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

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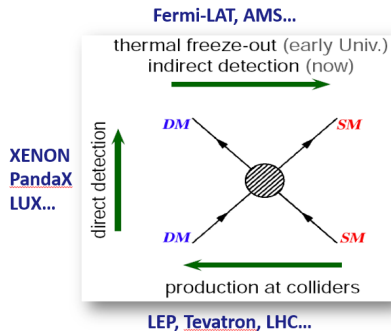
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Fermi-LAT, AMS...

thermal freeze-out (early Univ.)
indirect detection (now)

direct detection

DM → SM

DM → SM

production at colliders

LEP, Tevatron, LHC...

No new physics signal !

arXiv:2207.03764

FIG. 5

FIG. 7

Simple WIMP DM Theory:

DM mass: $m_{\mathrm{DM}} \sim 100$ GeV

Relic density: $\langle \sigma v \rangle \simeq 10^{-26} \mathrm{cm}^3 s^{-1}$

SI scattering: $\sigma_{\tilde{\chi}-N}^{\mathrm{SI}} \sim 10^{-45} \mathrm{cm}^2$,

SD scattering: $\sigma_{\tilde{\chi}-N}^{\mathrm{SD}} \sim 10^{-39} \mathrm{cm}^2$.
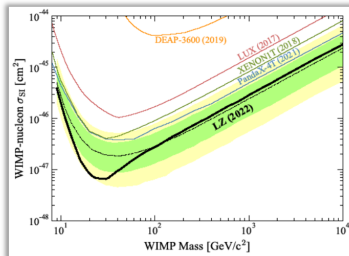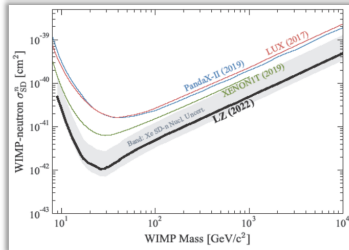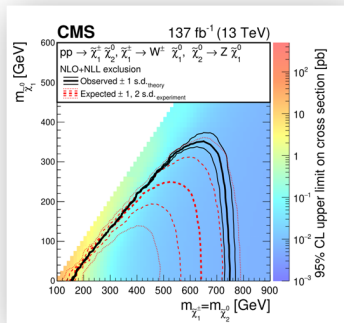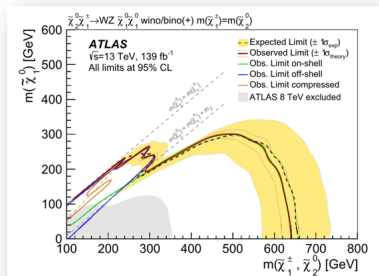
Latest LHC searches for Tri- and Bi-lepton signals.

1. Simplified model for a specified process.
2. Invalid for a specific theory: complex decay chain, multiple production processes, and various signals to be analyzed.
3. Elaborated Monte Carlo simulations are necessary.

Why Does Bino-dominated DM Become Less Popular?

- MSSM: Full expression complicated; $\mu/m_{\tilde{\chi}_1^0}$ is Higgsino/DM mass.

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

$$\sigma_{\tilde{\chi}_1^0-N}^{\text{SD}} \simeq 10^{-39} \text{ cm}^2 \left(\frac{C_{\tilde{\chi}_1^0\tilde{\chi}_1^0 Z}}{0.1}\right)^2$$

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

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

- **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!**

$$m_Z^2 = 2(m_{H_d}^2 - m_{H_u}^2 \tan^2\beta)/(\tan^2\beta - 1) - \mathbf{2\mu^2}.$$

A tuning of 1% in EWSB. **Significantly worsen in Giudice-Masiero Mechan**

Why Does Bino-dominated DM Become Less Popular?

Solutions: Go beyond minimal realizations of WIMP miracle.

DM EFTs	Examples	DM Abundance	$\bar{\chi} - N$ 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/Mediator	Suppressed	Fine-tuning: $\Delta > 30$; Tight LHC constraints.
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 → Z_3-NMSSM → General NMSSM**.
- Generate neutrino mass: **Type-I NMSSM → ISS-NMSSM → B-L NMSSM**.

Why Does Z_3-NMSSM not naturally Explain DM Exp.?

- Field content and gauge group

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

- Superpotential — an ad hoc Z_3 discrete symmetry

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

Try to economically solve μ-problem and ....

- DM may be Bino- or Singlino-dominated. <u>For Bino-dom. case:</u>
  LZ Experiment: $\mu \gtrsim 380$ GeV,   **Higgs Data:** $\lambda\mu \lesssim 100$ GeV.
  DM physics is the same as that of MSSM since $\lambda \lesssim 0.3$.

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: $\mu \equiv \frac{\lambda}{\sqrt{2}} v_s$

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

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

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

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

Singlino-dominated DM:

- DM-Nucleon Scattering in the alignment limit:

$$
\sigma^{\mathrm{SI}}_{\tilde{\chi}^0_1 - N} \simeq 5 \times 10^{-45} \mathrm{cm}^2 \times \left(\frac{\mathcal{A}}{0.1} \right)^2, \quad \sigma^{\mathrm{SD}}_{\tilde{\chi}^0_1 - N} \simeq 10^{-39} \ \mathrm{cm}^2 \left(\frac{\mathrm{C}_{\tilde{\chi}^0_1 \tilde{\chi}^0_1 \mathrm{Z}}}{0.1} \right)^2,
$$

$$
\mathcal{A} \simeq \left(\frac{125 \mathrm{GeV}}{m_h} \right)^2 V_h^{\mathrm{SM}} C_{\tilde{\chi}^0_1 \tilde{\chi}^0_1 h} + \left(\frac{125 \mathrm{GeV}}{m_{h_s}} \right)^2 V_{h_s}^{\mathrm{SM}} C_{\tilde{\chi}^0_1 \tilde{\chi}^0_1 h_s}
$$

$$
\simeq \sqrt{2} \left(\frac{125 \mathrm{GeV}}{m_h} \right)^2 \lambda \frac{\lambda v}{\mu} \frac{(m_{\tilde{\chi}^0_1}/\mu - \sin 2\beta)}{1 - (m_{\tilde{\chi}^0_1}/\mu)^2},
$$

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

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

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

Experiment: $\lambda \lesssim 0.1$, DM-$\tilde{H}$ coannihilation to obtain proper abudance.
Bayesian evidence is heavily suppressed $\rightarrow$ A fine-tuning theory!

Advantages of Singlino-dominated DM in GNMSSM

- Chiral Superfields

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

- Superpotential — no ad hoc symmetry!

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

1. Solving 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: $\mu_{eff} \equiv \frac{\lambda}{\sqrt{2}} v_s$, $\mu_{tot} \equiv \mu + \mu_{eff}$.

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

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

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

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

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

  Note: $\tan\beta$, λ, κ, $\mu_{\mathbf{tot}}$, and $m_{\tilde{\chi}_1^0}$. $\mu_{\mathbf{tot}}$: **Higgsino mass**.

  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 $(A_{\mathrm{NSM}}, \mathrm{Im}(S))$:

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

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

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

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

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

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

GNMSSM: Higgs Sector

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

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

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

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

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

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

$$\equiv \frac{\lambda v}{\sqrt{2}}\left[2\mu_{\text{tot}} - (A_\lambda + m_N)\sin 2\beta\right],$$

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

- 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.

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

GNMSSM: Input Parameters

Input parameters in the original Lagrangian:

- Soft-breaking masses: $m_{H_u}^2$, $m_{H_d}^2$, and m_S^2;
- 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}, $m_{\tilde{\chi}_1^0}$, **and** μ_{tot}.

- Vacuum expectation values: v_u, v_d, v_s;
- Yukawa couplings in Higgs sector: λ and κ;
- Electroweakino masses: $m_{\tilde{\chi}_1^0} \simeq m_N$, and Higgsino mass μ_{tot};
- Higgs boson masses: $m_{H^\pm}^2 \simeq m_A^2$, $m_{A_s} \simeq m_B$, 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:

- **Bayesian analyses (assuming all inputs flat distributed): DM is primarily preferred to be Singlino-dominated.**

- **Singlet-dominated particles form a secluded DM sector:** Measured DM 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.**

GNMSSM: Other Distinct Features

Characteristics:

① **Free from the domain wall and tadpole problems**;

② **More stable vacuum than the MSSM**;

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

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: $m_{\tilde{\chi}_1^0} \gtrsim 260\text{GeV}, \ \mu \gtrsim 550\text{GeV}, \ v_s \gtrsim 2 \text{ TeV}$;
GNMSSM: $m_{\tilde{\chi}_1^0} \gtrsim 100\text{GeV}, \ \mu_{tot} \gtrsim 200\text{GeV}, \ v_s < 1 \text{ TeV}$.

⑤ **Bayesian evidence is much larger than that of Z_3-NMSSM**.

GNMSSM: Possible problems and solutions

Possible problems:

- What's the origin of the S field?
- Why is λ small? Is there other reason than the Higgs data for it?
- Which value A_λ is preferred?
- What's the origin of neutrino mass?

Solution:

R-symmetry: the largest subgroup of automorphism group of supersymmetry algebra which commutes with Lorenz group.

R-symmetry + Seesaw mechanism!

Secluded DM sector: $\hat{S}$ and $\hat{\nu}_R$ form ..., Higgs or Neutrino Portal. $\tilde{S}\tilde{S} \to \nu_R \bar{\nu}_R$ or $\tilde{\nu}_R \tilde{\nu}_R \to SS$.

Technical Support

Results are based on global fits of supersymmetric theories.

1. Specially designed clusters → **New Development: IB Network, Data transition speed: 200G/s.**

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.

Table 1: Experimental analyses of the electroweakino production processes.

Scenario	Final State	Name
$\tilde\chi_2^0\tilde\chi_1^\pm \to WZ\tilde\chi_1^0\tilde\chi_1^0$	$n\ell(n\geq 2) + nj(n\geq 0) + E_T^{miss}$	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 $(36.1fb^{-1})$
$\tilde\chi_2^0\tilde\chi_1^\pm \to \ell\tilde\nu\ell\tilde\ell$	$n\ell(n=3) + E_T^{miss}$	CMS-SUS-16-039 $(35.9fb^{-1})$ ATLAS-1803-02762 $(36.1fb^{-1})$
$\tilde\chi_2^0\tilde\chi_1^\pm \to \tilde\tau\nu\ell\tilde\ell$	$2\ell + 1\tau + E_T^{miss}$	CMS-SUS-16-039 $(35.9fb^{-1})$
$\tilde\chi_2^0\tilde\chi_1^\pm \to \tilde\tau\nu\tilde\tau\tau$	$3\tau + E_T^{miss}$	CMS-SUS-16-039 $(35.9fb^{-1})$
$\tilde\chi_2^0\tilde\chi_1^\pm \to Wh\tilde\chi_1^0\tilde\chi_1^0$	$n\ell(n\geq 1) + nb(n\geq 0) + nj(n\geq 0) + E_T^{miss}$	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 $(35.9fb^{-1})$
$\tilde\chi_1^\mp\tilde\chi_1^\pm \to WW\tilde\chi_1^0\tilde\chi_1^0$	$2\ell + E_T^{miss}$	ATLAS-1908-08215 $(139fb^{-1})$ CMS-SUS-17-010 $(35.9fb^{-1})$
$\tilde\chi_1^\mp\tilde\chi_1^\pm \to 2\tilde\ell\nu(\tilde\nu\ell)$	$2\ell + E_T^{miss}$	ATLAS-1908-08215 $(139fb^{-1})$ CMS-SUS-17-010 $(35.9fb^{-1})$
$\tilde\chi_2^0\tilde\chi_1^\mp \to h/ZW\tilde\chi_1^0\tilde\chi_1^0, \tilde\chi_1^0 \to \gamma/Z\tilde G$ $\tilde\chi_1^\pm\tilde\chi_1^\mp \to WW\tilde\chi_1^0\tilde\chi_1^0, \tilde\chi_1^0 \to \gamma/Z\tilde G$	$2\gamma + n\ell(n\geq 0) + nb(n\geq 0) + nj(n\geq 0) + E_T^{miss}$	ATLAS-1802-03158 $(36.1fb^{-1})$
$\tilde\chi_2^0\tilde\chi_1^\pm \to ZW\tilde\chi_1^0\tilde\chi_1^0, \tilde\chi_1^0 \to h/Z\tilde G$ $\tilde\chi_1^\pm\tilde\chi_1^\mp \to WW\tilde\chi_1^0\tilde\chi_1^0, \tilde\chi_1^0 \to h/Z\tilde G$ $\tilde\chi_2^0\tilde\chi_1^0 \to Z\tilde\chi_1^0\tilde\chi_1^0, \tilde\chi_1^0 \to h/Z\tilde G$ $\tilde\chi_1^\mp\tilde\chi_1^0 \to W\tilde\chi_1^0\tilde\chi_1^0, \tilde\chi_1^0 \to h/Z\tilde G$	$n\ell(n\geq 4) + E_T^{miss}$	ATLAS-2103-11684 $(139fb^{-1})$
$\tilde\chi^{0,\pm}\tilde\chi^{0,\mp} \to \tilde\chi^0_i\tilde\chi^0_j + \chi_{soft} \to ZZ/H\tilde G\tilde G$	$n\ell(n\geq 2) + nb(n\geq 0) + nj(n\geq 0) + E_T^{miss}$	CMS-SUS-16-039 $(35.9fb^{-1})$ CMS-SUS-17-004 $(35.9fb^{-1})$

Conclusion

1. **The so-called 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 naturally coincide with 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! DM correlates with SUSY search!** Go forward to explore them with fancy ideas and more sophisticated techniques.