Light singlino DM of the natural NMSSM

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The natural Z_3-symmetric NMSSM

- **The superpotential of the Z_3-symmetric NMSSM is given by**

$$\mathcal{W} = \mathcal{W}_{\rm MSSM}|_{\mu=0} + \lambda \widehat{S}\widehat{H}_u.\widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3 \,, \qquad (1)$$

where $\mathcal{W}_{\rm MSSM}|_{\mu=0}$ is the MSSM superpotential without the μ-term. The μ-term is generated when 'S' acquires *vev* $\langle S\rangle = v_s$ (i.e., $\mu_{\rm eff} = \lambda v_s$).

- **The symmetric 5×5 neutralino mass matrix is given by**

$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu_{\rm eff} & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 2\kappa v_s \end{pmatrix} . \qquad (2)$$

The above mass-matrix can be diagonalized by a matrix N, i.e.,

$$N^* \mathcal{M}_0 N^\dagger = {\rm diag}(\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0, \chi_5^0) \,. \qquad (3)$$

The resulting neutralino mass-eigenstates (χ_i^0, in order of increasing mass as 'i' varies from 1 to 5).

- **On the other hand, the 2×2 chargino mass matrix of the NMSSM is given by**

$$\mathcal{M}_C = \begin{pmatrix} M_2 & g_2 v_u \\ g_2 v_d & \mu_{\rm eff} \end{pmatrix} . \tag{4}$$

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

$$U^* \mathcal{M}_C V^\dagger = {\rm diag}(m_{\chi_1^\pm}, m_{\chi_2^\pm}) \,; \quad {\rm with} \;\; m_{\chi_1^\pm} < m_{\chi_2^\pm} \,. \tag{5}$$

- **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 (ewinos) with masses $\sim \mu_{\rm eff}$, which are dominantly higgsino-like.**

- **In particular, we are interested in a scenario where, $2\kappa v_s \lesssim \mu_{\rm eff}$ (i.e., $\kappa \lesssim \lambda/2$). This could lead to a singlino-dominated LSP with mass $m_{\chi_1^0} \sim 2\kappa v_s$.**

Motivation and objectives

- **Motivated by a low value of the effective higgsino mass parameter ($\mu_{\rm eff}$) to ensure an enhanced degree of 'naturalness' in a Z_3-symmetric NMSSM scenario, we explore the viability of relatively low $\mu_{\rm eff}$ (preferably $\lesssim 300$ GeV) with the LSP being singlino-dominated ($> 95\%$), which is a DM candidate.**

- **In such a scenario, light ewinos generally derive significant constraints from their null searches at the colliders. Their usual decay modes 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 $\mu_{\rm eff}$ 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 clean multi-lepton final states.**

- **Clearly, presence of a light h/a could lead to a sizable $\mathrm{BR}(\chi_{2,3}^0 \to \chi_1^0 h/a)$ thus depleting the lepton-rich events. This can potentially weaken the limit on $\mu_{\rm eff}$.**

- **In the Z_3-symmetric NMSSM scenario with small values of $\mu_{\rm eff}$, when the coefficient 'κ' of the superpotential term $\frac{\kappa}{3}\widehat{S}^3$ gets vanishingly small:**

  1. **a 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.**

  2. **a light singlino-dominated LSP (χ_1^0) with a critical higgsino admixture (thanks to a not so large $\mu_{\rm eff}$) is naturally present in the spectrum.**

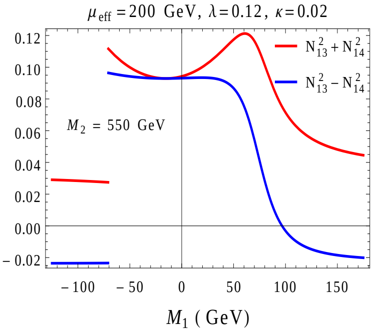
  3. **the higgsino admixture in the singlino-dominated LSP could now enable the LSP annihilate efficiently enough in the early Universe yielding DM relic in the right ballpark and make it sensitive to DM Direct Detection (DMDD) experiments.**

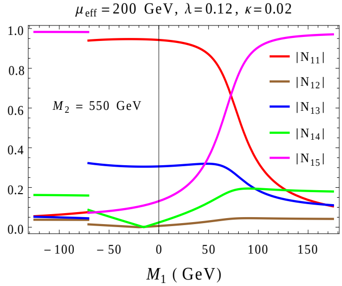
  4. **the light scalars (a_1 and h_1) could offer new annihilation 'funnels' that are efficient handles on the DM Relic Density (DMRD).**

- **The purpose is to find how such a scenario could still be compatible with all pertinent experimental data from both DM and collider fronts.**

The relevant interactions and spectrums

- 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 $\alpha_{Z\chi_1^0\chi_1^0} \sim |N_{13}^2 - N_{14}^2|$.
- The higgsino content of the LSP $(N_{13}^2 + N_{14}^2)$ could contribute significantly to the DMDD-SI cross section (for the DM-nucleon scattering process mediated by the singlet-like Higgs).
- Clearly, a cross-over point of the blue (representing $|N_{13}|$) and the green (representing $|N_{14}|$) curves explains a vanishing value for $N_{13}^2 - N_{14}^2$.
- Over this region, the quantity $N_{13}^2 + N_{14}^2$ (controlling the DMDD-SI rate) also grows smoothly with a decreasing M_1.





- **Scan-ranges adopted for various model parameters are summarized in the following table:**

λ	$\lvert\kappa\rvert$	$\tan\beta$	$\lvert\mu_{\rm eff}\rvert$ (GeV)	$\lvert A_\lambda\rvert$ (TeV)	$\lvert A_\kappa\rvert$ (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

- **The soft masses for the $SU(3)$ gaugino (M_3), 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.**

- **Again, in this work we confine ourselves to a region of parameter space for which the LSP is a singlino-dominated ($> 95\%$) with $M_1 < \mu_{\rm eff}$.**

Results

- **Results are obtained via a random scan over the parameter space of the Z_3-symmetric NMSSM using the package** `NMSSMTools`**.**

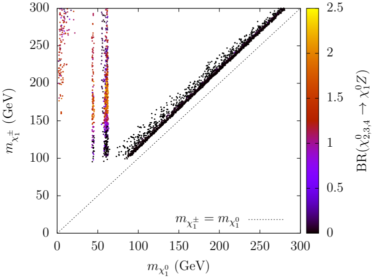
- **Experimental constraints (at 2σ level) implemented in** `NMSSMTools` **are automatically imposed on our analysis. These include various constraints:**
    1. **from the LEP experiments, including the invisible decay width of the Z-boson, and those on the B-physics observables.**
    2. **from the DM sector (i.e., those involving DMRD, DMDD-SI and DMDD-SD) DM-related computations are done using** `micrOMEGAs` **that is built-in to** `NMSSMTools`**.**
    3. **from Higgs boson searches at LEP, Tevatron and the LHC which are considered/checked using** `HiggsBounds` **and** `HiggsSignals`**.**

- **Finally, we employ the package** `CheckMATE` **to check our benchmark points if they are passing all relevant LHC analyses.**

Impact of DM and collider bounds

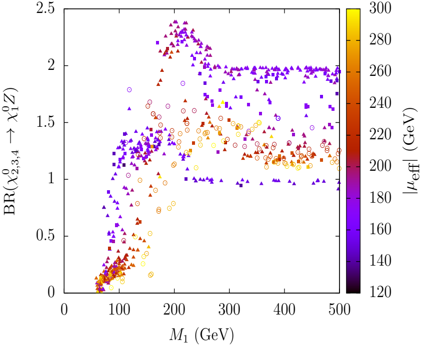
- **In the present work, bounds from the DM sector are as follows.**
  1. **DMRD within 10% of the central value of $\Omega h^2 = 0.119$, i.e., $0.107 < \Omega h^2 < 0.131$.**
  2. $\sigma^{\rm SI}_{\chi_1^0 - p(n)} < 4.1 \times 10^{-47}$ **cm^2 (the strongest DMDD-SI bound, at $m_{\chi_1^0} \simeq 30$ GeV).**
  3. $\sigma^{\rm SD}_{\chi_1^0 - p(n)} < 6.3 \times 10^{-42}$ **cm^2.**

- **Four 'allowed' regions have been obtained:**
  1. **The dark patch along the diagonal (coannihilation region).**
  2. **Two strips at LSP masses with the SM Higgs and Z-boson funnels, i.e., for $m_{\chi_1^0} = m_{h_{\rm SM}}/2$ and at $m_{\chi_1^0} = m_Z/2$, respectively.**
  3. **a region with lighter LSP masses ($\lesssim 20$ GeV) having funnels in light singlet scalars, a_1/h_1.**



- **As mentioned, the points of tiny BR($\chi^0_{2,3,4} \to \chi^0_1 Z$) (in darker shades in the funnel strips) could evade some pertinent collider bounds. Clearly these points need to be checked against LHC data. We undertake this exercise using `CheckMATE` with reference to a few benchmark points picked from all the three funnel regions.**

- **Here, the plot displays BR($\chi^0_{2,3,4} \to \chi^0_1 Z$) with the three specific (funnel) ranges for the associated $m_{\chi^0_1}$ being indicated by three different symbols: '▲' for the SM Higgs funnel, '■' for the Z-boson funnel and '○' for the singlet-like scalar(s) funnel.**
- **This plot clearly reveals that to achieve a dominant (≥ 1.5) combined branching fraction to every other mode save $\chi^0_1 Z$, one requires $M_1 < \mu_{\text{eff}}$.**



- **A key ingredient that renders these points in the funnel strips are compatible with constraints from the DMDD experiments (in particular, DMDD-SD) and the LHC experiments, is a relatively small M_1.**

Benchmark scenarios

	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
$\mu_{\rm eff}$ (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
`CheckMATE` result r-value	Allowed 0.97	Allowed 0.57	Allowed 0.81	Allowed 0.70	Allowed 0.90

	Singlet funnel	Z-boson funnel		SM-like Higgs funnel	
$\mathrm{BR}(\chi_1^\pm \to \chi_1^0 W^\pm)$	0.13	0.37	0.47	0.59	0.39
$\mathrm{BR}(\chi_1^\pm \to \chi_2^0 W^\pm)$	0.87	0.63	0.53	0.41	0.61
$\mathrm{BR}(\chi_2^0 \to \chi_1^0 Z)$	0.00	0.00	0.00	0.00	0.00
$\mathrm{BR}(\chi_2^0 \to \chi_1^0 h_1)$	0.92	1.00	0.95	1.00	0.00
$\mathrm{BR}(\chi_2^0 \to \chi_1^0 h_2)$	0.00	0.00	0.00	0.00	0.00
$\mathrm{BR}(\chi_2^0 \to \chi_1^0 a_1)$	0.08	0.00	0.03	0.00	1.00
$\mathrm{BR}(\chi_3^0 \to \chi_1^0 Z)$	0.04	0.22	0.25	0.18	0.06
$\mathrm{BR}(\chi_3^0 \to \chi_2^0 Z)$	0.25	0.19	0.24	0.33	0.22
$\mathrm{BR}(\chi_3^0 \to \chi_1^0 h_1)$	0.00	0.01	0.02	0.00	0.01
$\mathrm{BR}(\chi_3^0 \to \chi_2^0 h_1)$	0.01	0.03	0.16	0.07	0.01
$\mathrm{BR}(\chi_3^0 \to \chi_1^0 h_2)$	0.07	0.10	0.33	0.41	0.29
$\mathrm{BR}(\chi_3^0 \to \chi_2^0 h_2)$	0.63	0.45	0.00	0.00	0.41
$\mathrm{BR}(\chi_3^0 \to \chi_1^0 a_1)$	0.00	0.00	0.00	0.01	0.00
$\mathrm{BR}(\chi_4^0 \to \chi_1^0 Z)$	0.09	0.18	0.38	0.67	0.36
$\mathrm{BR}(\chi_4^0 \to \chi_2^0 Z)$	0.74	0.54	0.54	0.30	0.52
$\mathrm{BR}(\chi_4^0 \to \chi_1^0 h_1)$	0.00	0.01	0.00	0.00	0.00
$\mathrm{BR}(\chi_4^0 \to \chi_2^0 h_1)$	0.00	0.00	0.00	0.00	0.00
$\mathrm{BR}(\chi_4^0 \to \chi_1^0 h_2)$	0.03	0.17	0.07	0.01	0.03
$\mathrm{BR}(\chi_4^0 \to \chi_2^0 h_2)$	0.14	0.10	0.00	0.00	0.08
$\mathrm{BR}(\chi_4^0 \to \chi_2^0 a_1)$	0.00	0.00	0.01	0.02	0.01
$\mathrm{BR}(\chi_4^0 \to \chi_2^0 a_2)$	0.00	0.00	0.00	0.00	0.00

Conclusions

- **For light singlino-like LSP of mass $\lesssim m_{h_{\rm SM}}/2$, with a purity level $> 95\%$ and small $\mu_{\rm eff}$, three DM-annihilation funnels in $h_{\rm SM}$, Z and singlet-like scalars have been obtained.**
- **We have demonstrated that allowing for a smaller value of M_1 helps achieve the right balance among various relevant interaction strengths and decay branching fractions thus offering simultaneous agreement with data from both DM experiments and the colliders.**

Thank you