MSSM Higgs Bosons in the Intense Coupling Regime

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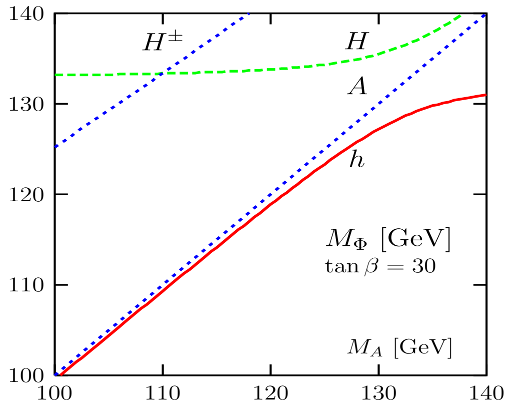
1. The intense-coupling regime

The intense-coupling [1, 2] regime in the MSSM Higgs sector is such a regime when mass of the CP-odd Higgs boson A is close to the critical mass, the maximal (minimal) value of the CP-even h (H) Higgs boson, and $\tan\beta$ is rather large. In this scenario masses of all neutral Higgses are close to each other, decay widths are large. All Higgses couple maximally to electroweak gauge bosons and strongly to standard third generation fermions.

Figures 1,2,3 show main phenomenological features of the intense-coupling regime. If M_A close to the maximal h boson mass, $M_h^{\max} \simeq 130$ GeV, the mass differences $M_A - M_h$ and $M_H - M_A$ are less than 5 GeV. $M_{H^\pm}$ does not exceed 160 GeV, which implies that charged Higgs bosons can always be produced in top quark decays, $t \to H^+ b$. The branching ratios of the neutral Higgs particles to $b\bar{b}$ and $\tau^+\tau^-$ are dominant, with values $\sim 90\%$ and $\sim 10\%$, respectively. The total widths of the neutral Higgs particles are about 1-2 GeV(for $M_A \sim 130$ GeV, $\tan\beta = 30$), two orders of magnitude larger than



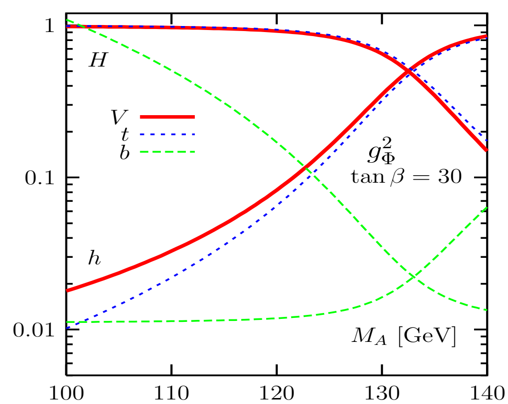


Figure 1: *The masses of the MSSM Higgs bosons (left) and the normalized couplings of the CP-even Higgs bosons to vector bosons and the third-generation quarks (right) as a function of M_A for tan$\beta = 30$. For the b-quark couplings, the values $10 \times g^{-2}_{\Phi bb}$ are plotted.*

the width of the SM Higgs. So, it is a difficult problem how to resolve the three neutral Higgs bosons in the intense-coupling regime when their masses are close to each other.

In our analyzes we set $\tan\beta = 30$, common stop masses $M_S = 1$ TeV, trilinear Higgs-stop coupling $A_t \simeq \sqrt{6} M_S$ (maximal mixing scenario). For MSSM parameter, Higgs boson decay widths and branching fractions calculation we use the package `HDECAY` [3] with the link to the `FeynHiggs` [4], while the program `CompHEP` [5] is used for calculations of the cross section and event generation. With the help of the new `CompHEP-PYTHIA` interface [6] which is based on the Les Houches Accord 1 format [7], unweighted events from CompHEP are processed through `PYTHIA 6.2` [8] for fragmentation and hadronization.

2. Discrimination of the three neutral Higgs bosons at the LHC [2]

At the LHC three neutral Higgs bosons will be produced mainly in the gluon-gluon and $b\bar{b}$ fusion processes $gg, b\bar{b} \to \Phi = h, H, A$ and in association with one or two b-quarks (b-jets) $g, b \to b\Phi$, $gg/q\bar{q} \to b\bar{b} + \Phi \to b\bar{b}$ (see [9]

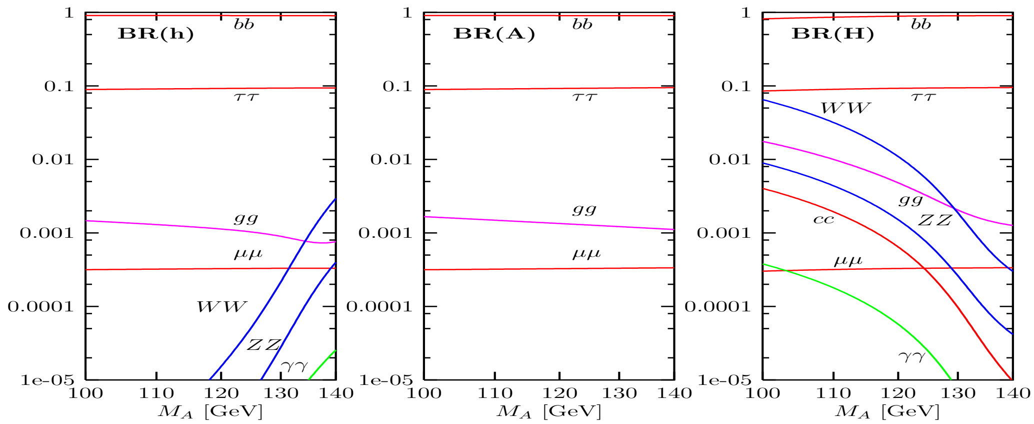


Figure 2: *Some branching ratios of the neutral MSSM Higgs bosons h, A, H as a function of M_A for $\tan\beta = 30$.*

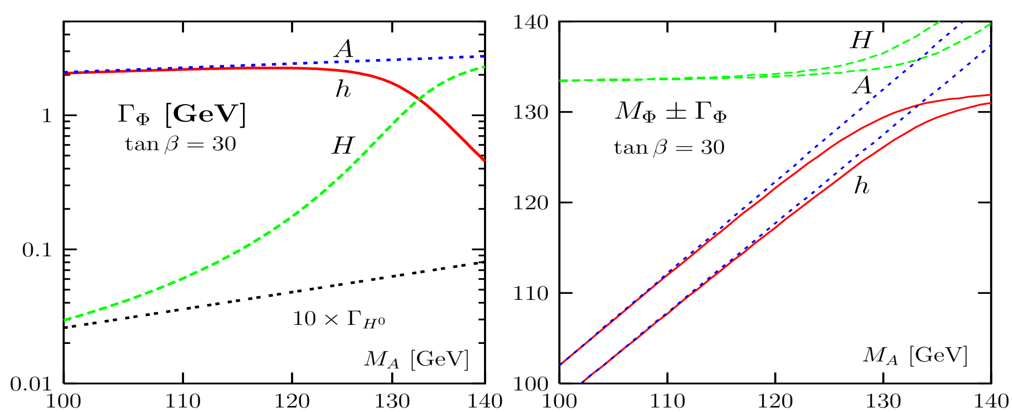


Figure 3: *Total decay widths Γ_Φ (left) and the mass bands $M_\Phi \pm \Gamma_\Phi$ (right) for the neutral MSSM Higgs bosons as a function of M_A and for $\tan\beta = 30$.*

and references therein for details of NLO rate computations). The Higgs-strahlung and vector-boson fusion processes as well as associated Higgs and top quarks production have smaller cross sections [1].

In spite of Higgs decays to $b\bar{b}$, $\tau^+\tau^-$ -pairs has large branching ratios these channels are difficult for discovery because of large QCD background and not enough τ mass resolution (of the order of 10 to 20 GeV). As one can see from the Fig.2 the decay branching fraction of the Higgs bosons to two photons in the intense coupling regime is too small. Although the branching ratio to muon pairs is rather small, BR($\Phi \to \mu^+\mu^-$) $\sim 3.3 \times 10^{-4}$, the dimuon mass resolution is expected to be about 1 GeV, i.e. comparable to the total decay width of $M_\Phi \sim 130$ GeV, and therefore the channels with muons in the final states are the most promising. [1]

The analysis of the process $pp(\to h, H, A) \to \mu^+\mu^-$ shows [2] that the signal rate is fairly large but when the overwhelming Drell–Yan background is added, the signal becomes invisible. The signal from $pp \to \mu^+\mu^- b\bar{b}$ is an order of magnitude smaller but the ratio of the signal to the complete 4-fermion SM background gets much better, so at least two peaks on top of the background can be recognized. Details of simulations including as an example a CMS detector response can be found in Ref. [2]. The results of the study for the parameter point P1 (MA=125 GeV) are shown in Fig. 4, assuming an integrated luminosity of 100 fb^{-1}. For this case the signal cross section for the heavier CP-even H boson is significantly smaller than those for the lighter CP-even h and pseudoscalar A bosons. The latter particles are too close in mass ($\Delta M = 1.7$ GeV) to be resolved, and only one single broad peak for h/A and small peak for the heavier H boson are visible. The analysis was also performed for $M_A = 130$, 135 GeV and $\tan\beta = 30$ (denoted as point P2 and P3 respectively). In case P2, it would be possible to recognize better the H boson with an integrated luminosity of 100 fb^{-1}. However, h and A signal discrimination could not be achieved. For $M_A = 135$, all three neutral h, A and H bosons have comparable signal rates, and their mass differences are sufficiently large and peaks could be separated.

[1] Another possibility at the LHC is to use diffractive Higgs production [10], applying a recoil mass technique similar to e^+e^- collisions. However, good proton beam energy resolution and precise luminosity measurements are very crucial to resolve the Higgs signals for accurate mass determinations.

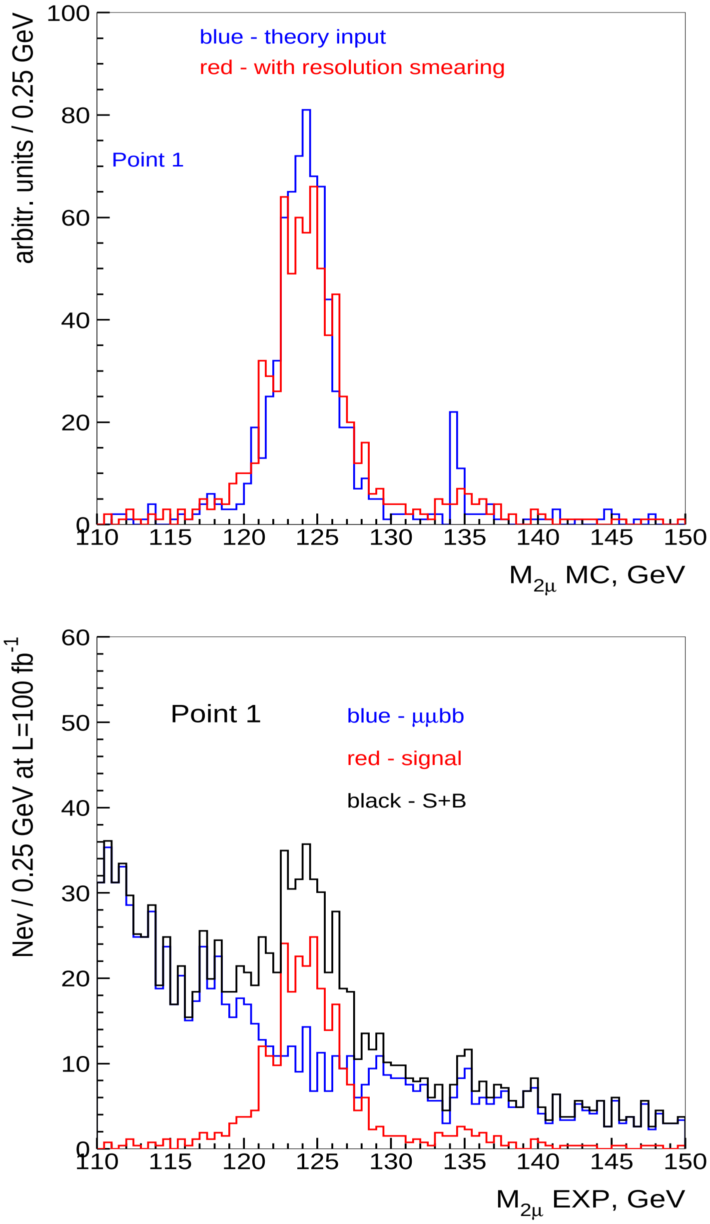


Figure 4: $\mu^+\mu^-$ *invariant mass distributions for the signal without and with detector resolution smearing (left) and for the signal and background with detector response (right) for* $M_A = 125$ *GeV and* $\tan\beta = 30$.

3. Discrimination in e^+e^- collisions [11]

In e^+e^- collisions, the CP-even Higgs bosons can be produced in the Higgsstrahlung, $e^+e^- \to Z + h/H$, and vector-boson fusion, $e^+e^- \to \nu\bar{\nu} + h/H$, processes. The CP-odd particle can not be probed in these channels since it has no couplings to gauge bosons at tree level. It can be produced in association with the h or H in the reaction $e^+e^- \to A + h/H$. Studies have shown that in the intense-coupling regime the vector-boson fusion processes, $e^+e^- \to \nu\bar{\nu} + h/H$, are hardly usable to explore the individual Higgs boson states. On the contrary, Higgsstrahlung and Higgs pair production processes, as will be demonstrated, have some realistic potential to measure the masses of the h, H, and A Higgs bosons.

The cross sections for Higgsstrahlung and pair production processes are mutually complementary and can be expressed as

$$\begin{aligned} \sigma(e^+e^- \to Z + h/H) &= \sin^2/\cos^2(\beta - \alpha)\sigma_{\rm SM} \\ \sigma(e^+e^- \to A + h/H) &= \cos^2/\sin^2(\beta - \alpha)\bar{\lambda}\sigma_{\rm SM} \end{aligned}$$

where $\sigma_{\rm SM}$ is the SM Higgs cross section and $\bar{\lambda} \sim 1$ for $\sqrt{s} \gg M_A$ accounts for P–wave suppression near threshold. Rather large production cross sections $\sigma_{\rm SM}$, being of the order of 10-100 fb at c.m. energy $\sqrt{s} = 300$ GeV, allow to have large number of signal events for all three neutral Higgs bosons with an integrated luminosity of $\int \mathcal{L} \sim 0.5 - 1$ ab^{-1}. Accumulation of such a luminosity might be achievable at a linear e^+e^- collider as proposed e.g. in [12]. In Fig.5 the cross sections for Higgsstrahlung and Higgs pair production are shown for the MSSM parameter points P1, P2, and P3. In e^+e^- collisions, Higgsstrahlung processes offer the most promising way to discriminate between the two CP-even Higgs particles, since the pseudoscalar boson A is not involved. As was widely demonstrated for the SM Higgs boson, recoil mass measurements in both leptonic and hadronic Z decays allow very precise determination of its mass with e.g. an uncertainty of ~ 40 MeV for $M_H \sim 120$ GeV [12]. In the intense-coupling scenario, where the two scalar Higgs bosons h and H are close in mass and are often produced with similar rates, the impact of initial state radiation (ISR) and beamstrahlung is more important and should be carefully taken into account. Detailed simulations including signal and all main background reactions using the program packages CompHEP and PYTHIA and the detector response code SIMDET [14] reveal that the most promising way for measuring h and H masses is to select

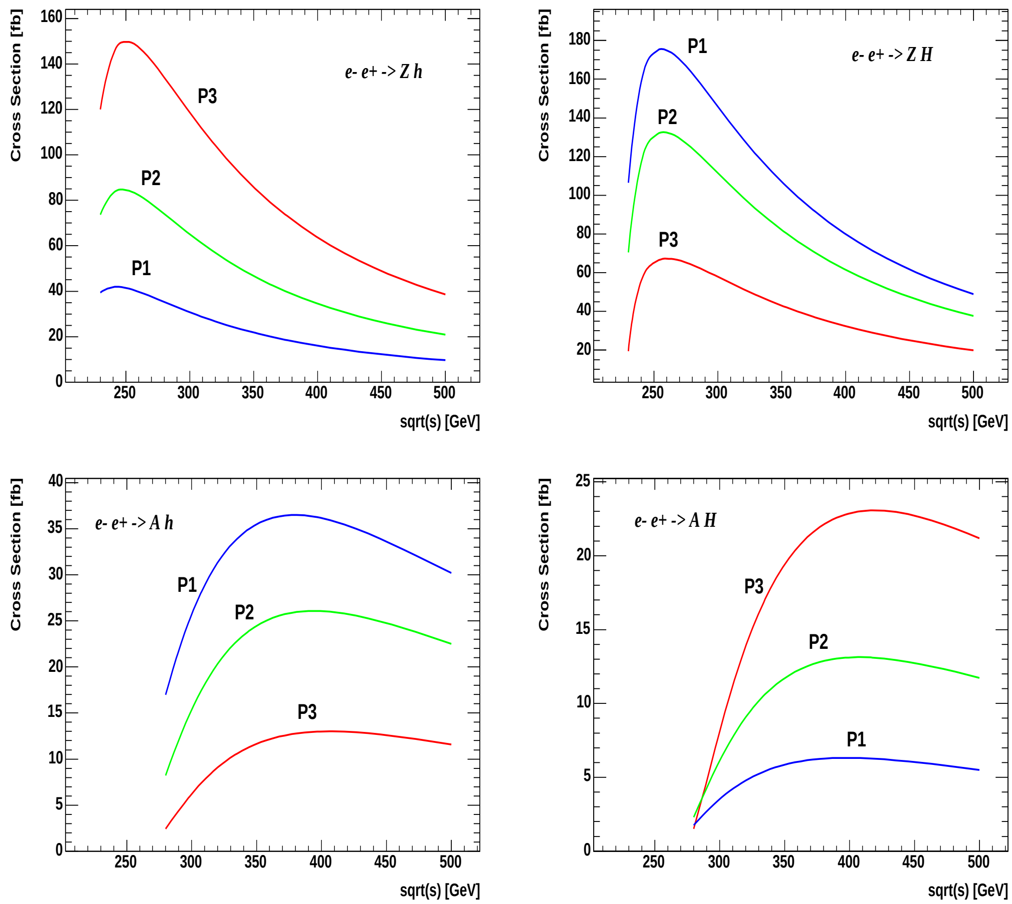


Figure 5: *Cross sections for the Higgs–strahlung (upper plots) and for the Higgs pair processes (lower plots) production for the MSSM parameter points P1, P2, and P3 with MA = 125, 130, 135 GeV*

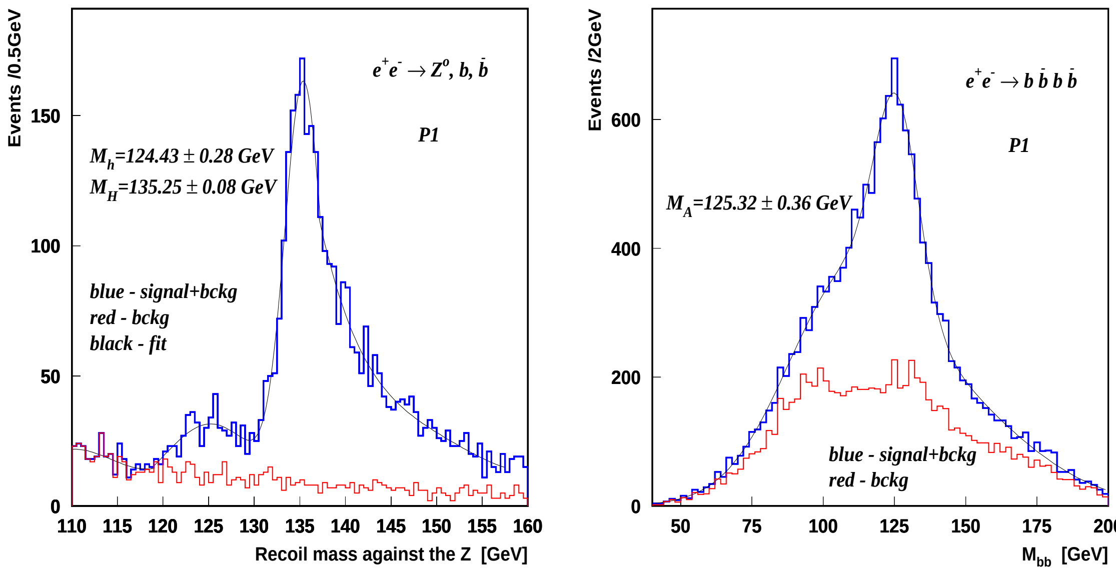


Figure 6: *The recoil mass distributions for the signal and backgrounds including ISR, beamstrahlung and detector smearing for the parameter points P1 after cuts and b-tagging (Left). The invariant mass of two b-jets associated to the A boson after cuts and selection procedures for the parameter points P1 (Right).*

first the $l^+l^-b\bar{b}$ event sample ($l = e/\mu$) and then apply the recoil Z boson mass technique. Without cuts and b-tagging, however, signals from h and H bosons cannot be resolved. If some realistic b-tagging and the following kinematical requirements

- the dilepton invariant mass should be within $M_{l^+l^-} = 90 \pm 6$ GeV,
- each jet energy has to have $E_j \geq 12$ GeV,
- the angle between two jets is $\angle(jet1, jet2) \geq 95$ degrees,
- and only two jets per event

are applied, separation of the two Higgs signals seems possible and their masses might be accessible. Results of simulations for the case of TESLA, as an example, and for the MSSM parameter points P1 are shown in the Fig. 6(Left). The selection efficiencies found are 68% for the signal reaction, 22% for $l^+l^-b\bar{b}$, 6.4% for $l^+l^-c\bar{c}$ and 0.1% for $l^+l^-q\bar{q}$ ($q = u, d, s$) background processes. As indicated in the Fig. 6(Left) masses for the h and H Higgs particles can be determined with precisions of the order of 80-280 MeV at e.g. 300 GeV collider energy and 500 fb^{-1} accumulated luminosity. At higher center-of-mass energies, Higgs mass determination will be significantly worse due to smaller production cross sections, degraded energy resolution of the more energetic leptons and stronger impact of ISR and beamstrahlung.

The complementary pair production channels $e^+e^- \to A + h/H$ allow to probe the CP-odd A boson. Since h and H boson masses will be known from utilizing the recoiling mass technique, attention should be directed to the A particle and its mass determination, either via reconstruction of $b\bar{b}$ and/or $\tau^+\tau^-$ invariant masses or through a threshold scan. The first method has been discussed in [13] for heavy Higgs bosons in the reaction $e^+e^- \to HA \to 4b$ at $\sqrt{s} = 800$ GeV. In the case of the decoupling limit discussed in [15], precisions of about 100 MeV for boson masses were obtained far above thresholds utilizing the $b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$ final states.

In the intense coupling regime, the three neutral Higgs bosons contribute to the $b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$ final states. Since typical b-jet energy resolutions are close to or somewhat larger than the Higgs mass differences, it is not a trivial task to differentiate between $A \to b\bar{b}$ and $h/H \to b\bar{b}$ decays. After selecting 4 b-jet events by means of b-tagging, we consider all three possible combinations of 2 b-jet pairs. Only one of them is the 'physical' combination, where both b-quarks in each pair correspond to one of the Higgs particles. The other two combinations are combinatorial background.

Due to well defined kinematics in the process $e^+e^- \to A(h/H) \to (b\bar{b})(b\bar{b})$ the angle between two b-jets in the Higgs decay

$$angle(b\bar{b}) \simeq 2 * arctg\left(2 * \sqrt{\frac{M_\Phi^2 - 4m_b^2}{(\sqrt{s})^2 - 4M_\Phi^2}}\right) \quad (1)$$
$$(M_\Phi = M_A, M_h, M_H),$$

is about 115^0 for our parameter set and independent on the Higgs particle since their masses are almost degenerated. A sharp distribution is evident for the 'correct' (signal) b-jet pair, while combinatorial b-jet background pairing leads to a flat distribution. In addition, b-jet pairs from Higgs decays are more centrally produced than combinatorial background. Thus, separation of 'physical' combinations from combinatorial background might be achieved by means of the following cuts: $-0.95 < cos(b_1 b_2) < -0.3$ and $|cos(\theta_{bb-pair})| < 0.7$, with $cos(b_1 b_2)$ the cosine of the angle between two b jets and θ the polar angle of the $b\bar{b}$ system. 'Physical' pairs are selected with an efficiency of about 85%, whereas background combinations with about 20%.

Finally, selection of the pseudoscalar boson A from the (A h) and (A H) pairing relies on the 'combinatorial mass difference' method [11]. Resulting $b\bar{b}$ mass spectra for the MSSM parameter points P1 are shown in Fig. 6(Right). Only that 2 b-jet mass is displayed which has been assigned to the A boson. As fits to these histogram revealed, the mass of the pseudoscalar Higgs boson A can be measured with an accuracy of 300 to 400 MeV, taking into account the measured masses of the h and H particles with their corresponding errors. Such precisions, although larger than those for the SM Higgs, are smaller than typical mass differences $M_A - M_h$ or $M_H - M_A$.

5. Conclusions

The intense-coupling regime where $\tan\beta$ is rather large and the three neutral h, H and A MSSM Higgs bosons have comparable masses close to the critical point $M_h^{\max}$, is one of the most difficult scenario to be resolved completely. The detection of the individual Higgs boson signals is very challenging at the LHC. Only in the associated Higgs production mechanism with $b\bar{b}$ pairs, with at least one tagged b-jet, and with Higgs decays into the clean muon-pair final states, there is a chance of observing the three signals and resolve between them. This would be possible only if the Higgs mass differences are larger than 3-5 GeV.

In e^+e^- collisions, thanks to the clean environment and the complementarities of possible production channels, separation of the three Higgs bosons seems possible. The Higgsstrahlung processes allow at first to probe the h and H bosons and to measure their masses from the recoiling mass spectrum to the Z boson. Best results are expected here by selecting the $2b{-}jets{+}l^+l^-$ event sample and imposing b-jet tagging. Then associated CP-even and CP-odd Higgs production would allow to probe the pseudoscalar A boson by direct reconstruction of its decay products. At collision energies $\sqrt{s} \simeq 300$ GeV and an integrated luminosity of 500 fb^{-1}, uncertainties of mass measurements for the three neutral Higgs particles are expected to be about 400 MeV or less. This is smaller than typical Higgs mass differences in this scheme. Higher precisions might be obtained by measuring the $e^+e^- \to A+h/H$ cross sections across the respective threshold where they rise as $\sigma \sim \beta^3$.

The LHC and LC interplay may be very important to study the intense coupling scenario completely. Measured characteristics at the LC allow then to measure several other quantities at the LHC, like the glue-glue-Higgs couplings and BR($\Phi \to \mu^+\mu^-$). On the other hand, if Higgs masses are not completely accessible at the LHC, any broad peak information assists the choice of the appropriate energy at the LC.

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