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Aubert, B
Barate, R
Boutigny, D
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Measurement of Time-Dependent CP Asymmetries in $B^0 \rightarrow D^{(*)\pm} \pi^\mp$ Decays and Constraints on $\sin(2\beta + \gamma)$

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 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 K. Ford,⁶ T. J. Harrison,⁶ C. M. Hawkes,⁶ D. J. Knowles,⁶ S. E. Morgan,⁶ R. C. Penny,⁶ A. T. Watson,⁶ N. K. Watson,⁶ K. Goetzen,⁷ T. Held,⁷ H. Koch,⁷ B. Lewandowski,⁷ M. Pelizaeus,⁷ K. Peters,⁷ H. Schmuecker,⁷ M. Steinke,⁷ J. T. Boyd,⁸ N. Chevalier,⁸ W. N. Cottingham,⁸ M. P. Kelly,⁸ T. E. Latham,⁸ C. Mackay,⁸ F. F. Wilson,⁸ K. Abe,⁹ T. Cuhadar-Donszelmann,⁹ C. Hearty,⁹ T. S. Mattison,⁹ J. A. McKenna,⁹ D. Thiessen,⁹ P. Kyberd,¹⁰ A. K. McKemey,¹⁰ L. Teodorescu,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. Bruinsma,¹² M. Chao,¹² D. Kirkby,¹² A. J. Lankford,¹² M. Mandelkern,¹² R. K. Mommsen,¹² W. Roethel,¹² D. P. Stoker,¹² C. Buchanan,¹³ B. L. Hartfiel,¹³ J. W. Gary,¹⁴ J. Layter,¹⁴ B. C. Shen,¹⁴ K. Wang,¹⁴ D. del Re,¹⁵ H. K. Hadavand,¹⁵ E. J. Hill,¹⁵ D. B. MacFarlane,¹⁵ H. P. Paar,¹⁵ Sh. Rahatlou,¹⁵ V. Sharma,¹⁵ J. W. Berryhill,¹⁶ C. Campagnari,¹⁶ B. Dahmes,¹⁶ N. Kuznetsova,¹⁶ S. L. Levy,¹⁶ O. Long,¹⁶ A. Lu,¹⁶ M. A. Mazur,¹⁶ J. D. Richman,¹⁶ W. Verkerke,¹⁶ T. W. Beck,¹⁷ J. Beringer,¹⁷ A. M. Eisner,¹⁷ C. A. Heusch,¹⁷ W. S. Lockman,¹⁷ T. Schalk,¹⁷ R. E. Schmitz,¹⁷ B. A. Schumm,¹⁷ A. Seiden,¹⁷ M. Turri,¹⁷ W. Walkowiak,¹⁷ D. C. Williams,¹⁷ M. G. Wilson,¹⁷ J. Albert,¹⁸ E. Chen,¹⁸ G. P. Dubois-Felsmann,¹⁸ A. Dvoretzki,¹⁸ R. J. Erwin,¹⁸ D. G. Hitlin,¹⁸ I. Narsky,¹⁸ T. Piatenko,¹⁸ F. C. Porter,¹⁸ A. Ryd,¹⁸ A. Samuel,¹⁸ S. Yang,¹⁸ S. Jayatilake,¹⁹ G. Mancinelli,¹⁹ B. T. Meadows,¹⁹ M. D. Sokoloff,¹⁹ T. Abe,²⁰ F. Blanc,²⁰ P. Bloom,²⁰ S. Chen,²⁰ P. J. Clark,²⁰ W. T. Ford,²⁰ U. Nauenberg,²⁰ A. Olivas,²⁰ P. Rankin,²⁰ J. Roy,²⁰ J. G. Smith,²⁰ W. C. van Hoek,²⁰ L. Zhang,²⁰ J. L. Harton,²¹ T. Hu,²¹ A. Soffer,²¹ W. H. Toki,²¹ R. J. Wilson,²¹ J. Zhang,²¹ D. Altenburg,²² T. Brandt,²² J. Brose,²² T. Colberg,²² M. Dickopp,²² R. S. Dubitzky,²² A. Hauke,²² H. M. Lacker,²² E. Maly,²² R. Müller-Pfefferkorn,²² R. Nogowski,²² S. Otto,²² J. Schubert,²² K. R. Schubert,²² R. Schwierz,²² B. Spaan,²² L. Wilden,²² D. Bernard,²³ G. R. Bonneaud,²³ F. Brochard,²³ J. Cohen-Tanugi,²³ P. Grenier,²³ Ch. Thiebaux,²³ G. Vasileiadis,²³ M. Verderi,²³ A. Khan,²⁴ D. Lavin,²⁴ F. Muheim,²⁴ S. Playfer,²⁴ J. E. Swain,²⁴ M. Andreotti,²⁵ V. Azzolini,²⁵ D. Bettoni,²⁵ C. Bozzi,²⁵ R. Calabrese,²⁵ G. Cibinetto,²⁵ E. Luppi,²⁵ M. Negrini,²⁵ L. Piemontese,²⁵ A. Sarti,²⁵ E. Treadwell,²⁶ F. Anulli,^{27,*} R. Baldini-Ferrolì,²⁷ M. Biasini,^{27,*} A. Calcaterra,²⁷ R. de Sangro,²⁷ D. Falciari,²⁷ G. Finocchiaro,²⁷ P. Patteri,²⁷ I. M. Peruzzi,^{27,*} M. Piccolo,²⁷ M. Pioppi,^{27,*} A. Zallo,²⁷ A. Buzzo,²⁸ R. Capra,²⁸ R. Contri,²⁸ G. Crosetti,²⁸ M. Lo Vetere,²⁸ M. Macri,²⁸ M. R. Monge,²⁸ S. Passaggio,²⁸ C. Patrignani,²⁸ E. Robutti,²⁸ A. Santroni,²⁸ S. Tosi,²⁸ S. Bailey,²⁹ M. Morii,²⁹ E. Won,²⁹ W. Bhimji,³⁰ D. A. Bowerman,³⁰ P. D. Dauncey,³⁰ U. Egede,³⁰ I. Eschrich,³⁰ J. R. Gaillard,³⁰ G. W. Morton,³⁰ J. A. Nash,³⁰ P. Sanders,³⁰ G. P. Taylor,³⁰ G. J. Grenier,³¹ S.-J. Lee,³¹ U. Mallik,³¹ J. Cochran,³² H. B. Crawley,³² J. Lamsa,³² W. T. Meyer,³² S. Prell,³² E. I. Rosenberg,³² J. Yi,³² M. Davier,³³ G. Grosdidier,³³ A. Höcker,³³ S. Laplace,³³ F. Le Diberder,³³ V. Lepeltier,³³ A. M. Lutz,³³ T. C. Petersen,³³ S. Plaszczynski,³³ M. H. Schune,³³ L. Tantot,³³ G. Wormser,³³ V. Brigljević,³⁴ C. H. Cheng,³⁴ D. J. Lange,³⁴ M. C. Simani,³⁴ D. M. Wright,³⁴ A. J. Bevan,³⁵ J. P. Coleman,³⁵ J. R. Fry,³⁵ E. Gabathuler,³⁵ R. Gamet,³⁵ M. Kay,³⁵ R. J. Parry,³⁵ D. J. Payne,³⁵ R. J. Sloane,³⁵ C. Touramanis,³⁵ J. J. Back,³⁶ P. F. Harrison,³⁶ H. W. Shorthouse,³⁶ P. B. Vidal,³⁶ C. L. Brown,³⁷ G. Cowan,³⁷ R. L. Flack,³⁷ H. U. Flaecher,³⁷ S. George,³⁷ M. G. Green,³⁷ A. Kurup,³⁷ C. E. Marker,³⁷ T. R. McMahon,³⁷ S. Ricciardi,³⁷ F. Salvatore,³⁷ G. Vaitsas,³⁷ M. A. Winter,³⁷ D. Brown,³⁸ C. L. Davis,³⁸ J. Allison,³⁹ N. R. Barlow,³⁹ R. J. Barlow,³⁹ P. A. Hart,³⁹ M. C. Hodgkinson,³⁹ F. Jackson,³⁹ G. D. Lafferty,³⁹ A. J. Lyon,³⁹ J. H. Weatherall,³⁹ J. C. Williams,³⁹ A. Farbin,⁴⁰ A. Jawahery,⁴⁰ D. Kovalskyi,⁴⁰ C. K. Lae,⁴⁰ V. Lillard,⁴⁰ D. A. Roberts,⁴⁰ G. Blaylock,⁴¹ C. Dallapiccola,⁴¹ K. T. Flood,⁴¹ S. S. Hertzbach,⁴¹ R. Kofler,⁴¹ V. B. Koptchev,⁴¹ T. B. Moore,⁴¹ S. Saremi,⁴¹ H. Staengle,⁴¹ S. Willocq,⁴¹ R. Cowan,⁴² G. Sciolla,⁴² F. Taylor,⁴² R. K. Yamamoto,⁴² D. J. J. Mangeol,⁴³ P. M. Patel,⁴³ S. H. Robertson,⁴³ A. Lazzaro,⁴⁴ F. Palombo,⁴⁴ J. M. Bauer,⁴⁵ L. Cremaldi,⁴⁵ V. Eschenburg,⁴⁵ R. Godang,⁴⁵ R. Kroeger,⁴⁵ J. Reidy,⁴⁵ D. A. Sanders,⁴⁵ D. J. Summers,⁴⁵ H. W. Zhao,⁴⁵ S. Brunet,⁴⁶ D. Cote-Ahern,⁴⁶ P. Taras,⁴⁶ H. Nicholson,⁴⁷ C. Cartaro,⁴⁸ N. Cavallo,^{48,†} G. De Nardo,⁴⁸ F. Fabozzi,^{48,†} C. Gatto,⁴⁸ L. Lista,⁴⁸ P. Paolucci,⁴⁸ D. Piccolo,⁴⁸ C. Sciacca,⁴⁸ M. A. Baak,⁴⁹ G. Raven,⁴⁹ J. M. LoSecco,⁵⁰ T. A. Gabriel,⁵¹

B. Brau,⁵² K. K. Gan,⁵² K. Honscheid,⁵² D. Hufnagel,⁵² H. Kagan,⁵² R. Kass,⁵² T. Pulliam,⁵² Q. K. Wong,⁵² J. Brau,⁵³ R. Frey,⁵³ C. T. Potter,⁵³ N. B. Sinev,⁵³ D. Strom,⁵³ E. Torrence,⁵³ F. Coleocchia,⁵⁴ A. Dorigo,⁵⁴ F. Galeazzi,⁵⁴ M. Margoni,⁵⁴ M. Morandin,⁵⁴ M. Posocco,⁵⁴ M. Rotondo,⁵⁴ F. Simonetto,⁵⁴ R. Stroili,⁵⁴ G. Tiozzo,⁵⁴ C. Voci,⁵⁴ M. Benayoun,⁵⁵ H. Briand,⁵⁵ J. Chauveau,⁵⁵ P. David,⁵⁵ Ch. de la Vaissière,⁵⁵ L. Del Buono,⁵⁵ O. Hamon,⁵⁵ M. J. J. John,⁵⁵ Ph. Leruste,⁵⁵ J. Ocariz,⁵⁵ M. Pivk,⁵⁵ L. Roos,⁵⁵ J. Stark,⁵⁵ S. T'Jampens,⁵⁵ G. Therin,⁵⁵ P. F. Manfredi,⁵⁶ V. Re,⁵⁶ P. K. Behera,⁵⁷ L. Gladney,⁵⁷ Q. H. Guo,⁵⁷ J. Panetta,⁵⁷ C. Angelini,⁵⁸ G. Batignani,⁵⁸ S. Bettarini,⁵⁸ M. Bondioli,⁵⁸ F. Bucci,⁵⁸ G. Calderini,⁵⁸ M. Carpinelli,⁵⁸ V. Del Gamba,⁵⁸ F. Forti,⁵⁸ M. A. Giorgi,⁵⁸ A. Lusiani,⁵⁸ G. Marchiori,⁵⁸ F. Martinez-Vidal,^{58,‡} M. Morganti,⁵⁸ N. Neri,⁵⁸ E. Paoloni,⁵⁸ M. Rama,⁵⁸ G. Rizzo,⁵⁸ F. Sandrelli,⁵⁸ J. Walsh,⁵⁸ M. Haire,⁵⁹ D. Judd,⁵⁹ K. Paick,⁵⁹ D. E. Wagoner,⁵⁹ N. Danielson,⁶⁰ P. Elmer,⁶⁰ C. Lu,⁶⁰ V. Miftakov,⁶⁰ J. Olsen,⁶⁰ A. J. S. Smith,⁶⁰ H. A. Tanaka,⁶⁰ E. W. Varnes,⁶⁰ F. Bellini,⁶¹ G. Cavoto,^{60,61} R. Faccini,⁶¹ F. Ferrarotto,⁶¹ F. Ferroni,⁶¹ M. Gaspero,⁶¹ M. A. Mazzoni,⁶¹ S. Morganti,⁶¹ M. Pierini,⁶¹ G. Piredda,⁶¹ F. Safai Tehrani,⁶¹ C. Voena,⁶¹ S. Christ,⁶² G. Wagner,⁶² R. Waldi,⁶² T. Adye,⁶³ N. De Groot,⁶³ B. Franek,⁶³ N. I. Geddes,⁶³ G. P. Gopal,⁶³ E. O. Olaiya,⁶³ S. M. Xella,⁶³ R. Aleksan,⁶⁴ S. Emery,⁶⁴ A. Gaidot,⁶⁴ S. F. Ganzhur,⁶⁴ P.-F. Giraud,⁶⁴ G. Hamel de Monchenault,⁶⁴ W. Kozanecki,⁶⁴ M. Langer,⁶⁴ M. Legendre,⁶⁴ G. W. London,⁶⁴ B. Mayer,⁶⁴ G. Schott,⁶⁴ G. Vasseur,⁶⁴ Ch. Yeche,⁶⁴ M. Zito,⁶⁴ M. V. Purohit,⁶⁵ A. W. Weidemann,⁶⁵ F. X. Yumiceva,⁶⁵ D. Aston,⁶⁶ R. Bartoldus,⁶⁶ N. Berger,⁶⁶ A. M. Boyarski,⁶⁶ O. L. Buchmueller,⁶⁶ M. R. Convery,⁶⁶ D. P. Coupal,⁶⁶ D. Dong,⁶⁶ J. Dorfan,⁶⁶ D. Dujmic,⁶⁶ W. Dunwoodie,⁶⁶ R. C. Field,⁶⁶ T. Glanzman,⁶⁶ S. J. Gowdy,⁶⁶ E. Grauges-Pous,⁶⁶ T. Hadig,⁶⁶ V. Halyo,⁶⁶ T. Hryn'ova,⁶⁶ W. R. Innes,⁶⁶ C. P. Jessop,⁶⁶ M. H. Kelsey,⁶⁶ P. Kim,⁶⁶ M. L. Kocian,⁶⁶ U. Langenegger,⁶⁶ D. W. G. S. Leith,⁶⁶ J. Libby,⁶⁶ S. Luitz,⁶⁶ V. Luth,⁶⁶ H. L. Lynch,⁶⁶ H. Marsiske,⁶⁶ R. Messner,⁶⁶ D. R. Muller,⁶⁶ C. P. O'Grady,⁶⁶ V. E. Ozcan,⁶⁶ A. Perazzo,⁶⁶ M. Perl,⁶⁶ S. Petrak,⁶⁶ B. N. Ratcliff,⁶⁶ A. Roodman,⁶⁶ A. A. Salnikov,⁶⁶ R. H. Schindler,⁶⁶ J. Schwiening,⁶⁶ G. Simi,⁶⁶ A. Snyder,⁶⁶ A. Soha,⁶⁶ J. Stelzer,⁶⁶ D. Su,⁶⁶ M. K. Sullivan,⁶⁶ J. Va'vra,⁶⁶ S. R. Wagner,⁶⁶ M. Weaver,⁶⁶ A. J. R. Weinstein,⁶⁶ W. J. Wisniewski,⁶⁶ D. H. Wright,⁶⁶ C. C. Young,⁶⁶ P. R. Burchat,⁶⁷ A. J. Edwards,⁶⁷ T. I. Meyer,⁶⁷ B. A. Petersen,⁶⁷ C. Roat,⁶⁷ M. Ahmed,⁶⁸ S. Ahmed,⁶⁸ M. S. Alam,⁶⁸ J. A. Ernst,⁶⁸ M. A. Saeed,⁶⁸ M. Saleem,⁶⁸ F. R. Wappler,⁶⁸ W. Bugg,⁶⁹ M. Krishnamurthy,⁶⁹ S. M. Spanier,⁶⁹ R. Eckmann,⁷⁰ H. Kim,⁷⁰ J. L. Ritchie,⁷⁰ R. F. Schwitters,⁷⁰ J. M. Izen,⁷¹ I. Kitayama,⁷¹ X. C. Lou,⁷¹ S. Ye,⁷¹ F. Bianchi,⁷² M. Bona,⁷² F. Gallo,⁷² D. Gamba,⁷² C. Borean,⁷³ L. Bosisio,⁷³ G. Della Ricca,⁷³ S. Dittongo,⁷³ S. Grancagnolo,⁷³ L. Lanceri,⁷³ P. Poropat,^{73,§} L. Vitale,⁷³ G. Vuagnin,⁷³ R. S. Panvini,⁷⁴ Sw. Banerjee,⁷⁵ C. M. Brown,⁷⁵ D. Fortin,⁷⁵ P. D. Jackson,⁷⁵ R. Kowalewski,⁷⁵ J. M. Roney,⁷⁵ H. R. Band,⁷⁶ S. Dasu,⁷⁶ M. Datta,⁷⁶ A. M. Eichenbaum,⁷⁶ J. R. Johnson,⁷⁶ P. E. Kutter,⁷⁶ H. Li,⁷⁶ R. Liu,⁷⁶ F. Di Lodovico,⁷⁶ A. Mihalyi,⁷⁶ A. K. Mohapatra,⁷⁶ Y. Pan,⁷⁶ R. Prepost,⁷⁶ S. J. Sekula,⁷⁶ J. H. von Wimmersperg-Toeller,⁷⁶ J. Wu,⁷⁶ S. L. Wu,⁷⁶ Z. Yu,⁷⁶ and H. Neal⁷⁷

(BABAR Collaboration)

¹Laboratoire de Physique des Particules, F-74941 Annecy-le-Vieux, France

²Università di Bari, Dipartimento di Fisica and INFN, I-70126 Bari, Italy

³Institute of High Energy Physics, Beijing 100039, China

⁴University of Bergen, Institute of Physics, N-5007 Bergen, Norway

⁵Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720

⁶University of Birmingham, Birmingham B15 2TT, United Kingdom

⁷Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany

⁸University of Bristol, Bristol BS8 1TL, United Kingdom

⁹University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1

¹⁰Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom

¹¹Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

¹²University of California at Irvine, Irvine, California 92697, USA

¹³University of California at Los Angeles, Los Angeles, California 90024, USA

¹⁴University of California at Riverside, Riverside, California 92521, USA

¹⁵University of California at San Diego, La Jolla, California 92093, USA

¹⁶University of California at Santa Barbara, Santa Barbara, California 93106, USA

¹⁷University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA

¹⁸California Institute of Technology, Pasadena, California 91125, USA

¹⁹University of Cincinnati, Cincinnati, Ohio 45221, USA

²⁰University of Colorado, Boulder, Colorado 80309, USA

²¹Colorado State University, Fort Collins, Colorado 80523, USA

²²Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany

- ²³*Ecole Polytechnique, LLR, F-91128 Palaiseau, France*
- ²⁴*University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*
- ²⁵*Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy*
- ²⁶*Florida A&M University, Tallahassee, Florida 32307, USA*
- 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*Imperial College London, London SW7 2BW, United Kingdom*
- ³¹*University of Iowa, Iowa City, Iowa 52242, USA*
- ³²*Iowa State University, Ames, Iowa 50011-3160, USA*
- ³³*Laboratoire de l'Accélérateur Linéaire, F-91898 Orsay, France*
- ³⁴*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
- ³⁵*University of Liverpool, Liverpool L69 3BX, United Kingdom*
- ³⁶*Queen Mary, University of London, E1 4NS, United Kingdom*
- ³⁷*University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom*
- ³⁸*University of Louisville, Louisville, Kentucky 40292, USA*
- ³⁹*University of Manchester, Manchester M13 9PL, United Kingdom*
- ⁴⁰*University of Maryland, College Park, Maryland 20742, USA*
- ⁴¹*University of Massachusetts, Amherst, Massachusetts 01003, USA*
- ⁴²*Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA*
- ⁴³*McGill University, Montréal, Quebec, Canada H3A 2T8*
- ⁴⁴*Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy*
- ⁴⁵*University of Mississippi, University, Mississippi 38677, USA*
- ⁴⁶*Université de Montréal, Laboratoire René J. A. Lévesque, Montréal, Quebec, Canada H3C 3J7*
- ⁴⁷*Mount Holyoke College, South Hadley, Massachusetts 01075, USA*
- ⁴⁸*Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy*
- ⁴⁹*NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands*
- ⁵⁰*University of Notre Dame, Notre Dame, Indiana 46556, USA*
- ⁵¹*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
- ⁵²*The Ohio State University, Columbus, Ohio 43210, USA*
- ⁵³*University of Oregon, Eugene, Oregon 97403, USA*
- ⁵⁴*Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy*
- ⁵⁵*Universités Paris VI et VII, Lab de Physique Nucléaire H. E., F-75252 Paris, France*
- ⁵⁶*Università di Pavia, Dipartimento di Elettronica and INFN, I-27100 Pavia, Italy*
- ⁵⁷*University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
- ⁵⁸*Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy*
- ⁵⁹*Prairie View A&M University, Prairie View, Texas 77446, USA*
- ⁶⁰*Princeton University, Princeton, New Jersey 08544, USA*
- ⁶¹*Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185, Roma, Italy*
- ⁶²*Universität Rostock, D-18051 Rostock, Germany*
- ⁶³*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, United Kingdom*
- ⁶⁴*DSM/Dapnia, CEA/Saclay, F-91191, Gif-sur-Yvette, France*
- ⁶⁵*University of South Carolina, Columbia, South Carolina 29208, USA*
- ⁶⁶*Stanford Linear Accelerator Center, Stanford, California 94309, USA*
- ⁶⁷*Stanford University, Stanford, California 94305-4060, USA*
- ⁶⁸*State University of New York, Albany, New York 12222, USA*
- ⁶⁹*University of Tennessee, Knoxville, Tennessee 37996, USA*
- ⁷⁰*University of Texas at Austin, Austin, Texas 78712, USA*
- ⁷¹*University of Texas at Dallas, Richardson, Texas 75083*
- ⁷²*Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy*
- ⁷³*Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy*
- ⁷⁴*Vanderbilt University, Nashville, Tennessee 37235, USA*
- ⁷⁵*University of Victoria, Victoria, British Columbia, Canada V8W 3P6*
- ⁷⁶*University of Wisconsin, Madison, Wisconsin 53706, USA*
- ⁷⁷*Yale University, New Haven, Connecticut 06511, USA*
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We present a measurement of CP -violating asymmetries in fully reconstructed $B^0 \rightarrow D^{(*)\pm} \pi^\mp$ decays in approximately 88×10^6 $Y(4S) \rightarrow B\bar{B}$ decays collected with the $BABAR$ detector at the PEP-II asymmetric-energy B factory at SLAC. From a time-dependent maximum-likelihood fit we obtain the following for the CP -violating parameters: $a = -0.022 \pm 0.038$ (stat) ± 0.020 (syst),

$a^* = -0.068 \pm 0.038$ (stat) ± 0.020 (syst), $c_{\text{lep}} = +0.025 \pm 0.068$ (stat) ± 0.033 (syst), and $c_{\text{lep}}^* = +0.031 \pm 0.070$ (stat) ± 0.033 (syst). Using other measurements and theoretical assumptions we interpret the results in terms of the angles of the Cabibbo-Kobayashi-Maskawa unitarity triangle, and find $|\sin(2\beta + \gamma)| > 0.69$ at 68% confidence level. We exclude the hypothesis of no CP violation [$\sin(2\beta + \gamma) = 0$] at 83% confidence level.

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In the standard model, CP violation in the weak interactions between quarks manifests itself as a nonzero area of the Cabibbo-Kobayashi-Maskawa (CKM) unitarity triangle [1]. While it is sufficient to measure one of its angles α , β , or γ to be different from 0° or 180° to demonstrate the existence of CP violation, the unitarity triangle needs to be overconstrained with different measurements to test the CKM mechanism. Measurements of β free from theoretical uncertainties exist [2,3], but there are no such measurements of α and γ . This Letter reports the measurement of CP -violating asymmetries in $B^0 \rightarrow D^{(*)\pm} \pi^\mp$ decays [4] in $Y(4S) \rightarrow B\bar{B}$ decays and its interpretation in terms of constraints on $|\sin(2\beta + \gamma)|$ [5,6].

The time evolution of $B^0 \rightarrow D^{(*)\pm} \pi^\mp$ decays is sensitive to γ because of the interference between the CKM-favored decay $\bar{B}^0 \rightarrow D^{(*)+} \pi^-$, whose amplitude is proportional to the CKM matrix elements $V_{cb}V_{ud}^*$, and the doubly CKM-suppressed decay $B^0 \rightarrow D^{(*)+} \pi^-$, whose amplitude is proportional to $V_{cd}V_{ub}^*$. The relative weak phase between the two amplitudes is γ , which, when combined with $B^0\bar{B}^0$ mixing, yields a weak phase difference of $2\beta + \gamma$ between the interfering amplitudes.

The decay rate distribution for $B^0 \rightarrow D^\pm \pi^\mp$ decays is

$$f^\pm(\eta, \Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \times [1 \mp S_\zeta \sin(\Delta m_d \Delta t) \mp \eta C \cos(\Delta m_d \Delta t)], \quad (1)$$

where τ is the B^0 lifetime, neglecting the decay width difference, Δm_d is the $B^0\bar{B}^0$ mixing frequency, and $\Delta t = t_{\text{rec}} - t_{\text{tag}}$ is the time of the $B^0 \rightarrow D^\pm \pi^\mp$ decay (B_{rec}) relative to the decay of the other B (B_{tag}). In this equation the upper (lower) sign refers to the flavor of B_{tag} as B^0 (\bar{B}^0), while $\eta = +1$ (-1) and $\zeta = +$ ($-$) for the final state $D^- \pi^+$ ($D^+ \pi^-$). In the standard model, the S and C parameters can be expressed as

$$S_\pm = -\frac{2\text{Im}(\lambda_\pm)}{1 + |\lambda_\pm|^2}, \quad C = \frac{1 - r^2}{1 + r^2}, \quad (2)$$

where $\lambda_\pm = r^\pm e^{-i(2\beta + \gamma \mp \delta)}$. Here δ is the relative strong phase and r is the magnitude of the ratio of the suppressed and the favored amplitudes. The same equations apply for $B^0 \rightarrow D^{*\pm} \pi^\mp$ decays, with r and δ replaced by the parameters r^* and δ^* , respectively [7].

The analysis strategy is similar to that of the time-dependent mixing measurement performed at $BABAR$ [8]. To identify the flavor of B_{tag} , each event is assigned by a

neural network to one of four hierarchical, mutually exclusive tagging categories: one lepton and two kaon categories based on the charges of identified leptons and kaons, and a fourth category for remaining events. The effective tagging efficiency is $(28.1 \pm 0.7)\%$ [2]. The time difference Δt is calculated from the separation along the beam collision axis, Δz , between the B_{rec} and B_{tag} decay vertices. We determine the B_{rec} vertex from its charged tracks. The B_{tag} decay vertex is obtained by fitting tracks that do not belong to B_{rec} , imposing constraints from the B_{rec} momentum and the beam-spot location. The Δt resolution is approximately 1.1 ps.

The expected CP asymmetry in these decays is small ($r^{(*)} \approx |V_{ub}^* V_{cd} / V_{ud}^* V_{cb}| \approx 0.02$), and therefore this measurement is sensitive to the interference between the $b \rightarrow u$ and $b \rightarrow c$ amplitudes in the decay of B_{tag} . To account for this effect we use a parametrization different from Eq. (2), which is described in Ref. [9] and summarized here. For each tagging category (i) the interference is parametrized in terms of the effective parameters r'_i and δ'_i . Neglecting terms of order $r^{(*)2}$ and $r_i'^2$, for each tagging category the ΔT distribution becomes

$$f_i^{\pm(*)}(\eta, \Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \times [1 \mp (a^{(*)} \mp \eta b_i - \eta c_i^{(*)}) \sin(\Delta m_d \Delta t) \mp \eta \cos(\Delta m_d \Delta t)], \quad (3)$$

where, in the standard model,

$$\begin{aligned} a^{(*)} &= 2r^{(*)} \sin(2\beta + \gamma) \cos\delta^{(*)}, \\ b_i &= 2r'_i \sin(2\beta + \gamma) \cos\delta'_i, \\ c_i^{(*)} &= 2 \cos(2\beta + \gamma) (r^{(*)} \sin\delta^{(*)} - r'_i \sin\delta'_i). \end{aligned} \quad (4)$$

Semileptonic B decays do not have a doubly CKM-suppressed amplitude contribution, and hence $r'_{\text{lep}} = 0$. Given that we have two B decay modes and four tagging categories, we use two a parameters (one for each final state), three b parameters (one for each nonlepton tagging category), and eight c parameters (one for each combination of tagging category and final state). Results are quoted only for the four parameters $a^{(*)}$ and $c_{\text{lep}}^{(*)}$, which are independent of the unknowns r'_i and δ'_i . The other parameters are allowed to float in the fit, but, as they depend on r'_i and δ'_i , they do not contribute to the interpretation of the result in terms of $\sin(2\beta + \gamma)$.

This measurement is based on 88×10^6 $Y(4S) \rightarrow B\bar{B}$ decays, corresponding to an integrated luminosity of

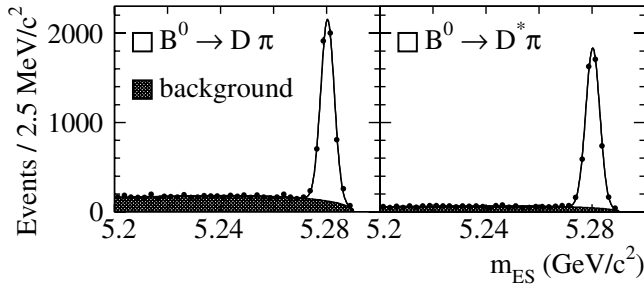


FIG. 1. Distributions of m_{ES} in the ΔE signal region for events with tagging information in the $B^0 \rightarrow D^\pm \pi^\mp$ (left plot) and the $B^0 \rightarrow D^{*\pm} \pi^\mp$ sample (right plot).

82 fb^{-1} , collected with the *BABAR* detector [10] at the PEP-II asymmetric-energy B factory at SLAC. We use a Monte Carlo simulation of the *BABAR* detector based on GEANT4 [11] to validate the analysis procedure and to estimate some of the backgrounds.

The event selection and the reconstruction of $B^0 \rightarrow D^{(*)\pm} \pi^\mp$ candidates are detailed in Ref. [8]. Signal and background are discriminated by two kinematic variables: the beam-energy substituted mass, $m_{ES} \equiv \sqrt{(\sqrt{s}/2)^2 - p_B^{*2}}$, and the difference between the B candidate's measured energy and the beam-energy, $\Delta E \equiv E_B^* - (\sqrt{s}/2)$, where E_B^* (p_B^*) is the energy (momentum) of the B candidate in the e^+e^- center-of-mass frame, and \sqrt{s} is the total center-of-mass energy. The signal region is defined as $|\Delta E| < 3\sigma$, where the resolution σ is mode dependent and approximately 20 MeV, as determined from data. Figure 1 shows the m_{ES} distribution for candidates in the ΔE signal region. The m_{ES} distribution is fit with the sum of a threshold function [12], which accounts for the background from random combinations of tracks, and a Gaussian distribution with a fitted width of about 2.5 MeV/ c^2 describing the signal. After tagging, the Gaussian yield is 5207 ± 87 and 4746 ± 78 events for the $B^0 \rightarrow D^\pm \pi^\mp$ and $B^0 \rightarrow D^{*\pm} \pi^\mp$ sample, respectively,

with corresponding purities of $(84.9 \pm 0.5)\%$ and $(94.4 \pm 0.4)\%$ in a $\pm 3\sigma$ region around the nominal B mass. Backgrounds from B^0 decays that peak in the m_{ES} signal region were estimated with Monte Carlo simulation to constitute $(0.21 \pm 0.06)\%$ and $(0.13 \pm 0.05)\%$ of the $B^0 \rightarrow D^\pm \pi^\mp$ and $B^0 \rightarrow D^{*\pm} \pi^\mp$ yields, respectively. For backgrounds from B^\pm decays, the corresponding figures are $(0.93 \pm 0.23)\%$ and $(0.93 \pm 0.10)\%$.

An unbinned maximum-likelihood fit is performed on the selected B candidates using the ΔT distribution in Eq. (3), convolved with a resolution function composed of three Gaussian distributions. Incorrect tagging dilutes the parameters $a^{(*)}$, $c_i^{(*)}$, and the coefficient of $\cos(\Delta m_d \Delta t)$ by a factor $D_i = 1 - 2w_i$ [2,9], where w_i is the mistag fraction. The resolution function and the parameters associated with flavor tagging are determined from the data and are consistent with previous *BABAR* analyses [2]. The combinatorial background is parametrized as the sum of a component with zero lifetime and one with an effective lifetime fixed to the value obtained from simulation. The fraction of each component and the Δt resolution parameters are left free in the fit to the data. The background coming from B^\pm mesons is modeled with an exponential decay with the B^\pm lifetime, and its size is fixed to the value predicted by simulation. The background from B^0 mesons is neglected in the nominal fit, but is considered in evaluating the systematic uncertainties.

The results from the fit to the data are

$$\begin{aligned} a &= -0.022 \pm 0.038 \text{ (stat)} \pm 0.020 \text{ (syst)}, \\ a^* &= -0.068 \pm 0.038 \text{ (stat)} \pm 0.020 \text{ (syst)}, \\ c_{\text{lep}} &= +0.025 \pm 0.068 \text{ (stat)} \pm 0.033 \text{ (syst)}, \\ c_{\text{lep}}^* &= +0.031 \pm 0.070 \text{ (stat)} \pm 0.033 \text{ (syst)}. \end{aligned} \quad (5)$$

All other fitted b and c parameters are consistent with zero. Figure 2 shows the fitted Δt distributions for events from the lepton tagging category, which has the lowest level of background and mistag probability.

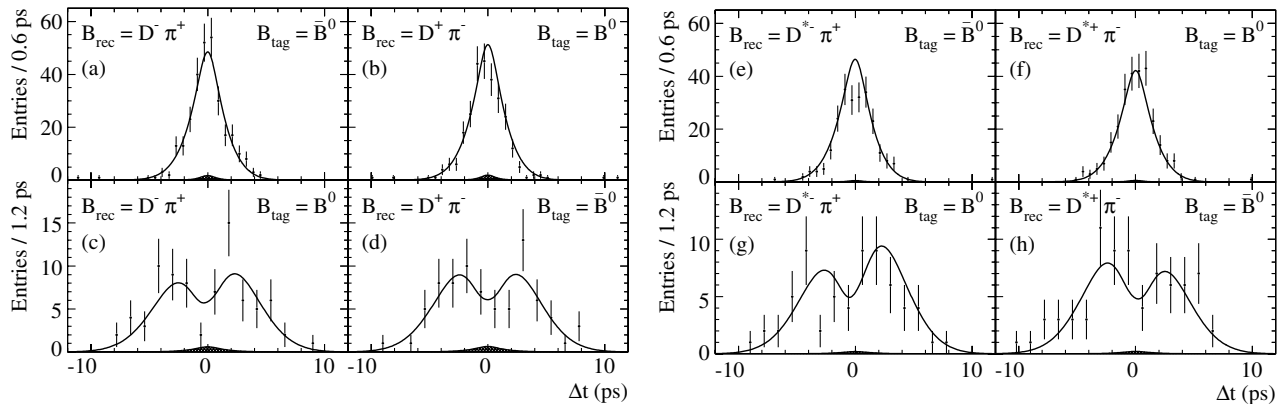


FIG. 2. Distributions of Δt for the $B^0 \rightarrow D^\pm \pi^\mp$ (a)–(d) and $B^0 \rightarrow D^{*\pm} \pi^\mp$ (e)–(h) candidates tagged with leptons, split by tagging flavor and reconstructed final state. The lines are fit projections and hatched regions represent background.

The systematic uncertainties on the parameters in Eq. (5) has been calculated in a manner similar to that used in Ref. [8]. A small bias in the Δt measurement could result in a bias on the c parameters in Eq. (3). For instance, a realistic Δt bias of 0.024 ps results in a shift in c_{lep}^* of 0.002. We are immune from this effect because we fit for tagging category dependent biases in the resolution function directly on data. Nonetheless, the impact of a possible mismeasurement of Δt has been estimated by varying the assumptions on the resolution function, the position of the beam spot, the absolute z scale, the internal alignment of the vertex detector, and quality criteria on the reconstructed vertex. The corresponding error on $a^{(*)}$ is $\sigma_a = 0.015$, while that on $c^{(*)}$ is $\sigma_c = 0.026$. The systematic uncertainties on the fit technique ($\sigma_a = 0.013$, $\sigma_c = 0.020$) include the upper limit on the fit bias estimated from samples of fully simulated events, the uncertainty on the B^0 lifetime and Δm_d [13], and the impact of neglecting higher order terms in $r^{(*)}$ or r_i' in Eq. (3). As a cross check, we performed the same fits on samples of 18 233 $B^- \rightarrow D^{(*)0} \pi^-$ and 1740 $\bar{B}^0 \rightarrow J/\psi K^{*0}$ candidates, where we find no significant CP asymmetries, as expected. The systematic uncertainties in tagging ($\sigma_a = 0.004$, $\sigma_c = 0.003$) are estimated allowing for different tagging efficiencies between B^0 and \bar{B}^0 and for different Δt resolutions for correctly and incorrectly tagged events. We also account for uncertainties on the background ($\sigma_a = 0.001$, $\sigma_c = 0.003$) by varying the effective lifetimes, dilutions, m_{ES} shape parameters and signal fractions, and background CP asymmetry up to 5 times the expected CP asymmetry for signal.

The results can be interpreted in terms of $\sin(2\beta + \gamma)$ [Eq. (4)] if the decay amplitude ratios $r^{(*)}$, expected to be $|V_{ub}^* V_{cd} / V_{ud}^* V_{cb}| \approx 0.02$, are known. Such small amplitude ratios cannot be determined from $B^0 \rightarrow D^{(*)\pm} \pi^\mp$ events directly, because the current data sample is too small. We estimate $r^{(*)}$ using the SU(3) symmetry relation $r^{(*)} = \tan\theta_C \sqrt{\mathcal{B}(B^0 \rightarrow D_s^{(*)+} \pi^-) / \mathcal{B}(B^0 \rightarrow D_s^{(*)-} \pi^+)} (f_{D_s^{(*)-}} / f_{D_s^{(*)+}})$ [5]. From the measurements of the Cabibbo angle $\tan\theta_C = 0.2250 \pm 0.0027$ [13], the branching fractions $\mathcal{B}(B^0 \rightarrow D^- \pi^+) = (0.30 \pm 0.04)\%$ [13], $\mathcal{B}(B^0 \rightarrow D^{*-} \pi^+) = (0.276 \pm 0.021)\%$ [13], $\mathcal{B}(B^0 \rightarrow D_s^+ \pi^-) = (2.7_{-0.6}^{+0.7} \pm 0.8) \times 10^{-5}$ [14], $\mathcal{B}(B^0 \rightarrow D_s^{*+} \pi^-) = (1.9_{-1.3}^{+1.2} \pm 0.5) \times 10^{-5}$ [14], and from calculations of the decay constant ratios $f_{D_s} / f_D = 1.11 \pm 0.01$ and $f_{D_s^*} / f_{D^*} = 1.10 \pm 0.02$ [15] we obtain

$$r = 0.019 \pm 0.004, \quad r^* = 0.017_{-0.007}^{+0.005}. \quad (6)$$

To obtain $\sin(2\beta + \gamma)$, we minimize the χ^2

$$\chi^2(2\beta + \gamma, \delta^{(*)}, r^{(*)}) = \sum_i \left(\frac{\tilde{x}_i - x_i}{\sigma_i} \right)^2 + \Delta(r^{(*)}), \quad (7)$$

where $x_i = a, a^*, c_{\text{lep}}, c_{\text{lep}}^*$ are functions of the physics parameters [Eq. (4)], and \tilde{x}_i are the corresponding mea-

sured values. $\Delta[r^{(*)}]$ is a continuous function that is set equal to 0 within 30% of the estimated $r^{(*)}$ [Eq. (6)], and is an offset quadratic outside this range, with the errors in Eq. (6). The additional 30% error attributed on $r^{(*)}$ is due to the unknown theoretical uncertainty on the validity of the SU(3) symmetry assumption and to neglecting W -exchange contributions to $A(B^0 \rightarrow D^{(*)+} \pi^-)$. This error estimate is consistent with the spread in $r^{(*)}$ obtained using a variety of theoretical models [16]. The σ_i are the quadratic sums of the statistical and systematic uncertainties in Eq. (5). Correlations between the \tilde{x}_i , at most 28%, have negligible influence on the results of this analysis. The simultaneous analysis of two B decay modes allows one to extract $|\sin(2\beta + \gamma)|$.

Figure 3 shows the minimum χ^2 for each value of $|\sin(2\beta + \gamma)|$. The absolute minimum occurs for $|\sin(2\beta + \gamma)| = 0.98$, where $\chi_{\text{min}}^2/\text{d.o.f.} = 0.44/1$. The values of $r^{(*)}$ that minimize the χ^2 are consistent with the input values within their statistical errors. Because of the large uncertainties on the fit parameters and their limited physical range, the χ^2 curve is nonparabolic. Thus to obtain a probabilistic interpretation to the results, we consider, for each of many values of $\sin(2\beta + \gamma)$, a large number of simulated experiments with the same characteristics as the data. We compute the consistency of the data with a given value of $\sin(2\beta + \gamma)$ by counting the fraction of simulated experiments for which $\chi^2(\sin(2\beta + \gamma)) - \chi_{\text{min}}^2$ is smaller than it is in the data. This fraction, the frequentist confidence level, is shown in the lower portion of Fig. 3, from which we read that $|\sin(2\beta + \gamma)| > 0.69$ at 68% C.L. We exclude the hypothesis of no CP violation [$\sin(2\beta + \gamma) = 0$] at 83% confidence level. In order to study the impact of the assumed theoretical error on $r^{(*)}$, we doubled it to 60%

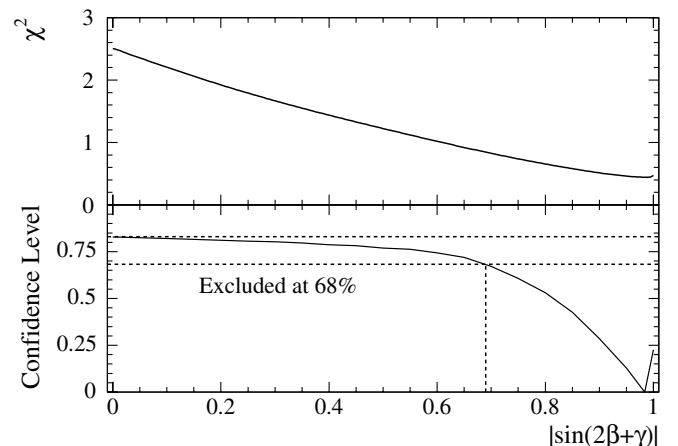


FIG. 3. Dependence of χ^2 on $|\sin(2\beta + \gamma)|$ (top) and of the frequentist confidence level of the agreement of the data with expectations as a function of the hypothesis on $|\sin(2\beta + \gamma)|$ (bottom). The assumptions on r and r^* are contained in the definition of χ^2 [Eq. (7)]. The dashed horizontal lines indicate the 68% and 83% confidence levels (defined in the text).

and we found that the lower limit on $|\sin(2\beta + \gamma)|$ at 68% C.L. drops from 0.69 to 0.60.

In conclusion, we studied the time-dependent CP -violating asymmetries in fully reconstructed $B^0 \rightarrow D^{(*)\pm} \pi^\mp$ decays, and measured the CP -violating parameters listed in Eq. (5). With some theoretical assumptions, we interpret the result in terms of $\sin(2\beta + \gamma)$ and we find that $|\sin(2\beta + \gamma)| > 0.69$ at 68% C.L. and that $\sin(2\beta + \gamma) = 0$ is excluded at 83% C.L.

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*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.

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