Discarding a 125.5 GeV heavy Higgs in an MSSM model with explicit CP-violation

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Eviction of a 125 GeV “heavy”-Higgs from the MSSM
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Theoretical Considerations

MSSM SUSY with CP violation in Higgs sector

- Higgs sector consisting of three neutral bosons (mixed scalar and pseudoscalar nature) and charged Higgs bosons.
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- We test models with a light Higgs between $90 \text{ GeV} \leq m_{H_1} \leq 110 \text{ GeV}$, and a second Higgs, in order of increasing mass, which corresponds to the experimental measurement of $m_{H_2} = 125.5 \text{ GeV}$. 
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- One-loop corrections to the scalar potential give rise to phases in the Lagrangian, causing CP violation and the mixing in the Higgs spectrum.

\[
\Phi_1 = \left( \frac{1}{\sqrt{2}} (v_1 + \phi_1 + i a_1) \right) ; \quad \Phi_2 = e^{i \xi} \left( \frac{1}{\sqrt{2}} (v_2 + \phi_2 + i a_2) \right) \\
a = a_1 \sin \beta + a_2 \cos \beta \\
M_H^2 = \begin{pmatrix} M_S^2 & M_{SP}^2 \\ M_{PS}^2 & M_P^2 \end{pmatrix}
\]
Theoretical Considerations

MSSM SUSY with CP violation in Higgs sector

- The parameters that define the Higgs sector are $m_{H^\pm}$ and $\tan \beta \equiv \frac{v_2}{v_1}$ (other parameters of our model are $\mu, A_t, \alpha(A_t), M_{SUSY}, M_2$ and the Higgs mixing matrix).
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- $m_{H^\pm}$ relates to the pseudoscalar Higgs mass matrix element $M_P^2$ as follows:

$$m_{H^\pm}^2 = M_P^2 + \frac{1}{2} \lambda_4 v^2 - Re(\lambda_5 e^{2i\xi})v^2$$
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- We consider the following upper limit for the third neutral scalar: $m_{H_3} \lesssim 200$ GeV.
Experimental bounds on SUSY particles

- Neutralino is mostly excluded below 500 GeV, whilst gluino masses are excluded up to 1.3 TeV.

- $m_{\tilde{t}}$ is bound to a low limit of 650 GeV except for certain conditions (degenerate stop-neutralino, lower bounded to 250 GeV).
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Scalar signal at $m=125.5$ GeV in the diphoton channel.

Current data puts the excess in the range $0.9 \leq \mu_{\gamma\gamma}^{LHC} \leq 1.5$. 
LHC Higgs Data: diphoton channel

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Diphoton channel in our MSSM model

- Decay width:

\[ \Gamma(H_i \rightarrow \gamma\gamma) = \frac{M_{H_i}^3 \alpha^2}{256\pi^3 v^2} \left[ |S_i^\gamma(M_{H_i})|^2 + |P_i^\gamma(M_{H_i})|^2 \right] \]
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- Contributions to the pseudoscalar part: \( q, \bar{q}, \tilde{\chi}_i^\pm \).
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- Contributions to the scalar part: $q, \bar{q}, W, \tilde{\chi}_i^\pm, H^\pm$.

- Contributions to the pseudoscalar part: $q, \bar{q}, \tilde{\chi}_i^\pm$.

- Higgs production (bb-fusion relevant for medium-high $\tan \beta$):

\[
\sigma(pp \rightarrow H_i) = K \delta_{gg \rightarrow H_i}^{LO} \tau_{H_i} \frac{d\mathcal{L}_{gg}^{LO}}{d\tau_{H_i}} + \delta_{bb \rightarrow H_i}^{QCD} \tau_{H_i} \frac{d\mathcal{L}_{bb}^{LO}}{d\tau_{H_i}}
\]
Analysis \((H_i \rightarrow \gamma\gamma)\)

- Contribution Approximations (scalar):
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  - W-boson: \(S_{HiW}^\gamma = -(\mathcal{U}_{i1} \cos \beta + \mathcal{U}_{i2} \sin \beta) F_1(\tau_{iW}); \quad \tau_{ij} = \frac{M_{H_i}^2}{4m_j}; \quad F_1(\tau_{hW}) \approx 8\)
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  - Top quark: \(S_{H_i,t}^\gamma = \frac{8}{3}u_{i2}F_t^S(\tau_{it})\)
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  - Top quark: $S_{H_it}^\gamma = \frac{8}{3} \mathcal{U}_{i2} F_t^S(\tau_{it})$
  - Bottom quark: $S_{H_ib}^\gamma = \frac{2}{3} \left( \text{Re} \left\{ \frac{\mathcal{U}_{i1} + \mathcal{U}_{i2} \kappa_d}{1 + \kappa_d \tan \beta} \right\} \tan \beta + \text{Im} \left\{ \frac{\kappa_d(1 + \tan^2 \beta)}{1 + \kappa_d \tan \beta} \right\} \right) \mathcal{U}_{i3} F_b^S(\tau_{ib})$
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  - **Quarks combined:** \(S_{H_i,t+b}^\gamma \approx 1.8 \mathcal{U}_{i2} + (-0.025 + 0.034) \left( \text{Re} \left\{ \frac{\tan \beta}{1 + \kappa_d \tan \beta} \right\} \mathcal{U}_{i1} + \text{Im} \left\{ \frac{\kappa_d \tan^2 \beta}{1 + \kappa_d \tan \beta} \right\} \mathcal{U}_{i3} \right)\)
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- **Contribution Approximations (scalar):**
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  - Supersymmetric contributions, negligible: \( S_{H_{i,b}}^\gamma \propto 1.2 \times 10^{-5} \tan \beta; \quad S_{H_{i,t}}^\gamma \lesssim 0.26 [-u_{i1} + 1.7 u_{i2} + u_{i3}] \)

\( S_{H_{i,\tilde{H}}}^\gamma \lesssim 0.15 \left( u_{i2} + \frac{M_{\tilde{H}}^2}{\mu^2} \right); \quad S_{H_{i,\tilde{X}}}^\gamma \lesssim -0.456 \left[ \frac{\sigma(\lesssim 1)}{\tan \beta} + \sigma(\lesssim 1) \right] \left[ \pm u_{i1} \pm u_{i2} \pm u_{i3} \right] \)
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  - bb-fusion:
    \[
    \sigma(pp \rightarrow H_i)_{bb} = 0.16 \frac{\tan^2 \beta}{(1 + \kappa_d \tan \beta)^2} (|U_{i1}|^2 + |U_{i3}|^2) \text{ pb}
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  - Gluon fusion:
    \[
    \sigma(pp \rightarrow H_i)_{gg} = 13 u_{i2}^2 - \frac{1.5 \tan \beta}{1 + \kappa_d \tan \beta} u_{i1} u_{i2} + \frac{0.1 \tan^2 \beta}{(1 + \kappa_d \tan \beta)^2} u_{i1}^2 + \frac{2}{1 + \kappa_d \tan \beta} + \frac{0.1 \tan^2 \beta}{(1 + \kappa_d \tan \beta)^2} + \frac{27}{\tan^2 \beta} u_{i3} \text{ pb}
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    \]
    \[
    + \left( \frac{2}{1 + \kappa_d \tan \beta} + \frac{0.1 \tan^2 \beta}{(1 + \kappa_d \tan \beta)^2} + \frac{27}{\tan^2 \beta} \right) U_{i3} \text{ pb}
    \]
  - *Hi total width (main channels are b quarks, W bosons and tau leptons):*
    \[
    \Gamma_{H_i} \approx \frac{g^2}{32\pi M_W^2} \left[ \tan^2 \beta (|U_{i1}|^2 + |U_{i3}|^2) (3m_b^2 + m_{\tau}^2) + 6.7 \times 10^{-4} \left( U_{i2} + \frac{U_{i1}}{\tan \beta} \right)^2 m_{H_i}^2 \right]
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Analysis \((H_i \rightarrow \gamma\gamma)\)

- Gluon fusion cross section and the total width would correspond to the SM prediction if \(H_2 \rightarrow h, \tan \beta = 1, U_{21}, U_{22} = 1\) and \(U_{23} = 0\). It decreases with \(\tan \beta\).
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- The diphoton decay width is consistent with that predicted by the SM.
LHC Higgs Data: diphoton channel

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- Current data binds the excess in the range $0.9 \leq \mu_{\gamma\gamma}^{LHC} \leq 1.5$
Analysis \((H_i \rightarrow \gamma\gamma)\)

- Peak enhancement according to up-component mixing:
Analysis \( (H_i \rightarrow \gamma\gamma) \)

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- The diphoton decay width is consistent with that predicted by the SM.
  - Strategy: increasing the diphoton channel by reducing the total width and enhancing the gluon fusion production cross section.

\[
\mathcal{U}_{21}, \mathcal{U}_{23} \lesssim \frac{1}{\tan \beta}; \mathcal{U}_{22} \approx 1
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Analysis ($H_i \rightarrow \gamma\gamma$)

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    \[ + \left( \frac{2}{1 + \kappa_d \tan \beta} + \frac{0.1 \tan^2 \beta}{(1 + \kappa_d \tan \beta)^2} + \frac{27}{\tan^2 \beta} \right) U_{i3} \text{ pb} \]

- $H_2$ total width (main channels are b quarks, W bosons and tau leptons):
  \[ \Gamma_{H_2} \approx \frac{g^2}{32 \pi M_W^2} \left[ \tan^2 \beta (|U_{i1}|^2 + |U_{i3}|^2) \left( 3m_b^2 + m_\tau^2 \right) + 6.7 \times 10^{-4} \left( U_{i2} + \frac{U_{i1}}{\tan \beta} \right)^2 m_{H_i}^2 \right] \]
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- The diphoton decay width is comparable to the predicted by the SM.
  - Strategy: increasing the diphoton channel by reducing the total width and enhancing the gluon fusion production cross section

\[
\mathcal{U}_{i1}, \mathcal{U}_{i3} \leq \frac{1}{\tan \beta}; \mathcal{U}_{i2} \approx 1
\]

- This leaves \(H_2\) mostly as an up-type Higgs. The other neutral Higgses will have a down-pseudoscalar mixing.
LHC Higgs Data

- Experimental observation in $H \rightarrow \tau \bar{\tau}$ channel.
Higgs decay into tau leptons

- Our assumption on the mixing components mostly decouple $H_2$ from the tau lepton.
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$$\Gamma_{j,\tau\tau} \approx \frac{g^2 m_H m_{\tau}^2}{32\pi M_W^2} \tan^2 \beta$$
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  \]
  \[
  \sigma(pp \rightarrow H_j)_{gg} \approx \frac{0.1\tan^2 \beta}{(1 + \kappa_d \tan \beta)^2} + \frac{45 + 25U_{j3}^2}{\tan^2 \beta} + \frac{2U_{j3}^2 - 1.4U_{j1}}{1 + \kappa_d \tan \beta} \text{ pb}
  \]
Experimental flavour constraints.

- $B_S^0 \rightarrow \mu^+\mu^-$ (LHCb) $\Rightarrow$ Constraining for high tan $\beta$ (already suppressed by $H_j \rightarrow \tau\bar{\tau}$).

$$BR(B_S^0 \rightarrow \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$$
Experimental flavour constraints.

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  \[ \text{BR}(B_s^0 \rightarrow \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9} \]

- $B \rightarrow X_s\gamma$ (BaBar and Belle) $\Rightarrow$ Very significant constraint for low $\tan \beta$.

  \[ \text{BR}(B \rightarrow X_s\gamma) = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4} \]
$B \to X_S \gamma$ constraints to our model

- The charged Higgs contribution is additive to that coming from the W-boson.

$$C_{H\pm} \simeq \frac{-0.2}{\tan \beta}$$
The charged Higgs contribution is additive to that coming from the W-boson.

\[ C_{7}^{H\pm} \approx \frac{-0.2}{\tan \beta} \]

The stop-chargino loop contribution can compensate the previous one depending on the sign of \( \text{Re}(\mu A_t) \).

\[ C_{7,8}^{\tilde{X}\pm} \approx 0.02 \frac{M_2}{\mu} \tan \beta; \; m_{\tilde{t}_1} \geq 650 \text{ GeV}; \]
The charged Higgs contribution is additive to that coming from the W-boson.

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The stop-chargino loop contribution can compensate the previous one depending on the sign of \( \text{Re}(\mu A_t) \).

\[ C_{7,8}^{\pm} \approx 0.02 \frac{M_2}{\mu} \tan \beta ; \quad m_{t_1} \geq 650 \text{ GeV} \]

Thus, there will be no compensation for low \( \tan \beta \) values.
Comparison with experimental bounds

- $H_1 \rightarrow \tau\bar{\tau}$ cross section ($m_{H_1} = 110$ GeV, $m_{H_3} = 160$ GeV):
Comparison with experimental bounds

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Blue dots accomplish diphoton decay boundaries.
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Green points also fulfill $\tau \bar{\tau}$ constraints for the three neutral Higgses of our model.
Comparison with experimental bounds

\[ H_1 \rightarrow \tau \bar{\tau} \text{ cross section} \ (m_{H_1} = 110 \text{ GeV}, m_{H_3} = 160 \text{ GeV}): \]

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LOW \( \tan \beta \) IS REQUIRED
$B \rightarrow X_s \gamma$ constraints to light Higgs models
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Blue squares, surviving all previous constraints, cannot live in a region below $2\sigma$
$B \rightarrow X_S \gamma$ constraints to light Higgs models

Light stop quark ($m_{\tilde{t}_1} < 650$ GeV)

- It should have a similar mass to that of the neutralino (to avoid detection), being restricted as $m_{\chi_1^0} \leq m_{\tilde{t}_1} \leq m_t + m_{\chi_1^0}$
Light stop quark ($m_{\tilde{t}_1} < 650$ GeV)

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- The stop-chargino contribution will gain strength in a term with the dependence:

$$C_{7,8}^+ \propto -\tan \beta \frac{m_{\tilde{t}_1}^2}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2}$$
$B \rightarrow X_S \gamma$ constraints to light Higgs models

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$$C_{7,8} \propto - \tan \beta \frac{m_\tilde{t}_1^2}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2}$$

It is still impossible to find a model compatible with the experimental constraint.
Conclusions

- The mechanism for reproducing data in the diphoton channel consists in having an almost purely up-type Higgs scalar.
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- Low \( \tan \beta \) parameter space is vanished by the indirect bound coming from \( B \to X_s \gamma \).
Conclusions

- The mechanism for reproducing data in the diphoton channel consists in having an almost purely up-type Higgs scalar.

- The most relevant constraint for high $\tan \beta$ parameter space is $H \rightarrow \tau \bar{\tau}$.

- Low $\tan \beta$ parameter space is vanished by the indirect bound coming from $B \rightarrow X_s \gamma$.

- The lightest MSSM neutral Higgs in must correspond to the measured $h$ with $m_h = 125.5\text{ GeV}$.
Aknowledgements
95% C.L. exclusion

- Given a point in the parameter space, it is safe to exclude it if it falls outside the 95% C.L. of the observable.

- In case the point agrees with the experimental data, it cannot be assured that the point is in agreement with data with that confidence level, giving rise to fake accepted points.

- The comparison has to be applied to each Higgs model independently.

A Higgs lighter than $m_h = 125.5$ GeV

- Pseudoscalar and down-type component reduce couplings to W-bosons, Z-bosons, and top quarks. LEP left some windows unexcluded.
- LEP mass limit for SM Higgs: $m_h > 114.4$ GeV
- Production by ‘Higgsstrahlung’:

- Light Higgs two-body decay is excluded.
- Cascade decays into more particles were not completely excluded.
Appendix A

Alleged evidence of a second Higgs at CMS

- A second peak appears at the diphoton exclusion plot, at a corresponding mass of $m_H = 136.5$ GeV.
- Though it survives consecutive analyses, there is no evidence in any other channel.
- We assume that $H_1$ at $m_{H_1} = 125$ GeV is an up-type Higgs.
- Intending to take advantage of the down component of this supposed $H_2$, we try to reproduce the peak proposing a light stau.
Appendix A

Alleged evidence of a second Higgs at CMS

- To enhance the stau effect we need big values of $\tan \beta$ (suppression in the tau-tau channel).
- It will be the dominant contribution of the diphoton decay, but not comparable to that of the first Higgs (W boson).
Appendix B

SUSY particle contributions to $H_i \rightarrow \gamma \gamma$

- **Charged Higgs**: 
  
  \[ g_{H_2 H^+} \approx (2\lambda_1 \cos \beta - \lambda_4 \cos \beta - 2 \cos \beta \text{Re}[\lambda_5] + \text{Re}[\lambda_6]) U_{21} + (\lambda_3 + \text{Re}[\lambda_6] \cos \beta - 2 \cos \beta \text{Re}[\lambda_7]) U_{22} + (2 \cos \beta \text{Im}[\lambda_5] - \text{Im}[\lambda_6]) U_{23} \]

- **Contribution to the decay width**: 
  
  \[ S_{H_2, H^+}^\gamma \leq -0.45 \left( \frac{2\lambda_1 - \lambda_4 - 2\text{Re}[\lambda_5]}{\tan \beta} + \text{Re}[\lambda_6] \right) U_{21} + \left( \lambda_3 + \frac{\text{Re}[\lambda_6] - 2\text{Re}[\lambda_7]}{\tan \beta} \right) U_{22} \]
Appendix B

SUSY particle contributions to $H_2 \rightarrow \gamma \gamma$

- Sbottom contribution:
  \[ S^\gamma_{H_2,\tilde{b}} \approx 1.2 \times 10^{-5} \tan^2 \beta \left( \frac{300 \text{ GeV}}{m_{\tilde{b}_1}} \right)^2 \left[ \text{Re}(A_b^* \mu) \frac{\mu^2}{m_{b_2}^2} U_{21} - \frac{\mu^2}{m_{b_2}^2} U_{22} + \text{Im}(A_b^* \mu) \frac{\mu^2}{m_{b_2}^2 \tan \beta} U_{23} \right] \]

- Stop contribution:
  \[ S^\gamma_{H_2,\tilde{t}} \]
  \[ \approx 0.45 \left[ -\text{Re} \left( \frac{\mu m_t}{m_{\tilde{t}_1}^2} R_{11}^* R_{21} \right) U_{21} + \text{Im} \left( \frac{\mu m_t}{m_{\tilde{t}_1}^2} R_{11}^* R_{21} \right) U_{23} \right] \]
Appendix B

SUSY particle contributions to $H_2 \rightarrow \gamma\gamma$

- Chargino contribution:

$$S_{H_2,\tilde{\chi}^\pm}^\gamma = \sqrt{2} g \sum_{i=1,2} \text{Re} \left[ V_{i1}^* U_{i2} G_2^{\phi_1} + V_{i2}^* U_{i1} G_2^{\phi_2} \right] \frac{v}{m_{\tilde{\chi}_i^+}} F_j^S \left( \tau_{2,\tilde{\chi}_i^\pm} \right);$$

With: $G_2^{\phi_1} = (U_{21} - i \sin \beta U_{23}); G_2^{\phi_2} = (U_{22} - i \cos \beta U_{23})$

- Leading to:

$$S_{H_2,\tilde{\chi}^\pm}^\gamma \approx 2.8 \left[ \cos \beta \frac{m_W^2}{\mu^2} U_{21} + \frac{m_W^2}{M_2^2} U_{22} \right]$$
Appendix C

MSSM Lagrangian: Scalar Potential

\[ \mathcal{L}_V = \mu_1^2 (\Phi_1^\dagger \Phi_1) + \mu_2^2 (\Phi_2^\dagger \Phi_2) + m_{12}^2 (\Phi_1^\dagger \Phi_2) + m_{12}^* (\Phi_2^\dagger \Phi_1) + \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \\
+ \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \\
+ \lambda_5^* (\Phi_2^\dagger \Phi_1)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_6^* (\Phi_1^\dagger \Phi_2)(\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + \\
+ \lambda_7^* (\Phi_2^\dagger \Phi_1)(\Phi_2^\dagger \Phi_1) \]

With \( \mu_{1,2}^2 = -m_{1,2} - |\mu|^2 \)
Appendix C

MSSM Lagrangian: Scalar Potential

\[
\lambda_1 = -\frac{g_w^2 + g^2}{8} \left( 1 - \frac{3}{8\pi^2} h_b^2 t \right) - \frac{3}{16\pi^2} h_b^4 \left\{ t + \frac{1}{2} X_b + \frac{1}{16\pi^2} \left[ \frac{3}{2} h_b^2 + \frac{1}{2} h_t^2 - 8 g_s^2 \right] [X_b t + t^2] \right\} \\
+ \frac{3}{192\pi^2} h_t^4 \frac{|\mu|^4}{M_{SUSY}^4} \left\{ 1 + \frac{1}{16\pi^2} \left[ 9 h_t^2 - 5 h_b^2 - 16 g_s^2 \right] t \right\} 
\]

(D3)

\[
\lambda_2 = -\frac{g_w^2 + g^2}{8} \left( 1 - \frac{3}{8\pi^2} h_t^2 t \right) - \frac{3}{16\pi^2} h_t^4 \left\{ t + \frac{1}{2} X_t + \frac{1}{16\pi^2} \left[ \frac{3}{2} h_t^2 + \frac{1}{2} h_b^2 - 8 g_s^2 \right] [X_t t + t^2] \right\} \\
+ \frac{3}{192\pi^2} h_b^4 \frac{|\mu|^4}{M_{SUSY}^4} \left\{ 1 + \frac{1}{16\pi^2} \left[ 9 h_b^2 - 5 h_t^2 - 16 g_s^2 \right] t \right\} 
\]

(D4)
Appendix C

MSSM Lagrangian: Scalar Potential

\[ \lambda_3 = -\frac{g^2 - g'^2}{4} \left\{ 1 - \frac{3}{16\pi^2} \left[ h_t^2 + h_b^2 \right] t \right\} - \frac{3}{8\pi^2} h_t^2 h_b^2 \left\{ t + \frac{1}{2} X_{tb} + \frac{1}{16\pi^2} \left[ h_t^2 + h_b^2 - 8g_s^2 \right] X_{tb} t + t^2 \right\} 
- \frac{3}{96\pi^2} h_t^4 \left[ \frac{\left| \mu \right|^2}{M_{SUSY}^2} - \frac{\left| \mu \right|^2 \left| A_t \right|^2}{M_{SUSY}^4} \right] \left\{ 1 + \frac{1}{16\pi^2} \left[ 6h_t^2 - 2h_b^2 - 16g_s^2 \right] t \right\} \]

\[ \lambda_4 = \frac{g^2}{2} \left\{ 1 - \frac{3}{16\pi^2} \left[ h_t^2 + h_b^2 \right] t \right\} - \frac{3}{8\pi^2} h_t^2 h_b^2 \left\{ t + \frac{1}{2} X_{tb} + \frac{1}{16\pi^2} \left[ h_t^2 + h_b^2 - 8g_s^2 \right] X_{tb} t + t^2 \right\} 
- \frac{3}{96\pi^2} h_t^4 \left[ \frac{\left| \mu \right|^2}{M_{SUSY}^2} - \frac{\left| \mu \right|^2 \left| A_t \right|^2}{M_{SUSY}^4} \right] \left\{ 1 + \frac{1}{16\pi^2} \left[ 6h_t^2 - 2h_b^2 - 16g_s^2 \right] t \right\} \]

\[ \text{(D5)} \]

\[ \text{(D6)} \]
Appendix C

MSSM Lagrangian: Scalar Potential

\[ \lambda_5 = \frac{3}{192\pi^2} h_t^4 \frac{\mu^2 A_t^2}{M_{SUSY}^4} \left\{ 1 + \frac{1}{16\pi^2} \left[ 2h_b^2 - 6h_t^2 + 16g_s^2 \right] t \right\} + \frac{3}{192\pi^2} h_b^4 \frac{\mu^2 A_b^2}{M_{SUSY}^4} \left\{ 1 + \frac{1}{16\pi^2} \left[ 2h_t^2 - 6h_b^2 + 16g_s^2 \right] t \right\} \]

\[ \lambda_6 = -\frac{3}{96\pi^2} h_t^4 \frac{\mu^2 A_t}{M_{SUSY}^4} \left\{ 1 - \frac{1}{16\pi^2} \left[ \frac{7}{2} h_b^2 - \frac{15}{2} h_t^2 + 16g_s^2 \right] t \right\} + \frac{3}{96\pi^2} h_b^4 \frac{\mu}{M_{SUSY}} \left[ \frac{6A_b}{M_{SUSY}} - \frac{|A_b|^2 A_b}{M_{SUSY}^3} \right] \left\{ 1 - \frac{1}{16\pi^2} \left[ \frac{1}{2} h_t^2 - \frac{9}{2} h_b^2 - 16g_s^2 \right] t \right\} \]
Appendix C

MSSM Lagrangian: Scalar Potential

\[ \lambda_7 = -\frac{3}{96 \pi^2} \frac{\mu^2 A_b}{M_{\text{SUSY}}^4} \left\{ 1 - \frac{1}{16 \pi^2} \left[ \frac{7}{2} h_t^2 - \frac{15}{2} h_b^2 + 16 g_s^2 \right] t \right\} + \frac{3}{96 \pi^2} \frac{\mu}{M_{\text{SUSY}}} \left[ \frac{6 A_t}{M_{\text{SUSY}}} - \frac{|A_t|^2 A_t}{M_{\text{SUSY}}^3} \right] \left\{ 1 - \frac{1}{16 \pi^2} \left[ \frac{1}{2} h_b^2 - \frac{9}{2} h_t^2 - 16 g_s^2 \right] t \right\} \]

\[ t = \ln \left[ \frac{M_{\text{SUSY}}^2}{m_t^2} \right] ; h_t = \frac{\sqrt{2} m_t (m_t)}{v \sin \beta} ; h_b = \frac{\sqrt{2} m_b (m_t)}{v \sin \beta} ; m_t (m_t) = \frac{\overline{m}_t}{1 + 4 \pi^2 \alpha_s (m_t)} \]

\[ X_t = \frac{2 |A_t|^2}{M_{\text{SUSY}}^2} \left[ 1 - \frac{|A_t|^2}{12 M_{\text{SUSY}}^2} \right] ; X_b = \frac{2 |A_b|^2}{M_{\text{SUSY}}^2} \left[ 1 - \frac{|A_b|^2}{12 M_{\text{SUSY}}^2} \right] \]

\[ X_{tb} = \frac{|A_t|^2 + |A_b|^2 + 2 Re[A_t^* A_b]}{2 M_{\text{SUSY}}^2} - \frac{|\mu|^2}{M_{\text{SUSY}}^4} - \frac{||\mu|^2 - A_b^* A_t|^2}{6 M_{\text{SUSY}}^2} \]
Appendix D

Higgs mass matrix

$$
\tilde{M}^2_p = \begin{pmatrix}
-\frac{c_\beta T_{\alpha_1} + s_\beta T_{\alpha_2}}{-c_\beta \tan \beta T_{\alpha_1} + c_\beta \cot \beta T_{\alpha_2}} & \frac{s_\beta T_{\alpha_1} - c_\beta T_{\alpha_2}}{v} \\
\frac{s_\beta T_{\alpha_1} - c_\beta T_{\alpha_2}}{c_\beta \tan \beta T_{\alpha_1} - c_\beta \cot \beta T_{\alpha_2}} & M^2_a
\end{pmatrix},
$$

(2.14)

$$
M^2_{SP} = v^2 \begin{pmatrix}
0 & \text{Im}(\lambda_5 e^{2i\xi}) s_\beta + \text{Im}(\lambda_6 e^{i\xi}) c_\beta \\
0 & \text{Im}(\lambda_5 e^{2i\xi}) c_\beta + \text{Im}(\lambda_7 e^{i\xi}) s_\beta
\end{pmatrix} - \frac{T_a}{v} \begin{pmatrix}
s_\beta & c_\beta \\
-c_\beta & s_\beta
\end{pmatrix},
$$

(2.15)

$$
M^2_S = \frac{s_\beta}{2} \begin{pmatrix}
T_{\alpha_1} & 0 \\
0 & T_{\alpha_2}
\end{pmatrix}
$$

$$
-\frac{2\lambda_1 c_\beta^2 + 2\text{Re}(\lambda_5 e^{2i\xi}) s_\beta^2 + 2\text{Re}(\lambda_6 e^{i\xi}) s_\beta c_\beta}{\lambda_3 s_\beta c_\beta + \text{Re}(\lambda_6 e^{i\xi}) c_\beta^2 + \text{Re}(\lambda_7 e^{i\xi}) s_\beta^2} - \frac{\lambda_3 s_\beta c_\beta + \text{Re}(\lambda_6 e^{i\xi}) c_\beta^2 + \text{Re}(\lambda_7 e^{i\xi}) s_\beta^2}{\lambda_3 s_\beta c_\beta + \text{Re}(\lambda_6 e^{i\xi}) c_\beta^2 + \text{Re}(\lambda_7 e^{i\xi}) s_\beta c_\beta}.
$$

(2.16)

**Loop corrections to the scalar mass:**

$$
\delta M^2_S \simeq \frac{3m^4}{2\pi^2 v^2 \sin^2 \beta} \log \frac{M^2_{SUSY}}{m_t^2} + \frac{X_t^2}{M^2_{SUSY}} \left( 1 - \frac{X_t^2}{12M^2_{SUSY}} \right).
$$