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:

  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

  \[ \Delta_{SM} \equiv \frac{\delta m_h^2}{(m_h^2/2)} \]

  \[ \Delta_{SM} < O(1) \Rightarrow \Lambda \sim 1\text{TeV} \quad \text{New physics at 1 TeV!} \]
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, \( \mu \) from superpotential, not SM Higgs mass parameter)

With

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

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

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

Define: \( \Delta_{EW} \equiv \max_i |C_i| / (M_Z^2/2) \), 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 \( \Sigma_u^u \) down while raising \( m_h \)
- \( \mu \) required to lie in \(100 - 300\) GeV range
Large log fine-tuning in the MSSM

Start with Higgs mass:

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

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

\[ X_t = m_{Q_3}^2 + m_{U_3}^2 + m_{H_u}^2 + A_t^2 \]

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

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

\[ \Delta_{HS} \equiv \delta m_{H_u}^2 / m_h^2 / 2 \lesssim 10 \implies m_{\tilde{t}_{1,2}}, m_{\tilde{b}_1} \lesssim 200 \text{ GeV} \quad m_{\tilde{g}} \lesssim 600 \text{ GeV} \]
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 $m_{H_u}^2 (m_{\text{weak}})$!

- 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 $\Delta_{EW}$...
EENZ/BG fine-tuning

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

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

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

\[
\begin{align*}
m_Z^2 &\approx -2.18 \mu^2 + 3.84 M_3^2 + 0.32 M_3 M_2 + 0.047 M_1 M_3 - 0.42 M_2^2 \\
&\quad + 0.011 M_2 M_1 - 0.012 M_1^2 - 0.65 M_3 A_t - 0.15 M_2 A_t \\
&\quad - 0.025 M_1 A_t + 0.22 A_t^2 + 0.004 M_3 A_b \\
&\quad - 1.27 m_{Hu}^2 - 0.053 m_{Hd}^2 \\
&\quad + 0.73 m_Q^2 + 0.57 m_U^2 + 0.049 m_D^2 - 0.052 m_L^2 + 0.053 m_{E_3}^2 \\
&\quad + 0.051 m_Q^2 - 0.11 m_U^2 + 0.051 m_D^2 - 0.052 m_L^2 + 0.053 m_{E_2}^2 \\
&\quad + 0.051 m_Q^2 - 0.11 m_U^2 + 0.051 m_D^2 - 0.052 m_L^2 + 0.053 m_{E_1}^2
\end{align*}
\]

BUT

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

\[ m_{Hu}^2 = m_{Hd}^2 = m_{16}^2(3) \equiv m_{0}^2 \]

-Blue gives \( \sim 0.014 m_{16}^2(1,2) \)
-Red gives \( \sim 0.027 m_{0}^2 \)
EENZ/BG fine-tuning

For any given hidden sector in supergravity, get

\[
\begin{align*}
m_0 & \sim a_{m_0} \cdot m^{3/2} \\
m_{1/2} & \sim a_{m_{1/2}} \cdot m^{3/2} \\
A_0 & \sim a_{A_0} \cdot m^{3/2}
\end{align*}
\]

This will give full cancellation/correlation possibilities!

\[
\begin{align*}
m_Z^2 & \sim -2\mu^2 - a \cdot m_{3/2}^2
\end{align*}
\]

- Can still have low fine-tuning if \(a\) is small
  - Both \(\mu^2\) and \(a \cdot m_{3/2}^2 \sim m_Z^2\)
- \(\Delta_{BG}\) 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 \(\Delta_{BG}\) starting to look like \(\Delta_{EW}\) and \(\Delta_{HS}\)!**
Radiatively-driven natural SUSY (RNS)

Baer, Barger, Huang, Mickelson, Mustafayev, Tata, Phys. Rev. D 87 (2013) 115028

Typical spectrum for low $\Delta_{EW}$ models

- light higgsino-like $\tilde{W}_1^\pm$ and $\tilde{Z}_{1,2}$ 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.

Figure: Baer, Barger, Mickelson; Phys. Rev. D 88, (2013) 095013, arXiv:1309.2984
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 $\mu$, $m_A$
- $m_h \approx 125$ GeV
- low $\mu \sim 100 - 200$ GeV
- stops at 1-3 TeV, large mixing

$m_0$, $m_{1/2}$, $A_0$, $\tan \beta$, $m_{H_u}$, $m_{H_d}$

$m_0 = 7025.0$ GeV
$m_{1/2} = 568.3$ GeV
$A_0 = -11426.6$ GeV
$\tan \beta = 8.55$

$m_\mu$ is consistent with low $\mu$.
Relic abundance of higgsino-like WIMPs

\[ <\sigma v> \text{ annihilate rate huge for higgsinos} \]
\[ \therefore \text{relic density is low: } \Omega h^2 \propto 1/ <\sigma v> \]

Green points excluded by detection experiments

Blue points- \( \Delta_{EW} < 100 \)
Red points- \( \Delta_{EW} < 50 \)

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

Dan Mickelson (University of Oklahoma) RNS with axion/WIMP DM May 5, 2014
Direct detection of higgsinos-rescaled for local abundance

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

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

$$\xi = \frac{\Omega^{std}_{\tilde{Z}_1}}{h^2/0.11}$$

-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

\[ \xi = \Omega_{\tilde{Z}_1}^{std} \frac{h^2}{0.11} \text{ - rescaling factor now } \textbf{squared} \]

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

gamma-ray signal \( \sim 10\text{-}20 \) times below current limits

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

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 $\mu$ problems via PQ symmetry breaking (Kim-Nilles)
- DM made up of both *axions* and higgsino-like WIMPs (SUSY DFSZ axion model)