Study of di-pion bottomonium transitions and search for the $h_0(1P)$ state

J. P. Lees, V. Poireau, V. Tisserand, J. Garra Tico, E. Grauges, M. Martinelli, D. A. Milanes, A. Palano, M. Pappagallo, G.Eigen, B. Stugu, L. Sun, D. N. Brown, L. T. Kerth, Yu. G. Kolomensky, G. Lynch, H. Koch, T. Schroeder, D. J. Asgeirsson, C. Hearty, T. S. Mattison, J. A. McKenna, A. Khan, V. E. Blinov, A. R. Buzyaev, V. V. Druzhinin, V. B. Golubev, E. A. Kravchenko, A. P. Onuchin, S. I. Serednyakov, Yu. I. Skovpen, E. P. Solodov, K. Yu. Todyshev, A. N. Yushkov, M. Bondioli, S. Curry, D. Kirkby, A. J. Lankford, M. Mandelkern, D. P. Stoker, H. Atmacan, J. W. Gary, F. Liu, O. Long, G. M. Vitug, C. Campagnari, T. M. Hong, D. Kovalskyi, J. D. Richman, C. A. West, A. M. Eisner, J. Kroseberg, W. S. Lockman, A. J. Martinez, T. Schalk, B. A. Schumm, A. Seiden, C. H. Cheng, D. A. Doll, B. Echenard, K. T. Flood, D. G. Hitlin, P. Ongmongkolkul, F. C. Porter, A. Y. Rakitin, R. Andreaissen, M. S. Dubrovin, B. T. Meadows, M. D. Sokoloff, P. C. Bloom, W. T. Ford, A. Gazu, M. Nagel, U. Nauenberg, J. G. Smith, S. R. Wagner, R. Ayad, W. H. Toki, B. Spaan, M. J. Koble, K. R. Schubert, R. Schwierz, D. Bernard, M. Verderi, P. J. Clark, S. J. Power, D. Bettoni, C. Bozzi, R. Calabrese, G. Cibinetto, E. Fioravanti, I. Garzia, E. Luppi, M. Munerato, M. Negrimi, L. Piemontese, R. Baldini-Ferroli, A. Calcaterra, D. de Sangro, G. Finocchiaro, M. Nicolaci, P. Patteri, I. M. Peruzzi, M. Piccolo, M. Rama, A. Zallo, R. Contrada, E. Guido, M. Lo Vetere, M. R. Monge, S. Passaggio, C. Patrignani, E. Robutti, B. Bluyian, V. Prasad, C. L. Lee, M. Morii, A. J. Edwards, A. Adamez, J. Marks, U. Uwer, F. U. Bernlochner, M. Ebert, H. M. Lacker, T. Lueck, P. D. Dauncey, M. Tibbetts, P. K. Behera, U. Mallik, C. Chen, J. Cochran, H. B. Crawley, W. T. Meyer, S. P. Prelic, E. I. Rosenberg, A. E. Rubin, A. V. Gritsan, Z. J. Guo, N. Arnaud, M. Davier, G. Grosdidier, F. Le Diberder, A. M. Lutz, B. Malaescu, P. Roulseau, M. H. Schune, A. Stocchi, G. Wormser, D. J. Lange, D. M. Wright, I. Bingham, C. A. Chavez, J. P. Coleman, J. R. Fry, E. Gabathuler, D. E. Hutchcroft, D. J. Payne, C. Touramanis, A. J. Bevan, F. Di Lodovico, S. Rocco, M. Sigamani, G. Cowan, S. Paramesvaran, D. N. Brown, C. L. Davis, A. G. Denig, M. Fritsch, W. Gradl, A. Hafner, E. Prencipe, K. E. Alwyn, D. Bailey, R. J. Barlow, G. Jackson, G. D. Lafferty, R. Cenci, B. Hamilton, A. Jawahery, D. A. Roberts, G. Simi, C. Dallapiccola, R. Cowan, D. Dujmic, G. Sciolli, D. Lindemann, P. M. Patel, S. H. Robertson, M. Schram, P. Biassoni, A. Lazzaro, V. Lombardo, F. Palombo, S. Stracka, L. Cremaldi, R. Godang, R. Kroeger, D. J. Summers, X. Nguyen, P. Taras, G. De Nardo, D. Monorchio, G. Onorato, C. Sciacca, G. Raven, H. L. Snoek, C. P. Jessop, K. J. Knoepfel, J. M. LoSecco, W. F. Wang, K. Honscheid, R. Kass, J. Brau, F.rey, N. B. Sinev, D. Strom, E. Torrence, E. Feltresi, N. Gagliardi, M. Margoni, M. Morandi, M. Posocco, M. Rotondo, F. Simonetto, R. Strölli, E. Ben-Haim, M. Bomben, G. R. Bonneau, H. Briand, G. Calderini, J. Chauvet, O. Hamon, Ph. Lerusse, G. Marchiori, J. Ocariz, S. Sitt, M. Biasini, E. Manoni, S. Pacetti, A. Rossi, C. Angelini, G. Batignani, S. Bettarini, M. Carpinelli, G. Casarosa, F. Forti, M. A. Giorgi, A. Luziania, N. Neri, B. Oberholzer, E. Paoloni, A. Perez, G. Rizzo, J. J. Walsh, D. Lopes Pegna, C. Lu, J. Olsen, A. J. S. Smith, A. V. Telnov, F. Amatini, G. Cavoto, R. Facchini, F. Ferrarotto, F. Ferroni, M. Gaspero, L. Gioli, M. A. Mazzoni, G. Priedda, C. Bünger, O. Grünberg, T. Hartmann, T. Leddig, H. Schröder, R. Waldi, T. Ayde, E. O. Olaya, F. W. Wilson, S. Emery, G. Hamed de Monchenault, G. Vasseur, Ch. Yèche, D. Aston, D. J. Bard, R. Bartoldus, J. F. Benitez, C. Cartaro, M. R. Convery, J. Dorfan, G. P. Dubois-Felsmann, W. Dunwoodie, R. C. Field, M. Franco Sevilla, G. B. Fulsom, A. M. Gabareen, M. T. Graham, P. Grenier, C. Hasi, W. R. Innes, M. H. Kelsey, H. Kim, P. Kim, M. L. Kocian, D. W. G. S. Leith, P. Lewis, S. Li, B. Lindquist, S. Luitz, V. Luth, H. L. Lynch, D. B. MacFarlane, D. R. Muller, H. Neaf, S. Nelson, I. Ofte, M. Perl, T. Pulliam, B. N. Ratcliff, A. Roodman, A. A. Salahikov, V. Santoro, R. H. Schindler, A. Snyder, D. Su, M. K. Sullivan, J. Va’vra, A. P. Wagner, M. Weaver, W. J. Wisniewski, M. Wittgen, D. H. Wright, H. W. Wulsin, A. K. Yarritu.
C. C. Young, 63 V. Ziegler, 63 W. Park, 64 M. V. Purohit, 64 R. M. White, 64 J. R. Wilson, 64 A. Randle-Conde, 65 S. J. Sekula, 65 M. Bellis, 66 P. R. Burchat, 66 T. S. Miyashita, 66 M. S. Alam, 67 J. A. Ernst, 67 R. Gorodesky, 68 N. Guttman, 68 D. R. Peimer, 68 A. Soffer, 68 P. Lund, 69 S. M. Spanier, 69 R. Eckmann, 70 J. L. Ritchie, 70 A. M. Ruland, 70 C. J. Schilling, 70 R. F. Schwitters, 70 B. C. Wray, 70 J. M. Izen, 71 X. C. Lou, 71 F. Bianchi, 72 D. Gamba, 72 L. Lanceri, 73 L. Vitale, 73 N. Lopez-March, 74 F. Martinez-Vidal, 74 A. Oyanguren, 74 H. Ahmed, 75 J. Albert, 75 Sw. Banerjee, 75 H. H. F. Choi, 75 G. J. King, 75 R. Kowalewski, 75 M. J. Lewczuk, 75 C. Lindsay, 75 I. M. Nugent, 75 J. M. Roney, 75 R. J. Sobie, 75 T. J. Gershon, 76 P. F. Harrison, 76 T. E. Latham, 76 E. M. T. Puccio, 76 H. R. Band, 77 S. Dasu, 77 Y. Pan, 77 R. Prepost, 77 C. O. Vuosalo, 77 and S. L. Wu 77

(The BABAR Collaboration)

1 Laboratoire d’Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74941 Annecy-Le-Vieux, France
2 Universitat de Barcelona, Facultat de Física, Departament ECM, E-08028 Barcelona, Spain
3 INFN Sezione di Bari; Dipartimento di Fisica, Università di Bari, I-70126 Bari, Italy
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 Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany
7 University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1
8 Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom
9 Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia
10 University of California at Irvine, Irvine, California 92697, USA
11 University of California at Riverside, Riverside, California 92521, USA
12 University of California at Santa Barbara, Santa Barbara, California 93106, USA
13 University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA
14 California Institute of Technology, Pasadena, California 91125, USA
15 University of Cincinnati, Cincinnati, Ohio 45221, USA
16 University of Colorado, Boulder, Colorado 80309, USA
17 Colorado State University, Fort Collins, Colorado 80523, USA
18 Technische Universität Dortmund, Fakultät Physik, D-44221 Dortmund, Germany
19 Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
20 Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS/IN2P3, F-91128 Palaiseau, France
21 University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
22 INFN Sezione di Ferrara; Dipartimento di Fisica, Università di Ferrara, I-44100 Ferrara, Italy
23 INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy
24 INFN Sezione di Genova; Dipartimento di Fisica, Università di Genova, I-16146 Genova, Italy
25 Indian Institute of Technology Guwahati, Guwahati, Assam, 781 039, India
26 Harvard University, Cambridge, Massachusetts 02138, USA
27 Harvey Mudd College, Claremont, California 91711
28 Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
29 Humboldt-Universität zu Berlin, Institut für Physik, Newtonstr. 15, D-12489 Berlin, Germany
30 Imperial College London, London, SW7 2AZ, United Kingdom
31 University of Iowa, Iowa City, Iowa 52242, USA
32 Iowa State University, Ames, Iowa 50011-3160, USA
33 Johns Hopkins University, Baltimore, Maryland 21218, USA
34 Laboratoire de l’Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d’Orsay, B. P. 34, F-91898 Orsay Cedex, France
35 Lawrence Livermore National Laboratory, Livermore, California 94550, USA
36 University of London, University of Liverpool, L69 7ZE, United Kingdom
37 Queen Mary, University of London, London, E1 4NS, United Kingdom
38 University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 OEX, United Kingdom
39 University of Louisville, Louisville, Kentucky 40292, USA
40 Johannes Gutenberg-Universität Mainz, Institut für Kernphysik, D-55099 Mainz, Germany
41 University of Manchester, Manchester M13 9PL, United Kingdom
42 University of Maryland, College Park, Maryland 20742, USA
43 University of Massachusetts, Amherst, Massachusetts 01003, USA
44 Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA
45 McGill University, Montréal, Québec, Canada H3A 2T8
46 INFN Sezione di Milano; Dipartimento di Fisica, Università di Milano, I-20133 Milano, Italy
47 University of Mississippi, University, Mississippi 38677, USA
48 Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7
49 INFN Sezione di Napoli; Dipartimento di Scienze Fisiche, Università di Napoli Federico II, I-80126 Napoli, Italy
We study inclusive di-pion decays using a sample of $108 \times 10^6 \ U(3S)$ events recorded with the BABAR detector. We search for the decay mode $\ U(3S) \to \pi^+\pi^- h_b(1P)$ and find no evidence for the bottomonium spin-singlet state $h_b(1P)$ in the invariant mass distribution recoiling against the $\pi^+\pi^-$ system. Assuming the $h_b(1P)$ mass to be $9.900 \ \text{GeV}/c^2$, we measure the upper limit on the branching fraction $\mathcal{B}(U(3S) \to \pi^+\pi^- h_b(1P)) < 1.2 \times 10^{-4}$, at 90% confidence level. We also investigate the $\chi_{bJ}(2P) \to \pi^+\pi^- \chi_{bJ}(1P)$, $\ U(3S) \to \pi^+\pi^- \ U(2S)$, and $\ U(2S) \to \pi^+\pi^- \ U(1S)$ di-pion transitions and present an improved measurement of the branching fraction of the $\ U(3S) \to \pi^+\pi^- \ U(2S)$ decay and of the $\ U(3S) \to \ U(2S)$ mass difference.

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Studies of $b\bar{b}$ (bottomonium) and $c\bar{c}$ (charmonium) bound states provide insight into inter-quark forces. The measurement of the hyperfine mass splitting between triplet and singlet states in quarkonium systems discriminates between various models and tests lattice QCD and potential nonrelativistic QCD calculations. Observation of the $P$-wave singlet ground state of charmonium, $h_{c}(1P)$, was recently confirmed and its mass precisely measured, yielding the hyperfine splitting for the charmonium $1P$ states $\Delta M_{hf}(1P)_{cc} \equiv \langle M(3P_J)_{cc} \rangle - \langle M(1P_J)_{cc} \rangle = +0.08 \pm 0.18 \ (\text{stat.}) \pm 0.12 \ (\text{syst.}) \ \text{MeV}/c^2$, where $\langle M(3P_J) \rangle$ is the spin-weighted average mass of the $J = 0, 1, 2$ ground states. The hyperfine splitting $\Delta M_{hf}(1P)_{bb} \equiv \langle M(3P_J)_{bb} \rangle - \langle M(1P_J)_{bb} \rangle$ for bottomonium states is expected to be no more than a few MeV/$c^2$. The $3P_J$ $b\bar{b}$ ground states are well-established, and their spin-weighted mass average is $\langle M(3P_J)_{bb} \rangle = [M(\chi_{b0}(1P)) + 3M(\chi_{b1}(1P)) + 5M(\chi_{b2}(1P))] / 9 = 9.89987 \pm 0.00027 \ \text{GeV}/c^2$. The $h_b(1P)$, hereafter referred to as the $h_b$, is expected to decay predominantly to $ggg$ (57% branching fraction), $\gamma \eta_b$ (41%), and $gg\gamma$ (2%), and its width is predicted to be of order 0.1 MeV.

We report, herein, a search for the $h_b$ through the hadronic transition $\ U(3S) \to \pi^+\pi^- h_b(1P)$. The CLEO Collaboration searched for the $h_b$ in the reactions $\ U(3S) \to \pi^0 h_b$ and $\ U(3S) \to \pi^+\pi^- h_b$, setting upper limits at 90% confidence level (CL) for the branching fractions $\mathcal{B}(\ U(3S) \to \pi^0 h_b) < 2.7 \times 10^{-3}$ and $\mathcal{B}(\ U(3S) \to \pi^+\pi^- h_b) < 1.8 \times 10^{-3}$, assuming the $h_b$ mass $m(h_b)$ to be $9.900 \ \text{GeV}/c^2$. The BABAR Collaboration recently reported evidence for the $h_b$ in $\ U(3S) \to \pi^0 h_b$. 
$h_b \rightarrow \eta \gamma$ decays \cite{1}. Preliminary results of a search for the $h_b$ in the reaction $e^+e^- \rightarrow \pi^+\pi^- h_b$, reporting the observation of the $h_b$ meson, have been announced by the Belle Collaboration \cite{2}. Theoretical predictions for $B_{\chi B}$ span one order of magnitude. References [9–11] predict a branching fraction between $2.2 \times 10^{-4}$ and $8.0 \times 10^{-4}$, while Ref. 12 predicts a rate of $10^{-4}$ or smaller.

The data sample used in this study was collected with the BABAR detector \cite{13} at the PEP-II asymmetric-energy $e^+e^-$ storage rings at the SLAC National Accelerator Laboratory. It consists of 25.6 fb$^{-1}$ of integrated luminosity collected at a $e^+e^-$ center-of-mass (c.m.) energy of 10.355 GeV, corresponding to the mass of the $\Upsilon(3S)$ resonance. The number of recorded $\Upsilon(3S)$ events is 108×10$^{6}$. An additional sample of 2.5 fb$^{-1}$ recorded at the $\Upsilon(3S)$ energy ("10%" sample) and a 2.6 fb$^{-1}$ sample collected 30 MeV below the $\Upsilon(3S)$ resonance ("off-peak" sample) are used for background and calibration studies.

The momenta of charged particles are reconstructed using a combination of a five-layer double-sided silicon-strip detector and a 40-layer drift chamber, both operating in the 1.5-T magnetic field of a superconducting solenoid. Photons are detected using a CsI(Tl) electromagnetic calorimeter, which is also inside the magnet coil. Charged hadron identification is achieved through measurements of particle energy loss in the tracking system and the Cherenkov angle obtained from a detector of internally reflected Cherenkov light.

The $\pi^+\pi^-$ pairs are selected from oppositely-charged tracks that originate from the $e^+e^-$ interaction region in hadronic events, hence excluding tracks arising from a photon conversion or the decay of a long-lived particle. We search for an $h_b$ signal using a fit to the spectrum of the mass $m_R$ recoiling against the $\pi^+\pi^-$ system, defined by:

$$m^2_R = (M_{\Upsilon(3S)} - E_{\pi\pi}^*)^2 - |P_{\pi\pi}^*|^2,$$

where $E_{\pi\pi}$ and $P_{\pi\pi}^*$ are, respectively, the measured $\pi\pi$ energy and momentum in the c.m. frame.

The $h_b$ signal is expected to appear as a peak in the $m_R$ distribution on top of a smooth non-peaking background from continuum events ($e^+e^- \rightarrow q\bar{q}$ with $q = u, d, s, c$) and bottomonium decays. Several other processes produce peaks in the recoil mass spectrum close to the signal region. Hadronic transitions $\Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(2S)$ (hereafter denoted $\Upsilon^{3-2}$) produce a peak centered at the $\Upsilon(2S)$ mass $m(\Upsilon(2S)) = 10.02326 \pm 0.00031$ GeV/c$^2$ \cite{14}. The cascade process $\Upsilon(3S) \rightarrow \Upsilon(2S)X$, $\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S)$ ($\Upsilon^{2-1}$) results in a peak centered at 9.791 GeV/c$^2$. The peak is offset from the $\Upsilon(1S)$ mass by approximately the $\Upsilon(3S)$ to $\Upsilon(2S)$ mass difference. Doppler shift and broadening further affect the position and width of this peak. When the $\Upsilon(2S)$ parent in $\Upsilon^{2-1}$ decays is produced through the $\Upsilon^{3-2}$ channel, a pion from the $\Upsilon(3S)$ decay can be combined with an oppositely-charged track from the $\Upsilon(2S)$ decay to produce a broad distribution centered around 9.9 GeV/c$^2$. The $\Upsilon(2S)$ is also produced through the initial-state radiation (ISR) process $e^+e^- \rightarrow \gamma_{ISR}\Upsilon(2S)$ ($\Upsilon^{2-1}_{ISR}$). Of the nine possible $\Upsilon(3S) \rightarrow \chi_{bJ}(2P)\gamma$, $\chi_{bJ}(2P) \rightarrow \pi^+\pi^-\chi_{bJ}(1P)$ decay chains ($\chi_{bJ}^{'+} = \{1, 2\}$), only those for $J' = J = \{1, 2\}$ have been reported \cite{14, 15}; these should generate two narrowly separated peaks near 9.993 GeV/c$^2$, while the contributions with $J' \neq J$ or with $J = 0$ are expected to be negligible.

Selection criteria are chosen by optimizing the ratio $S/\sqrt{B}$ between the expected $h_b$ signal yield ($S$) and the background ($B$). The signal sample for the optimization is provided by a detailed Monte Carlo (MC) simulation based on GEANT4 \cite{16}, EvtGen \cite{17}, and JETSET \cite{18}, while the background sample is obtained from the 10% sample, which is not used for the extraction of the signal. The natural width of the $h_b$ meson, which is predicted to be negligible in comparison with the experimental resolution in $m_R$ (0.009 GeV/c$^2$ r.m.s.), is set to zero in the simulation.

Since decays of the $h_b$ via three gluons or to $\eta \gamma$ are expected to exhibit a high track multiplicity, we require an event to have between 6 and 16 charged tracks, where the upper restriction reduces contributions due to random combinations of tracks. We further require the ratio of the second to zeroth Fox-Wolfram moment \cite{18} calculated using all charged tracks and unmatched neutral showers in the event to be less than 0.55. The total event energy in the laboratory frame must lie between 6 and 18 GeV, where the lower restriction reduces QED background.

Events must contain two oppositely-charged tracks, each of which is identified as a pion. The pion identification efficiency depends on momentum and polar angle, and is typically about 98%. This requirement provides a rejection factor of order 50 against electrons. The vertex of each reconstructed pion pair must lie within 0.41 cm and be less than 4$\sigma_L$ from the nominal interaction point $\chi_{bJ}$ decay chain, where $\sigma_L$ is the uncertainty evaluated on a candidate-by-candidate basis for the transverse flight length $L$. We demand the $\chi^2$ probability for the vertex fit to be greater than 0.001.

The phase-space distribution of $K_{\ell}^0$ decays extends up to $m_R$ values of approximately 9.86 GeV/c$^2$ and then rapidly decreases. To further suppress the background due to $K_{\ell}^0$ decays, we reject pairs of pions if their vertex is displaced from the nominal interaction point by more than 0.05 cm and 2$\sigma_L$ in the transverse plane and if they satisfy $\cos \alpha > 0.95$, where $\alpha$ is the angle between the direction of the di-pion candidate momentum and its flight direction in the transverse plane. Candidates removed from the nominal sample that satisfy all other selection criteria constitute a $K_{\ell}^0$-enriched control sample.

The selected data sample consists of approximately $137 \times 10^6 \pi^+\pi^-$ candidates in the range 9.750 < $m_R$ <
10.040 GeV/c², corresponding to an average of 2.4 selected di-pion candidates per event. The fit validation studies described below account for the effect of candidate multiplicity. We evaluate the di-pion reconstruction efficiency with MC events, by matching the reconstructed \( \pi^+\pi^- \) pairs to the simulated pairs emitted in the bottomonium transition under study on an event-by-event basis. The \( h_b \) signal efficiency is \( \epsilon = 41.8\% \) for \( m(h_b) = 9.900 \text{GeV}/c^2 \), with a \([-6, -3]\)\% variation of \( \epsilon \) over the \( m(h_b) \) range [9.880, 9.920] GeV/c². A lower reconstruction efficiency of 25.0\% (16.7\%) is found for the softer \( \pi^+\pi^- \) pairs produced in \( \chi_b^{J',J} \) (\( \Upsilon^{3\to2} \)) transitions. For the \( \Upsilon^{2\to1} \) transition, an efficiency of 47.2\% is obtained by averaging over the contributions from \( X = \gamma\gamma, \pi^0\pi^0, \) and \( \pi^+\pi^- \).

We perform a \( \chi^2 \) fit to the \( m_R \) spectrum in the range \( 9.750 < m_R < 10.040 \text{GeV}/c^2 \) with a model comprising eight components: non-peaking background, \( \Upsilon^{3\to2}, \Upsilon^{2\to1}, \chi_b^{1,1}, K_0^0 \to \pi^+\pi^- \), and the \( h_b \) signal. The \( m_R \) distributions of the signal and background are parameterized using probability density functions (PDFs). We define a two-sided Crystal Ball (TCB) function, which is a Gaussian for \( \alpha_L < (x-x_0)/\sigma < \alpha_R \), and transitions to the power-law tail function \( f(x) \) [20]:

\[
f(x) = e^{-\frac{1}{2}a^2}\left(\frac{n_i}{\alpha_i}\right)^{n_i}\left[\frac{|x-x_0|}{\sigma} + \frac{n_i}{\alpha_i} - \alpha_i\right]^{n_i},
\]

where \( x_0 \) and \( \sigma \) are the mean and width of the Gaussian, and the subscript \( i = L \) (\( i = R \)) applies to values \( x < x_0 \) (\( x > x_0 \)). We model the signal component with a symmetric \( (\alpha_L = \alpha_R, n_L = n_R) \) TCB shape.

The \( \Upsilon^{3\to2} \) and \( \Upsilon^{2\to1} \) peaks are described by sums of an asymmetric TCB shape and an asymmetric Gaussian. Contributions to \( \Upsilon^{3\to1} \) from \( X = \{\pi^+\pi^-, \pi^0\pi^0, \gamma\gamma\} \) are modeled separately because of the different Doppler broadening. Their relative fractions and relative peak positions are fixed according to the world-average values [4] and the MC-simulated \( m_R \) spectrum, respectively. For each peak, the ratios of the widths of the TCB and Gaussian functions are fixed to the values found from fitting the corresponding MC spectrum. The PDF of the peaking background from ISR \( \Upsilon(2S) \) production is parameterized as a symmetric TCB function whose parameters are determined from simulated events. The yield of \( \chi_b^{1,1} \) events in the \( \Upsilon(3S) \) sample, \([6.6 \pm 1.0 \text{stat.}] \times 10^4\), is determined using the off-peak data. A symmetric TCB function is used as the PDF for both the \( \chi_b^{1,1} \) and \( \chi_b^{2,2} \) contributions. The peak positions of the \( \chi_b^{J',J} \) components relative to the \( \Upsilon^{3\to2} \) peak are fixed according to the MC simulation. The parameters for the width and tail of the TCB function are common to both \( \chi_b^{J',J} \) peaks.

The \( K_0^0 \) background is modeled using empirical phase space functions derived from the MC. Knowledge about the \( K_0^0 \) transverse momentum distribution is obtained from fits to the \( \pi^+\pi^- \) invariant mass spectrum for the \( K_0^0 \)-enriched sample, and is used to correct discrepancies between the data and the MC simulation. The \( K_0^0 \) background yield, \((348 \pm 10) \times 10^3\), is obtained from an extrapolation of a fit to the \( m_R \) spectrum of the \( K_0^0 \)-enriched sample, using a scale factor of 2.5 determined from MC simulation. The non-peaking background PDF is parameterized by a sixth-order polynomial.

The signal (peaking background) PDF excludes random combinations of tracks that do not originate from the signal (background) bottomonium transition. Such misreconstructed combinations are included in the non-peaking term.

To improve fit stability, the fit is performed in two stages: a preliminary fit to fix background parameters followed by a final fit. The peaking background PDF parameters and yields are determined from the preliminary, \( \chi^2 \)-based fit in which the signal component is excluded from the model. The free parameters in the fit are: the yields of the continuum background and the peaking background components \( \Upsilon^{3\to2}, \Upsilon^{2\to1}, \) and \( \chi_b^{J',J} \); the continuum background PDF parameters; the overall \( m_R \) scale of the \( K_0^0 \) contribution; the peak positions of the \( \Upsilon^{3\to2} \) and \( \Upsilon^{2\to1} \) components; the overall widths of the PDFs for the \( \Upsilon^{3\to2}, \Upsilon^{2\to1}, \) and \( \chi_b^{J',J} \) components. The \( \chi^2 \) per degree of freedom after the preliminary fit is 364/272 \approx 1.3, where the largest contributions arise from a few isolated bins near 9.79 and 10.02 GeV/c². As the measurement is dominated by systematic uncertainties, we evaluate the \( \chi^2 \) distribution on simulated pseudoexperiments accounting for the dominant sources of systematic uncertainties, and we observe values of \( \chi^2 \) greater than 364 in more than 7% of the trials. In the final fit, all peaking-background parameters except the yields are fixed to the values extracted from the preliminary fit.

The final fit is performed as a scan over the values of the \( h_b \) peak position, with 39 steps in 1 MeV/c² intervals in the range \([9.880, 9.920] \text{GeV}/c^2\). At each step, a \( \chi^2 \) fit is performed for the signal and background yields and the continuum background parameters. The fit procedure is validated with simulated experiments, and systematic uncertainties are evaluated for each point of the scan.

Figure [1] shows the \( m_R \) spectrum and the fit result. The non-peaking background component dominates, with only the prominent \( \Upsilon^{3\to2} \) and \( \Upsilon^{2\to1} \) peaks clearly seen above this background. When comparing the fitted mass of the \( \Upsilon^{3\to2} \) peak with MC simulation, we observe a \( +0.44 \pm 0.02 \text{stat.} \) MeV/c² displacement in data, which corresponds to a difference of \( 331.50 \pm 0.02 \text{stat.} \pm 0.13 \text{syst.} \) MeV/c² between the \( \Upsilon(3S) \) and \( \Upsilon(2S) \) masses. The systematic uncertainty is dominated by uncertainties in the lineshape and in the track momentum measurement. Details of the latter may be found in Ref. [21]. Other sources of uncertainty have been investigated and found to be of minor significance. These include the fit bias, the c.m. boost
The following systematic uncertainties are associated with the interval $[9.75, 9.80]$: a 2.2 standard deviation ($\sigma$) excess (statistical only) at $m(h_b) = 9.916$ GeV/$c^2$. Therefore, we do not obtain evidence for an $h_b$ signal.

The inset of Fig. 2 shows an expanded view of the $h_b$ signal region. The significance of a signal is evaluated at each point of the scan using the ratio, $N/\sigma_N$, of the signal yield $N$ over its uncertainty $\sigma_N$. The largest enhancement over background is a 2.2 standard deviation ($\sigma$) excess (statistical only) at $m(h_b) = 9.900$ GeV/$c^2$. Therefore, we do not obtain evidence for an $h_b$ signal.

The fits $h_b$ signal yield for $m(h_b) = 9.900$ GeV/$c^2$ is $\sigma = \pm 1.1 \pm 2.4$ (statistical) $\times 10^3$ events. Results for the $\Upsilon^{3-2}$, $\Upsilon^{2-1}$, $\chi_b^{1-1}$, and $\chi_b^{2-2}$ component product branching fractions are presented in Table II.

In the following, reported quantities refer to $m(h_b) = 9.900$ GeV/$c^2$. The ranges spanned by varying $m(h_b)$ in the interval [9.880, 9.920] GeV/$c^2$ are given in parentheses. The following systematic uncertainties are associated with the signal yields. We observe a 10% discrepancy between the $m_R$ resolution values in data and MC for the $\Upsilon^{3-2}$ component, and translate this into an uncertainty of $0.1 \times 10^3$ ($0.0 \times 10^3$ to $0.4 \times 10^3$) events on the $h_b$ signal yield. A systematic uncertainty of $0.4 \times 10^3$ ($0.3 \times 10^3$ to $0.5 \times 10^3$) events is estimated by varying the PDF parameters fixed in the fit by $\pm 1 \sigma$, varying the overall width of the $h_b$ PDF by 10%, setting the yield of the ISR $\Upsilon(2S)$ component to $\pm 1 \sigma$ of the nominal value, and varying the $K^0$ component normalization and parameters within their uncertainties. Uncertainties related to the continuum background model amount to $0.2 \times 10^3$ ($0.0 \times 10^3$ to $0.7 \times 10^3$) events. The additive systematic uncertainties on the yields of the $\Upsilon^{3-2}$, $\chi_b^{1-1}$ and $\chi_b^{2-2}$ components also account for the modeling of the $\Upsilon^{3-2}$ tails and for the assumption that the contributions of the $\Upsilon(3S) \rightarrow \chi_b^{J'}(2P)\pi^+\pi^-\chi_b^{K'}$ decay chains with $J' \neq J$ or $J = 0$ are negligible.

The fit bias on the extracted yields, due to the choice of the fit model, is estimated with pseudoexperiments based

![Figure 1: The $m_R$ spectrum: data (points) with the fitted model (solid line) superimposed. The short-dashed line is the contribution from the continuum component. Also shown are the $\Upsilon^{2-1}$ (dashed curve around 9.79 GeV/$c^2$) and $\Upsilon^{3-2}$ (long-dashed curve around 10.02 GeV/$c^2$) components. The $h_b$ signal component is excluded from the superimposed model.](image1)

![Figure 2: The $m_R$ spectrum after subtraction of the continuum background component. The curves represent the fitted model (solid), the $\Upsilon_{ISR}$ (dotted), $K^0$ (double-dot-dashed), $\chi_b^{1-1}$ (dashed), and $\chi_b^{2-2}$ (dot-dashed) components. Inset: expanded view in the $h_b$ region after subtraction of continuum and peaking backgrounds.](image2)

![Figure 3: The $m_R$ spectrum in the $\chi_b^{J'}$ region after subtraction of continuum and $K^0$ background components: points represent data, while the curves represent the fitted model (solid), the $\chi_b^{1-1}$ (dashed), $\chi_b^{2-2}$ (dot-dashed), and $\Upsilon^{3-2}$ (long-dashed) components.](image3)
on fully simulated Monte Carlo samples. We estimate a fit bias on the $h_b$ signal yield of $-2.8 \times 10^3$ to $+0.4 \times 10^3$ events. Fit biases for the other di-pion transitions are listed in Table I. We do not correct the signal yields but rather assign the bias as a systematic uncertainty.

The following systematic uncertainties are associated with the reconstruction efficiency $\epsilon$. The uncertainty due to the track-reconstruction efficiency is 3%. To assess the impact of data-MC differences on the $\pi^+\pi^-$ candidate selection efficiencies, we compare the relative variations of the $\Upsilon$ yield in data and MC when excluding selection requirements one at a time, and assign the full observed discrepancy to the systematic uncertainty. A total uncertainty of 2.3% in $\epsilon$ is obtained, including the statistical uncertainty (0.6%) in the $\Upsilon$ yield. The uncertainty in the number of $\Upsilon(3S)$ events is 1.1%. The above multiplicative systematic uncertainties affect the product branching fractions of all di-pion transitions studied in this analysis. Differences in the selection efficiencies resulting from different angular distributions of the $h_b$ decay products and different $h_b$ hadronization models in the MC simulation contribute a 5% uncertainty. Model uncertainties in the simulation of the di-pion kinematics, bottomonium hadronization, and $\Upsilon(2S)$ production channel (where applicable) in the $\Upsilon$ and $\Upsilon(3S)$ decay chains result in systematic uncertainties on the efficiency of 1.3%, 0.5%, 0.6%, and 0.6%, respectively.

Product branching fractions are calculated by dividing the fitted yield by the efficiency and the number of $\Upsilon(3S)$ events, and are summarized in Table I. For $m(h_b) = 9.900 \text{ GeV}/c^2$ we find the branching fraction $B_T \equiv B[\Upsilon(3S) \rightarrow \pi^+\pi^- h_b] = (0.2 \pm 0.5 \pm 0.6) \times 10^{-4}$, where the first uncertainty is statistical and the second systematic, and set an upper limit (UL) $B_T < 1.2 \times 10^{-4}$ at 90% CL. The UL is calculated assuming a Gaussian sampling distribution $f(B_T)$ for $B_T$, which accounts for statistical and systematic uncertainties, and determining the value of UL for which $\int_0^{UL} f(B_T) dB_T = 0.9 \times \int_0^{\infty} f(B_T) dB_T$. Figure 4 reports the branching fractions $B_T$ and the 90% CL ULs as a function of the assumed $h_b$ mass. The triangles indicate the upper limits at 90% CL.

In summary, we present an inclusive analysis of the $\pi^+\pi^-$ recoil mass spectrum in $\Upsilon(3S)$ decays. We measure the branching fraction

$$B[\Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(2S)] = (3.00 \pm 0.02(\text{stat.}) \pm 0.14(\text{syst.}))%.$$ 

This value is in reasonable agreement with, and more precise than, the current world average $(2.45\pm0.23\%)^\text{[4]}$.

The measured $\Upsilon(3S)$-$\Upsilon(2S)$ mass difference is $331.50 \pm 0.02(\text{stat.}) \pm 0.13(\text{syst.}) \text{ MeV}/c^2$. 

| $h_b$ [m(h_b) = 9.900 GeV/c²] | $\Upsilon(3S) \rightarrow \pi^+\pi^- h_b$ | $\Upsilon(3S) \rightarrow \pi^+\pi^- \chi_b(1P)$ | $\Upsilon(3S) \rightarrow \pi^+\pi^- \chi_b(2P)$ | $\Upsilon(3S) \rightarrow \pi^+\pi^- \chi_b(3P)$ |
|----------------|----------------|----------------|----------------|----------------|
| Yield          | $-1106 \pm 2432$ | $31418 \pm 1851$ | $17385 \pm 1456$ | $543839 \pm 2928$ |
| $\epsilon$ (%) | 41.8            | 25.0            | 25.0            | 16.7            | 47.2            |
| Fit bias (10^{-3}) | $-0.06$         | $-0.09$         | $-0.04$         | $+0.2$          | $+0.8$          |
| Yield error (10^{-3}) | 0.01            | 0.06            | 0.06            | 0.6             | 0.4             |
| $\epsilon$ error (10^{-3}) | 0.00            | 0.05            | 0.03            | 1.3             | 0.8             |
| $B(10^{-3})$    | $\ldots$        | $1.16 \pm 0.07 \pm 0.12$ | $0.64 \pm 0.05 \pm 0.08$ | $\ldots$        |
| $\Upsilon(3S)$ | $-0.02 \pm 0.05 \pm 0.06$ | $9.2 \pm 0.6 \pm 0.9$ | $4.9 \pm 0.4 \pm 0.6$ | $30.0 \pm 0.2 \pm 1.4$ | $\ldots$ |

FIG. 4: Results for the $\Upsilon(3S) \rightarrow \pi^+\pi^- h_b$ branching fraction (points with statistical and systematic uncertainties) as a function of the assumed $h_b$ mass. The triangles indicate the upper limits at 90% CL.
We extract the product branching fractions
\[
B[T(3S) \to X\chi_b(2P)] \times B[\chi_b(2P) \to \pi^+\pi^-\chi_b] = (1.16 \pm 0.07 \pm 0.12) \times 10^{-3},
\]
\[
B[T(3S) \to X\chi_b(2P)] \times B[\chi_b(2P) \to \pi^+\pi^-\chi_b] = (0.64 \pm 0.05 \pm 0.08) \times 10^{-3}, \quad \text{and}
\]
\[
B[T(3S) \to X\Upsilon(2S)] \times B[\Upsilon(2S) \to \pi^+\pi^-\Upsilon] = (1.78 \pm 0.02 \pm 0.11)\%.
\]
A search for the $h_b$ state, the $1^P_1$ state of bottomonium, in $T(3S) \to \pi^+\pi^-h_b$ decays does not provide evidence for this decay mode, and assuming the $h_b$ mass to be 9.900 GeV/c$^2$, we set a 90\% CL upper limit $B_T < 1.2 \times 10^{-4}$. We exclude, at 90\% CL, values of $B_T$ above $1.8 \times 10^{-4}$ for a wide range of assumed $h_b$ mass values. These results disfavor the calculations of Refs. [9,11]. Similarly, a recent measurement of the $T(1S)D_J \to \Upsilon(1S)\pi^+\pi^-$ branching fraction [24] disfavors the calculations of Ref. [10,11]. The predictions of Ref. [12] are at least one order of magnitude smaller and are not contradicted by our result.

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* Now at Temple University, Philadelphia, Pennsylvania 19122, USA
† Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy
‡ Now at University of South Alabama, Mobile, Alabama 36688, USA
§ Also with Università di Sassari, Sassari, Italy.