Search for D^0-$\overline{D}^0$ Mixing and a Measurement of the Doubly Cabibbo-Suppressed Decay Rate in $D^0 \to K\pi$ Decays

B. Aubert,[1] R. Barate,[1] D. Boutigny,[1] J.-M. Gaillard,[1] A. Hicheur,[1] Y. Karyotakis,[1] J. P. Lees,[1] P. Robbe,[1] V. Tisserand,[1] A. Zghiche,[1] A. Palano,[2] A. Pompili,[2] J. C. Chen,[3] N. D. Qi,[3] G. Rong,[3] P. Wang,[3] Y. S. Zhu,[3] G. Eigen,[4] I. Ofte,[4] B. Stugu,[4] G. S. Abrams,[5] A.W. Borgland,[5] A. B. Breon,[5] D. N. Brown,[5] J. Button-Shafer,[5] R. N. Cahn,[5] E. Charles,[5] C. T. Day,[5] M. S. Gill,[5] A.V. Gritsan,[5] Y. Groysman,[5] R. G. Jacobsen,[5] R.W. Kadel,[5] J. Kadyk,[5] L. T. Kerth,[5] Yu. G. Kolomensky,[5] J. F. Kral,[5] G. Kukartsev,[5] C. LeClerc,[5] M. E. Levi,[5] G. Lynch,[5] L. M. Mir,[5] P. J. Oddone,[5] T. J. Orimoto,[5] M. Pripstein,[5] N. A. Roe,[5] A. Romosan,[5] M. T. Ronan,[5] V. G. Shelkov,[5] A. V. Telnov,[5] W. A. Wenzel,[5] T. J. Harrison,[6] C. M. Hawkes,[6] D. J. Knowles,[6] R. C. Penny,[6] A. T. Watson,[6] N. K. Watson,[6] T. Deppermann,[7] K. Goetzen,[7] H. Koch,[7] B. Lewandowski,[7] M. Pelizaeus,[7] K. Peters,[7] H. Schmuecker,[7] M. Steinke,[7] N. R. Barlow,[8] W. Bhimji,[8] J. T. Boyd,[8] N. Chevalier,[8] W. N. Cottingham,[8] C. Mackay,[8] F. F. Wilson,[8] C. Hearty,[9] T. S. Mattison,[9] J. A. McKenna,[9] D. Thiessen,[9] P. Kyberd,[10] A. K. McKemey,[10] V. E. Blinov,[11] A. D. Bukin,[11] V. B. Golubev,[11] V. N. Ivanchenko,[11] E. A. Kravchenko,[11] A. P. Onuchin,[11] S. I. Serednyakov,[11] Yu. I. Skovpen,[11] E. P. Solodov,[11] A. N. Yushkov,[11] D. Best,[12] M. Chao,[12] D. Kirkby,[12] A. J. Lankford,[12] M. Mandelkern,[12] S. McMahon,[12] R. K. Mommsen,[12] W. Roethel,[12] D. P. Stoker,[12] C. Buchanan,[13] H. K. Hadavand,[14] E. J. Hill,[14] D. B. MacFarlane,[14] H. P. Paar,[14] Sh. Rahatlou,[14] U. Schwanke,[14] V. Sharma,[14] J.W. Berryhill,[15] C. Campagnari,[15] B. Dahmes,[15] N. Kuznetsova,[15] S. L. Levy,[15] O. Long,[15] A. Lu,[15] M. A. Mazur,[15] J. D. Richman,[15] W. Verkerke,[15] J. Beringer,[16] A. M. Eisner,[16] M. Grothe,[16] C. A. Heusch,[16] W. S. Lockman,[16] T. Schalk,[16] R. E. Schmitz,[16] B. A. Schumm,[16] A. Seiden,[16] M. Turri,[16] W. Walkowiak,[16] D. C. Williams,[16] M. G. Wilson,[16] J. Albert,[17] E. Chen,[17] M. P. Dorsten,[17] G. P. Dubois-Felsmann,[17] A. Dvoretskii,[17] D. G. Hitlin,[17] I. Narsky,[17] F. C. Porter,[17] A. Ryd,[17] A. Samuel,[17] S. Yang,[17] S. Jayatilleke,[18] G. Mancinelli,[18] B. T. Meadows,[18] M. D. Sokoloff,[18] T. Barillari,[19] F. Blanc,[19] P. Bloom,[19] P. J. Clark,[19] W. T. Ford,[19] U. Nauenberg,[19] A. Olivas,[19] P. Rankin,[19] J. Roy,[19] J. G. Smith,[19] W. C. van Hoek,[19] L. Zhang,[19] J. L. Harton,[20] T. Hu,[20] A. Soffer,[20] W. H. Toki,[20] R. J. Wilson,[20] J. Zhang,[20] D. Altenburg,[21] T. Brandt,[21] J. Brose,[21] T. Colberg,[21] M. Dickopp,[21] R. S. Dubitzky,[21] A. Hauke,[21] H. M. Lacker,[21] E. Maly,[21] R. Müller-Pfefferkorn,[21] R. Nogowski,[21] S. Otto,[21] K. R. Schubert,[21] R. Schwierz,[21] B. Spaan,[21] L. Wilden,[21] D. Bernard,[22] G. R. Bonneaud,[22] F. Brochard,[22] J. Cohen-Tanugi,[22] Ch. Thiebaux,[22] G. Vasileiadis,[22] M. Verderi,[22] A. Khan,[23] D. Lavin,[23] F. Muheim,[23] S. Playfer,[23] J. E. Swain,[23] J. Tinslay,[23] C. Bozzi,[24] L. Piemontese,[24] A. Sarti,[24] E. Treadwell,[25] F. Anulli,[26,*] R. Baldini-Ferroli,[26] A. Calcaterra,[26] R. de Sangro,[26] D. Falciai,[26] G. Finocchiaro,[26] P. Patteri,[26] I. M. Peruzzi,[26,*] M. Piccolo,[26] A. Zallo,[26] A. Buzzo,[27] R. Contri,[27] G. Crosetti,[27] M. Lo Vetere,[27] M. Macri,[27] M. R. Monge,[27] S. Passaggio,[27] F. C. Pastore,[27] C. Patrignani,[27] E. Robutti,[27] A. Santroni,[27] S. Tosi,[27] S. Bailey,[28] M. Morii,[28] G. J. Grenier,[29] S.-J. Lee,[29] U. Mallik,[29] J. Cochran,[30] H. B. Crawley,[30] J. Lamsa,[30] W. T. Meyer,[30] S. Prell,[30] E. I. Rosenberg,[30] J. Yi,[30] M. Davier,[31] G. Grosdidier,[31] A. Höcker,[31] S. Laplace,[31] F. Le Diberder,[31] V. Lepeltier,[31] A. M. Lutz,[31] T. C. Petersen,[31] S. Plaszczynski,[31] M. H. Schune,[31] L. Tantot,[31] G. Wormser,[31] R. M. Bionta,[32] V. Brigljević,[32] C. H. Cheng,[32] D. J. Lange,[32] D. M. Wright,[32] A. J. Bevan,[33] J. R. Fry,[33] E. Gabathuler,[33] R. Gamet,[33] M. Kay,[33] D. J. Payne,[33] R. J. Sloane,[33] C. Touramanis,[33] M. L. Aspinwall,[34] D. A. Bowerman,[34] P. D. Dauncey,[34] U. Egede,[34] I. Eschrich,[34] G.W. Morton,[34] J. A. Nash,[34] P. Sanders,[34] G. P. Taylor,[34] J. J. Back,[35] G. Bellodi,[35] P. F. Harrison,[35] H.W. Shorthouse,[35] P. Strother,[35] P. B. Vidal,[35] G. Cowan,[36] H. U. Flaecher,[36] S. George,[36] M. G. Green,[36] A. Kurup,[36] C. E. Marker,[36] T. R. McMahon,[36] S. Ricciardi,[36] F. Salvatore,[36] G. Vaitsas,[36] M. A. Winter,[36] D. Brown,[37] C. L. Davis,[37] J. Allison,[38] R. J. Barlow,[38] A. C. Forti,[38] P. A. Hart,[38] F. Jackson,[38] G. D. Lafferty,[38] A. J. Lyon,[38] J. H. Weatherall,[38] J. C. Williams,[38] A. Farbin,[39] A. Jawahery,[39] D. Kovalskyi,[39] C. K. Lae,[39] V. Lillard,[39] D. A. Roberts,[39] G. Blaylock,[40] C. Dallapiccola,[40] K. T. Flood,[40] S. S. Hertzbach,[40] R. Kofler,[40] V. B. Koptchev,[40] T. B. Moore,[40] H. Staengle,[40] S. Willocq,[40] R. Cowan,[41] G. Sciolla,[41] F. Taylor,[41] R. K. Yamamoto,[41] D. J. J. Mangeol,[42] M. Milek,[42] P. M. Patel,[42] A. Lazzaro,[43] F. Palombo,[43] J. M. Bauer,[44] L. Cremaldi,[44] V. Eschenburg,[44] R. Godang,[44] R. Kroeger,[44] J. Reidy,[44] D. A. Sanders,[44] D. J. Summers,[44] H.W. Zhao,[44] C. Hast,[45] P. Taras,[45] H. Nicholson,[46] C. Cartaro,[47] N. Cavallo,[47] G. De Nardo,[47] F. Fabozzi,[47,†] C. Gatto,[47] L. Lista,[47] P. Paolucci,[47] D. Piccolo,[47] C. Sciacca,[47] M. A. Baak,[48] G. Raven,[48] J. M. LoSecco,[49] T. A. Gabriel,[50] B. Brau,[51] T. Pulliam,[51] J. Brau,[52] R. Frey,[52] M. Iwasaki,[52] C. T. Potter,[52] N. B. Sinev,[52] D. Strom,[52] E. Torrence,[52] F. Colecchia,[53] A. Dorigo,[53] F. Galeazzi,[53] M. Margoni,[53] M. Morandin,[53] M. Posocco,[53] M. Rotondo,[53] F. Simonetto,[53] R. Stroili,[53] G. Tiozzo,[53] C. Voci,[53] M. Benayoun,[54] H. Briand,[54] J. Chauveau,[54] P. David,[54] Ch. de la Vaissière,[54] L. Del Buono,[54] O. Hamon,[54] Ph. Leruste,[54] J. Ocariz,[54] M. Pivk,[54] L. Roos,[54] J. Stark,[54] S. T'Jampens,[54]

 0031-9007/03/91(17)/171801(7)$20.00

P. F. Manfredi,[55] V. Re,[55] L. Gladney,[56] Q. H. Guo,[56] J. Panetta,[56] C. Angelini,[57] G. Batignani,[57] S. Bettarini,[57] M. Bondioli,[57] F. Bucci,[57] G. Calderini,[57] M. Carpinelli,[57] F. Forti,[57] M. A. Giorgi,[57] A. Lusiani,[57] G. Marchiori,[57] F. Martinez-Vidal,[57,‡] M. Morganti,[57] N. Neri,[57] E. Paoloni,[57] M. Rama,[57] G. Rizzo,[57] F. Sandrelli,[57] J. Walsh,[57] M. Haire,[58] D. Judd,[58] K. Paick,[58] D. E. Wagoner,[58] N. Danielson,[59] P. Elmer,[59] C. Lu,[59] V. Miftakov,[59] J. Olsen,[59] A. J. S. Smith,[59] E.W. Varnes,[59] F. Bellini,[60] G. Cavoto,[59,60] D. del Re,[60] R. Faccini,[14,60] F. Ferrarotto,[60] F. Ferroni,[60] M. Gaspero,[60] E. Leonardi,[60] M. A. Mazzoni,[60] S. Morganti,[60] M. Pierini,[60] G. Piredda,[60] F. Safai Tehrani,[60] M. Serra,[60] C. Voena,[60] S. Christ,[61] G. Wagner,[61] R. Waldi,[61] T. Adye,[62] N. De Groot,[62] B. Franek,[62] N. I. Geddes,[62] G. P. Gopal,[62] E. O. Olaiya,[62] S. M. Xella,[62] R. Aleksan,[63] S. Emery,[63] A. Gaidot,[63] S. F. Ganzhur,[63] P.-F. Giraud,[63] G. Hamel de Monchenault,[63] W. Kozanecki,[63] M. Langer,[63] G.W. London,[63] B. Mayer,[63] G. Schott,[63] G. Vasseur,[63] Ch. Yeche,[63] M. Zito,[63] M.V. Purohit,[64] A.W. Weidemann,[64] F. X. Yumiceva,[64] D. Aston,[65] R. Bartoldus,[65] N. Berger,[65] A. M. Boyarski,[65] O. L. Buchmueller,[65] M. R. Convery,[65] D. P. Coupal,[65] D. Dong,[65] J. Dorfan,[65] D. Dujmic,[65] W. Dunwoodie,[65] R. C. Field,[65] T. Glanzman,[65] S. J. Gowdy,[65] E. Grauges-Pous,[65] T. Hadig,[65] V. Halyo,[65] T. Hryn'ova,[65] W. R. Innes,[65] C. P. Jessop,[65] M. H. Kelsey,[65] P. Kim,[65] M. L. Kocian,[65] U. Langenegger,[65] D.W. G. S. Leith,[65] S. Luitz,[65] V. Luth,[65] H. L. Lynch,[65] H. Marsiske,[65] S. Menke,[65] R. Messner,[65] D. R. Muller,[65] C. P. O'Grady,[65] V. E. Ozcan,[65] A. Perazzo,[65] M. Perl,[65] S. Petrak,[65] B. N. Ratcliff,[65] S. H. Robertson,[65] A. Roodman,[65] A. A. Salnikov,[65] R. H. Schindler,[65] J. Schwiening,[65] G. Simi,[65] A. Snyder,[65] A. Soha,[65] J. Stelzer,[65] D. Su,[65] M. K. Sullivan,[65] H. A. Tanaka,[65] J. Va'vra,[65] S. R. Wagner,[65] M. Weaver,[65] A. J. R. Weinstein,[65] W. J. Wisniewski,[65] D. H. Wright,[65] C. C. Young,[65] P. R. Burchat,[66] T. I. Meyer,[66] C. Roat,[66] S. Ahmed,[67] J. A. Ernst,[67] W. Bugg,[68] M. Krishnamurthy,[68] S. M. Spanier,[68] R. Eckmann,[69] H. Kim,[69] J. L. Ritchie,[69] R. F. Schwitters,[69] J. M. Izen,[70] I. Kitayama,[70] X. C. Lou,[70] S. Ye,[70] F. Bianchi,[71] M. Bona,[71] F. Gallo,[71] D. Gamba,[71] C. Borean,[72] L. Bosisio,[72] G. Della Ricca,[72] S. Dittongo,[72] S. Grancagnolo,[72] L. Lanceri,[72] P. Poropat,[72,§] L. Vitale,[72] G. Vuagnin,[72] R. S. Panvini,[73] Sw. Banerjee,[74] C. M. Brown,[74] D. Fortin,[74] P. D. Jackson,[74] R. Kowalewski,[74] J. M. Roney,[74] H. R. Band,[75] S. Dasu,[75] M. Datta,[75] A. M. Eichenbaum,[75] H. Hu,[75] J. R. Johnson,[75] R. Liu,[75] F. Di Lodovico,[75] A. K. Mohapatra,[75] Y. Pan,[75] R. Prepost,[75] S. J. Sekula,[75] J. H. von Wimmersperg-Toeller,[75] J. Wu,[75] S. L. Wu,[75] Z. Yu,[75] and H. Neal[76]

(The *BABAR* Collaboration)

[1]*Laboratoire de Physique des Particules, F-74941 Annecy-le-Vieux, France*
[2]*Università di Bari, Dipartimento di Fisica and INFN, I-70126 Bari, Italy*
[3]*Institute of High Energy Physics, Beijing 100039, China*
[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 San Diego, La Jolla, California 92093, USA*
[15]*University of California at Santa Barbara, Santa Barbara, California 93106, USA*
[16]*University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA*
[17]*California Institute of Technology, Pasadena, California 91125, USA*
[18]*University of Cincinnati, Cincinnati, Ohio 45221, USA*
[19]*University of Colorado, Boulder, Colorado 80309, USA*
[20]*Colorado State University, Fort Collins, Colorado 80523, USA*
[21]*Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany*
[22]*Ecole Polytechnique, LLR, F-91128 Palaiseau, France*
[23]*University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*
[24]*Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy*
[25]*Florida A&M University, Tallahassee, Florida 32307, USA*
[26]*Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy*
[27]*Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy*
[28]*Harvard University, Cambridge, Massachusetts 02138, USA*
[29]*University of Iowa, Iowa City, Iowa 52242, USA*

[30]Iowa State University, Ames, Iowa 50011-3160, USA
[31]Laboratoire de l'Accélérateur Linéaire, F-91898 Orsay, France
[32]Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[33]University of Liverpool, Liverpool L69 3BX, United Kingdom
[34]University of London, Imperial College, London, SW7 2BW, United Kingdom
[35]Queen Mary, University of London, E1 4NS, United Kingdom
[36]University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
[37]University of Louisville, Louisville, Kentucky 40292, USA
[38]University of Manchester, Manchester M13 9PL, United Kingdom
[39]University of Maryland, College Park, Maryland 20742, USA
[40]University of Massachusetts, Amherst, Massachusetts 01003, USA
[41]Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA
[42]McGill University, Montréal, Quebec, Canada H3A 2T8
[43]Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy
[44]University of Mississippi, University, Mississippi 38677, USA
[45]Université de Montréal, Laboratoire René J. A. Lévesque, Montréal, Quebec, Canada H3C 3J7
[46]Mount Holyoke College, South Hadley, Massachusetts 01075, USA
[47]Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy
[48]NIKHEF, National Institute for Nuclear Physics and High Energy Physics, 1009 DB Amsterdam, The Netherlands
[49]University of Notre Dame, Notre Dame, Indiana 46556, USA
[50]Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
[51]Ohio State University, Columbus, Ohio 43210, USA
[52]University of Oregon, Eugene, Oregon 97403, USA
[53]Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy
[54]Universités Paris VI et VII, Lab de Physique Nucléaire H. E., F-75252 Paris, France
[55]Università di Pavia, Dipartimento di Elettronica and INFN, I-27100 Pavia, Italy
[56]University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
[57]Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy
[58]Prairie View A&M University, Prairie View, Texas 77446, USA
[59]Princeton University, Princeton, New Jersey 08544, USA
[60]Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy
[61]Universität Rostock, D-18051 Rostock, Germany
[62]Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, United Kingdom
[63]DAPNIA, Commissariat à l'Energie Atomique/Saclay, F-91191 Gif-sur-Yvette, France
[64]University of South Carolina, Columbia, South Carolina 29208, USA
[65]Stanford Linear Accelerator Center, Stanford, California 94309, USA
[66]Stanford University, Stanford, California 94305-4060, USA
[67]State University of New York, Albany, New York 12222, USA
[68]University of Tennessee, Knoxville, Tennessee 37996, USA
[69]University of Texas at Austin, Austin, Texas 78712, USA
[70]University of Texas at Dallas, Richardson, Texas 75083, USA
[71]Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy
[72]Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy
[73]Vanderbilt University, Nashville, Tennessee 37235, USA
[74]University of Victoria, Victoria, British Columbia, Canada V8W 3P6
[75]University of Wisconsin, Madison, Wisconsin 53706, USA
[76]Yale University, New Haven, Connecticut 06511, USA

(Received 3 April 2003; published 21 October 2003)

We present results of a search for D^0-$\overline{D}^0$ mixing and a measurement of $R_{\rm D}$, the ratio of doubly Cabibbo-suppressed decays to Cabibbo-favored decays, using $D^0 \to K^+\pi^-$ decays from 57.1 fb^{-1} of data collected near $\sqrt{s} = 10.6$ GeV with the *BABAR* detector at the PEP-II collider. At the 95% confidence level, allowing for *CP* violation, we find the mixing parameters $x'^2 < 0.0022$ and $-0.056 < y' < 0.039$, and the mixing rate $R_{\rm M} < 0.16\%$. In the limit of no mixing, $R_{\rm D} = [0.357 \pm 0.022(\text{stat}) \pm 0.027(\text{syst})]\%$ and the *CP*-violating asymmetry $A_{\rm D} = 0.095 \pm 0.061(\text{stat}) \pm 0.083(\text{syst})$.

DOI: 10.1103/PhysRevLett.91.171801 PACS numbers: 13.25.Ft, 11.30.Er, 12.15.Ff

Within the standard model, the level of D^0-$\overline{D}^0$ mixing is predicted to be below the sensitivity of current experiments [1]. For this reason D^0-$\overline{D}^0$ mixing is a good place to look for signals of new physics beyond the standard model [2]. Because new physics may not conserve *CP*, it is important to consider *CP* violation when measuring mixing. Observation of CP violation in D^0-$\overline{D}^0$ mixing would be an unambiguous sign of new physics [1,3].

Mixing can be characterized by the two parameters $x \equiv \Delta m/\Gamma$ and $y \equiv \Delta\Gamma/2\Gamma$, where $\Delta m = m_1 - m_2$ ($\Delta\Gamma = \Gamma_1 - \Gamma_2$) is the difference in mass (width) between the two mass eigenstates and Γ is the average width.

The dominant two-body decay of the D^0 is the *right-sign* (RS) Cabibbo-favored (CF) decay $D^0 \to K^-\pi^+$. Evidence for mixing and CP violation, if present, will appear in the *wrong-sign* (WS) decay $D^0 \to K^+\pi^-$. Charge conjugates are implied unless otherwise stated. Two amplitudes contribute to the production of this final state: the tree-level amplitude for doubly Cabibbo-suppressed (DCS) decay of the D^0, and an amplitude for mixing followed by CF decay of the $\overline{D}^0$. Assuming that $x, y \ll 1$ and CP is conserved, and with the convention $\Delta\Gamma = \Gamma(CP = +1) - \Gamma(CP = -1)$, the time-dependent, WS decay rate $T_{\rm WS}(t)$ for $D^0 \to K^+\pi^-$ can be approximately [4] related to the RS decay rate $T_{\rm RS}(t)$ by

$$T_{\rm WS}(t) = T_{\rm RS}(t)\left(R_{\rm D} + \sqrt{R_{\rm D}}y' t + \frac{x'^2 + y'^2}{4}t^2\right). \quad (1)$$

In Eq. (1), t is the proper time of the D^0 decay measured in units of the D^0 lifetime τ_{D^0}, $T_{\rm RS}(t) \propto e^{-t}$, $R_{\rm D}$ is the time-integrated rate of the direct DCS decay $D^0 \to K^+\pi^-$ relative to the RS decay, and x', y' are related to x, y by $x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$ and $y' = -x\sin\delta_{K\pi} + y\cos\delta_{K\pi}$, where $\delta_{K\pi}$ is the relative strong phase between the CF and DCS amplitudes. Physics beyond the standard model may include additional phases that are not CP conserving. Such terms can be absorbed into a phase φ, described below. The time-integrated WS decay rate is

$$R_{\rm WS} = R_{\rm D} + \sqrt{R_{\rm D}}y' + \frac{x'^2 + y'^2}{2}. \quad (2)$$

Previous experiments have searched for mixing using wrong-sign hadronic [4–6] and semileptonic [7] D^0 decays, or have searched for width differences between $CP = +1$ and $CP = -1$ states directly [8–10]. Since x' appears only quadratically in Eq. (1), its sign cannot be determined in an analysis based on the WS decay alone.

To allow for CP violation, we apply Eq. (1) to D^0 and $\overline{D}^0$ separately. We determine $\{R_{\rm WS}^+, x'^{+2}, y'^+\}$ for D^0 candidates and $\{R_{\rm WS}^-, x'^{-2}, y'^-\}$ for $\overline{D}^0$ candidates. The separate D^0 and $\overline{D}^0$ results can be combined to form the quantities

$$A_{\rm D} = \frac{R_{\rm D}^+ - R_{\rm D}^-}{R_{\rm D}^+ + R_{\rm D}^-}, \qquad A_{\rm M} = \frac{R_{\rm M}^+ - R_{\rm M}^-}{R_{\rm M}^+ + R_{\rm M}^-}, \quad (3)$$

where $R_{\rm M}^\pm \equiv (x'^{\pm 2} + y'^{\pm 2})/2$. $A_{\rm D}$ and $A_{\rm M}$ are related to CP violation in the DCS decay and mixing amplitudes, respectively. CP violation in the interference of DCS decay and mixing is parametrized by the phase φ:

$$x'^{\pm} = \sqrt[4]{\frac{1 \pm A_{\rm M}}{1 \mp A_{\rm M}}}(x'\cos\varphi \pm y'\sin\varphi), \quad (4)$$

$$y'^{\pm} = \sqrt[4]{\frac{1 \pm A_{\rm M}}{1 \mp A_{\rm M}}}(y'\cos\varphi \pm x'\sin\varphi), \quad (5)$$

An offset in φ of $\pm\pi$ is equivalent to interchanging the labels of the two physical D^0 states. To avoid this labeling ambiguity, we use the convention that $|\varphi| < \pi/2$.

We select a very clean sample of RS and WS decays from a 57.1 fb^{-1} dataset collected with the *BABAR* detector [11] at the PEP-II e^+e^- storage ring. We fit for parameters describing mixing and DCS amplitudes from the WS decay-time distribution. To avoid potential bias, we finalized our data selection criteria and the procedures for fitting and extracting the statistical limits without examining the mixing results.

We select D^0 candidates from reconstructed $D^{*+} \to D^0\pi^+$ decays; this provides a clean sample of D^0 decays, and the charge of the pion (the "tagging pion") identifies the production flavor of the neutral D. We retain each RS and WS D^0 candidate whose invariant mass $m_{K\pi}$ is within 60 MeV$/c^2$ of the D^0 mass. We require the mass difference δm between the $D^{*+}$and the D^0 candidate to be less than $m_\pi + 25$ MeV$/c^2$. Only D^{*+} candidates with center-of-mass momenta above 2.6 GeV$/c$ are retained, thereby rejecting D^{*+} candidates from B decays.

We determine the D^0 vertex by requiring that the D^0 decay tracks originate from a common point with a probability $p(\chi^2) > 1\%$, and then determine the D^{*+} vertex by extrapolating the D^0 flight path back to the beam-beam interaction region. We constrain the trajectory of the tagging pion to originate from the D^{*+} vertex, and calculate the D^0 proper decay-time t from its flight length. The typical resolution is 0.2 ps.

We determine the mixing parameters by unbinned, extended maximum-likelihood fits to the RS and WS samples simultaneously. We consider four separate fit cases: (i) a general case allowing for possible CP violation (by treating WS D^0 and $\overline{D}^0$ candidates separately), fitting for $\{R_{\rm WS}^+, x'^{+2}, y'^+\}$ for D^0 candidates and $\{R_{\rm WS}^-, x'^{-2}, y'^-\}$ for $\overline{D}^0$ candidates; (ii) a case assuming CP conservation, not differentiating between D^0 and $\overline{D}^0$ candidates, fitting for $\{R_{\rm WS}, x'^2, y'\}$; (iii) a case assuming no mixing, but allowing CP violation in the DCS amplitudes, fitting for $\{R_{\rm D}, A_{\rm D}\}$; and (iv) a case assuming both CP conservation and no mixing, fitting for $R_{\rm D}$ only.

We assign each candidate to one of four categories based on its origin as D^0 or $\overline{D}^0$ and its decay as RS or WS. For each category we construct probability density functions (PDFs) that model signal and background components. The independent variables in the PDFs are $m_{K\pi}$, δm, the D^0 proper time t, and its error σ_t.

Within a category, the likelihood is a sum of PDFs, one for each signal or background component, weighted by the number of events for that component. Each component's PDF factorizes into a portion describing the behavior of each independent variable convoluted with a corresponding resolution function. The parameters describing the mass resolutions and shapes and the lifetime resolution are shared between PDFs. These are determined primarily by the large RS sample. We limit the fit to the fiducial range $|t| < 4$ ps and $\sigma_t < 0.4$ ps.

We characterize the WS background by three components: true D^0 decays that are combined with unassociated pions to form D^{*+} candidates; combinatorial background where one or both of the tracks in the D^0 candidate do not originate from a D^0 decay; and background where the kaon and the pion in the D^0 decay have both been misidentified, thus converting a RS decay into an apparent WS decay (double misidentification). Kaons (pions) are identified with an average efficiency of 84% (85%); the average misidentification rate is 3% (2%). Fitting the double misidentification background is particularly important due to the large size of the RS sample; its level as obtained from the fit agrees well with predictions based on our particle identification performance.

We normalize D^0 and $\overline{D}^0$ WS candidates separately, resulting in two signal and six background WS components. We assume CP conservation in the RS data; it has one signal and three background components.

We perform the fit in steps. Parameters corresponding to the $m_{K\pi}$ and δm distributions and the number of candidates in each category are determined first. Then these parameters are fixed while fitting the WS proper time distribution. The shapes of the distributions in $m_{K\pi}$ and δm allow the fit to differentiate between the various signal and background components. Figure 1 shows projections from the WS sample overlaid on the fit result.

We fit the RS decay-time distribution using a model that combines the RS signal decay-time distribution [$T_{RS}(t)$ in Eq. (1)] and the expected decay-time distributions of each background component, convolving each with a common decay-time resolution model that uses the decay-time error for each candidate and a scaling factor determined in the fit. For the WS signal component, we use the same resolution model but with a lifetime distribution including the mixing parameters as given by $T_{WS}(t)$ in Eq. (1) or its CP-violating counterparts. For the unassociated pion and double misidentification backgrounds, we also use the $T_{RS}(t)$ lifetime distribution because they are true D^0 decays. The combinatorial background is assigned a zero-lifetime distribution and a signal-type resolution model based on studies of mass sidebands and Monte Carlo (MC) samples.

Table I summarizes the fit results for the four cases. Figure 2 shows the decay-time distribution of the WS sample for the signal and a background region. We select a signal (background) region with 73% signal (50% combinatorial background) candidates based on the reconstructed values of $m_{K\pi}$ and δm. The selected signal region contains 64% of all signal events according to the fit. We observe about 120 000 RS (430 WS) signal decays.

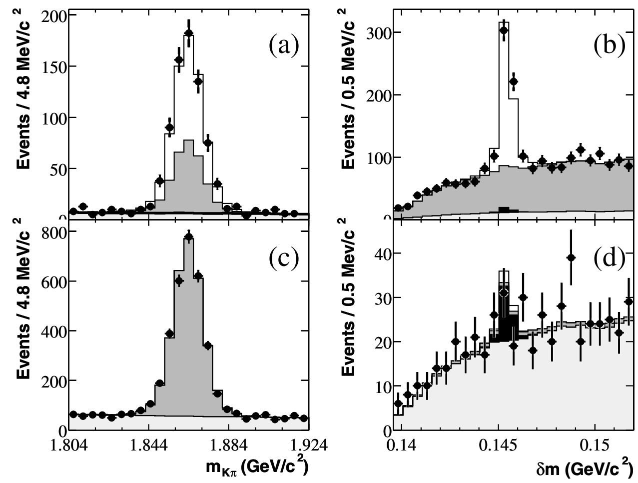

FIG. 1. The distribution of the WS data for (a) $m_{K\pi}$ with $144.5 < \delta m < 146.5$ MeV/c^2, (b) δm with $|m_{K\pi} - m_{D^0}| < 20$ MeV/c^2, (c) $m_{K\pi}$ with $150 < \delta m < 165$ MeV/c^2, and (d) δm with $25 < |m_{K\pi} - m_{D^0}| < 60$ MeV/c^2. Data are shown as points with the contributions from the fit overlaid: signal (open), unassociated pion background (dark shaded), double misidentification background (black), and combinatorial background (light shaded).

Our fit permits x'^2 to take unphysical negative values. We use a frequentist approach utilizing toy MC experiments to interpret nonphysical results and to construct 95% confidence-level (C.L.) contours in (x'^2, y'). In each toy MC experiment, we generate a WS dataset (the part sensitive to mixing) for a given (x'^2, y') with the same number of D^0 and $\overline{D}^0$ events as observed in the data, but with a decay-time distribution appropriate for the chosen point. Fit parameters for the $m_{K\pi}$ and δm distributions and other parameters not sensitive to mixing are fixed at their fitted values from data. The σ_t distribution and background fractions from the data fit are used as well. We fit each toy MC dataset, obtaining values for the mixing parameters and the corresponding log-likelihood surface. We construct contours such that for any point $\vec{\alpha}_c = (x_c'^2, y_c')$ on the contour 95% of the experiments

TABLE I. Fit parameter results determined by the full fit, with no constraint on x'^2 in the mixing-allowed cases. For the no-mixing cases, $R_{WS}^{(\pm)} = R_D^{(\pm)}$. The + (−) signifies D^0 ($\overline{D}^0$).

		Fit result ($/10^{-3}$)		
Fit case	Parameter	D^0	$\overline{D}^0$	$D^0 + \overline{D}^0$
Mixing allowed	$R_{WS}^{(\pm)}$	3.9	3.2	3.6
	$x'^{(\pm)2}$	−0.79	−0.17	−0.32
	$y'^{(\pm)}$	17	12	13
No mixing	$R_{WS}^{(\pm)}$	3.9	3.2	3.6

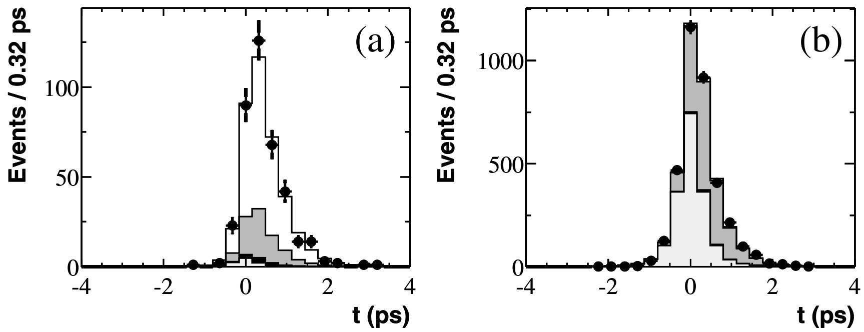

FIG. 2. The proper time distribution for the WS candidates in (a) the signal region (73% signal purity) and (b) a background region (50% combinatorial background). See Fig. 1 for component definitions.

generated at that point will have a log-likelihood difference $\Delta \ln\mathcal{L}(\vec{\alpha}_c) = \ln\mathcal{L}_{\max} - \ln\mathcal{L}(\vec{\alpha}_c)$ less than the corresponding value $\Delta \ln\mathcal{L}_{\rm data}(\vec{\alpha}_c)$ evaluated for the data. $\mathcal{L}_{\max}$ is the maximum-likelihood obtained from any fit [12].

Where we assume CP conservation, we apply this method to the combined D^0 and $\overline{D}^0$ WS samples. The resulting contour is shown by the dotted line in Fig. 3. The 95% C.L. for $R_{\rm D}$ and for $R_{\rm M}$ are obtained by finding their extreme values on the 95% C.L. contour.

To consider CP violation, we divide the WS sample into candidates produced as a D^0 or as a $\overline{D}^0$ and calculate separate contours for (x'^{+2}, y'^{+}) and (x'^{-2}, y'^{-}), each corresponding to a C.L. of $1 - \sqrt{0.05} = 77.6\%$. Each point on the D^0 contour is combined with each point on the $\overline{D}^0$ contour using Eqs. (3)–(5) to produce two potential solutions of $\{x'^2, y'\}$ for each relative sign of x'^{+} and x'^{-}. The outer envelope of these points is presented as the 95% C.L. contour in the (x'^2, y') plane (see Fig. 3). The peculiar shape of the contour arises from the two solutions for each point. This contour is more stringent than the CP-conserving case in some cases, which is acceptable since the definition of coverage is slightly different. No value for x'^2 exists if either x'^{+2} or $x'^{-2} < 0$.

We summarize results including uncertainties in Table II. We obtain limits on the mixing parameters by projecting the contours onto the corresponding coordinate axes. Since the no-mixing solution is well within the 95% C.L. contour, we cannot place limits on $A_{\rm M}$ and φ.

To estimate systematic uncertainties, we evaluate contributions from uncertainties in the PDF parametrization, detector effects, and event selection criteria. The small systematic effects of fixing the $m_{K\pi}$ and δm parameters and the number of events in each category in the final fit is evaluated by varying these parameters within statistical uncertainties while accounting for correlations.

For detector effects such as alignment errors or charge asymmetries, we measure their effect on the RS sample. Assuming that RS decay is exponential and has no direct CP violation, this method is very sensitive. The systematic error due to the size of the MC sample is insignificant since all distributions are obtained from the data.

Each systematic check yields a small shift in the mixing parameters. We use MC experiments to determine the significance of each shift using the same method employed for the 95% C.L. statistical contour. We scale the statistical contour with respect to the central fitted point by $\sqrt{1 + \sum m_i^2}$, where m_i is the relative significance of each check. For the general case, we carry out this procedure for the D^0 and $\overline{D}^0$ contours separately before combination. In all fits, the largest effect for x'^2 and y' is the D^{*+} momentum selection cut, with $m_i^2 = 0.24$; all others are at least 3 times smaller. For $R_{\rm D}$, the largest effect is the decay-time range. We show systematic error contours in Fig. 3 as a dashed line in the CP-conserving case and as a dash-dotted line in the general case.

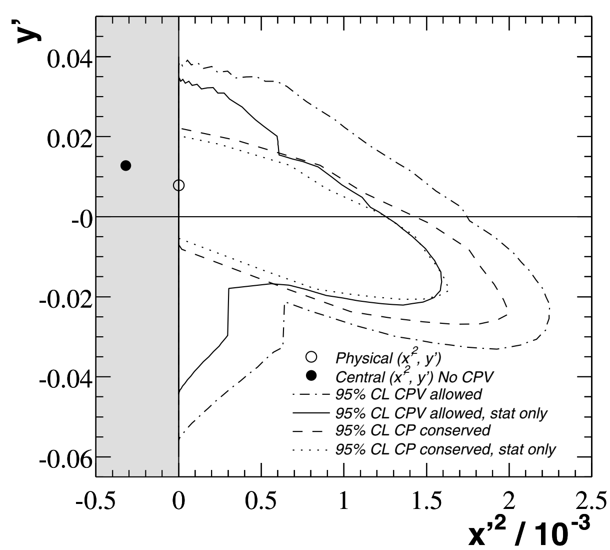

FIG. 3. 95% C.L. limits in x'^2, y' with and without CP violation (CPV) allowed. The solid point represents the most likely fit point assuming CP conservation and the open circle the same but allowing CP violation and forcing $x'^2 > 0$. The dotted (dashed) line is the statistical (statistical and systematic) contour for the case where no CP violation is allowed. The solid and dash-dotted lines are for the corresponding case where CP violation is allowed.

TABLE II. A summary of our results including systematic errors. A central value is reported for the full fit with x'^2 fixed at zero. The 95% C.L. are for the case where x'^2 was not constrained during the fit.

Fit case	Parameter	Central value ($x'^2 = 0$) ($/10^{-3}$)	95% C.L. interval ($/10^{-3}$)
CP violation allowed	R_D	3.1	$2.3 < R_D < 5.2$
	A_D	1.2	$-2.8 < A_D < 4.9$
	x'^2	0	$x'^2 < 2.2$
	y'	8.0	$-56 < y' < 39$
	R_M		$R_M < 1.6$
No *CP* violation	R_D	3.1	$2.4 < R_D < 4.9$
	x'^2	0	$x'^2 < 2.0$
	y'	8.0	$-27 < y' < 22$
	R_M		$R_M < 1.3$
No mixing	$R_D = [0.357 \pm 0.022(\mathrm{stat}) \pm 0.027(\mathrm{syst})]\%$		
	$A_D = 0.095 \pm 0.061(\mathrm{stat}) \pm 0.083(\mathrm{syst})$		
No *CP* violation or mixing	$R_D = [0.359 \pm 0.020(\mathrm{stat}) \pm 0.027(\mathrm{syst})]\%$		

We have set improved limits on D^0-$\overline{D}^0$ mixing and *CP* violation in WS decays of D^0 mesons. These are compatible with previous results [4–6] and with no mixing and no *CP* violation, agreeing with standard model predictions.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (U.S.A.), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from the A. P. Sloan Foundation, Research Corporation, and Alexander von Humboldt Foundation.

*Also with Università di Perugia, Perugia, Italy.
†Also with Università della Basilicata, Potenza, Italy.
‡Also with IFIC, Instituto de Física Corpuscular, CSIC-Universidad de Valencia, Valencia, Spain.
§Deceased.

[1] A. F. Falk *et al.*, Phys. Rev. D **65**, 054034 (2002).
[2] H. N. Nelson, hep-ex/9908021.
[3] G. Blaylock *et al.*, Phys. Lett. B **355**, 555 (1995).
[4] CLEO Collaboration, R. Godang *et al.*, Phys. Rev. Lett. **84**, 5038 (2000).
[5] E791 Collaboration, E. M. Aitala *et al.*, Phys. Rev. D **57**, 13 (1998).
[6] Tagged Photon Spectrometer (E691) Collaboration, J. C. Anjos *et al.*, Phys. Rev. Lett. **60**, 1239 (1988).
[7] E791 Collaboration, E. M. Aitala *et al.*, Phys. Rev. Lett. **83**, 32 (1999).
[8] FOCUS Collaboration, J. M. Link *et al.*, Phys. Lett. B **485**, 62 (2000).
[9] CLEO Collaboration, S. E. Csorna *et al.*, Phys. Rev. D **65**, 092001 (2002).
[10] Belle Collaboration, K. Abe *et al.*, Phys. Rev. Lett. **88**, 162001 (2002).
[11] BABAR Collaboration, B. Aubert *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 1 (2002).
[12] A. Stuart and J. K. Ord, *Kendall's Advanced Theory of Statistics* (Edward Arnold, London, 1991), Vol. 2, Chap. 23, 5th ed.