

# Comment on “New constraints of a light CP-odd Higgs boson and related NMSSM Ideal Higgs Scenarios” by Dermisek and Gunion (arXiv:1002.1971 [hep-ph])

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In two recent papers [1, 2] Dermisek and Gunion provide new constraints on a light CP-odd Higgs boson in the framework of the “ideal” NMSSM (and related scenarios) based on experimental data from LEP, CLEO, BaBar and CDF experiments. In this brief comment we argue that special care is still needed inside a narrow mass window where mixing of a pseudoscalar Higgs-like particle with  $\eta_b$  resonances below  $B\bar{B}$  can occur. We also stress that observables testing lepton universality and a possible distortion of the bottomonium mass spectrum can provide an alternative analysis at (Super) B-factories in the search of such an elusive light pseudoscalar Higgs-like object.

Recent measurements by BaBar [3], CLEO [4], ALEPH [5] and CDF [6] have allowed the authors of [1, 2] to provide new and stringent constraints on a light CP-odd Higgs boson (denoted here as  $A$ ) coupling to down-type fermions in the framework of the NMSSM (or similar models). However, a caveat is in order inside a narrow mass window where  $A - \eta_b$  mixing should occur [7, 8], ultimately resulting in a negative influence on the experimental detection of a new state typically expected to show up as a single peak in the invariant mass spectrum, because:

- i)* The total width of the physical (mixed) CP-odd Higgs state could substantially increase since the  $\eta_b$  resonance(s) would have total width(s) of  $\mathcal{O}(10)$  MeV, not negligible compared to experimental resolution as usually assumed in the experimental searches. Actually, since we are dealing with mixed states, what should be understood as pseudoscalar Higgs state is, to some extent, a matter of convention. It seems natural to call “Higgs” the mass eigenstate with the largest  $A$ -component ( $P_{i,4}$ ) of all four possible mixed states ( $\eta_i$ ,  $i = 1, 2, 3, 4$ ):

$$\eta_i = P_{i,1} \eta_b^0(1S) + P_{i,2} \eta_b^0(2S) + P_{i,3} \eta_b^0(3S) + P_{i,4} A$$

where  $\eta_b^0(nS)$  and  $A$  denote the unmixed states;  $P_{i,4}$  varies as a function of  $m_A$  as can be seen from the middle plot of Fig.1. The resulting mass spectrum is shown in the left-hand plot of Fig.1 (see [9] for more details).

- ii)* Production and decay into leptons of a CP-odd Higgs would be channeled through distinct physical particles with different masses. Therefore, a multi-peak scenario would show up instead of a single narrow peak, whenever a significant mixing occurs, in either the photon-energy spectrum (from radiative Upsilon decays at B factories), or the dimuon mass spectrum (at hadron colliders).

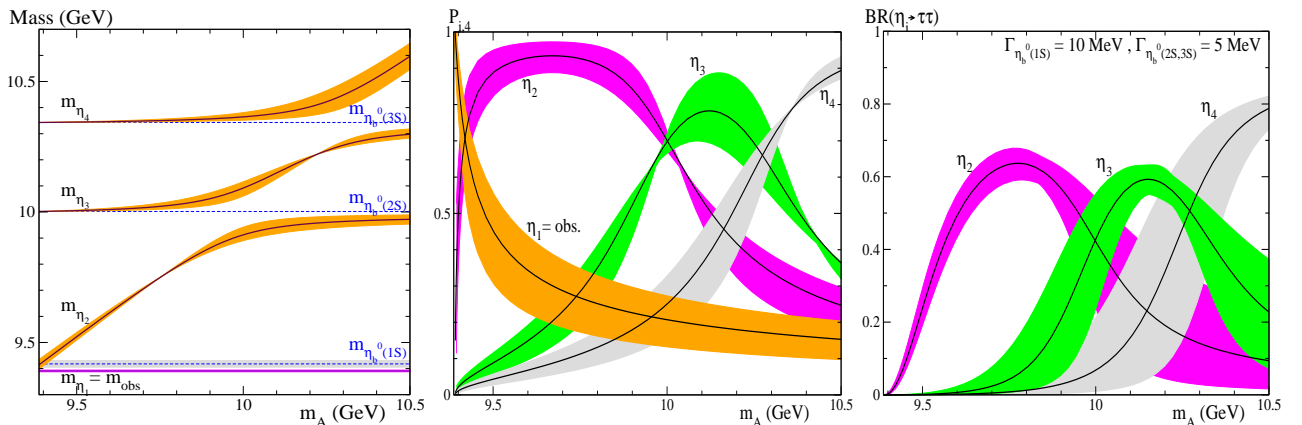


FIG. 1: *Left:* Masses of the physical (mixed) pseudoscalar states ( $\eta_{1,2,3,4}$ ) below  $B\bar{B}$  threshold as function of the unmixed  $A$  mass obtained in [9] by requiring that the difference between the perturbative QCD expectation and the measured  $\eta_b(1S)$  mass [10, 11] is entirely ascribed to the  $A - \eta_b(1S)$  mixing. *Middle:* The  $A$ -component  $P_{i,4}$  of all 4 eigenstates versus  $m_A$ . *Right:* Tauonic branching ratios of  $\eta_{2,3,4}$  eigenstates versus  $m_A$ ;  $BR(\eta_1 \rightarrow \tau^+\tau^-) < 8\%$  [3] is not shown in the plot. Solid (dashed) lines stand for the (un)mixed states and colored fringes indicate theoretical uncertainties [9].

For example, the  $\Upsilon(3S) \rightarrow \gamma\tau^+\tau^-$  decay rate via the new physics contribution would be significantly distributed among different channels (i.e. through intermediate  $\eta_{2,3,4}$  states) as  $m_A$  varies along the [9.4, 10.5] GeV range (see the right-hand plot of Fig.1), leading to weaker individual signals than expected. Moreover, let us mention that the Wilczek formula for  $\Upsilon \rightarrow \gamma A$  decays becomes unreliable to set exclusion limits above  $m_A \simeq 9$  GeV, because of large theoretical uncertainties due to bound state, QCD, and relativistic corrections [9, 12].

A similar argument related to the spreading of any light Higgs signal would equally apply to searches in the dimuon mass spectrum measured by CDF [6], despite the fact that the production mechanism (via quark-loop induced  $ggA$  coupling) of  $\eta_i$  states is different from the previous case. In addition, experimental smearing would likely lead to bumps rather than well-separated peaks in the mass spectrum under study. Therefore the constraints obtained in [1, 2] for a CP-odd Higgs with  $9.4 \lesssim m_A \lesssim 10.5$  GeV should still be taken with care, not definitely excluding larger couplings to down-type fermions accounting for the muon  $g - 2$  anomaly (see e.g. [13, 14] and references therein).

Let us finally comment on the LEP result recently reported by ALEPH [5] on the production and non-standard decay of a Higgs boson  $h$  into four taus through intermediate pseudoscalars  $A$ , where exclusion limits are set for a combined production cross section times branching ratios, namely

$$\xi^2 = \frac{\sigma(e^+e^- \rightarrow Zh)}{\sigma_{SM}(e^+e^- \rightarrow Zh)} \times BR(h \rightarrow AA) \times BR(A \rightarrow \tau^+\tau^-)^2$$

Notice that the above expression lacks exact physical meaning under the hypothesis of  $A - \eta_b$  mixing, for  $A$  could not be a (single) on-shell state anymore (as likely assumed in the ALEPH analysis) but a component of different  $\eta_i$  eigenstates as already argued before. Certainly, setting experimental limits on a quantity like  $\xi^2$  as done by ALEPH is definitely useful in the hunt for a light Higgs boson, but requires a reinterpretation of the factor  $BR(A \rightarrow \tau^+\tau^-)$  in terms of a set of  $\eta_i$  intermediate states in the subsequent analysis (e.g. observed versus expected upper limits). Let us recall, in this regard, the search for Yukawa production at LEP of a light neutral Higgs boson carried out by OPAL [15], where mixing with  $b\bar{b}$  bound states was taken into account in the data analysis (modifying the branching ratios into taus accordingly [7]), implying considerably looser bounds for the pseudoscalar Higgs coupling to down-type fermions, in this mass range.

On the other hand, observables based on inclusive measurements, e.g. testing lepton universality in  $\Upsilon$  decays (i.e. all leptonic branching ratios have to coincide aside lepton mass effects) [8, 16–18] could provide an alternative way to determine exclusion limits for a light pseudoscalar Higgs. In fact, a recent result from BaBar in  $\Upsilon(1S)$  decays finds no significant deviation from the SM expectation [19]. Let us emphasize, however, that lepton universality breaking should become experimentally sizeable for  $\Upsilon(2S)$  and  $\Upsilon(3S)$  decays as pointed out in [16]; thereby we strongly suggest the BaBar Collaboration extend their analysis to the two latter cases.

Finally, let us stress that a possible distortion of the  $\eta_b$  mass levels [9], as shown in the left-hand plot of Fig.1 could become another interesting way of seeking a light CP-odd Higgs in the range [9.4, 10.5] GeV. Although this searching strategy is free of the above-mentioned theoretical uncertainties plaguing the Wilczek formula, any new physics signal manifesting as unexpectedly large or small (even negative!) hyperfine splittings ( $m_{\Upsilon(nS)} - m_{\eta_b(nS)}$ ) requires a good control of both perturbative and non-perturbative (e.g. lattice) QCD calculations of the bottomonium system [20–22].

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