96 GeV Higgs phenomenology in the THDMS

Cheng Li, Gudrid Moortgat-Pick, Steven Paasch
in collaboration with Sven Heinemeyer

DESY, University Hamburg

Motivation

- Extend the 2HDM to the NMSSM-like Higgs structure (complex singlet and $\mathbb{Z}_3$ symmetry)
- Cosmological motivations like baryogenesis, gravitational waves etc.
- Alternative model interpret the 96 GeV "excess" in experiment

Outline

- Theoretical framework
- Testing for constraints
- Interpretation of 96 GeV excess (ongoing)
- Summary

Theoretical framework of THDMS

Two Higgs doublets

$$\Phi_1 = \begin{pmatrix} \chi_1^+ \\ v_1 + \frac{\rho_1 + i\eta_1}{\sqrt{2}} \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \chi_2^+ \\ v_2 + \frac{\rho_2 + i\eta_2}{\sqrt{2}} \end{pmatrix} \tag{1}$$

Additional complex singlet

$$S = v_S + \frac{\rho_S + i\eta_S}{\sqrt{2}} \tag{2}$$

$$\tan\beta = \frac{v_2}{v_1}, \qquad v = \sqrt{v_1^2 + v_2^2} = 174 \text{ GeV} \tag{3}$$

Symmetry

Fields	$\mathbb{Z}_2$	$\mathbb{Z}_3$
Φ_1	$+1$	$+1$
Φ_2	-1	$e^{i2\pi/3}$
S	$+1$	$e^{-i2\pi/3}$

Theoretical framework of THDMS

Higgs potential:

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

12 free parameters:

$$
\lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_1',\ \lambda_2',\ \lambda_3'',\ m_{12},\ \mu_{S1},\ \mu_{12},\ v_S,\ \tan\beta \tag{5}
$$

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

Theoretical framework of THDMS

Tree level Higgs mass matrices:

$$
\begin{aligned}
M_{S11}^2 &= 2\lambda_1 v^2 \cos^2\beta + (m_{12}^2 - \mu_{12} v_S)\tan\beta \\
M_{S22}^2 &= 2\lambda_2 v^2 \sin^2\beta + (m_{12}^2 - \mu_{12} v_S)\cot\beta \\
M_{S12}^2 &= (\lambda_3 + \lambda_4) v^2 \sin 2\beta - (m_{12}^2 - \mu_{12} v_S) \\
M_{S13}^2 &= (2\lambda_1' v_S \cos\beta + \mu_{12}\sin\beta) v \\
M_{S23}^2 &= (2\lambda_2' v_S \sin\beta + \mu_{12}\cos\beta) v \\
M_{S33}^2 &= \frac{\mu_{S1}}{2} v_S + \lambda_3'' v_S^2 - \mu_{12}\frac{v^2}{2v_S}\sin 2\beta
\end{aligned}
\qquad
\begin{aligned}
M_{P11}^2 &= (m_{12}^2 - \mu_{12} v_S)\tan\beta \\
M_{P22}^2 &= (m_{12}^2 - \mu_{12} v_S)\cot\beta \\
M_{P12}^2 &= -(m_{12}^2 - \mu_{12} v_S) \\
M_{P13}^2 &= \mu_{12} v \sin\beta \\
M_{P23}^2 &= -\mu_{12} v \cos\beta \\
M_{P33}^2 &= -\frac{3}{2}\mu_{S1} v_S - \mu_{12}\frac{v^2}{2v_S}\sin 2\beta \\
M_C^2 &= 2(m_{12}^2 - \mu_{12} v_S)\csc 2\beta - \lambda_4 v^2
\end{aligned}
\tag{6}
$$

Diagonalization $\longrightarrow$ mixing matrices R_{ij} $\longrightarrow$ parameterized by rotation angles α_i

Theoretical framework of THDMS

Express the free parameters in terms of tree level masses and mixing angles

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

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

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

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

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

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

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

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

$$\lambda_2' = \frac{1}{2v_S v\sin\beta}\left[\sum_i m_{h_i}^2 R_{i2}R_{i3} - \mu_{12}v\cos\beta\right] \quad (7)$$

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

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

Inputs of mass basis (12 parameters):

$$m_{h_{1,2,3}},\ m_{a_{1,2}},\ m_{h^\pm},\ \alpha_1,\ \alpha_2,\ \alpha_3,\ \alpha_4,\ v_S,\ \tan\beta \quad (8)$$

Working progress

According to the results of N2HDM, we focus on Type II Yukawa structure first.

- Implement the THDMS in the `SARAH`
- Use `SPheno` to generate the spectra ($\overline{\mathrm{DR}}$ scheme)
- Scan the parameter space

$$
\begin{aligned}
\alpha_1 &\in \{\pm 1.0, \pm 1.4\}, & \alpha_2 &\in \{\pm 1.2, \pm 1.5\}, & \alpha_3 &\in \{\pm 1.0, \pm 1.3\}, \\
\alpha_4 &\in \{1.56, 1.57\} & \tan\beta &\in \{1.0, 4.0\}, & v_S &\in \{1000, 7000\}\mathrm{GeV}, \\
m_{h_1} &\in \{90, 98\}\mathrm{GeV}, & m_{h_2} &\in \{122, 128\}\mathrm{GeV}, & m_{a_1} &\in \{200, 500\}\mathrm{GeV} \\
m_{h^\pm} &\in \{650, 1000\}\mathrm{GeV}, & m_{a_2} &\in \{650, 1000\}\mathrm{GeV}, & m_{h_3} &\in \{650, 1000\}\mathrm{GeV}
\end{aligned}
$$

- Calculate the signal strength of the excess:

$$
\mu_{\mathrm{LEP}} = |c_{h_1 VV}|^2 \frac{\mathrm{BR}(h_1 \to b\bar{b})}{\mathrm{BR}_{\mathrm{SM}}(h \to b\bar{b})}, \quad \mu_{\mathrm{CMS}} = |c_{h_1 tt}|^2 \frac{\mathrm{BR}(h_1 \to \gamma\gamma)}{\mathrm{BR}_{\mathrm{SM}}(h \to \gamma\gamma)} \tag{9}
$$

- Fit to the "excess":

$$
\chi^2 = \left(\frac{\mu_{\mathrm{LEP}} - 0.117}{0.057}\right)^2 + \left(\frac{\mu_{\mathrm{CMS}} - 0.6}{0.2}\right)^2 < 2.3 \tag{10}
$$

Testing for constraints

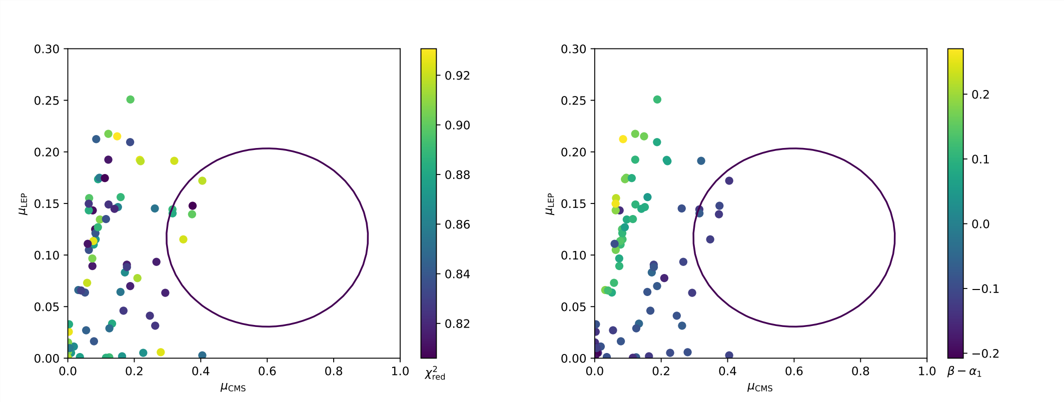
Theoretical constraints

- Tree-level unitarity $\longrightarrow$ `SARAH` & `SPheno` checks
- Vaccum stability $\longrightarrow$ `Vevacious` or `Evade` checks

Experimental constraints

- LEP, Tevatron & LHC Higgs searches $\longrightarrow$ `HiggsBounds`
- SM Higgs couplings $\longrightarrow$ `HiggsSignals`
- Electroweak precision observables $\longrightarrow$ Fit for S, T, U parameters
- Flavor physics $B \to X_s\gamma$ limit $\longrightarrow$ Lower bound for the $m_{h^\pm}$

Preliminary results



- We didn't add any requirement for the mixing angles
- We made a too strong cut for the `HiggsSignals` χ^2 results

Summary

Work done

- We implemented the THDMS model in `SARAH` and create the `SPheno` spectrum generator
- We add all constraints into the scan program
- We did a preliminary scan and found some "best-fit" points

Outlook

- We can make a more efficient scan and find more points
- We will estimate the 96 GeV excess for THDMS at future colliders
- We will try to distinguish THDMS from N2HDM

Thank you!