SUSY THRIVES

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Conjectures on the natural realization of WIMP DM in economic SUSY; Studies initiated in 2016.

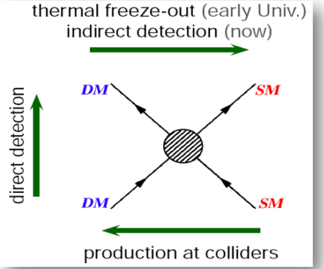
Outline

1. No Traditional WIMP DM
2. No SUSY
3. In what form should supersymmetry manifest itself?
4. Readily aligns with experimental observations
5. Conclusion

No Traditional WIMP DM

Fermi-LAT, AMS...

XENON
PandaX
LUX...



LEP, Tevatron, LHC...

No new physics signal !

arXiv:2410.17036

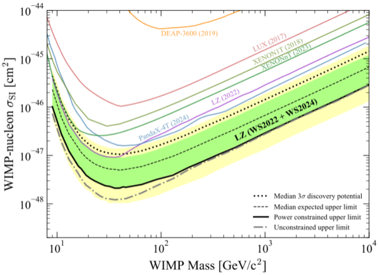


FIG. 5

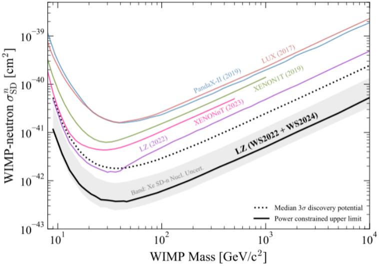


FIG. 6

Simple WIMP DM Theory:

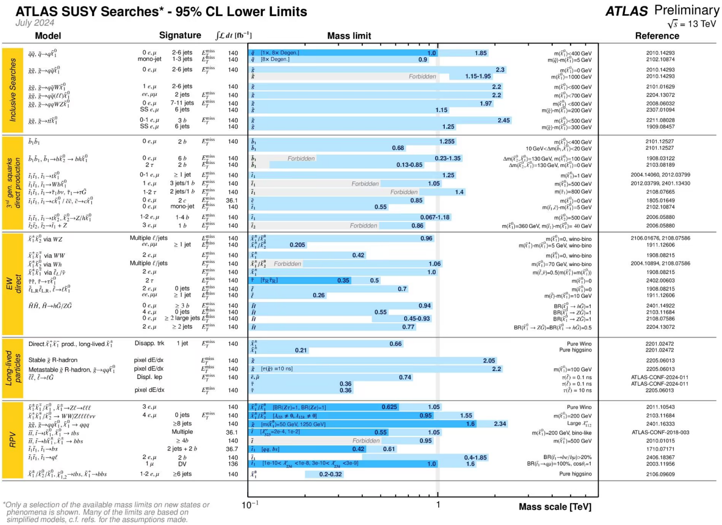
DM mass: $m_{\rm DM} \sim 100$ GeV;

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

SI scattering: $\sigma^{\rm SI}_{\tilde{\chi}-N} \sim 10^{-45} {\rm cm}^2$;

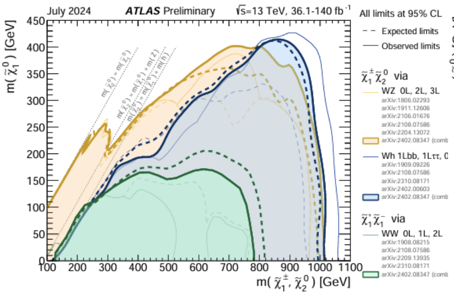
SD scattering: $\sigma^{\rm SD}_{\tilde{\chi}-N} \sim 10^{-39} {\rm cm}^2$.

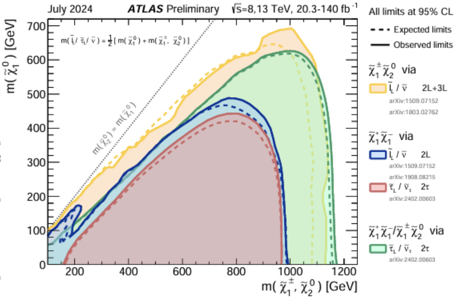
No SUSY



Mass reach of the ATLAS searches for Supersymmetry.

No SUSY





Latest LHC searches for Electroweakinos.

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.

In what form should supersymmetry manifest itself?

Isolated Theoretical Framework for DM:

- Containing a SM sector and a secluded DM sector;
- Feeble interactions between SM and DM sectors to suppress DM-nucleon scattering;
- "Weak" interactions in the DM sector to predict proper density.

Significant Alleviation of the LHC Constraints:

- Heavy sparticles cascading to intermediate non-LSP states;
- Lengthened decay chain: at least two steps;
- Complex decay products: multiple W/Z/h final states.

Two Directions to Build Models:

- Natural EWSB: MSSM $\rightarrow$ Z_3-NMSSM $\rightarrow$ General NMSSM.
- Neutrino mass: Type-I NMSSM $\rightarrow$ ISS-NMSSM $\rightarrow$ B-L NMSSM.
- New symmetry to reduce the number of input parameters!

Readily aligns with experimental observations

Only models with secluded DM sectors naturally accommodate DM candidates in the tens-of-GeV mass range
- the most difficult scenario to meet exp. data.

How conclusion are drawn?

MSSM

- No secluded DM sector;
- Severe parameter sensitivity in predicting the light DM.

Drawn naively from experimental data alone!

Z_3-NMSSM

- λ, κ and Singlino mass are correlated: $m_{\tilde{S}} = 2\kappa\mu_{\rm eff}/\lambda$;
- If Singlino played a role in DM physics,

$$\kappa \lesssim \frac{\lambda}{20} \times \frac{\mu_{\rm eff}}{1\ {\rm TeV}} \times \frac{m_{\tilde{S}}}{100\ {\rm GeV}};$$

- No secluded DM sector;
- Significant FT to accommodate the light DM.

Obtained purely from
(1) Experimental data;
(2) Reasonable inference.

GNMSSM

- λ, κ and Singlino mass are independent;
- $\tilde{S}$, h_s and A_s may form a secluded DM sector, specifically
  κ-controlled annihilation: $\tilde{S}\tilde{S} \to h_s A_s, h_s h_s, A_s A_s$;
  λ-controlled DM-nucleon scattering: $\sigma^{\rm SI}_{\chi-N} \propto \lambda^4$, $\sigma^{\rm SD}_{\chi-N} \propto \lambda^4$;
- Naturally predicting the light DM.

Based on:
(1) Our previous works;
(2) Sophisticated calculation.

Readily aligns with experimental observations

MSSM: the light DM should be Bino-like lightest neutralino.

Effective Couplings of DM:

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

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

Formula for Direct Detection:

- Spin-independent scattering:

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

- Spin-dependent scattering:

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

References

S. Baum, et. al., arXiv: 1712.09873.

J. Cao, et. al., arXiv: 1712.09873; Y. He, et. al., arXiv: 2303.02360.

Readily aligns with experimental observations

MSSM: The light DM should be Bino-like lightest neutralino.

Experimental Constraints:

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

Constrains are particularly tight for sub-TeV SUSY.

Useful Conclusions:

- DM annihilation: Z or h funnel;
- SUSY spectrum: $\mu \gtrsim 700$ GeV.

Valid only for light DM scenario.

Two Types of Fine-Tuning:

1. **Z boson mass**
   - Mass formula: $m_Z^2 = \frac{2(m_{H_d}^2+\Sigma_d)-2(m_{H_u}^2+\Sigma_u)\tan^2\beta}{\tan^2\beta-1} - 2\mu^2$;
   - This leads to 0.8% fine-tuning!
2. **DM annihilation**
   - The $1/\mu$ suppression of $C_{\chi\chi Z}$ and $C_{\chi\chi h}$ couplings requires m_χ to be precisely fine-tuned just below $m_Z/2$ or $m_h/2$ for correct Ωh^2;
   - New fine-tuning!

General conclusion: Low energy SUSY suffers sever FT problem.
If RGE effects are considered, problem becomes more severe.

Readily aligns with experimental observations

Z_3-NMSSM: The light DM should be Bino- or Singlino-like lightest $\tilde{\chi}_1^0$.

The Other Pertinent Couplings: relying not only on $\mu_{\rm eff}$ but also on λ and κ.

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

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

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

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

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

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

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

Formula for Direct Detections

- Spin-independent scattering:

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

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

References

S. Baum, et. al.
arXiv: 1712.09873.

J. Cao, et. al.,
arXiv: 1712.09873;
L. Meng, et. al.,
arXiv: 2405.07036.

Readily aligns with experimental observations

Z_3-NMSSM: Bino- or Singlino-like DM.

Additional Experimental Constraints:

- λ: Higgs data fit, Perturbativity, LZ experiment;
- κ: Z_3-symmetry - Singlino mass.

Dark Matter Phenomenology:

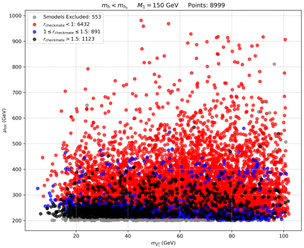
1. **Bino-like DM annihi.:** $\mu_{\rm eff} \gtrsim 700$ GeV, $\lambda \sim \mathcal{O}(0.1)$, $\kappa \lesssim \lambda/10$.
   - Bino-Singlino co-annihilation: Hardly achieve correct Ωh^2;
   - h_s and A_s funnels: More severe FT than the MSSM;
   - Z and h funnels: Scarcely improve the FT of the MSSM.
2. **Singlino-like DM annihi.:** $\lambda \lesssim 0.05$ **(LZ)**, $\kappa \lesssim \lambda/10$.
   - $\tilde{\chi}\tilde{\chi} \to h_s A_s, h_s h_s, A_s A_s$: Impossible to acquire correct Ωh^2;
   - h_s and A_s funnels: Severe FT.

All scenarios require fine-tuning because `No secluded DM,`
all relevant couplings are suppressed by $1/\mu_{\rm eff}$, λ, or κ.

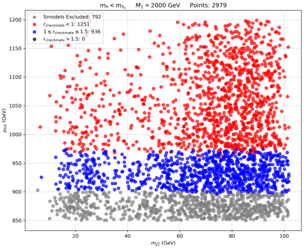
GNMSSM

1. **After considering all experimental constraints**:
   - κ may still remain large;
   - $C_{\chi\chi h_s}$ and $C_{\chi\chi A_s}$ are sizable, a distinct character.
   - Significantly alter the properties of Singlino-like DM;
   - Numerous theoretical advantages and rich SUSY phenomenology!

Loose LHC constraints:
$\tilde{\chi}_1^0$: $\tilde{S}$-like, $\tilde{\chi}_2^0$: $\tilde{B}$-like.
Forty LHC analyses used.



Tight LHC constraints:
$\tilde{\chi}_1^0$: $\tilde{S}$-like, $\tilde{\chi}_{2,3}^0$, $\tilde{\chi}_1^\pm$: $\tilde{H}$-like.
Forty LHC analyses used.



Left:

$\tilde{\chi}_{3,4}^0, \tilde{\chi}_1^\pm \to \tilde{\chi}_2^0 + W/Z/h$;

$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + W^*/Z^*/h^*$.

Right:

$\tilde{\chi}_{3,4}^0, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 + W/Z/h$.

Conclusion

Current Status of SUSY

- **The so – called WIMP crisis only means that the most economical WIMP scenarios are being challenged $\longrightarrow$** This motivates us to investigate more sophisticated theories!
- **Natural MSSM are under strong experimental pressure and appear highly unnatural $\longrightarrow$ No secluded DM sector!** This problem stems from the model itself, not from SUSY!
- **Occam's razor has been misapplied to the NMSSM!** The Z_3 symmetry induces FT issues in the NMSSM, obscuring its essential theoretical features.
- **GNMSSM deserves serious attention!** It is among the simplest supersymmetric theories that can naturally accommodate current experimental data.
  - **Bayesian statistics favors $\tilde{S}$-like DM, which can form a secluded DM sector!**
  - **It offers numerous notable theoretical advantages!**

Conclusion

Current Status of SUSY

- **Even after current experimental constraints, SUSY retains many virtues and remains the most promising framework!**
  - The present downturn may end soon;
  - SUSY might again rise to the research forefront.
- **Seemingly independent problems, such as DM, No-SUSY, and FT, may share a common physical origin!**
  - Explore the laws of nature with an open mind and ever-advancing techniques.
  - AI may be an useful tool. Numerous applications!

thanks!