Habemus MSSM ?

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A. Djouadi, JQ, arXiv:1304.1787

A. Djouadi, L. Maiani, G. Moreau, A. Polosa, JQ, V. Riquer, arXiv:1307.5205

The post–Higgs MSSM scenario :

- observation of the lighter h boson at a mass of $\approx 125\ GeV$.
- non-observation of superparticles at the LHC.

MSSM $\Rightarrow$ SUSY–breaking scale rather high, $M_S \gtrsim 1$ TeV.

1. $M_h \approx 125$ GeV fixes the dominant radiative corrections that enter the MSSM Higgs boson masses $\Rightarrow$ the Higgs sector can be described by only 2 free parameters (good approximation).
2. Main phenomenological consequence of these high M_S values :
   - reopen the low tan β region, tan $\beta \lesssim$ 3–5, which was for a long time buried under the LEP constraint on the lightest h mass when a low SUSY scale was assumed.
   - The heavier MSSM neutral H/A and charged $H^{\pm}$ states can be searched for in a variety of interesting final states.
3. We consider the direct supersymmetric radiative corrections :
   - the phenomenology of the lighter Higgs state can be described by its mass and 3 couplings.
   - We perform a fit of these couplings using the latest LHC data on the production and decay rates of the light h boson.

In the MSSM to break the electroweak symmetry one need 2 doublets of complex scalar fields :

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \text{ with } Y_{H_d} = -1 \quad , \quad H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \text{ with } Y_{H_u} = +1$$

The tree–level masses of the CP–even h and H bosons depend on M_A, $\tan\beta$ and M_Z.

However, many parameters of the MSSM such as the SUSY scale $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$, the stop/sbottom trilinear couplings $A_{t/b}$ or the higgsino mass μ enter M_h and M_H through radiative corrections.

In the basis (H_d, H_u), the CP–even Higgs mass matrix can be written as:

$$M_S^2 = M_Z^2 \begin{pmatrix} c_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & s_\beta^2 \end{pmatrix} + M_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + \begin{pmatrix} \Delta\mathcal{M}^2_{11} & \Delta\mathcal{M}^2_{12} \\ \Delta\mathcal{M}^2_{12} & \Delta\mathcal{M}^2_{22} \end{pmatrix}$$

where we have introduced the radiative corrections by a 2×2 matrix $\Delta\mathcal{M}^2_{ij}$.

One can then derive the neutral CP even Higgs boson masses and the mixing angle α that diagonalises the h, H states, $H = \cos\alpha H^0_d + \sin\alpha H^0_u$ & $h = -\sin\alpha H^0_d + \cos\alpha H^0_u$

$$M^2_{h/H} = \frac{1}{2}\left(M^2_A + M^2_Z + \Delta\mathcal{M}^2_{11} + \Delta\mathcal{M}^2_{22} \mp \sqrt{M^4_A + M^4_Z - 2M^2_A M^2_Z c_{4\beta} + C}\right)$$

$$\tan\alpha = \frac{2\Delta\mathcal{M}^2_{12} - (M^2_A + M^2_Z)s_\beta}{\Delta\mathcal{M}^2_{11} - \Delta\mathcal{M}^2_{22} + (M^2_Z - M^2_A)c_{2\beta} + \sqrt{M^4_A + M^4_Z - 2M^2_A M^2_Z c_{4\beta} + C}}$$

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

$\Delta\mathcal{M}^2_{22}$ involves the by far dominant stop–top sector correction, $\Delta\mathcal{M}^2_{22} \gg \Delta\mathcal{M}^2_{11}, \Delta\mathcal{M}^2_{12}$.

One can simply trade $\Delta\mathcal{M}^2_{22}$ for the by now known M_h using

$$\Delta\mathcal{M}^2_{22} = \frac{M^2_h(M^2_A + M^2_Z - M^2_h) - M^2_A M^2_Z c^2_{2\beta}}{M^2_Z c^2_\beta + M^2_A s^2_\beta - M^2_h}$$

In this case, one can simply write M_H and α in terms of $M_A, \tan\beta$ and M_h:

$$\text{hMSSM}: \quad M^2_H = \frac{(M^2_A + M^2_Z - M^2_h)(M^2_Z c^2_\beta + M^2_A s^2_\beta) - M^2_A M^2_Z c^2_{2\beta}}{M^2_Z c^2_\beta + M^2_A s^2_\beta - M^2_h}$$

$$\alpha = -\arctan\left(\frac{(M^2_Z + M^2_A)c_\beta s_\beta}{M^2_Z c^2_\beta + M^2_A s^2_\beta - M^2_h}\right)$$

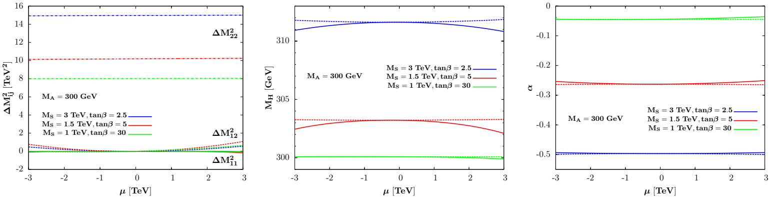
We first consider the radiative corrections when the subleading contributions proportional to $\mu, A_{t/b}$ are included in the form of : Degrassi, Slavich, Zwirner, 2001 ; Carena,Haber, 2003

$$\Delta\mathcal{M}^2_{11} = -\frac{v^2\sin^2\beta}{32\pi^2}\bar{\mu}^2\left[x_t^2\lambda_t^4(1+c_{11}\ell_S)+a_b^2\lambda_b^4(1+c_{12}\ell_S)\right]$$

$$\Delta\mathcal{M}^2_{12} = -\frac{v^2\sin^2\beta}{32\pi^2}\bar{\mu}\left[x_t\lambda_t^4(6-x_ta_t)(1+c_{31}\ell_S)-\bar{\mu}^2a_b\lambda_b^4(1+c_{32}\ell_S)\right]$$

$$\Delta\mathcal{M}^2_{22} = \frac{v^2\sin^2\beta}{32\pi^2}\left[6\lambda_t^4\ell_S(2+c_{21}\ell_S)+x_ta_t\lambda_t^4(12-x_ta_t)(1+c_{21}\ell_S)-\bar{\mu}^4\lambda_b^4(1+c_{22}\ell_S)\right]$$

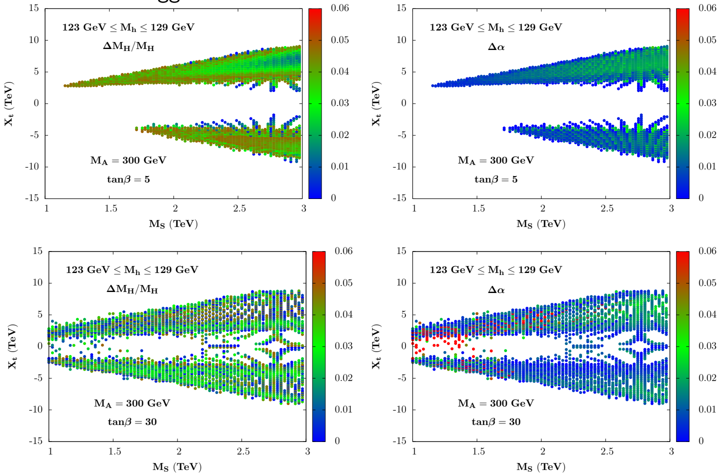
We calculate "approximate" and "exact" M_H and α values for $M_h = 126 \pm 3$GeV.



- Even for large μ, $\Delta M_H/M_H < 0.5\%$ and $\Delta\alpha \lesssim 0.015$.

$\Rightarrow$ The approximation of determining the parameters M_H and α from $\tan\beta, M_A$ and the value of M_h is extremely good.

To check more thoroughly the impact of the subleading corrections $\Delta\mathcal{M}^2_{11}$, $\Delta\mathcal{M}^2_{12}$: we perform a scan of the MSSM parameter space with the full two–loop radiative corrections to the Higgs sector :



For a chosen $(\tan\beta, M_A)$, $|\mu| \leq 3$ TeV, $|A_t, A_b| \leq 3M_S$, 1 TeV$\leq M_3 \leq$3 TeV and 0.5 TeV$\leq M_S \leq$3 TeV.

- In all cases, $\Delta M_H/M_H < 5\%$, very small values ($\ll \Gamma_H$).

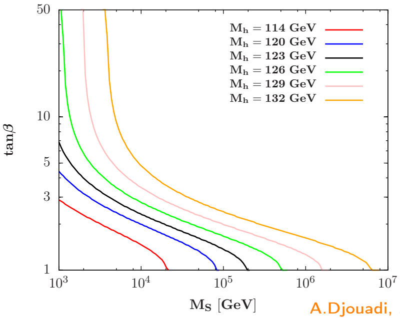
- $\Delta\alpha < 0.025$ for low $\tan\beta$ but at high $\tan\beta$ one can reach ≈ 0.05 in some rare situations (large μ which enhance the $\mu\tan\beta$ contributions).

- Nevertheless, at high enough $\tan\beta$, we are far in the decoupling regime already for $M_A \gtrsim 200$ GeV and such a difference does not significantly affect the couplings of the h/H bosons.

- Hence, even when including the full set of radiative corrections up to two loops, it is a very good approximation to derive the parameters M_H and α in terms of the inputs $\tan\beta$, M_A and the measured value of M_h (hMSSM).

- For the charged Higgs boson mass, the radiative corrections are much smaller for large enough M_A and one has $M_{H^\pm} \simeq \sqrt{M_A^2 + M_W^2}$.

- Large value of M_h+ non-observation of superparticles at the LHC $\Rightarrow$ suggest a high M_S.
- $\tan\beta \lesssim 3$ usually "excluded" by LEP2 ($M_h \gtrsim 114$ GeV) but it assumes $M_S \sim 1$TeV!
  But we can be more relaxed: $M_S \gg M_Z \Rightarrow \tan\beta \approx 1$ could be allowed!
  $\Rightarrow$ Let's reopen the low $\tan\beta$ regime and heavy Higgs searches.

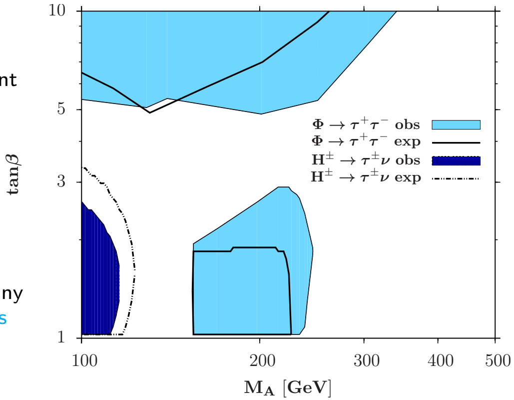


A.Djouadi, J.Q.,arXiv:1304.1787

- (hMSSM) We turn $M_h \sim M_Z|\cos 2\beta| + RC$ to $RC = 126 GeV - f(M_A, \tan\beta)$ ie. we trade the RC with the measured M_h
  $\Rightarrow$ MSSM with only 2 inputs at HO: M_A,$\tan\beta$ a model indep. effective approach!

Constraints from the heavier Higgs searches at high tan β :

- CMS $H/A \to \tau\tau$ analysis : constraint very restrictive for $M_A \lesssim 250$ GeV, excludes tan $\beta \gtrsim 5$.
- Caveat : ATLAS&CMS constraint apply for a specific benchmark : $X_t/M_S = \sqrt{6}$ and $M_S = 1$ TeV.
- Exclusion limit can be obtained in any MSSM scenario, CMS search limit is effective and excludes low tan β.



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$\to$ Low tan β areas, thought to be buried under the LEP2 exclusion bound on M_h, are now open territory for heavy MSSM Higgs hunting!

$\to$This can be done not only in these 2 channels but also in a plethora of channels...

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$	$g_{\Phi AZ}/g_{\Phi H^+W^-}$
h	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$	$\propto\cos(\beta-\alpha)$
H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$	$\propto\sin(\beta-\alpha)$
A	$\cot\beta$	$\tan\beta$	0	$\propto 0/1$

The decoupling limit is controlled by $g_{HVV}=\cos(\beta-\alpha)$:

$$g_{HVV} \xrightarrow{M_A\gg M_Z} \chi \equiv \frac{1}{2}\frac{M_Z^2}{M_A^2}\sin 4\beta - \frac{1}{2}\frac{\mathcal{M}_{22}^2}{M_A^2}\sin 2\beta \quad \to 0$$

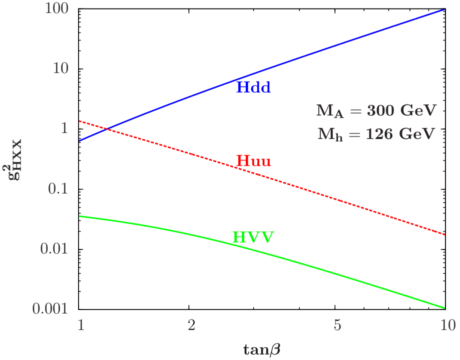
Tree–level part: doubly suppressed in both the tan $\beta \gg 1$ and tan $\beta \sim 1$ cases.

$$\sin 4\beta = \frac{4\tan\beta(1-\tan^2\beta)}{(1+\tan^2\beta)^2} \to \begin{cases} -4/\tan\beta & \text{for } \tan\beta \gg 1 \\ 1-\tan^2\beta & \text{for } \tan\beta \sim 1 \end{cases} \to 0$$

The radiative part : behave as $-\mathcal{M}_{22}^2/M_A^2 \times \cot\beta$, also vanishes at high tan β values $\Rightarrow$ the decoupling limit $g_{HVV}\to 0$ is reached very quickly at high tan β, as soon as $M_A \gtrsim M_h^{\max}$. Instead, for tan $\beta \approx 1$, this radiatively generated component is maximal. Departure from the decoupling limit!

$$\begin{array}{llll} g_{huu} & \xrightarrow{M_A\gg M_Z} & 1+\chi\cot\beta & \to 1 \\ g_{hdd} & \xrightarrow{M_A\gg M_Z} & 1-\chi\tan\beta & \to 1 \\ g_{Huu} & \xrightarrow{M_A\gg M_Z} & -\cot\beta+\chi & \to -\cot\beta \\ g_{Hdd} & \xrightarrow{M_A\gg M_Z} & +\tan\beta+\chi & \to +\tan\beta \end{array}$$

At low tan β : g_{HVV} is non–zero, g_{Htt} and g_{Att} are significant.
$\Rightarrow$ $H/A/H^{\pm}$ bosons can have sizable couplings to top quarks and massive gauge bosons if tan $\beta \sim 3$.



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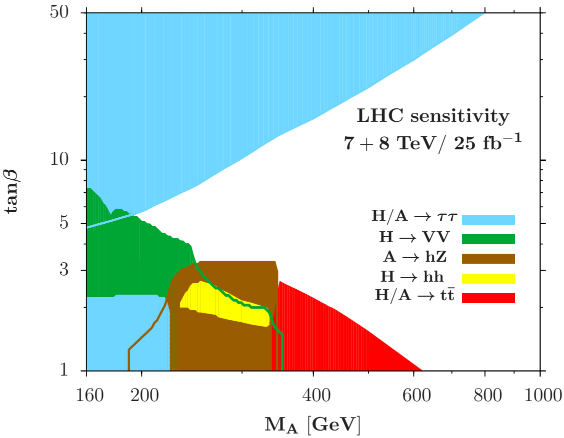
The main search channels for the H/A states :

- The **H** $\rightarrow$ **WW**, **ZZ** channels
- The **H/A** $\rightarrow$ **t$\bar{\text{t}}$** channels
- The **A** $\rightarrow$ **Zh** channel
- The **H** $\rightarrow$ **hh** channel



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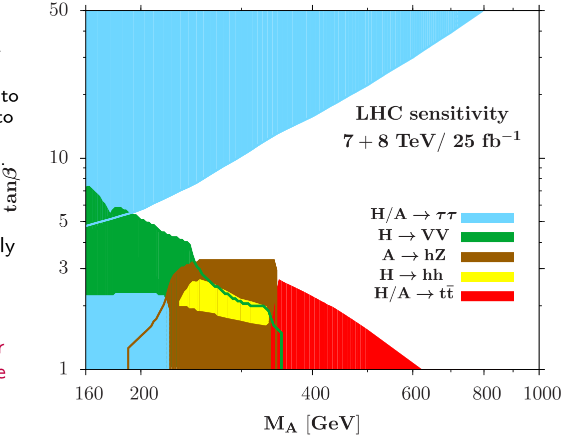
The $\mathbf{H/A \to t\bar{t}}$ channels

- It has not been considered in the case of the SM Higgs for 2 reasons :
  1. For $M_{H_{\rm SM}} \gtrsim 350$ GeV, $H_{\rm SM} \to WW, ZZ$ dominate over the $H_{\rm SM} \to t\bar{t}$.
  2. The $t\bar{t}$ background was thought to be overwhelmingly large (it had to be evaluated in a large mass window because of the large Γ_H).
- Situation different in the MSSM : $\Gamma_{H/A} \lesssim 20$ GeV for $\tan\beta \gtrsim 1$ and $M_{H,A} \lesssim 500$ GeV (and grow linearly with the Higgs masses beyond this value)
  $\Rightarrow$ one can integrate the $t\bar{t}$ continuum background in a smaller invariant mass bin and enhance the S/B ratio.
- BR($H/A \to t\bar{t}$) $\approx 100\%$ for $\tan\beta \lesssim 3$ if kinematically open.



Search for $H/A \to t\bar{t}$ will be more favorable for the MSSM at low $\tan\beta$ than in the SM.

- Knowing $[\tan\beta, M_A]$ and fixing $M_h = 125$ GeV, the couplings of the Higgs bosons can be derived, including the generally dominant radiative corrections that enter in the MSSM Higgs masses :

$$c_V^0 = \sin(\beta-\alpha)\ , \quad c_t^0 = \frac{\cos\alpha}{\sin\beta}\ , \quad c_b^0 = -\frac{\sin\alpha}{\cos\beta}$$

- However, there are also direct radiative corrections to the Higgs couplings not contained in the mass matrix. These can alter this simple picture!

- The $hb\bar{b}$ coupling : modified by additional one–loop vertex corrections,

$$c_b \approx c_b^0 \times [1 - \Delta_b/(1+\Delta_b) \times (1 + \cot\alpha\cot\beta)]$$

Δ_b : SUSY–QCD corr. with sbottom–gluino loops

- The $ht\bar{t}$ coupling : derived indirectly from $\sigma(gg\to h)$ and $BR(h\to\gamma\gamma)$,

$$c_t \approx c_t^0 \times \left[1 + \frac{m_t^2}{4m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - (A_t - \mu\cot\alpha)(A_t + \mu\tan\alpha)\ )\right]$$

- $c_c = c_t^0$ and $c_\tau = c_b^0$.

- Invisible decays? (Djouadi,Falkowski,Mambrini,JQ, arXiv:1205.3169)
$\Rightarrow$ neutralinos are relatively light and couple significantly to $h \to$ rather unlikely.

- If large direct corrections $\Rightarrow$ 3 independent h couplings :
  $c_c = c_t$, $c_\tau = c_b$ and $c_V = c_V^0$.

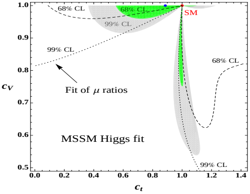
- To study the h state at the LHC, we define the effective Lagrangian :

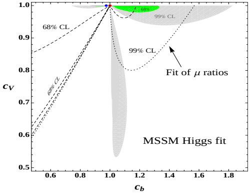
$$\begin{aligned}\mathcal{L}_h \quad = & \quad c_V \; g_{hWW} \; h \; W_\mu^+ W^{-\mu} + \; c_V \; g_{hZZ} \; h \; Z_\mu^0 Z^{0\mu} \\ - & \quad c_t \; y_t \; h\bar{t}_L t_R - c_t \; y_c \; h\bar{c}_L c_R - c_b \; y_b \; h\bar{b}_L b_R - c_b \; y_\tau \; h\bar{\tau}_L \tau_R \; + \; \mathrm{h.c.}\end{aligned}$$

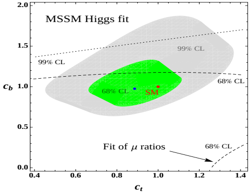
- We fit the Higgs signal strengths : $\mu_{\boldsymbol{X}} \simeq \frac{\sigma(\boldsymbol{pp}\to\boldsymbol{h})\times \mathrm{BR}(\boldsymbol{h}\to\boldsymbol{XX})}{\sigma(\boldsymbol{pp}\to\boldsymbol{h})_{\mathrm{SM}}\times \mathrm{BR}(\boldsymbol{h}\to\boldsymbol{XX})_{\mathrm{SM}}}$

Best-fit value : $c_t = 0.89$, $c_b = 1.01$ and $c_V = 1.02$ (ATLAS & CMS data).

If we neglect direct corrections $\rightarrow$ 2 parameters fits :



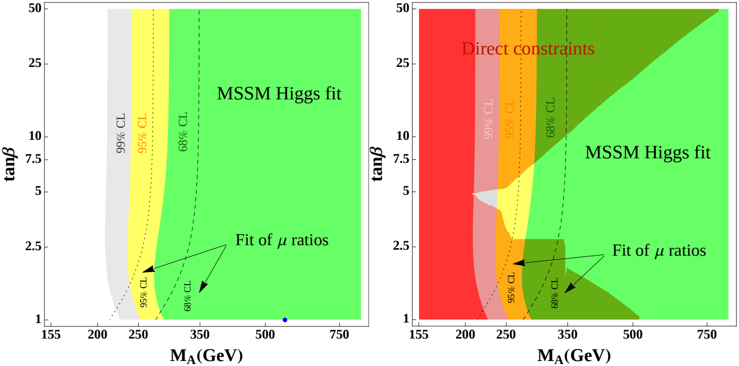




best-fit points : ($c_t = 0.88$, $c_V = 1.0$), ($c_b = 0.97$, $c_V = 1.0$) and ($c_t = 0.88$,$c_b = 0.97$)

Using the expressions defining the hMSSM one can perform a fit in the plane $[\tan\beta, M_A]$.

The best-fit point : $(\tan\beta = 1$ and $M_A = 557$ GeV$)$ or
$(M_H = 580$ GeV, $M_{H^\pm} = 563$ GeV, $\alpha = -0.837$ rad$)$.



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We also superimpose on these indirect limits, the direct constraints on the heavy $H/A/H^\pm$ boson searches performed by the ATLAS and CMS (as discussed earlier).

Conclusion :

- We have discussed the hMSSM, i.e. the MSSM that we seem to have after the discovery of the Higgs boson at the LHC.

  $\Rightarrow$ the MSSM Higgs sector can be described by only $(\tan\beta, M_A)$ if the information $M_h = 125$ GeV is used.

- $M_h \approx 125$ GeV and the non–observation of SUSY particles, seems to indicate that the soft–SUSY breaking scale might be large.

  $\Rightarrow$ We have considered the production of the heavier H,A and $H^{\pm}$ bosons of the MSSM at the LHC, focusing on the low $\tan\beta$ regime.

- We have shown that to describe the h properties when the direct radiative corrections are also important, we need the 3 couplings c_t, c_b and c_V.

  $\Rightarrow$ the best fit point turns out to be at low $\tan\beta$, $\tan\beta \approx 1$, and with a not too high CP–odd Higgs mass, $M_A \approx 560$ GeV. But it's to early to say anything!

- Except may be : the phenomenology of this point is quite interesting and accessible at the next LHC run.

- Correct relic abundance of the LSP can be easily obtained through $\chi_1^0\chi_1^0 \to A \to t\bar{t}$.