PHYSICAL REVIEW D **85,** 095013 (2012)

Phenomenology of light neutralinos in view of recent results at the CERN Large Hadron Collider

A. Bottino,[1] N. Fornengo,[1] and S. Scopel[2]

[1]*Dipartimento di Fisica Teorica, Università di Torino Istituto Nazionale di Fisica Nucleare, Sezione di Torino via P. Giuria 1, I-10125 Torino, Italy*

[2]*Department of Physics, Sogang University Seoul, 121-742, Korea*

(Received 11 January 2012; published 17 May 2012)

We review the status of the phenomenology of light neutralinos in an effective minimal supersymmetric extension of the standard model at the electroweak scale, in light of new results obtained at the CERN Large Hadron Collider. First, we consider the impact of the new data obtained by the CMS Collaboration on the search for the Higgs-boson decay into a tau pair, and by the CMS and LHCb Collaborations on the branching ratio for the decay $B_s \to \mu^+ + \mu^-$. Then, we examine the possible implications of the excess of events found by the ATLAS and CMS Collaborations in a search for a standard-model (SM)-like Higgs boson around a mass of 126 GeV, with a most likely mass region (95% C.L.) restricted to 115.5–131 GeV (global statistical significance about 2.3σ). From the first set of data, we update the lower bound of the neutralino mass to be about 18 GeV. From the second set of measurements, we derive that the excess around $m_H^{\rm SM} = 126$ GeV, which however needs a confirmation by further runs at the LHC, would imply a neutralino in the mass range 18 GeV $\lesssim m_\chi \lesssim$ 38 GeV, with neutralino-nucleon elastic cross sections fitting well the results of the dark matter direct search experiments DAMA/LIBRA and CRESST.

DOI: 10.1103/PhysRevD.85.095013 PACS numbers: 95.35.+d, 11.30.Pb, 12.60.Jv, 95.30.Cq

I. INTRODUCTION

The phenomenology of light neutralinos has been thoroughly discussed in Refs. [1–3] within an effective minimal supersymmetric extension of the standard model (MSSM) at the electroweak scale, where the usual hypothesis of gaugino-mass universality at the scale of grand unified theory of the supergravity models is removed (this model containing neutralinos of mass $m_\chi \lesssim 50$ GeV was dubbed light neutralino model (LNM) [3]); this denomination will also be maintained here.

In Refs. [1–3], it was shown that, in case of R-parity conservation, a light neutralino within the LNM, when it happens to be the lightest supersymmetric particle, constitutes an extremely interesting candidate for the dark matter in the Universe, with direct detection rates accessible to experiments of present generation. More specifically, the following results were obtained: (a) a lower bound on m_χ was derived from the cosmological upper limit on the cold dark matter density; (b) it was shown that the population of light neutralinos fits quite well the DAMA/LIBRA annual modulation results [4,5] over a wide range of m_χ; (c) this same population can explain also results of other direct searches for dark matter (DM) particles which show positive results (CoGeNT [6], CRESST [7]) or possible hints (two-event CDMS [8]) in some restricted intervals of m_χ [3,9,10].

It is obvious that the features of the light neutralino population, and its relevant properties (a–c), drastically depend on the intervening constraints which follow from new experimental results. Of particular impact over the details of the phenomenological aspects of the LNM are the new data obtained at the CERN Large Hadron Collider which, in force of its spectacular performance, is providing a profusion of new information. In this respect, the most relevant results of LHC concern: (i) the lower bounds on the squark and gluino masses, (ii) the correlated bounds on $\tan\beta$ (ratio of the two Higgs vacuum expectation values) and m_A (mass of the CP-odd neutral Higgs boson) derived from the searches for neutral Higgs bosons into a tau-lepton pair, (iii) a new strict upper bound on the branching ratio (BR) for the decay $B_s \to \mu^+ + \mu^-$, (iv) the indication of a possible signal (at a statistical significance of 2.3σ) for a SM-like Higgs boson with a mass of about 126 GeV [11,12].

The impact of item (i) on the LNM was already considered in Ref. [13]. In the present paper, we derive the consequences that the new bounds from searches for neutral Higgs bosons into a tau-lepton pair and from BR($B_s \to \mu^+ + \mu^-$) [items (ii) and (iii) above] have on the phenomenology of the light neutralinos and discuss the implications that a Higgs boson at about 126 GeV [item (iv)] could have, in case this preliminary experimental indication is confirmed in future LHC runs.

II. FEATURES OF THE LIGHT NEUTRALINO MODEL

The LNM is an effective MSSM scheme at the electroweak scale, with the following independent parameters: M_1, M_2, M_3, μ, $\tan\beta$, m_A, $m_{\tilde{q}_{12}}$, $m_{\tilde{t}}$, $m_{\tilde{l}_{12,L}}$, $m_{\tilde{l}_{12,R}}$, $m_{\tilde{\tau}_L}$, $m_{\tilde{\tau}_R}$, and A. We stress that the parameters are defined at the electroweak scale. Notations are as follows: M_1, M_2, and M_3 are the U(1), SU(2), and SU(3) gaugino masses (these parameters are taken here to be positive), μ is the Higgs mixing mass parameter, $\tan\beta$ the ratio of the two Higgs vacuum expectation values, m_A the mass of the CP-odd neutral Higgs boson, $m_{\tilde{q}_{12}}$ is a squark soft mass common to the squarks of the first two families, $m_{\tilde{t}}$ is the squark soft mass for the third family, $m_{\tilde{l}_{12,L}}$ and $m_{\tilde{l}_{12,R}}$ are the slepton soft mass common to the L, R components of the sleptons of the first two families, $m_{\tilde{\tau}_L}$ and $m_{\tilde{\tau}_R}$ are the slepton soft mass of the L, R components of the slepton of the third family, A is a common dimensionless trilinear parameter for the third family, $A_{\tilde{b}} = A_{\tilde{t}} \equiv A m_{\tilde{t}}$ and $A_{\tilde{\tau}} \equiv A(m_{\tilde{\tau}_L} + m_{\tilde{\tau}_R})/2$ (the trilinear parameters for the other families being set equal to zero). In our model, no gaugino-mass unification at a grand unified scale is assumed, and therefore M_1 can be sizably lighter than M_2. Notice that the present version of the LNM represents an extension of the model discussed in our previous papers [1–3], where a common squark and the slepton soft mass was employed for the 3 families.

The linear superposition of bino $\tilde{B}$, wino $\tilde{W}^{(3)}$, and of the two Higgsino states $\tilde{H}_1^o$, $\tilde{H}_2^o$ which defines the neutralino state of lowest mass m_χ is written here as

$$\chi \equiv a_1\tilde{B} + a_2\tilde{W}^{(3)} + a_3\tilde{H}_1^o + a_4\tilde{H}_2^o. \quad (1)$$

A. The cosmological bound

Since no gaugino-mass unification at a grand unified theory scale is assumed in our LNM (at variance with one of the major assumptions in minimal supergravity), in this model the neutralino mass is not bounded by the lower limit $m_\chi \gtrsim 50$ GeV that is commonly derived in minimal-supergravity schemes from the LEP lower bound on the chargino mass (of about 100 GeV). However, in the case of R-parity conservation the neutralino, when occurs to be the lightest supersymmetric particle, has a lower limit on its mass m_χ which can be derived from the cosmological upper bound on the cold dark matter (CDM) relic abundance $\Omega_{\rm CDM}h^2$. Actually, by employing this procedure, in Ref. [1] a value of 6–7 GeV for the lower limit of m_χ was obtained, and this value was subsequently updated to the value of about 8 GeV in Refs. [3,10] as derived from the experimental data available at that time. Now, with the advent of fresh data from LHC, the lower bound on m_χ has to be redetermined; this will be done in Sec. III A.

To set the general framework, let us recall that the neutralino relic abundance is given by

$$\Omega_\chi h^2 = \frac{x_f}{g_\star(x_f)^{1/2}} \frac{9.9\cdot 10^{-28}\ \mathrm{cm}^3\,\mathrm{s}^{-1}}{\widetilde{\langle\sigma_{\rm ann}v\rangle}}, \quad (2)$$

where $\widetilde{\langle\sigma_{\rm ann}v\rangle} \equiv x_f\langle\sigma_{\rm ann}v\rangle_{\rm int}$, $\langle\sigma_{\rm ann}v\rangle_{\rm int}$ being the integral from the present temperature up to the freeze-out temperature T_f of the thermally averaged product of the annihilation cross section times the relative velocity of a pair of neutralinos, x_f is defined as $x_f \equiv m_\chi/T_f$, and $g_\star(x_f)$ denotes the relativistic degrees of freedom of the thermodynamic bath at x_f. For $\widetilde{\langle\sigma_{\rm ann}v\rangle}$, we will use the standard expansion in S and P waves: $\widetilde{\langle\sigma_{\rm ann}v\rangle} \simeq \tilde{a} + \tilde{b}/(2x_f)$. Notice that in the LNM no coannihilation effects are present in the calculation of the relic abundance, due to the large mass splitting between the mass of the neutralino ($m_\chi < 50$ GeV) and those of sfermions and charginos.

The annihilation processes which contribute to $\widetilde{\langle\sigma_{\rm ann}v\rangle}$ at the lowest order are: (i) exchange of a Higgs boson in the s channel, (ii) exchange of a sfermion in the t channel, (iii) exchange of the Z boson in the s channel. In the physical region which we are going to investigate, which entails light values for the masses of supersymmetric Higgs bosons m_h, m_A, m_H (for the lighter CP-even h, the CP-odd A, and the heavier CP-even H, respectively) and a light mass for the stau $\tilde{\tau}$, the contribution of the Z exchange is largely subdominant compared to the first two which can be of the same order, with a dominance of the$A$-exchange contribution for $m_\chi \lesssim 28$ GeV, and a possible dominance of the $\tilde{\tau}$ exchange afterward (see numerical results in Fig. 3).

In our numerical evaluations, all relevant contributions to the pair annihilation cross section of light neutralinos are included. However, an approximate expression for $\Omega_\chi h^2$, valid for very light neutralinos, proves very useful to obtain an analytic formula for the lower bound for the neutralino mass. Indeed, for $m_\chi \lesssim 28$ GeV when $\widetilde{\langle\sigma_{\rm ann}v\rangle}$ is dominated by the A exchange, $\Omega_\chi h^2$ may be written as [1]

$$\Omega_\chi h^2 \simeq \frac{4.8\cdot 10^{-6}}{\mathrm{GeV}^2}\frac{x_f}{g_\star(x_f)^{1/2}}\frac{1}{a_1^2a_3^2\tan^2\beta} \times m_A^4\frac{[1-(2m_\chi)^2/m_A^2]^2}{m_\chi^2[1-m_b^2/m_\chi^2]^{1/2}}\frac{1}{(1+\epsilon_b)^2}, \quad (3)$$

where ϵ_b is a quantity which enters in the relationship between the b-quark running mass and the corresponding Yukawa coupling (see Ref. [14] and references quoted therein). For neutralino masses in the range $m_\chi =$ (10–20) GeV, $g_\star(x_f)^{1/2} \simeq 2.5$. In deriving this expression, one has taken into account that here the following hierarchy holds for the coefficients a_i of χ [3]:

$$|a_1| > |a_3| \gg |a_2|, |a_4|, \quad (4)$$

whenever $\mu/m_\chi \gtrsim$ a few. In Ref. [3], it is also shown that in this regime

$$a_1^2a_3^2 \simeq \frac{\sin^2\theta_W m_Z^2\mu^2}{(\mu^2+\sin^2\theta_W m_Z^2)^2} \simeq \frac{0.19\mu_{100}^2}{(\mu_{100}^2+0.19)^2}, \quad (5)$$

where μ_{100} is μ in units of 100 GeV. From this formula and the LEP lower bound $|\mu| \gtrsim 100$ GeV, we obtain $(a_1^2a_3^2)_{\max} \lesssim 0.13$. This upper bound is essentially equivalent to one which can be derived from the upper bound on the width for the Z-boson decay into a light neutralino pair: $(a_1^2 a_3^2)_{\max} \lesssim 0.12$ [3].

By imposing that the neutralino relic abundance does not exceed the observed upper bound for CDM, i.e., $\Omega_\chi h^2 \leq (\Omega_{\mathrm{CDM}} h^2)_{\max}$, we obtain the following lower bound on the neutralino mass:

$$m_\chi \frac{[1 - m_b^2/m_\chi^2]^{1/4}}{[1-(2m_\chi)^2/m_A^2]} \gtrsim 17\,\mathrm{GeV}\left(\frac{m_A}{90\,\mathrm{GeV}}\right)^2\left(\frac{15}{\tan\beta}\right) \times \left(\frac{0.12}{a_1^2 a_3^2}\right)^{(1/2)}\left(\frac{0.12}{(\Omega_{\mathrm{CDM}} h^2)_{\max}}\right)^{(1/2)}. \tag{6}$$

Here, we have taken as default value for $(\Omega_{\mathrm{CDM}} h^2)_{\max}$ the numerical value which represents the 2σ upper bound to $(\Omega_{\mathrm{CDM}} h^2)_{\max}$ derived from the results of Ref. [15]. For ϵ_b, we have used a value which is representative of the typical range obtained numerically in our model: $\epsilon_b = -0.08$.

B. Neutralino-nucleon elastic cross section

We turn now to the evaluation of the neutralino-nucleon elastic cross section $\sigma_{\mathrm{scalar}}^{(\mathrm{nucleon})}$, since we are interest here in the comparison of our theoretical evaluations with the most recent data from experiments of direct searches for DM particles.

Notice that we consider here only coherent neutralino-nucleus cross sections, thus spin-dependent couplings are disregarded, and the neutralino-nucleon cross sections are derived from the coherent neutralino-nucleus cross section in the standard way.

The neutralino-nucleon scattering then takes contributions from (h, A, H) Higgs-boson exchange in the t channel and from the squark exchange in the s channel; the A-exchange contribution is suppressed by kinematic effects. In the supersymmetric parameter region considered in the present paper, the contributions from the h and H exchanges are largely dominant over the squark exchange, with a sizable dominance of the h exchange over the H one (a quantitative analysis of this point will be given in Sec. III A in connection with Fig. 4). An approximate expression for $\sigma_{\mathrm{scalar}}^{(\mathrm{nucleon})}$, valid at small values of m_χ, is obtained by including only the dominant contribution of the h-boson exchange [3]:

$$\sigma_{\mathrm{scalar}}^{(\mathrm{nucleon})} \simeq 9.7 \times 10^{-42}\ \mathrm{cm}^2\left(\frac{a_1^2 a_3^2}{0.13}\right)\left(\frac{\tan\beta}{15}\right)^2 \times \left(\frac{90\ \mathrm{GeV}}{m_h}\right)^4\left(\frac{g_d}{290\ \mathrm{MeV}}\right)^2, \tag{7}$$

where

$$g_d \equiv [m_d\langle N|\bar{d}d|N\rangle + m_s\langle N|\bar{s}s|N\rangle + m_b\langle N|\bar{b}b|N\rangle], \tag{8}$$

and the matrix elements $\langle N|\bar{q}q|N\rangle$ denote the scalar quark densities of the d, s, b quarks inside the nucleon.

In Eq. (7), we have used as *reference* value for g_d the value $g_{d,\mathrm{ref}} = 290$ MeV employed in our previous papers [2,3]. We recall that this quantity is affected by large uncertainties [16] with $(g_{d,\max}/g_{d,\mathrm{ref}})^2 = 3.0$ and $(g_{d,\min}/g_{d,\mathrm{ref}})^2 = 0.12$ [2,3]. Notice that these uncertainties still persist [17,18]. Our reference value $g_{d,\mathrm{ref}} = 290$ MeV is larger by a factor 1.5 than the central value of Ref. [19], frequently used in the literature.

By employing Eqs. (3) and (7) we find that any neutralino configuration, *whose relic abundance stays in the cosmological range for CDM* [i.e., $(\Omega_{\mathrm{CDM}} h^2)_{\min} \leq \Omega_\chi h^2 \leq (\Omega_{\mathrm{CDM}} h^2)_{\max}$ with $(\Omega_{\mathrm{CDM}} h^2)_{\min} = 0.098$ and $(\Omega_{\mathrm{CDM}} h^2)_{\max} = 0.12$] and passes all particle-physics constraints, has an elastic neutralino-nucleon cross section given approximately by [3]

$$\sigma_{\mathrm{scalar}}^{(\mathrm{nucleon})} \simeq (2.7 - 3.4) \times 10^{-41}\ \mathrm{cm}^2\left(\frac{g_d}{290\ \mathrm{MeV}}\right)^2\left(\frac{m_A}{m_h}\right)^4 \times \frac{[1-(2m_\chi)^2/m_A^2]^2}{(m_\chi/(10\ \mathrm{GeV})^2[1-m_b^2/m_\chi^2]^{1/2}}. \tag{9}$$

Notice that in the range 90 GeV $\leq m_A \leq$ 120 GeV the maximal values of the ratio m_A/m_h are of order one within a few percent (see left panel of Fig. 2).

We recall that for neutralino configurations whose relic abundance stays below the cosmological range for CDM, i.e., have $\Omega_\chi h^2 < (\Omega_{\mathrm{CDM}} h^2)_{\min}$, one has to associate to $\sigma_{\mathrm{scalar}}^{(\mathrm{nucleon})}$ a local density rescaled by a factor $\xi = \rho_\chi/\rho_0$, as compared to the total local DM density ρ_χ; ξ is conveniently taken as $\xi = \min\{1, \Omega_\chi h^2/(\Omega_{\mathrm{CDM}} h^2)_{\min}\}$ [20].

Furthermore, we note that Eq. (9) is valid when the A-boson exchange is dominating in the neutralino pair annihilation process (in the s channel). As mentioned above, this occurs for $m_\chi \lesssim 28$ GeV. For higher neutralino masses, the actual values of $\sigma_{\mathrm{scalar}}^{(\mathrm{nucleon})}$ are somewhat higher than those provided by Eq. (9).

C. Constraints

To single out the physical supersymmetric configurations within our LNM, the following experimental constraints are imposed: accelerators data on supersymmetric and Higgs boson searches at the CERN e^+e^- collider LEP2 [21]; the upper bound on the invisible width for the decay of the Z boson into non-standard-model particles: $\Gamma(Z \to \chi\chi) < 3$ MeV [22,23]; measurements of the $b \to s + \gamma$ decay process [24]: $2.89 \leq \mathrm{BR}(b \to s\gamma) \cdot 10^4 \leq 4.21$ is employed here (this interval is larger by 25% with respect to the experimental determination [24] in order to take into account theoretical uncertainties in the supersymmetric contributions [25] to the branching ratio of the process (for the standard model calculation, we employ the next-to-next-to-leading-order results from Ref. [26]); the measurements of the muon anomalous magnetic moment $a_\mu \equiv (g_\mu - 2)/2$: for the deviation,

$\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm the}$, of the experimental world average from the theoretical evaluation within the standard model, we use here the (2σ) range $31 \le \Delta a_\mu \cdot 10^{11} \le 479$, derived from the latest experimental [27] and theoretical [28] data (the supersymmetric contributions to the muon anomalous magnetic moment within the MSSM are evaluated here by using the formulas in Ref. [29]); the search for charged Higgs bosons in top quark decay at the Tevatron [30]; the recently improved upper bound (at 95% C.L.) on the branching ratio for the decay $B_s \to \mu^+ + \mu^-$: $\mathrm{BR}(B_s \to \mu^+\mu^-) < 1.08 \times 10^{-8}$ [31] (see also Refs. [32,33]) and the constraints related to $\Delta M_{B,s} \equiv M_{B_s} - M_{\bar{B}_s}$ [34,35].

A further bound, which plays a most relevant role in constraining the supersymmetric parameter space, is represented by the results of searches for Higgs decay into a tau pair. Indeed, colliders have a good sensitivity to the search for decays ($\phi \to b\bar{b}$ or $\phi \to \tau\bar{\tau}$) (where $\phi = h, A, H$) in the regime of small m_A and large $\tan\beta$, because in this region of the supersymmetric parameters the couplings of one of the neutral Higgs bosons to the down fermions are enhanced [36]. This experimental investigation was thoroughly carried out at the Tevatron and is now underway at the LHC. No signal for these decays has been found so far, thus successive measurements have progressively disallowed substantial regions in the supersymmetric parameters space at small m_A and large $\tan\beta$.

However, at present the actual forbidden region is not yet firmly established. The most stringent bounds provided in the $m_A - \tan\beta$ plane are reported by the CMS Collaboration in a preliminary form in Refs. [37,38]. The first report refers to a luminosity of 1.6 fb^{-1}, the second one to a luminosity of 4.6 fb^{-1}. It is worth noting that, in the range 90 GeV $\le m_\chi \le$ 120 GeV, the bound on $\tan\beta$ given in the second report is less stringent than the limit given in the first one by a factor of (20–40)%. This circumstance suggests to take the present constraints with much caution. A conservative attitude is also suggested by the considerations put forward in Refs. [39,40] about the actual role of uncertainties in the derivation of the present bounds.

In Fig. 1, which displays the plane $m_A - \tan\beta$, we summarize the present situation as far as the constraints from the collider searches for the neutral Higgs decays into a tau pair are concerned. The dash-dotted line denotes the 95% C.L. upper bound reported in Ref. [38], accounting for a $+1\sigma$ theoretical uncertainty. The dashed line displays the expected upper bound (in case of no positive signal for an integrated luminosity of 3 fb^{-1}) as evaluated in Refs. [39,40]. We do not mean to attribute to this expected bound the meaning of the most realistic upper limit; we just take it as indicative of a conservative estimate of the bound, and thus as a reasonable upper extreme of the physical range to consider in our scan of the parameter space.

Notice that the regime of small $\tan\beta$ values is also compatible with one of the physical regions selected by the branching ratio $\mathrm{BR}(B \to \tau + \nu)$ (see Fig. 16 of Ref. [3]).

Also shown in Fig. 1 are the curves which correspond to a fixed value of m_χ; these are calculated from Eq. (6) by replacing the inequality with an equality symbol and setting, for definiteness, to 1 the two last factors of the right-hand side. Thus, for configurations with different values of $(a_1^2 a_3^2)^{1/2}$, the m_χ value associated to each isomass curve has to be scaled up by the factor $(a_1^2 a_3^2/0.12)^{1/2}$. The features of the scatter plot displayed in Fig. 1 and its implications will be discussed in the next section.

We recall that also the cosmological constraint $\Omega_\chi h^2 \le (\Omega_{\rm CDM} h^2)_{\rm max}$, discussed in Sec. II A, is implemented in our analysis.

The viability of very light neutralinos in terms of various constraints from collider data, precision observables, and rare meson decays is also considered in Ref. [41]. Perspectives for investigation of these neutralinos at LHC are analyzed in Refs. [42,43] and prospects for a very accurate mass measurement at ILC in Refs. [44].

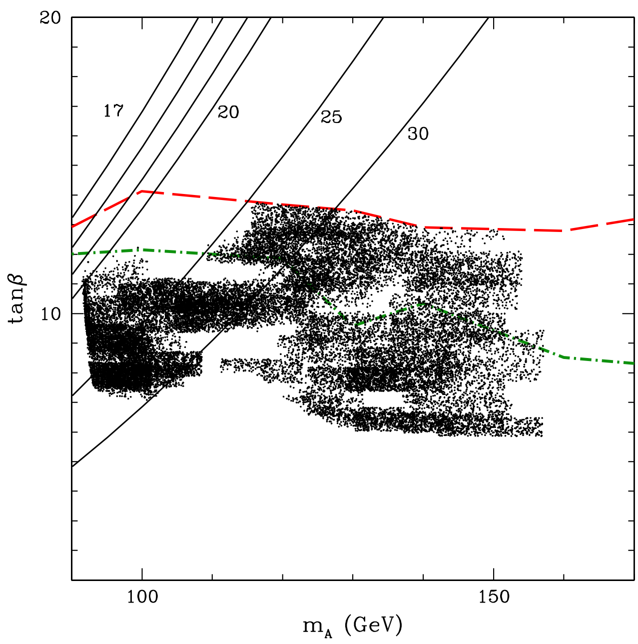

FIG. 1 (color online). Upper bounds in the $m_A - \tan\beta$ plane, derived from searches of the neutral Higgs decays into a tau pair at the LHC. The dash-dotted line denotes the 95% C.L. upper bound reported in Ref. [38]. The dashed line displays the expected upper bound (in case of no positive signal for an integrated luminosity of 3 fb^{-1}) as evaluated in Refs. [39,40]. The scatter plot denotes configurations of the LNM. The solid lines (some of which are labeled by numbers) denote the cosmological bound $\Omega_\chi h^2 \le (\Omega_{\rm CDM} h^2)_{\rm max}$ for a neutralino whose mass is given by the corresponding number (in units of GeV), as obtained by Eq. (6), with $\epsilon_b = -0.08$ and $(\Omega_{\rm CDM} h^2)_{\rm max} = 0.12$. For any given neutralino mass, the allowed region is above the corresponding line.