MSSM Dark Matter in Light of Higgs and LUX Results

W. Abdallah\textsuperscript{1,2} and S. Khalil\textsuperscript{1}

\textsuperscript{1}Center for Fundamental Physics, Zewail City of Science and Technology, 6th of October City, Giza 12588, Egypt
\textsuperscript{2}Department of Mathematics, Faculty of Science, Cairo University, Giza 12613, Egypt

Correspondence should be addressed to W. Abdallah; wabdallah@zewailcity.edu.eg

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The constraints imposed on the Minimal Supersymmetric Standard Model (MSSM) parameter space by the Large Hadron Collider (LHC) Higgs mass limit and gluino mass lower bound are revisited. We also analyze the thermal relic abundance of lightest neutralino, which is the Lightest Supersymmetric Particle (LSP). We show that the combined LHC and relic abundance constraints rule out most of the MSSM parameter space except a very narrow region with very large $\tan \beta$ ($\sim 50$). Within this region, we emphasize that the spin-independent scattering cross section of the LSP with a proton is less than the latest Large Underground Xenon (LUX) limit by at least two orders of magnitude. Finally, we argue that nonthermal Dark Matter (DM) scenario may relax the constraints imposed on the MSSM parameter space. Namely, the following regions are obtained: $m_0 \approx \mathcal{O}(4)$ TeV and $m_{1/2} \approx 600$ GeV for low $\tan \beta$ ($\sim 10$); $m_0 \sim m_{1/2} \approx \mathcal{O}(1)$ TeV or $m_0 \approx \mathcal{O}(4)$ TeV and $m_{1/2} \approx 700$ GeV for large $\tan \beta$ ($\sim 50$).

1. Introduction

The most recent observations by the Planck satellite confirmed that 26.8\% of the universe content is in the form of DM and the usual visible matter only accounts for 5\% [1]. The LSP remains one of the best candidates for the DM [2, 3]. It is a Weakly Interacting Massive Particle (WIMP) that can naturally account for the observed relic density of DM.

Despite the absence of direct experimental verification, Supersymmetry (SUSY) is still the most promising candidate for a unified theory beyond the Standard Model (SM). SUSY is a generalization of the space-time symmetries of the quantum field theory that links the matter particles (quarks and leptons) with the force-carrying particles and implies that there are additional “superparticles” necessary to complete the symmetry. In this regard, SUSY solves the problem of the quadratic divergence in the Higgs sector of the SM in a very elegant natural way. The most simple supersymmetric extension of the SM, which is the most widely studied, is known as the MSSM [4–11]. In this model, certain universality of soft SUSY breaking terms is assumed at grand unification scale. Therefore, the SUSY spectrum is determined by the following four parameters: universal scalar mass $m_0$, universal gaugino mass $m_{1/2}$, universal trilinear coupling $A_0$, and the ratio of the vacuum expectation values of Higgs bosons $\tan \beta$. In addition, due to $R$-parity conservation, SUSY particles are produced or destroyed only in pairs and therefore the LSP is absolutely stable, implying that it might constitute a possible candidate for DM, as first suggested by Goldberg in 1983 [12]. So although the original motivation of SUSY has nothing to do with the DM problem, it turns out that it provides a stable neutral particle and, hence, a candidate for solving the DM problem.

The landmark discovery of the SM-like Higgs boson at the LHC, with mass $\sim 125$ GeV [13, 14], might be an indication for the presence of SUSY. Indeed, the MSSM predicts that there is an upper bound of 130 GeV on the Higgs mass. However, this mass of lightest Higgs boson implies that the SUSY particles are quite heavy. This may justify the negative searches for SUSY at the LHC run-1 [15–18]. However, it is clearly generating a new “little hierarchy problem.”

Moreover, the relic density data [1] and upper limits on the DM scattering cross sections on nuclei (LUX [19] and other direct detection experiments [20, 21]) impose stringent constraints on the parameter space of the MSSM [22–25]. In fact, combining the collider, astrophysics, and rare decay
constraints [26–36] almost rules out the MSSM. It is tempting therefore to explore well motivated extensions of the MSSM, such as NMSSM [37, 38] and BLSM [39, 40], which may alleviate the little hierarchy problem of the MSSM through additional contributions to Higgs mass [37, 38, 41] and also provide new DM candidates [42–45] that may account for the relic density with no conflict with other phenomenological constraints.

In this paper, we analyze the constraints imposed by the Higgs mass limit and the gluino lower bound, which are the most stringent collider constraints, on the constrained MSSM (minimal SUGRA model, hereafter referred to as MSSM) parameter space. In particular, these constraints imply that the gaugino mass, $m_{1/2}$, resides within the mass range: 620 GeV $\leq m_{1/2} \leq$ 2000 GeV, while the other parameters are much less constrained. We study the effect of the measured DM relic density on the MSSM allowed parameter space. We also investigate the direct detection rate of the LSP at these allowed points in light of the latest LUX result. Finally, we show that if one assumes nonstandard scenario of cosmology with low reheating temperature, where the LSP may reach equilibrium before the reheating time, then the relic abundance constraints on $(m_0, m_{1/2})$ can be significantly relaxed.

The paper is organized as follows. In Section 2, we briefly introduce the MSSM and study the constraints on $(m_0, m_{1/2})$ plane from Higgs and gluino mass experimental limits. In Section 3, we study the thermal relic abundance of the LSP in the allowed region of parameter space. We show that the combined LHC and relic abundance constraints rule out most of the parameter space except the case of very large $\tan \beta$. We also provide the expected rate of direct LSP detection at these points with large $\tan \beta$ and TeV masses. Section 4 is devoted to nonthermal scenario of DM and how it can relax the constraints imposed on MSSM parameter space. Finally, we give our conclusions in Section 5.

2. MSSM after the LHC Run-I

The particle content of the MSSM is three generations of (chiral) quark superfields; the (vector) superfields are necessary to gauge $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge of the SM, and two (chiral) $SU(2)$ doublet Higgs superfields. The introduction of a second Higgs doublet is necessary in order to cancel the anomalies produced by the fermionic members of the first Higgs superfield and also to give masses to both up and down type quarks. The interactions between Higgs and matter superfields are described by the superpotential

$$W = h_Q Q^c U H_2 + h_Q Q^c D H_1 + h_Q L^c E H_1 + \mu H_1 H_2.$$  

Here, $Q_L$ contains $SU(2)$ (s) quark doublet and $U^c_L$, $D^c_L$ are the corresponding singlets, $s$ lepton doublets and singlets reside in $L_L$ and $E^c_L$, respectively. $H_1$ and $H_2$ denote Higgs superfields with hypercharge $Y = \pm 1/2$. Further, due to the fact that Higgs and lepton doublet superfields have the same

SU(3)$_C \times SU(2)_L \times U(1)_Y$ quantum numbers, we have additional terms that can be written as

$$W' = \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q^c_j D^c_k + \lambda''_{ijk} U^c_i D^c_j U^c_k + \mu_i L_i H_2.$$  

These terms violate baryon and lepton number explicitly and lead to proton decay at unacceptable rates. To forbid these terms, a new symmetry, called $R$-parity, is introduced, which is defined as $R_p = (-1)^{3Q_L + 2L}$, where $B$ and $L$ are baryon and lepton number and $S$ is the spin. There are two remarkable phenomenological implications of the presence of $R$-parity: (i) SUSY particles are produced or destroyed only in pair; (ii) the LSP is absolutely stable and, hence, it might constitute a possible candidate for DM.

In the MSSM, a certain universality of soft SUSY breaking terms at grand unification scale $M_X = 3 \times 10^{16}$ GeV is assumed. These terms are defined as $m_0$, the universal scalar soft mass, $m_{1/2}$, the universal gaugino mass, $A_0$, the universal trilinear coupling, $B$, and the bilinear coupling (the soft mixing between the Higgs scalars). In order to discuss the physical implication of soft SUSY breaking at low energy, we need to renormalize these parameters from $M_X$ down to electroweak scale, which has been performed using SARAH [46], and the spectrum has been calculated using SPheno [47, 48]. In addition, the MSSM contains another two free SUSY parameters: $\mu$ and $\tan \beta = \langle H_2 \rangle / \langle H_1 \rangle$. Two of these free parameters, $\mu$ and $B$, can be determined by the electroweak breaking conditions:

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

$$\sin 2\beta = \frac{2m_0^2}{m_1^2 + m_2^2}. $$

Thus, the MSSM has only four independent free parameters, $m_0, m_{1/2}, A_0, \tan \beta$, besides the sign of $\mu$, which determine the whole spectrum.

In the MSSM, the mass of the lightest Higgs state can be approximated, at the one-loop level, as [49–52]

$$m_h^2 \leq M_Z^2 + \frac{3g^2}{16\pi^2 M_W^2} \sin^2 \beta \log \left( \frac{m_1^2 m_2^2}{m_1^4} \right).$$  

Therefore, if one assumes that the stop masses are of order TeV, then the one-loop effect leads to a correction of order $\mathcal{O}(100)$ GeV, which implies that

$$m_h^2 \lesssim \sqrt{(90 \text{ GeV})^2 + (100 \text{ GeV})^2} = 135 \text{ GeV}. $$

The two-loop corrections reduce this upper bound by few GeVs [53–55]. Hence, the MSSM predicts the following upper bound for the Higgs mass: $m_h \lesssim 130$ GeV, which was consistent with the measured value of Higgs mass (of order 125 GeV) at the LHC [13, 14].

In Figure 1, we display the contour plot of the SM-like Higgs boson: $m_h \in [124, 126]$ GeV in $(m_0, m_{1/2})$
plane for different values of $A_0$ and $\tan \beta$. It is remarkable that the smaller the value of $A_0$ is, the smaller the value of $m_{1/2}$ is needed to satisfy this value of Higgs mass. It is also clear that the scalar mass $m_0$ remains essentially unconstrained by Higgs mass limit. It can vary from few hundred GeVs to few TeVs. Such large values of $m_{1/2}$ seem to imply a quite heavy SUSY spectrum, much heavier than the lower bound imposed by direct searches at the LHC experiments in centre of mass energies $\sqrt{s} = 7, 8$ TeV and total integrated luminosity of order $20 \text{fb}^{-1}$. Furthermore, the LHC lower limit on the gluino mass, $m_{\tilde{g}} \gtrsim 1.4$ TeV [56, 57], excluded the values of $m_{1/2} < 620$ GeV which was allowed by Higgs mass constraints for $m_0 > 4$ TeV.

Furthermore, this region is shown with dashed lines in Figure 1.

### 3. Dark Matter Constraints on MSSM Parameter Space

#### 3.1. The LSP as Dark Matter Candidate

The neutralinos $\chi_i$ ($i = 1, 2, 3, 4$) are the physical (mass) superpositions of two fermionic partners of the two neutral gauge bosons, called gaugino $\tilde{B}$ (bino) and $\tilde{W}_3$ (wino), and of the two neutral Higgs bosons, called Higgsinos $\tilde{H}_1^0$ and $\tilde{H}_2^0$. The neutralino mass matrix is given by [58–61]

$$
M_N = \begin{pmatrix}
M_1 & 0 & -M_Z \cos \beta \sin \theta_W & M_Z \sin \beta \sin \theta_W \\
0 & M_2 & M_Z \cos \beta \cos \theta_W & -M_Z \sin \beta \cos \theta_W \\
-M_Z \cos \beta \sin \theta_W & M_Z \cos \beta \cos \theta_W & 0 & -\mu \\
M_Z \sin \beta \sin \theta_W & -M_Z \sin \beta \cos \theta_W & -\mu & 0
\end{pmatrix},
$$

(7)
where $M_1$ and $M_2$ are related due to the universality of the gaugino masses at the grand unification scale, $M_1 = (3g_1^2/5g_2^2)M_2$, where $g_1, g_2$ are the gauge couplings of $U(1)_Y$ and $SU(2)_L$, respectively. This Hermitian matrix is diagonalized by a unitary transformation of the neutralino fields, $M_N^{\text{diag}} = N^\dagger M_N N$. The lightest eigenvalue of this matrix and the corresponding eigenstate, say $\chi$, has good chance of being the LSP. The lightest neutralino will be a linear combination of the original fields:

$$\chi = N_{11} B^0 + N_{12} W^0 + N_{13} T^0_1 + N_{14} P^0_2. \quad (8)$$

The phenomenology and cosmology of the neutralino are governed primarily by its mass and composition. A useful parameter for describing the neutralino composition is the gaugino “purity” function $f_\beta = |N_{11}|^2 + |N_{12}|^2$ [58–61]. If $f_\beta > 0.5$, then the neutralino is primarily gaugino and if $f_\beta < 0.5$, then the neutralino is primarily Higgsino. Actually, if $|\mu| > |M_2|$, the two lightest neutralino states will be determined by the gaugino components; similarly, the light char-gino will be mostly a charged wino, while if $|\mu| < |M_2|$, the two lighter neutralinos and the lighter chargino are all mostly Higgsinos, with mass close to $|\mu|$. Finally, if $|\mu| = |M_2|$, the states will be strongly mixed.

Here, two remarks are in order. (i) The abovementioned constraints in $m_{1\beta}$ from Higgs mass limit and gluino mass lower bound imply that $m_1 \geq 240$ GeV, which is larger than the limits obtained from direct searches at the LHC. Moreover, an upper bound of order one TeV is also obtained (from Higgs mass constraint). (ii) In this region of allowed parameter space, the LSP is essentially pure bino, as shown in Figure 2. This can be easily understood from the fact that $\mu$-parameter, determined by the radiative electroweak breaking condition, (3), is typically of order $m_\chi$ and hence it is much heavier than the gaugino mass $M_1$.

3.2. Relic Density. As advocated in the previous section, the LSP in MSSM, the lightest neutralino $\chi$, is a perfect candidate for DM. Here, we assume that $\chi$ was in thermal equilibrium with the SM particles in the early universe and decoupled when it was nonrelativistic. Once $\chi$ annihilation rate $\Gamma_\chi = \langle\sigma^{\text{ann}}\chi\nu\rangle n_\chi$ dropped below the expansion rate of the universe, $\Gamma_\chi \lesssim H$, the LSP particles stop to annihilate and fall out of equilibrium and their relic density remains intact till now. The above $\langle\sigma^{\text{ann}}\chi\nu\rangle$ refers to thermally averaged total cross section for annihilation of $\chi\chi$ into lighter particles times the relative velocity, $v$.

The relic density is then determined by the Boltzmann equation for the LSP number density ($n_\chi$) and the law of entropy conservation:

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle\sigma^{\text{ann}}\chi\nu\rangle \left[(n_\chi)^2 - (n^\text{eq}_\chi)^2\right],$$

$$\frac{ds}{dt} = -3Hs,$$  \hspace{1em} (9)

where $n^\text{eq}_\chi$ is the LSP equilibrium number density which, as a function of temperature $T$, is given by $n^\text{eq}_\chi = g_*\rho/\sqrt{2\pi}^3 m_\chi^{3/2} e^{-m_\chi/T}$. Here, $m_\chi$ and $g_*$ are the mass and the number of degrees of freedom of the LSP, respectively. $s$ is the entropy density. In the standard cosmology, the Hubble parameter $H$ is given by $H(T) = 2\pi\sqrt{\pi^2/45(T^2/M_{pl})}$, where $M_{pl} = 1.22 \times 10^{19}$ GeV and $g_*$ is the number of relativistic degrees of freedom, for MSSM $g_* = 228.75$. Let us introduce the variable $x = m_\chi/T$ and define $Y = n_\chi/s$ with $Y_{eq} = n^\text{eq}_\chi/s$. In this case, the Boltzmann equation is given by

$$\frac{dY}{dx} = \frac{1}{3H} \frac{ds}{dx} \langle\sigma^{\text{ann}}\chi\nu\rangle \left(Y^2 - Y_{eq}^2\right). \quad (10)$$

In radiation domination era, the entropy, as a function of the temperature, is given by

$$s(x) = \frac{2\pi^2}{45} g_*(x) m_\chi^3 x^{-3}, \quad \text{(11)}$$

which is deduced from the fact that $s = (\rho + p)/T$ and $g_*$ is the effective degrees of freedom for the entropy density. Therefore, one finds

$$\frac{ds}{dx} = -\frac{3s}{x}. \quad \text{(12)}$$

Thus, with assuming $g_*=g_*$, the following expression for the Boltzmann equation for the LSP number density is obtained:

$$\frac{dY}{dx} = -\sqrt{\frac{\pi g_*}{45 M_{pl} m_\chi \langle\sigma^{\text{ann}}\chi\nu\rangle}} \frac{\langle\sigma^{\text{ann}}\chi\nu\rangle}{x^2} \left(Y^2 - Y_{eq}^2\right). \quad \text{(13)}$$

If one considers the s-wave and p-wave annihilation processes only, the thermal average $\langle\sigma^{\text{ann}}\chi\nu\rangle$ then shows as

$$\langle\sigma^{\text{ann}}\chi\nu\rangle = a_\chi + \frac{6b_\chi}{x}, \quad \text{(14)}$$

**Figure 2:** The mass of lightest neutralino versus the purity function in the region of parameter space allowed by gluino and Higgs mass limits.
where $a_s$ and $b_s$ are the s-wave and p-wave contributions of annihilation processes, respectively. The relic density of the DM candidate is given by

$$\Omega h^2 = \frac{m_\chi s_0 Y_\chi(\infty)}{\rho_c / \hbar^2},$$

(15)

where $s_0 = 2282.15 \times 10^{-41} \text{GeV}^3$, $\rho_c = 8.0992 \hbar^2 \times 10^{-47} \text{GeV}^4$, and by solving the Boltzmann equation, one can find $Y_\chi(\infty)$ as follows [62]:

$$Y_\chi(\infty) = \frac{1}{\lambda_\chi} \left( \frac{a_s}{x(T_f)} + \frac{3b_s}{x^3(T_f)} \right)^{-1},$$

(16)

where $T_f$ is the freeze-out temperature, $\lambda_\chi = s(m_\chi)/H(m_\chi)$, and $x(T_f)$ is given by

$$x(T_f) = \ln \left[ \frac{\alpha_s \lambda_\chi (c + 2)}{\sqrt{x(T_f)}} \left( \frac{a_s + 6b_s}{x(T_f)} \right) \right].$$

(17)

where $\alpha_s = (45/2\pi^4)\sqrt{\pi/8}(g_s/g_s(T_f))$; the value $c = 1/2$ results in a typical accuracy of about 5–10% more than sufficient for our purposes here.

The lightest neutralino may annihilate into fermion-antifermion $(f\bar{f})$, $W^+W^-$, $ZZ$, $W^+H^-$, $ZA$, $ZH$, and $H^+H^-$ and all other contributions of neutral Higgs. For a bino-like LSP, that is, $N_{1i} = 1$ and $N_{i1} = 0$, $i = 2, 3, 4$, one finds that the relevant annihilation channels are the fermion-antifermion ones, as shown in Figure 3, and all other channels are instead suppressed. Also, the annihilation process mediated by $Z$-gauge boson is suppressed due to the small $Z\chi\chi$ coupling $\propto N_{13}^2 - N_{24}^2$, except at the resonance when $m_\chi \sim M_Z/2$, which is no longer possible due to the above-mentioned constraints. Furthermore, one finds that the t-channel annihilation (first Feynman diagram in Figure 3) is predominantly into leptons through the exchanges of the three slepton families ($\tilde{l}_i, \tilde{e}_i$), with $l = e, \mu, \tau$. The squarks exchanges are suppressed due to their large masses.

In Figure 4, we display the constraint from the observed limits of $\Omega h^2$ on the plane $(m_0, m_{1/2})$ for $A_0 = 0, 2000 \text{ GeV}$, $\tan \beta = 10, 50$, and $\mu > 0$. Here, we used micrOMEGAs [63] to compute the complete relic abundance of the lightest neutralino, taking into account the possibility of having coannihilation with the next-to-lightest supersymmetric particle, which is typically the lightest stau. Note that this type of coannihilation is not included in the approximated expressions in (14)–(17). In this figure, the red regions correspond to a relic abundance within the measured limits [1]:

$$0.09 < \Omega h^2 < 0.14.$$  

(18)

It is noticeable that, with low $\tan \beta$ ($\sim 10$), this region corresponds to light $m_{1/2} (< 500 \text{ GeV})$, where significant coannihilation between the LSP and stau took place. However, this possibility is now excluded by the Higgs and gluino mass constraints [64]. At large $\tan \beta$, another region is allowed due to possible resonance due to s-channel annihilation of the DM pair into fermion-antifermion via the pseudoscalar Higgs boson $A$ at $M_A = 2m_\chi$ [65]. For $A_0 = 0$, a very small part of this region is allowed by the Higgs mass constraint, while for large $A_0$ ($\sim 2 \text{ TeV}$) slight enhancement of this part can be achieved. In Figure 5, we zoom in on this region to show the explicit dependence of the relic abundance on the LSP mass and large values of $\tan \beta$. As can be seen from this figure, there is no point that can satisfy the relic abundance stringent constraints with $\tan \beta < 30$.

3.3. Direct Detection. Perhaps the most natural way of searching for the neutralino DM is provided by direct experiments, where the effects induced in appropriate detectors by neutralino-nucleus elastic scattering may be measured. The elastic-scattering cross section of the LSP with a given nucleus has two contributions: spin-dependent contribution arising from $Z$ and $\tilde{q}$ exchange diagrams and spin-independent (scalar) contribution due to the Higgs and squark exchange diagrams, which is typically suppressed. The effective scalar interaction of neutralino with a quark is given by

$$\mathcal{L}_{\text{scalar}} = f_\tilde{q} \bar{\chi} \tilde{q} \chi,$$

(19)

where $f_\tilde{q}$ is the neutralino-quark effective coupling. The scalar cross section of the neutralino scattering with target nucleus at zero momentum transfer is given by [2]

$$\sigma_{\text{SI}} = \frac{4m_\chi^2}{\pi} \left( Zf_p + (A - Z)f_n \right)^2,$$

(20)

where $Z$ and $A - Z$ are the number of protons and neutrons, respectively, $m_\chi = m_N m_f / (m_N + m_f)$, where $m_N$ is
Figure 4: LSP relic abundance constraints (red regions) on $(m_0, m_{1/2})$ plane for $\tan\beta$ and $A_0$ as in Figure 1. The LUX result is satisfied by the yellow region. The other color codes are as in Figure 1.

Figure 5: The relic abundance versus the mass of the LSP for different values of $\tan\beta$. Red points indicate $40 \leq \tan\beta \leq 50$ and blue points $30 \leq \tan\beta < 40$. All points satisfy the abovementioned constraints.

Figure 6: Spin-independent scattering cross section of the LSP with a proton versus the mass of the LSP within the region allowed by all constraints (from the LHC and relic abundance).

where $\nu$ is the neutrino velocity and $F(q^2)$ is the form factor [2]. In Figure 6, we display the MSSM prediction for spin-independent scattering cross section of the LSP with a proton ($\sigma^P_{SI} = \int_0^{4m^2_\nu} (d\sigma_{SI}/dq^2)_{f_n=f_p} dq^2$) after imposing the LHC constraints.
and relic abundance constraints. It is clear that our results for $\sigma_{SI}$ are less than the recent LUX bound (blue curve) by at least two orders of magnitude. This would explain the negative results of direct searches so far.

4. Nonthermal Dark Matter and MSSM Parameter Space

In the previous section, we assumed standard cosmology scenario where the reheating temperature $T_{RH}$ is very large; namely, $T_{RH} \gg T_f \approx 10$ GeV. However, the only constraint on the reheating temperature, which could be associated with decay of any scalar field, $\phi$, not only the inflaton field, is $T_{RH} \gtrsim 1$ MeV in order not to spoil the successful predictions of big bang nucleosynthesis.

A detailed analysis of the relic density with a low reheating temperature has been carried out in [66]. It was emphasized that, for a large annihilation cross section, $\langle \sigma v \rangle \gtrsim 10^{-14}$ GeV$^{-2}$ so that the neutralino reaches equilibrium before reheating, and if there are a large number of neutralinos produced by the scalar field $\phi$ decay, then the relic density is estimated as [67]

$$\Omega h^2 = \frac{3m_{\phi}^2 \Gamma_{\phi}}{2(2\pi^2/45) g_*(T_{RH}) T_{RH}^2 \langle \sigma v \rangle_{\chi} \rho_{\phi}/\rho}.$$  \hspace{1cm} (22)

Here, the reheating temperature is defined as [62]

$$T_{RH} = \left( \frac{90}{\pi^2 g_*(T_{RH})} \right)^{1/4} \left( \Gamma_{\phi} M_P \right)^{1/2},$$  \hspace{1cm} (23)

where the decay width $\Gamma_{\phi}$ is given by

$$\Gamma_{\phi} = \frac{1}{2\pi} \frac{m_{\phi}^3}{\Lambda^2}.\hspace{1cm} (24)$$

The scale $\Lambda$ is the effective suppression scale, which is of order the grand unification scale $M_X$. Therefore, for scalar field with mass $m_{\phi} = 10^7$ GeV, one finds $\Gamma_{\phi} = 10^{-11}$ GeV, and in our calculations, we have used $g_* = 10.75$ due to the consideration of a low reheating temperature scenario.

In Figure 7, we show the constraints imposed on the MSSM ($m_0$-$m_{1/2}$) plane in case of nonthermal relic abundance of the LSP for tan $\beta = 10, 50$ and $A_0 = 0, 2$ TeV. In this plot, we also imposed the LHC constraints, namely, the Higgs mass limit and the gluino mass lower bound, similar to the case of thermal scenario. It is clear from this figure that the stringent constraints imposed on the MSSM parameter space by thermal relic abundance are now relaxed and now low tan $\beta$ ($\sim 10$) is allowed but with very heavy $m_0$ ($\sim 0(4)$ TeV) and $m_{1/2} = 600$ GeV. In addition, the following two regions are now allowed with large tan $\beta$ ($\sim 50$): (i) $m_0 \sim m_{1/2} = \ldots$
(1) TeV; (ii) \( m_0 \approx O(4) \) TeV and \( m_{1/2} \approx 700 \) GeV. The SUSY spectrum associated with these regions of parameters space could be striking signature for nonthermal scenario at the LHC.

5. Conclusion

We have studied the constraints imposed on the MSSM parameter space by the Higgs mass limit and the gluino lower bound, which are the most stringent collider constraints obtained from the LHC run-I at energy 8 TeV. We showed that \( m_{1/2} \) resides within the mass range \( 620 \) GeV \( \leq m_{1/2} \leq 2000 \) GeV, while the other parameters \( (m_0, A_0, \tan \beta) \) are much less constrained. We also studied the effect of the measured DM relic density on the MSSM allowed parameter space. It turns out that most of the MSSM parameter space is ruled out except for few points around \( \tan \beta \sim 50 \), \( m_0 \sim 1 \) TeV, and \( m_{1/2} \sim 1.5 \) TeV. We calculated the spin-independent scattering cross section of the LSP with a proton in this allowed region. We showed that our prediction for \( \sigma_{SI}^{p} \) is less than the recent LUX bound by at least two orders of magnitude. We have also analyzed the nonthermal DM scenario for the LSP. We showed that the constraints imposed on the MSSM parameter space are relaxed and low \( \tan \beta \) is now allowed with \( m_0 = O(4) \) TeV and \( m_{1/2} = 600 \) GeV. Also two allowed regions are now associated with large \( \tan \beta \) (\( \sim 50 \)); namely, \( m_0 \sim m_{1/2} = O(1) \) TeV or \( m_0 = O(4) \) TeV and \( m_{1/2} = 700 \) GeV.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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