Radiatively-driven natural SUSY with mixed axion/WIMP dark matter

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With emphasis on the *WIMPs*, for more axions, stick around for Dr. Kyu Jung Bae's talk.

Status of SUSY

- $m_h = 125.5 \pm 0.5$ GeV
- Scalars in need of protective symmetry: SUSY
- m_h falls within narrow MSSM expectation
- m_h requires highly mixed TeV scale stops
- LHC: no SUSY yet; $m_{\tilde{g}} > 1.3$ TeV, $m_{\tilde{q}} > 1.7$ TeV
- MSSM fine-tuned at 0.1%?
- Is SUSY in trouble?
  - How does this conception arise?

SM fine-tuning

- Fine-tuning in the SM:

$$\text{Scalar potential: } V(\phi) = -\mu^2(\phi)^2 + \frac{\lambda}{2}(\phi)^4$$

$$m_h^2 = m_h^2 + \delta m_h^2$$

$$m_h^2 = \sqrt{2}\mu^2; \quad \delta m_h^2 \sim \frac{c}{16\pi^2}\Lambda^2$$

  - These two are *independent* if one is huge, can dial the other to huge negative

$$\Delta_{SM} \equiv \delta m_h^2/(m_h^2/2)$$

$$\Delta_{SM} < \mathcal{O}(1) \Rightarrow \Lambda \sim 1\text{TeV} \quad \text{New physics at 1 TeV!}$$

EWFT-simplest approach to fine-tuning

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \sim -m_{H_u}^2 - \mu^2$$

(weak-scale relation and parameters, μ from superpotential, not SM Higgs mass parameter)

With

$$\Sigma_u^u(\tilde{t}_{1,2}) = \frac{3}{16\pi^2}F(m_{\tilde{t}_{1,2}}^2)\left[f_t^2 - g_Z^2 \mp \frac{f_t^2 A_t^2 - 8g_Z^2(\frac{1}{4}-\frac{2}{3}x_W)\Delta_t}{m_{\tilde{t}_2}^2 - m_{\tilde{t}_2}^2}\right]$$

$$\Delta_t = (m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2)/2 + m_Z^2\cos 2\beta(\tfrac{1}{4} - \tfrac{2}{3}x_W) \text{ and } x_W \equiv \sin^2\theta_W$$

$$F(m^2) = \left(\log\frac{m^2}{Q^2} - 1\right) \text{ with scale choice of } Q^2 = m_{\tilde{t}_1}m_{\tilde{t}_2}$$

Define: $\Delta_{\rm EW} \equiv \max_i |C_i|/(M_Z^2/2)$, e.g. $C_{H_u} = -m_{H_u}^2\tan^2\beta/(\tan^2\beta - 1)$

- Necessary for $-m_{H_u}^2, \mu^2$, and $-\Sigma_u^u$ be near $m_Z^2/2$
- Large A_t from $A_0 \sim \pm 1.6m_0$ drives Σ_u^u down while raising m_h
- μ required to lie in $100 - 300$ GeV range

Large log fine-tuning in the MSSM

Start with Higgs mass:

$$m_h^2 \simeq \mu^2 + m_{H_u}^2 + \delta m_{H_u}^2$$

$$\frac{dm_{H_u}^2}{dt} = \frac{1}{8\pi^2}\left(-\frac{3}{5}g_1^2 M_1^2 - 3g_2^2 M_2^2 + \frac{3}{10}g_1^2 S + 3f_t^2 X_t\right)$$

$$X_t = m_{Q_3}^2 + m_{U_3}^2 + m_{H_u}^2 + A_t^2$$

Usually ignore gauge terms, S term, and m_{H_u} then integrate. Gives:

$$\delta m_{H_u}^2|_{rad} \simeq -\frac{3f_t^2}{8\pi^2}(m_{Q_3}^2 + m_{U_3}^2 + A_t^2)\ln\left(\Lambda^2/M_{\mathrm{SUSY}}^2\right)$$

$$\Delta_{HS} \equiv \delta m_{H_u}^2/m_h^2/2 \lesssim 10 \Longrightarrow m_{\tilde{t}_{1,2}}, m_{\tilde{b}_1} \lesssim 200 \text{ GeV} \quad m_{\tilde{g}} \lesssim 600 \text{ GeV}$$

Large log fine-tuning in the MSSM

BUT

- $m_{H_u}^2$ and $\delta m_{H_u}^2$ are **not independent**
- If one is dialed to be large, the other also changes $\Rightarrow$ Combine them:

$$(m_{H_u}^2 + \delta m_{H_u}^2)$$

  which is just $m_{H_u}^2(m_{\mathrm{weak}})$!
- Then we have

$$m_h^2 \simeq \mu^2 + m_{H_u}^2$$

  which allows cancellations not apparent in log only term!

Starting to look like Δ_{EW}...

EENZ/BG fine-tuning

Regrouping dependent terms similar to measure used by EENZ and BG:

$$\Delta_{\rm BG} \equiv \max_i |c_i| = \left| \frac{\partial \ln M_Z^2}{\partial \ln a_i} \right|$$

a_i are parameters of the theory. Expressing m_Z in terms of high scale parameters (Abe, Kobayashi, Omura; S.P. Martin):

$$\begin{aligned} m_Z^2 \quad \simeq \quad & -2.18\mu^2 + 3.84M_3^2 + 0.32M_3M_2 + 0.047M_1M_3 - 0.42M_2^2 \\ & +0.011M_2M_1 - 0.012M_1^2 - 0.65M_3A_t - 0.15M_2A_t \\ & -0.025M_1A_t + 0.22A_t^2 + 0.004M_3A_b \\ & -1.27m_{H_u}^2 - 0.053m_{H_d}^2 \\ & +0.73m_{Q_3}^2 + 0.57m_{U_3}^2 + 0.049m_{D_3}^2 - 0.052m_{L_3}^2 + 0.053m_{E_3}^2 \\ & +0.051m_{Q_2}^2 - 0.11m_{U_2}^2 + 0.051m_{D_2}^2 - 0.052m_{L_2}^2 + 0.053m_{E_2}^2 \\ & +0.051m_{Q_1}^2 - 0.11m_{U_1}^2 + 0.051m_{D_1}^2 - 0.052m_{L_1}^2 + 0.053m_{E_1}^2 \end{aligned}$$

BUT

$$m_{Q_{1,2}} = m_{U_{1,2}} = m_{D_{1,2}} = m_{L_{1,2}} = m_{E_{1,2}} \equiv m_{16}(1,2)$$

$$m_{H_u}^2 = m_{H_d}^2 = m_{16}^2(3) \equiv m_0^2$$

-Blue gives $\sim 0.014m_{16}^2(1,2)$

-Red gives $\sim 0.027m_0^2$

EENZ/BG fine-tuning

For any given hidden sector in supergravity, get

$$
\begin{aligned}
m_0 &\sim a_{m_0} \cdot m_{3/2} \\
m_{1/2} &\sim a_{m_{1/2}} \cdot m_{3/2} \\
A_0 &\sim a_{A_0} \cdot m_{3/2}
\end{aligned}
$$

This will give full cancellation/correlation possibilities!

$$\mathbf{m_Z^2 \simeq -2\mu^2 - a \cdot m_{3/2}^2}$$

- Can still have low fine-tuning if a is small
  - Both μ^2 and $a \cdot m_{3/2}^2 \sim m_Z^2$
- $\Delta_{\rm BG}$ measures EWFT in multi-parameter effective theories
  - With larger number of parameters, correlations are lost; leading to overestimate
- Value changes from theory to theory–model dependent even with same spectra unless correlations are considered

Now $\Delta_{\rm BG}$ starting to look like $\Delta_{\rm EW}$ and $\Delta_{\rm HS}$!

Radiatively-driven natural SUSY (RNS)

Baer, Barger, Huang, Mustafayev, Tata, *Phys. Rev. Lett.* 109 (2012) 161802
Baer, Barger, Huang, Mickelson, Mustafayev, Tata, *Phys. Rev.* D 87 (2013) 115028

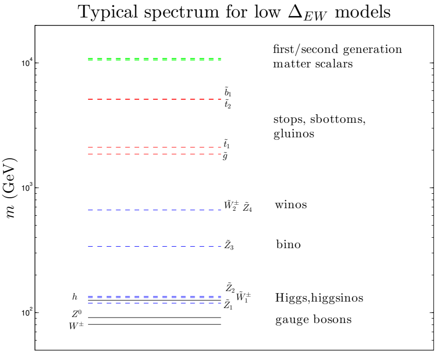
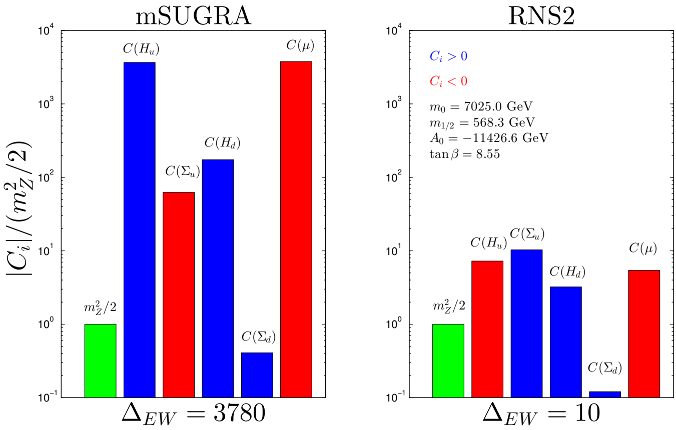


Figure: Baer, Barger, Mickelson; Phys. Rev. D 88, (2013) 095013, arXiv:1309.2984

- light higgsino-like $\widetilde{W}_1^\pm$ and $\widetilde{Z}_{1,2}$ with masses $\sim 100-300$ GeV
- gluinos with $m_{\tilde{g}} \sim 1-4$ TeV
- top squarks with $m_{\tilde{t}_1} \sim 1-2$ TeV and $m_{\tilde{t}_2} \sim 2-5$ TeV
- first/second generation squarks and sleptons with $m_{\tilde{q},\tilde{l}} \sim 1-8$ TeV-can be raised to 20-30 TeV if $m_0(1,2) > m_0(3)$ is allowed.

RNS in the NUHM2 model



- $m_0, m_{1/2}, A_0, \tan\beta, m_{H_u}, m_{H_d}$
  - Trade m_{H_u}, m_{H_d} for μ, m_A
- $m_h \approx 125$ GeV
- low $\mu \sim 100 - 200$ GeV
- stops at 1-3 TeV, large mixing

Relic abundance of higgsino-like WIMPs

$< \sigma v >$ annihilate rate huge for higgsinos
$\therefore$ relic density is low: $\Omega h^2 \propto 1/ < \sigma v >$

Green points excluded by detection experiments

Blue points- $\Delta_{\rm EW} < 100$
Red points- $\Delta_{\rm EW} < 50$

Thermally underproduced by factors of 10-20

Bulk of DM composed of axions–needed anyway to solve Strong CP fine-tuning

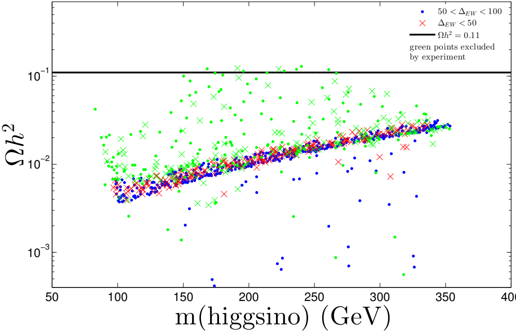


Figure: Baer, Barger, Mickelson; Phys. Lett. B 726 (2013) 330-336, arXiv:1303.3816

Direct detection of higgsinos-rescaled for local abundance

In RNS, WIMP scatters mainly via $\widetilde{Z} - \widetilde{Z} - h$

$\mathcal{L} \ni -X_{11}^h \widetilde{Z}_1 \widetilde{Z}_1 h \; X_{11}^h = -\frac{1}{2}\left(v_2^{(1)} \sin\alpha - v_1^{(1)} \cos\alpha\right)\left(g v_3^{(1)} - g' v_4^{(1)}\right)$ (non-negligible gaugino cont.)

$\xi = \Omega_{\widetilde{Z}_1}^{std} h^2 / 0.11$
-rescaling factor

New LUX results are already digging into parameter space!

Xe-1ton to be deployed soon!

Can test completely with a ton scale detector or equivalent (subject to minor caveats)

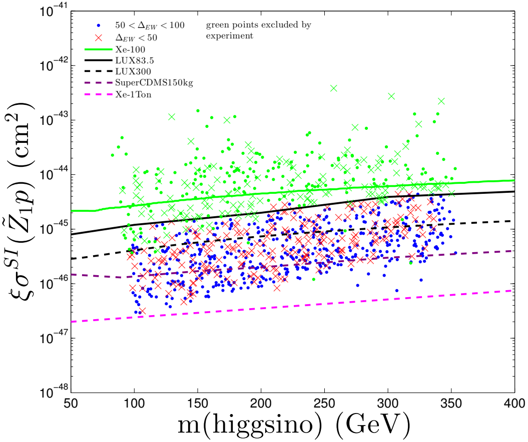


Figure: Baer, Barger, Mickelson; Phys. Lett. B 726 (2013) 330-336, arXiv:1303.3816

Indirect detection of higgsinos via halo annihilations

$\xi = \Omega^{std}_{\widetilde{Z}_1} h^2 / 0.11$ -rescaling factor now **squared**

Currently out of reach, but some parameter points exluded by direct detection experiments

gamma-ray signal $\sim$ 10-20 times below current limits

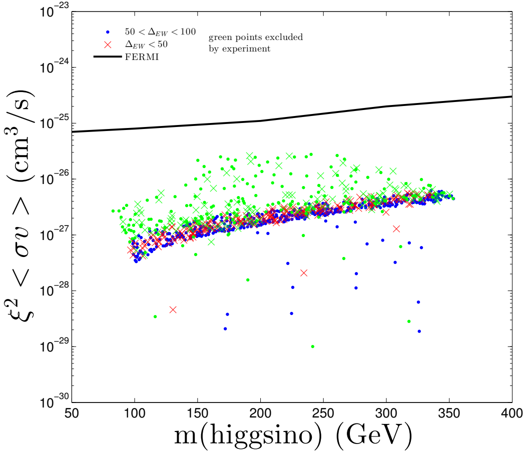


Figure: Baer, Barger, Mickelson; Phys. Lett. B 726 (2013) 330-336, arXiv:1303.3816

Indirect detection of higgsino-like WIMPs via solar neutrinos

No rescaling factor needed

Dependent on equilibration of capture rate and annihilation rate

ICECUBE limits penetrating parameter space

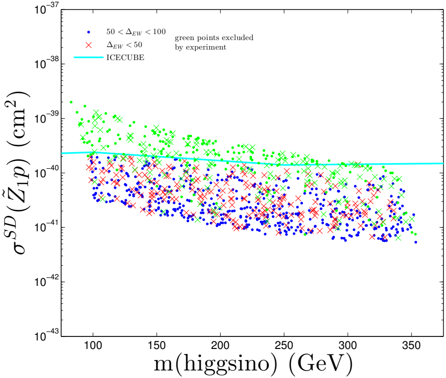


Figure: Baer, Barger, Mickelson; Phys. Lett. B 726 (2013) 330-336, arXiv:1303.3816

Summary

- Electroweak fine-tuning in SUSY is *not* in crisis! EWFT allowed at 10 % level in radiatively-driven natural SUSY
    - Leads to low $\mu \sim 100 - 300$ GeV
- All 3 measures of fine-tuning can agree when applied properly
- Thermal WIMP (higgsino) abundance low by factors of 10-20
- Reduced abundance of higgsino-like WIMPs seeable at ton-scale detectors (Xe 1-Ton to be deployed soon!)
- Can address the Strong CP and μ problems via PQ symmetry breaking (Kim-Nilles)
- DM made up of both axions and higgsino-like WIMPs (SUSY DFSZ axion model)