Supersymmetric Higgs singlet effects on FCNC observables

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RNH,A.Pilaftsis : in preparation
Outline

1. Gauge Singlet Superfields
2. Higgs boson FCNCs
3. Numerical Results
   - mnSSM
   - NMSSM
4. Conclusions
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The MSSM Superpotential

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

\[ \mathcal{W}_{\text{MSSM}} = h_e \hat{L} \hat{E} \hat{H}_1 + h_d \hat{Q} \hat{D} \hat{H}_1 + h_u \hat{Q} \hat{U} \hat{H}_2 + \mu \hat{H}_1 \hat{H}_2 \]

- Successful electroweak symmetry breaking requires \( \mu \sim M_{\text{SUSY}} \)
- However, \( \mu \) is a superpotential parameter unconnected to SUSY-breaking
- Should naturally be of the order \( M_{\text{GUT}} \) or \( M_{\text{Planck}} \)
Singlet Higgs Superfields

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

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

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

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

The singlet Higgs boson $S$ has no tree level couplings to any Standard Model fermions or gauge bosons.
This modified superpotential has a $U(1)_{\text{PQ}}$ symmetry

\[
\begin{array}{c|c}
\hat{Q}, \hat{U}, \hat{D}, \hat{L}, \hat{E} & U(1)_{\text{PQ}} \\
\hat{H}_1, \hat{H}_2 & -\frac{1}{2} \\
\hat{S} & 1 \\
\end{array}
\]

$U(1)_{\text{PQ}}$ is spontaneously broken by the VEV of $S$, leading to an electroweak-scale axion.

Explicit mechanisms of $U(1)_{\text{PQ}}$ 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

\[ \mathcal{W}_{\text{NMSSM}} = \mathcal{W}_{\text{Yuk}} + \lambda \hat{S} \hat{H}_1 \hat{H}_2 + \kappa \hat{S}^3 \]

- Also have the corresponding soft trilinear couplings $A_\lambda, A_\kappa$
- $\kappa$ breaks $U(1)_{\text{PQ}}$ to a discrete $Z_3$ subgroup
- Possible problems with cosmic domain walls \(^2\)

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The Minimal Non-minimal SSM

The Minimal Non-minimal SSM is based on the superpotential

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

- Also have the soft trilinear $A_\lambda$ 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 $Z_7^R$.

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Light Higgs singlet pseudoscalars

- If $U(1)_{PQ}$ 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, $\phi_S$ remains heavy
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Inhomogeneous Yukawa couplings of down-type quarks and leptons become enhanced at large values of $\tan \beta$ in the MSSM\textsuperscript{4}

\begin{equation}
\begin{aligned}
Q_jL & \xrightarrow{g} \Phi_2 \\
\tilde{Q}_j & \xrightarrow{\tilde{g}} \tilde{D}_i \\
\bar{d}_R & \xrightarrow{\Phi_2} Q_jL
\end{aligned}
\end{equation}

Analogous graphs for the Higgs singlet are also $\tan \beta$-enhanced in the NMSSM and mnSSM\textsuperscript{5}


\textsuperscript{5}RNH, A. Pilaftsis, arXiv: hep-ph/0612188
Direct flavour-changing interactions are generated at one-loop \(^6\)

\[ \tilde{U}_k \tilde{H}_u \tilde{H}_d \tilde{Q}_l \]

\[ \tilde{U}_k \tilde{H}_u \tilde{H}_d \tilde{Q}_l \]

\[ Q_{jL} \tilde{H}_u \tilde{H}_d \tilde{Q}_l \]

\[ Q_{jL} \tilde{H}_u \tilde{H}_d \tilde{Q}_l \]

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

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

\( \Delta_d[\Phi_1, \Phi_2, S] \) 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 $M_d$

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

- One-loop Yukawa interactions given by derivatives (HLET)

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

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

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Single-Higgs-Insertion Approximation

- We can approximate the dominant quantum corrections by

\[ \Delta_d = \frac{h_u^\dagger h_u}{16\pi^2} \frac{A_u}{\tilde{M}_Q^2} \lambda S^* \Phi_2^\dagger \]

- Approximation assumes Minimal Flavour Violation
- Leads to:

\[ \Delta_{d^S} = \Delta_{d^s} = \frac{v_2}{v_S^2} \Delta_{d^2} = \frac{v_2}{v_S} \Delta_{a^2} \]
The interaction Lagrangian describing the Higgs couplings to down-type fermions is written as

\[-\mathcal{L}_{FC} = \frac{g_2}{2M_W} \left[ H_\ddbar \left( \hat{M}_d g^L_{H_\ddbar \ddbar} P_L + g^R_{H_\ddbar \ddbar} \hat{M}_d P_R \right) \dd + A_j \ddbar \left( \hat{M}_d g^L_{A_j \ddbar \ddbar} P_L + g^R_{A_j \ddbar \ddbar} \hat{M}_d P_R \right) \dd \right] \quad (1)\]

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

$$\phi_i = O^{H}_{ij} H_j, \quad a_i = O^{A}_{ij} A_j$$
Effective Yukawa couplings

The Yukawa couplings are given by

\[
\begin{align*}
g_{H_i\bar{d}d}^L &= V^\dagger R_d^{-1} \left( \frac{O_{H1i}^1}{c_\beta} + \frac{O_{H2i}^2}{c_\beta} \Delta_{d}^{\phi_2} + \frac{O_{H3i}^3}{c_\beta} \Delta_{d}^{\phi_s} \right) V, \\
g_{H_i\bar{d}d}^R &= \left( g_{H_i\bar{d}d}^L \right)^\dagger, \\
g_{A_i\bar{d}d}^L &= i V^\dagger R_d^{-1} \left( O_{A1i}^1 t_\beta \left( 1 - \frac{1}{t_\beta} \Delta_{d}^{a_2} \right) + \frac{O_{A2i}^2}{c_\beta} \Delta_{d}^{a_s} \right) V, \\
g_{A_i\bar{d}d}^R &= \left( g_{A_i\bar{d}d}^L \right)^\dagger,
\end{align*}
\]
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\(^9\)

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B-physics Observables

$$\Delta M_{Bq}$$

$$C_{1}^{SLL(DP)} \sim \frac{m_{b}^{2}}{M_{W}^{2}} \left( \sum_{i=1}^{3} \frac{g_{H_{i} \bar{b}q}^{L} g_{H_{i} \bar{b}q}^{L}}{M_{H_{i}}^{2}} + \sum_{j=1}^{2} \frac{g_{A_{j} \bar{b}q}^{L} g_{A_{j} \bar{b}q}^{L}}{M_{A_{j}}^{2}} \right)$$

$$C_{2}^{LR(DP)} \sim \frac{m_{b} m_{q}}{M_{W}^{2}} \left( \sum_{i=1}^{3} \frac{|g_{H_{i} \bar{b}q}^{L}|^{2}}{M_{H_{i}}^{2}} + \sum_{j=1}^{2} \frac{|g_{A_{j} \bar{b}q}^{L}|^{2}}{M_{A_{j}}^{2}} \right)$$

$$\bar{B}_{q} \rightarrow \mu^{+} \mu^{-}$$

$$|C_{S}|^{2} \sim \left| \sum_{i=1}^{3} \frac{g_{H_{i} \bar{q}b}^{R} g_{H_{i} \bar{\mu} \mu}^{S}}{M_{H_{i}}^{2}} \right|^{2}$$

$$|C_{P}|^{2} \sim \left| \sum_{j=1}^{2} \frac{g_{A_{j} \bar{q}b}^{L} g_{A_{j} \bar{\mu} \mu}^{P}}{M_{A_{j}}^{2}} \right|^{2}$$
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Common parameters

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

We take

$$\tilde{M}_Q^2 = \tilde{M}_U^2 = \tilde{M}_D^2 = \tilde{M}_L^2 = \tilde{M}_E^2 = (1.7\text{TeV})^2$$

$$A_u = A_d = A_e = 2.0\text{TeV}$$

$$M_1 = M_2 = M_3 = 2.0\text{TeV}$$

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

- tree-level mnSSM Higgs sector depends on four parameters in addition to $\mu$ and $t_\beta$

\[ M_a = 1.5 \text{ TeV}, \quad m_{12}^2 = (1.0 \text{ TeV})^2, \quad \lambda = 0.3 \]

- 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-$\Delta M_{BS}$

![Graph showing $\Delta M_{BS}$ vs. $m_{A_1}$ for different models and measurements.](image)

- **mnSSM**
- **mnSSM ($\Delta d_{S}=0$)**
- **EXP MEASURED**
- **MSSM**
mnSSM-\(\Delta M_{BS}\)-Wilson Coefficients

\[ |C_{1,2}| \]

\[ m_{A_1} \]

\[ 0 \] \[ 20 \] \[ 40 \] \[ 60 \] \[ 80 \] \[ 100 \]

\[ 1e-06 \] \[ 1e-05 \] \[ 1e-04 \] \[ 0.001 \] \[ 0.01 \] \[ 0.1 \]
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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-$\Delta M_{B_S}$
NMSSM-$\Delta M_{B_d}$

![Graph showing the dependence of $\Delta M_{B_d}$ on $m_{A_1}$ for different models.](image)

- NMSSM
- NMSSM ($\Delta \phi_S=0$)
- MSSM
- EXP$^\text{MEASURED}$

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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