RECEIVED: November 7, 2017

REVISED: December 29, 2017

ACCEPTED: January 15, 2018

PUBLISHED: January 31, 2018

Exploring non-holomorphic soft terms in the framework of gauge mediated supersymmetry breaking

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ABSTRACT: It is known that in the absence of a gauge singlet field, a specific class of supersymmetry (SUSY) breaking non-holomorphic (NH) terms can be soft breaking in nature so that they may be considered along with the Minimal Supersymmetric Standard Model (MSSM) and beyond. There have been studies related to these terms in minimal supergravity based models. Consideration of an F-type SUSY breaking scenario in the hidden sector with two chiral superfields however showed Planck scale suppression of such terms. In an unbiased point of view for the sources of SUSY breaking, the NH terms in a phenomenological MSSM (pMSSM) type of analysis showed a possibility of a large SUSY contribution to muon $g - 2$, a reasonable amount of corrections to the Higgs boson mass and a drastic reduction of the electroweak fine-tuning for a higgsino dominated $\tilde{\chi}_1^0$ in some regions of parameter space. We first investigate here the effects of the NH terms in a low scale SUSY breaking scenario. In our analysis with minimal gauge mediated supersymmetry breaking (mGMSB) we probe how far the results can be compared with the previous pMSSM plus NH terms based study. We particularly analyze the Higgs, stop and the electroweakino sectors focusing on a higgsino dominated $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm$, a feature typically different from what appears in mGMSB. The effect of a limited degree of RG evolutions and vanishing of the trilinear coupling terms at the messenger scale can be overcome by choosing a non-minimal GMSB scenario, such as one with a matter-messenger interaction.

KEYWORDS: Supersymmetry Phenomenology

ARXIV EPRINT: [1710.10120](https://arxiv.org/abs/1710.10120)

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1 Introduction

The discovery of Higgs boson with a mass of 125 GeV [1–3] along with null search results for supersymmetry (SUSY) at the Large Hadron Collider (LHC) [4, 5] has in general enhanced the masses of the superpartners of the low energy supersymmetry models. This is even more prominent in models like minimal supergravity (mSUGRA) [6–11] or Constrained Minimal Supersymmetric Standard Model (CMSSM) where correlations among the masses via renormalization group evolution (RGE) effects make the spectra further heavy. In the Minimal Supersymmetric Standard Model (MSSM) [12–19], unless the third generation scalars are themselves too massive, the Higgs mass data translates into the requirement of a large top-squark left-right (L-R) mixing. This is required for obtaining the desired amount of radiative corrections for the mass of the CP-even lighter Higgs boson (h) [20]. This, on the other hand, increases the electroweak fine-tuning [21–35].

On the dark matter (DM) front, MSSM may provide with a suitable candidate like the lightest neutralino, the lightest supersymmetric particle (LSP) [36, 37]. The LSP in its bino dominated state needs very light sleptons to satisfy the DM relic density limits from PLANCK experiment [38]. Light sleptons is a rather disfavored scenario for most of the SUSY models in the post-Higgs discovery era. A bino can, however, be a favorable DM candidate, via its coannihilations with stau ($\tilde{\tau}_1$) or via its s-channel higgs exchange self-annihilation mechanism [39–42]. In spite of the above, even with the possibility of having a reasonably light LSP, the above coannihilation or resonance annihilations of binos require stringent correlations among unrelated SUSY parameters. A mixed bino-higgsino scenario like the Hyperbolic Branch [35, 43, 44]/Focus Point [45–51] zones can still have a reasonably light LSP. However, it is not so favorable via the spin-independent (SI) direct detection cross-section limits [52]. The reason lies in the larger values of Higgs- $\tilde{\chi}_1^0$ - $\tilde{\chi}_1^0$ couplings. On the other hand, in MSSM one can have a higgsino like LSP as a suitable dark matter candidate that can pair-annihilate efficiently via their couplings to the W/Z

gauge bosons [53–55]. Unlike a bino dominated LSP, a higgsino type of DM would not require any fine-adjustment of uncorrelated SUSY parameters. But a higgsino satisfying the observational relic density limits is typically quite heavy [53–55] ($\sim 1 \text{ TeV}$)¹ giving rise to a large electroweak fine-tuning in MSSM. It is thus desirable to have a model that has a higgsino like LSP but is able to guard fine-tuning to become large. We further note that a higgsino like LSP scenario of phenomenological MSSM (pMSSM) [57] is significantly free from the LHC bounds [58, 59].

The other issue at hand in MSSM is the stringent muon $g - 2$ constraint [60–62]. Satisfying the muon $g - 2$ constraint [63] in the MSSM is associated with a significant degree of reduction of parameter space. As we know, SUSY contributions to muon $g - 2$ are enhanced when the lighter electroweakinos ($\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$) or the lighter smuon mass $\tilde{\mu}_1$ become small. Concerning $\text{Br}(B \rightarrow X_s + \gamma)$ [64], the constraint can be effective in MSSM for a high $\tan \beta$ [65–68], the ratio of Higgs vacuum expectation values and non-decoupled zone of squark masses.

All the above that restrict the MSSM parameter space may be addressed reasonably well when one includes non-holomorphic (NH) soft terms on the top of the usual holomorphic soft terms of MSSM [69, 70]. Staying within an MSSM setup terms like $\phi^2 \phi^*$ or a higgsino mass term like $\psi\psi$ can be soft SUSY breaking in nature if there is no presence of a gauge singlet field [71]. There have been several works over the past two decades [69–82] that analyzed the effects of introducing NH soft terms.² There are three distinct signatures i) the trilinear NH terms may enhance L-R mixing thus influencing various phenomenologies, ii) higgsinos get an additional soft-term source, iii) the Higgs potential remains unaffected at the tree level thus electroweak fine-tuning may hardly change. The latter effect can give rise to a valid higgsino dark matter with low fine-tuning, whereas the L-R mixing effect may contribute to $(g - 2)_\mu$, $\text{Br}(B \rightarrow X_s + \gamma)$, or the higgs mass radiative corrections [69, 70, 78–81]. The NH soft terms can also influence on the scalar potential terms involving colored/charged scalars [82]. Thus, there are associated charge and color breaking (CCB) minima constraints that one must take care of in the limiting cases of large trilinear NH couplings.

All the above effects in combination may potentially cause very distinct outcomes in global analyses of low energy SUSY models [84–87]. In a model-dependent standpoint, one finds that such NH soft terms may arise out of interactions like $\frac{1}{M^3}[XX^*\Phi^2\Phi^*]_D$ and $\frac{1}{M^3}[XX^*D^\alpha\Phi D_\alpha\Phi]_D$ [71]. In the above one considers a scenario where supersymmetry is broken in the hidden sector via an auxiliary field F of the chiral superfield X . Φ is another chiral superfield and M refers to the mediation scale. Both these terms have a strength $\frac{|F|^2}{M^3} \sim \frac{M_W^2}{M}$ [70]. Clearly, there are large suppressions ($\sim 1/M$) for the NH soft terms in supergravity scenarios where M can be very large nearing the Planck scale. However, the suppression effects may be small if one considers a SUSY breaking mechanism that would allow a low mediation scale.

With the above motivation, we like to explore the effects of having NH soft terms in gauge mediated supersymmetry breaking (GMSB) where SUSY breaking may occur at a

¹The limit goes below 600 GeV for higgsinos undergoing sfermion coannihilations [56].

²See ref. [83] for an analysis with hard SUSY breaking terms.

smaller scale and the scale of mediation, the messenger scale is also low. We will try to gauge, how far the electroweak scale analysis with NH soft terms of ref. [70] referred as Non-Holomorphic Supersymmetric Standard Model (NHSSM) preserves its conclusion in a minimal GMSB (mGMSB) setup [88–95]. We remind that the mGMSB has gravitino as its dark matter candidate with its mass ranging from a few eV up to $\mathcal{O}(1)$ GeV [94, 96–101] whereas the Next-to-lightest-SUSY Particle (NLSP) is largely a bino dominated neutralino. We will focus here on realizing an mGMSB setup with higgsino as the NLSP. This is unlike the typical case of a bino like NLSP that is characteristic of GMSB types of analyses [88–94].³ We will investigate the effects of NH soft terms on NLSP decaying to a gravitino and a Z-boson $\tilde{\chi}_1^0 \rightarrow \tilde{G} + Z$ or $\tilde{\chi}_1^0 \rightarrow \tilde{G} + h$ [94, 98] while assuming the other higgs bosons to be much heavier than the NLSP.

We will now briefly describe the plan of the work. In section 2 we will outline the gauge mediated breaking SUSY mechanism and introduce non-holomorphic soft terms within the above framework. We will discuss the effect of NH terms on Higgs and electroweakinos. In section 3 we will describe the results of the relevant parameter scanning on the top-squark and higgs boson masses and investigate the phenomenologies involving $\text{Br}(B \rightarrow X_s + \gamma)$ and muon $g - 2$. We will compare our results with the scenario of MSSM with NH terms where one gives all the input parameters at the electroweak scale. Furthermore, focusing on a parameter space where the NLSP is a higgsino dominated lightest neutralino, a scenario typically unavailable in mGMSB, we will estimate the relevant NLSP decay widths for a higgsino producing gravitino and other particles like h and Z bosons. Finally, we will conclude in section 4.

2 Gauge mediated SUSY breaking and non-holomorphic soft terms

In the Gauge-Mediated-SUSY breaking (GMSB) Models [88–94] SUSY is broken in a hidden/secluded sector. In the absence of the knowledge of the hidden sector, one may consider a spurion S which is a chiral superfield, singlet under the SM group. SUSY breaking in this sector is realized via S acquiring a vacuum expectation value (vev) via its scalar and auxiliary components. Thus,

$$\langle S \rangle = M + \theta\theta\langle F \rangle. \quad (2.1)$$

The parameters M and $\sqrt{\langle F \rangle} \equiv \sqrt{F}$ are the fundamental scales related to GMSB. Apart from the hidden sector and the observable sector where MSSM fields reside, there is a messenger sector that itself experiences the SUSY breaking and mediates the SUSY breaking it is affected with, to the observable sector. The messenger sector connects to the hidden sector via the singlet spurion field S that goes into a superpotential containing superfields of the messenger and hidden sectors. This results into a SUSY breaking via the two vevs of the scalar and the auxiliary components of S namely, M and $\langle F \rangle$ causing a splitting of the masses of the messenger sector scalars ($m_{\phi, \tilde{\phi}}^2 = M^2 \pm \langle F \rangle$) and fermions ($m_{\psi, \tilde{\psi}} = M$). The fact that the scalars should not go tachyonic, so that the vacuum stability is unaffected

³Higgsino NSLP may be possible in an extended version of GMSB model that incorporates non-unified messenger sector and messenger-matter interactions [102].

demands $\langle F \rangle < M^2$.⁴ Considering a large M , we can integrate out the messenger scalars and fermions that are charged under the SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$. The low energy effective theory below M would then break supersymmetry in the observable sector. The observable sector soft terms like the masses and couplings are generated via messenger particles in loops. This ensures renormalizability, a positive feature of GMSB models. The MSSM soft terms thus obtained via gauge boson and gaugino interactions are also flavor blind. It is the messenger sector particles, assumed to be heavy for phenomenological reasons characterize the low energy phenomenology. The gaugino masses arise out of one-loop diagrams such as that involving a messenger scalar and a fermion. The scalar mass squares arise out of two loop diagrams that may include messenger scalars and fermions apart from gauge bosons and gauginos.

Thus, the gaugino masses m_λ and scalar mass squares $m_{\tilde{f}}^2$ read,

$$m_\lambda \sim \frac{g^2}{16\pi^2} \Lambda \left(1 + \mathcal{O} \left(\langle F \rangle^2 / M^4 \right) \right); \text{ and, } m_{\tilde{f}}^2 \sim \left(\frac{g^2}{16\pi^2} \right)^2 \Lambda^2 \left(1 + \mathcal{O} \left(\langle F \rangle^2 / M^4 \right) \right), \quad (2.2)$$

where $\Lambda = \frac{\langle F \rangle}{M}$, is the SUSY breaking scale in MSSM. The parameters m_λ and $m_{\tilde{f}}$ come with similar values. The trilinear parameters are small and considered to be vanishing at the messenger scale, a result of the fact that the messengers can only interact with SM fields via gauge interactions. Vanishing of trilinear couplings at the messenger scale may also be seen in ref. [95] that used wavefunction renormalization method without a need of using Feynman diagrams in this regard. The trilinear couplings associated with the third generation of scalars are however non-vanishing at the electroweak scale via renormalization group evolutions. A soft mass value of $m_{\tilde{f}} \sim 1 \text{ TeV}$ would set $\frac{\langle F \rangle}{M} \sim 10^5 \text{ GeV}$ (eq. (2.2)), though this neither specifies $\langle F \rangle$ nor M . We note that the scalars should not break vacuum stability, as mentioned before, demands $\langle F \rangle < M^2$. In its limiting case of an equality, one has $\frac{\langle F \rangle}{M} = M = 10^5 \text{ GeV}$. This results into $M = 10^5 \text{ GeV}$ and $\sqrt{\langle F \rangle} = 10^5 \text{ GeV}$. Considering the inequality itself, one obtains the lower bounds $M > 10^5 \text{ GeV}$ and $\sqrt{\langle F \rangle} > 10^5 \text{ GeV}$.

The upper limit of the messenger mass M comes from the relative degree of strengths of the gauge and gravity mediations since the superfield S may also cause gravity effects, though in much smaller strength, in addition to the SUSY breaking associated with a GMSB scenario. The scalar mass squares from the gravity and gauge mediated scenarios may now be compared. A representative factor of 1/1000 for the ratio of the two soft mass squares would mean $\frac{g^2}{16\pi^2} \frac{\langle F \rangle}{M} > 10^{3/2} \frac{\langle F \rangle}{M_P}$, where M_P is the Planck mass [94]. The above results into an approximate upper bound $M < 10^{15} \text{ GeV}$.⁵ Correspondingly, for a 1 TeV scalar mass, one finds $\sqrt{\langle F \rangle} < 10^{10} \text{ GeV}$. Summarizing, one finds,

$$10^5 < \sqrt{\langle F \rangle} < 10^{10} \text{ GeV}, \text{ and, } 10^5 < M < 10^{15} \text{ GeV}. \quad (2.3)$$

Considering the supergravity relation the gravitino mass is given by $m_{3/2} = \frac{F}{\sqrt{3}M_P}$. Depending on $\langle F \rangle$ (eq. (2.3)), the gravitino mass may range from $\sim 1 \text{ eV}$ to $\sim 1 \text{ GeV}$.

⁴Realistic scenarios rather satisfy $\langle F \rangle \ll M^2$.

⁵This is via considering a value of g corresponding to the strong coupling at the electroweak scale.

Now, within the MSSM framework the NH soft terms are given by [69, 70]:⁶

$$-\mathcal{L}'_{\text{soft}}{}^{NH} \supset \tilde{Q} \cdot H_d^c A'_u \tilde{U} + \tilde{Q} \cdot H_u^c A'_d \tilde{D} + \tilde{L} \cdot H_u^c A'_e \tilde{E} + \mu' \tilde{H}_u \cdot \tilde{H}_d + \text{h.c.} \quad (2.4)$$

Here, A'_i refers to three 3×3 matrices ($[A'_i]$) belonging to the family space of squarks/sleptons. We remind that the MSSM soft terms are generated in mGMSB via gauge and gaugino interactions that are flavor blind. The messenger sector particles occur only in loops. All the elements of $[A_i]$, the associated parameters for holomorphic trilinear interactions that arise at two-loop levels are considered to be zero at the messenger scale [17–19, 88–94]. We note that eq. (2.4) differs from the holomorphic trilinear soft SUSY breaking Lagrangian by a change in the Higgs fields. Thus, $H_{u,d}$ are replaced by their conjugates in eq. (2.4) with appropriate book-keeping for the associated scalar fields for hypercharge assignments. Hence, as with the elements of $[A_i]$, the same for $[A'_i]$ should also vanish at the same scale. With a limited zone of RG running typical to a GMSB scenario both $[A_i]$ and $[A'_i]$ terms are tiny at the electroweak scale for the first two generations. Thus $[A'_i]$ terms do not cause any violation of flavor changing neutral current (FCNC) constraints that are typically stringent for observables related to the first two generations of fermions.

As mentioned in section 1, terms like $\phi^2 \phi^*$ and a higgsino mass soft-term $\psi\psi$ (eq. (2.4)) may originate from D-term contributions like $\frac{1}{M^3}[XX^*\Phi^2\Phi^*]_D$ and $\frac{1}{M^3}[XX^*D^\alpha\Phi D_\alpha\Phi]_D$ [70, 71]. Since the terms are of strength $\frac{M_W^2}{M}$, a low mediation scale M such as that appears in a GMSB scenario may be relevant for probing the phenomenological implications. The parameters for trilinear non-holomorphic soft terms are small, similar to the same of trilinear holomorphic terms at the mediation scale M . We will keep the other D-term soft breaking NH interaction namely the higgsino mass soft term characterized by μ' (to be given at the scale M), to have an unknown SUSY breaking origin.⁷ This is considering the issue of an associated re-parametrization invariance of the higgsino mass soft term [73, 76, 80, 81]. Reparametrization comes from unrelated quantities like μ , the higgsino mixing superpotential parameter and the higgs scalar soft mass parameters $m_{H_U}^2$ and $m_{H_D}^2$. An assumption of an independent SUSY breaking mechanism to have a higgsino mass soft term essentially avoids such concerns (See discussions in [80, 81] along with the references therein).

Coming to the minimal GMSB, to preserve the gauge coupling unification one considers messengers to belong to a complete SU(5) representation or any other complete representation of a larger gauge group that includes SU(5) as a sub-group. With S as the spurion field mentioned before one has the superpotential,

$$W_{\text{mess}} = S\Phi\bar{\Phi}. \quad (2.5)$$

In the simplest case, there will be N_5 number of flavor of messenger copies Φ and $\bar{\Phi}$ transforming as 5 and $\bar{5}$ representations of SU(5). The soft SUSY breaking parameters like

⁶There can be an NH soft term like $\psi\lambda$ involving higgsinos and gauginos. This would however take us away from MSSM, hence ignored [71].

⁷Additionally, such a term cannot originate at a one-loop level in mGMSB, thus becoming suppressed.

gaugino and scalar masses are given as follows.

$$M_\alpha = \frac{g_\alpha^2}{16\pi^2} N_5 \Lambda g(x), \quad (\alpha = 1, 2, 3). \quad (2.6)$$

Here α refers to SM gauge group ($U(1)_Y$, $SU(2)_L$, & $SU(3)_c$).

$x = \frac{\langle F \rangle}{M^2}$, $\Lambda = \frac{\langle F \rangle}{M}$ and $g(x)$ is given as,

$$g(x) = \frac{1}{x^2} ((1+x)\log(1+x) + (1-x)\log(1-x)). \quad (2.7)$$

The scalar masses are given by,

$$m_{\tilde{f}}^2 = 2\Lambda^2 N_5 \sum_\alpha \left(\frac{g_\alpha^2}{16\pi^2} \right)^2 C_\alpha f(x). \quad (2.8)$$

Here, $f(x)$ is given by,

$$f(x) = \frac{1+x}{x^2} \left(\log(1+x) - 2\text{Li}_2\left(\frac{x}{1+x}\right) + \frac{1}{2}\text{Li}_2\left(\frac{2x}{1+x}\right) \right) + (x \rightarrow -x). \quad (2.9)$$

C_α is the quadratic Casimir of the representation of the gauge group factor G_α under which the scalar field $\tilde{f}$ transforms. For the gauge groups involved, the Casimirs are: $C_{SU(n)} = \frac{n^2-1}{2n}$ and $C_{U(1)} = (3/5)Y^2$. The Euler dilogarithm function $\text{Li}_2(x)$ is given by $\text{Li}_2(x) = -\int_0^x \frac{\log(1-t)}{t} dt$, for $0 < x < 1$. Under the assumption of $\langle F \rangle \ll M^2$ one has $g(x) \simeq 1$ and $f(x) \simeq 1$. This results into,

$$M_\alpha = \frac{g_\alpha^2}{16\pi^2} \Lambda N_5, \quad (2.10)$$

and,

$$m_{\tilde{f}}^2 = 2\Lambda^2 N_5 \sum_\alpha \left(\frac{g_\alpha^2}{16\pi^2} \right)^2 C_\alpha. \quad (2.11)$$

The following are the model parameters where the NH higgsino soft parameter μ'_0 is the input value of μ' at the messenger scale M at which the common NH trilinear coupling parameter A'_0 vanish.

$$\Lambda, M, \tan \beta, N_5, \text{sign}(\mu), \text{ and } \mu'_0. \quad (2.12)$$

The NH trilinear couplings of eq. (2.4) modify the off-diagonal elements of the scalar mass matrix as given below [69, 70].

$$M_u^2 = \begin{pmatrix} m_{\tilde{Q}}^2 + \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right) M_Z^2 \cos 2\beta + m_u^2 & -m_u(A_u - (\mu + A'_u) \cot \beta) \\ -m_u(A_u - (\mu + A'_u) \cot \beta) & m_u^2 + \frac{2}{3}\sin^2\theta_W M_Z^2 \cos 2\beta + m_u^2 \end{pmatrix}. \quad (2.13)$$

Similar mass matrices for sleptons (or a down-type of squarks) would have the off-diagonal term $-m_e(A_e - (\mu + A'_e) \tan \beta)$. Clearly, the NH trilinear couplings contribute to the off-diagonal elements where μ is replaced by $\mu + A'_f$ ($f = u, d, e$ etc.). The above indicates a more significant impact of L-R mixing for i) low values of $\tan \beta$ for the up type of squarks and ii) high values of $\tan \beta$ for down type of squarks or sleptons.

Now, the discovery of the Higgs boson with mass of 125.09 ± 0.24 GeV [1–3] is translated into a large amount of radiative corrections to the mass of the lighter neutral CP-even Higgs boson h . The above requirement causes an increase in the masses of the top-squarks in MSSM and/or one needs an appropriately large value of $|A_t|$, so as to have a stronger $\tilde{t}_L - \tilde{t}_R$ mixing. Thus, the NH soft trilinear parameter A'_t that affects the L-R mixing has important contributions toward the above radiative corrections for small values of $\tan \beta$.

The lightest CP-even higgs boson mass up to one loop can be read as follows [20].

$$m_{h,\text{top}}^2 = m_Z^2 \cos^2 2\beta + \frac{3g_2^2 \bar{m}_t^4}{8\pi^2 M_W^2} \left[\ln \left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{\bar{m}_t^2} \right) + \frac{X_t'^2}{m_{\tilde{t}_1} m_{\tilde{t}_2}} \left(1 - \frac{X_t'^2}{12 m_{\tilde{t}_1} m_{\tilde{t}_2}} \right) \right]. \quad (2.14)$$

Here, $X_t' = A_t - (\mu + A'_t) \cot \beta$. Clearly, $A'_t = 0$ corresponds to the MSSM result. Here $\bar{m}_t$ refers to the running top-quark mass that includes corrections from the electroweak, quantum chromodynamics (QCD) and SUSY QCD related effects [103]. The maximal mixing scenario refers to $X_t' = \sqrt{6} M_S$ where $M_S = \sqrt{\bar{m}_{\tilde{t}_1} \bar{m}_{\tilde{t}_2}}$. With a suitable A'_t , it is possible to satisfy the Higgs mass constraint with a relatively smaller value of $|A_t|$ in NHSSM, compared to MSSM.

The changes in the neutralino and chargino mass matrices are as shown below. Essentially, μ is replaced by $\mu + \mu'$ as in the tree level results.

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z \cos \beta \sin \theta_W & M_Z \sin \beta \sin \theta_W \\ 0 & M_2 & M_Z \cos \beta \cos \theta_W & -M_Z \sin \beta \cos \theta_W \\ -M_Z \cos \beta \sin \theta_W & M_Z \cos \beta \cos \theta_W & 0 & -(\mu + \mu') \\ M_Z \sin \beta \sin \theta_W & -M_Z \sin \beta \cos \theta_W & -(\mu + \mu') & 0 \end{pmatrix}. \quad (2.15)$$

$$M_{\tilde{\chi}^\pm} = \begin{pmatrix} M_2 & \sqrt{2} M_W \sin \beta \\ \sqrt{2} M_W \cos \beta & (\mu + \mu') \end{pmatrix}. \quad (2.16)$$

We note that the collider bound on the lighter chargino mass, except the issue of radiative corrections, will apply to essentially $|\mu + \mu'|$ instead of $|\mu|$ in case $\tilde{\chi}_1^\pm$ is higgsino dominated in nature. Since the Higgs potential is unaffected, the electroweak fine-tuning measure at tree level is still dependent on μ [70, 80, 81] rather than it has anything to do with μ' . A large higgsino mass with less electroweak fine-tuning becomes a possibility.

In contrast to the NHSSM that is based on electroweak scale inputs we should keep in mind that the dependence of relevant quantities especially μ on μ' and A'_t can be significant in NHmGMSB due to RGE effects. Besides, it is important to mention that a fine-tuning measure analyzed in a scenario with NH terms in a predictive model that uses RGEs can be less independent with respect to the higgsino mass [81]. This is unlike what is seen in electroweak fine-tuning in NHSSM as mentioned above.

3 Results

We have realized the non-holomorphic MSSM on a GMSB setup, that is going to be referred as the NHmGMSB model, by using the codes SARAH-4.9.1 [104–107] and SPheno-3.3.8 [108]. Two-loop RGEs of the MSSM soft parameters, plus the same at one-loop for

the NH soft parameters are used to generate the sparticle mass spectra [73, 74, 80, 113]. The codes use two-loop corrections for Higgs states [114, 115] and additionally compute all the relevant flavor observables [112]. As mentioned earlier, the free parameters that are to be scanned are

$$\Lambda, M_{\text{mess}}, {}^8 \tan \beta, N_5, \text{sign}(\mu) \text{ and } \mu'_0, \quad (3.1)$$

where the number of the messenger copies is taken to be one ($N_5 = 1$). At the messenger scale M_{mess} , the soft SUSY breaking mass parameters are given via eqs. (2.6), (2.8) and the values of (non) holomorphic trilinear coupling parameters (A'_0, A_0) are taken to be zero. Choosing $\text{sign}(\mu) = 1$ we scan the following volume of the mGMSB parameters.

$$\begin{aligned} 3.0 \times 10^5 \text{ GeV} &\leq \Lambda \leq 1.0 \times 10^6 \text{ GeV}, \\ 2 \times 10^6 \text{ GeV} &\leq M_{\text{mess}} \leq 10^8 \text{ GeV}, \\ \tan \beta &= 10 \text{ and } 40, \\ -4000 \text{ GeV} &\leq \mu'_0 \leq 4000 \text{ GeV}, \end{aligned} \quad (3.2)$$

with $m_t^{\text{pole}} = 173.5 \text{ GeV}$, $m_b^{\overline{MS}} = 4.18 \text{ GeV}$ and $m_\tau = 1.77 \text{ GeV}$ [116] and $M_{\text{SUSY}} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$. Additionally, we note that a higher value of M_{mess} than what is given in eq. (3.2) would not be so consistent with our motivation of choosing a low scale SUSY breaking model like mGMSB. This is in keeping with limiting the mediation scale suppression of the NH soft terms as mentioned in section 1. On the other hand, reducing M_{mess} further than the lower limit of eq. (3.2) would hardly provide with a reasonable range of RG running of both A_t and A'_t that is essential for satisfying the higgs mass data (without trying to compensate it via choosing a larger value of Λ).

The SUSY Higgs mass (m_h) limits [116] and the constraints from B-physics namely $B \rightarrow X_s + \gamma$, $B_s \rightarrow \mu^+ \mu^-$ are mentioned as below [116].

$$\begin{aligned} 122.1 \text{ GeV} &\leq m_h \leq 128.1 \text{ GeV}, \\ 2.99 \times 10^{-4} &\leq Br(B \rightarrow X_s + \gamma) \leq 3.87 \times 10^{-4} \text{ (} 2\sigma \text{)}, \\ 1.5 \times 10^{-9} &\leq Br(B_s \rightarrow \mu^+ \mu^-) \leq 4.3 \times 10^{-9} \text{ (} 2\sigma \text{)}. \end{aligned} \quad (3.3)$$

We consider a 3 GeV theoretical uncertainty in computing m_h as given above. Some of the reasons behind considering the spread are uncertainty in computing loop corrections up to three loops, top quark mass, renormalization scheme and scale dependence etc. [117–123].

We will now discuss the effect of introducing NH parameters within the mGMSB scenario and especially study the dependence of the SUSY spectra and observables of phenomenological interest on Λ , M_{mess} and μ'_0 . We remind that in this analysis the trilinear NH couplings are vanishing at the messenger scale whereas the higgsino mass soft-parameter μ'_0 is considered to arise from sources other than GMSB. This is following the discussion of section 2.

3.1 Effects on top-squarks and Higgs masses

Figures 1(a) and 1(b) represent the scatter plots of Higgs boson mass with Λ for $\tan \beta = 10$ and 40 respectively when M_{mess} and μ'_0 are scanned according to eq. (3.2). Here, the mass

⁸Henceforth we will refer M_{mess} as the messenger scale.

Figure 1. Scatter plots of m_h with Λ are shown for $\tan\beta = 10$ and 40 when M_{mess} and μ'_0 are scanned according to the ranges mentioned in eq. (3.2). The blue and yellow coloured regions correspond to NHmGMSB and mGMSB cases respectively.

of the lighter CP-even neutral Higgs boson h which is standard-model like in its couplings satisfies the range mentioned in eq. (3.3). The yellow and blue zone refer to the results of mGMSB and NHmGMSB respectively. The lower limit of Λ corresponding to the lower limit of m_h (eq. (3.3)) for any given scenario either mGMSB or NHmGMSB decreases with an increase in $\tan\beta$. The spread of points for m_h shown in blue (NHmGMSB) is quite large compared to the yellow region (mGMSB) for $\tan\beta = 10$. However, this is not so for the case of $\tan\beta = 40$. We note that $\mu + A'_t$ appearing in the off-diagonal elements of the top-squark mass matrix is suppressed by $\tan\beta$. The larger top-squark mixing causes more prominent spread for low $\tan\beta$. Regarding A'_t , it is seen that A'_t turns out to be negative. However, X'_t is not large enough to be in the maximal mixing zone characterized by $X'_t = \sqrt{6}M_S$. This is also true for $X_t (= A'_t - \mu \cot\beta)$ for the mGMSB case. Furthermore, it is found that A'_t at the EWSB scale approximately varies from -550 (-600) GeV to 550 (600) GeV for $\tan\beta = 10$ (40). A'_t comes with either sign because of its dependence via RGE on μ'_0 , while the latter is scanned for both positive and negative values. Additionally, we note that μ'_0 may also contribute [73, 74, 80] quite significantly to the value of μ which is obtained via REWSB. With all the above effects and estimates, X'_t is seen to be larger in the negative direction for $\tan\beta = 10$ than $\tan\beta = 40$. Because of a larger top-squark mixing, that results into a larger radiative corrections to the Higgs boson mass, the lowest value of Λ satisfying the lower limit of m_h for NHmGMSB is less than the same for mGMSB.

We will now explore the variation of Higgs boson mass m_h with top-squark mass $m_{\tilde{t}_1}$ for $\tan\beta = 10$ and 40 in figures 2(a) and figure 2(b) respectively, when Λ , M_{mess} , μ'_0 are scanned according to eq. (3.2). The colors carry the same convention as that of figure 1. For a given value of m_h , the lower limit of $m_{\tilde{t}_1}$ becomes smaller in NHmGMSB than that of mGMSB and this is more prominent for $\tan\beta = 10$ because of a larger influence of $(\mu + A'_t)$. For a given $m_{\tilde{t}_1}$, the amount of corrections in m_h via NH terms may reach up to nearly 1 GeV for $\tan\beta = 10$ and 0.5 GeV for $\tan\beta = 40$. On the other hand, for a given m_h , the

Figure 2. Scatter plots of m_h with stop mass $m_{\tilde{t}_1}$ are shown for $\tan \beta = 10$ and 40 . Λ , M_{mess} , μ'_0 are scanned according to the ranges mentioned in eq. (3.2). The colors carry the same convention as that of figure 1.

spread of $m_{\tilde{t}_1}$ is about 1 TeV from its minimum to the maximum value for NHmGMSB within which the scattered points for mGMSB reside.

Figures 3(a) and 3(b) show scatter plots of the lighter top-squark mass $m_{\tilde{t}_1}$ with Λ corresponding to $\tan \beta = 10$ and 40 respectively, where the Higgs boson mass (m_h) satisfies the range of eq. (3.3). The blue and yellow zones refer to the results of NHmGMSB and mGMSB respectively. The Higgs boson mass lower limit is reached for a smaller value of Λ for $\tan \beta = 40$ in comparison with $\tan \beta = 10$ for reasons described earlier. With the validity of the lower Λ zone for a larger $\tan \beta$ via the m_h lower limit, the top-squark mass $m_{\tilde{t}_1}$ finds its smallest value to be smaller for $\tan \beta = 40$ compared to the same for $\tan \beta = 10$. On the other hand, between $\tan \beta = 10$ and 40 , the relative difference of the lowest value of $m_{\tilde{t}_1}$ between NHmGMSB and mGMSB is more enhanced for the lower value of $\tan \beta$ primarily because of a lesser degree of suppression of the contribution of $\mu + A'_t$ in the top-squark mixing. The resulting reduction of $m_{\tilde{t}_1}$ in NHmGMSB (compared to mGMSB) is about 500 (200) GeV for $\tan \beta = 10$ (40).

We will now explore the role of the messenger scale M_{mess} in our analysis that would shed some light on the extent of RG evolutions of relevant parameters that have influence on the scalar masses including that of the Higgs boson as well as on the masses of the electroweakinos. The effects of evolutions are not likely to be as large as that occur in minimal supergravity (mSUGRA) [69] with much higher SUSY mediation scale, but as we have seen they may assist in lowering the top squark mass $m_{\tilde{t}_1}$ or enhancing m_h . Figure 4(a) and 4(b) show color contour plots in the (Λ vs M_{mess}) plane for NHmGMSB corresponding to $\tan \beta = 10$ and 40 respectively when μ'_0 is scanned as in eq. (3.2). The side panels show the values of m_h . The figures show strong dependence of Higgs mass on Λ (that sets the masses of the scalars as well as gauginos) and a weaker dependence on M_{mess} . However, we must mention that the upper limit of M_{mess} is chosen relatively small in our analysis. This is based on our motivation to have the NH terms of being associated with a lesser

Figure 3. Scatter plots of the lighter top-squark mass $m_{\tilde{t}_1}$ with Λ for $\tan\beta = 10$ and 40 for the scanning ranges mentioned in eq. (3.2). The blue and yellow zones refer to the results of NHmGMSB and mGMSB respectively.

Figure 4. Scatter plots of Λ against Messenger Scale M_{mess} for $\tan\beta = 10$ and 40 for NHmGMSB, corresponding to the scanning ranges mentioned in eq. (3.2). The side panels of each of the plots show the Higgs mass.

degree of mass suppression as mentioned in section 2, the reason of our working in a GMSB setup. A larger $M_{\text{mess}} \sim 10^{12}$ GeV (not shown in this work) may increase both A_t and A'_t significantly to higher values beyond what would be necessary to satisfy the Higgs boson mass limit for a reasonably chosen Λ .

It is important to note that there are a few beyond the mGMSB analyses [102, 124–128] for example those involving matter-messenger interactions in which the trilinear holomorphic soft terms may arise at one-loop level, thus becoming non-vanishing at the messenger scale. In such situations one obtains a significantly large amount of radiative corrections to m_h , a friendly feature to accommodate a Higgs boson as massive as 125 GeV in models

away from mGMSB. The NH trilinear terms will then similarly become non-vanishing at the above scale. Depending on the sign of μ'_0 , this may give rise to a larger A'_t at the electroweak scale. The above in turn that may result into a smaller $m_{\tilde{t}_1}$ or positively contributing toward the radiative corrections to the Higgs boson mass m_h . Thus a smaller Λ would be acceptable lowering the overall mass scale of sparticles. Additionally, as we will see below, the same consideration may significantly enhance the smuon mass mixing via a larger A'_μ . A large A'_μ may effectively contribute to the SUSY contribution to muon $g - 2$ significantly, because of an associated scaling by $\tan \beta$ [70].

3.2 Phenomenological implications through the electroweakino sector

As discussed in section 2 the electroweakino sectors are influenced by $\mu + \mu'$ particularly when the combination that is close to the higgsino mass is lesser than the masses of relevant gauginos M_1 and M_2 . We will discuss the phenomenological implications on $\text{Br}(B \rightarrow X_s + \gamma)$ and muon $g - 2$ in this context. The diagrams that are significant in MSSM for $\text{Br}(B \rightarrow X_s + \gamma)$ are the loops involving $t - H^\pm$ and $\tilde{t} - \tilde{\chi}_1^\pm$. Agreement of the SM result of $\text{Br}(B \rightarrow X_s + \gamma)$ with the experimental data demands delicate cancellation between the contributions of the above loops. In MSSM, $\text{Br}(B \rightarrow X_s + \gamma)$ increases with $\tan \beta$ [65]. Additionally, there are Next to Leading Order (NLO) contributions from squark-gluino loops due to corrections of bottom and top Yukawa couplings, particularly for large values of $\tan \beta$. Here we will discuss the effects on $\text{Br}(B \rightarrow X_s + \gamma)$ in relation to the results of ref. [70] that used unconstrained NH soft terms given at the weak scale (NHSSM). The $\tilde{t} - \tilde{\chi}_1^\pm$ loop that is relevant for our study does not have an appreciable effect from top squark L-R mixing since both A_t and A'_t that start from vanishing values at the messenger scale have only limited degree of evolutions. This is in contrast to the larger possible values assumed by the above trilinear parameters as analyzed in ref. [70]. Figure 5 shows the variation of $\text{Br}(B \rightarrow X_s + \gamma)$ with μ'_0 in NHmGMSB for a given Λ and M_{mess} . It shows some sharp increase in $\text{Br}(B \rightarrow X_s + \gamma)$ for a given zone of μ'_0 , particularly for a large $\tan \beta = 40$. It is found that this is indeed the region when $\mu + \mu'$ or the lighter chargino mass becomes small. The effect was also seen earlier [69, 79]. The corresponding mGMSB values of the same quantity are also shown where $m_{\tilde{\chi}_1^\pm}$ is not small. Apart from the cases with small $m_{\tilde{\chi}_1^\pm}$, $\text{Br}(B \rightarrow X_s + \gamma)$ does not impose any serious constraint on NHmGMSB parameter space even for a large value $\tan \beta$ because of the smallness of A_t and A'_t and large values of top-squark masses so as to satisfy the Higgs mass data. This is unlike NHSSM that recovers a large amount of parameter space discarded by $\text{Br}(B \rightarrow X_s + \gamma)$ in MSSM for a large value of $\tan \beta$ [70].

We will now discuss the SUSY contributions to $(g - 2)_\mu$, namely a_μ^{SUSY} ,⁹ in the context of NHmGMSB against the results of the NHSSM analysis made in ref. [70]. At the one-loop level, a_μ^{SUSY} involves contributions from $\tilde{\chi}_i^\pm - \tilde{\nu}_\mu$ and $\tilde{\chi}_i^0 - \tilde{\mu}$ loops [129–134]. In the NHSSM analysis of ref. [70], because of a strong L-R mixing via A'_μ , it is the $\tilde{\chi}_i^0 - \tilde{\mu}$ loop that contributes a significantly large amount to a_μ^{SUSY} . A'_μ can be as small as 100 GeV or even 50 GeV to show very prominent effects. The largeness of the effect in NHSSM comes

⁹ $a_\mu = \frac{1}{2}(g - 2)_\mu$.

Figure 5. The variation of $Br(B \rightarrow X_s + \gamma)$ with μ'_0 is shown for the shown values of Λ and M_{mess} . The red and blue lines correspond to $\tan \beta = 10$ and 40 respectively. Green filled circles on the top of the lines specify the corresponding mGMSB values.

Figure 6. Scatter plot of μ'_0 vs A'_μ where Λ and M_{mess} are varied according to the ranges mentioned in eqs. (3.2). The green points satisfy all the relevant constraints of eq. (3.3) while the orange points correspond to a region that satisfy the muon $g - 2$ constraint at 3σ level.

from an enhancement of A'_μ via $\tan \beta$ and the diagram containing bino- $\tilde{\mu}_{L,R}$ in the loop that contributes to a_μ^{SUSY} [135, 136]. In NHmGMSB, A'_μ that starts from a vanishing value at M_{mess} has only a limited degree of evolution [80] even with a large μ'_0 . As a result, with an inadequate level of enhancement of A'_μ , we do not expect any large amount of contributions from the bino-smuon loops due to L-R mixing, unlike the NHSSM results of ref. [70]. Figure 6 shows a scatter plot of μ'_0 vs A'_μ where Λ and M_{mess} are varied within the shown ranges of eq. (3.2). The green points are those that satisfy all the relevant constraints of eq. (3.3) while the orange points correspond to a region that satisfy the muon $g - 2$ constraint at 3σ level. The 3σ region spreads more toward the negative zone of μ'_0 . We should remind that μ is obtained via REWSB with a chosen positive sign, whereas μ'_0 assumes both the signs. Thus, a larger a_μ^{SUSY} via a lighter higgsino mass can be obtained only in the negative direction of μ'_0 .

Figure 7. Plot of a_μ^{SUSY} vs μ'_0 for fixed Λ and M_{mess} for $\tan\beta = 10$ and 40 . The corresponding mGMSB values of the same quantity are also shown by considering vanishing μ'_0 .

The fact that the large A'_μ regions are not associated with larger values of a_μ^{SUSY} , rather the region with smaller μ'_0 satisfy the 3σ ,¹⁰ level of the constraint predominantly for a negative region of μ' indicates the domination of charged and neutral higgsinos in the loop diagrams [135]. This is indeed displayed in figure 7 that shows a plot of μ'_0 vs a_μ^{SUSY} for a given Λ and M_{mess} . The figure shows a sharp rise in a_μ^{SUSY} for a small zone of μ'_0 that also increases with $\tan\beta$. It turns out that with the value of μ obtained from REWSB, and $\mu + \mu'$ being the tree level higgsino mass, this rise corresponds to the light higgsino zone.¹¹ The specific contributions to a_μ^{SUSY} arise from diagrams [135] like wino/higgsino-sneutrino and wino/higgsino- $\tilde{\mu}_L$, bino/higgsino- $\tilde{\mu}_L$ or bino/higgsino- $\tilde{\mu}_R$. There may also be a significant degree of cancellations between the above diagrams. The 3σ level of a_μ^{SUSY} region for μ'_0 as shown in figure 6 comes out to be around -1500 GeV to 200 GeV.

3.3 Higgsino like NLSP decays

The interaction Lagrangian of gravitino ψ_μ with other sparticles and SM particles is given by $\mathcal{L} = \sum_{\alpha=1}^3 \mathcal{L}^{(\alpha)}$ where α stands for a given gauge group out of $\text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y$ and $\mathcal{L}^{(\alpha)}$ being given as [137],

$$\mathcal{L}^{(\alpha)} = -\frac{i}{\sqrt{2}M_p} \left[\mathcal{D}_\mu^{(\alpha)} \phi^{*i} \bar{\psi}_\nu \gamma^\mu \gamma^\nu \chi_L^i - \mathcal{D}_\mu^{(\alpha)} \phi^i \bar{\chi}_L^i \gamma^\nu \gamma^\mu \psi_\nu \right] - \frac{i}{8M_p} \bar{\psi}_\mu [\gamma^\rho, \gamma^\sigma] \gamma^\mu \lambda^{(\alpha)a} F_{\rho\sigma}^{(\alpha)a}.$$

The covariant derivatives $\mathcal{D}_\mu^{(\alpha)}$ and $F_{\rho\sigma}^{(\alpha)a}$ are appropriately defined depending on the gauge group denoted by α and the generator index a [137].

The resulting decay widths $\Gamma(\tilde{\chi}_1^0 \rightarrow \tilde{G} + Z)$ and $\Gamma(\tilde{\chi}_1^0 \rightarrow \tilde{G} + h)$ [94, 98, 138–140] are given as below. This is keeping in mind that $\tilde{\chi}_1^0$, the NLSP candidate, is chosen to be higgsino dominated in nature and the decays into heavier Higgs bosons are kinematically disallowed. We also note that a higgsino type of NLSP couples only to the longitudinal Z

¹⁰We consider ref. [63] for the following: $a_\mu^{\text{SM}} = 11659182.3 \pm 4.3 (\times 10^{-10})$ and $a_\mu^{\text{exp}} = 11659209.1 \pm 6.3 (\times 10^{-10})$. This leads to a discrepancy of $26.8 \pm 7.6 (\times 10^{-10})$ (3.5σ).

¹¹ μ' has a limited degree of evolution from M_{mess} to the electroweak scale.

component. In realistic scenarios with small amount of gaugino mixing in NLSP, which we will though ignore here, $\Gamma(\tilde{\chi}_1^0 \rightarrow \tilde{G} \gamma)$ can be quite important. However, we will work only with an almost pure higgsino. For the above two decays we have,

$$\Gamma(\tilde{\chi}_1^0 \rightarrow \tilde{G} Z) \simeq \frac{m_{\tilde{\chi}_1^0}^5}{96\pi m_{\tilde{G}}^2 M_P^2} |-N_{13} \cos \beta + N_{14} \sin \beta|^2 \left(1 - \frac{m_Z^2}{m_{\tilde{\chi}_1^0}^2}\right)^4, \quad (3.4)$$

$$\Gamma(\tilde{\chi}_1^0 \rightarrow \tilde{G} h) \simeq \frac{m_{\tilde{\chi}_1^0}^5}{96\pi m_{\tilde{G}}^2 M_P^2} |-N_{13} \sin \alpha + N_{14} \cos \alpha|^2 \left(1 - \frac{m_h^2}{m_{\tilde{\chi}_1^0}^2}\right)^4, \quad (3.5)$$

where N_{13} and N_{14} are the higgsino related components of the LSP in the $\tilde{B}, \tilde{W}, \tilde{H}_d^0, \tilde{H}_u^0$ basis of the neutralino diagonalizing matrix N_{ij} [15]. The gravitino mass is given by,

$$m_{\tilde{G}} = \frac{\Lambda M_{\text{mess}}}{\sqrt{3} M_P}.$$

For our choice of parameter space $m_{\tilde{G}}$ is of order of few keV. This allows us to neglect it in the expression of the phase space factor compared to other masses involved in the calculation of decay widths in eqs. (3.4), (3.5). The total decay width of a higgsino type of NLSP is given by,

$$\Gamma^{\text{tot}} \equiv \Gamma_{\text{NLSP}}^{\text{tot}} \simeq \Gamma(\tilde{\chi}_1^0 \rightarrow \tilde{G} Z) + \Gamma(\tilde{\chi}_1^0 \rightarrow \tilde{G} h). \quad (3.6)$$

Γ^{tot} would be strongly influenced by Λ and M_{mess} since $\Gamma^{\text{tot}} \propto \frac{1}{(\Lambda M_{\text{mess}})^2}$. Γ^{tot} is also influenced by μ'_0 through the higgsino NLSP mass as well as the effect of higgsino mixing in N_{ij} s. We explore the decay widths of eqs. (3.4) and (3.5) against the NLSP mass in figure 8(a) and 8(b) respectively. The fixed values of the chosen parameters are $\text{sign}(\mu) = 1$, $\tan \beta = 35$, $\Lambda = 4.5 \times 10^5 \text{ GeV}$ and $M_{\text{mess}} = 8 \times 10^7 \text{ GeV}$. μ'_0 is scanned over a range -4 TeV to 4 TeV . Both the decay widths increase with NLSP mass as long as the NLSP is substantially a higgsino. This is so until $m_{\tilde{\chi}_1^0}$ is about 550 GeV . Once, the NLSP is found to be an admixture of a higgsino and bino or essentially a bino each of the decay widths is bound to decrease rapidly. This happens after it attains a peak similar to what is apparent in figure 8(a) or 8(b). In short of other relevant decay modes, eq. (3.6) would then no longer be valid. Regarding the composition of the NLSP and its effect on $\Gamma(\tilde{\chi}_1^0 \rightarrow \tilde{G} Z)$ and $\Gamma(\tilde{\chi}_1^0 \rightarrow \tilde{G} h)$ we would like to point out that both N_{13} and N_{14} change signs over the scanned region of parameter space. However, N_{14} plays a dominant role for both types of decays unless $\tan \beta$ is very small. In eq. (3.4) the N_{13} contribution is very subdominant since $\cos \beta$ is small. A similar subdominant role for N_{13} is also true in eq. (3.5) since we have a decoupling Higgs boson scenario where $\sin \alpha$ becomes small [20]. The above causes both $\Gamma(\tilde{\chi}_1^0 \rightarrow \tilde{G} Z)$ and $\Gamma(\tilde{\chi}_1^0 \rightarrow \tilde{G} h)$ to peak at similar values of the NLSP mass. Apart from the above, because of the possibility of both the signs for N_{13} and N_{14} , figures 8(a) and 8(b) show that each of the decay widths has two branches or in other words is a double-valued function of $m_{\tilde{\chi}_1^0}$ depending on the two cases $\mu > |\mu'|$ and $\mu < |\mu'|$. The heights of the decay widths of the two branches for each of $\Gamma(\tilde{\chi}_1^0 \rightarrow \tilde{G} Z)$ and $\Gamma(\tilde{\chi}_1^0 \rightarrow \tilde{G} h)$ differ because of a varying degree of radiative corrections to the NLSP mass. Considering

Figure 8. Plot of decay width vs. NLSP mass for $\tilde{\chi}_1^0 \rightarrow \tilde{G} + Z$ and $\tilde{\chi}_1^0 \rightarrow \tilde{G} + h$ channel for $\mu > 0$ when μ' is scanned over a range (eq. (3.2)) to probe the higgsino NLSP zone. The blue and red points refer to $\mu > |\mu'|$ and $\mu < |\mu'|$ respectively.

$m_{\tilde{\chi}_1^0} \simeq 575$ GeV (near the peaks) the approximate sum of the two decay widths is around 2.8×10^{-16} GeV for the given parameter point. This leads to $1/\Gamma^{\text{tot}} \simeq 2 \times 10^{-9}$ sec $\simeq 70$ cm. In general, the mean decay length of χ_1^0 as NLSP with energy E in the laboratory frame is given by [94, 139, 140],

$$d \simeq \left(E^2/m_{\tilde{\chi}_1^0}^2 - 1 \right)^{1/2} / \Gamma^{\text{tot}}. \quad (3.7)$$

Figure 9(a) shows a scatter plot of decay width Γ^{tot} vs. $m_{\tilde{\chi}_1^0}$ for a higgsino dominated NLSP over the scanned parameter region of eq. (3.2). The higgsino fraction is shown in graded color with a reference color bar on the right. Only highly higgsino dominated NLSP region is considered. Figure 9(b) shows a similar scatter plot in the plane of Γ^{tot} vs. $F (= \Lambda M_{\text{mess}})$ where the NLSP mass is shown in a graded color with a reference color bar on the right. The range of variation of Γ^{tot} is from 10^{-22} to 10^{-12} GeV implying $1/\Gamma^{\text{tot}}$ to be within $\simeq 10^{-3}$ sec to $\simeq 10^{-13}$ sec or $\simeq 1000$ km to 0.1 mm respectively. The decay lengths when computed in the laboratory frame would point out a long range of values indicating decays occurring both within and outside the detector. Collider studies of probing the higgsino NLSP decays for suitable values of ΛM_{mess} may be performed similar to the analyses made in refs. [141–145]. This is however beyond the scope of the present work.

Finally, we present two representative points A and B in table 1 for the spectra of NHmGMSB to demonstrate the degree of evolution of the parameters connected with the NH terms while choosing the lighter chargino and the NLSP to be higgsino dominated in nature. This is generally unavailable in mGMSB where the NLSP as the lightest neutralino it is typically bino dominated in its composition. The spectra is generally heavy because of the requirement of satisfying the Higgs boson mass limit. We remind that the effect of the NH terms can be increased significantly and the spectra may be lighter while that would also satisfy the muon $g - 2$ data, if we go beyond the mGMSB setup. This may

Figure 9. (a) Scatter plot of decay width Γ^{tot} vs. $m_{\tilde{\chi}_1^0}$ for a higgsino dominated NLSP over the scanned parameter region of eq. (3.2). The higgsino fraction is shown in graded color with a reference color bar on the right. (b) Similar scatter plot in the plane of Γ^{tot} vs. F where the NLSP mass is shown in a graded color with a reference color bar on the right.

be possible if the trilinear couplings for NH terms may have non-vanishing values at the messenger scale.

4 Conclusion

It was seen that SUSY models may include non-holomorphic terms like $\phi^2\phi^*$ and $\psi\psi$ that can be characterized as soft SUSY breaking in nature in the absence of a gauge singlet field. The broad applicability of the terms in various possible SUSY models makes such inclusion very important. In particular, the above terms may relax stringency to accommodate various phenomenological data in MSSM. These would be additional interactions than the usual soft SUSY breaking terms like that for the scalar masses (non-holomorphic) and trilinear and bilinear interactions that are holomorphic in nature. There have been studies on non-holomorphic MSSM referred as NHSSM that included such terms. The specific areas of impact that NHSSM makes are in the phenomenologies involving i) L-R mixing of squarks or sleptons via trilinear non-holomorphic terms containing the conjugate higgs fields, ii) higgsino mass soft SUSY breaking non-holomorphic term that results into higgsino components of electroweakinos to have parts coming from both superpotential as well as soft breaking origins and iii) the tree level electroweak fine-tuning to have no essential correlation with the higgsino mass, unlike MSSM. The authors of refs. [70, 82] performed phenomenological MSSM (pMSSM) type of analysis where all the soft parameters including the NH ones are provided at the weak scale. These were away from previous works that used mostly CMSSM inspired setup where in addition to the usual CMSSM inputs corresponding to the gauge coupling unification scale, the NH soft parameters were either given a) at the unification scale or b) at the electroweak scale. It was however shown that in the absence of a gauge singlet superfield, a hidden sector based F-type SUSY breaking scenario with two chiral superfields would lead to such NH soft terms [71]. The terms arise out of D-term contributions. On the other hand, supergravity scenarios with high scale SUSY breaking

Parameters	A	B
Λ	3.65×10^5	3.16×10^5
M_{mess}	9.742×10^6	8.073×10^6
$\tan \beta$	10	40
A'_0	0	0
μ'_0	-1898	-1144
A_t	-787	-686
A_b	-136	-430
A_τ	-14	-38
A'_t	-210	-147
A'_b	-55	-121
A'_τ	-23	-57
A'_μ	-1.4	-3.4
m_h	122.1	122.3
$m_H, m_{H^\pm}, m_A$	2047, 2047, 2047	1425, 1425, 1425
$m_{\tilde{t}_{1,2}}$	3090, 3458	2651, 2949
$m_{\tilde{b}_{1,2}}$	3357, 3453	2841, 2946
$m_{\tilde{\tau}_{1,2}}$	695, 1315	566, 594
$m_{\tilde{\chi}_{1,2}^0}$	432, 451	202, 212
$m_{\tilde{\chi}_{1,2}^\pm}$	446, 981	210, 846
$m_{\tilde{g}}$	2636	2311
NLSP Composition	$\tilde{\chi}_1^0 \approx 86\% \tilde{H}$ like	$\chi_1^0 \approx 98\% \tilde{H}$ like
$BR(B \rightarrow X_s + \gamma)$	3.22×10^{-4}	3.21×10^{-4}
$BR(B_s \rightarrow \mu^+ \mu^-)$	3.27×10^{-9}	3.28×10^{-9}
a_μ^{SUSY}	1.027×10^{-10}	7.88×10^{-10}

Table 1. Representative Points for NHmGMSB: all the dimensional parameters are in GeV.

could include such NH terms with mass scale suppression nearing the Planck scale [71]. Irrespective of the above, there have been analyses that worked out the phenomenologies of including such soft terms in a CMSSM setup or extensions like non-universal gaugino or non-universal Higgs scalar scenarios.

In this work, we first investigate the NH soft SUSY breaking models in a low scale SUSY breaking context. We choose to perform the analysis within a backbone provided by the minimal Gauge mediated SUSY Breaking (mGMSB) framework. We however assume that the higgsino mixing soft term parameter μ' to have a SUSY breaking origin away from mGMSB. Thus, by having an entirely independent SUSY breaking origin for

the higgsino mass soft term we essentially overcome any issue of the reparametrization invariance involving unrelated quantities as mentioned in the text. We focus on the degree of influence of the NH terms in an mGMSB setup (NHmGMSB) in comparison with the NHSSM work mentioned earlier. We note that the NH terms may affect various SUSY parameters including the Higgs scalar mass parameters through the RGEs. Thus, μ , as obtained via REWSB may be non-negligibly modified once the NH terms are included.

We show that the level of the L-R mixing of top-squarks can potentially reduce the $m_{\tilde{t}_1}$ to a reasonably large extent, in turn increasing the radiative corrections to Higgs boson mass. Thus, a smaller than required $|A_t|$ value can do the job of satisfying the lower bound of m_h compared to the mGMSB case since a compensating contribution may come from appropriate NH couplings. Of course, the enhancement of radiative corrections to the higgs boson mass is lesser when we compare our result with that of NHSSM. This is simply due to the limited degree of RG evolution of A_t and A'_t from M_{mess} down to the electroweak scale starting from their vanishing values at the higher scale. Regarding the effects on the electroweakino sector, we observe that the high level of enhancement (via a factor of $\tan\beta$) of the SUSY contributions to muon $g-2$ as that happens in NHSSM via A'_μ through the L-R mixing contributions of smuons is absent in NHmGMSB. This is because A'_μ does not become sufficiently large at the weak scale. The smallness of A'_μ can, however, be avoided in non-minimal GMSB cases where the NH trilinear coupling A'_0 need not be vanishing at the messenger scale. Simultaneously, the higgs boson mass m_h would receive a larger amount of radiative correction through enhanced A'_t . A larger a_μ^{SUSY} comes from the limited zone of light higgsino mass in NHmGMSB. The same light higgsino mass zone may enhance the $\text{Br}(B \rightarrow X_s + \gamma)$ contribution via the chargino loops. However, the constraint from $\text{Br}(B \rightarrow X_s + \gamma)$ is well satisfied at the 2σ level over the relevant parameter space of NHmGMSB simply because of generally large top-squark masses. This in turn arises from the requirement of satisfying the Higgs mass bound. We further estimate the decay of the lightest neutralino as NLSP into gravitino and Z -boson or h -boson while considering only a higgsino dominated NLSP. This is in contrast to a typical mGMSB scenario where $\tilde{\chi}_1^0$ is bino-dominated in its composition. We probed the entire parameter space of NHmGMSB to find a large degree of variation of decay lifetimes that may correspond to a decay length of less than a millimeter to hundreds of kilometer in the rest frame of the NLSP. Relevant collider analyses may be made by finding the length in the laboratory frame of the detector. Depending on whether the NLSP decay is happening within or outside the detector one can probe NHmGMSB for a higgsino type of NLSP. Finally, we have presented two representative points for the spectra of NHmGMSB to demonstrate the extent of RG evolutions parameters related to the NH soft terms. The two spectra are on the heavier side so as to accommodate the Higgs mass data. However, a non-minimal GMSB scenario that allows having non-vanishing trilinear parameters A_0 and A'_0 at the messenger scale would show a very significant effect on the scalar sector including the Higgs mass apart from potentially providing an enhanced a_μ^{SUSY} via a large L-R mixing of the smuons. This is beyond the focus of the present analysis. Finally, considering the generic nature of the NH soft terms, it is important to explore their effect in varying SUSY breaking scenarios and scales. It can also be significant in respect of global analyses of various SUSY models.

Acknowledgments

UC would like to thank Anirban Kundu and Sourov Roy for a brief discussion. UC and SM are grateful to Abhishek Dey for many helpful suggestions.

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