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# SUSY Decays of Higgs Particles

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**Abstract**

Among the possible decay modes of Higgs particles into supersymmetric states, neutralino and chargino decays play a prominent rôle. The experimental opportunities of observing such decay modes at LEP2 and at future $e^+e^-$ linear colliders are analyzed within the frame of the Minimal Supersymmetric extension of the Standard Model. For heavy Higgs particles, the chargino/neutralino decay modes can be very important, while only a small window is open for the lightest CP–even Higgs particle. If charginos/neutralinos are found at LEP2, such decay modes can be searched for in a small area of the parameter space, and invisible decays may reduce the exclusion limits of the lightest CP-even Higgs particle slightly; if charginos/neutralinos are not found at LEP2 in direct searches, the Higgs search will not be affected by the SUSY particle sector.

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**1.** New light will be shed on the Higgs sector of supersymmetric theories in the forthcoming LEP2 experiments [1]. In fact, if the parameter $\tan\beta$ in the Minimal Supersymmetric Standard Model ($\mathcal{MSSM}$) is realized within the range between 1 and 3 as suggested by unification of $b$–$\tau$ Yukawa couplings [2], prospects of discovering at least the lightest CP–even neutral Higgs boson $h$ at LEP2 are very good. At future $e^+e^-$ linear colliders, the entire parameter space can be explored. The lightest Higgs boson $h$ can be discovered with certainty, and the Higgs bosons $H, A$ and $H^\pm$ are accessible in major parts of the parameter space.

Most theoretical predictions of Higgs decay properties have focussed in the past on final states built up by the electroweak gauge bosons, standard quarks/leptons and cascade decays [3]. While decays to squarks and sleptons are expected to be less important and are in general forbidden kinematically for fairly light Higgs bosons, decays to neutralinos and charginos

$$\begin{aligned} h, H, A &\rightarrow \chi_i^0\chi_j^0 \ \text{ and } \ \chi_i^+\chi_j^-, \\ H^\pm &\rightarrow \chi_i^0\chi_j^\pm, \end{aligned} \tag{1}$$

[$i, j$ = 1–4 for neutral, and $i, j = 1, 2$ for charged states], in particular to the light $\chi_1^0$ states, could play a potentially important rôle [4, 5]. The final states would have interesting topologies. If R–parity is conserved and $\chi_1^0$ is the lightest supersymmetric stable particle (LSP), the $\chi_1^0\chi_1^0$ final states are invisible. In the other modes, $\chi_i^0$ and $\chi_i^\pm$ decay cascades [5, 6] would come with large missing energies in the events. For instance, the decays $h, A \rightarrow \chi_1^0\chi_2^0$ could lead to final states $\chi_1^0\chi_1^0 f\bar{f}$, with the two LSPs escaping undetected.

These novel decay modes can only be relevant if the standard decay modes are not overwhelming. Prime interest is therefore restricted to low to moderate $\tan\beta$ values since $b$ and $\tau$ decays are otherwise dominant. It turns out *a posteriori* that when $\chi$ decay channels are open, the branching ratios can be close to 100%, opening opportunities for the experimental analysis of the fundamental parameters in supersymmetric theories.

In this note, possible $\chi\chi$ decays of Higgs particles are analyzed in the parameter range of LEP2 and future $e^+e^-$ linear colliders which should eventually run with energies up to 2 TeV, sweeping the entire $\mathcal{MSSM}$ Higgs spectrum up to masses of order 1 TeV [7]. These unconventional Higgs decays, in particular the invisible $\chi_1^0\chi_1^0$ final states, could change the experimental analyses for discovering $\mathcal{MSSM}$ Higgs particles at the LHC rather dramatically, making the search of these particles much more difficult. This problem is much less severe at $e^+e^-$ colliders so that the $\mathcal{MSSM}$ Higgs parameter space can still be covered completely [8]. It would only be more difficult to detect the CP–odd $A$ particle for small $\tan\beta$ where it is produced only in association with the light CP–even particle $h$, leading to invisible events altogether if both particles decay into LSP final states. However, since the branching ratios for $\chi_1^0\chi_1^0$ is always less than unity [especially when other $\chi\chi$ decays are kinematically possible], such a problem can be solved by increasing the integrated luminosity.

In the subsequent analysis, the fact is taken into account that neither charginos nor neutralinos have been found at LEP1.5 [9].

**2.** Besides the conventional parameters of the $\mathcal{MSSM}$ Higgs sector, the $\chi$ masses and couplings to the Higgs particles are determined by the Higgs–higgsino mass parameter $\mu$ and the SU(2) gaugino mass parameter $M_2$.

The general chargino mass matrix [10],

$$\mathcal{M}_C = \left[ \begin{array}{cc} M_2 & \sqrt{2} M_W \sin\beta \\ \sqrt{2} M_W \cos\beta & \mu \end{array} \right], \tag{2}$$

is diagonalized by two matrices $U$ and $V$, leading to the $\chi^\pm_{1,2}$ masses

$$\begin{aligned} m_{\chi^\pm_{1,2}} = \quad & \frac{1}{\sqrt{2}} \Big\{ M_2^2 + \mu^2 + 2M_W^2 \\ & \mp \Big[ (M_2^2 - \mu^2)^2 + 4M_W^2 \cos^2 2\beta + 4M_W^2 (M_2^2 + \mu^2 + 2M_2\mu \sin 2\beta) \Big]^{\frac{1}{2}} \Big\}^{\frac{1}{2}} . \end{aligned} \tag{3}$$

When one of the two parameters $\mu$ or $M_2$ is large, one of the charginos corresponds to a pure gaugino state while the other corresponds to a pure higgsino state; in these cases the $\chi^\pm$ masses approach the asymptotic values:

$$\begin{aligned} |\mu| \gg M_Z \ \text{ and } \ M_2 \sim M_Z \quad &: \ m_{\chi_1^\pm} \sim M_2 \ , \ m_{\chi_2^\pm} \sim |\mu| ; \\ |\mu| \sim M_Z \ \text{ and } \ M_2 \gg M_Z \quad &: \ m_{\chi_1^\pm} \sim |\mu| \ , \ m_{\chi_2^\pm} \sim M_2 . \end{aligned} \tag{4}$$

The four-dimensional neutralino mass matrix depends on the same two mass parameters if the SUGRA relation $M_1 = \frac{5}{3} \tan^2\theta_W \ M_2 \simeq \frac{1}{2} M_2$ [10] is used. In the bino–wino–higgsino basis $(-i\tilde{B}, -i\tilde{W}_3, \tilde{H}_1^0, \tilde{H}_2^0)$ the matrix has the form

$$\mathcal{M}_N = \left[ \begin{array}{cccc} M_1 & 0 & -M_Z \sin\theta_W \cos\beta & M_Z \sin\theta_W \sin\beta \\ 0 & M_2 & M_Z \cos\theta_W \cos\beta & -M_Z \cos\theta_W \sin\beta \\ -M_Z \sin\theta_W \cos\beta & M_Z \cos\theta_W \cos\beta & 0 & -\mu \\ M_Z \sin\theta_W \sin\beta & -M_Z \cos\theta_W \sin\beta & -\mu & 0 \end{array} \right] . \tag{5}$$

It can be diagonalized analytically [11] by a single matrix $Z$; as the final results for the masses are rather involved, they should not be recorded here. Again, for large values of one of the parameters $\mu$ or $M_2$, two neutralinos are pure gaugino states while the two others are pure higgsino states, and the $\chi^0$ masses are given in these limits by

$$\begin{aligned} |\mu| \gg M_Z \ \text{ and } \ M_2 \sim M_Z \quad &: \ m_{\chi_1^0} \sim M_1 \ , \ m_{\chi_2^0} \sim M_2 \ , \ m_{\chi_3^0} \sim m_{\chi_4^0} \sim |\mu| , \\ |\mu| \sim M_Z \ \text{ and } \ M_2 \gg M_Z \quad &: \ m_{\chi_1^0} \sim m_{\chi_2^0} \sim |\mu| \ , \ \ m_{\chi_3^0} \sim M_1 \ , \ m_{\chi_4^0} \sim M_2 . \end{aligned} \tag{6}$$

A typical set of the neutralino/chargino masses [the lightest of which could be observed at LEP2] is shown as a function of $\mu$ in Fig.1a for $M_2 = 150$ GeV and $\tan\beta = 1.6$. The non–observation of chargino and neutralino production $e^+e^- \to \chi_1^+\chi_1^-$ and $\chi_2^0\chi_1^0$ at

LEP1.5 [9] roughly translates to lower limits on $2m_{\chi_1^+}$ and $m_{\chi_2^0}+m_{\chi_1^0}$ of 135 GeV, so that the range $-40$ GeV $\lesssim \mu \lesssim 140$ GeV is ruled out for $M_2 = 150$ GeV and $\tan\beta = 1.6$. [For $\mu = 0$ and also for moderate $\mu$ values, the lightest neutralino and chargino states could have been massless—these values are of course already ruled out by the negative search of chargino states at LEP1.]

**3.** The decay widths of the Higgs bosons $(H_k) = (H, h, A, H^\pm)$ into neutralino and chargino pairs are given by [4]

$$\Gamma(H_k \to \chi_i\chi_j) = \frac{G_F M_W^2}{2\sqrt{2}\pi}\frac{M_{H_k}\lambda^{1/2}}{1+\delta_{ij}} \quad \left[ (F_{ijk}^2 + F_{jik}^2)\left(1 - \frac{m_{\chi_i}^2}{M_{H_k}^2} - \frac{m_{\chi_j}^2}{M_{H_k}^2}\right) \right. \\ \left. -4\eta_k\epsilon_i\epsilon_j F_{ijk}F_{jik}\frac{m_{\chi_i}m_{\chi_j}}{M_{H_k}^2}\right], \tag{7}$$

where $\eta_{1,2,4} = +1$, $\eta_3 = -1$ and $\delta_{ij} = 0$ unless the final state consists of two identical (Majorana) neutralinos in which case $\delta_{ii} = 1$; $\epsilon_i = \pm 1$ is the sign of the neutralino mass eigenvalue [$\epsilon_i = 1$ for charginos]; $\lambda = (1 - m_{\chi_i}^2/M_{H_k}^2 - m_{\chi_j}^2/M_{H_k}^2)^2 - 4m_{\chi_i}^2 m_{\chi_j}^2/M_{H_k}^4$ is the usual two–body phase space function.

In the case of neutral Higgs boson decays, the coefficients $F_{ijk}$ are related to the elements of the matrices $U, V$ for charginos and $Z$ for neutralinos,

$$\begin{aligned} H_k \to \chi_i^+\chi_j^- \quad &: \quad F_{ijk} = \frac{1}{\sqrt{2}}\left[e_k V_{i1}U_{j2} - d_k V_{i2}U_{j1}\right], \\ H_k \to \chi_i^0\chi_j^0 \quad &: \quad F_{ijk} = \frac{1}{2}\left(Z_{j2} - \tan\theta_W Z_{j1}\right)\left(e_k Z_{i3} + d_k Z_{i4}\right) \ + \ i \leftrightarrow j, \end{aligned} \tag{8}$$

with the coefficients $e_k$ and $d_k$ given by

$$e_1/d_1 = \cos\alpha/-\sin\alpha \ , \ e_2/d_2 = \sin\alpha/\cos\alpha \ , \ e_3/d_3 = -\sin\beta/\cos\beta. \tag{9}$$

The partial widths of the neutral Higgs particles for decays to the lightest neutralino or chargino states can be written in a particularly simple form,

$$\Gamma(H_k \to \chi_1\chi_1) = \frac{G_F M_W^2}{2\sqrt{2}\pi} M_{H_k}\left[1 - \frac{4m_{\chi_1}^2}{M_{H_k}^2}\right]^p \ \kappa_k^2, \tag{10}$$

with $p = 3$ for $h, H$ and $p = 1$ for $A$, corresponding to P– and S–wave final states as required by the CP=$\pm$ quantum numbers of the Higgs bosons.

For the light scalar and the pseudoscalar Higgs decays to the lightest neutralinos, $h/A \to \chi_1^0\chi_1^0$, the coefficients $\kappa_k$ are given by

$$\begin{aligned} \kappa_h &= \left(Z_{12} - \tan\theta_W Z_{11}\right)\left(\sin\alpha Z_{13} + \cos\alpha Z_{14}\right), \\ \kappa_A &= \left(Z_{12} - \tan\theta_W Z_{11}\right)\left(-\sin\beta Z_{13} + \cos\beta Z_{14}\right). \end{aligned} \tag{11}$$

For the decays to the lightest charginos, $h/A \to \chi_1^+\chi_1^-$, the coefficients $\kappa_k$ are of the form

$$
\begin{aligned}
\kappa_h &= \frac{1}{\sqrt{2}}\left(\sin\alpha V_{11}U_{12} - \cos\alpha V_{12}U_{11}\right), \\
\kappa_A &= \frac{1}{\sqrt{2}}\left(-\sin\beta V_{11}U_{12} + \cos\beta V_{12}U_{11}\right).
\end{aligned} \tag{12}
$$

It follows from Eq.(11) that the Higgs bosons couple to mixtures of gaugino and higgsino components of the lightest neutralino, corresponding to the matrix elements $Z_{11}, Z_{12}$ and $Z_{13}, Z_{14}$ respectively. If the $\chi_1^0$ were either a pure gaugino or a pure higgsino state, the $h\chi_1^0\chi_1^0$ and $A\chi_1^0\chi_1^0$ couplings would vanish. The matrix elements are displayed for the same set of parameters as for the neutralino/chargino masses in Fig.1b. It is obvious from the figure that decays to LSPs play a less prominent rôle for $\mu < 0$ than for $\mu > 0$ since for negative $\mu$, the $\chi_1^0$ state tends to be either gaugino– or higgsino–like. In this case, only in a small $\mu$ window around $-M_1$ do the couplings reach the level of a few percent, as is shown in Fig.1c. [For the values $\tan\beta = 1.6$ and $M_A = 100$ GeV that were chosen for illustration, the couplings $\kappa_h$ and $\kappa_A$ are approximately equal.]

For the charged Higgs boson, the decay widths into neutralino/chargino pairs [4] are given by Eq.(7), with

$$
\begin{aligned}
F_{ij4} &= \cos\beta\left[Z_{j4}V_{i1} + \frac{1}{\sqrt{2}}\left(Z_{j2} + \tan\theta_W Z_{j1}\right)V_{i2}\right], \\
F_{ji4} &= \sin\beta\left[Z_{j3}U_{i1} - \frac{1}{\sqrt{2}}\left(Z_{j2} + \tan\theta_W Z_{j1}\right)U_{i2}\right].
\end{aligned} \tag{13}
$$

**4.** Examples of branching ratios are shown in Fig.2a for Higgs boson masses $M_h$ and $M_A$ typically accessible at LEP2. The partial decay widths to R–even particles are treated according to the current knowledge [3]. Whenever the $\chi_1^0\chi_1^0$ decay is kinematically allowed, the branching ratio is close to 100% for positive $\mu$ values. For $\mu < 0$ the branching ratio never exceeds the 20% level. As pointed out previously, the branching ratios become smaller for increasing $\tan\beta$, except when $h$ reaches its maximal mass value: the $hbb$ coupling is no longer enhanced in this case. These $M_h$ values are not accessible at LEP2, but they would be accessible at future colliders.

The branching ratios for the sum into all possible neutralino and chargino states are shown in Fig.2b for $(H, A, H^\pm)$ particles which can be produced at high–energy $e^+e^-$ colliders. Mixing [12] in the Higgs sector has been treated properly for $\mu \neq 0$, $A_t = \sqrt{6}M_S$ [so-called "maximal mixing"] and $A_b = 0$, with $M_S = 1$ TeV. These branching ratios are always large except in three cases: $(i)$ For $H$ in the mass range between 140 and 200 GeV, especially if $\mu > 0$, due to the large value of BR$(H \to hh)$; $(ii)$ For small $A$ masses and negative $\mu$ values as discussed above; and $(iii)$ For $H^\pm$ just above the $t\bar{b}$ threshold if not all the decay channels into heavy $\chi$ states are open. [A similar pattern holds for the other values of $\mu$ and $M_2$ discussed above.]

Even above the thresholds of decay channels including top quarks, the branching ratios for the decays into charginos and neutralinos are sizeable. For very large Higgs boson masses, they reach a common value of $\sim 40\%$ for $\tan\beta = 1.6$. In fact, as a consequence of the unitarity of the $U, V$ and $Z$ matrices, the total widths of the three Higgs boson decays to charginos and neutralinos do not depend on $M_2$, $\mu$ or $\tan\beta$ in the asymptotic regime $M_{H_k} \gg m_\chi$,

$$\Gamma(H_k \to \sum_{i,j} \chi_i \chi_j) = \frac{3 G_F M_W^2}{4\sqrt{2}\pi} M_{H_k} \left(1 + \frac{1}{3}\tan^2\theta_W\right), \tag{14}$$

giving rise to the branching ratio

$$\mathrm{BR}(H_k \to \sum_{i,j} \chi_i \chi_j) = \frac{\left(1 + \frac{1}{3}\tan^2\theta_W\right) M_W^2}{\left(1 + \frac{1}{3}\tan^2\theta_W\right) M_W^2 + m_t^2 \cot^2\beta + m_b^2 \tan^2\beta}, \tag{15}$$

Only the leading $t\bar{t}$, $b\bar{b}$ modes for neutral and the $t\bar{b}$ modes for the charged Higgs bosons need be included in the total widths. This branching ratio is shown in Fig.2c as a function of $\tan\beta$. It is always large, even for extreme values of $\tan\beta \sim 1$ or 50, where it still is at the 20% level.

**5.** To discuss the impact of invisible decays on the search of Higgs particles at LEP2, two cases must be distinguished.

($i$) The region in the $[\mu, M_2]$ parameter space in which CP-even $h$ Higgs boson decays into the lightest neutralino $\chi_1^0\chi_1^0$ can be observed at LEP2, is illustrated in Fig. 3a for the mass $M_h = 90$ GeV. The same mixing pattern as before has been considered: $\mu \neq 0$, $A_t = \sqrt{6}M_S$ and $A_b = 0$, with $M_S = 1$ TeV. To find the region which is experimentally accessible by the search for invisible decays of the Higgs boson, the product $R_{\rm inv} = \mathrm{BR}(h \to \chi_1^0\chi_1^0) \times \sin^2(\beta - \alpha)$ has to exceed 0.45 [13] under the LEP2 luminosity conditions. The small parameter range in which the invisible Higgs decays could be detected is shown in Fig. 3a together with the corresponding $[\mu, M_2]$ range which can be investigated by direct chargino and neutralino searches at LEP2, $e^+e^- \to \chi_i^+\chi_j^-$ and $\chi_i^0\chi_j^0$. For the latter, a minimum total cross-section of 100 fb [14], relevant for a total integrated luminosity of 150 pb$^{-1}$ that should be delivered each year to the four LEP experiments, was required for large mass splitting between the lightest neutralino and the charginos and other neutralinos, and the unavoidable loss of efficiency for small mass differences was parameterized in a realistic manner [15].

It can immediately be seen from this example that the region in which the light Higgs boson $h$ could be detected in the $\chi_1^0\chi_1^0$ decay mode is small if the LEP1.5 results are taken into account, and it is embedded completely in the area covered by direct neutralino and chargino searches. Since this holds true for any Higgs boson mass at all centre-of-mass energies of LEP2, the $[\mu, M_2]$ area cannot be extended through the Higgs boson search.

($ii$) The exclusion limits of the lightest CP–even Higgs boson $h$ are affected by invisible decay modes. This is shown at $\tan\beta = 1.6$ for a few examples of the parameters $\mu$ and

$M_2$ in Fig. 3b. It is well-known that LEP2 covers the entire $h$ mass range for $\tan\beta \lesssim 2$ if $h$ decays only into SM particles [13]. However, it is apparent from the examples in Fig. 3b that for $\mu$ and $M_2$ values in a small strip, adjacent to the upper right boundary of the crossed range in Fig. 3a, the exclusion limit is significantly smaller than the theoretical upper Higgs mass limit. For these values of $\mu$ and $M_2$, both $R_{\rm inv}$ and $R_{\rm vis} = {\rm BR}(h \to b\bar{b}) \times \sin^2(\beta - \alpha)$ drop below the lower limits, given in Figs.31 and 32 of Ref.[13], for which Higgs events could be detected in either of the two channels. Thus, in a small area of the SUSY parameter space Higgs bosons could escape undetected under the LEP2 running conditions even for low $\tan\beta$.

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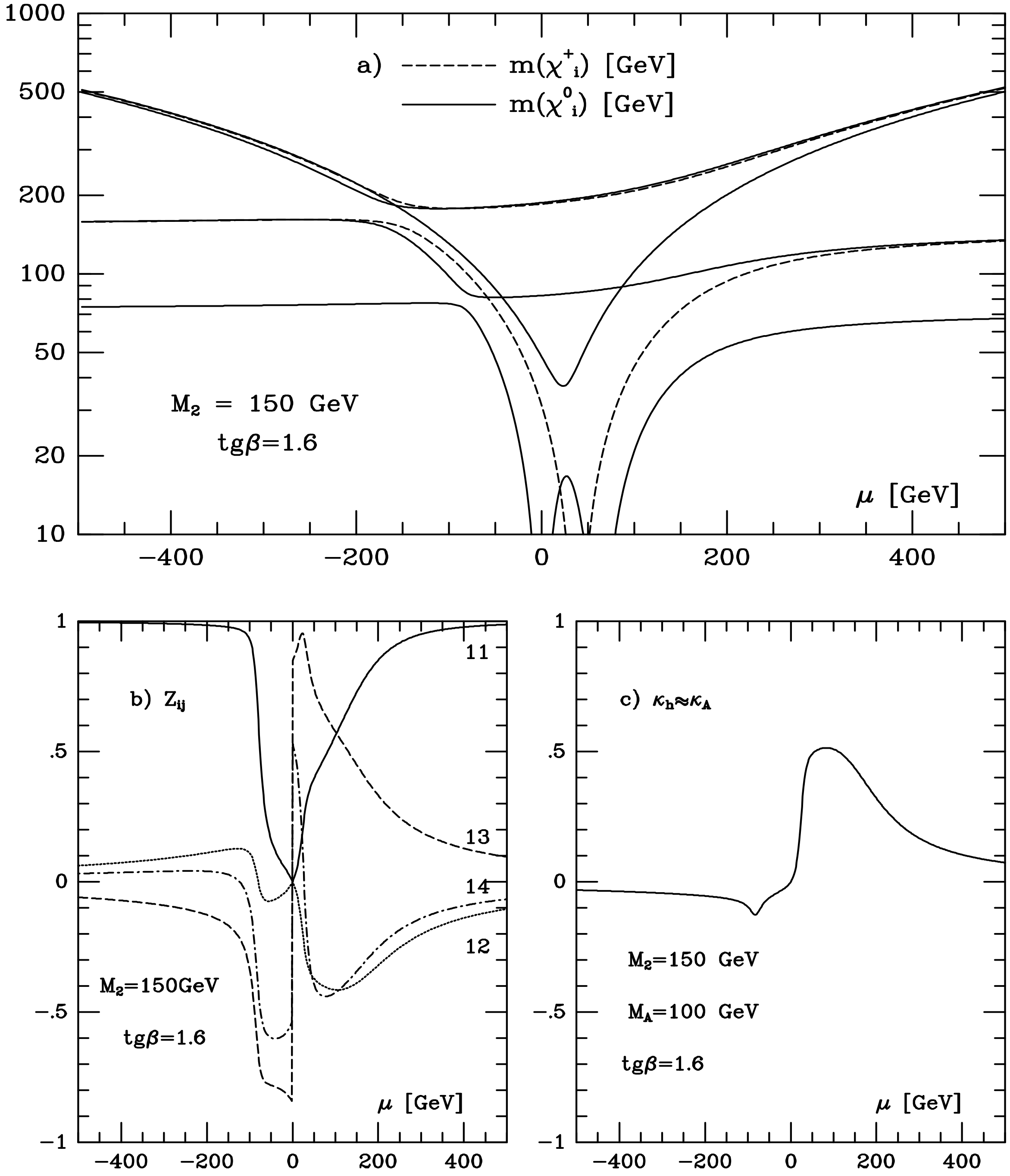


**Fig. 1:** *(a) Chargino [dashed lines] and neutralino [solid lines] masses as a function of $\mu$; (b) the mixing matrix elements $Z_{1i}$ of the lightest neutralino as a function of $\mu$; (c) the couplings $\kappa_h$ and $\kappa_A$ of the $h, A$ Higgs bosons to $\chi_1^0$ as a function of $\mu$. $M_2$ is fixed to 150 GeV and* $\tan\beta = 1.6$.

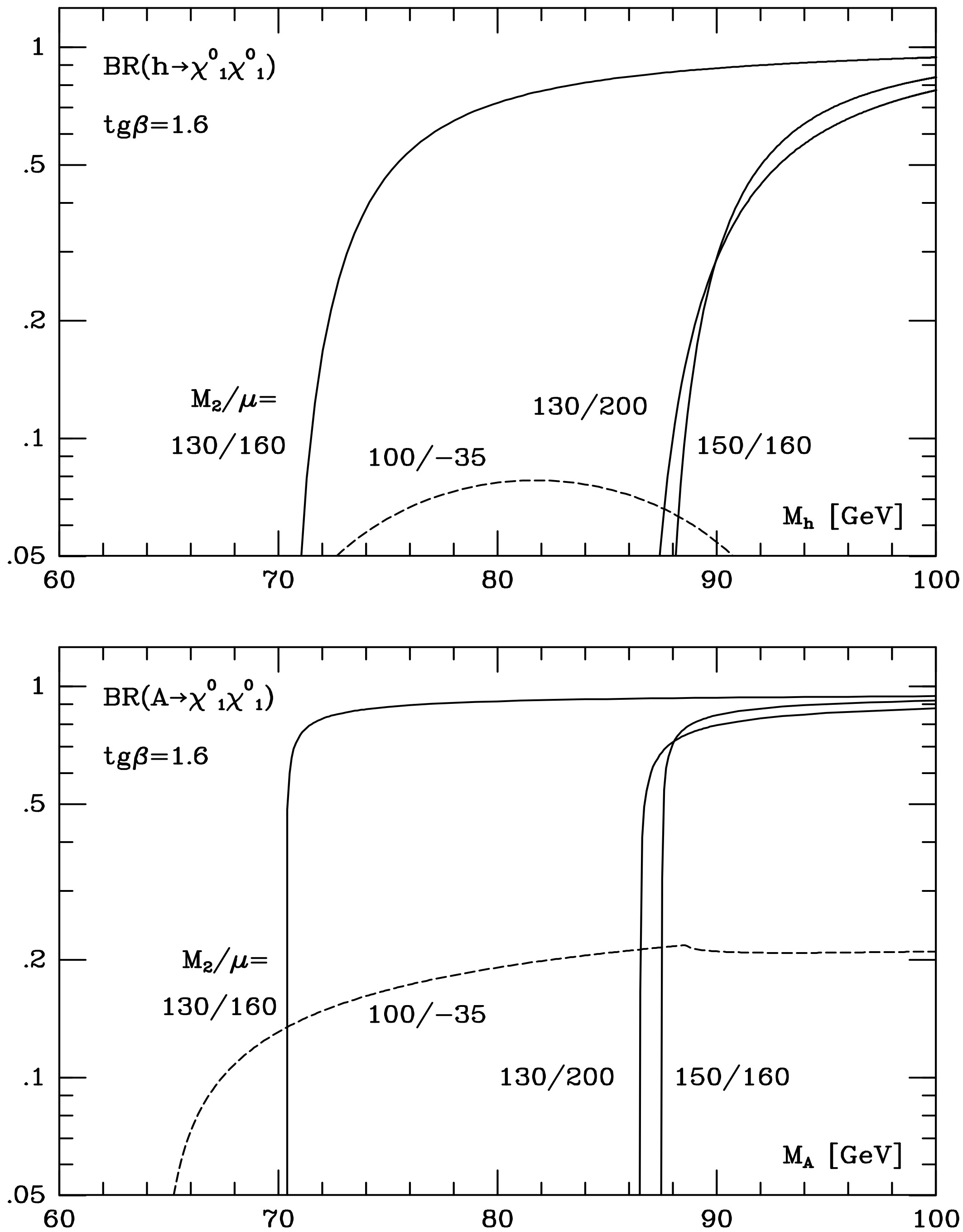


**Fig. 2a:** *Branching ratios of the decays of the h and A bosons into the lightest neutralino pair* $\chi_1^0\chi_1^0$ *as a function of the Higgs masses for a set of* $\mu$ *and* $M_2$ *values;* $\tan\beta = 1.6$.

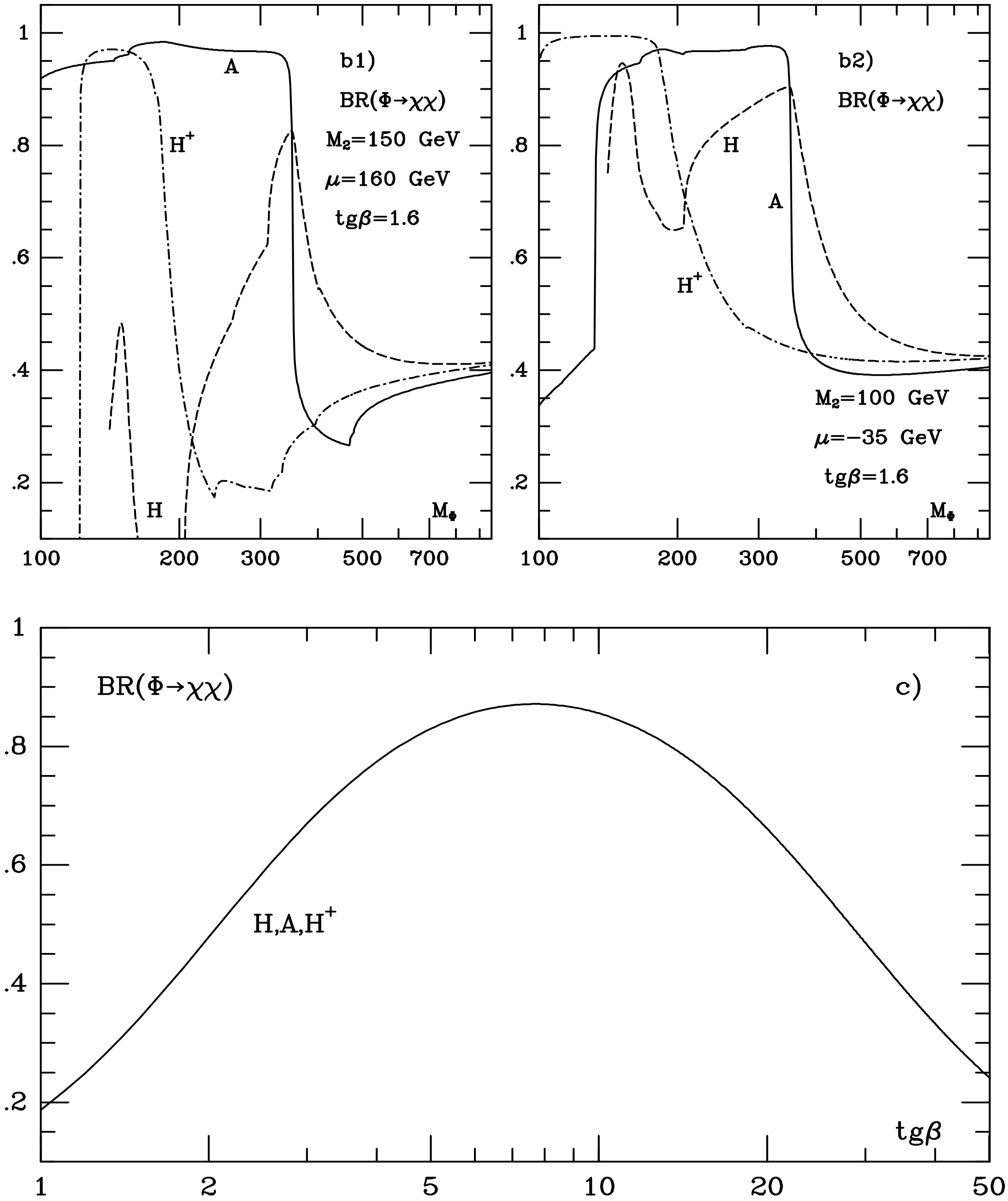


**Fig. 2b/c:** *Branching ratios of the decays of the heavy A [solid], H [dashed] and* $H^{\pm}$ *[dot–dashed] Higgs bosons into the sum of neutralino and chargino pairs as a function of the Higgs mass [for a set of* $\mu/M_2$ *values and* $\tan\beta$ *fixed to 1.6] in (b1) and (b2). The inclusive* $\chi\chi$ *decay branching ratio as a function of* $\tan\beta$ *in the asymptotic region* $[M_A \sim M_H \sim M_{H^\pm} = 1$ *TeV* $\gg m_\chi]$ *in (c).*

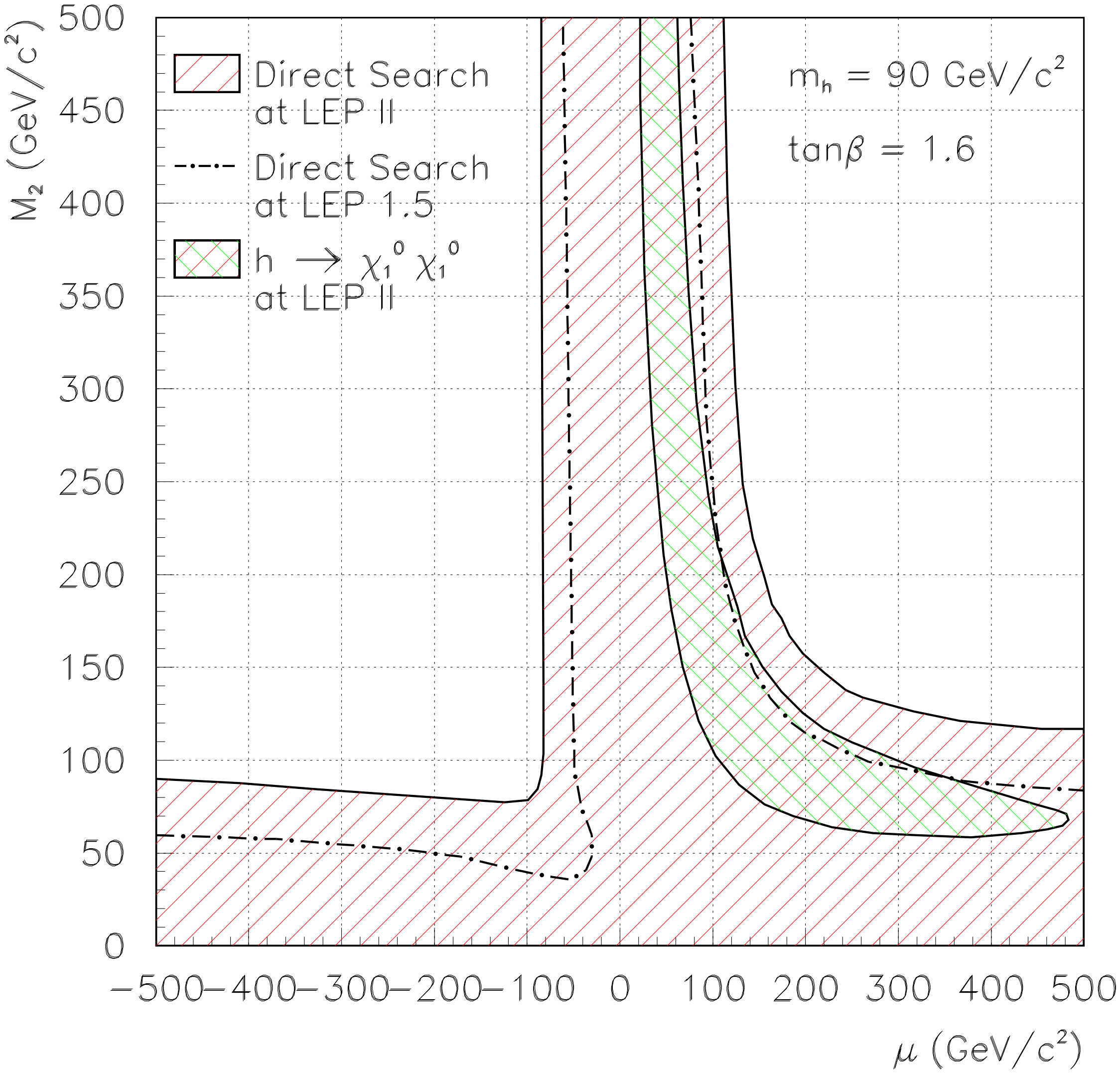


**Fig. 3a:** *In the $[\mu, M_2]$ parameter space, ranges covered at LEP2, with a centre-of-mass of 192 GeV and an integrated luminosity of 150 pb$^{-1}$ delivered to each of the four experiments, by the direct chargino and neutralino searches, and by the search for invisible Higgs decays $h \to \chi_1^0\chi_1^0$ for $M_h = 90$ GeV and $\tan\beta = 1.6$, (maximal mixing conditions). The dash–dotted lines represent the boundary of $[\mu, M_2]$ values after the LEP1.5 results are taken into account.*

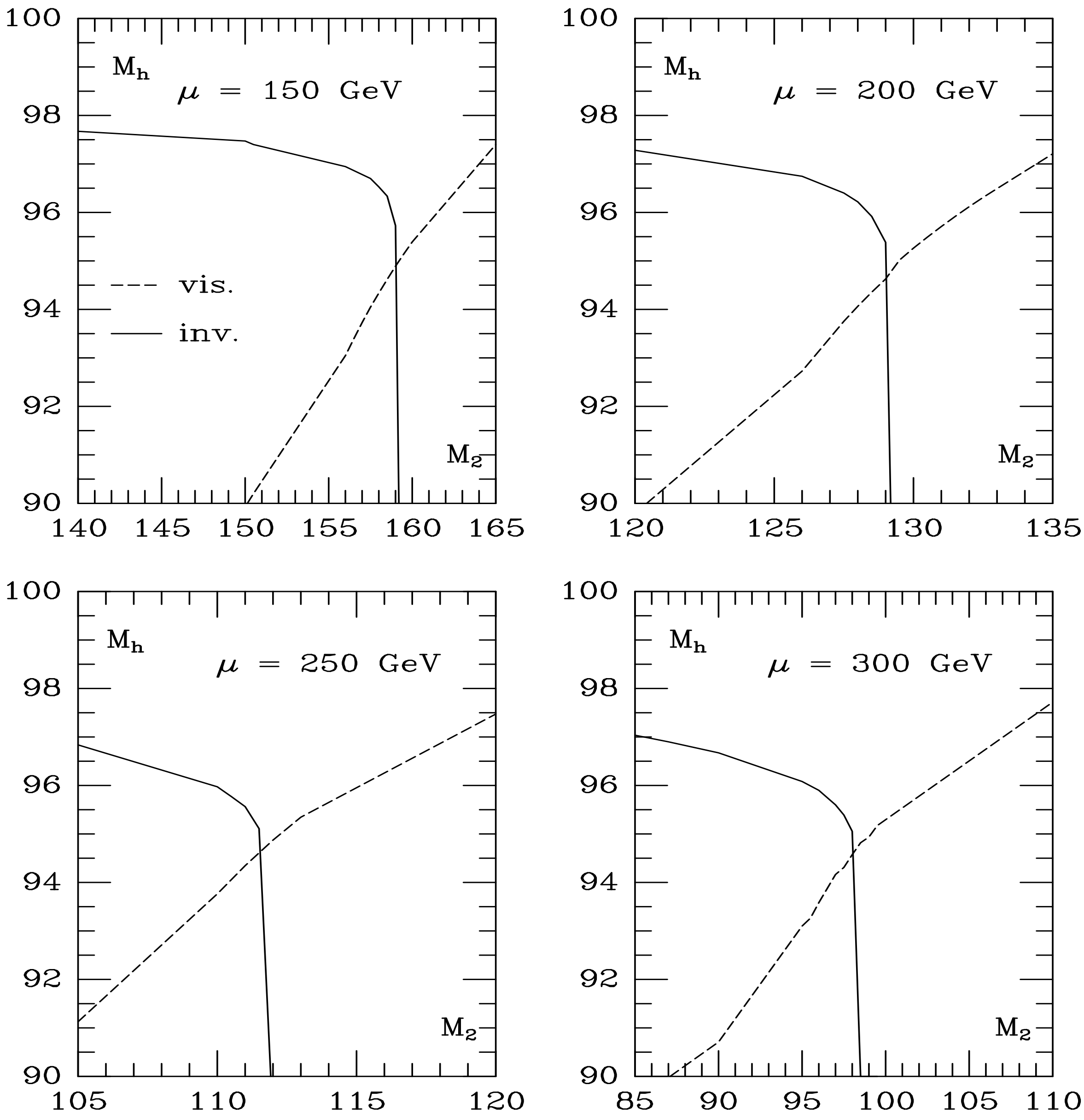


**Fig. 3b:** *Exclusion limits on the mass of the lightest CP–even Higgs boson h for a set of* $[\mu, M_2]$ *values and* $\tan\beta = 1.6$. *The full lines refer to the search based on the invisible* $\chi_1^0\chi_1^0$ *decay channel, the dashed lines to* $b\bar{b}$ *decays of* $h$. *The invisible decays are dominant whenever this channel is open, the fast fall–off corresponds to the kinematical boundary.*