Observation of CP Violation in $B^0 \to K^+\pi^-$ and $B^0 \to \pi^+\pi^-$

B. Aubert,[1] M. Bona,[1] D. Boutigny,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] X. Prudent,[1] V. Tisserand,[1] A. Zghiche,[1] J. Garra Tico,[2] E. Grauges,[2] L. Lopez,[3] A. Palano,[3] G. Eigen,[4] I. Ofte,[4] B. Stugu,[4] L. Sun,[4] G. S. Abrams,[5] M. Battaglia,[5] D. N. Brown,[5] J. Button-Shafer,[5] R. N. Cahn,[5] Y. Groysman,[5] R. G. Jacobsen,[5] J. A. Kadyk,[5] L. T. Kerth,[5] Yu. G. Kolomensky,[5] G. Kukartsev,[5] D. Lopes Pegna,[5] G. Lynch,[5] L. M. Mir,[5] T. J. Orimoto,[5] M. Pripstein,[5] N. A. Roe,[5] M. T. Ronan,[5,*] K. Tackmann,[5] W. A. Wenzel,[5] P. del Amo Sanchez,[6] C. M. Hawkes,[6] A. T. Watson,[6] T. Held,[7] H. Koch,[7] B. Lewandowski,[7] M. Pelizaeus,[7] T. Schroeder,[7] M. Steinke,[7] W. N. Cottingham,[8] D. Walker,[8] D. J. Asgeirsson,[9] T. Cuhadar-Donszelmann,[9] B. G. Fulsom,[9] C. Hearty,[9] N. S. Knecht,[9] T. S. Mattison,[9] J. A. McKenna,[9] A. Khan,[10] M. Saleem,[10] L. Teodorescu,[10] V. E. Blinov,[11] A. D. Bukin,[11] V. P. Druzhinin,[11] V. B. Golubev,[11] A. P. Onuchin,[11] S. I. Serednyakov,[11] Yu. I. Skovpen,[11] E. P. Solodov,[11] K. Yu. Todyshev,[11] M. Bondioli,[12] S. Curry,[12] I. Eschrich,[12] D. Kirkby,[12] A. J. Lankford,[12] P. Lund,[12] M. Mandelkern,[12] E. C. Martin,[12] D. P. Stoker,[12] S. Abachi,[13] C. Buchanan,[13] S. D. Foulkes,[14] J. W. Gary,[14] F. Liu,[14] O. Long,[14] B. C. Shen,[14] L. Zhang,[14] H. P. Paar,[15] S. Rahatlou,[15] V. Sharma,[15] J. W. Berryhill,[16] C. Campagnari,[16] A. Cunha,[16] B. Dahmes,[16] T. M. Hong,[16] D. Kovalskyi,[16] J. D. Richman,[16] T. W. Beck,[17] A. M. Eisner,[17] C. J. Flacco,[17] C. A. Heusch,[17] J. Kroseberg,[17] W. S. Lockman,[17] T. Schalk,[17] B. A. Schumm,[17] A. Seiden,[17] D. C. Williams,[17] M. G. Wilson,[17] L. O. Winstrom,[17] E. Chen,[18] C. H. Cheng,[18] A. Dvoretskii,[18] F. Fang,[18] D. G. Hitlin,[18] I. Narsky,[18] T. Piatenko,[18] F. C. Porter,[18] G. Mancinelli,[19] B. T. Meadows,[19] K. Mishra,[19] M. D. Sokoloff,[19] F. Blanc,[20] P. C. Bloom,[20] S. Chen,[20] W. T. Ford,[20] J. F. Hirschauer,[20] A. Kreisel,[20] M. Nagel,[20] U. Nauenberg,[20] A. Olivas,[20] J. G. Smith,[20] K. A. Ulmer,[20] S. R. Wagner,[20] J. Zhang,[20] A. M. Gabareen,[21] A. Soffer,[21] W. H. Toki,[21] R. J. Wilson,[21] F. Winklmeier,[21] Q. Zeng,[21] D. D. Altenburg,[22] E. Feltresi,[22] A. Hauke,[22] H. Jasper,[22] J. Merkel,[22] A. Petzold,[22] B. Spaan,[22] K. Wacker,[22] T. Brandt,[23] V. Klose,[23] H. M. Lacker,[23] W. F. Mader,[23] R. Nogowski,[23] J. Schubert,[23] K. R. Schubert,[23] R. Schwierz,[23] J. E. Sundermann,[23] A. Volk,[23] D. Bernard,[24] G. R. Bonneaud,[24] E. Latour,[24] V. Lombardo,[24] Ch. Thiebaux,[24] M. Verderi,[24] P. J. Clark,[25] W. Gradl,[25] F. Muheim,[25] S. Playfer,[25] A. I. Robertson,[25] Y. Xie,[25] M. Andreotti,[26] D. Bettoni,[26] C. Bozzi,[26] R. Calabrese,[26] A. Cecchi,[26] G. Cibinetto,[26] P. Franchini,[26] E. Luppi,[26] M. Negrini,[26] A. Petrella,[26] L. Piemontese,[26] E. Prencipe,[26] V. Santoro,[26] F. Anulli,[27] R. Baldini-Ferroli,[27] A. Calcaterra,[27] R. de Sangro,[27] G. Finocchiaro,[27] S. Pacetti,[27] P. Patteri,[27] I. M. Peruzzi,[27,†] M. Piccolo,[27] M. Rama,[27] A. Zallo,[27] A. Buzzo,[28] R. Contri,[28] M. Lo Vetere,[28] M. M. Macri,[28] M. R. Monge,[28] S. Passaggio,[28] C. Patrignani,[28] E. Robutti,[28] A. Santroni,[28] S. Tosi,[28] K. S. Chaisanguanthum,[29] M. Morii,[29] J. Wu,[29] R. S. Dubitzky,[30] J. Marks,[30] S. Schenk,[30] U. Uwer,[30] D. J. Bard,[31] P. D. Dauncey,[31] R. L. Flack,[31] J. A. Nash,[31] M. B. Nikolich,[31] W. Panduro Vazquez,[31] P. K. Behera,[32] X. Chai,[32] M. J. Charles,[32] U. Mallik,[32] N. T. Meyer,[32] V. Ziegler,[32] J. Cochran,[33] H. B. Crawley,[33] L. Dong,[33] V. Eyges,[33] W. T. Meyer,[33] S. Prell,[33] E. I. Rosenberg,[33] A. E. Rubin,[33] A. V. Gritsan,[34] Z. J. Guo,[34] C. K. Lae,[34] A. G. Denig,[35] M. Fritsch,[35] G. Schott,[35] N. Arnaud,[36] J. Béquilleux,[36] M. Davier,[36] G. Grosdidier,[36] A. Höcker,[36] V. Lepeltier,[36] F. Le Diberder,[36] A. M. Lutz,[36] S. Pruvot,[36] S. Rodier,[36] P. Roudeau,[36] M. H. Schune,[36] J. Serrano,[36] V. Sordini,[36] A. Stocchi,[36] W. F. Wang,[36] G. Wormser,[36] D. J. Lange,[37] D. M. Wright,[37] C. A. Chavez,[38] I. J. Forster,[38] J. R. Fry,[38] E. Gabathuler,[38] R. Gamet,[38] D. E. Hutchcroft,[38] D. J. Payne,[38] K. C. Schofield,[38] C. Touramanis,[38] A. J. Bevan,[39] K. A. George,[39] F. Di Lodovico,[39] W. Menges,[39] R. Sacco,[39] G. Cowan,[40] H. U. Flaecher,[40] D. A. Hopkins,[40] P. S. Jackson,[40] T. R. McMahon,[40] F. Salvatore,[40] A. C. Wren,[40] D. N. Brown,[41] C. L. Davis,[41] J. Allison,[42] N. R. Barlow,[42] R. J. Barlow,[42] Y. M. Chia,[42] C. L. Edgar,[42] G. D. Lafferty,[42] T. J. West,[42] J. I. Yi,[42] J. Anderson,[43] C. Chen,[43] A. Jawahery,[43] D. A. Roberts,[43] G. Simi,[43] J. M. Tuggle,[43] G. Blaylock,[44] C. Dallapiccola,[44] S. S. Hertzbach,[44] X. Li,[44] T. B. Moore,[44] E. Salvati,[44] S. Saremi,[44] R. Cowan,[45] P. H. Fisher,[45] G. Sciolla,[45] S. J. Sekula,[45] M. Spitznagel,[45] F. Taylor,[45] R. K. Yamamoto,[45] S. E. Mclachlin,[46] P. M. Patel,[46] S. H. Robertson,[46] A. Lazzaro,[47] F. Palombo,[47] J. M. Bauer,[48] L. Cremaldi,[48] V. Eschenburg,[48] R. Godang,[48] R. Kroeger,[48] D. A. Sanders,[48] D. J. Summers,[48] H. W. Zhao,[48] S. Brunet,[49] D. Côté,[49] M. Simard,[49] P. Taras,[49] F. B. Viaud,[49] H. Nicholson,[50] G. De Nardo,[51] F. Fabozzi,[51,‡] L. Lista,[51] D. Monorchio,[51] C. Sciacca,[51] M. A. Baak,[52] G. Raven,[52] H. L. Snoek,[52] C. P. Jessop,[53] J. M. LoSecco,[53] G. Benelli,[54] L. A. Corwin,[54] K. K. Gan,[54] K. Honscheid,[54] D. Hufnagel,[54] H. Kagan,[54] R. Kass,[54] J. P. Morris,[54] A. M. Rahimi,[54] J. J. Regensburger,[54] R. Ter-Antonyan,[54] Q. K. Wong,[54] N. L. Blount,[55] J. Brau,[55] R. Frey,[55] O. Igonkina,[55] J. A. Kolb,[55] M. Lu,[55] R. Rahmat,[55] N. B. Sinev,[55] D. Strom,[55] J. Strube,[55] E. Torrence,[55] N. Gagliardi,[56] A. Gaz,[56] M. Margoni,[56] M. Morandin,[56] A. Pompili,[56] M. Posocco,[56] M. Rotondo,[56] F. Simonetto,[56] R. Stroili,[56] C. Voci,[56] E. Ben-Haim,[57] H. Briand,[57] J. Chauveau,[57] P. David,[57] L. Del Buono,[57] Ch. de la Vaissière,[57] O. Hamon,[57] B. L. Hartfiel,[57] Ph. Leruste,[57] J. Malclès,[57] J. Ocariz,[57]

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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. Voena,[63] M. Ebert,[64] H. Schröder,[64] R. Waldi,[64] T. Adye,[65] G. Castelli,[65] B. Franek,[65] E. O. Olaiya,[65] S. Ricciardi,[65] W. Roethel,[65] F. F. Wilson,[65] R. Aleksan,[66] S. Emery,[66] M. Escalier,[66] A. Gaidot,[66] S. F. Ganzhur,[66] G. Hamel de Monchenault,[66] W. Kozanecki,[66] M. Legendre,[66] G. Vasseur,[66] Ch. Yèche,[66] M. Zito,[66] X. R. Chen,[67] H. Liu,[67] W. Park,[67] M. V. Purohit,[67] J. R. Wilson,[67] M. T. Allen,[68] D. Aston,[68] R. Bartoldus,[68] P. Bechtle,[68] N. Berger,[68] R. Claus,[68] J. P. Coleman,[68] M. R. Convery,[68] J. C. Dingfelder,[68] J. Dorfan,[68] G. P. Dubois-Felsmann,[68] D. Dujmic,[68] W. Dunwoodie,[68] R. C. Field,[68] T. Glanzman,[68] S. J. Gowdy,[68] M. T. Graham,[68] P. Grenier,[68] C. Hast,[68] T. Hryn'ova,[68] W. R. Innes,[68] M. H. Kelsey,[68] H. Kim,[68] P. Kim,[68] D. W. G. S. Leith,[68] S. Li,[68] S. Luitz,[68] V. Luth,[68] H. L. Lynch,[68] D. B. MacFarlane,[68] H. Marsiske,[68] R. Messner,[68] D. R. Muller,[68] C. P. O'Grady,[68] A. Perazzo,[68] M. Perl,[68] T. Pulliam,[68] B. N. Ratcliff,[68] A. Roodman,[68] A. A. Salnikov,[68] R. H. Schindler,[68] J. Schwiening,[68] A. Snyder,[68] J. Stelzer,[68] D. Su,[68] M. K. Sullivan,[68] K. Suzuki,[68] S. K. Swain,[68] J. M. Thompson,[68] J. Va'vra,[68] N. van Bakel,[68] A. P. Wagner,[68] M. Weaver,[68] W. J. Wisniewski,[68] M. Wittgen,[68] D. H. Wright,[68] A. K. Yarritu,[68] K. Yi,[68] C. C. Young,[68] P. R. Burchat,[69] A. J. Edwards,[69] S. A. Majewski,[69] B. A. Petersen,[69] L. Wilden,[69] S. Ahmed,[70] M. S. Alam,[70] R. Bula,[70] J. A. Ernst,[70] V. Jain,[70] B. Pan,[70] M. A. Saeed,[70] F. R. Wappler,[70] S. B. Zain,[70] W. Bugg,[71] M. Krishnamurthy,[71] S. M. Spanier,[71] R. Eckmann,[72] J. L. Ritchie,[72] A. M. Ruland,[72] C. J. Schilling,[72] R. F. Schwitters,[72] J. M. Izen,[73] X. C. Lou,[73] S. Ye,[73] F. Bianchi,[74] F. Gallo,[74] D. Gamba,[74] M. Pelliccioni,[74] M. Bomben,[75] L. Bosisio,[75] C. Cartaro,[75] F. Cossutti,[75] G. Della Ricca,[75] L. Lanceri,[75] L. Vitale,[75] V. Azzolini,[76] N. Lopez-March,[76] F. Martinez-Vidal,[76] D. A. Milanes,[76] A. Oyanguren,[76] J. Albert,[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. Chen,[79] S. Dasu,[79] K. T. 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. Neal[80]

(*BaBar* Collaboration)

[1]*Laboratoire de Physique des Particules, IN2P3/CNRS et Université de Savoie, F-74941 Annecy-Le-Vieux, France*
[2]*Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain*
[3]*Università di Bari, Dipartimento di Fisica and INFN, I-70126 Bari, Italy*
[4]*University of Bergen, Institute of Physics, N-5007 Bergen, Norway*
[5]*Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA*
[6]*University of Birmingham, Birmingham, B15 2TT, United Kingdom*
[7]*Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany*
[8]*University of Bristol, Bristol BS8 1TL, United Kingdom*
[9]*University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1*
[10]*Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom*
[11]*Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia*
[12]*University of California at Irvine, Irvine, California 92697, USA*
[13]*University of California at Los Angeles, Los Angeles, California 90024, USA*
[14]*University of California at Riverside, Riverside, California 92521, USA*
[15]*University of California at San Diego, La Jolla, California 92093, USA*
[16]*University of California at Santa Barbara, Santa Barbara, California 93106, USA*
[17]*University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA*
[18]*California Institute of Technology, Pasadena, California 91125, USA*
[19]*University of Cincinnati, Cincinnati, Ohio 45221, USA*
[20]*University of Colorado, Boulder, Colorado 80309, USA*
[21]*Colorado State University, Fort Collins, Colorado 80523, USA*
[22]*Universität Dortmund, Institut für Physik, D-44221 Dortmund, Germany*
[23]*Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany*
[24]*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France*
[25]*University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*
[26]*Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy*
[27]*Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy*

[28]*Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy*
[29]*Harvard University, Cambridge, Massachusetts 02138, USA*
[30]*Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany*
[31]*Imperial College London, London, SW7 2AZ, United Kingdom*
[32]*University of Iowa, Iowa City, Iowa 52242, USA*
[33]*Iowa State University, Ames, Iowa 50011-3160, USA*
[34]*Johns Hopkins University, Baltimore, Maryland 21218, USA*
[35]*Universität Karlsruhe, Institut für Experimentelle Kernphysik, D-76021 Karlsruhe, Germany*
[36]*Laboratoire de l'Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d'Orsay, B.P. 34, F-91898 ORSAY Cedex, France*
[37]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[38]*University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[39]*Queen Mary, University of London, E1 4NS, United Kingdom*
[40]*University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom*
[41]*University of Louisville, Louisville, Kentucky 40292, USA*
[42]*University of Manchester, Manchester M13 9PL, United Kingdom*
[43]*University of Maryland, College Park, Maryland 20742, USA*
[44]*University of Massachusetts, Amherst, Massachusetts 01003, USA*
[45]*Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA*
[46]*McGill University, Montréal, Québec, Canada H3A 2T8*
[47]*Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy*
[48]*University of Mississippi, University, Mississippi 38677, USA*
[49]*Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7*
[50]*Mount Holyoke College, South Hadley, Massachusetts 01075, USA*
[51]*Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy*
[52]*NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands*
[53]*University of Notre Dame, Notre Dame, Indiana 46556, USA*
[54]*Ohio State University, Columbus, Ohio 43210, USA*
[55]*University of Oregon, Eugene, Oregon 97403, USA*
[56]*Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy*
[57]*Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France*
[58]*University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
[59]*Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy*
[60]*Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy*
[61]*Prairie View A&M University, Prairie View, Texas 77446, USA*
[62]*Princeton University, Princeton, New Jersey 08544, USA*
[63]*Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy*
[64]*Universität Rostock, D-18051 Rostock, Germany*
[65]*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom*
[66]*DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France*
[67]*University of South Carolina, Columbia, South Carolina 29208, USA*
[68]*Stanford Linear Accelerator Center, Stanford, California 94309, USA*
[69]*Stanford University, Stanford, California 94305-4060, USA*
[70]*State University of New York, Albany, New York 12222, USA*
[71]*University of Tennessee, Knoxville, Tennessee 37996, USA*
[72]*University of Texas at Austin, Austin, Texas 78712, USA*
[73]*University of Texas at Dallas, Richardson, Texas 75083, USA*
[74]*Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy*
[75]*Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy*
[76]*IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain*
[77]*University of Victoria, Victoria, British Columbia, Canada V8W 3P6*
[78]*Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom*
[79]*University of Wisconsin, Madison, Wisconsin 53706, USA*
[80]*Yale University, New Haven, Connecticut 06511, USA*

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We report observations of *CP* violation in the decays $B^0 \to K^+\pi^-$ and $B^0 \to \pi^+\pi^-$ in a sample of 383×10^6 $\Upsilon(4S) \to B\bar{B}$ events. We find 4372 ± 82 $B^0 \to K^+\pi^-$ decays and measure the direct *CP*-violating charge asymmetry $\mathcal{A}_{K\pi} = -0.107 \pm 0.018(\text{stat})^{+0.007}_{-0.004}(\text{syst})$, which excludes the *CP*-conserving hypothesis with a significance of 5.5 standard deviations. In the same sample, we find

1139 ± 49 $B^0 \to \pi^+\pi^-$ decays and measure the CP-violating asymmetries $S_{\pi\pi} = -0.60 \pm 0.11(\mathrm{stat}) \pm 0.03(\mathrm{syst})$ and $C_{\pi\pi} = -0.21 \pm 0.09(\mathrm{stat}) \pm 0.02(\mathrm{syst})$. CP conservation in $B^0 \to \pi^+\pi^-$ ($S_{\pi\pi} = C_{\pi\pi} = 0$) is excluded at a confidence level $1 - \mathrm{C.L.} = 8 \times 10^{-8}$, corresponding to 5.4 standard deviations.

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The prediction of large CP-violating effects in the B-meson system [1] has been confirmed in recent years by the *BABAR* and Belle Collaborations, both in the interference of B decays to charmonium final states with and without B^0-$\bar{B}^0$ mixing [2] and directly in the interference between the decay amplitudes in $B^0 \to K^+\pi^-$ [3–5]. All measurements of CP violation to date are in agreement with indirect predictions from global standard-model (SM) fits [6] based on measurements of the magnitudes of the elements of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [7] and place important constraints [8] on the flavor structure of SM extensions.

The proper-time evolution of the asymmetry between B^0 and $\bar{B}^0$ decays to $\pi^+\pi^-$ is characterized by sine and cosine terms with amplitudes $S_{\pi\pi}$, which arises from interference between decays with or without B^0-$\bar{B}^0$ mixing, and $C_{\pi\pi}$, which is due to interference between the $b \to u$ "tree" and the higher-order $b \to d$ "penguin" decay amplitudes. Similarly, the direct-CP-violating asymmetry $\mathcal{A}_{K\pi}$ between the $\bar{B}^0 \to K^-\pi^+$ and $B^0 \to K^+\pi^-$ decay rates arises from interference between $b \to u$ tree and $b \to s$ penguin amplitudes. Negligible contributions to these asymmetry parameters would also enter from CP violation purely in B^0-$\bar{B}^0$ mixing, which has been determined to be very small [9]. The quantity $\sin 2\alpha_{\mathrm{eff}} = S_{\pi\pi}/\sqrt{1 - C_{\pi\pi}^2}$ can be related to $\alpha \equiv \arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*]$ through a model-independent analysis that uses the isospin-related decays $B^\pm \to \pi^\pm\pi^0$ and $B^0 \to \pi^0\pi^0$ [10]. Contributions from new particles could affect the asymmetries in these modes primarily through additional penguin B-decay amplitudes.

Previous evidence of direct CP violation in $B^0 \to K^+\pi^-$ has been reported by *BABAR* [3] and Belle [4]; additional measurements of $\mathcal{A}_{K\pi}$ have also been reported by the CDF [11] and CLEO [12] Collaborations. The Belle Collaboration recently reported [13] an observation of both time-dependent and direct CP violation in $B^0 \to \pi^+\pi^-$ decays using a sample of 535×10^6 $B\bar{B}$ pairs, while our previous measurement [14] on a sample of 227×10^6 $B\bar{B}$ pairs was statistically consistent with no CP violation. In this Letter, we present measurements of $\mathcal{A}_{K\pi}$, $S_{\pi\pi}$, and $C_{\pi\pi}$ in a sample of 383×10^6 $B\bar{B}$ pairs using an improved analysis technique with significantly increased sensitivity compared to our previous measurements.

In the *BABAR* detector [15], charged particles are detected and their momenta measured by a combination of a five-layer silicon vertex tracker and a 40-layer drift chamber (DCH) that covers 92% of the solid angle in the $\Upsilon(4S)$ center-of-mass (c.m.) frame, both operating in a 1.5-T solenoidal magnetic field. Discrimination among charged pions, kaons, and protons is provided by a combination of an internally reflecting ring-imaging Cherenkov detector (DIRC), which covers 84% of the c.m. solid angle in the central region of the *BABAR* detector and has a 91% reconstruction efficiency for pions and kaons with momenta above 1.5 GeV$/c$, and the ionization (dE/dx) measurements in the DCH. Electrons are explicitly removed based on a comparison of the track momentum and the associated energy deposition in a CsI(Tl) electromagnetic calorimeter and with additional information from dE/dx and DIRC Cherenkov angle (θ_{C}) measurements.

The analysis method retains many features of our previous $B^0 \to K^+\pi^-$ and $B^0 \to \pi^+\pi^-$ CP-violation measurements [3,14]. We reconstruct candidate decays $B_{\mathrm{rec}} \to h^+h^-$ ($h^\pm = \pi^\pm, K^\pm$) from pairs of oppositely charged tracks in the polar-angle range $0.35 < \theta_{\mathrm{lab}} < 2.40$ that are consistent with originating from a common decay point. The remaining particles are examined to infer (flavor tag) whether the other B meson in the event (B_{tag}) decayed as a B^0 or $\bar{B}^0$. We perform an unbinned extended maximum-likelihood (ML) fit simultaneously for the CP-violating asymmetries and the signal and background yields and parameters. The fit uses particle-identification, kinematic, event-shape, B_{tag} flavor, and Δt information, where Δt is the difference between the B_{rec} and B_{tag} decay times. The yields for the $K\pi$ final state are parametrized as $n_{K^\pm\pi^\mp} = n_{K\pi}(1 \mp \mathcal{A}_{K\pi}^{\mathrm{raw}})/2$, and the decay-rate distribution $f_+(f_-)$ for $B_{\mathrm{rec}} \to \pi^+\pi^-$ and $B_{\mathrm{tag}} = B^0(\bar{B}^0)$ is given by

$$f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}[1 \pm S_{\pi\pi}\sin(\Delta m_d \Delta t) \mp C_{\pi\pi}\cos(\Delta m_d \Delta t)], \tag{1}$$

where τ is the neutral B lifetime and Δm_d is the B^0-$\bar{B}^0$ mixing frequency, both fixed to their world averages [9].

The most significant improvement in sensitivity compared to our previous analysis comes from a 35% increase in the B_{rec} reconstruction efficiency that results from using dE/dx as a discriminating variable in the ML fit for the first time. The dE/dx measurements are used both to complement the discriminating power of θ_{C} for charged particles within the DIRC acceptance and as a standalone means of particle identification for tracks that have no DIRC information and were not included in our previous measurements. The dE/dx calibration takes into account variations in the mean value and resolution of dE/dx with respect to changes in the DCH running conditions over time and each track's charge, polar and azimuthal angles, and the number of ionization samples. The calibration is performed with large ($> 10^6$) high-purity samples of protons from $\Lambda \rightarrow p\pi^-$, pions and kaons from $D^{*+} \rightarrow D^0\pi^+(D^0 \rightarrow K^-\pi^+)$, and additional samples of pions from $\tau^- \rightarrow \pi^-\pi^+\pi^-\nu_\tau$ decays and from $K^0_S \rightarrow \pi^+\pi^-$ decays that occur in the vicinity of the interaction region.

We require at least one of the tracks in the $B_{\rm rec}$ decay candidate to have $\theta_{\rm C}$ measured with at least six signal photons; for such tracks, the value of $\theta_{\rm C}$ must agree within 4 standard deviations (σ) with either the pion or the kaon hypothesis. Thus, protons with six or more signal photons are removed, while proton-pion and proton-kaon combinations are possible for background candidates where one of the tracks has no usable $\theta_{\rm C}$ measurement. We construct $\theta_{\rm C}$ probability-density functions (PDFs) for the pion and kaon hypotheses and dE/dx PDFs for the pion, kaon, and proton hypotheses, separately for each charge. The $K - \pi$ separations provided by $\theta_{\rm C}$ and dE/dx are complementary: for $\theta_{\rm C}$, it varies from 2.5σ at 4.5 GeV/c to 13σ at 1.5 GeV/c [3], while for dE/dx it varies from less than 1.0σ at 1.5 GeV/c to 1.9σ at 4.5 GeV/c (Fig. 1).

Each B candidate is characterized by the energy difference $\Delta E = (q_\Upsilon \cdot q_B/\sqrt{s}) - \sqrt{s}/2$, which also provides additional discriminating power between the four possible final states ($\pi^+\pi^-$, $K^+\pi^-$, $K^-\pi^+$, and K^+K^-) and the beam-energy-substituted mass $m_{\rm ES} = [(s/2 + \vec{p}_\Upsilon \cdot \vec{p}_B)^2/E^2_\Upsilon - \vec{p}^{\,2}_B]^{1/2}$ [15]. Here q_Υ and q_B are the four-momenta of the $\Upsilon(4S)$ and the B candidate, respectively, $s \equiv (q_\Upsilon)^2$ is the square of the c.m. energy, $\vec{p}_\Upsilon$ and $\vec{p}_B$ are the laboratory three-momenta of the $\Upsilon(4S)$ and the B, respectively, and $E_\Upsilon \equiv q^0_\Upsilon$ is the laboratory energy of the $\Upsilon(4S)$. For signal events, the $m_{\rm ES}$ and ΔE PDFs are Gaussian functions with widths of 2.6 MeV/c^2 and 29 MeV, respectively. For the background, $m_{\rm ES}$ is parametrized with an empirical threshold function [16], and ΔE is parametrized with a second-order polynomial. We require $5.2 < m_{\rm ES} < 5.3$ GeV/c^2 and $|\Delta E| < 0.150$ GeV.

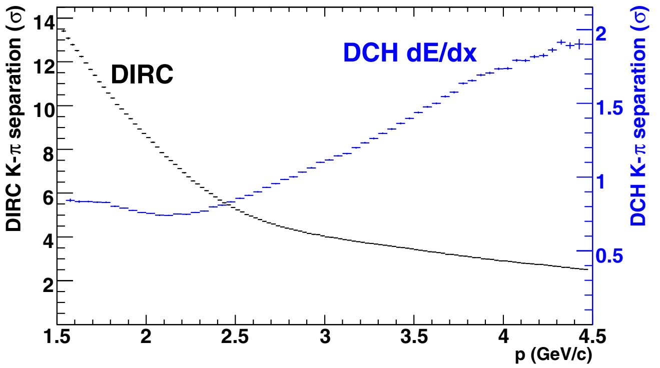

FIG. 1 (color online). The average difference between the expected values of DIRC $\theta_{\rm C}$ and DCH dE/dx for pions and kaons at $0.35 < \theta_{\rm lab} < 2.40$, divided by the uncertainty, as a function of laboratory momentum in $B^0 \rightarrow h^+h^-$ decays in *BABAR*.

The background arises predominantly from random combinations of tracks in $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) and $\tau^+\tau^-$ jetlike continuum events. We define the angle θ_S in the c.m. frame between the sphericity axes [17] of the B candidate and of all remaining charged and neutral particles in the event. For background events, $|\cos\theta_S|$ peaks sharply near 1, while for B decays the distribution is nearly flat. We require $|\cos\theta_S| < 0.9$, which removes approximately 64% of $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$, 52% of $c\bar{c}$, and 84% of $\tau^+\tau^-$ background. Contamination from $e^+e^- \rightarrow \tau^+\tau^-$ production is reduced to 2% of the total background by requiring the ratio of the second to zeroth Fox-Wolfram moments [18] to be less than 0.7, which has a negligible effect on the signal efficiency. The overall gain in signal reconstruction efficiency is 52% compared to our previous analysis. Additional continuum-background suppression in the fit is accomplished by the Fisher discriminant $\mathcal{F}$ described in Ref. [19]. We have studied the backgrounds from higher-multiplicity B decays and find them to be negligible, particularly due to their good separation from signal in ΔE.

The $B_{\rm tag}$ flavor is determined with a neural-net algorithm [20] that assigns the event to one of seven mutually exclusive tagging categories. The figure of merit for the tagging quality, measured in a data sample $B_{\rm flav}$ of fully reconstructed B^0 decays to $D^{(*)-}(\pi^+, \rho^+, a^+_1)$ or $J/\psi K^{*0}$, is the effective efficiency $Q = \sum_k \epsilon_k(1 - 2w_k)^2 = 0.305 \pm 0.003$, where ϵ_k and w_k are the efficiencies and mistag probabilities for events in tagging category k. Separate values of ϵ_k and w_k for each background category are determined in the ML fit.

The time difference $\Delta t \equiv \Delta z/\beta\gamma c$, where $\beta\gamma \approx 0.56$ is the known boost of the $\Upsilon(4S)$, is obtained by measuring the distance Δz along the beam (z) axis between the $B_{\rm rec}$ and $B_{\rm tag}$ decay vertices. We require $|\Delta t| < 20$ ps and $\sigma_{\Delta t} < 2.5$ ps, where $\sigma_{\Delta t}$ is the Δt uncertainty estimated separately for each event. The resolution function for signal candidates is a sum of three Gaussians [20] with parameters determined from a fit to the full $B_{\rm flav}$ sample. The background Δt distribution, common to all tagging categories, is modeled as a sum of three Gaussian functions with parameters determined in the final fit.

The likelihood for candidate j tagged in category k is obtained by summing the product of event yield n_i, tagging efficiency $\epsilon_{i,k}$, and probability $\mathcal{P}_{i,k}$ over all possible signal and background hypotheses i. We treat separately the cases where both or only one track has a $\theta_{\rm C}$ measurement. The extended likelihood function for tagging category k is

$$\mathcal{L}_k = \exp\left(-\sum_i n_i \epsilon_{i,k}\right) \prod_j \left[\sum_i n_i \epsilon_{i,k} \mathcal{P}_{i,k}(\vec{x}_j; \vec{\alpha}_i)\right]. \quad (2)$$

The probabilities $\mathcal{P}_{i,k}$ are evaluated as a product of PDFs for each of the independent variables $\vec{x}_j = \{m_{\rm ES}, \Delta E, \mathcal{F}, dE/dx, \theta_{\rm C}, \Delta t\}$, with parameters $\vec{\alpha}_i$. We use separate $\theta_{\rm C}$ and dE/dx PDFs for positively and negatively charged tracks. The Δt PDF for signal $\pi^+\pi^-$ decays is given by Eq. (1) modified to include the mistag probabilities for each tagging category and convolved with the signal resolution function. The Δt PDFs for signal $K\pi$ and background $K\pi$, πp, and Kp combinations take into account the correlation between the charge of the kaon or proton and the $B_{\rm tag}$ flavor; for signal $K\pi$, B^0-$\bar{B}^0$ mixing is also taken into account. The total likelihood $\mathcal{L}$ is the product of likelihoods for each tagging category and has 117 free parameters.

Fitting the final sample of 309 540 events, we find $n_{\pi\pi} = 1139 \pm 49$, $n_{K\pi} = 4372 \pm 82$, $n_{KK} = 10 \pm 17$, where all errors are statistical only, and measure the following asymmetries:

$$\begin{aligned} \mathcal{A}_{K\pi} &= -0.107 \pm 0.018(\text{stat})^{+0.007}_{-0.004}(\text{syst}), \\ S_{\pi\pi} &= -0.60 \pm 0.11(\text{stat}) \pm 0.03(\text{syst}), \\ C_{\pi\pi} &= -0.21 \pm 0.09(\text{stat}) \pm 0.02(\text{syst}). \end{aligned} \tag{3}$$

Here $\mathcal{A}_{K\pi}$ is the fitted value of the $K^\mp\pi^\pm$ event-yield asymmetry $\mathcal{A}^{\rm raw}_{K\pi}$ shifted by $+0.005^{+0.006}_{-0.003}$ to account for a bias that arises from the difference between the cross sections of K^+ and K^- hadronic interactions within the *BABAR* detector. We determine this bias from a detailed Monte Carlo simulation based on GEANT4 [21] version 7.1; it is independently verified with a calculation based on the known material composition of the *BABAR* detector [15] and the cross sections and material properties tabulated in Ref. [9]. The corrected $K^\mp\pi^\pm$ event-yield asymmetry in the background, where no observable *CP* violation is expected, is consistent with zero: $-0.006 \pm 0.004(\text{stat})^{+0.006}_{-0.003}(\text{syst})$.

A contour plot of the $(S_{\pi\pi}, C_{\pi\pi})$ confidence levels is shown in Fig. 2. The correlation between $S_{\pi\pi}$ and $C_{\pi\pi}$ is -0.07. Performing a fit that excludes Δt and using an event-weighting technique [22], in Fig. 3 we show the distributions of Δt for signal $\pi^+\pi^-$ events with $B_{\rm tag}$ tagged as B^0 or $\bar{B}^0$, and the asymmetry as a function of Δt, overlaid with the PDF curves that represent the result of the full fit.

To validate our results, we perform a number of consistency checks and systematic-error studies similar to those reported in Refs. [3,14]. For $\mathcal{A}_{K\pi}$, the dominant source of systematic uncertainty is the bias due to kaon hadronic interactions. We find that the systematic errors due to potentially imperfect understanding of the DIRC and DCH particle-identification performance are small for $\mathcal{A}_{K\pi}$ (0.002), $S_{\pi\pi}$ (0.007), and $C_{\pi\pi}$ (0.006). The dominant sources of systematic uncertainty on $S_{\pi\pi}$ are the signal Δt model (0.020) and flavor-tagging parameters (0.015), while for $C_{\pi\pi}$ the dominant uncertainties arise from tagging

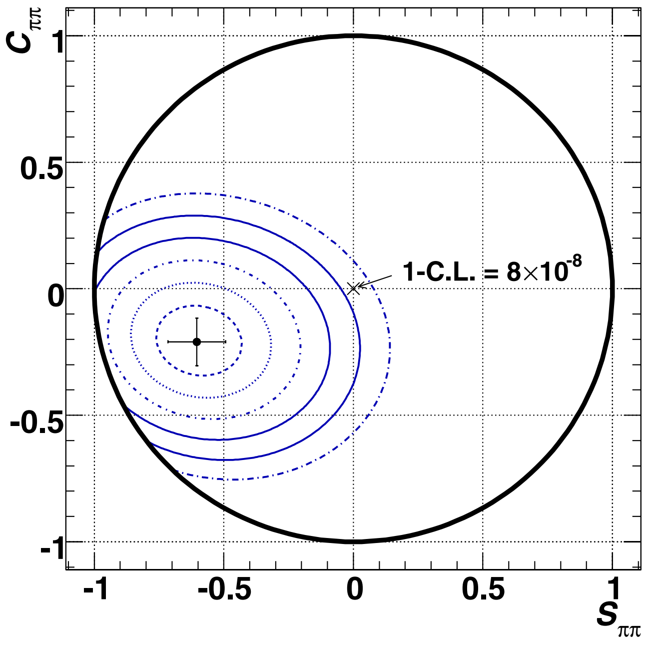

FIG. 2 (color online). $S_{\pi\pi}$ and $C_{\pi\pi}$: the central values, errors, and confidence-level (C.L.) contours for $1 - \text{C.L.} = 0.317$ (1σ), 4.55×10^{-2} (2σ), 2.70×10^{-3} (3σ), 6.33×10^{-5} (4σ), 5.73×10^{-7} (5σ), and 1.97×10^{-9} (6σ), calculated from the square root of the change in the value of $-2\ln\mathcal{L}$ compared with its value at the minimum. The systematic errors are included.

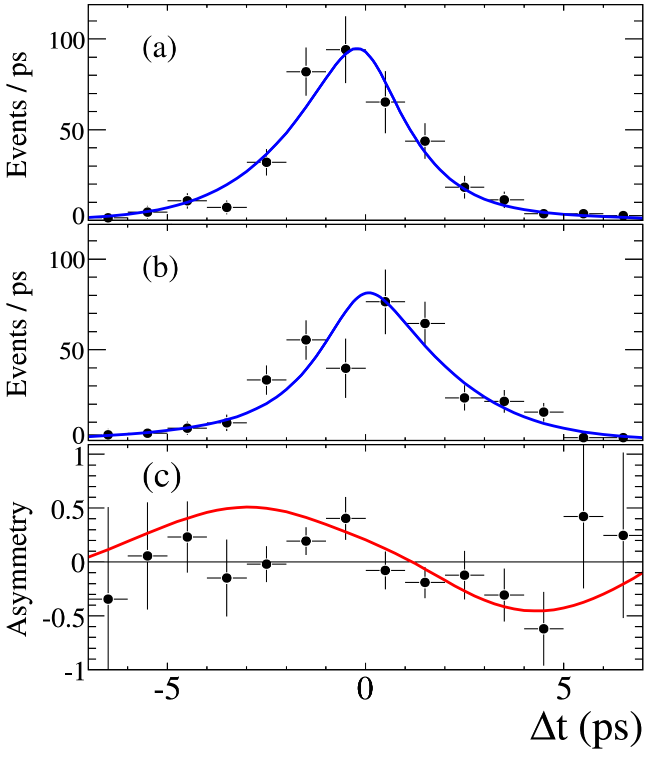

FIG. 3 (color online). The background-subtracted distributions of the decay-time difference Δt in signal $B \to \pi^+\pi^-$ events. The points with errors show the events where $B_{\rm tag}$ is identified as (a) B^0 or (b) $\bar{B}^0$. The asymmetry, defined as $(n_{B^0} - n_{\bar{B}^0})/(n_{B^0} + n_{\bar{B}^0})$, for signal events in each Δt bin, is shown in (c). The solid curves are the projection of the fit.

(0.014) and the potential effect [23] of doubly CKM-suppressed decays of the $B_{\rm tag}$ meson (0.016). As a final cross-check, we perform a fit allowing the mixing frequency and lifetime to vary simultaneously with $S_{\pi\pi}$ and $C_{\pi\pi}$. We find $\Delta m_d = 0.506 \pm 0.017\ {\rm ps}^{-1}$ and $\tau_{B^0} = 1.523 \pm 0.026$ ps, where the errors are statistical only, consistent with the world-average values, and the resulting shifts in the CP parameters are negligible. The total systematic uncertainties are calculated by summing all individual contributions in quadrature.

In summary, we observe direct CP violation in the decay $B^0 \to K^+\pi^-$ with a statistical significance of 5.5σ and CP violation in the time distribution of $B^0 \to \pi^+\pi^-$ decays with a significance of 5.4σ. We also determine that the mixing-induced CP-violating asymmetry $S_{\pi\pi}$ is nonzero with a significance of 5.1σ or greater for any value of $C_{\pi\pi}$. All results are consistent with, and supersede, our previously published measurements [3,14].

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[*] Deceased.

[†] Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy.

[‡] Also with Università della Basilicata, Potenza, Italy.

[§] Also with IPPP, Physics Department, Durham University, Durham DH1 3LE, United Kingdom.

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