# Lifting the Higgs Mass in a Generalized NMSSM

## The S-MSSM & the Little Hierarchy Problem

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by A. Delgado, CK, J.P. Olson and A. del la Puente

# Model-Building Beyond the MSSM

Two major problems motivate most 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 LEP bound (114 GeV) without heavy stops ($\gtrsim$ 1 TeV) 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 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 $\mu$-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 $m_{h^0}$:

$$m_{h^0}^2 \leq m_Z^2 \cos^2 2\beta + \frac{1}{2}\lambda^2 v^2 \sin^2 2\beta$$

Several problems & constraints as a solution to LHP:

## Low $\tan\beta$ Only

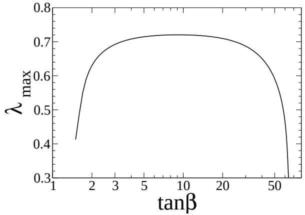
Since $\Delta m_{h^0}^2 \propto \sin^2 2\beta$, important only when $\tan\beta \simeq 1$, where in MSSM $m_{h^0} \to 0$.

## Perturbative Unification

Assuming gauge coupling unification is real, want $\lambda$ 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:

$$\mathcal{M}^2 = \begin{pmatrix} m_Z^2 \cos^2 2\beta + \frac{1}{2}\lambda^2 v^2 \sin^2 2\beta & 0 & \mathcal{M}_{13}^2 \\ - & m_{A^0}^2 & \mathcal{M}_{23}^2 \\ - & - & \mathcal{M}_{33}^2 \end{pmatrix}$$

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

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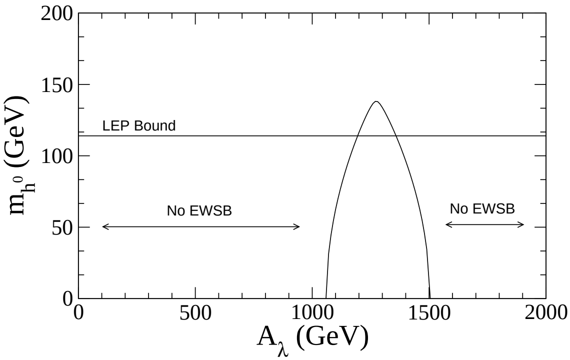
In particular,

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

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




$\Rightarrow$ $A_\lambda$ 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 $\mu$-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 $\mu, \mu_S \sim m_W$. But cleanly decouples to MSSM as $\mu_s \to \infty$.
- 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.*

# The Potential of the S-MSSM

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

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

# The Potential of the S-MSSM

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

Minimization conditions:

$$
\boxed{1} \quad \tfrac{1}{2} m_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu_{eff}^2,
$$

$$
\boxed{2} \quad \sin 2\beta = \frac{2B_{\mu,eff}}{m_{H_u}^2 + m_{H_d}^2 + 2\mu_{eff}^2 + \lambda^2 v^2}
$$

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:

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

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:

$$\mathcal{M}^2_{11} = m_Z^2 \cos^2 2\beta + \frac{1}{2}\lambda^2 v^2 \sin 2\beta$$

But:

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

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 $1/\mu_s$:

$$\begin{aligned} m^2_{A_1^0} &\simeq \frac{2B_\mu}{\sin 2\beta} + \frac{2\lambda^2 v^2}{\mu_s}\left(2A_\lambda - \frac{\mu}{\sin 2\beta}\right) \\ m^2_{A_2^0, H_2^0} &\simeq \mu_s^2 + 2\lambda^2 v^2 + m_s^2 \mp 2B_s \\ m^2_{h^0, H_1^0} &\simeq m^2_{h^0, H_1^0}\Big|_{\mathrm{MSSM}} + \frac{2\lambda^2 v^2}{\mu_s}\left(\mu \sin 2\beta - A_\lambda \mp \Delta\right) \end{aligned}$$

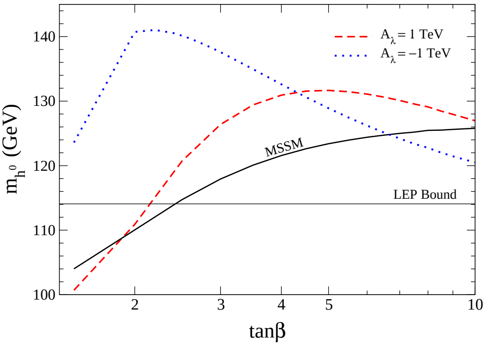
where

$$\Delta = \frac{A_\lambda (m_Z^2 - m^2_{A_1^0}) \cos^2 2\beta - \mu (m^2_{A_1^0} + m_Z^2) \sin 2\beta}{\sqrt{(m^2_{A_1^0} + m_Z^2)^2 - 4 m^2_{A_1^0} m_Z^2 \cos^2 2\beta}}$$

In Higgs decoupling limit, $m_{A^0_{1,2}} \to \infty$, mass of $h^0$ maximized:

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

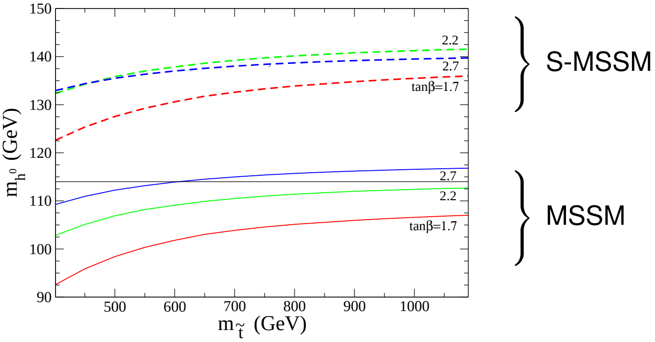
For $m_{\tilde{t}} = M_{\tilde{g}} = 2\mu = 1$ TeV, $A_t = \sqrt{6} m_{\tilde{t}}$ (max mixing), $A_\lambda = \pm 1$ TeV and $\mu_s = 2$ TeV:




- 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 $A_\lambda$ 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 $\lambda$, and MSSM contribution going to zero.

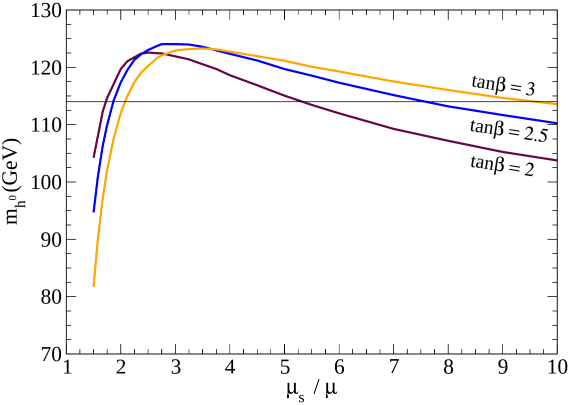
Can we bring down the stop masses?

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 $\mu_s$: ($m_{\tilde{t}_2} = 1$ 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 $\mu_s$ 2 to 4 times larger than $\mu$.
- But choice of $\mu_s$ is not very tuned – wide ranges work!

We've accomplished:

## Broken EW symmetry naturally

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

## NOT solved $\mu$-problem

Gave mass to charginos/neutralinos with explicit $\mu$-term.

## Raised the light Higgs mass

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

## 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).

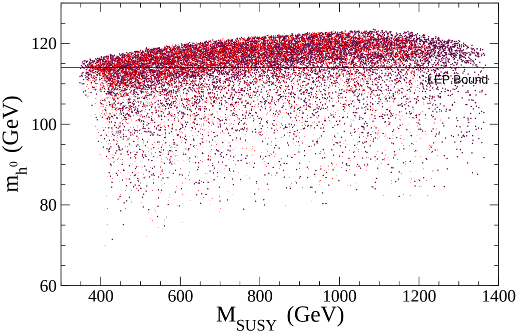
For S-MSSM soft masses:

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

We obtain $B_\mu, \mu$ from EWSB conditions

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

Random scan of parameter space:




$$2 \le \tan\beta \le 6$$
$$2 \le \mu_s/\mu \le 5$$
$$300\,\text{GeV} \le \mu \le 900\,\text{GeV}$$
$$M = 10^{10} \text{ and } 10^{13}\,\text{GeV}$$

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

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

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

# Conclusions

S-MSSM $=$ { Generalized NMSSM, with explicit supersymmetric mass terms at or near weak scale

By sacrificing the solution to $\mu$-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.
- 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.

At LHC, singlet will not be seen, but effects will be seen through Higgs mass which is too heavy given observed SUSY spectrum.