Nonminimal split SUSY

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Abstract

We present an extension of the minimal split supersymmetry model, which is capable of explaining the baryon asymmetry of the Universe. Instead of MSSM we start from NMSSM and split its spectrum in such a way that the low energy theory contains neutral particles, in addition to the content of minimal split supersymmetry. We discuss implications of these new fields on the electroweak phase transition and the production of the baryon asymmetry. We also consider possible dark matter candidates and EDM of electron and neutron in the model.

1 Introduction

In spite of approximate symmetry between particles and antiparticles, our visible Universe is asymmetric in baryons. An explanation of this fact ought to be addressed in any viable theory. Quantitatively, the measurements of the anisotropy of the cosmic microwave background constrain the baryon-to-photon ratio [1] to be in the range

$$6.1 \times 10^{-10} < \frac{n_B}{n_\gamma} < 6.9 \times 10^{-10}. \quad (1)$$

Three necessary conditions (Sakharov conditions) must be fulfilled in the early Universe to produce the baryon asymmetry [2]: baryon number violation, C- and CP-violation and departure from thermal equilibrium. One of the most interesting scenario for BAU production is electroweak baryogenesis (see Ref. [3]), in which baryon asymmetry is produced during the strongly first order electroweak phase transition. Unfortunately, this mechanism does not work in the Standard model, because the departure from thermal equilibrium is too weak (the phase transition is not of the first order [4]) and CP-violation by CKM phase is too small. Electroweak baryogenesis have been investigated in various extensions of the Standard Model (see *e.g.* [5],[6],[7],[8]).

Recently, motivated by vacua landscape in string theory and cosmological constant problem, models with "split supersymmetry" have been proposed [9, 10]. The spectrum of these models is governed by two scales. While the electroweak scale m_{ew} determines the masses of the Standard Model particles and new fermionic degrees of freedom (higgsinos and gauginos) the other MSSM particles (scalars) have masses of order of a splitting scale m_s, which generally may be in a wide range $10^4 - 10^{15}$ GeV. Such a pattern ensures the gauge coupling unification and split SUSY can be incorporated into a GUT.

Split SUSY enables one to avoid phenomenological difficulties with flavor and CP-violation and also provides natural dark matter candidates. But from the point of view of the electroweak

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baryogenesis, split supersymmetry, in its minimal version, shares some disadvantages of SM: the electroweak phase transition remains too weak, because the additional fermions do not contribute to the cubic term of the high-temperature effective potential and hence do not strengthen EWPT. It is of interest to find a viable scenario, which would be compatible with general split supersymmetry framework and would provide conditions required for effective electroweak baryogenesis.

We propose a model which keeps all phenomenologically interesting properties of the minimal split supersymmetry and at the same time is capable of producing the baryon asymmetry at EWPT. Instead of using MSSM as a starting point, we begin with Non-Minimal Supersymmetric Standard Model (NMSSM) and split its spectrum in such a way as to provide the low energy theory with all features required for successful electroweak baryogenesis. Indeed, additional light neutral scalar particles, which are left at low energies after the spectrum splitting, can make EWPT stronger. The model contains new sources of CP-violation. Apart from their crucial role in the generation of the required amount of the baryon asymmetry, they also contribute to the electric dipole moments (EDMs) of electron and neutron at the level detectable in the near future experiments. Also, we study the possibility that the lightest neutralino is dark matter particle. We find that along with gaugino- and higgsino-like candidates there is a region of parameter space where dark matter is mostly singlino.

2 The model

We consider the most general NMSSM. The relevant for our study part of the superpotential is [11]

$$W = \lambda \hat{N} \hat{H}_u \epsilon \hat{H}_d + \frac{1}{3} k \hat{N}^3 + \mu \hat{H}_u \epsilon \hat{H}_d + r \hat{N}. \tag{2}$$

$\hat{H}_u$ and $\hat{H}_d$ are Higgs doublets, $\hat{N}$ is a chiral superfield, which is a singlet with respect to the SM gauge group. Soft SUSY breaking terms for this model read

$$\begin{aligned} V_{soft} = \Big(\lambda A_\lambda N H_u \epsilon H_d + \frac{1}{3} k A_k N^3 + \mu B H_u \epsilon H_d + A_r N + h.c. \Big) \\ + m_u^2 H_u^\dagger H_u + m_d^2 H_d^\dagger H_d + m_N^2 |N|^2. \end{aligned} \tag{3}$$

We consider this model in the framework of split SUSY. For this purpose some parameters need to be fine-tuned, like in the minimal split SUSY, in such a way that the particle spectrum is split into two parts. To strengthen the electroweak phase transition, some scalars can be recruited [12]. To preserve gauge coupling unification, these particles should not contribute to the beta functions (or their contributions should be canceled), at least at the leading order. So in the minimal case, the low energy theory can contain (besides the usual split SUSY particles) singlets with respect to the SM gauge group.

Examining H_u, H_d, N sector we have found [13] that, like in the minimal split SUSY, one can split the particle spectrum by taking μB parameter of order of the squared splitting scale m_s^2. It means that the charged higgses, one scalar H^0 and one pseudoscalar A^0 from the Higgs sector become heavy. It is straightforward to check that the low energy effective Lagrangian is obtained by the same substitution for the Higgs doublets as in the minimal split SUSY [10]

$$H_u \to H \sin\beta, \quad H_d \to \epsilon H^* \cos\beta, \tag{4}$$

where H is the Standard Model Higgs doublet.

$$\mathcal{L} = \mathcal{L}_{\rm V} + \mathcal{L}_{\rm Y}.$$

It consists of two parts: the scalar potential

$$
\begin{aligned}
-\mathcal{L}_{\rm V} = \frac{\bar{g}^2}{8}\cos^2 2\beta\left(H^\dagger H\right)^2 + |r + kN^2 - \frac{\lambda}{2}\sin 2\beta H^\dagger H|^2 + |\lambda N + \mu|^2 H^\dagger H \\
+\left(-\frac{\lambda}{2}A_\lambda \sin 2\beta N H^\dagger H - \frac{\mu B}{2}\sin 2\beta H^\dagger H + \frac{1}{3}kA_k N^3 + A_r N + h.c.\right) \\
+\left(m_u^2 \sin^2\beta + m_d^2\cos^2\beta\right)H^\dagger H + m_N^2|N|^2
\end{aligned}
\quad (5)
$$

and the Yukawa interactions

$$
-\mathcal{L}_{\rm Y} = -\lambda N\tilde{H}_u\epsilon\tilde{H}_d - \lambda\sin\beta H^T\epsilon\left(\tilde{H}_d\tilde{n}\right) + \lambda\cos\beta\left(\tilde{n}\tilde{H}_u\right)H^* - kN\tilde{n}\tilde{n} + h.c., \quad (6)
$$

where $\tilde{H}^u$ and $\tilde{H}^d$ are higgsinos and $\tilde{n}$ is singlino, which is the fermionic component of the singlet chiral superfield $\hat{N}$. A special feature of our model, as compared to the minimal split SUSY, is that after splitting there remain relatively light singlet fields: complex scalar N and Majorana fermion $\tilde{n}$. The scalar field can be decomposed into CP-even S and CP-odd P real fields.

The Lagrangian (5), (6) describes interactions at the splitting scale m_s, which is taken below to be 10^9 GeV, if not stated otherwise. To obtain the low energy theory, the couplings in (5), (6) should be changed according to the renormalization group equations (RGE) of the theory. Below the splitting scale m_s, the theory is described by the following Lagrangian

$$
\begin{aligned}
-\mathcal{L}_{\rm V} = -m^2 H^\dagger H + \frac{\tilde{\lambda}}{2}\left(H^\dagger H\right)^2 + i\tilde{A}_1 H^\dagger H\left(N - N^*\right) + \tilde{A}_2 H^\dagger H\left(N + N^*\right) + \kappa_1|N|^2 H^\dagger H \\
-\kappa_2 H^\dagger H\left(N^2 + N^{*2}\right) + \tilde{m}_N^2|N|^2 + \lambda_N|N^2|^2 + \frac{1}{3}\tilde{A}_k\left(N^3 + N^{*3}\right) + \tilde{A}_r\left(N + N^*\right) \\
+\left(\frac{\tilde{m}^2}{2}N^2 + \frac{1}{2}\tilde{A}_3 N^2 N^* + \xi N^4 + \frac{\eta}{6}N^3 N^* + h.c.\right)
\end{aligned}
\quad (7)
$$

and

$$
\begin{aligned}
-\mathcal{L}_{\rm Y} = \frac{M_2}{2}\tilde{W}^a\tilde{W}^a + \frac{M_1}{2}\tilde{B}\tilde{B} + \left(\mu + \kappa N\right)\tilde{H}_u^T\epsilon\tilde{H}_d - kN\tilde{n}\tilde{n} \\
+H^\dagger\left(\frac{1}{\sqrt{2}}\tilde{g}_u\sigma^a\tilde{W}^a + \frac{1}{\sqrt{2}}\tilde{g}'_u\tilde{B} - \lambda_u\tilde{n}\right)\tilde{H}_u \\
+H^T\epsilon\left(-\frac{1}{\sqrt{2}}\tilde{g}_d\sigma^a\tilde{W}^a + \frac{1}{\sqrt{2}}\tilde{g}'_d\tilde{B} - \lambda_d\tilde{n}\right)\tilde{H}_d + h.c.,
\end{aligned}
\quad (8)
$$

where we added interactions between the Higgs bosons, higgsinos and gauginos. Comparing the Lagrangians (5), (7) and (6), (8), we may read off the matching conditions between the coupling constants, which are valid at the splitting scale m_s. The matching conditions provide the initial values for RGE. The coupling constants, additional to the minimal split SUSY, begin to contribute to the running of the gauge couplings only at 2-loop level and do not spoil their unification.

We take particular point in parameter space for the following analysis. There are three dimensionless parameters $\tan\beta$, λ, k, which *a priori* take any values compatible with the weak coupling regime in both high-energy and low-energy theories. In addition, the low-energy spectrum has to be phenomenologically viable. We take them to be

$$
\tan\beta = 10, \quad \lambda = 0.6, \quad k = -0.5. \quad (9)
$$

The coupling constants of low energy theory (7) and (8) were obtained by using RG equations (see Ref. [13] for details). The dimensionful parameters are taken at the electroweak scale. We do not assume universal boundary conditions for soft supersymmetry breaking terms. Below we vary some of the parameters keeping several relations between them to simplify the analysis. For m^2, $\tilde{m}_N^2$ and $\tilde{m}^2$ we substitute the corresponding expressions in terms of v, v_S and v_P, which follows from conditions on the minimum of the potential. Since we take μ to be imaginary and CP is violated in the Higgs sector, two scalars and one pseudoscalar generally mix. We restrict our considerations (the only reason is to reduce the number of free parameters) to the case where mixing is absent, i.e the corresponding squared mass matrix is diagonal; in fact this can be done by tuning trilinear constants $\tilde{A}_1$, $\tilde{A}_2$ and $\tilde{A}_k$. Therefore, the only sources of CP-violation we are left with are those in the fermionic sector. Nonzero $\tilde{A}_3$ is generated by radiative corrections, hence generically it is small and is not very important, so we set it equal to zero. We also choose $\tilde{A}_r = 0$ for concreteness. The free dimensionful parameters we are left with are vev's of singlet scalars v_S, v_P and gaugino masses M_1, M_2.

In our restricted parameter space we use RGE to obtain the Higgs boson mass m_h. The dependence of m_h on the splitting scale m_s is plotted in Fig. 1. We use initial conditions (9)

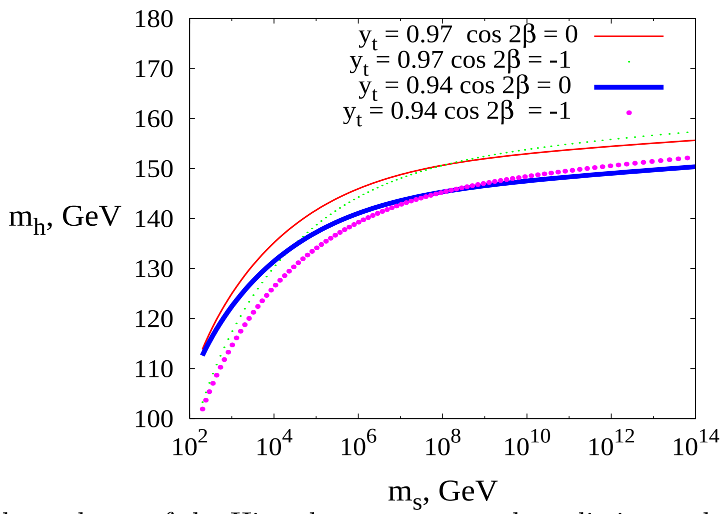

Figure 1: The dependence of the Higgs boson mass on the splitting scale m_s. Solid lines are for $\cos 2\beta = 0$ case, while dotted ones are for $\cos 2\beta = 1$. Top Yukawa coupling is equal to 0.97 for thin lines and 0.94 for thick lines.

for λ and k, and vary the value of β. In this analysis we take into account the experimental uncertainties in the determination of the top quark mass. The values of the tree level Higgs boson mass are generally within the same range as in the minimal split supersymmetry [9, 15]. The upper bound on m_h is increased in comparison with MSSM. We also have found that the dependence of the Higgs boson mass m_h on k is less than 1% in the whole perturbative range of k, while m_h increases from 144.6 GeV at $\lambda = 0.0$ to 160.0 GeV at $\lambda = 0.7$ (other parameters in this case are $k = -0.5,\ \cos 2\beta = 0,\ m_s = 10^9$ GeV).

3 Electroweak phase transition, BAU and dark matter

For successful electroweak baryogenesis the phase transition must be strongly first order, so that the condition $v_c/T_c \gtrsim 1.1$ should be valid. Finite temperature one-loop effective potential for the Higgs and singlet scalar fields reads as follows,

$$V_T(v, v_S, v_P) = V_{tree}(v, v_S, v_P) + V^{(1)}(v, v_S, v_P) + V_T^{(1)}(v, v_S, v_P). \tag{10}$$

Here the first and the second terms are the tree level part of the potential (7) and 1-loop contribution, respectively. The third term is 1-loop contribution at finite temperature.

We define the critical temperature T_c as a temperature at which the first bubbles of true vacuum begin to nucleate. It takes place when $S_3\,(T_c)\,/T_c \sim 130 - 140$ [12] where $S_3\,(T)$ is the free energy of critical bubble. We take a set of free dimensionfull parameters, which suuport the strongly first order phase transition. To find the critical bubble profile numerically we use the method, originally proposed in Ref. [16] for MSSM and further developed in Ref. [17]. The critical bubble profile (*i.e.* the dependence of the scalar fields on radial coordinate) is presented in Figure 2. Here $h(r)$, $S(r)$ $P(r)$ stand for Higgs, scalar and pseudoscalar fields, respectively.

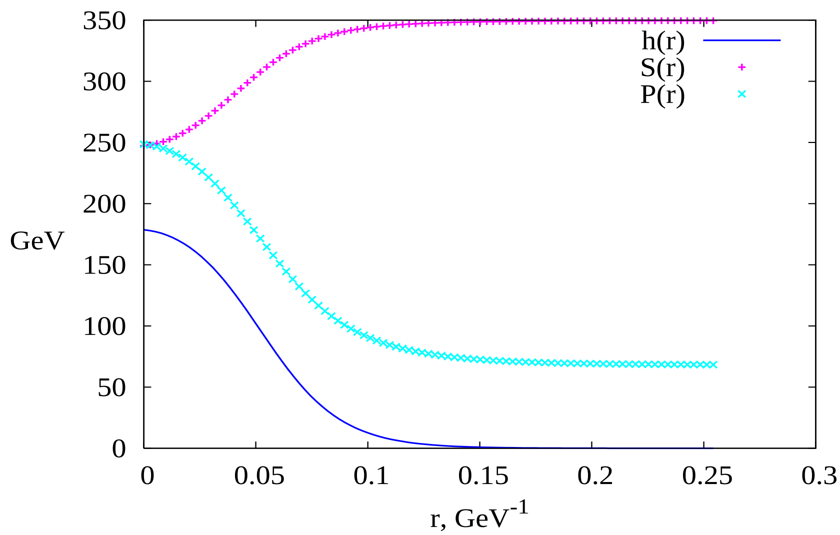

Figure 2: Example of the critical bubble profile.

For calculation of the baryon asymmetry we use diffusion approximation to the particle transport. CP-violating sources were computed in WKB approximation [18]. According to the semiclassical picture, particles and antiparticles have different dispersion relations in CP-violating background of the bubble wall [20]. Initially, the asymmetry in their densities emerges in the chargino sector and then, due to interactions and diffusion processes, it is transmitted into the densities of other particle species including left-handed fermions and, finally, to the baryon asymmetry. We derived the diffusion equations along the lines of Ref. [21]. The expressions for the sources come from Ref. [6].

In Fig. 3 we present the results for the baryon-to-entropy ratio $\Delta = n_B/s$ with entropy density s given by $s = 2\pi^2 g_{eff} T^3/45$, where g_{eff} is the effective number of relativistic degrees of freedom at the critical temperature. We plot the ratio Δ/Δ_0, where $\Delta_0 = 8.7 \cdot 10^{-11}$, which corresponds to $n_B/n_\gamma = 6.5 \cdot 10^{-10}$.

One of the consequences of the presence of additional sources of CP-violation is their contribution to the electron and neutron EDMs. Like in the minimal split SUSY model, there are three types of contributions to EDM of a fermion (lepton or quark), related to the exchange of $h_0\gamma$, W^+W^- and $h_0 Z$ bosons (see Refs. [22], [23], [24], [25]). The corresponding two-loop Feynman diagrams for SM fermion f (charged lepton or quark) are given in Fig. 4. For numerical calculations we use two sets of parameters (see Table 1) and randomly scan over the following parameter space, $0 < M_1, M_2 < 1000$ GeV. Also we take the coupling k to be complex, $k = |k|e^{i\phi_k}$, $(0 < \phi_k < \pi)$ to include the contribution of the phase invariant ϕ_2. The results for the electron and neutron EDMs as functions of the mass of the lightest chargino are presented in Figs. 5. We have taken into account the experimental bound on the mass of the lightest chargino $m_{\chi^+} > 104$ GeV [26].

Horizontal lines show the present experimental limit on the EDM of electron $|d_e| < 1.6 \cdot 10^{-27}$ e cm at 90% CL [27] and neutron $|d_n| < 3.0 \cdot 10^{-26}$ e cm at 90% CL [28].

In the minimal split SUSY dark matter candidates have been already investigated in Refs. [10], [22], [29]. In the first place, let us note that a generalization of R-parity can be introduced in

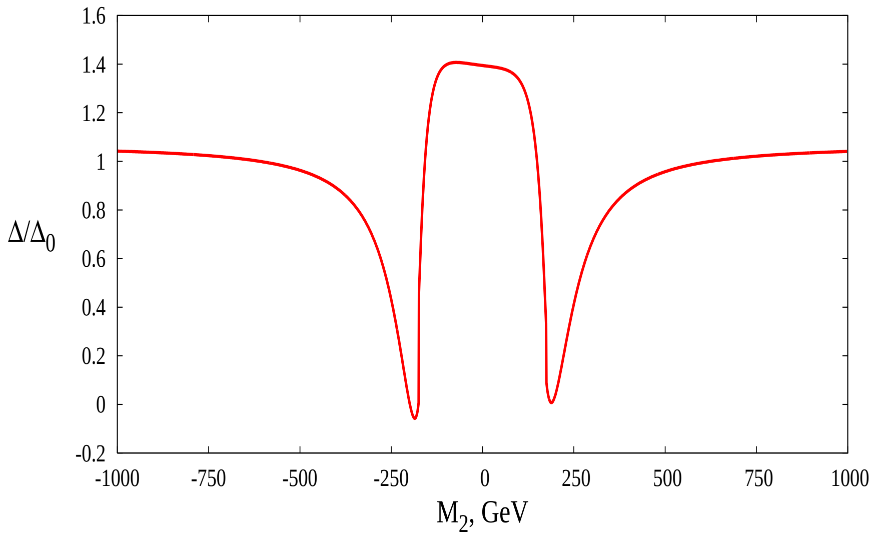

Figure 3: Plot of Δ/Δ_0 as a function of M_2.

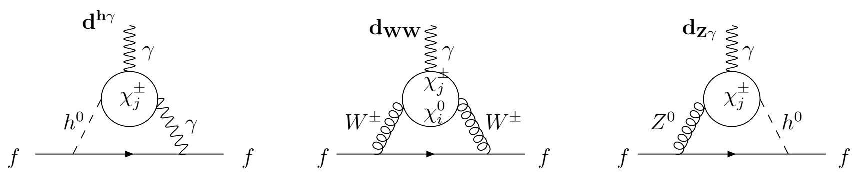

Figure 4: Feynman diagrams contributing to the fermion EDM in split SUSY

the nonminimal split SUSY: with respect to this R-parity all new fermionic fields are odd, while new (pseudo)scalars are even. Hence the lightest new fermion is the lightest superpartner and it is stable. To calculate the neutralino abundance, we modify the formulas for the annihilation cross sections presented in Ref. [30].

Adopting constraints discussed above, we first scan uniformly over the following parameter space: $|M_1|,\ |M_2| < 1000$ GeV, $|v_P| < 2000$ GeV, with v_S being in the region of correct electroweak vacuum (*i.e.* the electroweak breaking minimum is the global minimum of the potential) and squared mass matrix of the scalar fields being diagonal. The numerical results are presented in the left plot in Fig. 6, where we show the region in $(m_{\chi^+},\ m_\chi)$ plane favored by WMAP data: each point corresponds to a model in which neutralino abundance is within the range $0.094 < \Omega_{DM}h^2 < 0.129$ [1]. To check that the baryon asymmetry and dark matter problems can be solved simultaneously, we also scan uniformly over the region in the parameter space preferred by electroweak baryogenesis; namely, we use $|M_1|,\ |M_2| < 1000$ GeV, with other parameters corresponding to the set (2) in Tables 1 and 2. Points in $(M_1,\ M_2)$ plane, which correspond to correct neutralino abundance, are shown on the right plot in Fig. 6. On both plots green (light grey) crosses correspond to the dark matter particles which have considerable admixture of singlino ($|N_{55}| > 0.5$), while the red (dark grey) crosses correspond to the mostly bino LSP. The annihilation of DM particles (bino as well as singlino) with masses $m_\chi \sim 0.5M_h \sim 75$ GeV or $m_\chi \sim 0.5M_Z$ proceeds resonantly via Higgs or Z^0-boson exchange, respectively. On the right plot, this light neutralino corresponds to the red (dark grey) horizontal lines with $M_1 < 70$ GeV. The most part of the parameter space with singlino-like dark matter give relatively light LSP with mass in the range $50 - 200$ GeV although heavier candidates are not entirely excluded. We have found that in this case, considerable admixture of higgsinos is always present (numerically, we obtain $\left(|N_{53}|^2 + |N_{54}|^2\right)^{(1/2)} \sim 0.4 - 0.8$). Singlino dark matter with the mass $m_\chi \gtrsim 80$ GeV annihilates predominantly into W^+W^- gauge bosons, while for

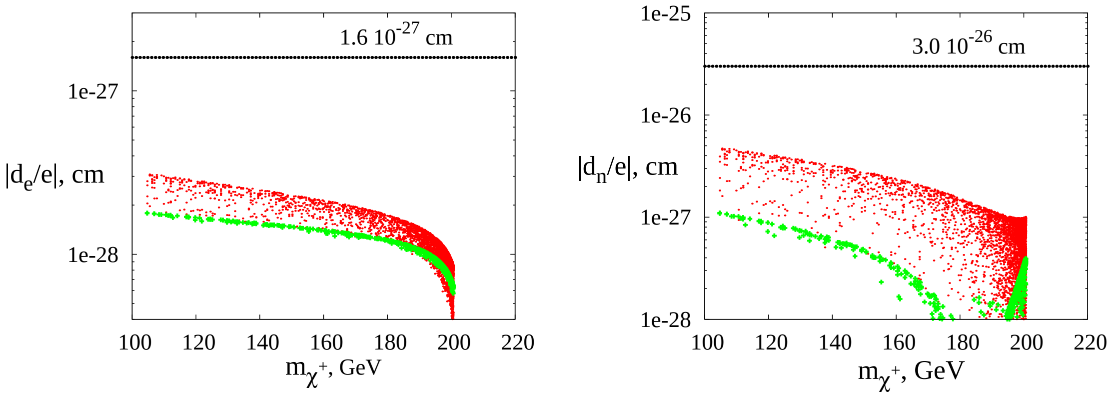

Figure 5: The EDM of electron (left) and neutron (right) as a function of the mass of the lightest chargino m_{χ^+}; dotted lines represent the experimental bound $|d_e| < 1.6 \cdot 10^{-27}$e cm and $|d_n| < 3.0 \cdot 10^{-26}$ e cm.

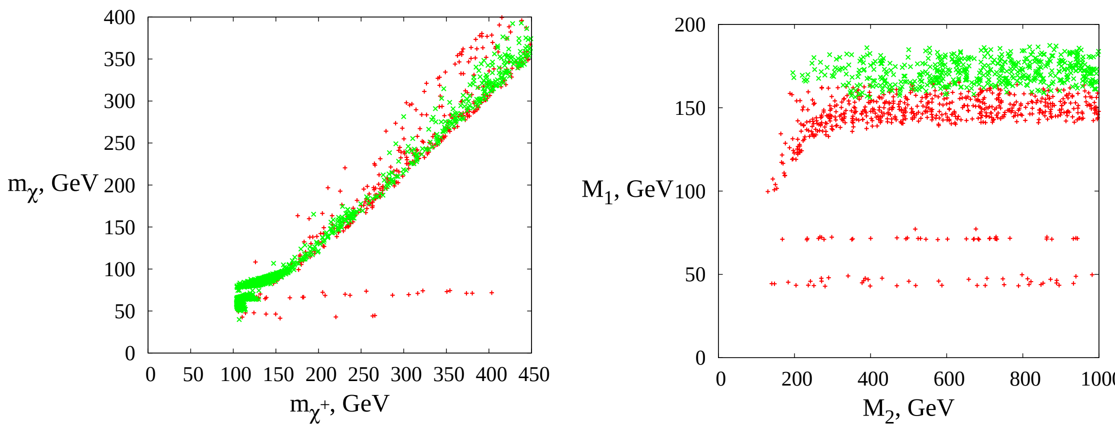

Figure 6: Points in (m_{χ^+}, m_χ) plane, *i.e.* the lightest chargino and the lightest neutralino (left) and in $(M_2,\ M_1)$ plane (right), which correspond to models with the correct relic abundance of singlino ($|N_{55}| > 0.5$, green (light grey) oblique crosses) and non-singlino (red / dark grey crosses) dark matter.

$m_\chi \sim 0.5 M_h$ or $0.5 M_Z$ the main channel is the resonant one, $\chi\chi \to h^*(Z^{0*}) \to f\bar{f}$. One concludes that dark matter problem can also be solved in the framework of considered models.

To summarize, the split NMSSM models are capable of solving both baryon asymmetry and dark matter problems and can be probed by the next generation of EDM experiments. The collider phenomenology of this model is quite similar to one of minimal split SUSY, if singlino-neutralino and higgs-singlet mixing is small. In the opposite case there are additional signatures of this model resembling ones in non-split NMSSM. We leave the study of LHC prospects in probing this model for the future.

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