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Branching Fractions and *CP*-Violating Asymmetries in Radiative B Decays to $\eta K\gamma$

B. Aubert,[1] M. Bona,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] E. Prencipe,[1] X. Prudent,[1] V. Tisserand,[1] J. Garra Tico,[2] E. Grauges,[2] G. Eigen,[3] B. Stugu,[3] L. Sun,[3] G. S. Abrams,[4] M. Battaglia,[4] D. N. Brown,[4] R. N. Cahn,[4] R. G. Jacobsen,[4] L. T. Kerth,[4] Yu. G. Kolomensky,[4] G. Kukartsev,[4] G. Lynch,[4] I. L. Osipenkov,[4] M. T. Ronan,[4,*] K. Tackmann,[4] T. Tanabe,[4] C. M. Hawkes,[5] N. Soni,[5] A. T. Watson,[5] H. Koch,[6] T. Schroeder,[6] D. Walker,[7] D. J. Asgeirsson,[8] T. Cuhadar-Donszelmann,[8] B. G. Fulsom,[8] C. Hearty,[8] T. S. Mattison,[8] J. A. McKenna,[8] M. Barrett,[9] A. Khan,[9] L. Teodorescu,[9] V. E. Blinov,[10] A. D. Bukin,[10] A. R. Buzykaev,[10] V. P. Druzhinin,[10] V. B. Golubev,[10] A. P. Onuchin,[10] S. I. Serednyakov,[10] Yu. I. Skovpen,[10] E. P. Solodov,[10] K. Yu. Todyshev,[10] M. Bondioli,[11] S. Curry,[11] I. Eschrich,[11] D. Kirkby,[11] A. J. Lankford,[11] P. Lund,[11] M. Mandelkern,[11] E. C. Martin,[11] D. P. Stoker,[11] S. Abachi,[12] C. Buchanan,[12] J. W. Gary,[13] F. Liu,[13] O. Long,[13] B. C. Shen,[13,*] G. M. Vitug,[13] Z. Yasin,[13] L. Zhang,[13] V. Sharma,[14] C. Campagnari,[15] T. M. Hong,[15] D. Kovalskyi,[15] M. A. Mazur,[15] J. D. Richman,[15] T. W. Beck,[16] A. M. Eisner,[16] C. J. Flacco,[16] C. A. Heusch,[16] J. Kroseberg,[16] W. S. Lockman,[16] T. Schalk,[16] B. A. Schumm,[16] A. Seiden,[16] L. Wang,[16] M. G. Wilson,[16] L. O. Winstrom,[16] C. H. Cheng,[17] D. A. Doll,[17] B. Echenard,[17] F. Fang,[17] D. G. Hitlin,[17] I. Narsky,[17] T. Piatenko,[17] F. C. Porter,[17] R. Andreassen,[18] G. Mancinelli,[18] B. T. Meadows,[18] K. Mishra,[18] M. D. Sokoloff,[18] F. Blanc,[19] P. C. Bloom,[19] W. T. Ford,[19] A. Gaz,[19] J. F. Hirschauer,[19] A. Kreisel,[19] M. Nagel,[19] U. Nauenberg,[19] A. Olivas,[19] J. G. Smith,[19] K. A. Ulmer,[19] S. R. Wagner,[19] R. Ayad,[20,†] A. Soffer,[20,‡] W. H. Toki,[20] R. J. Wilson,[20] D. D. Altenburg,[21] E. Feltresi,[21] A. Hauke,[21] H. Jasper,[21] M. Karbach,[21] J. Merkel,[21] A. Petzold,[21] B. Spaan,[21] K. Wacker,[21] M. J. Kobel,[22] W. F. Mader,[22] R. Nogowski,[22] K. R. Schubert,[22] R. Schwierz,[22] J. E. Sundermann,[22] A. Volk,[22] D. Bernard,[23] G. R. Bonneaud,[23] E. Latour,[23] Ch. Thiebaux,[23] M. Verderi,[23] P. J. Clark,[24] W. Gradl,[24] S. Playfer,[24] J. E. Watson,[24] K. S. Chaisanguanthum,[25] M. Morii,[25] R. S. Dubitzky,[26] J. Marks,[26] S. Schenk,[26] U. Uwer,[26] V. Klose,[27] H. M. Lacker,[27] L. Lopez[ab],[28] A. Palano[ab],[28] M. Pappagallo[ab],[28] M. Andreotti[ab],[29] D. Bettoni[a],[29] C. Bozzi[a],[29] R. Calabrese[ab],[29] A. Cecchi[ab],[29] G. Cibinetto[ab],[29] P. Franchini[ab],[29] E. Luppi[ab],[29] M. Negrini[ab],[29] A. Petrella[ab],[29] L. Piemontese[a],[29] V. Santoro[ab],[29] R. Baldini-Ferroli,[30] A. Calcaterra,[30] R. de Sangro,[30] G. Finocchiaro,[30] S. Pacetti,[30] P. Patteri,[30] I. M. Peruzzi,[30,§] M. Piccolo,[30] M. Rama,[30] A. Zallo,[30] A. Buzzo[a],[31] R. Contri[ab],[31] M. Lo Vetere[ab],[31] M. M. Macri[a],[31] M. R. Monge[ab],[31] S. Passaggio[a],[31] C. Patrignani[ab],[31] E. Robutti[a],[31] A. Santroni[ab],[31] S. Tosi[ab],[31] A. Lazzaro[ab],[32] V. Lombardo[a],[32] F. Palombo[ab],[32] G. De Nardo[ab],[33] L. Lista[a],[33] D. Monorchio[ab],[33] G. Onorato[ab],[33] C. Sciacca[ab],[33] G. Castelli[ab],[34] N. Gagliardi[ab],[34] M. Margoni[ab],[34] M. Morandin[a],[34] M. Posocco[a],[34] M. Rotondo[a],[34] F. Simonetto[ab],[34] R. Stroili[ab],[34] C. Voci[ab],[34] M. Biasini[ab],[35] R. Covarelli[ab],[35] E. Manoni[ab],[35] C. Angelini[ab],[36] G. Batignani[ab],[36] S. Bettarini[ab],[36] M. Carpinelli[ab],[36,¶] A. Cervelli[ab],[36] F. Forti[ab],[36] M. A. Giorgi[ab],[36] A. Lusiani[ac],[36] G. Marchiori[ab],[36] M. Morganti[ab],[36] N. Neri[ab],[36] E. Paoloni[ab],[36] G. Rizzo[ab],[36] J. J. Walsh[a],[36] F. Anulli[a],[37] E. Baracchini[ab],[37] G. Cavoto[a],[37] D. del Re[ab],[37] E. Di Marco[ab],[37] R. Faccini[ab],[37] F. Ferrarotto[a],[37] F. Ferroni[ab],[37] M. Gaspero[ab],[37] P. D. Jackson[a],[37] L. Li Gioi[a],[37] M. A. Mazzoni[a],[37] S. Morganti[a],[37] G. Piredda[a],[37] F. Polci[ab],[37] F. Renga[ab],[37] C. Voena[a],[37] F. Bianchi[ab],[38] D. Gamba[ab],[38] M. Pelliccioni[ab],[38] M. Bomben[ab],[39] L. Bosisio[ab],[39] C. Cartaro[ab],[39] G. Della Ricca[ab],[39] L. Lanceri[ab],[39] L. Vitale[ab],[39] D. J. Bard,[40] P. D. Dauncey,[40] J. A. Nash,[40] W. Panduro Vazquez,[40] M. Tibbetts,[40] P. K. Behera,[41] X. Chai,[41] M. J. Charles,[41] U. Mallik,[41] J. Cochran,[42] H. B. Crawley,[42] L. Dong,[42] W. T. Meyer,[42] S. Prell,[42] E. I. Rosenberg,[42] A. E. Rubin,[42] Y. Y. Gao,[43] A. V. Gritsan,[43] Z. J. Guo,[43] C. K. Lae,[43] A. G. Denig,[44] M. Fritsch,[44] G. Schott,[44] N. Arnaud,[45] J. Béquilleux,[45] A. D'Orazio,[45] M. Davier,[45] J. Firmino da Costa,[45] G. Grosdidier,[45] A. Höcker,[45] V. Lepeltier,[45] F. Le Diberder,[45] A. M. Lutz,[45] S. Pruvot,[45] P. Roudeau,[45] M. H. Schune,[45] J. Serrano,[45] V. Sordini,[45,**] A. Stocchi,[45] G. Wormser,[45] D. J. Lange,[46] D. M. Wright,[46] I. Bingham,[47] J. P. Burke,[47] C. A. Chavez,[47] J. R. Fry,[47] E. Gabathuler,[47] R. Gamet,[47] D. E. Hutchcroft,[47] D. J. Payne,[47] C. Touramanis,[47] A. J. Bevan,[48] C. K. Chukwudi,[48] K. A. George,[48] F. Di Lodovico,[48] R. Sacco,[48] M. Sigamani,[48] G. Cowan,[49] H. U. Flaecher,[49] D. A. Hopkins,[49] S. Paramesvaran,[49] F. Salvatore,[49] A. C. Wren,[49] D. N. Brown,[50] C. L. Davis,[50] K. E. Alwyn,[51] N. R. Barlow,[51] R. J. Barlow,[51] Y. M. Chia,[51] C. L. Edgar,[51] G. D. Lafferty,[51] T. J. West,[51] J. I. Yi,[51] J. Anderson,[52] C. Chen,[52] A. Jawahery,[52] D. A. Roberts,[52] G. Simi,[52]

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J. M. Tuggle,[52] C. Dallapiccola,[53] S. S. Hertzbach,[53] X. Li,[53] E. Salvati,[53] S. Saremi,[53] R. Cowan,[54] D. Dujmic,[54] P. H. Fisher,[54] K. Koeneke,[54] G. Sciolla,[54] M. Spitznagel,[54] F. Taylor,[54] R. K. Yamamoto,[54] M. Zhao,[54] S. E. Mclachlin,[55,*] P. M. Patel,[55] S. H. Robertson,[55] J. M. Bauer,[56] L. Cremaldi,[56] V. Eschenburg,[56] R. Godang,[56,††] R. Kroeger,[56] D. A. Sanders,[56] D. J. Summers,[56] H. W. Zhao,[56] S. Brunet,[57] D. Côté,[57] M. Simard,[57] P. Taras,[57] F. B. Viaud,[57] H. Nicholson,[58] M. A. Baak,[59] G. Raven,[59] H. L. Snoek,[59] C. P. Jessop,[60] K. J. Knoepfel,[60] J. M. LoSecco,[60] W. F. Wang,[60] G. Benelli,[61] L. A. Corwin,[61] K. Honscheid,[61] H. Kagan,[61] R. Kass,[61] J. P. Morris,[61] A. M. Rahimi,[61] J. J. Regensburger,[61] S. J. Sekula,[61] Q. K. Wong,[61] N. L. Blount,[62] J. Brau,[62] R. Frey,[62] O. Igonkina,[62] J. A. Kolb,[62] M. Lu,[62] R. Rahmat,[62] N. B. Sinev,[62] D. Strom,[62] J. Strube,[62] E. Torrence,[62] P. del Amo Sanchez,[63] E. Ben-Haim,[63] H. Briand,[63] G. Calderini,[63] J. Chauveau,[63] P. David,[63] L. Del Buono,[63] O. Hamon,[63] Ph. Leruste,[63] J. Ocariz,[63] A. Perez,[63] J. Prendki,[63] L. Gladney,[64] J. Biesiada,[65] D. Lopes Pegna,[65] C. Lu,[65] J. Olsen,[65] A. J. S. Smith,[65] A. V. Telnov,[65] M. Ebert,[66] T. Hartmann,[66] H. Schröder,[66] R. Waldi,[66] T. Adye,[67] B. Franek,[67] E. O. Olaiya,[67] W. Roethel,[67] F. F. Wilson,[67] S. Emery,[68] M. Escalier,[68] L. Esteve,[68] A. Gaidot,[68] S. F. Ganzhur,[68] G. Hamel de Monchenault,[68] W. Kozanecki,[68] G. Vasseur,[68] Ch. Yèche,[68] M. Zito,[68] X. R. Chen,[69] H. Liu,[69] W. Park,[69] M. V. Purohit,[69] R. M. White,[69] J. R. Wilson,[69] M. T. Allen,[70] D. Aston,[70] R. Bartoldus,[70] P. Bechtle,[70] J. F. Benitez,[70] R. Cenci,[70] J. P. Coleman,[70] M. R. Convery,[70] J. C. Dingfelder,[70] J. Dorfan,[70] G. P. Dubois-Felsmann,[70] W. Dunwoodie,[70] R. C. Field,[70] A. M. Gabareen,[70] S. J. Gowdy,[70] M. T. Graham,[70] P. Grenier,[70] C. Hast,[70] W. R. Innes,[70] J. Kaminski,[70] M. H. Kelsey,[70] H. Kim,[70] P. Kim,[70] M. L. Kocian,[70] D. W. G. S. Leith,[70] S. Li,[70] B. Lindquist,[70] S. Luitz,[70] V. Luth,[70] H. L. Lynch,[70] D. B. MacFarlane,[70] H. Marsiske,[70] R. Messner,[70] D. R. Muller,[70] H. Neal,[70] S. Nelson,[70] C. P. O'Grady,[70] I. Ofte,[70] A. Perazzo,[70] M. Perl,[70] B. N. Ratcliff,[70] A. Roodman,[70] A. A. Salnikov,[70] R. H. Schindler,[70] J. Schwiening,[70] A. Snyder,[70] D. Su,[70] M. K. Sullivan,[70] K. Suzuki,[70] S. K. Swain,[70] J. M. Thompson,[70] J. Va'vra,[70] A. P. Wagner,[70] M. Weaver,[70] C. A. West,[70] W. J. Wisniewski,[70] M. Wittgen,[70] D. H. Wright,[70] H. W. Wulsin,[70] A. K. Yarritu,[70] K. Yi,[70] C. C. Young,[70] V. Ziegler,[70] P. R. Burchat,[71] A. J. Edwards,[71] S. A. Majewski,[71] T. S. Miyashita,[71] B. A. Petersen,[71] L. Wilden,[71] S. Ahmed,[72] M. S. Alam,[72] R. Bula,[72] J. A. Ernst,[72] B. Pan,[72] M. A. Saeed,[72] S. B. Zain,[72] S. M. Spanier,[73] B. J. Wogsland,[73] R. Eckmann,[74] J. L. Ritchie,[74] A. M. Ruland,[74] C. J. Schilling,[74] R. F. Schwitters,[74] B. W. Drummond,[75] J. M. Izen,[75] X. C. Lou,[75] S. Ye,[75] V. Azzolini,[76] N. Lopez-March,[76] F. Martinez-Vidal,[76] D. A. Milanes,[76] A. Oyanguren,[76] J. Albert,[77] Sw. Banerjee,[77] B. Bhuyan,[77] H. H. F. Choi,[77] K. Hamano,[77] R. Kowalewski,[77] M. J. Lewczuk,[77] I. M. Nugent,[77] J. M. Roney,[77] R. J. Sobie,[77] T. J. Gershon,[78] P. F. Harrison,[78] J. Ilic,[78] T. E. Latham,[78] G. B. Mohanty,[78] H. R. Band,[79] X. Chen,[79] S. Dasu,[79] K. T. Flood,[79] Y. Pan,[79] M. Pierini,[79] R. Prepost,[79] C. O. Vuosalo,[79] and S. L. Wu[79]

(The *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]*University of Bergen, Institute of Physics, N-5007 Bergen, Norway*
[4]*Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA*
[5]*University of Birmingham, Birmingham, B15 2TT, United Kingdom*
[6]*Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany*
[7]*University of Bristol, Bristol BS8 1TL, United Kingdom*
[8]*University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1*
[9]*Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom*
[10]*Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia*
[11]*University of California at Irvine, Irvine, California 92697, USA*
[12]*University of California at Los Angeles, Los Angeles, California 90024, USA*
[13]*University of California at Riverside, Riverside, California 92521, USA*
[14]*University of California at San Diego, La Jolla, California 92093, USA*
[15]*University of California at Santa Barbara, Santa Barbara, California 93106, USA*
[16]*University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA*
[17]*California Institute of Technology, Pasadena, California 91125, USA*
[18]*University of Cincinnati, Cincinnati, Ohio 45221, USA*
[19]*University of Colorado, Boulder, Colorado 80309, USA*
[20]*Colorado State University, Fort Collins, Colorado 80523, USA*
[21]*Technische Universität Dortmund, Fakultät Physik, D-44221 Dortmund, Germany*
[22]*Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany*
[23]*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France*
[24]*University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*
[25]*Harvard University, Cambridge, Massachusetts 02138, USA*

[26]Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
[27]Humboldt-Universität zu Berlin, Institut für Physik, Newtonstr. 15, D-12489 Berlin, Germany
[28]INFN Sezione di Bari[a]; Dipartmento di Fisica, Università di Bari[b], I-70126 Bari, Italy
[29]INFN Sezione di Ferrara[a]; Dipartimento di Fisica, Università di Ferrara[b], I-44100 Ferrara, Italy
[30]INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy
[31]INFN Sezione di Genova[a]; Dipartimento di Fisica, Università di Genova[b], I-16146 Genova, Italy
[32]INFN Sezione di Milano[a]; Dipartimento di Fisica, Università di Milano[b], I-20133 Milano, Italy
[33]INFN Sezione di Napoli[a]; Dipartimento di Scienze Fisiche,
Università di Napoli Federico II[b], I-80126, Napoli, Italy
[34]INFN Sezione di Padova[a]; Dipartimento di Fisica, Università di Padova[b], I-35131 Padova, Italy
[35]INFN Sezione di Perugia[a]; Dipartimento di Fisica, Università di Perugia[b], I-06100 Perugia, Italy
[36]INFN Sezione di Pisa[a]; Dipartimento di Fisica,
Università di Pisa[b]; Scuola Normale Superiore di Pisa[c], I-56127 Pisa, Italy
[37]INFN Sezione di Roma[a]; Dipartimento di Fisica,
Università di Roma La Sapienza[b], I-00185 Roma, Italy
[38]INFN Sezione di Torino[a]; Dipartimento di Fisica Sperimentale, Università di Torino[b], I-10125 Torino, Italy
[39]INFN Sezione di Trieste[a]; Dipartimento di Fisica, Università di Trieste[b], I-34127 Trieste, Italy
[40]Imperial College London, London, SW7 2AZ, United Kingdom
[41]University of Iowa, Iowa City, Iowa 52242, USA
[42]Iowa State University, Ames, Iowa 50011-3160, USA
[43]Johns Hopkins University, Baltimore, Maryland 21218, USA
[44]Universität Karlsruhe, Institut für Experimentelle Kernphysik, D-76021 Karlsruhe, Germany
[45]Laboratoire de l'Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11,
Centre Scientifique d'Orsay, B. P. 34, F-91898 ORSAY Cedex, France
[46]Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[47]University of Liverpool, Liverpool L69 7ZE, United Kingdom
[48]Queen Mary, University of London, E1 4NS, United Kingdom
[49]University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
[50]University of Louisville, Louisville, Kentucky 40292, USA
[51]University of Manchester, Manchester M13 9PL, United Kingdom
[52]University of Maryland, College Park, Maryland 20742, USA
[53]University of Massachusetts, Amherst, Massachusetts 01003, USA
[54]Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA
[55]McGill University, Montréal, Québec, Canada H3A 2T8
[56]University of Mississippi, University, Mississippi 38677, USA
[57]Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7
[58]Mount Holyoke College, South Hadley, Massachusetts 01075, USA
[59]NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
[60]University of Notre Dame, Notre Dame, Indiana 46556, USA
[61]Ohio State University, Columbus, Ohio 43210, USA
[62]University of Oregon, Eugene, Oregon 97403, USA
[63]Laboratoire de Physique Nucléaire et de Hautes Energies,
IN2P3/CNRS, Université Pierre et Marie Curie-Paris6,
Université Denis Diderot-Paris7, F-75252 Paris, France
[64]University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
[65]Princeton University, Princeton, New Jersey 08544, USA
[66]Universität Rostock, D-18051 Rostock, Germany
[67]Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
[68]DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France
[69]University of South Carolina, Columbia, South Carolina 29208, USA
[70]Stanford Linear Accelerator Center, Stanford, California 94309, USA
[71]Stanford University, Stanford, California 94305-4060, USA
[72]State University of New York, Albany, New York 12222, USA
[73]University of Tennessee, Knoxville, Tennessee 37996, USA
[74]University of Texas at Austin, Austin, Texas 78712, USA
[75]University of Texas at Dallas, Richardson, Texas 75083, USA
[76]IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain
[77]University of Victoria, Victoria, British Columbia, Canada V8W 3P6
[78]Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom
[79]University of Wisconsin, Madison, Wisconsin 53706, USA

We present measurements of the *CP*-violation parameters S and C for the radiative decay $B^0 \to \eta K^0_S\gamma$; for $B \to \eta K\gamma$ we also measure the branching fractions and for $B^+ \to \eta K^+\gamma$ the time-integrated charge asymmetry $\mathcal{A}_{ch}$. The data, collected with the *BABAR* detector at the Stanford

Linear Accelerator Center, represent 465×10^6 $B\overline{B}$ pairs produced in e^+e^- annihilation. The results are $S = -0.18^{+0.49}_{-0.46} \pm 0.12$, $C = -0.32^{+0.40}_{-0.39} \pm 0.07$, $\mathcal{B}(B^0 \to \eta K^0\gamma) = (7.1^{+2.1}_{-2.0} \pm 0.4) \times 10^{-6}$, $\mathcal{B}(B^+ \to \eta K^+\gamma) = (7.7 \pm 1.0 \pm 0.4) \times 10^{-6}$, and $\mathcal{A}_{ch} = (-9.0^{+10.4}_{-9.8} \pm 1.4) \times 10^{-2}$. The first error quoted is statistical and the second systematic.

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Radiative B meson decays have long been recognized as a sensitive probe to test the standard model (SM) and to look for new physics (NP) [1, 2]. In the SM, flavor-changing neutral current processes, such as $b \to s\gamma$, proceed via radiative loop diagrams. The loop diagrams may also contain new heavy particles, and therefore are sensitive to NP. The measured branching fractions of inclusive $b \to s\gamma$ and exclusive radiative B decays are in agreement with SM predictions [2–4]. Recent estimates of the branching fraction of the inclusive $b \to s\gamma$ decay are affected by a theoretical uncertainties as large as the experimental ones [5].

In the SM the photon polarization in radiative decays is dominantly left (right) handed for b ($\bar{b}$) decays, resulting in the suppression of mixing-induced [6] *CP* asymmetries. Because we do not measure the photon helicity, we sum the decay rates for the left-handed and right-handed helicity states. Observation of significant *CP*-violation in these radiative decay modes would provide a clear sign of NP [7]. We search also for direct *CP* asymmetry in charged B decays, measuring the charge asymmetry $\mathcal{A}_{ch} \equiv (\Gamma^- - \Gamma^+)/(\Gamma^- + \Gamma^+)$, where Γ is the partial decay width of the B meson, and the superscript corresponds to its charge. This asymmetry in the SM is expected to be very small [8].

In this letter, we present the first measurement of the mixing-induced *CP* violation in the decay mode $B^0 \to \eta K^0\gamma$. Branching fractions for the decay modes $B^0 \to \eta K^0\gamma$ and $B^+ \to \eta K^+\gamma$ [9] and time-integrated charge-asymmetry for $B^+ \to \eta K^+\gamma$ have been measured previously by the Belle [10] and *BABAR* [11] Collaborations. We update our previous measurements with a data sample that is twice as large.

The results presented here are based on data collected with the *BABAR* detector [12] at the PEP-II asymmetric-energy e^+e^- collider [13] located at the Stanford Linear Accelerator Center. We use an integrated luminosity of 423 fb^{-1}, corresponding to 465 ± 5 million $B\overline{B}$ pairs, recorded at the $\Upsilon(4S)$ resonance (at a center-of-mass energy of $\sqrt{s} = 10.58$ GeV).

Description of the *BABAR* detector and of the reconstruction of charged and neutral particles can be found elsewhere [14]. The B decay daughter candidates are reconstructed through their decays $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$ ($\eta_{\gamma\gamma}$), and $\eta \to \pi^+\pi^-\pi^0$ ($\eta_{3\pi}$). Reconstruction and selection criteria of charged and neutral mesons, and primary photons and the study of continuum and $B\overline{B}$ backgrounds are described in our previous paper [11].

A B meson candidate is reconstructed by combining an η candidate, a charged or neutral kaon and a primary photon candidate. It is characterized kinematically by the energy-substituted mass $m_{\rm ES} \equiv \sqrt{(s/2 + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2}$ and energy difference $\Delta E \equiv E_B^* - \frac{1}{2}\sqrt{s}$, where the subscripts 0 and B refer to the initial $\Upsilon(4S)$ and to the B candidate in the lab-frame, respectively, and the asterisk denotes the $\Upsilon(4S)$ rest frame. We require $5.25 < m_{\rm ES} < 5.29$ GeV$/c^2$ and $|\Delta E| < 0.2$ GeV.

From a candidate $B\overline{B}$ pair we reconstruct a B^0 decaying into $\eta K^0_S\gamma$ ($B_{\rm rec}$). We also reconstruct the decay point of the other B meson ($B_{\rm tag}$) and identify its flavor. The difference $\Delta t \equiv t_{\rm rec} - t_{\rm tag}$ of the proper decay times $t_{\rm rec}$ and $t_{\rm tag}$ of the reconstructed and tag B mesons, respectively, is obtained from the measured distance between the $B_{\rm rec}$ and $B_{\rm tag}$ decay vertices and from the boost ($\beta\gamma = 0.56$) of the e^+e^- system. The Δt distribution [15] is given by:

$$F(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}[1 \mp \Delta w \pm (1-2w)\left(S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)\right)]. \quad (1)$$

The upper (lower) sign denotes a decay accompanied by a $B^0(\overline{B}^0)$ tag, τ is the mean B^0 lifetime, Δm_d is the mixing frequency, and the mistag parameters w and Δw are the average and difference, respectively, of the probabilities that a true B^0 is incorrectly tagged as a $\overline{B}^0$ or vice versa. In the flavor tagging algorithm [16] there are six mutually exclusive tagging categories of different response purities and untagged events with no tagging informations. Tagging and Δt informations are used for the measurement of the *CP*-violation parameters S and C in the decay mode $B^0 \to \eta K^0\gamma$.

We use the same technique developed for $B^0 \to \pi^0 K^0_S\gamma$ decays [15] to reconstruct the $B^0 \to \eta_{\gamma\gamma}K^0_S\gamma$ decay point, using the knowledge of the K^0_S trajectory and the average interaction point in a geometric fit. The extraction of Δt has been extensively validated in data [17] and in a full detector simulation. In about 70% of the selected events the Δt resolution is sufficient for the time-dependent *CP*-violation measurement. For the remaining events the Δt information is not used. For both $\eta_{\gamma\gamma}K^0_S\gamma$ and $\eta_{3\pi}K^0_S\gamma$ modes we use the events which satisfy the requirements $|\Delta t| < 20$ ps and $\sigma_{\Delta t} < 2.5$ ps, where $\sigma_{\Delta t}$ is the per-event error on Δt.

We obtain signal event yields and *CP*-violation parameters from unbinned extended maximum-likelihood (ML) fits. We indicate with j the species of event: signal, $q\bar{q}$

continuum background, $B\overline{B}$ peaking background (*BP*), and $B\overline{B}$ non-peaking background (*BNP*). The input observables are $m_{\rm ES}$, ΔE, the output of a Neural Network (*NN*), the η invariant mass m_η, and Δt. The *NN* combines four variables: the absolute values of the cosines of the polar angles with respect to the beam axis in the $\Upsilon(4S)$ frame of the B candidate momentum and the B thrust axis, the ratio of the second and zeroth Fox-Wolfram moments [18], and the absolute value of the cosine of the angle $\theta_{\rm T}$ between the thrust axis of the B candidate and that of the rest of the tracks and neutral clusters in the event, calculated in the $\Upsilon(4S)$ frame.

For each species j and tagging category c, we define a total probability density function (PDF) for event i as

$$\mathcal{P}^i_{j,c} \equiv \mathcal{P}_j({m_{\rm ES}}^i)\cdot\mathcal{P}_j(\Delta E^i)\cdot\mathcal{P}_j(NN^i)\cdot \mathcal{P}_j(m^i_\eta)\cdot\mathcal{P}_j(\Delta t^i,\sigma^i_{\Delta t};c)\,. \quad (2)$$

The factored form of the PDF is a good approximation since correlations between input observables are small. With n_j defined to be the number of events of the species j and $f_{j,c}$ the fraction of events of species j for each category c, we write the extended likelihood function for all events belonging to category c as

$$\mathcal{L}_c = \exp\Big(-\sum_j n_{j,c}\Big)\prod_i^{N_c}(n_{\rm sig}f_{{\rm sig},c}\mathcal{P}^i_{{\rm sig},c} + n_{q\bar{q}}f_{q\bar{q},c}\mathcal{P}^i_{q\bar{q}} + n_{BNP}f_{BNP,c}\mathcal{P}^i_{BNP} + n_{BP}f_{BP,c}\mathcal{P}^i_{BP}), \quad (3)$$

where $n_{j,c}$ is the yield of events of species j found by the fitter in category c and N_c the number of events of category c in the sample. We fix $f_{{\rm sig},c}$, $f_{BNP,c}$, and $f_{BP,c}$ to $f_{B_{\rm flav},c}$, the values measured with a large sample of B-decays to fully reconstructed flavor eigenstates ($B_{\rm flav}$) [19]. The total likelihood function $\mathcal{L}_d$ for decay mode d is given as the product over the seven tagging categories. Finally, when combining decay modes we form the grand likelihood $\mathcal{L} = \prod\mathcal{L}_d$.

The PDF $\mathcal{P}_{\rm sig}(\Delta t,\,\sigma_{\Delta t};c)$, for each category c, is the convolution of $F(\Delta t;\,c)$ (Eq. 1) with the signal resolution function (sum of three Gaussians) determined from the $B_{\rm flav}$ sample. The other PDF forms are: the sum of two Gaussians for $\mathcal{P}_{\rm sig}(m_{\rm ES})$, $\mathcal{P}_{\rm sig}(\Delta E)$, and $\mathcal{P}_{\rm sig}(m_\eta)$; the sum of three Gaussians for $\mathcal{P}_{q\bar{q}}\,(\Delta t)$, $\mathcal{P}_{BNP}(\Delta t)$, and $\mathcal{P}_{BP}(\Delta t)$; a non-parametric step function for $\mathcal{P}_j(NN)$ [20]; a linear dependence for $\mathcal{P}_{q\bar{q}}\,(\Delta E)$, $\mathcal{P}_{BNP}(\Delta E)$, and $\mathcal{P}_{BP}(\Delta E)$; a first-order polynomial plus a Gaussian for $\mathcal{P}_{q\bar{q}}\,(m_\eta)$, $\mathcal{P}_{BNP}(m_\eta)$, and $\mathcal{P}_{BP}(m_\eta)$; and for $\mathcal{P}_{q\bar{q}}\,(m_{\rm ES})$, $\mathcal{P}_{BNP}(m_{\rm ES})$, and $\mathcal{P}_{BP}(m_{\rm ES})$, the function $x\sqrt{1-x^2}\exp\left[-\xi(1-x^2)\right]$, with $x\equiv 2m_{\rm ES}/\sqrt{s}$ [21], where for the *BP* PDFs we add a Gaussian. We allow $q\bar{q}$ background PDF parameters to vary in the fit.

We determine the PDF parameters from Monte Carlo (MC) simulation for the signal and $B\overline{B}$ backgrounds, while using sideband data ($5.25 < m_{\rm ES} < 5.27$ GeV/c^2; $0.1 < |\Delta E| < 0.2$ GeV) to model the PDFs of continuum background. Large control samples of B decays to charmed final states with similar topology and a smearing procedure applied to photons during the event reconstruction are used to verify the simulated resolutions in $m_{\rm ES}$ and ΔE. Where the control data samples reveal differences from the MC in mass resolution, we shift or scale the resolution used in the likelihood fits. The largest shift in $m_{\rm ES}$ is 0.6 MeV/c^2. Any bias in the fit is determined from a large set of simulated experiments in which the $q\bar{q}$ and *BNP* backgrounds are generated from the PDFs, and into which we have embedded the expected number of *BP* and signal events chosen randomly from fully simulated MC samples.

We compute the branching fractions and charge asymmetry from fits made without Δt or flavor tagging. The free parameters in the fit are: the signal, $q\bar{q}$, *BNP* and *BP* background yields; the bin weights of the step function for $\mathcal{P}_{q\bar{q}}\,(NN)$; the slopes of $\mathcal{P}_{q\bar{q}}\,(\Delta E)$ and $\mathcal{P}_{q\bar{q}}\,(m_\eta)$; ξ; and for charged modes the signal and background $\mathcal{A}_{ch}$. We apply the same procedure to extract S and C. In this case we add in the fit the Δt variable and the flavor-tagging information. As free parameters we have also S, C, and the parameters of the $\mathcal{P}_{q\bar{q}}\,(\Delta t)$ PDF.

Table I lists the results of the fits. The corrected signal yield is the fitted yield minus the fit bias which is in the range $2-4\%$. The efficiency is calculated as the ratio of the number of signal MC events entering the ML fit to the total generated. We compute the branching fractions from the corrected signal yields, reconstruction efficiencies, daughter branching fractions, and the number of produced B mesons. We assume that the branching fractions of the $\Upsilon(4S)$ to B^+B^- and $B^0\overline{B}^0$ are each equal to 50%. We combine results from different channels by adding their likelihood functions, taking into account the correlated and uncorrelated systematic errors.

The statistical error on the signal yield, S, C and the signal charge asymmetry is taken as the change in the central value when the quantity $-2\ln\mathcal{L}$ increases by one unit from its minimum value. The significance $\mathcal{S}$ (σ) is the square root of the difference between the value of $-2\ln\mathcal{L}$ (with systematic uncertainties included) for zero signal and the value at its minimum.

Figure 1 shows, as representative fits, the projections onto $m_{\rm ES}$ and ΔE while Fig. 2 shows the projections onto Δt and the raw asymmetry between B^0 and $\overline{B}^0$ tags. In these projections a subset of the data is used for which the signal likelihood (computed without the variable plotted) exceeds a threshold that optimizes the sensitivity.

Figure 3 shows the distribution of the ηK invariant mass for signal events obtained by the event-weighting technique (sPlot) described in Ref. [22]. We use the covariance matrix and PDFs from the ML fit to determine a probability for each signal event. The resulting distri-

TABLE I: Number of events N in the sample, corrected signal yield, detection efficiency ϵ, daughter branching fraction product $\prod \mathcal{B}_i$, significance $\mathcal{S}$ (σ) (including systematic uncertainties), and measured branching fraction $\mathcal{B}$ with statistical error for each decay mode. For the combined measurements we give $\mathcal{S}$ (σ) and the branching fraction with statistical and systematic uncertainty. For the neutral mode we give the S and C parameters for each decay mode and for their combination. For the charged modes we also give the measured signal charge asymmetry $\mathcal{A}_{ch}$.

Mode	N	Yield	ϵ (%)	$\prod \mathcal{B}_i$(%)	$\mathcal{S}$ (σ)	$\mathcal{B}(10^{-6})$	$\mathcal{A}_{ch}$ (10^{-2})	S	C
$\eta_{\gamma\gamma} K^0\gamma$	3690	58^{+19}_{-18}	12	13.6	3.3	$7.4^{+2.5}_{-2.3}$		-0.04 ± 0.62	-0.24 ± 0.44
$\eta_{3\pi} K^0\gamma$	2282	24^{+13}_{-12}	10	7.8	2.1	$6.6^{+3.6}_{-3.2}$		-0.45 ± 0.81	-0.71 ± 0.87
$\boldsymbol{\eta K^0\gamma}$					**3.9**	$\mathbf{7.1^{+2.1}_{-2.0} \pm 0.4}$		$\mathbf{-0.18^{+0.49}_{-0.46} \pm 0.12}$	$\mathbf{-0.32^{+0.40}_{-0.39} \pm 0.07}$
$\eta_{\gamma\gamma} K^+\gamma$	11620	266^{+37}_{-36}	19	39.4	6.5	$7.8^{+1.1}_{-1.0}$	-4 ± 12		
$\eta_{3\pi} K^+\gamma$	10738	111^{+26}_{-24}	14	22.4	4.5	$7.4^{+1.7}_{-1.6}$	-24 ± 20		
$\boldsymbol{\eta K^+\gamma}$					**8.0**	$\mathbf{7.7 \pm 1.0 \pm 0.4}$	$\mathbf{-9.0^{+10.4}_{-9.8} \pm 1.4}$		

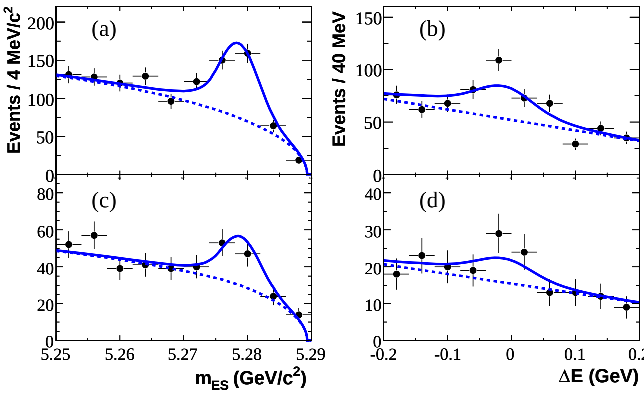

FIG. 1: The B candidate $m_{\rm ES}$ and ΔE projections (see text) for $\eta K^+\gamma$ (a, b), $\eta K^0\gamma$ (c, d). Points with error bars (statistical only) represent the data, the solid line the full fit function, and the dashed line its background component.

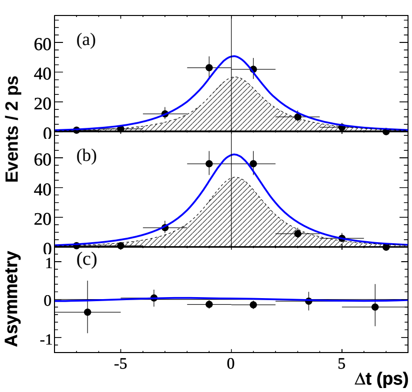

FIG. 2: Projections (see text) onto Δt of the data (points with error bars), fit function (solid line), and background function (dashed line), for (a) B^0 and (b) $\overline{B}^0$ tagged events, and (c) the raw asymmetry $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$ between B^0 and $\overline{B}^0$ tags.

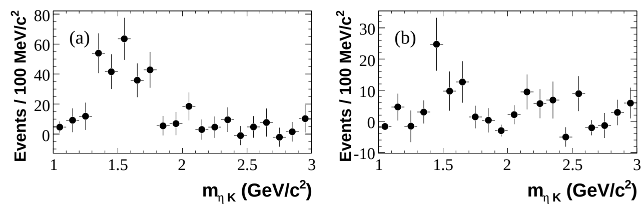

FIG. 3: Plot of ηK invariant mass for signal using the weighting technique described in the text for the combined sub-decay modes: (a) $B^+ \to \eta K^+\gamma$, (b) $B^0 \to \eta K^0\gamma$. Errors are statistical only.

butions (points with errors) are normalized to the signal yield. This mass distribution is useful to compare with theoretical predictions for radiative decays.

The main sources of systematic uncertainties for the time-dependent measurements come from the variation of the signal PDF shape parameters within their errors (0.08 for S, 0.04 for C), and from $B\overline{B}$ backgrounds (0.09 for S, 0.06 for C). Other minor sources are SVT alignment, beam spot position and size, and interference between the CKM-suppressed $\bar{b} \to \bar{u}c\bar{d}$ amplitude and the favored $b \to c\bar{u}d$ amplitude for some tag-side B decays [23]. The $B_{\rm flav}$ sample is used to determine the errors associated with the signal Δt resolutions, tagging efficiencies, and mistag rates. Published measurements [4] for τ and Δm_d are used to determine the errors associated with them. Summing all systematic errors in quadrature, we obtain ± 0.12 for S and ± 0.07 for C.

The main sources of systematic uncertainties for the branching fraction measurements include uncertainties in the PDF parameterization and ML fit bias. For the signal, the uncertainties in PDF parameters are estimated by comparing MC and data in control samples. Varying the signal PDF parameters within these errors, we estimate yield uncertainties of 3–23 events, depending on the mode. The uncertainty (1–3 events) from fit bias is taken as half the correction itself. Systematic uncertainties due to lack of knowledge of the primary photon spectrum are estimated to be in the range 2–3% depending on the decay mode. Uncertainties in our knowledge of the efficiency, found from auxiliary studies [14], include $0.4\% \times N_t$ and $1.8\% \times N_\gamma$, where N_t and N_γ are the numbers of tracks and photons, respectively, in the B candidate. There is a systematic error of 2.1% in the efficiency of K^0_S reconstruction. The uncertainty in the total number of $B\overline{B}$ pairs in the data sample is 1.1%. Published data [4] provide the uncertainties in the B daughter branching fraction products (0.7–1.8%).

A systematic uncertainty of 0.014 is assigned to $\mathcal{A}_{ch}$. This uncertainty is estimated from studies with signal MC events and data control samples and from calculation of the asymmetry due to particles interacting in the detector.

In conclusion, we measure the time-dependent CP violation parameters in the decay mode $B^0 \rightarrow \eta K^0_S\gamma$: $S = -0.18^{+0.49}_{-0.46} \pm 0.12$ and $C = -0.32^{+0.40}_{-0.39} \pm 0.07$. These results are consistent with no CP-violation in this mode. We also measure the branching fractions, in units of 10^{-6}, $\mathcal{B}(B^0 \rightarrow \eta K^0\gamma) = 7.1^{+2.1}_{-2.0} \pm 0.4$ and $\mathcal{B}(B^+ \rightarrow \eta K^+\gamma) = 7.7 \pm 1.0 \pm 0.4$, in agreement with the results from Belle [10] and the previous *BABAR* results [11]. The measured charge asymmetry in the decay $B^+ \rightarrow \eta K^+\gamma$ is consistent with zero. Its confidence interval at 90% confidence level is $[-0.25, 0.08]$.

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* Deceased
† Now at Temple University, Philadelphia, Pennsylvania 19122, USA
‡ Now at Tel Aviv University, Tel Aviv, 69978, Israel
§ Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy
¶ Also with Università di Sassari, Sassari, Italy
** Also with Università di Roma La Sapienza, I-00185 Roma, Italy
†† Now at University of South Alabama, Mobile, Alabama 36688, USA

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