Addendum to “Threshold corrections to $m_b$ and the $\bar{b}b \rightarrow H_i^0$ production in CP-violating SUSY scenarios”

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Abstract

In hep-ph/0401024 “Threshold corrections to $m_b$ and the $\bar{b}b \rightarrow H_i^0$ production in CP-violating SUSY scenarios”, we have pointed out that the production cross sections of the three neutral Higgs bosons through $\bar{b}b$ fusion can deviate substantially from those obtained in CP conserving scenarios, thanks to the nontrivial role played by the threshold corrections to $m_b$ combined with the CP-violating mixing in the neutral-Higgs-boson sector. The deviations are largest for values of the CP violating phases that maximize the mixing among at least two of the three neutral Higgs bosons. We complement our previous work focussing explicitly on the values of masses and widths of the three neutral Higgs bosons in this region of parameter space. We then address the issue of whether the three different peaks in the invariant mass distribution of the Higgs-decay products can be experimentally disentangled at the LHC.
The production cross sections of the three neutral Higgs bosons through \(b\)-quark fusion can deviate substantially from those obtained in CP conserving scenarios, thanks to the nontrivial role that the threshold corrections to \(m_b\) can play in these scenarios [1]. The largest deviations in the case of \(H_1\) and \(H_2\) are for values of \(\Phi_{A\mu}\) around 100°, with a large enhancement for the production cross section of \(H_1\), a large suppression for that of \(H_2\). The former is due to the fact that the component of the field \(a\) in \(H_1\) around these values of \(\Phi_{A\mu}\) is large, while it is depleted by a similarly large amount in \(H_2\). The cross section for \(H_3\) is also largely affected by the \(m_b\) corrections, but this deviation is roughly independent of \(\Phi_{A\mu}\).

In this region of large mixing the \(H_1\) and \(H_2\) bosons have very similar masses, as shown in the first column of Fig. 1 for three different values of \(\Phi_{\gamma\gamma} : 0^\circ, 90^\circ, 180^\circ\). In the first and the third column of this figure, the solid lines always represent \(H_1\), the dashed lines \(H_2\), the long-dashed ones \(H_3\). At \(\Phi_{A\mu} = 100^\circ\), the \(H_1\)-\(H_2\) mass difference is always below 5\,GeV, as shown by the second column of the same figure. As for the widths of these neutral Higgs bosons, \(\Gamma_{H_1}\) is always about 10 times larger than \(\Gamma_{H_2}\) at \(\Phi_{A\mu} = 100^\circ\). See the third column of Fig. 1. Notice that always at \(\Phi_{A\mu} = 100^\circ\), a factor of 10 is also the ratio of the production cross sections of \(H_1\) and \(H_2\), both at the LHC and at the Tevatron.

Given the degeneracy between \(H_1\) and \(H_2\), it is legitimate to worry whether a transition \(H_1 \rightarrow H_2\) can occur during propagation and before decay, due to the off-diagonal absorbitive parts in the \(3 \times 3\) matrix for the neutral Higgs boson propagator considered in Ref. 2. We have numerically checked the size of these off-diagonal parts and found that in our specific case they are negligible. We have nevertheless included these terms in our numerical calculations. Thus, near \(\sqrt{s} = m_{H_i}\), the partonic cross section for the \(\bar{b}b\)-fusion production of \(H_i\) and their subsequent decays into a final state f.s., \(\hat{\sigma}(\bar{b}b \rightarrow H_i \rightarrow \text{f.s.})\), hereafter denoted as \(\hat{\sigma}^{f.s.}\), is given, to a very good approximation, by the cross section with a single \(\hat{s}\)-channel resonance with mass \(m_{H_i}\) and width \(\Gamma_{H_i}\). Away from \(\sqrt{s} = m_{H_i}\), all Higgs bosons \(H_i\) contribute to the partonic cross section for the production of the same final state f.s..

The mass difference between \(H_1\) and \(H_2\) is, however, still small enough to question whether it is possible to disentangle the two corresponding peaks in the invariant mass distributions of the \(H_1\)- and \(H_2\)-decay products. There is no similar problem for the \(H_3\) eigenstate, that has a mass always larger than \(\sim 160\,\text{GeV}\) and therefore a splitting from \(H_2\) always larger than \(\sim 10\,\text{GeV}\). Since \(\Gamma_{H_2,H_3} \lesssim 2 - 3\,\text{GeV}\), we assume that this splitting can be experimentally resolved. As already observed, on the contrary, in the case of \(H_1\) and \(H_2\), the mass difference can be as small 2\,GeV around \(\Phi_A = 100^\circ\). It will therefore be very challenging to disentangle \(H_2\) from \(H_1\) experimentally. An analysis of these two Higgs bosons decay modes, of their differential cross section with respect to the invariant mass distribution of the decay products, and the experimental resolution of these decays, can help in this sense.

For our discussion we shall concentrate on the issue of production and possible problem of detection of \(H_1\) and \(H_2\) at the LHC only, where the best energy and momentum resolutions are for the Higgs-boson decays into muon and photon pairs. For these two decay modes, the invariant-mass resolutions are, respectively, \(\delta M_{\gamma\gamma} \sim 1\,\text{GeV}\) and \(\delta M_{\mu\mu} \sim 3\,\text{GeV}\) for a Higgs mass of \(\sim 100\,\text{GeV}\) [3].
Figure 1: The masses (left column) and widths (right column) of the neutral Higgs bosons as functions of $\Phi_{A\mu}$ for the CPX spectrum specified in Ref. [1] with $M_{\text{SUSY}} = 0.5$ TeV and $\tan \beta = 10$. Three values of $\Phi_{g\mu}$ are considered: $0^\circ$ (top row), $90^\circ$ (middle row) and $180^\circ$ (bottom row). The solid lines are for $H_1$, the dashed ones for $H_2$, and the long-dashed ones for $H_3$. The central column is for the mass difference between $H_2$ and $H_1$.

The $H_i$-differential production cross section through $b$-quark fusion with respect to the invariant mass distribution of the final state f.s. ($= \gamma \gamma$ or $\mu \mu$) is

$$\frac{d\sigma^{f.s.}}{d\sqrt{s}} = \frac{2}{\sqrt{s}} \hat{\sigma}^{f.s.}(\tau) \left( \frac{dL^{bb}}{d\tau} \right) = \frac{2}{\sqrt{s}} \hat{\sigma}^{f.s.}(\tau) \int_{\tau}^{1} dx \left[ \frac{\tau}{x} b_{\text{had}_1}(x, Q) \bar{b}_{\text{had}_2}(\frac{\tau}{x}, Q) + (b \leftrightarrow \bar{b}) \right],$$

where $\tau \equiv \hat{s}/s$, with $s$ the centre-of-mass energy squared of the considered hadron collider. The symbols $b_{\text{had}_1}(x, Q)$ and $\bar{b}_{\text{had}_2}(x, Q)$ indicate the $b$- and $\bar{b}$-quark distribution functions in the hadron had$_1$, and had$_1$ had$_2$ are $pp$ at the LHC (they would be $p\bar{p}$ at the Tevatron). The
partonic cross section $\hat{\sigma}^{f.s.}(s)$ can be written in a compact way for both final states $\bar{\mu}\mu$ and $\gamma\gamma$ as follows:

$$\hat{\sigma}^{f.s.}(s) = \frac{g_s^2 g_{1,2}^2}{16\pi s} \frac{\beta_{f.s.}}{\beta_b} \frac{1}{3} \frac{1}{N_{f.s.}} \sum_{\lambda} |\langle \lambda; \sigma \rangle^{f.s.}|^2,$$

where $\beta_f = (1 - 4m_f^2/s)^{1/2}$, $g_f = g m_f/2M_W = m_f/v$, and

$$g_{f.s.} = \left\{ \begin{array}{ll} \alpha\sqrt{s}/4\pi v & \beta_{f.s.} = \left\{ \begin{array}{ll} 1 & \text{for } f.s. = \gamma\gamma; \\
\beta_\mu & \text{for } f.s. = \bar{\mu}\mu \end{array} \right. 
\end{array} \right.$$

Finally, $\langle \lambda; \sigma \rangle^{f.s.}$ is the reduced helicity amplitude for the process $\bar{b}b \to H_I \to f.s.$ and $\sum_{\sigma,\lambda}$ indicate the sum over the helicities of the initial $b$-quarks, $\sigma$, and of the outgoing $\gamma$'s or $\mu$'s, $\lambda$. For $f.s. = \gamma\gamma$ it is:

$$\langle \lambda; \sigma \rangle^{\gamma\gamma} \equiv \sum_{i,j} \left( \sigma \beta_b g_{H_i,bb}^S + ig_{H_i,bb}^P \right) D_{ij}(s) \left[ S_j^I(s) - i\lambda P_j^I(s) \right],$$

for $f.s. = \bar{\mu}\mu$:

$$\langle \lambda; \sigma \rangle^{\mu\mu} \equiv \sum_{i,j} \left( \sigma \beta_b \left(g_{H_i,bb}^S + ig_{H_i,bb}^P \right) \right) D_{ij}(s) \left( \lambda \beta_\mu g_{H_i,\bar{\mu}\mu}^S - ig_{H_i,\bar{\mu}\mu}^P \right).$$

In both, $D_{ij}$ is the $3 \times 3$ propagator matrix, which, as already mentioned, has negligible off-diagonal terms in the specific case under consideration; $g_{H_i,bb}^{S,P}$ are the couplings denoted as $g_{H_i,bb}^S$ in Eqs. (15) and (16) of Ref. [1], and the symbols $g_{H_i,\bar{\mu}\mu}^{S,P}$ are: $g_{H_i,\bar{\mu}\mu}^S = O_{\phi,ij}/\cos \beta$ and $g_{H_i,\bar{\mu}\mu}^P = -O_{\phi,ij} \tan \beta$. The effective neutral Higgs boson couplings to two photons $S_j^I(s)$ and $P_j^I(s)$ can be found in Ref. [1].

As previously stated, in our specific case, near $\sqrt{s} = m_{H_i}$, the cross section $\hat{\sigma}^{f.s.}$ is well approximated by the cross section with a single $s$-channel resonance with mass $m_{H_i}$ and width $\Gamma_{H_i}$. The form of the helicity amplitudes in Eqs. (11) and (13) can be simplified in such a way that $\hat{\sigma}^{f.s.}$ and $d\sigma^{f.s.}/d\sqrt{s}$ reduce to the simple forms:

$$\hat{\sigma}^{f.s.}(s) \approx \frac{\sigma(bb \to H_i)}{\pi \Gamma_{H_i}} BR(H_i \to f.s.) m_{H_i},$$

$$\frac{d\sigma^{f.s.}}{d\sqrt{s}} \approx \frac{2}{\pi} \frac{\sigma(bb \to H_i)}{\Gamma_{H_i}} BR(H_i \to f.s.) \left( \frac{d\mathcal{L}^{bb}}{d\tau} \right),$$

where $\sigma(bb \to H_i)$ is the partonic cross section for the production of $H_i$ through $b$-quark fusion, shown in Ref. [1]. The dominant contribution to the widths $\Gamma_{H_1}$ and $\Gamma_{H_2}$ comes from the decays $H_{1,2} \to b\bar{b}$, at $\Phi_{A_H} \sim 100^\circ$. In this region, therefore, the ratios $\sigma(bb \to H_i)/\Gamma_{H_i}$ are roughly independent of $\Phi_{A_H}$, whereas $\sigma(bb \to H_i)$ and $\Gamma_{H_i}$, separately, are strongly dependent on it. Thus, still for $\Phi_{A_H} \sim 100^\circ$, given the degeneracy of $H_1$ and $H_2$, the relative heights of the peaks of $\hat{\sigma}^{f.s.}$ and $d\sigma^{f.s.}/d\sqrt{s}$ at $s = m_{H_1}^2$ and $s = m_{H_2}^2$ are practically determined by $BR(H_i \to f.s.)$ only.

In Figs. 2 and 3 we compare the values of both, the partonic cross section $\hat{\sigma}^{f.s.}$ and the differential hadronic cross section $d\sigma^{f.s.}/d\sqrt{s}$ for $f.s. = \gamma\gamma$ and $f.s. = \bar{\mu}\mu$ at two different
Figure 2: Cross sections $\hat{\sigma}^{\gamma\gamma}$ (upper two frames) $d\sigma^{\gamma\gamma}/d\sqrt{s}$ (lower two frames) at $\Phi_{A\mu} = 100^\circ$ and $\Phi_{A\mu} = 105^\circ$, versus $\sqrt{s}$. In all frames, it is $\tan\beta = 10$ and $\Phi_{g\mu} = 180^\circ$.

Figure 3: Same as in Fig. 2 for $\hat{\sigma}^{\bar{\mu}\mu}$ (upper two frames) and $d\sigma^{\bar{\mu}\mu}/d\sqrt{s}$ (lower two frames).
values of $\Phi_{A\mu}$: 100° and 105°. These two values of $\Phi_{A\mu}$ are sufficiently close to avoid a substantial reduction of the enhancing factor for $\sigma(\bar{b}b \to H_1)$ when going from $\Phi_{A\mu} = 100°$ to $\Phi_{A\mu} = 105°$. They are, however, separated enough for us to escape at $\Phi_{A\mu} = 105°$ the strong suppression that $\sigma(\bar{b}b \to H_2)$ and $\Gamma_{H_2}$ have at $\Phi_{A\mu} = 100°$.

For an easier comparison of the cross sections obtained for the two different decay channels of $H_1$ and $H_2$, we list explicitly in Table 1 the values of $m_{H_1}$, $\Gamma_{H_1}$, $\sigma(\bar{b}b \to H_i)$, $BR(H_i \to \gamma\gamma)$, and $BR(H_i \to \mu\mu)$ at $\Phi_{A\mu} = 100°$ and 105°. We notice:

- Going from $\Phi_{A\mu} = 100°$ to $\Phi_{A\mu} = 105°$, the mass of $H_2$ increases by less than 2.5 GeV. It is, at these two values of $\Phi_{A\mu}$, respectively only about 3 and 5 GeV larger than $m_{H_1}$, which, as explained in Ref. [1], has been fixed to 115 GeV for all values of $\Phi_{A\mu}$.

- At $\Phi_{A\mu} = 100°$, as already observed in Ref. [1], the value of the partonic cross sections $\sigma(\bar{b}b \to H_1)$ is about five times larger than $\sigma(\bar{b}b \to H_2)$. Similarly, $\Gamma_{H_2}$ is suppressed with respect to $\Gamma_{H_1}$ also by a factor of five. At $\Phi_{A\mu} = 105°$, on the contrary, both cross sections and widths for $H_1$ and $H_2$ are remarkably similar, and only a factor of 1.5-2 less than the maximal values of $\sigma(\bar{b}b \to H_1)$ and $\Gamma_{H_1}$ obtained at $\Phi_{A\mu} = 100°$.

- As for the branching ratios of $H_1$ and $H_2$ into $\gamma\gamma$ and $\mu\mu$, we notice that at $\Phi_{A\mu} = 100°$, the branching ratio $BR(H_1 \to \gamma\gamma)$ is about two order of magnitude smaller than $BR(H_2 \to \gamma\gamma)$, whereas it is of the same order of (actually 50% larger than) $BR(H_2 \to \gamma\gamma)$ at $\Phi_{A\mu} = 105°$. The strong suppression of $BR(H_1 \to \gamma\gamma)$ at $\Phi_{A\mu} = 100°$ is due to the large component of $a$ in $H_1$ at this value of $\Phi_{A\mu}$. On the contrary, the branching ratios $BR(H_1 \to \mu\mu)$ and $BR(H_2 \to \mu\mu)$ are of the same size for both values of $\Phi_{A\mu}$ considered.

Therefore, at $\Phi_{A\mu} = 100°$, when the neutral Higgs bosons decay into a pair of photons, we expect to see only one peak corresponding to $H_2$. Given the values of the invariant mass distribution in the lower-left frame of Fig. 2 for a luminosity of 100 fb$^{-1}$, we expect to have

Table 1: For $H_1$ and $H_2$ at two different values of $\Phi_{A\mu}$: 100°, 105°, we list here the values of masses and widths (in GeV), of the partonic cross sections for their resonant production (in pb) and of the branching ratios of their decays into a pair of $\mu$’s and a pair of $\gamma$’s. $\Phi_{g\mu}$ is fixed at 180° and $\tan\beta$ at 10.

| $\Phi_{A\mu}$ | $m_{H_1}$ [GeV] | $\Gamma_{H_1}$ [GeV] | $\sigma(\bar{b}b \to H_1)$ [pb] | $BR(H_1 \to \mu\mu)$ | $BR(H_1 \to \gamma\gamma)$ |
|--------------|----------------|------------------|----------------------|-----------------|------------------|
| $H_1$ 100°   | 115.0          | 0.9157           | 786.7                | $8.227 \times 10^{-5}$ | $3.996 \times 10^{-7}$ |
| $H_1$ 105°   | 115.0          | 0.5664           | 486.3                | $8.654 \times 10^{-5}$ | $9.883 \times 10^{-6}$ |
| $H_2$ 100°   | 117.7          | 0.1818           | 145.3                | $9.978 \times 10^{-5}$ | $4.858 \times 10^{-5}$ |
| $H_2$ 105°   | 120.1          | 0.5652           | 429.4                | $7.953 \times 10^{-5}$ | $6.219 \times 10^{-6}$ |
∼ 50 events in the $\sqrt{s}$ interval $[m_{H_2} - \delta M_{\gamma\gamma}/2, m_{H_2} + \delta M_{\gamma\gamma}/2]$, with $\delta M_{\gamma\gamma}$ the experimental invariant mass resolution mentioned above, ∼ 1 GeV. When $\Phi_{A\mu} = 105^\circ$, it is possible to detect two peaks and have, for the same luminosity, more than 30 (20) events in the two $\sqrt{s}$ intervals of 1 GeV centered around $m_{H_1}$ and $m_{H_2}$.

When $H_1$ and $H_2$ decay into a muon pair, although the cross sections are larger, a resolution of the two picks will be more difficult because of the worse experimental resolution $\delta M_{\mu\mu} \sim 3\text{ GeV}$. At $\Phi_{A\mu} = 100^\circ$, again for a luminosity of 100 fb$^{-1}$, it is possible to have more than 1,000 events in the interval $[m_{H_1} - \delta M_{\mu\mu}/2, m_{H_1} + \delta M_{\mu\mu}/2]$, and 200 events in $[m_{H_2} - \delta M_{\mu\mu}/2, m_{H_2} + \delta M_{\mu\mu}/2]$. Notice that $H_2$ is only 2.7 GeV away from $H_1$. For $\Phi_{A\mu} = 105^\circ$, more than 300 events are expected for both peaks, separated by 5 GeV, see the lower-right frame of Fig. 3.

For both values of $\Phi_{A\mu}$, by combining the muon-decay mode with the photon-decay mode, $H_2$ can be located more precisely and disentangled from $H_1$. At $\Phi_{A\mu} = 105^\circ$, actually, two well separated peaks may be observed. It is clear that these considerations are only a first step towards more dedicated analyses, which obviously require detector simulations and background studies.

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