tan(\beta) Enhanced Yukawa Couplings for Supersymmetric Higgs Singlets at One-Loop

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Outline

1. SUSY Higgs Singlets
2. One Loop Singlet Couplings
3. Phenomenology
   - mnSSM Results
   - NMSSM Results
4. Conclusions
Before SUSY breaking, models are defined by their gauge symmetries and Superpotential.

The MSSM superpotential contains only the Yukawa couplings and a Higgs mass term $\mu$.

$$\mathcal{W}_{\text{MSSM}} = h_i \hat{H}_1^T i \tau_2 \hat{\ell} \hat{E} + h_d \hat{H}_1^T i \tau_2 \hat{Q} \hat{D} + h_u \hat{Q}^T i \tau_2 \hat{H}_2 \hat{U} - \mu \hat{H}_1^T i \tau_2 \hat{H}_2$$

$\mu$ should naturally be of the order of the Planck scale, but successful electroweak symmetry breaking requires it to be much smaller, of the order $M_{\text{SUSY}}$. 
Effective $\mu$ Parameter

- Introduce a new Higgs field $\hat{S}$ and replace the $\mu$ term in the superpotential with

\[ \mathcal{W} = \ldots + \lambda \hat{S} \hat{H}_1^T i \tau \hat{H}_2 \]

- An effective $\mu$ term is then generated when $\hat{S}$ develops a VEV $\nu_S$

\[ \mu = \frac{\lambda \nu_S}{\sqrt{2}} \]

- The Singlet Higgs $\hat{S}$ does not have tree level couplings to any SM fermions or gauge bosons
Breaking the Peccei-Quinn Symmetry

This new superpotential contains a Peccei-Quinn symmetry which must be broken.¹

- NMSSM: add term $+\frac{1}{3}\kappa\hat{S}^3$ to $\mathcal{W}$
- mnSSM: use non-renormalisable supergravity terms + discrete $Z^5$ or $Z^7$ R symmetry (a.k.a. nMSSM, MNSSM)
- UMSSM: additional $U(1)'$ gauge symmetry
- ...
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Dominant 1-loop Graphs

\[ \tan \beta \text{ Enhanced MSSM coupling} \]

\[ \phi_2 \]

\[ \tilde{b}_L \quad \mu h_b \quad \tilde{b}_R \]

\[ b_L \quad m_{\tilde{g}} \quad b_R \]

Dominant 1-loop Graphs

\[ \tan \beta \text{ enhanced MSSM+S coupling} \]
Dominant 1-loop Graphs

\[ \tan \beta \text{ enhanced MSSM+S coupling} \]

\[ \begin{align*}
\langle \phi_2 \rangle & \quad \phi_S \\
\tilde{b}_L & \quad \lambda h_b \quad \tilde{b}_R \\
b_L & \quad m_{\tilde{g}} \quad b_R
\end{align*} \]
$Sb\bar{b}$ Coupling

- This SQCD graph gives the dominant contribution

$$\Delta_{b}^{\phi_{S}} \approx \left(\frac{2\alpha_{S}}{3\pi}\right) \frac{M_{3}\mu}{|\text{Max}(M_{3}, M_{\tilde{Q}})|^{2}} \frac{v_{2}}{v_{S}}$$

- Shows expected $v/v_{S}$ scaling behaviour, though this is broken by subdominant terms

- A similar mechanism gives a coupling to $\tau^{+}\tau^{-}$

- This is dominated by a chargino exchange graph, giving a dominant contribution

$$\Delta_{\tau}^{\phi_{S}} \approx \left(\frac{\alpha_{W}}{4\pi}\right) \frac{\mu}{M_{2}} \frac{v_{2}}{v_{S}}$$
Effective Lagrangian

General interaction Lagrangian for down-type quarks and leptons

\[-\mathcal{L}_{\phi\bar{b}b} = \bar{f}_R h_f \left\{ \Phi_1^0 + \frac{v_1}{\sqrt{2}} \Delta_f [\Phi_1, \Phi_2, S] \right\} f_L + \text{h.c.} \]

- \(\Delta_f [\Phi_1, \Phi_2, S]\) encodes all quantum corrections
- Taking the VEV gives \(m_f\), in terms of which we express the yukawa couplings

\[h_f = \frac{g_w m_f}{\sqrt{2} M_w (1 + \langle \Delta_f \rangle) c_\beta} \]

- A Higgs Low-Energy Theorem allows us to calculate the couplings at zero momentum by taking derivatives of \(\Delta_f\)
Calculating the Couplings- Higgs Low Energy Theorems

- HLET relates correlation functions which differ by the insertion of a zero momentum Higgs boson
  \[
  \lim_{p_H \to 0} \Gamma^{HAB}(p_H, p_A, p_B) = \frac{\partial}{\partial v} \Gamma^{AB}(p_A, -p_A)
  \]

- Can calculate one-loop couplings to fermions as the first derivative (w.r.t. the Higgs field) of the fermion self energy
  \[
  \Delta^\phi_i = \frac{v c_\beta}{\sqrt{2}} \left\langle \frac{\partial \Delta_f}{\partial \phi_i} \right\rangle
  \]

Interaction Lagrangian

In terms of the Higgs mass eigenstates, 

\[ -\mathcal{L}_{\phi ff}^{\text{eff}} = \left( \frac{g_w m_f}{\sqrt{2} M_w} \right) \sum_{i=1}^{3} g_{H_i ff}^S H_i \bar{f} f + \left( \frac{g_w m_f}{\sqrt{2} M_w} \right) \sum_{j=1}^{2} g_{A_{j ff}}^P A_j (\bar{f} i \gamma^5 f) \]

with 

\[ g_{H_i ff}^S = \frac{1}{(1 + \langle \Delta_f \rangle)} \left[ \frac{O_{1i}^H}{c_\beta} + \Delta_f \phi_2 \frac{O_{2i}^H}{c_\beta} + \Delta_f \phi_S \frac{O_{3i}^H}{c_\beta} \right] \]

\[ g_{A_{j ff}}^P = \frac{1}{(1 + \langle \Delta_f \rangle)} \left[ - (t_\beta + \Delta_f a_2) \frac{O_{1j}^A}{c_\beta} + \Delta_f a_s \frac{O_{2j}^A}{c_\beta} \right] \]

- SM-normalised effective couplings
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Higgs Scalar Mixing

- The one-loop couplings are $\tan \beta$ enhanced
- Can be comparable to SM yukawa couplings
- Tree-level couplings are also enhanced
- Mixing effects through $\phi_1(a_1)$ tend to dominate unless suppressed

\[ b \quad \phi_S \quad \times \quad \phi_1 \quad \bar{b} \]
General Strategy

- Difficult to suppress $\phi_1 \leftrightarrow \phi_S$ and $\phi_2 \leftrightarrow \phi_S$ mixing simultaneously
  (Mixing proportional to $\lambda \sim (v/v_S)$)
- Mixing effects between the pseudoscalars can be easily suppressed
- Concentrate on regions of parameter space where the $A_1 \sim a_S$
- Assume $\phi_1$ heavy so that it approximately decouples
Benchmark Parameters

\[ \begin{align*}
\mu &= 110 \text{ GeV}, \\
t_\beta &= 50, \\
M_{\tilde{Q}} &= 300 \text{ GeV}, \\
M_{\tilde{L}} &= 90 \text{ GeV}, \\
M_{\tilde{t}} &= 600 \text{ GeV}, \\
M_{\tilde{b}} &= 110 \text{ GeV}, \\
M_{\tilde{\tau}} &= 200 \text{ GeV}, \\
A_t &= 1 \text{ TeV}, \\
A_b &= 1 \text{ TeV}, \\
A_\tau &= 1 \text{ TeV}, \\
M_1 &= 400 \text{ GeV}, \\
M_2 &= 600 \text{ GeV}, \\
M_3 &= 400 \text{ GeV}.
\end{align*} \]

- Light sparticles in the loops
- S enters through squark mixing, take soft trilinear couplings large
- \( \mu \) small to avoid \( v / v_S \) suppression
Light Higgs Couplings in the mnSSM

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\[ \lambda \]

\[ g_{H_{1}bb}, g_{A_{1}bb} \]

\[ H_{1}(\Delta_{b}^{\phi_{S}} = 0), H_{2}(\Delta_{b}^{\phi_{S}} = 0), A_{1} \]
Light Higgs Masses in the mnSSM

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mnSSM Summary

- Mixing between the scalar bosons rules out this scenario for $\lambda \gtrsim 0.3$
- Singlet contribution suppresses the light $H_1$ decay rate
- Can provide the dominant decay mechanism for a light singlet pseudoscalar
The NMSSM allows a light pseudoscalar in the spectrum.

This scenario has attracted interest as a low fine-tuning model.

- A light $H_1$ decays to $A_1 A_1$ pairs.
- $A_1$ is singlet dominated (>98%) for minimum fine tuning.

Requires $A_\lambda \sim O(100\text{GeV})$, $A_\kappa \sim O(5\text{GeV})$, which can be naturally arranged in gauge/gaugino mediated SUSY breaking.

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Light Higgs Couplings in the NMSSM

\[ g_{H_1^{bb}}, g_{A_1^{ff}} \]

\[ H_1(\Delta_b^S = 0), \quad A_1^{bb}, \quad A_1^{\tau\tau} \]
In the minimally fine tuned scenario decays to $b\bar{b}$ are kinematically disallowed.

Loop corrections can provide a significant contribution to the $\tau^+\tau^-$ coupling.

Heavier pseudoscalars $m_{A_1} \sim 10\text{GeV}$ are not excluded if $m_{H_1} > 110\text{GeV}$.

Corrections to the $A_1 \rightarrow b\bar{b}$ coupling can then be comparable to the tree level (mixing) contribution previously considered.
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Summary and Outlook

- The one loop singlet couplings to down-type quarks and leptons are $\tan \beta$ enhanced, which compensates for their loop suppression.
- Mixing can be small between the pseudoscalars and one loop couplings can dominate $a_S$ decay in some regions of parameter space.
- In particular, this effect should be included in studies of the NMSSM with light pseudoscalars.
- Analogous singlet contributions to FCNCs may also be significant as there is no tree-level competition.