Chapter 8

BEYOND THE STANDARD MODEL

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1 General overview

During the last years, a large amount of new data on charmonium and bottomonium production and decays have been collected in B-factories, Tevatron, HERA and BEPC, greatly improving the accuracy of the measured widths and branching fractions. Such measurements, together with the soundness of the theoretical background based on effective field theories, could show up possible deviations from SM expectations, thereby pointing out the existence of NP. Lepton flavour and CP violation in heavy quarkonia decays are good examples of such precision physics. Moreover, in the past radiative decays of heavy quarkonium were employed in the search for axions and Higgs particles according to the Wilczek mechanism [1]. Recently, the possibility of relatively light non-standard Higgs bosons (which might have evaded LEP searches) has been pointed out in different scenarios beyond the SM [2–4]. Therefore, discovery strategies should be conducted to detect possible signals of new physics from heavy quarkonia decays.

2 Prospects to detect new physics

Heavy quarkonium offers an interesting place where probing NP which would manifest experimentally in different ways: a) slight but observable modifications of decay rates and branching fractions; b) unexpected topologies in decays; c) CP and lepton flavour violation, etc. Along this chapter we will discuss in some detail three proposals to search for new physics and the prospects to detect non-standard light particles based on decays of heavy quarkonium:

- CP test with J/ψ decays, probing the electric and chromo-dipole moments of charm quarks
- Lepton flavour violation in J/ψ's two-body decays
- non-standard Higgs-mediated leptonic decays of Upsilon resonances

Moreover, let us mention other possibilities (not developed further in this chapter) to seek NP:

- Inspired by string-like scenarios, field theories formulated in noncommutative spaces should be explored. In particular, noncommutative QCD corrections to the gluonic decays of heavy quarkonia have been analyzed in [5]. Despite proving the consistency of perturbative calculations in this model, the inclusion of such corrections does not change substantially the magnitudes of the hadronic widths, thereby making difficult the experimental test.
- A relatively light bottom squark and gluino sector in supersymmetry was put forward some time ago [6] to explain the longstanding discrepancy on the bottom hadroproduction cross-section between theory and experiment found at Tevatron [7, 8]. Under this hypothesis, interesting consequences could show up in bottomonium phenomenology [9–11], e.g., the decay modes

$$\Upsilon \to \tilde{b}\tilde{b}^* \quad ; \quad \chi_b \to \tilde{b}\tilde{b}^*, \quad \Upsilon \to \gamma\, \tilde{S} \quad ; \quad \Upsilon \to \gamma\, \eta_{\tilde{g}}$$

  If the bottom squark was relatively "stable" it might yield a $\tilde{B}^-$ or a $\tilde{B}^0$ "mesino" (the superpartner of the B meson) by picking up a $\bar{u}$ or a $\bar{d}$ quark, respectively. Such a meson has baryon number zero but would act like a heavy $\bar{p}$ (of mass $\sim 3-7$ GeV). In fact at LHC experiments it could fake a heavy muon in muon chambers but leaving some activity in the hadron calorimeter; ionization, time-of-flight and Cherenkov measurements would be consistent with a particle whose mass is heavier than a proton. However, recently a more accurate description of the b-quark fragmentation function has substantially reduced the difference between theoretical expectations and experimental results in bottom hadroproduction [12, 13]. Although the situation is not definitely settled, now the claim for a new physics contribution in bottom production is not compelling at all. Besides, a throughout analysis of the $e^+e^-\to hadrons$ cross-section from PEP, PETRA, TRISTAN, SLC and LEP allows the 95% C.L. exclusion of sbottom with mass below 7.5 GeV [14]. Also a light gluino mass less than 6.3 GeV has been excluded [15].

3 PRECISION TESTS USING J/ψ DECAYS

Huge amount of data (to be) collected in e^+e^- factories like BEPC (and the upgraded BEPCII) and CLEO should allow to test some aspects of the SM to an unprecedented accuracy. In the following sections we describe two research lines based on J/ψ rare decays.

3.1 CP test with J/ψ decays[1]

We open this review on searches for new physics by remarking that a nonzero electrical dipole moment (EDM) of a quark or a lepton implies that CP symmetry is violated. Actually, EDM's of quarks and leptons are very small from the SM (see [16–18] and references therein). If the EDM of a quark is found to be nonzero, it is likely an indication of new physics.

Since the operator for EDM does not converse helicities of quarks, its effect is suppressed in a high energy process by a factor m_q/E, where m_q is the quark mass and E is a large energy scale. For light quarks, useful information can be obtained through measurement of the EDM of the neutron [16]. So far there is no experimental information about EDM's of heavy quarks, like charm- and bottom-quark. J/ψ decays can provide information of EDM of charm quark and has the advantage that the effect of EDM will be not suppressed, because the large energy scale is around m_c. Since in radiative decays a $c\bar{c}$ pair is annihilated into a photon and gluons, it also provides a way to detecting the chromodipole moment of the charm quark. These moments are defined by the effective Lagrangian:

$$L_{CP} = -i\frac{d_c}{2}\bar{c}\gamma_5\sigma_{\mu\nu}F^{\mu\nu}c - i\frac{\tilde{d}_c}{2}\bar{c}\gamma_5\sigma_{\mu\nu}G^{\mu\nu}c, \tag{8.1}$$

where d_c is the electric dipole moment, $\tilde{d}_c$ is the chromodipole moment.

In general a CP symmetry test requires a large data sample because the effect of its possible violation is expected to be very small. In the following we focus on J/ψ decays [19] as large data samples already exist or will be collected at BEPC and CLEO-c. Indeed, such huge data samples (with $10^7 \sim 10^{10}$ J/ψ's) are very suited for CP tests. However, not every decay mode of J/ψ can be used for this purpose. For a J/ψ decay into a particle and its antiparticle, a CP test is not possible if these particles are spinless or their polarizations are not observed [18, 20]. It is only possible if polarizations of decay products are measured. The decay $J/\psi\to\Lambda\bar{\Lambda}$ is an example, where the polarizations can be determined through subsequential decays of Λ and $\bar{\Lambda}$ [21].

On the other hand, a CP test can be carried out for three-body decays, even without knowing the polarizations of the decay products. This is the case of the $J/\psi\to\gamma\phi\phi$ decay mode, which can provide useful information about the charm quark EDM. The reason for choosing this channel is because ϕ is a very narrow resonance, just above $K\bar{K}$ threshold, and can be clearly identified by its K^+K^- decay mode in experiment. In principle $J/\psi\to\gamma\rho\rho$ could also serve for the purpose, but experimentally the broad width of ρ meson makes it impossible to get a clean sample from this channel. Therefore, let us consider the decay in the rest-frame of J/ψ produced at a e^+e^- collider:

$$e^+(k_+) + e^-(k_-)\to J/\psi(P)\to\gamma(k) + \phi(p_1) + \phi(p_2), \tag{8.2}$$

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where momenta are given in brackets. Because the two ϕ mesons are identical particles, we require $p_1^0 > p_2^0$ to distinguish them in experiment. In our case two CP-odd observables can be constructed:

$$O_1 = \hat{\mathbf{k}}_+ \cdot \hat{\mathbf{p}}_\mathbf{1}\hat{\mathbf{k}}_+ \cdot (\hat{\mathbf{p}}_\mathbf{1} \times \hat{\mathbf{p}}_\mathbf{2}), \;\; O_2 = \hat{\mathbf{k}}_+ \cdot \hat{\mathbf{p}}_\mathbf{2}\hat{\mathbf{k}}_+ \cdot (\hat{\mathbf{p}}_\mathbf{1} \times \hat{\mathbf{p}}_\mathbf{2}), \tag{8.3}$$

where momenta with a hat denote their directions. From these oberservables, one can define the CP-asymmetry as

$$B_i = \langle \theta(O_i) - \theta(-O_i) \rangle \;\; (i = 1, 2), \tag{8.4}$$

where $\theta(x) = 1$ if $x > 0$ and is zero if $x < 0$. If these asymmetries are not zero, CP symmetry is violated.

In calculating these asymmetries, we will use nonrelativistic wave-functions for J/ψ and also for ϕ mesons. It should be noted that reliable predictions for various distributions can not be obtained with this approximation. Neverthesless, one may expect that for integrated asymmetries it could become a good approximation, especially because the integrated asymmetries will not depend on the wave functions at the origin.

The following CP asymmetries are obtained:

$$\begin{aligned} B_1 &= 4.2 \left[\frac{d_c}{10^{-10} e \text{ cm}} \right] - 1.2 \left[\frac{\tilde{d}_c}{10^{-10} e \text{ cm}} \right], \\ B_2 &= -3.9 \left[\frac{d_c}{10^{-10} e \text{ cm}} \right] + 1.3 \left[\frac{\tilde{d}_c}{10^{-10} e \text{ cm}} \right]. \end{aligned} \tag{8.5}$$

A statistic sensitivity to d_c and $\tilde{d}_c$ can be determined from these results by requiring that the asymmetry generated by these dipole moments should be larger than the statistical error. With the 5.8×10^7 J/ψ data sample at BES, the sensitivities of such CP asymmetries to these dipole moments are

$$d_c \sim 1.4 \times 10^{-13} e \text{ cm}, \quad \tilde{d}_c \sim 4.5 \times 10^{-13} e \text{ cm}. \tag{8.6}$$

With a 10^{10} data sample which will be collected in the near future, the sensitivities are:

$$d_c \sim 1.2 \times 10^{-14} e \text{ cm}, \quad \tilde{d}_c \sim 3.6 \times 10^{-14} e \text{ cm}. \tag{8.7}$$

To conclude this section: With large date samples of J/ψ, which are collected at BES and will be collected with BES III and CLEO-c program, a CP test is possible with J/ψ decays. By using the decay mode $J/\psi \to \gamma\phi\phi$, the electric- and chromo-dipole moment can be probed at order of $10^{-13} e$ cm $\sim$ $10^{-14} e$ cm.

3.2 Lepton flavour violation

In the SM, lepton flavour number is independently conserved provided that neutrinos are massless, although (being a global symmetry) there is no fundamental dynamical principle requiring its conservation. Actually, lepton flavour is violated in many extensions of the SM, such as grand unified theories [22], supersymmetric models [23], left-right symmetric models [24] and models where the electroweak symmetry is dynamically broken [25]. Recent results [26, 27] indicate that neutrinos indeed have nonzero masses and can mix with each other; therefore, lepton flavour is a broken symmetry in nature. Here, we focus on lepton flavour violation (LFV) via the two-body J/ψ decay (which conserves total lepton number):

$$J/\psi \to \ell\ell'$$

with ℓ and ℓ' denoting charged leptons of different species. This process could occur at tree-level induced by leptoquarks, sleptons (both in the t-channel) or mediated by Z' bosons (in the s-channel) [28, 29] in correspondence with the aforementioned scenarios.

The large sample (5.8×10^7 events) collected in leptonic decays of J/ψ resonances at BEPC and analized by BES up to now makes this search especially interesting; in fact, upper limits for different lepton combinations have already been set at 90% C.L. [30, 31]:

$$\begin{aligned} \mathcal{B}(J/\psi \to \mu\tau) &< 2.0 \times 10^{-6} \\ \mathcal{B}(J/\psi \to e\tau) &< 8.3 \times 10^{-6} \\ \mathcal{B}(J/\psi \to e\mu) &< 1.1 \times 10^{-6} \end{aligned}$$

In the future, larger samples collected at BEPC(II) should allow to test LFV at a higher precision, severely constraing new physics models. Similarly, estimates of the LFV Upsilon decay $\Upsilon \to \ell\ell'$ can be found in [29].

4 SEARCHES FOR LIGHT PSEUDOSCALARS IN Υ DECAYS

In many extensions of the 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-tuning 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 [32] was introduced in the framework of a two-Higgs doublet model (2HDM) to solve the strong CP problem. However, such an axial U(1) symmetry is anomalous and the pseudoscalar acquires a (quite low) mass which has been ruled out experimentally. Thus, theorists have looked for other models (by relaxing model parameter constraints) and axion-like particles, not running into conflict with present terrestrial experiments and astrophysical limits (see [33] and references therein).

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 gauge-singlet superfield is added to the Higgs sector [34]. 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 trillinear terms [2]. Moreover, the smallness of the mass is protected from renormalization group effects in the large $\tan\beta$ limit. Actually, there are other scenarios containing a light[2] pseudoscalar Higgs boson which could have escaped detection in the searches at LEP-II, e.g., a MSSM Higgs sector with explicit CP violation [4]. Another example is a minimal composite Higgs scenario [3] where the lower bound on the CP-odd scalar mass is quite loose, as low as ~ 100 MeV (from astrophysical constaints).

Thus we conclude that the existence of a relatively light pseudoscalar Higgs (to be denoted as A^0 hereafter) is not in contradiction with current experimental data and could be accomodated within well motivated extensions of the SM. Therefore, it is worth to revisit some of the "old" techniques to search for non-standard particles in quarkonia decays, also exploring new possibilities like a possible breakdown of lepton universality in Υ decays.

4.1 $\Upsilon(J/\psi) \to \gamma + X^0$

Heavy resonances have been helpful so far putting limits in the searches for extensions of the SM through the radiative decay channel

$$\Upsilon(J/\psi) \to \gamma + X^0$$

where X^0 stands for a weakly interacting (experimentally unseen) particle. This decay mode represents, in essence, the Wilczek mechanism [1] for the real emission of either a Higgs boson or an axion from quarkonium. The experimental signature would be very clean: the observation of a single photon with

[2]By "light" we consider here a broad interval which might reach a $\simeq 10$ GeV mass value

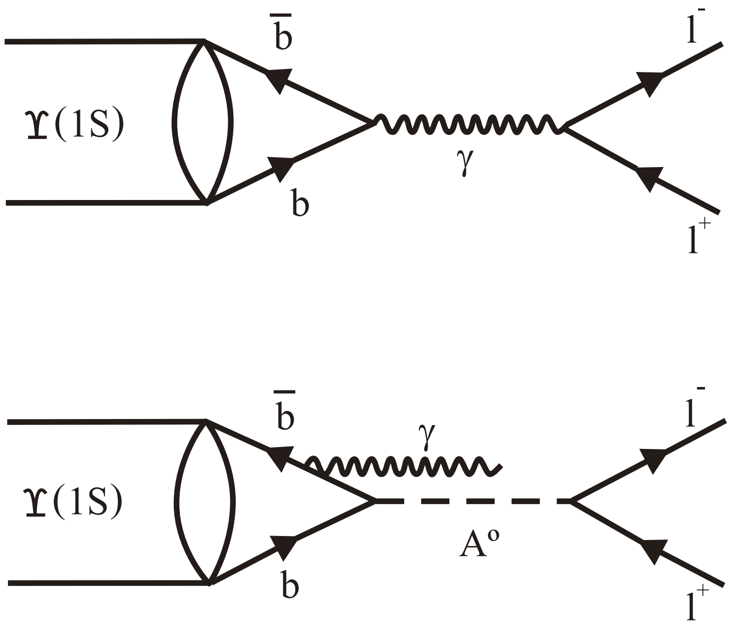

Fig. 8.1: $\Upsilon(1S)$ resonance into a charged lepton pair through a virtual photon; (b)[lower panel]: Hypothetical annihilation of an intermediate η_b^* state (subsequent to a M1 structural transition yielding a final-state soft photon) into a charged lepton pair through a CP-odd Higgs-like particle denoted by A^0.

a considerable missing energy in the event. Let us observe that this would be so if the X^0 is sufficiently stable, i.e., the probability to decay inside the detector (of typical size $r \sim$ 10 m) is quite small, $\Gamma_{X^0} << E_{X^0}/m_{X^0}r$, where E_{X^0} and m_{X^0} denote the (laboratory) energy and mass of the unseen particle, respectively. Notice, however, that the chances to leave unseen the detector decrease for values of m_{X^0} close to E_{X^0} as the Lorentz dilation factor approaches unity. To date, no evidence has been found and limits have been set as a function of the mass of the X^0 particle [35]. Note that such limits in Υ decays only exclude particles below $5-7$ GeV! [36] Thus, in view of the renewed interest in pseudoscalars whose mass may lie around 10 GeV, an open mind should be kept in those and related searches.

4.2 Non-standard Higgs-mediated leptonic decays of Υ resonances

In the previous section we considered the possibility of emission by heavy quarkonium of a real, long-lived but unseen particle. However, if the emitted particle width is large enough, the particle would promptly decay and its products could make possible its observation by the detector. On the other hand, virtual poduction of (off-shell) particles should be also analized. In this section we examine the possible existence of a CP-odd Higgs mediating the annihilation of the $b\bar{b}$ pair (subsequent to a magnetic dipole transition of the Upsilon resonance) into a final-state dilepton (see Fig. 8.1). This channel would constitute a rare decay mode of the Υ resonance, observable however if the Higgs mass is not too far from the Υ mass and the couplings are not small. In fact, rare decays have been traditionally employed for seeking new physics, in particular looking for extensions of the Higgs sector of the SM. Let us mention, as a significant example, the (flavor-changing neutral current) decays of B mesons into lepton pairs (e.g., $B^0_{s,d} {\rightarrow} \mu^+\mu-$), where a non-standard Higgs-mediated contribution could modify (enhancing) the SM decay rates [37].

As pointed out in a series of recent papers [38–40], bottomonium also offers the possibility of testing extensions of the SM by looking at possible non-standard Higgs-mediated leptonic decay channels of Upsilon resonances below the $B\bar{B}$ threshold, in addition to the dominating electromagnetic mode

$$\Upsilon(nS){\rightarrow}\gamma^*{\rightarrow}\ell^+\ell^- \quad (\ell = e, \mu, \tau, \ \ n = 1, 2, 3)$$

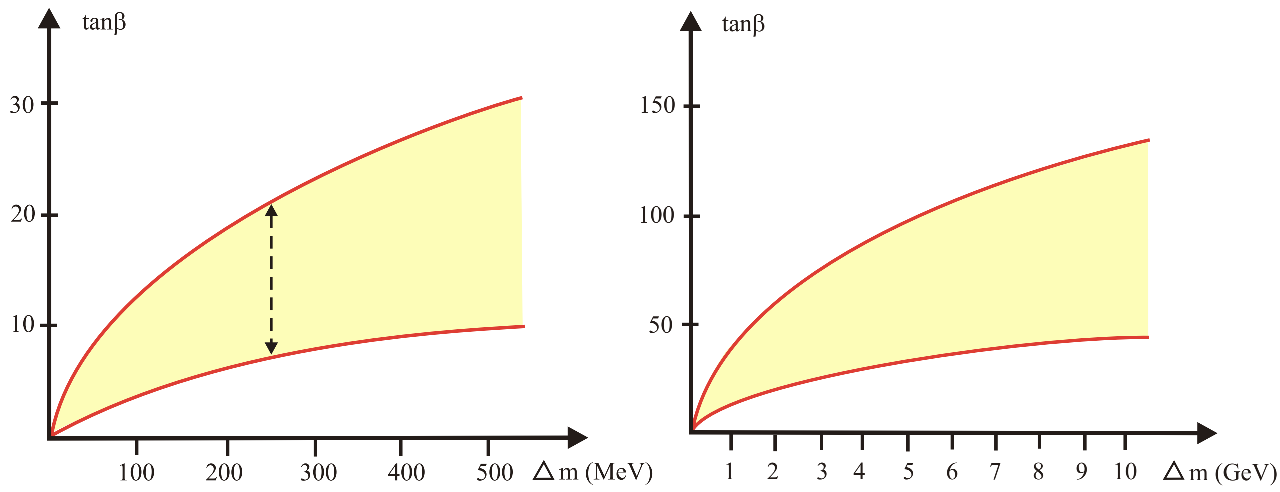

Fig. 8.2: Required $\tan\beta$ values (shaded area) as a function of Δm needed to account for a $\sim 10\%$ breakdown of lepton universality in Υ decays according to a 2HDM(II). The vertical dotted line shows the range of $\tan\beta$ for $\Delta m = 250$ MeV used in [39] as a reference value.

We shall focus as a theoretical background on a general 2DHM of the type II [34] where down fermions couple to the Higgs boson proportionally to the ratio ($\tan\beta$) of the two Higgs vacuum expectation values. Nevertheless, the main conclusions can be extended to different scenarios predicting other Higgs-like particles with analogous phenomenological features.

Let us assume that a prior magnetic dipole (M1) direct transition from the initial-state Υ can take place yielding a pseudoscalar $b\bar{b}$ intermediate state as shown in Fig. 8.1, subsequently annihilating into a lepton pair via a non-standard CP-odd Higgs boson A^0:

$$\Upsilon(nS) \to \gamma_s\, \eta_b^*(\to A^0 \to \ell^+\ell^-) \qquad (\ell = e, \mu, \tau,\;\; n = 1, 2, 3)$$

where γ_s stands for an undetected soft photon with energy in the range 35–150 MeV, depending on the still unknown $\Upsilon - \eta_b$ hyperfine splitting. As the photon is quite soft, the M1-transition probability $\mathcal{P}^{\Upsilon}(\eta_b^*\gamma_s)$ was roughly obtained in [39, 40] from a textbook expression relating on-shell states. A consequence of the existence of this kind of NP would be the “apparent”[3] breaking of lepton universality based on the two following keypoints:

- In the experimental determinations of the leptonic BF of the Upsilon resonances, the Higgs contribution would be unwittingly ascribed to the leptonic decay mode as the radiated photon would remain undetected. This would be especially the case for the $\tau^{\pm}$ channel[4]
- The leptonic (squared) mass dependence in the width from the Higgs contribution would introduce a dependence on the leptonic species in the leptonic BF. The effect would only be noticeable in the tauonic decay mode as the electron and muon masses are much smaller than the tau mass.

Current experimental data (see Table 8.1) may indeed hint that there is a difference of order 10% in the BFs between the tauonic channel on the one side, and the electronic and muonic modes on the other side [39]. The range of the $\tan\beta$ needed to account for such an effect is shown in Fig. 8.2 as a function of the mass difference (Δm) between the non-standard Higgs and the $\eta_b(1S)$ resonance, applying the

[3]In the sense that once the Higgs contribution were taken into account, lepton universality would be restored

[4]The leptonic mass squared with a final-state photon is given by $m_{\ell\ell}^2 = m_{\Upsilon}^2(1 - 2E_{\gamma}/m_{\Upsilon})$. Hence E_{γ} is much more limited by invariant mass reconstruction of either final-state electrons or muons than for tau's where such constraint is not applicable.

Table 8.1: Measured leptonic BF's and error bars in % of $\Upsilon(1S)$ and $\Upsilon(2S)$ (from [36]).

channel:	e^+e^-	$\mu^+\mu^-$	$\tau^+\tau^-$
$\Upsilon(1S)$	2.38 ± 0.11	2.48 ± 0.06	2.67 ± 0.16
$\Upsilon(2S)$	1.34 ± 0.20	1.31 ± 0.21	1.7 ± 1.6

factorization of the decay width used in [39]. The upper and lower curves correspond to the maximal and mimimal estimates of the M1-transition probability $\mathcal{P}^{\Upsilon}(\eta_b^*\gamma_s)$, respectively. For the large values of Δm, only the lower values of the shaded region would be acceptable, corresponding to the higher estimates of $\mathcal{P}^{\Upsilon}(\eta_b^*\gamma_s)$.

In addition to the postulated breaking of lepton universality, other experimental signatures which would eventually support the conjecture on a CP-odd Higgs boson showing up in bottomonium spectroscopy and decays are:

- A $\Upsilon - \eta_b$ hyperfine splitting larger than expected from quark potential models, caused by $A^0 - \eta_b$ mixing. A mass splitting significantly larger than 100 MeV could be hardly accomodated within the SM
- A rather large full width of the η_b resonances due to the NP channel (especially for high values of $\tan\beta$)
- If, instead, the η_b state is not too broad (as this would be the case for the lowest values of $\tan\beta$ in Fig. 8.2), one could look for monoenergetic photons with energy of order 100 MeV (hence above detection threshold) in those events mediated by the CP-odd Higgs boson (estimated to be about 10% of all Υ tauonic decays)

4.2.1 Spectroscopic consequences for bottomonium states

In view of our previous considerations, one can speculate about a quite broad η_b resonance (e.g., $\Gamma_{\eta_b} \gtrsim 30$ MeV)[5] which might partially explain why there was no observed signal from the hindered radiative decays of higher Upsilon resonances in the search performed by CLEO [41, 42]. Indeed the signal peak (which should appear in the photon energy spectrum) could be considerably smoothed — in addition to the spreading by the experimental measurement — and thereby might not be significantly distinguished from the background (arising primarily from π^0's decays). Of course, the matrix elements for the hindered M1 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 are ruled out by CLEO results (at least) at a 90% CL (see a compilation in [43]), though substancially lower rates are obtained in [44] where exchange currents play an essential role and currently cannot be excluded. Notice finally that a large full width of the η_b resonance would bring negative effects on the prospects for its detection at the Tevatron through the double-J/ψ decay: $\eta_b \to J/\psi + J/\psi$. Indeed, the expected BF would drop by about one order of magnitude with respect to the range between 7×10^{-5} and 7×10^{-3} assumed in [45].

Furthermore, another interesting possibility is linked to a $A^0 - \eta_b$ mixing [46] which could sizeably lower the mass of the mixed (physical) η_b state, especially for high $\tan\beta$ values starting from similar masses of the unmixed states [39]. Then the signal peak in the photon energy plot could be (partially) shifted off the search window used by CLEO [41, 42] towards higher γ energies (corresponding to a smaller η_b mass[6] perhaps contributing additionally to the failure to find evidence about the existence of the η_b resonances to date.

[5] One expects $\Gamma_{\eta_b(1S)} \simeq 4\,\mathrm{MeV}$ using the asymptotic expression $\Gamma_{\eta_b} \simeq m_b/m_c \times [\alpha_s(m_b)/\alpha_s(m_c)]^5 \times \Gamma_{\eta_c}$ and setting the measured $\Gamma_{\eta_c(1S)} = 16 \pm 3\,\mathrm{MeV}$ [36]

[6] This would be the case if the (unmixed) CP-odd Higgs boson had a mass greater than the (unmixed) η_b resonance [46]

The mass formula for the physical A^0 and η_b states in terms of the unmixed states (denoted as A^0_0 and η_{b0} respectively), and the off-diagonal mass matrix element $\delta m^2 \simeq 0.146 \times \tan\beta$ GeV^2, for quite narrow resonances (i.e., $\Gamma_{\eta_{b0}}$, $\Gamma_{A^0_0} \ll m_{\eta_{b0}}$, $m_{A^0_0}$) reads [39]:

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

which yields in the case of the physical η_b and A^0 particles for different mass intervals:

$$\begin{aligned} m_{\eta_b,A^0} &\simeq m_{\eta_{b0}} \mp \frac{\delta m^2}{2m_{\eta_{b0}}} \;;\; 0 < m^2_{A^0_0} - m^2_{\eta_{b0}} << 2\,\delta m^2 \\ m_{\eta_b,A^0} &\simeq m_{\eta_{b0},A^0_0} \mp \frac{(\delta m^2)^2}{2m_{\eta_{b0}}(m^2_{A^0_0} - m^2_{\eta_{b0}})} \;;\; m^2_{A^0_0} - m^2_{\eta_{b0}} >> 2\,\delta m^2 \end{aligned}$$

As a particular but significant example, assuming for the masses of the unmixed states $m_{\eta_{b0}} \simeq m_{A^0_0} = 9.4$ GeV and the moderate $\tan\beta = 12$ value, one gets for the physical states $m_{A^0} \simeq 9.5$ GeV and $m_{\eta_b} \simeq 9.3$ GeV respectively, which corresponds to a mass difference $m_{\Upsilon(1S)} - m_{\eta_b(1S)} \simeq 160$ MeV. Higher $\tan\beta$ values would, in principle, lead to larger mass shifts. However a caveat is in order: the hyperfine splitting (enhanced by the mixing) cannot raise unlimitedly, since the dependence on the third power of the photon energy in $\mathcal{P}^{\Upsilon}(\eta_b^*\gamma_s)$ (corresponding to a magnetic dipole transition) would eventually push up the new physics contribution for the tauonic BF beyond the postulated $\mathcal{O}(10\%)$ effect.

To end this section, let us point out that CLEO has completed detailed scans of the $\Upsilon(nS)$ ($n = 1, 2, 3$) resonances and we want to stress the relevance of these measurements (aside other applications) for testing more accurately the possible existence of NP by a more precise determination of the electronic, muonic and tauonic BFs of *all three* resonances below open bottom threshold. In case no lepton universality breaking is definitely found, some windows in the $\tan\beta$–m_{A^0} plane for such a non-standard CP-odd light Higgs boson would be closed.

5 SUMMARY

Quarkonium phenomenology should play an important role to explore new physics as it did in the past to develop the SM. Annihilation and radiative decays of resonances are well suited for testing symmetry conservation laws, as well as searching for (relatively) light particles arising in diverse scenarios beyond the SM, in addition to a much heavier sector.

The expected large statistics of J/ψ and Υ resonances, to be collected at e^+e^- and hadronic colliders along the next few years, makes heavy quarkonium physics especially convenient to conduct high precision studies and the quest for new particles and new phenomena. In this chapter, we have particularly developed three issues concerning CP and lepton-flavour violation in J/ψ decays, and a possible lepton universality breaking in Υ decays indicating the existence of a non-standard light Higgs boson. An open mind should be kept regarding those and other possible phenomena beyond the SM in heavy quarkonium physics.

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