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We present the results of the *BABAR* and Belle experiments on bottomonium spectroscopy and decay. We discuss the observation of the bottomonium ground state η_b, the observation of the inclusive $\Upsilon(1S)$ decay to open charm and the search for exotic $b\bar{b}$ resonances above the $\Upsilon(4S)$.

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1. Introduction

The discovery of the Υ resonances dates back to more than 30 years ago. Since then the $b\bar{b}$ states have been studied extensively, however some important aspects of the bottomonium system are not yet very well understood. Until recently the $b\bar{b}$ ground state, $\eta_b(1S)$ ($L = 0$, $S = 0$) was missing from the spin singlet spectroscopy, while the h_b state ($L = 1$, $S = 0$) has escaped observation until now. The $\Upsilon(1D)$ states, observed by the CLEO experiment, need a confirmation. Furthermore the importance of the color octet mechanism in the decay to open charm is not well understood. Finally the resonant structure above the $\Upsilon(4S)$ is not well known while, by analogy with the charmonium system, several exotic states are naturally expected in this region.

From the theoretical point of view the quarkonium system, like the charmonium one, is a powerful testing ground for QCD effective theories such as perturbative Non Relativistic QCD (pNRQCD), lattice Non Relativistic QCD (lattice NRQCD), and for potential models of $b\bar{b}$ bound states. Moreover since the bottom quark is heavy with respect to Λ_{QCD}, the perturbative calculations are expected to work better than in charmonium and therefore experimental measurements are expected to provide better inputs to the theory.

In order to study the bottomonium system the *BABAR* and Belle experiments have collected samples of data at the resonances below the $B\bar{B}$ threshold and above the $\Upsilon(4S)$. This set of data, summarized in Tab. 1, is more than an order of magnitude larger than the data available previously and offers unique opportunities to study the bottomonium system. In this article we discuss the *BABAR* and Belle experimental studies of the bottomonium spectroscopy and decay using these data. We report on: the observation of the $\eta_b(1S)$ meson [1, 2] and the measurement of its mass; the observation of the inclusive decay of $\Upsilon(1S)$ to $D^{*\pm}$ mesons [3] and the measurement of the branching fraction as a function of the $D^{*\pm}$ momentum; the study of the $b\bar{b}$ resonances above the open beauty threshold [4, 5].

Table 1: Summary of data collected below and above the $\Upsilon(4S)$ resonance by *BABAR* and Belle.

Resonance	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	Above $\Upsilon(4S)$
BABAR	-	100M	120M	$\sim 4\,\mathrm{fb}^{-1}$
Belle	100M	20M	11M	$\sim 30\,\mathrm{fb}^{-1}$
CLEO	20M	9M	6M	-

2. Observation of the η_b

The measurement of the η_b mass, together with the knowledge of the $\Upsilon(1S)$ mass, represents a precise measurement of the hyperfine splitting (HFS) of the $b\bar{b}$ system. The HFS is of key importance in understanding the spin-spin interactions in quarkonium models and in NRQCD. Theoretical estimates of this difference range from 40 MeV to 60 MeV [6, 7]. In addition the HFS is very sensitive to the value of α_s and could be used for a competitive measurement of it.

In order to search for the η_b the *BABAR* experiment reconstructed the inclusive photon energy spectrum from the two body decay $\Upsilon(2,3S) \rightarrow \gamma\eta_b$ and searched for the monochromatic photons in the center of mass (c.m.) frame. The study is based on a sample of 28 fb^{-1} (14 fb^{-1}) of data collected with the *BABAR* detector at the $\Upsilon(3S)$ ($\Upsilon(2S)$) resonance. These data-sets correspond to about 10^8 Υ mesons produced for each resonance. Theoretical predictions for the branching fraction range from 1-20$\times 10^{-4}$ [8]. In addition 44 fb^{-1} of data collected about 44 MeV below the $\Upsilon(4S)$ resonance (off-resonance) are used for background and efficiency studies.

The signal is extracted from a fit to the inclusive photon energy spectrum. The monochromatic photons from the decay appear as a peak at the energy $E_\gamma \simeq 900\,\text{MeV}$ (611 MeV) for $\Upsilon(3S)$ ($\Upsilon(2S)$) decays on top of a smooth non peaking background from continuum events and bottomonium decays. The signal is selected using simple criteria. The event is required to have at least four charged tracks and the ratio of the second to the zeroth Fox-Wolfram moment is required to be less than 0.98. In order to reduce the continuum background the angle between the thrust axis of the event (computed using all the charged tracks) and the direction of the signal photon in the c.m. frame is used. A principle source of background is π^0 decays therefore signal photon candidates are rejected if they form a π^0 candidate with another photon in the event. The final selection efficiency is 37% for the $\Upsilon(3S)$ analysis and 35.8% for the $\Upsilon(2S)$ one. The selection criteria have been optimized using about 7-9% of the data to model the background which is then discarded in the final analysis to avoid a selection bias.

The non peaking background is parametrized by an empirical smooth function determined from data. Two other peaks are produced near the region where the signal is expected. The $\Upsilon(1S)$ production via ISR $e^+e^- \to \gamma_{ISR}\Upsilon(1S)$ produces a peak at $E_\gamma = \frac{S-M^2_{\Upsilon(1S)}}{2\sqrt{(S)}} \simeq 856\,\text{MeV}$ for $\Upsilon(3S)$ running ($\simeq 544\,\text{MeV}$ for $\Upsilon(2S)$ running). It is critical to model correctly the shape and the yield of this background because, depending on the value of the η_b mass, it can overlap with the signal peak. The peak is modeled with a Chrystal Ball function (CB) which is a Gaussian function modified to have power law tail on the left side. The center is fixed to the value from the Υ masses while the yield is estimated from the off-resonance sample. As a validation the fit is performed also with the yield of the ISR component left free, and it is found to be consistent with this estimate.

Double radiative decays $\Upsilon(2,3)S \to \gamma\chi_{bJ}(1,2P)$, $\chi_{bJ}(1,2P) \to \gamma\Upsilon(1S)$ from the three χ_{bJ} states produce a single broad peak due to Doppler broadening and energy resolution. For the $\Upsilon(3S)$ analysis the peak is centered at $E_\gamma \simeq 760\,\text{MeV}$, while for the $\Upsilon(2S)$ case $E_\gamma \simeq 430\,\text{MeV}$. The peak is well separated from the signal and is used as a calibration for the energy. The shape of the peak is modeled with a superposition of three CB functions and the calibration offset for the energy of the photons is determined in the fit on data excluding the signal region. The energy calibration offset is then used to correct the energy of the photons in the signal region.

The p.d.f. for the signal peak is a non-relativistic Breit-Wigner convoluted with a CB to account for the experimental resolution. The width of the Breit-Wigner is fixed to $10\,\text{MeV}/c^2$ and is varied in the range 5-20 MeV/c^2 to estimate the systematic error. The data distribution in the signal region and the fit to the p.d.f. are shown in Fig. 1.

In the data from $\Upsilon(3S)$ decays the *BABAR* experiment finds a peak at a photon energy $E_\gamma = 921^{+2.1}_{-2.8} \pm 2.4\,\text{MeV}$ corresponding to an η_b mass of $m_{\eta_b} = 9388.9^{+3.1}_{-2.3} \pm 2.7\,\text{MeV}/c^2$ and an HFS of $71.4^{+2.3}_{-3.1} \pm 2.7\,\text{MeV}/c^2$. The signal has a significance corresponding to more than 10 standard deviations. The branching fraction $\Upsilon(3S) \to \gamma\eta_b$ is found to be $(4.8 \pm 0.5 \pm 0.6) \times 10^{-4}$.

In the data from the $\Upsilon(2S)$ decays the η_b mass is measured to be $9394.2^{+4.8}_{-4.9} \pm 2.0\,\text{MeV}/c^2$

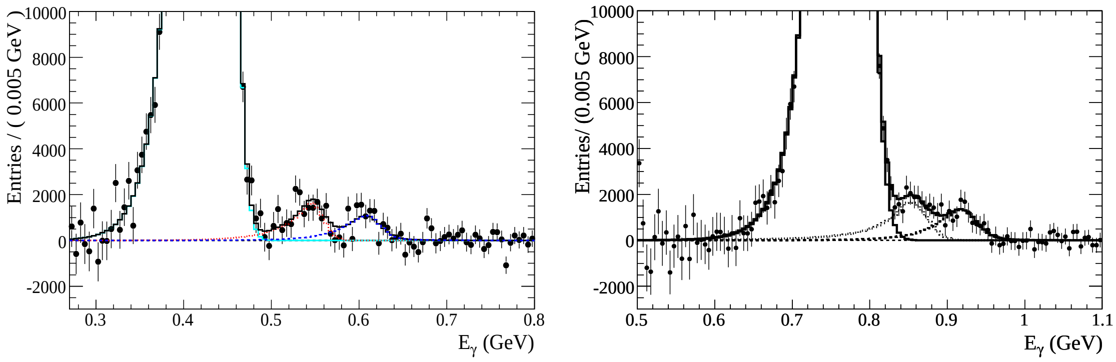

Figure 1: Inclusive photon energy distribution from the decay $\Upsilon(2S) \to \gamma\eta_b$ (left) and $\Upsilon(3S) \to \gamma\eta_b$ (right) after subtracting the non peaking background. The dots represent the distribution for data, the continuous line the fit to the χ_b peaks, the dotted line the fit to the $\gamma_{ISR}\Upsilon(1S)$ background and the dashed line represents the signal.

corresponding to an HFS of $66.1^{+4.9}_{-4.8} \pm 2.0$. The signal significance corresponds to 3.7 standard deviation because the continuum background is three times larger than in the $\Upsilon(3S)$ case. However the peaks corresponding to the χ_b and ISR background are better separated from the signal, therefore this is an important confirmation of the $\Upsilon(3S)$ result. The branching fraction for the process $\Upsilon(2S) \to \gamma\eta_b$ is found to be $(3.9 \pm 1.1^{+1.1}_{-0.9}) \times 10^{-4}$ and the ratio $\mathscr{B}[\Upsilon(2S) \to \gamma\eta_b]/\mathscr{B}[\Upsilon(3S) \to \gamma\eta_b] = 0.82 \pm 0.24^{+0.20}_{-0.19}$ is consistent with some of the theoretical estimates of the magnetic dipole transition to the η_b [8].

The combined mass measurement is $M(\eta_b) = 9390.8 \pm 3.2\,\mathrm{MeV}/c^2$ corresponding to an hyperfine mass splitting between the $\Upsilon(1S)$ and the η_b of $69.5 \pm 3.2\,\mathrm{MeV}/c^2$. This value is higher than the pNRQCD prediction [6] but is consistent with the present lattice NRQCD calculations [7].

3. Observation of $\Upsilon(1S)$ decays to $D^{*\pm}$

The experimental information on the final state content of bottomonia is scarce, in particular on the decays of bottomonium to open charm. The CLEO Collaboration observed [9] charm production in the decays of the χ_b states with branching fractions of the order of 10% and the ARGUS Collaboration searched [10] for the decay $\Upsilon(1S) \to D^{*\pm}X$ and set a limit on its branching fraction of $\mathscr{B} < 1.9\%$ at 90% confidence level.

The decay $\Upsilon(1S) \to D^{*\pm}X$ can be produced trough the virtual photon process $\Upsilon(1S) \to \gamma^* \to c\overline{c}$ followed by the hadronization of the $c\overline{c}$ system. The rate and D^* momentum distribution for this process can be accurately predicted from the properties of $\Upsilon(1S)$ and the charm fragmentation function. NRQCD predicts also other contributions to this decay such as the splitting of a virtual gluon (singlet) [11] and the annihilation of the $b\overline{b}$ system in an octet state [12]. The size of the octet contribution is expected to be approximately half of the singlet one and the two contributions can be distinguished by measuring the D^* momentum distribution in the rest frame of the $\Upsilon(1S)$.

The *BABAR* experiment searched for the inclusive decay of $\Upsilon(1S)$ mesons to $D^{*\pm}$ by reconstructing the transition $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$. This transition yields approximately $N_{\Upsilon(1S)} = 17.8 \times 10^6$ $\Upsilon(1S)$ decays in the *BABAR* set of data recorded at the $\Upsilon(2S)$ resonance. The transition is identified by reconstructing pair of oppositely charged tracks and requiring that the mass recoiling against the $\pi^+\pi^-$ system is consistent with the $\Upsilon(1S)$ mass. The recoil mass is defined as $M_{recoil} \equiv \sqrt{(P_{e^+e^-} - P_{\pi^+\pi^-})^2}$ where $P_{e^+e^-}$ is the known momentum of the beams and $P_{\pi^+\pi^-}$ is the reconstructed momentum of the pair of pions. To reduce the $\pi^+\pi^-$ combinatorial background the mass of the pion pair is required to be greater than $0.4\,\mathrm{GeV}/c^2$, the tracks are required to be identified as pions with a loose criterion and to originate from the same vertex. The plot on the left side of Fig. 2 shows the recoil mass distribution for the event sample passing the above selection criteria and a very loose D^* pre-selection; a signal region consisting of 2 standard deviations around the $\Upsilon(1S)$ mass is highlighted (cross hatching), as well as two sideband regions used for background studies.

The $D^{*\pm}$ mesons are reconstructed using the decay chain $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$. The soft pion and the D^0 candidates are constrained to originate from the interaction region and the mass difference between the D^* and the D^0 is required to be within 3 times the experimental resolution to reduce the combinatorial background from fake soft pions.

The sample is divided in intervals of 0.05 width of the scaled D^* momentum $\mathrm{x_p} = p_{D^*}/p_{\mathrm{m}ax}$ in the range [0.1,1.0], where P_{D^*} is the D^* momentum in the rest frame of the $\Upsilon(1S)$ and $P_{\mathrm{m}ax} = \sqrt{E^2_{\mathrm{m}ax} - m^2_{D^*}}$. The D^* yield is extracted from a fit to the D^0 invariant mass distribution for each interval. The D^0 mass distribution is obtained from the $K\pi$ invariant mass after two background subtractions. Combinatorial backgrounds, events that are not $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ decays, are removed by subtracting the lower and upper sidebands of the $\pi^+\pi^-$ recoil mass. In addition, the $K^-\pi^+$ mass distribution for "wrong-sign" $D^0(\to K^-\pi^+)\pi^-$ combinations (where the soft pion has the same charge as that of the kaon candidate) is used to subtract the D^0 combinatorial background.

The resulting D^0 mass distribution for each $\mathrm{x_p}$ interval is fitted to a double Gaussian p.d.f. (with a common mean) for the signal plus a linear function for background. The shape of the signal p.d.f. and the signal reconstruction efficiency are determined for each $\mathrm{x_p}$ interval using a Monte Carlo simulation. The reconstruction efficiency varies from 5% to 23% in the $\mathrm{x_p}$ range [0.1,1.0] mainly because of the variation of the soft pion reconstruction efficiency. The average efficiency on data is (17.7 ± 3)%. The efficiency corrected signal yield in the $\mathrm{x_p}$ range [0.1,1.0] is $n_{sig} = \Sigma_{\mathrm{x_p}} n_{sig}(\mathrm{x_p})/\varepsilon(\mathrm{x_p}) = 11845 \pm 596$ candidates where $n_{sig}(\mathrm{x_p})$ is the yield for a given $\mathrm{x_p}$ interval, and $\varepsilon(\mathrm{x_p})$ is the corresponding efficiency. The resulting branching fraction is

$$\mathscr{B}[\Upsilon(1S) \to D^{*\pm}X] = \frac{n_{\mathrm{sig}}}{k_{\mathrm{DCS}} \times \mathscr{B}_{\mathrm{decay}} \times N_{\Upsilon(1S)}} = (2.52 \pm 0.13(\mathrm{stat}) \pm 0.15(\mathrm{syst}))\%$$

where $K_{\mathrm{DCS}} = (99.62 \pm 0.02)$% is a correction factor to account for the subtraction of doubly Cabibbo suppressed D^0 decays, $\mathscr{B}_{\mathrm{decay}} = (2.65 \pm 0.04)$% is the product of the branching fractions in the D^* decay chain.

The main contributions to the systematic uncertainty come from the knowledge of the slow pion reconstruction efficiency(3%), the selection efficiency of $\Upsilon(1S)$ decays in the recoil mass signal region(2.8%) and the uncertainty in the decay branching fractions (2.7%).

The inclusive D^* yield as a function of $\mathrm{x_p}$ is shown in Fig. 2(right side). The solid line represents the yield expected from the virtual photon contribution. The shape of this contribution is obtained from the measured $c\bar{c}$ fragmentation function at $\sqrt{s} \simeq 10.5\,\mathrm{GeV}/c^2$ and the normalization is computed from: $\mathscr{B}[\Upsilon(1S) \to \gamma^* \to D^{*\pm}X] = \frac{\sigma_{D^{*\pm}}}{\sigma_{q\bar{q}}} \times R_{\mathrm{had}} \times \mathscr{B}[\Upsilon(1S) \to \mu^+\mu^-] = (1.52 \pm 0.20)\%$.

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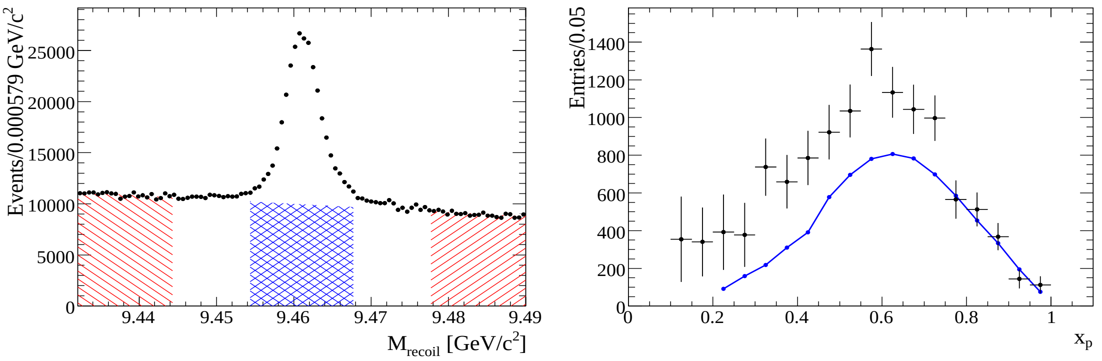

Figure 2: Left side: distribution of the recoil mass, M_{recoil}, for the selected $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ candidates. The cross hatching shows the signal region, and the lower and upper sideband regions are indicated by the diagonal shading. Right side: signal yield as a function of x_p. The dots represent the data and the solid line represents the expected contribution from the virtual photon process [13].

where, $R_{had} = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-) = 3.46 \pm 0.13$[14], $\mathscr{B}[\Upsilon(1S) \to \mu^+\mu^-] = (2.48 \pm 0.05)\%$, and $\frac{\sigma_{D^{*\pm}}}{\sigma_{q\bar{q}}} = (17.7 \pm 2.2)\%$ is the measured $D^{*\pm}$ yield from $e^+e^- \to q\bar{q}$ at $\sqrt{s} = 10.5$ GeV.

The measured branching fraction exceeds the expected rate from the QED virtual photon process by $(1.00 \pm 0.28)\%$ (including the systematic uncertainty) which corresponds to 3.6 standard deviations. While the measured x_p spectrum agrees in shape with that of the virtual photon process for $x_p > 0.75$, there is a significant excess for $x_p < 0.75$. The excess is compatible with the contribution expected [11] from the splitting of a virtual gluon, $(1.20 \pm 0.29)\%$, but there is no evidence for the octet process contribution, which is expected to have a shape similar to the virtual photon one.

4. Search for exotic resonances above the $\Upsilon(4S)$

Nonbaryonic charmonium states that do not behave like two quark states have been recently discovered [15]. These include exotic states with $J^{PC} = 1^{--}$ [$Y(4260)$, $Y(4350)$, $Y(4660)$] that can be produced at e^+e^- colliders. The corresponding bottomonium states are expected to have masses scaled up by the $\Upsilon(1S) - J/\psi$ mass difference $6360\,\text{MeV}/c^2$, between the $\Upsilon(4S)$ mass and 11.2 GeV$/c^2$. Moreover the Belle experiment has observed [16] an anomalously large $\Upsilon(1S)\pi\pi$ and $\Upsilon(2S)\pi\pi$ production rate near the peak of the $\Upsilon(10860)$ resonance. If these signals are attributed entirely to di-pion transitions from the $\Upsilon(10860)$ resonance, the corresponding partial widths are more than two orders of magnitude larger than those from corresponding transitions from the lower $\Upsilon(2S)$, $\Upsilon(3S)$ and $\Upsilon(4S)$ states. A possible explanation is again the bottomonium counterpart of the $\Upsilon(4260)$. The energy scan data above the $\Upsilon(4S)$ collected by the *BABAR* and Belle experiments are extremely helpful to investigate these puzzles.

The SLAC PEP-II e^+e^- collider delivered collisions at center of mass energies ($\sqrt{(s)}$) in the range 10.54-11.20 GeV [4] in 5 MeV steps. The *BABAR* detector collected approximately 25 pb^{-1} per step, for a total of about 3.3 fb^{-1}. This was then followed by a 600 pb^{-1} scan in the range of $\sqrt{(s)} = 10.96$ to 11.10 GeV, in 8 steps with non-regular energy spacing, in order to investigate the $\Upsilon(11020)$ region. This data set outclasses the previous scans by a factor >30 in the luminosity and in the size of the energy steps. *BABAR* measured for each step the $R_b(s) = \sigma_b/\sigma^0_{\mu\mu}(s)$ where $\sigma^0_{\mu\mu} = \frac{4\pi\alpha^2}{3s}$ and σ_b is the total cross section for $e^+e^- \to b\overline{b}(\gamma)$. The R_b ratio was extracted from the number of events passing a B hadron selection and from the number of di-muon events for each energy point and for a reference point below the open beauty threshold. To select the b-enriched sample it is required that the event contains at least three tracks, that the visible energy is greater than 4.5 GeV and that the charged tracks form a good vertex near the interaction point. In order to reject continuum and di-lepton events the ratio of the second to the zeroth Fox-Wolfram moment is required to be smaller than 0.2. The $\sqrt{s}$ at each point is extracted from a fit of the invariant mass of the di-muons. The measured value of R_b as a function of $\sqrt{s}$ is shown by the points in Fig. 3(left side). The data shows clear structures corresponding to the opening of the $B^{(*)}B^{(*)}$ and $B_S^{(*)}B_S^{(*)}$ thresholds. It is also evident that the $\Upsilon(10860)$ and $\Upsilon(11020)$ peaks have an asymmetric shape. Finally, the plateau above the $\Upsilon(11020)$ is clearly visible. The data points between 10.80 and 11.20 GeV are fitted to a simple model (continuous line in Fig. 3): a flat component representing non resonant continuum production, added incoherently to a second flat component interfering with Breit-Wigner shapes for the $\Upsilon(10860)$ and $\Upsilon(11020)$ resonant decays. The result of the fit shows some differences with respect to the world averaged parameters of the Υ resonances. In particular the total width of the $\Upsilon(5S)$ is $\Gamma_{\Upsilon(5S)} = 43 \pm 4\,\mathrm{MeV}$ while the world average is [17] $\Gamma^{PDG}_{\Upsilon(5S)} = 110 \pm 13\,\mathrm{MeV}$, the mass and width of the $\Upsilon(6S)$ are $M_{\Upsilon(6S)} = 10960 \pm 2\,\mathrm{MeV}$, $\Gamma_{\Upsilon(6S)} = 37 \pm 3$ while the world average values are $M^{PDG}_{\Upsilon(6S)} = 11019 \pm 8\,\mathrm{MeV}$ and $\Gamma^{PDG}_{\Upsilon(6S)} = 79 \pm 16\,\mathrm{MeV}$ [17]. These differences are significant but it should be kept in mind that a proper coupled channel approach [18] would be likely to modify the simple fit outlined above.

The KEKB e^+e^- energy-asymmetric collider performed a dedicated energy scan [5] at $\sqrt{(s)} \simeq 10.83, 10.88, 10.90, 10.93, 10.96,$ and 11.02 GeV/c^2 collecting a total of about 8 fb^{-1} of data in this scan. This adds to about 22 fb^{-1} of data collected previously [16] at the $\Upsilon(10860)$ peak. Using these data the Belle collaboration searched for the production of $\pi^+\pi^-\Upsilon(1S)$, $\pi^+\pi^-\Upsilon(2S)$ and $\pi^+\pi^-\Upsilon(3S)$ via e^+e^- annihilation. Events are required to have four tracks and an invariant mass less than 150 MeV/c^2 away from $\sqrt{s}$. Υ candidates are reconstructed in the di-muon channel. The kinematic variable ΔM, defined by the difference between $M(\mu^+\mu^-\pi^+\pi^-)$ and $M(\mu^+\mu^-)$, is used to identify the signal candidates. Signal yields are extracted from an unbinned extended maximum likelihood (ML) fit to the ΔM distribution. The measured cross sections obtained from the fit are shown by the points in figure 3(right side). The resonance parameters for the $\Upsilon(5S)$ are extracted from a fit of the cross section data to an S-wave Breit-Wigner (BW) function with a common mean and width. The central value of the mass $M_{\Upsilon(5S)} = 10889.6 \pm 1.8 \pm 1.5$ the total width $\Gamma_{\Upsilon(5S)} = 54.7^{+8.5}_{-7.2} \pm 2.5$ are incompatible with the known parameters for the $\Upsilon(5S)$ [17] suggesting the contribution of a bottomonium exotic state. However it should be noticed that this cross section data is quite compatible with the shape of the $\Upsilon(5S)$ peak measured by *BABAR*, especially considering the asymmetric distribution observed in the $\Upsilon(5S)$ region. It is more striking instead the absence of any significant contribution from the $\Upsilon(6S)$ region.

In conclusion we presented some recent results from *BABAR*and Belle on bottomonium spectroscopy and decay, and in particular the confirmation of the η_b observation in $\Upsilon(2S)$ decays, the observation of the inclusive $\Upsilon(1S)$ decay to open charm and the search for exotic $b\overline{b}$ resonances

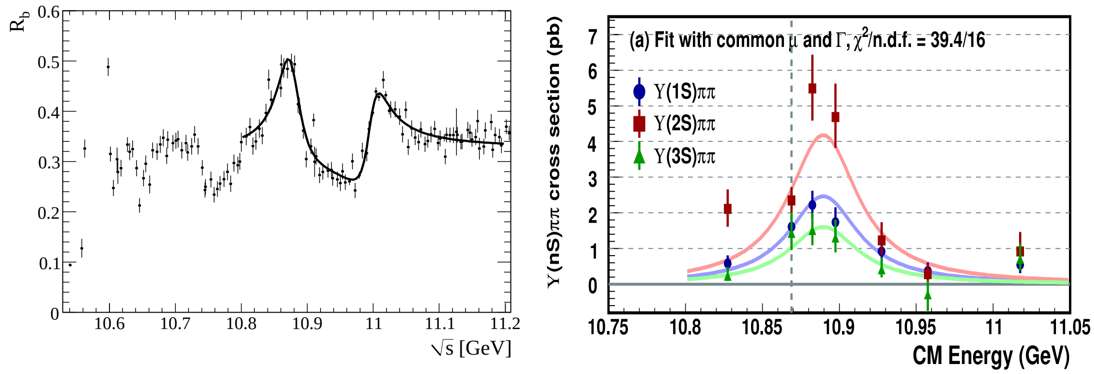

Figure 3: Left side: R_b measured by *BaBar* as a function of $\sqrt{s}$ with the result of the fit superimposed. Right side: cross section for $e^+e^- \to \Upsilon(NS)\pi^+\pi^-$, $(n = 1,2,3)$ measured by Belle as a function of $\sqrt{s}$ with the BW fit superimposed.

above the $\Upsilon(4S)$.

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