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Search for η_b in two-photon collisions at LEP II with the DELPHI detector

DELPHI Collaboration

Abstract

The pseudoscalar meson η_b has been searched for in two-photon interactions at LEP II. The data sample corresponds to a total integrated luminosity of 617 pb^{-1} at centre-of-mass energies ranging from 161 to 209 GeV. Upper limits at a confidence level of 95% on the product $\Gamma_{\gamma\gamma}(\eta_b)\times\mathrm{BR}(\eta_b)$ are 190, 470 and 660 eV/c^2 for the η_b decaying into 4, 6 and 8 charged particles, respectively.

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1 Introduction

Two-photon collisions are very useful in searching for the formation of pseudoscalar mesons with $J^{PC} = 0^{-+}$. The high energy and high luminosity of LEP II are additional motivations to look for the $b\bar{b}$ pseudoscalar quarkonium state η_b which has not yet been discovered [1,2].

Its mass, m_{η_b}, is estimated by several theoretical models [3]. It should lie below that of the Υ vector meson (m_Υ=9.46 GeV/c^2) and the mass shift, $\Delta m = m_\Upsilon - m_{\eta_b}$, is estimated to be in the range 10 to 130 MeV/c^2.

The cross-section for two-photon resonance R formation with C=+1

$$\mathrm{e^+e^-} \to \mathrm{e^+e^-}\gamma^*\gamma^* \to \mathrm{e^+e^-}R$$

is given by [4]

$$\sigma(\mathrm{e^+e^-} \to \mathrm{e^+e^-}R) = \int \sigma_{\gamma\gamma\to\eta_b} dL_{\gamma\gamma}(W^2),$$

with the cross-section

$$\sigma_{\gamma\gamma\to\eta_b}(W^2, q_1^2, q_2^2) = 8\pi\,(2J_R+1)\cdot\Gamma_{\gamma\gamma}(R)\cdot F^2(q_1^2, q_2^2)\cdot\frac{\Gamma_R}{(W^2-m_R^2)^2 + m_R^2\Gamma_R^2}.$$

Here $L_{\gamma\gamma}(W^2)$ is the two-photon luminosity function, W is the two-photon centre-of-mass energy, q_1^2 and q_2^2 are the squares of the virtual-photon four-momenta. The resonance R is characterised by its spin J_R, mass m_R, total width Γ_R and its two-photon partial width $\Gamma_{\gamma\gamma}(R)$. In "quasi-real" ($q^2 \sim 0$) photon interactions, the form factor $F^2(q_1^2, q_2^2)$ is constant and can be taken to be unity.

To compute the η_b production cross-section, the partial width $\Gamma_{\gamma\gamma}(\eta_b)$ must be known. Theoretical estimates [5] predict it to be in the range 260 to 580 eV/c^2. Setting m_{η_b} to 9.4 GeV/c^2 leads to an expected production cross-section $\sigma(\mathrm{e^+e^-} \to \mathrm{e^+e^-}\eta_b)$ of 0.14 to 0.32 pb at $\sqrt{s}$=200 GeV.

Most of the observations of η_c decays have been to four charged particles, both pions and kaons [6]. Hence the η_b has been similarly searched for in 4, 6 and 8 charged particle final states. The expected backgrounds come from the $\gamma\gamma \to q\bar{q}$ processes and the $\gamma\gamma \to \tau^+\tau^-$ channel.

From the ALEPH experiment, upper limits on $\Gamma_{\gamma\gamma}(\eta_b)\times\mathrm{BR}(\eta_b)$ [1] are :

$$\Gamma_{\gamma\gamma}(\eta_b)\times\mathrm{BR}(\eta_b \to 4 \text{ charged particles}) < 48 \text{ eV}/c^2,$$
$$\Gamma_{\gamma\gamma}(\eta_b)\times\mathrm{BR}(\eta_b \to 6 \text{ charged particles}) < 132 \text{ eV}/c^2.$$

The L3 experiment, looking for η_b in the decay modes $\eta_b \to K^+K^-\pi^0$, $\pi^+\pi^-\eta$, 2, 4 and 6 charged particles (only or associated with one π^0), observes 6 candidate events with 2.5 background events expected. This corresponds to a combined upper limit on $\Gamma_{\gamma\gamma}(\eta_b)\times\mathrm{BR}(\eta_b)$ [2]:

$$\Gamma_{\gamma\gamma}(\eta_b)\times\mathrm{BR}(\eta_b \to \text{analysed channels}) < 200 \text{ eV}/c^2.$$

In this paper we report on the search for η_b in the reaction

$$\mathrm{e^+e^-} \to \mathrm{e^+e^-}\gamma^*\gamma^* \to \mathrm{e^+e^-}\eta_b$$

with η_b decaying into the following final states:

$$\eta_b \to 4\pi^{\pm}(\mathrm{K}^{\pm}),$$
$$\eta_b \to 6\pi^{\pm}(\mathrm{K}^{\pm}),$$
$$\eta_b \to 8\pi^{\pm}(\mathrm{K}^{\pm}).$$

Here the charged K's in parentheses indicate that a pair of pions may be replaced by a pair of kaons with net zero strangeness.

2 Experimental procedure

The analysis presented here is based on the data taken with the DELPHI detector [7,8] in 1996-2000, covering a range of centre-of-mass energies from 161 to 209 GeV (average centre-of-mass energy: 195.7 GeV). The selected data set corresponds to the period when the Time Projection Chamber (TPC) was fully operational thus ensuring good particle reconstruction. This requirement reduces the integral luminosity for the analysis to 617 pb^{-1}.

For quasi-real photon interactions, the scattered $\mathrm{e}^{\pm}$ are emitted at very small polar angles. Hence there is no requirement on detecting them.

The $\mathrm{e}^+\mathrm{e}^- \to \mathrm{e}^+\mathrm{e}^-\eta_b$ candidate events are selected by requiring final states with 4, 6 or 8 tracks with zero net charge. Charged-particle tracks in the detector are accepted if the following criteria are met:

- particle transverse momentum $p_T > 150$ MeV/c;
- impact parameter of a track transverse to the beam axis $\Delta_{xy} < 0.5$ cm;
- impact parameter of a track along the beam axis $\Delta_z < 2$ cm;
- polar angle of a track $10^\circ < \theta < 170^\circ$;
- track length $l > 30$ cm;
- relative error of the track momentum $\Delta p/p < 30\%$.

No K^0_S reconstruction is attempted on each track pair. The identification of other neutral particles is made using calorimeter information. The calorimeter clusters which are not associated to charged-particle tracks are combined to form the signals from the neutral particles (γ, π^0, K^0_L, n). A minimum measured energy of 1 GeV for showers in the electromagnetic calorimeters and 2 GeV in the hadron calorimeters is required.

The selection of candidate events is achieved by applying the following criteria:

- no particle is identified as an electron or a muon by the standard lepton-identification algorithms [9];
- no particle is identified as a proton by the standard identification algorithm [9];
- there are no electromagnetic showers with energy $E_{shower} > 1$ GeV or converted γ's with energy $E_\gamma > 0.2$ GeV in the event.

To ensure that no particle from the η_b decay has escaped detection, the square of the total transverse momentum of charged particles , $(\sum \vec{p}_T)^2$, is required to be small. The actual cut value is estimated from a Monte Carlo sample of η_b events produced in $\gamma\gamma$ interactions. In this simulation the kinematical variables are generated using the algorithms developed by Krasemann et al. [10]. It is also assumed that the production amplitude factorizes into the quasi-real transverse photon flux and a covariant amplitude describing both the η_b production and decay [11]. The $\eta_b \to$ (4, 6, 8) charged-particle decay processes are assumed to be described by the phase-space momenta distribution. The generated events are passed through the standard DELPHI detector simulation and reconstruction programs [8]. The same selection criteria are applied on the simulated events as on the

data. Finally, an event is accepted on the basis of the trigger efficiency. Parametrized for a single track, as a function of its transverse momentum p_T, it ranges from 20% for $p_T < 0.5$ GeV/c to about 95% at $p_T > 2$ GeV/c [12]. Due to the high mass of the η_b resonant state and relatively large number of tracks in the final state, the overall trigger efficiency per event is about 93.6%, 94.5% and 94.6% for events with 4, 6 and 8 charged particles, respectively.

Fig.1 shows, in the visible invariant-mass interval 8 GeV/$c^2 < W_{vis} < 10$ GeV/c^2, the fraction of remaining events as a function of a cut, P_T^2, on $(\sum \vec{p}_T)^2$, for the 4 charged-particle channel. It decreases rapidly for $P_T^2 < 0.1$ GeV$^2/c^2$. Hence to preserve the statistics, 4, 6 charged-particle events with $(\sum \vec{p}_T)^2$ up to 0.08 GeV$^2/c^2$ and 8 charged-particle events with $(\sum \vec{p}_T)^2$ up to 0.06 GeV$^2/c^2$ were kept.

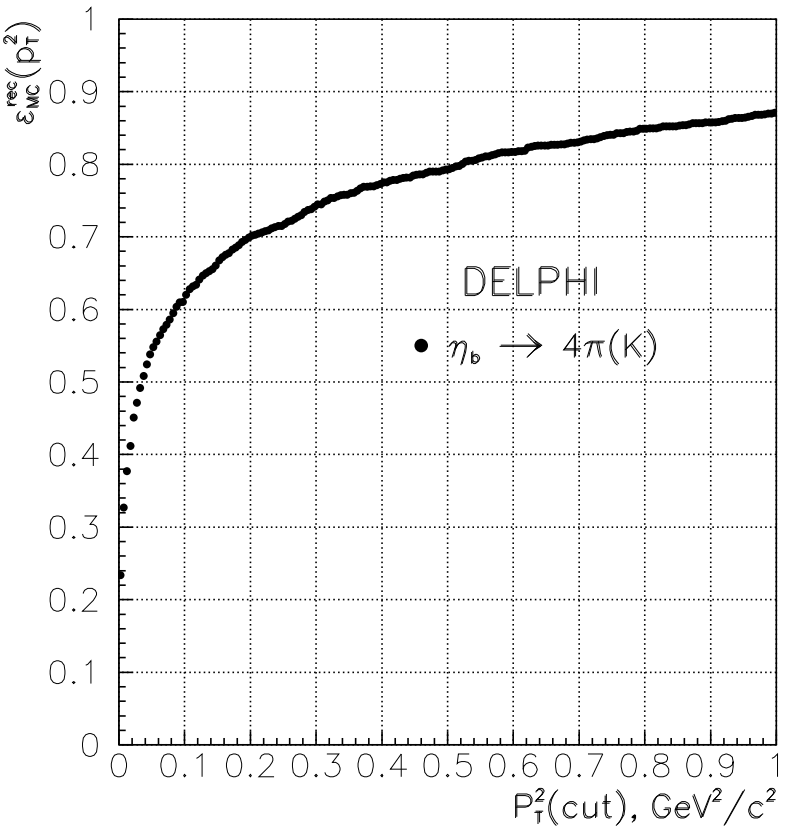

Figure 1: Efficiency of selected η_b Monte Carlo events of the 4 charged-particle channel, as a function of the cut $(\sum \vec{p}_T)^2 < P_T^2$, in the η_b search region: 8 GeV/$c^2 < W_{vis} < 10$ GeV/c^2.

The π/K identification is based on the TPC dE/dx and RICH [13] measurements which are used both separately and combined, in order to check the consistency, in a neural network-based algorithm [14]. In the η_b search region defined as 8 GeV/$c^2 < W_{vis} < 10$ GeV/c^2, the average $K^{\pm}$ identification efficiency is about 54% and the purity is 82%. The misidentification of charged pions as kaons is about 1.5%. After application of the selection criteria and requiring $W_{vis} > 5$ GeV/c^2, the 4, 6 and 8 charged-particle data samples contain 173, 328 and 113 events respectively.

The main background comes from inclusive $\gamma\gamma \to q\bar{q}$ channels. This background is estimated using a Monte Carlo sample generated with the PYTHIA 6.143 program [15].

The possible contamination of the $e^+e^- \to e^+e^-\tau^+\tau^-$ process is given special attention. To reduce it in the $\gamma\gamma \to 4\pi$ channel where it is most important, events of topology 1-3 with respect to the hemispheres defined by the thrust axis computed in the 4π centre-of-mass system and with an invariant mass, in each hemisphere, smaller than 1.8 GeV/c^2, are discarded. Only (1.0±0.3)% of η_b events are eliminated by this cut.

The mass resolution in the search region has been estimated from the Monte Carlo sample of $\gamma\gamma \to q\bar{q}$ interactions. It is about 200 MeV/c^2 FWHM for all topologies, as shown on Fig.2 for the 4 charged-particle events. We have chosen to search for a possible signal in ± one mass resolution interval around the predicted mass of 9.4 GeV/c^2.

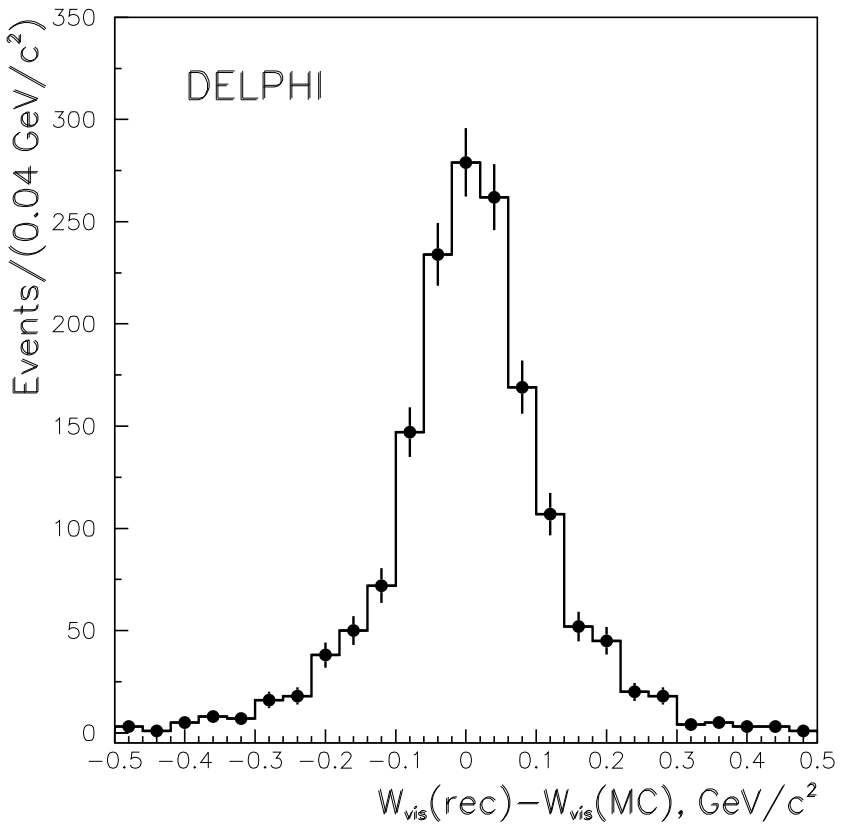

Figure 2: Difference between reconstructed and generated W_{vis} values for the selected 4 charged-particle events from the Monte Carlo $\gamma\gamma \to q\bar{q}$ sample, in the η_b search region.

3 Results

The visible invariant-mass spectra of the selected events are presented in Fig. 3. When an event has an odd number of $K^{\pm}$, the kaon mass is assigned sequentially to the other particles of opposite charge and the W_{vis} mass is simply taken as the average of the various mass combinations. The resulting mass shift, averaged over the 4, 6 and 8 particle samples, is about 120 MeV/c^2 in the η_b search region.

The distributions are well reproduced by the $\gamma\gamma \to q\bar{q}$ Monte Carlo simulation. The η_b candidates are expected to show up in the 9.2 to 9.6 GeV/c^2 mass region.

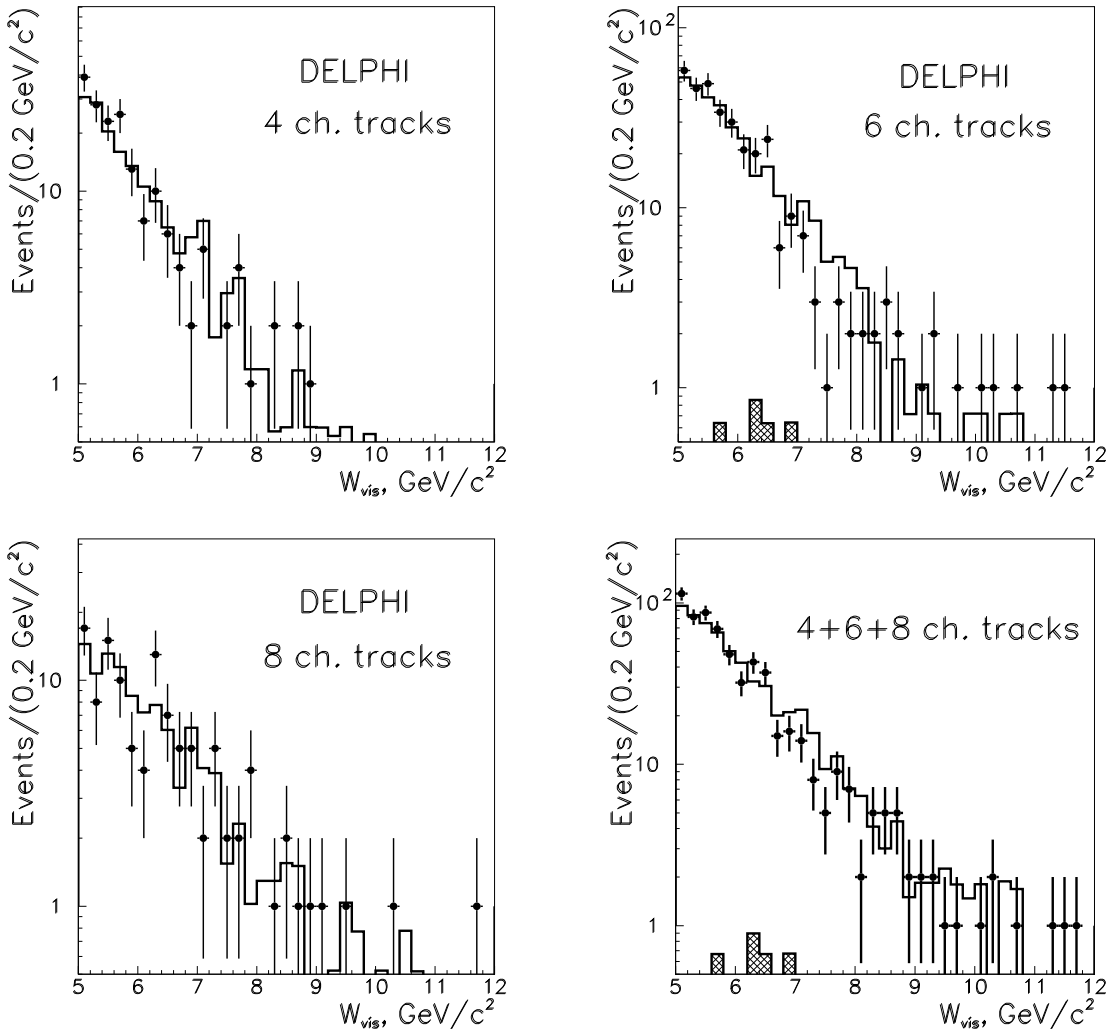

Figure 3: Invariant-mass distributions of selected events for 4, 6 and 8 charged-particle final states. Points with error bars are from the data; histograms present the expected number of background events from the $\gamma\gamma \to q\bar{q}$ simulation; shaded histograms correspond to the expected $e^+e^- \to e^+e^-\tau^+\tau^-$ background.

Table 1 gives the number of 4, 6 and 8 charged-particle events in the 9.2 to 9.6 GeV/c^2 mass region, together with the number of expected background events computed taking into account the overall reconstruction and selection efficiency. Among the 3 observed η_b candidates only the event with 8 charged particles contains one identified kaon.

In the search for rare processes with a few observed events that may be compatible with background, an upper limit for the signal S can be derived considering a Poisson process with a background b and taking into account uncertainties in the background and efficiencies [16]

$$\mathrm{CL} = 1 - \frac{\int g(b) f(\varepsilon) \sum_{k=0}^{n} P[k|(S\varepsilon + b)] d\varepsilon db}{\int g(b) \sum_{k=0}^{n} P(k|b) db}.$$

Here $P(k|x)$ is the Poisson probability of k events being observed, when x are expected; CL is a confidence level, n is the number of observed events. The probability-density

	η_b decay modes		
	4 ch.tracks (N_{bkg})	6 ch.tracks (N_{bkg})	8 ch.tracks (N_{bkg})
N_{obs} ($9.2 < W_{vis} < 9.6$ GeV/c^2)	0 (1.2)	2 (1.1)	1 (1.5)
N_{ev} (95% C.L. upper limit)	3.9	5.7	4.1
overall efficiency	5.9%	3.5%	1.8%
$\Gamma_{\gamma\gamma}(\eta_b)\times$BR($\eta_b$), eV/$c^2$ (95% C.L. upper limit)	190	470	660

Table 1: Number of observed 4, 6 and 8 charged-particle η_b candidates (N_{obs}), expected background events (N_{bkg}), 95% C.L. upper limits for signal events (N_{ev}), overall efficiency and 95% C.L. upper limits on $\Gamma_{\gamma\gamma}(\eta_b)\times$BR($\eta_b$).

functions for the background $g(b)$ and the efficiency $f(\varepsilon)$ are assumed to be Gaussian and restricted to the range where b and ε are positive.

Upper limits at the 95% confidence level were calculated for each channel and a limit on $\Gamma_{\gamma\gamma}(\eta_b)\times$BR($\eta_b$) could then be derived. The values are quoted in Table 1.

We considered as main sources of systematic uncertainties: the statistical error of the background, the generator used for the η_b signal and the theoretical uncertainties of the η_b parameters. The limited statistics of our Monte Carlo event sample introduces relative uncertainties of 3%, 5%, 4% for the channels with 4, 6 and 8 charged particles respectively. To appreciate the influence of the generators, we have used PHOT02 [1,17] which generates η_b events decaying into two gluon-jets. The relative differences in efficiency are of 24%, 11.4% and 6.1% for the 4, 6 and 8 charged particles channels. Varying the η_b mass within the range of 9.33 – 9.45 GeV/c^2 generates a relative uncertainty of 2.5% on N_{ev}, for each considered η_b decay channel. The three kinds of uncertainties were added quadratically to obtain the upper limits quoted in Table 1.

4 Conclusions

The pseudoscalar meson η_b has been searched for through its decays to 4, 6 and 8 charged-particles in two-photon interactions at LEP II. The data sample corresponds to a total integrated luminosity of 617 pb^{-1} collected at centre-of-mass energies ranging from 161 to 209 GeV.

Upper limits at a confidence level of 95% on the product $\Gamma_{\gamma\gamma}(\eta_b)\times$BR($\eta_b$) are 190, 470 and 660 eV/c^2 for the $\eta_b \to$ (4, 6, 8) charged particle decays, respectively.

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