One or More Higgs Bosons?

Kristjan Kannike

Scuola Normale Superiore di Pisa, Italy
NICPB, Estonia

Scalars 2013, Warsaw

. . . with Barbieri, Buttazzo, Sala & Tesi

2 NMSSM

$$\mathcal{W} \supset \lambda S H_1 H_2 + f(S)$$

- New contribution to Higgs mass:
  $m_{hh}^2 = m_Z^2 s_{2\beta}^2 + \Delta_t^2 + \lambda^2 v^2 c_{2\beta}^2$
- Small tuning $\Delta \leqslant 10$ see Gherghetta et al. 2012
- Extended Higgs sector: 3 CP-even scalars (assume no CPV)

3 Challenges

- How to overcome the abundance of parameters?
- How to constrain the models?

4 CP-Even Scalars

$$\mathcal{M}^2 = \begin{pmatrix} m_Z^2 \cos^2\beta + m_A^2 \sin^2\beta & (2v^2\lambda^2 - m_A^2 - m_Z^2)\cos\beta\sin\beta & vM_1 \\ (2v^2\lambda^2 - m_A^2 - m_Z^2)\cos\beta\sin\beta & m_A^2\cos^2\beta + m_Z^2\sin^2\beta + \Delta_t^2 & vM_2 \\ vM_1 & vM_2 & M_3^2 \end{pmatrix},$$

where $m_A^2 = m_{H^\pm}^2 - m_W^2 + \lambda^2 v^2$

- $\mathcal{M}^2 = R\,\mathrm{diag}(m_{h_3}, m_{h_1}, m_{h_2})\,R^T$

$$\begin{pmatrix} H_d^0 \\ H_u^0 \\ S \end{pmatrix} = R_\alpha^{12} R_\gamma^{23} R_\sigma^{13} \begin{pmatrix} h_3 \\ h_1 \\ h_2 \end{pmatrix}$$

- $h_1 = c_\gamma(-s_\alpha H_d^0 + c_\alpha H_u^0) + s_\gamma S$
- LHC: $m_{h_1} \approx 126$ GeV
- Define $\delta \equiv \alpha - \beta + \frac{\pi}{2}$
- In the SM limit $\delta = 0$

5 Angles – Analytically

$$\mathcal{M}^2 = \begin{pmatrix} m_Z^2 \cos^2\beta + m_A^2 \sin^2\beta & (2v^2\lambda^2 - m_A^2 - m_Z^2)\cos\beta\sin\beta & vM_1 \\ (2v^2\lambda^2 - m_A^2 - m_Z^2)\cos\beta\sin\beta & m_A^2\cos^2\beta + m_Z^2\sin^2\beta + \Delta_t^2 & vM_2 \\ vM_1 & vM_2 & M_3^2 \end{pmatrix}$$

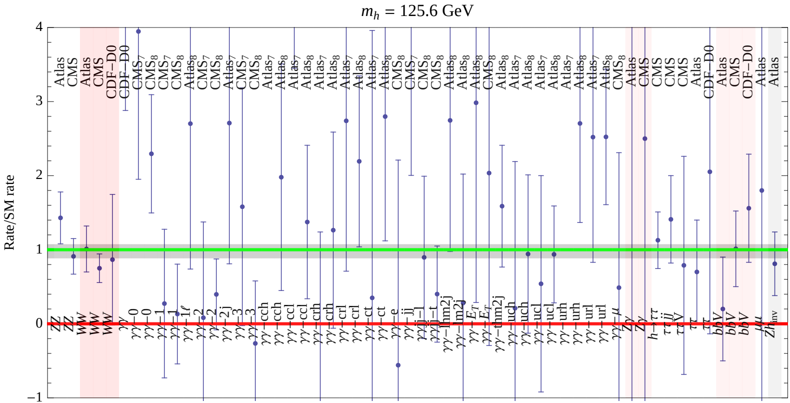
$\Rightarrow$

$$\delta, \gamma, \sigma = \delta, \gamma, \sigma(m_{h_1}^2, m_{h_2}^2, m_{h_3}^2, m_{H^\pm}^2; \lambda, t_\beta, \Delta_t)$$

6 Fit of Higgs Couplings

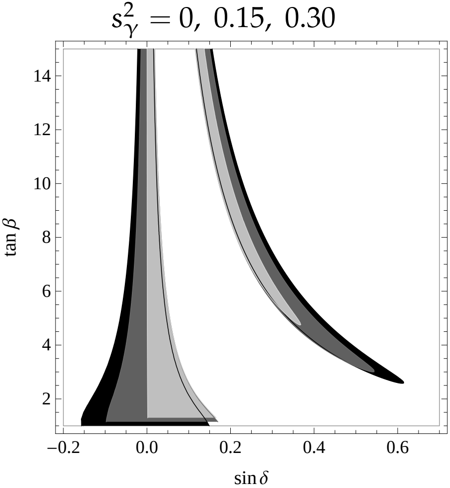
Tree-level Higgs couplings help constrain δ, t_β, γ:

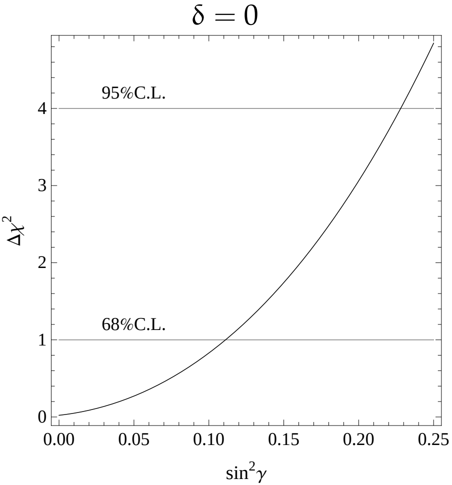
$$\frac{g_{h_1VV}}{g^{SM}_{hVV}} = c_\gamma c_\delta, \quad \frac{g_{h_1t\bar{t}}}{g^{SM}_{ht\bar{t}}} = c_\gamma(c_\delta + s_\delta \cot\beta), \quad \frac{g_{h_1b\bar{b}}}{g^{SM}_{hb\bar{b}}} = c_\gamma(c_\delta - s_\delta \tan\beta)$$



Giardino, K.K., Masina, Raidal, Strumia 2013

7 Fit of Higgs Couplings





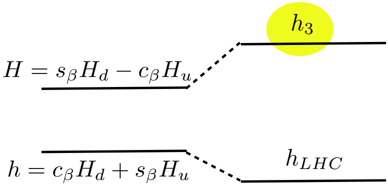
- 95 % CL on $\sin\delta$
- $s_\gamma^2 \geqslant 0.22$ @ 95% C.L.

1^{st} Limiting Case: S Decoupled

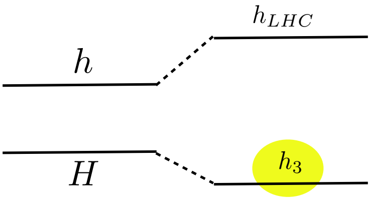
$S \approx h_2$ decoupled (similar to MSSM):

$m_{h_2} \to \infty$ and $\sigma, \gamma \to 0$

- $m_{h_1} < m_{h_3} \ll m_{h_2}$



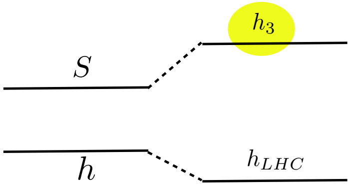
- $m_{h_3} < m_{h_1} \ll m_{h_2}$



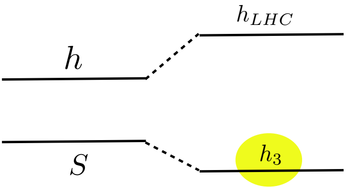
2^{nd} Limiting Case: H Decoupled

$H \approx h_3$ decoupled: $\delta, \sigma \to 0$
and $m_{h_3}, m_{H^\pm} \to \infty$

- $m_{h_1} < m_{h_2} \ll m_{h_3}$



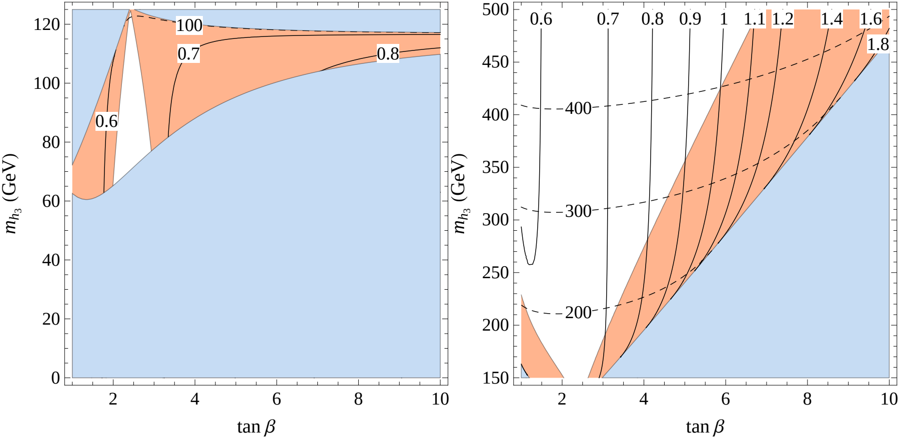
- $m_{h_2} < m_{h_1} \ll m_{h_3}$



S Decoupled

$\gamma, \sigma \to 0$ and $m_{h_2} \to \infty$

- $\Delta_t \lesssim 75$ GeV hardly relevant

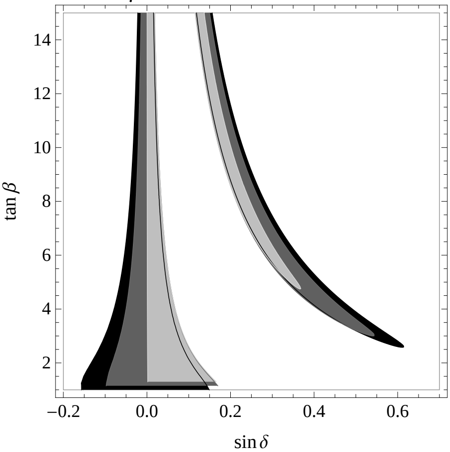


Solid lines – λ, dashed lines – $m_{H^\pm}$ (flavour tests: $m_{H^\pm} \gtrsim 300$ GeV)

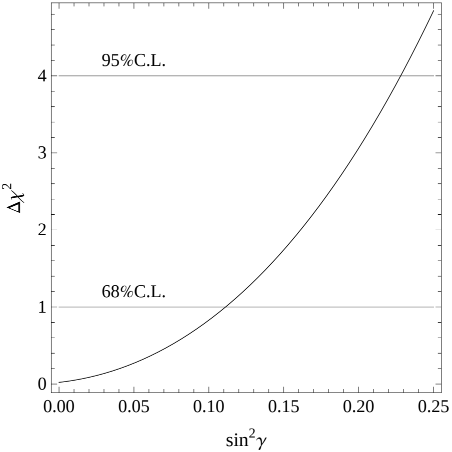
Blue – unphysical, reddish – excluded @ 95% C.L. by Higgs couplings

Fit of Higgs Couplings

$s_\gamma^2 = 0,\ 0.15,\ 0.30$



$\delta = 0$



- 95 % CL on $\sin\delta$
- $s_\gamma^2 \leqslant 0.22$ @ 95% C.L.

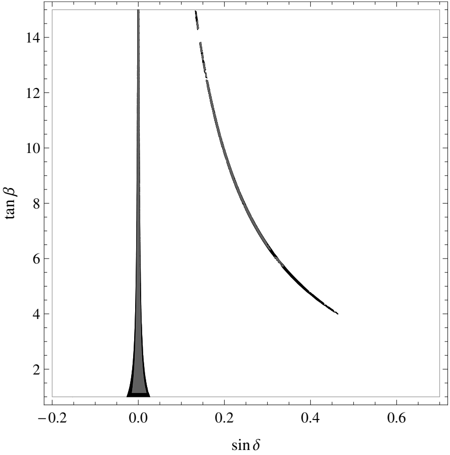
Projected Errors @ 14 TeV LHC with 300/fb

Take the signal strenghts equal to the SM and use

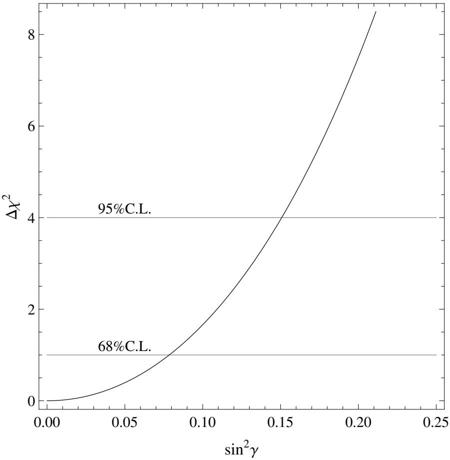
	ATLAS	CMS
$h \to \gamma\gamma$	0.16	0.15
$h \to ZZ$	0.15	0.11
$h \to WW$	0.30	0.14
$Vh \to Vb\bar{b}$	–	0.17
$h \to \tau\tau$	0.24	0.11
$h \to \mu\mu$	0.52	–

13 Fit of Higgs Couplings @ 14 TeV LHC with 300/fb

$s_\gamma^2 = 0,\ 0.15,\ 0.30$

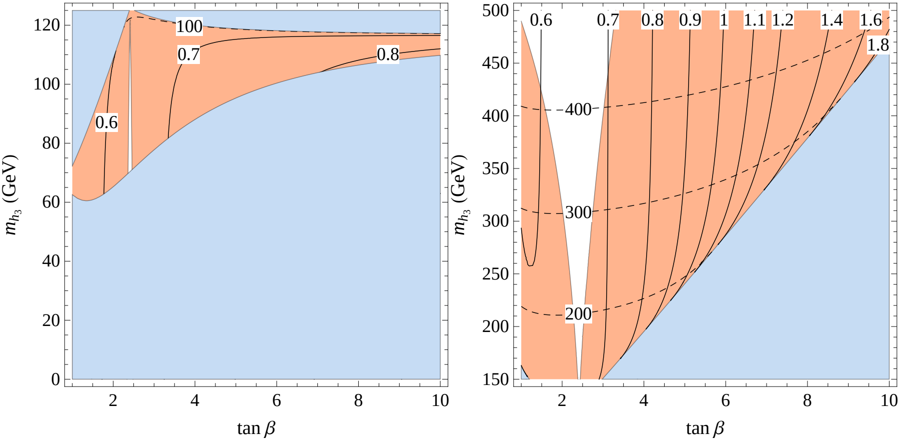


$\delta = 0$



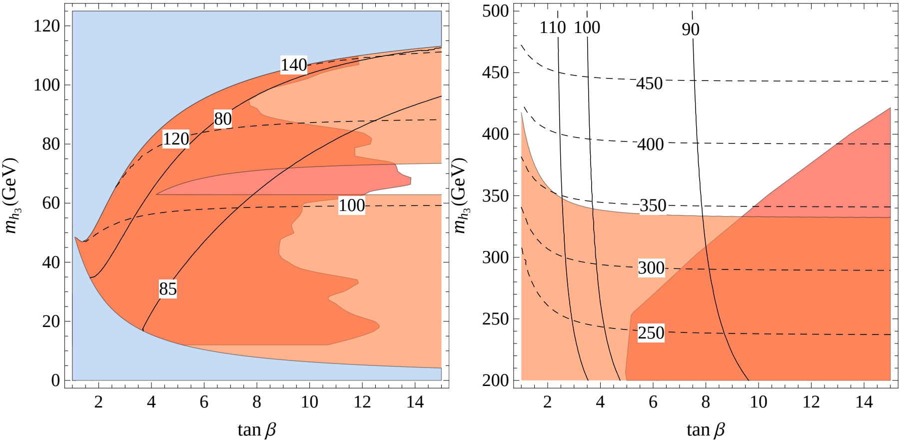
- 95 % CL on $\sin\delta$
- $s_\gamma^2 \geqslant 0.15$ @ 95% C.L.

S Decoupled @ 14 TeV LHC with 300/fb



- With ATLAS & CMS projected errors

MSSM for Comparison



Solid lines – Δ_t

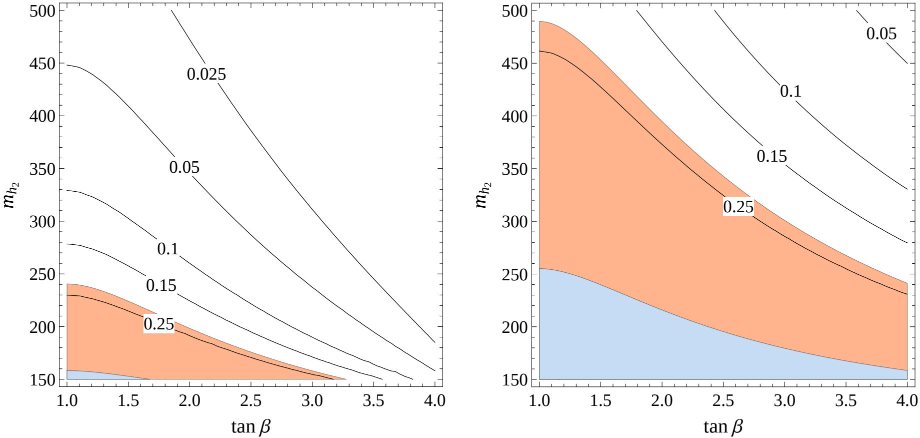
Pale red – exclyded by direct searches

- At 14 TeV LHC, $m_{h_3} < 1$ TeV can be excluded

H Decoupled, $m_{h_2} > 126$ GeV

$\delta, \sigma \to 0$ and $m_{h_3}, m_{H^\pm} \to \infty$

- All the couplings rescaled by c_γ; $s_\gamma^2 \leqslant 0.22$ @ 95% C.L.

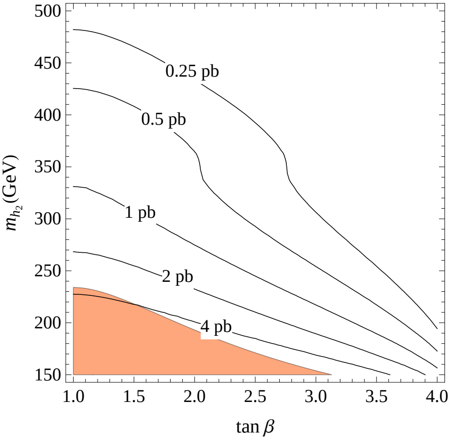


$\lambda = 0.8$ $\lambda = 1.4$

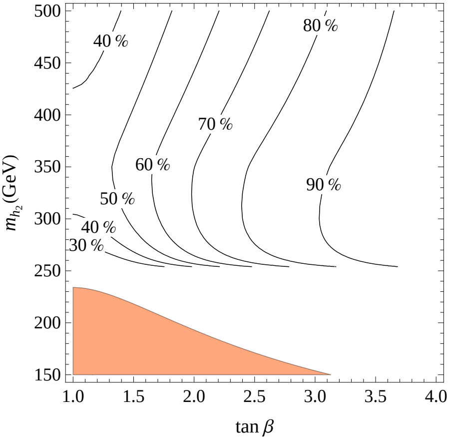
Isolines of s_γ^2

H Decoupled, $m_{h_2} > 126$ GeV

$\sigma(gg \to h_2)$ @ 14 TeV LHC



$BR(h_2 \to h_1 h_1)$

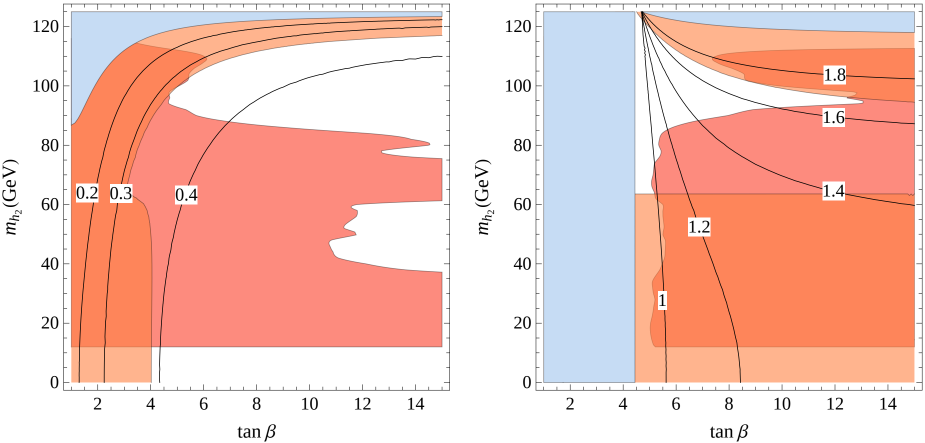


$$\lambda = 0.8, v_s = 2v$$

Isolines of s_γ^2

H Decoupled, $m_{h_2} < 126$ GeV

- Direct search bound from LEP $h \to b\bar{b}$



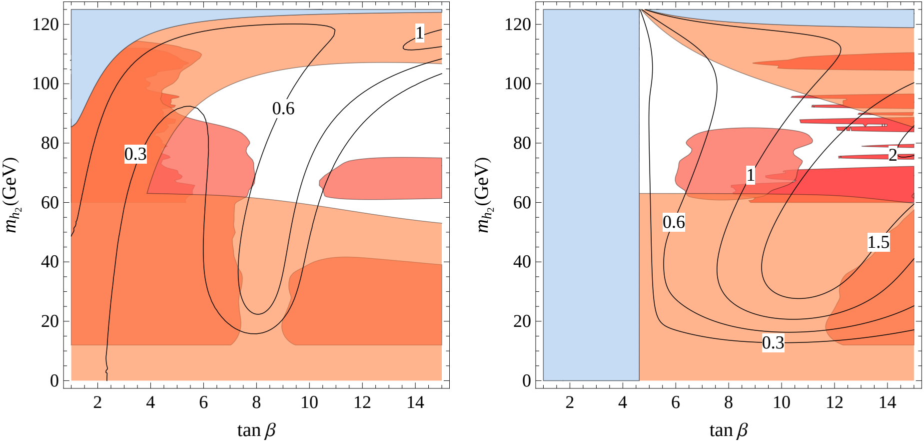
$\lambda = 0.1$, $\Delta_t = 85$ GeV, $v_s = v$ $\qquad$ $\lambda = 0.8$, $\Delta_t = 75$ GeV, $v_s = v$

Isolines of $\frac{g_{h^3}}{g^{SM}_{h^3}}$

$h_2 \to \gamma\gamma$: H 'Almost' Decoupled

Isolines of $\frac{\mu_{(h_2 \to \gamma\gamma)}}{\mu^{SM}_{(h \to \gamma\gamma)}}$

$m_{h_3} = 500$ GeV, $s_\sigma^2 = 0.001$, $v_s = v$



$\lambda = 0.1$, $\Delta_t = 85$ GeV $\qquad$ $\lambda = 0.8$, $\Delta_t = 75$ GeV

May be interesting at the LHC: Badziak, Olechowski, Pokorski 2013

Conclusions

- Analytical expressions for the mixing angles of CP-even scalars
- S-decoupled case: smallish λ; can be constrained from measurements of Higgs couplings
- H-decoupled case: harder to constrain
- H 'almost' decoupled case: look for $h_2 \to \gamma\gamma$ signal for light h_2

Mixing Angles

$$s_\gamma^2 = \frac{\det M^2 + m_{h_1}^2(m_{h_1}^2 - \operatorname{tr} M^2)}{(m_{h_1}^2 - m_{h_2}^2)(m_{h_1}^2 - m_{h_3}^2)},$$

$$s_\sigma^2 = \frac{m_{h_2}^2 - m_{h_1}^2}{m_{h_2}^2 - m_{h_3}^2} \frac{\det M^2 + m_{h_3}^2(m_{h_3}^2 - \operatorname{tr} M^2)}{\det M^2 - m_{h_2}^2 m_{h_3}^2 + m_{h_1}^2(m_{h_2}^2 + m_{h_3}^2 - \operatorname{tr} M^2)},$$

$$s_{2\delta} = \Big[2 s_\sigma c_\sigma s_\gamma \left(m_{h_3}^2 - m_{h_2}^2\right)\left(2\tilde{M}_{11}^2 - m_{h_1}^2 c_\gamma^2 - m_{h_2}^2(s_\gamma^2 + s_\sigma^2 c_\gamma^2)\right.$$
$$\left. - m_{h_3}^2(c_\sigma^2 + s_\gamma^2 s_\sigma^2)\right)$$
$$+ 2\tilde{M}_{12}^2\left(m_{h_3}^2\left(c_\sigma^2 - s_\gamma^2 s_\sigma^2\right) + m_{h_2}^2\left(s_\sigma^2 - s_\gamma^2 c_\sigma^2\right) - m_{h_1}^2 c_\gamma^2\right)\Big]$$
$$\times \Big[\left(m_{h_3}^2 - m_{h_2}^2 s_\gamma^2 - m_{h_1}^2 c_\gamma^2\right)^2 + \left(m_{h_2}^2 - m_{h_3}^2\right)^2 c_\gamma^4 s_\sigma^4$$
$$+ 2\left(m_{h_2}^2 - m_{h_3}^2\right)\left(m_{h_3}^2 + m_{h_2}^2 s_\gamma^2 - m_{h_1}^2\left(1 + s_\gamma^2\right)\right) c_\gamma^2 s_\sigma^2\Big]^{-1}$$