Physics Letters B 678 (2009) 380–386

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Higgs boson searches via dileptonic bottomonium decays

Saime Solmaz

Balıkesir University, Physics Department, TR10100, Balıkesir, Turkey

ARTICLE INFO

Article history:
Received 11 May 2009
Accepted 24 June 2009
Available online 27 June 2009
Editor: M. Cvetič

ABSTRACT

We explore the pseudoscalar η_b and the scalar χ_{b0} decays into $\ell^+\ell^-$ to probe whether it is possible to probe the Higgs sectors beyond that of the Standard Model. We, in particular, focus on the Minimal Supersymmetric Standard Model, and determine the effects of its Higgs bosons on the aforementioned bottomonium decays into lepton pairs. We find that the dileptonic branchings of the bottomonia can be sizeable for a relatively light Higgs sector.

1. Introduction

Having the LHC started, the search for physics at the terascale has entered a new phase. The ATLAS and CMS experiments at the LHC will search for new particles and forces while LHCb will provide a more accurate description of flavor physics. Each experiment, combined with others, will provide important information about nature of new physics awaiting discovery. It is thus rather timely to discuss and analyze ways of extracting TeV scale physics in relation to the measurements at the LHC experiments.

In terms of its content and goal, the present work falls in the interface between flavor physics and Higgs physics in that we aim at exploring finger prints of yet-to-be discovered Higgs sector (to be discovered at the CMS and ATLAS experiments [1]) in the leptonic decay distributions of heavy hadrons (to be accurately measured at the LHCb experiment [2]).

At present, we do not have any clue of what Higgs sector is awaiting for discovery at the LHC. On the other hand, the experiments at B factories have, by now, established a grand view of the flavor physics. The experimental precision is increasing steadily and has already started challenging our understanding of the flavor violation. Over the years, various B meson decay rates and charge asymmetries have been measured and novel quarkonium states have been discovered. The B meson inventory of the existing storage rings comes from the decays of $(b\bar{b})$ states (bottomonium states) produced at asymmetric electron–positron collisions (e.g. PEPII at SLAC and KEK-B at KEK). Of course, all kinds of bottomonia with varying spin and CP quantum numbers will be produced at the LHC in gluon–gluon or gluon–gluon–gluon fusion channels.

In principle, one ought to use every single opportunity to extract information about other sectors of a given theory by using the available information from B physics. Examples of such efforts involve quark EDMs [3] and flavor-violation Higgs connection [4]. The radiative, leptonic or semileptonic decays of hadrons are particularly suitable for strengthening experimental identification and theoretical prediction, and thus, in this work we attempt at answering the following question: *By measuring the decay rates of certain* $(b\bar{b})$ *states, preferably but not necessarily into* $\ell^+\ell^-$, *can we establish the existence and nature of Higgs bosons*? The choice of bottomonium system stems from not only its perturbative nature but also its appreciable coupling to Higgs fields.

In what follows, in regard to the question raised above, we will study a generic Higgs sector extending that of the SM. In the next section, we will provide an explicit discussion of the dileptonic Bottomonium decays into lepton pairs. In Section 3 we will numerically analyze the decay rates by taking MSSM to be the new physics candidate model and fixing the unknown parameters to two different data sets taken from LEP indications and from SPS1a point. In Section 4 we conclude.

2. Dileptonic bottomonium decays

The quarkonium systems have been under intense study since the discovery of the charm quark [5]. That light MeV-mass Higgs bosons could be produced in quarkonium decays was first discussed in [6,7]. The decays of additional TeV-mass heavy quark bound states into fermions as well as Higgs and gauge bosons have been analyzed in [8]. In this work we will discuss Higgs boson search via dileptonic bottomonium decays. The two sides, hadronic and Higgs aspects, of our discussions can be described as follows:

1. We will focus on bottomonium states, in particular, the pseudoscalar η_b (an S-wave $J^{PC} = 0^{-+}$ state) and the scalar χ_{b0} (a P-wave $J^{PC} = 0^{++}$ state). Unlike the charmonium system where such states have already been experimentally established, the experimental efforts still continue to establish quantum numbers of η_b and χ_{b0} though they have already

---

E-mail address: skerman@balikesir.edu.tr.

0370-2693/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.physletb.2009.06.054

been observed [9–12]. The experiments at Tevatron, B factories and LHC are expected to fully construct and measure partial widths of these $b\bar{b}$ mesons.

2. We will not restrict ourselves to Standard Model Higgs sector. In fact, we will consider models with two Higgs doublets, H_u and H_d one giving mass to down-type fermions other to up-type fermions, as encountered in the MSSM. (One may, of course, consider more general Yukawa structures [13].) The spectrum consists of three Higgs bosons: the CP-even ones h and H and a CP-odd one A. Their interactions with b quark and charged leptons are given by

$$-\mathcal{L}_{\text{higgs}} = g_h^f \bar{f} f h + g_H^f \bar{f} f H + g_A^f \bar{f} i\gamma_5 f A, \tag{1}$$

where $f = b, \ell$, and the Yukawa couplings g_X^f are given by

$$\begin{aligned} g_h^f &= h_f^{\text{SM}}\big[\sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)\big], \\ g_H^f &= h_f^{\text{SM}}\big[\cos(\beta-\alpha) + \tan\beta\sin(\beta-\alpha)\big], \\ g_A^f &= h_f^{\text{SM}}\tan\beta. \end{aligned} \tag{2}$$

Here $\tan\beta = \langle H_u^0\rangle/\langle H_d^0\rangle$, α is the mixing between $H_u^0 - \langle H_u^0\rangle$ and $H_d^0 - \langle H_d^0\rangle$ such that $\alpha = (1/2)\arcsin[-(m_A^2+m_Z^2)/(m_H^2 - m_h^2)\sin 2\beta]$, $h_f^{\text{SM}} = (g_2 m_f)/(2M_W)$ is the Yukawa coupling of fermion f in the SM. If there exists explicit CP violation sources in the theory then none of the Higgs bosons can possess definite CP quantum number, and thus they couple to fermions as $\bar{f}(a + ib\gamma_5)f$ as in, for instance, the MSSM with complex soft terms with one-loop Higgs potential [14].

Having specified the framework in both Higgs and meson sides, we now turn to an explicit computation of the decay rates of bottomonia. In this respect, the decay rates of η_b and χ_{b0} into lepton pairs are then given by

$$\begin{aligned} \Gamma\left(\eta_b \to \ell^+\ell^-\right) &= \frac{3}{8\pi^2}\frac{|R_S(0)|^2}{M_{\eta_b}^2}\beta_\ell \\ &\quad\times\left\{\left(\frac{g_A^b g_A^\ell}{1-r_A}\right)^2 + 4r_\ell\left(\frac{g_Z^2}{1-r_Z}\right)^2 \right. \\ &\quad\left. + 4\sqrt{r_\ell}\,\frac{g_Z^2 g_A^b g_A^\ell}{(1-r_A)(1-r_Z)}\right\}, \\ \Gamma\left(\chi_{b0} \to \ell^+\ell^-\right) &= \frac{27}{8\pi^2}\frac{|R'_P(0)|^2}{M_{\chi_{b0}}^4}\beta_\ell^3\left(\frac{g_h^b g_h^\ell}{1-r_h} + \frac{g_H^b g_H^\ell}{1-r_H}\right)^2, \end{aligned} \tag{3}$$

where $R_S(0)$ ($R'_P(0)$) is the S-wave (derivative of P-wave) quarkonium wavefunction at the origin [8], $g_Z = e/(4\sin\theta_W\cos\theta_W)$, $r_i = m_i^2/M_X^2$ ($i = \ell, A, h, H, Z$), and $\beta_\ell = (1 - 4m_\ell^2/M_X^2)^{1/2}$ where $X = \eta_b$ for $\eta_b \to \ell^+\ell^-$ and $X = \chi_{b0}$ for $\chi_{b0} \to \ell^+\ell^-$.

From these decay rates one notes that:

1. Thanks to their J^{PC} structures, the two bottomonia, η_b and χ_{b0}, explicitly distinguish between CP $= +1$ and CP $= -1$ Higgs bosons. This aspect proves very important for establishing the nature of the Higgs bosons as well as structure of the non-SM Higgs sector at the LHC and its successor NLC (see [3] for a detailed discussion of different J^{PC} mesons).
2. The couplings of the Higgs bosons to down-type fermions experience big enhancements at large $\tan\beta$ as preferred by LEP experiments. Indeed, contributions of A and H grow as $(\tan\beta/M_{H,A})^2$ which can provide a *detectable* signal for collider experiments such as the LHCb.
3. As is seen from (3), as a direct consequence of the quantum numbers of η_b meson, the decay $\eta_b \to \ell^+\ell^-$ exclusively involves the vector bosons and pseudoscalar Higgs bosons. On the other hand, again due to its quantum numbers, the decay $\chi_{b0} \to \ell^+\ell^-$ singles out the CP $= +1$ Higgs bosons. (Nevertheless, one keeps in mind that $\chi_{b0} \to \ell^+\ell^-$ can exhibit a non-negligible dependence on the masses of the pseudoscalar Higgs bosons depending on the details of the mixing angle α of the CP-even Higgs sector). This prime difference between the two mesons proves highly useful for probing the nature of the 'new physics' that will be discovered at the LHC. Depending on the nature of the deviations from the SM expectations, one might determine, within the experimental uncertainties, whether the new physics involve new pseudoscalar Higgs bosons (like the MSSM or NMSSM) or new scalar Higgs bosons (like MSSM or $U(1)'$ models or NMSSM) or new gauge bosons (like $U(1)'$ invariance of left–right symmetric models).
4. In (3) we have focused particularly on extended Higgs sectors (taken to be a generic two-doublet model fitting to the Higgs sector of the MSSM). However, one can consider extended gauge sectors as well. In this case, similar to the Z/W boson contributions, one expects anomalous behavior in $\eta_b \to \ell^+\ell^-$ (compared to the SM prediction) to arise also from extended gauge sectors containing Z'/W' gauge bosons. In this work we will not investigate this option since experimental bounds force Z'/W' to stay heavy (though in realistic models the Higgs sector itself behaves differently [15]).
5. In the decoupling limit [7,14], it turns out that $\beta - \alpha \sim \pi/2$ in which case h behaves as in the SM yet H and A Higgs bosons possess $\tan\beta$–enhanced Yukawa interactions.

In the next section we will perform a numerical study of the decay rates (3) in view of disentangling H and A effects from the rest. The analysis, once confirmed experimentally, might provide important information about the nature of the Higgs sector awaiting discovery at the LHC.

3. Numerical analysis

In this section we analyze the decay widths discussed above numerically. In doing this, the SM prediction for the decay rate will be compared with those of the MSSM for χ_{b0} and η_b decays, comparatively. In particular, we take Higgs boson of the SM degenerate in mass with the lightest Higgs boson of the MSSM, and consider the ratios

$$\begin{aligned} \frac{\Gamma^{\text{MSSM}}(\eta_b \to \ell^+\ell^-)}{\Gamma^{\text{SM}}(\eta_b \to \ell^+\ell^-)} &= 1 + \left(\frac{g_A^b g_A^\ell}{g_Z^2}\right)^2 \frac{1}{4r_\ell}\left(\frac{1-r_Z}{1-r_A}\right)^2 \\ &\quad + \left(\frac{g_A^b g_A^\ell}{g_Z^2}\right)\frac{1}{\sqrt{r_\ell}}\left(\frac{1-r_Z}{1-r_A}\right) \end{aligned} \tag{4}$$

and

$$\begin{aligned} \frac{\Gamma^{\text{MSSM}}(\chi_{b0} \to \ell^+\ell^-)}{\Gamma^{\text{SM}}(\chi_{b0} \to \ell^+\ell^-)} &= \left(\frac{g_h^b g_h^\ell}{h_b^{\text{SM}} h_\ell^{\text{SM}}}\right)^2 + \left(\frac{g_H^b g_H^\ell}{h_b^{\text{SM}} h_\ell^{\text{SM}}}\right)^2\left(\frac{1-r_h}{1-r_H}\right)^2 \\ &\quad + 2\frac{(g_h^b g_h^\ell g_H^b g_H^\ell)}{(h_b^{\text{SM}} h_\ell^{\text{SM}})^2}\left(\frac{1-r_h}{1-r_H}\right) \end{aligned} \tag{5}$$

in making the numerical estimates. The parameter values for which these ratios exceed unity significantly are expected to yield observable signals. In course of the analysis we scan the parameter space of the MSSM Higgs sector by varying m_h, m_H, m_A and $\tan\beta$ in a considerably wide range. We focus on two parameter ranges:

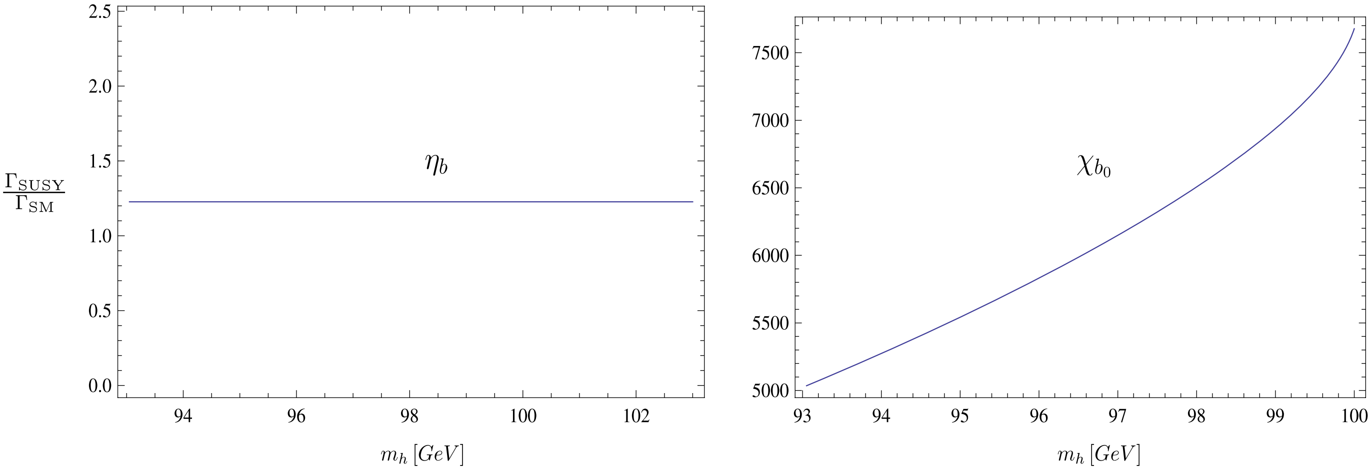

Fig. 1. Variation of the decay rate ratios against the lightest CP-even Higgs mass m_h for η_b (left panel) and χ_{b0} (right panel), for the `SPSI` parameter space.

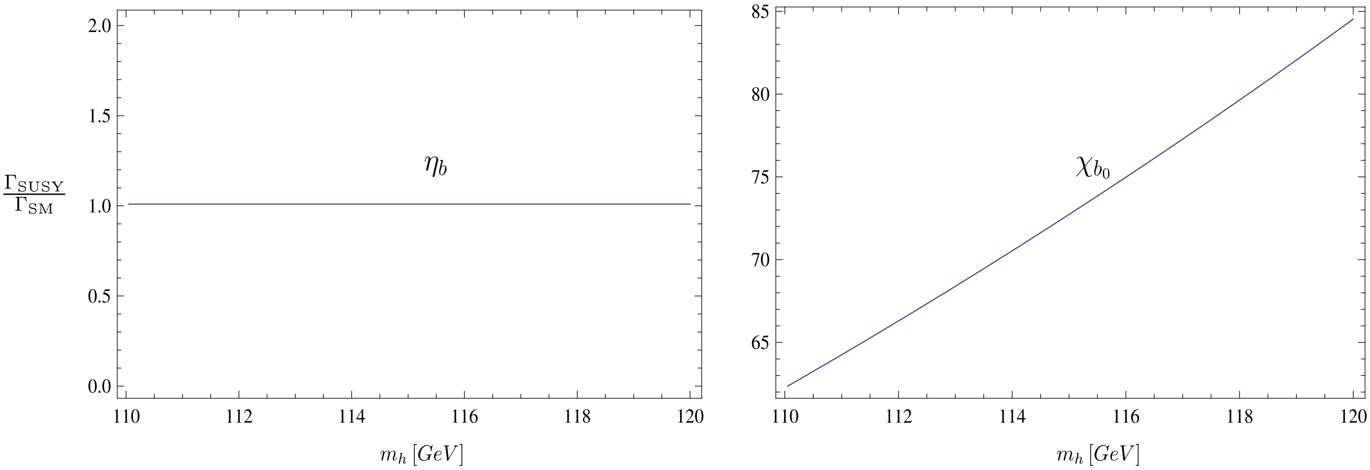

Fig. 2. The same as Fig. 1, but for `SPSII` parameter set.

- SUSY Parameter Space I (`SPSI`):

$$m_h = 98 \pm 5\ \text{GeV}, \qquad m_H = 115 \pm 5\ \text{GeV},$$
$$m_A = 89 \pm 5\ \text{GeV}, \qquad \tan\beta = 10 \pm 2.5, \tag{6}$$

which is inspired from the reanalysis of the LEP results mentioned in [15].

- SUSY Parameter Space II (`SPSII`):

$$m_h = 115 \pm 5\ \text{GeV}, \qquad m_H = 425 \pm 5\ \text{GeV}, \tag{7}$$
$$m_A = 424.9 \pm 5\ \text{GeV}, \qquad \tan\beta = 10 \pm 2.5, \tag{8}$$

which is inspired from the SPS1a parameter space of the MSSM.

In plotting a particular figure we vary one parameter while keeping the rest at their mid-values. Depicted in Fig. 1 (for `SPSI`) and Fig. 2 (for `SPSII`) are the ratios in (4) and (5) as a function of the lightest Higgs boson mass m_h. As can be seen from the left panels of the figures, the ratio of the SUSY prediction to the SM prediction does not vary for the η_b decay and these ratios are approximately 1.23 and 1.02 for Figs. 1 and 2, respectively. This can be easily understood from (4), to which the CP-even Higgs bosons do not contribute at all. The η_b decay would probe new $\text{CP} = -1$ Higgs bosons and new gauge bosons, as can be seen from the same equation. Nevertheless, the difference persistent in the MSSM's prediction can be an important clue for the future measurements.

While the impact of different data sets are sensible for the η_b decay, for the χ_{b0} decay it turns out to be much stronger as can be seen from the right panels of the same figures. For instance, the impact of increasing, the mass of the lightest CP-even Higgs boson can enhance the SUSY/SM ratio from 5050 to 7700 for `SPSI` parameter set. Similarly, it increases from 62.5 to 84.5 for `SPSII` set. Here, as a result of the quantum numbers of χ_{b0}, the contributions of the h and H bosons become clearly visible, which can be seen from (5). Normally, as m_h increases the r_h, and hence, the decay rate ratios increase but the dominant behavior is determined by the coupling terms. In any case, the prediction of the MSSM is very large than that of the SM prediction, which makes the χ_{b0} decay a promising candidate for probing the new CP-even Higgs bosons of the 'new physics'.

Depicted in Figs. 3 and 4, are variations of the decay rate ratios with the heavy CP-even Higgs boson mass, m_H. The general behavior is similar to those in Figs. 1 and 2, except that the χ_{b0} decay ratio decreases as m_H increases, for both of the parameter sets. This can be understand from (5) wherein the decay rate ratio is inversely proportional to m_H^2.

Depicted in Figs. 5 and 6 are the ratios of the decay rates as a function of the pseudoscalar Higgs boson mass m_A. As suggested by the left panels of the figures be (the η_b decays) the ratios decrease with increasing m_A to a small extend, for both of the pa-

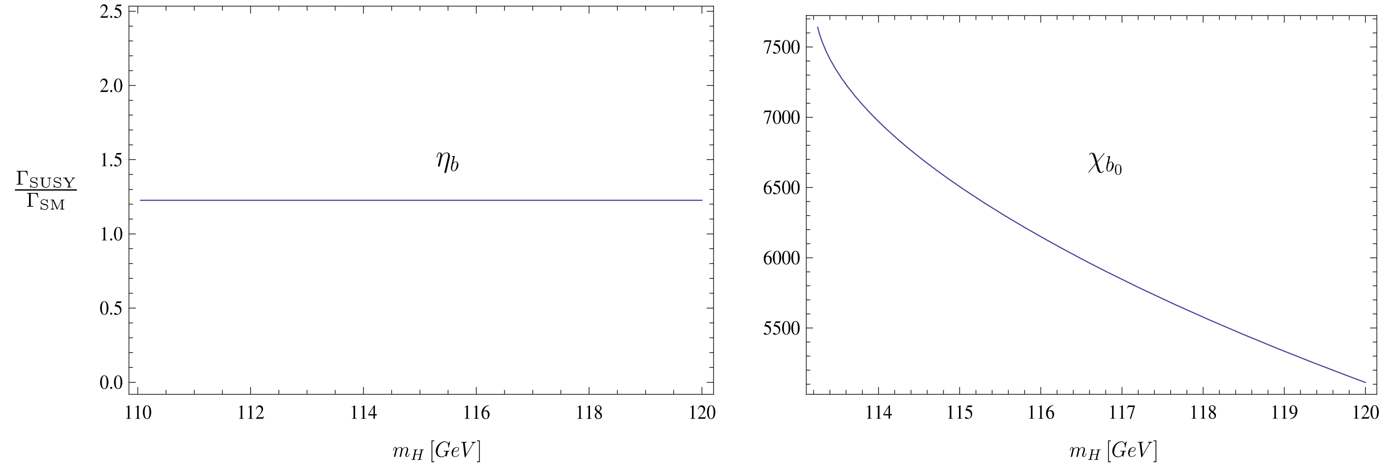

Fig. 3. Variation of the decay rate ratios against the heavy CP-even Higgs mass m_H for η_b (left panel) and χ_{b0} (right panel), for the SPSI parameter space.

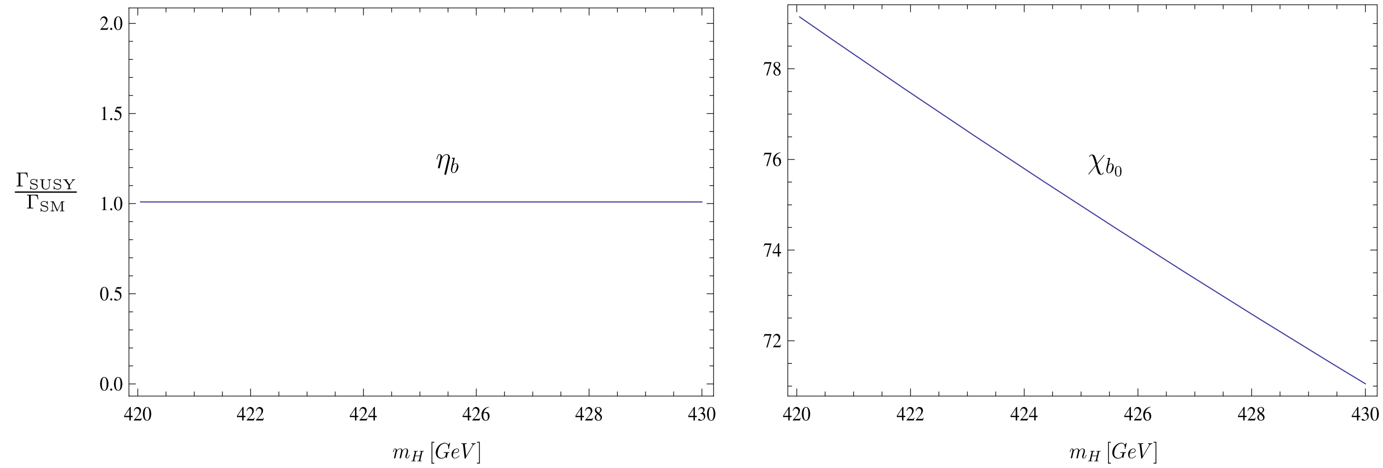

Fig. 4. The same as Fig. 3, but for SPSII parameter set.

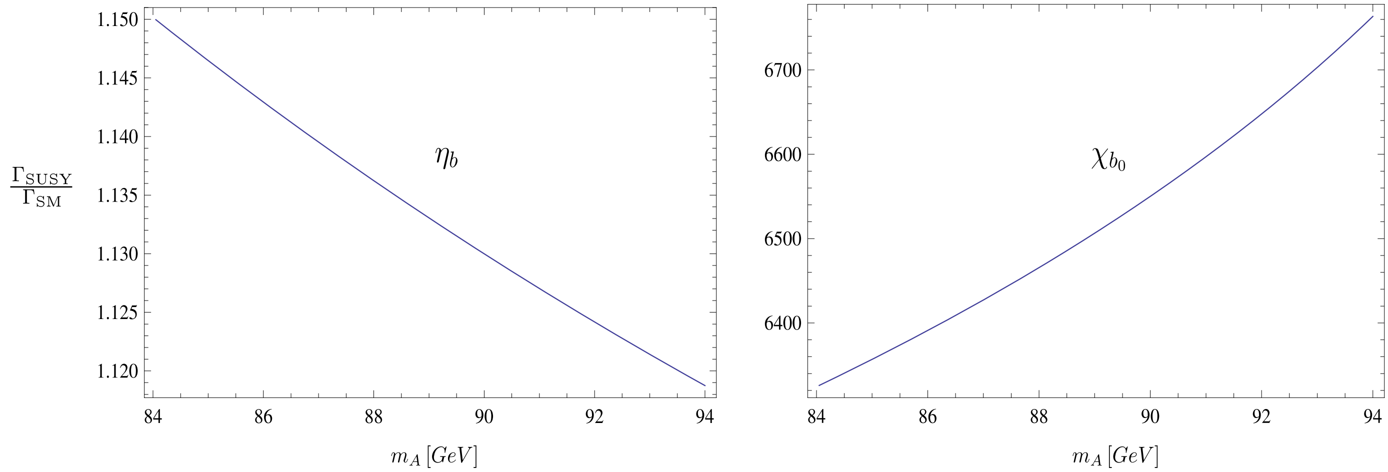

Fig. 5. Variation of the decay rate ratios against the CP-odd Higgs boson mass m_A for η_b (left panel) and χ_{b0} (right panel), for the SPSI parameter space.

rameter sets. For the χ_{b0} decays, the reaction response to variation in m_A is much more pronounced: The decay rate ratio ranges from 6325 to 6760 for SPSI, and does from 71.85 to 73.70 for SPSII. It is important to stress that, as suggested by formulae (5), the m_A dependence of the χ_{b0} decay follows from the dependencies of the H and h couplings on the Higgs mixing angle α.

Another important parameter for the MSSM is the ratio of the vacuum expectation values of the Higgs bosons, the $\tan\beta$. The $\tan\beta$ dependencies of the related decays are depicted in Figs. 7 and 8 for η_b and χ_{b0} for the two parameter sets employed in previous figures.

For the $\tan\beta$ values contained in SPSI and SPSII, η_b decay exhibits less sensitivity to $\tan\beta$ compared to χ_{b0} decay. Nevertheless, the η_b decay stands as a sensitive probe of $\tan\beta$ since it scales as $(\tan\beta)^4$, which becomes quite sizeable at large values of $\tan\beta$. For instance, as can be seen from the left panel of Fig. 7

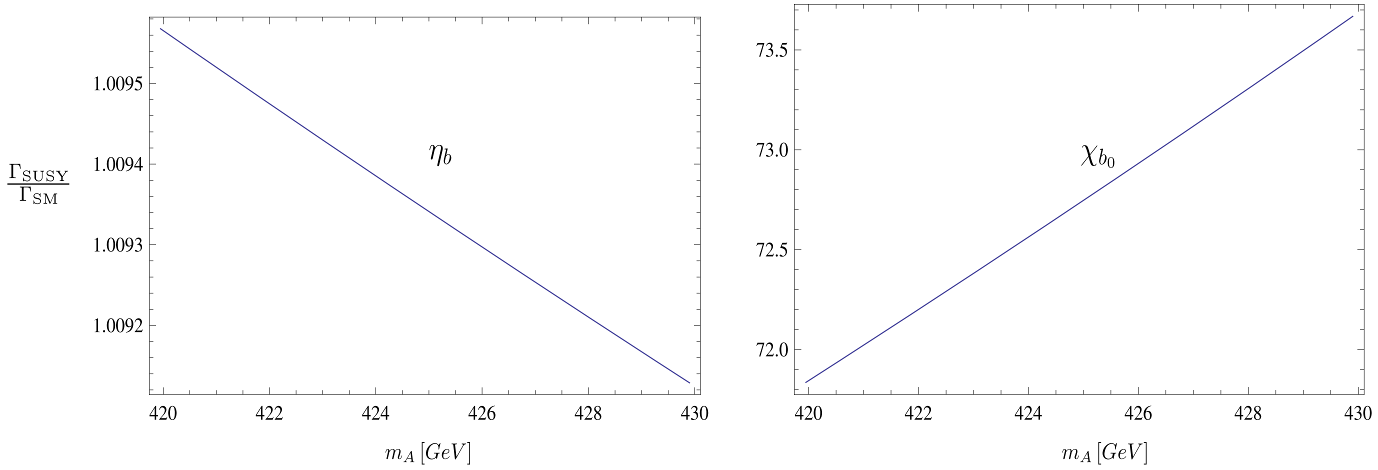

Fig. 6. The same as Fig. 5, but for `SPSII` parameter set.

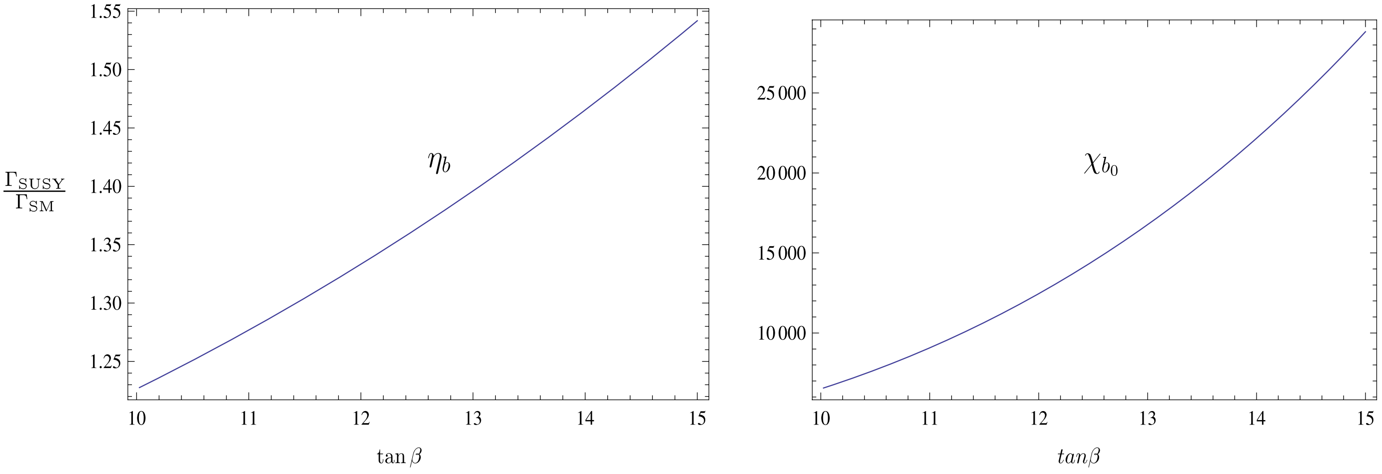

Fig. 7. Variation of the decay rate ratios against $\tan\beta$ for η_b (left panel) and χ_{b0} (right panel), for the `SPSI` parameter space.

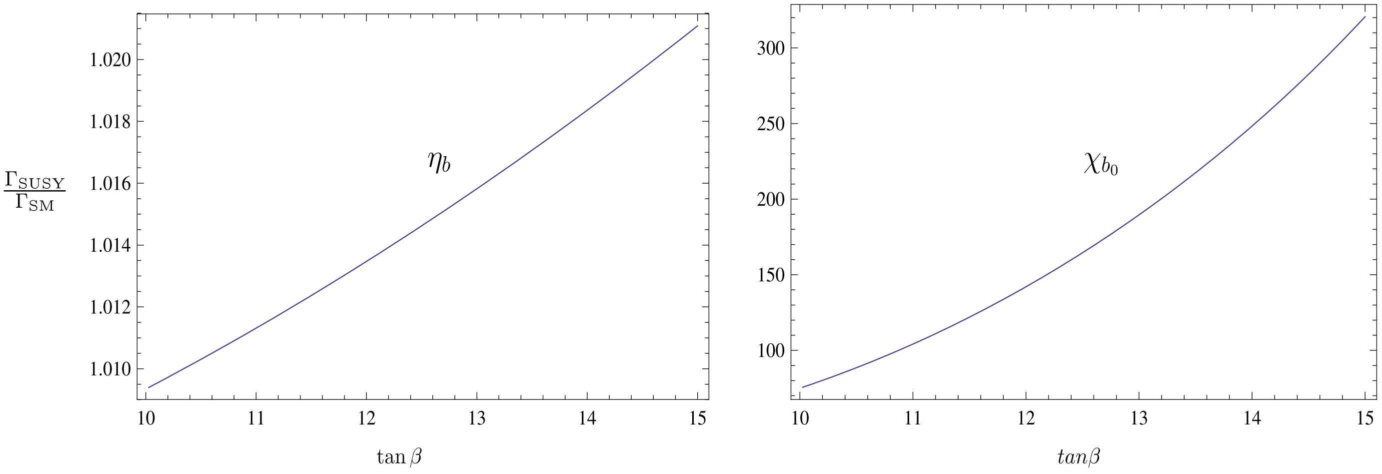

Fig. 8. The same as Fig. 7, but for `SPSII` parameter set.

MSSM's prediction can be ~ 1.5 times larger than of the SM for reasonable values of $\tan\beta$. The impact of the $\tan\beta$ variable for the χ_{b0} decays is always supportive to claim that the MSSM prediction can be four (right panel of Fig. 7) or two orders (right panel of Fig. 8) of magnitude larger than the SM results.

Our last figure is devoted to examining the decay rates in the decoupling limit i.e. the domain in which $m_A = m_H$ and it is much larger than m_h. For this aim, we take $\tan\beta = 10$, $m_h = 120$ GeV and vary $m_H = m_A$ from 124 to 920 GeV. The numerical results are depicted in Fig. 9. As can be seen from the left panel of the

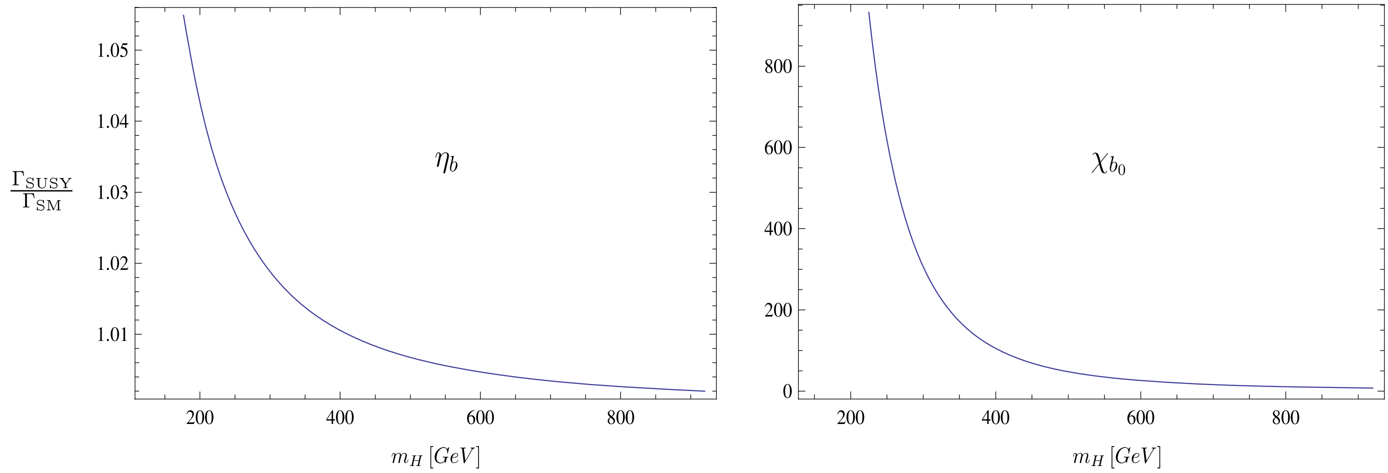

Fig. 9. Variations of the decay rate ratios against $m_H = m_A$. Here we fix the parameters as $\tan\beta = 10$ and $m_h = 120$ GeV.

Table 1
The branching ratios of the η_b decay for different potential models [8] in the SM and in the MSSM.

Decay	Potential	SM	MSSM(SPSI)	MSSM(SPSII)
$\eta_b \to \ell^+\ell^-$	Cornell	5.08×10^{-7}	6.23×10^{-7}	5.13×10^{-7}
	Richardson	2.37×10^{-7}	2.91×10^{-7}	2.39×10^{-7}
	Wisconsin	1.86×10^{-7}	2.29×10^{-7}	1.88×10^{-7}
	Coulomb	1.02×10^{-7}	1.25×10^{-7}	1.03×10^{-7}

Table 2
The branching ratios of the χ_{b0} decay as in Table 1.

Decay	Potential	SM(SPSI, SPSII)	MSSM(SPSI, SPSII)
$\chi_{b0} \to \ell^+\ell^-$	Coulomb	$(6.20 \times 10^{-16}, 3.25 \times 10^{-16})$	$(4.03 \times 10^{-12}, 2.36 \times 10^{-14})$
	others	$(6.20 \times 10^{-14}, 3.25 \times 10^{-14})$	$(4.03 \times 10^{-10}, 2.36 \times 10^{-12})$

very figure, η_b ratio decreases as $m_H = m_A$ increases and its prediction does not offer a difference more than $\sim 3\%$. The largest effect occurs when $m_H = m_A$ is not much larger than m_h, which actually means that the η_b decay cannot give any significant result in the decoupling regime.

Coming to χ_{b0}, however, one notes from the right panel of Fig. 9 that, χ_{b0} is very sensitive to the variation of $m_A = m_H$, especially for low values of the heavy Higgs bosons. As m_H converges to m_h the ratio $\Gamma^{\rm MSSM}(\chi_{b0} \to \ell^+\ell^-)/\Gamma^{\rm SM}(\chi_{b0} \to \ell^+\ell^-)$ can be enhanced up to ~ 900. Of course, this ratio can be further enhanced by increasing the $\tan\beta$. The lesson from this figure is that the $\chi_{b0} \to \ell^+\ell^-$ decay in supersymmetry is a candidate with significantly enhanced predictions with respect to the Standard Model rate.

Moreover, we estimated the branching ratios of the η_b and χ_{b0} decays into $\ell^+\ell^-$ pairs for both SM and MSSM processes using two parameter spaces: SPSI and SPSII. In doing this, different potential model wave functions are examined [8] to probe the arbitrariness in the potential dependency. Our findings are presented in Tables 1 and 2 for η_b and χ_{b0} decays, respectively. As input parameters we used $\Gamma_{\eta_b} = 10$ MeV taken from [16] and $\Gamma_{\chi_{b0}} = 320$ keV from [17].

As can be read from Table 1 our predictions for the branching ratios of the $\eta_b \to \ell^+\ell^-$ decay in the MSSM is ~ 1 (SPSII) and 1.2 (SPSI) times larger than the SM values. On the other hand, as can be read from Table 2, MSSM predictions for the $\chi_{b0} \to \ell^+\ell^-$ branching ratio can be as large as 73 (SPSII) or even 6500 (SPSI) times larger than that of the SM predictions.

It should be noticed for both of the decays that they are rare decays. It is possible to enhance the related predictions theoretically in the MSSM, as examined in this section, but experimental verification of such predictions is a challenging task.

4. Conclusion

In this work we have studied dileptonic bottomonium decays in regard to their sensitivity to Higgs bosons of either CP quantum number. We have found that, dileptonic branching of χ_{b0} is a highly sensitive probe of the extended Higgs sector in that the rate increases significantly compared to the SM prediction.

Theoretically, comparison of the η_b ratio with the χ_{b0} ratio shows that, for the selected parameter ranges, the likelihood of observing the Higgs bosons via dileptonic η_b decays turns out to be much smaller than those of χ_{b0} decays. On the other, experimentally, since the predictions of the branching ratios are at the order of $\sim 10^{-7}$ for the η and $\sim 10^{-10}$ for the χ decays, both in the SM and in the MSSM, η_b turns out to be a better candidate for the observation of the Higgs bosons over these rare decays.

The results found here, given the high-luminosity, high-energy nature of the LHC experiments, can be tested at the LHCb experiments is not at the B factories. Such a test, if conducted, would provide a confirmation strategy if not a discovery strategy for extended Higgs sectors. The recent paper by [18] also discusses the bottomonium decays with particular emphasis on light pseudoscalar Higgs which can be realized in the NMSSM.

Acknowledgements

I would like to thank to D.A. Demir for his contributions with inspiring and illuminating discussions in various stages of this work.

References

[1] G.L. Bayatian, et al., CMS Collaboration, J. Phys. G 34 (2007) 995;
ATLAS: Detector and physics performance technical design report. Volume 1. CERN-LHCC-99-14, ATLAS-TDR-14, 475pp. (1999).
[2] H. Hilke, T. Nakada, LHCb Technical Proposal, CERN-LHCC-98-004; LHCC-P-4 (1998).
[3] D.A. Demir, M.B. Voloshin, Phys. Rev. D 63 (2001) 115011, arXiv:hep-ph/0012123;
Z.Z. Aydin, U. Erkarslan, Phys. Rev. D 67 (2003) 036006, arXiv:hep-ph/0204238;
X.J. Bi, T.F. Feng, X.Q. Li, J. Maalampi, X.m. Zhang, arXiv:hep-ph/0412360;
A. Cordero-Cid, J.M. Hernandez, G. Tavares-Velasco, J.J. Toscano, J. Phys. G 35 (2008) 025004, arXiv:0712.0154 [hep-ph].
[4] D.A. Demir, Phys. Lett. B 571 (2003) 193, arXiv:hep-ph/0303249;
T. Ibrahim, P. Nath, Phys. Rev. D 68 (2003) 015008, arXiv:hep-ph/0305201;

J. Foster, K.i. Okumura, L. Roszkowski, Phys. Lett. B 609 (2005) 102, arXiv:hep-ph/0410323;
T. Hahn, W. Hollik, J.I. Illana, S. Penaranda, arXiv:hep-ph/0512315;
G. Isidori, P. Paradisi, Phys. Rev. D 73 (2006) 055017, arXiv:hep-ph/0601094;
M.A. Cakir, L. Solmaz, PMC Phys. A 2 (2008) 2, arXiv:hep-ph/0608093.
[5] V.A. Novikov, L.B. Okun, M.A. Shifman, A.I. Vainshtein, M.B. Voloshin, V.I. Zakharov, Phys. Rep. 41 (1978) 1.
[6] H.E. Haber, G.L. Kane, T. Sterling, Nucl. Phys. B 161 (1979) 493;
J.R. Ellis, M.K. Gaillard, D.V. Nanopoulos, C.T. Sachrajda, Phys. Lett. B 83 (1979) 339.
[7] H.E. Haber, A.S. Schwarz, A.E. Snyder, Nucl. Phys. B 294 (1987) 301.
[8] V.D. Barger, E.W.N. Glover, K. Hikasa, W.Y. Keung, M.G. Olsson, C.J. Suchyta, X.R. Tata, Phys. Rev. D 35 (1987) 3366;
V.D. Barger, E.W.N. Glover, K. Hikasa, W.Y. Keung, M.G. Olsson, C.J. Suchyta, X.R. Tata, Phys. Rev. D 38 (1988) 1632, Erratum.
[9] J. Irion, Crystal Ball Collaboration, Print-86-1026 (Harvard), Contributed to 23rd International Conference on High Energy Physics, Berkeley, CA, 16–23 July 1986;
A. Heister, et al., ALEPH Collaboration, Phys. Lett. B 530 (2002) 56, arXiv:hep-ex/0202011;
M. Levtchenko, L3 Collaboration, Prepared for 1st International Workshop on Frontier Science: Charm, Beauty, and CP, Frascati, Rome, Italy, 6–11 October 2002;
A. Sokolov, Nucl. Phys. B (Proc. Suppl.) 126 (2004) 266.
[10] T. Skwarnicki, Crystal Ball Collaboration, DESY 85/042 Talk presented at the Recontre de Moriond: QCD and Beyond, Les Arcs, France, 10–17 March 1985;
W.S. Walk, et al., Crystal Ball Collaboration, Phys. Rev. D 34 (1986) 2611;
H. Albrecht, et al., ARGUS Collaboration, Phys. Lett. B 160 (1985) 331;
T. Skwarnicki, et al., Crystal Ball Collaboration, Phys. Rev. Lett. 58 (1987) 972;
T. Affolder, et al., CDF Collaboration, Phys. Rev. Lett. 84 (2000) 2094, arXiv:hep-ex/9910025.
[11] E.L. Berger, J. Lee, Phys. Rev. D 65 (2002) 114003, arXiv:hep-ph/0203092;
N. Fabiano, Eur. Phys. J. C 26 (2003) 441, arXiv:hep-ph/0209283;
A. Hayashigaki, K. Suzuki, K. Tanaka, Phys. Rev. D 67 (2003) 093002, arXiv:hep-ph/0212067;
F. Maltoni, A.D. Polosa, Phys. Rev. D 70 (2004) 054014, arXiv:hep-ph/0405082;
M.B. Voloshin, Mod. Phys. Lett. A 19 (2004) 2895, arXiv:hep-ph/0410368.
[12] S. Eidelman, et al., Particle Data Group, Phys. Lett. B 592 (2004) 1.
[13] D. Atwood, L. Reina, A. Soni, Phys. Rev. D 55 (1997) 3156, arXiv:hep-ph/9609279.
[14] D.A. Demir, Phys. Lett. B 465 (1999) 177, arXiv:hep-ph/9809360;
D.A. Demir, Phys. Rev. D 60 (1999) 055006, arXiv:hep-ph/9901389;
A. Pilaftsis, C.E.M. Wagner, Nucl. Phys. B 553 (1999) 3, arXiv:hep-ph/9902371.
[15] D.A. Demir, L. Solmaz, S. Solmaz, Phys. Rev. D 73 (2006) 016001, arXiv:hep-ph/0512134.
[16] B. Aubert, BaBar Collaboration, arXiv:0903.1124 [hep-ex].
[17] M.A. Sanchis-Lozano, arXiv:hep-ph/0503266.
[18] F. Domingo, U. Ellwanger, E. Fullana, C. Hugonie, M.A. Sanchis-Lozano, arXiv:0810.4736 [hep-ph].