A 96 GeV Higgs Boson in the 2HDM plus singlet [arXiv:2112.11958]

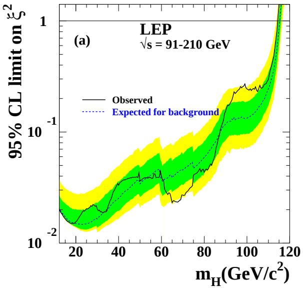
(now also including the new CMS $\tau^+\tau^-$ excess)

Planck 2022

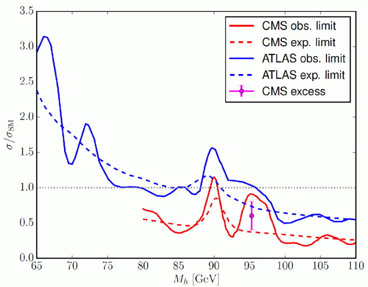
S. Heinemeyer, C. Li, F. Lika,
G. Moortgat-Pick, S. Paasch
Paris, June 2, 2022

Motivation

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



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



$$\mu_{\text{LEP}} = \frac{\sigma(e^+e^- \to Zh_1 \to Zb\bar{b})}{\sigma(e^+e^- \to ZH_{\text{SM}} \to Zb\bar{b})} = 0.117 \pm 0.057$$

$$\mu_{\text{CMS}} = \frac{\sigma(pp \to h_1 \to \gamma\gamma)}{\sigma(pp \to H_{\text{SM}} \to \gamma\gamma)} = 0.6 \pm 0.2$$

1. Extend the 2HDM to the NMSSM-like Higgs structure
2. The 96 GeV "excess" at LEP and CMS can be both accommodated by the type-II and type-IV 2HDM plus singlet simultaneously
3. Physics potential at future colliders to search for such a 96 GeV Higgs boson

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

$$S = v_S + \frac{\rho_S + i\eta_S}{\sqrt{2}} \tag{1}$$

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

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

Symmetry

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

12 free parameters:

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

Framework of N2HDM

Two Higgs doublets

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

Additional real singlet

$$S = v_S + \rho_S \tag{3}$$

Higgs potential [M. Muhlleitner et al. arXiv:1612.01309]:

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

Symmetry

	Φ_1	Φ_2	S
$\mathbb{Z}_2$	$+1$	-1	$+1$
$\mathbb{Z}_2'$	$+1$	$+1$	-1

11 free parameters:

$$\lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_5,\ \lambda_6,\ \lambda_7,\ \lambda_8,$$
$$m_{12},\ v_S,\ \tan\beta$$

Mixing angles in the 2HDM plus singlet

3 x 3 CP-even rotation matrix:

$$R = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -s_{\alpha_1} c_{\alpha_3} - c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ s_{\alpha_1} s_{\alpha_3} - c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} & -s_{\alpha_1} s_{\alpha_2} c_{\alpha_3} - c_{\alpha_1} s_{a3} & c_{\alpha_2} c_{\alpha_3} \end{pmatrix} \tag{5}$$

3 x 3 CP-odd rotation matrix:

$$R^A = \begin{pmatrix} -s_\beta c_{\alpha_4} & c_\beta c_{\alpha_4} & s_{\alpha_4} \\ s_\beta s_{\alpha_4} & -c_\beta s_{\alpha_4} & c_{\alpha_4} \\ c_\beta & s_\beta & 0 \end{pmatrix} \tag{6}$$

Express the Potential parameters in terms of the masses and mixing angles

N2HDM $\quad m_{h_{1,2,3}},\ m_A,\ m_{h^\pm},\ \alpha_1,\ \alpha_2,\ \alpha_3,\ m_{12},\ v_S,\ \tan\beta \quad (7)$

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

Couplings in the 2HDM plus singlet

Types of Yukawa couplings:

	type I	type II	lepton-specific	type IV (flipped)
$c_{h_i tt}$	$R_{i2}/\sin\beta$	$R_{i2}/\sin\beta$	$R_{i2}/\sin\beta$	$R_{i2}/\sin\beta$
$c_{h_i bb}$	$R_{i2}/\sin\beta$	$R_{i1}/\cos\beta$	$R_{i2}/\sin\beta$	$R_{i1}/\cos\beta$
$c_{h_i \tau\tau}$	$R_{i2}/\sin\beta$	$R_{i1}/\cos\beta$	$R_{i1}/\cos\beta$	$R_{i2}/\sin\beta$

Second-lightest Higgs Couplings (in the limit of $|R_{13}^2| \to 1$):

$$c_{h_2 tt} \sim \frac{\cos(\alpha_1 + \mathrm{sgn}(\alpha_2)\alpha_3)}{\sin\beta} |\sin\alpha_2|, \qquad c_{h_2 bb} \sim -\frac{\sin(\alpha_1 + \mathrm{sgn}(\alpha_2)\alpha_3)}{\cos\beta} |\sin\alpha_2|,$$

$$c_{h_2 VV} \sim \sin(\beta - \alpha_1 - \mathrm{sgn}(\alpha_2)\alpha_3) |\sin\alpha_2|$$

Alignment limit:

$$\sin(\beta - \alpha_1 - \mathrm{sgn}(\alpha_2)\alpha_3) \to 1$$

96 GeV "excess"

LEP signal strengths:

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

$$\mu_{\text{LEP}} \propto |c_{h_1VV}|^2 \propto \cos^2 \alpha_2 \qquad (9)$$

CMS signal strengths:

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

$$\mu_{\text{CMS}} \propto \frac{|c_{h_1tt}|^2}{|c_{h_1bb}|^2} \propto \left(\frac{\tan\alpha_1}{\tan\beta}\right)^2 \qquad (10)$$

Fitting to the ”excess”:

$$\chi^2 = \left(\frac{\mu_{\text{LEP}} - 0.117}{0.057}\right)^2 + \left(\frac{\mu_{\text{CMS}} - 0.6}{0.2}\right)^2 < 2.3 \qquad (11)$$

Testing for constraints

Theoretical constraints

- Tree-level perturbative unitarity [J. Horejsi, M. Kladiva arXiv.0510154]
- Boundedness from below [K.G. Klimenko Theor. Math. Phys. 62, 58–65 (1985)]
- Vaccum stability $\longrightarrow$ $\texttt{Evade}$ [J. Wittbrodt arXiv:1812.04644]

Experimental constraints

- LEP, Tevatron & LHC Higgs searches $\longrightarrow$ $\texttt{HiggsBounds}$ [T.Stefaniak et al. arxiv:2006.06007]
- SM Higgs couplings $\longrightarrow$ $\texttt{HiggsSignals}$ [T.Stefaniak et al. arxiv:2012.09197]
- Electroweak precision observables $\longrightarrow$ S, T, U parameters [M. Baak et al. arXiv.1209.2716]
- Flavor physics $B \to X_s\gamma$ limit $\longrightarrow$ Lower bound for the $m_{h^\pm}$ [O. Deschamps et al. arXiv.0907.5135]

Scan setup

We focus on the Type II Yukawa structure

- Implement the model in the `SARAH`. Use `SPheno` to generate the spectra.
- We keep the second lightest h_2 to be the SM-like Higgs
- We focus on a light, singlet-like h_1 Higgs-boson ~ 96 GeV
- Scan the parameter space

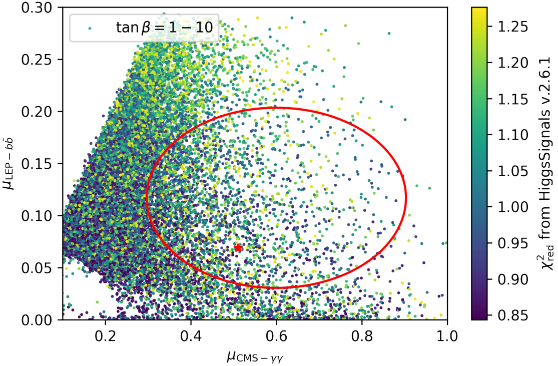
$$m_{h_1} \in \{95,\ 98\}\ \text{GeV}, \quad m_{h_2} = 125.1\ \text{GeV}, \quad v_S \in \{100,\ 2000\}\ \text{GeV}$$

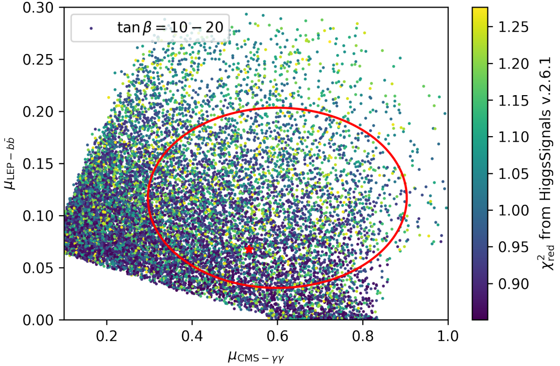
$$\frac{\tan\beta}{\tan\alpha_1} \in \{0, 1\}, \quad \alpha_2 \in \pm\{0.95,\ 1.3\}, \quad |\sin(\beta - \alpha_1 - |\alpha_3|)| \in \{0.98, 1\},$$

$$m_{a_1} \in \{200,\ 500\}\ \text{GeV}, \quad \alpha_4 \in \{\frac{\pi}{4},\ \frac{\pi}{2}\}$$

$\tan\beta$	$m_{h_3} \sim m_{a_2} \sim m_{H^\pm}$
$\{1, 10\}$	$\{800,\ 1200\}$ GeV
$\{10, 20\}$	$\{1000,\ 1700\}$ GeV

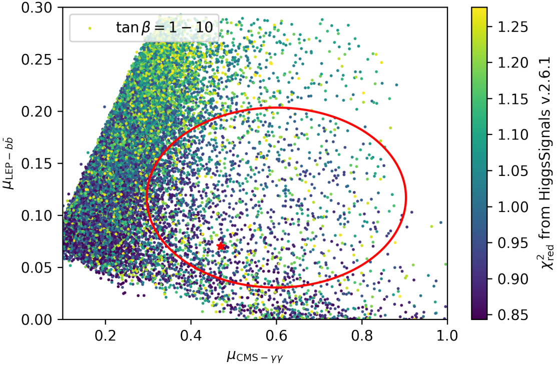
Results for the 2HDMS

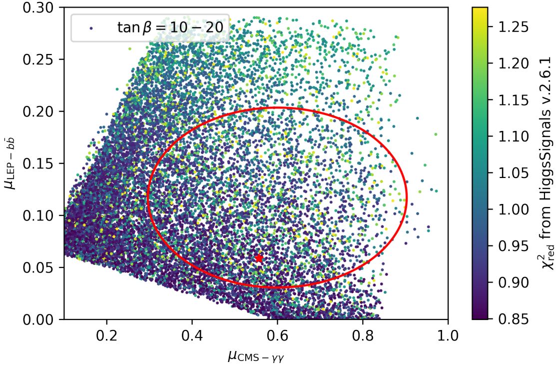




> 2HDMS is able to fit the excess for both low tan β and high tan β ranges.

Results for the N2HDM

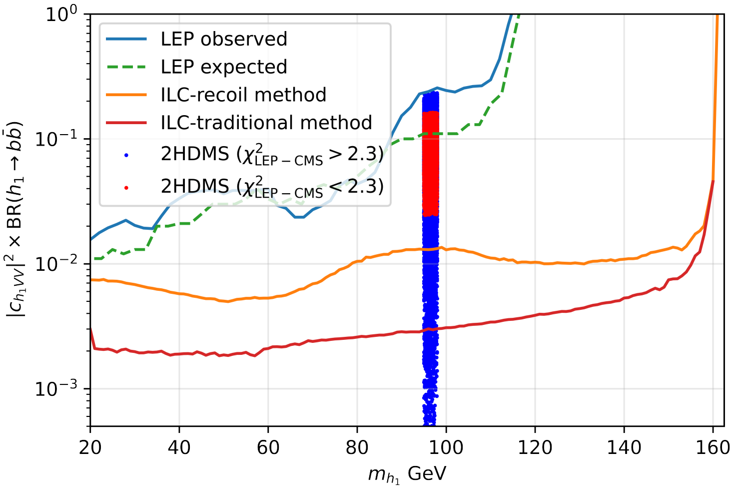




- N2HDM analysis for low tanβ was already carried out in [*T. Biekötter et. al, arXiv:1903.11661*], and we reproduce the results by using `SPheno`
- N2HDM can fit the excess for high tan β region as well

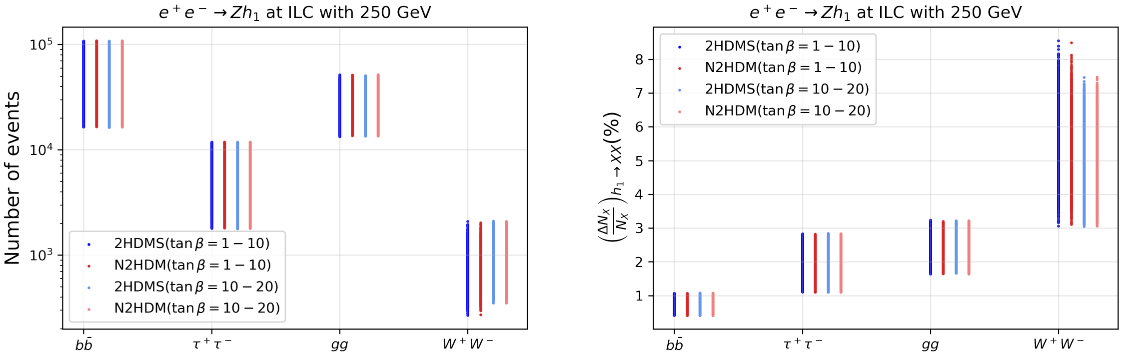
Predicted detection limits at ILC

Plot lines taken from [*P. Drechsel et al. arXiv.1801.09662*]



- The light 96 GeV Higgs can be detected at ILC (e^+e^- collider, $\sqrt{s} = 250$ GeV $L = 500$ fb^{-1})
- The N2HDM result is very similar

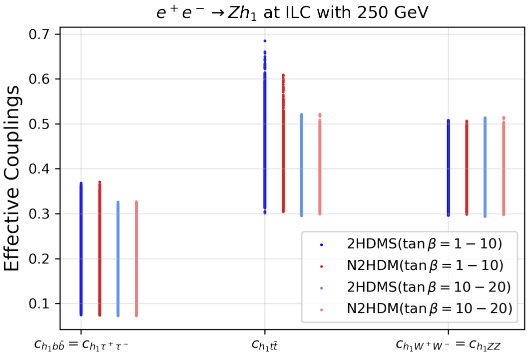
Direct searches at the ILC

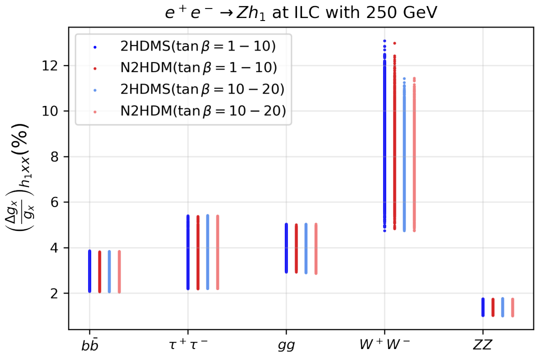


- ILC with $\sqrt{s} = 250$ GeV and an integrated luminosity of 2 ab^{-1}
- Similar number of events for both models with slightly different W^+W^- events in different $\tan\beta$ regions

Direct searches at the ILC

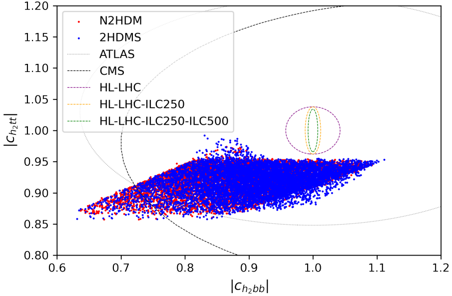
> New type of analysis for estimating the BSM Higgs couplings precision at the ILC

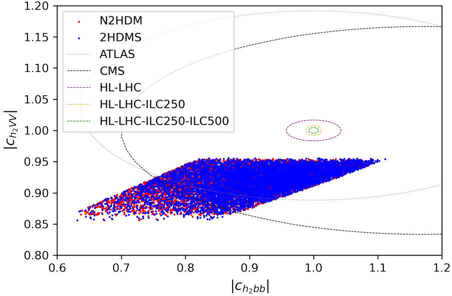




> Couplings precision are below 12% at the ILC with similar values for couplings in both models

Indirect searches at future colliders

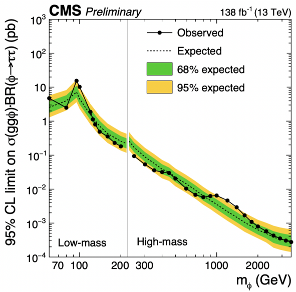




- The h_2 couplings with the 96 GeV excess can be distinguished from SM Higgs at HL-LHC and ILC.
- 2HDMS and N2HDM parameter space cover the same allowed region of h_2 couplings
- Possible way to distinguish the two models:
  - Discovery of the second CP-odd Higgs
  - Analysis of the doublet/singlet character of the CP-odd Higgs
  - Study the differences in the triple Higgs couplings, e.g. $\lambda_{h_1 h_1 h_1}$, $\lambda_{h_1 h_1 h_2}$ (work in progress)

CMS $\tau^+\tau^-$ excess at 95 GeV

[CMS-PAS-HIG-21-001]



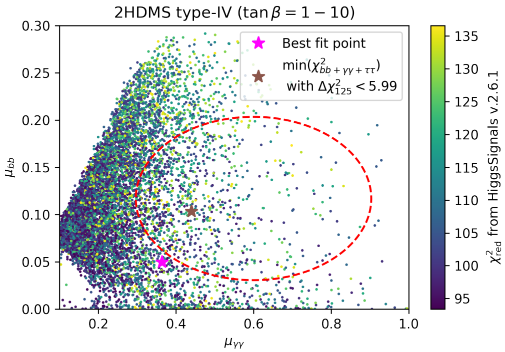
$$\mu_{\text{CMS}-\tau^+\tau^-} = \frac{\sigma(pp \to h_1 \to \tau^+\tau^-)}{\sigma(pp \to H_{\text{SM}} \to \tau^+\tau^-)} = 1.2 \pm 0.5 \tag{12}$$

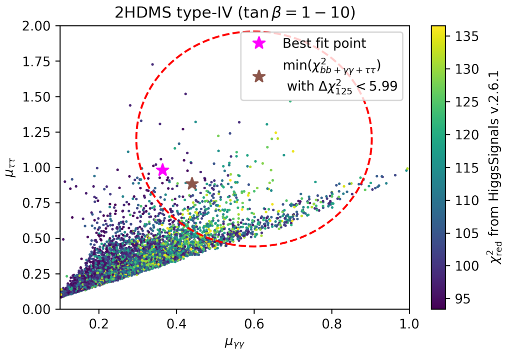
$$\chi^2 = \mu_{\text{LEP}-b\bar{b}} + \mu_{\text{CMS}-\gamma\gamma} + \mu_{\text{CMS}-\tau^+\tau^-} < 3.53 \tag{13}$$

- The type-IV model can accommodate the $\tau^+\tau^-$ excess better, but the type-II cannot not do well

[2203.13180]

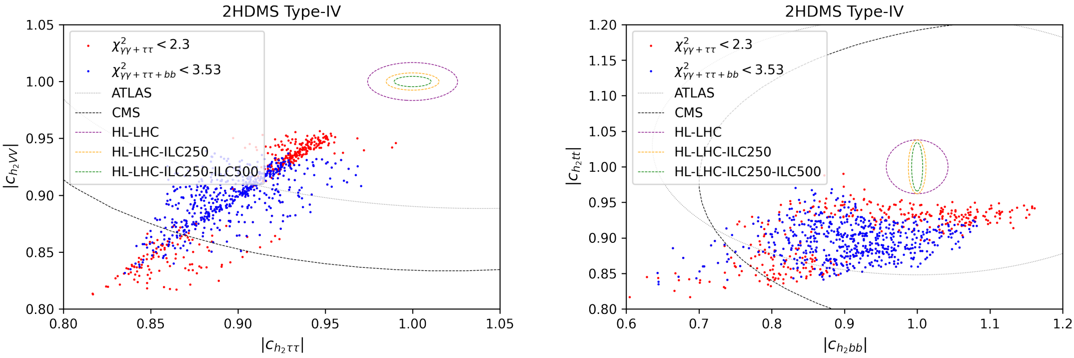
Type-IV 2HDMS





- The current CMS $\tau^+\tau^-$ excess can be accommodated by 2HDMS with Type-IV Yukawa coupling

Type-IV 2HDMS



> Including the independent LEP excess can make the $c_{h_2 VV}$ for 125 GeV Higgs lower

Summary

Conclusions

- We analyzed the $\mathbb{Z}_3$ invariant Two-Higgs-doublet model with complex singlet
- We found that the 2HDMS and N2HDM both are equally able to fit the 96 GeV excess for tan$\beta = 1 - 20$
- We estimate the experimental observables for direct h_1 searches and indirect searches at ILC and HL-LHC
- One cannot distinguish the 2HDMS and N2HDM by only comparing the observables of h_1 and h_2
- The current CMS $\tau^+\tau^-$ excess can be accommodated by the type-IV 2HDMS model

Outlook

- Distinguish the 2HDMS and N2HDM
  - Compare the CP-odd Higgs couplings by CP-odd Higgs searches
  - Study the triple-Higgs couplings and di-Higgs production for both N2HDM and 2HDMS

Thank you!

Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

S. Heinemeyer, C. Li, F. Lika, G. Moortgat-Pick, S. Paasch

cheng.li@desy.de

Backup

Higgs mass matrices:

$$
\begin{aligned}
M^2_{S11} &= 2\lambda_1 v^2 \cos^2\beta + (m^2_{12} - \mu_{12} v_S)\tan\beta \\
M^2_{S22} &= 2\lambda_2 v^2 \sin^2\beta + (m^2_{12} - \mu_{12} v_S)\cot\beta \\
M^2_{S12} &= (\lambda_3 + \lambda_4) v^2 \sin 2\beta - (m^2_{12} - \mu_{12} v_S) \\
M^2_{S13} &= (2\lambda'_1 v_S \cos\beta + \mu_{12}\sin\beta) v \\
M^2_{S23} &= (2\lambda'_2 v_S \sin\beta + \mu_{12}\cos\beta) v \\
M^2_{S33} &= \frac{\mu_{S1}}{2} v_S + \lambda''_3 v_S^2 - \mu_{12}\frac{v^2}{2v_S}\sin 2\beta
\end{aligned}
$$

$$
\begin{aligned}
M^2_{P11} &= (m^2_{12} - \mu_{12} v_S)\tan\beta \\
M^2_{P22} &= (m^2_{12} - \mu_{12} v_S)\cot\beta \\
M^2_{P12} &= -(m^2_{12} - \mu_{12} v_S) \\
M^2_{P13} &= \mu_{12} v \sin\beta \\
M^2_{P23} &= -\mu_{12} v \cos\beta \\
M^2_{P33} &= -\frac{3}{2}\mu_{S1} v_S - \mu_{12}\frac{v^2}{2v_S}\sin 2\beta \\
M^2_{C} &= 2(m^2_{12} - \mu_{12} v_S)\csc 2\beta - \lambda_4 v^2
\end{aligned}
\qquad (14)
$$

Backup

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

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

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

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

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

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

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

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

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

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

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