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Search for *CP* violation in neutral *D* meson Cabibbo-suppressed three-body decays

B. Aubert,[1] M. Bona,[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] M. Pappagallo,[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] R. G. Jacobsen,[5] J. A. Kadyk,[5] L. T. Kerth,[5] Yu. G. Kolomensky,[5] G. Kukartsev,[5] G. Lynch,[5] I. L. Osipenkov,[5] M. T. Ronan,[5,*] K. Tackmann,[5] T. Tanabe,[5] W. A. Wenzel,[5] C. M. Hawkes,[6] N. Soni,[6] A. T. Watson,[6] H. Koch,[7] T. Schroeder,[7] D. Walker,[8] D. J. Asgeirsson,[9] T. Cuhadar-Donszelmann,[9] B. G. Fulsom,[9] C. Hearty,[9] T. S. Mattison,[9] J. A. McKenna,[9] M. Barrett,[10] A. Khan,[10] M. Saleem,[10] L. Teodorescu,[10] V. E. Blinov,[11] A. D. Bukin,[11] A. R. Buzykaev,[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] J. W. Gary,[14] F. Liu,[14] O. Long,[14] B. C. Shen,[14,*] G. M. Vitug,[14] Z. Yasin,[14] L. Zhang,[14] H. P. Paar,[15] S. Rahatlou,[15] V. Sharma,[15] C. Campagnari,[16] T. M. Hong,[16] D. Kovalskyi,[16] M. A. Mazur,[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] M. G. Wilson,[17] L. O. Winstrom,[17] E. Chen,[18] C. H. Cheng,[18] D. A. Doll,[18] B. Echenard,[18] F. Fang,[18] D. G. Hitlin,[18] I. Narsky,[18] T. Piatenko,[18] F. C. Porter,[18] R. Andreassen,[19] G. Mancinelli,[19] B. T. Meadows,[19] K. Mishra,[19] M. D. Sokoloff,[19] F. Blanc,[20] P. C. Bloom,[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] R. Ayad,[21,+] A. M. Gabareen,[21] A. Soffer,[21,‡] W. H. Toki,[21] R. J. Wilson,[21] D. D. Altenburg,[22] E. Feltresi,[22] A. Hauke,[22] H. Jasper,[22] M. Karbach,[22] J. Merkel,[22] A. Petzold,[22] B. Spaan,[22] K. Wacker,[22] 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] Ch. Thiebaux,[24] M. Verderi,[24] P. J. Clark,[25] W. Gradl,[25] S. Playfer,[25] A. I. Robertson,[25] J. E. Watson,[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] R. S. Dubitzky,[30] J. Marks,[30] S. Schenk,[30] U. Uwer,[30] D. J. Bard,[31] P. D. Dauncey,[31] J. A. Nash,[31] W. Panduro Vazquez,[31] M. Tibbetts,[31] P. K. Behera,[32] X. Chai,[32] M. J. Charles,[32] U. Mallik,[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] Y. Y. Gao,[34] 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] A. D'Orazio,[36] M. Davier,[36] J. Firmino da Costa,[36] G. Grosdidier,[36] A. Höcker,[36] V. Lepeltier,[36] F. Le Diberder,[36] A. M. Lutz,[36] S. Pruvot,[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] I. Bingham,[38] J. P. Burke,[38] C. A. Chavez,[38] J. R. Fry,[38] E. Gabathuler,[38] R. Gamet,[38] D. E. Hutchcroft,[38] D. J. Payne,[38] C. Touramanis,[38] A. J. Bevan,[39] K. A. George,[39] F. Di Lodovico,[39] R. Sacco,[39] M. Sigamani,[39] G. Cowan,[40] H. U. Flaecher,[40] D. A. Hopkins,[40] S. Paramesvaran,[40] F. Salvatore,[40] A. C. Wren,[40] D. N. Brown,[41] C. L. Davis,[41] K. E. Alwyn,[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] C. Dallapiccola,[44] S. S. Hertzbach,[44] X. Li,[44] E. Salvati,[44] S. Saremi,[44] R. Cowan,[45] D. Dujmic,[45] P. H. Fisher,[45] K. Koeneke,[45] G. Sciolla,[45] M. Spitznagel,[45] F. Taylor,[45] R. K. Yamamoto,[45] M. Zhao,[45] S. E. Mclachlin,[46,*] P. M. Patel,[46] S. H. Robertson,[46] A. Lazzaro,[47] V. Lombardo,[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] L. Lista,[51] D. Monorchio,[51] C. Sciacca,[51] M. A. Baak,[52] G. Raven,[52] H. L. Snoek,[52] C. P. Jessop,[53] K. J. Knoepfel,[53] J. M. LoSecco,[53] G. Benelli,[54] L. A. Corwin,[54] K. Honscheid,[54] H. Kagan,[54] R. Kass,[54] J. P. Morris,[54] A. M. Rahimi,[54] J. J. Regensburger,[54] S. J. Sekula,[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] G. Castelli,[56] N. Gagliardi,[56] A. Gaz,[56] M. Margoni,[56] M. Morandin,[56] M. Posocco,[56] M. Rotondo,[56] F. Simonetto,[56] R. Stroili,[56] C. Voci,[56] P. del Amo Sanchez,[57] E. Ben-Haim,[57] H. Briand,[57] G. Calderini,[57] J. Chauveau,[57] P. David,[57] L. Del Buono,[57] O. Hamon,[57] Ph. Leruste,[57] J. Malclès,[57] J. Ocariz,[57] A. Perez,[57] J. Prendki,[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,‖] A. Cervelli,[60] F. Forti,[60] M. A. Giorgi,[60] A. Lusiani,[60] G. Marchiori,[60] M. Morganti,[60] N. Neri,[60] E. Paoloni,[60] G. Rizzo,[60] J. J. Walsh,[60] J. Biesiada,[61] Y. P. Lau,[61]

D. Lopes Pegna,[61] C. Lu,[61] J. Olsen,[61] A. J. S. Smith,[61] A. V. Telnov,[61] E. Baracchini,[62] G. Cavoto,[62] D. del Re,[62] E. Di Marco,[62] R. Faccini,[62] F. Ferrarotto,[62] F. Ferroni,[62] M. Gaspero,[62] P. D. Jackson,[62] M. A. Mazzoni,[62] S. Morganti,[62] G. Piredda,[62] F. Polci,[62] F. Renga,[62] C. Voena,[62] M. Ebert,[63] T. Hartmann,[63] H. Schröder,[63] R. Waldi,[63] T. Adye,[64] B. Franek,[64] E. O. Olaiya,[64] W. Roethel,[64] F. F. Wilson,[64] S. Emery,[65] M. Escalier,[65] A. Gaidot,[65] S. F. Ganzhur,[65] G. Hamel de Monchenault,[65] W. Kozanecki,[65] G. Vasseur,[65] Ch. Yèche,[65] M. Zito,[65] X. R. Chen,[66] H. Liu,[66] W. Park,[66] M. V. Purohit,[66] R. M. White,[66] J. R. Wilson,[66] M. T. Allen,[67] D. Aston,[67] R. Bartoldus,[67] P. Bechtle,[67] J. F. Benitez,[67] R. Cenci,[67] J. P. Coleman,[67] M. R. Convery,[67] J. C. Dingfelder,[67] J. Dorfan,[67] G. P. Dubois-Felsmann,[67] W. Dunwoodie,[67] R. C. Field,[67] T. Glanzman,[67] S. J. Gowdy,[67] M. T. Graham,[67] P. Grenier,[67] C. Hast,[67] W. R. Innes,[67] J. Kaminski,[67] M. H. Kelsey,[67] H. Kim,[67] P. Kim,[67] M. L. Kocian,[67] D. W. G. S. Leith,[67] S. Li,[67] B. Lindquist,[67] S. Luitz,[67] V. Luth,[67] H. L. Lynch,[67] D. B. MacFarlane,[67] H. Marsiske,[67] R. Messner,[67] D. R. Muller,[67] H. Neal,[67] S. Nelson,[67] C. P. O'Grady,[67] I. Ofte,[67] A. Perazzo,[67] M. Perl,[67] B. N. Ratcliff,[67] A. Roodman,[67] A. A. Salnikov,[67] R. H. Schindler,[67] J. Schwiening,[67] A. Snyder,[67] D. Su,[67] M. K. Sullivan,[67] K. Suzuki,[67] S. K. Swain,[67] J. M. Thompson,[67] J. Va'vra,[67] A. P. Wagner,[67] M. Weaver,[67] W. J. Wisniewski,[67] M. Wittgen,[67] D. H. Wright,[67] H. W. Wulsin,[67] A. K. Yarritu,[67] K. Yi,[67] C. C. Young,[67] V. Ziegler,[67] P. R. Burchat,[68] A. J. Edwards,[68] S. A. Majewski,[68] T. S. Miyashita,[68] B. A. Petersen,[68] L. Wilden,[68] S. Ahmed,[69] M. S. Alam,[69] R. Bula,[69] J. A. Ernst,[69] B. Pan,[69] M. A. Saeed,[69] S. B. Zain,[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] J. M. Izen,[72] X. C. Lou,[72] S. Ye,[72] F. Bianchi,[73] D. Gamba,[73] M. Pelliccioni,[73] M. Bomben,[74] L. Bosisio,[74] C. Cartaro,[74] F. Cossutti,[74] G. Della Ricca,[74] L. Lanceri,[74] L. Vitale,[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] K. Hamano,[76] R. Kowalewski,[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] H. R. Band,[78] X. Chen,[78] S. Dasu,[78] K. T. Flood,[78] P. E. Kutter,[78] Y. Pan,[78] M. Pierini,[78] R. Prepost,[78] C. O. Vuosalo,[78] and S. L. Wu[78]

(*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]*Princeton University, Princeton, New Jersey 08544, USA*
[62]*Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy*
[63]*Universität Rostock, D-18051 Rostock, Germany*
[64]*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom*
[65]*DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France*
[66]*University of South Carolina, Columbia, South Carolina 29208, USA*
[67]*Stanford Linear Accelerator Center, Stanford, California 94309, USA*
[68]*Stanford University, Stanford, California 94305-4060, USA*
[69]*State University of New York, Albany, New York 12222, USA*
[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]*Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy*
[74]*Università di Trieste, Dipartimento di Fisica and INFN, 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*
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Using 385 fb^{-1} of e^+e^- collision data collected at center-of-mass energies around 10.6 GeV, we search for time-integrated *CP* violation in the Cabibbo-suppressed decays $D^0/\bar{D}^0 \to \pi^-\pi^+\pi^0$ and $D^0/\bar{D}^0 \to K^-K^+\pi^0$ with both model-independent and model-dependent methods. Measurements of the asymmetries in amplitudes of flavor states and *CP* eigenstates provide constraints on theories beyond the standard

*Deceased
†Now at Temple University, Philadelphia, PA 19122, USA.
‡Now at Tel Aviv University, Tel Aviv, 69978, Israel.
§Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy.
‖Also with Universita' di Sassari, Sassari, Italy.

model, some of which predict CP violation in amplitudes at the 1% level or higher. We find no evidence of CP violation and hence no conflict with the standard model.

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Charge-parity violation (CPV) [1], manifested as an asymmetry between the decay rates of a particle and its CP-conjugate antiparticle, requires at least two interfering complex quantum mechanical amplitudes with different phases. The strong phase of each amplitude respects CP symmetry, while the weak phase changes sign under charge-conjugation. In the standard model (SM), direct CPV is due to relative weak phases that typically enter as a difference in phase between "tree level" and "penguin" [2] SM amplitudes. The penguin amplitudes in charm decays are, however, too small ($\mathcal{O}(0.1\%)$ [3]) to provide significant CPV. Extensions of the SM introduce additional amplitudes of $\mathcal{O}(1\%)$ [3–5] with relative weak phases that can produce CPV in charmed particle decays [6]. Current experimental searches [7–12] are approaching this level of sensitivity. Observation of CPV with current experimental sensitivities would provide strong evidence of new physics.

A recent theory paper [3] argues that singly Cabibbo-suppressed (SCS) D (meaning either D^0 or $\bar{D}^0$) decays are uniquely sensitive to CPV in $c \to u\bar{d}d$, $u\bar{s}s$ transitions and probe contributions from supersymmetric gluonic penguins. Such transitions do not affect the Cabibbo-favored ($c \to s\bar{d}u$) or doubly Cabibbo-suppressed ($c \to d\bar{s}u$) decays. Time-integrated CP asymmetries in D decays can have three components: direct CPV in decays to specific states, indirect CPV in $D^0 - \bar{D}^0$ mixing, and indirect CPV in interference of decays with and without mixing. Indirect CPV is predicted to be universal for amplitudes with final CP eigenstates, but direct CPV can be nonuniversal depending on the specifics of the new physics.

We search for time-integrated CPV in the three-body SCS decays $D \to \pi^-\pi^+\pi^0$, $K^-K^+\pi^0$. These decays proceed via CP eigenstates (e.g., $\rho^0\pi^0$, $\phi\pi^0$) and also via flavor states (e.g., $\rho^\pm\pi^\mp$, $K^{*\pm}K^\mp$), thus making it possible to probe CPV in both types of amplitudes and in the interference between them. Measuring interference effects in a Dalitz plot (DP) probes asymmetries in both the magnitudes and phases of the amplitudes, not simply in the overall decay rates. We adopt four approaches in our search for evidence of CPV, three of which are model independent. First, we quantify differences between the D^0 and $\bar{D}^0$ DPs in two dimensions. Second, we look for differences in the angular moments of the D^0 and $\bar{D}^0$ intensity distributions. Third, in a model-dependent approach, we look for CPV in the amplitudes describing intermediate states in the D^0 and $\bar{D}^0$ decays. Finally, we look for a phase-space-integrated asymmetry. The first two methods are sensitive to differences in the shapes of the D^0 and $\bar{D}^0$ DPs, allowing regions of phase space with CPV to be identified. The third method associates any CPV observed using the first two methods with specific intermediate amplitudes. The last method is insensitive to differences in the DP shapes, so complements the other methods. To minimize bias, we finalize the analysis procedure without looking at the data.

We perform the present analysis using 385 fb^{-1} of e^+e^- collision data collected at 10.58 GeV and 10.54 GeV center-of-mass (CM) energies with the BABAR detector [13] at the PEP-II storage rings. The event selection criteria are those used in our measurement of the branching ratios of the decays $D \to \pi^-\pi^+\pi^0$ and $D \to K^-K^+\pi^0$ [14]. In particular, we study D mesons produced in $D^{*+} \to D^0\pi^+$ and $D^{*-} \to \bar{D}^0\pi^-$ decays that distinguish between D^0 and $\bar{D}^0$. We require the D candidate CM momentum >2.77 GeV$/c$ and $|m_{D^{*\pm}} - m_D - 145.4\ \text{MeV}/c^2| < 0.6$ MeV$/c^2$. Here, m refers to a reconstructed invariant mass. Around ± 1 standard deviation of the nominal D mass, we find 82468 ± 321 $\pi^-\pi^+\pi^0$ and $11\,278 \pm 110$ $K^-K^+\pi^0$ signal events with purities of about 98%. We determine the signal reconstruction efficiency as a function of the position in the DP using simulated D^0 and $\bar{D}^0$ decays [14] from $e^+e^- \to c\bar{c}$ events, subjected to the same selection procedure that is applied to the data.

A direct comparison of the efficiency-corrected and background-subtracted DPs for D^0 and $\bar{D}^0$ events is the simplest way to look for CPV. Figure 1 shows the normalized residuals Δ in DP area elements, where

$$\Delta = (n_{\bar{D}^0} - R \cdot n_{D^0})/\sqrt{\sigma^2_{n_{\bar{D}^0}} + R^2 \cdot \sigma^2_{n_{D^0}}}, \tag{1}$$

and n denotes the number of events in a DP element and σ its uncertainty. The factor R, equal to 0.983 ± 0.006 for $\pi^-\pi^+\pi^0$ and 1.020 ± 0.016 for $K^-K^+\pi^0$, is the ratio of the number of efficiency-corrected $\bar{D}^0$ to D^0 events. This is introduced to allow for any asymmetry in the production cross section due to higher order QED corrections or in the branching fractions for D^0 and $\bar{D}^0$ decay to the same final state.

We calculate $\chi^2/\nu = (\sum_{i=1}^{\nu} \Delta_i^2)/\nu$, where ν is the number of DP elements: 1429 for $\pi^-\pi^+\pi^0$ and 726 for $K^-K^+\pi^0$. In an ensemble of simulated experiments with no CPV, we find the distribution of χ^2/ν values to have a mean of 1.012 ± 0.001 (1.021 ± 0.002) and a root mean square deviation of 0.018 (0.036) for $\pi^-\pi^+\pi^0$ ($K^-K^+\pi^0$). The measured value in the data is 1.020 for $\pi^-\pi^+\pi^0$ and 1.056 for $K^-K^+\pi^0$, so we obtain a one-sided Gaussian confidence level (CL) for consistency with no CPV of 32.8% for $\pi^-\pi^+\pi^0$ and 16.6% for $K^-K^+\pi^0$. The same analysis procedure, when applied to simulated samples with either 1% fractional change in magnitude or 1°

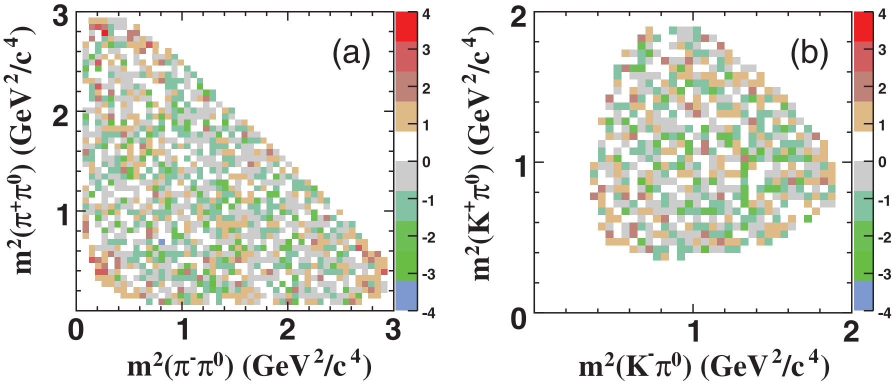

FIG. 1 (color). Normalized residuals in Dalitz plot elements, defined in Eq. (1), for (a) $D \to \pi^-\pi^+\pi^0$ and (b) $D \to K^-K^+\pi^0$.

change in phase between the D^0 and $\bar{D}^0$ amplitudes for decay to any of the main resonant states, gives a χ^2/ν that is about 2σ away from the no *CPV* hypothesis. Systematic uncertainties are small (as will be clear from the model-dependent results of Tables I and II) and have not been included in the CL calculation.

The angular moments of the cosine of the helicity angle of the D decay products reflect the spin and mass structure of intermediate resonant and nonresonant amplitudes [16]. We define the helicity angle θ_H for decays of the type $D \to r(AB)C$ as the angle between the momentum of A in the AB rest frame and the direction opposite to the D momentum in that same frame. The angular moments [17] of order l are defined as the efficiency-corrected invariant mass distributions of events weighted by spherical harmonics $Y_l^0(\theta_H) = \sqrt{1/2\pi}P_l(\cos\theta_H)$. Here, P_l are the Legendre polynomials of order l. To study differences between the D^0 and $\bar{D}^0$ amplitudes, we calculate the quantities X_l for $l = 0$–7, where

$$X_l = \frac{(\bar{P}_l - R \cdot P_l)}{\sqrt{\sigma^2_{\bar{P}_l} + R^2 \cdot \sigma^2_{P_l}}}, \qquad (2)$$

and P_l ($\bar{P}_l$) are obtained from D^0 ($\bar{D}^0$) events. Higher moments are zero within errors in both data and simulation. For illustration, we show the X_l distributions for $l = 0$–2, in Fig. 2.

We then define χ^2/ν of the angular moment distributions of a two-body channel summed over all intervals in invariant mass as

$$\chi^2/\nu = \Big(\sum_0^k \sum_{i=0}^7 \sum_{j=0}^7 X_i \rho_{ij} X_j\Big)/\nu, \qquad (3)$$

where $\nu = 8k$, k is the number of intervals, and ρ_{ij} is the correlation coefficient between X_i, X_j

TABLE I. Model-dependent *CP* asymmetry in the $D \to \pi^-\pi^+\pi^0$ Dalitz plots. The first and second errors are statistical and systematic, respectively. For details on the Dalitz plot parametrization and the a_r, ϕ_r, and f_r values, see Ref. [15]. As explained in the text, Δf_r is closely related to Δa_r and $\Delta\phi_r$

State	f_r(%)	Δa_r(%)	$\Delta\phi_r$(°)	Δf_r(%)
$\rho^+(770)$	68	$-3.2 \pm 1.7 \pm 0.8$	$-0.8 \pm 1.0 \pm 1.0$	$-1.6 \pm 1.1 \pm 0.4$
$\rho^0(770)$	26	$2.1 \pm 0.9 \pm 0.5$	$0.8 \pm 1.0 \pm 0.4$	$1.6 \pm 1.4 \pm 0.6$
$\rho^-(770)$	35	$2.0 \pm 1.1 \pm 0.8$	$-0.6 \pm 0.9 \pm 0.4$	$0.7 \pm 1.1 \pm 0.5$
$\rho^+(1450)$	0.1	$2 \pm 11 \pm 8$	$-30 \pm 25 \pm 9$	$0.0 \pm 0.1 \pm 0.1$
$\rho^0(1450)$	0.3	$13 \pm 8 \pm 6$	$-1 \pm 14 \pm 3$	$0.1 \pm 0.2 \pm 0.1$
$\rho^-(1450)$	1.8	$-3 \pm 6 \pm 5$	$8 \pm 7 \pm 3$	$-0.2 \pm 0.3 \pm 0.1$
$\rho^+(1700)$	4	$19 \pm 27 \pm 9$	$9 \pm 7 \pm 3$	$0.4 \pm 1.0 \pm 0.4$
$\rho^0(1700)$	5	$-31 \pm 20 \pm 12$	$-7 \pm 6 \pm 2$	$-1.3 \pm 0.8 \pm 0.3$
$\rho^-(1700)$	3	$-3 \pm 14 \pm 11$	$-3 \pm 8 \pm 3$	$-0.5 \pm 0.6 \pm 0.3$
$f_0(980)$	0.2	$0.0 \pm 0.1 \pm 0.2$	$-3 \pm 7 \pm 4$	$0.0 \pm 0.1 \pm 0.1$
$f_0(1370)$	0.4	$-0.3 \pm 1.3 \pm 1.2$	$7 \pm 14 \pm 5$	$-0.2 \pm 0.1 \pm 0.1$
$f_0(1500)$	0.4	$0.4 \pm 1.1 \pm 0.7$	$-1 \pm 12 \pm 1$	$0.0 \pm 0.1 \pm 0.1$
$f_0(1710)$	0.3	$-3 \pm 3 \pm 2$	$-25 \pm 13 \pm 11$	$0.0 \pm 0.1 \pm 0.1$
$f_2(1270)$	1.3	$8 \pm 4 \pm 5$	$2 \pm 5 \pm 2$	$0.1 \pm 0.1 \pm 0.1$
$\sigma(400)$	0.8	$-0.3 \pm 0.7 \pm 2.0$	$-4 \pm 7 \pm 3$	$-0.1 \pm 0.1 \pm 0.1$
Nonres	0.8	$12 \pm 7 \pm 8$	$11 \pm 9 \pm 4$	$0.2 \pm 0.3 \pm 0.2$

TABLE II. Model-dependent *CP* asymmetry in the $D \to K^- K^+ \pi^0$ Dalitz plots. The errors are statistical and systematic, respectively. We show the $a_0(980)$ contribution, when it is included in place of the $f_0(980)$, in square brackets. For details on the Dalitz plot parametrization and the a_r, ϕ_r, and f_r values, see Ref. [16]. We use Model I of Ref. [16] to obtain central values and Model II for the study of systematic errors.

State	f_r(%)	Δa_r(%)	$\Delta\phi_r$(°)	Δf_r(%)
$K^*(892)^+$	45	$2 \pm 3 \pm 2$	$10 \pm 12 \pm 3$	$0.8 \pm 1.1 \pm 0.4$
$K^*(1410)^+$	4	$101 \pm 65 \pm 37$	$1 \pm 21 \pm 6$	$1.7 \pm 1.8 \pm 0.6$
$K^+\pi^0(S)$	16	$-130 \pm 64 \pm 51$	$-9 \pm 10 \pm 6$	$-2.3 \pm 4.7 \pm 1.0$
$\phi(1020)$	19	$-1 \pm 2 \pm 1$	$-10 \pm 20 \pm 5$	$-0.4 \pm 0.8 \pm 0.2$
$f_0(980)$	7	$14 \pm 16 \pm 6$	$-12 \pm 25 \pm 8$	$0.4 \pm 2.6 \pm 0.2$
$[a_0(980)^0]$	[6]	$[19 \pm 16 \pm 6]$	$[-7 \pm 16 \pm 8]$	$[0.6 \pm 1.9 \pm 0.2]$
$f'_2(1525)$	0.1	$-38 \pm 74 \pm 8$	$6 \pm 36 \pm 12$	$0.0 \pm 0.1 \pm 0.3$
$K^*(892)^-$	16	$1 \pm 3 \pm 1$	$-7 \pm 4 \pm 2$	$1.7 \pm 1.3 \pm 0.4$
$K^*(1410)^-$	5	$133 \pm 93 \pm 68$	$-23 \pm 13 \pm 9$	$1.7 \pm 2.8 \pm 0.7$
$K^-\pi^0(S)$	3	$8 \pm 68 \pm 36$	$32 \pm 39 \pm 14$	$0.4 \pm 2.4 \pm 0.5$

$$\rho_{ij} = \frac{\langle X_i X_j\rangle - \langle X_i\rangle\langle X_j\rangle}{\sqrt{\langle X_i^2\rangle - \langle X_i\rangle^2} \cdot \sqrt{\langle X_j^2\rangle - \langle X_j\rangle^2}}. \qquad (4)$$

We determine the ρ_{ij} in each mass interval by simulating experiments with no *CPV*. We test the method on real data by randomly assigning events as D^0 or $\bar{D}^0$, and then calculating χ^2/ν for the difference in their angular moments. We repeat this experiment 500 times and find the resulting χ^2/ν distribution to be consistent with no *CPV*, validating our calculation of ρ_{ij}. We then look at the D flavor in the data and calculate the χ^2/ν values for the two-body channels with charge combinations +, − and +, 0. Finally, we obtain a one-sided Gaussian CL for consistency with no *CPV* using the reference value and root mean square deviation from simulation. We find the CL for no *CPV* to be 28.2% for the $\pi^+\pi^-$, 28.4% for the $\pi^+\pi^0$, 63.1% for the K^+K^-, and 23.8% for the $K^+\pi^0$ subsystems. Again, a 1% fractional change in magnitude or 1° change in phase of any of the main resonant amplitudes gives a χ^2/ν that is about 2σ away from the no *CPV* hypothesis.

The Dalitz plot amplitude $\mathcal{A}$ can be parametrized as a sum of amplitudes $A_r(s_+, s_-)$ for all relevant intermediate states r, each with a complex coefficient, i.e., $\mathcal{A} = \sum_r a_r e^{i\phi_r} A_r(s_+, s_-)$, where a_r and ϕ_r are real. Here, s_+ and s_- are the squared invariant masses of the pair of final state particles with charge combinations +, 0 and −, 0. The fit fraction for each process r is defined as $f_r \equiv \int |a_r A_r|^2 ds_+ ds_- / \int |\mathcal{A}|^2 ds_+ ds_-$. We model incoherent, *CP*-symmetric background empirically [15,16]. In the absence of *CPV*, we expect the values of a_r and ϕ_r (and hence f_r) to be identical for D^0 and $\bar{D}^0$ decay. The results obtained with this assumption are listed in Ref. [15] for $D \to \pi^-\pi^+\pi^0$ and in Ref. [16] for $D \to K^-K^+\pi^0$. To allow the possibility of *CPV* in the present analysis, we let a second process—not necessarily of SM origin—contribute to each of the amplitudes A_r, thus permitting the a_r, ϕ_r, f_r for D^0 and $\bar{D}^0$ to differ. We summarize the results of the fit to the data in terms of the differences $\Delta a_r = a_r^{\bar{D}^0} - a_r^{D^0}$, $\Delta\phi_r = \phi_r^{\bar{D}^0} - \phi_r^{D^0}$, and $\Delta f_r = f_r^{\bar{D}^0} - f_r^{D^0}$ in Table I for $\pi^-\pi^+\pi^0$ and in Table II for $K^-K^+\pi^0$. The *CP* asym-

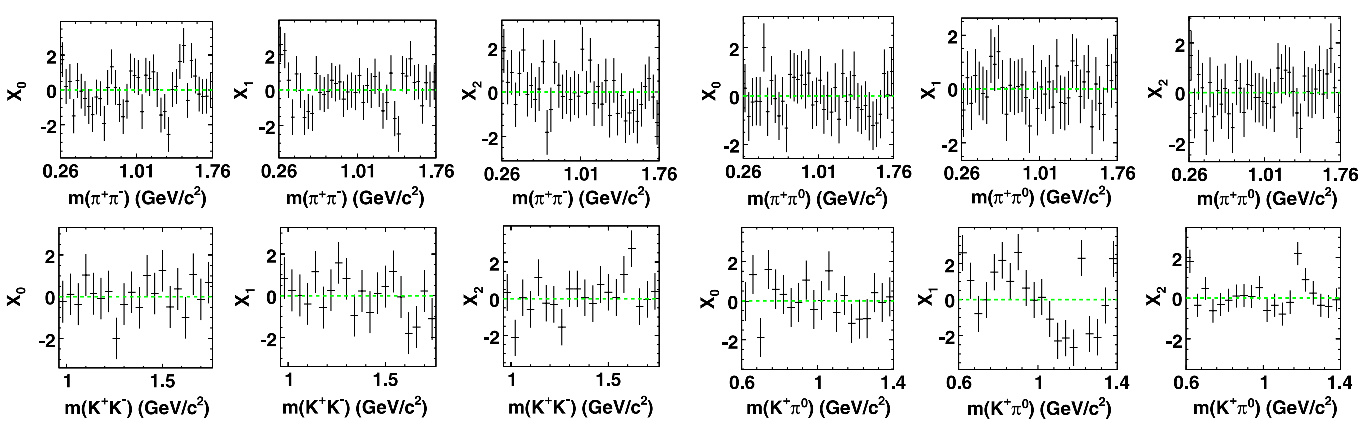

FIG. 2 (color online). Normalized residuals for the first three Legendre polynomial moments of the $\pi^-\pi^+$ (row 1), $\pi^+\pi^0$ (row 2), K^-K^+ (row 3), and $K^+\pi^0$ (row 4) subsystems. The confidence level for no *CP* violation (dashed line) is obtained from the first eight moments. The error bars represent $\pm 1\sigma$.

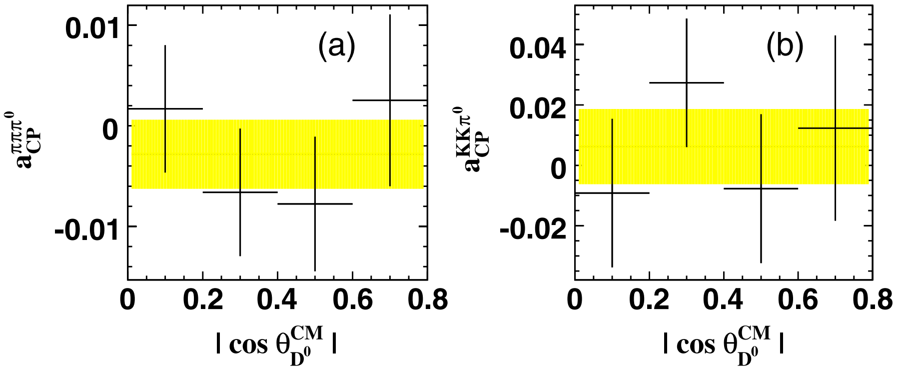

FIG. 3 (color online). Phase-space-integrated *CP* asymmetry as a function of the cosine of the polar angle of the reconstructed *D* candidate CM momentum for (a) $D \to \pi^-\pi^+\pi^0$ and (b) $D \to K^-K^+\pi^0$ decays. The dashed lines represent the central values, and the shaded regions the 1σ intervals.

metry in any amplitude, relative to that of the whole decay, is no larger than a few percent.

Systematic uncertainties in the quantities describing *CP* asymmetries, reported in Tables I and II, arise from experimental effects, and also from uncertainties in the models used to describe the data. We determine these separately, as described in Refs. [15,16], and add them in quadrature. For all variations described below, we assign the maximum deviation from the central value as a systematic uncertainty, accounting for correlations among parameters. For resonance lineshapes and form factors, we vary the parameters [18] by $\pm 1\sigma$. Similarly, we vary the signal efficiency parameters for separately for D^0 and $\bar{D}^0$ events by $\pm 1\sigma$, the ratios of particle-identification rates in data and simulation by $\pm 1\sigma$, and the background shapes by using simulation rather than data sidebands. We include uncertainties from $D^0 - \bar{D}^0$ misidentification, estimated from simulation, in the experimental systematic uncertainty.

To this point, we have described the investigation of time-integrated *CP* asymmetry in neutral *D* meson decays using information from the DP distributions. Differences in the overall branching fractions for the D^0 and $\bar{D}^0$ decays to $\pi^-\pi^+\pi^0$, $K^-K^+\pi^0$ would also indicate time-integrated *CPV*. This information is not captured by the differential comparisons of the DP structures already described, and is complementary to them. To correct for any production asymmetry in *D*-flavor assignment, we weight each event by the relative efficiency for flavor assignment, as described in Ref. [7]. Since there is an asymmetry [7] between the number of events reconstructed at forward and backward polar angles ($\theta_{D^0}^{\rm CM}$) of the *D* candidate CM momentum, we extract the *CP* asymmetry value, $a_{CP} \equiv \frac{N_{\bar{D}^0} - N_{D^0}}{N_{\bar{D}^0} + N_{D^0}}$, in intervals of $|\cos\theta_{D^0}^{\rm CM}|$. Here, *N* denotes the number of signal events. Any forward-backward asymmetry is canceled by averaging over symmetric intervals in $\cos\theta_{D^0}^{\rm CM}$, as shown in Eqs. 3–5 of Ref. [7]. In Fig. 3, we show the a_{CP} for events in the *D* mass window used in the DP analysis. We perform χ^2 minimization to obtain the central values: $[-0.31 \pm 0.41(\text{stat}) \pm 0.17(\text{syst})]\%$ for $\pi^-\pi^+\pi^0$ and $[1.00 \pm 1.67(\text{stat}) \pm 0.25(\text{syst})]\%$ for $K^-K^+\pi^0$ final states. The systematic uncertainties result from signal efficiency, particle-identification, background treatment, and $D^0 - \bar{D}^0$ misidentification. As a consistency check, we repeat the analysis with a larger *D* mass window ($\pm 2.5\sigma$) and find consistent results $[-0.28 \pm 0.34(\text{stat}) \pm 0.19(\text{syst})]\%$ for $\pi^-\pi^+\pi^0$ and $[0.62 \pm 1.24(\text{stat}) \pm 0.28(\text{syst})]\%$ for $K^-K^+\pi^0$.

In summary, our model-independent and model-dependent analyses show no evidence of *CPV* in the SCS decays $D \to \pi^-\pi^+\pi^0$ and $D \to K^-K^+\pi^0$. The intermediate amplitudes include well-defined flavor states (e.g., $\rho^\pm\pi^\mp$, $K^{*\pm}K^\mp$) and *CP*-odd eigenstates (e.g., $\rho^0\pi^0$, $\phi\pi^0$). With the null results of Refs. [7–10] for *CP*-even eigenstates $D \to K^+K^-$ and $D \to \pi^+\pi^-$, we conclude that any *CPV* in the SCS charm decays occurs at a rate which is not larger than a few percent. These results are in accord with the SM predictions, and provide constraints on some models beyond the SM [3].

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