A 96 GeV Higgs Boson in the 2HDMS

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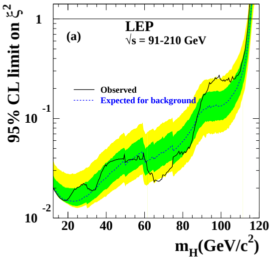
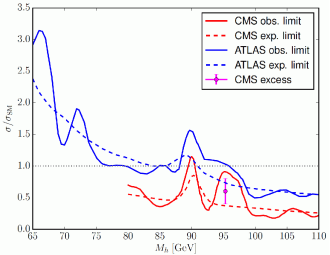
Motivation

[Phys. Lett. B 565 (2003): 61-75]



[T. Stefaniak et al. arxiv.1812.05864]
[CMS-PAS-HIG-17-013]
[ATLAS-CONF-2018-025]



1. Alternative model interpret the 96 GeV ”excess” in experiment
2. Extend the 2HDM to the NMSSM-like Higgs structure (complex singlet and $\mathbb{Z}_3$ symmetry)
3. Search the 96 GeV Higgs boson at the future linear colliders (e.g. ILC)
4. Cosmological features like baryogenesis, gravitational waves.

Overview

> Scan intervals

> Interpretation of 96 GeV excess

> Experimental observable at ILC

> Summary

Scanning for the parameter space

We focus on Type II Yukawa structure first.

- Implement the 2HDMS into the $\texttt{SARAH}\ 4.14.3$ and obtain the model file for $\texttt{SPheno}\ 4.0.4$
- Use $\texttt{SPheno}\ 4.0.4$ to generate the spectra with 2-loop correction ($\overline{\text{MS}}$ scheme)
- Find the points in the following parameter space (low tan β):

$$m_{h_1} \in \{80, 93\}\text{GeV}, \quad m_{h_2} \in \{110, 126\}\text{GeV}, \quad m_{a_1} \in \{200, 500\}\text{GeV}$$

$$m_{h^\pm} \in \{650, 1000\}\text{GeV}, \quad m_{a_2} \in \{650, 1000\}\text{GeV}, \quad m_{h_3} \in \{650, 1000\}\text{GeV}$$

$$v_S \in \{100, 2000\}\text{GeV} \quad \tan\beta \in \{1, 4\}, \quad \alpha_1 \in \{0.84, \frac{\pi}{2}\}$$

$$\alpha_2 \in \{\pm 0.93, \pm 1.27\}, \quad \alpha_3 \in \{\pm 1.2, \pm 1.5\}, \quad \alpha_4 \in \{1.25, \frac{\pi}{2}\}$$

- Testing for theoretical and experimental constraints

96 GeV "excess"

LEP signal strengths:

$$\mu_{\text{LEP}} = \frac{\sigma(e^+e^- \to Zh_1 \to Zb\bar{b})}{\sigma(e^+e^- \to ZH_{\text{SM}} \to Zb\bar{b})} = |c_{h_1VV}|^2 \frac{\text{BR}(h_1 \to b\bar{b})}{\text{BR}_{\text{SM}}(h \to b\bar{b})} = 0.117 \pm 0.057 \qquad (1)$$

CMS signal strengths:

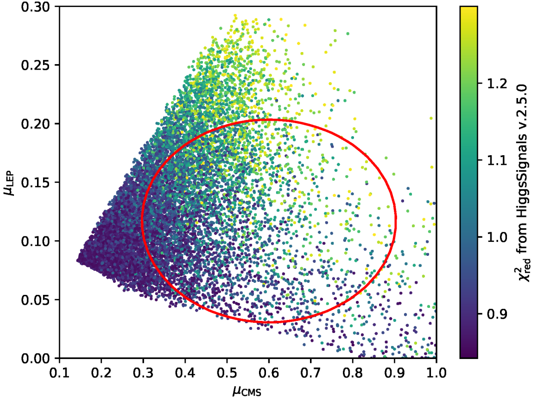
$$\mu_{\text{CMS}} = \frac{\sigma(pp \to h_1 \to \gamma\gamma)}{\sigma(pp \to H_{\text{SM}} \to \gamma\gamma)} = |c_{h_1tt}|^2 \frac{\text{BR}(h_1 \to \gamma\gamma)}{\text{BR}_{\text{SM}}(h \to \gamma\gamma)} = 0.6 \pm 0.2 \qquad (2)$$

Fitting to the ”excess”:

$$\chi^2 = \left(\frac{\mu_{\text{LEP}} - 0.117}{0.057}\right)^2 + \left(\frac{\mu_{\text{CMS}} - 0.6}{0.2}\right)^2 < 2.3 \qquad (3)$$

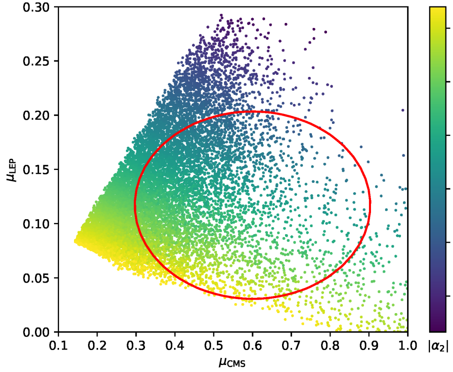
Scan result for tan $\beta = 1 \sim 4$

- Accept the points with $m_{h_1} = (96 \pm 2)$ GeV

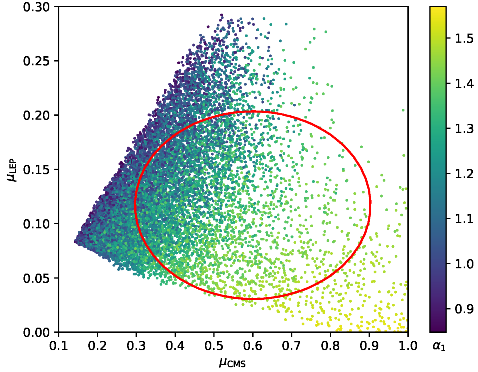


- Lots of ”best-fit” points

Scan result for tan $\beta = 1 \sim 4$



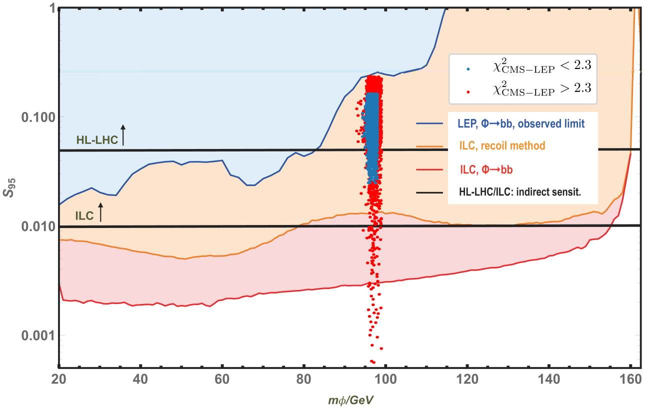
$c_{h_1 VV} \sim$ cos α_2 cos$(\beta - \alpha_1)$



$c_{h_1 bb} \sim$ cos α_1 cos α_2

Experimental observation

Experimental limit from [*G. Moortgat-Pick et al. arXiv.1801.09662*]

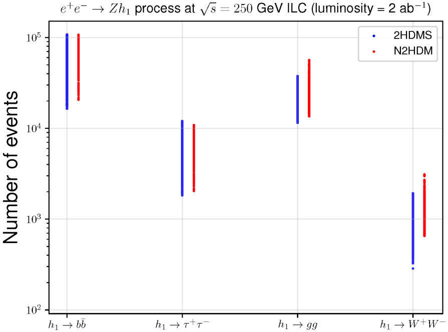


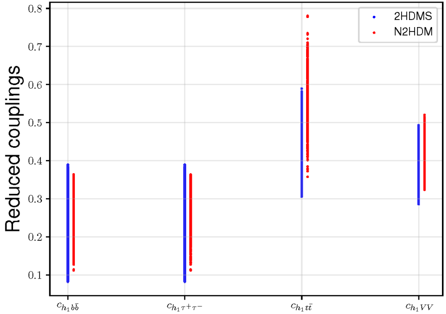
> The light 96 GeV Higgs can be detected at ILC

Observable and Comparison to N2HDM

How to distinguish the 2HDMS and N2HDM?

N2HDM data from *T.Biekoetter et al.*

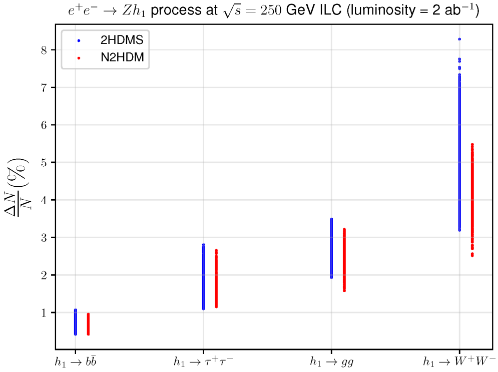


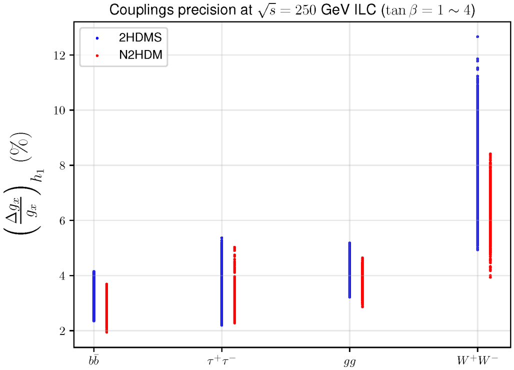


- 2HDMS could have the number of W^+W^- events slightly less than N2HDM
- 2HDMS could have the $c_{h_1 tt}$ coupling smaller than N2HDM

Observable and Comparison to N2HDM

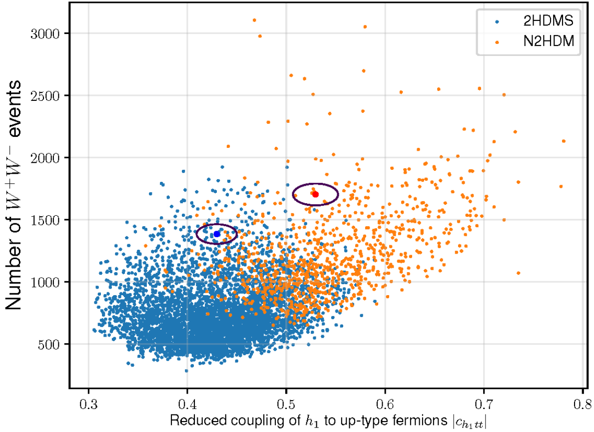
Method of uncertainties calculation from [*T. Barklow et al. arXiv.1708.08912*]





> Most of the uncertainties are below 10% at ILC

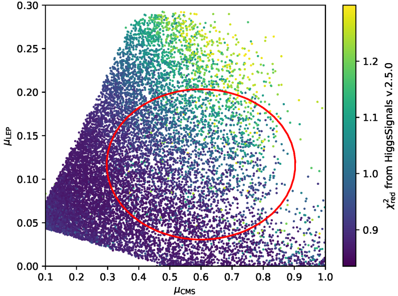
Observable and Comparison to N2HDM



> One could potentially distinguish the 2HDMS and N2HDM at ILC

Results for higher tan β range

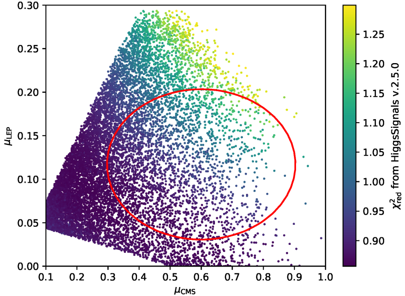
tan $\beta = \{4, 10\}$, $m_{h^\pm} = \{650, 1500\}$ GeV



N2HDM: More rigid at higher tan β range

$$M^2_{S13} = \lambda_7 v v_S \cos\beta$$
$$M^2_{S23} = \lambda_8 v v_S \sin\beta$$

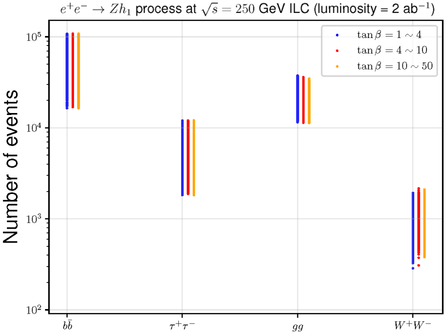
tan $\beta = \{10, 50\}$, $m_{h^\pm} = \{1000, 2500\}$ GeV

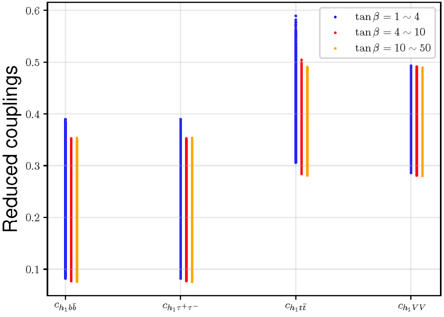


THDMS: Still flexible at higher tan β range

$$M^2_{S13} = (2\lambda'_1 v_S \cos\beta + \mu_{12} \sin\beta) v$$
$$M^2_{S23} = (2\lambda'_2 v_S \sin\beta + \mu_{12} \cos\beta) v$$

Results for higher $\tan\beta$ range





- Number of events for different $\tan\beta$ are almost the same
- The higher $\tan\beta$ could suppressed the upper limit of couplings for h_1

Summary

Conclusions

- We performed the scan and obtained lots of points that nicely fit to the 96 GeV ”excess”
- We found some theoretical and experimental distinction between 2HDMS and N2HDM
- We evaluated number of events for some processes and couplings measurement precision at ILC

Outlook

- We will study more about the couplings determination of 2HDMS
- We could study the light CP-odd Higgs sector of 2HDMS
- We could also study the baryogenesis based on 2HDMS

Thank you!

Contact

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Backup

Theoretical framework of 2HDMS

Two Higgs doublets

$$\Phi_1 = \begin{pmatrix} \chi_1^+ \\ v_1 + \frac{\rho_1 + i\eta_1}{\sqrt{2}} \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \chi_2^+ \\ v_2 + \frac{\rho_2 + i\eta_2}{\sqrt{2}} \end{pmatrix},$$

Additional complex singlet

$$S = v_S + \frac{\rho_S + i\eta_S}{\sqrt{2}} \qquad (4)$$

Convention of vacuum expectation values

$$\tan\beta = \frac{v_2}{v_1}, \qquad v = \sqrt{v_1^2 + v_2^2} = 174 \text{ GeV} \qquad (5)$$

$\mathbb{Z}_2$ Symmetry:

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \\ S \end{pmatrix} \to \begin{pmatrix} \Phi_1 \\ -\Phi_2 \\ S \end{pmatrix} \qquad (6)$$

$\mathbb{Z}_3$ Symmetry:

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \\ S \end{pmatrix} \to \begin{pmatrix} \Phi_1 \\ e^{i\frac{2\pi}{3}} \Phi_2 \\ e^{-i\frac{2\pi}{3}} S \end{pmatrix} \qquad (7)$$

Theoretical framework of 2HDMS

Higgs potential [S. Baum, N. Shah arXiv:1808.02667]:

$$
\begin{aligned}
V =& m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2 \\
&+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) - m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \\
&+ m_S^2 S^\dagger S + \lambda_1' (S^\dagger S)(\Phi_1^\dagger \Phi_1) + \lambda_2' (S^\dagger S)(\Phi_2^\dagger \Phi_2) \\
&+ \frac{\lambda_3''}{4}(S^\dagger S)^2 + \left(\frac{\mu_{S1}}{6} S^3 + \mu_{12} S \Phi_1^\dagger \Phi_2 + \text{h.c.} \right)
\end{aligned} \tag{8}
$$

12 free parameters:

$$
\lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_1',\ \lambda_2',\ \lambda_3'',\ m_{12},\ \mu_{S1},\ \mu_{12},\ v_S,\ \tan\beta \tag{9}
$$

- > m_{12} softly break the $\mathbb{Z}_2$, $\mathbb{Z}_3$ symmetry
- > μ_{12} softly break the $\mathbb{Z}_2$ symmetry

Theoretical framework of 2HDMS

Tree level Higgs mass matrices:

$$
\begin{aligned}
M_{S11}^2 &= 2\lambda_1 v^2 \cos^2\beta + (m_{12}^2 - \mu_{12} v_S)\tan\beta \\
M_{S22}^2 &= 2\lambda_2 v^2 \sin^2\beta + (m_{12}^2 - \mu_{12} v_S)\cot\beta \\
M_{S12}^2 &= (\lambda_3 + \lambda_4) v^2 \sin 2\beta - (m_{12}^2 - \mu_{12} v_S) \\
M_{S13}^2 &= (2\lambda_1' v_S \cos\beta + \mu_{12}\sin\beta) v \\
M_{S23}^2 &= (2\lambda_2' v_S \sin\beta + \mu_{12}\cos\beta) v \\
M_{S33}^2 &= \frac{\mu_{S1}}{2} v_S + \lambda_3'' v_S^2 - \mu_{12}\frac{v^2}{2v_S}\sin 2\beta
\end{aligned}
$$

$$
\begin{aligned}
M_{P11}^2 &= (m_{12}^2 - \mu_{12} v_S)\tan\beta \\
M_{P22}^2 &= (m_{12}^2 - \mu_{12} v_S)\cot\beta \\
M_{P12}^2 &= -(m_{12}^2 - \mu_{12} v_S) \\
M_{P13}^2 &= \mu_{12} v \sin\beta \\
M_{P23}^2 &= -\mu_{12} v \cos\beta \\
M_{P33}^2 &= -\frac{3}{2}\mu_{S1} v_S - \mu_{12}\frac{v^2}{2v_S}\sin 2\beta \\
M_C^2 &= 2(m_{12}^2 - \mu_{12} v_S)\csc 2\beta - \lambda_4 v^2
\end{aligned}
\qquad (10)
$$

Theoretical framework of 2HDMS

$$\tilde{\mu}^2 = \cos^2\alpha_4 m_{a1}^2 + \sin^2\alpha_4 m_{a2}^2$$

$$\lambda_1 = \frac{1}{2v^2\cos^2\beta}\left[\sum_i m_{h_i}^2 R_{i1}^2 - \tilde{\mu}^2\sin^2\beta\right]$$

$$\lambda_2 = \frac{1}{2v^2\sin^2\beta}\left[\sum_i m_{h_i}^2 R_{i2}^2 - \tilde{\mu}^2\cos^2\beta\right]$$

$$\lambda_3 = \frac{1}{v^2}\left[\frac{1}{\sin 2\beta}\sum_i m_{h_i}^2 R_{i1}R_{i2} + m_{h\pm}^2 - \tilde{\mu}^2\right]$$

$$\lambda_4 = \frac{\tilde{\mu}^2 - m_{h\pm}^2}{v^2}$$

$$m_{12}^2 = \mu_{12}v_S + \tilde{\mu}^2\sin\beta\cos\beta$$

$$\mu_{12} = \frac{m_{a1}^2 - m_{a2}^2}{v}\sin\alpha_4\cos\alpha_4$$

$$\lambda_1' = \frac{1}{2v_S v\cos\beta}\left[\sum_i m_{h_i}^2 R_{i1}R_{i3} - \mu_{12}v\sin\beta\right]$$

$$\lambda_2' = \frac{1}{2v_S v\sin\beta}\left[\sum_i m_{h_i}^2 R_{i2}R_{i3} - \mu_{12}v\cos\beta\right]$$

$$\lambda_3'' = \frac{1}{v_S^2}\left[\sum_i m_{h_i}^2 R_{i3}^2 + \mu_{12}\frac{v^2}{2v_S}\sin 2\beta - \frac{\mu_{S1}}{2}v_S\right]$$

$$\mu_{S1} = -\frac{2}{3v_S}\left[\sin^2\alpha_4 m_{a1}^2 + \cos^2\alpha_4 m_{a2}^2 + \frac{v}{2v_S}\sin 2\beta\mu_{12}\right]$$

Theoretical framework of 2HDMS

Scalar potential $\xrightarrow{\text{second derivative}}$ mass matrix $\xrightarrow{\text{diagonalization}}$ mass eigenvalues & mixing matrix

Parameterize the CP-even and CP-odd mixing matrices by 4 mixing angles $\alpha_{1,2,3,4}$:

$$R = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -s_{\alpha_1} c_{\alpha_3} - c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ s_{\alpha_1} s_{\alpha_3} - c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} & -s_{\alpha_1} s_{\alpha_2} c_{\alpha_3} - c_{\alpha_1} s_{\alpha_3} & c_{\alpha_2} c_{\alpha_3} \end{pmatrix} \quad (11)$$

$$R_A = \begin{pmatrix} c_\beta & s_\beta & 0 \\ -s_\beta c_{\alpha_4} & c_\beta c_{\alpha_4} & s_{\alpha_4} \\ s_\beta s_{\alpha_4} & -c_\beta s_{\alpha_4} & c_{\alpha_4} \end{pmatrix} \quad (12)$$

The mass matrices can be written in terms of the masses and mixing angles

$$M_S^2 = R^T \,\text{diag}\{m_{h_1}^2, m_{h_2}^2, m_{h_3}^2\} R, \qquad M_P^2 = R_A^T \,\text{diag}\{0, m_{a_1}^2, m_{a_2}^2\} R_A \quad (13)$$

Inputs of mass basis (12 parameters):

$$m_{h_{1,2,3}},\ m_{a_{1,2}},\ m_{h^\pm},\ \alpha_{1,2,3,4},\ v_S,\ \tan\beta \quad (14)$$

Testing for constraints

Theoretical constraints

- Perturbative unitarity $\longrightarrow$ 2→2 scattering matrix [J. Horejsi, M. Kladiva arXiv.0510154]
- Vacuum stability $\longrightarrow$ Boundedness from below [K.G. Klimenko Theor. Math. Phys. 62, 58–65 (1985)] and `Evade`

Experimental constraints

- LEP, Tevatron & LHC Higgs searches $\longrightarrow$ `HiggsBounds` 5.9.0
- SM Higgs couplings $\longrightarrow$ `HiggsSignals` 2.5.0
- Electroweak precision observable $\longrightarrow$ S, T, U parameters [M. Baak et al. arXiv.1209.2716]
- Flavor physics $B \to X_s\gamma$ limit $\longrightarrow$ Lower bound of the $m_{h^\pm}$ [O. Deschamps et al. arXiv.0907.5135]

Backup

N2HDM scalar potential:

$$\begin{aligned} V =& m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) \\ &+ \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left[\frac{\lambda_5}{2}(\Phi_1^\dagger \Phi_2)^2 - m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}\right] \\ &+ \frac{1}{2} m_S^2 S^2 + \frac{\lambda_6}{8} S^4 + \frac{\lambda_7}{2} S^2 (\Phi_1^\dagger \Phi_1) + \frac{\lambda_8}{2} S^2 (\Phi_2^\dagger \Phi_2) \end{aligned} \tag{15}$$

N2HDM CP-even Higgs mass matrix:

$$M_S^2 = \begin{pmatrix} \lambda_1 c_\beta^2 v^2 + t_\beta m_{12}^2 & \lambda_{345} c_\beta s_\beta v^2 - m_{12}^2 & \lambda_7 c_\beta v v_S \\ \lambda_{345} c_\beta s_\beta v^2 - m_{12}^2 & \lambda_2 s_\beta^2 v^2 + m_{12}^2 / t_\beta & \lambda_8 s_\beta v v_S \\ \lambda_7 c_\beta v v_S & \lambda_8 s_\beta v v_S & \lambda_6 v_S^2 \end{pmatrix} \tag{16}$$

Scan result for tan $\beta = 1 \sim 4$