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Authors
Aubert, B
Barate, R
Boutigny, D
et al.

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Measurement of the B^+/B^0 production ratio from the $\Upsilon(4S)$ meson using $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K_S^0$ decays

B. Aubert,[1] R. Barate,[1] D. Boutigny,[1] F. Couderc,[1] J.-M. Gaillard,[1] A. Hicheur,[1] Y. Karyotakis,[1] J. P. Lees,[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] 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] S. E. Morgan,[6] A. T. Watson,[6] N. K. Watson,[6] M. Fritsch,[7] K. Goetzen,[7] T. Held,[7] H. Koch,[7] B. Lewandowski,[7] M. Pelizaeus,[7] M. Steinke,[7] J. T. Boyd,[8] N. Chevalier,[8] W. N. Cottingham,[8] M. P. Kelly,[8] T. E. Latham,[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] L. Teodorescu,[10] V. E. Blinov,[11] A. D. Bukin,[11] V. P. Druzhinin,[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] I. Eschrich,[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] 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] 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] 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] P. Spradlin,[17] D. C. Williams,[17] M. G. Wilson,[17] J. Albert,[18] E. Chen,[18] G. P. Dubois-Felsmann,[18] A. Dvoretskii,[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. Jayatilleke,[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. 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] D. Altenburg,[22] T. Brandt,[22] J. Brose,[22] T. Colberg,[22] M. Dickopp,[22] E. Feltresi,[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] D. Bernard,[23] G. R. Bonneaud,[23] F. Brochard,[23] P. Grenier,[23] Ch. Thiebaux,[23] G. Vasileiadis,[23] M. Verderi,[23] D. J. Bard,[24] A. Khan,[24] D. Lavin,[24] F. Muheim,[24] S. Playfer,[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] A. Sarti,[25] E. Treadwell,[26] R. Baldini-Ferroli,[27] A. Calcaterra,[27] R. de Sangro,[27] G. Finocchiaro,[27] P. Patteri,[27] M. Piccolo,[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] G. Brandenburg,[29] M. Morii,[29] E. Won,[29] R. S. Dubitzky,[30] U. Langenegger,[30] W. Bhimji,[31] D. A. Bowerman,[31] P. D. Dauncey,[31] U. Egede,[31] J. R. Gaillard,[31] G. W. Morton,[31] J. A. Nash,[31] G. P. Taylor,[31] G. J. Grenier,[32] S.-J. Lee,[32] U. Mallik,[32] J. Cochran,[33] H. B. Crawley,[33] J. Lamsa,[33] W. T. Meyer,[33] S. Prell,[33] E. I. Rosenberg,[33] J. Yi,[33] M. Davier,[34] G. Grosdidier,[34] A. Höcker,[34] S. Laplace,[34] F. Le Diberder,[34] V. Lepeltier,[34] A. M. Lutz,[34] T. C. Petersen,[34] S. Plaszczynski,[34] M. H. Schune,[34] L. Tantot,[34] G. Wormser,[34] C. H. Cheng,[35] D. J. Lange,[35] M. C. Simani,[35] D. M. Wright,[35] A. J. Bevan,[36] J. P. Coleman,[36] J. R. Fry,[36] E. Gabathuler,[36] R. Gamet,[36] M. Kay,[36] R. J. Parry,[36] D. J. Payne,[36] R. J. Sloane,[36] C. Touramanis,[36] J. J. Back,[37] P. F. Harrison,[37] G. B. Mohanty,[37] C. L. Brown,[38] G. Cowan,[38] R. L. Flack,[38] H. U. Flaecher,[38] S. George,[38] M. G. Green,[38] A. Kurup,[38] C. E. Marker,[38] T. R. McMahon,[38] S. Ricciardi,[38] F. Salvatore,[38] G. Vaitsas,[38] M. A. Winter,[38] D. Brown,[39] C. L. Davis,[39] J. Allison,[40] N. R. Barlow,[40] R. J. Barlow,[40] P. A. Hart,[40] M. C. Hodgkinson,[40] G. D. Lafferty,[40] A. J. Lyon,[40] J. C. Williams,[40] A. Farbin,[41] W. D. Hulsbergen,[41] A. Jawahery,[41] D. Kovalskyi,[41] C. K. Lae,[41] V. Lillard,[41] D. A. Roberts,[41] G. Blaylock,[42] C. Dallapiccola,[42] K. T. Flood,[42] S. S. Hertzbach,[42] R. Kofler,[42] V. B. Koptchev,[42] T. B. Moore,[42] S. Saremi,[42] H. Staengle,[42] S. Willocq,[42] R. Cowan,[43] G. Sciolla,[43] F. Taylor,[43] R. K. Yamamoto,[43] D. J. J. Mangeol,[44] P. M. Patel,[44] S. H. Robertson,[44] A. Lazzaro,[45] F. Palombo,[45] J. M. Bauer,[46] L. Cremaldi,[46] V. Eschenburg,[46] R. Godang,[46] R. Kroeger,[46] J. Reidy,[46] D. A. Sanders,[46] D. J. Summers,[46] H. W. Zhao,[46] S. Brunet,[47] D. Côté,[47] P. Taras,[47] H. Nicholson,[48] C. Cartaro,[49] N. Cavallo,[49] F. Fabozzi,[49,*] C. Gatto,[49] L. Lista,[49] D. Monorchio,[49] P. Paolucci,[49] D. Piccolo,[49] C. Sciacca,[49] M. Baak,[50] G. Raven,[50] L. Wilden,[50] C. P. Jessop,[51] J. M. LoSecco,[51] T. A. Gabriel,[52] T. Allmendinger,[53] B. Brau,[53] K. K. Gan,[53] K. Honscheid,[53] D. Hufnagel,[53] H. Kagan,[53] R. Kass,[53] T. Pulliam,[53] R. Ter-Antonyan,[53] Q. K. Wong,[53] J. Brau,[54] R. Frey,[54] O. Igonkina,[54] C. T. Potter,[54] N. B. Sinev,[54] D. Strom,[54] E. Torrence,[54] F. Colecchia,[55] A. Dorigo,[55] F. Galeazzi,[55] M. Margoni,[55] M. Morandin,[55] M. Posocco,[55] M. Rotondo,[55] F. Simonetto,[55] R. Stroili,[55] G. Tiozzo,[55] C. Voci,[55] M. Benayoun,[56] H. Briand,[56] J. Chauveau,[56] P. David,[56] Ch. de la Vaissière,[56] L. Del Buono,[56] O. Hamon,[56] M. J. J. John,[56] Ph. Leruste,[56] J. Ocariz,[56] M. Pivk,[56] L. Roos,[56] S. T'Jampens,[56] G. Therin,[56] P. F. Manfredi,[57] V. Re,[57] P. K. Behera,[58] L. Gladney,[58] Q. H. Guo,[58] J. Panetta,[58] F. Anulli,[27,59] M. Biasini,[59] I. M. Peruzzi,[27,59] M. Pioppi,[59] C. Angelini,[60] G. Batignani,[60] S. Bettarini,[60] M. Bondioli,[60] F. Bucci,[60] G. Calderini,[60] M. Carpinelli,[60] V. Del Gamba,[60] F. Forti,[60] M. A. Giorgi,[60] A. Lusiani,[60] G. Marchiori,[60] F. Martinez-Vidal,[60,†] M. Morganti,[60] N. Neri,[60] E. Paoloni,[60] M. Rama,[60] G. Rizzo,[60] F. Sandrelli,[60] J. Walsh,[60] M. Haire,[61] D. Judd,[61] K. Paick,[61] D. E. Wagoner,[61] N. Danielson,[62] P. Elmer,[62] C. Lu,[62] V. Miftakov,[62] J. Olsen,[62] A. J. S. Smith,[62] E. W. Varnes,[62] F. Bellini,[63] G. Cavoto,[62,63] R. Faccini,[63] F. Ferrarotto,[63] F. Ferroni,[63] M. Gaspero,[63] L. Li Gioi,[63] M. A. Mazzoni,[63] S. Morganti,[63]

M. Pierini,[63] G. Piredda,[63] F. Safai Tehrani,[63] C. Voena,[63] S. Christ,[64] G. Wagner,[64] R. Waldi,[64] T. Adye,[65] N. De Groot,[65] B. Franek,[65] N. I. Geddes,[65] G. P. Gopal,[65] E. O. Olaiya,[65] S. M. Xella,[65] R. Aleksan,[66] S. Emery,[66] A. Gaidot,[66] S. F. Ganzhur,[66] P.-F. Giraud,[66] G. Hamel de Monchenault,[66] W. Kozanecki,[66] M. Langer,[66] M. Legendre,[66] G. W. London,[66] B. Mayer,[66] G. Schott,[66] G. Vasseur,[66] Ch. Yèche,[66] M. Zito,[66] M. V. Purohit,[67] A. W. Weidemann,[67] F. X. Yumiceva,[67] D. Aston,[68] R. Bartoldus,[68] N. Berger,[68] A. M. Boyarski,[68] O. L. Buchmueller,[68] M. R. Convery,[68] M. Cristinziani,[68] G. De Nardo,[68] D. Dong,[68] J. Dorfan,[68] D. Dujmic,[68] W. Dunwoodie,[68] E. E. Elsen,[68] R. C. Field,[68] T. Glanzman,[68] S. J. Gowdy,[68] T. Hadig,[68] V. Halyo,[68] T. Hryn'ova,[68] W. R. Innes,[68] M. H. Kelsey,[68] P. Kim,[68] M. L. Kocian,[68] D. W. G. S. Leith,[68] J. Libby,[68] S. Luitz,[68] V. Luth,[68] H. L. Lynch,[68] H. Marsiske,[68] R. Messner,[68] D. R. Muller,[68] C. P. O'Grady,[68] V. E. Ozcan,[68] A. Perazzo,[68] M. Perl,[68] S. Petrak,[68] B. N. Ratcliff,[68] A. Roodman,[68] A. A. Salnikov,[68] R. H. Schindler,[68] J. Schwiening,[68] G. Simi,[68] A. Snyder,[68] A. Soha,[68] J. Stelzer,[68] D. Su,[68] M. K. Sullivan,[68] J. Va'vra,[68] S. R. Wagner,[68] M. Weaver,[68] A. J. R. Weinstein,[68] W. J. Wisniewski,[68] M. Wittgen,[68] D. H. Wright,[68] C. C. Young,[68] P. R. Burchat,[69] A. J. Edwards,[69] T. I. Meyer,[69] B. A. Petersen,[69] C. Roat,[69] S. Ahmed,[70] M. S. Alam,[70] J. A. Ernst,[70] M. A. Saeed,[70] M. Saleem,[70] F. R. Wappler,[70] W. Bugg,[71] M. Krishnamurthy,[71] S. M. Spanier,[71] R. Eckmann,[72] H. Kim,[72] J. L. Ritchie,[72] A. Satpathy,[72] R. F. Schwitters,[72] J. M. Izen,[73] I. Kitayama,[73] X. C. Lou,[73] S. Ye,[73] F. Bianchi,[74] M. Bona,[74] F. Gallo,[74] D. Gamba,[74] C. Borean,[75] L. Bosisio,[75] F. Cossutti,[75] G. Della Ricca,[75] S. Dittongo,[75] S. Grancagnolo,[75] L. Lanceri,[75] P. Poropat,[75,‡] L. Vitale,[75] G. Vuagnin,[75] R. S. Panvini,[76] Sw. Banerjee,[77] C. M. Brown,[77] D. Fortin,[77] P. D. Jackson,[77] R. Kowalewski,[77] J. M. Roney,[77] H. R. Band,[78] S. Dasu,[78] M. Datta,[78] A. M. Eichenbaum,[78] J. J. Hollar,[78] J. R. Johnson,[78] P. E. Kutter,[78] H. Li,[78] R. Liu,[78] F. Di Lodovico,[78] A. Mihalyi,[78] A. K. Mohapatra,[78] Y. Pan,[78] R. Prepost,[78] S. J. Sekula,[78] P. Tan,[78] J. H. von Wimmersperg-Toeller,[78] J. Wu,[78] S. L. Wu,[78] Z. Yu,[78] and H. Neal[79]

(*BABAR* Collaboration)

[1]*Laboratoire de Physique des Particules, F-74941 Annecy-le-Vieux, France*
[2]*Università di Bari, Dipartimento di Fisica and INFN, I-70126 Bari, Italy*
[3]*Institute of High Energy Physics, Beijing 100039, China*
[4]*University of Bergen, Institute of Physics, N-5007 Bergen, Norway*
[5]*Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA*
[6]*University of Birmingham, Birmingham, B15 2TT, United Kingdom*
[7]*Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany*
[8]*University of Bristol, Bristol BS8 1TL, United Kingdom*
[9]*University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1*
[10]*Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom*
[11]*Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia*
[12]*University of California at Irvine, Irvine, California 92697, USA*
[13]*University of California at Los Angeles, Los Angeles, California 90024, USA*
[14]*University of California at Riverside, Riverside, California 92521, USA*
[15]*University of California at San Diego, La Jolla, California 92093, USA*
[16]*University of California at Santa Barbara, Santa Barbara, California 93106, USA*
[17]*Institute for Particle Physics, University of California at Santa Cruz, Santa Cruz, California 95064, USA*
[18]*California Institute of Technology, Pasadena, California 91125, USA*
[19]*University of Cincinnati, Cincinnati, Ohio 45221, USA*
[20]*University of Colorado, Boulder, Colorado 80309, USA*
[21]*Colorado State University, Fort Collins, Colorado 80523, USA*
[22]*Technische Universität Dresden, Institut für Kernund 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]*Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany*
[31]*Imperial College London, London SW7 2AZ, United Kingdom*
[32]*University of Iowa, Iowa City, Iowa 52242, USA*
[33]*Iowa State University, Ames, Iowa 50011-3160, USA*
[34]*Laboratoire de l'Accélérateur Linéaire, F-91898 Orsay, France*
[35]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[36]*University of Liverpool, Liverpool L69 72E, United Kingdom*
[37]*Queen Mary, University of London, E1 4NS, United Kingdom*

[38]*University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom*
[39]*University of Louisville, Louisville, Kentucky 40292, USA*
[40]*University of Manchester, Manchester M13 9PL, United Kingdom*
[41]*University of Maryland, College Park, Maryland 20742, USA*
[42]*University of Massachusetts, Amherst, Massachusetts 01003, USA*
[43]*Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA*
[44]*McGill University, Montréal, Quebec, Canada H3A 2T8*
[45]*Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy*
[46]*University of Mississippi, University, Mississippi 38677, USA*
[47]*Université de Montréal, Laboratoire René J. A. Lévesque, Montréal, Quebec, Canada H3C 3J7*
[48]*Mount Holyoke College, South Hadley, Massachusetts 01075, USA*
[49]*Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy*
[50]*NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands*
[51]*University of Notre Dame, Notre Dame, Indiana 46556, USA*
[52]*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[53]*Ohio State University, Columbus, Ohio 43210, USA*
[54]*University of Oregon, Eugene, Oregon 97403, USA*
[55]*Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy*
[56]*Universités Paris VI et VII, Laboratoire de Physique Nucléaire H. E., F-75252 Paris, France*
[57]*Università di Pavia, Dipartimento di Elettronica and INFN, I-27100 Pavia, Italy*
[58]*University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
[59]*Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy*
[60]*Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy*
[61]*Prairie View A&M University, Prairie View, Texas 77446, USA*
[62]*Princeton University, Princeton, New Jersey 08544, USA*
[63]*Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy*
[64]*Universität Rostock, D-18051 Rostock, Germany*
[65]*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, United Kingdom*
[66]*DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France*
[67]*University of South Carolina, Columbia, South Carolina 29208, USA*
[68]*Stanford Linear Accelerator Center, Stanford, California 94309, USA*
[69]*Stanford University, Stanford, California 94305-4060, USA*
[70]*State University of New York, Albany, New York 12222, USA*
[71]*University of Tennessee, Knoxville, Tennessee 37996, USA*
[72]*University of Texas at Austin, Austin, Texas 78712, USA*
[73]*University of Texas at Dallas, Richardson, Texas 75083, USA*
[74]*Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy*
[75]*Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy*
[76]*Vanderbilt University, Nashville, Tennessee 37235, USA*
[77]*University of Victoria, Victoria, British Columbia, Canada V8W 3P6*
[78]*University of Wisconsin, Madison, Wisconsin 53706, USA*
[79]*Yale University, New Haven, Connecticut 06511, USA*

We report a measurement of the production ratio of charged and neutral B mesons from $\Upsilon(4S)$ decays based on the ratio of efficiency-corrected yields for the charmonium modes $J/\psi K^+$ and $J/\psi K_s^0$ with 81.9 fb^{-1} of data collected with the *BABAR* detector on the $\Upsilon(4S)$ resonance at 10.580 GeV. We find a value of $1.006 \pm 0.036(\text{stat}) \pm 0.031(\text{syst})$ for the ratio $R^{+/0} = \Gamma(\Upsilon(4S) \rightarrow B^+ B^-)/\Gamma(\Upsilon(4S) \rightarrow B^0 \bar{B}^0)$.

A measurement of the B^+/B^0 production ratio

$$R^{+/0} = \frac{\Gamma(\Upsilon(4S) \rightarrow B^+ B^-)}{\Gamma(\Upsilon(4S) \rightarrow B^0 \bar{B}^0)}$$

from the $\Upsilon(4S)$ meson is an essential element in determining branching fractions and quark-mixing matrix elements at the B factory experiments. It can also provide information about the structure of the $\Upsilon(4S)$ meson that can be used to discriminate between available models.

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*Also with Università della Basilicata, Potenza, Italy.
[†]Also with IFIC, Instituto de Física Corpuscular, CSIC–Universidad de Valencia, Valencia, Spain.
[‡]Deceased.

Over the past 15 years it has been frequently assumed that $R^{+/0}$ is equal to one, although many models predict that this may not be the case. Early calculations predicted that the ratio could be up to 20% greater than one, due to large Coulomb corrections [1]. Taking into account the structure of the B and $\Upsilon(4S)$ reduces the effect of the Coulomb interaction and can even lead to the ratio being less than unity [2]. With the prospect of precision measurements from the B factories, there has been a recent revival in theoretical work on the subject. A more detailed calculation has been done in a non-relativistic effective field theory with B^* intermediate states in the pion potential, which introduces isospin-breaking in strong interactions. These calculations predict a value 1.1–1.2 [3]. Other calculations attempting to take into account the structure of the mesons and hadronic final state interactions predict a ratio 0.9–1.2 [4], but with rapid variation as a function of the center-of-mass energy near the $\Upsilon(4S)$ resonance. For the $\Upsilon(4S)$, there are published measurements of $R^{+/0}$ by CLEO $(1.04\pm0.07\pm0.04$ [5], $1.058\pm0.084\pm0.136$ [6]), *BABAR* $(1.10\pm0.06\pm0.05$ [7] with 20 fb^{-1}), and Belle $(1.01\pm0.03\pm0.09$ [8] with 29 fb^{-1}). Now that a significantly larger $\Upsilon(4S)$ data sample is available at *BABAR* we can reduce the statistical uncertainty to the point where it is possible to confront the various theoretical predictions.

In this analysis we use the decay modes $B^0\rightarrow J/\psi K_s^0$ and $B^+\rightarrow J/\psi K^+$ [9], where $J/\psi\rightarrow\ell^+\ell^-$ and $K_s^0\rightarrow\pi^+\pi^-$, to measure the B^+/B^0 production ratio. These decays are good candidates for measuring $R^{+/0}$ since isospin violation in the $B\rightarrow J/\psi K$ decays is expected to be small in the standard model, of order $\lambda^3\approx0.01$ [10] when rescattering is small, where λ is defined as the sine of the Cabibbo angle.

The data used in this analysis were collected with the *BABAR* detector at the SLAC PEP-II e^+e^- storage ring. The data sample corresponds to 81.9 fb^{-1} of integrated luminosity collected at the $\Upsilon(4S)$ resonance. The distribution of center-of-mass energies due to the beam-energy spread is Gaussian with $\sigma=4.6$ MeV [11]. The mean energy of our sample is 10.580 GeV, with all data accumulated within one sigma of this value.

The *BABAR* detector is fully described elsewhere [12]. It consists of a charged-particle tracking system, a Cherenkov detector (DIRC) for particle identification, an electromagnetic calorimeter, and a system for muon identification. The tracking system consists of a five layer, double-sided silicon vertex tracker and a 40-layer drift chamber (filled with a mixture of helium and isobutane), both in a 1.5-T magnetic field supplied by a superconducting solenoidal magnet. The DIRC is an imaging Cherenkov detector relying on total internal reflection in the radiator. The electromagnetic calorimeter consists of 6580 CsI(Tl) crystals. The iron flux return is segmented and instrumented with resistive plate chambers for muon identification.

Hadronic events are selected by requiring the presence of at least three tracks in the angular region $0.41<\theta_{LAB}<2.54$ rad, where θ_{LAB} is the polar angle with respect to the electron beam direction. The ratio between the 2nd and 0th order Fox-Wolfram [13] moments must be less than 0.5. We also require that the total energy of all particles in the event

TABLE I. Summary of the resolution for ΔE in data and the MC simulation.

Mode		$\sigma(\Delta E)$ (MeV)	
B	J/ψ	MC	Data
B^+	e^+e^-	11.42 ± 0.11	10.87 ± 0.25
B^+	$\mu^+\mu^-$	9.72 ± 0.07	9.25 ± 0.20
B^0	e^+e^-	9.50 ± 0.11	10.02 ± 0.42
B^0	$\mu^+\mu^-$	7.92 ± 0.07	8.52 ± 0.32

be greater than 4.5 GeV. The primary vertex, which is constructed from charged tracks with an impact parameter less than 1 mm in the plane transverse to the beam direction, must be within 0.5 cm of the beam spot in the plane transverse to the beam direction and within 6 cm along the beam direction.

We reconstruct candidates for J/ψ mesons in the decay modes $J/\psi\rightarrow e^+e^-$ and $\mu^+\mu^-$. For $J/\psi\rightarrow e^+e^-$ decays one track is required to pass a tight electron selection and the other a loose requirement [7], while for $J/\psi\rightarrow\mu^+\mu^-$ decays we require one track to pass a loose muon selection and the other a minimum-ionizing requirement [7]. The daughter tracks of the J/ψ candidate are required to have 12 hits in the drift chamber, lie in the angular range $0.41<\theta_{LAB}<2.409$ rad for electrons and $0.41<\theta_{LAB}<2.54$ rad for muons and have a transverse momentum of at least 100 MeV/c. To increase the efficiency of the event selection, the electron candidate tracks are combined with photon candidates to recover some of the energy lost in bremsstrahlung [7]. A geometric vertex constraint fit is applied to the lepton track pair. The invariant mass requirements for the $J/\psi\rightarrow e^+e^-$ and $J/\psi\rightarrow\mu^+\mu^-$ channels are $2.95<M_{e^+e^-}<3.14$ GeV/c^2 and $3.06<M_{\mu^+\mu^-}<3.14$ GeV/c^2. We require $|\cos\theta_\ell|$ to be less than 0.8 and 0.9 for $J/\psi\rightarrow e^+e^-$ and $J/\psi\rightarrow\mu^+\mu^-$, respectively. The helicity angle θ_ℓ is the angle in the J/ψ rest frame between the positively charged J/ψ daughter and the reversed K flight direction in the B meson rest frame.

We reconstruct K_s^0 meson candidates from two charged tracks, which are not required to originate from the interaction point or to have drift chamber hits, in contrast to the J/ψ daughters. The tracks are assigned the pion mass to compute $M_{\pi^+\pi^-}$, which is required to lie in the range 0.490–0.505 GeV/c^2. Also, in order to reject combinatorial background, we only retain candidates with a fitted K_s^0 vertex displaced more than 1 mm from the primary vertex. Candidates for K^+ mesons are assigned the kaon mass and are required to form a vertex with the J/ψ candidate. No particle identification requirements are made for this track.

The selection of B candidates relies on the kinematic constraints given by the $\Upsilon(4S)$ initial state. Two largely uncorrelated variables are used: the energy-substituted B mass $m_{ES}=\sqrt{(s/2+\mathbf{p}_0\cdot\mathbf{p}_B)^2/E_0^2-p_B^2}$, where the subscripts 0 and B refer to the e^+e^- system and the B candidate, respectively, s is the square of the center-of-mass energy, and energies (E) and momentum vectors (**p**) are computed in the laboratory
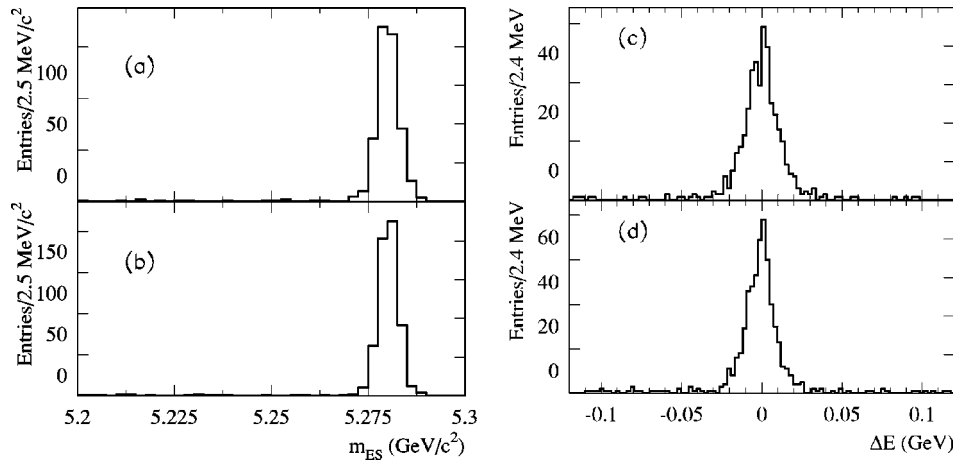
FIG. 1. Distribution of m_{ES} for $|\Delta E| < 3\sigma$ in the $B^0 \to J/\psi K_s^0$ sample for (a) $J/\psi \to e^+ e^-$ and (b) $J/\psi \to \mu^+ \mu^-$. Distribution of ΔE for $m_{ES} > 5.27$ GeV/c^2 in the $B^0 \to J/\psi K_s^0$ sample for (c) $J/\psi \to e^+ e^-$ and (d) $J/\psi \to \mu^+ \mu^-$.

frame; and $\Delta E = E_B^* - \sqrt{s}/2$, where E_B^* is the B candidate energy in the center-of-mass frame. In cases where multiple B candidates are present in the same event, 2% of the total in data and Monte Carlo (MC) simulations, only the one with the smallest absolute value of ΔE is retained.

The signal region in the m_{ES}-ΔE plane is defined by $5.27 < m_{ES} < 5.29$ GeV/c^2 and $|\Delta E| < 3\sigma(\Delta E)$. The observed resolutions for data and MC simulations for the different modes are listed in Table I. The m_{ES} sideband is defined by $5.20 < m_{ES} < 5.27$ GeV/c^2 and $|\Delta E| < 3\sigma(\Delta E)$. Upper and lower ΔE sidebands, used for the evaluation of systematic uncertainty, are defined as $50 < \Delta E < 120$ MeV and $-120 < \Delta E < -50$ MeV.

Since we are measuring the ratio of B^+ to B^0 efficiency-corrected yields many of the selection requirements are in common and have been optimized previously [7]. Therefore for this analysis, we have only reconsidered the optimization of the statistical uncertainty of the measurement due to those requirements that are different for the two modes. These requirements include the K_s^0 flight length, the K_s^0 mass window, and the ΔE window. The optimization of these variables maximizes the ratio $N_{cand}/\sqrt{\sigma^2(N_{cand}) + \sigma^2(N_{bkg})}$, where $\sigma(N_{cand})$ and $\sigma(N_{bkg})$ are the uncertainties on the number of signal candidates N_{cand} predicted by MC simulation and combinatorial background N_{bkg}, respectively, that pass the event selection procedure. N_{cand} is defined as the number of events in the signal region.

We fit the m_{ES} distribution in the m_{ES} sideband with an empirical phase-space-motivated function introduced by ARGUS [14]. The fitted distribution is then integrated over the signal region to determine the number of combinatorial background events N_{bkg}. In addition to combinatorial backgrounds there are other background sources, mostly in B decays to charmonium, that peak near the B mass in m_{ES}. These peaking sources are negligible for the neutral B sample, but include small contributions from $B^0 \to J/\psi K_s^0$ and $B^+ \to J/\psi \pi^+$ for the charged B sample. Requiring particle identifications on the K^+ candidate will reduce these contributions but introduces a larger systematic uncertainty. To determine the number of background events that peak in the m_{ES} signal region, N_{peak}, we use appropriately combined MC samples of continuum $e^+ e^-$ and generic [15] $B\bar{B}$ events (with signal events removed), which have been scaled to the integrated luminosity of the data sample. This distribution is then fitted with an ARGUS function as described above. We determine N_{peak} by counting the number of events in the signal region and subtracting the integral of the ARGUS function over this same region. The signal yield is then defined by $N_{signal} = N_{cand} - N_{bkg} - N_{peak}$. The observed distributions in m_{ES} and ΔE for $B^0 \to J/\psi K_s^0$ and $B^+ \to J/\psi K^+$ candidates in data are shown in Figs. 1 and 2, respectively.

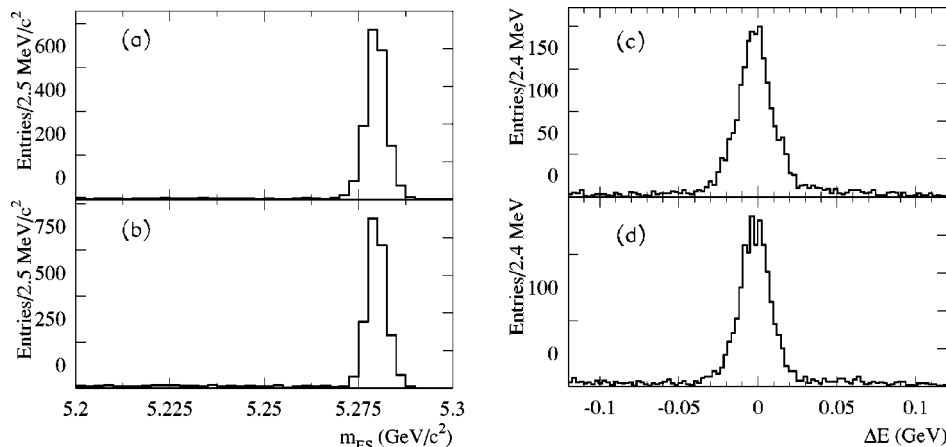The efficiency-corrected ratio of observed events is given by

FIG. 2. Distribution of m_{ES} for $|\Delta E| < 3\sigma$ in the $B^+ \to J/\psi K^+$ sample for (a) $J/\psi \to e^+ e^-$ and (b) $J/\psi \to \mu^+ \mu^-$. Distribution of ΔE for $m_{ES} > 5.27$ GeV/c^2 in the $B^+ \to J/\psi K^+$ for (c) $J/\psi \to e^+ e^-$ and (d) $J/\psi \to \mu^+ \mu^-$.

TABLE II. Summary of the relative systematic uncertainties on the efficiency-corrected yields.

Mode								
B	J/ψ	ϵ_{Trk}	ϵ_{K^+/π^+}	$\epsilon_{K_s^0}$	ARGUS Bkgd.	Peaking Bkgd.	Vary Selection	Total
B^+	e^+e^-	–	0.6	–	0.5	0.1	0.1	0.8
B^+	$\mu^+\mu^-$	–	0.6	–	0.6	0.4	1.0	1.4
B^0	e^+e^-	1.3	–	1.8	0.8	0.1	0.2	2.4
B^0	$\mu^+\mu^-$	1.3	–	1.8	0.5	0.1	1.3	2.6

$$\frac{N_{\text{signal}}^+/\epsilon_+}{N_{\text{signal}}^0/(f\epsilon_0)} = R^{+/0}\frac{\mathcal{B}(B^+\to J/\psi K^+)}{\mathcal{B}(B^0\to J/\psi K_s^0)}$$

$$= R^{+/0}\frac{2\Gamma(B^+\to J/\psi K^+)\tau_+}{\Gamma(B^0\to J/\psi K^0)\tau_0}$$

where $f = 68.60\pm0.27\%$ [16] is the $K_s^0\to\pi^+\pi^-$ branching fraction, $\tau_+/\tau_0 = 1.083\pm0.017$ [16] is the ratio of B^+ and B^0 lifetimes, and ϵ is the selection efficiency. Therefore, assuming isospin invariance in the $B\to J/\psi K$ decay, $\Gamma(B^+\to J/\psi K^+) = \Gamma(B^0\to J/\psi K^0)$ [17], the ratio of efficiency-corrected yields is determined from

$$R^{+/0} = \frac{N_{\text{signal}}^+\epsilon_0 f}{2N_{\text{signal}}^0\epsilon_+}\frac{\tau_0}{\tau_+}. \tag{1}$$

The ratio of efficiency-corrected yields is determined separately for $J/\psi\to e^+e^-$ and $J/\psi\to\mu^+\mu^-$ so that lepton identification efficiencies cancel. The separate measurements are then averaged, keeping track of correlated uncertainties, to produce a final value for $R^{+/0}$.

Sources of systematic uncertainties can be classified into those arising from uncertainties on efficiencies and those from candidate selection and backgrounds. The efficiency uncertainties are due to K_s^0 reconstruction, tracking, and kaon/pion tracking efficiency differences. In the ratio of the efficiency-corrected yields, the tracking uncertainty is due to the extra track required to reconstruct the $B^0\to J/\psi K_s^0$ mode. We determine the relative kaon/pion tracking reconstruction efficiency by comparing the ratio of efficiencies for $B^+\to J/\psi K^+$ and $B^+\to J/\psi\pi^+$ Monte Carlo. The systematic uncertainty of 0.6% is taken to be half the size of the estimated difference. Finally, for the uncertainty on the K_s^0 efficiency we take a sample of inclusive K_s^0 candidates that are binned in transverse momentum (p_T), laboratory polar angle

(θ_{LAB}), and transverse flight length (dr). A relative correction for the reconstruction of a displaced K_s^0 candidate is determined in each p_T and θ_{LAB} bin by assuming the tracking efficiency for a short-lived K_s^0 close to the interaction region is the same as for prompt tracks. Thus, the ratio of data to MC relative efficiency is normalized to unity for small dr and then used to derive a MC correction factor for larger displacements. By varying the size of the dr, p_T, and θ_{LAB} bins we determine a systematic uncertainty for this procedure. The normalization bin for the correction is well inside the radius of the beam pipe. We vary the definition of this bin as a check of the hypothesis that these tracks have the same efficiency as normal charged tracks.

The selection and background systematic uncertainties are attributed to the selection criteria, the ARGUS background shape, and the peaking background subtraction. The selection requirements on the K_s^0 mass, K_s^0 flight distance, and ΔE are varied within reasonable ranges. The K_s^0 mass and ΔE selection windows were increased and decreased from the nominal value by half a sigma and the K_s^0 vertex displacement requirement was removed. The largest difference from the nominal efficiency-corrected yield is taken conservatively as a systematic uncertainty. The continuum background systematic uncertainty is determined by varying the ARGUS parameter by two sigma to account for any model dependence. The peaking background uncertainty is evaluated from the discrepancy between data and MC simulations in the upper and lower ΔE sidebands. The larger of the two discrepancies is taken as the systematic uncertainty. This is a more conservative approach than using the uncertainties for the relevant branching fractions. Table II summarizes the sources of systematic uncertainty for this analysis.

Table III lists the efficiencies, background composition, and number of events in the signal region based on the one-dimensional fit with a $3(\sigma)$ ΔE requirement. Based on Eq. (1) we determine

TABLE III. Summary of values needed to determine the efficiency corrected yields.

Mode					
B	J/ψ	N_{cand}	N_{bkg}	N_{peak}	Efficiency (%)
B^+	e^+e^-	2213	19.5 ± 5.0	9.6 ± 3.2	40.8 ± 0.4
B^0	e^+e^-	502	2.6 ± 2.0	2.4 ± 1.5	29.9 ± 0.4
B^+	$\mu^+\mu^-$	2497	50.6 ± 7.2	33.5 ± 4.6	47.8 ± 0.4
B^0	$\mu^+\mu^-$	577	2.0 ± 1.5	2.4 ± 2.1	35.6 ± 0.4

$$R^{+/0}(e^+e^-) = 1.019 \pm 0.054(\text{stat}) \pm 0.031(\text{sys})$$

$$R^{+/0}(\mu^+\mu^-) = 0.994 \pm 0.049(\text{stat}) \pm 0.033(\text{sys})$$

$$R^{+/0}(avg) = 1.006 \pm 0.036(\text{stat}) \pm 0.031(\text{sys})$$

when assuming isospin conservation in $B \rightarrow J/\psi K$ decays. The data sample has a mean energy of 10.580 GeV and does not have sufficient spread to test the hypothesis of an energy-dependent production ratio.

We have confirmed that the result for the individual efficiency-corrected signal yields for the $J/\psi \rightarrow e^+e^-$ and $J/\psi \rightarrow \mu^+\mu^-$ channels is consistent among seven equal subsets of the full sample, as is the ratio of $e^+e^-/\mu^+\mu^-$.

To check our fitting technique we have performed a two-dimensional nonparametric fit to the data. This is done by fitting the data to a sum of contributions from five different sources $[e^+e^- \rightarrow q\bar{q}, \ e^+e^- \rightarrow c\bar{c}, \ \text{generic} \ \Upsilon(4S) \rightarrow B^0\bar{B}^0,$ generic $\Upsilon(4S) \rightarrow B^+B^-$, and signal] whose densities [18] in ΔE and m_{ES} are determined from a nonparametric fit to candidates from Monte Carlo samples. The two-dimensional fit is done in the region $5.200 < m_{\text{ES}} < 5.270 \ \text{GeV}/c^2$ and $0.030 < |\Delta E| < 0.120 \ \text{GeV}$. This technique has the advantage that we are not restricted to a small range in $|\Delta E|$. It also employs the MC predicted background distributions, rather than the empirical shape imposed by the ARGUS function. The nonparametric fit method finds results that are consistent with the simpler counting method, both for the full sample and for data subsets.

The observed value for $R^{+/0}$ is close to one, as has been assumed by most branching fraction measurements obtained on the $\Upsilon(4S)$, with a ratio as large as 1.2 disfavored at the four sigma level. Our measurement will aid in restricting models of $\Upsilon(4S)$ decays. It also allows a quantitative determination of the contribution from $R^{+/0}$ to all branching fractions that are determined at the B factories operating on the $\Upsilon(4S)$ resonance.

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