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Revisiting singlino dark matter of the natural Z_3-symmetric NMSSM in the light of LHC

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Abstract: Inspired by the fact that relatively small values of the effective higgsino mass parameter of the Z_3-symmetric Next-to-Minimal Supersymmetric Standard Model (NMSSM) could render the scenario 'natural', we explore the plausibility of having relatively light neutralinos and charginos (the electroweakinos or the ewinos) in such a scenario with a rather light singlino-like Lightest Supersymmetric Particle (LSP), which is a Dark Matter (DM) candidate, and singlet-dominated scalar excitations. By first confirming the indications in the existing literature that finding simultaneous compliance with results from the Large Hadron Collider (LHC) and those from various DM experiments with such light states is, in general, a difficult ask, we proceed to demonstrate, with the help of a few representative benchmark points, how exactly and to what extent could such a highly motivated 'natural' setup with a singlino-like DM candidate still remains plausible.

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1 Introduction

A key ingredient that renders a popular supersymmetry (SUSY) scenario like the phenomenological Minimal or Next-to-Minimal Supersymmetric Standard Model (pMSSM or pNMSSM) 'natural' [1–3] is a relatively small SUSY conserving higgsino mass parameter 'μ' in the pMSSM [4–7] or, similarly, μ_{eff} in the pNMSSM. In both scenarios, this would imply presence of at least two light neutralinos and a similarly light chargino (electroweakinos or ewinos) which are higgsino-like.

Though theoretically much motivated, such light ewinos generally derive significant constraints from their null searches at the colliders. These searches target pair or associated productions of such ewinos. A stronger set of bounds emerge in scenarios with significant mass-splits between such states and the lightest neutralino which is the Lightest SUSY Particle (LSP). The LSP is stable when a well-known discrete symmetry called R-parity is conserved and thus, can be a viable candidate for the Dark Matter (DM) [8, 9].

The usual decay modes of the charginos and the neutralinos, when their spectrum is not critically compressed and the squarks and the sleptons are much heavier, involve on/off-shell gauge and Higgs boson(s) and are as follows:

$$\chi_1^\pm \to \chi_1^0 W^{\pm(*)}, \;\; \chi_i^0 \to \chi_1^0 Z^{(*)}/h^{(*)}/a^{(*)}, \;\; \chi_i^0 \to \chi_1^\pm W^{\mp(*)}\,, \quad (i = 2,3,4,5)$$

where $h\,(a)$ is the scalar (pseudoscalar) Higgs boson. Then, the most stringent constraints on 'μ' or μ_{eff} usually come from the studies of associated $\chi_1^\pm \chi_{2,3}^0$ productions with $\chi_1^\pm \to \chi_1^0 W^{\pm(*)}$ and $\chi_{2,3}^0 \to \chi_1^0 Z$ leading to rather clean multi-lepton (up to 3 leptons) final states [10–13].[1] Clearly, presence of a light enough Higgs boson could lead to

[1] There have also been experimental searches involving two soft leptons [12, 14], opposite sign di-leptons, as well as final states with b-jets and photons [13], effectively constraining the chargino-neutralino spectra. The implications of these searches for our present study will be discussed in some detail later in this work.

a sizable branching fraction for $\chi_{2,3}^0 \to \chi_1^0 h/a$ thus depleting the lepton-rich events. This can potentially weaken the limit on 'μ' or $\mu_{\rm eff}$ [15, 16] thereby opening up the parameter space favored by 'naturalness'.

In the MSSM, an optimally healthy split between $\chi_{2,3}^0/\chi_1^\pm$ and χ_1^0 is not possible when $\mu \ll M_1, M_2$ for which these states are almost purely higgsinos and hence nearly degenerate, where M_1 and M_2 stand for the soft SUSY-breaking masses of the U(1) and SU(2) gauginos, respectively. However, with $M_1 < \mu < M_2$, one could find $m_{\chi_1^0} \sim M_1$, $m_{\chi_{2,3}^0} \sim \mu \sim m_{\chi_1^\pm}$ and hence would obtain reasonable mass-splits $\Delta m_{(\chi_{2,3}^0, \chi_1^0)}$ and $\Delta m_{(\chi_1^\pm, \chi_1^0)}$ leading to hard enough leptons/jets in the cascades. This renders these searches viable and hence yielding constraints.[2] Critical studies as to how strong and robust a constraint the LHC experiments could impose on such relatively light higgsino-like ewinos (and hence on 'μ') have recently been undertaken by various groups [18, 19]. Incidentally, the observed SM-like Higgs boson ($h_{\rm SM}$) of mass around 125 GeV could at best be the lightest of the MSSM Higgs bosons while all its cousins have to be much heavier (the so-called decoupling limit). Thus, there is only a limited scope for the decay $\chi_{2,3}^0 \to \chi_1^0 h_{\rm SM}$ to dominate over $\chi_{2,3}^0 \to \chi_1^0 Z$ and hence weakening of lepton-rich final states is not expected to be very common. Consequently, a notable relaxation on the masses of these light ewinos (and hence on 'μ') is unlikely to be a common occurrence.

In contrast, the situation can get very different in the NMSSM when the coefficient 'κ' of the superpotential term cubic in the singlet chiral superfield gets vanishingly small (the Peccei-Quinn symmetric limit). First, a rather light scalar (h_1) and a pseudoscalar (a_1) Higgs bosons with $m_{h_1,a_1} < m_Z$, both of which are singlet-dominated, are inevitable [20, 21]. The Higgs sector of the NMSSM has been studied in great details in refs. [22–39]. Second, a rather light singlino-dominated neutralino LSP (mass ranging from sub-GeV to a few tens of a GeV) is naturally present in the spectrum. These two together could easily allow for a much smaller value of $\mu_{\rm eff}$ leading to two next-to-LSP neutralino states ($\chi_{2,3}^0$) and the lighter chargino ($\chi_1^\pm$) all of which are higgsino-dominated with masses $\sim \mu_{\rm eff}$ and having prominent decays $\chi_{2,3}^0 \to \chi_1^0 h_1/a_1$. Also, these facilitate the simultaneous opening up of the decays $\chi_{2,3}^0 \to \chi_1^0 h_2(h_{\rm SM})$ thus reinforcing the combined branching fractions of $\chi_{2,3}^0$ to Higgs bosons over the same to Z-boson. Some specific consequences of such possibilities had been studied in the past which include rather light scalars decaying to (i) $\tau\bar{\tau}$ and leading to soft multi-lepton final state [40], (ii) $b\bar{b}$ [41] and (iii) two photons [42, 43]. For $m_{a_1} \lesssim 1$ GeV, even mesons can be produced out of a boosted pair of light quarks that a_1/h_1 might decay to.[3] Recently, there has also been an attempt to an

[2]For $M_2 < \mu$, $\chi_1^\pm$ becomes wino-dominated and degenerate in mass with a wino-dominated neutralino LSP. This would result in softer leptons/jets in the cascades of $\chi_1^\pm$ thus eroding experimental sensitivity to multi-lepton/jets final states, in general, and tri-lepton final state, in particular [17], while soft-lepton searches could emerge more relevant [12, 14].

[3]Furthermore, as we would appreciate later in this work, one could have a possible situation, without sacrificing much of the essential features of such a scenario, when even the decay $\chi_1^\pm \to \chi_2^0 W^{\pm^*}$ could compete with $\chi_1^\pm \to \chi_1^0 W^{\pm^*}$. The former would add to jet activity via the decay $\chi_2^0 \to \chi_1^0 h_1/a_1$ and hence could potentially alter bounds obtained from the studies which vetoes extra jets. Otherwise, BR($\chi_1^\pm \to \chi_1^0 W^{\pm^*}$) would remain 100% and hence collider constraints derived solely by studying $\chi_1^\pm$ pair production would hold in a robust manner.

effective field theory approach and its connection to the NMSSM having Higgs portals in the description of thermal DM [44].

On the DM front, presence of singlet-like light scalars along with a stable singlino-dominated LSP with a critical higgsino admixture (thanks to a not so large $\mu_{\rm eff}$), would have nontrivial consequences [45]. First, the higgsino admixture could now enable the LSP annihilate efficiently enough in the early Universe yielding DM relic in the right ballpark. Second, the same enhanced interaction of such an LSP could make it sensitive to DM Direct Detection (DMDD) experiments. Third, the light scalars (a_1 and h_1) could offer new annihilation 'funnels' that are efficient handles on the DM relic. Some aspects of such a singlino-higgsino mixed state has been discussed in ref. [46] in reference to both as a DM candidate and its implications for the LHC. Furthermore, in the context of DMDD experiments sensitive to spin-independent (SI) scattering, there may appear the so-called blind spots [47–51] either due to vanishing LSP-Higgs coupling or due to a destructive interference between the contributions from the CP-even Higgs bosons. These could suppress the DMDD-SI cross section to a value still allowed by experiments.

The collider and the DM aspects of such an NMSSM scenario are thus expected to be connected in a rather nontrivial way. It is encouraging to find a few recent works addressing these aspects, focussing mainly on one or the other of them. Their broad scopes are as follows.

- ref. [15] is the first one to discuss the case of a light singlino-like LSP as the DM candidate with light bino (higgsino)-like neutralino(s) and a higgsino-like chargino as the next heavier sparticle(s) and the combined constraint such a scenario draws from various DM and collider experiments. It points out the roles played by relatively light a_1/h_1 (i) in obtaining the DM Relic Density (DMRD) in the right ballpark, (ii) in complying with the DMDD constraints on the SI scattering cross section using the blind spot mechanism and (iii) in evading (degrading) the LHC bounds on such light ewinos.

- ref. [51] undertakes a detailed scan of the 'natural' NMSSM parameter space requiring relatively light higgsino-like states compatible with the relic density bound from Planck experiment [52, 53], the bound from DMDD experiments like XENON-1T [54, 55] and those from the 13 TeV run (with up to 36 fb^{-1} of data) of the LHC. In our current context, the most relevant finding is that only a singlino-dominated LSP with a small higgsino admixture ($\mu_{\rm eff} \simeq m_{\chi_1^0}$) might survive the combined constraints if $m_{\chi_1^0} \gtrsim 90$ GeV and, that also, for a compressed spectrum for the LSP and $\chi_1^\pm$.

- ref. [16] is mainly concerned with the impact of recent multi-lepton searches at the LHC on the ewinos of the NMSSM in the presence of light singlet scalars, h_1 and a_1. The study chooses to remain agnostic about the detailed bounds in the DM sector except for respecting only the upper bound on the relic density. The discussion on the scenario with a relatively light singlino-like LSP that could annihilate via singlet-Higgs funnel(s) are of particular relevance for our present work.

In this work we focus on an Z_3-symmetric NMSSM scenario with a relatively small $\mu_{\rm eff}$ (preferably less than $\sim 300\,\text{GeV}$ and not exceeding $500\,\text{GeV}$) that ensures enhanced 'naturalness' and with a singlino-enriched ($> 95\%$) LSP neutralino as the DM candidate with mass around or below the SM Higgs boson funnel, i.e. $\lesssim 62\,\text{GeV}$. The purpose is to find how such a scenario could still be compatible with all pertinent experimental data from both DM and collider fronts. Our study goes beyond what was found in ref. [51] which excludes the possibilities of having a singlino-dominated LSP below $\sim 90\,\text{GeV}$ and away from the coannihilation regime. As we would elucidate soon, allowing for some modest bino content in the lighter neutralinos by considering an appropriately small M_1 could provide us with a much lighter and a viable singlino-dominated DM candidate which finds right funnels in various light states like the SM Higgs boson, the Z-boson and even the lighter singlet-like Higgs states of the scenario to. This renders, not only the DM neutralino, but the entire system of lighter neutralinos 'well-tempered' [56]. Constraints imposed by us include the one on DMRD within 10% uncertainty, those from the DMDD experiments like XENON-1T studying the SI [54] and the spin-dependent (SD) [55, 57] DM-nucleon scattering cross sections. Our study also takes into account all relevant LHC analyzes that considers up to $\sim 36\,\text{fb}^{-1}$ worth data via use of the package `CheckMATE` [58, 59].

The paper is organized as follows. In section 2 we present the structures and the salient features of the NMSSM ewino and the Higgs sectors along with their interactions that are relevant to the present work. These are followed by a discussion on the nature of the spectrum in our scenario and on the important decay modes of the light ewinos to Higgs bosons. Section 3 contains our results where the impact of experimental bounds on the DM observables is quantitatively assessed leading to our choice of suitable benchmark points with low enough $\mu_{\rm eff}$. A dedicated `CheckMATE`-based analysis follows to assess the viability of the benchmark points in view of the LHC data. In section 4 we conclude.

2 The light ewinos and the light Higgs bosons

The superpotential of the Z_3-symmetric NMSSM is given by

$$\mathcal{W} = \mathcal{W}_{\rm MSSM}|_{\mu=0} + \lambda \widehat{S}\widehat{H}_u.\widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3\,, \tag{2.1}$$

where $\mathcal{W}_{\rm MSSM}|_\mu = 0$ is the MSSM superpotential sans the higgsino mass term (the μ-term), $\widehat{H}_u, \widehat{H}_d$ and $\widehat{S}$ are the usual MSSM SU(2) Higgs doublets and the NMSSM-specific singlet superfields, respectively while 'λ' and 'κ' are dimensionless coupling constants. The μ-term is generated dynamically from the second term when the singlet scalar field 'S' develops a vacuum expectation value (*vev*) $\langle S\rangle = v_{_S}$ (i.e., $\mu_{\rm eff} = \lambda v_{_S}$) thus offering a solution to the puzzling μ-problem [60]. The NMSSM-specific part of the soft SUSY-breaking Lagrangian is given by

$$-\mathcal{L}^{\rm soft} = -\mathcal{L}^{\rm soft}_{\rm MSSM}|_{B\mu=0} + m_S^2|S|^2 + \Big(\lambda A_\lambda S H_u \cdot H_d + \frac{\kappa}{3}A_\kappa S^3 + \text{h.c.}\Big)\,, \tag{2.2}$$

where m_S^2 is the squared soft SUSY-breaking mass for the singlet scalar field 'S' while A_λ and A_κ are the NMSSM-specific trilinear soft terms having dimensions of mass. In the following subsections we briefly discuss the sectors that are directly involved in the present study, i.e., the ewino and the Higgs sectors of the scenario.

2.1 The ewino sector

The ewino sector is comprised of the neutralino and the chargino sectors. The neutralino sector is augmented in the NMSSM by the presence of the singlino ($\tilde{S}$) state, when compared to the same for the MSSM. Thus, the symmetric 5×5 neutralino mass matrix, in the basis $\psi^0 = \{\widetilde{B},\ \widetilde{W}^0,\ \widetilde{H}_d^0,\ \widetilde{H}_u^0,\ \widetilde{S}\}$ is given by [22]

$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu_{\text{eff}} & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 2\kappa v_s \end{pmatrix}, \tag{2.3}$$

where g_1 and g_2 stand for the gauge couplings of the U(1) and SU(2) gauge groups, respectively, and $v_u = v\sin\beta$, $v_d = v\cos\beta$ such that $\tan\beta = v_u/v_d$ with $v = \sqrt{v_u^2 + v_d^2} \simeq 174\,\text{GeV}$. The above mass-matrix can be diagonalized by a matrix N, i.e.,

$$N^* \mathcal{M}_0 N^\dagger = \text{diag}(\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0, \chi_5^0)\,. \tag{2.4}$$

The resulting neutralino mass-eigenstates (χ_i^0, in order of increasing mass as 'i' varies from 1 to 5), in terms of the weak eigenstates (ψ_j^0, with $j = 1, \ldots, 5$), is given by

$$\chi_i^0 = N_{ij}\psi_j^0\ . \tag{2.5}$$

It is possible to find analytic expressions for the masses and the elements of the mixing matrix, N_{ij}, when two of the five states get decoupled. Hence, to start with, for our purposes, we consider the bino and the wino states to be decoupled. This would describe our basic setup fairly robustly with a rather light singlino-like LSP and a relatively small μ_{eff} (thus aiding 'naturalness') leading to two light higgsino-like states. Such a scenario can be realized for $\lambda v \ll |\mu_{\text{eff}}|$ along with $\kappa/\lambda \ll 1$. The ratios of higgsino to singlino admixtures in a given neutralino (in particular, in the LSP) would remain to be much instrumental in our present analysis. In the above-mentioned situation, these are given by [48, 61]

$$\frac{N_{i3}}{N_{i5}} = \frac{\lambda v}{\mu_{\text{eff}}} \frac{(m_{\chi_i^0}/\mu_{\text{eff}})\sin\beta - \cos\beta}{1 - (m_{\chi_i^0}/\mu_{\text{eff}})^2}, \qquad \frac{N_{i4}}{N_{i5}} = \frac{\lambda v}{\mu_{\text{eff}}} \frac{(m_{\chi_i^0}/\mu_{\text{eff}})\cos\beta - \sin\beta}{1 - (m_{\chi_i^0}/\mu_{\text{eff}})^2}, \tag{2.6}$$

where N_{i3}, N_{i4} and N_{i5} denote the two higgsino and the singlino components, respectively, in the i-th mass eigenstate with $i = 1, 2, 3$ and $m_{\chi_1^0} < m_{\chi_2^0} < m_{\chi_3^0}$.

Subsequently, we note that a relatively small value of M_1 ($\lesssim \mu_{\text{eff}}$) could have a nontrivial impact on the combined DM and collider phenomenology of such a scenario with light ewinos. However, this compels one to work with a 4×4 neutralino mass-matrix for which

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analytical expressions for N_{ij}, similar to those in eq. (2.6), would not be much illuminating. On top of that, when M_2 is allowed to become small, the eigenvalue problem seeks solution of a polynomial of degree 5 of which a general solution does not exist. Hence, for smaller values of M_1 and/or M_2, we adopt a numerical approach. On the other hand, the 2×2 chargino mass matrix of the NMSSM is structurally the same as that of the MSSM with $\mu \to \mu_{\rm eff}$ and, in the basis

$$\psi^+ = \begin{pmatrix} -i\widetilde{W}^+ \\ \widetilde{H}_u^+ \end{pmatrix}, \quad \psi^- = \begin{pmatrix} -i\widetilde{W}^- \\ \widetilde{H}_d^- \end{pmatrix}, \tag{2.7}$$

is given by [22]

$$\mathcal{M}_C = \begin{pmatrix} M_2 & g_2 v_u \\ g_2 v_d & \mu_{\rm eff} \end{pmatrix}. \tag{2.8}$$

As in the MSSM, this can be diagonalized by two 2×2 unitary matrices U and V:

$$U^* \mathcal{M}_C V^\dagger = {\rm diag}(m_{\chi_1^\pm}, m_{\chi_2^\pm}) \; ; \quad \text{with } \; m_{\chi_1^\pm} < m_{\chi_2^\pm} \; . \tag{2.9}$$

As noted in the Introduction, to ensure our scenario remains reasonably 'natural', we choose to work with relatively low values of $\mu_{\rm eff}$. This yields two light neutralinos along with a lighter chargino with masses $\sim \mu_{\rm eff}$, all of which can be dominantly higgsino-like. However, their actual masses and compositions depend much on the extent they mix with the singlino and the bino (for the neutralinos only) and with the wino states. In particular, we are interested in a scenario where, $2\kappa v_{_S} \lesssim \mu_{\rm eff}$ (i.e., for $\kappa \lesssim \lambda/2$). This could lead to a singlino-dominated LSP. However, it may contain a crucial higgsino admixture thus making it a viable DM candidate. Implications of such an LSP in the context of various DM and collider experiments have recently been studied in the literature [15, 16, 51], though as parts of more general studies.

Apart from the subtle role played by our proposed manoeuvring by allowing for $M_1 \lesssim \mu_{\rm eff}$, this brings in a fourth relatively light neutralino in the picture. We will further assume the wino-like neutralino to be the heaviest of them all and hence would require $M_2 > \mu_{\rm eff}, M_1$. This would help avoid stringent collider constraints by restricting heavier ewinos cascading via such wino-like states. In the next subsection, we discuss that such a scenario is necessarily accompanied by light singlet-like scalars which characterize our scenario of interest.

2.2 The Higgs sector

The superpotential of eq. (2.1) leads to the following Lagrangian containing soft masses and couplings for the NMSSM Higgs sector:

$$-\mathcal{L}^{\rm soft} \supset m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + \left(\lambda A_\lambda \, H_u \cdot H_d \; S + \frac{\kappa}{3} A_\kappa \, S^3 + {\rm h.c.} \right). \tag{2.10}$$

The neutral Higgs fields are parameterized about the real *vev*'s v_d, v_u and $v_{_S}$ for the three neutral fields H_d^0, H_u^0 and S, respectively as

$$H_d^0 = v_d + \frac{H_{dR} + iH_{dI}}{\sqrt{2}}, \quad H_u^0 = v_u + \frac{H_{uR} + iH_{uI}}{\sqrt{2}}, \quad S = v_{_S} + \frac{S_R + iS_I}{\sqrt{2}}, \tag{2.11}$$

where "R" and "I" denote, for each field, the CP-even and the CP-odd states, respectively. The CP-even squared mass matrix, $\mathcal{M}_S^2$, in the basis $\{H_{dR}, H_{uR}, S_R\}$, is given by [22]

$$\mathcal{M}_S^2 = \begin{pmatrix} g^2 v_d^2 + \mu_{\rm eff}(A_\lambda + \kappa v_s)\tan\beta & (2\lambda^2 - g^2)v_u v_d - \mu_{\rm eff}(A_\lambda + \kappa v_s) & \lambda(2\mu_{\rm eff}\, v_d - (A_\lambda + 2\kappa v_s)v_u) \\ (2\lambda^2 - g^2)v_u v_d - \mu_{\rm eff}(A_\lambda + \kappa v_s) & g^2 v_u^2 + \mu_{\rm eff}(A_\lambda + \kappa v_s)/\tan\beta & \lambda(2\mu_{\rm eff}\, v_u - (A_\lambda + 2\kappa v_s)v_d) \\ \lambda(2\mu_{\rm eff}\, v_d - (A_\lambda + 2\kappa v_s)v_u) & \lambda(2\mu_{\rm eff}\, v_u - (A_\lambda + 2\kappa v_s)v_d) & \lambda A_\lambda \frac{v_u v_d}{v_s} + \kappa v_s(A_\kappa + 4\kappa v_s) \end{pmatrix}, \tag{2.12}$$

where $g^2 = (g_1^2 + g_2^2)/2$. The squared mass of the singlet-like CP-even eigenstate (up to a mixing with the doublet states) is given by the (3,3) component, i.e.,

$$\mathcal{M}_{S,33}^2 = \lambda A_\lambda \frac{v_u v_d}{v_s} + \kappa v_s(A_\kappa + 4\kappa v_s). \tag{2.13}$$

Out of the other two eigenstates, one has to turn out to be the SM-like Higgs boson with mass $\sim 125\,\text{GeV}$, the other one being a relatively heavy, doublet-dominated neutral Higgs boson with its squared mass around $\mu_{\rm eff}(A_\lambda + \kappa v_s)/\sin 2\beta$. Thus, a more realistic basis to work in is $\{H_1, H_2, S_R\}$, where $H_1 = H_{dR}\cos\beta + H_{uR}\sin\beta$ and $H_2 = H_{dR}\sin\beta - H_{uR}\cos\beta$, such H_1 resembles the SM Higgs field. Similarly, in the basis $\{A, S_I\}$, where $A = \cos\beta\, H_{uI} + \sin\beta\, H_{dI}$, dropping the Goldstone mode, the CP-odd squared mass matrix $\mathcal{M}_P^2$ simplifies to [22]

$$\mathcal{M}_P^2 = \begin{pmatrix} m_A^2 & \lambda(A_\lambda - 2\kappa v_s)\, v \\ \lambda(A_\lambda - 2\kappa v_s)\, v & \lambda(A_\lambda + 4\kappa v_s)\frac{v_u v_d}{v_s} - 3\kappa A_\kappa\, v_s \end{pmatrix}, \tag{2.14}$$

with $m_A^2 = 2\mu_{\rm eff}(A_\lambda + \kappa v_s)/\sin 2\beta$ representing the squared mass of the doublet-like CP-odd scalar, as in the MSSM. The mass-squared for the singlet CP-odd scalar (modulo some mixing) is given by the (2,2) element of the above matrix, i.e.,

$$\mathcal{M}_{P,22}^2 = \lambda(A_\lambda + 4\kappa v_s)\frac{v_u v_d}{v_s} - 3\kappa A_\kappa\, v_s\,. \tag{2.15}$$

The mass eigenstates of the CP-even (h_i) and the CP-odd (a_i) sectors are given by [48, 50]

$$h_i = E_{h_i H_1} H_1 + E_{h_i H_2} H_2 + E_{h_i S_R} S_R, \quad (i = 1,2,3) \tag{2.16}$$

$$a_i = O_{a_i A} A + O_{a_i S_I} S_I, \quad (i = 1,2) \tag{2.17}$$

where E (3×3) and O (2×2) are the matrices that diagonalize the mass-squared matrices for the CP-even scalars in the basis $\{H_1, H_2, S_R\}$ and that for the CP-odd scalar of eq. (2.14).

Clearly, the scalar masses have rather complex dependencies on as many as six input parameters like λ, κ, A_λ, A_κ, $\mu_{\rm eff}$ and $\tan\beta$. However, for our scenario of interest with a light singlino-like LSP ($m_{\chi_1^0} \approx m_{\tilde{S}} \sim 2\kappa v_s$) and light singlet-like scalars (given by eqs. (2.13) and (2.15)), one could find the following (approximate) sum-rule [15, 62] relating their masses when the singlet-doublet mixing among the scalar (Higgs) states can be safely ignored, i.e., in the decoupling limit (λ, $\kappa \to 0$) or for a sizable $\tan\beta$ and not too large λ, κ and A_λ:

$$\mathcal{M}_{0,55}^2 \simeq \mathcal{M}_{S,33}^2 + \frac{1}{3}\mathcal{M}_{P,22}^2 \quad \Rightarrow \quad m_{\chi_1^0}^2 \simeq m_{h_1}^2 + \frac{1}{3}m_{a_1}^2\,. \tag{2.18}$$

This clearly indicates that the masses of the singlino and those for the singlet-like scalar and the pseudoscalar are rather closely tied. The relationship becomes handy in discussions on DM-annihilation via light scalar funnels [15, 51].

2.3 Interactions among the ewinos and the scalars

Interactions among the ewinos and the Higgs-like scalars states take the central stage in our present study. Their subtle dependence on various NMSSM parameters and their interplay crucially shape the phenomenology on both DM and collider fronts, sometimes in a rather complementary fashion.

To be a little more specific, conformity with the observed value of DMRD would depend not only on a mass-spectrum that offers efficient DM-annihilation mechanisms via funnels and/or coannihilations[4] but also on the strengths of the involved interactions. The latter, in turn, could also control the DM-nucleon interactions that are studied at the DMDD experiments. Hence requiring an efficient DM-annihilation to meet the DMRD observations might imply a strong enough DM-nucleon interaction strength that is ruled out by the DMDD experiments. The converse is also true. This highlights a built-in tension in finding a simultaneous explanation of the two crucial observations in the DM sector alone.

On the collider front, the interactions among the ewinos and the scalars determine the branching fractions of the former to the latter. Such modes include the ones beyond what are being routinely considered in the LHC analyzes in the context of 'simplified scenarios' and result in new final states. These are likely to result in relaxed mass-bounds on the higgsino-like states thus offering enhanced 'naturalness'. Interestingly enough, as we will discuss soon in section 3, these might also help satisfy the constraints in the DM sector. Thus, for decoupled sfermions and a gluino, the interactions that are of paramount importance are those among (i) various neutralinos and the gauge (Z-) boson and (ii) various neutralinos and Higgs bosons, of both CP-even (scalar) and CP-odd (pseudoscalar) types, from both doublet and the singlet sectors.

The neutralino DM interacts with the Z-boson only through its higgsino admixture. This interaction governs the self-annihilation of DM via Z-boson funnel thus controlling the DMRD as well as the DMDD-SD cross section and is given by $\alpha_{Z\chi_1^0\chi_1^0} \sim |N_{13}^2 - N_{14}^2|$ [63]. On the other hand, a doublet-like Higgs scalar has an MSSM-like interaction with a higgsino and a gaugino. In addition, in the Z_3-symmetric NMSSM, as can be gleaned from eq. (2.1), this also interacts with a higgsino and a singlino while the singlet-like scalar interacts with two higgsinos, both strengths being proportional to 'λ'. The $\widehat{S}^3$ term in eq. (2.1) further implies that the singlet scalar has an interaction with two singlinos whose strength goes as 'κ'. Thus, if the gaugino (bino and/or wino) admixture in a singlino-dominated LSP can be ignored (which is somewhat ensured by the neutralino mass matrix of the NMSSM),

[4] As mentioned in the Introduction, our focus would be on the region of the NMSSM parameter space where funnel-assisted annihilation of DM occurs. Note that we are interested in rather small values of μ_{eff} in the case of an uncompressed spectra. This leads to rather light χ_1^0, and funnel assisted annihilation provides an opportunity to achieve the right thermal relic abundance in these regions of the parameter space.

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the generic coupling of such an LSP with the CP-even Higgs scalars are given by [48]

$$\alpha_{h_i\chi_1^0\chi_1^0} \approx \sqrt{2}\lambda\Big[E_{h_iH_1}N_{15}(N_{13}\sin\beta + N_{14}\cos\beta) + E_{h_iH_2}N_{15}(N_{14}\sin\beta - N_{13}\cos\beta) + E_{h_iS_R}\left(N_{13}N_{14} - \frac{\kappa}{\lambda}N_{15}^2\right)\Big]. \tag{2.19}$$

The couplings $\alpha_{a_i\chi_1^0\chi_1^0}$ for the CP-odd scalar counterparts would be somewhat similar except for the appearance of an overall factor of imaginary 'i' and that in the rotated basis for the pseudoscalar sector there are only two massive eigenstates.

Furthermore, while the CP-even Higgs states from the doublet and the singlet sectors contribute to both DMRD and DMDD-SI, their CP-odd counterparts could contribute only to DMRD and practically nothing to any DMDD processes [64]. Ref. [48] discusses the issue of the blind spots for DM-nucleon interaction in a few specific and motivated scenarios in the Z_3-symmetric NMSSM. Among these, the scenario that is germane to our present study is the one (section 6) that discusses blind spots arising from destructive interference between CP-even singlet-like (h_1) and doublet-like (h_2, the observed SM-like Higgs boson) scalar states where $m_{h_1} < m_{h_2}$, while the heavier MSSM-like CP-even Higgs state is virtually decoupled. This yields a DM-nucleon SI cross section well below the threshold of sensitivity of the relevant DMDD-SI experiments.

Up to this point, the relative strengths of all the couplings that matter are essentially governed the ratios presented in eq. (2.6). It is now instructive to note that if the singlino-dominated LSP could be infused with a bino/wino component, it would alter the higgsino shares in the same. This can be achieved by allowing bino/wino to mix substantially with higgsinos, given that, at the lowest order, this only can (indirectly) induce some gaugino admixture in an otherwise singlino-dominated LSP. Hence such a regime would reign as long as M_1 (or M_2, though decreasing it beyond a point could attract severe experimental constraints) is not too far away from μ_{eff}. In certain regions of the NMSSM parameter space, with $m_{\tilde{S}} < M_1 < \mu_{\text{eff}}$, this causes the coupling-strength $\alpha_{Z\chi_1^0\chi_1^0}$ $(\sim |N_{13}^2 - N_{14}^2|)$ weakening to a minimum due to rather involved variations of N_{ij}'s as functions of M_1. This we will discuss soon in a little more detail. This would then diminish the DMDD-SD cross section thus helping us evade the related experimental bound. Clearly, under such circumstances, eq. (2.6) ceases to hold and improving the same in the presence of an active bino state is unlikely to be illuminating enough, given the complicated structure the situation presents. We thus take a numerical route for the rest of the present study and frequently confront the results with broad-based expectations for checking their basic sanity.

It may further be noted that the higgsino content of the LSP (given by $N_{13}^2 + N_{14}^2$) could contribute only partially to the DMDD-SI cross section (for the DM-nucleon scattering process mediated by the doublet CP-even Higgs bosons) while there could be a significant additional contribution from the singlet-like Higgs exchange in such a scattering. However, in the region of parameter space of our interest for which $\kappa \sim \mathcal{O}(10^{-2})$, this contribution is expected to be suppressed. An increase in the total higgsino fraction could attract severe experimental constraints from the DMDD-SI experiments. However, its effect may get subdued in the presence of blind spots in the SI processes. In this work

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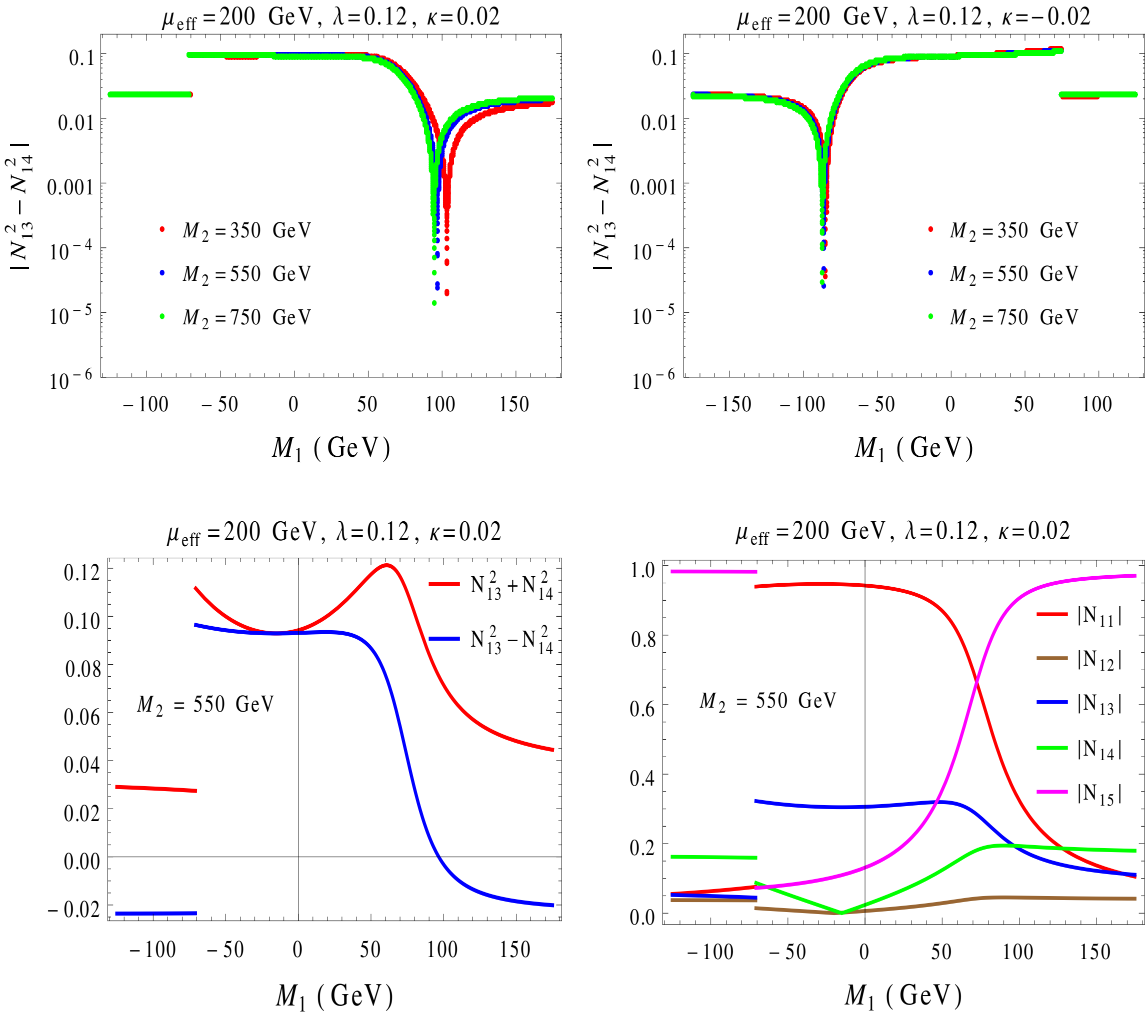

Figure 1. *Upper panel:* variation of the quantity $|N_{13}^2 - N_{14}^2|$ as a function of M_1 for three values of M_2 (350 GeV, 550 GeV and 750 GeV) for $\mu_{\rm eff} = 200$ GeV, $\lambda = 0.12$, and for $\kappa > 0$ (< 0) for upper left (upper right) plot. *Lower panel:* corroborative plots showing variations of the actuals (signed) values of the quantities $N_{13}^2 - N_{14}^2$ and $N_{13}^2 + N_{14}^2$ (left) and $|N_{1j}|$, ($j = 1, \ldots, 5$) (right) as functions of M_1 for a fixed value of M_2 ($= 550$ GeV). $\tan\beta$ is set to 40 throughout. Values of fixed input parameters are indicated at the top of each plot and are the same for all the plots. Plots are created using `SARAH-v4.9.0`-generated [65, 66] NMSSM model and hence present tree-level values only.

we exploit these two simultaneous effects in our favour, by manoeuvring M_1 and/or M_2, to find compliance with the DMDD data while still obtaining a thermal relic density within the Planck-allowed range.

In the upper panel of figure 1 we present the variations of the quantity $|N_{13}^2 - N_{14}^2|$ as a function of M_1 (which can take both signs), for three different values of M_2 (350 GeV, 550 GeV and 750 GeV) with $\mu_{\rm eff} = 200$ GeV, $\tan\beta = 40$ and with $\kappa > 0$ (< 0) on the upper left (upper right) plot. One clearly finds that the magnitude of $|N_{13}^2 - N_{14}^2|$ could practically drop to a vanishing level as M_1 decreases. However, as can be gleaned from the plots in the upper panel, for what exact value of M_1 this happens, depends on the input

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value of M_2, although it becomes more or less insensitive to M_2 for its larger values. These two plots also reveal that such a phenomenon occurs only for M_1 and 'κ' having no relative sign between them, a situation in which the mixing between the two involved sectors is known to get maximal. It is worth pointing out that even though the relevant null entry in the neutralino mass matrix (eq. (2.3)) prohibits a direct mixing between the bino and the singlino states, a possible mixing through the higgsino portal could give rise to something that drastic with important phenomenological consequence akin to a blind spot for DMDD-SI scattering, but this time occurring for DMDD-SD scattering. We exploit this effect in our study the results of which are presented in section 3. The onset of discontinuous flat line segments seen at the top left (right) part of the plots on left (right) has its origin in the bino-like LSP with a negative mass-eigenvalue turning instantly to a singlino-dominated one with a positive eigenvalue, for certain particular values of M_1 depending on values of other input parameters.

Plots in the lower panel of figure 1 explain the general behaviours of the ones in the upper panel by studying the variations of the components but referring only to the upper left plot having $\kappa > 0$. The left plot in the lower panel shows that the quantity $N_{13}^2 - N_{14}^2$ indeed changes sign while varying smoothly, passing through a vanishing value, as M_1 decreases. Over this region, the quantity $N_{13}^2 + N_{14}^2$ (controlling the DMDD-SI rate) also grows smoothly with a decreasing M_1. Patterns of these variations find support in the individual variations of $|N_{13}|$ and $|N_{14}|$ with M_1 as illustrated in the bottom right plot where, in particular, we see a cross-over point of the blue (representing $|N_{13}|$) and the green (representing $|N_{14}|$) curves thus explaining a vanishing value for $N_{13}^2 - N_{14}^2$ seen in the lower left plot. It worths a mention that the crucial variation is the one that of $|N_{13}|$. While it may not be outright unexpected that lowering of M_1 would immediately result in an enhanced bino admixture in the LSP, at the expense of mostly a decreasing singlino fraction in the same, it is somewhat curious to note that a decreasing M_1 boosts the otherwise subdominant higgsino content of the LSP in the form of $|N_{13}|$. It is possible that a decreasing M_1, given its healthy connection to the higgsino sector, drags the higgsino along on a collective bid to deplete the singlino content in the LSP. The discontinuity of the curves appearing for certain negative M_1 values in the upper left plot are also efficiently explained by the plots in the lower panels.

2.4 The spectrum and the decays

Discussions in the previous susbsections reveal that both the light (singlet-like) Higgs sector and the neutralino sector get simultaneously affected in a rather intricate way as 'κ' turns smaller. This includes non-trivial modifications of the involved couplings among these states via mixings effects in both sectors and resulting mass-splits between the physical states. Together these could alter the phenomenology in an essential manner and experimental analyzes need to take due note of the same.

As has been already pointed out, in the scenario under study, the lightest neutralino (the LSP) is singlino-like whereas the immediately heavier neutralinos, to start with, are higgsino-like. The latter could have enhanced decay branching fractions to singlet-like Higgs bosons, h_1 and a_1, which can become light enough for suitably small values of 'κ'.

Under such a circumstance, the SM-like Higgs boson is the second lightest CP-even Higgs boson ($h_2 \sim h_{\rm SM}$) and this is always the case in our present study. As mentioned in the Introduction, the decay branching fractions of the neutralinos to lighter (singlet-like) Higgs bosons could then compete with (or could even exceed) those for the popularly considered modes like $\chi^0_{2,3} \to \chi^0_1 Z^{(*)}/h_2(h_{\rm SM})$ and this is likely to relax the existing bounds on the ewino sector.

A further nontrivial alteration of the decay branching fractions of the higgsino-like neutralinos may take place if one allows for a bino/wino-like neutralino (now χ^0_2) sneak in below the formerly higgsino-like states (now $\chi^0_{3,4}$). Thus, more involved cascades could kick in, viz., $\chi^0_{3,4} \to \chi^0_2(\to \chi^0_1 h_i)Z/h_i$ (with $i = 1, 2, 3$ standing for the two light singlet-like and the SM-like Higgs bosons) thanks to some higgsino admixture in an otherwise gaugino (bino)-dominated χ^0_2. This would have important bearing on collider phenomenology. In section 3, we shall discuss how such an intermediate state plays a crucial role in finding an all-round compliance with the experimental results pertaining to the DM-sector (as pointed out in section 2.3) as those from the colliders.

In passing, it is to be noted that presence of light Higgs states would not directly affect the decay of the lighter chargino for which the experiments assume $\mathrm{BR}(\chi^\pm_1 \to \chi^0_1 W^{\pm(*)})$ to be 100% when the other Higgs states of the NMSSM, along with the sfermions, are all much heavier. Thus, at the first sight, it might appear that bounds imposed on the lighter chargino sector, in particular, by looking for its pair production, and, consequently, on $\mu_{\rm eff}$ (for a higgsino-like lighter chargino) would still hold and need to be respected. However, there are a couple of caveats. First, since the presence of a light singlino state could significantly modify the NMSSM neutralino spectrum through its mixing with the light higgsino states, a reasonable mass-split between $\chi^0_{2,3}$ and $\chi^\pm_1$ cannot be ruled out. This could open up competing decay modes of $\chi^\pm_1$ in the form $\chi^\pm_1 \to \chi^0_{2,3} W^{\pm(*)}$. While these would still lead to final states with leptons thanks to the presence of $W^{\pm(*)}$, the same are likely to be contaminated with the decay products of $\chi^0_{2,3}$, as noted in the last paragraph. Second, as discussed above in the case for the neutralinos, the competing decay mode in the form of $\chi^\pm_1 \to \chi^0_2 W^{\pm(*)}$ could again open up for the lighter chargino when we require, as discussed in section 2.3, M_1 to be brought down below $\mu_{\rm eff}$. In both cases, experimental bounds even from the study of chargino pair production would likely to get relaxed.[5]

As for the light Higgs states (h_1, a_1) appearing in the cascades of the lighter neutralinos, those could have significant branching fractions to $b\bar{b}$ similar to the case of the SM-like Higgs boson. However, in general, constraints derived from neutralino cascades involving such Higgs states are weaker when compared to those obtained with cascades involving $Z^{(*)}$ [13]. Thus, enhanced branching fraction for the decay $\chi^0_{2,3} \to \chi^0_1 h_1/a_1$ (at the expense of $\mathrm{BR}(\chi^0_{2,3} \to \chi^0_1 Z^{(*)})$) are expected to relax the existing experimental bounds on the ewino sector thus capable of opening up a more 'natural' region of the NMSSM parameter space.

[5]Note, however, that if $M_2 \lesssim \mu_{\rm eff}$, this would present us with a lighter chargino which is wino-like and close in mass with χ^0_2. Hence the second effect mentioned above would be absent and $\mathrm{BR}(\chi^\pm_1 \to \chi^0_1 W^\pm)$ would be 100%. This would thus invite the standard, stronger bound on M_2 from null searches for chargino pair production at the LHC.

Varying parameters	λ	$\|\kappa\|$	$\tan\beta$	$\|\mu_{\rm eff}\|$ (GeV)	$\|A_\lambda\|$ (TeV)	$\|A_\kappa\|$ (GeV)	M_1 (GeV)	M_2 (TeV)
	0.05–0.2	0.001–0.05	1–60	≤ 300	≤ 10	≤ 100	50–500	0.2–1

Table 1. Ranges of various model parameters adopted for scanning the Z_3-symmetric NMSSM parameter space. All parameters are defined at the scale $Q^2 = (2m_{\tilde{Q}}^2 + m_{\tilde{U}}^2 + m_{\tilde{D}}^2)/4$, except for $\tan\beta$ which is defined at m_Z (see text for details).

In this work we confine ourselves to a region of the Z_3-symmetric NMSSM parameter space for which the LSP is a singlino-dominated ($> 95\%$), the lighter chargino and two neutralinos are higgsino-like with masses $\lesssim 300$ GeV, with a further possibility of having an intermediate (gaugino-like) neutralino lighter than the higgsino-like states. In addition, the setup offers singlet-like scalars that are lighter than the SM-like Higgs bosons which could even turn out to be lighter than the LSP. Phenomenological possibilities discussed in the previous paragraphs are realized in such a set up. Scan-ranges adopted for various model parameters are summarized in table 1. The soft masses for the SU(3) gaugino (M_3), those for the sfermions and the soft trilinear parameters $A_{\tau,b,t}$ are all fixed at around 5 TeV while $A_{e,\mu}$ is set to zero.

3 Results

We now present our results for the broad scenario discussed in the previous section which is characterized by a light singlino LSP, accompanied by rather light singlet-like scalars, along with higgsino-dominated lighter chargino and neutralinos that ensure a healthy degree of 'naturalness'. The focus is on if such a scenario can be compatible with recent constraints pertaining to the DM sector (i.e., those involving DMRD, DMDD-SI and DMDD-SD) and those coming from various past and recent collider experiments that include the LEP and the LHC experiments. In particular, it emerges from the recent literature [16, 51] that such an all-round compliance is not easy to find. As pointed out in the Introduction, ref. [51] concludes that this may be only possible in the coannihilation region marked by a near-degeneracy of the singlino-dominated LSP and the higgsino-dominated chargino (and neutralinos). Our goal is to go beyond this and to find if such a thorough compliance with DM and collider data is possible away from the coannihilation region while still retaining the essential features of the broad scenario.

Results are obtained via a random scan over the parameter space of the Z_3-symmetric NMSSM using the package `NMSSMTools-v5.1.0` [67–69]. Experimental constraints (at 2σ level) implemented in `NMSSMTools` are automatically imposed on our analysis. These include various constraints from the LEP experiments, including the one pertaining to invisible decay width of the Z-boson, and those on the B-physics observables. Compliance with experimental results on $(g-2)_\mu$ is not demanded. In addition, constraints from various Higgs boson searches at LEP and Tevatron and compatibility to the Higgs boson observed at the LHC are considered/checked by using the packages `HiggsBounds-v4.3.1` [70, 71] and `HiggsSignals-v1.4.0` [72, 73], which, among other things, ensures compliance with the upper bound on the invisible decay width of the observed Higgs boson. DM-related computations are done using an adapted version of the package `micrOMEGAs-v4.3` [74–76] that is built-in to `NMSSMTools`. Finally, we employ the package `CheckMATE-v2.0.26` [58, 59] to check our benchmark points (that pass all relevant constraints including the DM-related ones) if they are passing all relevant LHC analyzes.

3.1 Impact of bounds from the DM sector

Unless otherwise stated, in the present work, bounds from the DM sector would imply strict adherence to a relic density within 10% of the central value of $\Omega h^2 = 0.119$ measured by the Planck experiment [52, 53], i.e., $0.107 < \Omega h^2 < 0.131$. Allowed maximum values for the DM-nucleon scattering cross sections are taken (somewhat conservatively, for DM-mass $\simeq 30\,\mathrm{GeV}$, for which the DMDD-SI bound is the strongest) to be $\sigma^{\mathrm{SI}}_{\chi_1^0-p(n)} < 4.1 \times 10^{-47}\,\mathrm{cm}^2$ [54] and $\sigma^{\mathrm{SD}}_{\chi_1^0-p(n)} < 6.3 \times 10^{-42}\,\mathrm{cm}^2$ [55].

In figure 2 we illustrate various relevant aspects of the regions of Z_3-symmetric NMSSM parameter space that are simultaneously compatible with all experimental data pertaining to DMRD, DMDD-SI and DMDD-SD. These aspects are as follows.

- The plot on the top is in the $m_{\chi_1^0} - m_{\chi_1^\pm}$ plane with the value of the combined branching fraction of $\chi^0_{2,3,4}$ in the decay mode $\chi^0_{2,3,4} \to \chi_1^0 Z$ indicated in the palette which could reach a possible maximum value of '3'. Visibly, over the dark patch along the diagonal, the singlino-dominated DM neutralino is nearly mass-degenerate with the lighter chargino ($\chi_1^\pm$) and the next two lighter neutralinos ($\chi^0_{2,3}$) all of which are higgsino-like. Hence coannihilation of the DM neutralino with these states is rather efficient. This renders DMRD in the right experimental ballpark.[6] It is also important to note that due to this degeneracy, the bounds on the ewino sector are also much relaxed over this region [14]. Hence parameter points from this region have a good chance to survive bounds obtained from both DM experiments and the LHC. In fact, ref. [51] pointed out this to be the only region for a singlino-dominated LSP which could exhibit such a simultaneous compliance with data. Note that given $M_1 < \mu_{\mathrm{eff}}$ is a possibility in our scan, there may be a situation when χ_2^0 becomes bino-dominated while $\chi^0_{3,4}$ become higssino-like. For such a spectrum, the decay $\chi_2^0 \to \chi_1^0 Z$ may be kinematically disfavoured while $\chi^0_{3,4} \to \chi_1^0 Z$ could open up and become relevant.

  In agreement with ref. [51], our scan also finds strips of DM-allowed points at LSP masses with the SM Higgs and Z-boson funnels, i.e., for $m_{\chi_1^0} = m_{h_2}/2$ and at $m_{\chi_1^0} = m_Z/2$, respectively. However, it appears that these strips extend to much higher values of $m_{\chi_1^\pm}$ (apparently limited only by our choice of the upper limit of μ_{eff} ($\lesssim 300\,\mathrm{GeV}$)) when compared to what was found in ref. [51]. Also, unlike in ref. [51], the bottom sections of the funnel strips for the SM Higgs boson and the Z-boson are found to be notably populated. We indeed notice that compliance with DMDD-SD data is facilitated with low values of M_1, as discussed in section 2.3. In

[6] If we assume that the LSP's contribution does not saturate the observed relic density, we would end up with a somewhat larger number of allowed points at low LSP mass (thus broadening the funnel strips) and in the vicinity of the coannihilation region. Note, however, that the enhanced magnitude of some relevant couplings that result in an increased DM-annihilation thus leading to such a drop in the thermal relic density could potentially make the DMDD cross sections breach the experimental constraints.

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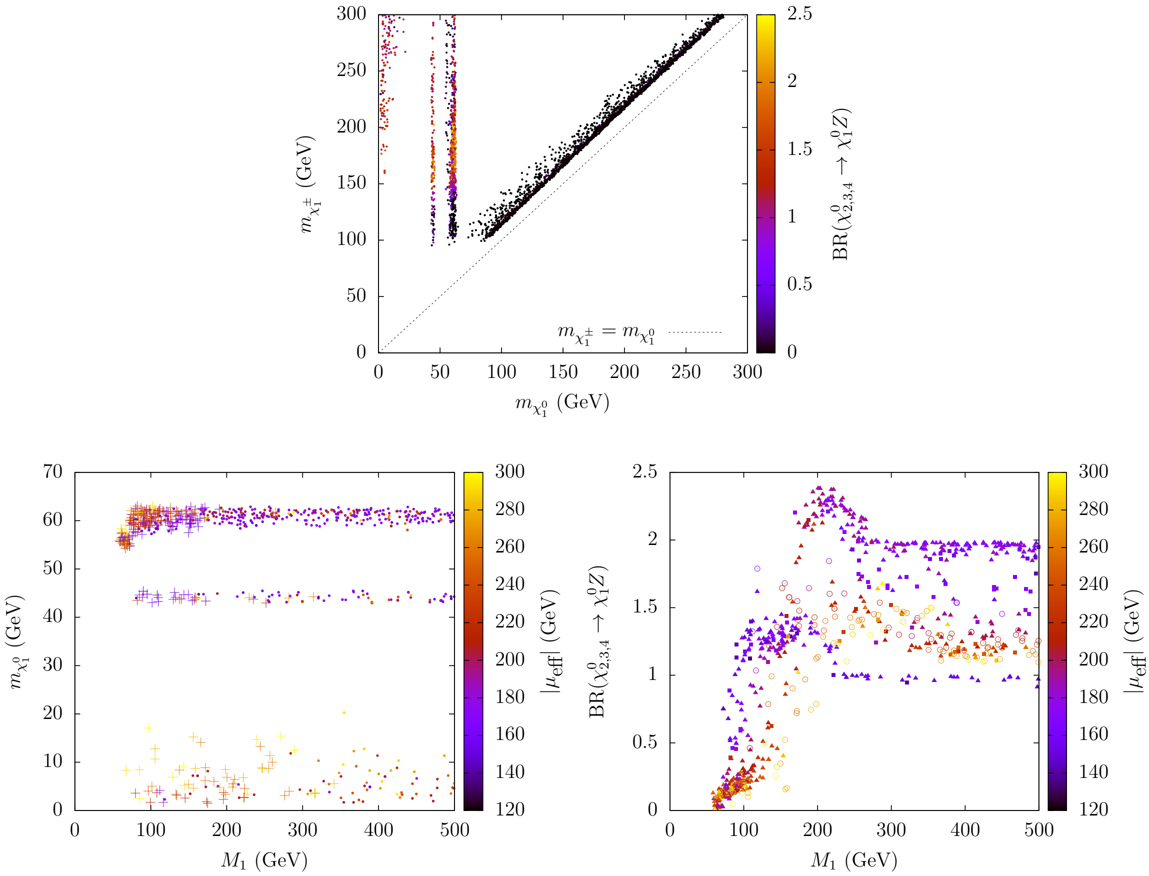

Figure 2. Scatter plots in various planes showing variations of relevant quantities via color-palettes for points in the Z_3-symmetric NMSSM parameter space, with singlino-dominated LSP, obtained via scanning of the same (see text for the ranges used for various free parameters) and are consistent with all the constraints discussed in the text including those from the Higgs sector, flavor sector, DMRD, DMDD-SI and DMDD-SD but before considering the LHC data pertaining to the ewino sector. See text for details.

this region there is a substantial mass difference between $\chi_1^\pm$ and χ_1^0 due to which hard enough leptons are expected from decays of $\chi_1^\pm$. Furthermore, the 3-body decays χ_2^0, $\chi_3^0 \to \ell\bar{\ell}\chi_1^0$ (presumably via an off-shell Z boson) could contribute significantly. Thus, this region is expected to get severely constrained from tri-lepton searches at the LHC [12, 13, 77]. One could as well expect a corresponding 3-body decay of $\chi_{2,3}^0$ that involves a bottom quark pair. Hence searches involving b-jets in the final states [13] are likely to get sensitive to the said region of parameter space.

Furthermore, we find a DM-allowed region with lighter LSP masses ($\lesssim$ 20 GeV) possessing funnels in light singlet scalars (mostly a_1, and only occasionally, h_1). Refs. [15, 45, 51] had correctly argued on the difficulty in realizing an a_1 funnel. However, as envisaged in ref. [15], we now find a generic region with a singlino-dominated LSP with mass $\lesssim$ 20 GeV that possesses a_1 funnel for even (an optimally) small 'λ' along with rather large A_λ. As predicted, the region indeed yields a rather light h_1

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which, ref. [51] argued, would yield too large a DMDD scattering rate to survive the experimental data. Here, it is our specific observation that a suitably low value of M_1 could again do the trick by pushing the DMDD rate down to a safe level.[7] A closer inspection reveals that funnels at work for a singlino-like LSP with mass $\lesssim 40\,\text{GeV}$ can be that of h_1 or a_1 or both, simultaneously. In addition, emergence of points only in discrete strips, even though the LSP and the light scalar masses are varying, are due to stringent requirement of having the relic density within a specific band about its observed central value while satisfying the DMDD bounds.

Of some interest are the points in darker shades in the funnel strips. These are the points for which the collective branching fractions in the decay modes of $\chi^0_{2,3,4}$ containing a real Z-boson are tiny. Thus, it may be expected that these could evade some pertinent collider bounds while being still consistent with all DM data, unless $m_{\chi_1^\pm}$ is too small, as is the case at the bottom of these strips. This is since the latter kinematically prohibits the decay(s) of one or more of the participating heavier neutralinos ($\chi^0_{2,3,4}$) to $\chi^0_1 Z$. Nevertheless, three-body decays (via an off-shell Z-boson) into leptonic final states may remain significant, as discussed before. In addition, we find regular (sparse) population of darker points within the strips representing h_{SM} (Z-boson and h_1/a_1) funnel(s) for higher values of $m_{\chi_1^\pm}$ as well. These result from opening up of new decay modes involving lighter Higgs bosons for $\chi^0_{2,3,4}$ due to genuine (dynamical) suppressions of the strengths for the $\chi^0_{2,3,4}\chi^0_1 Z$ interaction in the presence of competing $\chi^0_{2,3,4}\chi^0_1 h_i$ interactions. Clearly these points need to be subjected to thorough examination to ascertain their viability against LHC data. We undertake this exercise, for relevant final states involving leptons mostly, using `CheckMATE`in section 3.3 with reference to a few benchmark points picked from all the three funnel regions.

- The plots in the bottom row of figure 2 convey the interplay of M_1 and μ_{eff} keeping $m_{\chi_1^0}$ and the combined branching fraction $\text{BR}(\chi^0_{2,3,4} \to \chi^0_1 Z)$ in reference. Thus, while the left plot reveals the funnel strips over specific $m_{\chi_1^0}$ ranges (thus corresponding exactly to the plot on the top) having the branching fraction to Z-boson either less (indicated by '+' marks) or greater (indicated by circular blobs) than 1.5, the right plot explicitly displays the same branching fraction with the three specific (funnel) ranges for the associated $m_{\chi_1^0}$ being indicated by three different symbols: '▲' for the SM Higgs funnel, '■' for the Z-boson funnel and '○' for the singlet-like scalar(s) funnel. These two plots clearly reveal that to achieve a dominant (≥ 1.5) combined branching fraction to every other mode save $\chi^0_1 Z$ (thereby evading relevant collider bounds; represented by the '+' symbol) one requires $M_1 < \mu_{\text{eff}}$. It is somewhat curious to note that the combined branching fraction to Z-boson could systematically go down to a value of ≈ 1 but does not drop further if $M_1 > 250\,\text{GeV}$.

[7]Some such situations are discussed in ref. [16] as specific benchmark points. However, given that the work focuses on the impacts of the LHC data, it remains agnostic as to whether such points would satisfy various DM-related constraints but for the DMRD upper bound. We observe that most of these points possess a rather light h_1 (m_{h_1} ($\lesssim 20\,\text{GeV}$)) which would make it difficult to survive DMDD bounds unless for suitable $M_1 < \mu_{\text{eff}}$ thus yielding a bino-like χ^0_2.

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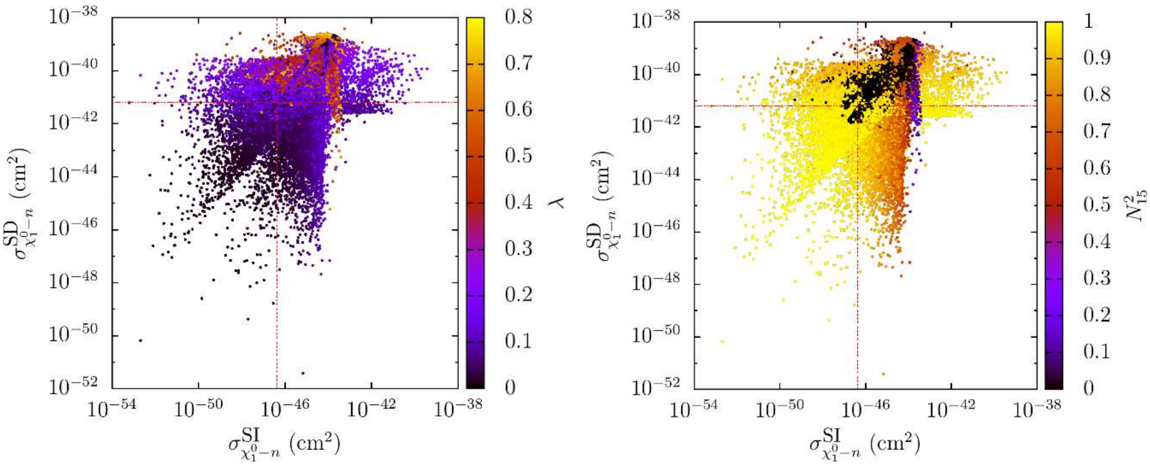

Figure 3. Scatter plots in the plane of $\sigma^{\rm SI}_{\chi_1^0-n} - \sigma^{\rm SD}_{\chi_1^0-n}$ indicating the values of λ (singlino fraction in the LSP ($= N_{15}^2$)) from the palette in the left (right) plot while satisfying $0.107 < \Omega h^2 < 0.131$. Observed upper bounds of the DMDD-SI and DMDD-SD cross sections are indicated by the red-dashed lines vertical and parallel, respectively, to the abscissa thus indicating that points in the bottom left quadrant simultaneously satisfy bounds on both.

In figure 3 we illustrate how the values of 'λ' (left) and hence N_{15}^2 (the singlino admixture in the LSP) are distributed in the $\sigma^{\rm SI}_{\chi_1^0-n} - \sigma^{\rm SD}_{\chi_1^0-n}$ plane. In both plots, points in the bottom left quadrant are the only ones that are allowed by both DMDD-SI and DMDD-SD data. From the left plot one can clearly see that low values of 'λ' ($\lesssim 0.2$) are preferred. This is not unexpected for the following reasons.

- First, the DMDD-SI cross section dominantly involves coupling of a DM(LSP) pair to the singlet-like Higgs bosons ($h_1\chi_1^0\chi_1^0$) which is enhanced for a mixed singlino-higgsino LSP. Given the higgsino admixture in an otherwise singlino-dominated LSP is proportional to 'λ' (for given fixed values of $m_{\chi_1^0}$ and $\mu_{\rm eff}$), the coupling in context grows with its value and could lead to a large enough SI cross section that is ruled out by the experiments.

- Second, the DMDD-SD cross section, in contrast, involves coupling of a DM(LSP) pair to a Z-boson. This, on the other hand, depends on the higgsino content of an otherwise singlino-dominated LSP and hence grows as λ^2 (for given fixed values of $m_{\chi_1^0}$ and $\mu_{\rm eff}$). This could result in a large enough SD cross section which again could be ruled out by relevant experiments.

The plot on the right first corroborates the correlation between 'λ' and N_{15}^2 that is explained above, i.e., the smaller is the value of 'λ', the smaller (larger) is the higgsino (singlino) admixture in the singlino-dominated LSP. Furthermore, one finds that the reddish/purple part on the right edge of the plot has an enhanced higgsino fraction in the LSP and hence always gets ruled out by DMDD-SI data. However, DMDD-SD data may still allow such 'λ' values (in the bottom right quadrant) which is due to somewhat smaller sensitivity of SD rates to 'λ', as hinted above. In contrast, the black regions are very special in the sense that these have the LSP which is bino-dominated (when M_1 goes below $m_{\tilde{S}} \sim 2\kappa v_S$ in our scan). The only admixture that is pertinent here is in the form of higgsinos (since bino does not mix directly to singlino at the lowest order) and 'λ' is likely to decouple from DM physics. Thus, a small higgsino admixture in the LSP could suffice to result in a large enough SI and SD cross sections that are ruled out by experiments. Nonetheless, we find a tiny bino-dominated region in the intersection of the two boundaries that separate the DD-allowed regions. For clarity, it may be mentioned that the points that appear in the allowed (bottom left) quadrant comply with all DM data and hence are the same data-points that show up in figure 2.

3.2 Benchmark scenarios

In this subsection we briefly discuss our strategy to choose a few representative benchmark points that worth thorough scrutiny against recent LHC data in order to establish their viability. We choose our benchmark points from the scan described earlier by ensuring that these all have a singlino-dominated (> 95%) LSP, have low values of μ_{eff} and satisfy basic experimental constraints mentioned earlier including those from the DM-sector. The scenarios are divided into three categories according to the DM-annihilation funnels at work, i.e., singlet (pseudo)scalar funnel, Z-boson funnel and SM-like Higgs funnel. Note that we have ensured, apart from satisfying the DMRD and the DMDD constraints, our benchmark points also satisfy various other constraints from indirect DM searches [78–80] thanks to a small annihilation cross-section at late times ($\langle\sigma v\rangle \lesssim \mathcal{O}(10^{-29})\,\text{cm}^3\,\text{s}^{-1}$). Next, we look for if the combined decay branching fraction of the heavier neutralinos to $\chi_1^0 Z$ could be on the smaller side so that such points stand higher chance of evading LHC constraints on the lighter ewino sector. Furthermore, we try to ensure that the decay branching fraction for $\chi_1^\pm \to \chi_2^0 W^\pm$ competes or even exceeds that for $\chi_1^\pm \to \chi_1^0 W^\pm$ adopted in the standard paradigm for experimental analyzes. This would further relax the existing bounds in this sector.

In table 2 we present these benchmark points by indicating the relevant input parameters, the resulting spectra, the contents of the LSP and the next-to-lightest neutralinos, various relevant branching fractions along with the values for the DM observables. Finally, we summarize for each of these points, their status in view of recent LHC analyzes obtained via `CheckMATE`.

3.3 Impact of recent LHC results: a `CheckMATE`-based analysis

In this section we describe the status of the benchmark scenarios presented in table 2 in the light of the LHC results. As can be seen, these scenarios feature a light higgsino-like chargino, $\chi_1^\pm$ and several light neutralinos, χ_i^0, with $i \in \{1, 3\}$ when only singlino- and higgsino-like states are considered and $i \in \{1, 4\}$ when, in addition, a light bino-like state is allowed.

It may be reiterated that when we consider only singlino- and higgsino-like light neutralinos in the presence of a light (pseudo-) scalar Higgs in the spectrum, the following

	Singlet (pseudo)scalar funnel	Z-boson funnel		SM-like Higgs funnel	
λ	8.72×10^{-2}	0.181	0.133	0.120	0.160
κ	2.43×10^{-3}	-1.28×10^{-2}	1.23×10^{-2}	1.74×10^{-2}	1.76×10^{-2}
$\tan\beta$	33.69	26.56	11.86	39.61	9.13
A_λ (TeV)	10.15	7.67	2.56	8.90	2.81
A_κ (GeV)	−58.25	51.42	−13.93	−35.90	−0.52
μ (GeV)	297.65	297.81	230.46	193.10	250.63
M_1 (GeV)	96.85	97.91	137.64	115.00	87.10
M_2 (GeV)	485.83	689.15	556.26	575.12	417.42
$m_{\chi_1^0}$ (GeV)	17.07	43.40	43.78	57.40	55.49
$m_{\chi_2^0}$ (GeV)	94.00	95.03	129.05	107.26	83.26
$m_{\chi_3^0}$ (GeV)	298.79	306.86	240.02	204.84	247.11
$m_{\chi_4^0}$ (GeV)	314.69	315.71	245.32	208.28	265.15
$m_{\chi_5^0}$ (GeV)	543.61	749.64	611.46	631.06	468.50
$m_{\chi_1^\pm}$ (GeV)	297.37	303.73	231.96	196.67	242.56
$m_{\chi_2^\pm}$ (GeV)	543.68	749.66	611.47	631.08	468.51
m_{h_1} (GeV)	8.49	41.11	40.68	48.17	52.62
m_{h_2} (GeV)	125.53	125.54	124.75	125.65	122.90
m_{a_1} (GeV)	37.65	56.25	34.23	55.12	20.47
N_{11}, N_{21}	0.03, 0.98	0.03, 0.98	0.05, 0.95	0.09, −0.93	0.17, −0.96
N_{12}, N_{22}	−0.01, −0.01	−0.01, −0.01	−0.02, −0.03	−0.02, 0.02	−0.03, 0.02
N_{13}, N_{23}	0.01, 0.15	−0.01, 0.15	0.02, 0.26	0.06, −0.28	0.05, −0.18
N_{14}, N_{24}	−0.05, −0.05	−0.10, −0.01	−0.10, −0.15	−0.12, 0.14	−0.12, 0.06
N_{15}, N_{25}	0.99, −0.03	0.99, 0.00	0.99, −0.07	0.98, 0.12	0.97, 0.18
BR($\chi_1^\pm\to\chi_1^0W^\pm$)	0.13	0.37	0.47	0.59	0.39
BR($\chi_1^\pm\to\chi_2^0W^\pm$)	0.87	0.63	0.53	0.41	0.61
BR($\chi_2^0\to\chi_1^0Z$)	0.00	0.00	0.00	0.00	0.00
BR($\chi_2^0\to\chi_1^0h_1$)	0.92	1.00	0.95	1.00	0.00
BR($\chi_2^0\to\chi_1^0h_2$)	0.00	0.00	0.00	0.00	0.00
BR($\chi_2^0\to\chi_1^0a_1$)	0.08	0.00	0.03	0.00	1.00
BR($\chi_3^0\to\chi_1^0Z$)	0.04	0.22	0.25	0.18	0.06
BR($\chi_3^0\to\chi_2^0Z$)	0.25	0.19	0.24	0.33	0.22
BR($\chi_3^0\to\chi_1^0h_1$)	0.00	0.01	0.02	0.00	0.01
BR($\chi_3^0\to\chi_2^0h_1$)	0.01	0.03	0.16	0.07	0.01
BR($\chi_3^0\to\chi_1^0h_2$)	0.07	0.10	0.33	0.41	0.29
BR($\chi_3^0\to\chi_2^0h_2$)	0.63	0.45	0.00	0.00	0.41
BR($\chi_3^0\to\chi_1^0a_1$)	0.00	0.00	0.00	0.01	0.00
BR($\chi_4^0\to\chi_1^0Z$)	0.09	0.18	0.38	0.67	0.36
BR($\chi_4^0\to\chi_2^0Z$)	0.74	0.54	0.54	0.30	0.52
BR($\chi_4^0\to\chi_1^0h_1$)	0.00	0.01	0.00	0.00	0.00
BR($\chi_4^0\to\chi_2^0h_1$)	0.00	0.00	0.00	0.00	0.00
BR($\chi_4^0\to\chi_1^0h_2$)	0.03	0.17	0.07	0.01	0.03
BR($\chi_4^0\to\chi_2^0h_2$)	0.14	0.10	0.00	0.00	0.08
BR($\chi_4^0\to\chi_2^0a_1$)	0.00	0.00	0.01	0.02	0.01
BR($\chi_4^0\to\chi_2^0a_2$)	0.00	0.00	0.00	0.00	0.00
Ωh^2	0.12447	0.12739	0.12713	0.13002	0.10723
$\sigma^{\rm SI}_{\chi_1^0-p(n)}$ (cm^2)	$0.8(1.1)\times10^{-47}$	$4.3(4.0)\times10^{-47}$	$2.5(2.3)\times10^{-47}$	$6.6(8.4)\times10^{-48}$	$4.7(5.1)\times10^{-47}$
$\sigma^{\rm SD}_{\chi_1^0-p(n)}$ (cm^2)	$2.3(1.7)\times10^{-43}$	$4.6(3.5)\times10^{-42}$	$3.8(2.9)\times10^{-42}$	$4.9(3.8)\times10^{-42}$	$5.8(4.4)\times10^{-42}$
`CheckMATE` result	Allowed	Allowed	Allowed	Allowed	Allowed
r-value	0.97	0.57	0.81	0.70	0.90
Analysis	CMS_SUS_16_039 [12]	CMS_SUS_16_039	CMS_SUS_16_039	CMS_SUS_16_039	CMS_SUS_16_039
Signal region	SR_G05	SR_A30	SR_A30	SR_A25	SR_A30

Table 2. Benchmark points in the Z_3-symmetric NMSSM parameter space offering different annihilation-funnels for a singlino-dominated DM neutralino along with resulting spectra, compositions of the DM and the next-to-lightest neutralinos, various relevant branching fractions of the light ewinos, the values of the DM relic density, the DMDD-SI and the DMDD-SD cross sections. Also indicated are the 'r'-values (see section 3.3) returned by `CheckMATE`along with the reference LHC analyzes and the most sensitive Signal Regions (SR). `NMSSMTools-v5.3.0` is used to generate the spectra and to calculate the decay branching fractions of various ewinos. The DM-observables are estimated with the `micrOMEGAs` package built-in in `NMSSMTools`. The fixed values of various soft parameters used are as follows: $M_3=m_{(\tilde{Q},\tilde{U},\tilde{D})_{1,2}}=m_{\tilde{L},\tilde{E}}=A_{b,t}=5$ TeV, $m_{(\tilde{Q},\tilde{U})_3}=5.5$ TeV and $A_\tau=5.6$ TeV.

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decay channels are of importance:

$$\chi_1^\pm \to \chi_1^0 W^\pm,\ \chi_i^0 \to \chi_1^0 Z/h/a, \quad (i=2,3)$$

where $h \equiv \{h_1, h_2(h_{\rm SM})\}$ ('a') represents a CP-even (CP-odd) Higgs boson. In the presence of a bino-like state in the spectrum, typically χ_2^0 for our benchmark points, the following additional decay modes can be relevant too:

$$\chi_1^\pm \to \chi_2^0 W^\pm,\ \chi_2^0 \to \chi_1^0 h/a,\ \chi_i^0 \to \chi_2^0 Z/h/a, \quad (i=3,4).$$

Depending on the mass-difference between the heavier higgsino-like states and χ_1^0, on- or off-shell gauge/scalar bosons may appear in the above decays of the light ewinos. Since we mainly focus on the uncompressed region, with rather sizable mass-split between the heavier higgsino-like states and χ_1^0, on-shell gauge bosons feature in all our benchmark scenarios.

Considering final states with leptons, the following final states are going to be relevant.

- Chargino pair production ($pp \to \chi_1^\pm \chi_1^\mp$) can lead to $2\ell + \not{E}_T$ (missing E_T or MET). In the presence of a bino-like χ_2^0, there could be significant number of events with up to four accompanying b-jets, assuming the Higgs boson in the cascade dominantly decays into two b-quarks.

- Chargino-heavier neutralinos associated production ($pp \to \chi_1^\pm \chi_{2,3,4}^0$) can lead to $3\ell + \not{E}_T$ and $\ell + 2b + \not{E}_T$. As in the previous case, the presence of a bino-like χ_2^0, either produced in the hard scattering or in the cascade of heavier neutralinos, might lead to final states with an enhanced b-jet multiplicity.

- Finally, heavier neutralino pair production could lead to up to $2\ell + 2$-jets$/4\ell + \not{E}_T$ where, in our case, the pairs of leptons come from the decay of on-shell Z-bosons. The presence of a bino-like χ_2^0 in the cascade, as before, would ensure enhanced b-jet multiplicity in the final state.

We use `CheckMATE-v2.0.26` to test our benchmark scenarios against relevant experimental analyzes by the ATLAS and the CMS collaborations (which are already implemented in `CheckMATE`and have been validated) at the 13 TeV LHC with up to 36 fb^{-1} worth data. The mono-jet/$\gamma + \not{E}_T$ [81, 82] are relevant for pair production of the lightest neutralino, together with an ISR jet or a photon. Searches for two soft leptons [14, 83] can be relevant for compressed spectra of light ewinos. While searches in these final states could, in general, put reasonable constraints on the chargino-neutralino spectra, these are not expected to be much constraining in the current context. In the case of mono-jet/mono-photon searches, the insensitivity stems from the small production cross-section of χ_1^0 pair in the present scenario. Soft lepton searches are insensitive since in our case the heavier ewinos and the lightest neutralino are already well-separated in mass.

Several other searches for strongly interacting particles have been performed by both the ATLAS and the CMS collaborations. The inclusion of b-tagged jets, together with leptons can be relevant in our present context. However, these searches consider large jet multiplicity (typically $\geq 4-6$ jets). Generic absence of large jet multiplicity in our situations make them immune to any constraint whatsoever derived from these searches.

The most relevant searches, in our case, involve multi-leptons and b-tagged jets along with $\not\!\!E_T$, low jet multiplicity [12, 77, 84].[8] Out of the multi-lepton analyzes implemented in the CheckMATEversion that we employed, the most stringent constraints appear to arise from the $3\ell + \not\!\!E_T$ final states, as well as from the ones with an opposite-sign di-lepton pair in the final states [12, 13, 77].[9]

We use MadGraph5-v2.4.3 [86] to simulate ewino pair/associated production. Events are generated for $pp \to \chi_j \chi_k$, ($\chi_j \in \{\chi_i^0, \chi_1^\pm\}$), with up to one additional parton in the final state. These result in 10 (15) distinct production channels when 3 (4) light neutralino states are considered. For each production channel, 0.3 million parton level events are generated. We then use the built-in version of PYTHIA6 [87, 88] for showering and hadronization and for decays of unstable particles. We have used the MLM [89, 90] prescription for the matching of jets from matrix elements with those from parton showers, as implemented in MadGraph.

Typically, on merging and matching of partonic jets, the number of simulated events per production channel reduces to around 0.2 million, on an average. Such a volume of generated event-samples is expected to be healthy enough to ensure a stable statistics and hence could be used for reliable estimates in subsequent analyzes. The cross sections for all the processes have been computed at the leading order in MadGraph. A flat K-factor of 1.25 [91] has been multiplied to the cross sections of all relevant ewino pair production processes to factor in the approximate NLO+NLL contributions. This is expected to help CheckMATE make conservative estimates of the lowest values of the ewino masses that the recent LHC data could allow. Finally, we have used CheckMATE [59] (see also [92–96]) to examine the viability of the benchmark scenarios in the light of 13 TeV LHC results. CheckMATEreports an r-value for each of the benchmark scenarios where $r = (S - 1.64\Delta S)/S95$ and 'S', ΔS and $S95$ denote the predicted number of signal events, its Monte Carlo error and the experimental limit on 'S' at 95% confidence level, respectively.

The benchmark scenarios in table 2 are so chosen that they yield $r < 1$ which, going by the CheckMATEconvention, are dubbed 'allowed' by the LHC analyzes employed for the purpose. We are aware of a stricter criteria used in some literature (say, $r < 0.67$ [16]) for definiteness in such a conclusion. In that sense, our approach is only semi-conservative. Thus, the best that can be said about these points is that most of them are on the verge of being ruled out by the LHC experiments and might soon get to be so with some additional data. However, at present, they are indicative of how low a μ_{eff} could still be viable under different scenarios when the LSP is singlino-dominated. Table 2 reveals that μ_{eff} as low as ~ 200 GeV cannot yet be ruled out with a reasonable certainty.

Recently the ATLAS collaboration has analyzed 139 fb^{-1} of data and has derived constraints by studying the pair production of charginos where they used the di-lepton

[8] Final states involving 'τ' leptons have also been considered in the literature [12, 85]. However, our benchmark scenarios are not sensitive to the signal regions discussed in those works.

[9] Final states with leptons and b-jets have been considered in ref. [13] and certain signal regions discussed there can be relevant for our present study. However, the experimental results have not been implemented in CheckMATEversion we used and hence it is beyond the scope of the present work.

$+\not{E}_T$ data for the purpose [97]. However, the analysis assumes that the chargino decays 100 % of the times to $\chi_1^0 W^\pm$. Since in the presence of a bino-like χ_2^0, as demonstrated in our benchmark scenarios, there is a substantial contribution from the decay mode $\chi_1^\pm \to \chi_2^0 W^\pm$, the constraints derived from the above analysis do not apply directly to our cases.

Further, we observe that inclusion of electroweak productions of heavier neutralinos ($\chi_{3,4}^0$, which though are not too heavy in the absolute sense) seems to play an important role in further exclusion of the $m_{\chi_1^\pm} - m_{\chi_1^0}$ plane (see table 2) beyond what is reported in the literature, although the possibilities find a mention there [15]. This is since these additional modes contribute to the final states that are instrumental in the exclusion.

4 Conclusions

A low value of $\mu_{\rm eff}$ is known to ensure an enhanced degree of 'naturalness' in a Z_3-symmetric NMSSM scenario. An interesting possibility in such a scenario is a light singlino-dominated LSP DM. These two together form the edifice of a singlino-higgsino LSP as a possible candidate for the DM. Motivated by these, in this work, we have explored in some detail the viability of relatively low values of $\mu_{\rm eff}$ with the LSP being singlino-dominated.

We agree with the observations made in the recent literature that for a singlino-dominated LSP it is not easy to meet the relevant constraints from the DM and the collider sectors simultaneously. Compliance has been reported only when the higgsino-like ewinos are nearly degenerate with the singlino-like LSP. This ensures its efficient coannihilation with a degenerate higgsino-like state thus producing a relic at the right (experimentally observed) ballpark. At colliders, this presents a compressed spectrum that results in relaxed bounds on the higgsino-like states which could then be light and still evading generic searches.

We have presented a rigorous analysis of regions of the target parameter space (with relatively light singlino-like LSP of mass $\lesssim m_{h_{\rm SM}}/2$, with a purity level $> 95\%$ and with relatively small $\mu_{\rm eff}$) which exhibit such an overall compliance with experimental data. These comprise of theoretically much-motivated regions that offer DM-annihilation funnels in the SM-like Higgs boson, in the Z-boson and in the singlet-like scalars. The higgsino admixture in the LSP DM is anyway necessary to secure their optimal annihilation in order to find compliance with the observed relic density. However, this needs moderation since otherwise the cross section for DM scattering off the nucleon in the DMDD experiments (in particular, DMDD-SD) becomes too large and violates the reported bounds.

We have demonstrated that allowing for a smaller value of M_1 and/or M_2 ($\sim \mu_{\rm eff}$) can be a helpful one-shot manoeuvre that could favorably tweak the dynamics and the kinematics simultaneously. This way it helps achieve the right balance among various relevant interaction strengths and decay branching fractions thus offering simultaneous compliance with data from both DM experiments and the colliders. In the process, productions and decays of heavier neutralinos (χ_3^0 and χ_4^0) become relevant and these influence the bounds that can be obtained on the parameter space from the experimental analyses. In a sense, this presents the scope and the requirement of an indispensable and nontrivial tempering of the singlino-like LSP for the purpose. Further studies in the area of tempered neutralinos in the NMSSM are in progress [98].

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