Ferrarotto,76 F. Ferroni,76 M. Gaspero,76 P. D. Jackson,76 L. Li Gioi,76 M. A. Mazzoni,76 S. Morganti,76 G. Piredda,76 F. Polci,76 F. Renga,76 C. Voe na,76 M. Ebert,77 Sw. Banerjee,77 B. Bhuyan,77 K. Hamano,77 R. Kowalewski,77 I. M. Nugent,77 J. M. Roney,77 R. J. Sobie,77 J. J. Back,78 P. F. Harrison,78 T. E. Latham,78 G. B. Mohanty,78 M. Pappagallo,78 H. R. Band,79 X. Ch en,79 S. Dasu,79 K. H. Flood,79 J. J. Hollar,79 P. E. Kutter,79 Y. Pan,79 M. Pierini,79 R. Prepost,79 S. L. Wu,79 Z. Yu,79 and H. Neal80

(BABAR Collaboration)

1Laboratoire de Physiques des Particules, IN2P3/CNRS et Université de Savoie, F-74941 Annecy-Le-Vieux, France
2Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain
3Università di Bari, Dipartimento di Fisica e INFN, I-70126 Bari, Italy
4University of Bergen, Institute of Physics, N-5007 Bergen, Norway
5Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA
6University of Birmingham, Birmingham, B15 2TT, United Kingdom
7Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany
8University of Bristol, Bristol BS8 1TL, United Kingdom
9University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1
10Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom
11Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia
12University of California at Irvine, Irvine, California 92697, USA
13University of California at Los Angeles, Los Angeles, California 90024, USA
14University of California at Riverside, Riverside, California 92521, USA
15University of California at San Diego, La Jolla, California 92093, USA
16University of California at Santa Barbara, Santa Barbara, California 93106, USA
17University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA
18California Institute of Technology, Pasadena, California 91125, USA
19University of Cincinnati, Cincinnati, Ohio 45221, USA
20University of Colorado, Boulder, Colorado 80309, USA
21Colorado State University, Fort Collins, Colorado 80523, USA
22Universität Dortmund, Institut für Physik, D-44221 Dortmund, Germany
23Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
24Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91125 Palaiseau, France
25University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
26Università di Ferrara, Dipartimento di Fisica e INFN, I-44140 Ferrara, Italy
27Laboratori Nazionali di Frascati dell’INFN, I-00044 Frascati, Italy
28Laboratoire de Physique des Particules, IN2P3/CNRS et Université de Savoie, F-74941 Annecy-Le-Vieux, France
29University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1
30Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom
31Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia
32University of California at Irvine, Irvine, California 92697, USA
33University of California at Los Angeles, Los Angeles, California 90024, USA
34University of California at Riverside, Riverside, California 92521, USA
35University of California at San Diego, La Jolla, California 92093, USA
36University of California at Santa Barbara, Santa Barbara, California 93106, USA
37University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA
38California Institute of Technology, Pasadena, California 91125, USA
39University of Cincinnati, Cincinnati, Ohio 45221, USA
40University of Colorado, Boulder, Colorado 80309, USA
41Colorado State University, Fort Collins, Colorado 80523, USA
42Universität Dortmund, Institut für Physik, D-44221 Dortmund, Germany
43Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
44Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91125 Palaiseau, France
45University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
46Università di Ferrara, Dipartimento di Fisica e INFN, I-44140 Ferrara, Italy
47Laboratori Nazionali di Frascati dell’INFN, I-00044 Frascati, Italy

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We present updated measurements of time-dependent $CP$ asymmetries in fully-reconstructed neutral $B$ decays to several $CP$ eigenstates containing a charmonium meson. The measurements use a data sample of $(383 \pm 4) \times 10^6 \ Y(4S) \to B\bar{B}$ decays collected with the BABAR detector at the PEP-II $B$ factory. We determine $\sin2\beta = 0.714 \pm 0.032$ (stat) $\pm 0.018$ (syst) and $|\lambda| = 0.952 \pm 0.022$ (stat) $\pm 0.017$ (syst).
The standard model (SM) of electroweak interactions describes CP violation as a consequence of an irreducible phase in the three-family Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. In the CKM framework, neutral $B$ decays to CP eigenstates containing a charmonium and a $K^{(*)}$ meson through tree-diagram dominated processes provide a direct measurement of $\sin 2\beta$ [2], where the angle $\beta$ is defined in terms of the CKM matrix elements $V_{ij}$ as $\arg(-V_{cd}V_{cb}^*)/(V_{cd}V_{ub}^*)$.

We report updated measurements, based on a sample of $(383 \pm 4) \times 10^6 Y(4S) \to B\bar{B}$ decays, of $\sin 2\beta$ and of the parameter $|\lambda|$. Here $\lambda = (q/p)(\bar{A}/A)$ [3], $q$ and $p$ are complex constants that relate the $B$-meson flavor eigenstates to the mass eigenstates, and $\bar{A}/A$ is the ratio of amplitudes of the decay of a $B^0$ or $B^0$ to the final state under study. We reconstruct $B^0$ decays to the final states $J/\psi K^0_S, J/\psi K^0_L, \psi(2S)K^0_S, \chi_cK^0_S, \eta K^0_S, J/\psi K^{*0}$ [4]. Since our previously published result [5], we have added $157 \times 10^6 B\bar{B}$ decays and applied improved event reconstruction algorithms to the entire data set. We have also developed a new $\eta_c K^0_S$ event selection based on the Dalitz plot structure of the $\eta_c \to K^0_S K^+ \pi^-$ decay, and have performed a more detailed study of the CP properties of the background events, which results in reduced systematic errors. We now include the $J/\psi K^0_S$ and $J/\psi K^{*0}$ modes in the sample to measure $|\lambda|$, and we report individual measurements of $\sin 2\beta$ and $|\lambda|$ for each of the CP decay modes used in the analysis. Finally, we present separate results for the $J/\psi K^0_S(\pi^+ \pi^- + \pi^0 \pi^0)$ [6], and $J/\psi K^{*0}(K^0_S + K^0_L)$ modes.

We identify (tag) the initial flavor of the reconstructed $B$ candidate, $B_{\text{rec}}$, using information from the other $B$ meson, $B_{\text{tag}}$, in the event. The decay rate $g_+ (g_-)$ for a neutral $B$ meson decaying to a CP eigenstate accompanied by a $B^0$ ($\bar{B}^0$) tag can be expressed as

$$g_{\pm} (\Delta t) = \frac{e^{-|\lambda|/\tau_{B^0}}}{4\tau_{B^0}} \left[ (1 \mp \Delta w) \pm (1 - 2w) \left( \frac{2\text{Im} \lambda}{1 + |\lambda|^2} \times \sin (\Delta m_d \Delta t) - \frac{1 - |\lambda|^2}{1 + |\lambda|^2} \cos (\Delta m_d \Delta t) \right) \right],$$

where $\Delta t \equiv t_{\text{rec}} - t_{\text{tag}}$ is the difference between the proper decay times of the reconstructed and tag $B$ mesons, $\tau_{B^0}$ is the neutral $B$ lifetime and $\Delta m_d$ is the mass difference of the $B$ meson mass eigenstates determined from $B^0$-$\bar{B}^0$ oscillations [7]. We assume that the corresponding decay-width difference $\Delta \Gamma_d$ is zero. The average mistag probability $w$ describes the effect of incorrect tags, and $\Delta w$ is the difference between the mistag probabilities for $B^0$ and $\bar{B}^0$. The sine term in Eq. (1) results from the interference between direct decay and decay after $B^0 - \bar{B}^0$ oscillation. A non-zero cosine term arises from the interference between decay amplitudes with different weak and strong phases (direct CP violation) or from CP violation in $B^0 - \bar{B}^0$ mixing. In the SM, CP violation in mixing and direct CP violation in $b \to c\bar{c}s$ decays are both negligible [3]. Under these assumptions, $\lambda = \eta_1 e^{-2i\beta}$, where $\eta_1 = \pm 1$ is the CP eigenvalue of the final state $f$. Thus, the time-dependent CP-violating asymmetry is

$$A_{CP}(\Delta t) = \frac{g_+(\Delta t) - g_-(\Delta t)}{g_+(\Delta t) + g_-(\Delta t)} = -(1 - 2w) \eta_1 \sin 2\beta \sin (\Delta m_d \Delta t).$$

The $B$ABAR detector is described in detail elsewhere [8]. We select a sample of neutral $B$ mesons ($B_{\text{CP}}$) decaying to the $\eta_f = -1$ final states $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_cK^0_S$, and $\eta K^0_S$, and to the $\eta_f = +1$ final state $J/\psi K^0_L$. We reconstruct $K^0_S \to \pi^+ \pi^-$, except in $J/\psi K^0_S$, where we also include $K^0_S \to \pi^0 \pi^0$. The charmonium mesons are reconstructed in the decays $J/\psi \to e^+ e^-$, $\mu^+ \mu^-$, $\psi(2S) \to e^+ e^-$, $\mu^+ \mu^-$, $J/\psi \pi^+ \pi^-$; $\chi_c \to J/\psi \gamma$ and $\eta_c \to K^0_S K^+ \pi^-$. We also reconstruct the $J/\psi K^{*0}(K^{*0} \to K^0_S \pi^0)$ final state, which can be $CP$ even or $CP$ odd due to the presence of even ($L = 0$) and odd ($L = 1$) orbital angular momentum contributions. Ignoring the angular information in $J/\psi K^{*0}$ results in a dilution of the measured $CP$ asymmetry by a factor $|1 - 2R_\perp|$, where $R_\perp$ is the fraction of the $L = 1$ contribution. In Ref. [9] we have measured $R_\perp = 0.23 \pm 0.010$ (stat) $\pm 0.005$ (syst), which gives an effective $\eta_1 = 0.504 \pm 0.033$ for $f = J/\psi K^{*0}$, after acceptance corrections.

In addition to the $CP$ modes described above, we use a sample of $B^0$ mesons ($B_{\text{flav}}$) decaying to the flavor eigenstates $D^{(*)+} h^+ (h^+ = \pi^+, \rho^+, a_1^+)$ and $J/\psi K^{*0}(K^{*0} \to K^+ \pi^-)$ to calibrate the flavor-tagging performance and $\Delta t$ resolution. We also perform studies to measure apparent $CP$ violation arising from $CP$-conserving processes using a control sample of $B^+$ mesons decaying to the final states $J/\psi K^{*0}(+), \psi(2S)K^+, \chi_c K^+$, and $\eta_c K^+$. The event selection and candidate reconstruction remain unchanged from those described in Refs. [5,10,11], with the exception of modes containing $\eta_c$ mesons. In Ref. [5] we reconstructed the $B^0 \to \eta_c K^0_S$ and $B^+ \to \eta_c K^+$ modes using the requirement $2.91 < m_{K^0_S K^+ \pi^0} < 3.05$ GeV$/c^2$. We now exploit the fact that the $\eta_c$ decays predominantly through a $K \pi$ resonance at around 1430 MeV$/c^2$ and a $K^0_S$ resonance close to threshold, and require that either $m_{K^0_S \pi^0}$ or $m_{K^+ \pi^-}$ be in the mass-range $[1.26, 1.63]$ GeV$/c^2$, or that $m_{K^+ \pi^-} \in [1.0, 1.4]$ GeV$/c^2$.

We calculate the time interval $\Delta t$ between the two $B$ decays from the measured separation $\Delta z$ between the decay vertices of $B_{\text{rec}}$ and $B_{\text{tag}}$ along the collision ($z$) axis.
The algorithm used to determine the flavor of the $B_{\text{tag}}$ at its decay to be either $B^0$ or $\bar{B}^0$ is described in detail in Ref. [5]. In brief, we define six mutually exclusive tagging categories in order of decreasing tag purity: lepton, kaon I, kaon II, kaon-pion, pion, and other. The figure of merit for tagging is the effective tagging efficiency $Q = \sum e_i(1 - 2w_i)^2$, where $e_i$ is the tagging efficiency of tagging category $i$. We measure $Q = (30.5 \pm 0.3)\%$, consistent with the results in Ref. [5].

We determine the composition of our final sample using

$$m_{\text{ES}} = \sqrt{E_{\text{beam}}^2 - p_B^2},$$

where $E_{\text{beam}}$ and $p_B$ are the beam energy and $B$ momentum in the $e^+e^-$ center-of-mass (c.m.) frame. For the $J/\psi K^0_L$ mode we instead use the difference $\Delta E$ between the candidate c.m. energy and $E_{\text{beam}}$. The composition of our final sample is shown in Fig. 1. We use events with $m_{\text{ES}} > 5.2$ GeV/$c^2$ ($|\Delta E| < 80$ MeV for $J/\psi K^0_L$) to determine the properties of the background contributions. We define a signal region $5.27 < m_{\text{ES}} < 5.29$ GeV/$c^2$ ($|\Delta E| < 10$ MeV for $J/\psi K^0_L$), which contains 12 677 CP candidate events that satisfy the tagging and vertexing requirements (see Table I). For all modes except $\eta K^0_S$ and $J/\psi K^0_L$, we use simulated events to estimate the fractions of events that peak in the $m_{\text{ES}}$ signal region due to cross-feed from other decay modes (peaking background). For the $\eta K^0_S$ mode, the cross-feed fraction is determined from a fit to the $m_{\text{ES}}$ and $m_{\text{ES}}$ distributions in data. For the $J/\psi K^0_L$ decay mode, the sample composition, effective $\eta$, and $\Delta E$ distribution of the individual background sources are determined either from simulation (for $B \rightarrow J/\psi X$) or from the $m_{c\bar{c}}$ sidebands in data (for non-$J/\psi$ background).

We determine $\sin 2\beta$ and $|\lambda|$ from a simultaneous maximum likelihood fit to the $\Delta t$ distribution of the tagged $B_{CP}$ and $B_{\text{flav}}$ samples. The $\Delta t$ distributions of the $B_{CP}$ sample are modeled by Eq. (1). Those of the $B_{\text{flav}}$ sample evolve according to Eq. (1) with $\lambda = 0$. The observed amplitudes for the CP asymmetry in the $B_{CP}$ sample and for flavor oscillation in the $B_{\text{flav}}$ sample are reduced by the same factor, 1−2w, due to flavor mistags. The $\Delta t$ distributions for the signal are convolved with a resolution function common to both the $B_{\text{flav}}$ and $B_{CP}$ samples, modeled by the sum of three Gaussian functions [10]. The combinatorial background is incorporated with an empirical description of its $\Delta t$ spectra, containing prompt and nonprompt lifetime components convolved with a resolution function [10] distinct from that of the signal. The peaking background is assigned the same $\Delta t$ distribution as the signal but with no CP violation, with the same $\Delta t$ resolution function.

In addition to $\sin 2\beta$ and $|\lambda|$, there are 68 free parameters in the CP fit. For the signal, these are the parameters of the $\Delta t$ resolution (7), the average mistag fractions $w$ and the differences $\Delta w$ between $B^0$ and $\bar{B}^0$ mistag fractions for each tagging category (12), and the difference between $B^0$ and $\bar{B}^0$ reconstruction and tagging efficiencies (7). The background is described by mistag fractions (24), parameters of the $\Delta t$ resolution (3) and $B_{\text{flav}}$ time dependence (3), and parameters for the CP background (8), including the apparent CP asymmetry of nonpeaking events in each tagging category. Finally, we allow for the possibility of direct CP violation in the $X_{c1}K^0_S$ background to $J/\psi K^{*0}$ (1), and in the main backgrounds to the $J/\psi K^0_L$ mode, coming from $J/\psi K^0_S$, $J/\psi K^{*0}$, and the remaining $J/\psi$ background (3 parameters). The effective $|\lambda|$ of the non-$J/\psi$ background is fixed from a fit to the $J/\psi$-candidate sidebands in $J/\psi K^0_L$. We fix $\tau_{J/\psi} = 1.530$ ps and $\Delta m_{J/\psi} = 0.507$ ps$^{-1}$ [7]. The determination of the mistag fractions and $\Delta t$ resolution function parameters for the signal is dominated by the $B_{\text{flav}}$ sample, about 10 times more abundant than the CP sample.

The fit to the $B_{CP}$ and $B_{\text{flav}}$ samples yields $\sin 2\beta = 0.714 \pm 0.032$ and $|\lambda| = 0.952 \pm 0.022$, where the errors are statistical only. The correlation between these two parameters is $-1.5\%$. We also perform a separate fit in which we allow different $\sin 2\beta$ and $|\lambda|$ values for each

FIG. 1. Distributions for $B_{CP}$ and $B_{\text{flav}}$ candidates satisfying the tagging and vertexing requirements: (a) $m_{\text{ES}}$ for the final states $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, and $\eta K^0_S$, (b) $\Delta E$ for the final state $J/\psi K^0_L$, (c) $m_{\text{ES}}$ for $J/\psi K^{*0}$($K^{*0} \rightarrow K^0 \pi^0$), and (d) $m_{\text{ES}}$ for the $B_{\text{flav}}$ sample. In each plot, the shaded region is the estimated background contribution.
TABLE I. Number of events $N_{\text{tag}}$ and signal purity $P$ in the signal region after tagging and vertexing requirements, and results of fitting for CP asymmetries in the $B_{\text{CP}}$ sample and various subsamples. In addition, fit results for the $B_{\text{flav}}$ and $B^+$ control samples demonstrate that no artificial CP asymmetry is found where we expect no CP violation ($\sin 2\beta = 0$, $|\lambda| = 1$). Errors are statistical only.

| Sample                        | $N_{\text{tag}}$ | $P$(%) | $\sin 2\beta$   | $|\lambda|$     |
|-------------------------------|------------------|--------|-----------------|-----------------|
| Full CP sample                | 12 677           | 75     | 0.714 ± 0.032   | 0.952 ± 0.022   |
| $J/\psi K_S^0(\pi^+\pi^-)$   | 4459             | 96     | 0.702 ± 0.042   | 0.976 ± 0.030   |
| $J/\psi K_S^0(\pi^0\pi^0)$   | 1086             | 88     | 0.617 ± 0.103   | 0.812 ± 0.058   |
| $\psi(2S)K^0_S$               | 687              | 83     | 0.947 ± 0.112   | 0.867 ± 0.079   |
| $X(1)K^0_S$                   | 313              | 89     | 0.759 ± 0.170   | 0.804 ± 0.102   |
| $\eta(K^0_S)$                 | 328              | 69     | 0.778 ± 0.195   | 0.948 ± 0.141   |
| $J/\psi K^0_L$                | 4748             | 55     | 0.734 ± 0.074   | 1.061 ± 0.063   |
| $J/\psi K^{(*)}$              | 1056             | 66     | 0.477 ± 0.271   | 0.954 ± 0.083   |
| $J/\psi K^0$                  | 10 275           | 76     | 0.697 ± 0.035   | 0.966 ± 0.025   |
| $J/\psi K^0_S$                | 5547             | 94     | 0.686 ± 0.039   | 0.950 ± 0.027   |
| $\eta_f = -1$                 | 6873             | 92     | 0.711 ± 0.036   | 0.935 ± 0.024   |
| 1999–2002 data                | 3084             | 79     | 0.735 ± 0.063   | 0.987 ± 0.045   |
| 2003–2004 data                | 4850             | 77     | 0.728 ± 0.052   | 0.940 ± 0.035   |
| 2005–2006 data                | 4725             | 74     | 0.681 ± 0.054   | 0.940 ± 0.037   |
| Lepton                        | 1349             | 80     | 0.728 ± 0.066   | 0.901 ± 0.043   |
| Kaon I                         | 1843             | 76     | 0.689 ± 0.063   | 0.986 ± 0.046   |
| Kaon II                        | 2948             | 72     | 0.751 ± 0.071   | 0.880 ± 0.044   |
| Kaon-Pion                      | 2321             | 73     | 0.654 ± 0.112   | 0.999 ± 0.075   |
| Pion                           | 2551             | 76     | 0.671 ± 0.167   | 0.927 ± 0.104   |
| Other                          | 1665             | 73     | 0.705 ± 0.504   | 1.506 ± 0.483   |
| $B_{\text{flav}}$ sample      | 123 893          | 85     | 0.018 ± 0.010   | 0.995 ± 0.007   |
| $B^+$ sample                   | 29598            | 94     | 0.012 ± 0.017   | 1.010 ± 0.012   |

charmomium decay mode, a fit to the $J/\psi K_S^0(\pi^+\pi^- + \pi^0\pi^0)$ mode, and a fit to the $J/\psi K^0(K^0_S + \bar{K}^0_S)$ sample. We split the data sample by run period and by tagging category. We perform the CP measurements on control samples with no expected CP asymmetry. The results of these fits are summarized in Table I. The difference in the $\eta_f \sin 2\beta$ value with respect to our previous publication [5] is partly due to the slightly different reconstruction algorithms and partly to the different selection; the two measurements are consistent when the systematic error is taken into account.

Figure 2 shows the $\Delta t$ distributions and asymmetries in yields between events with $B^0$ tags and $\bar{B}^0$ tags for the $\eta_f = -1$ and $\eta_f = +1$ samples as a function of $\Delta t$, overlaid with the projection of the likelihood fit result. We also performed the CP fit fixing $|\lambda| = 1$, which yields $\sin 2\beta = 0.713 \pm 0.032$ (stat).

The dominant systematic errors on $\sin 2\beta$ are due to limited knowledge of various background properties, including uncertainties in $J/\psi K^0_S$-specific backgrounds and in the amounts of peaking backgrounds and their CP asymmetries (0.010), to possible differences between the $B_{\text{flav}}$ and $B_{\text{CP}}$ tagging performances (0.009), to the description of the $\Delta t$ resolution functions (0.008), to the knowledge of the event-by-event beam spot position (0.005). The only sizeable systematic uncertainties on $|\lambda|$ are due to the possible interference between the suppressed $b \rightarrow c\bar{d}d$ amplitude with the favored $b \rightarrow c\bar{u}u$ amplitude for some tag side $B$ decays [12] (0.015), and to the CP content of the peaking backgrounds (0.006). The total systematic error on $\sin 2\beta(|\lambda|)$ is 0.018 (0.017). We detail in [13] the main systematic uncertainties on both $\sin 2\beta$ and $|\lambda|$ for the full sample, for the seven individual modes, and for the fits to the $J/\psi K^0$ and $J/\psi K^0_S$ samples.

The large $B_{\text{CP}}$ sample allows a number of consistency checks, including separation of the data by decay mode and tagging category. The results of those checks, all consistent within the errors, are listed in Table I. We observe no statistically significant asymmetry from fits to the control samples of non-CP decay modes.

In summary, we report improved measurements of $\sin 2\beta$ and $|\lambda|$ that supersede our previous results [5]. We measure $\sin 2\beta = 0.714 \pm 0.032$ (stat) ± 0.018 (syst) and $|\lambda| = 0.952 \pm 0.022$ (stat) ± 0.017 (syst), providing an improved model-independent constraint on the position of the apex of the unitarity triangle [14]. Our measurements agree...
within errors with the published results [15,16] and with
the theoretical estimates of the magnitudes of CKM matrix
elements in the context of the SM [17]. The measured
value of $|\lambda|$ is consistent with no direct CP violation
with a significance of 1.72 standard deviations. We report
the first individual measurements of $\sin 2\beta$ and $|\lambda|$ for each
of the decay modes within our CP sample, and of the
$J/\psi K^0(K_S^0 + K_L^0)$ sample.

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FIG. 2 (color online). (a) Number of $\eta_f = -1$ candidates
$(J/\psi K^0_S, \phi(2S)K^0_S, \chi_c^1 K^0_S$, and $\eta, K^0_S)$ in the signal region with
a $B^0$ tag ($N_{\psi B}$) and with a $\bar{B}^0$ tag ($N_{\psi \bar{B}}$), and (b) the raw
asymmetry, $(N_{\psi B} - N_{\psi \bar{B}})/(N_{\psi B} + N_{\psi \bar{B}})$, as functions of $\Delta t$.
Figures (c) and (d) are the corresponding distributions for the
$\eta_f = +1$ mode $J/\psi K^0_S$. To enhance the signal component, all
distributions exclude the other tagging category. The solid
dashed curves represent the fit projections in $\Delta t$ for $B^0$ ($\bar{B}^0$)
tags. The shaded regions represent the estimated background
contributions.

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