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Split NMSSM with electroweak baryogenesis

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Abstract: In light of the Higgs boson discovery and other results of the LHC we reconsider generation of the baryon asymmetry in the split Supersymmetry model with an additional singlet superfield in the Higgs sector (non-minimal split SUSY). We find that successful baryogenesis during the first order electroweak phase transition is possible within a phenomenologically viable part of the model parameter space. We discuss several phenomenological consequences of this scenario, namely, predictions for the electric dipole moments of electron and neutron and collider signatures of light charginos and neutralinos.

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Contents

1 Introduction

Any phenomenologically viable particle physics model should explain the observed asymmetry between matter and antimatter in the Universe. The analysis of the anisotropy and polarization of the cosmic microwave background provided by WMAP collaboration gives the following baryon-to-photon ratio [1]

$$\frac{n_B}{n_\gamma} = (6.19 \pm 0.14) \times 10^{-10}. \tag{1.1}$$

To generate the baryon asymmetry of the Universe, three Sakharov's conditions should be satisfied [2]: (i) baryon number violation, (ii) C- and CP-violation and (iii) departure from thermal equilibrium. The latter condition can be realized, in particular, during the strong first order electroweak phase transition (EWPT) which proceeds via nucleation and expansion of bubbles of new phase in the hot plasma of the early Universe (for a recent discussion see, e.g., refs. [3, 4]). The baryon number violation during the EWPT happens due to sphaleron processes in the symmetric phase, while the CP-violation is induced by the interaction of particles in plasma with the bubble walls.

In the Standard Model of particle physics (SM) the Sakharov's conditions are only partly fulfilled. In particular, baryon number is violated via electroweak sphaleron transitions at high temperatures. At the same time, the electroweak transition in the SM is not the first order phase transition, hence no sufficient departure from thermal equilibrium. And the contribution of CP-violating CKM phases is too small in any case to provide (1.1). Finally, the electroweak sphalerons in the broken phase are too fast and would wash out any baryon asymmetry generated during the EWPT [5, 6]. Therefore, electroweak baryogenesis is only possible in SM extensions. These models should contain additional sources of CP-violation. Moreover, if the baryon asymmetry emerges at the electroweak scale, there should be a mechanism making the EWPT to be the strongly first order. A lot of scenarios for baryogenesis during the EWPT have been proposed and studied, see e.g. refs. [7–15].

The Minimal Supersymmetric Standard Model (MSSM) is one of the most elegant ways to extend the SM framework. In particular, the quadratic divergences cancellation and the gauge couplings unification are the major reasons for the interest in supersymmetric models. Moreover, the lightest neutralino is a natural dark matter candidate in the MSSM [16, 17]. In general, however, the Higgs boson discovery [18, 19], and non-observation of superpartners at the LHC shrink severely the region of MSSM parameter space. For instance, squarks and gluinos have been searched for at the LHC [20, 21], and the lower bounds on their masses have been set at the level of 1–2 TeV.

An attractive MSSM extension with splitted superpartner spectrum (split MSSM) has been proposed in refs. [22, 23]. The squarks and sleptons in this scenario are very heavy, while neutralinos and charginos remain light. Nevertheless, the main advantages of SUSY, i.e. the gauge coupling unification and existence of dark matter candidate, remain intact in this class of models. Remarkably, the absence of FCNC processes [24] is naturally understood within this setup. Unfortunately, the electroweak baryogenesis can not be realized in minimal versions of the split SUSY. This can be cured by introducing a gauge singlet superfield to the Higgs sector of the split MSSM [25]. The main features of this split Next-to-Minimal Supersymmetric extension of the Standard Model, *split NMSSM*, are the following. There are two energy scales in the split NMSSM, electroweak $M_{\mathrm{EW}} \sim 100\,\mathrm{GeV}$ and splitting scale $M_S \gg M_{\mathrm{EW}}$. At M_{EW} scale, the spectrum of split NMSSM contains the SM particles, one Higgs doublet H, the higgsino components $\tilde{H}_{u,d}$, winos $\tilde{W}$, bino $\tilde{B}$, and in addition a singlet complex scalar field N and its superpartner singlino $\tilde{n}$. The sleptons, squarks and four out of seven scalar degrees of freedom in the Higgs sector have masses of order the splitting scale M_S. Hence, these particles are decoupled from the spectrum at low energies $E < M_S$. At the same time, interactions of the scalar components of the singlet N with the Higgs boson are described at M_{EW} by a generic potential, which includes trilinear terms. These couplings are capable of strengthening the first order EWPT. In comparison with our previous study of BAU in split NMSSM [25] several revisions and improvements have been made in the present paper:

- We revisit the scenario of ref. [25] in view of the Higgs boson discovery. With respect to what was known by the time when ref. [25] appeared, we include the one-loop threshold corrections to the Higgs boson mass at EW scale.

- Scanning over free dimensionless couplings $(k, \lambda, \tan\beta)$ we show that allowed parameter space in split NMSSM is shrunk severely. Nevertheless, the observed BAU (1.1) can be generated during strong first order EWPT for the splitting scale of order 10 TeV.

- We discuss some phenomenological implementation of split NMSSM in the light of the recent electron's EDM bound [26]. This experimental result also strongly constrains the viable parameter space of split NMSSM.

In [25] it has also been shown that apart from successful explanation of the BAU the model supports the lightest neutralino as a viable dark matter candidate. In this study we concentrate mainly on implications of our model in view of the baryon asymmetry and leave discussion of possible dark matter candidates and their signatures for future analysis.

This paper is organized as follows. In section 2 we discuss the structure of split NMSSM. In section 3 we explore the phenomenologically allowed region of the model parameters consistent with the Higgs boson of mass $m_H \simeq 125\,\text{GeV}$. In sections 4 and 5 we study the strong first order EWPT and the baryon asymmetry of the Universe, respectively, for the relevant split NMSSM parameter space. In section 6 we perform an analysis of the electron and neutron EDMs. There we also discuss the spectra of charginos and neutralinos, which can be probed at the LHC experiments. In appendix A we calculate one-loop renormalization group (RG) corrections to the Higgs boson mass, which are needed to find the allowed region of parameter space in the split NMSSM scenario.

2 Non-minimal split supersymmetry

In this section we discuss the Lagrangian and particle content of the split NMSSM. Above the splitting scale M_S, the model is described by generic[1] NMSSM superpotential

$$W = \lambda \hat{N}\hat{H}_u\epsilon\hat{H}_d + \frac{1}{3}k\hat{N}^3 + \mu\hat{H}_u\epsilon\hat{H}_d + r\hat{N}, \tag{2.1}$$

where $\hat{H}_{u,d}$ are superfields of the Higgs doublets, $\hat{N}$ is a chiral superfield singlet with respect to $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ gauge group. In our notations we closely follow ref. [25]. Soft supersymmetry breaking terms are described by the potential

$$-\mathcal{L}_{\text{soft}} = \left(\lambda A_\lambda N H_u\epsilon H_d + \frac{1}{3}kA_k N^3 + \mu B H_u\epsilon H_d + A_r N + \text{h.c.}\right) \tag{2.2}$$

$$+ m_u^2 H_u^\dagger H_u + m_d^2 H_d^\dagger H_d + m_N^2|N|^2. \tag{2.3}$$

Components of the Higgs doublets $H_{u,d}$ and singlet field N are defined as

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \qquad N = (S + iP)/\sqrt{2}, \tag{2.4}$$

where S and P are the scalar and pseudoscalar parts of the singlet N, correspondingly. We introduce the following notations: $\tan\beta \equiv \langle H_u^0\rangle/\langle H_d^0\rangle$, $v_S \equiv \langle S\rangle$ and $v_P \equiv \langle P\rangle$.

An explicit analysis of the particle spectrum in split NMSSM was performed in ref. [25]. We nevertheless briefly discuss the particle content of the scalar sector at energies below the splitting scale. There are ten scalar degrees of freedom at the splitting scale M_S, coming

[1] A quadratic in $\hat{N}$ term can be eliminated by a field redefinition.

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from (2.4). It is shown in ref. [25] that if the soft SUSY breaking parameter, $B\mu$, m_u^2 and m_d^2 are of order the squared splitting scale, M_S^2, then two charged Higgses, one pseudoscalar and one neutral scalar Higgs bosons are heavy and thus decoupled from the low energy spectrum, while a fine-tuning is required for the mass of the lightest Higgs boson H and two singlets, S, P to be at the electroweak scale. Three Goldstone modes are eaten by $W^{\pm}$ and Z^0 due to the Higgs mechanism. We emphasize that the particle spectrum in the split NMSSM (as well as in any split SUSY model) below M_S requires a fine-tuning of the soft dimensionful parameters [25].

The scalar lagrangian at energies below M_S has the form

$$
\begin{aligned}
-\mathcal{L}_{\mathrm{V}} = & -m^2 H^\dagger H + \frac{\tilde{\lambda}}{2}\left(H^\dagger H\right)^2 + i\tilde{A}_1 H^\dagger H\left(N^* - N\right) + \tilde{A}_2 H^\dagger H\left(N + N^*\right) + 2\kappa_1 |N|^2 H^\dagger H \\
& + \kappa_2 H^\dagger H\left(N^2 + N^{*2}\right) + \tilde{m}_N^2 |N|^2 + \lambda_N |N^2|^2 + \frac{1}{3}\tilde{A}_k\left(N^3 + N^{*3}\right) + \tilde{A}_r\left(N + N^*\right) \\
& + \left(\frac{\tilde{m}^2}{2} N^2 + \frac{1}{2}\tilde{A}_3 N^2 N^* + \xi N^4 + \frac{\eta}{6} N^3 N^* + \text{h.c.}\right),
\end{aligned}
\tag{2.5}
$$

here the quartic couplings $\tilde{\lambda}$, κ, κ_1, κ_2 and λ_N at the electroweak scale are related via renormalization group equations to g, g' λ, k and $\tan\beta$ at the scale M_S. For future references we present here only the matching condition for the Higgs quartic coupling at the splitting scale M_S,

$$
\tilde{\lambda}(M_S) = \frac{\bar{g}^2}{4}\cos^2 2\beta + \frac{\lambda^2}{2}\sin^2 2\beta, \tag{2.6}
$$

where $\bar{g}^2 \equiv g^2 + (g')^2$. Other matching conditions have been explicitly written in [25]. Soft fermion masses and Yukawa interactions below M_S are described by the Lagrangian

$$
\begin{aligned}
-\mathcal{L}_{\mathrm{Y}} = & \frac{M_2}{2}\tilde{W}^a\tilde{W}^a + \frac{M_1}{2}\tilde{B}\tilde{B} + (\mu + \kappa N)\,\tilde{H}_u^T \epsilon \tilde{H}_d - kN\tilde{n}\tilde{n} \\
& + H^\dagger\left(\frac{1}{\sqrt{2}}\tilde{g}_u\sigma^a\tilde{W}^a + \frac{1}{\sqrt{2}}\tilde{g}'_u\tilde{B} - \lambda_u\tilde{n}\right)\tilde{H}_u \\
& + H^T\epsilon\left(-\frac{1}{\sqrt{2}}\tilde{g}_d\sigma^a\tilde{W}^a + \frac{1}{\sqrt{2}}\tilde{g}'_d\tilde{B} - \lambda_d\tilde{n}\right)\tilde{H}_d + \text{h.c.},
\end{aligned}
\tag{2.7}
$$

where M_2 and M_1 are wino and bino soft mass parameters in $\mathrm{SU}(2)_L$ and $\mathrm{U}(1)_Y$ gaugino sectors, respectively. Matching equations for the dimensionful couplings in (2.5) also can be found in [25]. For simplicity we take their values directly at electroweak scale rather than solving RG equations for them from M_S down to electroweak energies. In order to reduce the number of trilinear couplings we assume that Higgs-scalar $(H - S)$ and Higgs-pseudoscalar $(H - P)$ mixing terms in their squared mass matrix are equal to zero at the EW energy scale. This implies appropriate relations for the trilinear couplings $\tilde{A}_1$ and $\tilde{A}_2$,

$$
\tilde{A}_1 = \sqrt{2}(\kappa_1 - \kappa_2)v_P, \qquad \tilde{A}_2 = -\sqrt{2}(\kappa_1 + \kappa_2)v_S. \tag{2.8}
$$

From the very beginning we admit explicit CP-violation by taking purely imaginary μ-term and from lagrangian (2.5) we relate its value through the following matching condition at M_S scale

$$
\operatorname{Im}\mu = \tilde{A}_1/\lambda \tag{2.9}
$$

neglecting small RG corrections.

With the all above assumptions, we are left with only seven independent dimensionful parameters of the model at the EW scale

$$(v_S, \quad v_P, \quad M_1, \quad M_2, \quad \tilde{A}_k, \quad \tilde{A}_3, \quad \tilde{A}_r). \tag{2.10}$$

Let us note that using minimization conditions for the potential (2.5), soft squared masses m^2, $\tilde{m}^2$ and $\tilde{m}_N^2$ can be re-expressed via vevs of the scalar fields [25]. In what follows to get numerical results, for concreteness, we set

$$\tilde{A}_3 = \tilde{A}_r = 0, \quad \tilde{A}_k = -1.1\,\text{GeV}, \tag{2.11}$$

at the EW scale, while scanning over all the other four parameters. We advertise that the two singlet vevs v_S and v_P play very prominent role in developing the EWPT, which is discussed below in section 4.

3 Predictions for the Higgs boson mass

In this section we describe the scanning over the set of three dimensionless parameters $(\tan\beta, \lambda, k)$ fixed at scale M_S and calculate the mass of the Higgs boson resonance. We outline the region of model parameter space consistent with the SM-like Higgs boson with mass about 125 GeV.

In our procedure we choose dimensionless couplings of the model at the splitting scale and calculate the value of the Higgs boson mass by solving RG equations at next-to-leading order in coupling constants (NLO). We start solving the truncated part of the RG equations from the EW up to the splitting scale for the SM couplings

$$(g', \quad g, \quad g_s, \quad y_t), \tag{3.1}$$

where g_s is $SU(3)_c$ gauge coupling and y_t denotes the top Yukawa coupling. Initial conditions for RG equations for these couplings at the EW scale are taken as follows [24]

$$\alpha_s(M_Z) = 0.118\,, \quad M_Z = 91.19\,\text{GeV}\,, \quad M_W = 80.39\,\text{GeV}, \quad \text{and} \quad y_t(M_t) = 0.95.$$

Next, we use complete set of the RG equations for dimensionless couplings of the split NMSSM

$$(g', \quad g, \quad g_s, \quad y_t, \quad \tilde{\lambda}), \quad (\tilde{g}_{u,d}, \quad \tilde{g}'_{u,d}, \quad \lambda_{u,d}, \quad \kappa, \quad \kappa_{1,2}, \quad k, \quad \lambda_N, \quad \xi, \quad \eta). \tag{3.2}$$

Corresponding RG equations can be found in ref. [25]. In order to obtain values of the couplings (3.2) at low energies, the values of $\tan\beta$, λ and k are chosen randomly at the splitting scale M_S from the following perturbative regions

$$-0.6 < k < 0.6, \quad 0 < \lambda < 0.7, \quad 0 < \tan\beta < 30. \tag{3.3}$$

Then we solve the complete set of the RG equations from M_S down to the EW scale by using matching condition for Yukawa and quartic couplings [25]. This procedure doesn't guarantee the correct value of top Yukawa coupling at low energy $y_t(M_t)$. Therefore,

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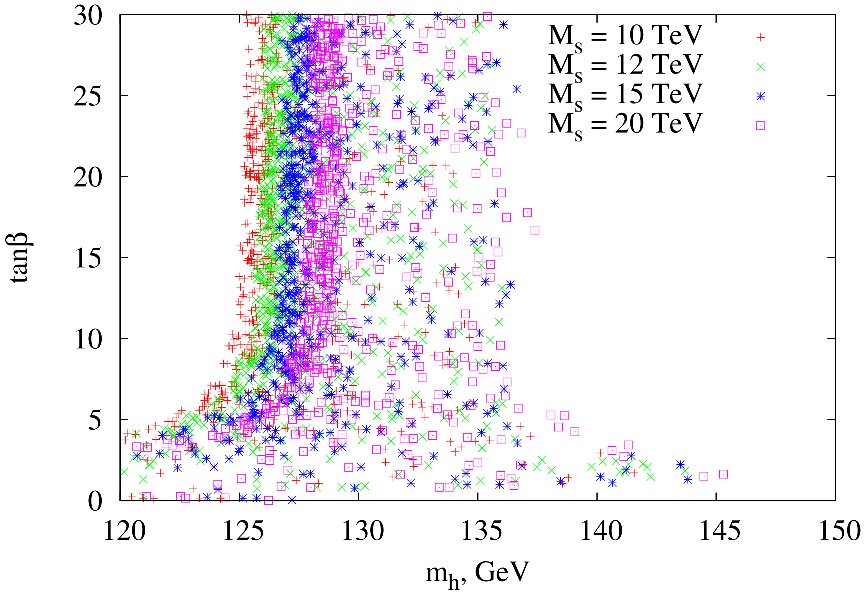

Figure 1. Prediction for the Higgs boson mass m_h as a function of M_S and $\tan\beta$. We assumed here that the Yukawa top coupling falls within the range $y_t^{\text{lower}} < y_t < y_t^{\text{upper}}$, see the main text for details.

we tune $y_t(M_S)$ to obtain the value of $y_t(M_t)$ within the error bars (for details see A.3 and refs. [25, 27]). We include a part of threshold correction [28] to the Higgs quartic coupling (2.6) at the splitting scale resulted in the following modification

$$\tilde{\lambda} \to \tilde{\lambda} + \delta\tilde{\lambda}, \tag{3.4}$$

where $\delta\tilde{\lambda}$ is a conversion term from $\overline{\text{DR}}$ to $\overline{\text{MS}}$ renormalization schemes at M_S,

$$\delta\tilde{\lambda} = -\frac{1}{16\pi^2}\left[\frac{9}{100}g_1^4 + \frac{3}{10}g_1^2 g_2^2 + \left(\frac{3}{4} - \frac{\cos^2 2\beta}{6}\right)g_2^4 + \frac{3}{400}(5g_2^2 + 3g_1^2)^2 \sin^2 4\beta\right]. \tag{3.5}$$

We use here the convention $g_1^2 = (5/3)g'^2$ and $g_2 = g$ adopted in Grand Unified Theories (GUT). The remaining part of the threshold correction to $\tilde{\lambda}$ depends on hierarchy of masses of heavy scalars near the splitting scale and it has not been taken into account. We should keep it in mind when interpreting the results. Next, we calculate the pole mass of the Higgs boson including one-loop threshold corrections at the electroweak scale, see appendix A for details. In figure 1 we show prediction for the Higgs boson mass obtained with various values of split scale M_S and $\tan\beta$. It follows from figure 1 that for most of the models the Higgs mass shifts by several GeVs if one increases the splitting scale M_S from 10 to 20 TeV for $\tan\beta > 10$. The similar behavior was observed in split MSSM [28]. This is attributed to a large quantum correction coming from heavy stops.

Now, we require that the pole mass of the Higgs boson (A.1) and y_t at $\overline{\mu} = M_t$ fall within the following ($\pm 1\sigma$) ranges

$$125.3\,\text{GeV} < m_h^{\text{pole}} < 125.9\,\text{GeV}, \quad y_t^{\text{lower}} < y_t < y_t^{\text{upper}}.$$

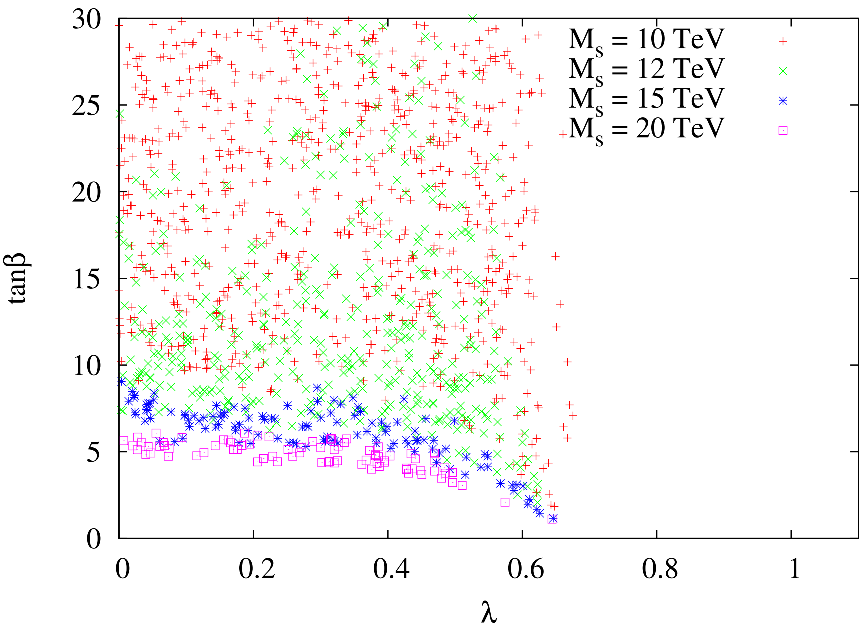

Figure 2. Allowed regions for $\tan\beta$ and $\lambda(M_S)$ for various values of the splitting scale M_S.

Here we use the average value $m_h = 125.6 \pm 0.3\,\text{GeV}$ from CMS [18] and ATLAS [19] combined results (for details see, e.g., ref. [24] and references therein). Lower and upper limits for y_t are extracted from eq. (A.29) and correspond to $M_t^{\text{lower}} = 172.3\,\text{GeV}$ and $M_t^{\text{upper}} = 174.1\,\text{GeV}$ respectively. In figure 2 we show the selected models in $(\tan\beta, \lambda)$-plane for the values of the splitting scale M_S varying from 10 to 20 TeV. One can see that for $\tan\beta > 5$ parameter λ can take arbitrary values in the allowed perturbative region. For $\tan\beta \simeq 1$ the allowed region shifts to the maximal values of λ which follows from the matching condition (2.6). We check that λ is in the perturbative regime up to the GUT scale. In addition, as follows from figure 2, the phenomenologically possible values of $\tan\beta$ grow with decreasing of the splitting scale M_S for $\lambda < 0.4$. This is again related to the balance between the tree-level and loop-induced contributions to the Higgs boson mass. The regions where $\tan\beta$ is either large ($\beta \to \pi/2$) or small ($\beta \to 0$) correspond to the decoupling of the second term in (2.6). We find that for $M_S \to \infty$ the allowed regions for $\tan\beta$ and λ shrink to $\tan\beta \to 1$ and $\lambda \to 0$, respectively.

As it follows from (2.6) the coupling k does not enter the matching condition for $\tilde{\lambda}$ at M_S and we find that the value of the Higgs boson mass in the model is almost independent of the coupling constant k within the perturbative ranges (3.3). In what follows, we choose two close benchmark setups for the free parameters

$$\text{Setup 1}: \qquad M_S = 12\,\text{TeV}\,,\ \tan\beta = 9.21\,,\ \lambda = 0.559\,,\ k = -0.5\,; \tag{3.6}$$

$$\text{Setup 2}: \qquad M_S = 10\,\text{TeV}\,,\ \tan\beta = 10.0\,,\ \lambda = 0.611\,,\ k = -0.5\,. \tag{3.7}$$

The both benchmark models are well inside the allowed regions in figure 2. For calculation of the threshold correction the relevant dimensionful parameters are taken to be $M_2 = 1\,\text{TeV}$, $M_1 = 300\,\text{GeV}$ and $\text{Im}\,\mu = 120\,\text{GeV}$. As it has been found in [25] the re-

	$\tilde{g}_u$	$\tilde{g}_d$	$\tilde{g}'_u$	$\tilde{g}'_d$	λ_u	λ_d	κ	κ_1	κ_2	λ_N
Setup 1	0.650	0.070	0.347	0.037	0.057	−0.513	0.560	0.251	−0.022	0.208
Setup 2	0.649	0.065	0.347	0.034	0.056	−0.560	0.609	0.297	−0.021	0.207

Table 1. Dimensionless couplings at the electroweak scale.

sulting baryon asymmetry is directly related to the value of λ. Thus the coupling λ is rather large for both chosen models. The relevant Yukawa and quartic couplings at the electroweak scale, $\overline{\mu} = M_t = 173.2\,\text{GeV}$, are presented in table 1. Below we use these couplings in the analysis of the strong first order EWPT (section 4), in the calculation of BAU (section 5) and to estimate the values of EDMs of the electron and neutron (section 6).

4 Strong first order EWPT

In this section we revisit the results of ref. [25] for the strongly first order electroweak phase transition in the split NMSSM within the region of the parameter space favored by the measured value of the Higgs boson mass ($m_h \simeq 125\,\text{GeV}$). The strength of EWPT in various versions of NMSSM has been studies previously in [25, 31–36]. In calculation of the one-loop effective potential at finite temperature $V_T^{\text{eff}}(h, S, P)$ we use the same procedure as described in ref. [25]. We apply it to find the region of parameter space where the first order EWPT is possible. In order to avoid baryon number washout after the phase transition the condition $v_c/T_c \gtrsim 1.1$ has to be satisfied [29] (see also recent revision in [30]). Here v_c is the Higgs VEV at the critical temperature T_c. We define T_c as a temperature at which one bubble of the broken phase begins to nucleate within a causal space-time volume of the Universe. The latter is determined by the Hubble parameter $\mathcal{H}(T)$ as

$$\mathcal{H}^{-4}(T) = (M_{\text{Pl}}^*/T^2)^4. \tag{4.1}$$

The bubble nucleation rate in a unit space-volume has the form

$$\Gamma(T) \simeq (\text{prefactor}) \times T^4 \exp(-S_3/T)\,, \tag{4.2}$$

where $S_3 = S_3(T)$ is the free energy of the critical bubble at a given temperature

$$S_3(T) = 4\pi \int_0^\infty dr\, r^2 \left[\frac{1}{2}\left(\frac{dh}{dr}\right)^2 + \frac{1}{2}\left(\frac{dS}{dr}\right)^2 + \frac{1}{2}\left(\frac{dP}{dr}\right)^2 + V_T^{\text{eff}}(h, S, P)\right]. \tag{4.3}$$

Here $h(r), S(r)$ and $P(r)$ are the radial configurations of the scalar fields, which minimize the functional S_3. Therefore, the probability that the bubble is nucleated inside a causal volume reads

$$P \sim \Gamma \cdot \mathcal{H}^{-4} \sim \frac{M_{\text{Pl}}^{*4}}{T^4} \exp(-S_3/T). \tag{4.4}$$

The first bubble nucleates when $P \sim 1$, which yields a rough estimate for the nucleation criterion $S_3(T)/T \sim 4 \ln\left(\frac{M_{\text{Pl}}^*}{T}\right) \sim 150$, where T is a typical temperature of order the electroweak energy scale, $T \simeq M_{\text{EW}}$. More accurate calculation reveals [37]

$$135 < S_3(T_c)/T_c < 140. \tag{4.5}$$

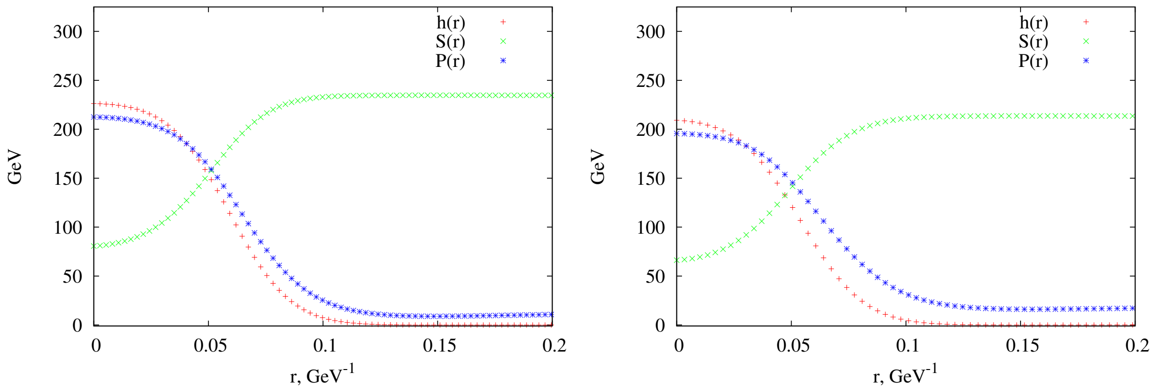

Figure 3. The critical bubble profile for the parameter set presented in tables 1 and 2. Left and right panels correspond to Setups (1) and (2), respectively.

	v_S	v_P	$\mathrm{Im}\,\mu$	T_c	v_c	S_c	P_c	S_s	P_s	S_3/T_c
Setup 1	60	220	151.68	67.5	233.29	60.04	219.35	234.53	11.79	136.41
Setup 2	47.5	202.5	149.7	79.0	220.88	47.59	201.29	213.31	18.65	139.58

Table 2. Parameters for the first order EWPT in the split NMSSM.

We recall that singlet vevs v_S and v_P are the input parameters of our model. The vacuum (v, v_S, v_P) is the global minimum of the effective potential $V^{\rm eff}_{T=0}$ in the broken phase. At the finite temperature $T \neq 0$, this broken minimum is shifted due to the thermal corrections

$$(v, v_S, v_P) \to (v_c, S_c, P_c). \tag{4.6}$$

In order to find numerically the profile of the critical bubbles, we use the method described in [38–41] and later modified in ref. [25]. Namely, starting with an ansatz bounce configuration we search iteratively the minimum of the functional, which includes a squared sum of scalar equations of motion with appropriate boundary conditions [25]. Scanning over (v_S, v_P) parameter space we find the bounce configurations, $h(r)$, $S(r)$ and $P(r)$, which minimize latter functional and satisfy the nucleation condition (4.5). In figure 3 we show dependence of the critical scalar fields on the radial coordinate for the selected benchmark models at their critical temperatures. The corresponding values of the relevant physical parameters are shown in table 2. All dimensionful parameters in table 2 are in GeV. We observe considerable change in the values of the pseudoscalar field P in the broken and in the symmetric phases. This will be the source of CP-violation for generation of the baryon asymmetry during the EWPT.

5 Baryon asymmetry

In this section we discuss the baryon asymmetry created during the EWPT in the hot electroweak plasma for the benchmark setups (3.6), (3.7) and parameters shown in table 2. We solve the relevant diffusion equations [25] for type i particle asymmetry number densities

n_i in plasma with CP-violating sources. See also ref. [42] for a more detailed analysis. We summarize below the main technical ingredients for BAU calculation.

The baryon asymmetry of the Universe, n_B, is created anomalously during the weak sphaleron transition in the symmetric phase [43]. This result can be expressed in the following form

$$n_B = -\frac{n_F \Gamma_{ws}}{v_w} \int_{-\infty}^{0} dz n_{\mathrm{Left}}(z) e^{z\mathcal{R}/v_w}, \tag{5.1}$$

where $\Gamma_{ws} = 6\kappa_{ws}\alpha_w^5 T$ is the weak sphaleron rate with $\kappa_{ws} = 20 \pm 2$ [46] and n_{Left} is the asymmetry density number of weak doublet fermions. The relaxation coefficient $\mathcal{R}$ is given by [47, 48] $\mathcal{R} = \frac{5}{4} n_F \Gamma_{ws}$, and $n_F = 3$ is the number of generations. It was shown in ref. [45], that left-handed fermion density is given by

$$n_{\mathrm{Left}} = A_t \cdot (n_h + n_H), \tag{5.2}$$

where the factor $A_t = -3y_t^2/(64\pi^2)$ describes the one-loop contribution of top quark to the statistical coefficients [25]. The combinations of the Higgs bosons and higgsino densities are

$$n_h = n_{H^+} + n_{H^0} + n_{\tilde{H}_u^+} + n_{\tilde{H}_u^0} + n_{\tilde{H}_d^-} + n_{\tilde{H}_d^0}, \tag{5.3}$$

$$n_H = n_{H^+} + n_{H^0} + n_{\tilde{H}_u^+} + n_{\tilde{H}_u^0} - n_{\tilde{H}_d^-} - n_{\tilde{H}_d^0}. \tag{5.4}$$

We emphasize that the densities n_i are local quantities which depend on $z + v_w t$, here z is the coordinate perpendicular to the bubble wall, and v_w is the wall velocity.

In the split NMSSM, CP-symmetry gets violated spontaneously while the bubble walls expand in the hot plasma. Indeed, the main source of CP-violation is associated with the complex chargino mass matrix

$$M_{ch} = \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}}\tilde{g}_u h(z) \\ \frac{1}{\sqrt{2}}\tilde{g}_d h(z) & \tilde{\mu}(z) \end{pmatrix}, \tag{5.5}$$

where we define the spatially-dependent effective higgsino mass parameter as follows

$$\tilde{\mu}(z) = \mu + \kappa \left(S(z) + iP(z)\right)/\sqrt{2}. \tag{5.6}$$

In the above expressions, $h(z)$, $S(z)$ and $P(z)$ are the kink approximations of the bubble walls [43]

$$h(z) = \frac{1}{2} v_c \left(1 - \tanh\left[\alpha\left(1 - \frac{2z}{L_w}\right)\right]\right), \tag{5.7}$$

$$\begin{pmatrix} S(z) \\ P(z) \end{pmatrix} = \begin{pmatrix} S_c \\ P_c \end{pmatrix} - \frac{1}{2}\begin{pmatrix} \Delta S \\ \Delta P \end{pmatrix}\left(1 + \tanh\left[\alpha\left(1 - \frac{2z}{L_w}\right)\right]\right), \tag{5.8}$$

here v_c, S_c and P_c are the critical values of the scalar fields (see, e.g. table 2), $\Delta S \equiv S_c - S_s$ and $\Delta P \equiv P_c - P_s$. We set velocity of the bubble wall[2] equal to $v_w = 0.1$, the coefficient α is taken to be $3/2$. The bubble wall width L_w may be chosen in the range $5/T_c < L_w < 30/T_c$ consistent with the special study [11] and the WKB thick-wall restriction, $L_w T_c > 1$.

[2]See, e.g. ref. [50] for calculation of the late time bubble wall velocity in a singlet-extended Standard Model.

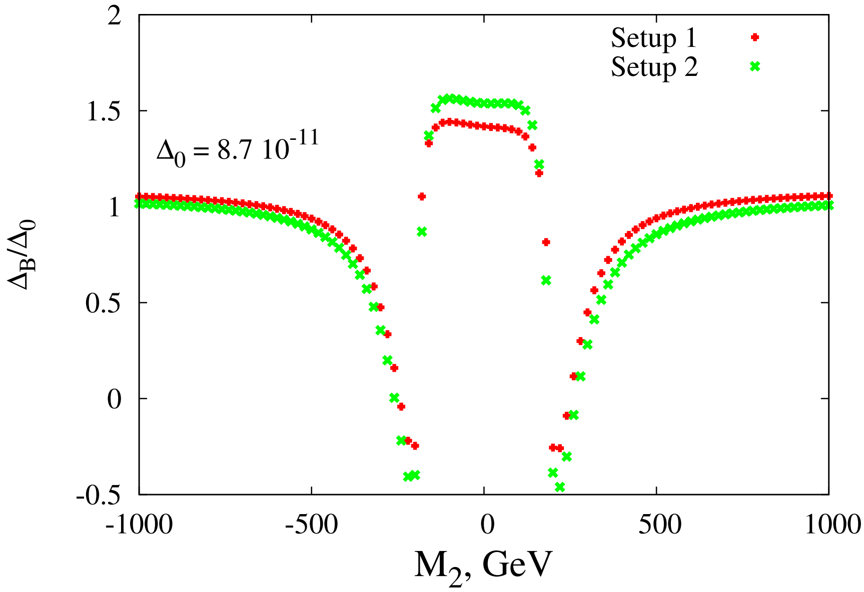

Figure 4. Plot of Δ_B/Δ_0 versus gaugino mass parameter M_2 for the parameter sets presented in tables 2 and 1.

We use the expressions for CP-violating sources from ref. [11] and numerically solve the set of diffusion equations for $n_h(z)$ and $n_H(z)$. Then, we calculate the asymmetry of left fermions using eq. (5.2) and by evaluating the integral (5.1) we obtain the baryon asymmetry generated during EWPT.

Let us consider the baryon-to-entropy ratio $\Delta_B = n_B/s$ with the entropy density

$$s = 2\pi^2 g_{\text{eff}} T^3/45,$$

where g_{eff} is the effective number of relativistic degrees of freedom at T_c. In figure 4 we show dependence of the baryon asymmetry Δ_B/Δ_0 on gaugino mass M_2 for different values of the wall thickness: namely, we take $L_w = 7/T_c$ and $L_w = 5/T_c$ for Setup 1 and 2, respectively. The value $\Delta_0 = 8.3 \times 10^{-11}$ corresponds to $n_B/n_\gamma = 6.2 \times 10^{-10}$ consistent with present measurements (1.1).

It follows from figure 4 that baryon asymmetry Δ_B is of order Δ_0 for large $M_2 \gtrsim 1\,\text{TeV}$. In this case, the heaviest chargino χ_2^+ (wino-like) decouples from the plasma, $|m_{\chi_2^+}| \simeq M_2$, and the lightest chargino (higgsino-like) acquires the mass $|m_{\chi_1^+}|$, which is determined by the effective $\tilde{\mu}(z)$-parameter in (5.6). Thus, the baryon asymmetry is generated due to the spontaneous CP-violation in the broken (and symmetric) phase. Detailed calculation of CP-violating sources [11] reveals that CP-violating sources in diffusion equations gain contributions which are proportional to the second derivative of $\text{Im}\,\tilde{\mu}(z)$ with respect to z coordinate. This means that baryon asymmetry Δ_B/Δ_0 is rather sensitive to the effective parameter,

$$\text{Im}(\tilde{\mu}'') \sim \kappa \Delta P/L_w^2. \tag{5.9}$$

In our numerical analysis, we tune the wall thickness L_w to obtain $\Delta_B/\Delta_0 \sim 1$ as $M_2 \to \infty$. At the same time from the very beginning we choose sufficiently large coupling κ (by taking

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large λ) and pseudoscalar VEV gradient $\Delta P = P_c - P_s$ and large value of $\tan\beta$. These features select models which are interesting for the realistic electroweak baryogenesis. As we will see in section 6 the latter condition is also preferred by present electron's EDM constraints. From figure 2 we see that large values of λ and $\tan\beta$ require moderate value of the splitting scale M_S, which hardly can be larger than 12–15 TeV.

In our analysis we can evaluate the baryon asymmetry in the limit $n_h \gg n_H$, following the approach, presented in ref. [49]. In this approximation the set of relevant diffusion equations [25] reduces to a single equation on n_h, and baryon asymmetry ratio, Δ_B/Δ_0, can be estimated analytically. In the limit when heaviest chargino decoupled, $m_{\chi_2^+} \approx M_2 \approx 1\,\text{TeV}$, one finds

$$\frac{\Delta_B}{\Delta_0} \approx 5.5 \cdot 10^2 \left(\frac{m_{\chi_1^+}}{T_c}\right)^2 \exp\left(-\frac{m_{\chi_1^+}}{T_c}\right) \frac{1}{(L_w T_c)^2}. \tag{5.10}$$

For $L_w = 5/T_c$, $T_c = 80\,\text{GeV}$ and $m_{\chi_1^+} = 239\,\text{GeV}$ this yields $\Delta_B/\Delta_0 \approx 10$. An order-of-magnitude discrepancy between the numerical, $\Delta_B/\Delta_0 \approx 1$, see figure 4, and analytic results (5.10), is due to the approximations which have been made for solving equation for n_h in the analytically approach. Let us note that here we estimate baryon asymmetry originated from chargino sector only. CP-violating sources from neutralino sector can change the calculated value of the asymmetry by a factor of order one.

6 EDM constraints and light chargino phenomenology

In this section we address some phenomenological implementation of the results discussed above. To begin with, we emphasize that current constraints on electric dipole moments of the electron and neutron provide strong limits for CP-violating physics in the split NMSSM. There are three relevant contributions to the EDM of electron or light quark [51, 54],

$$d_f = d_f^{H\gamma} + d_f^{HZ} + d_f^{WW},$$

where $d_f^{H\gamma}$, d_f^{HZ} and d_f^{WW} are the partial EDMs of fermion (lepton or quark), related to the exchange of $H\gamma$, HZ and W^+W^- bosons, respectively. General expressions for the electron's EDM d_e and neutron's EDM d_n were derived in ref. [54]. The values of d_e and d_n depend on chargino, $m_{\chi_i^+}$ $(i = 1, 2)$, and neutralino, $m_{\chi_j^0}$ $(j = 1, 5)$, masses as well as their mixing matrices.[3]

The most stringent upper limit on EDM of the electron, $|d_e/e| < 8.7 \times 10^{-29}\,\text{cm}$ at 90% CL, was obtained by ACME collaboration [26]. The current bound on neutron's EDM is $|d_n/e| < 3.0 \times 10^{-26}$ cm at 90 % CL [55]. In order to perform the numerical analysis for EDMs, we randomly scan over the following parameter space $0 < M_1, M_2 < 1000\,\text{GeV}$. In figure 5 we show dependence of $|d_e/e|$ on the lightest chargino mass $m_{\chi_1^+}$. One can see from the left panel of figure 5 that chargino masses in the ranges $225\,\text{GeV} < m_{\chi_1^+} < 239\,\text{GeV}$ and $220\,\text{GeV} < m_{\chi_1^+} < 235\,\text{GeV}$ are allowed for the Setup 1 and 2, respectively. We check that all these points correspond to large (about 1 TeV) values of M_2 and hence allow for

[3] We recall that neutralino state χ_j^0 in split NMSSM is a mixture of neutral bino $\tilde{B}^0$, wino $\tilde{W}^0$, higgsino $\tilde{H}_{u,d}^0$ and singlino $\tilde{n}$ states.

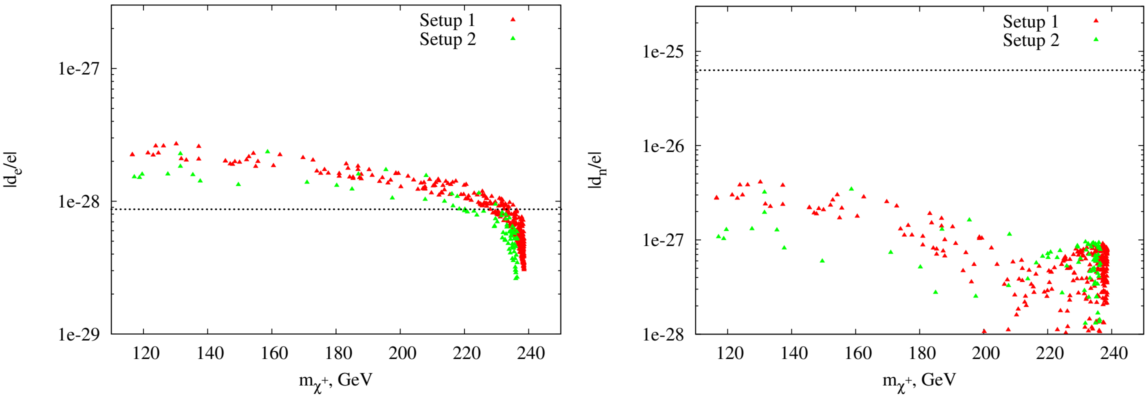

Figure 5. Left panel: the EDM of electron versus the lightest chargino mass $m_{\chi_1^+}$. Dotted lines represent the current experimental bound $|d_e/e| < 8.7 \times 10^{-29}$ cm. Right panel: the neutron's EDM with upper limit $|d_n/e| < 3.0 \times 10^{-26}$ cm. The relevant couplings, μ-terms and both singlet vevs v_S and v_P at $T = 0$ are given in tables 1 and 2.

correct value of the BAU. The numerical results for neutron EDM are shown on right panel of figure 5. One can see from figure 5 that predictions for the neutron EDMs satisfy the current experimental bound in all selected models. For the Setup 1 we present an examples of chargino and neutralino mass spectra which are consistent with the EDM bounds in figure 5 for $M_1 = 300$ GeV and $M_2 = 1$ TeV

- $m_{\chi_1^+} = 238.4$ GeV, $m_{\chi_2^+} = 1006.8$ GeV,
- $m_{\chi_1^0} = 133.9$ GeV, $m_{\chi_2^0} = 220.5$ GeV, $m_{\chi_3^0} = 268.0$ GeV, $m_{\chi_4^0} = 341.9$ GeV, $m_{\chi_5^0} = 1006.9$ GeV.

We find in this case, that LSP is singlino-like state with the mass $m_{\chi_1^0} = 133.9$ GeV. The dominant decay channel of the lightest chargino is $\chi_1^+ \to \chi_1^0 W^+$, which can be used to test split NMSSM model. In our analysis, we checked that the models satisfying EDM bounds are in agreement with the present CMS [56] and ATLAS [57] limits on chargino-neutralino production at LHC without light sleptons. Therefore, the split NMSSM is a phenomenologically viable and cosmologically attractive model which can be probed at the LHC run with pp collision energy of 13 TeV (and 14 TeV).

7 Conclusion

In this paper we revisit scenario of non-minimal split supersymmetry which contains at the electroweak scale, apart from minimal split supersymmetry particle content, singlet scalar and pseudoscalar states. We observe that within the phenomenologically allowed domain of the parameter space with the mass of the Higgs boson equal to 125 GeV it is possible to find particular models in which the strongly first order electroweak phase transition can be realized and moreover the needed amount of the baryon asymmetry of the Universe is generated. These models predict existence of light chargino state required for successful baryogenesis. We also find relatively light LSP with large admixture of

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singlino like state. Therefore, it can be considered as a potential dark matter candidate as suggested in ref. [25]. Predictions for the electric dipole moment of electron in these models are found to be about or somewhat larger than 2–3 $\cdot 10^{-29}e$ cm which is only by factor 3–4 smaller than the current upper limit on this quantity. This makes the searches for EDMs a promising tool to probe the split NMSSM.

We conclude by noting that in the previous study of this model [25] we also discussed the lightest neutralino as a viable dark matter candidate. In the present paper we have studied the possibility of successful baryon asymmetry production during the EWPT and related implications. We note that the phenomenologically allowed from the BAU investigation part of the parameter space of the model is very close to that of studied in [25]. We expect that the lightest neutralino can be produced in the Early Universe at the observed amount. However, a careful analysis is needed which should take into account experimental constraints from direct and indirect dark matter searches. We plan to discuss phenomenology of dark matter candidates in this model in the separate publication [62].

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A One loop corrections to Higgs mass in split NMSSM

In this appendix we calculate one-loop RG corrections to the mass of Higgs boson in split NMSSM scenario following refs. [27, 59]. In particular, in ref. [59] the radiative corrections to the Higgs mass were calculated in the NMSSM in ref. [59], while they were derived explicitly in split MSSM in ref. [27]. However, split MSSM computations [27] can be straightforwardly extended to the split NMSSM case by taking into account the radiative corrections from scalars, charginos and neutralinos,

$$(m_h^{\text{pole}})^2 = (m_h^{\text{tree}})^2(\overline{\mu}) + \delta_h^{\text{SM}}(\overline{\mu}) + \delta_h^{(S,P)}(\overline{\mu}) + \delta_h^{(C,N)}(\overline{\mu}), \tag{A.1}$$

where $(m_h^{\text{tree}})^2 = \tilde{\lambda}(\overline{\mu})v^2$ is the three level Higgs boson mass at $\overline{\mu}$ scale (dimensional renormalization scale in $\overline{\text{MS}}$ scheme); the remnant one-loop corrections in (A.1) are defined below in sections A.1 and A.2. We use the experimental value of the Higgs pole mass (A.1) to plot the figures for the allowed region of split NMSSM parameters in the main text.

A.1 Tree level potential of scalar sector in the broken phase

Applying the general results of ref. [59] we rewrite (2.5) in the broken phase,

$$H = (\phi_1 + v)/\sqrt{2}, \qquad N = (\phi_2 + v_S + i(\phi_3 + v_P))/\sqrt{2}, \tag{A.2}$$

where we denote perturbations of the scalar fields about the vacuum as $(\phi_1, \phi_2, \phi_3) = (h, S, P)$. Then, substituting (A.2) into (2.5) and using minimization conditions at the tree level, one can obtain

$$\mathcal{L}_V \supset -\sum_{ijkl} \lambda_{\phi_i\phi_j\phi_k\phi_l}\phi_i\phi_j\phi_k\phi_l - \sum_{ijk} \lambda_{\phi_i\phi_j\phi_k}\phi_i\phi_j\phi_k - \sum_{ij}\frac{1}{2}m^2_{\phi_i\phi_j}\phi_i\phi_j. \tag{A.3}$$

The quartic and trilinear couplings which are relevant for the calculation of the Higgs boson self energy and tadpoles in the scalar sector of the split NMSSM can be written as

$$\lambda_{\phi_1\phi_1\phi_1\phi_1} = \frac{1}{8}\tilde{\lambda}, \qquad \lambda_{\phi_1\phi_1\phi_2\phi_2} = \frac{1}{12}(\kappa_1+\kappa_2), \quad \lambda_{\phi_1\phi_1\phi_3\phi_3} = \frac{1}{12}(\kappa_1-\kappa_2), \tag{A.4}$$

$$\lambda_{\phi_1\phi_1\phi_1} = \frac{1}{2}\tilde{\lambda}v, \qquad \lambda_{\phi_1\phi_2\phi_2} = \frac{1}{3}(\kappa_1+\kappa_2)v, \quad \lambda_{\phi_1\phi_3\phi_3} = \frac{1}{3}(\kappa_1-\kappa_2)v, \tag{A.5}$$

$$\lambda_{\phi_1\phi_3\phi_2} = \lambda_{\phi_1\phi_2\phi_3} = 0. \tag{A.6}$$

The parameters of the scalar squared mass matrix read

$$m^2_{\phi_3\phi_3} = (\kappa_1-\kappa_2)v^2 + \lambda_N(3v_P^2+v_S^2) - \tilde{\lambda}(v_P^2+v_S^2), \tag{A.7}$$

$$m^2_{\phi_2\phi_3} = m^2_{\phi_3\phi_2} = -\sqrt{2}\tilde{A}_k v_P + 2\lambda_N v_P v_S. \tag{A.8}$$

$$m^2_{\phi_1\phi_1} = \tilde{\lambda}v^2, \;\; m^2_{\phi_2\phi_2} = (\kappa_1+\kappa_2)v^2 + \lambda_N(v_P^2+3v_S^2) + \Big(-\tilde{\lambda}+\tilde{A}_k/(\sqrt{2}v_S)\Big)(v_P^2+v_S^2), \tag{A.9}$$

$$m^2_{\phi_1\phi_3} = m^2_{\phi_3\phi_1} = m^2_{\phi_1\phi_2} = m^2_{\phi_2\phi_1} = 0. \tag{A.10}$$

One should diagonalize its 2×2 submatrix for the singlets $m^2_{\phi_i\phi_j}$, with $i,j = 2,3$, since off-diagonal mixings of ϕ_2 and ϕ_3 with the Higgs field ϕ_1 are set to be zero (A.10) (see also discussion before eq. (2.8)). We denote the singlet eigenstates by h_i and diagonalize $m^2_{\phi_i\phi_j}$ by an orthogonal matrix R_{ij}, such that

$$h_i = R_{ij}\phi_j. \tag{A.11}$$

The couplings that enter the calculation of the Higgs boson mass radiative corrections can be expressed as

$$\lambda_{\phi_i\phi_j h_k h_l} = 6\,R_{ka}\,R_{lb}\,\lambda_{\phi_i\phi_j\phi_a\phi_b}, \qquad \lambda_{\phi_i h_k h_l} = 3\,R_{ka}\,R_{lb}\,\lambda_{\phi_i\phi_a\phi_b}. \tag{A.12}$$

Following the prescription of ref. [59] we write down one-loop contribution of the scalar singlets to the Higgs boson mass[4]

$$\delta_h^{(S,P)}(m_h,\overline{\mu}) = \frac{1}{v}\,T_h^{(S,P)}(\overline{\mu}) - \Pi_h^{(S,P)}(m_h,\overline{\mu}), \tag{A.13}$$

where the Higgs boson self energy is

$$16\pi^2\,\Pi_h^{(S,P)}(p^2,\overline{\mu}) = \sum_{k=2,3} 2\lambda_{\phi_1\phi_1 h_k h_k} A_0(m_{h_k}) + \sum_{k,l=2,3} 2\lambda_{\phi_1 h_k h_l}\lambda_{\phi_1 h_k h_l} B_0(p, m_{h_k}, m_{h_l}), \tag{A.14}$$

and the tadpole contributions are

$$16\pi^2 T_h^{(S,P)}(\overline{\mu}) = \sum_{k=2,3} \lambda_{\phi_1 h_k h_k} A_0(m_{h_k}). \tag{A.15}$$

[4] Here only scalars ϕ_2 and ϕ_3 are taken into account; all signs and prefactors correspond to notations from ref. [59].

The loop functions $A_0(m)$ and $B_0(p, m_1, m_2)$ depend on the renormalization scale $\overline{\mu}$ and can be written in the form

$$A_0(m) = m^2\left(C_{\rm UV} + 1 - \ln\frac{m^2}{\overline{\mu}^2}\right), \quad B_0(p, m_1, m_2) = C_{\rm UV} - \ln\frac{p^2}{\overline{\mu}^2} - f_B(x_+) - f_B(x_-), \tag{A.16}$$

where $C_{\rm UV} = 1/\epsilon - \gamma_E + \ln 4\pi$, $f_B(x) = \ln(1-x) - x\ln(1-x^{-1}) - 1$ with

$$x_\pm = \frac{s \pm \sqrt{s^2 - 4p^2(m_1^2 - i\epsilon)}}{2p^2}, \quad s = p^2 - m_2^2 + m_1^2. \tag{A.17}$$

A simplified formula for $B_0(p^2, m_1, m_2)$ at $p^2 = 0$ read [60],

$$B_0(0, m_1, m_2) = -\ln\frac{M^2}{\overline{\mu}^2} + 1 + \frac{m^2}{m^2 - M^2}\ln\frac{M^2}{m^2}, \tag{A.18}$$

where $M = \max(m_1, m_2)$ and $m = \min(m_1, m_2)$.

A.2 Chargino-neutralino sector of split NMSSM

The Lagrangian of interest for chargino/neutralino sector is

$$\begin{aligned} -\mathcal{L}^{(C,N)}_{\rm int} &= -\frac{1}{2}h\,\bar{\chi}^0_i\left(R^{N*}_{(ij)}P_L + R^N_{(ij)}P_R\right)\chi^0_j + \qquad (A.19)\\ &+\left(g\bar{\chi}^+_i\gamma^\mu\left(C^R_{ij}P_R + C^L_{ij}P_L\right)\chi^0_j W^+_\mu + \frac{1}{\sqrt{2}}\bar{\chi}^+_i\left(R^C_{ij}P_R + L^C_{ij}P_L\right)\chi^+_j h + \text{h.c.}\right), \end{aligned}$$

where

$$R^N_{ij} = (\tilde{g}_u N_{i2} - \tilde{g}'_u N_{i1})N_{j4} - (\tilde{g}_d N_{i2} - \tilde{g}'_d N_{i1})N_{j3} + \sqrt{2}(\lambda_u N_{i4} - \lambda_d N_{i3})N_{j5} \tag{A.20}$$

$$R^N_{(ij)} = \frac{1}{2}(R^N_{ij} + R^N_{ji}), \qquad R^C_{ij} = (L^C_{ji})^* = \tilde{g}^*_u V_{i2}U_{j1} + \tilde{g}^*_d V_{i1}U_{j2}, \tag{A.21}$$

$$C^L_{ij} = N_{i2}V^*_{j1} - \frac{1}{\sqrt{2}}N_{i4}V^*_{j2}, \qquad C^R_{ij} = N^*_{i2}U_{j1} + \frac{1}{\sqrt{2}}N^*_{i3}U_{j2}. \tag{A.22}$$

Following ref. [27], let us consider the contribution of chargino and neutralino to the Higgs boson mass at one-loop level,

$$\delta^{(C,N)}_h = \Sigma^{(C,N)}_h(m_h, \overline{\mu}) + \frac{1}{v}T^{(C,N)}_h(\overline{\mu}) + \frac{\tilde{\lambda}v^2}{m^2_W}\Pi^{(C,N)}_{WW}(0, \overline{\mu}) \tag{A.23}$$

where $T^{(C,N)}_h = T^{(C)}_h + T^{(N)}_h$ is the Higgs boson tadpole contribution which involves terms

$$16\pi^2\,T^{(C)}(\overline{\mu}) = -2\sqrt{2}\sum_{i=1}^{2}\text{Re}\left[R^C_{ii}M^C_i A_0(M^C_i)\right], \tag{A.24}$$

$$16\pi^2\,T^{(N)}(\overline{\mu}) = 2\sum_{i=1}^{5}\text{Re}\left[R^N_{(ii)}M^N_i A_0(M^N_i)\right] \tag{A.25}$$

from chargino and and neutralino sector, respectively. The relevant self energies read $\Sigma_h^{(C,N)} = \Sigma_h^{(C)} + \Sigma_h^{(N)}$, where

$$16\pi^2\Sigma_h^{(C)}(p^2,\overline{\mu}) = \sum_{i,j=1}^{2}\left[\frac{1}{2}(|L^C_{ij}|^2+|R^C_{ij}|^2)\Big(A_0(M_i^C)+A_0(M_j^C)+\right. \tag{A.26}$$

$$\left.+\,((M_i^C)^2+(M_j^C)^2-p^2)B_0(p^2,M_i^C,M_j^C)\Big)+2\mathrm{Re}M_i^C M_j^C R^C_{ij}(L^C_{ij})^* B_0(p^2,M_i^C,M_j^C)\right],$$

$$16\pi^2\Sigma_h^{(N)}(p^2,\overline{\mu}) = \sum_{i,j=1}^{5}\left[|R^N_{(ij)}|^2\Big(A_0(M_i^N)+A_0(M_j^N)+\right. \tag{A.27}$$

$$\left.+\,((M_i^N)^2+(M_j^N)^2-p^2)B_0(p^2,M_i^N,M_j^N)\Big)+2\mathrm{Re}M_i^N M_j^N R^N_{(ij)}(R^N_{(ij)})^* B_0(p^2,M_i^N,M_j^N)\right].$$

The last term in eq. (A.23) is the corrections from the contribution of chargino and neutralino into the $W^\pm$ boson self-energy

$$16\pi^2\,\Pi_{WW}^{(C,N)}(0,\overline{\mu}) =$$

$$= g^2\sum_{i=1}^{5}\sum_{j=1}^{2}\left((C^L_{ij}C^{L*}_{ij}+C^R_{ij}C^{R*}_{ij})\left[a^2\left(\ln\frac{a^2}{\overline{\mu}^2}-\frac{1}{2}\right)+b^2\left(\ln\frac{b^2}{\overline{\mu}^2}-\frac{1}{2}\right)+\frac{a^2b^2}{a^2-b^2}\ln\frac{a^2}{b^2}\right]+\right.$$

$$\left.+\,2(C^L_{ij}C^{R*}_{ij}+C^R_{ij}C^{L*}_{ij})\frac{ab}{a^2-b^2}\left[-a^2\left(\ln\frac{a^2}{\overline{\mu}^2}-1\right)+b^2\left(\ln\frac{b^2}{\overline{\mu}^2}-1\right)\right]\right), \tag{A.28}$$

where $a = M_j^C$ and $b = M_i^N$ are the mass eigenstates of chargino and neutralino, respectively. For the explicit calculation of Higgs mass (A.1), one should set $C_{\mathrm{UV}} = 0$ in (A.13) and (A.23).

A.3 One-loop correction to Yukawa coupling of top quark

The mass of the Higgs boson at one-loop level is quite sensitive to the Yukawa coupling of top quark, y_t. Hence, it is important to include the RG effects and threshold corrections from top quark sector for explicit analysis of one-loop corrections to the Higgs boson mass in the split NMSSM. Here we briefly summarize the results of [27] concerning corrections related to y_t. The top quark Yukawa coupling at the scale $\overline{\mu}$ can be extracted from its pole mass $M_t = 173.2 \pm 0.9\,\mathrm{GeV}$ [58],

$$y_t(\overline{\mu}) = \sqrt{2}\frac{M_t}{v}(1+\delta_t(\overline{\mu})), \tag{A.29}$$

where the threshold correction $\delta_t(\overline{\mu})$ is the sum of the QCD, EW and split NMSSM terms

$$\delta_t(\overline{\mu}) = \delta_t^{\mathrm{QCD}}(\overline{\mu}) + \delta_t^{\mathrm{EW}}(\overline{\mu}) + \delta_t^{(C,N)}(\overline{\mu}). \tag{A.30}$$

Explicit 3-loop calculation of $\delta_t^{\mathrm{QCD}}(\overline{\mu})$ was performed by [61] and at $\overline{\mu} = M_t$ it yields

$$\delta_t^{\mathrm{QCD}}(\overline{\mu}=M_t) = -\frac{4}{3}\left(\frac{\alpha_3(M_t)}{\pi}\right) - 9.1\left(\frac{\alpha_3(M_t)}{\pi}\right)^2 - 80\left(\frac{\alpha_3(M_t)}{\pi}\right)^3 \approx -0.060. \tag{A.31}$$

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The contribution of the EW term $\delta_t^{\rm EW}$ is negligible [27], $|\delta_t^{\rm EW}| < 0.001$. The term $\delta_t^{(C,N)}$ from chargino and neutralino in split NMSSM is given through the relation

$$\delta_t(\overline{\mu}) = -\frac{\Pi_{WW}^{(C,N)}(0,\overline{\mu})}{2M_W^2}, \tag{A.32}$$

where $\Pi_{WW}^{(C,N)}(0,\overline{\mu})$ is defined by eq. (A.28).

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