The 126 GeV Higgs Boson in a general MSSM model with explicit CP-violation

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1 Introduction
- Motivation
- Theoretical model: Generalised CP-Violating MSSM

2 Experimental Results
- $\gamma\gamma$ and $\tau\tau$ channels
- Flavour Constraints

3 Model Analysis
- Light Higgs spectrum
- Heavy Higgs spectrum

4 Summary
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Motivation

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- Identity of the observed scalar resonance in the LHC experiments.
- New particles?
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For our analysis:

- Latest LHC results on Higgs observables.
- Indirect constraints from low energy process.
- Semi-analytic approach.
Outline

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4 Summary
**Framework**: generic MSSM defined at the EW scale with explicit CP Violation.
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- We only fix the lightest Higgs mass, $m_{h^0} = 126$ GeV.
- The rest of parameters are free, independent and only constrained by experimental results.
- No imposition of the correct EWSB (Higgs mixings and masses, and the $\mu$ parameter free and independent).
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This scheme can be thought as the most general one encompassing all the possible MSSM realizations.

It is also the most conservative analysis since we scrutinize the allowed areas in the parameter space, even when some of these points may not be possible in a complete model.
Higgs sector: type II 2HdM considering CP-violating phases.
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Two scalar doublets,

\[ \Phi_1 = \begin{pmatrix} \frac{1}{\sqrt{2}}(\nu_1 + \phi_1 + i\alpha_1) \\ \phi_1^- \end{pmatrix} \quad \Phi_2 = e^{i\xi} \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(\nu_2 + \phi_2 + i\alpha_2) \end{pmatrix} \]
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And the (non-diagonal) mass matrix in the basis \((\phi_1, \phi_2, a)\) as:

\[ M^2_H = \begin{pmatrix} M^2_S & M^2_{SP} \\ M^2_{PS} & M^2_P \end{pmatrix} \]

This \(3 \times 3\) matrix is diagonalized by an unitary matrix \(U\).

\[ U \cdot M^2_H \cdot U^T = \text{Diag} \left( m^2_{h_1}, m^2_{h_2}, m^2_{h_3} \right) \]
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4. Summary
For both, the $\gamma\gamma$ and $\tau\bar{\tau}$ channels, we use the signal strength to distinguish the accepted points in the parameter space:

$$\mu_X = \frac{\sigma(pp \to h) \times BR(h \to X)}{\sigma(pp \to h)_{SM} \times BR(h \to X)_{SM}}$$

$\mu_X = 0$ corresponds to the background-only hypothesis and $\mu_X = 1$ with the SM Higgs signal.
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- \( \gamma \gamma \) channel: ATLAS and CMS results at 2\( \sigma \).

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\left\{ \begin{array}{l}
\mu_{\gamma \gamma}^{ATLAS} = 1.6 \pm 0.3 \\
\mu_{\gamma \gamma}^{CMS} = 0.78^{+0.28}_{-0.26}
\end{array} \right. \quad \Rightarrow \quad 0.75 \leq \mu_{\gamma \gamma}^{LHC} \leq 1.55
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- \(\tau\bar{\tau}\) channel: CMS and ATLAS limits as a function of the Higgs mass.
For masses up to 150 GeV, CMS sets the strongest bound at 95% C.L. whereas for heavy masses there exists a previous ATLAS analysis with masses up to 500 GeV.

It is expected the ATLAS bound will be improved nearly an order of magnitude in an updated analysis with the new data.
In November the CMS collaboration presented an analysis of the full data set with masses up to 1 TeV. The analysis discriminates between Higgses produced through gluon fusion and in association with b quarks.
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In our calculations we include some indirect constraints such as $B \to X_s \gamma$, $B_s \to \mu^+ \mu^-$ and the top decay $t \to bH^+$. The strongest bound is setting by $B \to X_s \gamma$ which experimental limits come from BaBar and Belle B-factories and CLEO. The current world average for $E_{\gamma} > 1.6$ GeV given by HFAG is:

$$\text{BR}(B \to X_s \gamma) = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$$

The 95\% C.L. range in our analysis:

$$2.99 \leq \text{BR}(B \to X_s \gamma) \times 10^{-4} \leq 3.87$$
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The diphoton production cross section for $h_1^0$ is giving by:

$$\sigma_{\gamma\gamma} = \sigma(pp \rightarrow h_1^0) \times BR(h_1^0 \rightarrow \gamma\gamma) = \sigma(pp \rightarrow h_1^0) \times \frac{\Gamma(h_1^0 \rightarrow \gamma\gamma)}{\Gamma(h_1^0)}$$
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\]

The experimental constraint tells us:

\[
0.75 \leq \mu_{\gamma\gamma} \leq 1.55 \quad \implies \quad \sigma_{\gamma\gamma} \sim \sigma_{\gamma\gamma}^{SM}
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$$
\sigma^{LO}(pp \rightarrow h_1^0) \approx \left[ 13 U_{12}^2 - \frac{1.5 \tan\beta}{1 + \kappa_d \tan\beta} U_{12} U_{11} + \frac{0.1 \tan^2\beta}{(1 + \kappa_d \tan\beta)^2} U_{11}^2 \right. \\
+ \left. \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_{13}^2 \right] \\
+ 0.16 \frac{\tan^2\beta}{(1 + \kappa_d \tan\beta)^2} \left( |U_{11}|^2 + |U_{13}|^2 \right);
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Diphoton signal

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+ 0.16 \frac{\tan^2\beta}{(1 + \kappa_d \tan\beta)^2} \left( |U_{11}|^2 + |U_{13}|^2 \right);
$$

The decay width into two photons has two contributions: the scalar amplitude and the pseudoscalar amplitude. The SM amplitude has a value: $S_{SM}^\gamma = -6.55$

The total decay width is dominated by $h_1^0 \rightarrow WW^*$ and decays to down-type fermions ($\tan^2\beta$ enhanced).

$$
\text{BR}(h_1^0 \rightarrow \gamma\gamma) \approx 4.65 \cdot 10^{-3} \frac{|S^\gamma/6.5|^2 + |P^\gamma/6.5|^2}{(U_{11}^2 + U_{13}^2) \tan^2\beta + 0.38 \left( U_{12} + \frac{U_{11}}{\tan\beta} \right)^2}.
$$
Diphoton signal

Allowed $U_{12}$ values considering the diphoton signal strength. Cyan color, $\tan \beta < 5$. Magenta color, $\tan \beta \in [5, 9]$. Blue color, $\tan \beta \in [9, 30]$. Red color, $\tan \beta > 30$. 

![Graph showing $U_{12}$ vs. MSSM parameters with color-coded regions for different tan beta values.](image-url)
Diphoton signal

Condition

Suppression of the down-type component in the 126 GeV Higgs boson composition in order to reproduce the SM production cross section in the $\gamma\gamma$ channel.
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That means:

- Having a lightest Higgs $h_1^0$ predominantly up-type $h_u^0$
- In terms of the mixing mass matrix elements:

\[
U_{12} \approx 1 \\
U_{11}, U_{13} \leq \frac{1}{\tan \beta}
\]
Watch out!

- Now $h_2^0$ and $h_3^0$, large down-type components:

$$U_{12} \simeq 1 \Rightarrow U_{a2} \lesssim \frac{1}{\tan \beta} \Rightarrow (|U_{a1}|^2 + |U_{a3}|^2) \sim 1 \text{ for } i = 2, 3$$

- Disagreement with actual $\tau \bar{\tau}$ bounds?
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Decay width into two $\tau$ leptons:

$$\Gamma \left( h_a^0 \to \tau^+ \tau^- \right) \simeq \frac{g^2 m^2\tau m_{h_a}}{32\pi M_W^2} \tan^2 \beta, \quad \text{for } a = 2, 3$$
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**Decay width** into two $\tau$ leptons:

$$\Gamma \left( h_a^0 \to \tau^+ \tau^- \right) \approx \frac{g^2 m_\tau^2 m_{h_a}}{32\pi M_W^2} \tan^2 \beta, \quad \text{for } a = 2, 3$$

**Total decay width**:

$$\Gamma \left( h_a^0 \right) \approx \frac{g^2 m_{h_a}}{32\pi M_W^2} (3 m_b^2 + m_\tau^2) \tan^2 \beta, \quad \text{for } a = 2, 3$$
Production cross section dominated by the $b$-contribution in the gluon fusion process and the $b\bar{b}$ fusion process.

$$\sigma(pp \rightarrow h_a^0) \simeq \left[ 0.07 \left( \frac{\tau_{h_a} d\mathcal{L}^{bb}/d\tau_{h_a}}{1000\text{pb}} \right) + 0.04 \left( \frac{\tau_{h_a} d\mathcal{L}^{gg}/d\tau_{h_a}}{1.1 \cdot 10^6\text{pb}} \right) \right] \frac{\tan^2 \beta}{(1 + \kappa_d \tan \beta)^2} \text{ pb}$$

where $\tau_{h_a} = m_{h_a}^2/s$, we have taken into account that $\mathcal{U}_{a1}^2 + \mathcal{U}_{a3}^2 \sim 1$ for $a = 2, 3$ and we have used the gluon and $b\bar{b}$ luminosities at $m_{h_a} = 150$ GeV.
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- Medium-large $\tan \beta$, $\tan \beta \gtrsim 15$, there will be no acceptable points in the parameter space.
Production cross section dominated by the $b$-contribution in the gluon fusion process and the $b\bar{b}$ fusion process.

\[
\sigma(pp \to h_0^0) \simeq \left[ 0.07 \left( \frac{\tau_{ha} dL^{bb} / d\tau_{ha}}{1000 \text{pb}} \right) + 0.04 \left( \frac{\tau_{ha} dL^{gg} / d\tau_{ha}}{1.1 \cdot 10^6 \text{pb}} \right) \right] \frac{\tan^2\beta}{(1 + \kappa_d \tan\beta)^2} \text{pb}
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- Medium-large $\tan\beta$, $\tan\beta \gtrsim 15$, there will be no acceptable points in the parameter space.

- For low $\tan\beta$ some points survive in the parameter space.
Parameter space points classified according to their compatibility with the CMS limits in the $\tau\bar{\tau}$ channel using 4.9 fb$^{-1}$ at $\sqrt{s} = 7$ TeV and 19.4 fb$^{-1}$ at $\sqrt{s} = 8$ TeV for Higgs masses up to 150 GeV.
Indirect constraints

Some points survive low $\tan \beta$ regime due to a relaxation in the $\tau \bar{\tau}$ channel. Our last step will be consider an additional indirect constraints: the low energy process, $B \rightarrow X_s \gamma$. 

The branching ratio for $B \rightarrow X_s \gamma$ can be expressed as:

$$BR(B \rightarrow X_s \gamma) = a + a_{77} \delta C_7 + a_{88} \delta C_8 + Re(a_{78} \delta C_7 \delta C_8^*)$$

where $a = 3.0 \times 10^{-4}$ is the SM W-contribution. $a_{77}$, $a_{88}$, $a_7$, $a_8$ and $a_{78}$ are numerical coefficients. $\delta C_7$, $\delta C_8 = C_{\pm, 7} + C_{\pm, 8}$ Wilson coefficients that contain the charged-Higgs and stop-chargino loop contributions. At low $\tan \beta$, this branching ratio receives a sizeable contribution from the charged Higgs that cannot be compensated by the stop-chargino contribution.
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Parameter space points classified according to their compatibility with indirect processes. All these points satisfy the CMS limits in the $\tau\bar{\tau}$ channel as well as the diphoton signal for $h_1^0$. 

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{indirect_constraints.png}
\caption{Parameter space points classified according to their compatibility with indirect processes.}
\end{figure}
Indirect constraints

Parameter space points classified according to their compatibility with indirect processes. All these points satisfy the CMS limits in the $\tau\bar{\tau}$ channel as well as the diphoton signal for $h_1^0$. Imposing ATLAS bounds for $t \to bH^+$ only blue points survive.
Parameter space points classified according to their compatibility with indirect processes. All these points satisfy the CMS limits in the $\tau\bar{\tau}$ channel as well as the diphoton signal for $h_1^0$. Imposing ATLAS bounds for $t \rightarrow bH^+$ only blue points survive. However, none of them satisfy $B \rightarrow X_s\gamma$ constraint.
The analysis for a light MSSM Higgs spectrum is conclusive:

- Ruled out light extra Higgs bosons
- The diphoton and $\tau\tau$ signals in addition to $B \to X_s \gamma$ are enough to rule out the possibility of a light Higgs spectrum.
- Note that the possibility of having a second resonance at 136 GeV is also discarded.

What will happen for heavy masses, $m_{H^\pm} > m_t$?
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Heavy extra Higgs states

For these masses, there are new accessible decay channels for the extra Higgs states that can reduce the $h_a^0 \rightarrow \tau \bar{\tau}$ branching ratio:

1. $H_i \rightarrow WW$ or $H_i \rightarrow WW^*$ in case that $m_{H_i} < 2M_W$.
2. $H_i \rightarrow ZZ$ or $H_i \rightarrow ZZ^*$ in case that $m_{H_i} < 2M_Z$.
3. $H_i \rightarrow H_j H_k$.
4. $H_i \rightarrow H_j Z$ or $H^\pm \rightarrow H_j W^\pm$. 
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How is now the parameter space for these masses?
Heavy extra Higgs states

This plot shows how constrained is the parameter space when $\tau\bar{\tau}$ ATLAS searches up to 500 GeV, with 4.8fb$^{-1}$ at $\sqrt{s} = 7$ TeV, are used.
Heavy extra Higgs states

This plot shows how constrained is the parameter space when CMS searches in the \( \tau \bar{\tau} \) channel, with 4.9\( fb^{-1} \) at \( \sqrt{s} = 7 \) TeV and 19.7\( fb^{-1} \) at \( \sqrt{s} = 8 \) TeV, are used to restrict the parameter space. Yellow points satisfy all the constraints except CMS recent \( \tau \bar{\tau} \) data while blue points fulfill also the recent CMS constraints at 95% C.L.
Conclusion for heavy extra Higgs masses.

- Latest CMS results allow us to discard a significant region in the MSSM space parameter. In fact, $m_{h_2} \gtrsim 250$ GeV is absolutely needed and this bound is higher for low and larger $\tan \beta$ values.

- A better bound will be established once ATLAS $\tau\tau$ data will be improved. Probably it would allow us to eliminate the possibility of $m_{h_0} \lesssim 300$ GeV.
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- CMS data in the $\tau\bar{\tau}$ channel together with indirect constraints eliminate the possibility of any extra Higgs state with mass below 250 GeV.
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- CMS data in the $\tau\bar{\tau}$ channel together with indirect constraints eliminate the possibility of any extra Higgs state with mass below 250 GeV.

- The combination of the latest experimental searches with indirect constraints is an excellent weapon to search for additional Higgs states.
Latest LHC results, specially the CMS improved $\tau\bar{\tau}$ limits, have been used in this analysis.

Lightest Higgs as the $126$ GeV discovered boson and the $\gamma\gamma$ channel give us a strong condition over the mixings for the Higgs sector.

CMS data in the $\tau\bar{\tau}$ channel together with indirect constraints eliminate the possibility of any extra Higgs state with mass below $250$ GeV.

The combination of the latest experimental searches with indirect constraints is an excellent weapon to search for additional Higgs states.

This semi-analytic approach is a powerful technique that provides a much better understanding on the physics of the model.
Thanks for your attention!

Acknowledgments
Backup
Main consequences of explicit radiative CP violation in the Higgs sector.

It leads to mixing mass terms between the CP-even and CP-odd Higgs fields. Thus, one has to consider a $3 \times 3$ mass matrix for the neutral physical Higgs states.

$$
\mathcal{M}^2_H = \begin{pmatrix}
M^2_S & M^2_{SP} \\
M^2_{PS} & M^2_P
\end{pmatrix}
$$

where $M_{SP} = M^T_{PS}$ contains the CP-violating mixings.

$$
M^2_{SP} \sim \mathcal{O} \left( \frac{m_t^4 |\mu| |A_t|}{32 P^2 v^2 M^2_{susy}} \right) \sin \phi_{CP} \left[ 6, \frac{|A^2_t|}{M^2_{susy}}, 2 \Re \{\mu A_t\} \right]
$$

From these expression we see that large effects in the Higgs sector appear due to the presence of CP-violating phases when $\text{Im} \left\{ \mu A_{t,b} \right\} \gtrsim M^2_{susy}$ and $M^2_P$ is not much larger than $v^2$. 

The top decay to charged Higgs has been searched for at ATLAS. The new results that we used in our analysis had been released on ATLAS-CONF-2013-090.

This bound becomes the main discriminating channel for very light charged Higgs masses (up to \(m_{H^\pm} = 160\) GeV). There are however regions where this role is played by \(B \rightarrow X_s \gamma\).
The Higgs decay width into two photon within a MSSM context is given by:

\[
\Gamma(h^0_a \rightarrow \gamma\gamma) = \frac{\alpha^2 m_{h^a}^3}{256\pi^3 v^2} \left[ |S^\gamma_a(m_{h^a})|^2 + |P^\gamma_a(m_{h^a})|^2 \right]
\]

where the scalar amplitude receives contributions from the W boson, quarks, squarks, charginos and charged Higgs.

\[
S^\gamma_W \simeq -8.3 \left( U_{a2} + \frac{U_{a1}}{\tan \beta} \right)
\]

\[
S^\gamma_{b+t} \simeq 1.8 U_{a2} + (-0.025 + i \, 0.034) \left[ \text{Re} \left\{ \frac{\tan \beta}{1 + \kappa_d \tan \beta} \right\} U_{a1} + \text{Im} \left\{ \frac{\kappa_d \tan^2 \beta}{1 + \kappa_d \tan \beta} \right\} U_{a3} \right]
\]

\[
S^\gamma_{H^\pm} = -g_{h^0_H H^\pm} \frac{v^2}{2 m_{H^\pm}^2} F_0(\tau_{aH^\pm}) \lesssim -0.45 \left\{ \left( \frac{2 \lambda_1 - \lambda_4 - 2 \text{Re}\{\lambda_5\}}{\tan \beta} \right) U_{a2} \right. \\
\left. + \left( \frac{\lambda_3 + \text{Re}\{\lambda_6\} - 2 \text{Re}\{\lambda_7\}}{\tan \beta} \right) U_{a2} \right. \\
\left. + \left( \frac{2 \text{Re}\{\lambda_5\}}{\tan \beta} - \text{Im}\{\lambda_6\} \right) U_{a3} \right\}
\]
Diphoton Higgs decay width

\[ S^\gamma_b \approx 1.2 \cdot 10^{-5} \tan^2 \beta \left( \frac{300 \text{ GeV}}{m_{b_1}} \right)^2 \left[ \frac{\Re \{ A_b^* \mu \} }{m^2_{b_2}} U_{a1} - \frac{\mu^2}{m^2_{b_2}} U_{a2} + \frac{\Im \{ A_b^* \mu \} }{m^2_{b_2} \tan \beta} U_{a3} \right] \]

\[ S^\gamma_{\tilde{\tau}} \approx 3.0 \cdot 10^{-5} \tan^2 \beta \left( \frac{200 \text{ GeV}}{m_{\tilde{\tau}_1}} \right)^2 \left[ \frac{\Re \{ A_{\tilde{\tau}}^* \mu \} }{m^2_{\tilde{\tau}_2}} U_{a1} - \frac{\mu^2}{m^2_{\tilde{\tau}_2}} U_{a2} + \frac{\Im \{ A_{\tilde{\tau}}^* \mu \} }{m^2_{\tilde{\tau}_2} \tan \beta} U_{a3} \right] \]

\[ S^\gamma_{\tilde{t}} \approx 0.45 \left( 1 - \frac{m^2_{\tilde{t}_1}}{m^2_{\tilde{t}_2}} \right) \left[ -\Re \left\{ \frac{\mu m_t R_{11}^* R_{21}^*}{m^2_{\tilde{t}_1}} \right\} U_{a1} + \Re \left\{ \frac{A_t^* m_t R_{11}^* R_{21}^*}{m^2_{\tilde{t}_1}} \right\} U_{a2} \right. \\
\left. + \Im \left\{ \frac{\mu m_t R_{11}^* R_{21}^*}{m^2_{\tilde{t}_1}} \right\} U_{a3} \right] + 0.45 \left( \frac{m^2_t |R_{11}|^2}{m^2_{\tilde{t}_1}} + \frac{m^2_t |R_{12}|^2}{m^2_{\tilde{t}_2}} \right) U_{a2} \]

\[ S^\gamma_{\chi^\pm} \approx 2.8 \left[ \cos \beta \frac{M^2_W}{\mu^2} U_{a1} + \frac{M^2_W}{M^2_2} U_{a2} \right] \lesssim 0.15 \left[ U_{a2} + \frac{M^2_W}{\mu^2} U_{a1} \right] \]
Diphoton Higgs decay width

Therefore, the dominant contributions come from the W boson and top quark, with the bottom quark sizeable only for very large $\tan \beta$ and the stop one important for light stops.

\[
S^\gamma_{h_0} \simeq U_{a1} \left( -\frac{8.3}{\tan \beta} + (-0.025 + i 0.034) \Re \left\{ \frac{\tan \beta}{1 + \kappa_d \tan \beta} \right\} - 0.45 \left( 1 - \frac{m_{t_1}^2}{m_{t_2}^2} \right) \Re \left\{ \frac{\mu m_t R_{11}^* R_{21}}{m_{t_2}^2} \right\} \right) + \\
U_{a2} \left( -6.5 + 0.45 \left( 1 - \frac{m_{t_1}^2}{m_{t_2}^2} \right) \Re \left\{ \frac{A_t^* m_t R_{11}^* R_{21}^*}{m_{t_1}^2} \right\} + 0.45 \left( \frac{m_t^2 |R_{11}|^2}{m_{t_1}^2} + \frac{m_t^2 |R_{12}|^2}{m_{t_2}^2} \right) \right) + \\
U_{a3} \left( (-0.025 + i 0.034) \Im \left\{ \frac{\kappa_d \tan^2 \beta}{1 + \kappa_d \tan \beta} \right\} + 0.45 \Im \left\{ \frac{\mu m_t R_{11}^* R_{21}}{m_{t_2}^2} \right\} \right)
\]

Regarding the pseudoscalar amplitude, the same discussion before applies to it and as it only receives contributions from quarks and charginos remains much smaller than the SM one and can be neglected.

Therefore the scalar amplitude has to be compared with the SM one, $S^\gamma_{SM} \simeq -6.55$. 
On the other hand, the total decay width is mainly given by the decays into $WW^*$ and down-type fermions, this last one enhanced by $\tan^2 \beta$ in contrast to the SM decay.

$$\Gamma_{h_a} \simeq \frac{g^2 m_{h_a}}{32\pi M_W} \left[ \tan^2 \beta (U_{a1}^2 + U_{a3}^2)(3m_b^2 + m_{\tau}^2) + I_{PS} \left( U_{a2} + \frac{U_{a1}}{\tan \beta} \right)^2 \right]$$

The decay into two gluons is always subdominant and can be safely neglected.
The two main Higgs production processes are gluon fusion and, specially for large $\tan\beta$, the $b\bar{b}$ fusion. Other mechanism, such as vector boson fusion, will be always sub-dominant.

Taking into account QCD corrections, the $b\bar{b}$ fusion production cross section is given by:

$$\hat{\sigma}_{b\bar{b}\rightarrow h_a}^{QCD} = \frac{4\pi^2}{9m_{h_a}} \Gamma_{h_a\rightarrow b\bar{b}} = \frac{\pi}{6} \frac{g^2 m_b^2}{4M_W^2} K^b_a \left( \frac{m_b(m_{h_a})}{m_b(m_t)} \right)^2 \beta_b \left( \beta_b^2 |g^b_S|^2 + |g^b_P|^2 \right)$$

Considering only the main threshold corrections to the bottom couplings, the cross section can be approximated as:

$$\hat{\sigma}_{b\bar{b}\rightarrow h_a}^{QCD} \approx \frac{\pi}{6} \frac{g^2 m_b^2}{4M_W^2} K^b_a \left( \frac{m_b(m_{h_a})}{m_b(m_t)} \right)^2 \frac{\tan^2 \beta}{(1 + \kappa_d \tan \beta)^2} \left( |U_{a1}|^2 + |U_{a3}|^2 \right)$$

$$\approx 6.8 \cdot 10^{-5} K^b_a \left( \frac{m_b(m_{h_a})}{m_b(m_t)} \right)^2 \frac{\tan^2 \beta}{(1 + \kappa_d \tan \beta)^2} \left( |U_{a1}|^2 + |U_{a3}|^2 \right)$$

where the QCD factor goes from 1.28 to 0.89 for masses between (126, 1000) GeV.
Partonic Higgs production

At leading order, the cross section for the production of Higgs particles through the gluon fusion process is given by:

$$\sigma^{\text{LO}}_{gg\rightarrow h_a} = \hat{\sigma}^{\text{LO}}_{gg\rightarrow h_a} \delta \left(1 - \frac{m_{h_a}^2}{\hat{s}}\right) = \frac{\pi^2}{8m_{h_a}} \Gamma^{\text{LO}}_{h_a\rightarrow gg} \delta \left(1 - \frac{m_{h_a}^2}{\hat{s}}\right)$$

$$\hat{\sigma}^{\text{LO}}_{gg\rightarrow h_a} = \frac{\alpha_s^2(Q)m_{h_a}^2}{256\pi v^2} \left(|S^g_a|^2 + |P^g_a|^2\right) \approx 4 \cdot 10^{-6} \left(|S^g_a|^2 + |P^g_a|^2\right)$$

where the scalar form factor, $S^g_a$, gets contributions from quarks and squarks whereas the pseudoscalar form factor, $P^g_a$, only from quarks. Analogously to the photonic amplitudes, the sbottom and stop contributions can be safely neglected so that the gluon fusion cross section can be approximated as:

$$\hat{\sigma}^{\text{LO}}_{gg\rightarrow h_a} \approx 4 \cdot 10^{-6} \left[0.49 U^{2}_{a2} - \frac{0.056 \tan \beta}{1 + \kappa_d \tan \beta} U_{a2} U_{a1} + \frac{0.004 \tan^2 \beta}{(1 + \kappa_d \tan \beta)^2} U^{2}_{a1} \right.$$

$$\left. + \left(\frac{0.08}{1 + \kappa_d \tan \beta} + \frac{0.004 \tan^2 \beta}{(1 + \kappa_d \tan \beta)^2} + \frac{1}{\tan^2 \beta}\right) U^{2}_{a3}\right]$$

where we can see that the first term, that comes from the top quark contribution, is dominant for $U_{a2} \sim 1$. 

Hadronic Higgs production

The $b\bar{b}$ fusion contribution to the hadronic cross section can be obtained in the narrow-width approximation from the partonic cross section by multiplying the $b\bar{b}$ luminosity.

$$
\sigma_{bb}^{QCD}(pp \to h_a) = \hat{\sigma}_{bb \to h_a}^{QCD} \frac{d\mathcal{L}_{bb}^{LO}}{d\tau_{h_a}}
$$

For the 126 GeV Higgs boson and considering $\sqrt{s} = 8$ TeV, $\tau d\mathcal{L}_{bb}^{LO}/d\tau \simeq 2300$ pb, so that the expression before can be approximated as:

$$
\sigma_{bb}^{QCD}(pp \to h_a) \simeq 0.16 \frac{\tan^2 \beta}{(1 + \kappa_d \tan \beta)^2} \left( |U_{a1}|^2 + |U_{a3}|^2 \right)
$$

Notice that associated Higgs production with heavy quarks $gg/q\bar{q} \to b\bar{b} + h_a^0$ is equivalent to the $b\bar{b} \to h_a^0$ inclusive process if we do not require to observe the final state b-jets and one consider the b-quark a massless parton in a five active flavour scheme.
Hadronic Higgs production

Again, the proton-proton cross section at NLO for the gluon fusion process can be obtained in the narrow-width approximation in terms of the gluon luminosity and the so-called K-factors:

$$\sigma^{LO}_{gg}(pp \to h_a) = K \hat{\sigma}^{LO}_{gg \to h_a} \frac{d\mathcal{L}^{LO}_{gg}}{d\tau_{h_a}}$$

For the 126 GeV Higgs boson and $\sqrt{s} = 8$ TeV the gluon luminosity is $\tau d\mathcal{L}^{LO}_{gg} / d\tau \simeq 3 \cdot 10^6$ pb and $K \simeq 2.2$ so that the expression before can be approximated as:

$$\sigma^{LO}_{gg}(pp \to h_a = 126 \text{ GeV}) \simeq \left[ 13U_{a2}^2 - \frac{1.5 \tan \beta}{1 + \kappa_d \tan \beta} U_{a2} U_{a1} + \frac{0.1 \tan^2 \beta}{(1 + \kappa_d \tan \beta)^2} U_{a1}^2 \right]$$

$$+ \left( \frac{2}{1 + \kappa_d \tan \beta} + \frac{0.1 \tan^2 \beta}{(1 + \kappa_d \tan \beta)^2} + \frac{27}{\tan^2 \beta} \right) U_{a3}^2$$
The latest CMS constraints discriminate between the production of Higgs bosons in association with b quarks and through gluon fusion mechanism. For this first process, at least one b-tagged jet with $p_T > 20$ GeV is required and not more than one jet with $p_T > 30$ GeV.

Therefore, the theoretical production cross section for this process has to be obtained using the MSTW2008 pdf in the 5-flavour scheme with the $bg \rightarrow h_a b$ cross section and a 30 GeV $p_T$ cut on the final b-jet.

$$
\frac{d\hat{\sigma}_{gb\rightarrow h_a b}}{dt} = -\frac{1}{s^2} \frac{\alpha_S(\mu)}{24} \left( \frac{y_b(\mu)}{\sqrt{2}} \right)^2 \frac{M_{h_a}^4 + u^2}{st}
$$

where $s$, $t$, $u$ are the Mandelstan variables. The total $pp$ cross section is then obtained as,

$$
\sigma(pp \rightarrow h_a b) = 4\hat{\sigma}_{gb\rightarrow h_a b} \int_\tau^1 \frac{dx}{x} b(x, M^2) g(\tau/x, M^2)
$$

where $\tau = (p_g + p_b)^2/s$ and the factor 4 is due to the b-quark coming from one of the two protons and the conjugated process $g \bar{b} \rightarrow h_a \bar{b}$. 
The branching ratio for the $B \to X_s \gamma$ decay is given by:

$$BR(B \to X_s \gamma) = \left[ a + a_{77} \delta C_7^2 + a_{88} \delta C_8^2 + \text{Re}(a_7 \delta C_7) + \text{Re}(a_8 \delta C_8) + \text{Re}(a_{78} \delta C_7 \delta C_8^*) \right]$$

- $a = 3.0 \times 10^{-4}$ is the SM W-contribution.
- $a_{77}, a_{88}, a_7, a_8$ and $a_{78}$ numerical coefficients.
- $\delta C_{7,8} = C_{7,8}^{H^\pm} + C_{7,8}^{\chi^\pm}$ Wilson coefficients that contain the charged-Higgs and stop-chargino loop contributions.

The charged-Higgs contribution is:

$$C_{7,8}^{H^\pm} = \frac{f_{7,8}^{(1)}(y_t)}{3 \tan^2 \beta} + \frac{1 + (\Delta h_d/h_d(1 + \tan \beta) - \delta h_d/h_d(1 - \cot \beta))}{1 + \delta h_d/h_d + \Delta h_d/h_d \tan \beta} \frac{f_{7,8}^{(2)}(y_t)}{f_{7,8}^{(1)}(y_t)}$$

The chargino contribution has opposite sign and is given by:

$$C_{7,8}^{\chi^\pm} = \frac{1}{\cos \beta} \left\{ \sum_{a=1,2} \frac{U_{a2} V_{a1} M_W}{\sqrt{2} m_{\tilde{\chi}_a^\pm}} F_{7,8} \left( x_{q\tilde{\chi}_a^\pm}, x_{t_1\tilde{\chi}_a^\pm}, x_{t_2\tilde{\chi}_a^\pm} \right) + \frac{U_{a2} V_{a2} \tilde{m}_t}{2 m_{\tilde{\chi}_a^\pm} \sin \beta} G_{7,8} \left( x_{t_1\tilde{\chi}_a^\pm} \right) \right\}$$
The chargino contribution can be approximated as:

$$C_{7,8}^{\chi^\pm} \simeq -\frac{M_W^2}{M_2^2} \frac{M_2}{\mu} \tan \beta \left( f^{(3)}_{7,8} \left( x_{q\tilde{q}} \right) - f^{(3)}_{7,8} \left( x_{\tilde{t}_1\tilde{\chi}_1^\mp} \right) \right)$$

$$- \frac{A_t}{\mu} \tan \beta \frac{M_W^2}{M_2^2} \frac{m_t^2}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} \left( f^{(3)}_{7,8} \left( x_{\tilde{t}_1\tilde{\chi}_1^\pm} \right) - f^{(3)}_{7,8} \left( x_{\tilde{t}_2\tilde{\chi}_1^\pm} \right) \right)$$

The charged-Higgs contribution, for medium-large $\tan \beta$, can be approximated by the second term in the expression before. This way, a partial cancellation is possible between this two contributions.

$$C_{7,8}^{H^\pm} \simeq \frac{f^{(2)}_7(y_t)}{1 + \delta h_d/h_d + \Delta h_d/h_d \tan \beta}$$

However, for low $\tan \beta$ values the first term becomes important and it is not possible to achieve this kind of cancellation. It is for this regime where this bound is absolutely necessary in order to constrain the parameter space.

1. Identify the most sensitive observable for a given point in the parameter space using the expected experimental limits.

2. Use the observed limit at 95% C.L. to exclude the corresponding region in case of disagreement.

3. For a positive signal, the situation becomes more subtle because the above procedure may lead to fake surviving regions which contain the 126 GeV Higgs. Then, this procedure has to be applied to each individual Higgs state independently.

The excluded region are then ruled out at a level slightly stronger than 95% C.L.