The search for a light CP-odd Higgs and light dark matter at colliders

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Abstract. The possible existence of a light CP-odd Higgs boson in the NMSSM, mixing with \(\eta_b\) resonances, can yield sizable effects on the bottomonium spectroscopy and decays to be observed at (Super) B factories. On the other hand, recent findings from astroparticle and cosmology favoring a light dark matter constituent with mass about 10 GeV or less cast a new interest into the search for invisible decays of \(T\) resonances performed at B factories.

1. Introduction
As is well-known, certain symmetries in the field Lagrangian describing a possible new physics scenario can contain exceptionally light physical particles whereas the scale of the theory may be much greater. In particular, the Next-to-Minimal Supersymmetric Standard Model (NMSSM, see [1] and references therein), can yield a light CP-odd scalar \(A_1\) of mass \(m_{A_1}\) about 10 GeV in the Higgs spectrum while evading LEP and B physics bounds (see e.g. Fig.3 of Ref.[2]).

In the simplest version of the NMSSM, the scale invariant superpotential and associated soft trilinear couplings read

\[
W = \lambda SH_u H_d + \frac{1}{3} \kappa S^3 + \ldots, \quad V_{soft} = (\lambda A_{\lambda} S H_u H_d + \frac{1}{3} \kappa A_{\kappa} S^3) + h.c. + \ldots
\]

A vev of the singlet field \(s \equiv \langle S \rangle\) generates an effective \(\mu_{eff} = \lambda s\) term, and it is convenient to define also an effective \(B_{eff} = A_{\lambda} + \kappa s\) term. The Higgs sector of the NMSSM contains six independent parameters, which can be chosen as \(\lambda, \kappa, A_{\lambda}, A_{\kappa}, \tan \beta, \mu_{eff}\).

On the other hand, two physical pseudoscalar states appear in the Higgs spectrum of the NMSSM, as superpositions of the MSSM-like state \(A_{MSSM}\) and the singlet-like state \(A_S\),

\[
A_1 = \cos \theta_A A_{MSSM} + \sin \theta_A A_S,
\]

where \(\theta_A\) is the mixing angle.

To a good approximation (for moderate \(A_{\lambda}\), small \(A_{\kappa}\) and large \(\tan \beta\)), the mass of the lightest CP-odd Higgs boson and \(\cos \theta_A\) can be written as [3]

\[
m_{A_1}^2 \simeq 3\kappa s \left( \frac{3\lambda^2 v^2 A_{\lambda} \sin 2\beta}{2\mu_{eff} B_{eff} - 3\kappa s A_{\kappa} \sin 2\beta} - A_{\kappa} \right); \quad \cos \theta_A \simeq -\frac{\lambda v (A_{\lambda} - 2\kappa s) \sin 2\beta}{2\mu_{eff} B_{eff} + 3\kappa s A_{\kappa} \sin 2\beta}.
\]
The reduced coupling $X_d$ of the light physical $A_1$ Higgs boson to down-type quarks and leptons (normalized with respect to the coupling of the CP-even Higgs boson of the Standard Model) is given by

$$X_d = \cos \theta_A \tan \beta .$$

(4)

At first sight the r.h.s. expression in Eq.(3) seems to imply (from $\sin 2\beta \sim 2/\tan \beta$ for large $\tan \beta$) that $\cos \theta_A$ decreases indeed with $\tan \beta$ – this would be the case in the PQ-symmetry-limit ($A_\kappa \to 0$) or R-symmetry-limit ($A_\lambda \to 0$), where the second term in the denominator tends to zero. On the other hand, it follows from the minimization equations of the scalar potential of the NMSSM (as in the MSSM), for fixed soft Higgs mass terms and $\mu_{\text{eff}}$, that $\tan \beta$ is proportional to $1/|\mu_{\text{eff}}B_{\text{eff}}|$ for large $\tan \beta$ [4], hence large values of $\tan \beta$ are associated to small values of $|B_{\text{eff}}|$ (since $|\mu_{\text{eff}}| > 100$ GeV from the lower bound on chargino masses). It is useful to replace $|B_{\text{eff}}|$ by the parameter

$$M_A^2 = \frac{2\mu_{\text{eff}}B_{\text{eff}}}{\sin 2\beta} ,$$

(5)

which sets the scale for the masses of the complete $SU(2)$ multiplet of Higgs states including a scalar, a pseudoscalar and a charged Higgs as in the MSSM (in our case, the corresponding pseudoscalar is the heavier one $A_2$). In terms of $M_A^2$, $X_d$ can be written approximately as

$$X_d \simeq -\frac{\Lambda v (A_\kappa - 2\kappa s)}{M_A^2 + 3\kappa s A_\kappa} \times \tan \beta ,$$

(6)

and it is reasonable to examine the large $\tan \beta$ region keeping $M_A$ fixed.

It also follows from the l.h.s expression in Eq.(3) that there exist always values of $A_\kappa$ of the same sign as $A_\lambda$ (typically both negative) where $m_{A_1}$ is small [5], while $\cos \theta_A \simeq 0.1 - 0.6$ and hence $X_d$ is not suppressed. This requires a moderate fine-tuning of $A_\kappa$ (or $M_A$). To summarize, the following conditions can be fulfilled simultaneously in the NMSSM, which yield possibly observable effects in $Y$ decays:

- $m_{A_1} \lesssim 10.5$ GeV from, e.g., appropriate values of $A_\kappa$;
- a large value of $X_d$, if $\tan \beta$ is large while $M_A$ in the denominator of (6) remains moderate.
Figure 2. Left: The $A$-components $|P_A|_4$ for all 4 eigenstates as functions of $m_A$. Right: The branching ratios into $\tau^+ \tau^-$ for the eigenstates $\eta_2$, $\eta_3$ and $\eta_4$ as functions of $m_A$.

2. Mixing of $A_1$ with the $\eta_b(nS)$ resonances

In the presence of a pseudoscalar Higgs boson with a mass close to one of the different $\eta_b(nS)$ resonances, a significant mixing between these states can occur [6]. For the $\eta_b^0(1S) - \eta_b^0(2S) - \eta_b^0(3S) - A$ mass matrix we make the ansatz

$$M^2 = \begin{pmatrix} m_{\eta_b^0(1S)}^2 & 0 & 0 & \delta m_1^2 \\ 0 & m_{\eta_b^0(2S)}^2 & 0 & \delta m_2^2 \\ 0 & 0 & m_{\eta_b^0(3S)}^2 & \delta m_3^2 \\ \delta m_1^2 & \delta m_2^2 & \delta m_3^2 & m_A^2 \end{pmatrix}. \tag{7}$$

The diagonal elements $m_{\eta_b^0(nS)}^2$ are assumed to be known (within errors) from QCD with for $m_{\eta_b^0(1S)}^2$. The results depend only weakly on the $\eta_b^0(2S)$ and $\eta_b^0(3S)$ masses, for which we take $m_{\eta_b^0(2S)}^2 = 10002$ MeV, $m_{\eta_b^0(3S)}^2 = 10343$ MeV. The off-diagonal elements $\delta m_n^2$ can be computed in the framework of a non-relativistic quark model in terms of the radial wave functions at the origin [6, 7].

In order that one eigenvalue of $M^2$ coincides with the BABAR result ([25]) subsequently denoted as $m_{\eta_b^0}$, $m_A$ in (7) has to satisfy

$$m_A^2 = m_{\eta_b^0}^2 + \frac{\delta m_1^4}{m_{\eta_b^0(1S)}^2 - m_{\eta_b^0}^2} + \frac{\delta m_2^4}{m_{\eta_b^0(2S)}^2 - m_{\eta_b^0}^2} + \frac{\delta m_3^4}{m_{\eta_b^0(3S)}^2 - m_{\eta_b^0}^2}. \tag{8}$$

Once $m_A$ is expressed in terms of $X_d$, $X_d$ remains the only unknown parameter in $M^2$. Varying $m_{\eta_b^0}$, $m_{\eta_b^0(1S)}$ and $\delta m_i^2$, we obtain for $X_d$ as a function of $m_A$ the result shown in Fig. 1.

Now the masses of all 4 eigenstates of $M^2$ can be computed, which are shown together with the error bands from $m_{\eta_b^0}$, $m_{\eta_b^0(1S)}$ and $\delta m_i^2$ (in orange/grey) in Fig. 1 as functions of $m_A$. Henceforth we denote the 4 eigenstates of $M^2$ by $\eta_i$, $i = 1 \ldots 4$ where, by construction, $m_{\eta_1} \equiv m_{\eta_b^0}$. For clarity we have indicated in Fig. 1 our assumed values for $m_{\eta_b^0(nS)}$ as horizontal dashed lines. For $m_A$ not far above 9.4 GeV (where $X_d$ is relatively small) the effects of the mixing on the states $\eta_b^0(2S)$ and $\eta_b^0(3S)$ are negligible, but for larger $m_A$ the spectrum can differ considerably from the one expected without the presence of $A$!
We have considered both resonant and non-resonant production:

\begin{align*}
B(e^+e^-) & \quad B(\mu^+\mu^-) & \quad B(\tau^+\tau^-) & \quad R_{\tau/\mu}(nS) & \quad R_{\tau/\mu}(nS) \\
Y(1S) & : 2.38 \pm 0.11 & 2.48 \pm 0.05 & 2.60 \pm 0.10 & 0.09 \pm 0.06 & 0.05 \pm 0.04 \\
Y(2S) & : 1.91 \pm 0.16 & 1.93 \pm 0.17 & 2.00 \pm 0.21 & 0.05 \pm 0.14 & 0.04 \pm 0.06 \\
Y(3S) & : 2.18 \pm 0.21 & 2.18 \pm 0.21 & 2.29 \pm 0.30 & 0.05 \pm 0.16 & 0.05 \pm 0.16 \\
\end{align*}

Table 1. Measured leptonic branching ratios $B(Y(nS) \rightarrow \ell \ell)$ (in %) and error bars (summed in quadrature) of $Y(1S)$, $Y(2S)$, and $Y(3S)$ resonances.

Next we consider the branching ratios of the eigenstates into $\tau^+ \tau^-$, which are induced by their $A$-components in the decomposition of the eigenstates into the states before mixing, as

$$\eta_i = P_{i,1} \eta_h^0(1S) + P_{i,2} \eta_h^0(2S) + P_{i,3} \eta_h^0(3S) + P_{i,4} A.$$ (9)

where analytic expressions for the coefficients $P_{i,j}$ can be found in [8]. In Fig. 2 we show our results for the $A$-components $P_{i,4}$ for all 4 eigenstates together with the error bands from $m_{\text{obs}}$, $m_{\eta_h^0(1S)}$, and $\delta m_i^2$, and the corresponding branching fractions into taus induced by the mixing.

In view of (9) let us finally remark that what should be understood as a Higgs state is, to some extent, a matter of convention. It seems natural to call “Higgs” the mass eigenstate with $m < m_A$, which is the case for the lightest CP-odd Higgs boson as a function of $\delta m_i^2$.

3. Possible lepton universality breaking

At present, a direct detection of a CP-odd Higgs with a mass in the particularly interesting region $9.4 \text{ GeV} \lesssim m_{A_1} \lesssim 10.5 \text{ GeV}$ via a peak in the photon spectrum seems to be quite difficult. As pointed out in [10], one manifestation of the existence of such a light CP-odd Higgs boson of mass could be a breakdown of LU (lepton universality) in $Y$ decays, if the (not necessarily soft) radiated photon escapes undetected in the experiment, or simply is not specifically searched for in the analysis of events. (The leptonic width is, in fact, an inclusive quantity with a sum over an infinite number of photons.)

Higgs-mediated $Y$ decays would lead to an excess of its tauonic branching ratio (BR), which can be assessed through the ratio

$$R_{\tau/\ell} = \frac{B_{\tau\tau} - B_{\ell\ell}}{B_{\ell\ell}} = \frac{B_{\tau\tau}}{B_{\ell\ell}} - 1$$ (10)

where $B_{\tau\tau}$ denotes the tauonic, and $B_{\ell\ell}$ the electronic ($\ell = e$) or muonic ($\ell = \mu$) branching ratios of the $Y$ resonance, respectively. A statistically significant non-zero value of $R_{\tau/\ell}$ would be a strong argument in favour of a pseudoscalar Higgs boson mediating the process.

In Table 1 we summarize the current situation of LU obtained from [11]. As already mentioned in the introduction, a $\sim 1 \sigma$ effect seems visible in most cases, leading to an overall (positive) $\sim 2 \sigma$ effect.

We have estimated the possible amount of LU breaking in the NMSSM with $m_{A_1}$ in the 9.4-10.5 GeV range and large $X_d$ in order to verify whether it can be assessed experimentally [7]. In the set of plots of Fig. 3, $R_{\tau/\ell}$ is shown for $Y(1S)$, $Y(2S)$ and $Y(3S)$, as a function of $m_{A_1}$. We have considered both resonant and non-resonant production:

$$R_{\tau/\ell} = R_{\tau/\ell}^h + R_{\tau/\ell}^{A_1}$$ (11)

through a dipole transition yielding an $\eta_h$ resonance or via Wilczek mechanism, respectively [7].
A light CP-odd Higgs boson into a LDM pair. Let us remark the interest of this quest in connection with the possibility of the dark matter candidate (either scalar, Dirac or Majorana fermion) inasmuch the decaying mediators (like CP-odd or CP-even Higgs bosons) actually vanishes no matter the character of applies to LDM candidates with mass less than half the $\frac{1}{2}m_\text{S}$ which is only one order of magnitude above the SM expectation. Notice that this bound only invisible decay modes up to observable rates \cite{14, 15}. Interestingly, from the astroparticle and cosmological side DAMA and CoGeNT experiments have recently reported on the observation of events compatible with a light dark matter candidate with a mass inside the interval [5, 10] GeV \cite{16}. Such a mass range for Light Dark Matter (LDM) constituents is especially attractive in certain cosmological scenarios, e.g., the Asymmetric Dark Matter model where the cosmological dark matter density arises from the baryon asymmetry of the universe and is expected to have a mass of order $1 - 10$ GeV (see \cite{17} and references therein).

Searches for the $\Upsilon(1S) \rightarrow$ invisible mode have been carried out by Argus \cite{19}, CLEO \cite{20}, Belle \cite{21} and BaBar \cite{22}, making use of the cascade decay: $\Upsilon(2S,3S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$, where the dipion provides the tagging of the $\Upsilon(1S)$ decaying into an invisible mode. The most recent experimental data from BaBar \cite{22} provide the following upper limit at the 90% CL:

$$B[\Upsilon(1S) \rightarrow \text{invisible}] < 3 \times 10^{-4}$$  \hspace{1cm} (12)$$

which is only one order of magnitude above the SM expectation. Notice that this bound only applies to LDM candidates with mass less than half the $\Upsilon(1S)$ mass.

However, as stressed in \cite{23} the above invisible decay mode induced by scalar or pseudoscalar mediators (like CP-odd or CP-even Higgs bosons) actually vanishes no matter the character of the dark matter candidate (either scalar, Dirac or Majorana fermion) inasmuch the decaying resonance is a $J^{PC} = 1^{-+}$ state. Actually, in order to get a non-vanishing decay rate, a new vector $U$-boson associated to the gauging of an extra $U(1)$ symmetry would be required \cite{23}. Hence a different type of search has been performed at B factories by looking at the decay $\Upsilon \rightarrow \gamma + \text{invisible}$ which can proceed via a light scalar or pseudoscalar Higgs mediator decaying into a LDM pair. Let us remark the interest of this quest in connection with the possibility of a light CP-odd Higgs boson $A_1$ which could naturally become the mediator of the decay into undetected dark matter particles: $\Upsilon \rightarrow \gamma A_1(\rightarrow \text{invisible})$. The result for $\Upsilon(3s)$ decays \cite{24} is

$$B[\Upsilon(3S) \rightarrow \gamma + \text{invisible}] < (0.7 - 30) \times 10^{-6} \text{ at } 90\% \text{ CL, } s_{\text{inv}}^{1/2} < 7.8 \text{ GeV}$$  \hspace{1cm} (13)$$

4. Invisible decays of $\Upsilon$ resonances

Measurements of invisible (meaning undetected) decay rates of $\psi$ and $\Upsilon$ resonances at Charm and B factories can discover or place strong constraints on dark matter scenarios where candidate dark matter constituents are lighter than the $b$-quark \cite{12}.

According to the SM, invisible decays of the $\Upsilon(1S)$ can proceed via $b\bar{b}$ annihilation into a $\nu \bar{\nu}$ pair with a branching fraction $B(\Upsilon(1S) \rightarrow \nu \bar{\nu}) \simeq 10^{-5}$ \cite{13}, well below current experimental sensitivity. However, models containing low-mass dark matter components might enhance such invisible decay modes up to observable rates \cite{14, 15}. Interestingly, from the astroparticle and cosmological side DAMA and CoGeNT experiments have recently reported on the observation of events compatible with a light dark matter candidate with a mass inside the interval [5, 10] GeV \cite{16}. Such a mass range for Light Dark Matter (LDM) constituents is especially attractive in certain cosmological scenarios, e.g., the Asymmetric Dark Matter model where the cosmological dark matter density arises from the baryon asymmetry of the universe and is expected to have a mass of order $1 - 10$ GeV (see \cite{17} and references therein).

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where $s_{inv}$ denotes the invariant-mass squared of the hypothetical LDM pair.

Improving limits from searches of this type at higher mass encounters experimental systematic challenges because the energy of the final state photon gets progressively lower, where resolution, fake photon candidates, and noise are all typically less favorable than at higher photon energies. Nevertheless, such improvements, if achieved, would provide important constraints on theoretical possibilities by reaching higher LDM masses.

5. Conclusions and outlook

We have emphasized that the interval $9.4 \text{ GeV} < m_{A_1} < 10.5 \text{ GeV}$ can have an effect on the $\eta_b(1S)$ mass as measured by Babar via mixing, and explain the possibly excessive $\Upsilon(1S) - \eta_b(1S)$ hyperfine splitting. In addition, violation of lepton universality in inclusive radiative $\Upsilon$ decays can be a signal for an additional CP-odd Higg which could (should) be tested in current or forthcoming experiments at (Super) B factories [26, 27].

Finally, recent findings from astroparticle and cosmology favoring a light dark matter constituent with mass about 10 GeV or less add a new interest to the search for invisible decays of $\Upsilon$ resonances performed at (Super) B factories.

Acknowledgments

This work was supported by grants FPA2008-02878 and GVROMETEO2010-056.

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