Singlino DM in General Next-to-Miminmal Supersymmetric Standard Model

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1. Why is the attractiveness of Bino-dominated DM fading?
2. Why doesn't Z_3-NMSSM explain DM experiments naturally?
3. Advantages of Singlino-dominated DM in GNMSSM
4. Conclusions

Why Does Bino-dominated DM Become Less Favored?

- Take the MSSM as an example:

$$\sigma^{\mathrm{SI}}_{\tilde{\chi}^0_1-N} \simeq 5\times 10^{-45}\ \mathrm{cm}^2 \left(\frac{\mathrm{C}_{\tilde{\chi}^0_1\tilde{\chi}^0_1\mathrm{h}}}{0.1}\right)^2 \left(\frac{\mathrm{m_h}}{125\mathrm{GeV}}\right)^2$$

$$\sigma^{\mathrm{SD}}_{\tilde{\chi}^0_1-N} \simeq 10^{-39}\ \mathrm{cm}^2 \left(\frac{\mathrm{C}_{\tilde{\chi}^0_1\tilde{\chi}^0_1\mathrm{Z}}}{0.1}\right)^2$$

$$C_{\tilde{\chi}^0_1\tilde{\chi}^0_1 h} \simeq e\tan\theta_W \frac{m_Z}{\mu\left(1-m^2_{\tilde{\chi}^0_1}/\mu^2\right)}\left(\sin 2\beta + \frac{m_{\tilde{\chi}^0_1}}{\mu}\right)$$

$$C_{\tilde{\chi}^0_1\tilde{\chi}^0_1 Z} \simeq \frac{e\tan\theta_W\cos 2\beta}{2}\,\frac{m_Z^2}{\mu^2 - m^2_{\tilde{\chi}^0_1}}$$

- **Conservative bounds on Higgsino mass:**

  LZ Experiment: $\mu \gtrsim 380$ GeV, **LZ + LHC +** a_μ**:** $\mu \gtrsim 500$ GeV.

- **Higgsino mass is related with electroweak symmetry breaking!**

$$m_Z^2 = 2(m^2_{H_d} - m^2_{H_u}\tan^2\beta)/(\tan^2\beta - 1) - \boldsymbol{2\mu^2}.$$

A tuning of 1% in EWSB. The situation will become worse if no DM is found.

Why Does Bino-dominated DM Become Less Favored?

Solutions: Go beyond minimal realizations of WIMP miracle.

DM EFTs	Examples	Annihilation	$\tilde{\chi} - N$ Scattering	Remarks
SM+DM	SM+S_{real}	Weak/contact interactions	$\sigma_{\rm SI} \gtrsim 10^{-45}{\rm cm}^2$ and/or $\sigma_{\rm SD} \gtrsim 10^{-39}{\rm cm}^2$	Experimentally excluded.
			Suppressed by cancellation	Symmetry!
		Feeble interaction: h/Z funnels	Suppressed	Increasingly Fine-tuned: $\Delta > 150$.
SM+DM+X	MSSM with Light Gauginos	Coannihilation	Suppressed	Fine-tuning: $\Delta > 30$; Tight LHC constraitns.
SM+DM+XY	GNMSSM ISS-NMSSM	May form **secluded DM sector**	Suppressed	No tuning; **three portals to SM**.

Why is the dark matter still called WIMP?

Weak interactions in the DM sector to predict proper Ωh^2, feeble connections between SM and DM sectors to suppress ...

At least two directions to build models:

- Realize naturally EWSB: **MSSM** $\rightarrow$ **Z_3-NMSSM** $\rightarrow$ **General NMSSM**.
- Generate neutrino mass: **Type-I NMSSM** $\rightarrow$ **ISS-NMSSM** $\rightarrow$ **B-L NMSSM**.

Why Doesn't Z_3-NMSSM Explain DM Exp. Naturally?

- Field content and gauge group

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(\mathrm{U}(1) \otimes \mathrm{SU}(2) \otimes \mathrm{SU}(3))$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6}, \mathbf{2}, \mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1, \mathbf{1}, \mathbf{1})$
$\hat{\mathbf{s}}$	$\mathbf{S}$	$\tilde{S}$	**1**	$(0, \mathbf{1}, \mathbf{1})$

- Superpotential — an ad hoc Z_3 discrete symmetry

$$W_{\mathrm{NMSSM}} = W_{\mathrm{Yukawa}} + \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{3} \kappa \hat{S}^3$$

Try to solve μ-problem and little hierarchy problem.

- DM may be Bino- or Singlino-dominated. For Bino-dom. case: **DM physics is the same as that of MSSM since** $\lambda \lesssim 0.3$.

  LZ Experiment: $\mu \gtrsim 380$ GeV, **Higgs Data:** $\lambda\mu \lesssim 100$ GeV.

Singlino-dominated DM:

- Neutralino mass matrix — diagonalized by a rotation matrix N

$$\mathcal{M} = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & \frac{2\kappa}{\lambda}\mu \end{pmatrix}$$

- DM mass and its couplings are approximated by: $\mu \equiv \frac{\lambda}{\sqrt{2}} v_s$

$$m_{\tilde{\chi}_1^0} \approx \frac{2\kappa}{\lambda}\mu + \frac{\lambda^2 v^2}{\mu^2}(\mu \sin 2\beta - \frac{2\kappa}{\lambda}\mu) \simeq \frac{2\kappa}{\lambda}\mu, \qquad N_{15} \simeq 1,$$

$$\frac{N_{13}}{N_{15}} = \frac{\lambda v}{\sqrt{2}\mu} \frac{(m_{\tilde{\chi}_1^0}/\mu)\sin\beta - \cos\beta}{1 - \left(m_{\tilde{\chi}_1^0}/\mu\right)^2}, \qquad \frac{N_{14}}{N_{15}} = \frac{\lambda v}{\sqrt{2}\mu} \frac{(m_{\tilde{\chi}_1^0}/\mu)\cos\beta - \sin\beta}{1 - \left(m_{\tilde{\chi}_1^0}/\mu\right)^2},$$

$$C_{\tilde{\chi}_1^0 \tilde{\chi}_1^0 h_i} \simeq \frac{\sqrt{2}\mu}{v} \left(\frac{\lambda v}{\mu}\right)^2 \frac{V_{h_i}^{\rm SM}(m_{\tilde{\chi}_1^0}/\mu - \sin 2\beta)}{1 - (m_{\tilde{\chi}_1^0}/\mu)^2} + \ldots,$$

$$C_{\tilde{\chi}_1^0 \tilde{\chi}_1^0 Z} \simeq \frac{m_Z}{\sqrt{2}v} \left(\frac{\lambda v}{\mu}\right)^2 \frac{\cos 2\beta}{1 - (m_{\tilde{\chi}_1^0}/\mu)^2},$$

Z_3-NMSSM: DM Properties

Singlino-dominated DM:

- DM properties are described by **four** independent parameters:

$$\tan\beta, \quad \lambda, \quad \mu, \quad m_{\tilde{\chi}_1^0} \text{ or } \kappa, \quad \text{and } 2\kappa/\lambda < 1.$$

- DM-Nucleon Scattering in the alignment limit:

$$\begin{aligned}
\sigma^{\rm SI}_{\tilde{\chi}_1^0-N} &\simeq 5\times 10^{-45}{\rm cm}^2 \times \left(\frac{\mathcal{A}}{0.1}\right)^2, \quad \sigma^{\rm SD}_{\tilde{\chi}_1^0-N} \simeq 10^{-39}\ {\rm cm}^2 \left(\frac{C_{\tilde{\chi}_1^0\tilde{\chi}_1^0 Z}}{0.1}\right)^2, \\
\mathcal{A} &\simeq \left(\frac{125{\rm GeV}}{m_h}\right)^2 V_h^{\rm SM} C_{\tilde{\chi}_1^0\tilde{\chi}_1^0 h} + \left(\frac{125{\rm GeV}}{m_{h_s}}\right)^2 V_{h_s}^{\rm SM} C_{\tilde{\chi}_1^0\tilde{\chi}_1^0 h_s} \\
&\simeq \sqrt{2}\left(\frac{125{\rm GeV}}{m_h}\right)^2 \lambda \frac{\lambda v}{\mu} \frac{(m_{\tilde{\chi}_1^0}/\mu - \sin 2\beta)}{\mathbf{1 - (m_{\tilde{\chi}_1^0}/\mu)^2}}, \\
C_{\tilde{\chi}_1^0\tilde{\chi}_1^0 Z} &\simeq \frac{m_Z}{\sqrt{2}v}\left(\frac{\lambda v}{\mu}\right)^2 \frac{\cos 2\beta}{\mathbf{1 - (m_{\tilde{\chi}_1^0}/\mu)^2}}.
\end{aligned}$$

LZ Experiment: $\lambda \lesssim 0.1$, **DM-$\tilde{H}$ coannihilation to obtain proper abudance.**

Bayesian evidence is heavily suppressed → A fine-tuning theory!

Advantages of Singlino-dominated DM in GNMSSM

- Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(\mathrm{U}(1) \otimes \mathrm{SU}(2) \otimes \mathrm{SU}(3))$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6}, \mathbf{2}, \mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{d}$	$\tilde{d}^*_R$	d^*_R	3	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}^*_R$	u^*_R	3	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}^*_R$	e^*_R	3	$(1, \mathbf{1}, \mathbf{1})$
$\hat{s}$	S	$\tilde{S}$	1	$(0, \mathbf{1}, \mathbf{1})$

- Superpotential — no ad hoc symmetry!

$$W_{\mathrm{GNMSSM}} = W_{\mathrm{Y}} + \lambda \hat{S}\hat{H}_u \cdot \hat{H}_d + \frac{1}{3}\kappa \hat{S}^3 + \mu \hat{H}_u \cdot \hat{H}_d + \frac{1}{2}\mu' \hat{S}^2 + \xi \hat{S}$$

1. Free from domain wall and tadpole problems in Z_3-NMSSM.
2. Z_3-violating terms originate from unified theories with a Z_4^n or Z_8^n sym..
3. The $\xi \hat{S}$ term can be eliminated by field redefinitions.

GNMSSM: DM Mass and Couplings

Singlino-dominated DM:

- Neutralino mass matrix: $\mu_{eff} \equiv \frac{\lambda}{\sqrt{2}} v_s$, $\mu_{tot} \equiv \mu + \mu_{eff}$.

$$m_{\tilde{\chi}_i^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2} g_1 v_d & \frac{1}{2} g_1 v_u & 0 \\ 0 & M_2 & \frac{1}{2} g_2 v_d & -\frac{1}{2} g_2 v_u & 0 \\ -\frac{1}{2} g_1 v_d & \frac{1}{2} g_2 v_d & 0 & -\mu_{\mathbf{tot}} & -\frac{1}{\sqrt{2}} v_u \lambda \\ \frac{1}{2} g_1 v_u & -\frac{1}{2} g_2 v_u & -\mu_{\mathbf{tot}} & 0 & -\frac{1}{\sqrt{2}} v_d \lambda \\ 0 & 0 & -\frac{1}{\sqrt{2}} v_u \lambda & -\frac{1}{\sqrt{2}} v_d \lambda & \mathbf{m_N} \end{pmatrix}$$

Mass and couplings of the singlino-dominated DM are given by:

$$m_{\tilde{\chi}_1^0} \simeq m_N + \frac{1}{2} \frac{\lambda^2 v^2 (m_{\tilde{\chi}_1^0} - \mu_{tot} \sin 2\beta)}{m_{\tilde{\chi}_1^0}^2 - \mu_{tot}^2} \simeq \mathbf{m_N}, \quad \mathbf{m_N} \equiv \frac{\mathbf{2\kappa}}{\lambda} \mu_{\mathbf{eff}} + \mu',$$

$$C_{\tilde{\chi}_1^0 \tilde{\chi}_1^0 h_i} = C^{\mathrm{Z_3-NMSSM}}_{\tilde{\chi}_1^0 \tilde{\chi}_1^0 h_i} |_{\mu \to \mu_{tot}}, \qquad C_{\tilde{\chi}_1^0 \tilde{\chi}_1^0 Z} = C^{\mathrm{Z_3-NMSSM}}_{\tilde{\chi}_1^0 \tilde{\chi}_1^0 Z} |_{\mu \to \mu_{tot}}.$$

- DM properties are described by **five** independent parameters:

$\tan\beta,\ \lambda,\ \kappa,\ \mu_{\mathrm{tot}},\ and\ m_{\tilde{\chi}_1^0}$. $\mu_{\mathbf{tot}}$: **Higgsino mass**.

Note:

Different from Z_3-NMSSM, $m_{\tilde{\chi}_1^0}$, λ, and κ are not correlated!

- In the limit $\lambda \to 0$, matrix decomposition: $5 \times 5 = 4 \oplus 1$, **decoupled**!

GNMSSM: Higgs Sector

Soft-breaking terms:

$$-\mathcal{L}_{soft} = \left[\lambda A_\lambda S H_u \cdot H_d + \frac{1}{3} A_\kappa \kappa S^3 + m_3^2 H_u \cdot H_d + \frac{1}{2} {m'_S}^2 S^2 + h.c.\right] + m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2.$$

CP-odd Higgs mass matrix in bases $(A_{\rm NSM}, {\rm Im}(S))$:

$$\mathcal{M}^2_{P,11} = \frac{2\left[\mu_{eff}(\lambda A_\lambda + \kappa \mu_{eff} + \lambda \mu') + \lambda m_3^2\right]}{\lambda \sin 2\beta} \equiv \mathbf{m_A^2},$$

$$\mathcal{M}^2_{P,22} = \frac{(\lambda A_\lambda + 4\kappa\mu_{eff} + \lambda\mu')\sin 2\beta}{4\mu_{eff}} \lambda v^2 - \frac{\kappa \mu_{eff}}{\lambda}(3A_\kappa + \mu') - \frac{\mu}{2\mu_{eff}} \lambda^2 v^2 - 2{m'_S}^2$$

$$\mathcal{M}^2_{P,12} = \frac{v}{\sqrt{2}}(\lambda A_\lambda - 2\kappa\mu_{eff} - \lambda\mu') \equiv \frac{\boldsymbol{\lambda} \mathbf{v}}{\sqrt{\mathbf{2}}}(\mathbf{A}_\lambda - \mathbf{m_N}).$$

- In the limit $\lambda \to 0$, matrix decomposition: $2 \times 2 = 1 \oplus 1$, **singlet decoupled**!
- m_A: hevay doublet mass scale, $m_B \equiv \sqrt{\mathcal{M}^2_{P,22}}$: CP-odd singlet Higgs mass.

$$m_3^2 = \frac{\lambda \mathbf{m_A^2}\, sin2\beta - 2\kappa\mu_{\rm eff}^2 - 2\lambda\mu_{\rm eff}\mu' - 2\lambda\mu_{\rm eff} A_\lambda}{2\lambda}$$

$$m_S'^2 = -\frac{1}{2}\left[\mathbf{m_B^2} + \frac{\mu}{2\mu_{\rm eff}}\lambda^2 v^2 + \frac{\kappa\mu_{\rm eff}}{\lambda}(3A_\kappa + \mu') - \frac{(\lambda A_\lambda + 4\kappa\mu_{\rm eff} + \lambda\mu')\, sin2\beta}{4\mu_{\rm eff}}\lambda v^2\right]$$

GNMSSM: Higgs Sector

CP-even Higgs mass matrixin in bases $(H_{\rm NSM}, H_{\rm SM}, {\rm Re}[S])$:

$$\mathcal{M}^2_{S,11} = m_A^2 + \frac{1}{2}(2m_Z^2 - \lambda^2 v^2)\sin^2 2\beta,$$

$$\mathcal{M}^2_{S,12} = -\frac{1}{4}(2m_Z^2 - \lambda^2 v^2)\sin 4\beta,$$

$$\mathcal{M}^2_{S,13} = -\frac{1}{\sqrt{2}}(\lambda A_\lambda + 2\kappa\mu_{eff} + \lambda\mu')v\cos 2\beta \equiv -\frac{\lambda}{\sqrt{2}}(A_\lambda + m_N)v\cos 2\beta,$$

$$\mathcal{M}^2_{S,22} = m_Z^2 \cos^2 2\beta + \frac{1}{2}\lambda^2 v^2 \sin^2 2\beta,$$

$$\mathcal{M}^2_{S,23} = \frac{v}{\sqrt{2}}\left[2\lambda(\mu_{eff} + \mu) - (\lambda A_\lambda + 2\kappa\mu_{eff} + \lambda\mu')\sin 2\beta\right],$$

$$\equiv \frac{\lambda \mathbf{v}}{\sqrt{\mathbf{2}}}[\mathbf{2}\mu_{\mathbf{tot}} - (\mathbf{A}_\lambda + \mathbf{m_N})\sin \mathbf{2}\beta],$$

$$\mathcal{M}^2_{S,33} = \frac{\lambda(A_\lambda + \mu')\sin 2\beta}{4\mu_{eff}}\lambda v^2 + \frac{\mu_{eff}}{\lambda}(\kappa A_\kappa + \frac{4\kappa^2\mu_{eff}}{\lambda} + 3\kappa\mu') - \frac{\mu}{2\mu_{eff}}\lambda^2 v^2,$$

- In the limit $\lambda \to 0$, matrix decomposition: $3 \times 3 = 2 \oplus 1$, **singlet decoupled**!
- $m_C \equiv \sqrt{\mathcal{M}^2_{S,33}}$: CP-even singlet Higgs mass.

$$A_\kappa = \frac{\mathbf{m_C^2} + \frac{\mu}{2\mu_{\rm eff}}\lambda^2 v^2 - \frac{\lambda(A_\lambda+\mu')sin2\beta}{4\mu_{\rm eff}}\lambda v^2 - \frac{4\kappa^2}{\lambda^2}\mu_{\rm eff}^2 - \frac{3\kappa}{\lambda}\mu_{\rm eff}\mu'}{\frac{\mu_{\rm eff}}{\lambda}\kappa}$$

GNMSSM: Input Parameters

Input parameters in the original Lagrangian:

- Soft-breaking masses: $m^2_{H_u}$, $m^2_{H_d}$, and m^2_S;
- Yukawa couplings in Higgs sector: λ and κ;
- Soft-breaking trilinear coefficients A_λ and A_κ;
- Bilinear mass parameters μ and μ', and their soft-breaking parameters m_3^2 and ${m'_S}^2$.

Physical inputs: λ, κ, $\tan\beta$, v_s, $m_{H^\pm}$, m_{h_s}, m_{A_s}, $m_{\tilde{\chi}^0_1}$, and μ_{tot}.

- Vacuum expectation values: v_u, v_d, v_s;
- Yukawa couplings in Higgs sector: λ and κ;
- Electroweakino masses: $m_{\tilde{\chi}^0_1} \simeq m_N$, and Higgsino mass μ_{tot};
- Higgs boson masses: $m^2_{H^\pm} \simeq m^2_A$, $m_{A_s} \simeq m_B$, and $m_{h_s} \simeq m_C$;
- Soft-breaking trilinear coefficients A_λ, **which is an insensitive parameter for all observables.**

GNMSSM: Key Features

Important applications of the Singlino-dominated DM:

- **Singlet-dominated particles form a secluded DM sector: proper abundance is generated by**
  - s**-wave process** $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to h_s A_s$**, occuring by** s**-channel exchange of Higgs bosons and** t**-channel exchange of neutralinos**:

$$|C_{\tilde{\chi}_1^0 \tilde{\chi}_1^0 h_s}| = |C_{\tilde{\chi}_1^0 \tilde{\chi}_1^0 A_s}| = \sqrt{2}\kappa \simeq 0.2 \times \left(\frac{m_{\tilde{\chi}_1^0}}{300 \text{ GeV}} \right)^{1/2};$$

  - p**-wave process** $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to h_s h_s, A_s A_s$**, via adjusting** κ;
  - h_s/A_s**-funnels, via adjusting** m_{h_s}/m_{A_s}.
- **DM-nucleon scatterings suppressed by** λ^4**:**
  Current LZ experiment requires $\lambda \lesssim 0.1$**. Future DD expt. will further suppress** λ**, but not affect GNMSSM phenomenology.**
- **Bayesian analyses:**
  DM is primarily preferred to be Singlino-dominated.

GNMSSM: Other Distinct Features

Characteristics:

1. **Free from the domain wall and tadpole problems**;
2. **More stable vacuum than the MSSM**;

$$V_{\min}^{\rm des} = \cdots - \frac{\kappa^2}{\lambda^4}\mu_{eff}^4 - \frac{1}{3}\frac{\kappa A_\kappa}{\lambda^3}\mu_{eff}^3.$$

3. **Significant alleviation of the LHC constraints**.
   Heavy sparticles prefer to decay into NLSP or NNLSP first. Their decay chains are thus lengthened and their decay products become more complex.
4. **Every EW parameter takes natural values**.
   Considering LZ + LHC + a_μ,
   Z_3-NMSSM: $m_{\tilde{\chi}_1^0} \gtrsim 260\text{GeV}, \ \mu \gtrsim 550\text{GeV}, \ v_s \gtrsim 2$ TeV;
   GNMSSM: $m_{\tilde{\chi}_1^0} \gtrsim 100\text{GeV}, \ \mu_{tot} \gtrsim 200\text{GeV}, \ v_s < 1$ TeV.
5. **Bayesian evidence is much larger than that of Z_3-NMSSM**.

Technical Support

Results are based on global fits of supersymmetric theories.

1. Specially designed clusters.
2. SARAH suite for calculation.
   - Model building: SARAH-4.14.3;
   - Spectrum generator: SPheno-4.0.4;
   - DM physics calculator: MicrOMEGAs-5.0.4;
   - Higgs physics calculator: HiggsSingal-2.2.3, HiggsBounds-5.3.2;
   - Flavor physics calculator: FlavorKit;
   - MC simulation: MadGraph_aMC@NLO, PYTHIA8, and Delphes;
   - LHC SUSY search: SModelS-2.1.1, CheckMATE-2.0.29.
3. Scan strategy: parallel MultiNest algorithm.
   High performance:
   Simultaneous computation of more than 10^6 programes.
4. Members of the developers for the package CheckMATE.
   Reproduce more than 40 experimental analyses.

Technical Support

Table 1: Experimental analyses of the electroweakino production processes.

Scenario	Final State	Name
$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to WZ\tilde{\chi}_1^0\tilde{\chi}_1^0$	$n\ell(n \geq 2) + nj(n \geq 0) + \mathrm{E}_\mathrm{T}^\mathrm{miss}$	CMS-SUS-20-001($137fb^{-1}$) ATLAS-2106-01676($139fb^{-1}$) CMS-SUS-17-004($35.9fb^{-1}$) CMS-SUS-16-039($35.9fb^{-1}$) ATLAS-1803-02762($36.1fb^{-1}$) ATLAS-1806-02293($36.1fb^{-1}$)
$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to \ell\tilde{\nu}\ell\tilde{\ell}$	$n\ell(n = 3) + \mathrm{E}_\mathrm{T}^\mathrm{miss}$	CMS-SUS-16-039($35.9fb^{-1}$) ATLAS-1803-02762($36.1fb^{-1}$)
$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to \tilde{\tau}\nu\ell\tilde{\ell}$	$2\ell + 1\tau + \mathrm{E}_\mathrm{T}^\mathrm{miss}$	CMS-SUS-16-039($35.9fb^{-1}$)
$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to \tilde{\tau}\nu\tilde{\tau}\tau$	$3\tau + \mathrm{E}_\mathrm{T}^\mathrm{miss}$	CMS-SUS-16-039($35.9fb^{-1}$)
$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to Wh\tilde{\chi}_1^0\tilde{\chi}_1^0$	$n\ell(n \geq 1) + nb(n \geq 0) + nj(n \geq 0) + \mathrm{E}_\mathrm{T}^\mathrm{miss}$	ATLAS-1909-09226($139fb^{-1}$) CMS-SUS-17-004($35.9fb^{-1}$) CMS-SUS-16-039($35.9fb^{-1}$) ATLAS-1812-09432($36.1fb^{-1}$) CMS-SUS-16-034($35.9fb^{-1}$) CMS-SUS-16-045($35.9fb^{-1}$)
$\tilde{\chi}_1^\mp\tilde{\chi}_1^\pm \to WW\tilde{\chi}_1^0\tilde{\chi}_1^0$	$2\ell + \mathrm{E}_\mathrm{T}^\mathrm{miss}$	ATLAS-1908-08215($139fb^{-1}$) CMS-SUS-17-010($35.9fb^{-1}$)
$\tilde{\chi}_1^\mp\tilde{\chi}_1^\pm \to 2\tilde{\ell}\nu(\tilde{\nu}\ell)$	$2\ell + \mathrm{E}_\mathrm{T}^\mathrm{miss}$	ATLAS-1908-08215($139fb^{-1}$) CMS-SUS-17-010($35.9fb^{-1}$)
$\tilde{\chi}_2^0\tilde{\chi}_1^\mp \to h/ZW\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to \gamma/Z\tilde{G}$ $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp \to WW\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to \gamma/Z\tilde{G}$	$2\gamma + n\ell(n \geq 0) + nb(n \geq 0) + nj(n \geq 0) + \mathrm{E}_\mathrm{T}^\mathrm{miss}$	ATLAS-1802-03158($36.1fb^{-1}$)
$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to ZW\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to h/Z\tilde{G}$ $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp \to WW\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to h/Z\tilde{G}$ $\tilde{\chi}_2^0\tilde{\chi}_1^0 \to Z\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to h/Z\tilde{G}$ $\tilde{\chi}_1^\mp\tilde{\chi}_1^0 \to W\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to h/Z\tilde{G}$	$n\ell(n \geq 4) + \mathrm{E}_\mathrm{T}^\mathrm{miss}$	ATLAS-2103-11684($139fb^{-1}$)
$\tilde{\chi}_i^{0,\pm}\tilde{\chi}_j^{0,\mp} \to \tilde{\chi}_1^0\tilde{\chi}_1^0 + \chi_{soft} \to ZZ/H\tilde{G}\tilde{G}$	$n\ell(n \geq 2) + nb(n \geq 0) + nj(n \geq 0) + \mathrm{E}_\mathrm{T}^\mathrm{miss}$	CMS-SUS-16-039($35.9fb^{-1}$) CMS-SUS-17-004($35.9fb^{-1}$)

Conclusion

1. **WIMP crisis just means that the simplest realizations of the WIMP miracle are facing challenges** $\longrightarrow$
   More elaborate theories are encouraged.
2. **Occam razor was incorrectly applied to the NMSSM**.
   Specifically, the Z_3-NMSSM is too restricted to exhibit all the essential characteristics of the NMSSM.
3. **It is time to explore the phenomenology of GNMSSM**, which is one of the simplest supersymmetric theories to explain naturally current experiments.
   - **Signlino DM is primarily preferred by Bayesian statistics!**
   - **The GNMSSM has many distinct theoretical advantages!**
4. **Seemingly independent problems may have common physical origins!**
   Go forward to explore them with creative ideas and more sophisticated techniques.

thanks!