The Little Hierarchy Problem in a Generalized NMSSM

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Based on Phys. Rev. Lett. **105**, 091802 (2010) [arXiv:1005.1282]
and Phys. Rev. **D82**, 035006 (2010) [arXiv:1005.4901]
by A. Delgado, CK, J.P. Olson and A. del la Puente
Plus a forthcoming work

Two major problems motivate much of SUSY model-building:

- SUSY flavor (& CP) problem = *How do we add scalar superpartners without generating large, new FCNC's and CPV?*

  $\Rightarrow$ <u>*insert your favorite here*</u> – *mediated SUSY breaking*

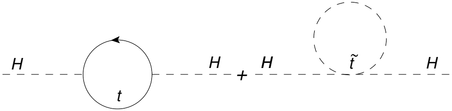
- Little hierarchy problem (LHP) = *How do we push light Higgs mass above the LEP bound (114 GeV) without heavy stops ($\gtrsim$ 1 TeV) and/or large A_t ($\sim \sqrt{6} m_{\tilde{t}}$)?*

  Extend Higgs sector
  Extend symmetries of MSSM
  Impose strong couplings
  Impose low cutoff
  Add new operators
  Hide Higgs from LEP

The Little Hierarchy Problem

Weak-scale SUSY postulated to solve (big) hierarchy problem:

$\delta m^2_{weak} =$



$$= \frac{3y^2}{8\pi^2}\left(\Lambda^2 - \Lambda^2\right) + \frac{3y^2}{16\pi^2} m^2_{\tilde{t}} \log\left(\frac{\Lambda}{m_{weak}}\right)$$

To maintain m^2_{weak}, need $m_{\tilde{t}} \lesssim 1$ TeV.

BUT, the physical Higgs mass scales differently:

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{8\pi^2 v^2} \log\left(\frac{m^2_{\tilde{t}}}{m_t^2}\right)$$

To get $m_h \gtrsim 114\,\text{GeV}$ requires logarithmically large $m_{\tilde{t}}$, but that destabilizes weak scale quadratically!

The NMSSM & Little Hierarchy Problem

Classic extension of MSSM $\Longrightarrow$ the Next-to-MSSM (NMSSM):

$$W = W_{Yukawa} + \lambda S H_u H_d + \frac{1}{3}\kappa S^3$$

Many advantages over MSSM:

- No μ-term! Generated by $\mu_{eff} = \lambda\langle S\rangle$.
- New quartic term in V from F_S:

$$|F_S|^2 = |\lambda H_u H_d + \kappa S^2|^2 = |\lambda|^2 |H_u H_d|^2 + \cdots$$

- New upper bound on m_{h^0}:

$$m_{h^0}^2 \leq m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$$

(Haber & Sher; Drees; Espinosa & Quiros; Kane, Kolda & Wells; $\cdots$)

Several problems & constraints as a solution to LHP:

Low $\tan\beta$ Only

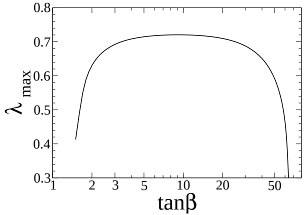
Since $\Delta m^2_{h^0} \propto \sin^2 2\beta$, important only when $\tan\beta \simeq 1$, where $m_{h^0} \to 0$ in MSSM.

Perturbative Unification

Assuming gauge coupling unification is real, want λ perturbative up to GUT scale. But

$$\frac{d\lambda}{dt} = \frac{\lambda}{16\pi^2}\left(3y_t^2 + 4\lambda^2 + 2\kappa^2 - 3g_2^2 + \cdots\right)$$

Demanding $\lambda(M_{GUT}) \lesssim 4\pi$ requires $\lambda(m_W) \lesssim 0.7$.



Higgs-Singlet Mixing

Any mixing of singlet into h^0 decreases mass

- must tune mass matrix parameters to suppress mixing
- no one term controls mixing!

In large m_{A^0} limit of NMSSM, CP-even scalar matrix takes form:

$$\mathcal{M}^2 = \left(\begin{array}{cc|c} m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta & (m_Z^2 - \lambda^2 v^2) \sin 2\beta \cos 2\beta & \mathcal{M}_{13}^2 \\ - & m_{A^0}^2 & \mathcal{M}_{23}^2 \\ \hline - & - & \mathcal{M}_{33}^2 \end{array} \right)$$

where $\mathcal{M}_{i3}^2$ are all naturally $O(M_{SUSY}^2) \approx O(m_W^2)$.

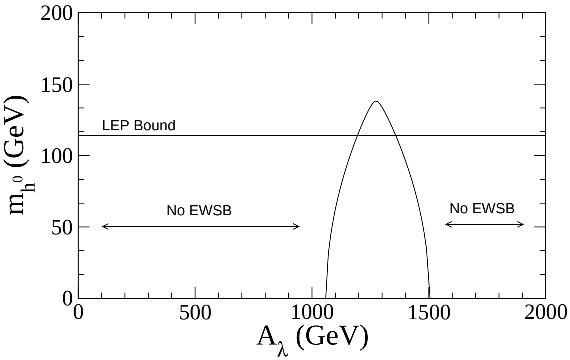
In particular,

$$\mathcal{M}_{13}^2 \propto 2\lambda v_s - (A_\lambda + 2\kappa v_s) \sin 2\beta$$

Any $S - h^0$ mixing will reduce m_{h^0}, so we need $\mathcal{M}_{13}^2 \simeq 0$:

$$\longrightarrow A_\lambda \simeq \left(\frac{2\lambda}{\sin 2\beta} - 2\kappa \right) v_s.$$

A typical NMSSM case: ($\lambda = 0.7$, $\kappa = 0.05$, $M_{\tilde{g}} = 500\,\text{GeV}$,
$m_{\tilde{t}} = 1\,\text{TeV}$, $A_t = \sqrt{6} m_{\tilde{t}}$)



$\Rightarrow$ A_λ must be tuned to get EW symmetry breaking,
and even more to get m_{h^0} above LEP bound.

The problem?

Maybe we are asking too much of the singlet

- ~~Solve the μ-problem~~
- Solve the little hierarchy problem

The S-MSSM

Allow (almost) all possible terms in W:

$$W = W_{Yukawa} + (\mu + \lambda S)H_u H_d + \frac{1}{2}\mu_s S^2 + \frac{1}{3}\kappa S^3$$

- Assume $\mu \sim m_W$. S cleanly decouples to MSSM as $\mu_s \to \infty$. We assume μ_s large compared to other weak-scale masses.
- For simplicity, take $\kappa \simeq 0$ – wouldn't usually play big role anyway.

Not the final UV theory, but may describe low-E effective theory.

Why isn't this model already well-studied?

- It doesn't solve μ-problem! Instead it has two μ-problems!
  - $\Rightarrow$ We study lots of models with μ-problems, like CMSSM, GMSB, AMSB, ...
- We've left out dangerous tadpole terms which can't be eliminated by symmetries, and these destabilize the hierarchy.

  In usual NMSSM, W possesses Z_3 symmetry, prevents tadpole terms:

$$W \sim \xi S, \quad V_{soft} \sim \xi' S$$

  But in S-MSSM, Z_3 broken (softly) by μ, μ_s. At n-loops, one generates tadpoles with

$$\xi \sim \left(\frac{1}{16\pi^2}\right)^n \mu_{(s)}\Lambda, \quad \xi' \sim \left(\frac{1}{16\pi^2}\right)^n M_{SUSY}\mu_{(s)}\Lambda$$

  If $\Lambda \gg m_W$, hierarchy can be destabilized!

The bad and not-so-bad about the tadpoles:

- Setting $\xi = 0$ in W is technically natural. We only generate it by integrating out heavy fields, $W = S\bar{\Phi}\Phi$. This can also be disallowed in a technically natural way.
- SUSY-breaking ξ'-tadpole is more dangerous. For example, can arise from non-minimal Kähler potential:

$$K = S^\dagger S + (S + S^\dagger)\Phi^\dagger \Phi / M_{PL} \longrightarrow \xi' \sim F_\Phi^2 / M_{PL}$$

  . . . or from coupling to heavy fields induced by supergravity.

- BUT S need not be singlet all the way to M_{PL}. Λ could be low.
- Adding new field(s) whose vev give μ, μ_s would restore Z_3.
- Discrete R-symmetries can rule out tadpole contributions.

- We assume that S-MSSM is valid below some scale Λ which may not be much greater than m_W OR there is a discrete R-symmetry present.

The Potential of the S-MSSM

$$V = (m_{H_u}^2 + |\mu + \lambda S|^2)|H_u|^2 + (m_{H_d}^2 + |\mu + \lambda S|^2)|H_d|^2 + (m_s^2 + \mu_s^2)|S|^2$$
$$+ \left[B_s S^2 + \left(\lambda \mu_s S^\dagger + B_\mu + \lambda A_\lambda S\right) H_u H_d + h.c.\right] + \lambda^2 \left|H_u H_d\right|^2$$
$$+ \tfrac{1}{8}(g^2 + g'^2)\left(|H_u|^2 - |H_d|^2\right)^2 + \tfrac{1}{2} g^2 |H_u^\dagger H_d|^2.$$

- Three soft scalar masses, two *B*-terms, one *A*-term
- New quartic coupling will raise Higgs mass!

The Potential of the S-MSSM

$$\begin{aligned} V &= (m_{H_u}^2 + |\mu + \lambda S|^2)|H_u|^2 + (m_{H_d}^2 + |\mu + \lambda S|^2)|H_d|^2 + (m_s^2 + \mu_s^2)|S|^2 \\ &+ \left[B_s S^2 + \left(\lambda \mu_s S^\dagger + B_\mu + \lambda A_\lambda S\right) H_u H_d + h.c.\right] + \lambda^2 \left|H_u H_d\right|^2 \\ &+ \tfrac{1}{8}(g^2 + g'^2)\left(|H_u|^2 - |H_d|^2\right)^2 + \tfrac{1}{2} g^2 |H_u^\dagger H_d|^2. \end{aligned}$$

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The Potential of the S-MSSM

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\begin{aligned}
V &= (m_{H_u}^2 + |\mu + \lambda S|^2)|H_u|^2 + (m_{H_d}^2 + |\mu + \lambda S|^2)|H_d|^2 + (m_s^2 + \mu_s^2)|S|^2 \\
&+ \left[B_s S^2 + \left(\lambda \mu_s S^\dagger + B_\mu + \lambda A_\lambda S\right) H_u H_d + h.c.\right] + \lambda^2 \left|H_u H_d\right|^2 \\
&+ \tfrac{1}{8}(g^2 + g'^2)\left(|H_u|^2 - |H_d|^2\right)^2 + \tfrac{1}{2} g^2 |H_u^\dagger H_d|^2.
\end{aligned}
$$

Minimization conditions:

$$
\begin{aligned}
\boxed{1} \quad \tfrac{1}{2} m_Z^2 &= \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu_{eff}^2, \\
\boxed{2} \quad \sin 2\beta &= \frac{2B_{\mu,eff}}{m_{H_u}^2 + m_{H_d}^2 + 2\mu_{eff}^2 + \lambda^2 v^2}
\end{aligned}
$$

where $v_{s,u,d} = \langle\{S, H_u, H_d\}\rangle$, with $v = (v_u^2 + v_d^2)^{1/2} = 174\,\text{GeV}$.

$$
\begin{aligned}
\mu_{eff} &= \mu + \lambda v_s, \\
B_{\mu,eff} &= B_\mu + \lambda v_s(\mu_s + A_\lambda).
\end{aligned}
$$

The Potential of the S-MSSM

$$
\begin{aligned}
V &= (m_{H_u}^2 + |\mu + \lambda S|^2)|H_u|^2 + (m_{H_d}^2 + |\mu + \lambda S|^2)|H_d|^2 + (m_s^2 + \mu_s^2)|S|^2 \\
&+ \left[B_s S^2 + \left(\lambda \mu_s S^\dagger + B_\mu + \lambda A_\lambda S\right) H_u H_d + h.c.\right] + \lambda^2 \left|H_u H_d\right|^2 \\
&+ \tfrac{1}{8}(g^2 + g'^2)\left(|H_u|^2 - |H_d|^2\right)^2 + \tfrac{1}{2} g^2 |H_u^\dagger H_d|^2 .
\end{aligned}
$$

Minimization conditions:

$$
\begin{aligned}
\boxed{3} \quad v_s &= \frac{\lambda v^2}{2} \frac{(\mu_s + A_\lambda)\sin 2\beta - 2\mu}{\mu_s^2 + \lambda^2 v^2 + m_s^2 + 2B_s} \\
&\simeq \frac{\lambda v^2}{2\mu_s} \sin 2\beta \quad \text{for large } \mu_s \\
&\longrightarrow \quad 0 \quad \text{as } \mu_s \to \infty
\end{aligned}
$$

Unlike NMSSM:

- v_s typically quite small.
- breaks EW symmetry very generically – conditions same as in MSSM, no additional tunings required.

Scalar Masses

CP-even mass matrix similar to NMSSM. In particular:

$$\mathcal{M}_{11}^2 = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin 2\beta$$

But:

$$\begin{aligned} \mathcal{M}_{13}^2 &\simeq -\lambda v \mu_s \sin 2\beta + \cdots \\ \mathcal{M}_{33}^2 &\simeq \mu_s^2 \end{aligned}$$

Both good and bad:

- $S - h^0$ mixing $\rightarrow 0$ as $\mu_s \rightarrow \infty$
- All effects of S on mass matrix decouple as $\mu_s \rightarrow \infty$!
- We want to live in intermediate regime – is this fine tuned?

Find Higgs spectrum as an expansion in $1/\mu_s$:

$$m^2_{A^0_1} \simeq \frac{2B_\mu}{\sin 2\beta} + \frac{2\lambda^2 v^2}{\mu_s}\left(2A_\lambda - \frac{\mu}{\sin 2\beta}\right)$$

$$m^2_{A^0_2, H^0_2} \simeq \mu_s^2 + 2\lambda^2 v^2 + m_s^2 \mp 2B_s$$

$$m^2_{h^0, H^0_1} \simeq m^2_{h^0, H^0_1}\Big|_{\mathrm{MSSM}} + \frac{2\lambda^2 v^2}{\mu_s}\left(\mu \sin 2\beta - A_\lambda \mp \Delta\right)$$

where

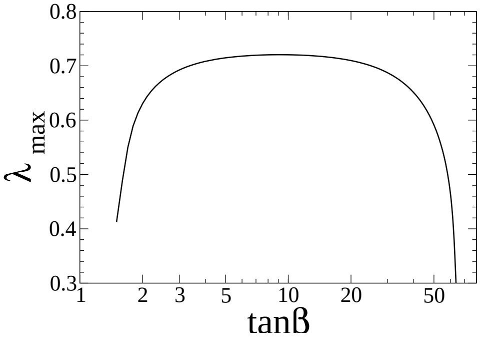
$$\Delta = \frac{A_\lambda (m_Z^2 - m^2_{A^0_1}) \cos^2 2\beta - \mu (m^2_{A^0_1} + m_Z^2) \sin 2\beta}{\sqrt{(m^2_{A^0_1} + m_Z^2)^2 - 4 m^2_{A^0_1} m_Z^2 \cos^2 2\beta}}$$

In Higgs decoupling limit, $m_{A^0_1} \to \infty$, mass of h^0 maximized:

$$m^2_{h^0} \simeq m_Z^2 \cos^2 2\beta + \frac{2\lambda^2 v^2}{\mu_s}\left(2\mu \sin 2\beta - A_\lambda \sin^2 2\beta\right) + \cdots$$

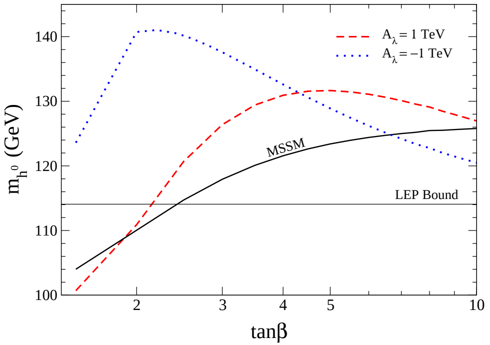
In principle, $m_{h^0} \to \infty$ as $\lambda \to \infty$.

BUT if we apply perturbative unification constraint, maximum λ depends on $\tan\beta$:



Max λ falls off quickly for $\tan\beta \lesssim 2$ or $\gtrsim 50$.

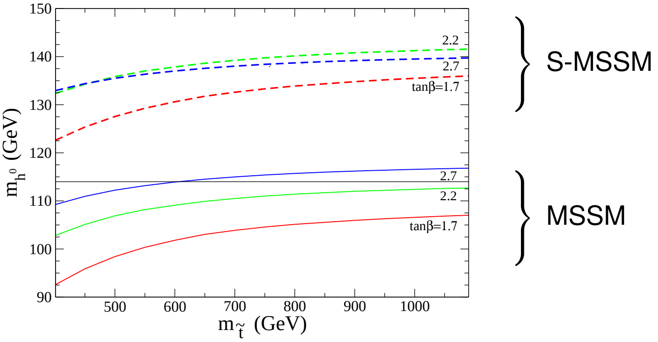
For $m_{\tilde{t}} = M_{\tilde{g}} = 2\mu = 1$ TeV, $A_t = \sqrt{6} m_{\tilde{t}}$ (max mixing), $A_\lambda = \pm 1$ TeV and $\mu_s = 2$ TeV:



- All masses calculated using full one-loop V_{eff} plus leading 2-loop corrections from FeynHiggs.
- Because of $\sin 2\beta$ term, effect persists to higher $\tan\beta$ than NMSSM.
- Different signs of A_λ dominate at different $\tan\beta$ due to $1/\mu_s^2$ terms.
- Enhancement disappears as $\tan\beta \to 1$ due to perturbative unification constraint on λ, and MSSM contribution going to zero.

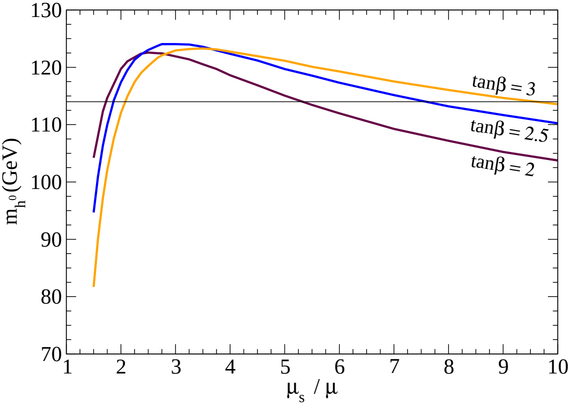
Can we bring down the stop masses?

For maximal mixing scenario: ($\mu = 500\,\text{GeV}$, $\mu_s = 2\,\text{TeV}$)



- Even for $m_{\tilde{t}} \simeq 400\,\text{GeV}$, S-MSSM produces h^0 well above LEP bound.

Dependence on μ_s: ($m_{\tilde{t}_2} = 1$ TeV, $A_t \simeq 0$)



- Falls quickly as $\mu_s \to m_W$, falls slowly as $\mu_s \to \infty$.
- For maximum m_{h^0}, S-MSSM prefers μ_s 2 to 4 times larger than μ.
- But choice of μ_s is not very tuned – wide ranges work!

What's been accomplished so far:

Broken EW symmetry naturally

Assuming μ_s not very small, $V(S)$ stabilized by μ_s term, $\langle S \rangle$ small.
No cancellations among parameters required.
Vacuum structure is very MSSM-like.

NOT solved μ-problem

Gave mass to charginos/neutralinos with explicit μ-term.

Raised the light Higgs mass

For large, but not too large, values of μ_s, we have raised m_{h^0} to as much as 140 GeV, with no tunings among parameters required.

Hard to tell from MSSM

Phenomenology is essentially that of MSSM, except m_{h^0} is too big given "observed" stop masses.

But . . .

Will this survive embeddings into a more complete model, *e.g.*, a SUSY-breaking scheme?

Gauge-Mediated S-MSSM

To test S-MSSM in more complete theory, embed into gauge-mediated scheme:

$$W = W_{SMSSM} + X\bar{\Phi}\Phi$$

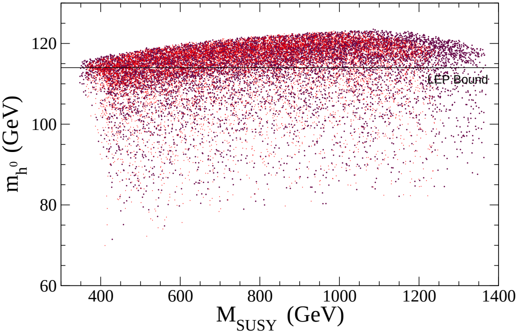
with $\langle X \rangle = M + \theta^2 F$ and messengers $\bar{\Phi}, \Phi$ in $\bar{\mathbf{5}}, \mathbf{5}$ of SU(5).
For S-MSSM soft masses:

$$\begin{aligned} M_i(M) &= \frac{\alpha_i}{4\pi}\frac{F}{M} \\ m^2_{\tilde{f}}(M) &= \sum_{i=gauge} 2C_i^f \frac{\alpha_i^2}{16\pi^2}\left(\frac{F}{M}\right)^2 \\ A_{\lambda,Q,\cdots} &\simeq 0 \\ B_s, m_s^2 &\simeq 0 \end{aligned}$$

We obtain B_μ, μ from EWSB conditions

$\Rightarrow$ We do NOT solve $\mu - B_\mu$ problem of GMSB.

Random scan of parameter space:



$2 \leq \tan\beta \leq 6$

$2 \leq \mu_s/\mu \leq 5$

$300\,\text{GeV} \leq \mu \leq 900\,\text{GeV}$

$M = 10^{10}$ and 10^{13} GeV

$$M_{SUSY} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

For $M_{SUSY} = 500\,\text{GeV}$, half of points above LEP bound.

GMSB models usually require $M_{SUSY} > 2\,\text{TeV}$ because $A_t \simeq 0$.

Recap of argument so far:

- We want contributions to m_h from F_S (raises m_h), but we don't want S mixing into h (lowers m_h).
- Mixing is controlled by μ_s. As μ_s grows, mixing decreases, but so do F_S contributions to m_h.
- For μ_s of 1 to 5 TeV, mixing is small but F_S contributions still sizable, able to push m_h over 130 to 140 GeV.
- Little hierarchy problem is solved!

- But what if $\mu_s \ll m_W$?? It would appear to be a disaster, with large $h - S$ mixing, and two light states for LEP to find.

$\Rightarrow$ *That's not the case!*

Consider minimization of potential again:

$$\lambda v_s = \frac{\lambda^2 v^2}{2} \frac{(\mu_s + A_\lambda)\sin 2\beta - 2\mu}{\lambda^2 v^2 + \mu_s^2 + m_s^2 + 2B_s}$$

$$\simeq \tfrac{1}{2} A_\lambda \sin 2\beta - \mu \quad \text{for small } \mu_s^2, m_s^2, B_s$$

$$\Rightarrow \mu_{\rm eff} \simeq \tfrac{1}{2} A_\lambda \sin 2\beta \text{ independent of } \mu!$$

The heavy, MSSM-like pseudoscalar has mass

$$m_A^2 \simeq \frac{2B_{\mu,\rm eff}}{\sin 2\beta} + \lambda^2 v^2 \qquad (A_\lambda \gg B_\mu)$$

where

$$B_{\mu,\rm eff} \simeq B_\mu + \tfrac{1}{2} A_\lambda^2 \sin 2\beta - \mu A_\lambda$$

Note that we can arrange cancellations among B_μ, A_λ and λv to obtain *very* light A^0 (as in Dermisek & Gunion), but doesn't come out automatically.

For scalar mass matrix, rotate by angle β and work in "Goldstone" / Higgs decoupling basis:

$$\mathcal{M}^2 = \begin{pmatrix} m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta & (m_Z^2 - \lambda^2 v^2) \sin 2\beta \cos 2\beta & 0 \\ & m_A^2 + (m_Z^2 - \lambda^2 v^2) \sin^2 2\beta & \lambda v A_\lambda \cos 2\beta \\ & & \lambda^2 v^2 \end{pmatrix}$$

For small singlet mass terms (m_s^2, B_s, μ_s) and large m_A, the singlet does not mix into the SM-like Higgs *at all*!

The F_S contributions to m_h are nearly maximized. Only suppression is usual mixing of H^0 into h^0, pushing down the h^0 mass:

$$m_h^2 = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta - \frac{(m_Z^2 - \lambda^2 v^2)^2}{m_A^2} \sin^2 2\beta \cos^2 2\beta$$

And even this mixing is smaller than usual: m_Z^2 vs. $m_Z^2 - \lambda^2 v^2$.

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For small singlet mass terms (m_s^2, B_s, μ_s) and large m_A, the singlet does not mix into the SM-like Higgs *at all*!

The zero in $\mathcal{M}_{13}^2$ is corrected by terms $\sim (m_s^2, B_s, \mu_s^2)/(\lambda^2 v^2)$.
We seem to need small m_s^2, etc, while keeping A_λ large.
Not entirely natural because

$$\frac{dm_s^2}{d\log Q} \sim \frac{1}{8\pi^2}\lambda^2 A_\lambda^2$$

Suggests a model with low messenger scales (*i.e.*, gauge mediation).

For scalar mass matrix, rotate by angle β and work in "Goldstone" / Higgs decoupling basis:

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For small singlet mass terms (m_s^2, B_s, μ_s) and large m_A, the singlet does not mix into the SM-like Higgs *at all*!

BUT, we don't really need to suppress m_s^2, μ_s, B_s too much.
For example, turn on m_s^2:

$$\delta m_h^2 \simeq \left(\frac{m_s^2}{m_A^2} \right) 2A_\lambda \sin 2\beta \, (A_\lambda \sin 2\beta - 2\mu).$$

SO m_h^2 goes up *or* down depending on details. This is because h is no longer lightest scalar eigenvalue!

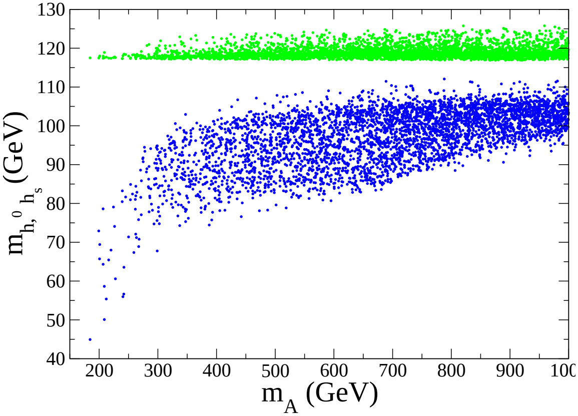
For the mostly singlet particles:

$$m_{A_s}^2 \simeq \mu_s^2 + \lambda^2 v^2 - \frac{\lambda^2 v^2 A_\lambda^2}{m_A^2},$$
$$m_{h_s}^2 \simeq \mu_s^2 + \lambda^2 v^2 - \frac{\lambda^2 v^2 A_\lambda^2}{m_A^2} \cos^2 2\beta \qquad (m_{A_s} < m_{h_s})$$

It would be quite natural for the associated singlinos to be lightest sparticles and thus dark matter candidates, but not studied in detail.

A random scatter of points with $B_\mu < 1000^2\,\mathrm{GeV}^2$, $A_\lambda < 700\,\mathrm{GeV}$, $\mu < 500\,\mathrm{GeV}$, $\mu_s < 50\,\mathrm{GeV}$, $m_s^2 = B_s = 0$

And: $\tan\beta = 2$, $m_{\tilde{t}} = 500\,\mathrm{GeV}$ and $A_t = 0$ → little stop mixing



Key: Black = h^0, Green=h_s

A random scatter of points with $B_\mu < 1000^2\,\mathrm{GeV}^2$, $A_\lambda < 700\,\mathrm{GeV}$, $\mu < 500\,\mathrm{GeV}$, $\mu_s < 50\,\mathrm{GeV}$, $m_s^2 = B_s = 0$

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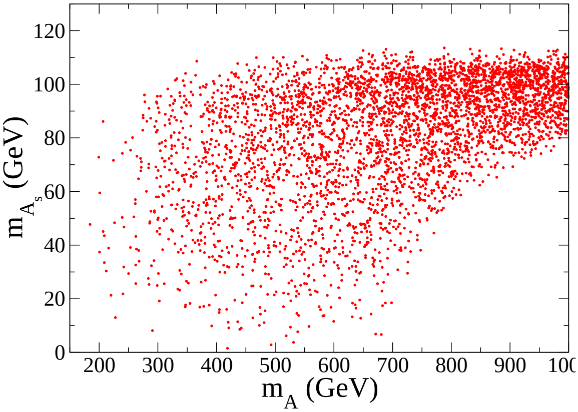
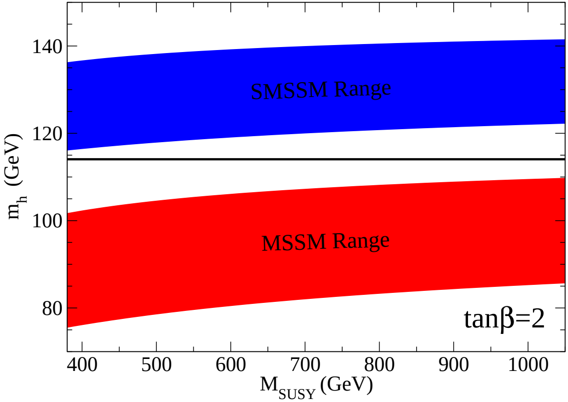
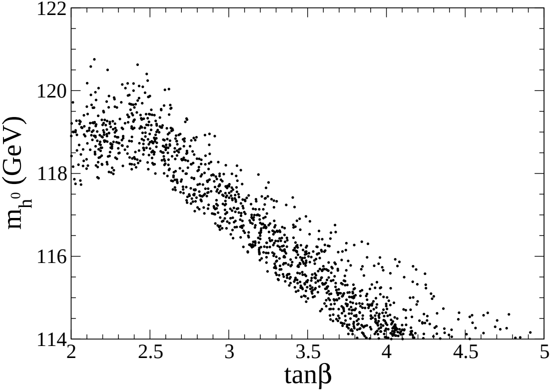


We can also plot some inputs with varying stop masses and A_t between no-mixing and max-mixing scenarios ($\tan\beta = 2$):



Key: Black = 114 GeV, Red = MSSM, Blue=S-MSSM

Finally we can vary $\tan\beta$ while sampling parameter space with $A_t = 0$:



Thus this model requires $\tan\beta \lesssim 4.5 - 5$ in order to push m_h above LEP bound.

Can models such as these be motivated?

- From a Z_{4R} or Z_{8R} symmetry

  G. Ross *et al.* have shown only two anomaly-free discrete symmetries forbid B, L-violating terms in W:

	10	$\bar{\mathbf{5}}$	H_u	H_d	S
Z_{4R}	1	1	0	0	2
Z_{8R}	1	5	0	4	6

  Under both groups, most general W is $W_{\rm SMSSM} + \kappa S^3$.

  Under Z_{8R}:

$$\frac{\mu_s}{\mu} = \frac{\kappa}{2\lambda}$$

  generating the light S-MSSM if κ is small.

Can models such as these be motivated?

- As a Froggat-Nielsen model

  Model has a softly-broken PQ symmetry when $\kappa \to 0$:

  $$PQ(\lambda) = 0; \quad PQ(\mu) = -2; \quad PQ(\mu_s) = 4; \quad PQ(\kappa) = 6$$

  Likewise for A, B-terms.

  Suppose PQ symmetry was an exact symmetry broken by a vev Θ and communicated to MSSM at a scale M where $\Theta/M \sim O(1/10)$. Then we expect:

  $$\lambda \sim 1 \gg \kappa \quad \text{and} \quad A_\lambda > \mu, B_\mu > \mu_s, B_s > A_\kappa$$

  This, plus $m_s^2 \ll \lambda^2 v^2$, is what we need for the light S-MSSM case.

Conclusions

$$\text{S-MSSM} = \left\{ \begin{array}{l} \text{Generalized NMSSM, with} \\ \text{explicit supersymmetric mass terms} \\ \text{at or near weak scale} \end{array} \right.$$

By sacrificing the solution to μ-problem, the S-MSSM:

- Eliminates tunings among parameters in NMSSM to break EW symmetry and raise Higgs mass and solve little hierarchy problem.
- Pushes the Higgs mass above LEP bound (up to 140 GeV) for wide ranges of $\mu_s \gtrsim 1$ TeV, $\tan\beta \lesssim 10$ and $m_{\tilde{t}} \gtrsim 300$ GeV.
- At LHC, singlet will not be seen, but effects will be seen through Higgs mass which is too heavy given observed SUSY spectrum.
- Embeds easily into gauge-mediated SUSY-breaking scheme, producing Higgs masses over 120 GeV for fairly generic parameters and $m_{\tilde{t}}$ as low as 350 GeV.
- For $\mu_s \ll \lambda v$, mostly-singlet scalars become lightest state but unseen at LEP. Doublet-singlet mixing is generically small, and can even raise SM-like Higgs mass. Typically pushes m_h up to 125 GeV. New light states present in model.