Physics Letters B 530 (2002) 56–66

PHYSICS LETTERS B

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

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PII: S0370-2693(02)01329-1

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Received 1 February 2002; accepted 5 February 2002

Editor: L. Montanet

**Abstract**

A search for the pseudoscalar meson $\eta_\mathrm{b}$ is performed in two-photon interactions at LEP 2 with an integrated luminosity of 699 $\mathrm{pb}^{-1}$ collected at $\mathrm{e}^+\mathrm{e}^-$ 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 $\Gamma_{\gamma\gamma}(\eta_\mathrm{b}) \times \mathrm{BR}(\eta_\mathrm{b} \to 4$ charged particles$) < 48$ eV, $\Gamma_{\gamma\gamma}(\eta_\mathrm{b}) \times \mathrm{BR}(\eta_\mathrm{b} \to 6$ charged particles$) < 132$ eV are obtained at 95% confidence level, which correspond to upper limits of 9.0% and 25% on these branching ratios. 

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## 1. Introduction

The $\mathrm{b\bar{b}}$ ground state, the $\eta_\mathrm{b}$ 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, $\Delta m$, between the $\eta_\mathrm{b}$ and the $\Upsilon$ ($m_\Upsilon = 9.46\ \mathrm{GeV}/c^2$) are summarized in Table 1 and those of the partial decay width of the $\eta_\mathrm{b}$ into two photons, $\Gamma_{\gamma\gamma}(\eta_\mathrm{b})$, in Table 2. For the former, values ranging from $\Delta m = 34$ to $141\ \mathrm{MeV}/c^2$ are obtained. For the latter, a value of $\Gamma_{\gamma\gamma}(\eta_\mathrm{b}) = 557 \pm 85$ 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 $\alpha_s$. It yields an exclusive $\eta_\mathrm{b}$ production cross section of $0.304 \pm 0.046$ pb in $\mathrm{e^+e^-}$ collisions at $\sqrt{s} = 197$ GeV. The branching ratios of the $\eta_\mathrm{b}$ 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 $\eta_\mathrm{c}$ decay branching fraction into four charged particles, in agreement with the measured value of $9.3 \pm 1.8\%$ [2].) Six and seven exclusive $\eta_\mathrm{b}$ are therefore expected to be produced in the 699 $\mathrm{pb}^{-1}$ of data collected by ALEPH above the WW threshold, in the four- and six-charged-particle final states, respectively.

A measurement of the $\eta_\mathrm{b}$ 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 $\mathrm{BR}(\Upsilon(3\mathrm{S}) \to \pi\pi \mathrm{h_b}) \times \mathrm{BR}(\mathrm{h_b} \to \gamma\eta_\mathrm{b}) < 0.45\%$ at 90% C.L. for an $\Upsilon$–$\eta_\mathrm{b}$ splitting between 50 and 110 $\mathrm{MeV}/c^2$ [6]. The CLEO Collaboration has published a 90% C.L. upper limit on the product of the branching ratios $\mathrm{BR}(\Upsilon(3\mathrm{S}) \to \pi^+\pi^- \mathrm{h_b}) \times \mathrm{BR}(\mathrm{h_b} \to \gamma\eta_\mathrm{b})$ of about 0.1% for the $\eta_\mathrm{b}$ mass range from 9.32 to 9.46 $\mathrm{GeV}/c^2$ with a photon energy ranging from 434 to 466 MeV and the $\mathrm{h_b}$ mass restricted to $9.900 \pm 0.003\ \mathrm{GeV}/c^2$ [7].

In this Letter, a search is presented for the $\eta_\mathrm{b}$ 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 $\Delta m = m(\Upsilon) - m(\eta_\mathrm{b})$ 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 $\Gamma_{\gamma\gamma}(\eta_\mathrm{b})$

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

## 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 $\delta p_t/p_t = 6 \times 10^{-4} p_t \oplus 0.005$ ($p_t$ 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, $\chi_h = (\mathrm{d}E/\mathrm{d}x_{\mathrm{meas}} - \mathrm{d}E/\mathrm{d}x_{\mathrm{exp,h}})/\sigma_{\mathrm{exp,h}}$, 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 $K_S$ mesons at this stage. The $\mathrm{d}E/\mathrm{d}x$ measurement, when available, must be consistent with the pion or kaon hypothesis ($\chi^2_{\pi,K} < 9$); 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 $20^\circ$ 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 $\chi^2_e < 9$, 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 $\theta_{\mathrm{thrust}}$ larger than $45^\circ$ 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 $\pm 1$ 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 $\eta_b$ 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 ($2(\pi^+\pi^-)$, $\pi^+\pi^-K^+K^-$, $2(K^+K^-)$, $K_S K^+\pi^-$). Four other samples of 2500 events each are generated for the final state with six charged particles ($3(\pi^+\pi^-)$, $2(\pi^+\pi^-)K^+K^-$, $\pi^+\pi^-2(K^+K^-)$, $3(K^+K^-)$). 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 $\pi$–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 $\eta_b$ 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 $\eta_b$ 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 $\eta_b$ is forced to decay into a pair of $\phi$ 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 $\sum \vec{p}_{t,i}$, $\theta_{\mathrm{thrust}}$, 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 $\sum \vec{p}_{t,i}$, $\theta_{\mathrm{thrust}}$, and hemisphere mass are applied. The ratio is fitted with an exponential function up to $m = 6\ \mathrm{GeV}/c^2$ ($m = 7\ \mathrm{GeV}/c^2$) for the four- (six-) charged-particle topology. The average of the values of this function at $m = 6\ \mathrm{GeV}/c^2$ ($m = 7\ \mathrm{GeV}/c^2$) and at $m = 9.4\ \mathrm{GeV}/c^2$ 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 $0.30 \pm 0.25$ ($0.70 \pm 0.34$) 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 $\varepsilon$, the observed number of events $n$ is converted [23] into an upper limit on the signal events $\mu$ into a confidence level $\alpha$ 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 $\varepsilon$ 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

$$\Gamma_{\gamma\gamma}(\eta_b) \times \mathrm{BR}(\eta_b \to 4 \text{ charged particles}) < 48\ \mathrm{eV},$$
$$\Gamma_{\gamma\gamma}(\eta_b) \times \mathrm{BR}(\eta_b \to 6 \text{ charged particles}) < 132\ \mathrm{eV}.$$

With a two-photon width of $557 \pm 85$ eV, upper limits on the branching ratios $\mathrm{BR}(\eta_b \to 4$ charged particles$) < 9.0\%$ and $\mathrm{BR}(\eta_b \to 6$ 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 $9.45\ \mathrm{GeV}/c^2$. 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 $\mathrm{K}^-$ ($\chi^2_\pi = 6.0$ 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,

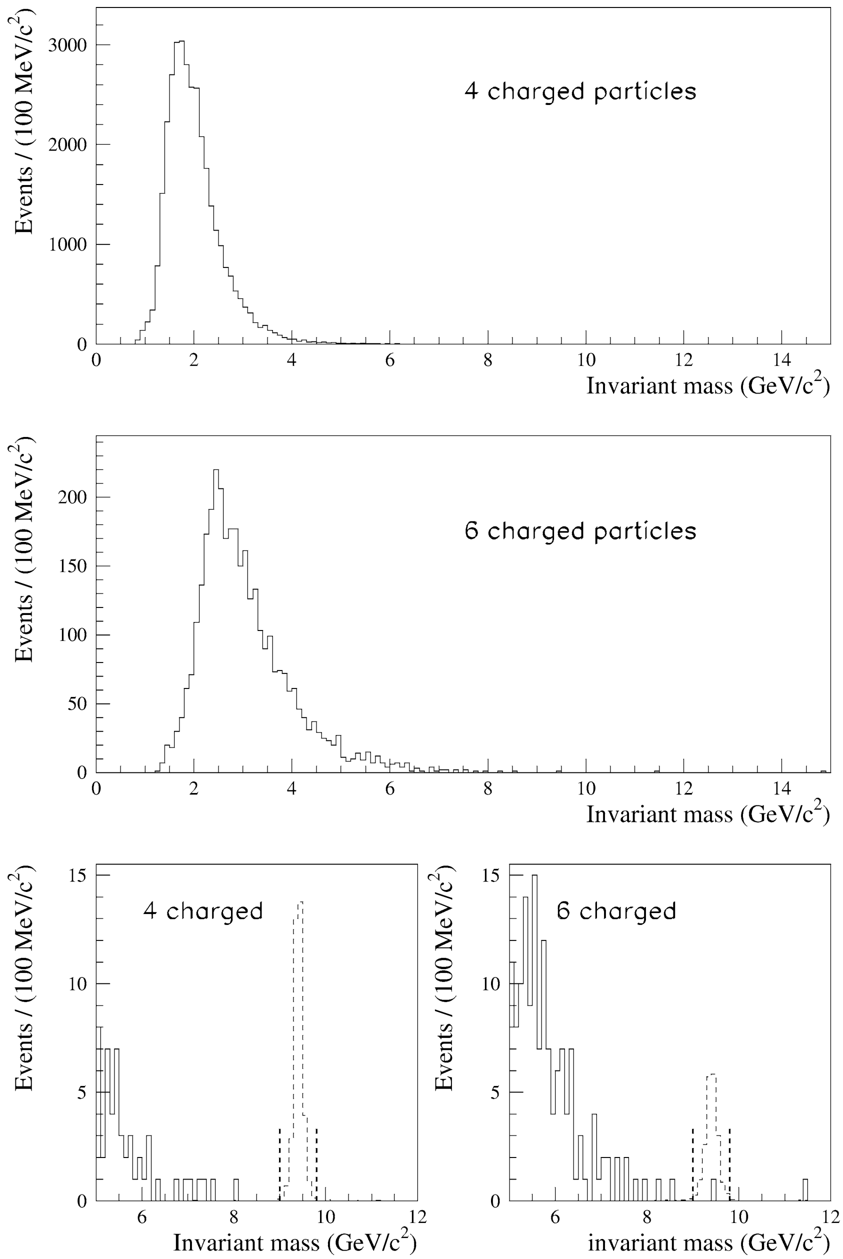


Fig. 1. Invariant mass distribution of selected events for four- and six-charged-particle final states (solid line: data). The dashed line represents the expected signal for a 100% branching ratio into the mode under consideration. The signal region is indicated by the vertical dashed lines.

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 $\eta_c$ 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

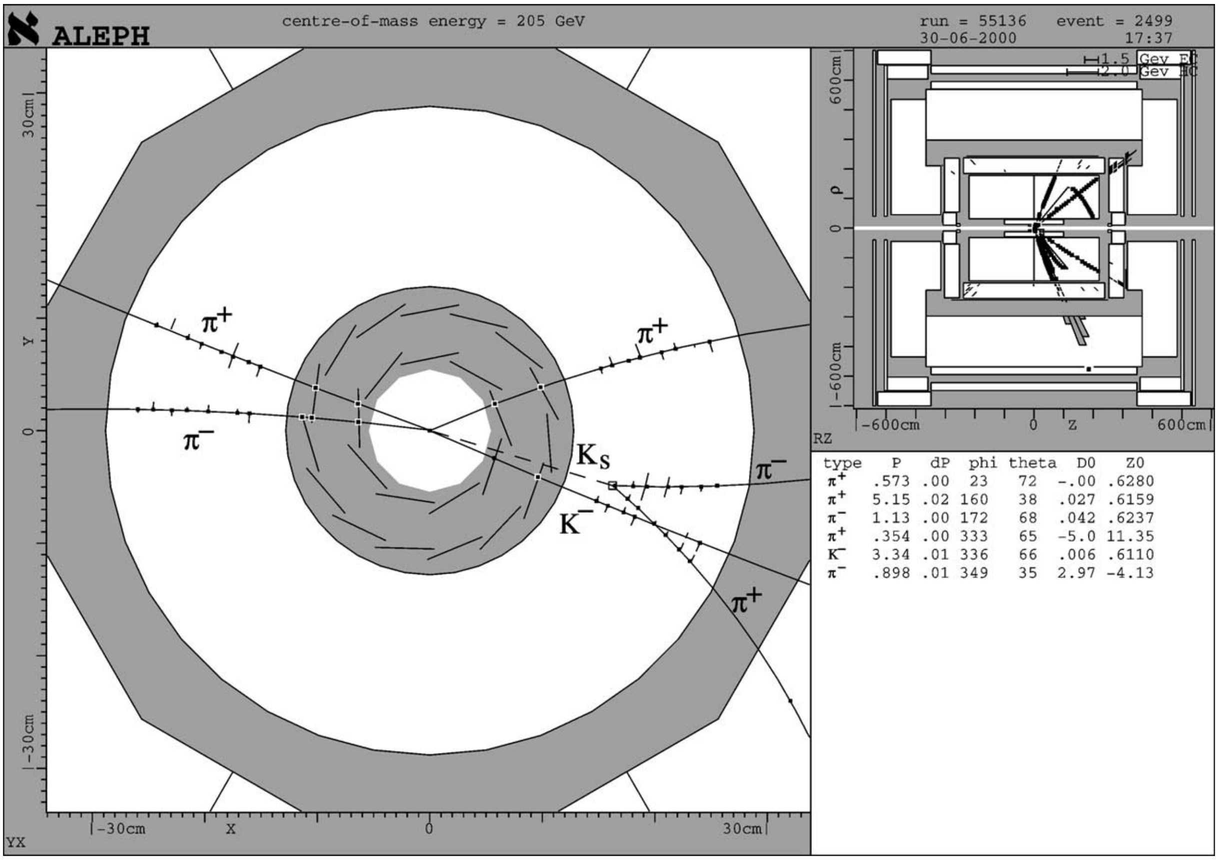


Fig. 2. An $r\phi$ view of the $\eta_b \to K_S K^- \pi^+ \pi^- \pi^+$ candidate event with the reconstructed mass of $9.30 \pm 0.02 \pm 0.02\ \mathrm{GeV}/c^2$, selected in the signal region. The track coordinates recorded in the VDET and the ITC are shown. The tracks are appropriately labeled. The plot to the right shows an $rz$ view of the ALEPH apparatus. Information is given for each track: particle type, momentum ($\mathrm{GeV}/c$), momentum error ($\mathrm{GeV}/c$), 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 $\eta_c$ meson is fitted and is found consistent with the world average value [2] within its statistical accuracy of $4.7\ \mathrm{MeV}/c^2$. 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 $21\ \mathrm{MeV}/c^2$ is obtained for the mass estimate of the $\eta_b$ candidate. The $\eta_c$ 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 $0.9\ \mathrm{MeV}/c^2$. The number of observed $\eta_c$ mesons is consistent with previous measurements [2,22,24].

## 5. Summary

With an integrated luminosity of $699\ \mathrm{pb}^{-1}$ collected at $e^+e^-$ centre-of-mass energies between 181 and 209 GeV, the pseudoscalar meson $\eta_b$ 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 $\eta_b$ has a reconstructed invariant mass of $9.30 \pm 0.02 \pm 0.02\ \mathrm{GeV}/c^2$. The observation of one event is consistent with the number of events expected from background.

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

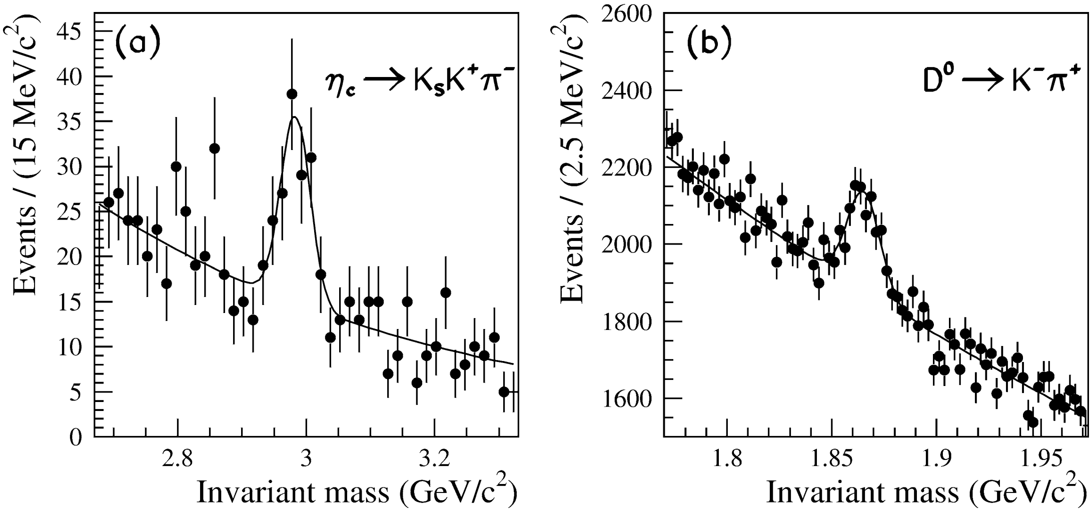


Fig. 3. (a) Invariant mass distribution of the selected events of the $K_S K^+ \pi^-$ control sample showing the signal of the $\eta_c$ meson. (b) The $D^0$ signal reconstructed in its $K^- \pi^+$ decay mode.

$BR(\eta_b \to 4$ 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 $\eta_b$ 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 $\eta_c$, 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.