A light non-standard Higgs boson: to be or not to be at a (Super) B factory?

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Abstract. A light non-standard Higgs boson decaying mainly into $\tau^+\tau^-$ has not been yet ruled out by LEP searches in several scenarios. We verify that, in the context of the Next-to-Minimal-Supersymmetric Standard Model, a low-mass CP-odd (mostly but not completely singlet-like) Higgs boson can couple strongly enough to down-type fermions to be detected in radiative Υ decays into tauonic pairs at a high-luminosity B factory. Possible spectroscopic effects of a mixing with η_b resonances are also analyzed.

PACS. 14.80.Cp Non-standard-model Higgs bosons – 13.25.Gv Decays of J/psi, Upsilon, and other quarkonia

1 Introduction

In spite of intensive searches performed at LEP, the possibility of a light non-standard Higgs boson has not been excluded yet in several scenarios beyond the Standard Model (SM). Moreover, the LHC might not be able to find a signal from a light Higgs boson whose mass is below the $B\bar{B}$ threshold. A Super B factory can thus play an important and complementary role in this regard [1].

From a theoretical viewpoint, the existence of a light pseudoscalar Higgs is not unexpected in certain non-minimal extensions of the SM. As an especially appealing example, the next-to-minimal supersymmetric standard model (NMSSM) gets a gauge singlet added to the MSSM two-doublet Higgs sector, leading to seven physical Higgs bosons, five of them neutral including two pseudoscalars [2]. Interestingly, the authors of [3] interpret, within the NMSSM, the excess of $Z+b$-jets events found at LEP as a signal of a SM-like Higgs decaying partly into $b\bar{b}\tau^+\tau^-$, but dominantly into τ's via two light pseudoscalars. Let us also mention the exciting connection with possible light neutralino dark matter [4] and its detection at B factories [5].

The possibility of light Higgs particles can be extended to scenarios with more than one gauge singlet [6], and even to the MSSM with a CP-violating Higgs sector [7,8] as LEP bounds can be evaded [9,10]. In the CP-violating benchmark scenario and several variants, the combined LEP data show large domains of the parameter space which are not excluded, down to the lowest Higgs mass values [11]. A similar conclusion applies to a two Higgs doublet model of type II (2HDM(II)) [2], where some windows for a very light Higgs are still open [12]. In addition, Little Higgs models have an extended structure of global symmetries (among which there can appear $U(1)$ factors) broken both spontaneously and explicitly, leading to possible light pseudoscalar particles in the Higgs spectrum [9]. Finally, let us mention the $g-2$ muon anomaly that might require a light CP-odd Higgs boson [13] to reconcile the experimental value with the SM result [14].

2 A light CP-odd Higgs in the NMSSM?

As is well-known, the NMSSM provides an elegant solution to the μ problem of the MSSM via the introduction of a singlet superfield $\hat{S}$ in the Higgs sector. As compared to the three independent parameters of the MSSM (usually chosen as $\tan\beta$, μ and M_A), the Higgs sector of the NMSSM requires six parameters, namely, $\lambda,\ \kappa,\ A_\lambda,\ A_\kappa,\ \tan\beta, \mu_{eff}$, where $\mu_{eff} = \lambda s$ is the effective μ-term generated from the vev of the singlet field, $s \equiv < S >$; λA_λ and κA_κ appear in the trilinear soft-supersymmetric-breaking terms of the potential. Our sign conventions are: λ and $\tan\beta$ always positive, while $\kappa,\ A_\lambda,\ A_\kappa,\ \mu_{eff}$ are allowed to have either sign. In the limit of either slightly broken R or Peccei-Quinn (PQ) symmetries, the lightest (CP-odd) Higgs boson [1] can be much lighter than the other Higgs bosons.

The non-singlet fraction of the A^0 is defined by $\cos\theta_A$:

$$A^0 = \cos\theta_A A_{MSSM} + \sin\theta_A A_s$$

where θ_A is the mixing angle between the singlet component and the MSSM-like component of the A^0.

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[1] The lightest CP-odd Higgs will be denoted as A^0 throughout this work instead of the more common A_1 in the NMSSM pointing out that a light pseudocalar Higgs-like particle might also exist in other scenarios.

The 2×2 square mass matrix for the CP-odd Higgs bosons has the following matrix elements [15]

$$M_{11}^2 = \frac{2\lambda s}{\sin 2\beta}(A_\lambda + \kappa s), \;\; M_{12}^2 \; = \; \lambda v(A_\lambda - 2\kappa s)$$

$$M_{22}^2 = 2\lambda\kappa v^2 \sin 2\beta + \lambda A_\lambda \frac{v^2 \sin 2\beta}{2s} - 3\kappa A_\kappa s$$

Defining $\Delta M^2 = \sqrt{(M_{11}^2 - M_{22}^2)^2 + 4(M_{12}^2)^2}$, the eigenstate mass of the lightest CP-odd Higgs boson can be written as

$$m_{A^0}^2 = \frac{1}{2}[M_{11}^2 + M_{22}^2 - \Delta M^2] \qquad (1)$$

and the mixing angle reads

$$\cos\theta_A = -\frac{M_{11}^2 - M_{22}^2}{\Delta M^2} \qquad (2)$$

For small trilinear couplings, the mass of the lightest CP-odd Higgs boson and $\cos\theta_A$ can be approximated by

$$m_{A^0}^2 \simeq 3s\left(\frac{3\lambda A_\lambda}{2\sin 2\beta}\cos^2\theta_A - \kappa A_\kappa \sin^2\theta_A\right) \qquad (3)$$

$$\cos\theta_A \simeq -\frac{\lambda v(A_\lambda - 2\kappa s)\sin 2\beta}{2\lambda s(A_\lambda + \kappa s) + 3\kappa A_\kappa s \sin 2\beta} \qquad (4)$$

From Eqs.(3-4) one can see that, under the protective symmetries mentioned in the Introduction, a small A^0 mass can be achieved in two ways:

(i) : $|\cos\theta_A| \simeq 0$ and $\sin\theta_A \simeq 1$, the A^0 is almost entirely singlet and the CP-odd Higgs mass is given from Eq.(3) by $m_{A_0^0}^2 \simeq -3\kappa A_\kappa s$, which can be very small under a PQ symmetry. Likewise the A^0 coupling to down-type fermions ($\sim \cos\theta_A \tan\beta$) would remain small even at large $\tan\beta$ since $\cos\theta_A \sim \sin 2\beta \simeq 2/\tan\beta$.

(ii) : $|\cos\theta_A|$ is not so small (e.g. $|\cos\theta_A| \simeq 0.1 - 0.5$) but still keeping the mostly singlet nature of the A^0. The two terms inside the bracket of Eq.(3) tend to cancel (especially for large $\tan\beta$ due to the $\sin 2\beta$ in the denominator of the first term) provided that λA_λ and κA_κ have the same sign, resulting in a low m_{A^0} value [16]. This possibility should be realized along the straight line on the $\lambda - \kappa$ plane where $|\cos\theta_A|$ is enhanced but keeping, we insist, the singlet character of the A^0 to a large extent (at the $\sim 1\%$ probability level).

Therefore, following *(ii)*, a low A^0 mass (e.g. $m_{A^0} < 2m_b$) can easily emerge at large $\tan\beta$ with, at the same time, a fairly enhanced coupling to b quarks and τ leptons, yielding observable effects in Υ decays as advocated in a series of papers [17,18,19]. In fact, different sets of NMSSM parameters can lead to this possibility, notably those yielding moderate $|\lambda A_\lambda|$ and small $|\kappa A_\kappa|$ values (evaluated at the scale m_Z) with $\mu_{eff} \simeq 150$ GeV, likely corresponding to the smallest degree of fine-tuning according to the analysis of LEP Higgs event excess [20,16].

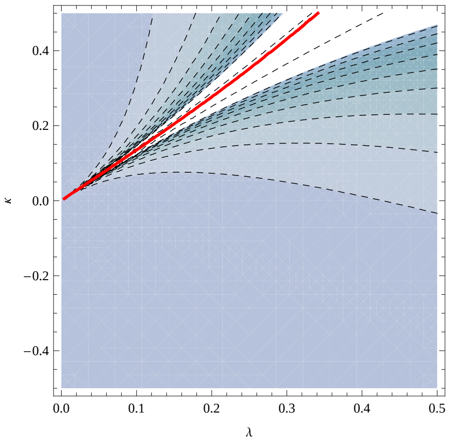

Fig. 1. Contour dashed lines for $X_d = 0.5, 1, ..., 4.5$ on the $\lambda - \kappa$ plane from Eq.(2) setting $A_\lambda = -200$, $A_\kappa = -15$, $\mu_{eff} = 150$ (at the scale m_Z, all in GeV) and $\tan\beta = 50$. The unshaded area stands for $X_d \geq 5$; the innermost dashed line corresponds to $X_d = 10$ while the thick red line represents $m_{A^0} = 10$ GeV.

Defining $X_d = \cos\theta_A \tan\beta$, the contour lines on the $\lambda - \kappa$ plane for $X_d = 0.5, 1, ..., 4.5$ and $X_d = 10$ are displayed in Fig.1 (the unshaded area standing for $X_d \geq 5$, when Υ leptonic decays should start to become sensitive to the A^0-mediated annihilation channels). In our plot we employed Eq.(2) setting as reference values: $A_\lambda = -200$ GeV, $A_\kappa = -15$ GeV and $\mu_{eff} = 150$ GeV, with $\tan\beta = 50$. Let us remark that somewhat smaller values of $\tan\beta$ ($\tan\beta > 25$) lead to qualitatively similar plots.

Indeed one could expect from Eq.(4) an enhancement of $|\cos\theta_A|$ (and therefore of $|X_d|$) in the vicinity of the straight line defined by $\lambda A_\lambda + \kappa\ \mu_{eff} = 0$ since then both $\sin 2\beta$ terms tend to cancel in the ratio (exactly cancelling out along the straight line). Thus, the product $|\cos\theta_A \tan\beta|$ can further increase at large $\tan\beta$, although limited by experimental bounds if the coupling to b quarks becomes too large. Values of $|X_d| \sim 10$ are still allowed in the NMSSM [21].

The thick red line in Fig.1 stands for $m_{A^0} = 10$ GeV obtained from Eq.(1), lying close to the $X_d = 10$ contour-line and expectedly leading to a slight but observable lepton universality (LU) breakdown in Υ decays, to be commented in Sect. 4.

3 Mixing of the A^0 and η_b resonances

The mixing between a CP-odd Higgs and a η_b resonance is described by the introduction of off-diagonal elements denoted by δm^2 in the mass matrix [22]

$$\mathcal{M}_0^2 = \begin{pmatrix} m_{A_0^0}^2 - i m_{A_0^0}\Gamma_{A_0^0} & \delta m^2 \\ \delta m^2 & m_{\eta_{b0}}^2 - i m_{\eta_{b0}}\Gamma_{\eta_{b0}} \end{pmatrix}$$

where the subindex '0' indicates unmixed states: $m_{A_0^0}$ ($\Gamma_{A_0^0}$) and $m_{\eta_{b0}}$ ($\Gamma_{\eta_{b0}}$) denote the masses (widths) of the pseudocalar Higgs boson and resonance, respectively.

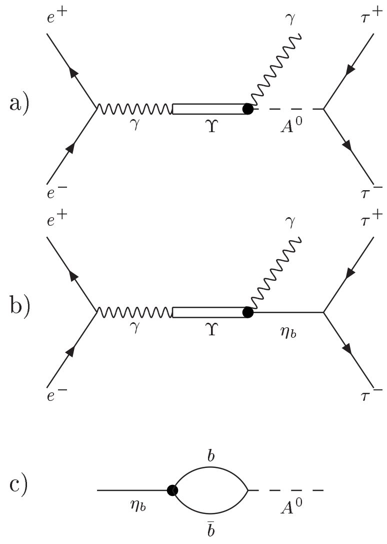

Fig. 2. Process $e^+e^- \to \Upsilon \to \gamma\,\tau^+\tau^-$ with a) pseudoscalar Higgs, b) η_b, as intermediate states; c) Mixing diagram

The A^0 and η_b physical (mixed) states can be written as

$$A^0 = \cos\alpha\ A_0^0\ +\ \sin\alpha\ \eta_{b0}$$
$$\eta_b = \cos\alpha\ \eta_{b0}\ -\ \sin\alpha\ A_0^0$$

assuming $[|\cos\alpha|^2 + |\sin\alpha|^2]^{1/2} \simeq 1$. The definition of the mixing angle α and a lengthier discussion can be found in [23] (and references therein).

The off-diagonal element δm^2 can be computed (see Fig.1c) within the framework of a nonrelativistic quark potential model to be $\delta m^2(\text{GeV}^2) \approx\ 0.146 \times X_d$ [23]. Notice that δm^2 is proportional to X_d.

3.1 Radiative decay of the Υ into $\tau^+\tau^-$

In Ref.[23] we employed the mixing formalim to describe both resonant and non-resonant Υ decays into a photon and a tauonic pair as depicted in Fig.2.

The couplings of the physical A^0 and η_b states to a $\tau^+\tau^-$ pair are given by

$$g_{A^0\tau\tau} = \cos\alpha\ g_{A_0^0\tau\tau} + \sin\alpha\ g_{\eta_{b0}\tau\tau}$$
$$g_{\eta_b\tau\tau} = \cos\alpha\ g_{\eta_{b0}\tau\tau} - \sin\alpha\ g_{A_0^0\tau\tau}$$

The full widths Γ_{A^0} and Γ_{η_b} of the physical states can also be expressed in terms of the widths of the unmixed states according to the simple formulae:

$$\Gamma_{A^0} = |\cos\alpha|^2\ \Gamma_{A_0^0}\ +\ |\sin\alpha|^2\ \Gamma_{\eta_{b0}} \tag{5}$$
$$\Gamma_{\eta_b} = |\cos\alpha|^2\ \Gamma_{\eta_{b0}}\ +\ |\sin\alpha|^2\ \Gamma_{A_0^0} \tag{6}$$

In the SM we can very approximately set $g_{\eta_{b0}\tau\tau} \simeq 0$ and thus $g_{A^0\tau\tau} \simeq g_{A_0^0\tau\tau}\cos\alpha$, $\quad g_{\eta_b\tau\tau} \simeq -g_{A_0^0\tau\tau}\sin\alpha$ where $g_{A_0^0\tau\tau}$ can be obtained from the Yukawa coupling strength [23]. Therefore, in our description of the process shown in Fig.2b, the η_b actually decays into $\tau^+\tau^-$ through its mixing with the A^0 boson.

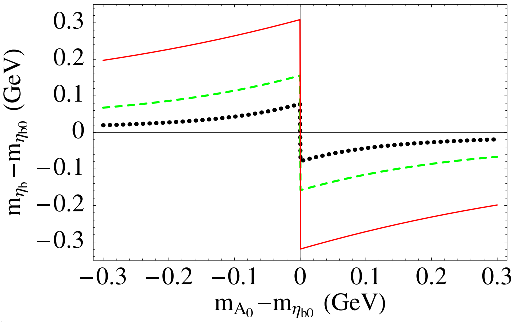

Fig. 3. Shift of the η_b physical mass induced by the mixing with a pseudoscalar Higgs boson, versus $m_{A_0^0} - m_{\eta_{b0}}$ for: dotted (black) line: $X_d = 10$, dashed (green) line: $X_d = 20$, solid (red) line: $X_d = 40$. The mass of the η_b mixed state is decreased (increased) if $m_{A_0^0} > m_{\eta_{b0}}$ ($m_{A_0^0} < m_{\eta_{b0}}$), ultimately implying a larger (smaller) $\Upsilon - \eta_b$ mass splitting than expected in the SM.

3.2 Spectroscopic effects

In addition, spectroscopic effects can appear in $b\bar{b}(^1S_0)$ states of the bottomonium family if the $A_0^0 - \eta_{b0}$ mixing sizeably shifts the masses of the physical states. In Fig.3 we plot $m_{\eta_b(1S)} - m_{\eta_{b0}(1S)}$ versus $m_{A_0^0} - m_{\eta_{b0}}$. Such a shift has to be added (with its sign) to the QCD expected $m_{\Upsilon(1S)} - m_{\eta_b(1S)}$ hyperfine splitting, whose theoretical prediction is achieving a remarkable precision [24]. As a consequence, if $m_{\eta_{b0}} < m_{A_0^0}$, the hyperfine splitting could increase considerably with respect to the SM expectations even at moderate $|X_d|$. On the contrary, if $m_{\eta_{b0}} > m_{A_0^0}$ the observed hyperfine splitting should shrink, and even the $\Upsilon(nS)$ and $\eta_b(nS)$ mass levels might be reversed at large enough $|X_d|$. However, this spectacular effect, if overlooked, would paradoxically render hard the experimental observation of such a η_b state!

4 Testing Lepton Universality in Υ decays

As emphasized in previous work (see [17] and references therein), the new physics contribution would be unwittingly ascribed to the Υ tauonic channel thereby breaking LU if the (not necessarily soft) radiated photon escapes undetected in the experiment (the leptonic width is, in fact, an inclusive quantity with a sum over an infinite number of photons).

Experimentally, the relative importance of the Higgs-mediated channel can be assessed via the ratio

$$\mathcal{R}_{\tau/\ell} = \frac{\mathcal{B}_{\tau\tau} - \mathcal{B}_{\ell\ell}}{\mathcal{B}_{\ell\ell}} = \frac{\mathcal{B}_{\tau\tau}}{\mathcal{B}_{\ell\ell}} - 1 \tag{7}$$

where $\mathcal{B}_{\tau\tau}$ and $\mathcal{B}_{\ell\ell}$ denote the tauonic and ($\ell = e$) electronic or ($\ell = \mu$) muonic branching fractions of the Υ resonance, respectively. A (statistically significant) non-null value of $\mathcal{R}_{\tau/\ell}$ would imply the rejection of LU (predicting $\mathcal{R}_{\tau/\ell} \simeq 0$) and a strong argument suggesting the existence of a pseudoscalar Higgs boson mediating the process as shown in Fig.2.

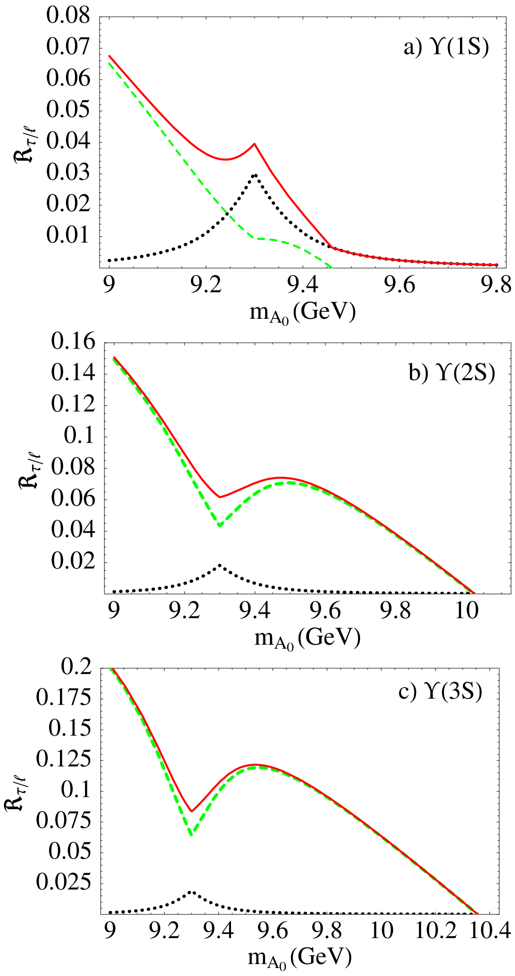

Fig. 4. $R_{\tau/\ell}$ versus the pseudoscalar Higgs mass for *a*) $\Upsilon(1S)$, *b*) $\Upsilon(2S)$, and *c*) $\Upsilon(3S)$ decays using $X_d = 10$, $m_{\eta_{b0}} = 9.3$ GeV, and $\Gamma_{\eta_{b0}} = 5$ MeV, respectively. Resonant (dotted black line) and non-resonant (dashed green line) decays are added in the solid red line. Larger (smaller) values of X_d obviously yield higher (lower) expectations for $R_{\tau/\ell}$.

A thorough discussion of the physics underlying those diagrams, useful expressions, values of the physical parameters and the corresponding numerical analysis providing $R_{\tau/\ell}$ as plotted in the set of figures 4, can be found in Ref.[23].

By inspection, a bump can be observed in Fig.4a due to the resonant contribution, while a dip appears in Figs.4b and 4c on account of the suppressed non-resonant channel, not compensated by the resonant channel. In spite of that, the higher $R_{\tau/\ell}$ values obtained for the $\Upsilon(2S)$ and $\Upsilon(3S)$ (due to the dominant Wilczek mechanism of Fig.2a) allow us to conclude that radiative decays of the latter resonances look more promising than the $\Upsilon(1S)$ decays for the experimental observation of LU breaking at the few percent level at a B factory. This conclusion is important if a specific test of LU were to be put forward by experimental collaborations [1].

5 Conclusions

A mass of about 10 GeV can be easily obtained for the lightest CP-odd Higgs boson in the NMSSM with values of $|X_d| = |\cos\theta_A| \times \tan\beta \simeq 10$, at large $\tan\beta$. The A^0 would still keep its predominantly singlet nature ($\cos^2\theta_A \sim$ few %), at the same time allowing a sizeable enhancement of its Yukawa coupling to down-type fermions (though escaping LEP bounds). Thus, we emphasize the relevance of testing LU in Υ decays to the few percent level at presently running B factories, and the role to be played by a future Super Flavor factory if this effect were confirmed.

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