The Higgs intense-coupling regime in constrained SUSY models and its astrophysical implications

Abdelhak Djouadi and Yann Mambrini

Laboratoire de Physique Théorique, CNRS and Université Paris–Sud
Bt. 210, F–91405 Orsay Cedex, France
E-mail: `Abdelhak.Djouadi@th.u-psud.fr`, `Yann.Mambrini@th.u-psud.fr`

ABSTRACT: We analyze the Higgs intense–coupling regime, in which all Higgs particles of the Minimal Supersymmetric Standard Model are light with masses of the same order and the value of $\tan\beta$ the ratio of vacuum expectation values of the two Higgs fields is large, in the framework of Supergravity scenarios with non–universal soft Supersymmetry breaking scalar masses in the Higgs sector. In particular, we calculate the relic density abundance of the lightest neutralino candidate for cold dark matter and the rates in direct and indirect detection at present and future experiments. We first show that while in the mSUGRA model this regime is disfavored by present data, there are regions in the parameter space of models with non–universal Higgs masses where it can occur. We then show that because of the large value of $\tan\beta$ and the relatively low values of the neutral Higgs boson masses, the cross section for neutralino–nucleon scattering is strongly enhanced in this regime and would allow for the observation of a signal in direct detection experiments such as CDMS–Soudan. The expected sensitivity of gamma–ray detectors like GLAST might be also sufficient to observe the annihilation of neutralinos in such a regime.

KEYWORDS: Supersymmetric Standard Model, Beyond Standard Model, Supersymmetry Phenomenology.

JHEP12(2006)001

Contents

1. Introduction

In the Minimal Supersymmetric Standard Model (MSSM) [1], the Higgs sector has to be extended to include two doublets fields to achieve the breaking of the $SU(2)_L \times U(1)_Y$ electroweak gauge symmetry in a consistent way. This leads to the existence of five Higgs particles: two CP–even Higgs bosons h and H, a CP–odd or pseudoscalar Higgs boson A, and two charged Higgs particles $H^\pm$ [1, 2]. At the tree–level, the spectrum is determined by two basic parameters: the mass of the pseudoscalar Higgs boson M_A and the ratio of the vacuum expectation values of the Higgs fields, $\tan\beta = v_2/v_1$. If the pseudoscalar Higgs particle is very heavy, $M_A \gg M_Z$, one is in the so–called decoupling regime [3] in which the lightest CP–even h particle is SM–like and has a mass that is close to the Z boson mass while the other CP–even Higgs particle H and the charged $H^\pm$ bosons are very heavy and degenerate in mass with the pseudoscalar A boson, $M_H \approx M_{H^\pm} \approx M_A$. The MSSM Higgs sector reduces then to the one of the SM, but with a Higgs particle that it rather light: $M_h^{\max} \approx M_Z$ at the tree–level but $M_h^{\max} \sim 100$–140 GeV, depending on $\tan\beta$ and the strength of the important radiative corrections which need to be included [2, 4]. In the opposite scenario, in which $M_A \lesssim M_Z$ [5] called the anti–decoupling regime in ref. [2], it is the lighter CP–even h which is degenerate in mass with the A boson, while the heavier H boson is SM–like with a mass close to $M_H^{\min} \simeq M_h^{\max}$.

An intermediate scenario, the so–called intense–coupling regime [6], is characterized by a rather large value of $\tan\beta$ and a mass for the pseudoscalar A boson that is close but

not equal to the maximal (minimal) value of the CP–even h (H) boson mass. In such a scenario, an almost mass degeneracy of the neutral Higgs particles of the model occurs, $M_h \approx M_A \approx M_H \approx$ 100–140 GeV, while the couplings of both the CP–even h and H particles to gauge bosons and isospin up–type fermions are suppressed, and their couplings to down–type fermions, and in particular b–quarks and τ leptons, are strongly enhanced. The decays of both Higgs particles therefore approach those of the pseudoscalar Higgs boson which does not couple to massive gauge bosons as a result of CP invariance, and for which the couplings to isospin $-\frac{1}{2}$ $(+\frac{1}{2})$ fermions are (inversely) proportional to $\tan\beta$.

This scenario leads to a very interesting collider phenomenology which has been discussed in detail in ref. [6]. In particular, it has been shown that one has to face a rather difficult situation for the detection of these particles at the LHC, since the branching ratios of the usual interesting decays which allow the detection of the CP–even Higgs bosons are too small and cannot be used anymore, while the dominant $b\bar{b}$ and $\tau^+\tau^-$ decay modes have too large backgrounds. Even when using some rare Higgs decays, the detection of the three individual Higgs bosons is very challenging in general and in some cases even impossible at the LHC. At the future International Linear e^+e^- Collider (ILC), the three peaks can be resolved but the measurement of the masses of the particles is more difficult than in other scenarios.

The studies on the intense coupling regime mentioned above have been performed only in the framework of an effective low–energy MSSM in which the parameters which break softly Supersymmetry (SUSY) are incorporated by hand, leading to a Higgs sector that is practically disconnected from the SUSY particle sector. However, it would be more interesting to consider constrained SUSY models, which are theoretically more appealing and which have a smaller number of basic input parameters. A scenario that is widely used as a benchmark for constrained Grand Unified SUSY Theories (SUSY GUTs), is the minimal Supergravity model (mSUGRA) [7] in which there are only five input parameters: a universal value m_0 for the soft SUSY–breaking masses of all the scalars, a universal soft SUSY–breaking gaugino mass parameter $M_{1/2}$, a common trilinear Higgs–sfermion coupling A_0 [the three of which are defined at the GUT scale, $M_{\rm GUT} \sim 2 \times 10^{16}$ GeV], $\tan\beta$ and the sign of the Higgs–higgsino mass parameter μ. An interesting question is whether the intense coupling regime can occur in such a scenario.

A second question that one might ask is whether this Higgs scenario is compatible with cosmological observations and, in particular, with the observed amount of dark matter in the universe. Indeed, it is now well established that luminous matter makes up only a small fraction of the observed mass in the universe and a weakly interacting massive particle, identified in the MSSM with the stable lightest neutralino, is one of the leading candidates for the "dark" component which is needed to explain astrophysical data on galactic rotation curves [9], cluster of galaxies, or large scale flows [10], and which has been recently measured via the anisotropies of the cosmic microwave background by the WMAP satellite with a very good precision [11]. A related question is whether in such a scenario, the lightest neutralino of the MSSM would lead to observable effects in the present and near future experiments which are devoted to the direct and indirect detection of these dark matter particles.

In this paper, we attempt to answer to these questions. We show that in the framework of the mSUGRA model, the particle spectrum is so constrained that the intense coupling regime is realized only in a very limited area of the parameter space; in addition, because it occurs only for extremely large values of $\tan\beta$, the obtained spectrum could potentially lead to a conflict with experimental data from collider physics. We then investigate the Non Universal Higgs Mass (NUHM) model, discussed in refs. [12, 13] for instance, in which the equality of the soft SUSY–breaking masses of the two Higgs fields m_{H_1} and m_{H_2} with the common mass term m_0 for squarks and sleptons at the GUT scale is relaxed. Such a non–universality structure might, for instance, occur in SUSY GUTs in which the fields H_1 and H_2 belong to different multiplets [12]; it can also be obtained in the low–energy limit of some phenomenologically appealing string scenarios such as heterotic orbifold models [14] and effective heterotic Anomaly Mediated SUSY Breaking scenarios [15]. The NUHM model is then equivalent to an effective low energy MSSM where, in addition to the mSUGRA parameters, on has the higgsino mass parameter μ and the pseudoscalar Higgs boson mass M_A as free input parameters which are, however, subject to some constraints for the model to be viable. This additional freedom will allow to realize the intense Higgs coupling regime, while complying with all known accelerator and astrophysical data, in a much larger region of the parameter space compared to the mSUGRA case.

The paper is organized as follows. In section 2 we review the NUHM model and discuss the impact of non–universal scalar mass parameters on the Higgs sector as well as on the cosmological relic density of the dark matter lightest neutralino and on its detection in direct and indirect searches. In section 3, we analyze the Higgs intense regime in the NUHM model: we first explain the procedure to obtain the spectrum and the various constraints that we impose on it, and then present two concrete examples in which this regime is realized; we then discuss the implications of these scenarios for the relic density of the neutralino and its direct and indirect detection rates. For completeness, we briefly discuss in section 4, the case of the mSUGRA model. A brief conclusion is given in section 5.

2. The NUHM model

2.1 The impact of non–universality on the Higgs sector

Let us first recall that in the mSUGRA model, in addition to the four basic continuous input parameters, the common soft SUSY–breaking scalar m_0 and gaugino $M_{1/2}$ mass parameters and trilinear coupling A_0, defined at the GUT scale, and the ratio of vevs $\tan\beta$, the sign of the Higgs–higgsino parameter μ is also free. This is due to the fact that μ^2 is determined by the minimization of the scalar Higgs potential which leads to electroweak symmetry breaking (EWSB). At the tree level, one has in terms of $\tan\beta$ and the two soft SUSY–breaking Higgs mass terms defined at the SUSY breaking scale $M_S = \mathcal{O}(1 \text{ TeV})$,

$$\mu^2 = \frac{m_{H_1}^2 - m_{H_2}^2 \tan^2\beta}{\tan^2\beta - 1} - \frac{1}{2}M_Z^2\,, \tag{2.1}$$

which, for reasonably large values of $\tan\beta$ ($\gtrsim 5$), can be approximated by

$$\mu^2 \approx -m_{H_2}^2 - \frac{1}{2}M_Z^2\,, \tag{2.2}$$

with $m_{H_2}^2$ being negative to effectively generate EWSB. Again at the tree level, the mass of the CP–odd Higgs boson is given by

$$M_A^2 = m_{H_1}^2 + m_{H_2}^2 + 2\mu^2 \,, \tag{2.3}$$

which can approximately be rewritten using eq. (2.2)

$$M_A^2 \approx m_{H_1}^2 - m_{H_2}^2 - M_Z^2 \,, \tag{2.4}$$

The masses of the neutral CP–even Higgs bosons and the charged Higgs particle are then obtained from the usual tree–level relations

$$M_{h,H}^2 = \frac{1}{2}\left[M_A^2 + M_Z^2 \mp \sqrt{(M_A^2 + M_Z^2)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta} \right]$$
$$M_{H^\pm}^2 = M_A^2 + M_W^2 \tag{2.5}$$

Of course, to have a more accurate determination of all the Higgs boson masses and proper EWSB, it is important that the radiative corrections are included; see refs. [2, 4] for reviews.

In the non–universal Higgs mass (NUHM) model, the universality of the soft SUSY– breaking Higgs mass parameters at the GUT scale is relaxed, that is $m_{H_1} \neq m_{H_2} \neq m_0$. This non–universality might, for instance, occur in GUT constructions where the fields H_1 and H_2 belong to different multiplets. This model is then equivalent to the "effective low energy" MSSM where in addition to the mSUGRA parameters, on has μ and M_A as free input parameters. In this paper, we will parameterize this non–universality through two dimensionless parameters δ_1 and δ_2, which measure the relative deviation from the mSUGRA case at the GUT scale, as follows

$$m_{H_1}^2(M_{\rm GUT}) = m_0^2(M_{\rm GUT})(1 + \delta_1)\,, \quad m_{H_2}^2(M_{\rm GUT}) = m_0^2(M_{\rm GUT})(1 + \delta_2) \tag{2.6}$$

from which one can clearly see that lower (larger) values of m_{H_1} (m_{H_2}), corresponding to $\delta_1 < 0$ $(\delta_2 > 0)$, imply a lighter A boson. Thus, contrary to the mSUGRA case where the CP–odd A boson is very heavy for reasonable values of m_0 [except in the so–called focus point region where m_0 is large and with high values of $\tan\beta$, see ref. [16] for instance], here, one can use the additional freedom and adjust the parameters $\delta_{1,2}$ in such way that the obtained value of M_A is not too large. In particular, for high values of $\tan\beta$, one can realize the scenario in which the Higgs sector of the model is in the intense coupling regime, i.e. $M_A \approx 100$–130 GeV which leads to the relation $M_A \approx M_H \approx M_h$.

Such a departure from universality leads to drastic consequences not only in the Higgs sector, but also in the chargino and neutralino sectors as the Higgs mass parameters m_{H_1} and m_{H_2} enter in the determination of μ which enters as a basic input parameter in the mass matrices of these states. This would for instance alter the nature of the dark matter lightest neutralino with a possibly large impact on its cosmological relic density abundance and its detection rates, as will be summarized in the next subsections.
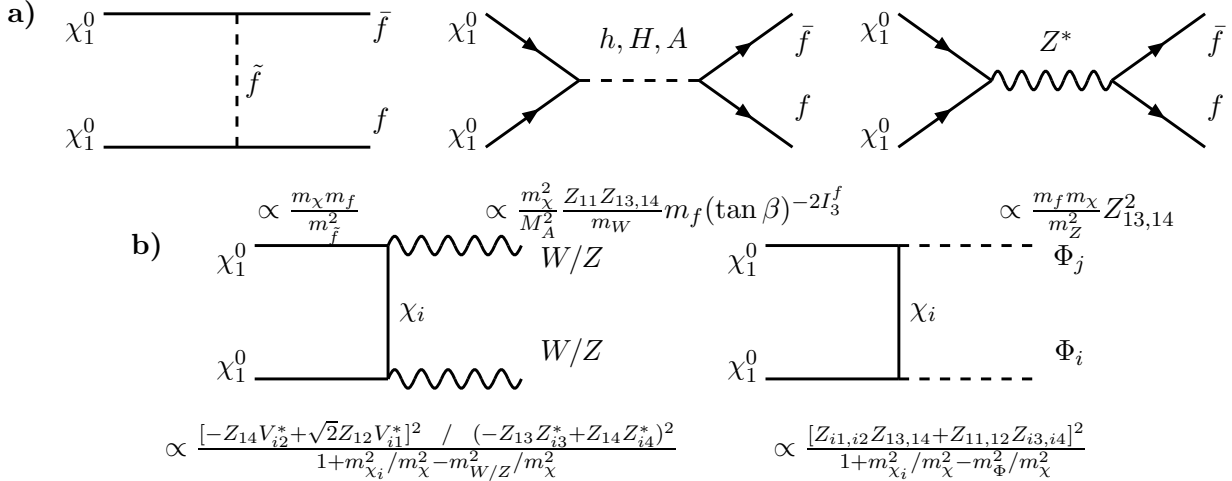
a)

$$\propto \frac{m_\chi m_f}{m_{\tilde f}^2} \qquad \propto \frac{m_\chi^2}{M_A^2}\frac{Z_{11}Z_{13,14}}{m_W}m_f(\tan\beta)^{-2I_3^f} \qquad \propto \frac{m_f m_\chi}{m_Z^2}Z_{13,14}^2$$

b)

$$\propto \frac{[-Z_{14}V_{i2}^*+\sqrt{2}Z_{12}V_{i1}^*]^2 \ / \ (-Z_{13}Z_{i3}^*+Z_{14}Z_{i4}^*)^2}{1+m_{\chi_i}^2/m_\chi^2-m_{W/Z}^2/m_\chi^2} \qquad \propto \frac{[Z_{i1,i2}Z_{13,14}+Z_{11,12}Z_{i3,i4}]^2}{1+m_{\chi_i}^2/m_\chi^2-m_\Phi^2/m_\chi^2}$$

Figure 1: Feynman diagrams for LSP neutralino annihilation into a fermion pair (a) and into massive gauge bosons and Higgs bosons (b). The relevant parts of the amplitudes are shown explicitly. V and Z are the chargino and neutralino mixing matrices.

2.2 Consequences on the LSP relic density

In the MSSM there are four neutralinos, χ_i^0 with $i=1,2,3,4$, among which the lightest one χ_1^0 is the lightest SUSY particle (LSP) and the SUSY candidate for the cold dark matter in the universe. Being a superposition of the bino, wino and higgsino fields, respectively denoted by $\widetilde{B}^0, \widetilde{W}_3^0$ and $\widetilde{H}_1^0, \widetilde{H}_2^0$, the χ_1^0 neutralino texture can be written as

$$\chi_1^0 = Z_{11}\widetilde{B}^0 + Z_{12}\widetilde{W}_3^0 + Z_{13}\widetilde{H}_2^0 + Z_{14}\widetilde{H}_1^0 \ . \tag{2.7}$$

where Z_{ij} are elements of the matrix which diagonalizes the 4×4 neutralino mass matrix. It is commonly defined that χ_1^0 is mostly gaugino–like if $P \equiv |Z_{11}|^2 + |Z_{12}|^2 > 0.9$, higgsino– like if $P < 0.1$, and a mixed state otherwise. In the NUHM scenario, one can choose the values of m_{H_1} and m_{H_2} at the GUT scale in such a way that the electroweak symmetry breaking conditions lead to a low value for μ. As a consequence, the lightest neutralino is generally higgsino–like or a mixed bino–higgsino state.

This has very important consequences on the relic density, which is inversely proportional to the LSP annihilation cross section. In Fig. 1, we display the Feynman diagrams of the main processes contributing to the annihilation cross section of the neutralinos to fermions (a), $\chi_1^0\chi_1^0 \to f\bar{f}$, and to gauge or Higgs bosons (b), $\chi_1^0\chi_1^0 \to VV$ and $\Phi_i\Phi_j$ with $V = W, Z$ and $\Phi_i = h, H, A$ and $H^\pm$, together with the expressions of the relevant parts of the amplitudes [17]. From these diagrams and the LSP neutralino texture given by eq. (2.7), one can make the following remarks.

- For LSP annihilation into light fermions [in general τ–leptons and to a lesser extent b quarks], the diagram with t–channel sfermion exchange contributes only if χ_1^0 is bino–like or if it is higgsino–like when $\tan\beta$ is large [as higgsinos couple to isospin down–type fermions proportionally to $m_f(\tan\beta)^{-2I_3^f}$]. For a higgsino–like LSP, the coupling to the Z boson is also small, being proportional to $|Z_{13}|^2 - |Z_{14}|^2$, and the annihilation channel $\chi_1^0\chi_1^0 \xrightarrow{Z} f\bar{f}$ is enhanced only for mixed higgsino–gaugino states.

- The annihilation through Higgs boson exchange, $\chi_1^0 \chi_1^0 \xrightarrow{A,h,H} f\bar{f}$, contributes substantially only close to the pole of the Higgs boson exchanged in the s–channel and if the LSP is a mixed state in which case the coupling to the Higgs boson is large [both the Z_{11} and $Z_{13}(Z_{14})$ matrix elements are large]; the dominant final state is $b\bar{b}$ for which the amplitude, $\propto m_b \tan\beta$, is enhanced for large values of $\tan\beta$. Note that the dominant component is due to the exchange of the pseudoscalar A boson as its s–wave contribution is not suppressed by the small velocity of the neutralinos, in contrast to the p–wave exchange of the CP–even h and H bosons.

- The annihilation into WW/ZZ bosons is efficient only for higgsino–like or mixed neutralinos when the elements $Z_{13}(Z_{14})$ are large. There is also an annihilation diagram through s–channel CP–even h, H bosons exchange but which gives only a small contribution as one is far from the Higgs boson poles and/or the Higgs couplings to neutralino and gauge bosons are suppressed; in addition, the p–wave contributions are suppressed by the small velocity of the LSPs.

- Since in the intense coupling regime all the Higgs particles are light, annihilation into a Higgs boson and a massive gauge boson, e.g. $\chi_1^0 \chi_1^0 \to AZ$ or $H^\pm W^\mp$, and two Higgs bosons, e.g. $\chi_1^0 \chi_1^0 \to Ah$ or $H^+ H^-$, can occur if the neutralino LSP is heavy enough, $m_{\chi_1^0} \gtrsim 150$ GeV. The dominant contribution is due to neutralino or chargino exchange; the $Z(h, H)$ exchange diagrams give small contributions for $Ah(AZ)$ annihilation as one is far from s–channel poles in this case.

- For higgsino–like LSPs, the co–annihilation processes with the lightest chargino and the next–to–lightest neutralino are very efficient because of the degeneracy $m_{\chi_1^\pm} \sim m_{\chi_2^0} \sim m_{\chi_1^0}$ and lead to the right density only for very heavy LSPs [18]. There are additional diagrams which might contribute to the LSP cross section such as co–annihilation with the lightest sfermion [19] [in general $\tilde{\tau}_1$] when it is almost degenerate with the LSP.

2.3 The impact on the detection of neutralinos

Let us now discuss the expected signal of the intense coupling regime of the NUHM model in the two most promising search strategies for weakly interacting massive particle (WIMP) dark matter candidates: the search of the elastic scattering of ambient neutralinos off a nucleus in a laboratory detector through nuclear recoils, the "direct search" [20, 21], and the search for interesting decays products of WIMP annihilation into standard particles such as gamma rays, positrons, neutrinos etc.., the so–called "indirect detection" [21, 22].

The strength of the direct detection signal is directly proportional to the neutralino–nucleon scattering cross section, $\sigma(\chi_1^0 N \to \chi_1^0 N)$. The matrix element for this scattering, mediated by squark and Z boson exchange as well as Higgs boson exchange diagrams [the crossed diagrams of those shown in Fig. 1a] receives both spin–dependent and spin–independent contributions. The former play a sub-dominant role in most direct search experiments, which employ fairly heavy nuclei. The spin–independent contribution in turn is usually dominated by Higgs boson exchange diagrams, where the Higgs bosons couple either directly to light (u, d, s) quarks in the nucleon, or couple to two gluons through a loop

of heavy (c, b, t) quarks or squarks. Only scalar Higgs couplings to neutralinos contribute in the non–relativistic limit and therefore, in the absence of CP–violation in the Higgs sector of the NUHM model discussed here, one only needs to include the contributions of the two neutral CP–even h and H particles. The contribution of the CP–even Higgs boson which has enhanced couplings to down–type quarks for $\tan\beta \gg 1$ is by far dominating. Thus, while in mSUGRA models only the contribution of the generally heavy H boson is relevant, in the intense coupling regime, both the h and H particles will play a role.

Many direct detection experiments have been and are presently carried out around the world. Recent collaborations such as CDMS [23] and EDELWEISS [24] have explored the regions of parameter space corresponding to a WIMP–nucleon cross section of $\sigma \gtrsim 10^{-6}$ pb. Future experiments will have improved sensitivity and, for example, GEDEON [25] will be able to explore a WIMP–nucleon cross section of $\sigma \gtrsim 3 \times 10^{-8}$ pb. Similar cross sections will also be tested by the EDELWEISS II experiment while CDMS–Soudan [26] [an extension of the CDMS experiment in the Soudan mine], will be able to test $\sigma \gtrsim 2 \times 10^{-8}$ pb [in our study, we will take the more conservative bound of 4×10^{-7} pb which corresponds to the present sensitivity of the experiment].

On the other hand, there are also promising methods for the indirect detection of WIMPs through the analysis of their annihilation into SM particles [with some of the contributing diagrams are the same as those depicted in Fig. 1] and the search for their stable decay and fragmentation products, i.e. neutrinos, photons, protons, antiprotons, electrons and positrons [16]. While electrons and protons are undetectable in the sea of matter particles in the universe, neutrinos, photons, positrons and anti-protons could be detected over the background due to ordinary particle interactions. An interesting possibility consists of detecting the gamma rays produced by these annihilations in the galactic halo. For this purpose, one uses atmospheric Cherenkov telescopes or space–based gamma–ray detectors. Planed experiments will reach significant sensitivity and, for instance, the GLAST telescope [27], which is scheduled for launch in 2007, will be able to detect a flux of gamma rays from dark matter particles of the order of $\Phi_\gamma \sim 10^{-10}$ photons $\text{cm}^{-2}\text{s}^{-1}$.

The detection of the neutralinos have been discussed at length in the mSUGRA scenario, see ref. [8] for reviews. The rates can be increased in different ways when the structure of mSUGRA for the soft SUSY–breaking scalar terms is abandoned in the Higgs sector [20 – 22]. In direct detection for instance, the neutralino–nucleon elastic cross section, where the exchange of the CP–even Higgs bosons gives the dominant contribution as discussed above, can be considerably enhanced when decreasing the pseudoscalar Higgs mass and, thus, the heavy Higgs boson mass, through a particular choice of the non–universality parameters δ_1 and δ_2. Concerning the prospects for the indirect detection of the neutralinos, we have seen that it is possible to enhance the annihilation channel involving the exchange of the CP–odd Higgs boson A by reducing its mass $(\delta_1 < 0, \delta_2 > 0)$ and have a larger yield for the interesting decay products of the b–quarks in the reaction $\chi_1^0\chi_1^0 \xrightarrow{A} b\bar{b}$. In addition, by increasing the higgsino component of the lightest neutralino $(\delta_2 > 0)$, one would have a larger cross section for the annihilation processes $\chi_1^0\chi_1^0 \to WW/H^+H^-$ for instance which

allow to look for interesting decay products of the gauge and Higgs bosons.

3. The analysis

3.1 The determination of the spectrum and constraints

In the present analysis, we use the Fortran code `SuSpect` [28] to solve the (two–loop) Renormalization Group Equations for the gauge and Yukawa couplings and the soft SUSY–breaking parameters, to achieve proper electroweak symmetry breaking with the (two–loop) scalar potential, and to calculate the spectrum of the physical SUSY particles and Higgs bosons including radiative corrections. We follow the procedure outlined in ref. [29], except that we allow for non–universality for the soft SUSY–breaking Higgs mass parameters as explained in the previous section. In addition to leading to a consistent electroweak symmetry breaking [i.e. obtaining a reasonable value for μ, M_A and M_Z as well as no charge or color breaking (CCB) minima] and to a phenomenologically viable spectrum [no tachyonic sparticles and Higgs bosons and and LSP that is not charged], a given set of input parameters has to satisfy experimental constraints. The ones relevant for this study are as follows [30].

- The total cross section for the production of any pair of sparticles at the highest LEP energy (209 GeV) must be less than 20 fb. This leads for instance to an upper bound of ≈ 100 GeV on the chargino and slepton/ 3d generation squark masses. The masses of the gluino and first/second generation squarks should be larger than ≈ 200 GeV to cope with the Tevatron exclusion bounds.

- Searches for neutral Higgs bosons at LEP impose a lower bound on M_h which, in the decoupling limit when $M_A \gg M_Z$, is close to 114 GeV. Allowing for a theoretical uncertainty of ≈ 3 GeV, one requires $M_h > 111$ GeV in this case. For small M_A values, the bound should be of the order of $M_h \sim M_A \gtrsim M_Z$.

- Quantum corrections from superparticles to electroweak observables can be incorporated through the ρ parameter which should obey the upper bound $\delta\rho_{\mathrm{SUSY}} < 2.2 \cdot 10^{-3}$ at the 2σ level. However, it turns out that this constraint is always superseded by either the LEP Higgs search limit or by the CCB constraint.

- Recent measurements of the muon magnetic moment lead to a constraint on the SUSY contribution $-5.7 \cdot 10^{-10} \leq a_\mu^{\mathrm{SUSY}} \leq 4.7 \cdot 10^{-9}$ where, for the determination of the hadronic SM contributions, both data from e^+e^- annihilation into hadronic final states and data from semileptonic τ decays are used, leading to less than 1σ deviation between the experimentally measured value and the theoretical prediction in the SM.

- Allowing for experimental and theoretical errors, the branching ratio for radiative b decays should be $2.33 \cdot 10^{-4} \leq \mathrm{B}(b \to s\gamma) \leq 4.15 \cdot 10^{-4}$. The branching ratio for the very rare decay into $\mu^+\mu^-$ should be bounded by $\mathrm{B}(B_s \to \mu^+\mu^-) < 2.9 \times$

10^{-7} [31]. We note however, that both the $b \to s\gamma$ and $B_s \to \mu^+\mu^-$ constraints have a different status from those discussed earlier, as a small amount of squark flavor mixing would make these observable compatible with the experimental values while having a negligible effect on the other (flavor conserving) observables, such as signals at colliders.

The theoretical constraints are implemented directly in the Fortran code `SuSpect`; the program implements also the experimental constraints mentioned above except for the rate $\mathrm{B}(B_s \to \mu^+\mu^-)$ which we determine using the code `microMEGAS` [33].

In addition to these constraints from "collider experiments", we also require that the calculated χ_1^0 cosmological relic density has to be in the the 99% confidence level WMAP narrow range, that is

$$0.087 \leq \Omega_\chi h^2 \leq 0.138 \tag{3.1}$$

where $\Omega \equiv \rho/\rho_c$ with $\rho_c \simeq 2 \cdot 10^{-29} h^2 \mathrm{g/cm^3}$ is the "critical" mass density that yields a flat universe and the dimensionless parameter h the scaled Hubble constant describing the expansion of the universe. The result for the relic density has been obtained using the code `microMEGAS` [33].

We also take into account the most recent astrophysical bounds, in addition to the WMAP constraint. For the evaluation of the neutralino–nucleon cross section for direct detection and the gamma–ray fluxes relevant for the indirect detection, we use the latest released version of the program `DarkSUSY` [34]. We have included the relevant sensitivities and uncertainties in both detection methods. The measurement of the WIMP–nucleon cross section depends on the velocity distribution of the WIMP candidate in the neighborhood of the sun and it has been shown in ref. [35] that the astrophysical uncertainties can affect the experimental sensitivities by a factor of two. Moreover, the modelization of the π–nucleon interaction can induce theoretical uncertainties in the calculation of the scattering WIMP–nucleon cross section, estimated to be a factor five at its maximum [36]; rather large QCD corrections and uncertainties are also present [37]. We will assume in this study an uncertainty factor of 2 coming from the astrophysical uncertainty on the WIMPs speed in our galaxy and a factor of 3 in the calculation of $\sigma(\chi_1^0 N \to \chi_1^0 N)$. Concerning LSP indirect detection, most of the uncertainties are coming from the model used for the dark matter halo. For illustration, we will use in this paper a cuspy Navarro Frenk and White (NFW) profile [38], keeping in mind that a cuspier one [such as the one proposed by Moore in ref. [40]] or a smoother (Isothermal) one, will give fluxes that are two orders of magnitude higher and lower, respectively.

3.2 The spectrum in the intense coupling regime

In the present study, we choose for illustration two NUHM scenarios. In the first one, we fix $\tan\beta = 30$, the common sfermion mass to $m_0 = 2$ TeV, the common gaugino mass to $M_{1/2} = 180$ GeV and the trilinear coupling in such a way that $A_t = 3$ TeV to maximize the mixing in the Higgs sector and thus the mass of the lightest h boson in order to pass easily the LEP2 constraint $M_h \gtrsim 114$ GeV in the decoupling regime when the theoretical uncertainty of ~ 3 GeV is included. We also fix the non–universality parameter to $\delta_1 = -1$,
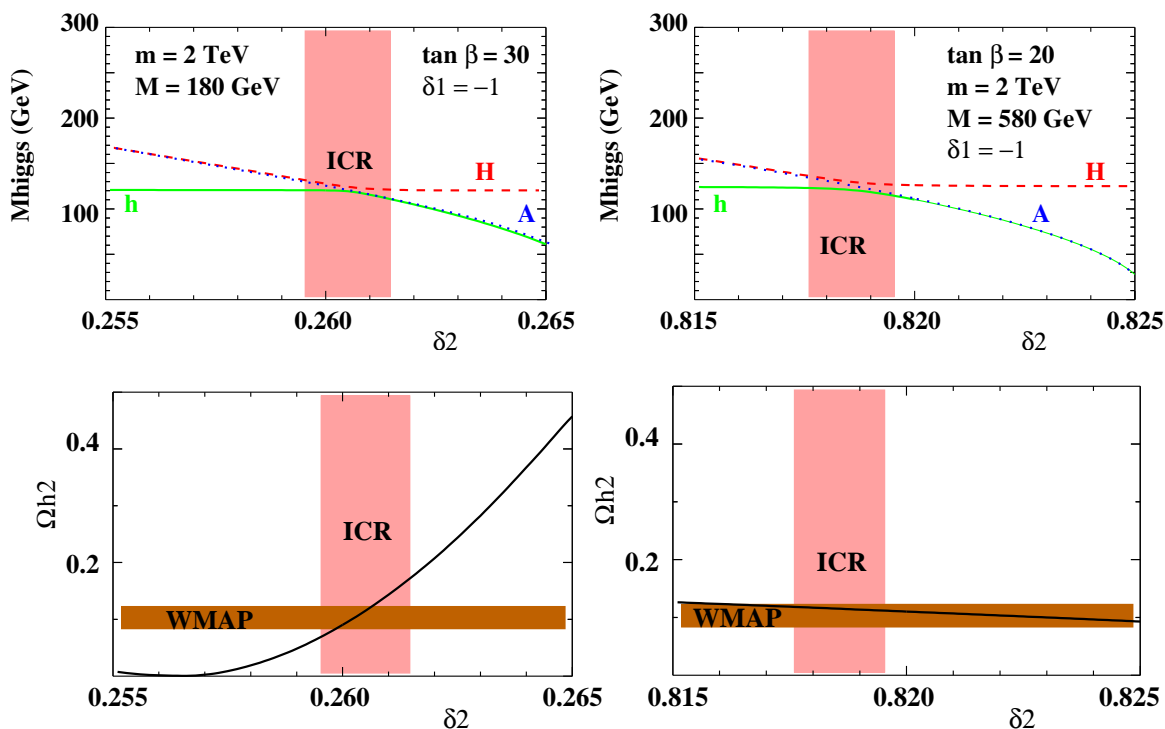
Figure 2: The neutral Higgs boson masses as a function of the parameter δ_2 in the two scenarios discussed in the text (top) and the cosmological relic density of the LSP neutralino (bottom). The pink vertical bands display the intense coupling regime while the brown horizontal lines show the WMAP range for the LSP relic density.

but vary the other parameter δ_2 in a narrow range to have a pseudoscalar A boson mass of the same order as the masses of the CP–even h and H bosons. In a second scenario, we choose a slightly lower value of $\tan\beta$, $\tan\beta = 20$, and a larger value of the universal gaugino mass, $M_{1/2} = 580$ GeV; all the other parameters are the same as in the previous case.

In the upper part of Fig. 2, we display the masses of the three neutral Higgs bosons as a function of the parameter δ_2 in the two scenarios. The pink vertical bands correspond to the areas in which $|M_{H,h} - M_A| \leq 10$ GeV, that is, to the intense coupling regime which appears around $\delta_2 = 0.260$ in the first case and $\delta_2 = 0.818$ in the second case. These two values of δ_2 lead to an almost mass degeneracy of the neutral Higgs particles $M_h \sim M_H \sim M_A \sim 120$ GeV and define the points **A** and **B** corresponding to the initial values at the GUT scale : $m_{H_1} = 0$ and, respectively, $m_{H_2} = 1.26 m_0$ and $m_{H_2} = 1.818 m_0$. In the lower part of Fig. 2, we display the cosmological relic density of the LSP neutralino, again as a function of δ_2, and compare it to the WMAP narrow band. For the values of δ_2 which correspond to the points **A** and **B**, we see that the WMAP constraint is obeyed.

In the two scenarios, the output for the Higgs boson masses are shown in Table 1 for the values of the parameters δ_2 which correspond to the selected points **A** and **B**. We also display the masses of the two lighter neutralinos $m_{\chi_1^0}$ and $m_{\chi_2^0}$ and the value of the parameter μ. As can be seen, in point **A**, the LSP χ_1^0 is rather light while the μ parameter is very large: the LSP is thus almost bino–like and the lighter chargino is almost mass

	inputs	M_Φ	m_{χ_i}	$\Omega_\chi h^2$	BR($\chi_1^0\chi_1^0 \to X$)
A	$\tan\beta = 30$ $\delta_2 = 0.260$ $M_{1/2} = 180$ GeV	$M_h = 120.4$ GeV $M_H = 126.5$ GeV $M_A = 126.4$ GeV	$m_{\chi_1^0} = 78$ GeV $m_{\chi_2^0} = 155$ GeV $\mu = 846$ GeV	0.09	$b\bar{b} : 90\%$ $\tau\tau : 10\%$
B	$\tan\beta = 20$ $\delta_2 = 0.818$ $M_{1/2} = 580$ GeV	$M_h = 124$ GeV $M_H = 136$ GeV $M_A = 134$ GeV	$m_{\chi_1^0} = 241$ GeV $m_{\chi_2^0} = 351$ GeV $\mu = 362$ GeV	0.12	$b\bar{b}(t\bar{t}) : 13\%(12\%)$ $hA(hh) : 27\%(1\%)$ $ZH(Zh) : 16\%(5\%)$ $W^\pm H^\mp : 22\%$ $WW : 2\%$

Table 1: Sample spectra obtained in the non–universal scenarios **A** and **B** (with some of the parameters indicated and $m_0 = 2$ TeV), together with the value of the neutralino relic density and the fractions of the main subprocesses contributing to it.

degenerate with the wino–like χ_2^0, while the heavier neutralinos and chargino are higgsino–like and have masses close to μ. In point **B**, the values of the gaugino and higgsino mass parameters are of the same order, $M_2 \approx \mu$, and all neutralinos and charginos are thus mixed states with masses that are quite close to each other. The LSP neutralino has a mass which is relatively large, exceeding the W/Z boson and all Higgs boson masses and even the top quark mass.

In Table 1, we also display the result for the LSP relic density $\Omega_\chi h^2$ and for the fractions of the various final states which contribute, B($\chi_1^0\chi_1^0 \to X$) $\equiv \sigma(\chi_1^0\chi_1^0 \to X)/\sigma(\chi_1^0\chi_1^0 \to$ all). As we have assumed heavy scalar fermions in both scenarios, $m_0 = 2$ TeV, the main annihilation channel for the LSP neutralinos, leading to a relic density compatible with the WMAP result, is the Higgs boson [mainly A and to a lesser extent h/H] exchange contributions in the case of point **A**. As can be seen in the table, in this case, the pseudoscalar A boson mass is close to twice the LSP neutralino mass and the $Ab\bar{b}$ coupling is very strong for $\tan\beta = 30$; this enhances the annihilation process $\chi_1^0\chi_1^0 \xrightarrow{A} b\bar{b}$ which reaches a branching fraction of 90 %. For point **B** with larger values of $M_{1/2}$ and μ, higher values of the parameter δ_2 are needed to increase m_{H_2} and keep a light pseudoscalar A boson, as can be seen from eq. (2.4). Since here, the A–pole is too far from the $2m_{\chi_1^0}$ threshold, the contribution of the annihilation process $\chi_1^0\chi_1^0 \to b\bar{b}$ to the LSP relic density is only at the level of 10%; the $\chi_1^0\chi_1^0 \to t\bar{t}$ annihilation process, which has roughly the same probability as $\chi_1^0\chi_1^0 \to b\bar{b}$, occurs mainly through Z boson exchange. In fact, since in this scenario one has $m_{\chi_1^0} \sim 250$ GeV, all Higgs particles can occur as final states in the annihilation of the LSPs and, since the LSP is a bino–higgsino mixed state with strong couplings to the Higgs bosons, the fraction of the processes involving at least one final Higgs particle is larger than 70%.

Finally, in Fig. 3, we show the result of a scan in the $(M_{1/2}, \delta_2)$ plane, starting with the basic inputs for $m_0 = 2$ TeV, $\tan\beta = 30$ (left) and 20 (right) and $\delta_1 = -1$; the position of the points **A** and **B** analyzed earlier are marked by a cross. In the white area, all the points fulfill the experimental and theoretical constraints discussed previously, except for
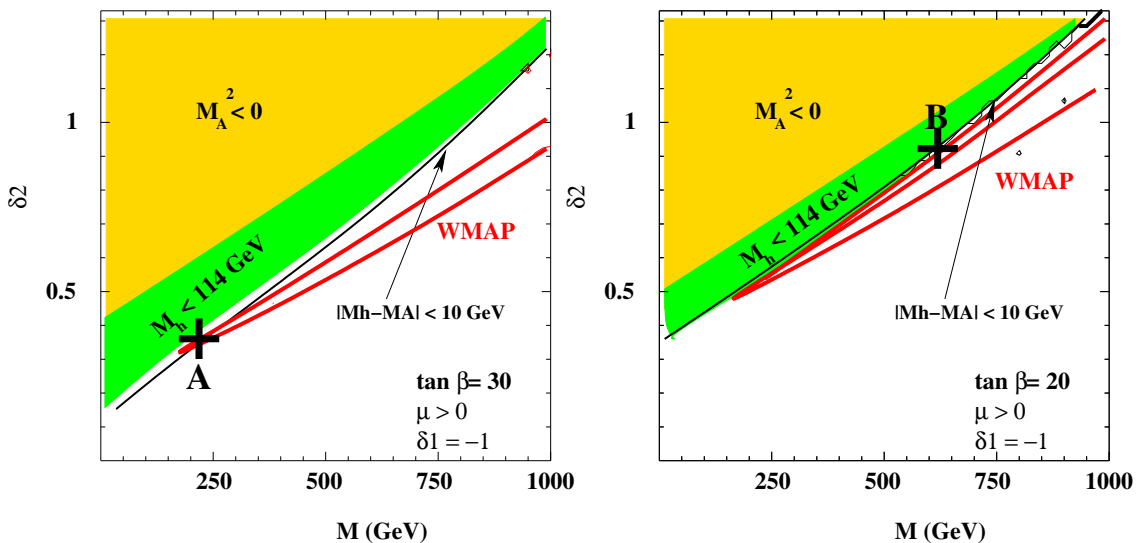
Figure 3: The allowed $(M_{1/2}, \delta_2)$ parameter space in the NUHM model with $\tan\beta = 30$ (left) and $\tan\beta = 20$ (right), $\mu > 0$, $A_t = 3$ TeV, $m_0 = 2$ TeV and $\delta_1 = -1$. We indicate in the plot the points **A** and **B** defined in the text, the WMAP range, the area in which $M_h \leq 114$ GeV, and the intense coupling regime (black solid lines).

the WMAP constraint which is obeyed only in the red narrow strips [between the strips, the relic density is either too high or too low, compared to the WMAP value]. The intense coupling regime, defined by the requirement $|M_{H,h} - M_A| < 10$ GeV, is represented by the thin black lines. In the (green) areas above these lines, the lightest h boson has a mass smaller than the LEP2 limit, $M_h \lesssim 114$ GeV. A third region exists also for the $\tan\beta = 30$ case, but is inside the exclusion region $M_h \lesssim 114$ GeV. One notices that increasing the value of δ_2 for a given value of $M_{1/2}$, finally leads to a region in which $M_A^2 < 0$: the $m_{H_2}^2$ term is not sufficiently negative at the electroweak scale to compensate the $m_{H_1}^2$ term in eq. (2.4).

3.3 Prospects for dark matter detection

Let us now turn to the prospects for detecting the LSP dark matter candidate in these two scenarios. In direct detection, as a consequence of the light Higgs bosons with strongly enhanced couplings to down–type quarks that are present, the scalar or spin–independent LSP–nucleon scattering cross section can be extremely large as the process is mainly mediated by the exchange of the two CP–even Higgs bosons h and H. As can be seen in the upper part of Fig. 4, where the expected $\chi_1^0 N \to \chi_1^0 N$ scattering cross section and the CDMS–Soudan sensitivity [which depends on the neutralino mass] in which the various uncertainties discussed in section 2.3 are incorporated, the intense–coupling regime is within the reach of the CDMS–Soudan detector. For instance, in point **A** with $\delta_2 = 0.260$, one has $\sigma(\chi_1^0 N \to \chi_1^0 N) = 1.2 \times 10^{-7}$ pb which is only slightly lower than the present CDMS sensitivity of 4×10^{-7} pb and much larger than the expected sensitivity of 2×10^{-8} pb. In the second scenario, one obtains an even larger cross section despite of the larger value of the LSP mass and the smaller value of $\tan\beta$. For instance, in point **B** with $\delta_2 = 0.818$,
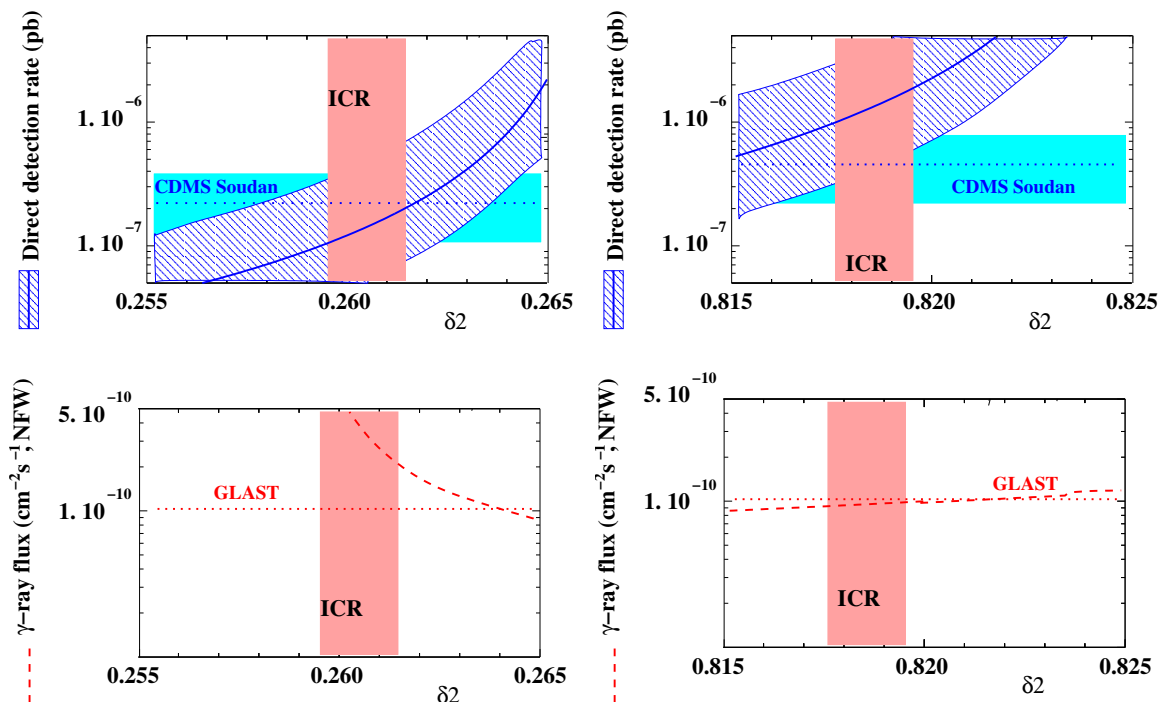
Figure 4: Upper curves: the rate for the LSP–nucleon cross section including the various errors (hatched bands) compared to the expected sensitivity of the CDMS–Soudan experiment (horizontal blue bands) as a function of the non–universality parameter δ_2. Lower curves: the obtained gamma ray flux in photons $cm^{-2}s^{-1}$ using the NFW profile as a function of δ_2 (dashed curves) and the expected sensitivity of the GLAST experiment (dotted curves). The left (right) handed plots are for the scenarios discussed previously with $M_{1/2} = 180$ GeV (580 GeV) and the other parameters as described in the text.

one obtains $\sigma(\chi_1^0 N) = 10^{-6}$ pb. This is due to the fact that here, the LSP is a mixed bino–higgsino state with larger couplings to the Higgs bosons [in the first scenario, the larger value of $\tan\beta$ and the smaller LSP mass were partly compensated by the smaller Higgs couplings to the almost bino–like neutralino]. Note that such high values for the LSP–nucleon scattering cross section have also been obtained in ref. [20] in the case of light pseudoscalar Higgs bosons not pertaining to the intense–coupling regime.

Concerning indirect LSP detection, we have calculated the rate in the framework of the NUHM model, assuming the NFW profile [38] within a solid angle of $\Delta\Omega = 10^{-5}$ sr and found in the two scenarios fluxes around or larger than $\sim 10^{-10} cm^{-2}s^{-1}$, which is within the reach of a detector like GLAST. This is shown in the lower parts of Fig. 4, where we display the obtained gamma ray flux as a function of δ_2 and compare it to the expected sensitivity of the experiment. To be more precise, we find a flux of $\Phi_\gamma^{\mathrm{NFW}} = 5.6 \times 10^{-10} cm^{-2}s^{-1}$ for point **A** and $\Phi_\gamma^{\mathrm{NFW}} = 8.4 \times 10^{-11} cm^{-2}s^{-1}$, for point **B**. In the first case, the obtained flux is much larger than in the second case because of the stronger enhancement of the annihilation channel through A–boson exchange and the smaller value of the LSP neutralino mass.

Thus, one can conclude that the two scenarios that we have chosen to illustrate the Higgs intense coupling regime in the NUHM model are in a sense orthogonal, as point **A**

will be more easily probed in indirect detection experiments whereas point **B** can be best probed in direct LSP detection[1].

4. The mSUGRA case

For completeness, let us briefly discuss the intense coupling regime in the mSUGRA framework with universal Higgs mass parameters. As mentioned earlier, the pseudoscalar Higgs boson mass and the μ parameter tend to be quite large in this case, except in the focus point region when both the common scalar mass m_0 and $\tan\beta$ are large. This, however, occurs only in a tiny part of the parameter space near the region where electroweak symmetry breaking is not achieved [in general because either $M_A^2 < 0$ or $\mu^2 < 0$ or both]. The Higgs intense coupling regime occurs thus in an even smaller region of the parameter space and one has to tune severely some of the input parameters to realize it.

For some of the input parameters already used in the NUHM model, $m_0 = 2$ TeV and $A_t = 3$ TeV, and assuming $\mu > 0$ and $M_{1/2} = 350$ GeV for instance, one obtains using the program SuSpect, the intense coupling regime only for values of $\tan\beta$ very close to $\tan\beta = 53.87$ as is exemplified in Fig. 5, where the neutral Higgs boson masses are shown in this mSUGRA scenario as a function of $\tan\beta$. For the particular value $\tan\beta = 53.87$, one has a pseudoscalar Higgs boson mass of $M_A \simeq 122$ GeV leading to $M_h \simeq 117$ GeV and $M_H \simeq 124$ GeV for the masses of the CP–even Higgs particles. For the chosen inputs, one also obtains a relatively large value for the higgsino mass parameter, $\mu \simeq 440$ GeV, with a lightest neutralino mass of $m_{\chi_1^0} \simeq 150$ GeV. The LSP is thus almost bino–like with only a small higgsino component. However, this component is large enough to lead to a substantial annihilation rate of the LSP neutralino into Higgs bosons. Indeed, one obtains for instance $B(\chi_1^0\chi_1^0 \to hA + HA)$ and $B(\chi_1^0\chi_1^0 \to HZ + hZ)$ of, respectively, 12% and 8% the dominant channel being annihilation into $b\bar{b}$ and $\tau^+\tau^-$ final states which has an overall fraction close to 70%. The obtained value for the LSP cosmological relic density in this scenario is $\Omega_\chi h^2 \simeq 0.1$ which is within the WMAP range. Because of the very high value of $\tan\beta$, the couplings of the rather light CP–even neutral Higgs bosons h and H to $b\bar{b}$ states are extremely strong, leading to a large LSP–nucleon scattering cross section, $\sigma(\chi_1^0 N \to \chi_1^0 N) \sim 2 \times 10^{-6}$ pb, which can be easily probed by the CDMS experiment. The indirect detection rate of the lightest neutralino is also significant as one obtains a gamma–ray flux of the order of $\Phi_\gamma^{\rm NFW} \sim 2 \times 10^{-10} {\rm cm}^{-2}{\rm s}^{-1}$ which can be observed by GLAST.

However, there is a potential problem with this particular scenario. For such a large value of $\tan\beta$ and a low pseudoscalar Higgs boson mass M_A, the decay rate $B(B_s \to \mu^+\mu^-) \propto \tan^6\beta/M_A^2$ is huge [as already noticed in ref. [32] for instance] and one obtains for the point introduced above $B(B_s \to \mu^+\mu^-) \sim 4 \times 10^{-5}$ to be compared with the Tevatron experimental bound of $B(B_s \to \mu^+\mu^-) \sim 2.9 \times 10^{-7}$ [31]. As discussed in section 3.1, the two–orders of magnitude discrepancy between these two values will need some flavor mixing

---

[1]Recently, it has been pointed out [39] that HESS results can indeed influence the GLAST sensitivity by a factor of 2 to 5 depending on the astrophysical model. Of course, this is independent of the SUGRA model and does not change the general conclusion of the comparison between the points **A** and **B**.
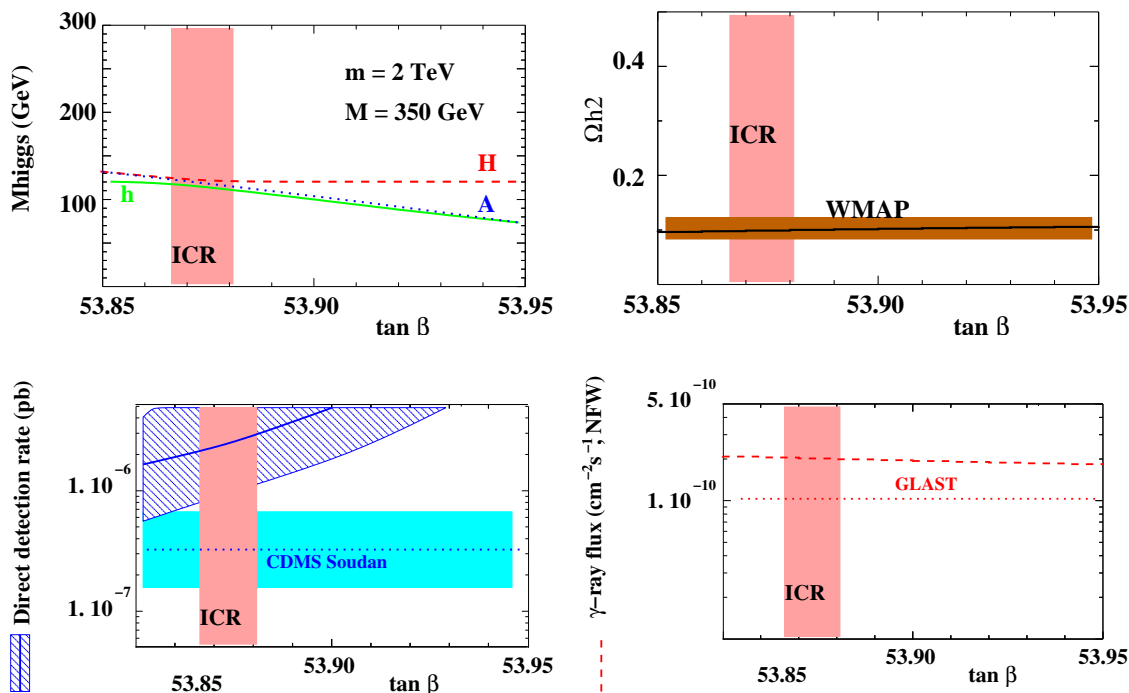
Figure 5: The same as in Figs. 2 and 4 but for the mSUGRA model with universal Higgs mass parameters and as a function of $\tan\beta$ with basic inputs $m_0 = 2$ TeV, $A_t = 3$ TeV, $M_{1/2} = 350$ GeV and $\mu > 0$.

to be resolved. [Note that we have a similar problem for the point **A** of the NUHM model, but the difference between the obtained $B_s \to \mu^+\mu^-$ rate and the experimental bound is much smaller and can be attributed to theoretical uncertainties.]

Nevertheless, if this problem can be circumvented, one would be very close to definitely test this scenario. Indeed, the cross section for the associated production of the neutral Higgs bosons in association with $b\bar{b}$ pairs, $p\bar{p} \to gg/q\bar{q} \to b\bar{b} + A, h, H$, will be extremely large at the Tevatron for the considered values of $\tan\beta$ and M_A. With the luminosity that is presently collected at the Tevatron, values $\tan\beta \sim 50$ are already ruled out for $M_A \sim 100$ GeV [41] and the 2007 projection for the increase of the Tevatron luminosity would allow to observe or rule out a Higgs boson signal in this process for pseudoscalar Higgs bosons masses of $M_A \sim 120$ GeV [42].

5. Conclusions

In this paper, we have investigated the possibility of realizing the intense coupling regime, in which all the Higgs bosons of the MSSM have comparable masses and the parameter $\tan\beta$ is large, in the framework of the constrained MSSM. We have pointed out that this interesting regime is possible within the mSUGRA model, but when all the scalar fermion and Higgs soft SUSY–breaking mass terms are unified at the GUT scale, this happens in a very limited range of the parameter space: large values of $\tan\beta$, $\gtrsim 50$, are needed which might lead to a severe conflict with the measured value of the $B_s \to \mu^+\mu^-$ branching rate and potentially, with the search of the MSSM Higgs bosons at the Tevatron. In contrast,

relaxing the universality of the SUSY–breaking scalar masses of the two MSSM Higgs fields at the high scale, $m_{H_1} \neq m_{H_2} \neq m_0$, leads to more freedom which allows to reach this regime in a much larger area of the SUGRA parameter space. We have provided examples of scenarios in which the intense coupling regime is realized in the NUHM model and where, not only all known theoretical requirements and collider experiment constraints are fulfilled, but also where the generated relic density of the lightest neutralino of the MSSM is compatible with the WMAP measurement of the amount of cold dark matter in the universe.

These scenarios have a very interesting phenomenology. They lead by definition to light MSSM Higgs bosons which can be observed at the next generation of colliders such as the LHC and the ILC [and also at the Tevatron if the value of $\tan\beta$ is very large]. In addition, because of the large $\tan\beta$ and low M_A values which are implied by these models, the rates for direct and indirect detection of the LSP cold dark matter neutralino are large enough for this particle to be observed in near future experiments such as CDMS–Soudan and GLAST. Furthermore, since at least the spectrum of spin–1/2 superparticles needed to generate the right cosmological density for the LSP is relatively light, the heavier charginos and neutralinos [and possibly the gluinos] could also be produced at the next generation of collider experiments. This would allow to precisely measure the couplings of these particles [in particular the couplings to the Higgs bosons in possible cascades [43] might add some information] and determine the parts of the MSSM Lagrangian which enter in the expressions of the relic density and the detection rates. Thus, using the future collider data and assuming standard cosmology, one would be able to check that the LSP neutralino makes indeed the entire dark matter of the universe and that the detection rates observed in astrophysical experiments are indeed those predicted by the model. In this respect, these scenarios, if realized in Nature, would highlight the complementarity between collider physics searches and precision measurements and astroparticle physics searches.

Acknowledgments

References

[1] For on reviews Supersymmetry and the MSSM, see: P. Fayet and S. Ferrara, *Supersymmetry, Phys. Rept.* **32** (1977) 249;
H.P. Nilles, *Supersymmetry, supergravity and particle physics, Phys. Rept.* **110** (1984) 1;
H.E. Haber and G.L. Kane, *The search for supersymmetry: probing physics beyond the standard model, Phys. Rept.* **117** (1985) 75;
M. Drees, R.M. Godbole and P. Roy, *Theory and Phenomenology of Sparticles*, World Scientific, Spring 2004;

For a detailed discussion of the Higgs sector, see: J.F. Gunion, H.E. Haber, G.L. Kane and S. Dawson, *The Higgs Hunter's Guide*, Addison–Wesley, Reading, USA, 1990.

[2] For a recent review of the Higgs sectors of the SM and MSSM, see A. Djouadi, *The anatomy of electro-weak symmetry breaking, I. The Higgs boson in the standard model*, `hep-ph/0503172`.

[3] H.E. Haber and Y. Nir, *The decay $z \to a^0 a^0$ neutrino anti-neutrino and $e^+ e^- \to a^0 a^0 z$ in two Higgs doublet models*, *Phys. Lett.* **B 306** (1993) 327 [`hep-ph/9302228`];
H.E. Haber, *Challenges for nonminimal Higgs searches at future colliders*, `hep-ph/9505240`;
A. Dobado, M.J. Herrero and S. Penaranda, *The Higgs sector of the MSSM in the decoupling limit*, *Eur. Phys. J.* **C 17** (2000) 487 [`hep-ph/0002134`];
J.F. Gunion and H.E. Haber, *The CP-conserving two-Higgs-doublet model: the approach to the decoupling limit*, *Phys. Rev.* **D 67** (2003) 075019 [`hep-ph/0207010`].

[4] For reviews, see: M. Carena and H. E. Haber, Prog. Part. Nucl. Phys. 50 (2003) 63;
S. Heinemeyer, *MSSM Higgs physics at higher orders*, *Int. J. Mod. Phys.* **A 21** (2006) 2659 [`hep-ph/0407244`];
B.C. Allanach, A. Djouadi, J.L. Kneur, W. Porod and P. Slavich, *Precise determination of the neutral Higgs boson masses in the MSSM*, *JHEP* **09** (2004) 044 [`hep-ph/0406166`].

[5] J.F. Gunion, A. Stange and S. Willenbrock, *Weakly-coupled Higgs bosons*, `hep-ph/9602238`.

[6] E. Boos, A. Djouadi, M. Muhlleitner and A. Vologdin, *The MSSM Higgs bosons in the intense-coupling regime*, *Phys. Rev.* **D 66** (2002) 055004 [`hep-ph/0205160`];
E. Boos, A. Djouadi and A. Nikitenko, *Detection of the neutral MSSM Higgs bosons in the intense- coupling regime at the LHC*, *Phys. Lett.* **B 578** (2004) 384 [`hep-ph/0307079`];
E. Boos, V. Bunichev, A. Djouadi and H.J. Schreiber, *Prospects of mass measurements for neutral MSSM Higgs bosons in the intense-coupling regime at a linear collider*, *Phys. Lett.* **B 622** (2005) 311 [`hep-ph/0412194`].

[7] A.H. Chamseddine, R. Arnowitt and P. Nath, *Locally supersymmetric grand unification*, *Phys. Rev. Lett.* **49** (1982) 970;
R. Barbieri, S. Ferrara and C.A. Savoy, *Gauge models with spontaneously broken local supersymmetry*, *Phys. Lett.* **B 119** (1982) 343;
L.J. Hall, J.D. Lykken and S. Weinberg, *Supergravity as the messenger of supersymmetry breaking*, *Phys. Rev.* **D 27** (1983) 2359.

[8] For a detailed review on SUSY dark matter, see: G. Jungman, M. Kamionkowski and K. Griest, *Supersymmetric dark matter*, *Phys. Rept.* **267** (1996) 195 [`hep-ph/9506380`];
For more recent reviews, see G. Bertone, D. Hooper and J. Silk, *Phys. Rept.* 405 (2005) 279;
J.L. Feng, *Supersymmetry and cosmology*, *ECONF* **C0307282** (2003) L11 [`hep-ph/0405215`];
M. Drees, *Supersymmetric dark matter 2004*, `hep-ph/0410113`;
K.A. Olive, *Dark matter candidates in supersymmetric models*, `hep-ph/0412054`;
C. Muñoz, *Dark matter detection in the light of recent experimental results*, *Int. J. Mod. Phys.* **A 19** (2004) 3093 [`hep-ph/0309346`].

[9] For reviews, see e.g. M. Persic, P. Salucci and F. Stel, *The universal rotation curve of spiral galaxies, I. The dark matter connection*, *Mon. Not. Roy. Astron. Soc.* **281** (1996) 27 [`astro-ph/9506004`];
M. Persic, P. Salucci and F. Stel, *The universal rotation curve of spiral galaxies: 1. the dark matter connection*, *Mon. Not. Roy. Astron. Soc.* **281** (1996) 27 [`astro-ph/9506004`].

[10] For a review, see W.L. Freedman, *Determination of cosmological parameters*, *Phys. Scripta* **T85** (2000) 37–46 [`astro-ph/9905222`].

[11] C.L. Bennett et al., *First year wilkinson microwave anisotropy probe (wmap) observations: preliminary maps and basic results*, *Astrophys. J. Suppl.* **148** (2003) 1 [`astro-ph/0302207`]; WMAP collaboration, D.N. Spergel et al., *First year wilkinson microwave anisotropy probe (wmap) observations: determination of cosmological parameters*, *Astrophys. J. Suppl.* **148** (2003) 175 [`astro-ph/0302209`]; L. Verde et al., *First year wilkinson microwave anisotropy probe (WMAP) observations: parameter estimation methodology*, *Astrophys. J. Suppl.* **148** (2003) 195 [`astro-ph/0302218`].

[12] D. Matalliotakis and H.P. Nilles, *Implications of nonuniversality of soft terms in supersymmetric grand unified theories*, *Nucl. Phys.* **B 435** (1995) 115 [`hep-ph/9407251`]; H. Baer, A. Mustafayev, S. Profumo, A. Belyaev and X. Tata, *Neutralino cold dark matter in a one parameter extension of the minimal supergravity model*, *Phys. Rev.* **D 71** (2005) 095008 [`hep-ph/0412059`]; *Direct, indirect and collider detection of neutralino dark matter in SUSY models with non-universal Higgs masses*, *JHEP* **07** (2005) 065 [`hep-ph/0504001`].

[13] P. Nath and R. Arnowitt, *Non-universal soft SUSY breaking and dark matter*, *Phys. Rev.* **D 56** (1997) 2820 [`hep-ph/9701301`]; J.R. Ellis, K.A. Olive and Y. Santoso, *The MSSM parameter space with non-universal Higgs masses*, *Phys. Lett.* **B 539** (2002) 107 [`hep-ph/0204192`]; J.R. Ellis, T. Falk, K.A. Olive and Y. Santoso, *Exploration of the MSSM with non-universal Higgs masses*, *Nucl. Phys.* **B 652** (2003) 259 [`hep-ph/0210205`].

[14] A. Brignole, L.E. Ibáñez and C. Muñoz, *Towards a theory of soft terms for the supersymmetric standard model*, *Nucl. Phys.* **B 422** (1994) 125 [`hep-ph/9308271`]; A. Brignole, L.E. Ibáñez, C. Muñoz and C. Scheich, *Some issues in soft SUSY breaking terms from dilaton/moduli sectors*, *Z. Physik* **C 74** (1997) 157 [`hep-ph/9508258`].

[15] P. Binetruy, M.K. Gaillard and B.D. Nelson, *One loop soft supersymmetry breaking terms in superstring effective theories*, *Nucl. Phys.* **B 604** (2001) 32 [`hep-ph/0011081`]; P. Binetruy, A. Birkedal-Hansen, Y. Mambrini and B.D. Nelson, *Phenomenological aspects of heterotic orbifold models at one loop*, *Eur. Phys. J.* **C 47** (2006) 481 [`hep-ph/0308047`].

[16] J.L. Feng, K.T. Matchev and F. Wilczek, *Prospects for indirect detection of neutralino dark matter*, *Phys. Rev.* **D 63** (2001) 045024 [`astro-ph/0008115`].

[17] M. Drees and M.M. Nojiri, *The neutralino relic density in minimal $N = 1$ supergravity*, *Phys. Rev.* **D 47** (1993) 376 [`hep-ph/9207234`].

[18] K. Griest and D. Seckel, *Three exceptions in the calculation of relic abundances*, *Phys. Rev.* **D 43** (1991) 3191; S. Mizuta and M. Yamaguchi, *Coannihilation effects and relic abundance of higgsino dominant lsp_s*, *Phys. Lett.* **B 298** (1993) 120 [`hep-ph/9208251`]; J. Edsjö and P. Gondolo, *Neutralino relic density including coannihilations*, *Phys. Rev.* **D 56** (1997) 1879 [`hep-ph/9704361`].

[19] J.R. Ellis, T. Falk and K.A. Olive, *Neutralino stau coannihilation and the cosmological upper limit on the mass of the lightest supersymmetric particle*, *Phys. Lett.* **B 444** (1998) 367 [`hep-ph/9810360`]; M.E. Gomez, G. Lazarides and C. Pallis, *Supersymmetric cold dark matter with yukawa unification*, *Phys. Rev.* **D 61** (2000) 123512 [`hep-ph/9907261`];

J.R. Ellis, T. Falk, K.A. Olive and M. Srednicki, *Astropart. Phys.* 13 (2000) 181;
C. Boehm, A. Djouadi and M. Drees, *Light scalar top quarks and supersymmetric dark matter*, *Phys. Rev.* **D 62** (2000) 035012 [`hep-ph/9911496`].

[20] V. Berezinsky, A. Bottino, J. R. Ellis, N. Fornengo, G. Mignola and S. Scopel, *Astropart. Phys.* 5 (1996) 1;
D.G. Cerdeno and C. Muñoz, *Neutralino dark matter in supergravity theories with non-universal scalar and gaugino masses*, *JHEP* **10** (2004) 015 [`hep-ph/0405057`];
V. Bertin, E. Nezri and J. Orloff, *Neutralino dark matter beyond cmssm universality*, *JHEP* **02** (2003) 046 [`hep-ph/0210034`];
A. Birkedal-Hansen and B.D. Nelson, *Relic neutralino densities and detection rates with nonuniversal gaugino masses*, *Phys. Rev.* **D 67** (2003) 095006 [`hep-ph/0211071`].

[21] Y. Mambrini and E. Nezri, *Dark matter and colliders searches in the MSSM*, `hep-ph/0507263`;
H. Baer, T. Krupovnickas, S. Profumo and P. Ullio, *Model independent approach to focus point supersymmetry: from dark matter to collider searches*, *JHEP* **10** (2005) 020 [`hep-ph/0507282`];
H. Baer, A. Mustafayev, E.-K. Park, S. Profumo and X. Tata, *Mixed higgsino dark matter from a reduced* SU(3) *gaugino mass: consequences for dark matter and collider searches*, *JHEP* **04** (2006) 041 [`hep-ph/0603197`];
H. Baer et al. in ref. [12].

[22] P. Ullio, *Astropart. Phys.* 21 (2004) 267;
A. Bottino, F. Donato, N. Fornengo and S. Scopel, *Indirect signals from light neutralinos in supersymmetric models without gaugino mass unification*, *Phys. Rev.* **D 70** (2004) 015005 [`hep-ph/0401186`];
Y. Mambrini and C. Muñoz, *A comparison between direct and indirect dark matter search*, *JCAP* **10** (2004) 003 [`hep-ph/0407352`];
Y. Mambrini and C. Munoz, *Astropart. Phys.* 24 (2005) 208.

[23] CDMS collaboration, D.S. Akerib et al., *New results from the cryogenic dark matter search experiment*, *Phys. Rev.* **D 68** (2003) 082002 [`hep-ex/0306001`].

[24] A. Benoit et al., *Improved exclusion limits from the edelweiss wimp search*, *Phys. Lett.* **B 545** (2002) 43 [`astro-ph/0206271`].

[25] A. Morales, *Searching for wimp dark matter: the case for germanium ionization detectors*, `hep-ex/0111089`.

[26] M. Blennow and T. Ohlsson, *Exact series solution to the two flavor neutrino oscillation problem in matter*, *J. Math. Phys.* **45** (2004) 4053 [`hep-ph/0405033`].

[27] N. Gehrels and P. Michelson, *Astropart. Phys.* 11 (1999) 277.

[28] A. Djouadi, J.-L. Kneur and G. Moultaka, *Suspect: a fortran code for the supersymmetric and Higgs particle spectrum in the MSSM*, `hep-ph/0211331`;
see also the web page `http://www.lpta.univ-montp2.fr/kneur/Suspect`.

[29] A. Djouadi, M. Drees and J.L. Kneur, *Constraints on the minimal supergravity model and prospects for SUSY particle production at future linear* e^+e^- *colliders*, *JHEP* **08** (2001) 055 [`hep-ph/0107316`]; *Neutralino dark matter in msugra: reopening the light Higgs pole window*, *Phys. Lett.* **B 624** (2005) 60 [`hep-ph/0504090`]; *Updated constraints on the minimal supergravity model*, *JHEP* **03** (2006) 033 [`hep-ph/0602001`].

[30] PARTICLE DATA GROUP, W. M. Yao et al., *J. Phys.* **G 33** (2006) 1;
S. Eidelman et al., *Phys. Lett.* **B 592** (2004) 1.

[31] CDF collaboration, D. Acosta et al., *Search for $b_s^0 \to \mu^+\mu^-$ and $b_d^0 \to \mu^+\mu^-$ decays in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV*, *Phys. Rev. Lett.* **93** (2004) 032001 [hep-ex/0403032];
D0 collaboration, V.M. Abazov et al., *A search for the flavor-changing neutral current decay $b_s^0 \to \mu^+\mu^-$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV with the dø detector*, *Phys. Rev. Lett.* **94** (2005) 071802 [hep-ex/0410039].

[32] S. Baek, D.G. Cerdeno, Y.G. Kim, P. Ko and C. Muñoz, *Direct detection of neutralino dark matter in supergravity*, *JHEP* **06** (2005) 017 [hep-ph/0505019].

[33] G. Belanger, F. Boudjema, A. Pukhov and A. Semenov, *MicrOmegas: a program for calculating the relic density in the MSSM*, *Comput. Phys. Commun.* **149** (2002) 103 [hep-ph/0112278]; *MicrOmegas2.0: a program to calculate the relic density of dark matter in a generic model*, hep-ph/0607059.

[34] P. Gondolo et al., *DarkSUSY: computing supersymmetric dark matter properties numerically*, *JCAP* **07** (2004) 008 [astro-ph/0406204];
see also the web page http://www.physto.se/~edsjo/darksusy.

[35] A. Bottino, F. Donato, N. Fornengo and S. Scopel, *Do current wimp direct measurements constrain light relic neutralinos?*, *Phys. Rev.* **D 72** (2005) 083521 [hep-ph/0508270].

[36] J.R. Ellis, K.A. Olive, Y. Santoso and V.C. Spanos, *Update on the direct detection of supersymmetric dark matter*, *Phys. Rev.* **D 71** (2005) 095007 [hep-ph/0502001].

[37] M. Spira, A. Djouadi, D. Graudenz and P.M. Zerwas, *Higgs boson production at the LHC*, *Nucl. Phys.* **B 453** (1995) 17 [hep-ph/9504378];
A. Djouadi, J. Kalinowski and P.M. Zerwas, *Two- and three-body decay modes of SUSY Higgs particles*, *Z. Physik* **C 70** (1996) 435 [hep-ph/9511342];
A. Djouadi and M. Drees, *QCD corrections to neutralino nucleon scattering*, *Phys. Lett.* **B 484** (2000) 183 [hep-ph/0004205].

[38] J.F. Navarro, C.S. Frenk and S.D.M. White, *The structure of cold dark matter halos*, *Astrophys. J.* **462** (1996) 563 [astro-ph/9508025].

[39] G. Zaharijas and D. Hooper, *Challenges in detecting gamma-rays from dark matter annihilations in the galactic center*, *Phys. Rev.* **D 73** (2006) 103501 [astro-ph/0603540].

[40] B. Moore et al., *Mon. Not. Roy. Astron. Soc.* **310** (1999) 1147.

[41] D0 collaboration, V.M. Abazov et al., *Search for neutral Higgs bosons decaying to tau pairs in $p\bar{p}$ collisions at $\sqrt{s} = 1.9$ 6-tev*, *Phys. Rev. Lett.* **97** (2006) 121802 [hep-ex/0605009];
CDF collaboration, A. Abulencia et al., *Search for neutral MSSM Higgs bosons decaying to tau pairs in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV*, *Phys. Rev. Lett.* **96** (2006) 011802 [hep-ex/0508051].

[42] M. Carena, D. Hooper and P. Skands, *Implications of direct dark matter searches for MSSM Higgs searches at the Tevatron*, *Phys. Rev. Lett.* **97** (2006) 051801 [hep-ph/0603180].

[43] A. Datta, A. Djouadi, M. Guchait and F. Moortgat, *Detection of MSSM Higgs bosons from supersymmetric particle cascade decays at the LHC*, *Nucl. Phys.* **B 681** (2004) 31 [hep-ph/0303095].