Supersymmetric Higgs singlet effects on FCNC observables

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- RNH,A.Pilaftsis : in preparation

Outline

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The MSSM Superpotential

- The interactions of the MSSM are determined by the gauge structure and the superpotential.

$$\mathcal{W}_{\mathrm{MSSM}} = \mathbf{h}_e \hat{L}\hat{E}\hat{H}_1 + \mathbf{h}_d \hat{Q}\hat{D}\hat{H}_1 + \mathbf{h}_u \hat{Q}\hat{U}\hat{H}_2 + \mu \hat{H}_1\hat{H}_2$$

- Successful electroweak symmetry breaking requires $\mu \sim M_{\mathrm{SUSY}}$
- However, μ is a superpotential parameter unconnected to SUSY-breaking
- Should naturally be of the order M_{GUT} or M_{Planck}

Singlet Higgs Superfields

- This μ-problem can be aleviated by introducing a gauge-singlet Higgs superfield $\hat{S}$ and modifying the superpotential to

$$\mathcal{W}_{\mathrm{MSSM+S}} = \mathcal{W}_{\mathrm{Yuk}} + \lambda \hat{S} \hat{H}_1 \hat{H}_2$$

- An effective μ term is generated at the SUSY-breaking scale when S takes a VEV

$$\mu_{\mathrm{eff}} = \frac{\lambda v_S}{\sqrt{2}}$$

- The singlet Higgs boson S has no tree level couplings to any Standard Model fermions or gauge bosons

Peccei-Quin Symmetry Breaking

- This modified superpotential has a $U(1)_{\rm PQ}$ symmetry

	$U(1)_{\rm PQ}$
$\hat{Q},\ \hat{U},\ \hat{D},\ \hat{L},\ \hat{E}$	$-\frac{1}{2}$
$\hat{H}_1,\ \hat{H}_2$	1
$\hat{S}$	-2

- $U(1)_{\rm PQ}$ is spontaneously broken by the VEV of S, leading to an electroweak-scale axion
- Explicit mechanisms of $U(1)_{\rm PQ}$ breaking distinguish several models in the literature [1]

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

The Next-to-Minimal SSM

- The Next-to-Minimal SSM is based on the superpotential

$$\mathcal{W}_{\rm NMSSM} = \mathcal{W}_{\rm Yuk} + \lambda \hat{S}\hat{H}_1\hat{H}_2 + \kappa \hat{S}^3$$

- Also have the corresponding soft trilinear couplings A_λ, A_κ
- κ breaks $U(1)_{\rm PQ}$ to a discrete Z_3 subgroup
- Possible problems with cosmic domain walls [2]

[2] S.A. Abel, S. Sarkar, P.L. White, arXiv: hep-ph/9506359

The Minimal Non-minimal SSM

- The Minimal Non-minimal SSM is based on the superpotential

$$\mathcal{W}_{\rm mnSSM} = \mathcal{W}_{\rm Yuk} + \lambda \hat{S}\hat{H}_1\hat{H}_2 + t_F\hat{S}$$

- Also have the soft trilinear A_λ and soft tadpole t_S.
- The tadpole terms are generated by supergravity effects [3]
- These are suppressed to the six- or seven-loop level by imposing a discrete R-symmetry Z_5^R or Z_7^R.

[3] C. Panagiotakopoulos, A. Pilaftsis, arXiv: hep-ph/0008268

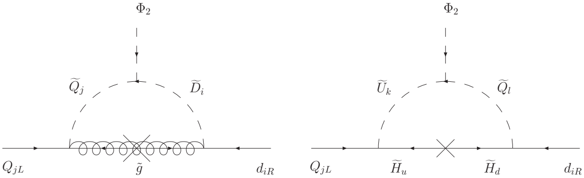
Light Higgs singlet pseudoscalars

- If $U(1)_{\mathrm{PQ}}$ is only weakly broken a_S is a pseudo-Goldstone boson
- A_1 can be very light and predominantly singlet in either model as we approach this limit
- The mnSSM obeys a tree-level mass-sum rule so that the light pseudoscalar is always accompanied by a quasi-degenerate light scalar
- Within the NMSSM, ϕ_S remains heavy

Outline

$\tan\beta$-Enhanced threshold corrections

- Inhomogeneous Yukawa couplings of down-type quarks and leptons become enhanced at large values of $\tan\beta$ in the MSSM [4]



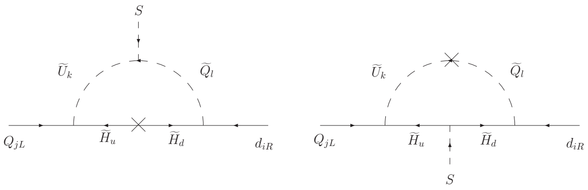
- Analogous graphs for the Higgs singlet are also $\tan\beta$-enhanced in the NMSSM and mnSSM [5]

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

[5] RNH, A. Pilaftsis, arXiv: hep-ph/0612188

Flavour Changing Higgs singlet Yukawa couplings

- Direct flavour-changing interactions are generated at one-loop [6]



[6] G. Hiller, arXiv: hep-ph/0404220

Effective Lagrangian

- We write the general interaction between the Higgs bosons and down-type quarks using an effective Lagrangian approach

$$-\mathcal{L}^{d}_{\rm eff}[\Phi_1,\Phi_2,S] = \bar{d}^0_{iR}\mathbf{h}_d\left(\Phi_1^{\dagger} + \Delta_d[\Phi_1,\Phi_2,S]\right)_{ij} Q^0_{jL} + \mathrm{h.c.}$$

- $\Delta_d[\Phi_1,\Phi_2,S]$ is a Coleman-Weinberg-type functional of the background Higgs fields [7]

[7] J. Ellis, J.S. Lee, A. Pilaftsis, arXiv: 0708.2079, Plenary talk by A. Pilaftsis

Self Energy and Yukawa Interactions

- VEV of previous expression allows us to express h_d in terms of M_d

$$\mathbf{h}_d = \frac{\sqrt{2}}{v_1}\widehat{\mathbf{M}}_d \mathbf{V}^\dagger \, \mathbf{R}^{-1}, \quad \mathbf{R} = \mathbf{1} + \frac{\sqrt{2}}{v_1} \left\langle \Delta_d \right\rangle$$

- One-loop Yukawa interactions given by derivatives (HLET) [8]

$$\Delta_d^{\phi_{2,S}} = \sqrt{2} \left\langle \frac{\delta}{\delta \phi_{2,S}} \Delta_d \right\rangle$$

$$\Delta_d^{a_{2,S}} = i \, \sqrt{2} \left\langle \frac{\delta}{\delta a_{2,S}} \Delta_d \right\rangle$$

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

Single-Higgs-Insertion Approximation

- We can approximate the dominant quantum corrections by

$$\Delta_d = \frac{\mathbf{h}_u^\dagger \mathbf{h}_u}{16\pi^2} \frac{A_u}{\widetilde{M}_Q^2} \lambda S^* \Phi_2^\dagger$$

- Approximation assumes Minimal Flavour Violation
- Leads to:

$$\Delta_d^{\phi_S} = \Delta_d^{a_S} = \frac{v_2}{v_S} \Delta_d^{\phi_2} = \frac{v_2}{v_S} \Delta_d^{a_2}$$

Interaction Lagrangian

- The interaction Lagrangian describing the Higgs couplings to down-type fermions is written as

$$-\mathcal{L}_{\rm FC} = \frac{g_2}{2M_W}\Big[H_i\bar{d}_R\left(\widehat{\mathbf{M}}_d\ \mathbf{g}^L_{H_i\bar{d}d}P_L + \mathbf{g}^R_{H_i\bar{d}d}\ \widehat{\mathbf{M}}_d P_R\right)d + A_j\bar{d}_R\left(\widehat{\mathbf{M}}_d\ \mathbf{g}^L_{A_j\bar{d}d}P_L + \mathbf{g}^R_{A_j\bar{d}d}\ \widehat{\mathbf{M}}_d P_R\right)d\Big] \qquad (1)$$

- The Higgs boson mass eigenstates H_i, A_j are given in terms of the weak eigenstates by

$$\phi_i = O^H_{ij}H_j,\ a_i = O^A_{ij}A_j$$

Effective Yukawa couplings

- The Yukawa couplings are given by

$$
\begin{aligned}
\mathbf{g}^L_{H_i\bar{d}d} &= \mathbf{V}^\dagger \mathbf{R}_d^{-1} \left(\frac{\mathcal{O}^H_{1i}}{c_\beta} + \frac{\mathcal{O}^H_{2i}}{c_\beta} \Delta_d^{\phi_2} + \frac{\mathcal{O}^H_{3i}}{c_\beta} \Delta_d^{\phi_S} \right) \mathbf{V} \,, \\
\mathbf{g}^R_{H_i\bar{d}d} &= \left(\mathbf{g}^L_{H_i\bar{d}d} \right)^\dagger \,, \\
\mathbf{g}^L_{A_i\bar{d}d} &= i\, \mathbf{V}^\dagger \mathbf{R}_d^{-1} \left(\mathcal{O}^A_{1i} t_\beta \left(\mathbf{1} - \frac{1}{t_\beta} \Delta_d^{a_2} \right) + \frac{\mathcal{O}^A_{2i}}{c_\beta} \Delta_d^{a_S} \right) \mathbf{V} \,, \\
\mathbf{g}^R_{A_i\bar{d}d} &= \left(\mathbf{g}^L_{A_i\bar{d}d} \right)^\dagger \,,
\end{aligned}
$$

Double-penguin contributions

- The additional singlet Higgs fields contribute to observables such as $B_q - \bar{B}_q$ mixing and $\bar{B}_q \rightarrow \mu^+\mu^-$
- No charged component- observables such as $B \rightarrow X_s\gamma$ unchanged from MSSM predictions[9]

[9] A.J. Buras, P.H. Chankowski, J. Rosiek, L. Slawianowska,arXiv: hep-ph/0107048

B-physics Observables

ΔM_{B_q}

$$C_1^{\mathrm{SLL(DP)}} \sim \frac{m_b^2}{M_W^2}\left(\sum_{i=1}^{3}\frac{\mathbf{g}^L_{H_i\bar{b}q}\mathbf{g}^L_{H_i\bar{b}q}}{M_{H_i}^2}+\sum_{j=1}^{2}\frac{\mathbf{g}^L_{A_j\bar{b}q}\mathbf{g}^L_{A_j\bar{b}q}}{M_{A_j}^2}\right)$$

$$C_2^{\mathrm{LR(DP)}} \sim \frac{m_b m_q}{M_W^2}\left(\sum_{i=1}^{3}\frac{|\mathbf{g}^L_{H_i\bar{b}q}|^2}{M_{H_i}^2}+\sum_{j=1}^{2}\frac{|\mathbf{g}^L_{A_j\bar{b}q}|^2}{M_{A_j}^2}\right)$$

$\bar{B}_q \to \mu^+\mu^-$

$$|C_S|^2 \sim \left|\sum_{i=1}^{3}\frac{\mathbf{g}^R_{H_i\bar{q}b}\mathbf{g}^S_{H_i\bar{\mu}\mu}}{M_{H_i}^2}\right|^2 \quad |C_P|^2 \sim \left|\sum_{j=1}^{2}\frac{\mathbf{g}^L_{A_j\bar{q}b}\mathbf{g}^P_{A_j\bar{\mu}\mu}}{M_{A_j}^2}\right|^2$$

Outline

Common parameters

- We assume MFV
- Strong constraints from $B \to X_s\gamma$ calculated using CPsuperH for corresponding MSSM parameters

We take

$$\widetilde{M}_Q^2 = \widetilde{M}_U^2 = \widetilde{M}_D^2 = \widetilde{M}_L^2 = \widetilde{M}_E^2 = (1.7\mathrm{TeV})^2$$
$$A_u = A_d = A_e = 2.0\mathrm{TeV}$$
$$M_1 = M_2 = M_3 = 2.0\mathrm{TeV}$$

- Also $\mu = 140$ GeV and $t_\beta = 50$ throughout

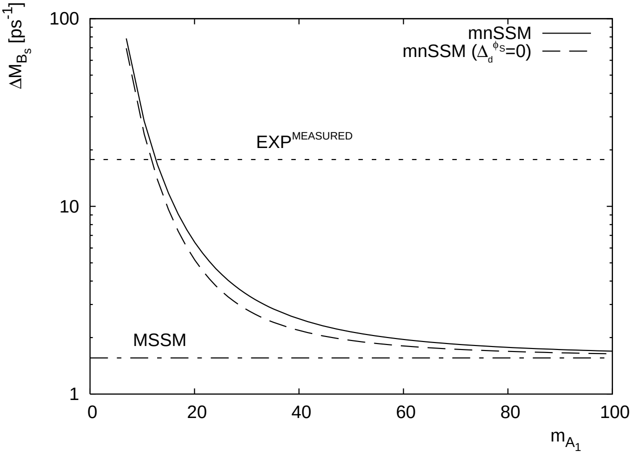
mnSSM Parameters

- tree-level mnSSM Higgs sector depends on four parameters in addition to μ and t_β

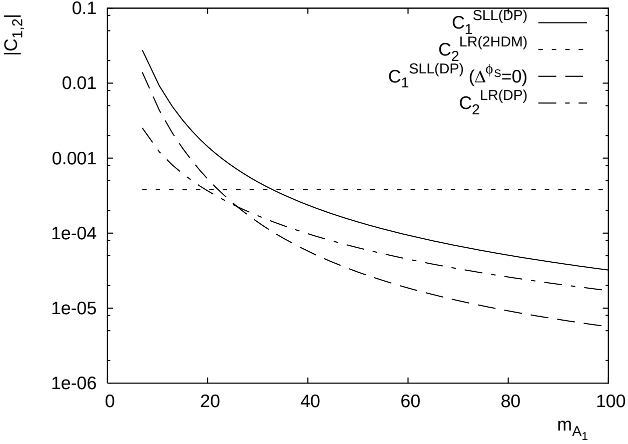
$$M_a = 1.5\ \mathrm{TeV}, \quad m_{12}^2 = (1.0\ \mathrm{TeV})^2, \quad \lambda = 0.3$$

- We allow $t_S \sim m_{a_S}^2 \sim m_{\phi_S}^2$ to vary
- With these parameters the Higgs pseudoscalar mixing angle is approximately $\cos\theta_A = O_{21}^A \sim 0.17$

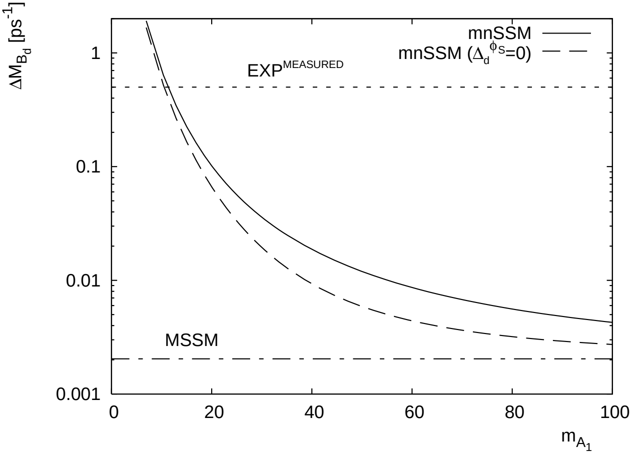
mnSSM-ΔM_{B_S}



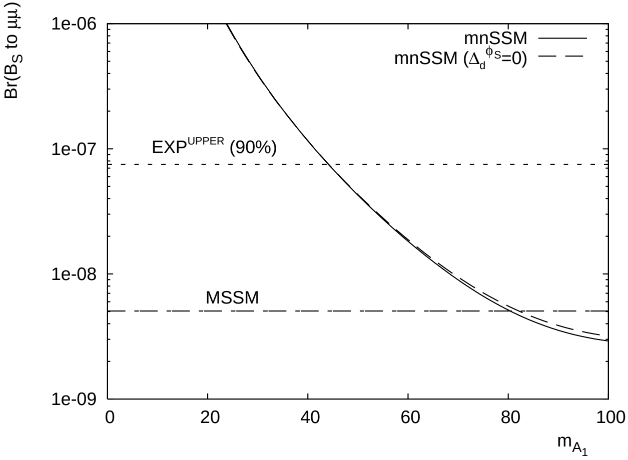
mnSSM-ΔM_{B_s}-Wilson Coefficients



mnSSM-ΔM_{B_d}



mnSSM-Br($B_S \to \mu^+\mu^-$)



NMSSM parameters

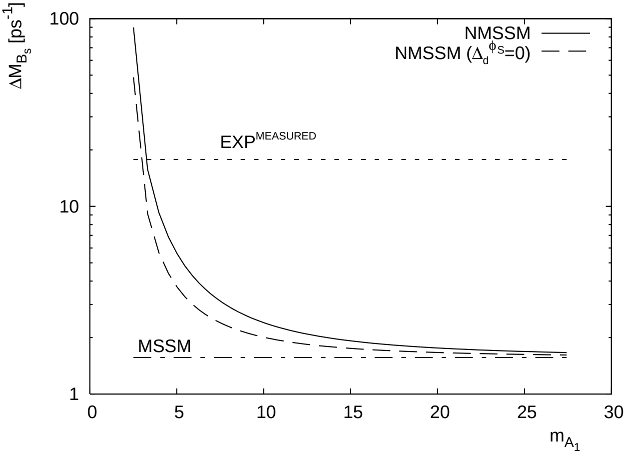
- Also depends on four parameters $+\mu,\ t_\beta$
- Singlet scalar/pseudoscalar not constrained to be quasi-degenerate
- No cancellation- require much smaller singlet-doublet mixing

We fix:

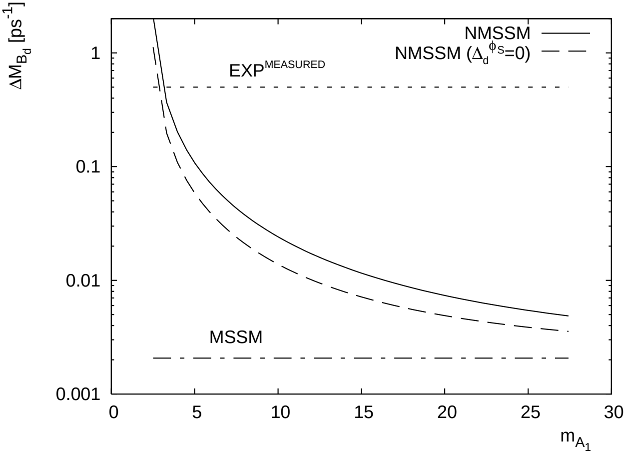
$$\lambda = 0.4, \quad \kappa = -0.5, \quad \cos\theta_A = 0.018$$

- Vary m_{A_1}

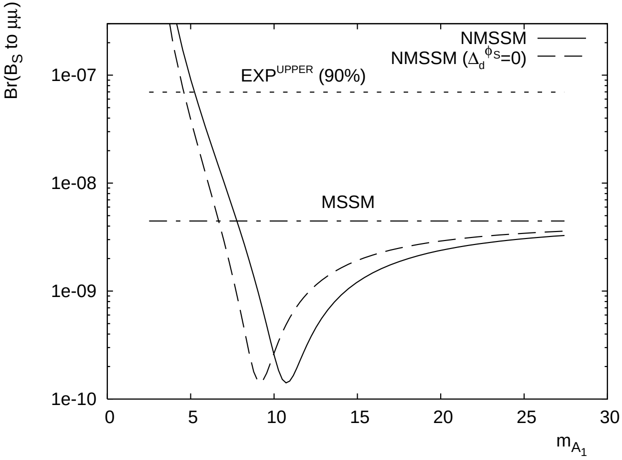
NMSSM-ΔM_{B_S}



NMSSM-ΔM_{B_d}



NMSSM-Br($B_S \to \mu^+\mu^-$)



Outline

Summary and Outlook

- Light Higgs singlet superfields can play a significant role on FCNC observables for large $\tan\beta$
  -the direct coupling is important
- mnSSM and NMSSM have very different phenomenology in this limit due to the tree-level mass sum rule of the mnSSM
- Additional sources of CP-violation amongst the soft SUSY-breaking parameters may further highlight this difference