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

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Outline

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The Minimal Supersymmetric Standard Model

- 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 μ

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

- μ 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_{SUSY}

Effective μ Parameter

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

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

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

$$\mu = \frac{\lambda v_S}{\sqrt{2}}$$

- 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]

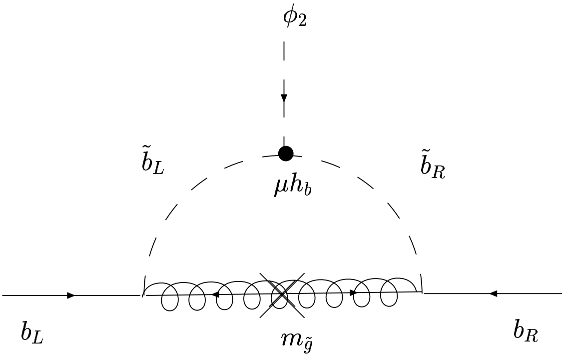
- NMSSM: add term $+\frac{1}{3}\kappa\hat{S}^3$ to $\mathcal{W}$
- mnSSM: use non-renormalisable supergravity terms + discrete Z^5 or Z^7 R symmetry
- UMSSM: additional $U(1)'$ gauge symmetry
- sMSSM: additional $U(1)'$ gauge symmetry + add $+\lambda_s\hat{S}_1\hat{S}_2\hat{S}_3$ to superpotential
- ...

[1] See E. Accomando *et al.*, arXiv: hep-ph/0608079 and references within

Outline

Dominant 1-loop Graphs

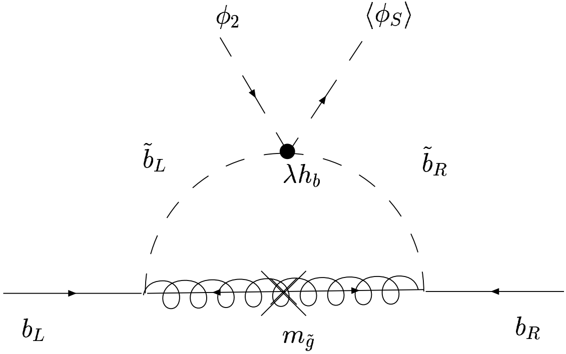
tan β Enhanced MSSM coupling [2]



[2] T. Banks, Nucl. Phys. B **303** (1988) 172;
L.J. Hall, R. Rattazzi and U. Sarid, arXiv: hep-ph/9306309

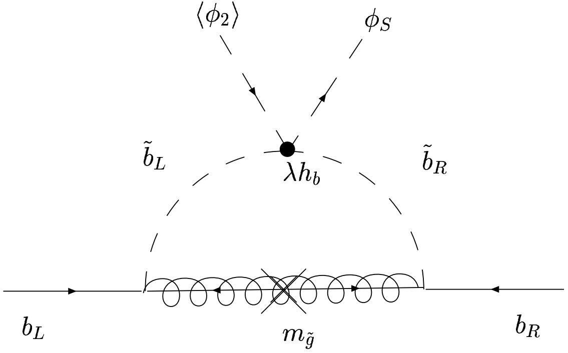
Dominant 1-loop Graphs

tan β enhanced MSSM+S coupling



Dominant 1-loop Graphs

$\tan\beta$ enhanced MSSM+S coupling



Singlet Couplings

- ϕ_2 and ϕ_S do not couple to b quarks or τs at tree level
- Loop corrections are known to produce an effective Yukawa coupling for ϕ_2 of the order $\sim h_f^{\mathrm{SM}}$ for large $\tan\beta$ [3]
- Expect a corresponding one-loop coupling for ϕ_S of the order $\sim (v/v_S)\, h_f^{SM}$

[3] eg. J.A. Coarasa, R.A. Jimenez and J. Sola, arXiv:hep-ph/9511402

Calculating the Couplings- Higgs Low Energy Theorems

- HLET relates correlation functions which differ by the insertion of a zero momentum Higgs boson[4]

$$\lim_{p_H \to 0} \Gamma^{HAB}(p_H, p_A, p_B) = \frac{\partial}{\partial v} \Gamma^{AB}(p_A, -p_A)$$

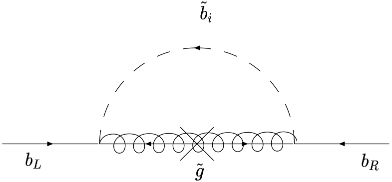
- Can calculate one-loop couplings to fermions as the first derivative (w.r.t. the Higgs field) of the fermion self energy

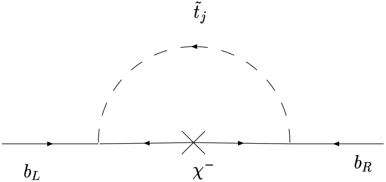
$$\Delta_f^{\phi_i} = \frac{v c_\beta}{\sqrt{2}} \left\langle \frac{\partial \Delta_f}{\partial \phi_i} \right\rangle$$

[4] eg. B.A. Kniehl and M. Spira, arXiv: hep-ph/9505225

b Quark Self Energy

- SUSY contributions well known from the MSSM [5]
- $\tan\beta$ enhanced terms from gluino-squark and chargino-squark loops





[5] eg. M. Carena, D. Garcia, U. Nierste and C.E.M. Wagner, hep-ph/9912516

$Sb\bar{b}$ Coupling

- The SQCD graph gives the dominant contribution after applying the HLET

$$\Delta_b^{\phi_S} \approx \left(\frac{2\alpha_S}{3\pi}\right) \frac{M_3\mu}{|\mathrm{Max}(M_3, M_{\tilde{Q}})|^2} \frac{v_2}{v_S}$$

- Shows expected v/v_S scaling behaviour, though this is broken by subdominant terms
- Coupling to $\tau^+\tau^-$ pairs can be calculated in the same way, 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

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

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

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

Interaction Lagrangian

In terms of the Higgs mass eigenstates,

$$-\mathcal{L}^{\mathrm{eff}}_{\phi\bar{f}f} = \left(\frac{g_W m_f}{\sqrt{2}M_W}\right)\sum_{i=1}^{3} g^S_{H_i ff} H_i \bar{f} f + \left(\frac{g_W m_f}{\sqrt{2}M_W}\right)\sum_{j=1}^{2} g^P_{A_j ff} A_j \left(\bar{f} i\gamma^5 f\right)$$

with

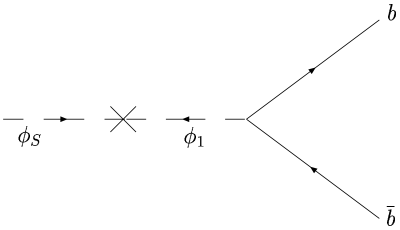
$$g^S_{H_i ff} = \frac{1}{(1+\langle\Delta_f\rangle)}\left[\frac{O^H_{1i}}{c_\beta} + \Delta_f^{\phi_2}\frac{O^H_{2i}}{c_\beta} + \Delta_f^{\phi_S}\frac{O^H_{3i}}{c_\beta}\right]$$

$$g^P_{A_j ff} = \frac{1}{(1+\langle\Delta_f\rangle)}\left[-\left(t_\beta + \Delta_f^{a_2}\right) O^A_{1j} + \Delta_f^{a_S}\frac{O^A_{2j}}{c_\beta}\right]$$

Outline

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



General Strategy

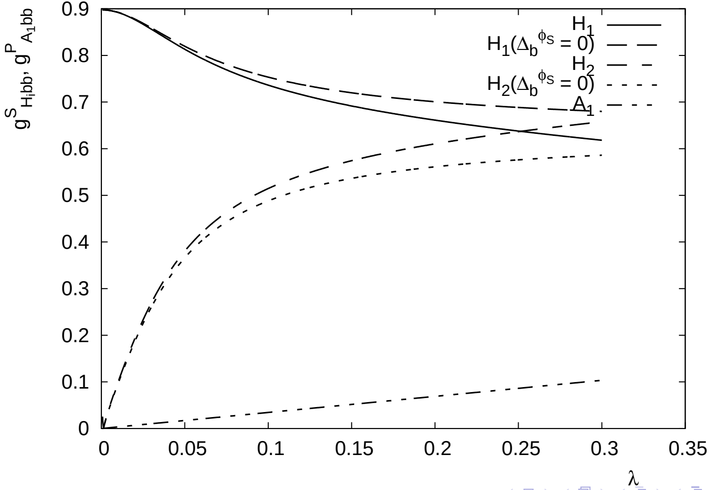
- Difficult to suppress $\phi_1 \leftrightarrow \phi_S$ and $\phi_2 \leftrightarrow \phi_S$ mixing simultaneously
- Mixing effects between the pseudoscalars can be easily suppressed
- Concentrate on regions of parameter space where the $A_1 \sim a_S$
- Assume ϕ_1 heavy so that it approximately decouples

Benchmark Parameters

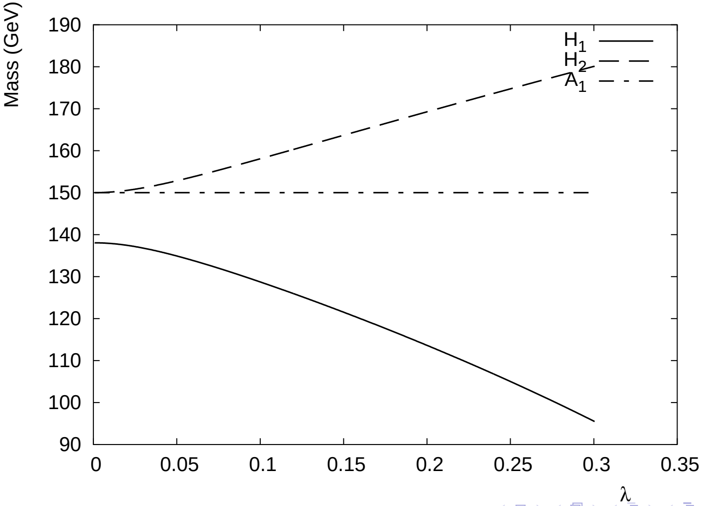
$$\begin{array}{lll} \mu = 110\,\mathrm{GeV}, & t_\beta = 50, & \\ M_{\tilde{Q}} = 300\,\mathrm{GeV}, & M_{\tilde{L}} = 90\,GeV, & \\ M_{\tilde{t}} = 600\,\mathrm{GeV}, & M_{\tilde{b}} = 110\,\mathrm{GeV}, & M_{\tilde{\tau}} = 200\,\mathrm{GeV}, \\ A_t = 1\,\mathrm{TeV}, & A_b = 1\,\mathrm{TeV}, & A_\tau = 1\,\mathrm{TeV}, \\ M_1 = 400\,\mathrm{GeV}, & M_2 = 600\,\mathrm{GeV}, & M_3 = 400\,\mathrm{GeV}\,. \end{array}$$

- Light sparticles in the loops
- S enters through squark mixing, take soft trilinear couplings large
- μ small to avoid v/v_S suppression

Light Higgs Couplings in the mnSSM



Light Higgs Masses in the mnSSM



mnSSM Summary

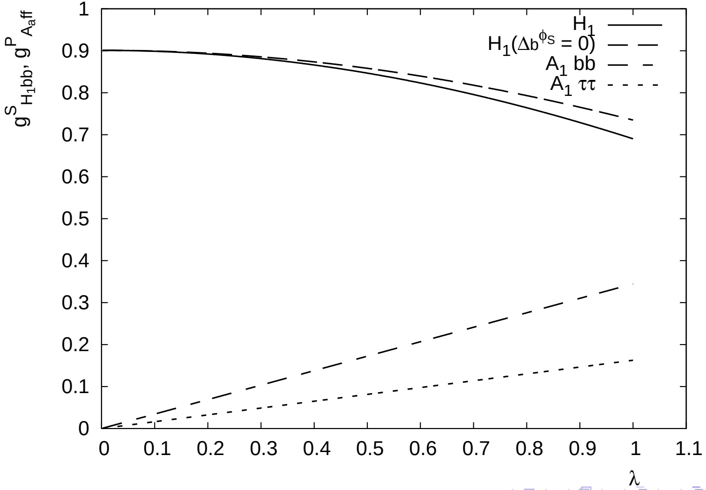
- Mixing between the scalar bosons rules out this scenario for $\lambda \gtrsim 0.3$
- Singlet contribution suppresses the light H_1 decay rate
- Can provide the dominant decay mechanism for a light singlet psuedoscalar

NMSSM mass spectrum

- The NMSSM allows a light pseudoscalar in the spectrum
- This has recently attracted attention as an "invisible Higgs" scenario
- A light Higgs decays to $A_1 A_1$ pairs
- A_1 thought to decay into photons if singlet dominated

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

Light Higgs Couplings in the NMSSM



NMSSM summary

- Both $A_1 \to b\bar{b}$ and $A_1 \to \tau^+\tau^-$ channels can be significant even in the zero mixing limit
- Hadronic decays can not be neglected in the "invisible Higgs" scenario

Outline

1. SUSY Higgs Singlets
2. One Loop Singlet Couplings
   - $\tan\beta$ Enhanced Graphs
   - General Effective Lagrangian
3. Phenomenology
   - mnSSM Results
   - NMSSM Results
4. Conclusions

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 particular, this effect should be included in studies of the NMSSM "invisible Higgs" scenario
- Analogous singlet contribution to FCNCs may be significant as there is no tree-level competition