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Measurement of the branching fractions for $\psi(2S) \to e^+e^-$ and $\psi(2S) \to \mu^+\mu^-$

The *BABAR* Collaboration

B. Aubert,[1] D. Boutigny,[1] J.-M. Gaillard,[1] A. Hicheur,[1] Y. Karyotakis,[1] J. P. Lees,[1] P. Robbe,[1] V. Tisserand,[1] A. Palano,[2] A. Pompili,[2] G. P. Chen,[3] J. C. Chen,[3] N. D. Qi,[3] G. Rong,[3] P. Wang,[3] Y. S. Zhu,[3] G. Eigen,[4] P. L. Reinertsen,[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] A. R. Clark,[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] J. F. Kral,[5] C. LeClerc,[5] M. E. Levi,[5] T. Liu,[5] G. Lynch,[5] P. J. Oddone,[5] A. Perazzo,[5] M. Pripstein,[5] N. A. Roe,[5] A. Romosan,[5] M. T. Ronan,[5] V. G. Shelkov,[5] A. V. Telnov,[5] W. A. Wenzel,[5] P. G. Bright-Thomas,[6] T. J. Harrison,[6] C. M. Hawkes,[6] D. J. Knowles,[6] S. W. O'Neale,[6] R. C. Penny,[6] A. T. Watson,[6] N. K. Watson,[6] T. Deppermann,[7] K. Goetzen,[7] H. Koch,[7] M. Kunze,[7] B. Lewandowski,[7] K. Peters,[7] H. Schmuecker,[7] M. Steinke,[7] J. C. Andress,[8] N. R. Barlow,[8] W. Bhimji,[8] N. Chevalier,[8] P. J. Clark,[8] W. N. Cottingham,[8] N. De Groot,[8] N. Dyce,[8] B. Foster,[8] J. D. McFall,[8] D. Wallom,[8] F. F. Wilson,[8] K. Abe,[9] C. Hearty,[9] T. S. Mattison,[9] J. A. McKenna,[9] D. Thiessen,[9] S. Jolly,[10] A. K. McKemey,[10] J. Tinslay,[10] V. E. Blinov,[11] A. D. Bukin,[11] D. A. Bukin,[11] A. R. Buzykaev,[11] V. B. Golubev,[11] V. N. Ivanchenko,[11] A. A. Korol,[11] E. A. Kravchenko,[11] A. P. Onuchin,[11] A. A. Salnikov,[11] S. I. Serednyakov,[11] Yu. I. Skovpen,[11] V. I. Telnov,[11] A. N. Yushkov,[11] D. Best,[12] A. J. Lankford,[12] M. Mandelkern,[12] S. McMahon,[12] D. P. Stoker,[12] A. Ahsan,[13] K. Arisaka,[13] C. Buchanan,[13] S. Chun,[13] J. G. Branson,[14] D. B. MacFarlane,[14] S. Prell,[14] Sh. Rahatlou,[14] G. Raven,[14] V. Sharma,[14] C. Campagnari,[15] B. Dahmes,[15] P. A. Hart,[15] N. Kuznetsova,[15] S. L. Levy,[15] O. Long,[15] A. Lu,[15] J. D. Richman,[15] W. Verkerke,[15] M. Witherell,[15] S. Yellin,[15] J. Beringer,[16] D. E. Dorfan,[16] A. M. Eisner,[16] A. A. Grillo,[16] M. Grothe,[16] C. A. Heusch,[16] R. P. Johnson,[16] W. S. Lockman,[16] T. Pulliam,[16] H. Sadrozinski,[16] T. Schalk,[16] R. E. Schmitz,[16] B. A. Schumm,[16] A. Seiden,[16] M. Turri,[16] W. Walkowiak,[16] D. C. Williams,[16] M. G. Wilson,[16] E. Chen,[17] G. P. Dubois-Felsmann,[17] A. Dvoretskii,[17] D. G. Hitlin,[17] S. Metzler,[17] J. Oyang,[17] F. C. Porter,[17] A. Ryd,[17] A. Samuel,[17] M. Weaver,[17] S. Yang,[17] R. Y. Zhu,[17] S. Devmal,[18] T. L. Geld,[18] S. Jayatilleke,[18] G. Mancinelli,[18] B. T. Meadows,[18] M. D. Sokoloff,[18] T. Barillari,[19] P. Bloom,[19] M. O. Dima,[19] S. Fahey,[19] W. T. Ford,[19] D. R. Johnson,[19] U. Nauenberg,[19] A. Olivas,[19] P. Rankin,[19] J. Roy,[19] S. Sen,[19] J. G. Smith,[19] W. C. van Hoek,[19] D. L. Wagner,[19] J. Blouw,[20] J. L. Harton,[20] M. Krishnamurthy,[20] A. Soffer,[20] W. H. Toki,[20] R. J. Wilson,[20] J. Zhang,[20] T. Brandt,[21] J. Brose,[21] T. Colberg,[21] M. Dickopp,[21] R. S. Dubitzky,[21] A. Hauke,[21] E. Maly,[21] R. Müller-Pfefferkorn,[21] S. Otto,[21] K. R. Schubert,[21] R. Schwierz,[21] B. Spaan,[21] L. Wilden,[21] D. Bernard,[22] G. R. Bonneaud,[22] F. Brochard,[22] J. Cohen-Tanugi,[22] S. Ferrag,[22] E. Roussot,[22] S. T'Jampens,[22] Ch. Thiebaux,[22] G. Vasileiadis,[22] M. Verderi,[22] A. Anjomshoaa,[23] R. Bernet,[23] A. Khan,[23] D. Lavin,[23] F. Muheim,[23] S. Playfer,[23] J. E. Swain,[23] M. Falbo,[24] C. Borean,[25] C. Bozzi,[25] S. Dittongo,[25] L. Piemontese,[25] E. Treadwell,[26] F. Anulli,[27,*] R. Baldini-Ferroli,[27] A. Calcaterra,[27] R. de Sangro,[27] D. Falciai,[27] G. Finocchiaro,[27] P. Patteri,[27] I. M. Peruzzi,[27,*] M. Piccolo,[27] Y. Xie,[27] A. Zallo,[27] S. Bagnasco,[28] A. Buzzo,[28] R. Contri,[28] G. Crosetti,[28] M. Lo Vetere,[28] M. Macri,[28] M. R. Monge,[28] S. Passaggio,[28] F. C. Pastore,[28] C. Patrignani,[28] M. G. Pia,[28] E. Robutti,[28] A. Santroni,[28] M. Morii,[29] R. Bartoldus,[30] R. Hamilton,[30] U. Mallik,[30] J. Cochran,[31] H. B. Crawley,[31] P.-A. Fischer,[31] J. Lamsa,[31] W. T. Meyer,[31] E. I. Rosenberg,[31] G. Grosdidier,[32] C. Hast,[32] A. Höcker,[32] H. M. Lacker,[32] S. Laplace,[32] V. Lepeltier,[32] A. M. Lutz,[32] S. Plaszczynski,[32] M. H. Schune,[32] S. Trincaz-Duvoid,[32] G. Wormser,[32] R. M. Bionta,[33] V. Brigljević,[33] D. J. Lange,[33] M. Mugge,[33] K. van Bibber,[33] D. M. Wright,[33] M. Carroll,[34] J. R. Fry,[34] E. Gabathuler,[34] R. Gamet,[34] M. George,[34] M. Kay,[34] D. J. Payne,[34] R. J. Sloane,[34] C. Touramanis,[34] M. L. Aspinwall,[35] D. A. Bowerman,[35] P. D. Dauncey,[35] U. Egede,[35] I. Eschrich,[35] N. J. W. Gunawardane,[35] J. A. Nash,[35] P. Sanders,[35] D. Smith,[35] D. E. Azzopardi,[36] J. J. Back,[36] P. Dixon,[36] P. F. Harrison,[36] R. J. L. Potter,[36] H. W. Shorthouse,[36] P. Strother,[36] P. B. Vidal,[36]

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M. I. Williams,[36] G. Cowan,[37] S. George,[37] M. G. Green,[37] A. Kurup,[37] C. E. Marker,[37] P. McGrath,[37] T. R. McMahon,[37] S. Ricciardi,[37] F. Salvatore,[37] I. Scott,[37] G. Vaitsas,[37] D. Brown,[38] C. L. Davis,[38] J. Allison,[39] R. J. Barlow,[39] J. T. Boyd,[39] A. C. Forti,[39] J. Fullwood,[39] F. Jackson,[39] G. D. Lafferty,[39] N. Savvas,[39] E. T. Simopoulos,[39] J. H. Weatherall,[39] A. Farbin,[40] A. Jawahery,[40] V. Lillard,[40] J. Olsen,[40] D. A. Roberts,[40] J. R. Schieck,[40] G. Blaylock,[41] C. Dallapiccola,[41] K. T. Flood,[41] S. S. Hertzbach,[41] R. Kofler,[41] V. G. Koptchev,[41] T. B. Moore,[41] H. Staengle,[41] S. Willocq,[41] B. Brau,[42] R. Cowan,[42] G. Sciolla,[42] F. Taylor,[42] R. K. Yamamoto,[42] M. Milek,[43] P. M. Patel,[43] F. Palombo,[44] J. M. Bauer,[45] L. Cremaldi,[45] V. Eschenburg,[45] R. Kroeger,[45] J. Reidy,[45] D. A. Sanders,[45] D. J. Summers,[45] J. P. Martin,[46] J. Y. Nief,[46] R. Seitz,[46] P. Taras,[46] V. Zacek,[46] H. Nicholson,[47] C. S. Sutton,[47] N. Cavallo,[48,†] G. De Nardo,[48] F. Fabozzi,[48] C. Gatto,[48] L. Lista,[48] P. Paolucci,[48] D. Piccolo,[48] C. Sciacca,[48] J. M. LoSecco,[49] J. R. G. Alsmiller,[50] T. A. Gabriel,[50] T. Handler,[50] J. Brau,[51] R. Frey,[51] M. Iwasaki,[51] N. B. Sinev,[51] D. Strom,[51] F. Colecchia,[52] F. Dal Corso,[52] A. Dorigo,[52] F. Galeazzi,[52] M. Margoni,[52] G. Michelon,[52] M. Morandin,[52] M. Posocco,[52] M. Rotondo,[52] F. Simonetto,[52] R. Stroili,[52] E. Torassa,[52] C. Voci,[52] M. Benayoun,[53] H. Briand,[53] J. Chauveau,[53] P. David,[53] Ch. de la Vaissière,[53] L. Del Buono,[53] O. Hamon,[53] F. Le Diberder,[53] Ph. Leruste,[53] L. Roos,[53] J. Stark,[53] S. Versillé,[53] P. F. Manfredi,[54] V. Re,[54] V. Speziali,[54] E. D. Frank,[55] L. Gladney,[55] Q. H. Guo,[55] J. Panetta,[55] C. Angelini,[56] G. Batignani,[56] S. Bettarini,[56] M. Bondioli,[56] M. Carpinelli,[56] F. Forti,[56] M. A. Giorgi,[56] A. Lusiani,[56] F. Martinez-Vidal,[56] M. Morganti,[56] N. Neri,[56] E. Paoloni,[56] M. Rama,[56] G. Rizzo,[56] F. Sandrelli,[56] G. Simi,[56] G. Triggiani,[56] J. Walsh,[56] M. Haire,[57] D. Judd,[57] K. Paick,[57] L. Turnbull,[57] D. E. Wagoner,[57] J. Albert,[58] P. Elmer,[58] C. Lu,[58] K. T. McDonald,[58] V. Miftakov,[58] S. F. Schaffner,[58] A. J. S. Smith,[58] A. Tumanov,[58] E. W. Varnes,[58] G. Cavoto,[59] D. del Re,[59] R. Faccini,[14,59] F. Ferrarotto,[59] F. Ferroni,[59] E. Lamanna,[59] E. Leonardi,[59] M. A. Mazzoni,[59] S. Morganti,[59] G. Piredda,[59] F. Safai Tehrani,[59] M. Serra,[59] C. Voena,[59] S. Christ,[60] R. Waldi,[60] T. Adye,[61] B. Franek,[61] N. I. Geddes,[61] G. P. Gopal,[61] S. M. Xella,[61] R. Aleksan,[62] G. De Domenico,[62] S. Emery,[62] A. Gaidot,[62] S. F. Ganzhur,[62] P.-F. Giraud,[62] G. Hamel de Monchenault,[62] W. Kozanecki,[62] M. Langer,[62] G. W. London,[62] B. Mayer,[62] B. Serfass,[62] G. Vasseur,[62] Ch. Yèche,[62] M. Zito,[62] N. Copty,[63] M. V. Purohit,[63] H. Singh,[63] F. X. Yumiceva,[63] I. Adam,[64] P. L. Anthony,[64] D. Aston,[64] K. Baird,[64] N. Berger,[64] E. Bloom,[64] A. M. Boyarski,[64] F. Bulos,[64] G. Calderini,[64] M. R. Convery,[64] D. P. Coupal,[64] D. H. Coward,[64] J. Dorfan,[64] W. Dunwoodie,[64] R. C. Field,[64] T. Glanzman,[64] G. L. Godfrey,[64] S. J. Gowdy,[64] P. Grosso,[64] T. Haas,[64] T. Himel,[64] T. Hryn'ova,[64] M. E. Huffer,[64] W. R. Innes,[64] C. P. Jessop,[64] M. H. Kelsey,[64] P. Kim,[64] M. L. Kocian,[64] U. Langenegger,[64] D. W. G. S. Leith,[64] S. Luitz,[64] V. Luth,[64] H. L. Lynch,[64] H. Marsiske,[64] S. Menke,[64] R. Messner,[64] K. C. Moffeit,[64] R. Mount,[64] D. R. Muller,[64] C. P. O'Grady,[64] M. Perl,[64] S. Petrak,[64] H. Quinn,[64] B. N. Ratcliff,[64] S. H. Robertson,[64] L. S. Rochester,[64] A. Roodman,[64] T. Schietinger,[64] R. H. Schindler,[64] J. Schwiening,[64] V. V. Serbo,[64] A. Snyder,[64] A. Soha,[64] S. M. Spanier,[64] J. Stelzer,[64] D. Su,[64] M. K. Sullivan,[64] H. A. Tanaka,[64] J. Va'vra,[64] S. R. Wagner,[64] A. J. R. Weinstein,[64] W. J. Wisniewski,[64] D. H. Wright,[64] C. C. Young,[64] P. R. Burchat,[65] C. H. Cheng,[65] D. Kirkby,[65] T. I. Meyer,[65] C. Roat,[65] R. Henderson,[66] W. Bugg,[67] H. Cohn,[67] A. W. Weidemann,[67] J. M. Izen,[68] I. Kitayama,[68] X. C. Lou,[68] F. Bianchi,[69] M. Bona,[69] D. Gamba,[69] A. Smol,[69] L. Bosisio,[70] G. Della Ricca,[70] L. Lanceri,[70] P. Poropat,[70] G. Vuagnin,[70] R. S. Panvini,[71] C. M. Brown,[72] R. Kowalewski,[72] J. M. Roney,[72] H. R. Band,[73] E. Charles,[73] S. Dasu,[73] F. Di Lodovico,[73] A. M. Eichenbaum,[73] H. Hu,[73] J. R. Johnson,[73] R. Liu,[73] Y. Pan,[73] R. Prepost,[73] I. J. Scott,[73] S. J. Sekula,[73] J. H. von Wimmersperg-Toeller,[73] S. L. Wu,[73] Z. Yu,[73] T. M. B. Kordich,[74] and H. Neal[74]

[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, Inst. of Physics, N-5007 Bergen, Norway*
[5]*Lawrence Berkeley National Laboratory and University of California, Berkeley, CA 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, BC, 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, CA 92697, USA*
[13]*University of California at Los Angeles, Los Angeles, CA 90024, USA*
[14]*University of California at San Diego, La Jolla, CA 92093, USA*
[15]*University of California at Santa Barbara, Santa Barbara, CA 93106, USA*

[16] University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, CA 95064, USA
[17] California Institute of Technology, Pasadena, CA 91125, USA
[18] University of Cincinnati, Cincinnati, OH 45221, USA
[19] University of Colorado, Boulder, CO 80309, USA
[20] Colorado State University, Fort Collins, CO 80523, USA
[21] Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062, Dresden, Germany
[22] Ecole Polytechnique, F-91128 Palaiseau, France
[23] University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
[24] Elon University, Elon University, NC 27244-2010, USA
[25] Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy
[26] Florida A&M University, Tallahassee, FL 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, MA 02138, USA
[30] University of Iowa, Iowa City, IA 52242, USA
[31] Iowa State University, Ames, IA 50011-3160, USA
[32] Laboratoire de l'Accélérateur Linéaire, F-91898 Orsay, France
[33] Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[34] University of Liverpool, Liverpool L69 3BX, United Kingdom
[35] University of London, Imperial College, London, SW7 2BW, United Kingdom
[36] Queen Mary, University of London, E1 4NS, United Kingdom
[37] University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
[38] University of Louisville, Louisville, KY 40292, USA
[39] University of Manchester, Manchester M13 9PL, United Kingdom
[40] University of Maryland, College Park, MD 20742, USA
[41] University of Massachusetts, Amherst, MA 01003, USA
[42] Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, MA 02139, USA
[43] McGill University, Montréal, Canada QC H3A 2T8
[44] Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy
[45] University of Mississippi, University, MS 38677, USA
[46] Université de Montréal, Laboratoire René J. A. Lévesque, Montréal, Canada QC H3C 3J7
[47] Mount Holyoke College, South Hadley, MA 01075, USA
[48] Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy
[49] University of Notre Dame, Notre Dame, IN 46556, USA
[50] Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
[51] University of Oregon, Eugene, OR 97403, USA
[52] Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy
[53] Universités Paris VI et VII, Lab de Physique Nucléaire H. E., F-75252 Paris, France
[54] Università di Pavia, Dipartimento di Elettronica and INFN, I-27100 Pavia, Italy
[55] University of Pennsylvania, Philadelphia, PA 19104, USA
[56] Università di Pisa, Scuola Normale Superiore and INFN, I-56010 Pisa, Italy
[57] Prairie View A&M University, Prairie View, TX 77446, USA
[58] Princeton University, Princeton, NJ 08544, USA
[59] Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy
[60] Universität Rostock, D-18051 Rostock, Germany
[61] Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
[62] DAPNIA, Commissariat à l'Energie Atomique/Saclay, F-91191 Gif-sur-Yvette, France
[63] University of South Carolina, Columbia, SC 29208, USA
[64] Stanford Linear Accelerator Center, Stanford, CA 94309, USA
[65] Stanford University, Stanford, CA 94305-4060, USA
[66] TRIUMF, Vancouver, BC, Canada V6T 2A3
[67] University of Tennessee, Knoxville, TN 37996, USA
[68] University of Texas at Dallas, Richardson, TX 75083, USA
[69] Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy
[70] Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy
[71] Vanderbilt University, Nashville, TN 37235, USA
[72] University of Victoria, Victoria, BC, Canada V8W 3P6
[73] University of Wisconsin, Madison, WI 53706, USA
[74] Yale University, New Haven, CT 06511, USA

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We measure the branching fractions of the $\psi(2S)$ meson to the leptonic final states e^+e^- and $\mu^+\mu^-$ relative to that for $\psi(2S) \to J/\psi\,\pi^+\pi^-$. The method uses $\psi(2S)$ mesons produced in the decay of B mesons at the $\Upsilon(4S)$ resonance in a data sample collected with the *BABAR* detector at the Stanford

Linear Accelerator Center. Using previous measurements for the $\psi(2S) \to J/\psi\,\pi^+\pi^-$ branching fraction, we determine the e^+e^- and $\mu^+\mu^-$ branching fractions to be $0.0078 \pm 0.0009 \pm 0.0008$ and $0.0067 \pm 0.0008 \pm 0.0007$ respectively.

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The branching fraction of the $\psi(2S)$ to e^+e^- has previously been measured in e^+e^- collider experiments operating at the mass of the $\psi(2S)$ resonance [1] and in $p\bar{p}$ experiments [2, 3]. The $\psi(2S) \to \mu^+\mu^-$ branching fraction has been measured with substantially larger uncertainty in e^+e^- experiments [4] and in $\pi^- Be$ collisions [5]. This paper reports new measurements of these quantities by the *BABAR* experiment, operating at the PEP-II e^+e^- collider at the Stanford Linear Accelerator Center.

PEP-II collides 9 GeV electrons on 3.1 GeV positrons to create a center-of-mass system with energy 10.58 GeV moving along the z axis with a Lorentz boost of $\beta\gamma = 0.56$. At this energy, $\Upsilon(4S)$ resonance production makes up 23% of the total hadronic cross section. The $\Upsilon(4S)$ is assumed to decay 100% to a pair of B mesons. A large, clean sample of $\psi(2S)$ mesons is produced in the B decays. The e^+e^- and $\mu^+\mu^-$ branching fractions are obtained through their ratio to $J/\psi\,\pi^+\pi^-$, which is known with much better precision. This technique provides a significantly lower uncertainty on the $\mu^+\mu^-$ branching fraction than the current world average.

The data set used for this analysis corresponds to an integrated luminosity of $20.33 \pm 0.30\,\mathrm{fb}^{-1}$ recorded at 10.58 GeV, and contains $(22.3 \pm 0.4) \times 10^6$ $\Upsilon(4S)$ mesons. An additional $2.6\,\mathrm{fb}^{-1}$ has been recorded at an energy 40 MeV below the $\Upsilon(4S)$ resonance.

The *BABAR* detector is described in detail in reference [6]. The momenta of charged particles are measured and their trajectories reconstructed with two detector systems located in a 1.5-T solenoidal magnetic field: a five-layer, double-sided silicon vertex tracker (SVT) and a 40 layer drift chamber (DCH). The fiducial volume covers the polar angular region $0.41 < \theta < 2.54$ rad, which is 86% of the solid angle in the center of mass. The transverse momentum resolution is 0.47% at 1 GeV/c.

The energies of electrons and photons are accurately measured by a CsI(Tl) calorimeter (EMC) in the fiducial volume $0.41 < \theta < 2.41$ rad (84% of the center-of-mass solid angle) with energy resolution at 1 GeV of 3.0%. Muons are detected in the IFR—the flux return of the solenoid, which is instrumented with resistive plate chambers. The DIRC, a unique Cherenkov radiation detection device, identifies charged particles.

The branching fractions of interest are obtained by comparison to that of $\psi(2S) \to J/\psi\,\pi^+\pi^-$. The number of $\psi(2S)$ mesons reconstructed in the final states e^+e^- (N_{ee}), $\mu^+\mu^-$ ($N_{\mu\mu}$) and $J/\psi\,\pi^+\pi^-$, with $J/\psi \to e^+e^-$ ($N_{ee\pi\pi}$) or $J/\psi \to \mu^+\mu^-$($N_{\mu\mu\pi\pi}$), is related to the total number of $\psi(2S)$ mesons produced in our data set $N_{\psi(2S)}$ by:

$$N_{ee} = N_{\psi(2S)} \cdot \mathcal{B}_{ee} \cdot \epsilon_{ee}, \tag{1}$$

$$N_{\mu\mu} = N_{\psi(2S)} \cdot \mathcal{B}_{\mu\mu} \cdot \epsilon_{\mu\mu}, \tag{2}$$

$$N_{ee\pi\pi} = N_{\psi(2S)} \cdot \mathcal{B}_{J/\psi\,\pi^+\pi^-} \cdot \mathcal{B}_{J/\psi\to ee} \cdot \epsilon_{ee\pi\pi}, \tag{3}$$

$$N_{\mu\mu\pi\pi} = N_{\psi(2S)} \cdot \mathcal{B}_{J/\psi\,\pi^+\pi^-} \cdot \mathcal{B}_{J/\psi\to \mu\mu} \cdot \epsilon_{\mu\mu\pi\pi}. \tag{4}$$

$\mathcal{B}_{ee}$, $\mathcal{B}_{\mu\mu}$ and $\mathcal{B}_{J/\psi\,\pi^+\pi^-}$ are the branching fractions of the $\psi(2S)$ to e^+e^-, $\mu^+\mu^-$, and $J/\psi\,\pi^+\pi^-$ respectively. We use world averages for $\mathcal{B}_{J/\psi\to ee}$, the J/ψ branching fraction to e^+e^-, and for $\mathcal{B}_{J/\psi\to\mu\mu}$, the branching fraction to $\mu^+\mu^-$ [7]. ϵ_{ee} and $\epsilon_{\mu\mu}$ are the efficiencies for events containing $\psi(2S)$ mesons decaying to e^+e^- and $\mu^+\mu^-$ respectively to satisfy the event selection and meson reconstruction requirements; $\epsilon_{ee\pi\pi}$ and $\epsilon_{\mu\mu\pi\pi}$ are the efficiencies for $\psi(2S) \to J/\psi\,\pi^+\pi^-$ decays with $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$ respectively.

Equations 1, 3, 4 can be combined to give two expressions for the e^+e^- to $J/\psi\,\pi^+\pi^-$ branching ratio :

$$\frac{\mathcal{B}_{ee}}{\mathcal{B}_{J/\psi\,\pi^+\pi^-}} = \mathcal{B}_{J/\psi\to ee} \cdot \frac{N_{ee}}{N_{ee\pi\pi}} \cdot \frac{\epsilon_{ee\pi\pi}}{\epsilon_{ee}}, \tag{5}$$

$$\frac{\mathcal{B}_{ee}}{\mathcal{B}_{J/\psi\,\pi^+\pi^-}} = \mathcal{B}_{J/\psi\to\mu\mu} \cdot \frac{N_{ee}}{N_{\mu\mu\pi\pi}} \cdot \frac{\epsilon_{\mu\mu\pi\pi}}{\epsilon_{ee}}. \tag{6}$$

Similarly,

$$\frac{\mathcal{B}_{\mu\mu}}{\mathcal{B}_{J/\psi\,\pi^+\pi^-}} = \mathcal{B}_{J/\psi\to ee} \cdot \frac{N_{\mu\mu}}{N_{ee\pi\pi}} \cdot \frac{\epsilon_{ee\pi\pi}}{\epsilon_{\mu\mu}}, \tag{7}$$

$$\frac{\mathcal{B}_{\mu\mu}}{\mathcal{B}_{J/\psi\,\pi^+\pi^-}} = \mathcal{B}_{J/\psi\to\mu\mu} \cdot \frac{N_{\mu\mu}}{N_{\mu\mu\pi\pi}} \cdot \frac{\epsilon_{\mu\mu\pi\pi}}{\epsilon_{\mu\mu}}. \tag{8}$$

A number of systematic errors due to uncertainties in efficiency cancel in these expressions.

We obtain a $B\overline{B}$ enriched sample by requiring events to have visible energy E greater than 4.5 GeV and a ratio of the second to the zeroth Fox-Wolfram moment, R_2 [8], less than 0.5. Both E and R_2 are calculated from tracks and neutral clusters in the respective fiducial volumes noted above. The same tracks are used to construct a primary event vertex, which is required to be located within 6 cm of the beam spot in z and within 0.5 cm of the beam line. The beam spot rms size is approximately 0.9 cm in z, 120 μm horizontally, and 5.6 μm vertically.

There must be at least three tracks in the fiducial volume satisfying the following quality criteria: they must have transverse momentum greater than 0.1 GeV/c, momentum less than 10 GeV/c, at least 12 hits in the DCH, and approach within 10 cm of the beam spot in z and within 1.5 cm of the beam line.

Finally, to suppress a substantial background from radiative Bhabha ($e^+e^-\gamma$) events in which the photon converts to an e^+e^- pair, five or more tracks are required in events containing $\psi(2S) \to e^+e^-$ or $J/\psi \to e^+e^-$ candidates.

The efficiency of the event selection—and the meson reconstruction efficiency described below—is calculated with a complete detector simulation of $B \to \psi(2S)X$ events [9]. The simulation of $\psi(2S)$ and J/ψ decays to lepton pairs includes final state radiation [10]. The event selection efficiencies are 0.912 ± 0.002 for $\psi(2S) \to e^+e^-$, 0.945 ± 0.002 for $\psi(2S) \to \mu^+\mu^-$, 0.967 ± 0.001 for $e^+e^-\pi^+\pi^-$, and 0.972 ± 0.001 for $\mu^+\mu^-\pi^+\pi^-$. The difference in the e^+e^- and $\mu^+\mu^-$ efficiencies is due largely to the requirement of five tracks. The quoted uncertainties are those due to simulation statistics only. The event efficiencies appear as ratios in equations 5–8; the systematic errors on the ratios are small compared to the other uncertainties and systematic errors discussed below.

The lepton candidates used to construct J/ψ or $\psi(2S)$ mesons via e^+e^- or $\mu^+\mu^-$ decays must be in the restricted angular region $0.41 < \theta < 2.41\,\text{rad}$ and satisfy the track quality criteria listed above.

Electron candidates must include an energy deposition in the EMC of at least three crystals, with shape consistent with an electromagnetic shower and magnitude at least 75% of the track momentum. At least one candidate must have energy between 89% and 120% of the track momentum and a Cherenkov signal in the DIRC consistent with the expectation for an electron. If possible, photons radiated by electrons traversing material prior to the DCH are recombined with the track. Such photons must have EMC energy greater than 30 MeV, a polar angle θ within 35 mrad of the electron direction and an azimuth that is either within 50 mrad of the electron direction or between the electron direction and the location of the electron shower in the EMC.

Muon candidates must deposit less than 0.5 GeV in the EMC (2.3 times the minimum-ionizing peak), penetrate at least two interaction lengths λ of material, and have a pattern of hits consistent with the trajectory of a muon. We require the material traversed by one candidate be within $1\,\lambda$ of that expected for a muon; for the other candidate, this is relaxed to $2\,\lambda$.

The J/ψ or $\psi(2S)$ meson mass is obtained in an $\ell^+\ell^-$ final state after constraining the two tracks to a common origin.

The reconstruction of $\psi(2S) \to J/\psi\pi^+\pi^-$ uses a $J/\psi \to e^+e^-$ candidate with mass between 3.05 and $3.12\,\text{GeV}/c^2$ or a $J/\psi \to \mu^+\mu^-$ candidate with $3.07 < m < 3.12\,\text{GeV}/c^2$. 74% of $J/\psi \to e^+e^-$ decays and 91% of $J/\psi \to \mu^+\mu^-$ fall within these ranges. All tracks in the fiducial volume not used in the J/ψ reconstruction are used as pion candidates. To avoid systematic errors and retain high efficiency, the tracks are not required to satisfy any specific quality requirements. A pair of oppositely-charged pions is required to have mass $m_{\pi\pi}$ in the region $0.45 < m_{\pi\pi} < 0.60\,\text{GeV}/c^2$. The $\psi(2S)$ mass is obtained after constraining the four tracks in the final state to a common origin.

$\psi(2S)$ candidates in all final states are required to have momentum less than $1.6\,\text{GeV}/c$ as measured in the $\Upsilon(4S)$ rest frame. This requirement is fully efficient for $\psi(2S)$ mesons produced in B decays.

The J/ψ and $\psi(2S)$ reconstruction efficiencies are determined by simulation and include contributions from acceptance, track quality, particle identification and, for $\psi(2S) \to J/\psi\pi^+\pi^-$, the J/ψ and $\pi^+\pi^-$ mass windows. The efficiency and systematic error on lepton identification have been obtained from data by comparing the ratio of J/ψ mesons in B decays in which one or both leptons satisfy the requirements. The efficiency and systematic error of the track-quality selection have been studied by comparing the independent SVT and DCH tracking efficiencies in hadronic events. The meson reconstruction efficiency is 0.602 ± 0.004 for the e^+e^- case, 0.535 ± 0.004 for $\mu^+\mu^-$, 0.207 ± 0.002 for $e^+e^-\pi^+\pi^-$, and 0.211 ± 0.002 for $\mu^+\mu^-\pi^+\pi^-$, where the uncertainties are simulation statistics only.

The e^+e^- efficiency is higher than $\mu^+\mu^-$ in $\psi(2S) \to \ell^+\ell^-$ or $J/\psi \to \ell^+\ell^-$ reconstruction because electron identification is more efficient than muon identification. Conversely, a J/ψ decaying to e^+e^- is less likely to be reconstructed in the specified mass window than one decaying to $\mu^+\mu^-$. Together, these two effects result in little difference between the $e^+e^-\pi^+\pi^-$ and $\mu^+\mu^-\pi^+\pi^-$ efficiencies. Overall, the $J/\psi\pi^+\pi^-$ efficiencies are lower than $\ell^+\ell^-$ due to the reconstruction of the pion pair. The efficiencies appearing in equations 1–4 are the product of these meson reconstruction efficiencies and the event selection values given earlier.

Lepton identification uncertainty is 1.8% for e^+e^- and 1.4% for $\mu^+\mu^-$, and cancels in branching ratios where the $\psi(2S)$ and J/ψ decay to the same final state, equations 5 and 8. A 2.4% systematic error on the efficiency of the track quality requirements applied to the J/ψ and $\psi(2S)$ in the $\ell^+\ell^-$ final state cancels in all four ratios.

The number of mesons in the e^+e^- and $\mu^+\mu^-$ final states is extracted by a fit to the mass distribution of candidates (Fig. 1). A third-order Chebychev polynomial is used for backgrounds. The signals are fit by probability distribution functions (pdfs) obtained from a complete simulation of $B \to \psi(2S)X$ events, with $\psi(2S) \to e^+e^-$ or $\psi(2S) \to \mu^+\mu^-$. Only candidates constructed from the correct combination of particles are used in the pdf. The signal pdfs are convoluted with a Gaussian distribution to match the mass resolution of $12\,\text{MeV}/c^2$ observed in a data sample of 14,000 $J/\psi \to \mu^+\mu^-$ decays.

Despite the algorithm to recover radiated photons, the pdf for the e^+e^- final state is sensitive to the fraction of events in which one or both electrons undergo bremsstrahlung. The pdf is adjusted to reflect the frac-

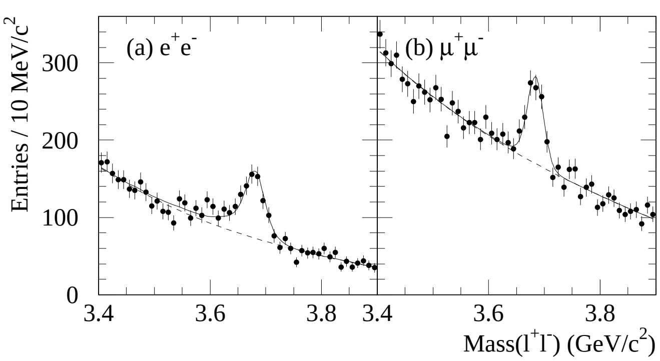

FIG. 1: Mass distribution of (a) $\psi(2S) \to e^+e^-$ and (b) $\psi(2S) \to \mu^+\mu^-$ candidates.

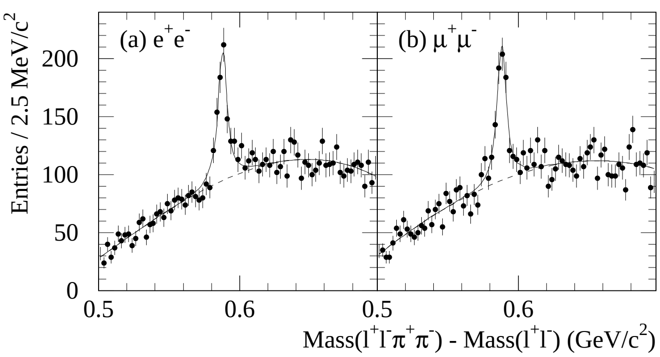

FIG. 2: Mass difference between the $\psi(2S)$ and J/ψ candidates in the decay $\psi(2S) \to J/\psi\,\pi^+\pi^-$ with the J/ψ reconstructed in the (a) e^+e^- and (b) $\mu^+\mu^-$ final states.

tion obtained in a study of the mass distribution of 15,000 $J/\psi \to e^+e^-$ decays in data. To enhance the sensitivity of the study, the algorithm to recover radiated photons is not used in the reconstruction of the J/ψ.

For $\psi(2S) \to J/\psi\,\pi^+\pi^-$, an analogous fit procedure is performed to the distribution of the mass difference between the $\psi(2S)$ and the J/ψ candidates (Fig. 2). This quantity reduces the impact of J/ψ mass resolution, including final state radiation and bremsstrahlung. The distribution predicted by the simulation is convoluted with a Gaussian distribution whose standard deviation is left as a free parameter in the fit. The mass difference resolution is $3.2\,\mathrm{MeV}/c^2$.

The signal yields returned by the fits are 552 ± 50 for e^+e^-, 437 ± 44 for $\mu^+\mu^-$, 474 ± 44 for $e^+e^-\pi^+\pi^-$, and 498 ± 42 for $\mu^+\mu^-\pi^+\pi^-$, where errors are statistical only. Systematic errors on the fitting technique are obtained by performing the fits on multiple simulated data sets containing both signal and background events. Additional contributions come from varying the mass regions included in the fit and increasing or decreasing the power of the background polynomial. Fitting systematics are 2.3% for e^+e^-, 5.3% for $\mu^+\mu^-$, 5.4% for $e^+e^-\pi^+\pi^-$, and 2.1% for $\mu^+\mu^-\pi^+\pi^-$. These systematic errors are conservative in the sense that the procedure to derive them incorporates a component of the statistical error, which would be reduced with additional data.

We repeat the analysis with the data recorded below the $\Upsilon(4S)$ resonance. The total $\psi(2S)$ yield, summed over the four modes, is 5 ± 12 events, indicating that the contribution of continuum-produced $\psi(2S)$ mesons is negligible in the on-resonance sample.

The two values for the e^+e^- to $J/\psi\,\pi^+\pi^-$ branching ratio obtained with equations 5 and 6 are in good agreement: the result found with $\mu^+\mu^-\pi^+\pi^-$ is 0.97 ± 0.14 times that with $e^+e^-\pi^+\pi^-$. By construction, this ratio is identical for the $\mu^+\mu^-$ final state. The results from equations 5 and 6 are combined, distinguishing correlated and uncorrelated statistical and systematic errors, to give:

$$\mathcal{B}_{ee}/\mathcal{B}_{J/\psi\,\pi^+\pi^-} = 0.0252 \pm 0.0028 \pm 0.0011, \qquad (9)$$

where the first error is statistical and the second systematic. Similarly, equations 7 and 8 are combined to obtain

$$\mathcal{B}_{\mu\mu}/\mathcal{B}_{J/\psi\,\pi^+\pi^-} = 0.0216 \pm 0.0026 \pm 0.0014. \qquad (10)$$

The systematic errors are dominated by the fitting technique. Other contributions, which are the same for both results, include 1.6% for particle identification, 1.2% for the uncertainty in J/ψ branching fractions, and 0.9% for differences between the simulated and measured [11] $\pi^+\pi^-$ mass and angular distributions in the $J/\psi\,\pi^+\pi^-$ final states.

We use the current world average value of 0.310 ± 0.028 for the $\psi(2S) \to J/\psi\,\pi^+\pi^-$ branching fraction [7] to extract results for the $\psi(2S)$ leptonic branching fractions:

$$\mathcal{B}_{ee} = 0.0078 \pm 0.0009 \pm 0.0008, \qquad (11)$$

$$\mathcal{B}_{\mu\mu} = 0.0067 \pm 0.0008 \pm 0.0007. \qquad (12)$$

The ratio of the leptonic branching fractions can be derived without the use of the $\psi(2S) \to J/\psi\,\pi^+\pi^-$ sample:

$$\frac{\mathcal{B}_{\mu\mu}}{\mathcal{B}_{ee}} = \frac{N_{\mu\mu}}{N_{ee}} \cdot \frac{\epsilon_{ee}}{\epsilon_{\mu\mu}} = 0.86 \pm 0.12 \pm 0.05. \qquad (13)$$

The systematic error is dominated by the uncertainty in the fitting technique.

In summary, we have measured the branching ratios $\mathcal{B}_{ee}/\mathcal{B}_{J/\psi\,\pi^+\pi^-}$ and $\mathcal{B}_{\mu\mu}/\mathcal{B}_{J/\psi\,\pi^+\pi^-}$. We multiply these by the world average for the $J/\psi\,\pi^+\pi^-$ branching fraction to obtain the branching fraction of the $\psi(2S)$ to e^+e^- and to $\mu^+\mu^-$. These results are consistent with earlier measurements, but have, in the case of $\mu^+\mu^-$, a substantially smaller uncertainty.

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* Also with Università di Perugia, Perugia, Italy
† Also with Università della Basilicata, Potenza, Italy

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