arXiv:0908.0761
hep-ex
August 7, 2009

BABAR-PUB-09/023
SLAC-PUB-13737

# Measurement of $D^0$-$\overline{D}^0$ Mixing using the Ratio of Lifetimes for the Decays $D^0 \to K^-\pi^+$ and $K^+K^-$

B. Aubert,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] E. Prencipe,[1] X. Prudent,[1] V. Tisserand,[1] J. Garra Tico,[2] E. Grauges,[2] M. Martinelli[ab],[3] A. Palano[ab],[3] M. Pappagallo[ab],[3] G. Eigen,[4] B. Stugu,[4] L. Sun,[4] M. Battaglia,[5] D. N. Brown,[5] B. Hooberman,[5] L. T. Kerth,[5] Yu. G. Kolomensky,[5] G. Lynch,[5] I. L. Osipenkov,[5] K. Tackmann,[5] T. Tanabe,[5] C. M. Hawkes,[6] N. Soni,[6] A. T. Watson,[6] H. Koch,[7] T. Schroeder,[7] D. J. Asgeirsson,[8] C. Hearty,[8] T. S. Mattison,[8] J. A. McKenna,[8] M. Barrett,[9] A. Khan,[9] A. Randle-Conde,[9] V. E. Blinov,[10] A. D. Bukin,[10,*] A. R. Buzykaev,[10] V. P. Druzhinin,[10] V. B. Golubev,[10] A. P. Onuchin,[10] S. I. Serednyakov,[10] Yu. I. Skovpen,[10] E. P. Solodov,[10] K. Yu. Todyshev,[10] M. Bondioli,[11] S. Curry,[11] I. Eschrich,[11] D. Kirkby,[11] A. J. Lankford,[11] P. Lund,[11] M. Mandelkern,[11] E. C. Martin,[11] D. P. Stoker,[11] H. Atmacan,[12] J. W. Gary,[12] F. Liu,[12] O. Long,[12] G. M. Vitug,[12] Z. Yasin,[12] V. Sharma,[13] C. Campagnari,[14] T. M. Hong,[14] D. Kovalskyi,[14] M. A. Mazur,[14] J. D. Richman,[14] T. W. Beck,[15] A. M. Eisner,[15] C. A. Heusch,[15] J. Kroseberg,[15] W. S. Lockman,[15] A. J. Martinez,[15] T. Schalk,[15] B. A. Schumm,[15] A. Seiden,[15] L. Wang,[15] L. O. Winstrom,[15] C. H. Cheng,[16] D. A. Doll,[16] B. Echenard,[16] F. Fang,[16] D. G. Hitlin,[16] I. Narsky,[16] P. Ongmongkolkul,[16] T. Piatenko,[16] F. C. Porter,[16] R. Andreassen,[17] G. Mancinelli,[17] B. T. Meadows,[17] K. Mishra,[17] M. D. Sokoloff,[17] P. C. Bloom,[18] W. T. Ford,[18] A. Gaz,[18] J. F. Hirschauer,[18] M. Nagel,[18] U. Nauenberg,[18] J. G. Smith,[18] S. R. Wagner,[18] R. Ayad,[19,†] W. H. Toki,[19] R. J. Wilson,[19] E. Feltresi,[20] A. Hauke,[20] H. Jasper,[20] T. M. Karbach,[20] J. Merkel,[20] A. Petzold,[20] B. Spaan,[20] K. Wacker,[20] M. J. Kobel,[21] R. Nogowski,[21] K. R. Schubert,[21] R. Schwierz,[21] D. Bernard,[22] E. Latour,[22] M. Verderi,[22] P. J. Clark,[23] S. Playfer,[23] J. E. Watson,[23] M. Andreotti[ab],[24] D. Bettoni[a],[24] C. Bozzi[a],[24] R. Calabrese[ab],[24] A. Cecchi[ab],[24] G. Cibinetto[ab],[24] E. Fioravanti[ab],[24] P. Franchini[ab],[24] E. Luppi[ab],[24] M. Munerato[ab],[24] M. Negrini[ab],[24] A. Petrella[ab],[24] L. Piemontese[a],[24] V. Santoro[ab],[24] R. Baldini-Ferroli,[25] A. Calcaterra,[25] R. de Sangro,[25] G. Finocchiaro,[25] S. Pacetti,[25] P. Patteri,[25] I. M. Peruzzi,[25,‡] M. Piccolo,[25] M. Rama,[25] A. Zallo,[25] R. Contri[ab],[26] E. Guido,[26] M. Lo Vetere[ab],[26] M. R. Monge[ab],[26] S. Passaggio[a],[26] C. Patrignani[ab],[26] E. Robutti[a],[26] S. Tosi[ab],[26] K. S. Chaisanguanthum,[27] M. Morii,[27] A. Adametz,[28] J. Marks,[28] S. Schenk,[28] U. Uwer,[28] F. U. Bernlochner,[29] V. Klose,[29] H. M. Lacker,[29] T. Lueck,[29] A. Volk,[29] D. J. Bard,[30] P. D. Dauncey,[30] M. Tibbetts,[30] P. K. Behera,[31] M. J. Charles,[31] U. Mallik,[31] J. Cochran,[32] H. B. Crawley,[32] L. Dong,[32] V. Eyges,[32] W. T. Meyer,[32] S. Prell,[32] E. I. Rosenberg,[32] A. E. Rubin,[32] Y. Y. Gao,[33] A. V. Gritsan,[33] Z. J. Guo,[33] N. Arnaud,[34] J. Béquilleux,[34] A. D'Orazio,[34] M. Davier,[34] D. Derkach,[34] J. Firmino da Costa,[34] G. Grosdidier,[34] F. Le Diberder,[34] V. Lepeltier,[34] A. M. Lutz,[34] B. Malaescu,[34] S. Pruvot,[34] P. Roudeau,[34] M. H. Schune,[34] J. Serrano,[34] V. Sordini,[34,§] A. Stocchi,[34] G. Wormser,[34] D. J. Lange,[35] D. M. Wright,[35] I. Bingham,[36] J. P. Burke,[36] C. A. Chavez,[36] J. R. Fry,[36] E. Gabathuler,[36] R. Gamet,[36] D. E. Hutchcroft,[36] D. J. Payne,[36] C. Touramanis,[36] A. J. Bevan,[37] C. K. Clarke,[37] F. Di Lodovico,[37] R. Sacco,[37] M. Sigamani,[37] G. Cowan,[38] S. Paramesvaran,[38] A. C. Wren,[38] D. N. Brown,[39] C. L. Davis,[39] A. G. Denig,[40] M. Fritsch,[40] W. Gradl,[40] A. Hafner,[40] K. E. Alwyn,[41] D. Bailey,[41] R. J. Barlow,[41] G. Jackson,[41] G. D. Lafferty,[41] T. J. West,[41] J. I. Yi,[41] J. Anderson,[42] C. Chen,[42] A. Jawahery,[42] D. A. Roberts,[42] G. Simi,[42] J. M. Tuggle,[42] C. Dallapiccola,[43] E. Salvati,[43] R. Cowan,[44] D. Dujmic,[44] P. H. Fisher,[44] S. W. Henderson,[44] G. Sciolla,[44] M. Spitznagel,[44] R. K. Yamamoto,[44] M. Zhao,[44] P. M. Patel,[45] S. H. Robertson,[45] M. Schram,[45] P. Biassoni[ab],[46] A. Lazzaro[ab],[46] V. Lombardo[a],[46] F. Palombo[ab],[46] S. Stracka[ab],[46] L. Cremaldi,[47] R. Godang,[47,¶] R. Kroeger,[47] P. Sonnek,[47] D. J. Summers,[47] H. W. Zhao,[47] M. Simard,[48] P. Taras,[48] H. Nicholson,[49] G. De Nardo[ab],[50] L. Lista[a],[50] D. Monorchio[ab],[50] G. Onorato[ab],[50] C. Sciacca[ab],[50] G. Raven,[51] H. L. Snoek,[51] C. P. Jessop,[52] K. J. Knoepfel,[52] J. M. LoSecco,[52] W. F. Wang,[52] L. A. Corwin,[53] K. Honscheid,[53] H. Kagan,[53] R. Kass,[53] J. P. Morris,[53] A. M. Rahimi,[53] S. J. Sekula,[53] Q. K. Wong,[53] N. L. Blount,[54] J. Brau,[54] R. Frey,[54] O. Igonkina,[54] J. A. Kolb,[54] M. Lu,[54] R. Rahmat,[54] N. B. Sinev,[54] D. Strom,[54] J. Strube,[54] E. Torrence,[54] G. Castelli[ab],[55] N. Gagliardi[ab],[55] M. Margoni[ab],[55] M. Morandin[a],[55] M. Posocco[a],[55] M. Rotondo[a],[55] F. Simonetto[ab],[55] R. Stroili[ab],[55] C. Voci[ab],[55] P. del Amo Sanchez,[56] E. Ben-Haim,[56] G. R. Bonneaud,[56] H. Briand,[56] J. Chauveau,[56] O. Hamon,[56] Ph. Leruste,[56] G. Marchiori,[56] J. Ocariz,[56] A. Perez,[56] J. Prendki,[56] S. Sitt,[56] L. Gladney,[57] M. Biasini[ab],[58] E. Manoni[ab],[58] C. Angelini[ab],[59] G. Batignani[ab],[59] S. Bettarini[ab],[59] G. Calderini[ab],[59,**] M. Carpinelli[ab],[59,††] A. Cervelli[ab],[59] F. Forti[ab],[59] M. A. Giorgi[ab],[59] A. Lusiani[ac],[59] M. Morganti[ab],[59] N. Neri[ab],[59] E. Paoloni[ab],[59] G. Rizzo[ab],[59] J. J. Walsh[a],[59] D. Lopes Pegna,[60] C. Lu,[60] J. Olsen,[60] A. J. S. Smith,[60] A. V. Telnov,[60] F. Anulli[a],[61] E. Baracchini[ab],[61] G. Cavoto[a],[61] R. Faccini[ab],[61] F. Ferrarotto[a],[61] F. Ferroni[ab],[61] M. Gaspero[ab],[61] P. D. Jackson[a],[61] L. Li Gioi[a],[61] M. A. Mazzoni[a],[61] S. Morganti[a],[61] G. Piredda[a],[61] F. Renga[ab],[61] C. Voena[a],[61] M. Ebert,[62] T. Hartmann,[62] H. Schröder,[62] R. Waldi,[62] T. Adye,[63] B. Franek,[63] E. O. Olaiya,[63] F. F. Wilson,[63] S. Emery,[64] L. Esteve,[64] G. Hamel de Monchenault,[64] W. Kozanecki,[64] G. Vasseur,[64] Ch. Yèche,[64] M. Zito,[64] M. T. Allen,[65]

*Submitted to the Physical Review D*

Work supported in part by US Department of Energy contract DE-AC02-76SF00515

D. Aston,[65] R. Bartoldus,[65] J. F. Benitez,[65] R. Cenci,[65] J. P. Coleman,[65] M. R. Convery,[65] J. C. Dingfelder,[65] J. Dorfan,[65] G. P. Dubois-Felsmann,[65] W. Dunwoodie,[65] R. C. Field,[65] M. Franco Sevilla,[65] B. G. Fulsom,[65] A. M. Gabareen,[65] M. T. Graham,[65] P. Grenier,[65] C. Hast,[65] W. R. Innes,[65] J. Kaminski,[65] M. H. Kelsey,[65] H. Kim,[65] P. Kim,[65] M. L. Kocian,[65] D. W. G. S. Leith,[65] S. Li,[65] B. Lindquist,[65] S. Luitz,[65] V. Luth,[65] H. L. Lynch,[65] D. B. MacFarlane,[65] H. Marsiske,[65] R. Messner,[65,*] D. R. Muller,[65] H. Neal,[65] S. Nelson,[65] C. P. O'Grady,[65] I. Ofte,[65] M. Perl,[65] B. N. Ratcliff,[65] A. Roodman,[65] A. A. Salnikov,[65] R. H. Schindler,[65] J. Schwiening,[65] A. Snyder,[65] D. Su,[65] M. K. Sullivan,[65] K. Suzuki,[65] S. K. Swain,[65] J. M. Thompson,[65] J. Va'vra,[65] A. P. Wagner,[65] M. Weaver,[65] C. A. West,[65] W. J. Wisniewski,[65] M. Wittgen,[65] D. H. Wright,[65] H. W. Wulsin,[65] A. K. Yarritu,[65] C. C. Young,[65] V. Ziegler,[65] X. R. Chen,[66] H. Liu,[66] W. Park,[66] M. V. Purohit,[66] R. M. White,[66] J. R. Wilson,[66] M. Bellis,[67] P. R. Burchat,[67] A. J. Edwards,[67] T. S. Miyashita,[67] S. Ahmed,[68] M. S. Alam,[68] J. A. Ernst,[68] B. Pan,[68] M. A. Saeed,[68] S. B. Zain,[68] A. Soffer,[69] S. M. Spanier,[70] B. J. Wogsland,[70] R. Eckmann,[71] J. L. Ritchie,[71] A. M. Ruland,[71] C. J. Schilling,[71] R. F. Schwitters,[71] B. C. Wray,[71] B. W. Drummond,[72] J. M. Izen,[72] X. C. Lou,[72] F. Bianchi[ab],[73] D. Gamba[ab],[73] M. Pelliccioni[ab],[73] M. Bomben[ab],[74] L. Bosisio[ab],[74] C. Cartaro[ab],[74] G. Della Ricca[ab],[74] L. Lanceri[ab],[74] L. Vitale[ab],[74] V. Azzolini,[75] N. Lopez-March,[75] F. Martinez-Vidal,[75] D. A. Milanes,[75] A. Oyanguren,[75] J. Albert,[76] Sw. Banerjee,[76] B. Bhuyan,[76] H. H. F. Choi,[76] K. Hamano,[76] G. J. King,[76] R. Kowalewski,[76] M. J. Lewczuk,[76] I. M. Nugent,[76] J. M. Roney,[76] R. J. Sobie,[76] T. J. Gershon,[77] P. F. Harrison,[77] J. Ilic,[77] T. E. Latham,[77] G. B. Mohanty,[77] E. M. T. Puccio,[77] H. R. Band,[78] X. Chen,[78] S. Dasu,[78] K. T. Flood,[78] Y. Pan,[78] R. Prepost,[78] C. O. Vuosalo,[78] and S. L. Wu[78]

(The BABAR Collaboration)

[1]*Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74941 Annecy-Le-Vieux, France*
[2]*Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain*
[3]*INFN Sezione di Bari[a]; Dipartimento di Fisica, Università di Bari[b], 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 British Columbia, Vancouver, British Columbia, Canada V6T 1Z1*
[9]*Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom*
[10]*Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia*
[11]*University of California at Irvine, Irvine, California 92697, USA*
[12]*University of California at Riverside, Riverside, California 92521, USA*
[13]*University of California at San Diego, La Jolla, California 92093, USA*
[14]*University of California at Santa Barbara, Santa Barbara, California 93106, USA*
[15]*University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA*
[16]*California Institute of Technology, Pasadena, California 91125, USA*
[17]*University of Cincinnati, Cincinnati, Ohio 45221, USA*
[18]*University of Colorado, Boulder, Colorado 80309, USA*
[19]*Colorado State University, Fort Collins, Colorado 80523, USA*
[20]*Technische Universität Dortmund, Fakultät Physik, D-44221 Dortmund, Germany*
[21]*Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany*
[22]*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France*
[23]*University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*
[24]*INFN Sezione di Ferrara[a]; Dipartimento di Fisica, Università di Ferrara[b], I-44100 Ferrara, Italy*
[25]*INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy*
[26]*INFN Sezione di Genova[a]; Dipartimento di Fisica, Università di Genova[b], I-16146 Genova, Italy*
[27]*Harvard University, Cambridge, Massachusetts 02138, USA*
[28]*Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany*
[29]*Humboldt-Universität zu Berlin, Institut für Physik, Newtonstr. 15, D-12489 Berlin, Germany*
[30]*Imperial College London, London, SW7 2AZ, United Kingdom*
[31]*University of Iowa, Iowa City, Iowa 52242, USA*
[32]*Iowa State University, Ames, Iowa 50011-3160, USA*
[33]*Johns Hopkins University, Baltimore, Maryland 21218, USA*
[34]*Laboratoire de l'Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d'Orsay, B. P. 34, F-91898 Orsay Cedex, France*
[35]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[36]*University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[37]*Queen Mary, University of London, London, E1 4NS, United Kingdom*
[38]*University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom*
[39]*University of Louisville, Louisville, Kentucky 40292, USA*
[40]*Johannes Gutenberg-Universität Mainz, Institut für Kernphysik, D-55099 Mainz, Germany*
[41]*University of Manchester, Manchester M13 9PL, United Kingdom*

[42]*University of Maryland, College Park, Maryland 20742, USA*
[43]*University of Massachusetts, Amherst, Massachusetts 01003, USA*
[44]*Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA*
[45]*McGill University, Montréal, Québec, Canada H3A 2T8*
[46]*INFN Sezione di Milano*[a]*; Dipartimento di Fisica, Università di Milano*[b]*, I-20133 Milano, Italy*
[47]*University of Mississippi, University, Mississippi 38677, USA*
[48]*Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7*
[49]*Mount Holyoke College, South Hadley, Massachusetts 01075, USA*
[50]*INFN Sezione di Napoli*[a]*; Dipartimento di Scienze Fisiche, Università di Napoli Federico II*[b]*, I-80126 Napoli, Italy*
[51]*NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands*
[52]*University of Notre Dame, Notre Dame, Indiana 46556, USA*
[53]*Ohio State University, Columbus, Ohio 43210, USA*
[54]*University of Oregon, Eugene, Oregon 97403, USA*
[55]*INFN Sezione di Padova*[a]*; Dipartimento di Fisica, Università di Padova*[b]*, I-35131 Padova, Italy*
[56]*Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France*
[57]*University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
[58]*INFN Sezione di Perugia*[a]*; Dipartimento di Fisica, Università di Perugia*[b]*, I-06100 Perugia, Italy*
[59]*INFN Sezione di Pisa*[a]*; Dipartimento di Fisica, Università di Pisa*[b]*; Scuola Normale Superiore di Pisa*[c]*, I-56127 Pisa, Italy*
[60]*Princeton University, Princeton, New Jersey 08544, USA*
[61]*INFN Sezione di Roma*[a]*; Dipartimento di Fisica, Università di Roma La Sapienza*[b]*, I-00185 Roma, Italy*
[62]*Universität Rostock, D-18051 Rostock, Germany*
[63]*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom*
[64]*CEA, Irfu, SPP, Centre de Saclay, F-91191 Gif-sur-Yvette, France*
[65]*SLAC National Accelerator Laboratory, Stanford, California 94309 USA*
[66]*University of South Carolina, Columbia, South Carolina 29208, USA*
[67]*Stanford University, Stanford, California 94305-4060, USA*
[68]*State University of New York, Albany, New York 12222, USA*
[69]*Tel Aviv University, School of Physics and Astronomy, Tel Aviv, 69978, Israel*
[70]*University of Tennessee, Knoxville, Tennessee 37996, USA*
[71]*University of Texas at Austin, Austin, Texas 78712, USA*
[72]*University of Texas at Dallas, Richardson, Texas 75083, USA*
[73]*INFN Sezione di Torino*[a]*; Dipartimento di Fisica Sperimentale, Università di Torino*[b]*, I-10125 Torino, Italy*
[74]*INFN Sezione di Trieste*[a]*; Dipartimento di Fisica, Università di Trieste*[b]*, I-34127 Trieste, Italy*
[75]*IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain*
[76]*University of Victoria, Victoria, British Columbia, Canada V8W 3P6*
[77]*Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom*
[78]*University of Wisconsin, Madison, Wisconsin 53706, USA*

(Dated: August 7, 2009)

We measure the rate of $D^0$-$\overline{D}^0$ mixing with the observable $y_{CP} = (\tau_{K\pi}/\tau_{KK}) - 1$, where $\tau_{KK}$ and $\tau_{K\pi}$ are respectively the mean lifetimes of $CP$-even $D^0 \to K^+K^-$ and $CP$-mixed $D^0 \to K^-\pi^+$ decays, using a data sample of $384\,\mathrm{fb}^{-1}$ collected by the BABAR detector at the SLAC PEP-II asymmetric-energy $B$ Factory. From a sample of $D^0$ and $\overline{D}^0$ decays where the inital flavor of the decaying meson is not determined, we obtain $y_{CP} = [1.12 \pm 0.26(\mathrm{stat}) \pm 0.22(\mathrm{syst})]\%$, which excludes the no-mixing hypothesis at $3.3\sigma$, including both statistical and systematic uncertainties. This result is in good agreement with a previous BABAR measurement of $y_{CP}$ obtained from a sample of $D^{*+} \to D^0\pi^+$ events, where the $D^0$ decays to $K^-\pi^+$, $K^+K^-$, and $\pi^+\pi^-$, which is disjoint with the untagged $D^0$ events used here. Combining the two results taking into account statistical and systematic uncertainties, where the systematic uncertainties are assumed to be $100\%$ correlated, we find $y_{CP} = [1.16 \pm 0.22(\mathrm{stat}) \pm 0.18(\mathrm{syst})]\%$, which excludes the no-mixing hypothesis at $4.1\sigma$.

PACS numbers: 13.25.Ft, 12.15.Ff, 11.30.Er

[*]Deceased
[†]Now at Temple University, Philadelphia, Pennsylvania 19122, USA
[‡]Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy
[§]Also with Università di Roma La Sapienza, I-00185 Roma, Italy
[¶]Now at University of South Alabama, Mobile, Alabama 36688, USA
[**]Also with Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France
[††]Also with Università di Sassari, Sassari, Italy

Several recent results [1–4] show evidence for mixing in the $D^0$-$\overline{D}^0$ system consistent with predictions of possible Standard Model contributions [5–9]. These results also constrain many new physics models [10–14], and increasingly precise $D^0$-$\overline{D}^0$ mixing measurements will provide even stronger constraints. One manifestation of $D^0$-$\overline{D}^0$ mixing is differing $D^0$ decay time distributions for decays to different $CP$ eigenstates [15]. We present here a measurement of this lifetime difference using a sample of $D^0$ and $\overline{D}^0$ decays in which the initial flavor of the decaying meson is unknown.

Assuming $CP$ conservation in mixing, the two neutral $D$ mass eigenstates $|D_1\rangle$ and $|D_2\rangle$ can be represented as

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\overline{D}^0\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\overline{D}^0\rangle , \end{aligned} \tag{1}$$

where $|p|^2 + |q|^2 = 1$. The rate of $D^0$-$\overline{D}^0$ mixing can be characterized by the parameters $x \equiv \Delta m/\Gamma$ and $y \equiv \Delta\Gamma/2\Gamma$, where $\Delta m = m_1 - m_2$ and $\Delta\Gamma = \Gamma_1 - \Gamma_2$ are respectively the differences between the mass and width eigenvalues of the states in Eq. (1), and $\Gamma = (\Gamma_1 + \Gamma_2)/2$ is the average width. If either $x$ or $y$ is non-zero, mixing will occur, altering the decay time distribution of $D^0$ and $\overline{D}^0$ mesons decaying into final states of specific $CP$ [16].

In the limit of small mixing, and no $CP$ violation in mixing or in the interference between mixing and decay (assumptions which are consistent with current experimental results), the mean lifetimes of decays to a $CP$ eigenstate of a sample of $D^0$ ($\tau_{hh}^{D^0}$) and $\overline{D}^0$ ($\tau_{hh}^{\overline{D}^0}$), along with the mean lifetime of decays to a state of indefinite $CP$ ($\tau_{K\pi}$), can be combined into the quantity

$$y_{CP} = \frac{\langle\tau_{K\pi}\rangle}{\langle\tau_{hh}\rangle} - 1, \tag{2}$$

where $\langle\tau_{hh}\rangle = (\tau_{hh}^{D^0} + \tau_{hh}^{\overline{D}^0})/2$. Noting that the untagged $K^-\pi^+$ [17] final state is a mixture of Cabbibo-favored and doubly Cabbibo-suppressed $D^0$ and $\overline{D}^0$ decays with a purely exponential lifetime distribution, along with a very small admixture of mixed $D^0$ decays, an analogous expression also holds for $\langle\tau_{K\pi}\rangle$. Given the current experimental evidence indicating a small mixing rate, the lifetime distribution for all $hh$ and $K\pi$ final states is exponential to a good approximation. If $y_{CP}$ is zero there is no $D^0$-$\overline{D}^0$ mixing attributable to a width difference, although mixing caused by a mass difference may be present. In the limit of no direct $CP$ violation, $y_{CP} = y$.

We measure the $D^0$ mean lifetime in the $D^0$ decay modes $K^-\pi^+$ and $K^+K^-$, where the initial flavor of the decaying $D^0$ is not identified (the *untagged* sample). This sample excludes $D^0$ mesons which can be reconstructed as part of $D^{*+} \to D^0\pi^+$ decays, as these decays (the *tagged* sample) are the subject of an earlier *BABAR* analysis [18] whose results are combined with those of the current analysis. To avoid potential bias, we finalized our data selection criteria, fitting methodology, sources of possible systematic uncertainties to be examined, and method of calculating statistical limits for the current untagged analysis alone and in combination with the tagged analysis, prior to examining the mixing results from the untagged data. In general, systematic uncertainties related to the reconstruction of signal events cancel in the lifetime ratio. However, uncertainties related to the somewhat differing backgrounds present in the $K^-\pi^+$ and $K^+K^-$ final states lead to larger systematic uncertainties in the untagged analysis compared to those of the tagged analysis, which has much higher signal purity .

We use $384\,\mathrm{fb}^{-1}$ of $e^+e^-$ colliding-beam data recorded at, and slightly below, the $\Upsilon(4S)$ resonance (center-of-mass [CM] energy $\sqrt{s} \sim 10.6\,\mathrm{GeV}$) with the *BABAR* detector [19] at the SLAC National Accelerator Laboratory PEP-II asymmetric-energy $B$ Factory. Candidate $D^0$ signal decays are reconstructed in the final states $K^-\pi^+$ and $K^+K^-$. The selection of events and reconstruction of $D^0$ signal candidates closely follows that of our previous tagged analysis [18]. We require $K^+$ and $\pi^+$ candidates to satisfy particle identification criteria based on $\mathrm{d}E/\mathrm{d}x$ ionization energy loss and Cherenkov angle measurements. We fit oppositely charged pairs of these candidates with appropriate mass hypotheses to a common vertex to form a $D^0$ candidate. The decay time $t$ of each $D^0$ candidate with invariant mass within the range $1.80 - 1.93$ GeV/$c^2$, along with its estimated uncertainty $\sigma_t$, is determined from a combined fit to the $D^0$ production and decay vertices, with a constraint that the production point be consistent with the $e^+e^-$ interaction region as determined on an event-by-event basis. We retain only candidates with a $\chi^2$-based probability for the fit $P(\chi^2) > 0.1\%$, and with $-2 < t < 4\,\mathrm{ps}$ and $\sigma_t < 0.5\,\mathrm{ps}$.

We further require the helicity angle $\theta_H$, defined as the angle between the positively charged track in the $D^0$ rest frame and the $D^0$ direction in the laboratory frame, to satisfy $|\cos\theta_H| < 0.7$, which aids in the rejection of purely combinatorial background events. Contributions from true $D^0$ mesons produced in $B$ meson decay are reduced to a negligible amount by rejecting $D^0$ candidates with momentum in the $e^+e^-$ CM frame less than $2.5\,\mathrm{GeV}/c$. For events with multiple candidates sharing one or more tracks, we retain only the candidate with the highest $P(\chi^2)$. The fraction of events with multiple signal candidates is $\sim 0.05\%$ for the $K^+K^-$ final state, and $\sim 0.3\%$ for $K^-\pi^+$.

The invariant mass distributions for the final $D^0 \to K^-\pi^+$ and $D^0 \to K^+K^-$ samples are shown in Fig. 1. For the lifetime fits, we use only events within $\pm 10\,\mathrm{MeV}/c^2$ of the $D^0$ signal peak $1.8545 < M_{D^0} < 1.8745\,\mathrm{GeV}/c^2$ (the *lifetime fit mass region*). The $K^-\pi^+$ and $K^+K^-$ signal yields within this region and their purity are given in Table I. Events within the mass sideband regions $1.81 < M_{D^0} < 1.83\,\mathrm{GeV}/c^2$ and $1.90 < M_{D^0} < 1.92\,\mathrm{GeV}/c^2$ are used to determine the combinatorial background decay time distribution within the lifetime fit mass region. In addition to purely combinatorial backgrounds, there are small background contributions from decays of non-signal charm parents where two of the decay products are selected as the daughters of a signal decay and subsequently pass the final event selection. These misreconstructed charm backgrounds are accounted for using simulated events. Their contribution is $\sim 0.7\%$ ($\sim 3.8\%$) of the total number of background events in the $K^-\pi^+$ ($K^+K^-$)

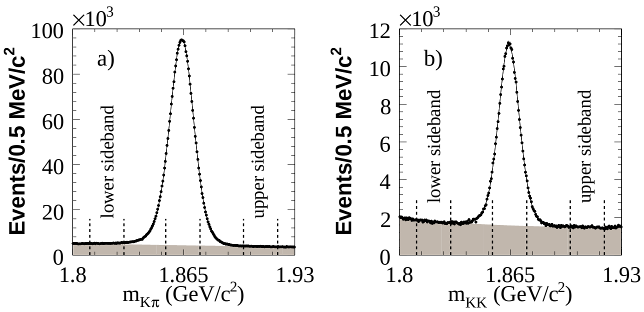


FIG. 1: (a) $D^0 \to K^-\pi^+$ and (b) $D^0 \to K^+K^-$ invariant mass distribution with the data (points), total fit (line) and background contribution (solid) overlaid. The innermost dashed lines on either side of the signal peaks delimit the lifetime fit mass region, with lower and upper mass sidebands shown on either side.

TABLE I: $D^0 \to K^-\pi^+$ and $D^0 \to K^+K^-$ signal yield and purity in the lifetime fit mass region.

| Sample | Signal Yield (x $10^3$) | Purity (%) |
|---|---|---|
| $K^-\pi^+$ | $2710.2 \pm 3.4$ | 94.2 |
| $K^+K^-$ | $263.6 \pm 1.0$ | 80.9 |

signal region.

The mean $D^0$ lifetime is determined from a fit essentially identical to the one performed in the previous tagged analysis [18], using the reconstructed decay time $t$ and the decay time uncertainty $\sigma_t$ for events within the lifetime fit mass region. Three categories of events are accounted for in the lifetime fit: signal decays, combinatorial background, and misreconstructed charm events.

The decay time distribution of signal events is described by an exponential convolved with a resolution function which is taken as the sum of three Gaussian functions with widths proportional to $\sigma_t$. The functional form of this probability density function (PDF) for signal events is

$$\begin{aligned}\mathcal{R}_X(t,\sigma_t;\tau_X) &= f_{t3}\mathcal{D}(t,\sigma_t;S_Xs_3,t_0,\tau_X)\\ &+ (1-f_{t3})\Big[f_{t2}\mathcal{D}(t,\sigma_t;S_Xs_2,t_0,\tau_X)\\ &+ (1-f_{t2})\mathcal{D}(t,\sigma_t;S_Xs_1,t_0,\tau_X)\Big],\end{aligned} \quad (3)$$

where $f_{ti}$ (with $i = 1\ldots3$) parameterizes the contribution of each individual resolution function, $s_i$ is a scaling factor associated with each Gaussian, $\tau_X$ (where $X = K\pi, KK$) is the lifetime parameter determined by the fit, $t_0$ is an offset to the mean of the resolution function, and where

$$\mathcal{D}(t,\sigma_t;s,t_0,\tau) = C_{\sigma_t}\int \exp(-t_{\rm true}/\tau)\exp\left(-\frac{(t-t_{\rm true}+t_0)^2}{2(s\cdot\sigma_t)^2}\right)\,dt_{\rm true} \quad (4)$$

with normalization coefficient $C_{\sigma_t}$. Up to an overall scale factor in the width, the resolution function is identical for both final states. We account for a small ($\sim 1\%$) difference in the $K^-\pi^+$ and $K^+K^-$ resolution function width using an additional fixed scale factor $S_X$. The value of $S_{KK}$ is determined from the data, with $S_{K\pi}$ fixed to 1.0. Possible biases resulting from this assumption are included as part of the study of systematic uncertainties. All other resolution function parameters are shared among the two modes, and all parameters are allowed to vary in a simultaneous extended unbinned maximum likelihood fit to both final states.

The decay time distribution of the combinatorial background is described by a sum of two Gaussians and a modified Gaussian with a power-law tail to account for a small number of events with large reconstructed lifetimes. The widths of these Gaussians are not scaled using event-by-event uncertainties. Events in the lower and upper $K^-\pi^+$ ($K^+K^-$) mass sidebands are fit separately, and a weighted average of the results of these fits is used to parameterize the PDF for $K^-\pi^+$ ($K^+K^-$) combinatorial events in the lifetime fit mass region.

Misreconstructed charm background events have one or more of the charm decay products either not reconstructed or reconstructed with the wrong particle hypothesis. In the $K^-\pi^+$ ($K^+K^-$) final state, $\sim 60\%$ ($\sim 95\%$) of these events are from true $D^0$ decays, with the balance coming from charged $D$ and charm baryon decays. The charm background is long-lived and is described using an exponential convolved with a resolution function consisting of two Gaussians with a shared mean and widths that depend on $\sigma_t$. Because the number of these events in the $K^-\pi^+$ ($K^+K^-$) sample is small relative to the total background, an effective lifetime distribution taken from simulated events and summed over all $K^-\pi^+$ ($K^+K^-$) charm backgrounds is used in the $K^-\pi^+$ ($K^+K^-$) lifetime fit.

Since the lifetime fit PDFs depend on the event-by-event decay time uncertainty, PDFs describing the distribution of decay time uncertainties for each of the event classes are required to avoid bias in the likelihood estimator used in the data fit [20]. We extract these distributions directly from the data. For combinatorial events, the distribution of decay time uncertainties is taken from a weighted average of the distributions extracted from the lower and upper mass sidebands. The decay time uncertainty distribution for signal events is obtained by subtracting the combinatorial background uncertainty distribution from the uncertainty distribution of all (*i.e.*, background plus signal) candidates present in the lifetime fit mass region. The signal distribution is also used for the relatively small number of misreconstructed charm background events.

The results of the lifetime fits are shown in Figs. 2 and 3, along with a plot of the point-by-point residuals for each fit normalized by the statistical uncertainty associated with a data point. We find the $D^0 \to K^-\pi^+$ mean lifetime $\tau_{K\pi} = 410.39 \pm 0.38(\rm stat)\,fs$ and the $D^0 \to K^+K^-$ mean lifetime $\tau_{KK} = 405.85 \pm 1.00(\rm stat)\,fs$, yielding $y_{CP} = [1.12 \pm 0.26(\rm stat)]\%$. The statistical significance of this mixing result without taking into account systematic uncertainties is $4.3\sigma$. This untagged result is in good agreement with our previous tagged analysis [18]. When the two results are combined, we find $y_{CP} = [1.16 \pm 0.22(\rm stat)]\%$, a result with a

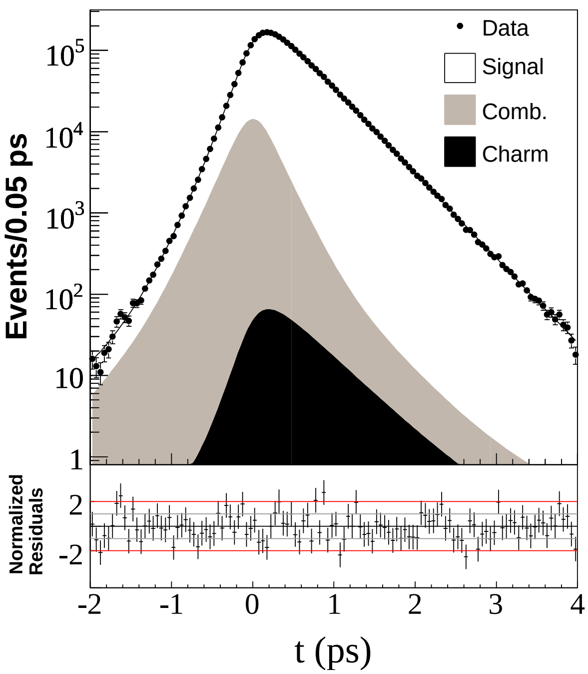


FIG. 2: $D^0 \to K^-\pi^+$ decay time distribution with the data (points), total lifetime fit (line), combinatorial background (gray) and charm background (black) contributions overlaid.

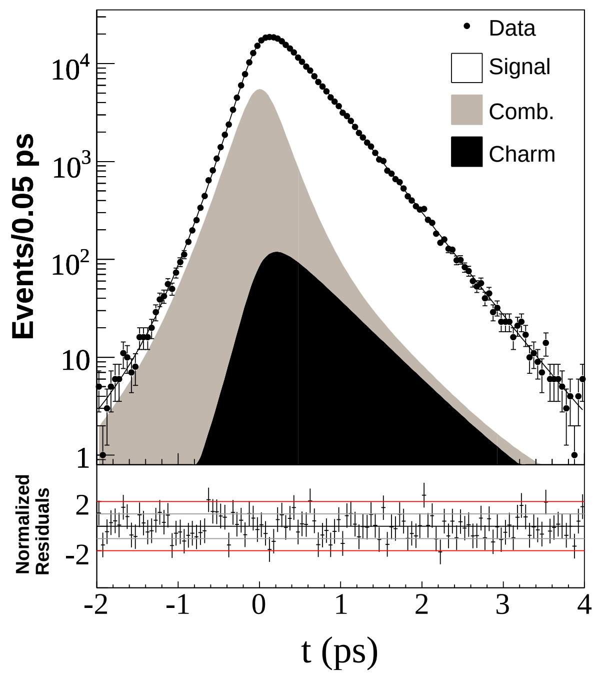


FIG. 3: $D^0 \to K^+K^-$ decay time distribution with the data (points), total lifetime fit (line), combinatorial background (gray) and charm background (black) contributions overlaid.

statistical significance of $5.3\sigma$, excluding any systematic uncertainties.

Numerous cross-checks have been performed to assure the unbiased nature of the fit model and to validate the assumptions used in its construction. We have performed fits to datasets composed of fully simulated signal and background events in the proportions seen in the actual data, and find no bias in the measurement of individual $\tau_{K\pi}$ and $\tau_{KK}$ lifetimes for simulated signal events generated at $411.6\,\mathrm{fs}$ (very near the nominal $D^0 \to K^-\pi^+$ lifetime value [16]), or for a lifetime value $\sim 10\%$ greater than this for $D^0 \to K^+K^-$ . We additionally find no significant variations in the reconstruction efficiency for signal decays as a function of the true decay time.

Many of the systematic uncertainties associated with the individual lifetime measurements cancel to a great extent in the ratio of lifetimes. We consider as possible sources of systematic uncertainty: variations in the signal and background fit models, changes to the event selection, and detector effects that might introduce biases in the lifetime measurements.

We test the assumption of a shared signal resolution model by separately fitting each mode using completely independent resolution functions, and assign as a systematic uncertainty the magnitude of the change $|\Delta y_{CP}|$ in $y_{CP}$ relative to the result of the nominal fit. We additionally perform the nominal fit using a double Gaussian signal resolution model, and similarly assign a systematic uncertainty. The total uncertainty associated with the choice of signal resolution model is 0.016%.

To estimate possible biases correlated with the extent and position of the lifetime fit mass region, the size of the mass window is varied by $\pm 2$ and $\pm 5\,\mathrm{MeV}/c^2$ without changing the mass region center, and the center is shifted by $\pm 0.5\,\mathrm{MeV}/c^2$ while retaining the nominal $20\,\mathrm{MeV}/c^2$ width. The total systematic uncertainty obtained from variations in the lifetime fit mass window is 0.110%.

The modeling of the misreconstructed charm background is taken from simulated events, and we vary the expected contribution from these events by $\pm 15\%(\pm 5\%)$ for the $K^-\pi^+$ ($K^+K^-$) final state. These bounds are conservatively assigned based on the results of other BABAR charm analyses in which the background modes here are fully reconstructed, and in which data and simulated event yields are found to agree within a few percent. We additionally vary the effective lifetime used in the charm background lifetime fit PDFs by the same percentages, which corresponds to $> \pm 2\sigma$ in the statistical uncertainty given the number of simulated events used. The largest $|\Delta y_{CP}|$ value within each of these two classes of variations is assigned as a systematic uncertainty, 0.0585% for the normalization variations and 0.0624% for the effective lifetime variations, which are then added in quadrature.

We account for a possible bias associated with obtaining the combinatorial lifetime PDF in the lifetime fit mass region from data in the lower and upper mass sidebands by fluctuating the PDF parameters taking into account the correlations and statistical errors resulting from the sideband fits. We construct 100 PDF variations for each of the lower and upper sidebands for each of the final states, and then perform the nominal lifetime fit using each variation. We separately compute

TABLE II: Systematic uncertainties.

| Uncertainty Source | $\|\Delta y_{CP}\|$ (%) |
|---|---|
| Signal resolution model | 0.016 |
| Mass window | 0.110 |
| Misreconstructed Charm model | 0.086 |
| Combinatorial PDF | 0.115 |
| $\sigma_t$ selection | 0.069 |
| Overlap candidate selection | 0.017 |
| Detector effects | 0.093 |
| Total | 0.216 |

the RMS of the 100 $\Delta y_{CP}$ values associated with each of the four sets of variations, and assign the largest RMS, 0.115%, as a systematic uncertainty.

We evaluate systematic uncertainties associated with the selection of the final dataset by individually varying the selection criteria. We change the maximum allowed decay time uncertainty by $\pm 0.1\,\mathrm{ps}$, and assign the largest $|\Delta y_{CP}|$ value, 0.069%, as a systematic uncertainty. We vary the way in which signal candidates that share tracks with other signal candidates are selected by removing all overlapping candidates, and separately by also retaining all such candidates, and again take the larger of the resulting two $|\Delta y_{CP}|$ values, 0.017%, as a systematic uncertainty.

We account for possible detector effects which might bias the lifetime ratio by using several different detector configurations to re-reconstruct simulated event samples with statistics greater than the actual data for each configuration. These configurations include vertex detector misalignments, along with boost and beamspot variations, whose extent is based on residual uncertainties in studies of mu-pair and cosmic events. The misalignment configurations introduce changes of up to $4\,\mathrm{fs}$ in both $KK$ and $K\pi$ lifetimes, as well as changes in the offset parameter $t_o$ of up to $5\,\mathrm{fs}$. Since the same simulated event sample is reconstructed for each set of detector configuration, the variations are dominated by systematic effects. The total systematic uncertainty arising from this source is 0.093%.

Table II shows the contribution from each source of systematic uncertainty given above. The total is calculated as the sum in quadrature of each of the individual items. In addition to the contributions quantified in the table, we also look for possible biases by fitting the data separated in: several different data-taking periods; several different azimuthal and polar angle bins in the laboratory frame for the $D^0$ candidate; several bins of the opening angle in the laboratory frame between the two $D^0$ daughters; several bins of the $D^0$ helicity angle; and several bins of the $D^0$ momentum in the CM frame. We observed no significant biases in any of these cases.

In our previously published tagged analysis [18], we combined the tagged result with the result of an untagged *BABAR* analysis done using a much smaller dataset [21], and this previous untagged result is superseded by the result here, which is $y_{CP}(\text{untagged}) = [1.12\pm0.26(\mathrm{stat})\pm0.22(\mathrm{syst})]\%$, which excludes the no-mixing hypothesis at $3.3\sigma$, including both statistical and systematic uncertainties. Our previous tagged result [18] is $y_{CP}(\text{tagged}) = [1.24\pm0.39(\mathrm{stat})\pm0.13(\mathrm{syst})]\%$. These results contain no events in common, and are thus statistically uncorrelated by construction. However, the degree of correlation in the systematic uncertainties is substantial, and we conservatively assume a $100\%$ correlation in the systematics shared between the two analyses. Combining the tagged and untagged results taking into account both statistical and systematic uncertainties [22], we find $y_{CP}(\text{correlated}) = [1.16 \pm 0.22(\mathrm{stat}) \pm 0.18(\mathrm{syst})]\%$. Summing statistical and systematic uncertainties in quadrature, the significance of this measurement is $4.1\sigma$.

We are grateful for the extraordinary contributions of our PEP-II colleagues in achieving the excellent luminosity and machine conditions that have made this work possible. The success of this project also relies critically on the expertise and dedication of the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and the kind hospitality extended to them. This work is supported by the US Department of Energy and National Science Foundation, the Natural Sciences and Engineering Research Council (Canada), the Commissariat à l'Energie Atomique and Institut National de Physique Nucléaire et de Physique des Particules (France), the Bundesministerium für Bildung und Forschung and Deutsche Forschungsgemeinschaft (Germany), the Istituto Nazionale di Fisica Nucleare (Italy), the Foundation for Fundamental Research on Matter (The Netherlands), the Research Council of Norway, the Ministry of Education and Science of the Russian Federation, Ministerio de Educación y Ciencia (Spain), and the Science and Technology Facilities Council (United Kingdom). Individuals have received support from the Marie-Curie IEF program (European Union) and the A. P. Sloan Foundation.

[1] B. Aubert *et al.* [*BABAR* Collaboration], Phys. Rev. Lett. **98**, 211802 (2007).
[2] M. Staric *et al.* [Belle Collaboration], Phys. Rev. Lett. **98**, 211803 (2007).
[3] K. Abe *et al.* [Belle Collaboration], Phys. Rev. Lett. **99**, 131803 (2007).
[4] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **100**, 121802 (2008).
[5] L. Wolfenstein, Phys. Lett. B **164**, 170 (1985).
[6] J. F. Donoghue, E. Golowich, B. R. Holstein, and J. Trampetic, Phys. Rev. D **33**, 179 (1986).
[7] I. I. Y. Bigi and N. G. Uraltsev, Nucl. Phys. B **592**, 92 (2001).
[8] A. F. Falk, Y. Grossman, Z. Ligeti, and A. A. Petrov, Phys. Rev. D **65**, 054034 (2002).
[9] A. F. Falk, Y. Grossman, Z. Ligeti, Y. Nir, and A. A. Petrov, Phys. Rev. D **69**, 114021 (2004).
[10] G. Burdman and I. Shipsey, Ann. Rev. Nucl. Part. Sci. **53**, 431 (2003).

[11] A. A. Petrov, Int. J. Mod. Phys. A **21**, 5686 (2006).
[12] E. Golowich, S. Pakvasa, and A. A. Petrov, Phys. Rev. Lett. **98**, 181801 (2007).
[13] E. Golowich, J. Hewett, S. Pakvasa, and A. A. Petrov, Phys. Rev. D **76**, 095009 (2007).
[14] E. Golowich, J. Hewett, S. Pakvasa, and A. A. Petrov, Phys. Rev. D **79**, 114030 (2009).
[15] T. h. Liu, *Workshop on the Future of High Sensitivity Charm Experiments: CHARM2000, Batavia, IL, 7-9 Jun 1994* [arXiv:hep-ph/9408330].
[16] C. Amsler *et al.* [Particle Data Group], Phys. Lett. B **667**, 1 (2008).
[17] Charge conjugation is implied throughout.
[18] B. Aubert *et al.* [*BABAR* Collaboration], Phys. Rev. D **78**, 011105 (2008).
[19] B. Aubert *et al.* [*BABAR* Collaboration], Nucl. Instrum. Meth. A **479**, 1 (2002).
[20] G. Punzi, in *Proceedings of the Conference on Statistical Problems in Particle Physics, Astrophysics, and Cosmology*, 2003, Stanford, edited by L. Lyons, R. Mount, and R. Reitmeyer [arXiv:physics/0401045].
[21] B. Aubert *et al.* [*BABAR* Collaboration], Phys. Rev. Lett. **91**, 121801 (2003).
[22] L. Lyons *et al.*, Nucl. Instrum. Meth. A **270**, 110 (1988).