The Right-Handed Slepton Bulk Region for Dark Matter in Generalized No-scale $\mathcal{F}$-$SU(5)$ with Effective Super-Natural Supersymmetry

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References:

- T. Leggett, T. Li, J. A. Maxin, D. V. Nanopoulos and J. W. Walker, arXiv:1403.3099 [hep-ph]; Phys. Lett. B **740**, 66 (2015) [arXiv:1408.4459 [hep-ph]].
- G. Du, T. Li, D. V. Nanopoulos and S. Raza, Phys. Rev. D **92**, no. 2, 025038 (2015) [arXiv:1502.06893 [hep-ph]].
- R. Ding, T. Li, F. Staub and B. Zhu, Phys. Rev. D **93**, no.9, 095028 (2016) [arXiv:1510.01328 [hep-ph]].
- T. Li, S. Raza and X. C. Wang, Phys. Rev. D **93**, no.11, 115014 (2016) [arXiv:1510.06851 [hep-ph]].
- T. Li, J. A. Maxin, D. V. Nanopoulos and X. Yin, [arXiv:2310.03622 [hep-ph]]; Papers in preparations.

Outline

Outline

Motivation for New Physics beyong the Standard Model

- The convincing evidence

  Dark energy; dark matter; neutrino masses and mixing; baryon asymmetry; inflation; ...

- Fine-tuning problems

  cosmological constant problem; gauge hierarchy problem; strong CP problem; SM fermion masses and mixings; ...

- Aesthetic problems

  Interaction and fermion unification; gauge coupling unification; charge quantization; too many parameters; ...

- The electroweak vacuum stability problem

  The stability problem can be easily solved in the new physics models.

- New Physics beyond the SM!
- Question: why do we still believe in supersymmetry?

Motivations for Supersymmetry

- Generalization of the Poincare Algebra; The most general symmetry of the S-matrix; The local supersymmetry includes gravity naturally, *i.e.*, supergravity, etc.
- Supersymmetry provides a natural solution to the gauge hiearchy problem.
- Supersymmetry partially solves the cosmological constant problem: $M_{\rm Pl} \to M_{SUSY}$.
- Supersymmetry is a bridge between the promising low energy phenomenology and the high-energy fundamental physics such as the Grand Unified Theory and String Theory.

The Supersymmetric Standard Models (SSMs)

- Solving the gauge hierarchy problem
- Gauge coupling unification
- Radiatively electroweak symmetry breaking
- Natural dark matter candidates
- Electroweak baryogenesis
- Electroweak precision: R parity
- μ problem in the MSSM: $\mu H_d H_u$.

The Grand Unified Theories: $SU(5)$ and $SO(10)$

- Unification of the gauge interactions, and unifications of the SM fermions
- Charge quantization
- Gauge coupling unification in the MSSM, and Yukawa unification
- Radiative electroweak symmetry breaking due to the large top quark Yukawa coupling
- Weak mixing angle at weak scale M_Z
- Neutrino masses and mixings by seesaw mechanism
- Prediction: dim-6 proton decay via heavy gauge boson exchange.

Problems

- Gauge symmetry breaking
- Doublet-triplet splitting problem
- Proton decay problem
- Fermion mass problem: $m_e/m_\mu = m_d/m_s$

String Models

- Calabi-Yau compactification of heterotic string theory
- Orbifold compactification of heterotic string theory
- D-brane models on Type II orientifolds
- Free fermionic string model builing
- $\mathcal{F}$-Theory Model Building

Supersymmetry is a bridge between the promising low energy phenomenology and high-energy fundamental physics.

Particle Physics Paradigm

String Theory $\rightarrow$ String Models $\rightarrow$ GUTs $\rightarrow$ SSMs $\rightarrow$ SM

Interesting Questions in Supersymmetry Phenomenology

- How to solve the supersymmetry electroweak fine-tuning problem?
- Whether there exists the bulk region for dark matter?
- Can we probe the entire bulk region at the future experiments?

Outline

The LHC Supersymmetry Search Contraints:

- The gluino mass low bound is around 2.3 TeV in the CMSSM/mSUGRA
- The first two-generation squark mass low bounds are around 1.9 TeV.
- The stop/sbottom mass low bounds are around 1.3 TeV.
  The SSMs are fine-tuned!!!

Supersymmetry at the Current and Future Colliders

- The wrong impression is that supersymmetry was excluded at the LHC?
- Can we rule out supersymmetry at the LHC, VLHC, $\mathrm{FCC_{hh}}$ and SppC?
  No! No!! No!!!
- Points: supersymmetry breaking soft mass scale can be pushed to be much higher than 1 TeV, while gauge coupling unification can still be realized due to the logarithmic RGE running and threshold corrections around the GUT scale.
- Conclusion: supersymmetry will defintely not die in the near future!!!

Natural Supersymmetry

The interesting question: can we rule out the natural supersymmetry at the $\mathrm{FCC_{hh}}$ and SppC? Or can we solve the supersymmetry electroweak fine-tuning problem naturally?

Fine-Tuning Definition

- Fine-tuning Definition [1]: the quantitative measure $\Delta_{\rm FT}^{\rm EENZ-BG}$ for fine-tuning is the maximum of the logarithmic derivative of M_Z with respect to all the fundamental parameters a_i at the GUT scale

$$\Delta_{\rm FT}^{\rm EENZ-BG} = {\rm Max}\{\Delta_i^{\rm GUT}\}~, \quad \Delta_i^{\rm GUT} = \left|\frac{\partial {\rm ln}(M_Z)}{\partial {\rm ln}(a_i^{\rm GUT})}\right|~.$$

[1] J. R. Ellis, K. Enqvist, D. V. Nanopoulos and F. Zwirner, Mod. Phys. Lett. A **1**, 57 (1986); R. Barbieri and G. F. Giudice, Nucl. Phys. B **306**, 63 (1988).

Question: Super-Natural Supersymmetry

Can we propose a supersymmetry scenario whose the EENZ-BG fine-tuning measure is automatically 1 or order 1 ($\mathcal{O}(1)$)?

Fundamental physics principles: simplicity and naturalness.

Super-Natural Supersymmetry [2]

- Fine-Tuning Definition:

$$\Delta_{\rm FT} ~=~ {\rm Max}\{\Delta_i^{\rm GUT}\}~, ~~~ \Delta_i^{\rm GUT} ~=~ \left|\frac{\partial {\rm ln}(M_Z)}{\partial {\rm ln}(a_i^{\rm GUT})}\right|~.$$

- Natural Solution:

$$M_Z^n ~=~ f_n\left(\frac{M_Z}{M_*}\right)~M_*^n~.$$

$$\frac{\partial {\rm ln}(M_Z^n)}{\partial {\rm ln}(M_*^n)} ~\simeq~ \frac{M_*^n}{M_Z^n}\frac{\partial M_Z^n}{\partial M_*^n} ~\simeq~ \frac{1}{f_n}f_n \simeq \mathcal{O}(1)~.$$

- For no-scale supergravity and M-theory on S^1/Z_2, we have $M_* = M_{1/2}$ and $M_* = M_{3/2}$, respectively.

[2] T. Leggett, T. Li, J. A. Maxin, D. V. Nanopoulos and J. W. Walker, arXiv:1403.3099 [hep-ph]; Phys. Lett. B **740**, 66 (2015) [arXiv:1408.4459 [hep-ph]]; G. Du, T. Li, D. V. Nanopoulos and S. Raza, Phys. Rev. D **92**, no. 2, 025038 (2015) [arXiv:1502.06893 [hep-ph]]; T. Li, S. Raza and X. C. Wang, Phys. Rev. D **93**, no. 11, 115014 (2016) [arXiv:1510.06851 [hep-ph]]

The Super-Natural Supersymmetry and Its Generalizations

- The Kähler potential and superpotential can be calculated in principle or at least inspired from a fundamental theory such as string theory with suitable compactifications. In other words, one cannot add arbitrary high-dimensional terms in the Kähler potential and superpotential.
- There is one and only one chiral superfield or modulus whose F-term breaks supersymmetry. And all the supersymmetry breaking soft terms are obtained from the above Kähler potential and superpotential.
- All the other mass parameters, if there exist such as the μ term in the MSSM, must arise from supersymmetry breaking.

Effectively Super-Natural Supersymmetry

- A supersymmetry breaking scenario is natural if all the fundamental parameters that have large EENZ-BG fine-tuning measures are correlated.
- In our generalized No-Scale SUGRA presented here, the finetuning measures for the SUSY breaking soft terms M1X, M0, and A0 are all small, and only M5 might have a large fine-tuning measure. Therefore, our generalized No-Scale SUGRA is approximately Super-Natural SUSY, and thus indeed natural. More specifically, it is only a small deviation from Super-Natural SUSY, and hence the simplest scenario for Effective Super-Natural SUSY, where only one fundamental parameter may have a large EENZ-BG fine-tuning measure.

Outline

SUSY Dark Matter Scenarios

- **Bulk region**

  The sfermions (supersymmetric partners of the SM fermions) are light.

- **The Z/Higgs funnels or Z/Higgs resonances**

  The LSP neutralino mass is about half of the masses of the Z boson, SM Higgs, CP-even Higgs H_0, or CP-odd Higgs A_0.

- **Coannihilations**

  The sfermion masses are close to the LSP neutralino

- **Mixing scenario or well-tempered scenario**

  The LSP neutralino has enough Wino or Higgsino component to significantly increase the annihilation cross section

SUSY Dark Matter Scenarios

- The bulk region may be the most natural.
- Because the LHC SUSY searches have given strong constraints on the SUSY parameter space, the possible bulk region is the light right-handed sleptons and LSP neutralino coannihilations.
- This is an interesting scenario for the SUSY searches at the $\mathrm{FCC_{ee}}$ and CEPC.
- Question: Is it possible to have such kind of viable bulk region for dark matter in a natural SUSY scenario?

Outline

Flipped $SU(5) \times U(1)_X$ Models: [5]

- Doublet-triplet splitting via missing partner mechanism [3].
- No dimension-five proton decay problem.
- Little hierarchy problem in string models: $M_{\rm String} \sim 20 \times M_{\rm GUT}$

$$M_{\rm String} = g_{\rm String} \times 5.27 \times 10^{17} \ {\rm GeV} \ .$$

- Testable flipped $SU(5) \times U(1)_X$ models: TeV-scale vector-like particles [4].

[3] I. Antoniadis, J. R. Ellis, J. S. Hagelin and D. V. Nanopoulos, Phys. Lett. B **194**, 231 (1987).

[4] J. Jiang, T. Li and D. V. Nanopoulos, Nucl. Phys. B **772**, 49 (2007).

[5] S. M. Barr, Phys. Lett. B **112**, 219 (1982); J. P. Derendinger, J. E. Kim and D. V. Nanopoulos, Phys. Lett. B **139**, 170 (1984).

Flipped $SU(5) \times U(1)_X$ Models:

- Free-fermionic string construction [6].
- F-theory model building [7].
- Heterotic String Constructions: Calabi-Yau [8]; Orbifold [9].
- Orbifold GUTs [10].

[6] J. L. Lopez, D. V. Nanopoulos and K. j. Yuan, Nucl. Phys. B **399**, 654 (1993).

[7] C. Beasley, J. J. Heckman and C. Vafa, JHEP **0901**, 059 (2009); J. Jiang, T. Li, D. V. Nanopoulos and D. Xie, Phys. Lett. B **677**, 322 (2009); Nucl. Phys. B **830**, 195 (2010).

[8] A. E. Faraggi, R. S. Garavuso and J. M. Isidro, Nucl. Phys. B **641**, 111 (2002)

[9] J. E. Kim and B. Kyae, Nucl. Phys. B **770**, 47 (2007).

[10] S. M. Barr and I. Dorsner, Phys. Rev. D **66**, 065013 (2002).

$\mathcal{F}$-$SU(5)$ Models

- The gauge group $SU(5) \times U(1)_X$ can be embedded into $SO(10)$ model.
- Generator $U(1)_{Y'}$ in $SU(5)$

$$T_{\rm U(1)_{Y'}} = {\rm diag}\left(-\frac{1}{3}, -\frac{1}{3}, -\frac{1}{3}, \frac{1}{2}, \frac{1}{2}\right) ~.$$

- Hypercharge

$$Q_Y = \frac{1}{5}\left(Q_X - Q_{Y'}\right) ~.$$

- SM fermions

$$F_i = (\mathbf{10}, \mathbf{1}),~~ \bar{f}_i = (\bar{\mathbf{5}}, -\mathbf{3}),~~ \bar{l}_i = (\mathbf{1}, \mathbf{5})~,$$

$$F_i = (Q_i, D_i^c, N_i^c),~~ \overline{f}_i = (U_i^c, L_i),~~ \overline{l}_i = E_i^c~.$$

- Higgs particles:

$$H = (\mathbf{10}, \mathbf{1}),~~ \overline{H} = (\overline{\mathbf{10}}, -\mathbf{1}),~~ h = (\mathbf{5}, -\mathbf{2}),~~ \overline{h} = (\bar{\mathbf{5}}, \mathbf{2})~,$$

$$H = (Q_H, D_H^c, N_H^c)~,~~ \overline{H} = (\overline{Q}_{\overline{H}}, \overline{D}^c_{\overline{H}}, \overline{N}^c_{\overline{H}})~,$$

$$h = (D_h, D_h, D_h, H_d)~,~~ \overline{h} = (\overline{D}_{\overline{h}}, \overline{D}_{\overline{h}}, \overline{D}_{\overline{h}}, H_u)~.$$

- Flip

$$U \leftrightarrow D~,~~ N \leftrightarrow E~,~~ H_d \leftrightarrow H_u~.$$

Symmetry breaking:

- Superpotential

$$W_{\rm GUT} = \lambda_1 HHh + \lambda_2 \overline{HHh} + \Phi(\overline{H}H - M_{\rm H}^2) ~.$$

- There is only one F-flat and D-flat direction along the N_H^c and $\overline{N_H^c}$ directions: $< N_H^c > = < \overline{N_H^c} > = M_{\rm H}$.
- The doublet-triplet splitting due to the missing partner mechanism
- No dimension-5 proton decay problem.

$\mathcal{F}$-$SU(5)$ Models

- To achieve the string scale gauge coupling unification, we introduce sets of vector-like particles in complete $SU(5) \times U(1)_X$ multiplets, whose contributions to the one-loop beta functions of the $U(1)_Y$, $SU(2)_L$ and $SU(3)_C$ gauge symmetries, Δb_1, Δb_2 and Δb_3 respectively, satisfy $\Delta b_1 < \Delta b_2 = \Delta b_3$.
- To avoid the Landau pole problem for the gauge couplings, we can only introduce the following two sets of vector-like particles around the TeV scale, which could be observed at the LHC

$$Z1 : XF = (\mathbf{10}, \mathbf{1}) \equiv (XQ,~ XD^c,~ XN^c)~,~~ \overline{XF} = (\overline{\mathbf{10}}, -\mathbf{1})~;$$
$$Z2 : XF~,~~ \overline{XF}~,~~ Xl = (\mathbf{1}, -\mathbf{5})~,~~ \overline{Xl} = (\mathbf{1}, \mathbf{5}) \equiv XE^c~.$$

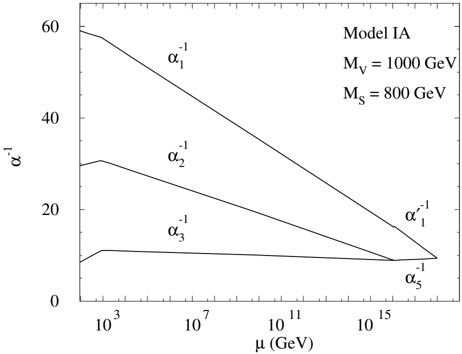


Figure: Gauge coupling unification in the Type IA model.

No-Scale Supergravity [11]:

- The vacuum energy vanishes automatically due to the suitable Kähler potential.
- At the minimum of the scalar potential, there are flat directions which leave the gravitino mass $M_{3/2}$ undertermined.
- The super-trace quantity $\mathrm{Str}\mathcal{M}^2$ is zero at the minimum.

$$K = -3\ln(T + \overline{T} - \sum_i \overline{\Phi}_i \Phi_i) \ .$$

[11] E. Cremmer, S. Ferrara, C. Kounnas and D. V. Nanopoulos, Phys. Lett. B **133**, 61 (1983); A. B. Lahanas and D. V. Nanopoulos, Phys. Rept. **145**, 1 (1987).

No-Scale Supergravity:

- mSUGRA/CMSSM: $M_{1/2}$, M_0, A, $\tan\beta$, $\mathrm{sign}(\mu)$.
- No-scale boundary condition: $M_{1/2} \neq 0$, $M_0 = A = B_\mu = 0$
- Natural solution to CP violation and FCNC problem.
- Disfavored by phenomenology: $M_0 = 0$ at traditional GUT scale.
- No-scale $\mathcal{F}$-$SU(5)$

No-scale supergravity can be realized in the compactification of the weakly coupled heterotic string theory [12] and the compactification of M-theory on S^1/Z_2 at the leading order [13].

[12] E. Witten, Phys. Lett. B **155**, 151 (1985).

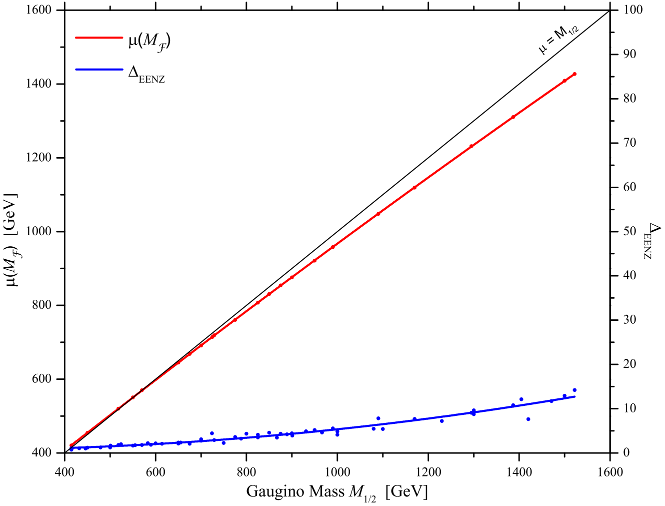
[13] T. Li, J. L. Lopez and D. V. Nanopoulos, Phys. Rev. D **56**, 2602 (1997).

$\mathcal{F}$-$SU(5)$

- These models can be realized in heterotic string constructions, free fermionic string constructions, and F-theory model building.
- These models may be tested in the next LHC run.
- The Higgs boson mass can be around 126 GeV.
- The proton decay $p \to e^+\pi^0$ from the heavy gauge boson exchange is within the reach of the future DUSEL and Hyper-Kamiokande experiments for a majority of the most plausible parameter space.
- The dark matter is within the reach of the XENON1T experiment.

Miracle of Vector-Like Particles

- String scale gauge coupling unification.
- Dimension-six proton decay.
- Lifting the lightest CP-even Higgs boson mass.
- Special sparticle spectra.


$\mu(M_{\mathcal{F}})$
Δ_{EENZ}
$\mu = M_{1/2}$
$\mu(M_{\mathcal{F}})$ [GeV]
Δ_{EENZ}
Gaugino Mass $M_{1/2}$ [GeV]
1600
1400
1200
1000
800
600
400
100
90
80
70
60
50
40
30
20
10
0
400
600
800
1000
1200
1400
1600

The Generalized No-Scale Supergravity

- At the $SU(5) \times U(1)_X$ unification scale (string scale), we vary the $SU(5)$ gaugino mass M_5 from 1200 GeV to 5000 GeV, yielding a large gluino mass.
- To produce a light Bino, we vary the $U(1)_X$ gaugino mass M_{1X} from 100 GeV to 600 GeV.
- Note that No-Scale SUGRA is obtained at tree level and can be violated at one loop, so we assume the universal supersymmetry breaking soft mass M_0 and trilinear soft term A_0 are smaller than about 1% of M_5.
- We span $\tan\beta$ from 2 to 65, and the vector-like particle mass scale M_V from 1 TeV to 10 TeV.

Effective Super-Natural SUSY

- A supersymmetry breaking scenario is natural if all the fundamental parameters that have large EENZ-BG fine-tuning measures are correlated.
- In our generalized No-Scale SUGRA, the fine-tuning measures for the SUSY breaking soft terms M_{1X}, M_0, and A_0 are all small, and only M_5 might have a large fine-tuning measure.
- Our generalized No-Scale SUGRA is approximately Super-Natural SUSY, and thus indeed natural.
  More specifically, it is only a small deviation from Super-Natural SUSY, and hence the simplest scenario for Effective Super-Natural SUSY.

The Criteria for Right-Handed Slepton Bulk Region

- The ratio of the mass difference $\mathcal{R}_\phi \equiv (m_\phi - m_{\tilde{\chi}_1^0})/m_{\tilde{\chi}_1^0}$ is more important than the absolute mass difference, where ϕ is $\tilde{\tau}_1$ (light stau) or $\tilde{e}_R$ (light selectron).
- Comprehensive numerical studies that we present in this work show that $\mathcal{R}_\phi \gtrsim 10\%$ is a conservative criterion to formulate the bulk region, *i.e.*, the observed dark matter density is obtained via traditional annihilations, not from coannihilations or resonances, etc.

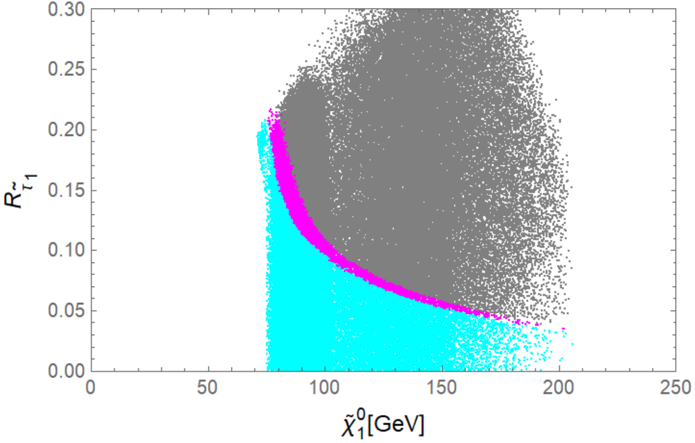


Figure: Bulk region in Generalized No-Scale $\mathcal{F}$-$SU(5)$. Cyan, magenta, gray points correspond to under-saturated, saturated, over-saturated DM relic density.

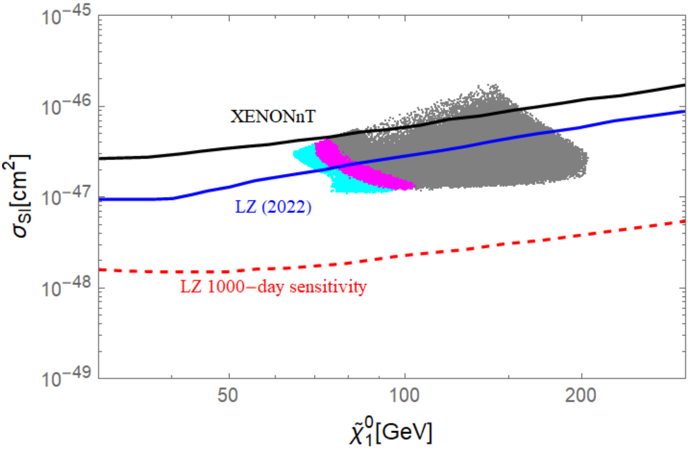


Figure: Generalized No-Scale $\mathcal{F}$-$SU(5)$ bulk region LSPs plot in reference to spin-independent DM-nuclei cross sections from XENONnT and LUX-ZEPLIN. Cyan, magenta, gray points correspond to under-saturated, saturated, over-saturated DM relic density with $\mathcal{R}_{\tilde{\tau}_1} \gtrsim 10\%$. We underscore the significance of the 1000-day LUX-ZEPLIN run that should fully probe the $\mathcal{F}$-$SU(5)$ bulk and about 50% of the pMSSM bulk (not shown).

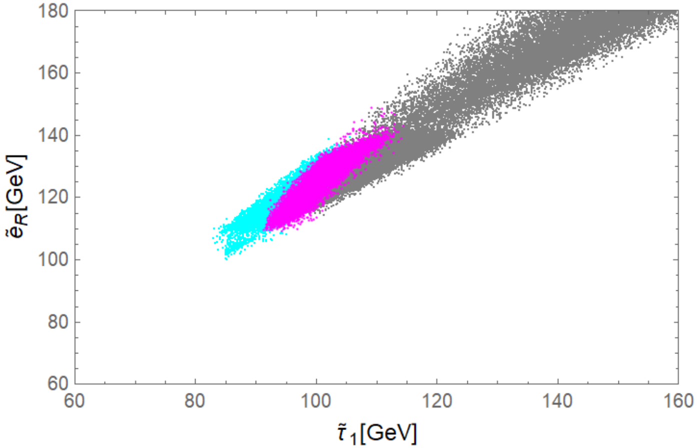


Figure: Light right-handed slepton masses in the Generalized No-Scale $\mathcal{F}$-$SU(5)$ bulk region. Cyan, magenta, gray points correspond to under-saturated, saturated, over-saturated DM relic density with $\mathcal{R}_{\tilde{\tau}_1} \gtrsim 10\%$.

The Light Right-Handed Stau Bulk Region in $\mathcal{F}$-$SU(5)$

- The LSP neutralino is Bino dominant.
- The mass hierarchy in $\mathcal{F}$-$SU(5)$ is $m_{\tilde{\chi}_1^0} < m_{\tilde{\tau}_1} < m_{\tilde{e}_R} = m_{\tilde{\mu}_R}$.
- If the Bino contributes all the DM abundance, the ratio $\mathcal{R}_{\tilde{\tau}_1} \gtrsim 10\%$ implies $m_{\tilde{\chi}_1^0} \leq 103.0$ GeV.
- The upper bounds on $\tilde{\tau}_1$ and $\tilde{e}_R$ are around 115 GeV and 150 GeV, respectively.

The Light Right-Handed Stau Bulk Region in $\mathcal{F}$-$SU(5)$

- The entire viable parameter space can be probed by the the 1000-day LUX-ZEPLIN experiment within the next a few years.
- The proton lifetime via dimension-six proton decay is around $3-4\times 10^{34}$ years, so it is within reach of the future Hyper-Kamiokande experiment.
- The entire viable parameter space can be probed by the Future Circular Collider (FCC-ee) at CERN, Circular Electron Positron Collider (CEPC)

The pMSSM

The methodology just discussed is extended to include the much less constrained generic pMSSM. The pMSSM contains 22 free parameters, and we input M_A and μ in lieu of $m_{H_u}^2$ and $m_{H_d}^2$. The scanning ranges of the pMSSM parameters are as follows:

$$
\begin{aligned}
& 20 \text{ GeV} \leq M_1 \leq 1000 \text{ GeV} && 2 \leq tan\beta \leq 65 \\
& 1000 \text{ GeV} \leq M_2 \leq 5000 \text{ GeV} && 1000 \text{ GeV} \leq M_A, \mu \leq 6000 \text{ GeV} \\
& 1200 \text{ GeV} \leq M_3 \leq 5000 \text{ GeV} && M_1 \leq m_{\tilde{e}_R}, m_{\tilde{\tau}_R} \leq 2M_1 \\
& 2500 \text{ GeV} \leq m_{\tilde{q}}, m_{\tilde{Q}}, m_{\tilde{u}_R}, m_{\tilde{t}_R}, m_{\tilde{d}_R}, m_{\tilde{b}_R} \leq 5000 \text{ GeV} \\
& 700 \text{ GeV} \leq m_{\tilde{l}} \leq 2000 \text{ GeV} && 1200 \text{ GeV} \leq m_{\tilde{L}} \leq 5000 \text{ GeV} \\
& -5000 \text{ GeV} \leq A_u, A_d, A_e, A_t, A_b, A_\tau \leq 5000 \text{ GeV}
\end{aligned}
$$

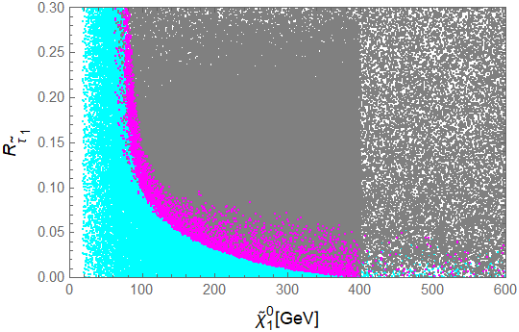


Figure: Bulk region in the pMSSM.

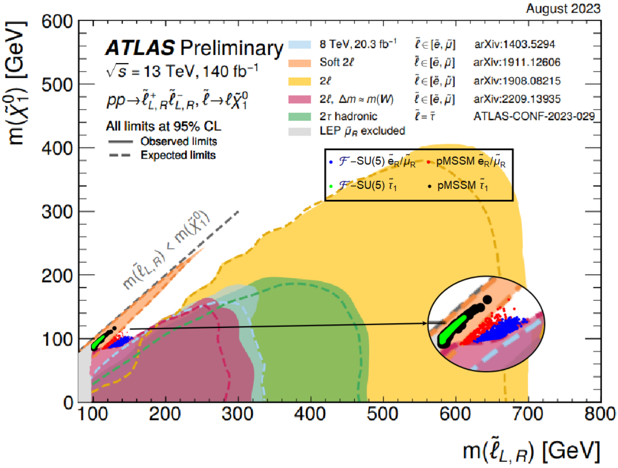


Figure: Generalized No-Scale $\mathcal{F}$-$SU(5)$ and pMSSM bulk regions superimposed over the August 2023 ATLAS Summary Plot [?] of SUSY searches for electroweak production of sleptons.

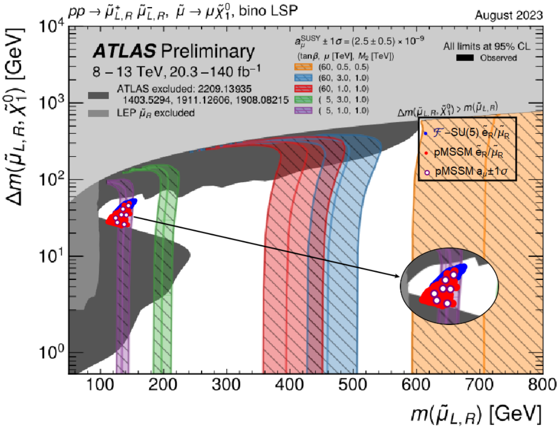


Figure: Generalized No-Scale $\mathcal{F}$-$SU(5)$ and pMSSM bulk regions superimposed over the August 2023 ATLAS Summary Plot of SUSY searches for electroweak production of smuons, plot here in terms of $\Delta m = (\tilde{\mu}_{L,R}, \tilde{\chi}^0_1)$ for a Bino LSP, emphasizing consistency of the bulk with recent muon anomalous magnetic moment measurements . The inset is a zoom of the bulk.

The Light Right-Handed Stau Bulk Region in the pMSSM

- All pMSSM points with an $\tilde{e}_R$ NLSP are excluded by the ATLAS soft lepton SUSY search.
- Therefore, like Generalized No-Scale $\mathcal{F}$-$SU(5)$, the only viable pMSSM region in the bulk is for the case $m_{\tilde{\chi}_1^0} < m_{\tilde{\tau}_1} < m_{\tilde{e}_R} = m_{\tilde{\mu}_R}$.
- Numerical findings disclose the ratio $\mathcal{R}_{\tilde{\tau}_1} \gtrsim 10\%$ implies $m_{\tilde{\chi}_1^0} \leq 117.7$ GeV. The upper bound on the light stau mass is about 160 GeV.
- The bulk alone can explain recent muon anomalous magnetic moment measurements.

Outline

Summary

- We propose Generalized No-Scale Supergravity, the simplest scenario for Effective Super-Natural Supersymmetry, which solve the supersymmetry electroweak fine-tuning problem naturally.
- A light right-handed slepton bulk region is realized in $\mathcal{F}$-$SU(5)$ and the pMSSM.
- The bulk may be beyond the LHC reach, though can be probed at the 1000-day LUX-ZEPLIN, Future Circular Collider (FCC-ee) at CERN, Circular Electron Positron Collider (CEPC), and Hyper-Kamiokande experiments.

Thank You Very Much for Your Attention!