Prospects of probing new physics in bottomonium decays and spectroscopy *

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Abstract

A non-standard light CP-odd Higgs boson could induce a slight (but observable) lepton universality breaking in Upsilon leptonic decays. Moreover, mixing between such a pseudoscalar Higgs boson and η_b states might shift their mass levels, thereby modifying the values of the \( M_{\Upsilon(nS)} - M_{\eta_b(nS)} \) hyperfine splittings predicted in the standard model. Besides, η_b resonances could be broader than expected with potentially negative consequences for discovery in both e^+e^- and hadron colliders. A scenario with a CP violating Higgs sector is also considered. Finally, further strategies to search for a light Higgs particle in bottomonium decays are outlined.

PACS numbers: 14.80.Cp, 13.25.Gv, 14.80.-j

Keywords: Non-standard Higgs, New Physics, bottomonium leptonic decays, lepton universality

1 Introduction

The search for “new” physics (NP) beyond the standard model (SM) has become one of the hottest topics of the current decade. In most extensions of the SM, new scalar (CP-even) and pseudoscalar (CP-odd) states appear in the physical spectrum. While the masses of these particles should be typically of the same order as the weak scale, if the theory possesses a global symmetry its spontaneous breakdown gives rise to a massless Goldstone boson, the “axion”, originally introduced in the framework of a two-Higgs doublet model (2HDM) \( \uparrow \) 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.

In the next to minimal supersymmetric standard model (NMSSM), where a new singlet superfield is added to the Higgs sector to solve the so-called \( \mu \)-problem \( \uparrow \), 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. This model has received considerable attention and the associated phenomenology should be examined with great care in different experimental environments \( \uparrow \). For example, it is likely that a SM-like Higgs boson would decay into two (possibly) much lighter pseudoscalar Higgses presenting difficulties for detection at the LHC \( \uparrow \).

*Research under grant FPA2002-00612 and GV-GRUPOS03/094.
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Also Little Higgs models can naturally lead to the existence of light pseudoscalars (not absorbed as longitudinal components of $Z'$ states) on account of spontaneously broken $U(1)$ subgroups [5]. Moreover, there are other scenarios containing a light Higgs which could have escaped detection in the searches performed at LEP-II [6], e.g. a MSSM Higgs sector with explicit CP violation [7]. Another example is a minimal composite Higgs scenario [8] where the lower bound on the CP-odd scalar mass is quite loose, as low as $\sim 100$ MeV (from astrophysical constraints). On the other hand, it has been extensively argued in the literature (see e.g. [9, 10]) that a light pseudoscalar Higgs should be required (in a two-loop calculation) to account for the anomalous magnetic moment of the muon.

Long time ago, the authors of references [11, 12] pointed out the possibility of detecting a light Higgs particle in quarkonium decays. Recently, in a series of papers [13, 14, 15], this investigation has been followed further by considering a possible NP contribution to the leptonic decays of $\Upsilon(nS)$ resonances (see figure 1) below $B\bar{B}$ threshold via the decay mode:

$$\Upsilon(nS) \rightarrow \gamma_A^0 (\rightarrow \ell^+\ell^-) ; \ell = e, \mu, \tau$$

where $\gamma_s$ stands for a soft (undetected!) photon and $A^0$ denotes a (real or virtual) non-standard light CP-odd Higgs boson. Our later development is based upon the following keypoints:

- Such a NP contribution would be unwittingly ascribed to the leptonic branching fraction: $B_{\ell\ell} = B(\Upsilon \rightarrow \ell^+\ell^-)$ of the Upsilon. Notice that the experimental determination of the leptonic width does include soft photons either from the initial- or final-state [16].

- A leptonic (squared) mass dependence of the decay width (stemming from the Higgs contribution) would lead to an “apparent” lepton universality breakdown. Actually, only in the tauonic channel would this NP contribution significantly alter the measured branching fraction (BF), as we shall later show. Let us also note that those $\Upsilon$ decays breaking lepton universality within the SM (like a direct $Z^0$-exchange annihilation or a two-photon (one-loop) annihilation of an intermediate $\eta_b$ state) are negligible [14].

The electromagnetic decay width of the $\Upsilon(nS)$ resonance into a dilepton as a first approximation is given by [17]:

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

where $\alpha \simeq 1/137$ is the electromagnetic fine structure constant; $m_{\Upsilon}$ denotes the mass of initial-state vector resonance, $R_n(0)$ its non-relativistic radial wave function at the origin; $Q_b$ is the charge of the relevant (bottom) quark ($1/3$ in units of $e$); $K(x_{\ell}) = (1 + 2x_{\ell})(1 - 4x_{\ell})^{1/2}$ is a (smoothly) decreasing function of $x_{\ell} = m_{\ell}^2/M^2_{\Upsilon}$ with $m_{\ell}$ the lepton mass.

In order to check our conjecture by assessing the relative importance of the postulated NP contribution, we defined in [13, 18] the ratio:

$$R_{\tau} = \frac{\Gamma(\Upsilon(nS) \rightarrow \gamma_s \tau^+\tau^-)}{\Gamma_{\ell\ell}^{(em)}} = \frac{B_{\tau\tau} - \bar{B}_{ee}}{\bar{B}_{ee}}$$

where $\bar{B}_{ee} = (B_{ee} + B_{\mu\mu})/2$ stands for the mean BF of the electronic and muonic modes of the $\Upsilon(nS)$. A (statistically significant) non-null value of $R_{\tau}$ would imply the rejection of lepton universality (predicting $R_{\tau} = 0$) and a strong argument supporting the existence of a pseudoscalar Higgs boson mediating the tauonic channel as shown in Eq. (1).

\[1\] In the sense that lepton universality would be restored once the Higgs contribution were taken into account.
Figure 1: (a): Conventional electromagnetic annihilation of the \( \Upsilon(1S) \) resonance into a \( \ell^+\ell^- \) pair. (b): Non-standard Higgs-mediated annihilation subsequent to a (soft) photon emission either on the continuum or through an intermediate \( b\bar{b} \) bound state.

Table 1 shows current experimental data (from [16]) and the corresponding \( R_\tau \) values for the \( \Upsilon(1S) \) and \( \Upsilon(2S) \) resonances, the latter with a big error. Nevertheless, we can conclude that those results don’t preclude the possibility of a \( \sim 10\% \) breaking of lepton universality (i.e. \( R_\tau \sim 0.1 \)). Forthcoming data from CLEO on-going analysis will definitely settle this point \(^2\), thus checking our conjecture.

For theoretical estimates we will assume that fermions couple to the \( A^0 \) field according to the interaction term

\[
\mathcal{L}^f_{\text{int}} = -\xi_f^{A^0} \frac{A^0}{v} m_f (i\gamma_5) f
\]

in the effective Lagrangian, with \( v \sim 246 \text{ GeV} \); \( \xi_f^{A^0} \) depends on the fermion type, whose mass is denoted by \( m_f \). In what follows, we will focus on a 2HDM of type II [1]: \( \xi_f^{A^0} = \tan \beta \) for down-type fermions where \( \tan \beta \) stands for the ratio of two Higgs doublets vacuum expectation values. Let us remark that \( \xi_f^{A^0} = \cot \beta \) in the corresponding Yukawa coupling of up-type fermions. Large values of \( \tan \beta \) would imply a large coupling of the \( A^0 \) to the bottom quark but a small coupling to the charm quark. This fact has crucial phenomenological consequences in our proposal as a Higgs-mediated contribution would only affect bottomonium decays but not charmonium decays. Thus, in this work we focus on \( \Upsilon \) resonances to find out a possible signal of NP.

Table 1: Measured leptonic branching fractions \( \mathcal{B}_{\ell\ell} \) (in \%) and error bars (summed in quadrature) of \( \Upsilon(1S) \) and \( \Upsilon(2S) \) resonances (from [16]); \( R_\tau \) is defined in Eq. (3).

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

\(^2\) New determinations of the muonic BF of the \( \Upsilon(1S) \), \( \Upsilon(2S) \) and \( \Upsilon(3S) \) resonances are available from CLEO (not used in Table 1) but not the tauonic BF yet [17, 20, 21].
2 Estimates according to a 2HDM(II)

In this section we deal with different Higgs-mediated decay channels, either on the “continuum” i.e. without formation of bound $b\bar{b}$ states subsequent to the photon emission in process (1), or via intermediate $\eta_b$ states. We will consider both off-shell and on-shell Higgs production according to whether the Higgs mass is greater or smaller than the decaying Upsilon mass, respectively.

2.1 Perturbative calculation without intermediate bound states

Let us perform a perturbative calculation of the three body decay $\Upsilon(nS) \to \gamma s A^{0*} (\to \ell^+ \ell^-)$ on the “continuum” by writing the decay width as the integral over phase space

$$\Gamma[\Upsilon(nS) \to \gamma \ell^+ \ell^-] = \frac{1}{32M_\Upsilon^3 (2\pi)^3} \times \int |A(\Upsilon(nS) \to \gamma \ell^+ \ell^-)|^2 \, dm_{\ell\ell} \, dm_{\ell\gamma}$$

with

$$|A(\Upsilon(nS) \to \gamma \ell^+ \ell^-)|^2 = \frac{64m_\ell^2 m_\gamma^2 Q_b^2 |R_n(0)|^2 \tan^4 \beta}{M_\Upsilon [m_{\ell\ell}^2 - M_{A^0}^2] v^4} \times m_\ell^2$$

Under the assumption that $M_{A^0} \gtrsim M_\Upsilon$, i.e. no on-shell production of the CP-odd Higgs boson is kinematically allowed, we carry out the phase space integration in Eq. (4); the leading term turns out to be

$$\Gamma[\Upsilon(nS) \to \gamma \ell^+ \ell^-] \simeq \frac{\alpha |R_n(0)|^2}{144\pi^3 v^4} \left[ \log \left( \frac{M_{A^0}^2}{M_{A^0}^2 - M_\Upsilon^2} \right) - 1 \right] \times m_\ell^2 ; \quad M_{A^0} > M_\Upsilon$$

Only for the tauonic mode would the NP contribution be noticeable because of the Higgs coupling proportional to the lepton mass, while the contribution to the electronic and muonic modes is currently beyond experimental test (see Table 1). Thus one obtains for the ratio (3):

$$R_\tau \simeq \frac{M_\tau^2 \tan^4 \beta}{64\pi^3 v^4} \left[ \log \left( \frac{M_{A^0}^2}{M_{A^0}^2 - M_\Upsilon^2} \right) - 1 \right] \times m_\tau^2$$

In order to get $R_\tau \simeq 0.1$ (as suggested by current data shown in Table 1) from the continuum setting $M_{A^0} \approx 10$ GeV, rather large values of $\tan \beta$ are required, e.g. $\tan \beta \gtrsim 50$ for $M_{A^0} - M_\Upsilon = 0.25$ GeV, as concluded in [14].

2.2 Intermediate bound states

In Ref. [14] we used time-ordered perturbation theory to incorporate the effect of intermediate $b\bar{b}$ bound states in the process (1). We found that the main contribution should come from a $\eta_b$ state subsequent to an allowed dipole magnetic (M1) transition of the $\Upsilon$ vector resonance, i.e.

$$\Upsilon \to \gamma s \eta_b (\to A^{0*} \to \ell^+ \ell^-) ; \quad \ell = e, \mu, \tau$$

Thus, the total decay width can be factorized as [14]

$$\Gamma[\Upsilon \to \gamma s \ell^+ \ell^-] = \Gamma^{M1}_{\Upsilon \to \gamma s \eta_b} \times \frac{\Gamma[\eta_b \to \ell^+ \ell^-]}{\Gamma_{\eta_b}}$$

where $\Gamma[\eta_b \to \ell^+ \ell^-]$ and $\Gamma_{\eta_b}$ denote the leptonic width and the total width of the $\eta_b$ resonance respectively; $\Gamma^{M1}_{\Upsilon \to \gamma s \eta_b}$ stands for the M1 transition width.
Dividing both sides of (9) by the Υ total width, we get the cascade decay formula

$$
\mathcal{B}[\Upsilon \to \gamma_s \ell^+ \ell^-] = \mathcal{B}[\Upsilon \to \gamma_s \eta_b] \times \mathcal{B}[\eta_b \to \ell^+ \ell^-]
$$

The branching ratio for a magnetic dipole (M1) transition between Υ(nS) and η_b(nS) states can be written in a non-relativistic approximation as

$$
\mathcal{B}[\Upsilon \to \gamma_s \eta_b] = \frac{\Gamma_{\Upsilon \to \gamma_s \eta_b}}{\Gamma_{\Upsilon}} \approx \frac{1}{\Gamma_{\Upsilon}} \frac{4\alpha Q_t^2 k^3}{3m_b^2} \tag{10}
$$

where \(k\) stands for the soft photon energy (approximately equal to the hyperfine splitting \(M_\eta - M_{\eta_b}\)). Hindered M1 transitions of the Υ(2S) and Υ(3S) resonances into η_b(2S) and η_b(1S) states should also be taken into account as potential contributions to the process (8) for such resonances.

The decay width of the η_b into a dilepton mediated by a \(A^0\) boson reads in a 2HDM(II)

$$
\Gamma[\eta_b \to \ell^+ \ell^-] = \frac{3m_b^4 m_\ell^2 (1 - 4x_\ell)^{1/2} |R_\alpha(0)|^2 \tan^4 \beta}{2\pi^2 (M_{\eta_b} - M_{A^0})^2 v^4} \approx \frac{3m_b^4 m_\ell^2 \tan^4 \beta}{32\pi^2 Q_t^2 \alpha^2 (1 + 2x_\ell) \Delta M^2 v^4} \times \Gamma^{(em)}_{\ell\ell}
$$

where \(\Delta M = |M_{A^0} - M_{\eta_b}|\) stands for the (absolute) mass difference between the η_b and \(A^0\) states; \(\Gamma^{(em)}_{\ell\ell}\) is given in Eq (2). Note again that only for the tauonic mode, would the NP contribution to the Υ leptonic decay be significant \(^3\). Finally one gets

$$
\mathcal{R}_\tau \simeq \left[ \frac{m_b^2 k^3 \tan^4 \beta}{8\pi^2 \alpha (1 + 2x_\tau) \Gamma_{\Upsilon} v^4} \right] \times \frac{m_\ell^2}{\Delta M^2} \tag{11}
$$

For large \(\tan \beta (\gtrsim 35)\) the NP contribution would almost saturate the η_b decay, i.e. \(\Gamma_{\eta_b} \approx \Gamma[\eta_b \to \tau^+ \tau^-]\); thus \(\mathcal{B}[\eta_b \to \tau^+ \tau^-] \approx 1\) and consequently

$$
\mathcal{R}_\tau \simeq \frac{\mathcal{B}[\Upsilon \to \gamma_s \eta_b]}{B_{ee}} \simeq 1 - 10\% \tag{12}
$$

for \(k = 50 - 150\) MeV and \(\Delta M = 0.25\) GeV. In fact, the quest for a light Higgs particle would coincide with the search for η_b states!

On the other hand, it is well known that higher Fock components beyond the heavy quark-antiquark pair can play an important role in both production and decays of heavy quarkonium \(^{22}\). Thus, in \(^{14, 15}\) we relied, as a factorization alternative to Eq. (9), on the separation between long- and short-distance physics following the main lines of Non-Relativistic QCD \(^{22}\) - albeit replacing a gluon by a photon in the usual Fock decomposition of hadronic bound states. Hence we considered the existence in the Upsilon resonance of the \(b\bar{b}\) pair in a spin-singlet and color-singlet state, i.e. a \(|\eta_b^* + \gamma_s\rangle\) Fock component with probability \(\mathcal{P}(\eta_b^* \gamma_s) \simeq 10^{-4}\) \(^{14}\). Thus the total decay width can be factorized as

$$
\Gamma[\Upsilon \to \gamma_s \tau^+ \tau^-] = \mathcal{P}(\eta_b^* \gamma_s) \times \Gamma[\eta_b^* \to \tau^+ \tau^-] \tag{12}
$$

In order to get a 10% lepton universality breaking effect, a value of \(\tan \beta \simeq 15\) is required setting again \(\Delta M = 0.25\) GeV as a reference value. Those ranges of \(\tan \beta\) needed for larger values of \(\Delta M\) can be found in \(^{13}\).

\(^3\)Leaving aside the unlikely case when the Upsilon and Higgs masses were very close (within the MeV range)
2.3 On-shell Higgs production from $\Upsilon$ radiative decays

Let us consider now a scenario where the Upsilon state lies slightly above the lightest (CP-odd) Higgs state, i.e. $M_{A^0} \lesssim M_{\Upsilon}$. Then the decay into an on-shell $A^0$ can proceed via the radiative process $\Upsilon \rightarrow \gamma + A^0$, whose width satisfies the ratio \[ \frac{\Gamma[\Upsilon \rightarrow \gamma A^0]}{\Gamma[\Upsilon \rightarrow \mu^+ \mu^-]} \approx \frac{m_b^2 \tan^2 \beta}{2\pi \alpha v^2} \left(1 - \frac{M_{A^0}^2}{M_{\Upsilon}^2}\right)^2 ; \quad M_{A^0} < M_{\Upsilon} \]

On the other hand, the decay width of a CP-odd Higgs boson into a tauonic or a $c\bar{c}$ pair in the 2HDM(II) can be obtained, respectively, from the expressions: \[ \Gamma[A^0 \rightarrow \tau^+ \tau^-] \approx \frac{m_b^2 \tan^2 \beta}{8\pi v^2} M_{A^0} (1 - 4x_{\tau})^{1/2} \quad (13) \]
\[ \Gamma[A^0 \rightarrow c\bar{c}] \approx \frac{3m_b^2 \cot^2 \beta}{8\pi v^2} M_{A^0} (1 - 4x_c)^{1/2} \quad (14) \]

where $x_{\tau} = m_\tau^2/M_{A^0}^2$ and $x_c = m_c^2/M_{A^0}^2$. Below open bottom production and above $\tau^+ \tau^-$ threshold, the $A^0$ decay mode would be dominated by the tauonic channel even for moderate $\tan \beta$. Therefore, the radiative decay should be almost saturated by the channel: \[ \Upsilon \rightarrow \gamma + A^0 (\rightarrow \tau^+ \tau^-) \]

since $B[A^0 \rightarrow \tau^+ \tau^-] \approx 1$; then one may conclude that \[ R_{\tau} \approx \frac{2M_{\Upsilon}^2 \tan^2 \beta}{\pi \alpha v^2} \left(1 - \frac{M_{A^0}^2}{M_{\Upsilon}^2}\right) \]

Setting, e.g., $\tan \beta = 15$, one gets $R_{\tau} \approx 10\%$. In using a relativistic theory of the decay of Upsilon into a Higgs boson plus photon in the mass range 7-9 GeV, the ratio is substantially smaller (by an order-of-magnitude) than that of the nonrelativistic calculation presented above \[25\]. Then somewhat larger values of $\tan \beta$ would be needed to yield $R_{\tau} = 0.1$.

Furthermore, also a light non-standard CP-even Higgs boson (usually denoted as $h^0$) has not been discarded by LEP searches \[6\]. In such a case, the cascade decay \[ \Upsilon \rightarrow \gamma \chi_{b0} (\rightarrow h^0 \rightarrow \tau^+ \tau^-) \]

could also ultimately contribute to enhance the tauonic decay modes of the $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances and should not be overlooked. In fact, a discrimination between different sorts of Higgs bosons (i.e. determining the CP quantum numbers) might be performed by realizing whether the $\chi_{b0}$ resonances play a role as intermediate states in the process (1).

The decay width of a $\chi_{b0}$ resonance into a tauonic pair via a CP-even Higgs boson is \[11\] \[ \Gamma[\chi_{b0} \rightarrow \tau\tau] = \frac{27m_b^2m_c^2(1 - 4x_c)^{3/2}|R_{\chi_{b0}}'(0)|^2 \tan^4 \beta}{8\pi^2(M_{\chi_{b0}}^2 - M_{A^0}^2)^2 v^4} \quad (15) \]

where $R_{\chi_{b0}}'(0)$ denotes the derivative of the $\chi_{b0}(nS)$ radial wave function at the origin, yielding $\Gamma[\chi_{b0} \rightarrow \tau\tau] \approx 20$ keV for $|R_{\chi_{b0}}'(0)|^2 \approx 1.5$ GeV\(^5\) \[20\], $\tan \beta = 15$ and $M_{\chi_{b0}} - M_{A^0} = 0.25$ GeV as reference values. In order to get a branching fraction estimate, let us normalize this width to \[ \Gamma_{\chi_{b0}} \approx \Gamma[\chi_{b0} \rightarrow gg] = \frac{96\alpha_S^2|R_{\chi_{b0}}'(0)|^2}{M_{\chi_{b0}}^4} \]
Setting $\alpha_s(M_T) \simeq 0.15$ one gets $\mathcal{B}[\chi_{b0} \to \tau^+\tau^-] \simeq 6\%$. Now, since the radiative $\Upsilon$ decay rates into $\chi_{b0}$ are of order $3-5\%$ [16], we can estimate for the combined branching ratio

$$
\mathcal{B}[\Upsilon \to \gamma_s \tau^+\tau^-] = \mathcal{B}[\Upsilon \to \gamma_s \chi_{b0}] \times \mathcal{B}[\chi_{b0} \to \tau^+\tau^-] \simeq 0.002 - 0.003
$$

yielding $R_\tau \simeq 10\%$. Obviously, the search for a light Higgs via this cascade decay channel does not apply to the $\Upsilon(1S)$ resonance.

### 3 Possible spectroscopic consequences

The existence of a light Higgs boson can have consequences besides altering the tauonic decay rate of Upsilon resonances. Indeed, the mixing of the $A^0$ with a pseudoscalar resonance could modify the properties of both $\Upsilon(nS)$. In particular, the resulting mass shift of the $\eta_b$ state 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 pNRQCD [28]. The masses of the mixed (physical) states in terms of the unmixed ones (denoted as $A^0_0, \eta_{b0}$) are:

$$
M^2_{\eta_b, A^0} = \frac{1}{2}(M^2_{A^0_0} + M^2_{\eta_{b0}}) \pm \frac{1}{2} \left[ (M^2_{A^0_0} - M^2_{\eta_{b0}})^2 + 4(\delta M^2)^2 \right]^{1/2}
$$

(17)

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

$$
M^2_{\eta_b, A^0} \simeq M_{\eta_{b0}} \mp \frac{\delta M^2}{2M_{\eta_{b0}}}; \quad 0 < M^2_{A^0_0} - M^2_{\eta_{b0}} \ll 2 \delta M^2,
$$

$$
M^2_{\eta_b, A^0} \simeq M_{\eta_{b0}, A^0_0} \mp \frac{(\delta M^2)^2}{2M_{\eta_{b0}}(M^2_{A^0_0} - M^2_{\eta_{b0}})}; \quad M^2_{A^0_0} - M^2_{\eta_{b0}} \gg 2 \delta M^2
$$

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 $\mathcal{B}[\Upsilon(1S) \to \gamma \eta_b(1S)] \simeq 10^{-2}$. A caveat is thus in order: a quite large $M_{\Upsilon} - M_{\eta_b}$ difference may lead to an unrealistic M1 transition rate 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 on these grounds.

On the other hand, broad $\eta_b$ states would be possible due to the NP contribution, notably for large $\tan \beta$ values. Thus one can speculate why no evidence of hindered M1 radiative decays of higher Upsilon resonances into $\eta_b(1S)$ and $\eta_b(2S)$ states was found in the search performed by CLEO [20, 30, 21]. The corresponding signal peak (which should appear in the photon energy spectrum) could be considerably smoothed - in addition to the spreading from the experimental measurement - and thereby might not be significantly distinguished from the background (arising primarily from $\pi^0$'s). Of course, the matrix elements for hindered transitions are expected to be small and difficult to predict as they are generated by relativistic and finite size corrections. Nevertheless, most of the theoretical calculations (see a compilation in Ref. [31]) are ruled out by CLEO results (at least) at 90% CL, though substantially lower rates are obtained in [32] where exchange currents play an essential role and therefore cannot be currently excluded.

Large widths of $\eta_b$ resonances would also bring negative effects for their detection in hadron colliders like the Tevatron through the decay modes: $\eta_b \to J/\psi + J/\psi$ [33], and the recently proposed $\eta_b \to D^* D^{(*)}$ [34], as the respective branching fractions would drop by about one order of magnitude with respect to the SM calculations.
4 A MSSM scenario with CP violation

It has been pointed out in the literature \[35, 7, 36\] that CP violation in the Higgs sector of the MSSM can occur quite naturally, representing an interesting option to generate CP violation beyond the SM. Then, the three neutral MSSM Higgs bosons could mix together and the resulting three neutral MSSM Higgs bosons: \(H_1, H_2, H_3\) \((M_{H_1} < M_{H_2} < M_{H_3})\) would have mixed parities. Under this scenario, Higgs couplings to the \(Z\) boson would vary; the \(H_1 ZZ\) coupling can be significantly suppressed \[37\] thus raising the possibility of a relatively light \(H_1\) boson having escaped detection at LEP 2 for the range \(10 \lesssim \tan \beta \lesssim 40\) (higher values of \(\tan \beta\) were not considered in the search). Interestingly, for several choices of model parameters and a Higgs mass about 10 GeV, the region of \(\tan \beta\) not excluded experimentally by LEP searches \[6\] is in accordance with the requirements found in this work to give rise to a \(\sim 10\%\) breakdown of lepton universality in \(\Upsilon\) decays.

Finally notice that the \(H_1\) Higgs boson can couple both to scalar and pseudoscalar states. Hence the \(\chi_{b0}\) resonances might play a role as intermediate states in \(\Upsilon(2S)\) and \(\Upsilon(3S)\) decays: \(\Upsilon \rightarrow \gamma \chi_{b0} \rightarrow H_1 \rightarrow \tau^+ \tau^-\), as mentioned in section 2.3 for a CP-even Higgs boson.

5 Summary

Heavy quarkonium physics has reached a level of maturity enabling the search for new phenomena beyond the SM \[38\]. In this paper, possible hints of new physics in bottomonium systems and suggestions to conduct an experimental search for new evidence have been pointed out:

a) Current experimental data do not preclude the possibility of lepton universality breaking at a significance level of 10% \[14\], interpreted in terms of a light CP-odd Higgs boson for a reasonable range of \(\tan \beta\) values in a 2HDM(II). In fact, direct searches at LEP don’t exclude a non-standard Higgs boson for some regions of model parameters in different scenarios, notably in a CPX MSSM \[6\] and the NMSSM \[2\].

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 \(M_{A_0^0} > M_{\eta_b}\); the opposite if \(M_{A_0^0} < M_{\eta_b}\). Furthermore, large \(\eta_b\) widths would also be expected for large \(\tan \beta\) 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 despite intensive searches performed at CLEO \[30, 20\]. Negative effects would also come up in the prospects to detect \(\eta_b\) resonances in hadron colliders like the Tevatron.

c) After the recent results by CLEO \[19, 20, 21\] on the muonic BF of all three \(\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)\) resonances, new results for the tauonic BF from on-going CLEO analysis are eagerly awaited. Indeed, distinct degrees of lepton universality breaking (if any) in Upsilon decays might lead to a Higgs mass estimate as one expects that the closer the resonance mass to the mediating Higgs boson mass is, the bigger NP effect shows up in the tauonic BF.

d) The detection of (quasi)monoenergetic photons (assuming a sharp intermediate \(\eta_b\) state) in \(\sim 10\%\) events of the tauonic decay sample would represent the “smoking gun” of a Higgs boson mediating the decay, allowing the determination of its mass. Moreover, polarization studies of final-state \(\tau^\pm\) in \(\Upsilon\) decays \[39\] could help to establish also the CP quantum numbers of the Higgs boson.
e) On the contrary, if lepton universality in $\Upsilon$ decays were confirmed, mass windows still open for a light Higgs boson in scenarios beyond the SM could be closed in parameter regions hardly reachable by other experiments, e.g. those performed at hadron colliders $^{10,11}$. This would be especially the case for a Higgs particle below open bottom production.

Acknowledgements

I gratefully acknowledge S. Baranov, N. Brambilla, J.F. Gunion, A. Vairo, the Quarkonium Working Group and the Analysis Group of the CLEO Collaboration for useful comments and discussions.

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