Searching for New Physics in Leptonic Decays of Bottomonium [*]

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Abstract

New Physics can show up in various well-known processes already studied in the Standard Model, in particular by modifying decay rates to some extent. In this work I examine leptonic decays of Υ resonances of bottomonium below $B\bar{B}$ production, subsequent to a magnetic dipole radiative structural transition of the vector resonance yielding a pseudoscalar continuum state, searching for the existence of a light Higgs-like neutral boson that would imply a slight but experimentally measurable breaking of lepton universality.

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 possible existence of Higgs-like bosons (hereafter referred as "Higgs") beyond the Standard Model (SM) has already a long history in modern physics. For instance, let us mention the two-Higgs-doublet model (2HDM) [1] - including the minimal supersymmetric model as one of its specific realizations - allowing for five scalar or pseudoscalar bosons, three of which neutral and, perhaps, one of them at least quite light. Another example of this kind is the axion model, originally introduced in [2, 3] as a consequence of the spontaneous breaking of the global $U(1)_{PQ}$ axial symmetry. Nowadays, the axion is a pseudoscalar field appearing in a variety of theories with different meanings including superstring theory, yielding sometimes a massless particle and others a massive one: in astrophysics the axion represents a good candidate of the cold dark matter component of the Universe. In fact, there are other scenarios, e.g. spontaneously broken lepton-number symmetry [4, 5], leading to very light or even massless bosons (Majorons) which might be detected in very rare decays of strange and beauty particles [6]. On the other hand, another kind of (neutral) scalar particles (familons) with either flavor-changing or flavor-conserving couplings to fermions, arise assuming a global family symmetry spontaneously broken [7]. To end this quick outlook beyond the SM, a scalar particle (the radion) proposed in the framework of the Randall-Sundrum model [8] of extra dimensions, corresponding to the quantum excitations of the interbrane separation [9], could mix with the standard Higgs and couple to SM fields [10]. Also Kaluza-Klein (scalar) gravitons in an ADD scenario [11, 12] could eventually lead to measurable deviations from the SM [13, 14].

Although there are well established lower mass bounds for the standard Higgs (e.g. from LEP searches [15]), the situation may be different in several scenarios and models beyond the SM where such constraints would not apply, leaving still room for light Higgs bosons (see [16, 17, 18] for example). Needless to say, any possible experimental signal or discovery strategy of Higgs-like particles should be examined with great attention.

In this regard, let us remind that the search for axions or light Higgs in the decays of heavy resonances has several attractive features. Firstly, the couplings of the former to fermions are proportional to their masses and therefore enhanced with respect to lighter mesons. Second, theoretical predictions are more reliable, especially with the recent development of effective theories like non relativistic quantum chromodynamics (NRQCD) [19], appropriate to deal with such bound states from first principles. Indeed, intensive searches for a light Higgs-like boson (to be generically denoted by ϕ^0 in this paper) have been performed so far according to the so-called Wilczek mechanism [20] in the radiative decay of vector heavy quarkonia like the Upsilon resonance (i.e. $\Upsilon \to \gamma \phi^0$). So far, none of all these searches has been successful, but have provided valuable constraints on the mass values of light Higgs bosons [1].

Nevertheless, in this Letter I will focus on a possible signal of New Physics based on the "apparent" breaking of lepton universality in bottomonium decays: *stricto sensu*, lepton universality implies that the electroweak couplings to gauge fields of all charged lepton species should be the same. According to the interpretation given in this work, the possible dependence on the leptonic mass of the leptonic branching fractions of Υ resonances below the $B\bar{B}$ threshold (if experimentally confirmed by forthcoming measurements) might be viewed as a hint of the existence of a Higgs of mass about 10 GeV.

2 Searching for a light Higgs-like boson in Υ leptonic decays

Let us get started by writing the well-known Van Royen-Weisskopf formula [21] including the color factor [1] for the leptonic width of a vector quarkonium state without neglecting leptonic masses,

$$\Gamma^0_{\ell\ell} \;=\; 4\alpha^2 Q_b^2 \; \frac{|R_n(0)|^2}{M_\Upsilon^2} \;\times\; K(x) \tag{1}$$

where $\alpha \simeq 1/137$ is the electromagnetic fine structure constant; M_Υ denotes the mass of the vector particle (a $\Upsilon(nS)$ resonance in this particular case) and Q_b is the charge of the relevant (bottom) quark ($1/3$ in units of e); $R_n(0)$ stands for the non-relativistic radial wave function of the $b\bar{b}$ bound state at the origin; finally, the "kinematic" factor K reads

$$K(x) \;=\; (1+2x)(1-4x)^{1/2} \tag{2}$$

where $x = m_\ell^2/M_\Upsilon^2$. Leptonic masses are usually neglected in Eq.(1) (by setting K equal to unity) except for the decay into $\tau^+\,\tau^-$ pairs. Let us note that $K(x)$ is a decreasing function of x: the higher leptonic mass the smaller decay rate. However, such x-dependence is quite weak for bottomonium.

In this work, I am conjecturing the existence of a light Higgs-like particle whose mass is close to the Υ mass and which could show up in the sequential decay:

$$\Upsilon \to \gamma \; \phi^0(\to \ell^+\ell^-) \quad ; \quad \ell = e, \mu, \tau \tag{3}$$

Actually, this process may be seen as a continuum radiative transition that in principle permits the coupling of the bottom quark-antiquark pair to a particle of variable mass and J^{PC}: $0^{++}, 0^{-+}, 1^{++}, 2^{++}...$ (always positive charge conjugation). In the present investigation, we will confine our attention to the two first possibilities: a scalar or a pseudoscalar boson.

Let us remark that if indeed the ϕ^0 mass were quite close to the Υ mass, on the one hand the (pseudo)scalar propagator could enhance the width of process (3); on the other hand, the emitted photon would become soft enough to remain experimentally below detection threshold and the contribution (3) would be experimentally ascribed to the leptonic channel, thereby (slightly) increasing its decay rate. Both related points constitute cornerstones along this paper and will be discussed in more detail.

2.1 An intermediate spin-singlet $b\bar{b}$ state?

Motivated by the study of heavy quarkonia production and decay, where intermediate non-perturbative states are thought to play an important (sometimes leading) role [19], one may envisage the existence of equivalent intermediate hadronic stages after the radiative decay of a vector resonance as shown in Eq.(3), before annihilating into a charged lepton pair [2].

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[1] As is well known, gluon exchange in the short range part of the quark-antiquark potential makes significant corrections to Eq.(1) but without relevant consequences in our later discussion.

[2] I leave aside the discussion on the possible formation of the η_b state (still unobserved at present except for a recent claim [22]): in such a case only the 0^{-+} state and a sharply defined mass would be allowed. Nevertheless, notice that the foreseen mass difference between the $\Upsilon(1S)$ and η_b states, recently estimated in [23] to be 36-55 MeV, makes in practice almost no difference with respect to our later analysis based on a continuum state.

In a naive quark model, quarkonium is treated as a nonrelativistic bound state of a quark-antiquark pair in a static color field which sets up an instantaneous confining potential. Indeed this picture has been remarkably successful in accounting for the properties of heavy quarkonia. However, it overlooks gluons whose wavelengths are larger that the bound state size: dynamical gluons permit a Fock decomposition of physical quarkonium states beyond the leading non-relativistic description.

Thus, in a vector resonance like the $\Upsilon(1S)$, the heavy quark pair can be in a spin-trilet, color-singlet state in the lowest Fock state, but the $b\bar{b}$ system could also exist in a configuration other than $J^P = 1^-$ since the soft degrees of freedom can carry the remaining quantum numbers, although with a smaller probability. Chromoelectric and chromomagnetic transitions can connect different Fock states in physical processes subject to selection rules and governed by distinct probabilities. These ideas have been cast into the rigorous framework of an effective non-relativistic theory for the strong interaction (NRQCD) [19], widely applied to heavy quarkonia phenomenology (see, for example, [24, 25] and references therein). Furthermore, the authors of [26] have shown the physical relevance of soft gluon emission in the (semi)leptonic decays of the B_c meson. Let us finally mention that the possibility of intermediate bound states in electromagnetic decays of quarkonia in particular and its physical consequences have been discussed elsewhere [27], without resorting to a Fock decomposition.

At this point, one may wonder about the possibility of reaching different $b\bar{b}$ bound states starting from an initial spin-triplet color-singlet configuration by radiation of soft photons, instead of gluons, via electric and magnetic transitions. However, the situation is not quite the same as in "standard" NRQCD. In effect, let us emphasize one of consequences of the the crucial difference between photons and gluons: since the latter carry color, a lower energy bound always applies in soft emission at the final stage hadronization (corresponding, for instance, to a pion mass). On the contrary, no such infrared cut-off exists for photons, except for the experimental detection threshold which properly regularizes the infrared divergences [28]. Moreover, (soft) single gluon emission from quarkonia would leave the heavy quark-antiquark pair in a color-octet state, thereby forbidding its subsequent annihilation into a charged lepton pair. Therefore, soft photon emission in leptonic decays of Υ resonances can have important consequences beyond purely radiative corrections.

In fact, several authors [29, 30] suggested long time ago that a scalar (h^0) Higgs of mass near 10 GeV could enhance the tauonic decay of the χ_{b0} resonance, proposing a close look at the cascade decay with an e^+e^- machine working on the $\Upsilon(2S)$ resonance:

$$\Upsilon(2S) \to \gamma \; \chi_{b0}(\to h^0 \to \tau^+\tau^-) \tag{4}$$

where the radiative decay corresponds (mainly) to an electric dipole (E1) transition. Actually, our underlying idea is not too far from theirs, although now the structural magnetic dipole (M1) transition should no lead to a P-wave resonance, but likely to a S-wave pseudoscalar continuum bound state. Indeed, let us note that a E1 transition would involve the product of a S-wave initial-state function, peaking at the origin, with a P-wave final-state function, vanishing at the origin; in the long wavelength limit the overlap should be small. Besides, it seems unrealistic a continuum P-wave $b\bar{b}$ state whose mass is smaller than the initial S-wave state mass. The last argument can be extended to other quantum numbers of the continuum resonance and, consequently, I dismiss all possibilities but a pseudoscalar $b\bar{b}$ bound state after photon emission in the process (3).
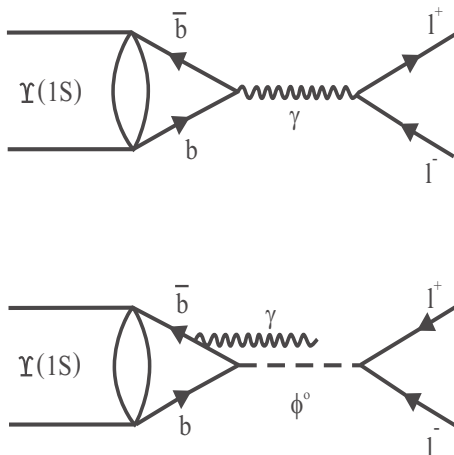
Figure 1: (a)[upper panel]: Electromagnetic annihilation of a $b\bar{b}[^3S_1^{(1)}]$ bound state (a $\Upsilon(1S)$ resonance in particular) into a charged lepton pair through a vector particle (i.e. a photon); (b)[lower panel]: Hypothetical annihilation of a color-singlet $b\bar{b}[^1S_0^{(1)}]$ state (assuming that the $b\bar{b}[^3S_1^{(1)}]$ resonance state has previously undergone a M1 transition into a pseudoscalar continuum state, caused by soft photon emission) into a charged lepton pair through a pseudoscalar Higgs-like boson (represented by a dashed line in the figure and denoted by ϕ^0 in the text).

In sum, magnetic dipole transitions of the Υ into a non-perturbative $b\bar{b}[^1S_0^{(1)}]$ state (I am using spectroscopic notation and stressing its color-singlet status by keeping the superscript (1) widely used in NRQCD) can play a noticeable role in a process like (3). The corresponding width can be estimated with the aid of a text-book formula [31]:

$$\Gamma^{M1}_{\Upsilon(1S)\to\gamma_s b\bar{b}[^1S_0^{(1)}]} \simeq \frac{16\alpha}{3}\left(\frac{Q_b}{2m_b}\right)^2 k^3 \tag{5}$$

where k denotes the energy of the soft photon γ_s, radiated from either the heavy quark or the heavy antiquark inside bottomonium, as shown in figure 1.b; the mass of the Upsilon resonance will be approximately taken as twice the bottom quark mass throughout the paper, i.e. $M_\Upsilon \simeq 2m_b$. Actually, the above equation should provide just an order-of-magnitude estimate since, for instance, the density of the continuum $b\bar{b}[^1S_0^{(1)}]$ states is not taken into account [3]; but, in reality, the main uncertainty comes from the value used for the soft "typical" photon energy, i.e. the input k in Eq.(5).

In this regard, note that typical widths of resonance peaks in e^+e^- machines are of the order of one or few tens of MeV for the Υ family below open bottom production (much larger than resonance widths themselves). On the other hand, usual thresholds for photon detection are of order 50 MeV. Moreover, in the case of tauonic decays, event selection is based on either semileptonic or hadronic inclusive decays of the τ's (usually requiring a "back-to-back" topology) with similar (probably larger) uncertainties as in the electron or muonic channels, concerning a soft photon escaping detection [34].

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[3]One could improve somewhat Eq.(5) by means of a multiplicative overlap factor of the wave functions of both resonances as in [32]. Note however that for closely spaced states this overlap factor should be near unity. See also Ref. [33] for a thorough calculation of chromoelectric and chromomagnetic transitions in heavy quarkonium.

Therefore, letting the photon energy k vary over the range $10 - 50$ MeV, one gets from (5) the interval $\Gamma^{M1}_{\Upsilon(1S)\to\gamma_s b\bar{b}[^1S_0^{(1)}]} \simeq 4.3{\times}10^{-5} - 5.4{\times}10^{-3}$ keV. Let us stress that those small k values do justify the use of Eq.(5) for magnetic dipole transitions since the wavelengths of the radiated photons are quite larger than the size of quarkonium (of order $\simeq \mathcal{O}(1)$ GeV^{-1}).

Next, dividing the partial width given in Eq.(5) by the total width of the resonance, $\Gamma_{tot} = 52.5$ keV [35], one gets the probability that the M1 transition takes place, i.e.

$$\mathcal{P}^{M1}_{\Upsilon(1S)\to\gamma_s b\bar{b}[^1S_0^{(1)}]} = \frac{\Gamma^{M1}_{\Upsilon(1S)\to\gamma_s b\bar{b}[^1S_0^{(1)}]}}{\Gamma_{tot}} \simeq \frac{1}{\Gamma_{tot}} \frac{4\alpha Q_b^2}{3m_b^2} k^3 \simeq 8.2{\cdot}10^{-7} - 10^{-4} \qquad (6)$$

The latter quantity can be interpreted as a kind of branching fraction (BF) for the radiative decay of the $\Upsilon(1S)$ into the supposed continuum $b\bar{b}$ spin-singlet resonance, under the experimental constraint of the photon energy upper cut-off. The range shown in Eq.(6) seems realistic when compared to the measured BF for the channel $J/\psi\to\gamma\eta_c$, (of order 1% [35]) taking into account the different mass and electric charge for the charm and bottom quarks.

Subsequently, the pseudoscalar $b\bar{b}[^1S_0^{(1)}]$ state could decay into a charged lepton pair at tree-level via the conjectured neutral boson, as will be discussed in more detail in the next section.

Finally let us emphasize that, in this experimental context, soft photons (mainly radiated by the initial-state colliding electrons in e^+e^- machines and by the final-state outgoing leptons) are those whose energies do not exceed the experimental detection threshold and thereby can not be observed [4]. Nevertheless, as is well-known soft radiation corrections must be included in the theoretical analysis [38, 35] for a meaningful comparison with the experimental results for the leptonic branching fraction: $\mathcal{B}_{\ell\ell} = \Gamma_{\ell\ell}/\Gamma_{tot}$. In an analogous fashion, photons from the conjectured M1 transition of the Υ resonance would merge with the aforementioned bulk of soft radiation, without changing significantly the invariant mass of the lepton pair (i.e. within mass reconstruction windows), or passing trigger and off-line selection criteria, ultimately contributing to the measured leptonic BF.

2.2 Effects of a light neutral Higgs on the leptonic decay width

In this Letter, we are focusing on vector $\Upsilon(nS)$ states of the bottomonium family below open flavor (i.e. $n < 4$) [5] decaying into a charged lepton pair plus a *soft* photon:

$$\Upsilon(nS)\to \gamma_s\, b\bar{b}[^1S_0^{(1)}](\to \phi^0\to \ell^+\ell^-) \quad ; \quad \ell = e, \mu, \tau \qquad (7)$$

where the soft (I stress it once more: *unobserved*) γ_s comes from a *prompt* M1 transition of the Υ resonance, as sketched in figure 1.b.

The decay width $\Gamma_{\gamma_s\ell\ell}$ will be written in a factored form reflecting the two-step process: prior formation of an intermediate (mainly) pseudoscalar state of account of soft

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[4]In the language of low-energy effective theories such photons would be properly designed as ultrasoft [36, 37].

[5]The $\Upsilon(3S)$ state is excluded in the present analysis since only experimental data available for the muonic channel [35] are currently available; see http://pdg.lbl.gov for regular updates.

magnetic radiation, followed by its annihilation into a charged lepton pair mediated by a (pseudo)scalar Higgs:

$$\Gamma_{\gamma_s \ell \ell} = \mathcal{P}^{M1}_{\Upsilon(1S) \to \gamma_s b\bar{b}[^1S_0^{(1)}]} \times \tilde{\Gamma}_{\ell\ell} \tag{8}$$

where $\tilde{\Gamma}_{\ell\ell}$ is the annihilation width of the $b\bar{b}[^1S_0^{(1)}]$ state into a lepton pair via ϕ^0 Higgs exchange. Furthermore, fermions are supposed to couple to the ϕ^0 field according to a Yukawa interaction term in the effective Lagrangian,

$$\mathcal{L}^{\bar{f}f}_{int} = -\xi^\phi_f \frac{\phi^0}{v} m_f \bar{f}(i\gamma_5)f \tag{9}$$

where $v = 246$ GeV stands for the vacuum expectation value of the standard Higgs boson; ξ^ϕ_f denotes a factor depending on the type of the Higgs boson, which could enhance the coupling with a fermion (quark or lepton) of type "f". In particular, ϕ^0 couples to the final-state leptons proportionally to their masses, ultimately required because of spin-flip in the interaction of a fermion with a (pseudo)scalar, expectedly providing an experimental signature for checking the existence of a light Higgs in our study. Lastly, note that the $i\gamma_5$ matrix stands only in the case of a pseudoscalar ϕ^0 field.

In this paper, I am tentatively assuming that the mass of the sought light Higgs stands close to the $\Upsilon(1)$ resonance but below $B\bar{B}$ production: $m_{\phi^0} \simeq 2m_b$. As will be argued from current experimental data in the next section, I suppose specifically that m_{ϕ^0} lies somewhere between the $\Upsilon(1S)$ and $\Upsilon(2S)$ masses, i.e.

$$m_{\Upsilon(1S)} \lesssim m_{\phi^0} \lesssim m_{\Upsilon(2S)} \tag{10}$$

Now, I define the mass difference: $\delta m = |m_{\phi^0} - m_\Upsilon|$, where Υ denotes either a $1S$ or a $2S$ state. Accepting for simplicity that the Higgs stands halfway between the mass values of both resonances, I will set $\delta m \simeq 0.25$ GeV for an order-of-magnitude calculation. Hence I write approximately for the scalar tree-level propagator of the ϕ^0 particle in (7),

$$\frac{1}{(m_\Upsilon^2 - m_{\phi^0}^2)^2} \simeq \frac{1}{16 \; m_b^2 \; \delta m^2} \tag{11}$$

where the width of the Higgs boson has been neglected [6] for it should be very narrow due the smallness of m_{ϕ^0} and, moreover, standing below bottom open production according to the inequality (10).

Performing a comparison between the widths of both leptonic decay processes (i.e. $\tilde{\Gamma}_{\ell\ell}$ versus $\Gamma^0_{\ell\ell}$), one concludes with the aid of Eqs.(9-11) and (1) that

$$\tilde{\Gamma}_{\ell\ell} \approx \frac{3m_b^4 m_\ell^2 K(x)|R_n(0)|^2 \xi_b^2 \xi_\ell^2}{2\pi^2(m_\Upsilon^2 - m_{\phi^0}^2)^2 v^4} \simeq \frac{3\xi_b^2 \xi_\ell^2}{32\pi^2 Q_b^2 \alpha^2} \frac{m_b^4 m_\ell^2}{\delta m^2 v^4} \times \Gamma^0_{\ell\ell} \tag{12}$$

with $K(x)$ defined in Eq.(2).

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[6]In case that the resonance and the ϕ^0 would stand closer than one Higgs width, there would be a mixing between both states further enhancing the decay into lepton pairs [30, 39], deserving a separate study.

Above I used a non-relativistic approximation [7], assuming the same wave function at the origin for both the Υ vector state and the $b\bar{b}[^1S_0^{(1)}]$ intermediate bound state on account of heavy-quark spin symmetry [19].

Finally, the BF for channel (7) can be readily obtained from Eq.(8), with the help of Eqs. (5) and (12), as

$$\mathcal{B}_{\Upsilon \to \gamma_s \ell\ell} = \left[\frac{m_b^2 m_\ell^2 k^3 \xi_b^2 \xi_\ell^2}{8\pi^2 \alpha \Gamma_{tot} \delta m^2 v^4} \right] \times \mathcal{B}_{\ell\ell} \tag{13}$$

so one can compare the relative rates by means of the following dimensionless ratio

$$\mathcal{R} = \frac{\mathcal{B}_{\Upsilon \to \gamma_s \ell\ell}}{\mathcal{B}_{\ell\ell}} = \left[\frac{m_b^2 k^3 \xi_b^2 \xi_\ell^2}{8\pi^2 \alpha \Gamma_{tot} v^4} \right] \times \frac{m_\ell^2}{\delta m^2} \tag{14}$$

where we are assuming that the main contribution to the leptonic channel comes from the photon exchange graph of figure 1.a. Let us point out once again that since γ_s is undetected, the Higgs contribution of figure 1.b would be experimentally ascribed to the leptonic channel of the Υ resonance.

For the sake of a comparison with other Higgs searches, I will identify in the following the ξ_f factor with the 2HDM (type II) parameter for the universal down-type fermion coupling to a CP-odd Higgs, i.e. $\xi_b = \xi_\ell = \tan\beta$, defined as the ratio of the vacuum expectation values of two Higgs fields [1]. Inserting numerical values, one gets the interval

$$\mathcal{R} \simeq (3.6 \cdot 10^{-9} - 4.5 \cdot 10^{-7}) \times \tan^4\beta \times m_\ell^2 \tag{15}$$

where use was made of the approximation $m_{\phi^0} \simeq 2m_b \simeq 10$ GeV, and the range $10 - 50$ MeV for the soft photon energy k; m_ℓ is expressed in GeV.

3 Lepton universality breaking: hypothesis testing

Now, I will confront the above predictions with the experimental results on Υ leptonic decays [35] summarized in Table 1. (Notice that although those BF's were often determined from raw data under the assumption of lepton universality, its possible small breaking would not alter considerably the final figures.) Indeed, from inspection of Table 1 one realizes that experimental data favor a slight but steady increase of the decay rate with the lepton mass in all cases. In spite of that, current error bars (σ_ℓ) are still too large (especially in the case of the $\Upsilon(2S)$) to permit a thorough check of the lepton mass dependence as expressed in (15).

Nevertheless, I will apply below a hypothesis test in order to draw, if possible, a statistically significant conclusion about lepton universality breaking. To this end, I present in Table 2 the differences $\Delta_{\ell\ell'}$ between BF's of distinct channels obtained from Table 1. In order to treat all of them in equal footing, such differences are divided by their respective experimental errors $\sigma_{\ell\ell'}$ (see Table 2).

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[7]More precisely, I used the static approximation for heavy quarks inside quarkonium (i.e. null relative momentum); then, the decay amplitude of the pseudoscalar state into a 0^{++} (CP-even) Higgs vanishes and only a 0^{-+} (CP-odd) Higgs couples to pseudoscalar quarkonium in this limit. Therefore, the Higgs hunted in this work could be properly denoted by A^0 though I will keep using the generic ϕ^0 symbol for it, though standing hereafter for a CP-odd Higgs.

Table 1: Measured leptonic BF's ($\mathcal{B}_{\ell\ell}$) and error bars (σ_ℓ) in %, of $\Upsilon(1S)$ and $\Upsilon(1S)$ (from [35]).

channel:	e^+e^-	$\mu^+\mu^-$	$\tau^+\tau^-$
$\Upsilon(1S)$	2.38 ± 0.11	2.48 ± 0.06	2.67 ± 0.16
$\Upsilon(2S)$	1.18 ± 0.20	1.31 ± 0.21	1.7 ± 1.6

Table 2: All six differences $\Delta_{\ell\ell'}$ (obtained from Table 1) between the leptonic BF's (in %) of $\Upsilon(1S)$ and $\Upsilon(2S)$ resonances separately. Subscript $\ell\ell'$ denotes the difference between channels into $\ell\bar{\ell}$ and $\ell'\bar{\ell'}$ lepton pairs respectively, i.e. $\Delta_{\ell\ell'} = \mathcal{B}_{\ell'\ell'} - \mathcal{B}_{\ell\ell}$; the $\sigma_{\ell\ell'}$ values were obtained from Table 1 by summing the error bars in quadrature, i.e. $\sigma_{\ell\ell'} = \sqrt{\sigma_\ell^2 + \sigma_{\ell'}^2}$. Only two $\Delta_{\ell\ell'}/\sigma_{\ell\ell'}$ values for each resonance can be considered as truly independent, amounting altogether to a total number of four independent points.

channels	$\Delta_{\ell\ell'}$	$\sigma_{\ell\ell'}$	$\Delta_{\ell\ell'}/\sigma_{\ell\ell'}$
$\Upsilon(1S)_{e\mu}$	0.1	0.125	$+0.8$
$\Upsilon(1S)_{\mu\tau}$	0.19	0.17	$+1.12$
$\Upsilon(1S)_{e\tau}$	0.29	0.19	$+1.53$
$\Upsilon(2S)_{e\mu}$	0.13	0.29	$+0.45$
$\Upsilon(2S)_{\mu\tau}$	0.39	1.61	$+0.24$
$\Upsilon(2S)_{e\tau}$	0.52	1.61	$+0.32$

On the other hand, we are especially interested in the *alternative* hypothesis based on the existence of a light Higgs boson enhancing the decay rate as a growing function of the leptonic squared mass, in opposition to the kinematic factor (2). Therefore, the *region of rejection* of our statistical test should lie only on *one side* (or *tail*) of the $\Delta_{\ell\ell'}/\sigma_{\ell\ell'}$ variable distribution (i.e. positive values if $m_{\ell'} > m_\ell$), in particular above a preassigned *critical value* [40]. In other words, I will perform a *one-tailed test* [40] using the sample consisting of four independent BF differences between the electronic and the muonic and tauonic channels respectively (i.e. $\Delta_{e\mu}/\sigma_{e\mu}$, $\Delta_{e\tau}/\sigma_{e\tau}$) for both $\Upsilon(1S)$ and $\Upsilon(2S)$ resonances shown in Table 2. I will assume that such differences follow a normal probability distribution. Then, the mean of the four $\Delta_{e\ell'}/\sigma_{e\ell'}$ values ($\ell' = \mu, \tau$) turns out to be 0.775.

Next, I define the *test statistic*: $T = \langle \Delta_{e\ell'}/\sigma_{e\ell'} \rangle \times \sqrt{N} = 1.55$, where $N = 4$ stands for the number of independent points. (Note that we are dealing with a Gaussian of unity variance after dividing all differences by their respective errors.) Now, choosing the *critical value* to be $\simeq 1.3$, the lepton universality hypothesis [playing the role of the *null hypothesis* in our test, predicting a mean zero (or slightly less) value] can be *rejected* at a *significance level* of 10% since $T > 1.3$ [8]. Certainly, this result alone is not statistically significant enough to make any serious claim about the rejection of the lepton universality hypothesis in this particular process, but points out the interest to investigate further the alternative hypothesis stemming from Eq.(15).

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[8]Let us recall [40] that in a (simple) hypothesis test, the *significance level* (or *error of the first kind*) represents the percentage of all decisions such that the null hypothesis was rejected when it should, in fact, have been accepted.

4 Final results and discussion

On the grounds of the hypothesis test carried out in the previous section, I conclude that current experimental data shown in Table 1 are compatible with a (small) breaking of lepton universality in Υ leptonic decays at a significance level of 10%. Indeed, there seems to be a slight but measurable increase of the leptonic decay rate, by a $\mathcal{O}(10)\%$ factor, from the electronic channel to the tauonic channel, which can be interpreted theoretically following the 2HDM upon a reasonable choice of its parameters.

Actually, from Eq.(15) one obtains that, under the assumption of a Higgs boson of mass about 10 GeV to explain such a 10% enhancement, $\tan\beta$ should roughly lie over the range:

$$16 \lesssim \tan\beta \lesssim 54 \tag{16}$$

depending on the value of k, namely from 50 MeV to 10 MeV, whose limits remain somewhat arbitrary however. Thus a caveat is in order: the above interval is purely indicative as it only takes into account the probability range on the M1 transition estimated according to Eq.(5), and not other sources of uncertainty. In this regard I have not considered, for example, the possible mixing of the CP-odd Higgs with the pseudoscalar $b\bar{b}$ system stemming from the Υ after photon radiation, which nevertheless could modify notably the properties of the former [39].

It is worthwhile to remark that the $\tan\beta$ interval of Eq.(16) is compatible with the range needed to interpret the $g - 2$ muon anomaly in terms of a light CP-odd Higgs (A^0) resulting from a two-loop calculation [18, 41] [9]. In this regard, other authors considered a CP-even Higgs (h^0) in a one-loop calculation [17] also yielding parametric values very close to ours; nevertheless, note that the possibility of a scalar Higgs, contributing to the Υ leptonic decay as conjectured in this work, was discarded in our study since the corresponding partial width vanishes in the (leading) static approximation for the $b\bar{b}[^1S_0^{(1)}]$ intermediate state.

In summary, I have pointed out in this Letter a possible breaking of lepton universality in Υ leptonic decays, interpreted in terms of a neutral CP-odd Higgs of mass around 10 GeV, introducing a m_ℓ^2 dependent contribution in the partial width. (Notice that higher-order corrections within the SM can not imply such a quadratic dependence on the leptonic mass.) Pictorially, one could say that the Higgs is "hidden" in part because the (undetected) M1 photon, stemming from the assumed prompt structural transition, merges with the bulk of soft photon radiation incorporated into the very definition of the leptonic BF [35].

I end by emphasizing the interest in more accurate data on leptonic BF's of Υ resonances, particularly considering the exciting possibility of a signal of New Physics as pointed out in this work. Hopefully, B factories working below open bottom production will provide in a near future new and likely more precise measurements of the leptonic BF's for the Υ family, perhaps requiring specific dedicated data-taking periods if a light CP-odd Higgs discovery strategy would be conducted including a complementary search for a CP-even Higgs in accordance with the process (4).

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[9]However, after correcting a sign mistake in the so-called hadronic light by light contribution in the $g - 2$ calculation [42, 43] the discrepancy with respect to the SM becomes smaller than initially expected. Still the situation is under close scrutiny (see, for example, [44]).

Acknowledgements

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