Decays of $\Upsilon(nS, n \neq 4)$ states at B factories

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Abstract

A review of most recent results in bottomonium physics at B factories is given. Besides the discovery of the long sought ground state η_b, the first evidences of exclusive decays of χ_b states to light hadrons, of the suppressed inclusive decay $\Upsilon(1S) \to D^{*\pm}$ have characterized the last two years of studies on the narrow states. Great progress has also been made experimentally, on $b\bar{b}$ production above bottom threshold. At the energy of $\Upsilon(5S)$ and above, the asymmetric B factories detected exclusive decays to narrow bottomonium and to three- and four-body final states, at unexpectedly large rates. Finally, I will report about the most recent searches for physics effects beyond the Standard Model (light Higgs, dark matter candidates, lepton flavor violation) in bottomonium decays.

1. Introduction

At the beginning of the new millenium, during its last two years of operation (2002-3) at $\sqrt{s} \approx$ 10GeV, the CLEO collaboration integrated O(10^7) data samples of $\Upsilon(1,2,3S)$ decays on the peak of narrow bottomonia. While these data were being taken, at the 1^{st} QWG workshop [1], many participants urged the asymmetric B-factories to plan for further running below $B\bar{B}$ threshold. The CLEO runs yielded a number of important discoveries: the $\Upsilon(1D)$ states, the $\chi_b(2P) \to \chi_b(1P)\pi\pi$ and $\chi_b(2P) \to \omega\Upsilon(1S)$ transitions, new limits on lepton flavor violation or lepton universality violation in Υ decays, but left some major questions unanswered, because of lack of statistics, in particular in the sector of parabottomonia, i.e. the bound states with S=0 (shown as dashed lines in Fig.1.).

The analysis of the CLEO data sets is still under way, and I will review its most recent outcomes, together with the results from the asymmetric B-factories. In 2006, BELLE integrated about 11M $\Upsilon(3S)$ decays, to search for dark matter candidates in the $\Upsilon(1S)$ decay pattern, tagged by the occurrence of the transition $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$. In 2008, BABAR devoted its last three months of running to $\Upsilon(2,3S)$ and a scan on the region $10.54 < \sqrt{s/GeV} < 11.2$, while BELLE collected record samples at $\Upsilon(1S,5S)$ peaks, and a large sample at $\Upsilon(2S)$. The total amount of luminosity integrated by CLEO, BELLE, and BABAR at the narrow bottomonium resonances, $\Upsilon(1,2,3S)$, and above $\Upsilon(4S)$, is summarized in Table 1.

Table 1. $\Upsilon(nS, n \neq 4)$ datasets after year 2000 at B-factories

Expt.	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(5-6S)$
CLEO	20M	9M	6M	0.5 fb^{-1}
BELLE	98M	44M	11M	100 fb^{-1}
BABAR	-	100M	122M	3.3 fb^{-1}

The analysis of O(10^8) samples of narrow bottomonia from asymmetric B-factories has just started and has already yielded important results, which will be summarized in the present review, together with the progress made above bottom threshold.

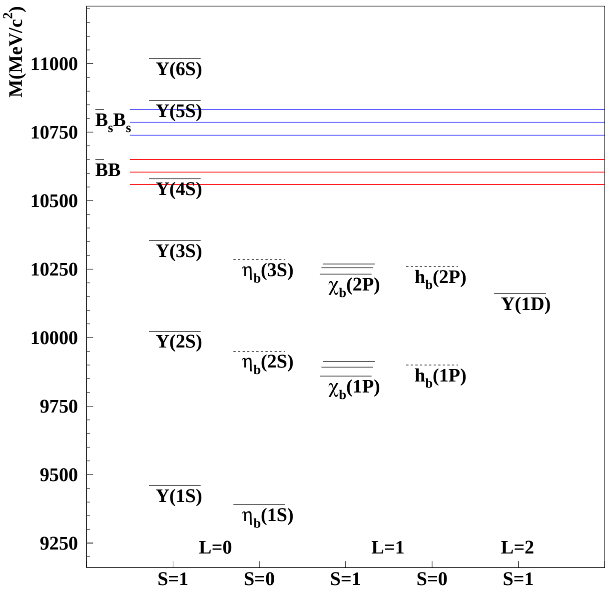

Fig. 1. Bottomonium spectrum: the undiscovered states $\eta_b(2,3S), h_b(1,2P)$ are shown as dashed lines

2. Search for parabottomonia

A major milestone has been reached in 2008 by BABAR collaboration, with the discovery of the ground state of parabottomonium, the η_b(1S) [2]. Such state is reachable by hindered M1 transitions from the $\Upsilon(2,3S)$ states. Detection of the η_b peak is challenged by the presence of O(10^2) larger peaking background in the proximity, due to the favored E1 transitions from $\chi_b(1,2P)$ to the $\Upsilon(1S)$. Moreover, an extra source of peaking background, of size comparable to the yield expected by the η_b signal, comes from the radiative return photon from $e^+e^- \to \gamma_{ISR}\Upsilon(1S)$. As very little is known on η_b decay pattern, it is very difficult to device cuts which would allow to increase the S/B ratio. The cuts were optimized on a test sample containing about one tenth of the total dataset.

Photons from π^0 decay are a significant source of background: candidate photons were rejected if they matched the π^0 mass within 15 MeV with any other photon in the detector, with $E_{lab} >$ 50 MeV.

The main improvement introduced by BABAR with respect to previous analyses, is a cut on the angle θ_T between the inclusive candidate photon and the thrust axis of the recoiling system. In continuum, events mostly have a two jet topology and therefore the inclusive candidate photon is likely to be correlated to one of the two jets. The η_b is a pseudoscalar state, and therefore we ex-

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pect a flat distribution in $cos\theta_T$. After such preliminary cuts, the smooth photon spectrum outside the peak region is fitted with an empirical function and subtracted. Figure 2. shows the peaks in the region of interest. All monochromatic photon peaks were fitted with a Crystal Ball resolution function.

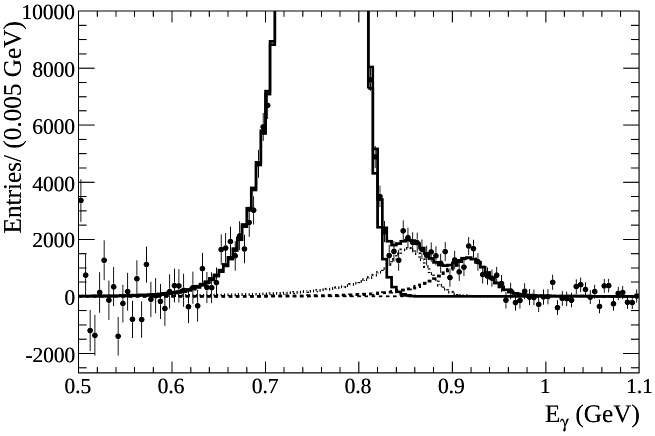

Fig. 2. The inclusive photon spectrum at 3S from BABAR, after continuum subtraction: the peaks from $\chi_{b1,2} \rightarrow \Upsilon(1S)$, ISR production of $\Upsilon(1S)$ and $\Upsilon(3S) \rightarrow \eta_b$ are visible, left to right in the plot.

Soon after, BABAR confirmed the observation of the η_b also from the analysis of the 2S data sample[3]. Cuts were optimized as in the 3S analysis. Given the larger peak cross section at the 2S, the $cos\theta_T$ threshold could be raised at 0.8, and the minimum E_{lab} for photons checked for π^0 rejection could be lowered to 40 MeV. The results from the two analyses can be compared in Table 2.

Table 2. η_b properties measured by BABAR

Transition	$\Upsilon(2S) \rightarrow \eta_b$	$\Upsilon(3S) \rightarrow \eta_b$
E_γ	$610.5^{+4.5}_{-4.3} \pm 1.8$	$921.2^{+2.1}_{-2.8} \pm 2.4$
M(η_b)	$9392.9^{+4.6}_{-4.8} \pm 1.8$	$9388.9^{+3.1}_{-2.3} \pm 2.7$
ΔM_{hf}	$67.4^{+4.8}_{-4.5} \pm 1.9$	$71.4^{+2.3}_{-3.1} \pm 2.7$
BR×10^4	$4.2^{+1.1}_{-1.0} \pm 0.9$	$4.8 \pm 0.5 \pm 1.2$

The observed hyperfine splitting is 30 MeV larger than the one predicted by NLL NRQCD calculations [4], praised as one of the most robust achievements of theory in this field. Earlier results at leading order hit closer to the observed result [5, 6].

While BELLE and CLEO are poised to provide an independent evidence of the ground state $\eta_b(1S)$, the challenge is now open to measure its width. Concerning the higher excitations, the search for the direct M1 transition $\Upsilon(mS) \rightarrow \gamma\eta_b(mS))$ seems hopeless with the current statistical samples. The large sample integrated by BABAR at the $\Upsilon(3S)$ peak can be studied to search for the $\Upsilon(3S) \rightarrow \gamma\eta_b(2S)$ transition or for the cascade

$$\Upsilon(3S) \rightarrow \pi^0 h_b(1P) \rightarrow \pi^0\gamma\eta_b(1S)$$

. It is also worth to mention that the recent observation of a large rate of $\Upsilon(4S) \rightarrow \eta\Upsilon(1S)$ [7], may suggest new ways to search for the remaining bottomonia, via hadronic transitions from above $B\bar{B}$ threshold.

3. Inclusive and exclusive decays of Υ's and χ_b's

In the continuum, charm meson production from the QED process $e^+e^- \rightarrow q\bar{q}$ is enhanced by the Z_q^2 term. This fact is usually quoted to stress the importance of B-factories in D meson physics. On the contrary, leading order QCD calculations suggest that vector bottomonium decays would scarcely contain charm. This prediction was confirmed by the upper limit set by ARGUS at 1.9% on inclusive $D*\pm$ production from $\Upsilon(1S)$ [8]. Lately, BABAR succeeded to detect [9] the long sought inclusive transition $\Upsilon(1S) \rightarrow D^{*\pm} + X)$ and to measure its branching ratio BR=2.59 ± 0.13 ± 0.15%, a value which exceeds the quoted ARGUS upper limit. The D^* meson is observed via its decay mode $D^{*\pm} \rightarrow D^0\pi^\pm; D^0 \rightarrow K^-\pi^+$. The momentum spectrum is significantly softer than the one of the continuum process $e^+e^- \rightarrow c\bar{c} \rightarrow D^{*\pm} + X$, and goes to zero at $p_D \simeq 0.75 p_{max}$.

Among the other bottomonia, only χ_{b1} is expected to show large ratios of production of inclusive charmonium, as the dominance of the $gq\bar{q}$ contribution to the decay leads to predict flavor blindness, i.e. branching fractions close to 1/4, in the decay pattern for such states. Quantitative estimates for the other χ_b states were made possible by the advent of NRQCD, which allows to overcome the infrared log divergences [10]. Theory predictions are shown in Table 3.

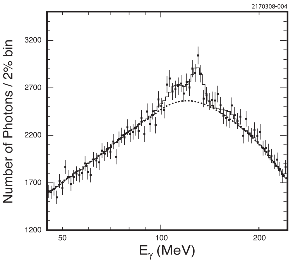

Fig. 3. Inclusive photon spectrum from $\Upsilon(2S)$ decays containing a D^0 meson

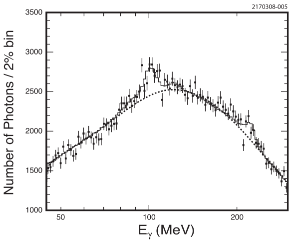

Fig. 4. Inclusive photon spectrum from $\Upsilon(3S)$ decays containing a D^0 meson

CLEO has then searched for inclusive production of D^0 mesons in χ_b decays [11]. CLEO selected events containing a D^0 meson, reconstructed in $K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^-\pi^+$ (total BR = 25%) and searching for peaks in the inclusive photon spectrum, as shown in Figures 3. and 3.. Results are summarized and can be compared with theory in table 3.

Table 3. Fractions of $\chi_b \rightarrow LH$ decays containing D^0 mesons: measurements, upper limits at 90% CL, and theory predictions

State	B($D^0 + X$)/B(LH)	UL	NRQCD
$\chi_{b0}(1P)$	$9.6 \pm 6.2 \pm 0.8 \pm 0.8\%$	17.9%	6.3%
$\chi_{b1}(1P)$	$24.8 \pm 3.8 \pm 2.2 \pm 3.6\%$		23.7%
$\chi_{b2}(1P)$	$9.8 \pm 3.5 \pm 0.9 \pm 0.9\%$	14.6%	10.8%
$\chi_{b0}(2P)$	$8.7 \pm 6.4 \pm 0.9 \pm 0.7\%$	17.7%	4.9%
$\chi_{b1}(2P)$	$25.3 \pm 4.3 \pm 2.5 \pm 2.4\%$		22.1%
$\chi_{b2}(2P)$	$0.4 \pm 3.5 \pm 0.4 \pm 0.1\%$	6.1%	7.4%

Searches for radiative transitions to hidden charm are underway at BELLE, inspired by recent theory predictions [13], which expect $BR \sim 0.5 \cdot 10^{-5}$. At the same time, inclusive transitions to charmonium, measured at CLEO [14], suggest that production of higher excitations is as likely as production of J/ψ; will it be possible to detect inclusive production of X(3872) or Y(4260) at BELLE or BABAR?

CLEO has also published [12] the first results from a broad search of exclusive decay modes to light hadrons of the $\chi_b(1,2P)$ states. Full reconstruction of 659 channels was performed, but only 14 decay modes exceeded 5 σ significance. Such effort, if repeated on 10 to 100 larger samples, may result in exclusive evidence of the direct transitions $\Upsilon(nS) \rightarrow \eta_b(nS)$ and possibly to a measurement of the width of the $\eta_b(nS)$ states.

Table 4. Exclusive BR$\chi_{b1}(1,2P) \rightarrow LH$, in units 10^{-4}

Decay mode	$\Upsilon(2S) \rightarrow \chi_{b1}(1P)$	$\Upsilon(3S) \rightarrow \chi_{b1}(2P)$
$2\pi 2K\pi^0$	$1.4 \pm 0.3 \pm 0.3$	$3.9 \pm 0.8 \pm 0.9$
$3\pi 1KK_S^0$	$0.9 \pm 0.3 \pm 0.2$	$1.4 \pm 0.5 \pm 0.3$
$3\pi 1KK_S^0 2\pi^0$	< 4.2	$9.7 \pm 3.0 \pm 2.6$
$4\pi 2\pi^0$	$5.5 \pm 0.9 \pm 1.4$	$7.4 \pm 1.6 \pm 1.9$
$4\pi 2K$	$1.0 \pm 0.3 \pm 0.2$	$1.2 \pm 0.4 \pm 0.3$
$4\pi 2K\pi^0$	$1.0 \pm 0.3 \pm 0.2$	$1.2 \pm 0.4 \pm 0.3$
$4\pi 2K 2\pi^0$	$5.9 \pm 1.4 \pm 1.7$	$12.1 \pm 2.9 \pm 3.3$
$5\pi KK_S^0 1\pi^0$	$6.4 \pm 1.6 \pm 1.6$	$8.5 \pm 2.3 \pm 2.2$
6π	$1.3 \pm 0.3 \pm 0.3$	$1.5 \pm 0.4 \pm 0.3$
$6\pi 2\pi^0$	$11.9 \pm 1.8 \pm 3.2$	$15.0 \pm 3.0 \pm 4.0$
$6\pi 2K$	$1.8 \pm 0.4 \pm 0.4$	$2.5 \pm 0.7 \pm 0.6$
$6\pi 2K\pi^0$	$5.2 \pm 1.1 \pm 1.4$	$7.7 \pm 1.7 \pm 2.1$
8π	$1.8 \pm 0.4 \pm 0.5$	$2.2 \pm 0.6 \pm 0.5$
$8\pi 2\pi^0$	$9.6 \pm 2.4 \pm 2.9$	$24.1 \pm 4.7 \pm 7.2$

The branching ratios of the $\chi_{b1,2}$ exclusive decays observed by CLEO are summarized in Table 4. and Table 5. The largest branching fractions belong to transitions with 6,8 pions. At any given value of N_π, decays containing a neutral pair are favored on those with a charged pair.

Table 5. Exclusive BR$\chi_{b2}(1,2P) \rightarrow LH$, in units 10^{-4}

Decay mode	$\Upsilon(2S) \rightarrow \chi_{b2}(1P)$	$\Upsilon(3S) \rightarrow \chi_{b2}(2P)$
$2\pi 2K\pi^0$	$0.6 \pm 0.3 \pm 0.2$	< 1.4
$3\pi 1KK_S^0$	< 0.7	< 1.2
$3\pi 1KK_S^0 2\pi^0$	$3.8 \pm 1.4 \pm 1.0$	< 8.7
$4\pi 2\pi^0$	$2.5 \pm 0.8 \pm 0.6$	$5.1 \pm 1.6 \pm 1.3$
$4\pi 2K$	$0.8 \pm 0.2 \pm 0.2$	$1.2 \pm 0.4 \pm 0.3$
$4\pi 2K\pi^0$	$1.5 \pm 0.5 \pm 0.4$	$3.2 \pm 1.1 \pm 0.8$
$4\pi 2K 2\pi^0$	$2.8 \pm 1.1 \pm 0.7$	$6.2 \pm 2.3 \pm 1.7$
$5\pi KK_S^0 1\pi^0$	< 3.6	< 5.8
6π	$0.5 \pm 0.2 \pm 0.1$	$1.2 \pm 0.4 \pm 0.3$
$6\pi 2\pi^0$	$7.3 \pm 1.6 \pm 2.0$	$15.9 \pm 3.3 \pm 4.3$
$6\pi 2K$	< 0.6	$1.9 \pm 0.7 \pm 0.5$
$6\pi 2K\pi^0$	$2.6 \pm 0.8 \pm 0.7$	$5.5 \pm 1.6 \pm 1.5$
8π	$0.6 \pm 0.2 \pm 0.2$	$1.2 \pm 0.5 \pm 0.3$
$8\pi 2\pi^0$	$13.2 \pm 3.1 \pm 4.0$	$16.5 \pm 4.6 \pm 5.0$

4. $b\bar{b}$ spectroscopy above open flavor threshold

The B factories have also scanned the energy range above open bottom threshold with two different strategies: BELLE has performed a six-point scan with about 1 fb^{-1} per point, BABAR focused on a low luminosity (25 pb^{-1} per point), high granularity scan. BELLE run was motivated by an anomalously large $\pi\pi\Upsilon(2S)$ cross section at the $\Upsilon(5S)$ peak energy, if compared to the yield at $\Upsilon(4S)$ peak. The maximum yield in $\pi\pi\Upsilon(1,2,3S)$ was actually observed 30 MeV above the known 5S peak [15], and suggested the existence of a new state, maybe analogous to Y(4260), in the bottomonium system. The data were fitted using the same excitation curve for all the channels, yielding a mass average of $10889 \pm 1.8 \pm 1.5$ MeV/c^2 and a width of $54.7^{+8.5}_{-7.2} \pm 2.5$ MeV, or with three independent Breit-Wigner curves: fit results are given in Table 6.

Table 6. Parameters of the three excitation curves describing the resonant process $e^+e^- \rightarrow \Upsilon(1,2,3S)\pi\pi$ studied by BELLE in the proximity of the $\Upsilon(5S)$ peak

n	Peak σ(pb)	Mass(MeV)	Width(MeV)
1S	$2.03^{+0.27}_{-0.22} \pm 0.15$	$10887.4^{+4.1}_{-4.5} \pm 1.6$	$74^{+19}_{-14} \pm 3$
2S	$5.77^{+0.90}_{-0.80} \pm 0.67$	$10890.3^{+2.3}_{-1.9} \pm 1.4$	$37.0^{+7.9}_{-6.2} \pm 3.1$
3S	$1.65^{+0.36}_{-0.32} \pm 0.21$	$10882.3^{+7.2}_{-7.3} \pm 1.5$	$52^{+20}_{-14} \pm 1$

BABAR scan [16], shown in figure 5., suggests instead that the simple Breit-Wigner parametrization is not adequate for the description of the complex dynamics in the proximity of the $B^{(*)}\bar{B}^{(*)}$ and $B_s^{(*)}\bar{B}_s^{(*)}$ thresholds. A strong qualitative agreement is observed between the experimental behavior of the ratio $R_b = \sigma(b\bar{b})/\sigma(\mu\mu)$ and the theory predictions based on the coupled channel approach[17], published in 1984.

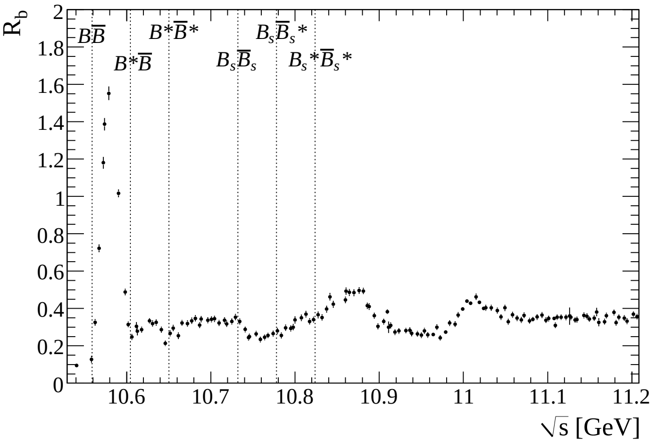

Fig. 5. Scan of the $b\bar{b}$ cross section between 5S and 6S.

Given the variety of structures, it is reasonable to expect some insight from the exclusive deconvolution of the two-body (i.e.$B\bar{B}, B\bar{B}^*, B^*\bar{B}^*$) and more body decay modes. BELLE has analyzed a sample of 7.1M $B\bar{B}$ pairs [18, 19] taken at the $\Upsilon(5S)$ peak. Charged B mesons were reconstructed in 2 decay channels, $K^\pm J/\psi$ and $D^0\pi^\pm$ (with $J/\psi \rightarrow l^+l^-$ and $D^0 \rightarrow K\pi, K\pi\pi\pi$.

Neutral B mesons were reconstructed in $K^{*,0}J/\psi$ and $D^\pm\pi^\mp$, with $D^\pm \rightarrow K^\pm\pi^\pm\pi^\mp$. The B^* mesons were reconstructed via their radiative decays to B mesons. BELLE discovered that the 3- and 4-body decay modes, i.e. $B^{(*)}\bar{B}^{(*)}\pi, B^{(*)}\bar{B}^{(*)}\pi\pi$, add up to 16.5% of the total of $b\bar{b}$ pairs, in striking contrast with theory predictions, which range from 0.03% [20] to 0.3%[21]. Such large discreppancy may partly be accounted for as a feeddown from ISR produced two-body decays of $\Upsilon(4S)$.

5. New physics searches in Υ decays

In the last five years, a number of alternative theories have been devised to explain the non-observation of the scalar Higgs boson at LEP. Among the others, an extension of MSSM, the next-to-minimal supersimmetry model, predicts that the scalar Higgs boson should decay to a pair of light CP-odd Higgs bosons, hereafter denoted as A^0 [22, 23, 24, 25]. If $M(A^0) < 2m_b$, this would naturally explain the failure of the searches for Higgs to b-jets done at LEP and Tevatron. Recent theory papers have then hypothesized that the A^0 can be observed in the radiative decays of Υ resonances, with BF ranging from 10^{-6} up to 10^{-4}.

If $M(A^0) > 2m_\tau$, direct searches for the A^0 aim to find bumps in the photon spectrum of low multiplicity $\gamma\tau^+\tau^-$ events, with either both τ's decaying leptonically (i.e. in $\mu\nu\bar{\nu}$ or in $e\nu\bar{\nu}$), or allowing one of the two τ's to decay via $\pi\nu$. If $M(A^0) < 2m_\tau$, A^0 should decay preferentially to $\mu^+\mu^-$, therefore γ bumps are looked for in the process $e^+e^- \to \gamma\mu^+\mu^-$.

BABAR results on $A_0 \to \mu^+\mu^-$ [26, 27] with new record samples supersede previous ones from CLEO [28]. BABAR searched for a peak in M($\mu^+\mu^-$) in the range 0.212-9.3 GeV, corresponding to about 1500 independent bins, from samples of 99M $\Upsilon(2S)$ and 122M $\Upsilon(3S)$ decays. No significant fluctuations were observed. By assuming that the branching fractions scale as $BR(\Upsilon(nS) \to \gamma A^0)/BR(\Upsilon(nS) \to l^+l^-) = (f_\Upsilon^2/2\pi\alpha)(1-M_{A^0}^2/m_{\Upsilon(nS)}^2)$, BABAR [27] combined the limits from both states and set 90%C.L. limits on $f_\Upsilon^2 B_{\mu\mu}$ below $3{\cdot}10^{-6}$ in most of the range under the τ threshold, as shown in Fig.6..

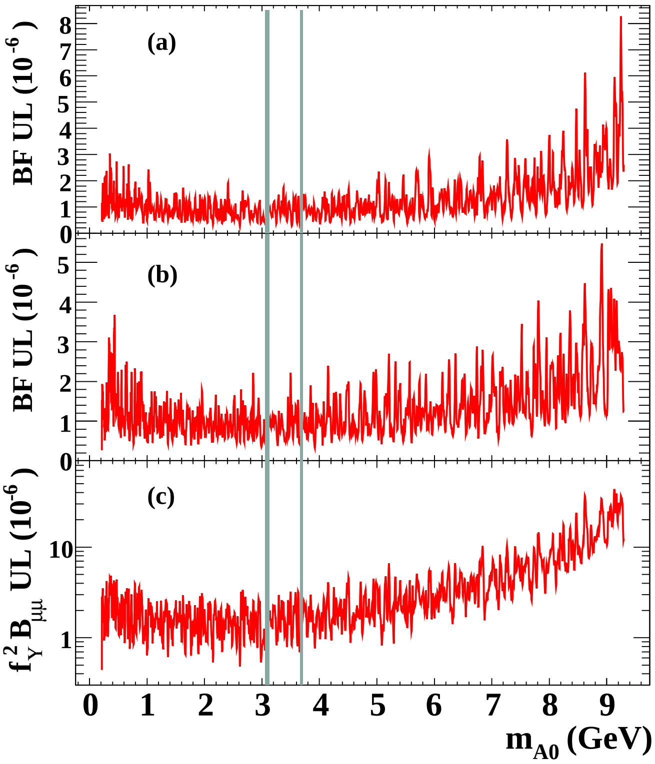

Fig. 6. BABAR upper limits on $B(A^0 \to \mu\mu)$ at 2S(top), 3S(middle), combined(bottom)

Searches of the A_0 in the region between $\tau^+\tau^-$ threshold and bottomonium aim to find bumps in the photon spectrum of $\gamma\tau\tau$ events. This process was already studied at CLEO, with data taken at the 1S peak, setting upper limits on BR, ranging from 10^{-5} (on the low mass range) up to 48×10^{-5} (close to $\Upsilon(1S)$ mass). BABAR has further lowered these limits, using the 122 M $\Upsilon(3S)$ decays. Most of residual background is dominated by QED continuum $e^+e^- \to \gamma\tau^+\tau^-$ or higher order QED processes, such as $e^+e^- \to e^+e^-e^+e^-$ or $e^+e^- \to e^+e^-\mu^+\mu^-$. 90% C.L. limits on BR$(\Upsilon(3S) \to A^0)\times$BR$(A^0 \to \tau^+\tau^-)$ at few 10^{-5} level were set on the full range (see Figure7., with the exception of the range $9.52 < m_{\tau\tau} < 9.61 GeV/c^2$, because of the irreducible peaking background from $\chi_b(2P)$ radiative decays.

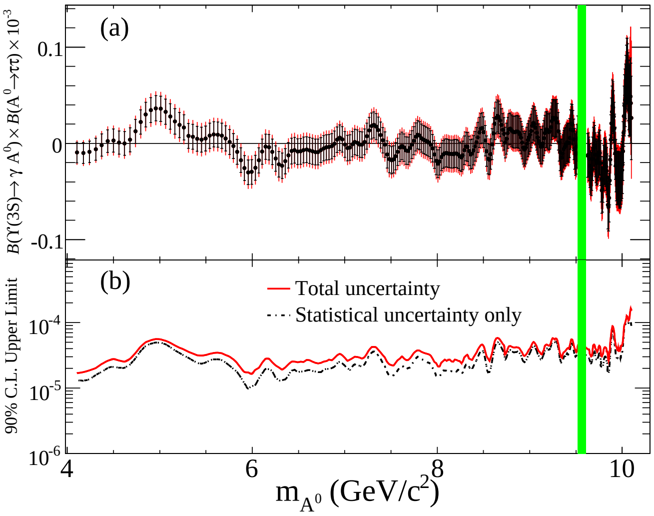

Fig. 7. BABAR upper limits on $B(A^0 \to \tau\tau)$

If the light Higgs boson has a mass which is very close to η_b, the two radiative processes may interfere, resulting in shifts in η_b mass and couplings [29], and the appearance of an additional contribution to the $\Upsilon(nS)$ decay to $\tau^+\tau^-$, as the low energy radiative photon is likely to escape detection. A value of the ratio $\mathcal{R}_{\tau\tau} = BR(\Upsilon(nS) \to \tau\tau)/BR(\Upsilon(nS) \to \mu\mu)$ significantly larger than one, would therefore indicate a violation of lepton universality. Searches for such violation in $\Upsilon(nS)$ decays were performed by the CLEO collaboration [30] on the three narrow Υ states. This year, BABAR has improved [31] the measurement for the $\Upsilon(1S)$, from a sample of tagged $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$ decays. The transition to $\Upsilon(1S)$ was tagged by measuring the recoil momentum of the dipion pair. Events with exactly 4 charged tracks were accepted, therefore selecting only 1-prong decays of τ's. The most recent measurements of $\mathcal{R}_{\tau\tau}$ are shown in Table 7.

Table 7. Lepton universality violation tests at CLEO and BABAR

Exp.	State	$\mathcal{R}_{\tau\tau}$
CLEO[30]		
	$\Upsilon(1S)$	$1.02 \pm 0.02 \pm 0.05$
	$\Upsilon(2S)$	$1.04 \pm 0.04 \pm 0.05$
	$\Upsilon(3S)$	$1.05 \pm 0.08 \pm 0.05$
BABAR [31]		
	$\Upsilon(1S)$	$1.009 \pm 0.010 \pm 0.024$

Besides the lepton universality violation described above, also charged lepton flavor violation can be investigated in Υ decays. Such process, not expected in Standard Model, can be mediated by new particles at $\approx$ TeV scale in loop diagrams. Searches for $\Upsilon(3S) \to e^\pm\tau^\mp, e^\pm\mu^\mp$ decays were done at BABAR with the current record sample of $\Upsilon(3S)$ decays [32]. In the

$e\tau$ sample, the τ was requested to decay either leptonically in $\mu\nu\bar{\nu}$ or hadronically in $\pi^{\pm}\pi^0\nu$, $pi^{\pm}\pi^0\pi^0\nu$. In the $\mu\tau$ sample, τ leptonic decay mode was limited to $e\nu\bar{\nu}$. Control samples of $77.7 fb^{-1}$ taken on $\Upsilon(4S)$ peak, and 2.6 pb^{-1} taken 30 MeV below the $\Upsilon(3S)$ resonance, were analysed as a cross check, expecting no signal from the QED continuum process. No statistically significant signal was observed, allowing to put 90%C.L. limits on the $\mathrm{B}(\Upsilon(3S) \rightarrow e\tau, \mu\tau)$ at $(5, 4.1) \times 10^{-6}$ respectively. Such result represents the first limit on $e\tau$ and an improvement of a factor four with respect to previous CLEO limit on $\mu\tau$ [33].

Searches for decays of $\Upsilon(1S)$ to light dark matter candidates were pioneered by BELLE [34]: triggering on the low momentum $\pi^+\pi^-$ pair, and looking for events without other tracks or extra energy in the calorimeter a peak in the recoil momentum spectrum was searched for in events without other tracks, to search for evidence of $\Upsilon(1S)$ decays in final products escaping undetected the experimental apparatus. Events on the $\Upsilon(1S)$ recoil peak have to be naturally expected, mainly from $e^+e^-, \mu^+\mu^-$ which are emitted back-to-back at shallow angles, as these detectors are not fully hermetic in polar angle.

Table 8. Search for $\Upsilon(1S) \rightarrow$ *invisible* decays: expected and observed events, and 90%C.L. upper limits from BELLE[34] and BABAR[35]

Ref.	N_{exp}	N_{obs}	$\mathrm{BR}(\Upsilon(1S) \rightarrow invisible)$
[34]	$133.2^{19.7}_{14.7}$	38±39	$<2.5\times10^{-3}$
[35]	2451±38	2326±105	$<3\times10^{-4}$

An excess of events with respect to MonteCarlo expectations would be therefore interpreted as evidence of invisible decays of the Υ. Standard Model expectations for $\mathrm{BR}(\Upsilon(1S) \rightarrow invisible)= \mathrm{BR}(\Upsilon(1S) \rightarrow \nu\bar{\nu})$ are at $\mathrm{O}(10^{-5})$ level. Expected and observed yields, as well as 90% C.L. experimental limits are summarized in Table 8.

6. Conclusions and acknowledgements

The current review is a short summary of the intense activities which in the last two years have revived experimental and theoretical interest in the sector of bottomonium. The author wishes to thank all the physicists in BABAR and BELLE experiments, who participated to this effort, the CLEO colleagues, who inspired many of the measurements, and the theory experts in QWG (and beyond), who helped defining priorities and action items on this topic. Personally, the author would like to thank Y.Sakai, T.Browder, K.Trabelsi, C.Z.Yuan, O.Long, C.Patrignani and B.Heltsley for fruitful discussions on the subjects addressed in this review.

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