Bottomonium at *BABAR*

Francesco Renga (for the *BABAR* Collaboration)

"Sapienza" Università di Roma and INFN Roma

Abstract. Originally designed for CP violation studies in the B meson system, the B-Factories recently showed an exciting capability for improving our experimental knowledge in the field of hadron spectroscopy. Here I will present some of the most recent *BABAR* results concerning bottomonium spectroscopy. In particular, I'll report the first observation of the ground state η_b in $\Upsilon(nS) \to \gamma\eta_b$ and the results of an energy scan in the range of 10.54 to 11.20 GeV, that produced a new measurement of the $e^+e^- \to b\bar{b}$ cross section in the region of the $\Upsilon(4S)$ and candidate $\Upsilon(5S)$ and $\Upsilon(6S)$ resonances, with an integrated luminosity 30 times larger than the previous scans.

1. Introduction

In the last few years, quarkonium spectroscopy received significant contributions from the B-Factory experiments *BABAR* and Belle. This impact have been recently boosted by the decision of the *BABAR* Collaboration [1] of running the PEP-II B-Factory at different Center of Mass (CM) energies, with the main goal of investigating bottomonium properties at a deeper level. About $\sim 28\,\mathrm{fb}^{-1}$ have been collected at the $\Upsilon(3S)$ resonance, providing the largest sample available worldwide at this CM energy. A sample of $\sim 14.5\,\mathrm{fb}^{-1}$ has been collected at the $\Upsilon(2S)$ resonance, and an energy scan of the region above the $\Upsilon(4S)$ resonance has been performed.

Here I will report some of the first results obtained in these unique samples: the discovery of the η_b in $\Upsilon(3S) \to \gamma\eta_b$ [2], confirmed in $\Upsilon(2S) \to \gamma\eta_b$ [3], and a measurement of the inclusive cross section $\sigma(e^+e^- \to b\bar{b})$ in the range of 10.54 to 11.20 GeV [4].

2. The η_b Discovery

The $\eta_b(1S)$ (simply η_b hereafter) is the ground state of the bottomonium spectrum, discovered by the *BABAR* collaboration in the $\Upsilon(3S) \to \eta_b\gamma$ decay channel, by exploiting a sample of (109 ± 1) million of $\Upsilon(3S)$. The mass of the η_b was expected to lie around $9.4\,\mathrm{GeV}/c^2$, hence the analysis consists of the search for a monochromatic photon of about 900 MeV in the $\Upsilon(3S)$ rest frame, accompanied by a set of charged tracks and electromagnetic clusters consistent with a hadronic η_b decay.

Photons are identified as calorimeter clusters isolated from tracks and with a shape consistent with an electromagnetic shower, by requiring a lateral momentum [5] less than 0.55. A π^0 veto is also applied, by rejecting photons that, combined with other neutral clusters in the event, give an invariant mass consistent with a π^0 hypothesis within $15\,\mathrm{MeV}/c^2$. In order to achieve a better resolution and a lower background, only the central part of the electromagnetic calorimeter ($0.762 < \cos(\theta_{\gamma,LAB}) < 0.890$) is used in this analysis. Hadronic η_b decays are selected by

[1] A description of the *BABAR* detector can be found elsewhere [1].

requiring at least four tracks in the event. In order to reject the QED background, we require the ratio R_2 between the 0^{th} and 2^{nd} order Fox-Wolfram moments [6] to be less than 0.98. A selection is finally applied on the angle between the photon and the η_b thrust axis [7, 8]. After this selection, the background is composed of a non-peaking contribution from light mesons decays and peaking contributions from the initial state radiation (ISR) process $e^+e^- \to \gamma_{ISR}\Upsilon(1S)$ and the bottomonium transitions $\chi_{bJ}(2P) \to \gamma\Upsilon(1S)$ $(J = 0,\, 1,\, 2)$.

In figure 1 the photon spectrum after the selection is shown. A binned maximum likelihood (ML) fit of the spectrum is performed in the region between 0.5 and 1.1 GeV with four components: non-peaking background, $\chi_{bJ}(2P) \to \gamma\Upsilon(1S)$, $\gamma_{ISR}\Upsilon(1S)$ and the η_b signal. The non-peaking background is parameterized with a probability density function (PDF) given by $\mathcal{P}(E_\gamma) = A\left(C + \exp\left[-\alpha E_\gamma - \beta E_\gamma^2\right]\right)$. The $\chi_{bJ}(2P) \to \gamma\Upsilon(1S)$ background is described by the superposition of three Crystal Ball (CB) PDFs [9], one for each J state. The ISR background is parameterized by a single CB PDF while the signal is described by the convolution of a Breit-Wigner and a CB PDF. The photon spectrum after non-peaking background rejection is also shown in figure 1. The fit yields $19200 \pm 2000 \pm 2100$ signal events, corresponding to $\mathcal{B}(\Upsilon(3S) \to \eta_b\gamma) = (4.8 \pm 0.5 \pm 1.2) \times 10^{-4}$. A significance of more than 10 standard deviations has been associated to this signal.

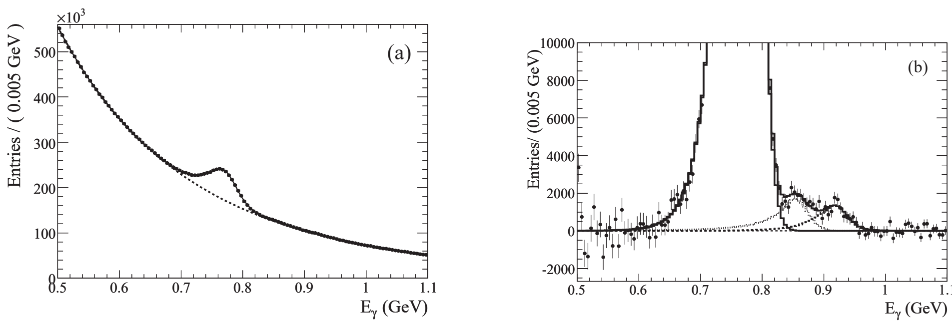


Figure 1. (a) Spectrum of E_γ. The dashed line show the non-peaking background component. (b) Spectrum of E_γ after subtracting the non-peaking background component, with PDFs for $\chi_{bJ}(2P)$ peak (solid), ISR $\Upsilon(1S)$ (dot), η_b signal (dash) and the sum of all three (solid).

The measured η_b mass is $(9388.9^{+3.1}_{-2.3} \pm 2.7)\,\mathrm{MeV}/c^2$, corresponding to a hyperfine splitting of $M(\Upsilon(1S)) - M(\eta_b) = (71.4^{-2.3}_{+3.1} \pm 2.7)\,\mathrm{MeV}/c^2$. It is in agreement with recent lattice results [10], but a significant disagreement is found with respect to QCD calculations [11].

This result has been confirmed by a similar analysis performed on the $\Upsilon(2S)$ data sample, looking for $\Upsilon(2S) \to \eta_b\gamma$. In this case, a lower energy photon is present, implying a larger non-peaking background but also a better absolute energy resolution, allowing for a better separation of the signal from the other peaking components. We obtained $M(\eta_b) = (9392.9^{+4.6}_{-4.8} \pm 1.8)\,\mathrm{MeV}/c^2$ and $\mathcal{B}(\Upsilon(2S) \to \eta_b\gamma) = (4.2^{+1.1}_{-1.0} \pm 0.9) \times 10^{-4}$, with a 3.5σ signal significance. The corresponding fit is shown in figure 2.

3. $\sigma(e^+e^- \to b\bar{b})$ scan above the $\Upsilon(4S)$ resonance

The recent discovery of exotic charmonium-like states [12] suggest the possibility of the existence of similar bottomonium-like states. A naive scaling of the new states, according to the typical mass difference between bottomonia and charmonia, suggests that new bottomonium states could lie in the region between the $\Upsilon(4S)$ and the candidate $\Upsilon(5S)$ and $\Upsilon(6S)$. The *BABAR* Collaboration performed an energy scan of this region in order to investigate this possibility.

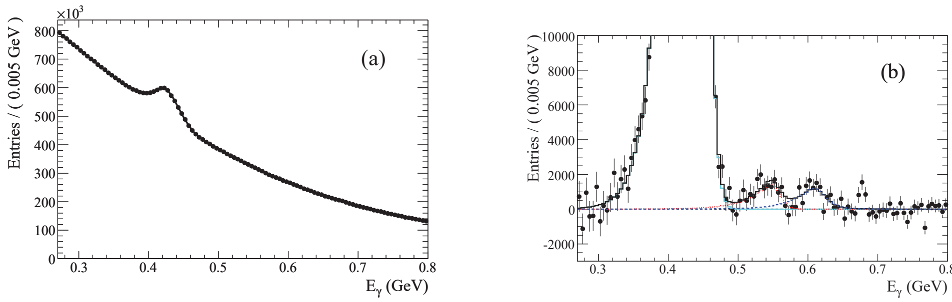


Figure 2. (a) Spectrum of E_γ in the $\Upsilon(2S) \to \eta_b \gamma$ analysis. (b) Spectrum of E_γ after subtracting the non-peaking background component, with PDFs for $\chi_{bJ}(2P)$ peak (solid), ISR $\Upsilon(1S)$ (dot), η_b signal (dash) and the sum of all three (solid).

The CM energy $\sqrt{s}$ has been moved from 10.54 to 11.20 GeV, in steps of 5 MeV, collecting about 25 pb^{-1} per step, for a total of 3.3 fb^{-1}. An additional scan of the $\Upsilon(6S)$ region, with 8 steps of 600 pb^{-1} has been also performed. The *BABAR* scan improves by a factor of 30 the statistics of the previous scans [13, 14], with 4 times finer steps.

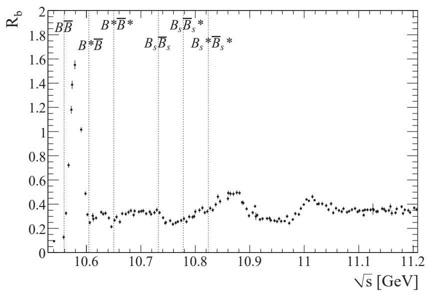
We adopted an inclusive analysis strategy, looking for unexpected structures in the hadronic ratio $R_b = \sigma(e^+e^- \to b\overline{b})/\sigma_0(e^+e^- \to \mu^+\mu^-)$, where $\sigma_0(e^+e^- \to \mu^+\mu^-) = 4\pi\alpha^2/3s$ is the point like $e^+e^- \to \mu^+\mu^-$ cross section. We normalized our measurement to the measured $e^+e^- \to \mu^+\mu^-$ cross section, by writing $R_b = k \times N_{b\overline{b}}/N_{\mu^+\mu^-}$, where $N_{b\overline{b}}$ ($N_{\mu^+\mu^-}$) is the number of produced $b\overline{b}$ ($\mu^+\mu^-$) pairs and k account for radiative corrections to the point-like $\mu^+\mu^-$ cross section (estimated from MC calculation using KK2f [15]).

In order to estimate $N_{b\overline{b}}$ and $N_{\mu^+\mu^-}$, we need to reconstruct and select a $b\overline{b}$ and a $\mu^+\mu^-$ sample, and correct the number of observed events for background contamination and signal efficiency. The $b\overline{b}$ sample is selected by requiring at least three tracks in the event and a reconstructed energy of at least 4.5 GeV. The vertex of the tracks is required to be within 5 mm from the beam crossing in the transverse plane and 6 cm along the beam axis. The selection requirement $R_2 < 0.2$ is also applied to reject the $e^+e^- \to q\overline{q}$, $q = (u, d, s, c)$ background. Dimuon events are selected by requiring exactly two tracks with invariant mass larger than 7.5 GeV/c^2, a polar angle $\theta < 0.7485$ and a collinearity better than 10°.

The first scan point, at 10.54 GeV, where no $b\overline{b}$ production is expected, is used as a reference point to evaluate the background contaminating the $b\overline{b}$ sample. Two components are present: residual $q\overline{q}$ background and two-photons $e^+e^- \to \gamma^*\gamma^*e^+e^- \to Xe^+e^-$. Their cross sections are estimated at the reference point and scaled according to the expected trend ($\sqrt{s}$ for the $q\overline{q}$ background and $\log(s)$ for the two-photon background), while background efficiencies are evaluated by means of MC simulation for different CM energies. Similar simulations are used in order to estimate the signal efficiency.

The $\mu^+\mu^-$ sample is also used for a precise measurement of the center of mass energy for each scan point, extracted by means of a fit of the $\mu^+\mu^-$ invariant mass spectrum. This strategy has been validated by using data collected around the $\Upsilon(3S)$ peak and comparing the results with the most precise determination of the $\Upsilon(3S)$ peak position [16].

Figure 3 shows the result of the scan. The presence of several thresholds in the explored region makes difficult the interpretation of the results. Two evident structures between 10.60 and 10.75 GeV are present, in agreement with theoretical predictions [17]. A fit for the extraction of the $\Upsilon(5S)$ and $\Upsilon(6S)$ masses and widths has been also performed and is shown in figure 4. The two resonances are modeled with two Breit-Wigner functions and a flat continuum is added. These components are also allowed to partially interfere. The results are quoted in Table 1



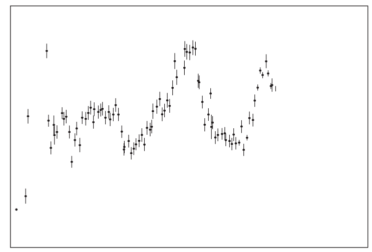


Figure 3. Measured R_b as a function of the center of mass energy $\sqrt{s}$, with the position of the $e^+e^- \to B_{(s)}^{(*)}\overline{B}_{(s)}^{(*)}$ thresholds.