ELSEVIER

Physics Letters B 530 (2002) 56–66

PHYSICS LETTERS B

www.elsevier.com/locate/npe

Search for $\gamma\gamma \to \eta_b$ in e^+e^- collisions at LEP 2

ALEPH Collaboration

A. Heister, S. Schael

Physikalisches Institut das RWTH-Aachen, D-52056 Aachen, Germany

R. Barate, R. Brunelière, I. De Bonis, D. Decamp, C. Goy, S. Jezequel, J.-P. Lees, F. Martin, E. Merle, M.-N. Minard, B. Pietrzyk, B. Trocmé

Laboratoire de Physique des Particules (LAPP), IN^2P^3-CNRS, F-74019 Annecy-le-Vieux Cedex, France

G. Boix [25], S. Bravo, M.P. Casado, M. Chmeissani, J.M. Crespo, E. Fernandez, M. Fernandez-Bosman, Ll. Garrido [15], E. Graugés, J. Lopez, M. Martinez, G. Merino, R. Miquel [4], Ll.M. Mir [4], A. Pacheco, D. Paneque, H. Ruiz

Institut de Física d'Altes Energies, Universitat Autònomade Barcelona, E-08193 Bellaterra (Barcelona), Spain [7]

A. Colaleo, D. Creanza, N. De Filippis, M. de Palma, G. Iaselli, G. Maggi, M. Maggi, S. Nuzzo, A. Ranieri, G. Raso [24], F. Ruggieri, G. Selvaggi, L. Silvestris, P. Tempesta, A. Tricomi [3], G. Zito

Dipartimento di Fisica, INFN Sezione di Bari, I-70126 Bari, Italy

X. Huang, J. Lin, Q. Ouyang, T. Wang, Y. Xie, R. Xu, S. Xue, J. Zhang, L. Zhang, W. Zhao

Institute of High Energy Physics, Academia Sinica, Beijing, People's Republic of China [8]

D. Abbaneo, P. Azzurri, T. Barklow [30], O. Buchmüller [30], M. Cattaneo, F. Cerutti, B. Clerbaux, H. Drevermann, R.W. Forty, M. Frank, F. Gianotti, T.C. Greening [26], J.B. Hansen, J. Harvey, D.E. Hutchcroft, P. Janot, B. Jost, M. Kado [4], P. Mato,

0370-2693/02/$ – see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0370-2693(02)01329-1

A. Moutoussi, F. Ranjard, L. Rolandi, D. Schlatter, G. Sguazzoni, W. Tejessy, F. Teubert, A. Valassi, I. Videau, J.J. Ward

European Laboratory for Particle Physics (CERN), CH-1211 Geneva 23, Switzerland

F. Badaud, S. Dessagne, A. Falvard [20], D. Fayolle, P. Gay, J. Jousset, B. Michel, S. Monteil, D. Pallin, J.M. Pascolo, P. Perret

Laboratoire de Physique Corpusculaire, Université Blaise Pascal, IN^{2}P^3-CNRS, Clermont-Ferrand, F-63177 Aubière, France

J.D. Hansen, J.R. Hansen, P.H. Hansen, B.S. Nilsson

Niels Bohr Institute, 2100 Copenhagen, DK, Denmark [9]

A. Kyriakis, C. Markou, E. Simopoulou, A. Vayaki, K. Zachariadou

Nuclear Research Center Demokritos (NRCD), GR-15310 Attiki, Greece

A. Blondel [12], J.-C. Brient, F. Machefert, A. Rougé, M. Swynghedauw, R. Tanaka, H. Videau

Laboratoire de Physique Nucléaire et des Hautes Energies, Ecole Polytechnique, IN^{2}P^3-CNRS, F-91128 Palaiseau Cedex, France

V. Ciulli, E. Focardi, G. Parrini

Dipartimento di Fisica, Università di Firenze, INFN Sezione di Firenze, I-50125 Firenze, Italy

A. Antonelli, M. Antonelli, G. Bencivenni, F. Bossi, P. Campana, G. Capon, V. Chiarella, P. Laurelli, G. Mannocchi [5], F. Murtas, G.P. Murtas, L. Passalacqua

Laboratori Nazionali dell'INFN (LNF-INFN), I-00044 Frascati, Italy

A. Halley, J. Kennedy, J.G. Lynch, P. Negus, V. O'Shea, A.S. Thompson

Department of Physics and Astronomy, University of Glasgow, Glasgow G128QQ, United Kingdom [10]

S. Wasserbaech

Department of Physics, Haverford College, Haverford, PA 19041-1392, USA

R. Cavanaugh, S. Dhamotharan, C. Geweniger, P. Hanke, V. Hepp, E.E. Kluge, G. Leibenguth, A. Putzer, H. Stenzel, K. Tittel, S. Werner [19], M. Wunsch [19]

Kirchhoff-Institut für Physik, Universität Heidelberg, D-69120 Heidelberg, Germany [16]

R. Beuselinck, D.M. Binnie, W. Cameron, G. Davies, P.J. Dornan, M. Girone [1], R.D. Hill, N. Marinelli, J. Nowell, H. Przysiezniak [2], S.A. Rutherford, J.K. Sedgbeer, J.C. Thompson [14], R. White

Department of Physics, Imperial College, London SW7 2BZ, United Kingdom [10]

V.M. Ghete, P. Girtler, E. Kneringer, D. Kuhn, G. Rudolph

Institut für Experimentalphysik, Universität Innsbruck, A-6020 Innsbruck, Austria [18]

E. Bouhova-Thacker, C.K. Bowdery, D.P. Clarke, G. Ellis, A.J. Finch, F. Foster, G. Hughes, R.W.L. Jones, M.R. Pearson, N.A. Robertson, M. Smizanska

Department of Physics, University of Lancaster, Lancaster LA1 4YB, United Kingdom [10]

O. van der Aa, C. Delaere, V. Lemaitre

Institut de Physique Nucléaire, Département de Physique, Université Catholique de Louvain, 1348 Louvain-la-Neuve, Belgium

U. Blumenschein, F. Hölldorfer, K. Jakobs, F. Kayser, K. Kleinknecht, A.-S. Müller, G. Quast [6], B. Renk, H.-G. Sander, S. Schmeling, H. Wachsmuth, C. Zeitnitz, T. Ziegler

Institut für Physik, Universität Mainz, D-55099 Mainz, Germany [16]

A. Bonissent, P. Coyle, C. Curtil, A. Ealet, D. Fouchez, P. Payre, A. Tilquin

Centre de Physique des Particules de Marseille, Univ. Méditerranée, IN^{2}P^3-CNRS, F-13288 Marseille, France

F. Ragusa

Dipartimento di Fisica, Università di Milano e INFN Sezione di Milano, I-20133 Milano, Italy

A. David, H. Dietl, G. Ganis [27], K. Hüttmann, G. Lütjens, W. Männer, H.-G. Moser, R. Settles, G. Wolf

Max-Planck-Institut für Physik, Werner-Heisenberg-Institut, D-80805 München, Germany [16]

J. Boucrot, O. Callot, M. Davier, L. Duflot, J.-F. Grivaz, Ph. Heusse, A. Jacholkowska [32], C. Loomis, L. Serin, J.-J. Veillet, J.-B. de Vivie de Régie [28], C. Yuan

Laboratoire de l'Accélérateur Linéaire, Université de Paris-Sud, IN^{2}P^3-CNRS, F-91898 Orsay Cedex, France

G. Bagliesi, T. Boccali, L. Foà, A. Giammanco, A. Giassi, F. Ligabue, A. Messineo, F. Palla, G. Sanguinetti, A. Sciabà, R. Tenchini [1], A. Venturi [1], P.G. Verdini

Dipartimento di Fisica dell'Università, INFN Sezione di Pisa, e Scuola Normale Superiore, I-56010 Pisa, Italy

O. Awunor, G.A. Blair, J. Coles, G. Cowan, A. Garcia-Bellido, M.G. Green, L.T. Jones, T. Medcalf, A. Misiejuk, J.A. Strong, P. Teixeira-Dias

Department of Physics, Royal Holloway & Bedford New College, University of London, Egham, Surrey TW20 OEX, United Kingdom [10]

R.W. Clifft, T.R. Edgecock, P.R. Norton, I.R. Tomalin

Particle Physics Department, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 OQX, United Kingdom [10]

B. Bloch-Devaux, D. Boumediene, P. Colas, B. Fabbro, E. Lançon, M.-C. Lemaire, E. Locci, P. Perez, J. Rander, J.-F. Renardy, A. Rosowsky, P. Seager [13], A. Trabelsi [21], B. Tuchming, B. Vallage

CEA, DAPNIA/Service de Physique des Particules, CE-Saclay, F-91191 Gif-sur-Yvette Cedex, France [17]

N. Konstantinidis, A.M. Litke, G. Taylor

Institute for Particle Physics, University of California at Santa Cruz, Santa Cruz, CA 95064, USA [22]

C.N. Booth, S. Cartwright, F. Combley [31], P.N. Hodgson, M. Lehto, L.F. Thompson

Department of Physics, University of Sheffield, Sheffield S3 7RH, United Kingdom [10]

K. Affholderbach [23], A. Böhrer, S. Brandt, C. Grupen, J. Hess, A. Ngac, G. Prange, U. Sieler

Fachbereich Physik, Universität Siegen, D-57068 Siegen, Germany [16]

C. Borean, G. Giannini

Dipartimento di Fisica, Università di Trieste e INFN Sezione di Trieste, I-34127 Trieste, Italy

H. He, J. Putz, J. Rothberg

Experimental Elementary Particle Physics, University of Washington, Seattle, WA 98195, USA

S.R. Armstrong, K. Berkelman, K. Cranmer, D.P.S. Ferguson, Y. Gao [29], S. González, O.J. Hayes, H. Hu, S. Jin, J. Kile, P.A. McNamara III, J. Nielsen, Y.B. Pan, J.H. von Wimmersperg-Toeller, W. Wiedenmann, J. Wu, S.L. Wu, X. Wu, G. Zobernig

Department of Physics, University of Wisconsin, Madison, WI 53706, USA [11]

G. Dissertori

Institute for Particle Physics, ETH Hönggerberg, 8093 Zürich, Switzerland

Received 1 February 2002; accepted 5 February 2002

Editor: L. Montanet

Abstract

A search for the pseudoscalar meson η_b is performed in two-photon interactions at LEP 2 with an integrated luminosity of 699 pb^{-1} collected at e^+e^- centre-of-mass energies from 181 GeV to 209 GeV. One candidate event is found in the six-charged-particle final state and none in the four-charged-particle final state, in agreement with the total expected background of about one event. Upper limits of $\Gamma_{\gamma\gamma}(\eta_b) \times \mathrm{BR}(\eta_b \to 4 \text{ charged particles}) < 48$ eV, $\Gamma_{\gamma\gamma}(\eta_b) \times \mathrm{BR}(\eta_b \to 6 \text{ charged particles}) < 132$ eV are obtained at 95% confidence level, which correspond to upper limits of 9.0% and 25% on these branching ratios. © 2002 Elsevier Science B.V. All rights reserved.

[1] Also at CERN, 1211 Geneva 23, Switzerland.
[2] Now at LAPP, 74019 Annecy-le-Vieux, France.
[3] Also at Dipartimento di Fisica di Catania and INFN Sezione di Catania, 95129 Catania, Italy.
[4] Now at LBNL, Berkeley, CA 94720, USA.
[5] Also Istituto di Cosmo-Geofisica del C.N.R., Torino, Italy.
[6] Now at Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany.
[7] Supported by CICYT, Spain.
[8] Supported by the National Science Foundation of China.
[9] Supported by the Danish Natural Science Research Council.
[10] Supported by the UK Particle Physics and Astronomy Research Council.
[11] Supported by the US Department of Energy, grant DE-FG0295-ER40896.
[12] Now at Departement de Physique Corpusculaire, Université de Genève, 1211 Genève 4, Switzerland.
[13] Supported by the Commission of the European Communities, contract ERBFMBICT982874.
[14] Also at Rutherford Appleton Laboratory, Chilton, Didcot, UK.
[15] Permanent address: Universitat de Barcelona, 08208 Barcelona, Spain.
[16] Supported by the Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie, Germany.
[17] Supported by the Direction des Sciences de la Matière, C.E.A.
[18] Supported by the Austrian Ministry for Science and Transport.
[19] Now at SAP AG, 69185 Walldorf, Germany.
[20] Now at Groupe d' Astroparticules de Montpellier, Université de Montpellier II, 34095 Montpellier, France.
[21] Now at Département de Physique, Faculté des Sciences de Tunis, 1060 Le Belvédère, Tunisia.
[22] Supported by the US Department of Energy, grant DE-FG03-92ER40689.
[23] Now at Skyguide, Swissair Navigation Services, Geneva, Switzerland.
[24] Also at Dipartimento di Fisica e Tecnologie Relative, Università di Palermo, Palermo, Italy.
[25] Now at McKinsey and Compagny, Avenue Louis Casal 18, 1203 Geneva, Switzerland.
[26] Now at Honeywell, Phoenix, AZ, USA.
[27] Now at INFN Sezione di Roma II, Dipartimento di Fisica, Università di Roma Tor Vergata, 00133 Roma, Italy.
[28] Now at Centre de Physique des Particules de Marseille, Univ. Méditerranée, F-13288 Marseille, France.
[29] Also at Department of Physics, Tsinghua University, Beijing, People's Republic of China.
[30] Now at SLAC, Stanford, CA 94309, USA.
[31] Deceased.
[32] Also at Groupe d' Astroparticules de Montpellier, Université de Montpellier II, 34095 Montpellier, France.

1. Introduction

The $b\bar{b}$ ground state, the η_b meson, has not yet been observed. Because of their initial state, two-photon collisions are well suited for the study of pseudoscalar mesons, for which $J^{PC} = 0^{-+}$. The high $\gamma\gamma$ cross section and the high LEP luminosity and energy, as well as the low background from other processes, make LEP 2 a good environment to search for this meson.

Theoretical estimates (from pertubative QCD and lattice nonrelativistic QCD) of the mass difference, Δm, between the η_b and the Υ ($m_\Upsilon = 9.46\ \mathrm{GeV}/c^2$) are summarized in Table 1 and those of the partial decay width of the η_b into two photons, $\Gamma_{\gamma\gamma}(\eta_b)$, in Table 2. For the former, values ranging from $\Delta m = 34$ to 141 MeV/c^2 are obtained. For the latter, a value of $\Gamma_{\gamma\gamma}(\eta_b) = 557 \pm 85$ eV, chosen in this Letter, is obtained from the average of the first order estimates (488 eV) shifted by 69 eV at the second order in α_s. It yields an exclusive η_b production cross section of 0.304 ± 0.046 pb in e^+e^- collisions at $\sqrt{s} = 197$ GeV. The branching ratios of the η_b into four and six charged particles are estimated as in Ref. [1] to be 2.7% and 3.3%, respectively. (The same estimate gives 9.9% for the η_c decay branching fraction into four charged particles, in agreement with the measured value of $9.3 \pm 1.8\%$ [2].) Six and seven exclusive η_b are therefore expected to be produced in the 699 pb^{-1} of data collected by ALEPH above the WW threshold, in the four- and six-charged-particle final states, respectively.

A measurement of the η_b mass and of its decay modes would therefore provide a test of pQCD and NRQCD [3–5]. Searches have already been conducted by the CUSB and CLEO Collaborations in the cascade decay of the $\Upsilon(3S)$: the CUSB Collaboration finds for the product of the branching ratios $\mathrm{BR}(\Upsilon(3S) \to \pi\pi h_b) \times \mathrm{BR}(h_b \to \gamma\eta_b) < 0.45\%$ at 90% C.L. for an Υ–η_b splitting between 50 and 110 MeV/c^2 [6]. The CLEO Collaboration has published a 90% C.L. upper limit on the product of the branching ratios $\mathrm{BR}(\Upsilon(3S) \to \pi^+\pi^- h_b) \times \mathrm{BR}(h_b \to \gamma\eta_b)$ of about 0.1% for the η_b mass range from 9.32 to 9.46 GeV/c^2 with a photon energy ranging from 434 to 466 MeV and the h_b mass restricted to $9.900 \pm 0.003\ \mathrm{GeV}/c^2$ [7].

In this Letter, a search is presented for the η_b meson via its decay into four and six charged particles. The search is performed in quasireal two-photon interactions where the meson is produced exclusively. This Letter is organized as follows. A description of the ALEPH detector is given in Section 2. The data analysis with event selection, efficiency calculation, background estimate and systematic uncertainty determination is described in Section 3. The results of the search are presented in Section 4. Finally, in Section 5 a summary is given.

Table 1
Estimates for the mass splitting $\Delta m = m(\Upsilon) - m(\eta_b)$ from QCD calculations

	$\Delta m\ [\mathrm{MeV}/c^2]$	Ref.
Lattice NRQCD	45–100	[3,8,9]
Lattice potential	60–110	[10]
pQCD	36– 55	[11]
$1/m$ expansion	34–114	[12]
Potential model	60–141	[13–15]

Table 2
Estimates for the two-photon width $\Gamma_{\gamma\gamma}(\eta_b)$

	$\Gamma_{\gamma\gamma}(\eta_b)$ [eV]	Ref.
Estimates $\mathcal{O}(\alpha_s)$		
Potential model	500 ± 30	[16]
Potential model, $\Gamma_{e^+e^-}(\Upsilon)$	490 ± 40	[16]
NRQCD	460	[17]
NRQCD, $\Gamma_{e^+e^-}(\Upsilon)$	501	[18]
Estimates $\mathcal{O}(\alpha_s^2)$		
NRQCD, $\Gamma_{e^+e^-}(\Upsilon)$	570 ± 50	[18]
Used in this Letter	557 ± 85	

2. ALEPH detector

A detailed description of the ALEPH detector and its performance can be found in Ref. [19]. The central part of the ALEPH detector is dedicated to the reconstruction of the trajectories of charged particles. The trajectory of a charged particle emerging from the interaction point is measured by a two-layer silicon strip vertex detector (VDET), a cylindrical drift

chamber (ITC) and a large time projection chamber (TPC). The three tracking detectors are immersed in a 1.5 T axial magnetic field provided by a superconducting solenoidal coil. Together they measure charged particle transverse momenta with a resolution of $\delta p_{\mathrm{t}}/p_{\mathrm{t}} = 6 \times 10^{-4} p_{\mathrm{t}} \oplus 0.005$ (p_{t} in GeV/c). The TPC also provides a measurement of the specific ionization $\mathrm{d}E/\mathrm{d}x_{\mathrm{meas}}$. An estimator may be formed to test a particle hypothesis, $\chi_{\mathrm{h}} = (\mathrm{d}E/\mathrm{d}x_{\mathrm{meas}} - \mathrm{d}E/\mathrm{d}x_{\mathrm{exp,h}})/\sigma_{\mathrm{exp,h}}$, where $\mathrm{d}E/\mathrm{d}x_{\mathrm{exp,h}}$ and $\sigma_{\mathrm{exp,h}}$ denote the expected specific ionization and the estimated uncertainty for the particle hypothesis h, respectively.

Photons are identified in the electromagnetic calorimeter (ECAL), situated between the TPC and the coil. The ECAL is a lead/proportional-tube sampling calorimeter segmented in $0.9^\circ \times 0.9^\circ$ projective towers read out in three sections in depth. It has a total thickness of 22 radiation lengths and yields a relative energy resolution of $0.18/\sqrt{E} + 0.009$, with E in GeV, for isolated photons. Electrons are identified by their transverse and longitudinal shower profiles in ECAL and their specific ionization in the TPC.

The iron return yoke is instrumented with 23 layers of streamer tubes and forms the hadron calorimeter (HCAL). The latter provides a relative energy resolution of charged and neutral hadrons of $0.85/\sqrt{E}$, with E in GeV. Muons are distinguished from hadrons by their characteristic pattern in HCAL and by the muon chambers, composed of two double-layers of streamer tubes outside HCAL.

The information from the tracking detectors and the calorimeters are combined in an energy-flow algorithm [19]. For each event, the algorithm provides a set of charged and neutral reconstructed particles, called *energy-flow objects* in the following.

3. Analysis

3.1. Event selection

The search is performed in the four- and six-charged-particle modes, where four (or six) charged energy-flow objects with a net charge zero are required. In order to keep the efficiency high, loose selection cuts are chosen. No attempt is made to reconstruct $\mathrm{K_S}$ mesons at this stage. The $\mathrm{d}E/\mathrm{d}x$ measurement, when available, must be consistent with the pion or kaon hypothesis ($\chi^2_{\pi,\mathrm{K}} < 9$); the more likely hypothesis is used for mass assignment. When no $\mathrm{d}E/\mathrm{d}x$ information is available the pion mass is assigned to the particle. No neutral energy-flow object with $E > 1$ GeV must be present within 20° of the beam axis. No muon and no electron (as defined by the ECAL) must be observed. Events are also excluded if a photon conversion is detected, where the electron and positron are identified by requiring $\chi^2_{\mathrm{e}} < 9$, and the pair invariant mass is smaller than 25 MeV/c^2.

The total transverse momentum of charged particles in the event ($\sum \vec{p}_{t,i}$) must be smaller than 250 MeV/c. The energy-flow objects in the event are boosted into their centre-of-mass frame and the thrust is computed in this frame. The thrust axis must form an angle θ_{thrust} larger than 45° with respect to the beam axis to reject events from the $\gamma\gamma$ continuum background. The $\gamma\gamma \to \tau^+\tau^-$ background is reduced to a negligible fraction by the rejection of events in which both hemispheres, as defined by the thrust axis, have a net charge of ± 1 and an invariant mass less than 1.8 GeV/c^2.

3.2. Signal efficiency

Selection and reconstruction efficiencies are studied with events generated with PHOT02 [20] in which the η_{b} mass is set to 9.4 GeV/c^2 and the total width to 7 MeV/c^2. The width is calculated under the assumption that the two-gluon decay is dominant [2,21,22]. Four samples of 2500 events each are generated for the final state with four charged particles ($2(\pi^+\pi^-)$, $\pi^+\pi^-\mathrm{K}^+\mathrm{K}^-$, $2(\mathrm{K}^+\mathrm{K}^-)$, $\mathrm{K_S K}^+\pi^-$). Four other samples of 2500 events each are generated for the final state with six charged particles ($3(\pi^+\pi^-)$, $2(\pi^+\pi^-)\mathrm{K}^+\mathrm{K}^-$, $\pi^+\pi^-2(\mathrm{K}^+\mathrm{K}^-)$, $3(\mathrm{K}^+\mathrm{K}^-)$). For the decays, it is assumed that the momenta are distributed according to phase space. The event samples are passed through the detector simulation and reconstruction programs. The mass resolution of the selected events is about 0.14 GeV/c^2 and is dominated by wrong mass assignment from π–K misidentification. A signal region between 9.0 and 9.8 GeV/c^2 is chosen. The event selection efficiencies averaged over the four decay channels are found to be 16.7% and 9.3% for the four- and six-charged-track channels, respectively.

3.3. Systematic uncertainties

The lack of knowledge of the decay modes and kinematics of the η_b meson is the source of the dominant systematic uncertainties in the analysis. The uncertainty on the selection efficiency due to the unknown decay mode of the η_b meson is estimated from the spread of the efficiencies of the four simulated decay modes. The relative uncertainty is 7.5% and 20.4% for the four- and six-charged-particle final states. In order to check the effect of the selection efficiency due to the assumption of phase space decays, the η_b is forced to decay into a pair of ϕ mesons, each giving two charged kaons. In this case a relative increase of 10% in the detection efficiency is found.

Further studies are performed without the final cut on neutral energy or with modified cuts on $\sum \vec{p}_{t,i}$, θ_{thrust}, and hemisphere mass. An uncertainty of 5.5% is estimated. The limited statistics of simulated events contribute an uncertainty of 2.4% and 3.2% for the two decay modes, respectively.

A total relative uncertainty of 9.7% (21.4%) on the selection efficiency is calculated for the four- (six-) charged-track channel.

3.4. Background estimate

The background estimate suffers from the low statistics of the simulated events selected and from the poor description of the shape of the invariant mass spectra. The background, dominated by $\gamma\gamma$ continuum production, is therefore estimated from data by means of a fit to the ratio of the mass spectra after all cuts are applied and before the final cuts on $\sum \vec{p}_{t,i}$, θ_{thrust}, and hemisphere mass are applied. The ratio is fitted with an exponential function up to $m = 6$ GeV/c^2 ($m = 7$ GeV/c^2) for the four- (six-) charged-particle topology. The average of the values of this function at $m = 6$ GeV/c^2 ($m = 7$ GeV/c^2) and at $m = 9.4$ GeV/c^2 is then multiplied by the number of events in the signal region before the final cuts to obtain the background estimate. Half of the difference between these two values is taken as the systematic uncertainty on the estimate. The background in the signal region is determined to be 0.30 ± 0.25 (0.70 ± 0.34) events for the four- (six-) charged-particle topology.

4. Results

Invariant mass spectra of the selected events are shown in Fig. 1. A total of 33727 (3432) events is selected in the four- (six-) charged-particle final states. In the signal region, only one event is found in the six-prong topology.

4.1. Cross section upper limit

From the knowledge of the background b and the efficiency ε, the observed number of events n is converted [23] into an upper limit on the signal events μ into a confidence level α given by

$$1-\alpha = \frac{\int g(b) f(\varepsilon) \sum_{i=0}^{n} P(i \mid \mu\varepsilon + b)\, \mathrm{d}\varepsilon\, \mathrm{d}b}{\int g(b) \sum_{i=0}^{n} P(i \mid b)\, \mathrm{d}b},$$

where $P(j \mid x)$ is the Poisson probability that j events be observed, when x are expected. The probability density functions for the background $g(b)$ and the efficiency $f(\varepsilon)$ are assumed to be Gaussian, but restricted to the range where b and ε are positive. Upper limits of 3.06 (4.69) events at 95% confidence level are calculated for the four- (six-) prong topology. This translates into the upper limits

$$\Gamma_{\gamma\gamma}(\eta_b) \times \mathrm{BR}(\eta_b \to 4 \text{ charged particles}) < 48 \text{ eV},$$

$$\Gamma_{\gamma\gamma}(\eta_b) \times \mathrm{BR}(\eta_b \to 6 \text{ charged particles}) < 132 \text{ eV}.$$

With a two-photon width of 557 ± 85 eV, upper limits on the branching ratios $\mathrm{BR}(\eta_b \to 4 \text{ charged particles}) < 9.0\%$ and $\mathrm{BR}(\eta_b \to 6 \text{ charged particles}) < 25\%$ are derived.

4.2. Mass of the candidate

The raw reconstructed mass of the candidate, as obtained from the measured momenta of the six charged particles and with masses assigned according to the $\mathrm{d}E/\mathrm{d}x$ measurement, is 9.45 GeV/c^2. The mass estimate can be refined with additional information visible from the event display shown in Fig. 2. Two of the six tracks form a secondary vertex compatible with the decay of a $\mathrm{K_S}$ into $\pi^+\pi^-$. This hypothesis is supported by the presence of a third track compatible with a K^- ($\chi^2_\pi = 6.0$ and $\chi^2_\mathrm{K} = 3.8 \times 10^{-5}$). The secondary vertex is therefore fitted to this hypothesis, and the five particles (three charged pions,

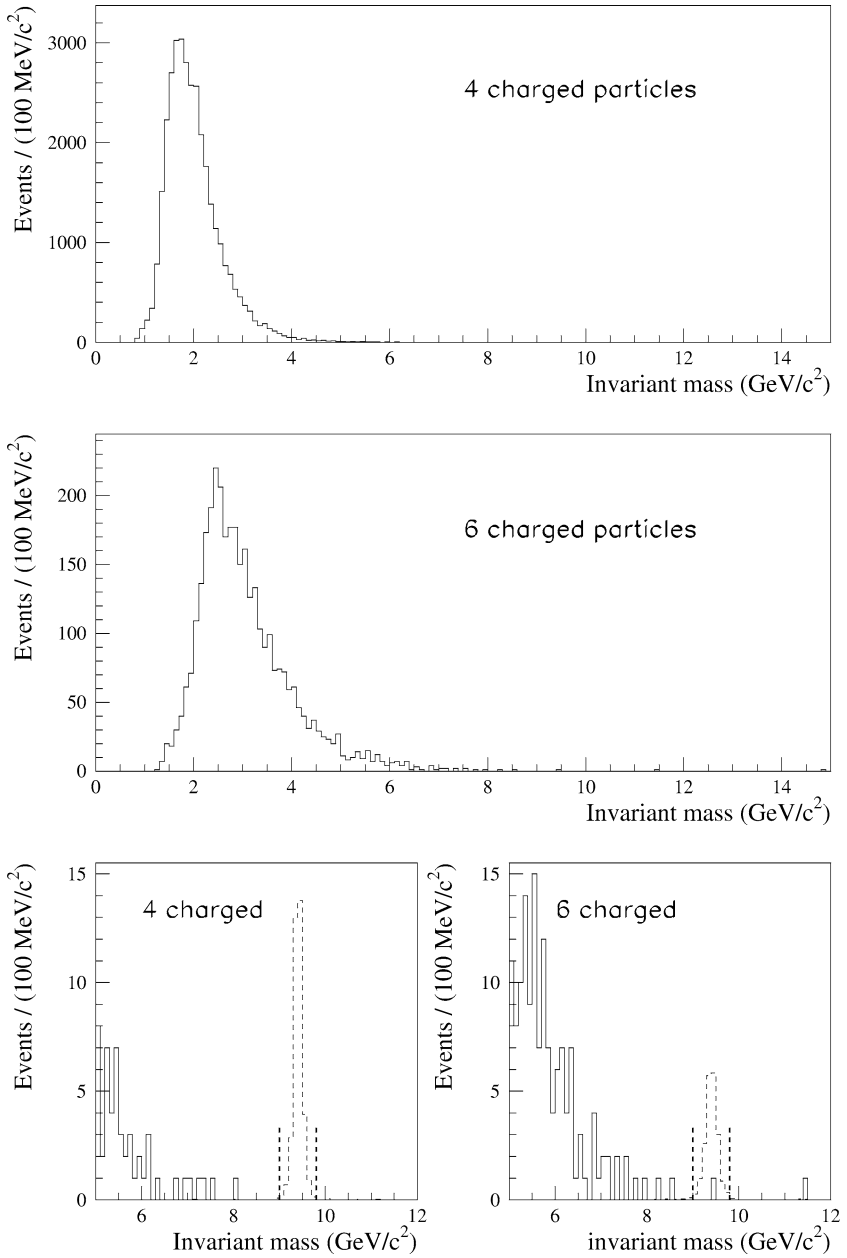

Fig. 1. Invariant mass distribution of selected events for four- and six-charged-particle final states (solid line: data). The dashed line represents the expected signal for a 100% branching ratio into the mode under consideration. The signal region is indicated by the vertical dashed lines.

one charged kaon and one K_S) are forced to originate from a common primary vertex. A mass of $9.30 \pm 0.02 \pm 0.02\ \mathrm{GeV}/c^2$ is derived from these constraints.

A control sample of η_c mesons is selected in the $K_S K^+\pi^-$ decay mode, without the final cuts but that on the total transverse momentum, which is relaxed to $\sum \vec{p}_{t,i} < 500\ \mathrm{MeV}/c$. The analysis is repeated with

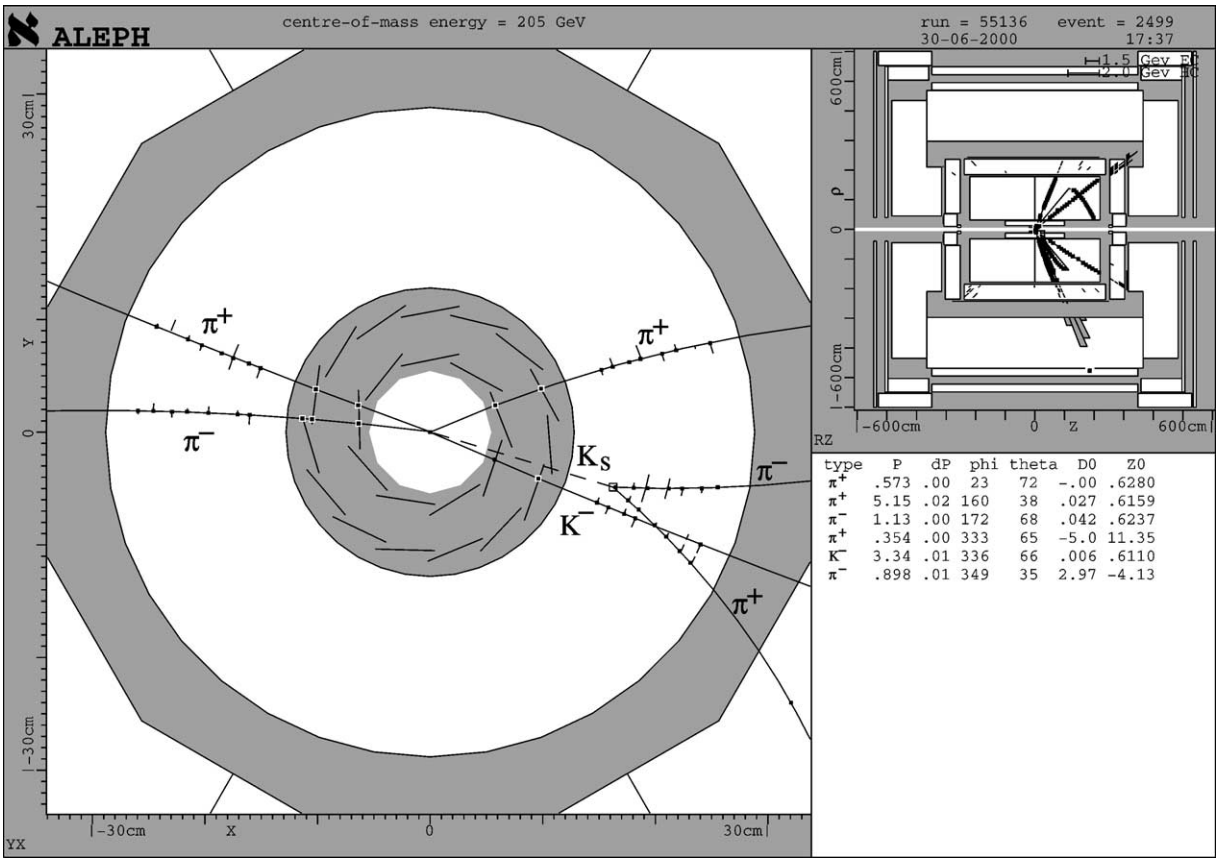

Fig. 2. An $r\phi$ view of the $\eta_b \to K_S K^- \pi^+ \pi^- \pi^+$ candidate event with the reconstructed mass of $9.30 \pm 0.02 \pm 0.02$ GeV/c^2, selected in the signal region. The track coordinates recorded in the VDET and the ITC are shown. The tracks are appropriately labeled. The plot to the right shows an rz view of the ALEPH apparatus. Information is given for each track: particle type, momentum (GeV/c), momentum error (GeV/c), azimuthal and polar angle (degrees), transverse and longitudinal impact parameter (cm).

this control sample for the study of the systematic uncertainty on the mass determination. The mass of the η_c meson is fitted and is found consistent with the world average value [2] within its statistical accuracy of 4.7 MeV/c^2. A systematic uncertainty of the same size is assigned. The total uncertainty is then rescaled with the mass ratio $m(\text{candidate})/m(\eta_c)$ and a systematic uncertainty of 21 MeV/c^2 is obtained for the mass estimate of the η_b candidate. The η_c signal is shown in Fig. 3 together with the D^0 signal as observed in its $K^-\pi^+$ decay mode. The fitted D^0 mass agrees with the world average value [2] within its statistical accuracy of 0.9 MeV/c^2. The number of observed η_c mesons is consistent with previous measurements [2,22,24].

5. Summary

With an integrated luminosity of 699 pb^{-1} collected at e^+e^- centre-of-mass energies between 181 and 209 GeV, the pseudoscalar meson η_b is searched for in its decays to four and six charged particles. One candidate is retained in the decay mode into six charged particles, while no candidate is found in the four-charged-particle decay mode. The candidate η_b has a reconstructed invariant mass of $9.30 \pm 0.02 \pm 0.02$ GeV/c^2. The observation of one event is consistent with the number of events expected from background.

Upper limits on $\Gamma_{\gamma\gamma}(\eta_b) \times \text{BR}$ of 48 and 132 eV, corresponding to limits on the branching ratios

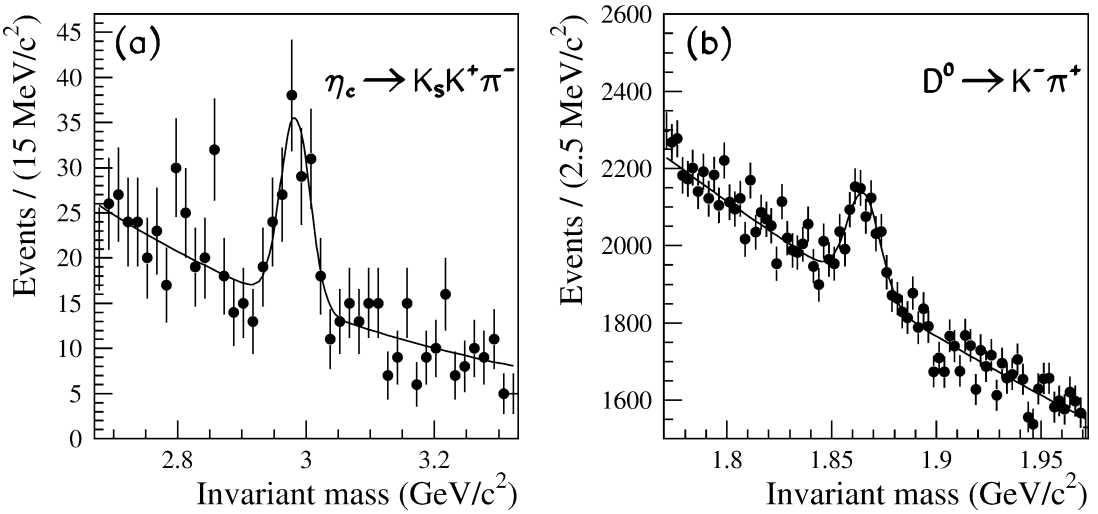

Fig. 3. (a) Invariant mass distribution of the selected events of the $K_S K^+\pi^-$ control sample showing the signal of the η_c meson. (b) The D^0 signal reconstructed in its $K^-\pi^+$ decay mode.

BR($\eta_b \to$ 4 charged particles) $< 9.0\%$ and BR($\eta_b \to$ 6 charged particles) $< 25\%$, are obtained at a confidence level of 95%.

Acknowledgements

We wish to thank our colleagues in the CERN accelerator divisions for the successful operation of LEP. We are indebted to the engineers and technicians in all our institutions for their contribution to the excellent performance of ALEPH. Those of us from non-member countries thank CERN for its hospitality. We would like to thank Ted Barnes and Gunnar Bali for discussions.

References

[1] A. Böhrer, Search for the η_b Meson, in: M. Kienzle (Ed.), Proc. of PHOTON 2001, Ascona, Switzerland, 2001, World Scientific, Singapore, 2001, to appear.
[2] Particle Data Group, Eur. Phys. J. C 15 (2000) 1.
[3] G.S. Bali, Phys. Rep. 343 (2001) 1.
[4] E.S. Ackleh, T. Barnes, Phys. Rev. D 45 (1992) 232.
[5] S. Godfrey, J.L. Rosner, Phys. Rev. D 64 (2001) 074011.
[6] CUSB Collaboration, Phys. Rev. Lett. 66 (1991) 3113.
[7] CLEO Collaboration, Phys. Rev. D 49 (1994) 40.
[8] A.X. El-Khadra, hep-ph/9508266, and private communications.
[9] L. Marcantonio et al., Nucl. Phys. (Proc. Suppl.) 94 (2001) 363;
C.T.H. Davies, private communications.
[10] G.S. Bali, K. Schilling, A. Wachter, Phys. Rev. D 56 (1997) 2566.
[11] N. Brambilla, Y. Sumino, A. Vairo, Phys. Lett. B 513 (2001) 381;
N. Brambilla, private communications.
[12] S. Narison, Phys. Lett. B 387 (1996) 162.
[13] T. Barnes, hep-ph/0103142;
T. Barnes, F.E. Close, private communications.
[14] E.J. Eichten, C. Quigg, Phys. Rev. D 49 (1994) 5845.
[15] D. Ebert, R.N. Faustov, V.O. Galkin, hep-ph/0006186.
[16] N. Fabiano, Two-photon width of η_c, in: M. Kienzle (Ed.), Proc. of PHOTON 2001, Ascona, Switzerland, 2001, World Scientific, Singapore, 2001, and private communications.
[17] G.A. Schuler, F.A. Berends, R. van Gulik, Phys. Lett. B 523 (1998) 423.
[18] A. Czarnecki, K. Melnikov, Phys. Lett. B 519 (2001) 212, and private communications.
[19] ALEPH Collaboration, Nucl. Instrum. Methods A 294 (1990) 121;
ALEPH Collaboration, Nucl. Instrum. Methods A 303 (1991) 393;
B. Mours et al., Nucl. Instrum. Methods A 379 (1996) 121;
B. Mours et al., Nucl. Instrum. Methods A 360 (1995) 481.
[20] ALEPH Collaboration, Phys. Lett. B 313 (1993) 509.
[21] F.E. Close, An Introduction to Quarks and Partons, Academic Press, London, 1981.
[22] CLEO Collaboration, Phys. Rev. Lett. 85 (2000) 3095.
[23] G. Zech, Nucl. Instrum. Methods A 277 (1989) 608.
[24] L3 Collaboration, Phys. Lett. B 461 (1999) 155.