SUSY THRIVES

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

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SUSY: a Healthy Theory

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



No SUSY

						$\sqrt{s} = 13$
Model	Sign	ature	9 JL	dt (fb ⁻	Mass limit	Reference
φη. ηφη ⁰	0 r. µ 2- mono-jet 1-	6 jets 3 jets	E_{T}^{min}	140 140	i [1x.0x.Depen] 1.0 1.85 m ² (1 < 00.0 k i [3x.Depen] 0.9 mit/(1 ≤ 0 e ×	2010.14293 2102.10874
88.3-498	0 r. µ 2-	8 jets	E_{T}^{min}	140	2.3 mt/)=064	2010.14293 2010.14293
$\chi \chi$, $\chi \rightarrow q q W \chi_1^0$	1 r. p 2-	6 jets		140	t 2.2 m ⁽¹⁾ +60 GeV	2101.01629
38.3-~qqu(1)41	CC. (3) 2	tjets	E_T^{max}	140	ž 2.2 m(t)/-700 GeV	2204.13072
$kk, k \rightarrow qqWZk_1^{\prime\prime}$	0 κ.μ 7-1 SS κ.μ 6	11 jets jets	Entro	140 140	2 1.57 m(i) <500 GeV 2 1.15 m()-m(i) = 200 GeV	2006.09032 2307.01094
$\lambda \hat{x}, \lambda \rightarrow t \hat{x}_1^0$	0-1 e.μ SS e.μ 6	3.5 i jets	E_T^{miss}	140 140	2.45 m(1)<500 GeV 2 1.25 m(1)=500 GeV	2211.08028 1909.08457
hihi	0 e, p	2.5	E_{T}^{\min}	140	5. 1.255 mtf c400 6e4 5. 0.68 10 GeV-/rai/, f c20 GeV	2101.12527 2101.12527
$\bar{b}_1 \bar{b}_1, \bar{b}_1 \rightarrow \delta \bar{k}_2^0 \rightarrow \delta h \bar{k}_1^0$	0 r.p 2 r	6 h 2 h	$\frac{E_{Lin}^{miss}}{E_{T}^{him}}$	140 140	δ. Forbidden 0.23-1.35 Δm(t), t)=100 GeV, m(t)=100 GeV δ. 0.13-0.85 Δm(t), t)=120 GeV, m(t)=00 GeV	1506.03122 2103.08189
$h\bar{h}, \bar{h} \rightarrow \hat{K}^{0}$	0-1 e.µ ≥	1 jet	Eres	140	i 1.25 m(r)=1.64V	2004.14060, 2012.02799
$\tilde{i}_1 \tilde{i}_1, \tilde{i}_1 \rightarrow W h \tilde{h}_1^D$	1 c.p 3 j	ets/1.b	E_T^{min}	140	l ₁ Forbilden 1.05 m(ℓ)=500.0eV	2012.03799, 2401.13430
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}_1 hv, \tilde{t}_1 \rightarrow \tau \tilde{G}$	1-2 r 2 j	ets/1.b	E_T^{max}	140	Terbiddan 1.4 m(t.)+600 GeV	2108.07665
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \mathcal{K}_1 / \bar{c} \tilde{c}, \tilde{c} \rightarrow c \mathcal{K}_1$	0 c. p mo	2 c mo-jet	E_T^{Lim}	140	2 0.85 mt/)-/-044	1805.01649 2102.10874
$\tilde{I}_1 \tilde{I}_1, \tilde{I}_1 \rightarrow t \tilde{K}_2^0, \tilde{K}_2^0 \rightarrow Z/h \tilde{K}_1^0$ $\tilde{I}_2 \tilde{I}_2, \tilde{I}_2 \rightarrow t \tilde{I}_1 + Z$	1-2 σ.μ 1 3 σ.μ	1.5	Erito	140 140	Γι 0.067-1.18 m(1)=600 GeV Γ ₂ Forbitter 0.06 m(1)=392 GeV, m(1)=40 GeV	2006.05880 2006.05880
$\bar{k}_1^{\dagger} \bar{k}_2^{0}$ via WZ	Multiple (/jets cc./d/ >	1 jet	Ethios	140 140	17/2 0.96 (10)-0, who bins 17/2 0.96 (10)-0, who bins 17/2 (10) 0.04 who bins	2105.01676, 2105.07586 1911.12905
STRT MA WW	2 6.0		ETto	140	i 0.42 million wine time	1906.08215
$\tilde{X}_{1}^{A}\tilde{X}_{2}^{B}$ was W.b	Multiple //jets		E_T^{min}	140	k ² /k ² Forbidden 1.06 mil ²)=70 GeV, who binc	2004.10694, 2108.07566
R ² R ² via (2,19	26.8		E_T^{max}	140	$\tilde{t}_{1}^{k} = 1.0$ m(\tilde{r}_{1}^{k})=0.5(m(\tilde{r}_{1}^{k})=m(\tilde{r}_{1}^{k})	1908.08215
5 TT. T-+TE	27		AT.	140	f (Fg/g) 0.35 0.5 m(f)-0	2402.03933
$\ell_{L,R}\ell_{L,R}, \ell \rightarrow \ell \mathcal{K}_1^*$	2 κ.μ 0 ατ.μμ ≥	i jets i jet	Etter	140 140	0.7 m(i)=0 2 0.26 m(i) m(i)=10 GeV	1908.08215 1911.12505
$BB, B \rightarrow MG/ZG$	0 r. p 2	:3b	L'ano	140	0.94 BR(C - AG)-1	2401.14922
	$0 r, \mu \ge 2 h$	arge job	2 faint	140	n 0.45-0.93 Bh(t) - 200-1	2106.07596
	2 c.μ ≥	2 jets	E_T^{max}	140	\hat{H} 0.77 $BR(\hat{r}_{1}^{2} \rightarrow 2\hat{O})_{2}BR(\hat{r}_{1}^{2} \rightarrow 4\hat{O})_{2}0.5$	2204.13072
Direct $\hat{x}_1^* \hat{x}_1^*$ prod., long-lived \hat{x}_1^*	Disapp. trk	1 jet	\mathcal{E}_T^{miss}	140	1 0.86 Pure Wex 1 0.21 Pure https://	2201.62472 2201.62472
Stable 2 R-hadron	pixel dE/dx		L'aiss	140	2.05	2205.09013
Metastable g R-hadron, g→ quft	pixel dE/dk		E_T^{min}	140	ž (rrž) =10 rs) 2.2 m(ř.)=100 GeV	2206.09013
$\mathcal{U}, \ell \rightarrow \ell G$	Displ. lep		E_T^{max}	140	6,0 0.74 mD = 0.1m	ATLAS-CONF-2024-011
	pixel dE/dx		$E_T^{\rm mbo}$	140	r 0.36 r(i) = 0.16	2205.06013
$\hat{x}_{1}^{\dagger}\hat{x}_{1}^{\dagger}/\hat{t}_{1}^{\dagger}, \hat{x}_{1}^{\dagger} \rightarrow Z \ell \rightarrow \ell \ell \ell$	3 с. р		rmin.	140	k ¹ /k ⁸ /(RP(Zr)=1, EP(Zr)=1) 0.625 1.05 Pure West	2011.10543
$\chi_1^*\chi_1^*/\chi_2^* \rightarrow WW)Z\ell\ell\ell\ellrr$	46.p 0	r jensk Billefer	27	140	47/6 1.00 # 9. /10. # 91 0.95 1.55 mt/()=200 GeV	2103.11684
$\overline{\mu} : \overline{\mu} \rightarrow q \mu q (1, A) \rightarrow q \bar{q} \bar{q}$ $\overline{\mu} : \overline{\mu} \rightarrow q \bar{k}^{0} : \overline{k}^{0} : \rightarrow q \bar{k} \bar{k}^{0}$	M	uitiple		36.1	1.6 2.34 Ling Aug	ATLAS-CONF-2019-000
$\vec{n}, \vec{i} \rightarrow b\hat{\pi}_{1}^{\pm}, \hat{k}_{1}^{\pm} \rightarrow bbs$		2.45		140	7 Forbiddan 0.95 m(7)-600 GeV	2010.01015
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bx$	2.ja	ts + 2 ð		38.7	ř. [av. hr] 0.42 0.61	1710.07171
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow q t$	2 κ.μ 1 μ	2.b DV		140 136	i, [to:16x, i] _{2xx} <tod.3a-16x, i]<sub="">2xx <tod) (-201)<="" -sh(-h)),="" 1.0="" 1.6="" bp(j,="" td=""><td>2406.18367 2003.11956</td></tod)></tod.3a-16x,>	2406.18367 2003.11956
						1

ATLAS SUSV Searchee* - 95% CL Lower Limite

Mass reach of the ATLAS searches for Supersymmetry.

SUSY: a Healthy Theory

ATI AS Preliminary

No SUSY



Latest LHC searches for Electroweakinos.

- Simplified model for a specified process;
- 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;
- \bullet Complex decay products: multiple W/Z/h final states.

Two Directions to Build Models:

- Natural EWSB: MSSM \rightarrow Z₃-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!

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.

Z₃-NMSSM

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

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

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

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: $\sigma_{\chi-N}^{SL} \propto \lambda^4$, $\sigma_{\chi-N}^{SD} \propto \lambda^4$;
- Naturally predicting the light DM.

Drawn naively from experimental data alone!

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

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

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

References

Effective Couplings of DM:

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

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

Formula for Direct Detection:

• Spin-independent scattering:

$$\begin{split} \mathbf{r}_{\tilde{B}-N}^{\mathrm{SI}} &\simeq 5 \times 10^{-45} \mathrm{cm}^2 \times \left[\left(\frac{C_{\tilde{B}\tilde{B}H_{\mathrm{SM}}}}{0.1} \right) \left(\frac{125 \mathrm{~GeV}}{m_h} \right)^2 \right. \\ &\left. - \cot 2\beta \left(\frac{C_{\tilde{B}\tilde{B}H_{\mathrm{NSM}}}}{0.1} \right) \left(\frac{125 \mathrm{~GeV}}{m_H} \right)^2 \right]^2. \end{split}$$

• Spin-dependent scattering:

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

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

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

Experimental Constraints:

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

Useful Conclusions:

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

Two Types of Fine-Tuning:

- **0** 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 $C_{\chi\chi\chi}$ 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!

Constrains are particularly tight for sub-TeV SUSY.

Valid only for light DM scenario.

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

Z₃-NMSSM: The light DM should be **Bino-** or Singlino-like lightest $\tilde{\chi}_1^0$.

The Other Pertinent Couplings: relying not only on μ_{eff} but also on λ and κ .

$$\begin{split} C_{\bar{B}\bar{B}Re[S]} &= iC_{\bar{B}\bar{B}Im[S]} = -\frac{\lambda g_{1}^{2}\sin 2\beta}{2}\frac{v^{2}}{\mu_{\text{eff}}^{2}}, \\ C_{\bar{B}\bar{S}H_{\text{BM}}} &= -2\sqrt{2}\lambda g_{1}\cos 2\beta\frac{v}{\mu_{\text{eff}}}, \quad iC_{\bar{B}\bar{S}A_{\text{BM}}} = -\sqrt{2}\lambda g_{1}\cos 2\beta\frac{\left(M_{1}+M_{\bar{S}}\right)v}{\mu_{\text{eff}}^{2}} \\ C_{\bar{B}\bar{S}H_{\text{BM}}} &= \sqrt{2}\lambda g_{1}\frac{v}{\mu_{\text{eff}}} \left[2\sin 2\beta + \frac{\left(M_{1}-M_{\bar{S}}\right)}{\mu_{\text{eff}}}\right], \\ C_{\bar{B}\bar{S}H_{\text{BM}}} &= iC_{\bar{B}\bar{S}Im[S]} = \sqrt{2}\lambda^{2}g_{1}\cos 2\beta\frac{v^{2}}{\mu_{\text{eff}}^{2}}, \quad C_{\bar{B}\bar{S}Z} = \frac{\sqrt{2}\lambda g_{1}^{2}\sin 2\beta}{\sin \theta_{W}}\frac{v^{2}}{\mu_{\text{eff}}^{2}}, \\ C_{\bar{S}\bar{S}H_{\text{BM}}} &= -2\lambda^{2}\sin 2\beta\frac{v}{\mu_{\text{eff}}} + 2\lambda^{2}\frac{m_{\bar{S}\bar{W}}}{\mu_{\text{eff}}^{2}}, \quad C_{\bar{S}\bar{S}H_{\text{BM}}} = -2\lambda^{2}\cos 2\beta\frac{v}{\mu_{\text{eff}}}, \\ C_{\bar{S}\bar{S}H_{\text{BM}}} &= -2\lambda^{2}\sin 2\beta\frac{v}{\mu_{\text{eff}}}, \quad C_{\bar{S}\bar{S}H_{\text{BM}}} = -2\lambda^{2}\cos 2\beta\frac{v}{\mu_{\text{eff}}}, \\ C_{\bar{S}\bar{S}R_{\text{B}}[S]} &= iC_{\bar{S}\bar{S}Im[S]} = \lambda^{3}\sin 2\beta\frac{v^{2}}{\mu_{\text{eff}}^{2}} - 2\kappa\left(1-\lambda^{2}\frac{v^{2}}{\mu_{\text{eff}}^{2}}\right), \\ iC_{\bar{S}\bar{S}A_{\text{BM}}} &= 2\lambda^{2}\frac{v}{\mu_{\text{eff}}} \left[1-\sin 2\beta\frac{\mu_{\text{B}}}{\mu_{\text{eff}}}\right], \quad C_{\bar{S}\bar{S}Z} = -\frac{\lambda^{2}g_{1}\cos 2\beta}{\sin \theta_{W}}\frac{v^{2}}{\mu_{\text{eff}}^{2}}. \end{split}$$

Formula for Direct Detections

• Spin-independent scattering:

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

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

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

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

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:

9 Bino-like DM annihi.: $\mu_{\text{eff}} \gtrsim 700 \text{ GeV}, \ \lambda \sim \mathcal{O}(0.1), \ \kappa \lesssim \lambda/10.$

- 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 $1/\mu_{\text{eff}}$, λ , or κ . Junjie Cao (Zhengzhou University) SUSY: a Healthy Theory May 23, 2025

GNMSSM

4 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.







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 → This motivates us to investigate more sophisticated theories!
- Natural MSSM are under strong experimental pressure and appear highly unnatural → 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!

