Evidence for D^0-$\overline{D}^0$ Mixing

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] 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. 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] 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] 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] M. J. Kobel,[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] G. Calderini,[57] J. Chauveau,[57] P. David,[57] L. Del Buono,[57] Ch. de la Vaissière,[57] O. Hamon,[57] Ph. Leruste,[57] J. Malclès,[57] J. Ocariz,[57] A. Perez,[57] L. Gladney,[58] M. Biasini,[59] R. Covarelli,[59] E. Manoni,[59] C. Angelini,[60]

G. Batignani,[60] S. Bettarini,[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] J. Kaminski,[68] M. H. Kelsey,[68] H. Kim,[68] P. Kim,[68] M. L. Kocian,[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] I. Ofte,[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 present evidence for D^0-$\overline{D}^0$ mixing in $D^0 \to K^+\pi^-$ decays from 384 fb^{-1} of e^+e^- colliding-beam data recorded near $\sqrt{s} = 10.6$ GeV with the *BABAR* detector at the PEP-II storage rings at the Stanford Linear Accelerator Center. We find the mixing parameters $x'^2 = [-0.22 \pm 0.30(\text{stat}) \pm 0.21(\text{syst})] \times 10^{-3}$ and $y' = [9.7 \pm 4.4(\text{stat}) \pm 3.1(\text{syst})] \times 10^{-3}$ and a correlation between them of -0.95. This result is inconsistent with the no-mixing hypothesis with a significance of 3.9 standard deviations. We measure R_D, the ratio of doubly Cabibbo-suppressed to Cabibbo-favored decay rates, to be $[0.303 \pm 0.016(\text{stat}) \pm 0.010(\text{syst})]\%$. We find no evidence for CP violation.

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Quantum-mechanical mixing of neutral-meson particle-antiparticle states has been observed in the K [1], B [2], and B_s [3] systems but not yet in the D system. D mesons, which contain a charm quark, are the only system where contributions of down-type quarks in the mixing loop can be explored. In the standard model (SM), the D^0-$\overline{D}^0$ mixing rate is expected to be very small (10^{-4} or less), due to Glashow-Iliopoulos-Maiani suppression of the first two quark generations and Cabibbo-Kobayashi-Maskawa suppression of the third [4]. Long-distance effects from intermediate states coupling to both D^0 and $\overline{D}^0$ also contribute, making precise prediction and interpretation difficult [5]. We present evidence for D mixing consistent with these expectations and with previous experimental limits [6].

To the extent that only the first two generations are involved, CP violation is expected to be well below the sensitivity of this experiment, although non-SM processes could enhance either mixing or CP violation. We compare D^0 and $\overline{D}^0$ samples separately and find no evidence for CP violation.

We study the right-sign (RS), Cabibbo-favored (CF) decay $D^0 \to K^-\pi^+$ [7] and the wrong-sign (WS) decay $D^0 \to K^+\pi^-$. The latter can be produced via the doubly Cabibbo-suppressed (DCS) decay $D^0 \to K^+\pi^-$ or via mixing followed by a CF decay $D^0 \to \overline{D}^0 \to K^+\pi^-$. The DCS decay has a small rate R_D of order $\tan^4\theta_C \approx 0.3\%$ relative to CF decay, with θ_C the Cabibbo angle. We distinguish D^0 and $\overline{D}^0$ by their production in the decay $D^{*+} \to \pi_s^+ D^0$, where the π_s^+ is referred to as the "slow pion." In RS decays, the π_s^+ and the kaon have opposite charges, while in WS decays the charges are the same. The time dependence of the WS decay rate is used to separate the contributions of DCS decays from D^0-$\overline{D}^0$ mixing.

The D^0 and $\overline{D}^0$ mesons are produced as flavor eigenstates but evolve and decay as mixtures of the eigenstates D_1 and D_2 of the Hamiltonian, with masses and widths M_1, Γ_1 and M_2, Γ_2, respectively. Mixing is characterized by the mass and lifetime differences $\Delta M = M_1 - M_2$ and $\Delta\Gamma = \Gamma_1 - \Gamma_2$. Defining the parameters $x = \Delta M/\Gamma$ and $y = \Delta\Gamma/2\Gamma$, where $\Gamma = (\Gamma_1 + \Gamma_2)/2$, we approximate the time dependence of the WS decay of a meson produced as a D^0 at time $t = 0$ in the limit of small mixing ($|x|, |y| \ll 1$) and CP conservation as

$$\frac{T_{\text{WS}}(t)}{e^{-\Gamma t}} \propto R_D + \sqrt{R_D} y' \Gamma t + \frac{x'^2 + y'^2}{4}(\Gamma t)^2, \qquad (1)$$

where $x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$, $y' = -x\sin\delta_{K\pi} + y\cos\delta_{K\pi}$, and $\delta_{K\pi}$ is the strong phase between the DCS and CF amplitudes.

We study both CP-conserving and CP-violating cases. For the CP-conserving case, we fit for the parameters R_D, x'^2, and y'. To search for CP violation, we apply Eq. (1) to the D^0 and $\overline{D}^0$ samples separately, fitting for the parameters $\{R_D^\pm, x'^{2\pm}, y'^\pm\}$ for D^0 $(+)$ decays and $\overline{D}^0$ $(-)$ decays.

We use 384 fb^{-1} of e^+e^- colliding-beam data recorded near $\sqrt{s} = 10.6$ GeV with the *BABAR* detector [8] at the PEP-II asymmetric-energy storage rings. We select D^0 candidates by pairing oppositely charged tracks with a $K^\mp\pi^\pm$ invariant mass $m_{K\pi}$ between 1.81 and 1.92 GeV$/c^2$. Each pair is identified as $K^\mp\pi^\pm$ using a likelihood-based particle identification algorithm. We require the π_s^+ to have a momentum in the laboratory frame greater than 0.1 GeV$/c$ and in the e^+e^- center-of-mass (c.m.) frame below 0.45 GeV$/c$.

To obtain the proper decay time t and its error σ_t for each D^0 candidate, we refit the $K^\mp$ and $\pi^\pm$ tracks, constraining them to originate from a common vertex. We also require the D^0 and π_s^+ to originate from a common vertex, constrained by the position and size of the e^+e^- interaction region. The vertical rms size of each beam is typically 6 μm [8]. We require the χ^2 probability of the vertex-constrained combined fit $P(\chi^2)$ to be at least 0.1% and the $m_{K\pi\pi_s} - m_{K\pi}$ mass difference Δm to satisfy $0.14 < \Delta m < 0.16$ GeV$/c^2$.

To remove D^0 candidates from B-meson decays and to reduce combinatorial backgrounds, we require each D^0 to have a momentum in the c.m. frame greater than 2.5 GeV$/c$. We require $-2 < t < 4$ ps and $\sigma_t < 0.5$ ps (the most probable value of σ_t for signal events is 0.16 ps). For D^{*+} candidates sharing one or more tracks with other D^{*+} candidates, we retain only the candidate with the highest $P(\chi^2)$. After applying all criteria, we keep approximately 1 229 000 RS and 64 000 WS D^0 and $\overline{D}^0$ candidates. To avoid potential bias, we finalized the analysis procedure without examining the mixing results.

The mixing parameters are determined in an unbinned, extended maximum-likelihood fit to the RS and WS data samples over the four observables $m_{K\pi}$, Δm, t, and σ_t. The fit is performed in several stages. First, RS and WS signal and background shape parameters are determined from a fit to $m_{K\pi}$ and Δm and are not varied in subsequent fits. Next, the D^0 proper-time resolution function and lifetime are determined in a fit to the RS data using $m_{K\pi}$ and Δm to separate the signal and background components. We fit to the WS data sample using three different models. The first model assumes both CP conservation and the absence of mixing. The second model allows for mixing but assumes no CP violation. The third model allows for both mixing and CP violation.

The RS and WS $\{m_{K\pi}, \Delta m\}$ distributions are described by four components: signal, random π_s^+, misreconstructed D^0, and combinatorial background. The signal component has a characteristic peak in both $m_{K\pi}$ and Δm. The random π_s^+ component models reconstructed D^0 decays combined with a random slow pion and has the same shape in $m_{K\pi}$ as signal events but does not peak in Δm. Misreconstructed D^0 events have one or more of the D^0 decay products either not reconstructed or reconstructed with the wrong particle hypothesis. They peak in Δm but not in $m_{K\pi}$. For RS events, most of these are semileptonic D^0 decays. For WS events, the main contribution is RS $D^0 \to K^-\pi^+$ decays where the K^- and the π^+ are misidentified as π^- and K^+, respectively. Combinatorial background events are those not described by the above components; they do not exhibit any peaking structure in $m_{K\pi}$ or Δm.

The functional forms of the probability density functions (PDFs) for the signal and background components are chosen based on studies of Monte Carlo (MC) samples. However, all parameters are determined from two-dimensional likelihood fits to data over the full $m_{K\pi}$ and Δm region.

We fit the RS and WS data samples simultaneously with shape parameters describing the signal and random π_s^+ components shared between the two data samples. We find $1\,141\,500 \pm 1200$ RS signal events and 4030 ± 90 WS signal events. The dominant background component is the random π_s^+ background. Projections of the WS data and fit are shown in Fig. 1.

The measured proper-time distribution for the RS signal is described by an exponential function convolved with a resolution function whose parameters are determined by the fit to the data. The resolution function is the sum of three Gaussians with widths proportional to the estimated event-by-event proper-time uncertainty σ_t. The random π_s^+ background is described by the same proper-time distribution as signal events, since the slow pion has little weight in the vertex fit. The proper-time distribution of the combinatorial background is described by a sum of two Gaussians, one of which has a power-law tail to account for a small long-lived component. The combinatorial background and real D^0 decays have different σ_t distributions, as determined from data using a background-subtraction technique [9] based on the fit to $m_{K\pi}$ and Δm.

The fit to the RS proper-time distribution is performed over all events in the full $m_{K\pi}$ and Δm region. The PDFs for signal and background in $m_{K\pi}$ and Δm are used in the proper-time fit with all parameters fixed to their previously determined values. The fitted D^0 lifetime is found to be consistent with the world-average lifetime [10].

The measured proper-time distribution for the WS signal is modeled by Eq. (1) convolved with the resolution function determined in the RS proper-time fit. The random π_s^+ and misreconstructed D^0 backgrounds are described by the RS signal proper-time distribution since they are real D^0 decays. The proper-time distribution for WS data is shown in Fig. 2. The fit results with and without mixing are shown as the overlaid curves.

The fit with mixing provides a substantially better description of the data than the fit with no mixing. The significance of the mixing signal is evaluated based on the change in negative log likelihood with respect to the minimum. Figure 3 shows confidence-level (C.L.) contours calculated from the change in log likelihood ($-2\Delta \ln\mathcal{L}$) in two dimensions (x'^2 and y') with systematic uncertainties included. The likelihood maximum is at the unphysical value of $x'^2 = -2.2 \times 10^{-4}$ and $y' = 9.7 \times 10^{-3}$. The value of $-2\Delta \ln\mathcal{L}$ at the most likely point in the physically

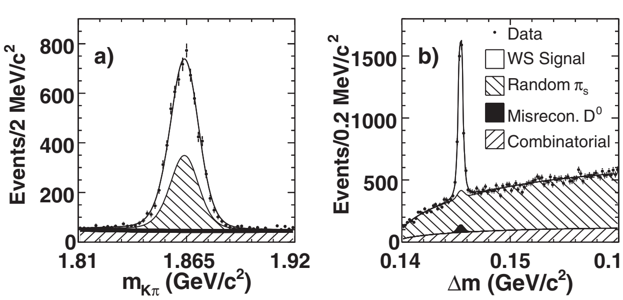

FIG. 1. (a) $m_{K\pi}$ for WS candidates with $0.1445 < \Delta m < 0.1465$ GeV$/c^2$ and (b) Δm for WS candidates with $1.843 < m_{K\pi} < 1.883$ GeV$/c^2$. The fitted PDFs are overlaid.

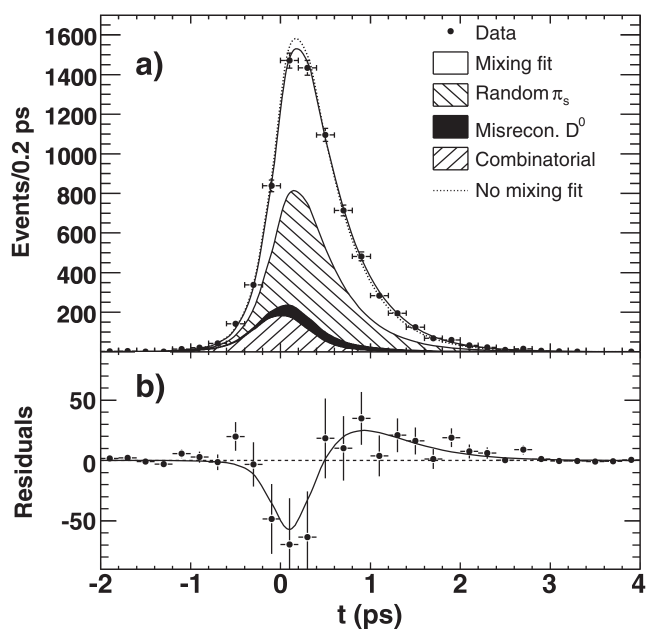

FIG. 2. (a) Projections of the proper-time distribution of combined D^0 and $\overline{D}^0$ WS candidates and fit result integrated over the signal region $1.843 < m_{K\pi} < 1.883$ GeV$/c^2$ and $0.1445 < \Delta m < 0.1465$ GeV$/c^2$. The result of the fit allowing (not allowing) mixing but not CP violation is overlaid as a solid (dashed) curve. (b) The points represent the difference between the data and the no-mixing fit. The solid curve shows the difference between fits with and without mixing.

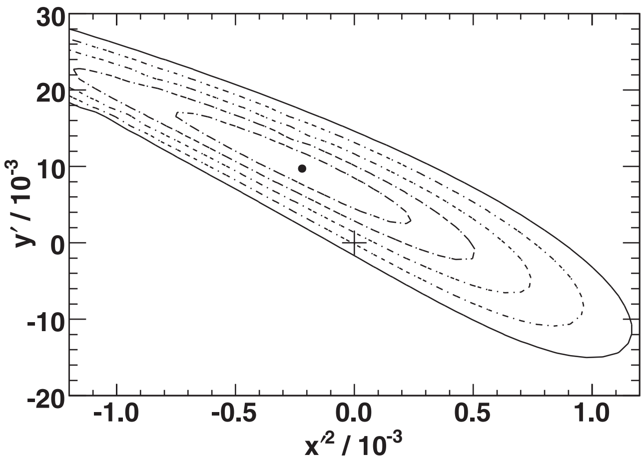

FIG. 3. The central value (point) and C.L. contours for $1 - \text{C.L.} = 0.317(1\sigma)$, $4.55 \times 10^{-2}(2\sigma)$, $2.70 \times 10^{-3}(3\sigma)$, $6.33 \times 10^{-5}(4\sigma)$, and $5.73 \times 10^{-7}(5\sigma)$, calculated from the change in the value of $-2\ln\mathcal{L}$ compared with its value at the minimum. Systematic uncertainties are included. The no-mixing point is shown as a plus sign (+).

allowed region ($x'^2 = 0$ and $y' = 6.4 \times 10^{-3}$) is 0.7 units. The value of $-2\Delta\ln\mathcal{L}$ for no mixing is 23.9 units. Including the systematic uncertainties, this corresponds to a significance equivalent to 3.9 standard deviations ($1 - \text{C.L.} = 1 \times 10^{-4}$) and thus constitutes evidence for mixing. The fitted values of the mixing parameters and R_D are listed in Table I. The correlation coefficient between the x'^2 and y' parameters is -0.95.

Allowing for the possibility of CP violation, we calculate the values of $R_D = \sqrt{R_D^+ R_D^-}$ and $A_D = (R_D^+ - R_D^-)/(R_D^+ + R_D^-)$ listed in Table I, from the fitted $R_D^\pm$ values. The best fit points ($x'^{2\pm}$, $y'^{\pm}$) shown in Table I are more than 3 standard deviations away from the no-mixing hypothesis. The shapes of the ($x'^{2\pm}$, $y'^{\pm}$) C.L. contours are similar to those shown in Fig. 3. All cross-checks indicate that the close agreement between the separate D^0 and $\overline{D}^0$ fit results is coincidental.

TABLE I. Results from the different fits. The first uncertainty listed is statistical and the second systematic.

Fit type	Parameter	Fit results ($/10^{-3}$)
No CP viol. or mixing	R_D	$3.53 \pm 0.08 \pm 0.04$
No CP violation	R_D	$3.03 \pm 0.16 \pm 0.10$
	x'^2	$-0.22 \pm 0.30 \pm 0.21$
	y'	$9.7 \pm 4.4 \pm 3.1$
CP violation allowed	R_D	$3.03 \pm 0.16 \pm 0.10$
	A_D	$-21 \pm 52 \pm 15$
	x'^{2+}	$-0.24 \pm 0.43 \pm 0.30$
	y'^{+}	$9.8 \pm 6.4 \pm 4.5$
	x'^{2-}	$-0.20 \pm 0.41 \pm 0.29$
	y'^{-}	$9.6 \pm 6.1 \pm 4.3$

As a cross-check of the mixing signal, we perform independent $\{m_{K\pi}, \Delta m\}$ fits with no shared parameters for intervals in proper time selected to have approximately equal numbers of RS candidates. The fitted WS branching fractions are shown in Fig. 4 and are seen to increase with time. The slope is consistent with the measured mixing parameters and inconsistent with the no-mixing hypothesis.

We validated the fitting procedure on simulated data samples using both MC samples with the full detector simulation and large parametrized MC samples. In all cases, we found the fit to be unbiased. As a further cross-check, we performed a fit to the RS data proper-time distribution allowing for mixing in the signal component; the fitted values of the mixing parameters are consistent with no mixing. In addition, we found the staged fitting approach to give the same solution and confidence regions as a simultaneous fit in which all parameters are allowed to vary.

In evaluating systematic uncertainties in R_D and the mixing parameters, we considered variations in the fit model and in the selection criteria. We also considered alternative forms of the $m_{K\pi}$, Δm, proper-time, and σ_t PDFs. We varied the t and σ_t requirements. In addition, we considered variations that keep or reject all D^{*+} candidates sharing tracks with other candidates.

For each source of systematic error, we compute the significance $s_i^2 = 2[\ln\mathcal{L}(x'^2, y') - \ln\mathcal{L}(x_i'^2, y_i')]/2.3$, where (x'^2, y') are the parameters obtained from the standard fit, $(x_i'^2, y_i')$ the parameters from the fit including the ith systematic variation, and $\mathcal{L}$ the likelihood of the standard fit. The factor 2.3 is the 68% confidence level for 2 degrees of freedom. To estimate the significance of our results in (x'^2, y'), we reduce $-2\Delta\ln\mathcal{L}$ by a factor of $1 + \Sigma s_i^2 = 1.3$ to account for systematic errors. The largest contribu-

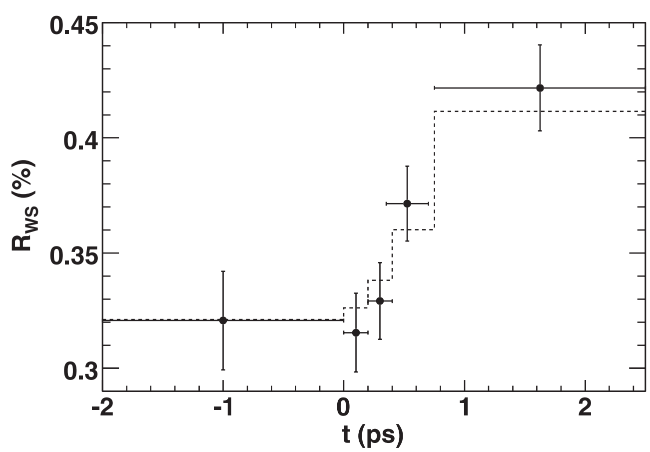

FIG. 4. The WS branching fractions from independent $\{m_{K\pi}, \Delta m\}$ fits to slices in measured proper time (points). The dashed line shows the expected wrong-sign rate as determined from the mixing fit shown in Fig. 2. The χ^2 with respect to expectation from the mixing fit is 1.5; for the no-mixing hypothesis (a constant WS rate), the χ^2 is 24.0.

tion to this factor, 0.06, is due to uncertainty in modeling the long decay time component from other D decays in the signal region. The second largest component, 0.05, is due to the presence of a nonzero mean in the proper-time signal resolution PDF. The mean value is determined in the RS proper-time fit to be 3.6 fs and is due to small misalignments in the detector. The error of 15×10^{-3} on A_D is primarily due to uncertainties in modeling the differences between K^+ and K^- absorption in the detector.

We have presented evidence for D^0-$\overline{D}^0$ mixing. Our result is inconsistent with the no-mixing hypothesis at a significance of 3.9 standard deviations. We measure $y' = [9.7 \pm 4.4(\text{stat}) \pm 3.1(\text{syst})] \times 10^{-3}$, while x'^2 is consistent with zero. We find no evidence for CP violation and measure R_D to be $[0.303 \pm 0.016(\text{stat}) \pm 0.010(\text{syst})]\%$. The result is consistent with SM estimates for mixing.

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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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