# Hints of new physics in bottomonium decays and spectroscopy *

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A non-standard light CP-odd Higgs boson could induce a slight (but observable) lepton universality breakdown in Upsilon leptonic decays. Moreover, the mixing between such a pseudoscalar Higgs boson and $\eta_b$ states might shift the mass levels of the latter, thereby changing the values of the $m_{\Upsilon(nS)} - m_{\eta_b(nS)}$ splittings predicted in the standard model. Besides, also the $\eta_b$ width could be broader than expected, with potentially negative consequences for its discovery in both $e^+e^-$ and hadron colliders.

## 1. Lepton symmetry breaking

In many extensions of the standard model (SM), new scalar and pseudoscalar states appear in the physical spectrum. Admittedly, the masses of these particles are typically of the same order as the weak scale and, in principle, a fine-tunning is required to make them much lighter. Nevertheless, if the theory possesses a global symmetry, its spontaneous breakdown gives rise to a massless Goldstone boson, the "axion". The original axion was introduced in the framework of a two-Higgs doublet model (2HDM) [1] to solve the strong CP problem. However, such an axial U(1) symmetry is anomalous and the pseudoscalar acquires a (quite low) mass ruled out experimentally.

On the other hand, if the global symmetry is explicitly (but slightly) broken, one expects a pseudo-Nambu-Goldstone boson in the theory which, for a range of model parameters, still can be significantly lighter than the other scalars. A good example is the so-called next to minimal supersymmetric standard model (NMSSM) where a new singlet superfield is added to the Higgs sector [1]. The mass of the lightest CP-odd Higgs can be naturally small due to a global symmetry of the Higgs potential only softly broken by trilinear terms [2]. Moreover, the smallness of the mass is protected from renormalization group effects in the region of large $\tan\beta$ (defined as a ratio of two Higgs vacuum expectation values). Actually, there are other scenarios containing a light [3] pseudoscalar Higgs boson which could have escaped detection in the searches at LEP-II, e.g. a MSSM Higgs sector with explicit CP violation [3]. Another example is a minimal composite Higgs scenario [4] where the lower bound on the CP-odd scalar mass is quite loose, as low as $\sim 100$ MeV (from astrophysical constaints).

In this work we consider a possible New Physics (NP) contribution to the leptonic decays of $\Upsilon$ resonances below $B\bar{B}$ threshold via the decay modes:

$$\Upsilon \rightarrow \gamma_{\mathbf{s}}\ \eta_b^*(\rightarrow A^0 \rightarrow \ell^+\ell^-)\ ;\ \ell = e, \mu, \tau$$

where $\gamma_s$ stands for a soft (undetected) photon, $A^0$ denotes a non-standard light CP-odd Higgs boson and $\eta_b^*$ a spin-singlet $b\bar{b}$ virtual state. Here we will mainly focus on the $\Upsilon(1S)$ state.

Our later development is based upon the following keypoints:

- Such a NP contribution would be unwittingly ascribed to the leptonic branching fraction (BF) of Upsilon resonances
- A leptonic (squared) mass dependence in the width from the Higgs contribution would lead to an "apparent" lepton universality breakdown

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[3] By "light" we consider here a broad interval which might reach a $\mathcal{O}(10)$ GeV mass value

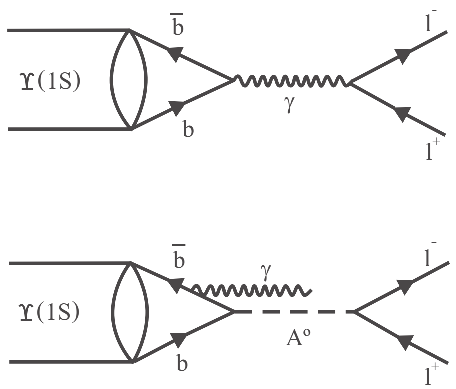


Figure 1. (a): Conventional electromagnetic annihilation of the $\Upsilon(1S)$ resonance into a $\ell^+\ell^-$ pair. (b): Annihilation mediated by a CP-odd Higgs boson ($A^0$) subsequent to a M1 transition of the $\Upsilon$ into a virtual $\eta_b^*$ state.

Our theoretical analysis relies on the factorization of the decay width:

$$\Gamma_{\Upsilon \to \gamma_s \ell\ell} = \frac{\Gamma^{M1}(\Upsilon \to \eta_b^* \gamma_s) \times \Gamma_{\eta_b^* \to \ell\ell}}{\Gamma}$$

where $\Gamma$ is an unknown parameter to be interpreted as a width; $\Gamma_{\eta_b^* \to \ell\ell}$ denotes the annihilation width of the intermediate $\eta_b^*$ state into a lepton pair; the width of a M1 transition is given in the nonrelativistic approximation by [5]: $\Gamma^{M1}_{\Upsilon \to \gamma_s \eta_b^*} \simeq 4\alpha Q_b^2 k^3/3m_b^2$, with $Q_b$ and $m_b$ denoting the electric charge and mass of the bottom quark respectively; $\alpha$ stands for the fine structure constant and $k$ is the soft photon energy, approximately equal to the (yet unknown) hyperfine splitting $m_\Upsilon - m_{\eta_b}$, assumed to be in the range $\simeq 35 - 150$ MeV.

For $\Gamma$ close to $\Gamma_{\eta_b^*}$, the ratio $\Gamma_{\eta_b^* \to \ell\ell}/\Gamma$ may be interpreted as the $\eta_b^*$ branching fraction into a lepton pair; the width of the whole process is

$$\Gamma_{\Upsilon \to \gamma_s \ell\ell} \; = \; \Gamma^{M1}_{\Upsilon \to \gamma_s \eta_b^*} \; \times \; \frac{\Gamma_{\eta_b^* \to \ell\ell}}{\Gamma_{\eta_b^*}} \qquad (1)$$

leading to the cascade decay formula

$$BF[\Upsilon \to \gamma_s \ell\ell] \; = \; BF[\Upsilon \to \gamma_s \eta_b^*] \times BF[\eta_b^* \to \ell\ell]$$

This result can be obtained using a time-ordered perturbative calculation [5] for an almost on-shell intermediate $\eta_b^*$ state - consistent with the emission of a soft photon.

On the other hand, higher Fock components beyond the heavy quark-antiquark pair can play an important role in both production and decays of heavy quarkonium [6]. In fact, $\Gamma^{M1}_{\Upsilon \to \gamma_s \eta_b^*}/\Gamma$ may be interpreted as the probability $\mathcal{P}^{\Upsilon}(\eta_b^* \gamma_s)$ that a $\eta_b^* + \gamma_s$ configuration exists as a Fock state inside the $\Upsilon$ resonance during a typical time of order $1/k$ much longer than the typical annihilation time, of order $1/m_b$ [5]. Thus, the $b\bar{b}$ annihilation would eventually free a quasi-real photon $\gamma_s$.

Therefore, we will factorize the decay width as

$$\Gamma_{\Upsilon \to \gamma_s \ell\ell} = \mathcal{P}^{\Upsilon}(\eta_b^* \gamma_s) \times \Gamma_{\eta_b^* \to \ell\ell} \qquad (2)$$

in accordance with a non relativistic effective theory [6]. Note that the processes underlying factorizations of Eqs. (1) and 2 should be competitive.

## 2. Estimates according to a 2HDM(II)

In order to make numerical estimates we will assume that fermions couple to the $A^0$ field according to the effective Lagrangian

$$\mathcal{L}_{int}^{\bar{f}f} \; = \; -\xi_f^{A^0} \; \frac{A^0}{v} m_f \bar{f}(i\gamma_5)f$$

with $v \simeq 246$ GeV and $\xi_f^{A^0}$ depends on the fermion type. In this work we focus on a 2HDM of type II [1], whence $\xi_f^{A^0} = \tan\beta$ for down-type fermions; thus [7,5]

$$\Gamma_{\eta_b^* \to \ell\ell} \; = \; \frac{3}{32\pi^2 Q_b^2 \alpha^2} \frac{m_b^4 m_\ell^2 \tan^4\beta}{(1+2x_\ell)\Delta m^2 v^4} \times \Gamma_{\ell\ell}^{(em)}$$

where $\Delta m = |m_{A^0} - m_{\eta_b}|$ and the electromagnetic decay width into a dilepton is given by the Van-Royen Weisskopf formula:

$$\Gamma_{\ell\ell}^{(em)} = 4\alpha^2 Q_b^2 \; \frac{|R_n(0)|^2}{M_\Upsilon^2} \; \times \; K(x_\ell)$$

where $K(x_\ell) = (1+2x_\ell)(1-4x_\ell)^{1/2}$ is a (smoothly) decreasing function of $x_\ell = m_\ell^2/M_\Upsilon^2$ with $m_\ell$ the lepton mass. Only for the tauonic mode would the NP contribution to the $\Upsilon$ leptonic decay be significant.

Table 1
Measured leptonic branching fractions $\mathcal{B}_{\ell\ell}$ and error bars (in %) of $\Upsilon(1S)$ and $\Upsilon(2S)$ (from [8]).

| channel: | $e^+e^-$ | $\mu^+\mu^-$ | $\tau^+\tau^-$ | $\mathcal{R}_\tau$ |
|---|---|---|---|---|
| $\Upsilon(1S)$ | $2.38 \pm 0.11$ | $2.48 \pm 0.06$ | $2.67 \pm 0.16$ | $0.10 \pm 0.07$ |
| $\Upsilon(2S)$ | $1.34 \pm 0.20$ | $1.31 \pm 0.21$ | $1.7 \pm 1.6$ | $0.28 \pm 1.21$ |

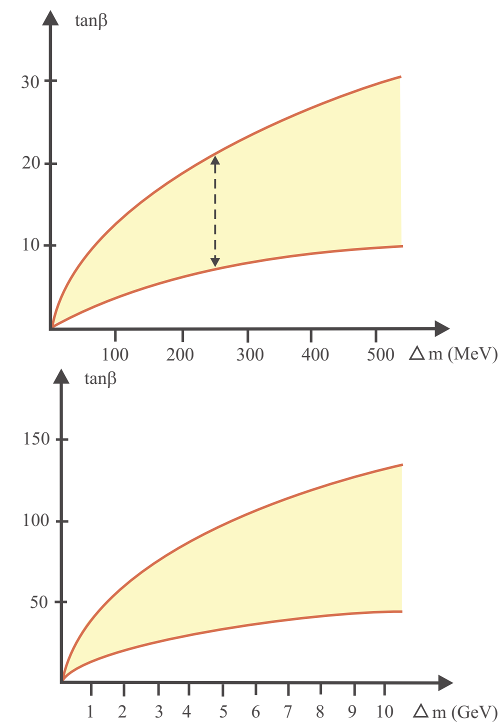


Figure 2. $\tan\beta - \Delta m$ values (shaded area) required to yield a $\mathcal{O}(10)\%$ lepton universality breaking effect using the factorization Eq. (2) and setting $\Gamma = 50$ keV [9]. The arrow in the upper plot indicates the range of $\tan\beta$ using $\Delta m = 250$ MeV [5]. The upper and lower curves in both plots correspond to the minimal ($k = 35$ MeV) and maximal ($k = 150$ MeV) estimates of the M1-transition probability $\mathcal{P}^{\Upsilon}(\eta_b^*\gamma_s)$, respectively. For (relatively) large values of $\Delta m$ (i.e. large Higgs mass values) only the lower values of the shaded region are acceptable, corresponding to the highest estimates of $\mathcal{P}^{\Upsilon}(\eta_b^*\gamma_s)$.

To check our conjecture we define the ratio:

$$\mathcal{R}_\tau = \frac{\Gamma_{\Upsilon \to \gamma_s \tau\tau}}{\Gamma_{\ell\ell}^{(em)}} = \frac{\mathcal{B}_{\tau\tau} - \bar{\mathcal{B}}_{\ell\ell}}{\bar{\mathcal{B}}_{\ell\ell}}$$

where $\bar{\mathcal{B}}_{\ell\ell} = (\mathcal{B}_{ee} + \mathcal{B}_{\mu\mu})/2$ stands for the mean BF of the electronic and muonic modes. A (statistically significant) non-null value of $\mathcal{R}_\tau$ would imply the rejection of lepton universality (predicting $\mathcal{R}_\tau = 0$) and a strong argument supporting the existence of a pseudoscalar Higgs boson.

If the factorization of Eq. (1) is adopted assuming $\Gamma \simeq \Gamma_{\eta_b^*} \simeq \Gamma_{\eta_b}$, one gets

$$\Gamma_{\Upsilon \to \gamma_s\, \tau\tau} \;=\; \Gamma^{M1}_{\Upsilon \to \gamma_s \eta_b^*} \;\times\; \frac{\Gamma_{\eta_b^* \to \tau\tau}}{\Gamma_{\eta_b^*}}$$

For large $\tan\beta$ ($\geq 35$) the NP contribution would almost saturate the $\eta_b^*$ decay: $\Gamma_{\eta_b^*} \simeq \Gamma_{\eta_b^* \to \tau\tau}$; thus

$$\mathcal{R}_\tau \simeq \frac{\Gamma^{M1}_{\Upsilon \to \gamma_s \eta_b^*}/\Gamma_\Upsilon}{\bar{\mathcal{B}}_{\ell\ell}} \simeq 1 - 10\ \%$$

for $k = 50 - 150$ MeV.

Instead relying on the factorization of Eq. (2), one gets

$$\mathcal{R}_\tau \simeq \left[\frac{m_b^2 k^3 \tan^4\beta}{8\pi^2\alpha(1+2x_\tau)\Gamma_\Upsilon v^4}\right] \times \frac{m_\tau^2}{\Delta m^2}$$

Current experimental data (see Table 1) indicate that there might be a difference of order 10% in the BF's between the tauonic channel on the one side, and the electronic and muonic modes on the other side. The range of $\tan\beta$ needed to account for such an effect, applying the factorization of Eq. (2), is shown in Fig. 2 as a function of the mass difference ($\Delta m$) between the postulated non-standard Higgs boson and the $\eta_b(1S)$ resonance. For the factorization of Eq. (1) with $\tan\beta \geq 35$, an agreement can be found for $k > 50$ MeV.

## 3. Possible spectroscopic consequences

The mixing of the $A^0$ with a pseudoscalar resonance could modify the properties of both [10,11]. In particular, it might cause a disagreement between the experimental determination of the $m_{\Upsilon(nS)} - m_{\eta_b(nS)}$ hyperfine splittings and theoretical predictions based on quark potential models, lattice NRQCD or pQCD. The masses of the mixed (physical) states in terms of the unmixed ones (denoted as $A_0^0, \eta_{b0}$) are:

$$
\begin{aligned}
m^2_{\eta_b,A^0} &\simeq \frac{1}{2}(m^2_{A_0^0} + m^2_{\eta_{b0}}) \\
&\pm \frac{1}{2}\left[\ (m^2_{A_0^0} - m^2_{\eta_{b0}})^2 + 4(\delta m^2)^2\ \right]^{1/2}
\end{aligned}
$$

where $\delta m^2 \simeq 0.146 \times \tan\beta$ GeV$^2$ [10]. For some mass intervals, the above formula simplifies to:

$$
\begin{aligned}
m_{\eta_b,A^0} &\simeq m_{\eta_{b0}} \mp \frac{\delta m^2}{2m_{\eta_{b0}}}\ ; \\
&\quad 0 < m^2_{A_0^0} - m^2_{\eta_{b0}} << 2\ \delta m^2, \\
m_{\eta_b,A^0} &\simeq m_{\eta_{b0}} \mp \frac{(\delta m^2)^2}{2m_{\eta_{b0}}(m^2_{A_0^0} - m^2_{\eta_{b0}})}\ ; \\
&\quad m^2_{A_0^0} - m^2_{\eta_{b0}} >> 2\ \delta m^2
\end{aligned}
$$

Setting $\tan\beta = 20$ and $m_{\eta_{b0}} \simeq m_{A_0^0} = 9.4$ GeV, as an illustrative example, one gets $m_{\eta_b} \simeq 9.24$ GeV and $m_{A^0} \simeq 9.56$ GeV yielding $BF[\Upsilon(1S) \to \gamma\eta_b(1S)] \simeq 10^{-2}$. A caveat is thus in order: a quite large $m_{\Upsilon} - m_{\eta_b}$ difference may lead to an unrealistic $\mathcal{P}^{\Upsilon}(\eta_b^*\gamma_s)$, requiring smaller $\tan\beta$ values, in turn inconsistently implying a smaller mass shift; hence no hyperfine splitting greater than $\sim 200$ MeV should be expected.

## 4. Summary

In this paper, possible hints of new physics in bottomonium systems have been pointed out:

a) Current experimental data do not preclude the possibility of lepton universality breaking at a significance level of 10%, interpreted in terms of a light CP-odd Higgs boson for a reasonable range of $\tan\beta$ values

b) Mixing between the CP-odd Higgs and $\eta_b$ states can yield $m_{\Upsilon(nS)} - m_{\eta_b(nS)}$ splittings larger than expected within the SM if $m_{A_0^0} > m_{\eta_{b0}}$; the opposite if $m_{A_0^0} < m_{\eta_{b0}}$

c) Broad $\eta_b$ widths are also expected for high $\tan\beta$ values. All that might explain the failure to find any signal from hindered $\Upsilon(2S)$ and $\Upsilon(3S)$ magnetic dipole transitions into $\eta_b$ states. There could be also negative effects on the prospects to detect $\eta_b$ resonances in hadron colliders like the Tevatron through the decay modes: $\eta_b \to J/\psi + J/\psi$ [12], and the recently proposed $\eta_b \to D^* D^{(*)}$ [13], as the respective BF's would drop by about one order of magnitude with respect to the SM calculations

d) New results on tauonic BF's of all three $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ from CLEO on-going analysis are eagerly awaited

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