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Improved Measurements of *CP*-Violating Asymmetries in $B^0 \to \pi^+\pi^-$ Decays

The *BABAR* Collaboration

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Abstract

We present preliminary updated measurements of the CP-violating parameters $S_{\pi\pi}$ and $C_{\pi\pi}$ in $B^0 \to \pi^+\pi^-$ decays. Using a sample of 227 million $\Upsilon(4S) \to B\overline{B}$ decays collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider at SLAC, we observe 467 ± 33 signal decays and measure $S_{\pi\pi} = -0.30 \pm 0.17\,(\text{stat}) \pm 0.03\,(\text{syst})$, and $C_{\pi\pi} = -0.09 \pm 0.15\,(\text{stat}) \pm 0.04\,(\text{syst})$.

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Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

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The *BABAR* Collaboration,

B. Aubert, R. Barate, D. Boutigny, F. Couderc, J.-M. Gaillard, A. Hicheur, Y. Karyotakis, J. P. Lees, V. Tisserand, A. Zghiche

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

A. Palano, A. Pompili

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

J. C. Chen, N. D. Qi, G. Rong, P. Wang, Y. S. Zhu

Institute of High Energy Physics, Beijing 100039, China

G. Eigen, I. Ofte, B. Stugu

University of Bergen, Inst. of Physics, N-5007 Bergen, Norway

G. S. Abrams, A. W. Borgland, A. B. Breon, D. N. Brown, J. Button-Shafer, R. N. Cahn, E. Charles, C. T. Day, M. S. Gill, A. V. Gritsan, Y. Groysman, R. G. Jacobsen, R. W. Kadel, J. Kadyk, L. T. Kerth, Yu. G. Kolomensky, G. Kukartsev, G. Lynch, L. M. Mir, P. J. Oddone, T. J. Orimoto, M. Pripstein, N. A. Roe, M. T. Ronan, V. G. Shelkov, W. A. Wenzel

Lawrence Berkeley National Laboratory and University of California, Berkeley, CA 94720, USA

M. Barrett, K. E. Ford, T. J. Harrison, A. J. Hart, C. M. Hawkes, S. E. Morgan, A. T. Watson

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

M. Fritsch, K. Goetzen, T. Held, H. Koch, B. Lewandowski, M. Pelizaeus, M. Steinke

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

J. T. Boyd, N. Chevalier, W. N. Cottingham, M. P. Kelly, T. E. Latham, F. F. Wilson

University of Bristol, Bristol BS8 1TL, United Kingdom

T. Cuhadar-Donszelmann, C. Hearty, N. S. Knecht, T. S. Mattison, J. A. McKenna, D. Thiessen

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

A. Khan, P. Kyberd, L. Teodorescu

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

A. E. Blinov, V. E. Blinov, V. P. Druzhinin, V. B. Golubev, V. N. Ivanchenko, E. A. Kravchenko, A. P. Onuchin, S. I. Serednyakov, Yu. I. Skovpen, E. P. Solodov, A. N. Yushkov

Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

D. Best, M. Bruinsma, M. Chao, I. Eschrich, D. Kirkby, A. J. Lankford, M. Mandelkern, R. K. Mommsen, W. Roethel, D. P. Stoker

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

C. Buchanan, B. L. Hartfiel

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

S. D. Foulkes, J. W. Gary, B. C. Shen, K. Wang

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

D. del Re, H. K. Hadavand, E. J. Hill, D. B. MacFarlane, H. P. Paar, Sh. Rahatlou, V. Sharma
University of California at San Diego, La Jolla, CA 92093, USA

J. W. Berryhill, C. Campagnari, B. Dahmes, O. Long, A. Lu, M. A. Mazur, J. D. Richman, W. Verkerke
University of California at Santa Barbara, Santa Barbara, CA 93106, USA

T. W. Beck, A. M. Eisner, C. A. Heusch, J. Kroseberg, W. S. Lockman, G. Nesom, T. Schalk, B. A. Schumm, A. Seiden, P. Spradlin, D. C. Williams, M. G. Wilson
University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, CA 95064, USA

J. Albert, E. Chen, G. P. Dubois-Felsmann, A. Dvoretskii, D. G. Hitlin, I. Narsky, T. Piatenko, F. C. Porter, A. Ryd, A. Samuel, S. Yang
California Institute of Technology, Pasadena, CA 91125, USA

S. Jayatilleke, G. Mancinelli, B. T. Meadows, M. D. Sokoloff
University of Cincinnati, Cincinnati, OH 45221, USA

T. Abe, F. Blanc, P. Bloom, S. Chen, W. T. Ford, U. Nauenberg, A. Olivas, P. Rankin, J. G. Smith, J. Zhang, L. Zhang
University of Colorado, Boulder, CO 80309, USA

A. Chen, J. L. Harton, A. Soffer, W. H. Toki, R. J. Wilson, Q. Zeng
Colorado State University, Fort Collins, CO 80523, USA

D. Altenburg, T. Brandt, J. Brose, M. Dickopp, E. Feltresi, A. Hauke, H. M. Lacker, R. Müller-Pfefferkorn, R. Nogowski, S. Otto, A. Petzold, J. Schubert, K. R. Schubert, R. Schwierz, B. Spaan, J. E. Sundermann
Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany

D. Bernard, G. R. Bonneaud, F. Brochard, P. Grenier, S. Schrenk, Ch. Thiebaux, G. Vasileiadis, M. Verderi
Ecole Polytechnique, LLR, F-91128 Palaiseau, France

D. J. Bard, P. J. Clark, D. Lavin, F. Muheim, S. Playfer, Y. Xie
University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom

M. Andreotti, V. Azzolini, D. Bettoni, C. Bozzi, R. Calabrese, G. Cibinetto, E. Luppi, M. Negrini, L. Piemontese, A. Sarti
Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy

E. Treadwell
Florida A&M University, Tallahassee, FL 32307, USA

F. Anulli, R. Baldini-Ferroli, A. Calcaterra, R. de Sangro, G. Finocchiaro, P. Patteri, I. M. Peruzzi, M. Piccolo, A. Zallo
Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy

A. Buzzo, R. Capra, R. Contri, G. Crosetti, M. Lo Vetere, M. Macri, M. R. Monge, S. Passaggio, C. Patrignani, E. Robutti, A. Santroni, S. Tosi
Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy

S. Bailey, G. Brandenburg, K. S. Chaisanguanthum, M. Morii, E. Won
Harvard University, Cambridge, MA 02138, USA

R. S. Dubitzky, U. Langenegger

Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany

W. Bhimji, D. A. Bowerman, P. D. Dauncey, U. Egede, J. R. Gaillard, G. W. Morton, J. A. Nash, M. B. Nikolich, G. P. Taylor

Imperial College London, London, SW7 2AZ, United Kingdom

M. J. Charles, G. J. Grenier, U. Mallik

University of Iowa, Iowa City, IA 52242, USA

J. Cochran, H. B. Crawley, J. Lamsa, W. T. Meyer, S. Prell, E. I. Rosenberg, A. E. Rubin, J. Yi

Iowa State University, Ames, IA 50011-3160, USA

M. Biasini, R. Covarelli, M. Pioppi

Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy

M. Davier, X. Giroux, G. Grosdidier, A. Höcker, S. Laplace, F. Le Diberder, V. Lepeltier, A. M. Lutz, T. C. Petersen, S. Plaszczynski, M. H. Schune, L. Tantot, G. Wormser

Laboratoire de l'Accélérateur Linéaire, F-91898 Orsay, France

C. H. Cheng, D. J. Lange, M. C. Simani, D. M. Wright

Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

A. J. Bevan, C. A. Chavez, J. P. Coleman, I. J. Forster, J. R. Fry, E. Gabathuler, R. Gamet, D. E. Hutchcroft, R. J. Parry, D. J. Payne, R. J. Sloane, C. Touramanis

University of Liverpool, Liverpool L69 72E, United Kingdom

J. J. Back,[1] C. M. Cormack, P. F. Harrison,[1] F. Di Lodovico, G. B. Mohanty[1]

Queen Mary, University of London, E1 4NS, United Kingdom

C. L. Brown, G. Cowan, R. L. Flack, H. U. Flaecher, M. G. Green, P. S. Jackson, T. R. McMahon, S. Ricciardi, F. Salvatore, M. A. Winter

University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom

D. Brown, C. L. Davis

University of Louisville, Louisville, KY 40292, USA

J. Allison, N. R. Barlow, R. J. Barlow, P. A. Hart, M. C. Hodgkinson, G. D. Lafferty, A. J. Lyon, J. C. Williams

University of Manchester, Manchester M13 9PL, United Kingdom

A. Farbin, W. D. Hulsbergen, A. Jawahery, D. Kovalskyi, C. K. Lae, V. Lillard, D. A. Roberts

University of Maryland, College Park, MD 20742, USA

G. Blaylock, C. Dallapiccola, K. T. Flood, S. S. Hertzbach, R. Kofler, V. B. Koptchev, T. B. Moore, S. Saremi, H. Staengle, S. Willocq

University of Massachusetts, Amherst, MA 01003, USA

[1]Now at Department of Physics, University of Warwick, Coventry, United Kingdom

R. Cowan, G. Sciolla, S. J. Sekula, F. Taylor, R. K. Yamamoto
Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, MA 02139, USA

D. J. J. Mangeol, P. M. Patel, S. H. Robertson
McGill University, Montréal, QC, Canada H3A 2T8

A. Lazzaro, V. Lombardo, F. Palombo
Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy

J. M. Bauer, L. Cremaldi, V. Eschenburg, R. Godang, R. Kroeger, J. Reidy, D. A. Sanders, D. J. Summers, H. W. Zhao
University of Mississippi, University, MS 38677, USA

S. Brunet, D. Côté, P. Taras
Université de Montréal, Laboratoire René J. A. Lévesque, Montréal, QC, Canada H3C 3J7

H. Nicholson
Mount Holyoke College, South Hadley, MA 01075, USA

N. Cavallo,[2] F. Fabozzi,[2] C. Gatto, L. Lista, D. Monorchio, P. Paolucci, D. Piccolo, C. Sciacca
Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy

M. Baak, H. Bulten, G. Raven, H. L. Snoek, L. Wilden
NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands

C. P. Jessop, J. M. LoSecco
University of Notre Dame, Notre Dame, IN 46556, USA

T. Allmendinger, K. K. Gan, K. Honscheid, D. Hufnagel, H. Kagan, R. Kass, T. Pulliam, A. M. Rahimi, R. Ter-Antonyan, Q. K. Wong
Ohio State University, Columbus, OH 43210, USA

J. Brau, R. Frey, O. Igonkina, C. T. Potter, N. B. Sinev, D. Strom, E. Torrence
University of Oregon, Eugene, OR 97403, USA

F. Colecchia, A. Dorigo, F. Galeazzi, M. Margoni, M. Morandin, M. Posocco, M. Rotondo, F. Simonetto, R. Stroili, G. Tiozzo, C. Voci
Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy

M. Benayoun, H. Briand, J. Chauveau, P. David, Ch. de la Vaissière, L. Del Buono, O. Hamon, M. J. J. John, Ph. Leruste, J. Malcles, J. Ocariz, M. Pivk, L. Roos, S. T'Jampens, G. Therin
Universités Paris VI et VII, Laboratoire de Physique Nucléaire et de Hautes Energies, F-75252 Paris, France

P. F. Manfredi, V. Re
Università di Pavia, Dipartimento di Elettronica and INFN, I-27100 Pavia, Italy

[2]Also with Università della Basilicata, Potenza, Italy

P. K. Behera, L. Gladney, Q. H. Guo, J. Panetta
University of Pennsylvania, Philadelphia, PA 19104, USA

C. Angelini, G. Batignani, S. Bettarini, M. Bondioli, F. Bucci, G. Calderini, M. Carpinelli, F. Forti, M. A. Giorgi, A. Lusiani, G. Marchiori, F. Martinez-Vidal,[3] M. Morganti, N. Neri, E. Paoloni, M. Rama, G. Rizzo, F. Sandrelli, J. Walsh
Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy

M. Haire, D. Judd, K. Paick, D. E. Wagoner
Prairie View A&M University, Prairie View, TX 77446, USA

N. Danielson, P. Elmer, Y. P. Lau, C. Lu, V. Miftakov, J. Olsen, A. J. S. Smith, A. V. Telnov
Princeton University, Princeton, NJ 08544, USA

F. Bellini, G. Cavoto,[4] R. Faccini, F. Ferrarotto, F. Ferroni, M. Gaspero, L. Li Gioi, M. A. Mazzoni, S. Morganti, M. Pierini, G. Piredda, F. Safai Tehrani, C. Voena
Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy

S. Christ, G. Wagner, R. Waldi
Universität Rostock, D-18051 Rostock, Germany

T. Adye, N. De Groot, B. Franek, N. I. Geddes, G. P. Gopal, E. O. Olaiya
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom

R. Aleksan, S. Emery, A. Gaidot, S. F. Ganzhur, P.-F. Giraud, G. Hamel de Monchenault, W. Kozanecki, M. Legendre, G. W. London, B. Mayer, G. Schott, G. Vasseur, Ch. Yèche, M. Zito
DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France

M. V. Purohit, A. W. Weidemann, J. R. Wilson, F. X. Yumiceva
University of South Carolina, Columbia, SC 29208, USA

D. Aston, R. Bartoldus, N. Berger, A. M. Boyarski, O. L. Buchmueller, R. Claus, M. R. Convery, M. Cristinziani, G. De Nardo, D. Dong, J. Dorfan, D. Dujmic, W. Dunwoodie, E. E. Elsen, S. Fan, R. C. Field, T. Glanzman, S. J. Gowdy, T. Hadig, V. Halyo, C. Hast, T. Hryn'ova, W. R. Innes, M. H. Kelsey, P. Kim, M. L. Kocian, D. W. G. S. Leith, J. Libby, S. Luitz, V. Luth, H. L. Lynch, H. Marsiske, R. Messner, D. R. Muller, C. P. O'Grady, V. E. Ozcan, A. Perazzo, M. Perl, S. Petrak, B. N. Ratcliff, A. Roodman, A. A. Salnikov, R. H. Schindler, J. Schwiening, G. Simi, A. Snyder, A. Soha, J. Stelzer, D. Su, M. K. Sullivan, J. Va'vra, S. R. Wagner, M. Weaver, A. J. R. Weinstein, W. J. Wisniewski, M. Wittgen, D. H. Wright, A. K. Yarritu, C. C. Young
Stanford Linear Accelerator Center, Stanford, CA 94309, USA

P. R. Burchat, A. J. Edwards, T. I. Meyer, B. A. Petersen, C. Roat
Stanford University, Stanford, CA 94305-4060, USA

S. Ahmed, M. S. Alam, J. A. Ernst, M. A. Saeed, M. Saleem, F. R. Wappler
State University of New York, Albany, NY 12222, USA

[3]Also with IFIC, Instituto de Física Corpuscular, CSIC-Universidad de Valencia, Valencia, Spain
[4]Also with Princeton University, Princeton, USA

W. Bugg, M. Krishnamurthy, S. M. Spanier
University of Tennessee, Knoxville, TN 37996, USA

R. Eckmann, H. Kim, J. L. Ritchie, A. Satpathy, R. F. Schwitters
University of Texas at Austin, Austin, TX 78712, USA

J. M. Izen, I. Kitayama, X. C. Lou, S. Ye
University of Texas at Dallas, Richardson, TX 75083, USA

F. Bianchi, M. Bona, F. Gallo, D. Gamba
Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy

L. Bosisio, C. Cartaro, F. Cossutti, G. Della Ricca, S. Dittongo, S. Grancagnolo, L. Lanceri, P. Poropat,[5] L. Vitale, G. Vuagnin
Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy

R. S. Panvini
Vanderbilt University, Nashville, TN 37235, USA

Sw. Banerjee, C. M. Brown, D. Fortin, P. D. Jackson, R. Kowalewski, J. M. Roney, R. J. Sobie
University of Victoria, Victoria, BC, Canada V8W 3P6

H. R. Band, B. Cheng, S. Dasu, M. Datta, A. M. Eichenbaum, M. Graham, J. J. Hollar, J. R. Johnson, P. E. Kutter, H. Li, R. Liu, A. Mihalyi, A. K. Mohapatra, Y. Pan, R. Prepost, P. Tan, J. H. von Wimmersperg-Toeller, J. Wu, S. L. Wu, Z. Yu
University of Wisconsin, Madison, WI 53706, USA

M. G. Greene, H. Neal
Yale University, New Haven, CT 06511, USA

[5]Deceased

1 INTRODUCTION

In the standard model, all *CP*-violating effects arise from a single phase in the Cabibbo-Kobayashi-Maskawa quark-mixing matrix [1]. In this context, neutral B decays to the *CP* eigenstate $\pi^+\pi^-$ can exhibit mixing-induced *CP* violation through interference between decays with and without B^0–$\overline{B}^0$ mixing, and direct *CP* violation through interference between the $b \to u$ tree and $b \to d$ penguin decay processes [2]. Both effects are observable in the time evolution of the asymmetry between B^0 and $\overline{B}^0$ decays to $\pi^+\pi^-$, where mixing-induced *CP* violation leads to a sine oscillation with amplitude $S_{\pi\pi}$ and direct *CP* violation leads to a cosine oscillation with amplitude $C_{\pi\pi}$. In the absence of the penguin process, $C_{\pi\pi} = 0$ and $S_{\pi\pi} = \sin 2\alpha$, with $\alpha \equiv \arg\left[-V_{\rm td}V^*_{\rm tb}/V_{\rm ud}V^*_{\rm ub}\right]$, while significant tree-penguin interference leads to $C_{\pi\pi} \neq 0$ and $S_{\pi\pi} = \sqrt{1 - C^2_{\pi\pi}}\sin 2\alpha_{\rm eff}$. The difference between $\alpha_{\rm eff}$ and α can be determined from a model-independent analysis using the isospin-related decays $B^\pm \to \pi^\pm\pi^0$ and B^0, $\overline{B}^0 \to \pi^0\pi^0$ [3, 4].

The Belle collaboration recently reported [5] an observation of *CP* violation in $B^0 \to \pi^+\pi^-$ decays using a data sample of 152 million $B\overline{B}$ pairs, while our previous measurement [6] on a sample of 88 million $B\overline{B}$ pairs was consistent with no *CP* violation. In this paper we report improved measurements of the *CP*-violating parameters $S_{\pi\pi}$ and $C_{\pi\pi}$ using a data sample comprising 227 million $B\overline{B}$ pairs collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider at SLAC.

2 THE *BABAR* DETECTOR

The *BABAR* detector is described in detail elsewhere [7]. The primary components used in this analysis are a charged-particle tracking system consisting of a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) surrounded by a 1.5-T solenoidal magnet, an electromagnetic calorimeter (EMC) comprising 6580 CsI(Tl) crystals, and a detector of internally reflected Cherenkov light (DIRC) providing K–π separation over the range of laboratory momentum relevant for this analysis (1.5–4.5 GeV/c).

3 ANALYSIS METHOD

The analysis method is similar to that used in our previous measurement of these quantities [6]. We reconstruct a sample of neutral B mesons ($B_{\rm rec}$) decaying to final states with two charged tracks, and examine the remaining particles in each event to determine whether the second B meson ($B_{\rm tag}$) decayed as a B^0 or $\overline{B}^0$ (flavor tag). The *CP* asymmetry parameters in $B^0 \to \pi^+\pi^-$ decays are determined with a maximum likelihood fit including information about the flavor of $B_{\rm tag}$ and the difference Δt between the decay times of the $B_{\rm rec}$ and $B_{\rm tag}$ decays. The decay rate distribution f_+ (f_-) when $B_{\rm rec} \to \pi^+\pi^-$ and $B_{\rm tag} = B^0$ ($\overline{B}^0$) is given by

$$f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left[1 \pm S_{\pi\pi}\sin(\Delta m_d \Delta t) \mp C_{\pi\pi}\cos(\Delta m_d\Delta t)\right], \quad (1)$$

where τ is the mean B^0 lifetime and Δm_d is the mixing frequency due to the neutral-B-meson eigenstate mass difference.

We first perform a maximum-likelihood fit that uses kinematic, event-shape, and particle-identification information to determine signal and background yields corresponding to the four distinguishable final states ($\pi^+\pi^-$, $K^+\pi^-$, $K^-\pi^+$, K^+K^-). The results of this fit are described in Ref. [8], which reports our observation of direct *CP* violation in $B^0 \to K^+\pi^-$ decays. The parameters $S_{\pi\pi}$ and $C_{\pi\pi}$ are obtained from a second fit adding B-flavor and decay-time information, where the yields and $K\pi$ asymmetries for signal and backgrond events are fixed to the values obtained in the first fit.

3.1 Event Selection

We reconstruct two-body neutral-B decays from pairs of oppositely-charged tracks located within the geometric acceptance of the DIRC and originating from a common decay point near the interaction region. We require that each track have an associated Cherenkov-angle (θ_c) measured with at least five signal photons detected in the DIRC, where the value of θ_c must agree within 4σ with either the pion or kaon particle hypothesis. The last requirement efficiently removes events containing high-momentum protons. Electrons are removed based on energy-loss measurements in the SVT and DCH, and on a comparison of the track momentum and associated energy deposited in the EMC.

Identification of pions and kaons is primarily accomplished by including θ_c as a discriminating variable in the maximum likelihood fit. We construct probability density functions (PDFs) for θ_c from a sample of approximately 430000 $D^{*+} \to D^0\pi^+$ ($D^0 \to K^-\pi^+$) decays reconstructed in data, where $K^{\mp}/\pi^{\pm}$ tracks are identified through the charge correlation with the $\pi^{\pm}$ from the $D^{*\pm}$ decay. The PDFs are constructed separately for K^+, K^-, π^+, and π^- tracks as a function of momentum and polar angle using the measured and expected values of θ_c, and its uncertainty. The average K–π separation, defined as the difference between the expected angles for the kaon and pion mass hypotheses divided by the average uncertainty, varies from 12 standard deviations (σ) at a laboratory momentum of $1.5\,\mathrm{GeV}/c$, to 2σ at $4.5\,\mathrm{GeV}/c$.

Signal decays are identified using two kinematic variables: (1) the difference ΔE between the energy of the B candidate in the e^+e^- center-of-mass (CM) frame and $\sqrt{s}/2$ and (2) the beam-energy substituted mass $m_{\mathrm{ES}} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$. Here, $\sqrt{s}$ is the total CM energy, and the B momentum $\mathbf{p_B}$ and the four-momentum of the initial state ($E_i, \mathbf{p_i}$) are defined in the laboratory frame. For signal decays, ΔE and m_{ES} are distributed according to Gaussian distributions with resolutions of $27\,\mathrm{MeV}$ and $2.6\,\mathrm{MeV}/c^2$, respectively. The distribution of m_{ES} peaks near the B mass for all four final states. To simplify the likelihood fit, we reconstruct the kinematics of the B candidate using the pion mass for all tracks. With this choice, $B^0 \to \pi^+\pi^-$ decays peak near $\Delta E = 0$. For B decays with one or two kaons in the final state, the ΔE peak position is shifted and parameterized as a function of the kaon momentum in the laboratory frame. The average shifts with respect to zero are $-45\,\mathrm{MeV}$ and $-91\,\mathrm{MeV}$, respectively, and this separation in ΔE provides additional discriminating power in the fit. We require $5.20 < m_{\mathrm{ES}} < 5.29\,\mathrm{GeV}/c^2$ and $|\Delta E| < 150\,\mathrm{MeV}$. The large sideband region in m_{ES} is used to determine background-shape parameters, while the wide range in ΔE allows us to separate B decays to all four final states in the same fit.

We have studied potential backgrounds from higher-multiplicity B decays and find them to be negligible near $\Delta E = 0$. The dominant source of background is the process $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$), which produces a distinctive jet-like topology. In the CM frame we define the angle θ_S between the sphericity axis [9] of the B candidate and the sphericity axis of the remaining particles in the event. For background events, $|\cos\theta_S|$ peaks sharply near unity, while it is nearly flat for signal decays. We require $|\cos\theta_S| < 0.8$, which removes approximately 80% of this background. Ad-

Table 1: Average tagging efficiency ϵ, average mistag fraction w, mistag fraction difference $\Delta w = w(B^0) - w(\overline{B}^0)$, and effective tagging efficiency Q for signal events in each tagging category. The quantities are measured in the $B_{\rm flav}$ sample.

Category	ϵ (%)	w (%)	Δw (%)	Q (%)
`Lepton`	9.6 ± 0.1	3.4 ± 0.5	0.1 ± 0.8	8.3 ± 0.3
`Kaon I`	16.7 ± 0.1	8.6 ± 0.5	-1.8 ± 0.8	11.4 ± 0.3
`Kaon II`	19.3 ± 0.1	20.0 ± 0.5	-3.0 ± 0.9	7.2 ± 0.2
`Inclusive`	20.1 ± 0.1	30.7 ± 0.6	-4.4 ± 0.9	3.0 ± 0.2
`Untagged`	34.3 ± 0.2			
Total Q				29.9 ± 0.5

ditional background suppression is accomplished by including the Fisher discriminant $\mathcal{F}$ described in Ref. [6] as one of the variables in the maximum likelihood fit.

3.2 B-Flavor Identification and Decay-Time Reconstruction

We use a multivariate technique [10] to determine the flavor of the $B_{\rm tag}$ meson. Separate neural networks are trained to identify primary leptons, kaons, soft pions from D^* decays, and high-momentum charged particles from B decays. Events are assigned to one of five mutually exclusive tagging categories based on the estimated average mistag probability and the source of the tagging information (Table 1). The quality of tagging is expressed in terms of the effective efficiency $Q = \sum_k \epsilon_k (1-2w_k)^2$, where ϵ_k and w_k are the efficiencies and mistag probabilities, respectively, for events tagged in category k. Table 1 summarizes the tagging performance measured in a data sample $B_{\rm flav}$ of fully reconstructed neutral B decays to $D^{(*)-}(\pi^+, \rho^+, a_1^+)$. The assumption of equal tagging efficiencies and mistag probabilities for signal $\pi^+\pi^-$, $K^+\pi^-$, and K^+K^- decays is validated in a detailed Monte Carlo simulation. Separate background efficiencies for the different decay modes are determined simultaneously with $S_{\pi\pi}$ and $C_{\pi\pi}$ in the fit.

The time difference $\Delta t = \Delta z/\beta\gamma c$ is obtained from the known boost of the e^+e^- system ($\beta\gamma = 0.56$) and the measured distance Δz along the beam (z) axis between the $B_{\rm rec}$ and $B_{\rm tag}$ decay vertices. We require $|\Delta t| < 20\,{\rm ps}$ and $\sigma_{\Delta t} < 2.5\,{\rm ps}$, where $\sigma_{\Delta t}$ is the error on Δt determined separately for each event. The resolution function for signal candidates is a sum of three Gaussians, identical to the one described in Ref. [10], with parameters determined from a fit to the $B_{\rm flav}$ sample (including events in all five tagging categories). The background Δt distribution is modeled as the sum of three Gaussian functions, where the common parameters used to describe the background shape for all tagging categories are determined simultaneously with the *CP* parameters in the maximum likelihood fit.

3.3 Maximum Likelihood Fit

We use an unbinned extended maximum likelihood fit to extract *CP* parameters from the $B_{\rm rec}$ sample. The likelihood for candidate j tagged in category k is obtained by summing the product of event yield n_i, tagging efficiency $\epsilon_{i,k}$, and probability $\mathcal{P}_{i,k}$ over the eight possible signal and background hypotheses i (referring to $\pi^+\pi^-$, $K^+\pi^-$, $K^-\pi^+$, and K^+K^- combinations). The extended likelihood function for category k is

$$\mathcal{L}_k = \exp\left(-\sum_i n_i \epsilon_{i,k}\right) \prod_j \left[\sum_i n_i \epsilon_{i,k} \mathcal{P}_{i,k}(\vec{x}_j; \vec{\alpha}_i)\right]. \quad (2)$$

The yields for the $K\pi$ final state are parameterized as $n_{K^\pm\pi^\mp} = n_{K\pi}\left(1 \mp \mathcal{A}_{K\pi}\right)/2$, where $\mathcal{A}_{K\pi}$ is the direct-CP-violating asymmetry [8]. The probabilities $\mathcal{P}_{i,k}$ are evaluated as the product of PDFs for each of the independent variables $\vec{x}_j = \{m_{\rm ES}, \Delta E, \mathcal{F}, \theta_c^+, \theta_c^-, \Delta t\}$, where θ_c^+ and θ_c^- are the Cherenkov angles for the positively- and negatively-charged tracks. The Δt PDF for signal $\pi^+\pi^-$ decays is given by Eq. 1, modified to include the w_k and Δw_k for each tag category, and convolved with the signal resolution function. The Δt PDF for signal $K\pi$ decays takes into account B^0–$\overline{B}^0$ mixing and the correlation between the charge of the kaon and the flavor of $B_{\rm tag}$.

There are 46 free parameters in the fit:

- 12 parameters describing the background PDFs for $m_{\rm ES}$, ΔE, and $\mathcal{F}$;
- 8 parameters describing the background Δt PDF;
- 12 background flavor-tagging efficiencies;
- 12 background flavor-tagging efficiency asymmetries; and
- $S_{\pi\pi}$ and $C_{\pi\pi}$.

The signal and background yields and $K\pi$ asymmetries were determined in a separate fit that does not use flavor-tagging or Δt information [8]. Out of a fitted sample of 68030 events, we find $n_{\pi\pi} = 467 \pm 33$, $n_{K\pi} = 1606 \pm 51$, and $n_{KK} = 3 \pm 12$ decays, and measure $\mathcal{A}_{K\pi} = -0.133 \pm 0.030$, where all errors are statistical only. We fix τ and Δm_d to their world-average values [11]. The total likelihood $\mathcal{L}$ is the product of likelihoods for each tagging category, and the free parameters are determined by maximizing the quantity $\ln \mathcal{L}$.

4 PHYSICS RESULTS

The fit to the $B_{\rm rec}$ sample yields

$$\begin{aligned} S_{\pi\pi} &= -0.30 \pm 0.17\,({\rm stat}) \pm 0.03\,({\rm syst}), \\ C_{\pi\pi} &= -0.09 \pm 0.15\,({\rm stat}) \pm 0.04\,({\rm syst}). \end{aligned}$$

The correlation between $S_{\pi\pi}$ and $C_{\pi\pi}$ is -1.6%, and the correlations with all other free parameters are less than 1%. These preliminary results are consistent with our previously published measurements [6], and are combined with our measurements of the branching fractions for the isospin-related decay modes $\pi^\pm\pi^0$ and $\pi^0\pi^0$ to determine model-independent bounds on α (see Ref. [4]).

Figure 1 shows distributions of $m_{\rm ES}$ and ΔE for events enhanced in signal $\pi^+\pi^-$ decays. We apply additional requirements on probability ratios based on all PDFs except the variable being plotted. The solid curves are projections of the maximum likelihood fit for the sum of signal and all background components, while the dashed curves indicate the sum of $q\bar{q}$ and $B^0 \to K^+\pi^-$ cross-feed background. Figure 2 shows distributions of Δt for events with $B_{\rm tag}$ tagged as B^0 or

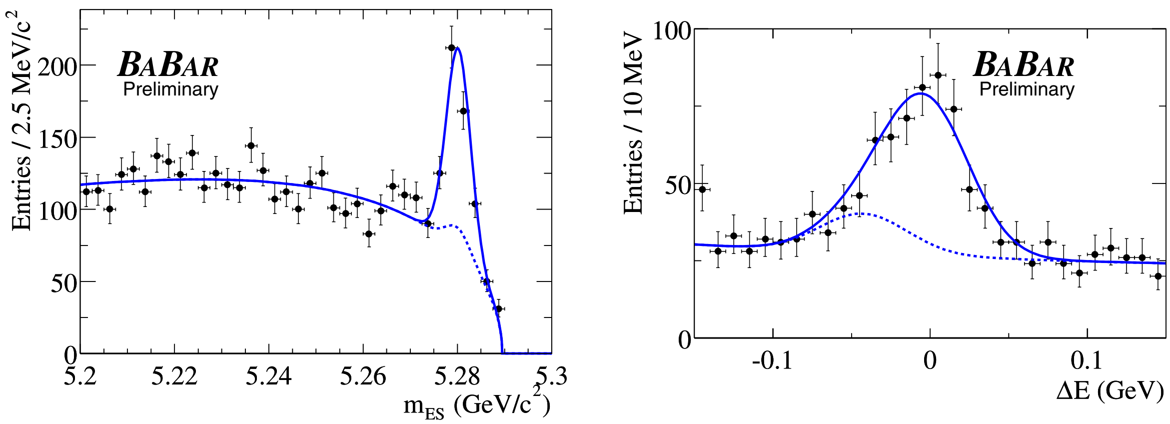

Figure 1: Distributions of (left) $m_{\rm ES}$ and (right) ΔE for events (points with error bars) enhanced in signal $\pi^+\pi^-$ decays using additional requirements on probability ratios. Solid curves represent projections of the maximum likelihood fit, dashed curves represent $q\bar{q}$ and $K\pi \to \pi\pi$ cross-feed background.

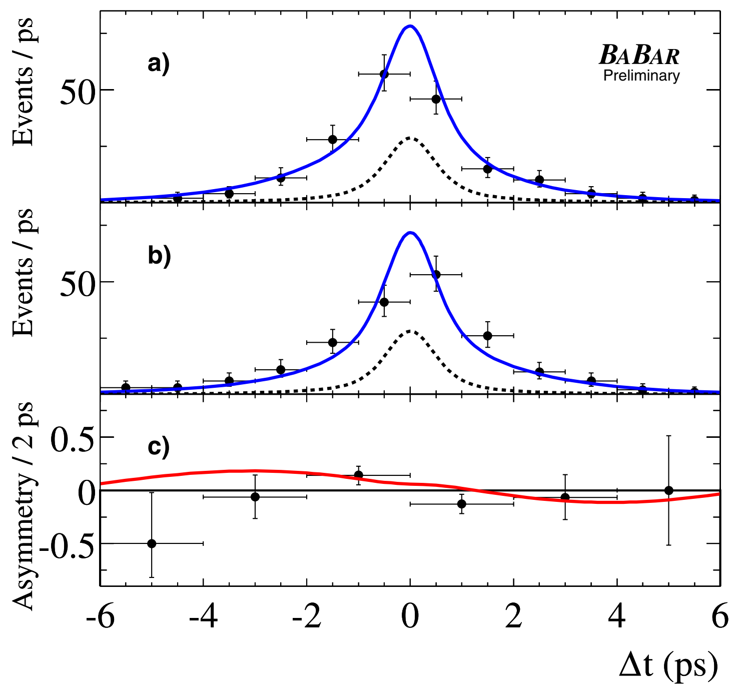

Figure 2: Distribution of the decay-time difference Δt for events enhanced in signal $B^0 \to \pi^+\pi^-$ decays using additional requirements on probability ratios. The top two plots show events where $B_{\rm tag}$ is identified as (a) B^0 (n_{B^0}) or (b) $\overline{B}^0$ ($n_{\overline{B}^0}$). Solid curves indicate the projection of the maximum likelihood fit including signal and background, while the dashed curves show the contribution from background events. (c) The asymmetry (points with errors), defined as $(n_{B^0} - n_{\overline{B}^0}) / (n_{B^0} + n_{\overline{B}^0})$, for different bins in Δt, and the projection of the full fit (solid curve).

$\overline{B}^0$, and the asymmetry as a function of Δt for signal $\pi\pi$ decays selected with requirements on probability ratios including all PDFs except Δt.

As a consistency check on the Δt resolution function, we perform a B^0–$\overline{B}^0$ mixing study using the large number of $K\pi$ signal decays in the $B_{\rm rec}$ sample. Floating τ and Δm_d along with $S_{\pi\pi}$, $C_{\pi\pi}$, and $\mathcal{A}_{K\pi}$, we find values consistent with the world averages ($\tau = 1.60 \pm 0.04\,{\rm ps}$ and $\Delta m_d = 0.523 \pm 0.028\,{\rm ps}^{-1}$), and the CP parameters are consistent with the nominal fit results.

5 SYSTEMATIC STUDIES

Table 2 summarizes the contributions to the total systematic uncertainty from the dominant sources. These include imperfect knowledge of the PDF shape parameters; the B-flavor-tagging parameters (Table 1); the alignment of the SVT; the event-by-event beam-spot position; the potential effect of doubly Cabibbo-suppressed decays of the $B_{\rm tag}$ meson [12], and the B lifetime and mixing frequency. In addition, to confirm that we are sensitive to non-zero values of $S_{\pi\pi}$ and $C_{\pi\pi}$, we fit a large sample of Monte-Carlo simulated signal decays with large values of the *CP* parameters. The fit results are consistent with the generated values, and we assign the sum in quadrature of the statistical uncertainty and the difference between the fitted and generated values as a conservative systematic error accounting for potential bias. The effect of uncertainty on the signal and background yields and $K\pi$ asymmetries is negligible for both $S_{\pi\pi}$ and $C_{\pi\pi}$. The total systematic uncertainty is calculated by summing in quadrature the individual contributions.

Table 2: Summary of systematic uncertainties on $S_{\pi\pi}$ and $C_{\pi\pi}$ (see text for details). The total uncertainty is calculated as the sum in quadrature of the individual contributions.

Source	$S_{\pi\pi}$	$C_{\pi\pi}$
PDF parameters	0.017	0.018
B-flavor identification	0.005	0.015
SVT alignment	0.010	0.002
Beam spot	0.010	0.010
Tag-side interference	0.008	0.023
τ_{B^0} and Δm_d	0.001	0.004
Potential bias	0.013	0.007
Total	0.027	0.035

6 SUMMARY

In summary, we present preliminary updated measurements of the *CP*-violating asymmetries $S_{\pi\pi}$ and $C_{\pi\pi}$ occuring in the time distributions of $B^0 \rightarrow \pi^+\pi^-$ decays. We find $S_{\pi\pi} = -0.30 \pm 0.17 \pm 0.03$ and $C_{\pi\pi} = -0.09 \pm 0.15 \pm 0.04$, which are consistent with our previous measurements and with the hypothesis $S_{\pi\pi} = C_{\pi\pi} = 0$. These results do not confirm the observation of large *CP* violation reported in Ref. [5].

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