

Key points in constructing natural SUSY EFTs

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An 11-year research program addressing the naturalness problem of low-energy supersymmetry (a mechanism to protect scalar mass from large radiative corections) in the post-LHC era.

The work focuses on extensions of the MSSM, with the goal of constructing a theory that maintains fine-tuning at the percent level even in the face of prospective experimental constraints.



- 1 Naturalness: philosophical aesthetics & nature's inclination?
- 2 LHC searches for SUSY
- 3 Dark Matter Direct Detection Experiments
- 4 Neutron Electric Dipole Moment
- 5 B-L NMSSM - Kill three birds with one stone!
- 6 Conclusions

Key points in constructing feasible SUSY EFTs

1. Incorporating a mechanism to generate μ -parameter

SUSY EFT: Low-energy effective theory with manifest supersymmetry valid below the SUSY breaking scale:

- **Basic elements:** Gauge group, Chiral superfields, EWSB, etc.
- **arXiv:1309.2984 by Howard Baer, et. al.:**

A natural SUSY EFT must incorporate an appropriate mechanism to generate μ -parameter, while soft SUSY breaking parameters can be taken as theoretical inputs.

Messenger between hidden and visible sectors:

Gravity, Gauge, or Anomaly-mediation.

- **Supergravity:** When incorporating gravitational effects, the EFT contains supergravity multiplet where the gravitino emerges as the superpartner of the graviton. **Gravitino:** Light in GMSB, while heavy in mSUGRA.
- **Strong CP problem:** A SUSY EFT may include axion superfield, depending on model construction.

WIMP Miracle 的本质

物理内涵:

暗物质的残留密度通过“热退耦”这一抹平初始条件的统计物理机制，被唯一且自然地锚定在电弱/TeV 相互作用标度上。

场论描述:

一个早期与标准模型粒子热浴同温、因而丧失初条件记忆的守恒暗荷，其共动丰度由某个有效粒子数目改变率在 $\Gamma_{\text{eff}} \sim H$ 处的冻结唯一确定；而当这个有效率恰好取弱标度值 $\langle \sigma v \rangle_{\text{eff}} \sim \alpha^2/m_{\text{weak}}^2$ 时，自动给出观测到的 $\Omega_{\text{DM}} h^2 \approx 0.12$ 。

要点:

1. 包含稳定暗物质的粒子体系 曾处于宇宙早期的热力学系统中；
该体系中携带暗荷粒子类型可以大于 1，遵从玻尔兹曼分布。
2. 其总粒子数通过 某个有效耗散网络 保持化学平衡： $\Gamma_{\text{eff}} > H$ ；
 - ◇ Γ_{eff} ：能量传输率，受粒子的玻尔兹曼分布影响；
 - ◇ $H \propto T^2/M_{\text{Pl}}$ ：描述哈勃膨胀；该条件非常容易满足。
3. $\Gamma_{\text{eff}} \sim H$ 时发生热冻结，对应宇宙温度大致固定在 $m_{\text{DM}}/20$ 左右（非相对论性，冷暗物质）；共动丰度与热力学系统相关，并由此而确定。
4. 弱尺度质量和耦合自然给出观测所需的残留密度。
5. 残留密度原则上可以与暗物质与原子核散射截面无关。

2. Employing inert DM to break the crossing symmetry between Ωh^2 and $\sigma_{\chi-N}$, which is predicted by simple WIMP DM theories.

Popular scenarios include (totally six mechanisms)

- **Secluded DM scenario:**

Natural symmetry breaking through a **complex** framework;

- **Co-annihilation scenario:**

Sometimes natural $\cdots$ **simple** $\cdots$;

- **Resonant scenario:**

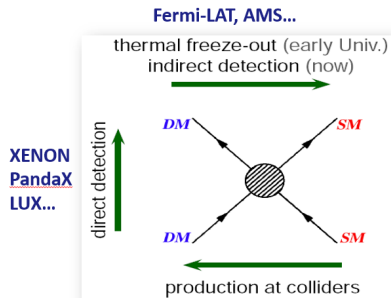
Usually unnatural, h - and Z -funnels have been excluded;

- **Leptophilic DM:**

Becoming unnatural even through a **complex** framework;

- $\cdots$

DM direct detection experiments



No new physics signal !

Simple WIMP DM Theory:

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

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

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

SD scattering: $\sigma_{\tilde{\chi}-N}^{\text{SD}} \sim 10^{-39} \text{ cm}^2$.

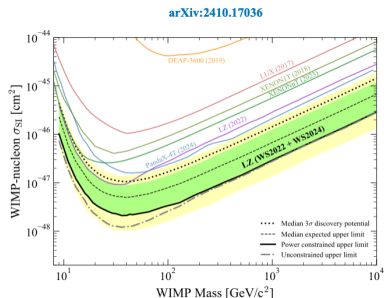


FIG. 5

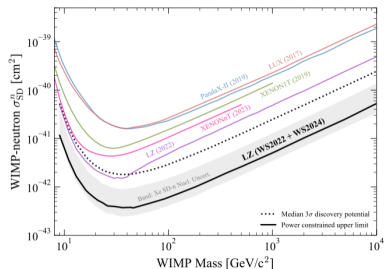


FIG. 6

Examples-I: no secluded DM sector

Scenario: MSSM, $\tilde{\chi}_1^0 \lesssim 100$ GeV. Ωh^2 : $\tilde{\chi}_1^0$ should be Bino-like.

Effective Couplings of DM:

$$C_{\tilde{B}\tilde{B}H_{\text{SM}}} = g_1^2 \frac{v}{\mu} \left(\sin 2\beta + \frac{m_{\tilde{\chi}_1^0}}{\mu} \right), \quad C_{\tilde{B}\tilde{B}H_{\text{NSM}}} = g_1^2 \cos 2\beta \frac{v}{\mu},$$

$$-iC_{\tilde{B}\tilde{B}A_{\text{NSM}}} = g_1^2 \frac{v}{\mu} \left(1 + \sin 2\beta \frac{m_{\tilde{\chi}_1^0}}{\mu} \right), \quad C_{\tilde{B}\tilde{B}Z} = \frac{g_1^3 \cos 2\beta v^2}{2 \sin \theta_W \mu^2}.$$

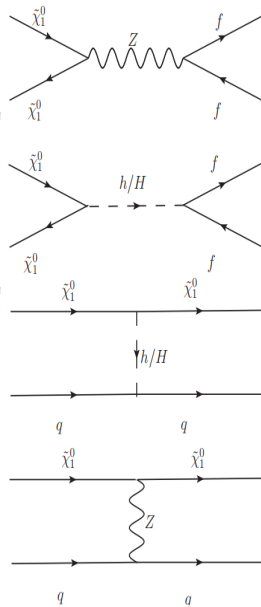
Formula for Direct Detection:

- **Spin-independent** scattering:

$$\sigma_{\tilde{B}-N}^{\text{SI}} \simeq 5 \times 10^{-45} \text{cm}^2 \times \left[\left(\frac{C_{\tilde{B}\tilde{B}H_{\text{SM}}}}{0.1} \right) \left(\frac{125 \text{ GeV}}{m_h} \right)^2 - \cot 2\beta \left(\frac{C_{\tilde{B}\tilde{B}H_{\text{NSM}}}}{0.1} \right) \left(\frac{125 \text{ GeV}}{m_H} \right)^2 \right]^2.$$

- **Spin-dependent** scattering:

$$\sigma_{\tilde{B}-N}^{\text{SD}} \simeq C_N \times \left(\frac{C_{\tilde{B}\tilde{B}Z}}{0.1} \right)^2.$$



Phenomenology-I: No secluded DM sector in MSSM

Two Types of Fine-Tuning:

① Z boson mass

- ◇ **Mass formula:** $m_Z^2 = \frac{2(m_{H_d}^2 + \Sigma_d) - 2(m_{H_u}^2 + \Sigma_u) \tan^2 \beta}{\tan^2 \beta - 1} - 2\mu^2$;
- ◇ **0.8% fine-tuning** without considering $\tilde{g}$ effect from RGE!

② DM annihilation

- ◇ The $1/\mu$ suppression of $C_{\tilde{B}\tilde{B}Z}$ and $C_{\tilde{B}\tilde{B}h}$ couplings requires m_χ to be precisely around $m_Z/2$ or $m_h/2$ for correct Ωh^2 ;
- ◇ **New fine-tuning!**

Latest Conclusions:

- ① h and Z resonant annihilation mechanisms have been **excluded** by LZ-2024 results alone;
 $m_{\tilde{\chi}_1^0} \gtrsim 200$ GeV from LHC search for compressed spectrum.
- ② Heavy Higgs resonant annihilation is **strongly disfavored** by LZ-2024 results:

$$C_{\tilde{B}\tilde{B}H_{\text{SM}}} = g_1^2 \frac{v}{\mu} \left(\sin 2\beta + \frac{m_{\tilde{\chi}_1^0}}{\mu} \right) \sim \frac{g_1^2}{2} \frac{v}{\mu}, \quad C_{\tilde{B}\tilde{B}H_{\text{NSM}}} = g_1^2 \frac{v}{\mu}.$$

Phenomenology-I: No secluded DM sector in MSSM

Cases where **SI LZ constraints are stronger than LHC constraints**.

m_A	Negative $m_{\tilde{\chi}_1^0}/\mu$	Positive $m_{\tilde{\chi}_1^0}/\mu$
1TeV	$\tan\beta \lesssim 9$	$\tan\beta \lesssim 25$
2TeV	$\tan\beta \lesssim 10$	$\tan\beta \lesssim 27$

Experimental Constraints:

- Higgs data fit: $m_h \simeq 125$ GeV;
- LHC search for extra Higgs bosons;
- LHC search for supersymmetry;
- DM direct detection experiment LZ.

Preferred mass spectra:

- **LHC search for SUSY:** $\mu \gtrsim 900$ GeV;
- **LZ SD constraints:** $\mu \gtrsim 700$ GeV for $\tan\beta > 4$;
- **LZ SI constraints:** Sometimes stronger than LHC constraints.

Phenomenology-I: No secluded DM sector in MSSM

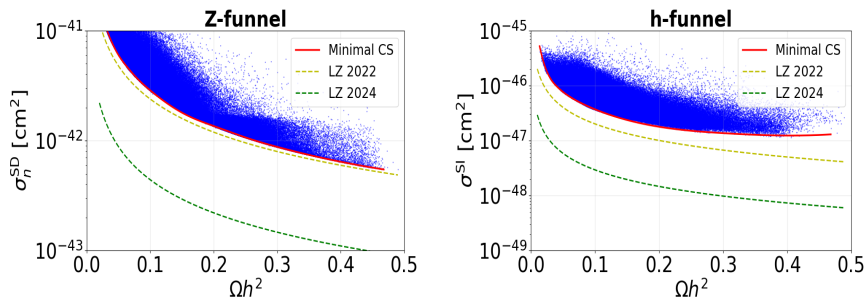


Figure: $\Omega h^2 - \sigma_{\tilde{\chi}_1^0-N}^{\text{SD}}$ and $\Omega h^2 - \sigma_{\tilde{\chi}_1^0-N}^{\text{SI}}$ correlations for Z-funnel region (left panel) and h-funnel region (right panel). Radiative corrections to all involved quantities have been included.

- 1 Excessively large μ suppresses $C_{\tilde{B}\tilde{B}Z}$ and $C_{\tilde{B}\tilde{B}h}$, precluding the measured relic density even at resonance.
- 2 Conversely, the density requirement sets lower bounds on $\sigma_{\chi-N}^{\text{SD}}$ and $\sigma_{\chi-N}^{\text{SI}}$ at Z- and h-funnel regions, respectively.

Phenomenology-II: Secluded DM sector in GNMSSM

• Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1) \otimes SU(2) \otimes SU(3))$
$\hat{q}$	$\tilde{q}$	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	$(\frac{1}{3}, \mathbf{1}, \bar{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3}, \mathbf{1}, \bar{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1, \mathbf{1}, \mathbf{1})$
$\hat{s}$	S	$\tilde{S}$	1	$(0, \mathbf{1}, \mathbf{1})$

• Superpotential — no ad hoc symmetry!

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

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

GNMSSM: DM Mass and Couplings

Singlino-dominated DM

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

- Neutralino mass matrix in basis $(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S})$:

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

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

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

Theoretical features at the cost of model economy:

- ◇ All particle masses are independent: $m_N, \mu_{tot}, m_{h_s}, m_{A_s}, m_h, \dots$;
- ◇ All couplings are independent: $\lambda, \kappa, g_1, g_2, g_s$;
- ◇ Singlet-related parameters are scarcely limited: $m_{\tilde{\chi}_1^0}/m_N, m_{h_s},$

$$m_{A_s}, \kappa. \quad \tilde{S}\text{-dominated DM: } |m_N| \lesssim \mu_{tot}, |M_1|, |M_2|;$$

In contrast, Z_3 -NMSSM: $2|\kappa| \lesssim \lambda$ to predict $\tilde{S}$ -dominated DM.

Scenario: GMSSM, $\tilde{\chi}_1^0 \lesssim 100$ GeV. $\tilde{\chi}_1^0$: Bino- or Singlino-like.

Key characteristics of DM physics:

- For Bino-like DM, they are same as those of the MSSM;
- For Singlino-like DM, $\tilde{S}$, h_s and A_s may form a **secluded** DM sector, specifically
 κ -controlled annihilations: $\tilde{S}\tilde{S} \rightarrow h_s A_s, h_s h_s, A_s A_s$;
 λ -controlled DM-nucleon scatterings: $\sigma_{\chi-N}^{\text{SI}} \propto \lambda^2 \kappa^2$, $\sigma_{\chi-N}^{\text{SD}} \propto \lambda^4$.
Consequently, the light DM scenario easily aligns with experimental results.

Phenomenology-II: Secluded DM sector in GNMSSM

Other involved couplings: relying on μ_{tot} , λ , and κ .

$$C_{\tilde{B}\tilde{B}Re[S]} = iC_{\tilde{B}\tilde{B}Im[S]} = -\frac{\lambda g_1^2 \sin 2\beta}{2} \frac{v^2}{\mu_{\text{tot}}^2},$$

$$C_{\tilde{B}\tilde{S}H_{\text{SM}}} = -2\sqrt{2}\lambda g_1 \cos 2\beta \frac{v}{\mu_{\text{tot}}}, \quad iC_{\tilde{B}\tilde{S}A_{\text{NSM}}} = -\sqrt{2}\lambda g_1 \cos 2\beta \frac{(M_1 + M_{\tilde{S}})v}{\mu_{\text{tot}}^2},$$

$$C_{\tilde{B}\tilde{S}H_{\text{NSM}}} = \sqrt{2}\lambda g_1 \frac{v}{\mu_{\text{tot}}} \left[2\sin 2\beta + \frac{(M_1 - M_{\tilde{S}})}{\mu_{\text{tot}}} \right],$$

$$C_{\tilde{B}\tilde{S}Re[S]} = iC_{\tilde{B}\tilde{S}Im[S]} = \sqrt{2}\lambda^2 g_1 \cos 2\beta \frac{v^2}{\mu_{\text{tot}}^2}, \quad C_{\tilde{B}\tilde{S}Z} = \frac{\sqrt{2}\lambda g_1^2 \sin 2\beta}{\sin \theta_W} \frac{v^2}{\mu_{\text{tot}}^2},$$

$$C_{\tilde{S}\tilde{S}H_{\text{SM}}} = -2\lambda^2 \sin 2\beta \frac{v}{\mu_{\text{tot}}} + 2\lambda^2 \frac{m_{\tilde{S}} v}{\mu_{\text{tot}}^2}, \quad C_{\tilde{S}\tilde{S}H_{\text{NSM}}} = -2\lambda^2 \cos 2\beta \frac{v}{\mu_{\text{tot}}},$$

$$C_{\tilde{S}\tilde{S}Re[S]} = iC_{\tilde{S}\tilde{S}Im[S]} = \lambda^3 \sin 2\beta \frac{v^2}{\mu_{\text{tot}}^2} - 2\kappa \left(1 - \lambda^2 \frac{v^2}{\mu_{\text{tot}}^2} \right),$$

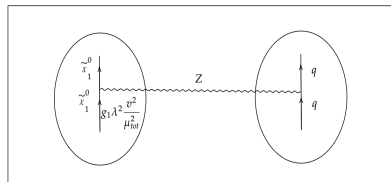
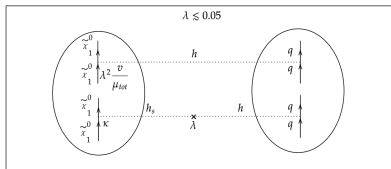
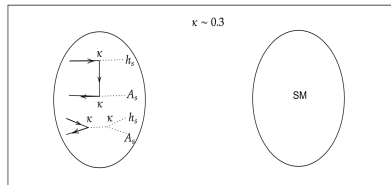
$$iC_{\tilde{S}\tilde{S}A_{\text{NSM}}} = 2\lambda^2 \frac{v}{\mu_{\text{tot}}} \left[1 - \sin 2\beta \frac{m_{\tilde{S}}}{\mu_{\text{tot}}} \right] \quad C_{\tilde{S}\tilde{S}Z} = -\frac{\lambda^2 g_1 \cos 2\beta}{\sin \theta_W} \frac{v^2}{\mu_{\text{tot}}^2}.$$

Formula for Direct Detections

- Spin-independent scattering:

$$\sigma_{\tilde{\chi}-N}^{\text{SI}} \simeq 5 \times 10^{-45} \text{cm}^2 \times \left[\left(\frac{125 \text{ GeV}}{m_h} \right)^2 \left(\frac{C_{\tilde{\chi}\tilde{\chi}h}}{0.1} \right) + \left(\frac{125 \text{ GeV}}{m_H} \right)^2 \left(\frac{C_{\tilde{\chi}\tilde{\chi}H}}{0.1} \right) + \left(\frac{125 \text{ GeV}}{m_{h_s}} \right)^2 \left(\frac{C_{\tilde{\chi}\tilde{\chi}h_s}}{0.1} \right) \right]^2.$$

- Spin-dependent scattering: $\sigma_{\tilde{\chi}-N}^{\text{SD}} \simeq C_N \times \left(\frac{C_{\tilde{\chi}\tilde{\chi}Z}}{0.1} \right)^2.$



Phenomenology-II: Secluded DM sector in GNMSSM

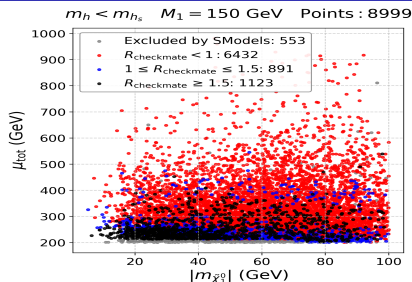


Figure: Samples, surviving all experimental constraints except those from LHC, are projected onto $m_{\tilde{\chi}_1^0} - \mu_{\text{tot}}$ plane.

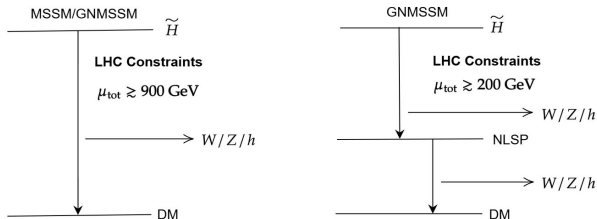


Figure: Different cases of LHC constraints.

Note Added:

- SUSY DM is not always WIMP; popular non-WIMP candidates include **gravitino** and **axion-axino**.
- Key points 2 **can not be applied to $\tilde{G}$ and $a/\tilde{a}$** .
- Gravitino DM $\tilde{G}$: $g_{\tilde{G}} \sim m_{\text{soft}}/(m_{\tilde{G}} M_{\text{Pl}})$
 - ✓ Couplings with ordinary matter are suppressed by M_{Pl} for $1 \text{ KeV} \lesssim m_{\tilde{G}} \lesssim 1 \text{ MeV} \Rightarrow$ **Hard to directly detect!**
 - ✓ Collider signatures dominated by long-lived NLSPs $\Rightarrow 10^{-9} \text{ s} \lesssim \tau \lesssim 10^{-6} \text{ s}$ relevant for **FASER**;
 - ✓ **UV freeze in mechanism $\Rightarrow$ Strong constraints to acquire measured relic density: $T_R \sim (10 - 10^4) \text{ GeV}$;**
 - ✓ For other mass range, strongly constrained by cosmology!
- **WIMP: strongly constrained by DD experiments;**
 $\tilde{G}$: usually involving non-standard cosmology,
e.g., predicting the low T_R needs fine-tuning:
 $Y_{\text{Inflator}} \sim 10^{-11}$, significantly weaker than gravity!
- $a/\tilde{a}$: **Different story from $\tilde{G}$ given that their couplings only depend on f_a , although some properties are similar.**

Details of $\tilde{G}$ DM candidate:

- Produced through **non-standard early-Universe mechanisms: non-thermal production, scatterings in the thermal plasma, and delayed decays of heavier particles.**
- Highly model dependent DM mass. However, relic density, BBN, small-scale structure, and reheating constraints often select **specific mass ranges**, sometimes favoring **light DM**.
- **Strongly constrained by conventional cosmology**, including Ωh^2 , BBN, T_R , τ_{NLSP} , and structure formation.
- DM itself usually **does not** affect the production rates or the early stages of collider cascade decays. Instead, **a long-lived NLSP may alter the collider-signature topology** from **conventional prompt missing- E_T events** to **displaced vertices, delayed decays, disappearing tracks, or other long-lived-particle signatures.**

Conclusion: **MSSM**

MSSM is disfavored by naturalness argument!

- Owing to intrinsic structure in its theoretical framework, **the fine-tuning of MSSM** is at **0.01%** level, i.e., $\Delta_{FT}^{BG} \sim 10000$;
 - ◇ Barbieri-Giudice Measurement:

$$\Delta_{FT}^{BG} \equiv \max \left(\frac{\partial \ln O}{\partial \ln p_i} \right)$$

O : a physics observable, e.g., m_Z , Ωh^2 , etc.;
 p_i : i th input parameter of the theory.

- ◇ Expected Δ_{FT}^{BG} during the LEP era: $\Delta_{FT}^{BG} \lesssim 10$;
 - ◇ Acceptable Δ_{FT}^{BG} in the post-LHC era: $\Delta_{FT}^{BG} \lesssim 300$.
- **Only** constraints from Ωh^2 measurement and LZ experiment **have excluded** Z - and h -resonant annihilation mechanisms;
- **Additionally**, LHC searches for compressed spectrum set a lower bound on DM mass, $m_{\tilde{\chi}_1^0} \gtrsim 200$ GeV.

Conclusion: **Beyond MSSM**

Unexpected theoretical advantages in gauge extensions;
B-L extended NMSSM: an **economic** extension that can
alleviate FT problem of MSSM to $\mathcal{O}(1\%)$ even when future ..

- ① Economic extension of MSSM - No dimensional parameters in its superpotential;
- ② Elegant solution to μ -problem - **Free from domain-wall problem with a minimal framework**;
- ③ Automatically explaining the conservation of R -parity;
- ④ Dynamically generating neutrino mass and mixing;
- ⑤ Singlino-modulated and sequestered DM - **Naturally suppressed DM-nucleon scattering**;
- ⑥ Well-motivated DM annihilation - **BLino - Higgsino coannihilation**;
- ⑦ Simple phenomenology - **Similar to MSSM, with Higgsino acting as DM candidate. ...**

Conclusion: **WIMP**

Recent advancements in WIMP DM theory:

- Keep the idea of freeze-out and thermal relic;
- Introduce more complex structure to break crossing symmetry between Ωh^2 and $\sigma_{\chi-N}$;
- **Phenomenology** significantly **differs** from traditional MSSM prediction because of **gauge-singlet nature of DM**, which leads to **lengthened decay chain** of sparticles.

E.g., $m_{\tilde{H}} \simeq 200$ GeV is experimentally allowed!

No hints of DM and sparticles in experiments are consistent with this picture!

Examples

1. Secluded DM Sector

Singlino-dominated DM in GNMSSM:

$$pp \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^\pm \rightarrow 4\{\mathbf{W/Z/h}\} E_T^{\text{Miss}}$$

τ -flavored righthanded sneutrino DM in seesaw extension:

$$pp \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^\pm \rightarrow 2\tau 2\{\mathbf{W/Z/h}\} E_T^{\text{Miss}}$$

Conclusion: **WIMP**

Example

2. Co-annihilation

- ◇ **Most natural co-annihilation: same gauge multiplet;**
 - ✓ Higgsino $SU(2)_L$ doublet: $m_{\tilde{\chi}_1^0} \simeq 1.1$ TeV for measured Ωh^2 ;
 - ✓ Wino $SU(2)_L$ triplet: $m_{\tilde{\chi}_1^0} \simeq 3.0$ TeV for measured Ωh^2 , **excluded by DM indirect search experiments.**
- ◇ **Another natural co-annihilation: Higgsino-partnered.**
BLino-Higgsino co-annihilation in B-L NMSSM is well-motivated, and yields measured Ωh^2 for any mass value.

Phenomenology of B-L NMSSM:

Similar to MSSM with **Higgsino** acting as **DM candidate**, except for the subtlety about Higgsino signal:

- (1) **Missing momentum;**
- (2) **Displaced vertex;**
- (3) **Missing track;**
- (4) **“Orphan” signal,**

which **depends** on the Higgsino mass spectrum and lifetime, and also on LHC search strategies.

thanks!