Searching for a light Higgs in \( \Upsilon \) leptonic decays

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Leptonic decays of vector-states of bottomonium are analyzed searching for a light pseudoscalar Higgs-like neutral boson manifesting via an apparent breaking of lepton universality.

1. INTRODUCTION

Although there are well established lower mass bounds for the standard Higgs (e.g. from LEP searches [1]), the situation may be different in several scenarios and models beyond the standard model (SM) where such constraints would not apply, leaving still room for light Higgs bosons (see [2,3] 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) [4], appropriate to deal with such bound states from first principles.

Indeed, intensive searches for a light Higgs-like boson (to be generically denoted by \( \phi^0 \) in this paper) have been performed according to the so-called Wilczek mechanism [5] 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 [6].

Nevertheless, in this work 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 \( \Upsilon \) resonances below the \( BB \) threshold (if experimentally confirmed by forthcoming measurements) might be viewed as a hint of the existence of a Higgs of mass about 10 GeV.

1.1. Searching for a light Higgs in \( \Upsilon \) leptonic decays

Let us write the well known Van Royen-Weisskopf formula including color, expressing the leptonic decay width of the \( \Upsilon(1S) \) vector resonance without neglecting leptonic masses:

\[
\Gamma_{\ell^+\ell^-} = 4\alpha^2 Q_b^2 \left| R_n(0) \right|^2 \frac{M_{\Upsilon}}{M_{\ell^+}} K(x)
\]

where \( \alpha \approx 1/137 \) is the electromagnetic fine structure constant; \( M_{\Upsilon} \) denotes the mass of the \( \Upsilon \) particle and \( Q_b \) is the charge of the bottom quark (1/3 in units of e); \( R_n(0) \) is the non-relativistic radial wave function of the \( b\bar{b} \) bound state at the origin; finally \( K(x) = (1 + 2x)(1 - 4x)^{1/2} \) with \( x = m_{\ell^+}^2/M_{\Upsilon}^2 \). 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 paper, we will consider the sequential decay

\[
\Upsilon \to \gamma \phi^0 \to \ell^+\ell^- ; \quad \ell = e, \mu, \tau
\]
1.2. An intermediate spin-singlet $b\bar{b}$ state?

In a vector resonance like the $\Upsilon(1S)$, the heavy quark pair can be in a $^3S_1$ color-singlet state in the lowest Fock state, but the $Q\bar{Q}$ system could also exist with other quantum numbers than $J^P = 1^-$ since the soft degrees of freedom can carry the remaining quantum numbers, although with a smaller probability. These ideas have been cast into the rigorous formulation of NRQCD [4] and extensively applied to heavy quarkonia production and decay. Moreover, one can wonder about the possibility of reaching such Fock states by emission of soft photons instead of soft gluons. Let us note however a crucial difference between the two: photons carry color and hence, there exists a lower cutoff corresponding to a minimum amount of energy “taken away” in the hadronization stage (corresponding to a pion mass for instance). However, this is not the case for photons. Actually, the experimental determination of the leptonic branching fraction (BF) $B_{\ell\ell}$ actually includes decays accompanied by a large number number of soft photons [8].

On the other hand, magnetic dipole (M1) transitions can connect spin-triplet and spin-singlet states by emission of soft photons from heavy quark lines (see Fig. 1). The probability for this process can be obtained by dividing the corresponding width [7] by by the total width of the resonance, $\Gamma_{\text{tot}} = 52.5$ KeV [8], i.e.

$$P_{\Upsilon(1S)\rightarrow \gamma_s(b\bar{b})[1S_0]} = \frac{1}{\Gamma_{\text{tot}}} \frac{4\alpha Q^2}{3m_b^2} k^3 \quad (3)$$

where $k$ denotes the energy of the soft photon $\gamma_s$ varying in the range $k = 10 - 50$ MeV. Let us also remark that soft photons in this experimental context are those whose energies do not exceed the experimental resolution and hence are actually not observed $^3$.

$^3$Typical widths of resonance peaks in $e^+e^-$ machines are of the order of few tens of MeV for the $\Upsilon$ family below open bottom production. Moreover, typical low energy cutoffs for photon detection are of the order of 50 MeV. Notice also that the use of Eq (3) as an estimate for the magnetic dipole transition is justified since the respective wave-lengths of the radiated photons are quite larger than the size of quarkonium (of order $\approx \text{GeV}^{-1}$).

1.3. Effects of a light “Higgs” on $B_{\ell\ell}$

Let us focus on the bottomonium family of $\Upsilon(nS)$ states below open flavor (i.e. $n < 4$; the $\Upsilon(3S)$ state is however discarded in the present analysis since only experimental data for the muonic channel [8] are currently available) decaying into a lepton pair plus a soft photon $\gamma_s$:

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

where the soft (I stress it once more: unobserved) $\gamma_s$ comes from a M1 transition of the $\Upsilon$ resonance, as sketched in Fig. 1.b. I will write the decay width $\Gamma_{\Upsilon,\ell\ell}$ corresponding to the formation of an intermediate state followed by its annihilation via a Higgs particle.

![Figure 1](image-url)
an scalar or pseudoscalar in the factored form:

\[ \Gamma_{\gamma,\ell\ell} = \mathcal{P}_{\mathcal{T}(1S)\to\gamma,\ell\ell}[S_0] \times \tilde{\Gamma}_{\ell\ell} \]

where \( \tilde{\Gamma}_{\ell\ell} \) stands for the annihilation width of the \( b\bar{b} \) pair in a spin-singlet state into a lepton pair via a Higgs \( (\phi^0) \) boson as depicted in Fig.1. Furthermore, fermions are assumed to couple to the \( \phi^0 \) field according to a Yukawa interaction term in the effective Lagrangian:

\[ \mathcal{L}^{\rm int}_{\text{Yuk}} = -\xi_f \phi^0 \frac{v}{\sqrt{2}} m_f (i\gamma_5) \bar{f} \]

where \( v = 246 \text{ GeV} \) stands for the vacuum expectation value of the standard Higgs boson; \( \xi_f \) denotes a factor depending on the type of the Higgs boson, which could enhance the coupling with a fermion (quark or lepton) of type \( \ell \). Lastly, note that the \( i\gamma_5 \) matrix stands only in the case of a pseudoscalar \( \phi^0 \) field.

Now, let us tentatively assume that the mass of the light Higgs sought stands close to the \( \Upsilon(1S) \) resonance but below \( BB \) production: \( m_{\phi^0} \approx 2m_b \). As will be argued from current experimental data in the next section, I am supposing specifically that \( m_{\phi^0} \) lies somewhere between the \( \Upsilon(1S) \) and \( \Upsilon(2S) \) masses, i.e.

\[ m_{\Upsilon(1S)} \leq m_{\phi^0} \leq m_{\Upsilon(2S)} \]

Next, let us define the mass difference: \( \delta m = |m_{\phi^0} - m_{\Upsilon}| \), where \( \Upsilon \) denotes either a 1S or a 2S state. Accepting for simplicity that the Higgs stands halfway between the mass values of both resonances, \( \delta m \approx 0.25 \text{ GeV} \) for an order-of-magnitude calculation. Hence the scalar tree-level \( \phi^0 \) propagator can be written approximately as

\[ \frac{1}{(m^2_{\Upsilon} - m^2_{\phi^0})^2} \approx \frac{1}{16 \pi^2 \delta m^2} \]

where the width of the Higgs boson has been neglected for it should be very narrow due the smallness of \( m_{\phi^0} \) and, moreover, standing below bottom open production.

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

\[ \mathcal{R} = \frac{B_{\Upsilon\to\gamma,\ell\ell}}{B_{\ell\ell}} = \left[ \frac{m_b^2 k^3 \xi_f^2 S^2}{8\pi^2 \alpha \Gamma_{\text{tot}} v^4} \right] \times \frac{m_b^2}{\delta m^2} \]

where we are assuming that the main contribution to the leptonic channel comes from the photon exchange graph of Fig. 1.a. Let us point out once again that since \( \gamma_8 \) is undetected, the Higgs contribution of figure 1.b would be experimentally ascribed to the leptonic channel of the \( \Upsilon \) resonance.

For the sake of a comparison with other Higgs searches, I will identify the \( \xi_f \) 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 [6]. Inserting numerical values,

\[ \mathcal{R} \approx (3.6 \times 10^{-9} - 4.5 \times 10^{-7}) \times \tan^4 \beta \times m_b^2 \]

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

## 2. HYPOTHESIS TEST ON LEPTON UNIVERSALITY

From inspection of experimental data presented in Table 1, one realizes a slight but steady increase of the decay rate with the lepton mass. In spite of that, current error bars \( (\sigma_{\ell}) \) 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 Eq.(9). 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 \( \Delta_{\ell\ell} \) divided by their respective errors \( \sigma_{\ell\ell} \), between BF’s of distinct channels obtained from Table 1. Then applying a one-tailed test [9], I define the region of rejection above a preassigned critical value of the \( \Delta_{\ell\ell}/\sigma_{\ell\ell} \) variable (i.e. positive values if \( m_{\ell} > m_{\ell'} \)), assuming a normal distribution.

The mean of the four \( \Delta_{\ell\ell}/\sigma_{\ell\ell} \) values \( (\ell' = \mu, \tau \) for both \( \Upsilon(1S) \) and \( \Upsilon(1S) \) resonances) turns out to be 0.775. Next, I define the test statistic: \( T = (\Delta_{\ell\ell}/\sigma_{\ell\ell}) \times \sqrt{N} = 1.55 \), where \( N = 4 \) stands for the number of independent points. (Note also that we are dealing with a Gaussian of unity variance.) Choosing the critical value to be \( \approx 1.3 \), the lepton universality hypothesis [playing the role of
Table 1
Branching fractions \( B_{\ell\ell} \) (in %) of \( \Upsilon(1S) \) and \( \Upsilon(2S) \) leptonic decays (from [8]).

| 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 \( \Delta_{\ell\ell} \) (from Table 1) between the leptonic branching fractions (in %) corresponding to \( \Upsilon(1S) \) and \( \Upsilon(2S) \) resonances separately, i.e. \( \Delta_{\ell\ell} = B_{\ell\ell} - B_{\ell\ell} \); the \( \sigma_{\ell\ell} \) values were obtained from Table 1 by summing error bars in quadrature. Note that only two \( \Delta_{\ell\ell}/\sigma_{\ell\ell} \) for each resonance can be considered as truly independent.

| 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              |

the null hypothesis in our test, predicting a mean zero (or slightly less) value can be rejected at a significance level of 10\% since \( T > 1.3 \). Certainly, this result 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.(9).

In order to explain the observed \( \mathcal{O}(10)\% \) enhancement from the electronic to the tauonic channel (see Table 1), one gets

\[
16 \leq \tan \beta \leq 54 \tag{10}
\]

depending on the value of \( k \), namely from 50 MeV to 10 MeV in (9). 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.(3), and not other sources of uncertainty. It is also worthwhile to remark that the interval (9) 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 [10] \(^4\).

3. SUMMARY

I have pointed out in this paper a possible breaking of lepton universality in \( \Upsilon \) leptonic decays, interpreted in terms of a neutral CP-odd Higgs of mass around 10 GeV, introducing a \( m_\ell^2 \) dependent contribution in the partial width.

I end by emphasizing the interest in more accurate data on leptonic BF's of \( \Upsilon \) 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 \( \Upsilon \) family.

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\(^4\)However, after correcting a sign mistake in the so-called hadronic light by light contribution in the \( g-2 \) calculation the discrepancy with respect to the SM becomes smaller than initially expected [11].