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Results on bottomonium physics at BaBar

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Summary. — Recently bottomonium physics has received significant contributions from the *BABAR* experiment, thanks to the choice of running the PEP-II B-factory at different center-of-mass (CM) energies in the bottomonium region. Here I will report a selection of the latest results: the first observation of the $\eta_b(1S)$, the search for a light Higgs boson in $\Upsilon(3S)$ radiative decays and the measurement of the $e^+e^- \to b\bar{b}$ cross-section exploiting the energy scan above the $\Upsilon(4S)$ resonance.

PACS 13.20.Gd – Decays of J/ψ, Υ, and other quarkonia.
PACS 13.25.Hw – Decays of bottom mesons.
PACS 14.40.Nd – Bottom mesons ($|B| > 0$).
PACS 14.65.Fy – Bottom quarks.

1. – Introduction

Despite it had been originally thought as a CP-violation primer, the *BABAR* experiment (described elsewhere [1]) has obtained important results also in bottomonium spectroscopy. Recently, about $28\,\mathrm{fb}^{-1}$ of data have been collected at an energy in the CM frame equal to the mass of the $\Upsilon(3S)$ resonance, while $\sim 14.5\,\mathrm{fb}^{-1}$ have been collected at the $\Upsilon(2S)$ energy, providing the largest samples available at both CM energies, mainly devoted to investigate the bottomonium properties. Finally, an energy scan above the $\Upsilon(4S)$ energy has been performed, recording an integrated luminosity of $\sim 4\,\mathrm{fb}^{-1}$.

A selection of the most recent results obtained by *BABAR* exploiting these data samples will be shown here: the discovery of the $\eta_b(1S)$ in $\Upsilon(3S) \to \gamma\eta_b$ [2], confirmed in $\Upsilon(2S) \to \gamma\eta_b$ [3], the search for a light Higgs boson in $\Upsilon(3S) \to \gamma A^0, A^0 \to \mu^+\mu^-$ decays [4] and a measurement of the inclusive cross-section $e^+e^- \to b\bar{b}$ in the range between 10.54 and 11.20 GeV [5].

2. – The η_b discovery

The $\eta_b(1S)$ (hereafter referred to as η_b) is the pseudo-scalar partner of the $\Upsilon(1S)$ and corresponds to the ground state of the bottomonium family. It has been discovered by the *BABAR* Collaboration, studying the decays $\Upsilon(3S) \to \gamma\eta_b$ of a sample of $(109 \pm 1) \cdot 10^6$ $\Upsilon(3S)$. The analysis aims to the search of a peak due to a monochromatic photon in the inclusive photon energy spectrum in the $\Upsilon(3S)$ CM frame. The signal yield appears

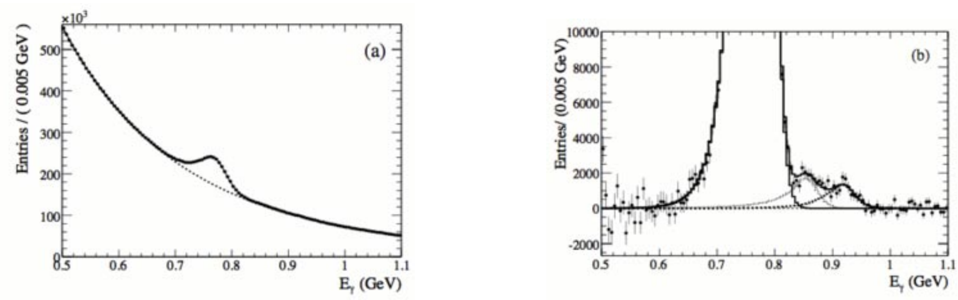

Fig. 1. – (a) Inclusive γ spectrum, with the fit overlaid on the data points. The dashed line corresponds to the non-peaking background component. (b) Inclusive γ spectrum after subtracting the non-peaking background component, with PDFs for $\chi_{bJ}(2P)$ (solid), ISR $\Upsilon(1S)$ (dot), η_b (dashed) and the sum (solid).

around 900 MeV on top of a smooth non-peaking background from continuum events (*i.e.* $e^+e^- \to q\bar{q}$, with $q = u, d, s, c$) and from bottomonium decays. Besides, other background contributions produce peaking structures near to the expected signal region, and need to be identified. Double radiative decays $\Upsilon(3S) \to \gamma\chi_{bJ}(2P)$, $\chi_{bJ}(2P) \to \gamma\Upsilon(1S)$, with $J = 0, 1, 2$, are responsible for three peaks, merged in one centered at 760 MeV, due to photon energy resolution and Doppler broadening because of the motion of the $\chi_{bJ}(2P)$ in the CM frame. Moreover, the radiative production of the $\Upsilon(1S)$ through initial state radiation (ISR) $e^+e^- \to \gamma_{\mathrm{ISR}}\Upsilon(1S)$ generates a peak near 860 MeV.

The photon spectrum is shown in fig. 1. The signal extraction exploits a binned maximum-likelihood fit with four components: the non-peaking background, parameterized with a probability density function (PDF) given by $\mathcal{P}(E_\gamma) = A(C + \exp[-\alpha E_\gamma - \beta E_\gamma^2])$; the double radiative decays, described by the superposition of three Crystal Ball [6] (CB) PDFs; the $\Upsilon(1S)$ ISR production, parameterized by a CB PDF; the η_b signal described by the convolution of a non-relativistic Breit-Wigner and a CB PDF.

A signal is observed with a significance of more than 10 standard deviations, and 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 $M(\Upsilon(1S)) - M(\eta_b) = (71.4^{+2.3}_{-3.1} \pm 2.7)\,\mathrm{MeV}/c^2$. This value is in agreement with recent lattice QCD results [7], but is larger than most predictions based on potential models [8].

This result has been confirmed by a similar analysis performed on the data sample

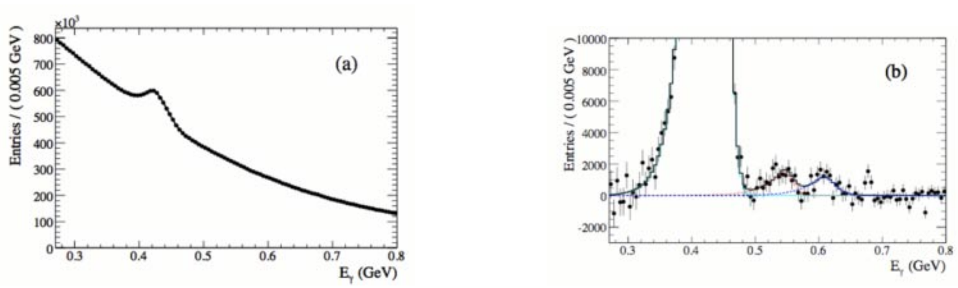

Fig. 2. – (a) Inclusive γ spectrum in the $\Upsilon(2S) \to \gamma\eta_b$ analysis, with the fit overlaid on the data points. The dashed line corresponds to the non-peaking background component. (b) Inclusive γ spectrum after subtracting the non-peaking background component, with PDFs for $\chi_{bJ}(1P)$ peak (solid), ISR $\Upsilon(1S)$ (dot), η_b signal (dashed) and the sum (solid).

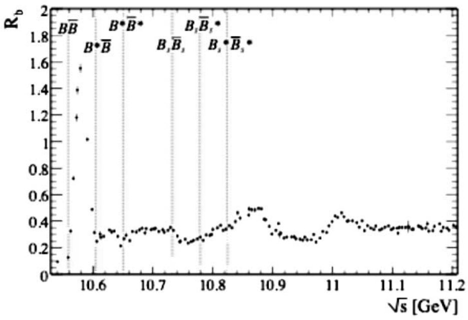

Fig. 3. – Measured $R_b(\sqrt{s})$, with the position of the $e^+e^- \to B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}$ thresholds (dotted lines).

consisting of $(91.6\pm0.9)\cdot10^6$ $\Upsilon(2S)$, exploiting the decays $\Upsilon(2S) \to \gamma\eta_b$. The photon has a lower energy, implying a greater level of non-peaking background, but also a better energy resolution. Figure 2 shows the photon spectrum and the corresponding fit. The result obtained for the η_b mass is $(9392.9^{+4.6}_{-4.8} \pm 1.8)\,\mathrm{MeV}/c^2$, with a 3.5 standard deviations significance(1).

3. – The search for a light Higgs boson

In scenarios of extension of the Standard Model, the existence of a light pseudo-scalar Higgs boson (A^0 hereafter) is predicted, and for masses below $\sim 10\,\mathrm{GeV}/c^2$, A^0 may be observed at the B-factories [9]. Several *BaBar* analyses are looking for A^0, and here I will focus on the results obtained by the search of A^0 in the decays $\Upsilon(3S) \to \gamma A^0$, with $A^0 \to \mu^+\mu^-$; this final state should be the dominant one if $m_{A^0} < 2m_\tau$. An additional motivation for such a search is given by the observation, realized by the HyperCP experiment, of three anomalous events in the $\Sigma \to p\mu^+\mu^-$ final state, interpreted as a light scalar with mass of $214.3\,\mathrm{MeV}/c^2$ decaying into a pair of muons [10].

The signal yield, as a function of the assumed mass m_{A^0} in the interval $0.212 \leq m_{A^0} \leq 9.3\,\mathrm{GeV}/c^2$, is extracted with a series of unbinned maximum likelihood fits to the quantity $\sqrt{m^2_{\mu\mu} - 4m^2_\mu}$, where $m_{\mu\mu}$ (m_μ) is the invariant mass of both (one) of the muons. This variable has a smooth distribution for the continuum background across the entire region of interest, while sources of peaking background arise from J/ψ, $\psi(2S)$ and $\Upsilon(1S)$ decays.

No significant excess of events has been observed; in particular, no significant signal has been found at the HyperCP mass. An upper limit on the branching fraction $\mathcal{B}(\Upsilon(3S) \to \gamma A^0) \times \mathcal{B}(A^0 \to \mu^+\mu^-)$ is set, ranging from $0.25\cdot10^{-6}$ to $5.2\cdot10^{-6}$ at 90% of confidence level(2). These limits supersede those reported by the CLEO Collaboration [11], and rule out much of the parameter space allowed by the light Higgs models [9].

(1) The result of this analysis has now been updated to $M(\eta_b) = (9394.2^{+4.8}_{-4.9}(\mathrm{stat.}) \pm 2.0(\mathrm{syst.}))$ with a significance of 3 standard deviations.
(2) The result of this analysis has now been updated, with the limits on the branching fraction ranging from $0.27\cdot10^{-6}$ to $5.5\cdot10^{-6}$ at 90% of confidence level.

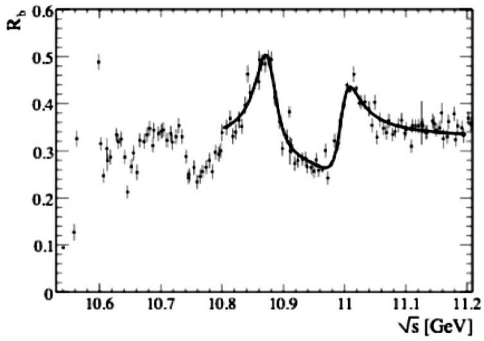

Fig. 4. – Fit of the $\Upsilon(5S)$ and $\Upsilon(6S)$ resonances shapes.

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

The recent discovery of candidates for exotic states with $c\bar{c}$ content [12] stimulates a similar search in the bottomonium family. Scaling up by the mass difference between the J/ψ and the $\Upsilon(1S)$, one would expect to find the corresponding exotic states in a mass region above the $\Upsilon(4S)$ and below 11.20 GeV. This region contains also the $\Upsilon(10860)$ and $\Upsilon(11020)$ states, which are the candidates for the $\Upsilon(5S)$ and the $\Upsilon(6S)$. The *BABAR* Collaboration realized an energy scan of this region in order to investigate this possibility.

The data acquisition has been performed moving the CM energy $\sqrt{s}$ from 10.54 to 11.20 GeV, in steps of 5 MeV, collecting about 3.3 fb^{-1}, followed by an additional scan of the $\Upsilon(6S)$ region, with eight steps of 600 pb^{-1}. This dataset outclasses the previous scans [13, 14] by a factor of 30, with four times finer steps.

For each step, the inclusive hadronic cross-section $R_b(s) = \sigma_{bb(\gamma)}(s)/\sigma^0_{\mu\mu}(s)$ has been measured, where $\sigma_{bb(\gamma)}$ is the cross-section of $e^+e^- \to b\bar{b}(\gamma)$ events and $\sigma^0_{\mu\mu} = 4\pi\alpha^2/3s$ is the cross-section of $e^+e^- \to \mu^+\mu^-$ events, used as normalization factor.

The result is shown in fig. 3, where clear structures appear at the opening of several thresholds. Indeed, the presence of thresholds in the explored region makes the interpretation of the results difficult. Two evident structures between 10.60 and 10.75 GeV are present, in agreement with theoretical predictions [15]. As shown in fig. 4, a fit is realized between 10.80 and 11.20 GeV, using a flat component (representing $b\bar{b}$-continuum states not interfering with resonance decays) added incoherently to a second flat component

TABLE I. – *Results of the BABAR fit and comparison with the present world averages* [16] *for the* $\Upsilon(5S)$ *and the* $\Upsilon(6S)$ *candidates.*

	BABAR	PDG
M($\Upsilon(5S)$) (GeV/c^2)	(10.876 ± 0.002)	(10.865 ± 0.008)
$\Gamma(\Upsilon(5S))$ (MeV/c^2)	(43 ± 4)	(110 ± 13)
M($\Upsilon(6S)$) (GeV/c^2)	(10.996 ± 0.002)	(11.019 ± 0.008)
$\Gamma(\Upsilon(6S))$ (MeV/c^2)	(37 ± 3)	(79 ± 16)

interfering with two relativistic Breit-Wigner functions, mimicking the $\Upsilon(5S)$ and $\Upsilon(6S)$ candidates' behavior. The results are summarized in table I and differ substantially from the present world averages [16], based on smaller statistics and coarser granularity. More detailed studies of the spectrum and of exclusive final states are awaited for soon.

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