The post-Higgs MSSM scenario

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Introduction

LHC: $m_H \sim 125$ GeV, supersymmetry ?

$M_{\text{SUSY}} \geq 1$ TeV (decoupling limit), h, $H, A, H^{\pm}$

M_Z: MSSM is a SM-like theory

$\longrightarrow$ The restriction of the parameter space or simplification of the model

Free parameters: $m_A, \tan\beta, M_{\text{SUSY}}, A_t, A_b, \mu$

Threshold radiative corrections

Assumptions: RGE's contributions and 1,2 generations of squarks are neglected

Two forms of 2HDM potential

A flavour state

$$U_{eff}(\Phi_1,\Phi_2) = -\mu_1^2(\Phi_1^\dagger\Phi_1) - \mu_2^2(\Phi_2^\dagger\Phi_2) - {\mu_{12}}^2(\Phi_1^\dagger\Phi_2) - ({\mu_{12}}^2)^*(\Phi_2^\dagger\Phi_1) \tag{1}$$
$$+\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \frac{{\lambda_5}^*}{2}(\Phi_2^\dagger\Phi_1)^2 + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + {\lambda_6}^*(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_1)$$
$$+\lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + {\lambda_7}^*(\Phi_2^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$

[Dubinin M., Semenov A., Eur.J. Phys., 2003] ...

$$\Phi_i = \left(\begin{array}{c} -i\omega_i^+ \\ \frac{1}{\sqrt{2}}(v_i + \eta_i + i\chi_i) \end{array} \right), \qquad \langle\Phi_i\rangle = \frac{1}{\sqrt{2}} \left(\begin{array}{c} 0 \\ v_i \end{array} \right), \qquad i = 1,2 \tag{2}$$

$$\tan\beta = \frac{v_2}{v_1}, \qquad v = \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV}$$

M_{SUSY}:

MSSM $\qquad \lambda_{1,2}^{\text{SUSY}} = \frac{g_1^2 + g_2^2}{8}, \qquad \lambda_3^{\text{SUSY}} = \frac{g_2^2 - g_1^2}{4}, \qquad \lambda_4^{\text{SUSY}} = -\frac{g_2^2}{2}, \qquad \lambda_{5,6,7}^{\text{SUSY}} = 0.$

m_{top}: $\qquad \lambda_i = \lambda_i^{\text{SUSY}} - \Delta\lambda_i$

Mass state

$$U(h,H,A,H^{\pm},G^0,G^{\pm}) = \frac{m_h^2}{2}h^2 + \frac{m_H^2}{2}H^2 + \frac{m_A^2}{2}A^2 + m_{H^\pm}^2 H^+H^- + inter(3) + inter(4) \tag{3}$$

[Akhmetzyanova, Dolgopolov, Dubinin, Phys.Rev.D71, 2005] ...

The relation between mass and flavour states

$$\begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix} = \mathcal{O}_\alpha \begin{pmatrix} h \\ H \end{pmatrix}, \qquad \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix} = \mathcal{O}_\beta \begin{pmatrix} G^0 \\ A \end{pmatrix}, \qquad \begin{pmatrix} \omega_1^{\pm} \\ \omega_2^{\pm} \end{pmatrix} = \mathcal{O}_\beta \begin{pmatrix} G^{\pm} \\ H^{\pm} \end{pmatrix}$$

where rotation matrix

$$\mathcal{O}_X = \begin{pmatrix} \cos X & -\sin X \\ \sin X & \cos X \end{pmatrix}, \qquad X = \alpha, \beta. \tag{4}$$

Masses of CP-even Higgs bosons and mixing angle

1

$$
\begin{aligned}
m_h^2 &= s_{\alpha+\beta}^2 m_Z^2 + c_{\alpha-\beta}^2 m_A^2 - v^2(\Delta\lambda_1 s_\alpha^2 c_\beta^2 + \Delta\lambda_2 c_\alpha^2 s_\beta^2 \\
&- 2(\Delta\lambda_3 + \Delta\lambda_4) c_\alpha c_\beta s_\alpha s_\beta + \mathrm{Re}\Delta\lambda_5 (s_\alpha^2 s_\beta^2 + c_\alpha^2 c_\beta^2) \\
&- 2c_{\alpha+\beta}(\mathrm{Re}\Delta\lambda_6 s_\alpha c_\beta - \mathrm{Re}\Delta\lambda_7 c_\alpha s_\beta)), \\
m_H^2 &= c_{\alpha+\beta}^2 m_Z^2 + s_{\alpha-\beta}^2 m_A^2 - v^2(\Delta\lambda_1 c_\alpha^2 c_\beta^2 + \Delta\lambda_2 s_\alpha^2 s_\beta^2 \\
&+ 2(\Delta\lambda_3 + \Delta\lambda_4) c_\alpha c_\beta s_\alpha s_\beta + \mathrm{Re}\Delta\lambda_5 (c_\alpha^2 s_\beta^2 + s_\alpha^2 c_\beta^2) \\
&+ 2s_{\alpha+\beta}(\mathrm{Re}\Delta\lambda_6 c_\alpha c_\beta + \mathrm{Re}\Delta\lambda_7 s_\alpha s_\beta)), \\
\tan 2\alpha &= \frac{s_{2\beta}(m_A^2 + m_Z^2) + v^2((\Delta\lambda_3 + \Delta\lambda_4) s_{2\beta} + 2c_\beta^2 \mathrm{Re}\Delta\lambda_6 + 2s_\beta^2 \mathrm{Re}\Delta\lambda_7)}{c_{2\beta}(m_A^2 - m_Z^2) + v^2(\Delta\lambda_1 c_\beta^2 - \Delta\lambda_2 s_\beta^2 - \mathrm{Re}\Delta\lambda_5 c_{2\beta} + (\mathrm{Re}\Delta\lambda_6 - \mathrm{Re}\Delta\lambda_7) s_{2\beta})},
\end{aligned}
\tag{5}
$$

[Akhmetzyanova, Dolgopolov, Dubinin, Phys.Rev.D71, 2005]

2

$$
\begin{aligned}
m_{H,h}^2 &= \frac{1}{2}(m_A^2 + m_Z^2 + \Delta\mathcal{M}_{11}^2 + \Delta\mathcal{M}_{22}^2 \pm \sqrt{m_A^4 + m_Z^4 - 2m_A^2 m_Z^2 c_{4\beta} + C}), \\
\tan 2\alpha &= \frac{2\Delta\mathcal{M}_{12}^2 - (m_Z^2 + m_A^2) s_{2\beta}}{(m_Z^2 - m_A^2) c_{2\beta} + \Delta\mathcal{M}_{11}^2 - \Delta\mathcal{M}_{22}^2},
\end{aligned}
\tag{6}
$$

[Djouadi et al., arXiv:1307.5205v1, 2013]

... where

$$\mathcal{M}_Y^2 = \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{21}^2 & \mathcal{M}_{22}^2 \end{pmatrix}, \qquad \mathcal{M}_{ij}^2 = \frac{\partial^2 U}{\partial Y_i \partial Y_j}, \qquad Y = \eta, \chi, \omega^\pm, \qquad i,j = 1,2 \quad (7)$$

$$\mathcal{M}_\eta^2 = \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 \end{pmatrix} + \begin{pmatrix} \Delta\mathcal{M}_{11}^2 & \Delta\mathcal{M}_{12}^2 \\ \Delta\mathcal{M}_{12}^2 & \Delta\mathcal{M}_{22}^2 \end{pmatrix}, \quad (8)$$

$$\mathcal{M}_{11}^2 = m_A^2 s_\beta^2 + m_Z^2 c_\beta^2, \qquad \mathcal{M}_{22}^2 = m_A^2 c_\beta^2 + m_Z^2 s_\beta^2, \qquad \mathcal{M}_{12}^2 = -s_\beta c_\beta (m_A^2 + m_Z^2), \quad (9)$$

$$\begin{aligned} \Delta\mathcal{M}_{11}^2 &= -v^2(\Delta\lambda_1 c_\beta^2 + \mathrm{Re}\Delta\lambda_5 s_\beta^2 + \mathrm{Re}\Delta\lambda_6 s_{2\beta}), \\ \Delta\mathcal{M}_{22}^2 &= -v^2(\Delta\lambda_2 s_\beta^2 + \mathrm{Re}\Delta\lambda_5 c_\beta^2 + \mathrm{Re}\Delta\lambda_7 s_{2\beta}), \\ \Delta\mathcal{M}_{12}^2 &= -v^2(\Delta\lambda_{34} s_\beta c_\beta + \mathrm{Re}\Delta\lambda_6 c_\beta^2 + \mathrm{Re}\Delta\lambda_7 s_\beta^2), \end{aligned} \quad (10)$$

$$C = 4\Delta\mathcal{M}_{12}^4 + (\Delta\mathcal{M}_{11}^2 - \Delta\mathcal{M}_{22}^2)^2 - 2(m_A^2 - m_Z^2)(\Delta\mathcal{M}_{11}^2 - \Delta\mathcal{M}_{22}^2)c_{2\beta} - 4(m_A^2 + m_Z^2)\Delta\mathcal{M}_{12}^2 s_{2\beta}$$

[Djouadi et al., arXiv:1307.5205v1, 2013]

Simplified representation for heavy CP-even Higgs boson mass

$$m_H^2 = m_A^2 + m_Z^2 - m_h^2 + \Delta\mathcal{M}_{11}^2 + \Delta\mathcal{M}_{22}^2 \quad (11)$$

How to calculate these radiative corrections $\Delta\lambda_i$?

hMSSM scenario

[Djouadi et al., arXiv:1307.5205v1, 2013]; Lee, Wagner; Slavich P.; Spira M. (2014)

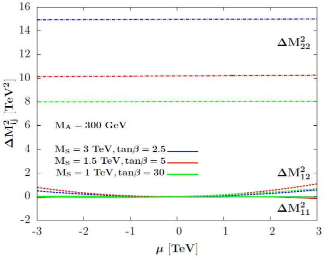
Assuptions:
1-loop (ϵ-approximation) + 2-loop (leading logarithmic contributions)

$$\Delta\mathcal{M}_{11} \sim 0, \qquad \Delta\mathcal{M}_{12} \sim 0, \qquad \Delta\mathcal{M}_{22} \neq 0$$

$$\Delta\mathcal{M}^2_{22} = \frac{m_h^2(m_A^2 + m_Z^2 - m_h^2) - m_A^2 m_Z^2 c_{2\beta}^2}{m_Z^2 c_\beta^2 + m_A^2 s_\beta^2 - m_h^2},$$

$$m_H^2 = \frac{(m_A^2 + m_Z^2 - m_h^2)(m_Z^2 c_\beta^2 + m_A^2 s_\beta^2) - m_A^2 m_Z^2 c_{2\beta}^2}{m_Z^2 c_\beta^2 + m_A^2 s_\beta^2 - m_h^2},$$

$$\alpha = -\arctan\left(\frac{(m_Z^2 + m_A^2) s_\beta c_\beta}{m_Z^2 c_\beta^2 + m_A^2 s_\beta^2 - m_h^2}\right)$$



$m_h = 123 - 129$ ГэВ

Free parameters: $m_A, \tan\beta, M_S$

Is it true for more precise approach?

Additional nonleading D-term contributions in threshold corrections + w.f.r. contributions

1-loop

[Akhmetzyanova, Dolgopolov, Dubinin (2005)]; Haber, Hampfling (1993); Carena, Ellis, Pilaftsis, Wagner (2000)

+ 2-loop **[Carena et al., arXiv:hep-ph/9504316v2, 1995]; Pilaftsis, Wagner (1999); Demir (1999); Choi, Lee (2000); Heinemeyer (2001),**

$$\mathrm{Im} A_{t,b} = \mathrm{Im}\mu = 0$$

For instance,

$$\lambda_1 = \frac{g_2^2+g_1^2}{8} + \frac{3}{32\pi^2}\Big[h_b^4 \frac{|A_b|^2}{M_{\rm SUSY}^2}\left(2-\frac{|A_b|^2}{6M_{\rm SUSY}^2}\right) - h_t^4\frac{|\mu|^4}{6M_{\rm SUSY}^4} + 2h_b^4 l + \frac{g_2^2+g_1^2}{4\,M_{\rm SUSY}^2}(h_t^2|\mu|^2 - \\ -h_b^2|A_b|^2)\Big] + \Delta\lambda_1^{\rm w.f.r.} + \frac{1}{768\pi^2}\left(11g_1^4+9g_2^4-36\,(g_1^2+g_2^2)\,h_b^2\right) l - \Delta\lambda_1[2-\mathtt{loop}], \quad (12)$$

$$\Delta\lambda_1[2-\mathtt{loop}] = -\frac{3}{16\pi^2}h_b^4\frac{1}{16\pi^2}\left(\frac{3}{2}h_b^2+\frac{1}{2}h_t^2-8g_{\rm S}^2\right)(X_b l + l^2) + \\ + \frac{3}{192\pi^2}h_t^4\frac{1}{16\pi^2}\frac{|\mu|^4}{M_{\rm SUSY}^4}(9h_t^2-5h_b^2-16g_{\rm S}^2)l, \quad (13)$$

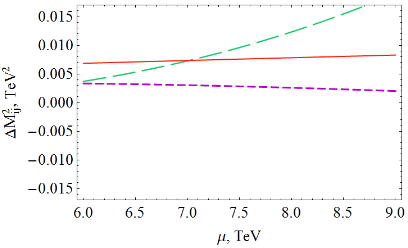
$$\Delta\lambda_1^{\rm w.f.r.} = \frac{1}{2}(g_1^2+g_2^2)A'_{11}, \qquad l = \log\frac{M_{SUSY}^2}{\sigma^2} \quad (14)$$

$$A'_{ij} = -\frac{3(1-l/2)}{96\,\pi^2\,M_{SUSY}^2}\left(h_t^2\begin{bmatrix} |\mu|^2 & -\mu^* A_t^* \\ -\mu A_t & |A_t|^2\end{bmatrix} + h_b^2\begin{bmatrix} |A_b|^2 & -\mu^* A_b^* \\ -\mu A_b & |\mu|^2\end{bmatrix}\right) \quad (15)$$

Numerical analysis of $\Delta\mathcal{M}^2_{ij}$

$m_h = 123 - 129$ GeV

a) $M^{\text{SUSY}} = 1$ TeV, $\tan\beta = 30$;
b) $M^{\text{SUSY}} = 1.5$ TeV, $\tan\beta = 5$;
c) $M^{\text{SUSY}} = 3$ TeV, $\tan\beta = 2.5$;
d) $M^{\text{SUSY}} = 3.5$ TeV, $\tan\beta = 1$



Набор	μ, TeV	A, TeV	$\Delta\mathcal{M}^2_{11}$, TeV^2	$\Delta\mathcal{M}^2_{12}$, TeV^2	$\Delta\mathcal{M}^2_{22}$, TeV^2
$\tan\beta = 1$, $M^{\text{SUSY}} = 3.5$ TeV	3 10	15.649 5.159	-0.001 0.008	0.007 0.010	0.018 0.003
$\tan\beta = 2.5$, $M^{\text{SUSY}} = 3$ TeV	5 10	13.651 10.187	0.002 0.012	0.008 0.001	0.007 0.011
$\tan\beta = 30$, $M^{\text{SUSY}} = 5$ TeV	40 60	24.039 29.128	0.134 0.451	0.033 0.093	0.006 0.009

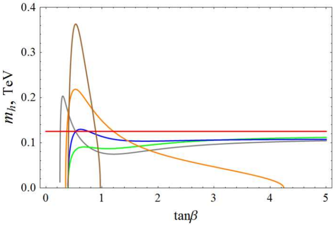
Numerical values of $\Delta\mathcal{M}^2_{ij}$, where $m_A = 1$ TeV, $A_{t,b} = A$ such that it accommodates the mass $m_h = 125$ GeV.

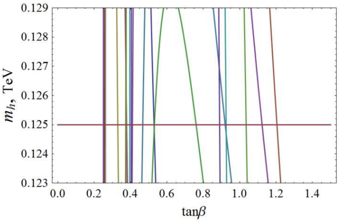
+ radiative corrections of other approaches

[Djouadi et al., arXiv:1307.5205v1, 2013; Cheung et. al., 1411.7329v3[hep-ph], 2015], see the previous slide

$\Delta\mathcal{M}^2_{11,12}$ must not be neglected. 5 free parameters: m_A, $\tan\beta$, μ, $A_{t,b} = A$, M_S

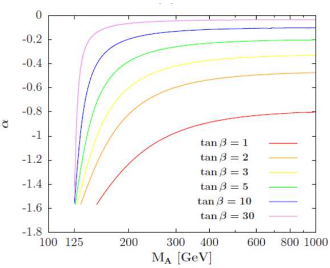
Consequences for observables

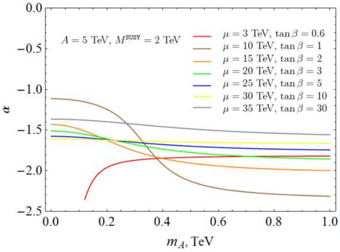




The hMSSM (Orsay+Rome, 2014)

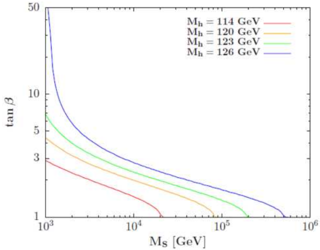
$\mu = 3$ TeV, $m_A = 1$ TeV



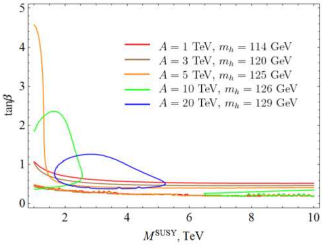


The hMSSM (Orsay+Rome, 2014)

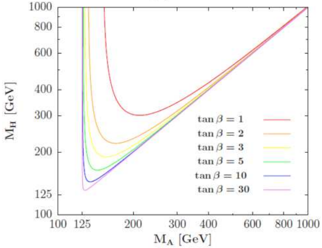
$\mu = 3$ TeV, $m_A = 1$ TeV



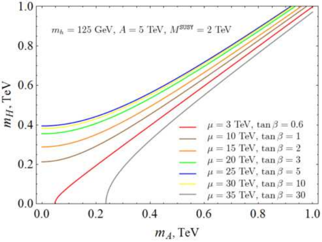
(a)



(б)



(в)



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Conclusion

- The simplified MSSM scenarios are a very attrctive scenarios. However theirs results for Higgs masses and couplings may not respect a sufficient degree of precision.
- The "decoupling limit" is a good approximation in the sense that results are stable with respect to m_A.
- The preferred range of the MSSM parameter space is $-2.5 < \alpha < -1$, $\tan\beta \sim 1$ for the meaningful parametric sets.
- If $M_{SUSY} < 3$ TэВ then the preferred range is $\tan\beta \leq 10$ for $|A, \mu| < 7$ TeV.

Thanks for your attention