

A 96 GeV Higgs Boson in the 2HDM plus singlet

[arXiv:2112.11958], published in Phys. Rev. D

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

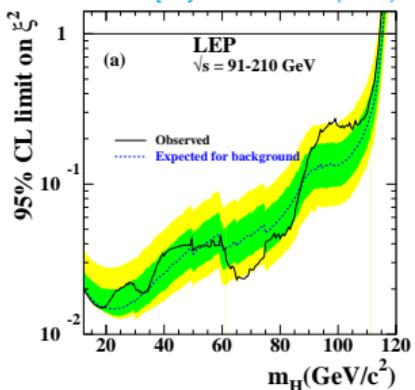
Sven Heinemeyer, **Cheng Li**, Florian Lika,
Gudrid Moortgat-Pick, Steven Paasch

Ioannina, SUSY 2022

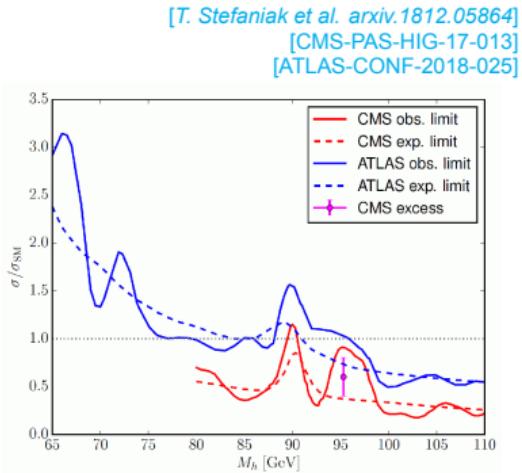
July 1st, 2022

Motivation

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



$$\mu_{\text{LEP}} = \frac{\sigma(e^+e^- \rightarrow Z h_1 \rightarrow Z b\bar{b})}{\sigma(e^+e^- \rightarrow Z H_{\text{SM}} \rightarrow Z b\bar{b})} = 0.117 \pm 0.057$$



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

- 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

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

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

$$\begin{aligned} V = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \\ & + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) - m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \\ & + m_S^2 S^\dagger S + \lambda'_1 (S^\dagger S) (\Phi_1^\dagger \Phi_1) + \lambda'_2 (S^\dagger S) (\Phi_2^\dagger \Phi_2) \\ & + \frac{\lambda''_3}{4} (S^\dagger S)^2 + \left(\frac{\mu_{S1}}{6} S^3 + \mu_{12} S \Phi_1^\dagger \Phi_2 + \text{h.c.} \right) \end{aligned} \tag{2}$$

Additional complex singlet

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

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

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

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

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

Additional real singlet

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

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:

$$R = \begin{pmatrix} c_{\alpha_1}c_{\alpha_2} & s_{\alpha_1}c_{\alpha_2} & s_{\alpha_2} \\ -s_{\alpha_1}c_{\alpha_3} - c_{\alpha_1}s_{\alpha_2}s_{\alpha_3} & c_{\alpha_1}c_{\alpha_3} - s_{\alpha_1}s_{\alpha_2}s_{\alpha_3} & c_{\alpha_2}s_{\alpha_3} \\ s_{\alpha_1}s_{\alpha_3} - c_{\alpha_1}s_{\alpha_2}c_{\alpha_3} & -s_{\alpha_1}s_{\alpha_2}c_{\alpha_3} - c_{\alpha_1}s_{\alpha_3} & c_{\alpha_2}c_{\alpha_3} \end{pmatrix} \quad (5)$$

3 x 3 CP-odd rotation matrix:

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

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

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

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



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 $|R_{13}^2| \rightarrow 1$):

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

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

Alignment limit:

$$\sin(\beta - \alpha_1 - \text{sgn}(\alpha_2)\alpha_3) \rightarrow 1$$



96 GeV "excess"

LEP signal strengths:

$$\begin{aligned}\mu_{\text{LEP}} &= \frac{\sigma(e^+e^- \rightarrow Zh_1 \rightarrow Zb\bar{b})}{\sigma(e^+e^- \rightarrow ZH_{\text{SM}} \rightarrow Zb\bar{b})} = |c_{h_1 VV}|^2 \frac{\text{BR}(h_1 \rightarrow b\bar{b})}{\text{BR}_{\text{SM}}(h \rightarrow b\bar{b})} = 0.117 \pm 0.057 \\ \mu_{\text{LEP}} &\propto |c_{h_1 VV}|^2 \propto \cos^2 \alpha_2\end{aligned}\quad (9)$$

CMS signal strengths:

$$\begin{aligned}\mu_{\text{CMS}} &= \frac{\sigma(pp \rightarrow h_1 \rightarrow \gamma\gamma)}{\sigma(pp \rightarrow H_{\text{SM}} \rightarrow \gamma\gamma)} = |c_{h_1 tt}|^2 \frac{\text{BR}(h_1 \rightarrow \gamma\gamma)}{\text{BR}_{\text{SM}}(h \rightarrow \gamma\gamma)} = 0.6 \pm 0.2 \\ \mu_{\text{CMS}} &\propto \frac{|c_{h_1 tt}|^2}{|c_{h_1 bb}|^2} \propto \left(\frac{\tan \alpha_1}{\tan \beta}\right)^2\end{aligned}\quad (10)$$

Fitting to the "excess":

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



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)]
- > Vacuum stability → Evade [J. Wittbrodt arXiv:1812.04644]

Experimental constraints

- > LEP, Tevatron & LHC Higgs searches → HiggsBounds [T.Stefaniak et al. arxiv:2006.06007]
- > SM Higgs couplings → HiggsSignals [T.Stefaniak et al. arxiv:2012.09197]
- > Electroweak precision observables → S , T , U parameters [M. Baak et al. arXiv.1209.2716]
- > Flavor physics $B \rightarrow X_s \gamma$ limit → 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

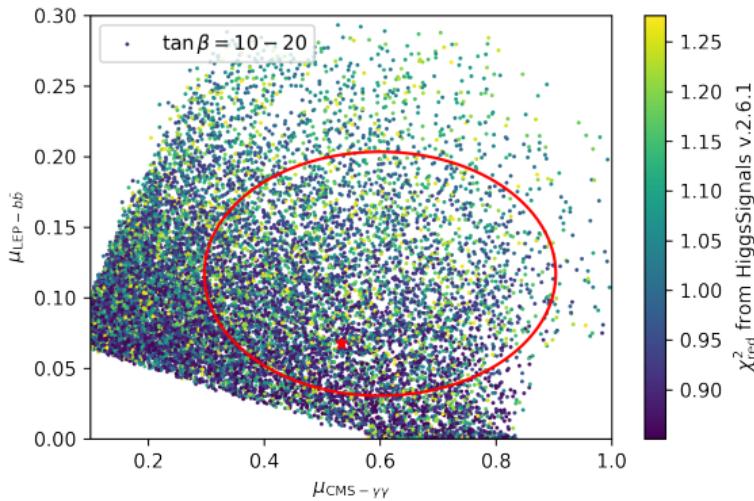
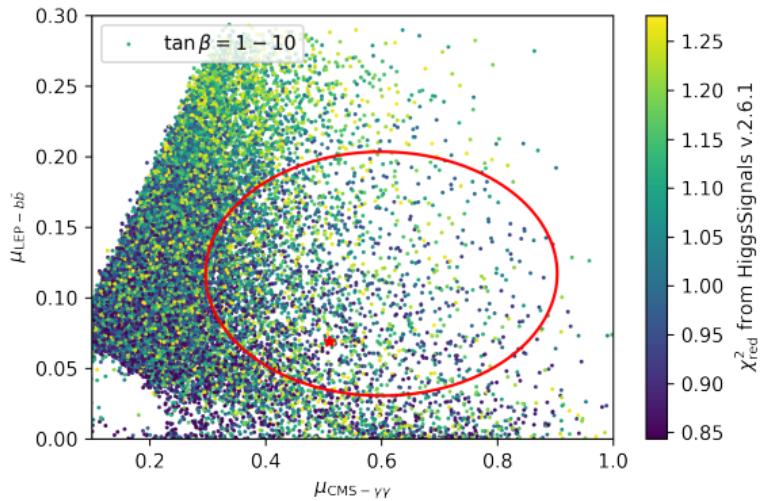
$$m_{h_1} \in \{95, 98\} \text{ GeV}, \quad m_{h_2} = 125.1 \text{ GeV}, \quad v_S \in \{100, 2000\} \text{ GeV}$$

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

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

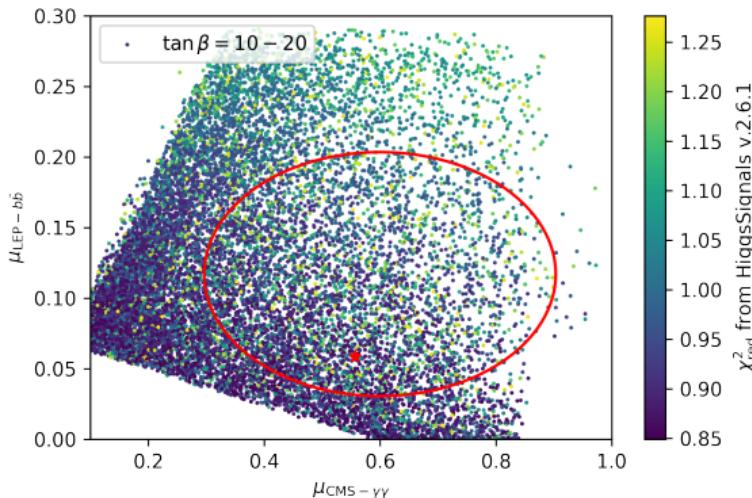
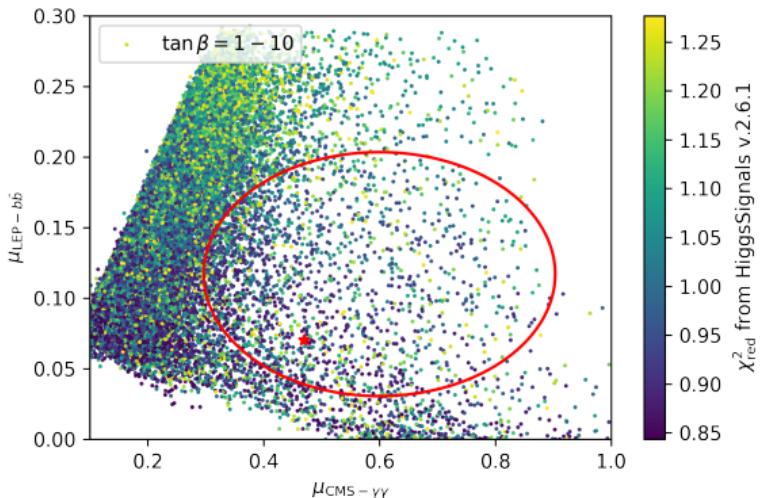
$\tan \beta$	$m_{h_3} \sim m_{a_2} \sim m_{H^\pm}$
{1, 10}	{800, 1200} GeV
{10, 20}	{1000, 1700} GeV

Results for the 2HDMs



- 2HDMs is able to fit the excess for both low $\tan\beta$ and high $\tan\beta$ ranges.

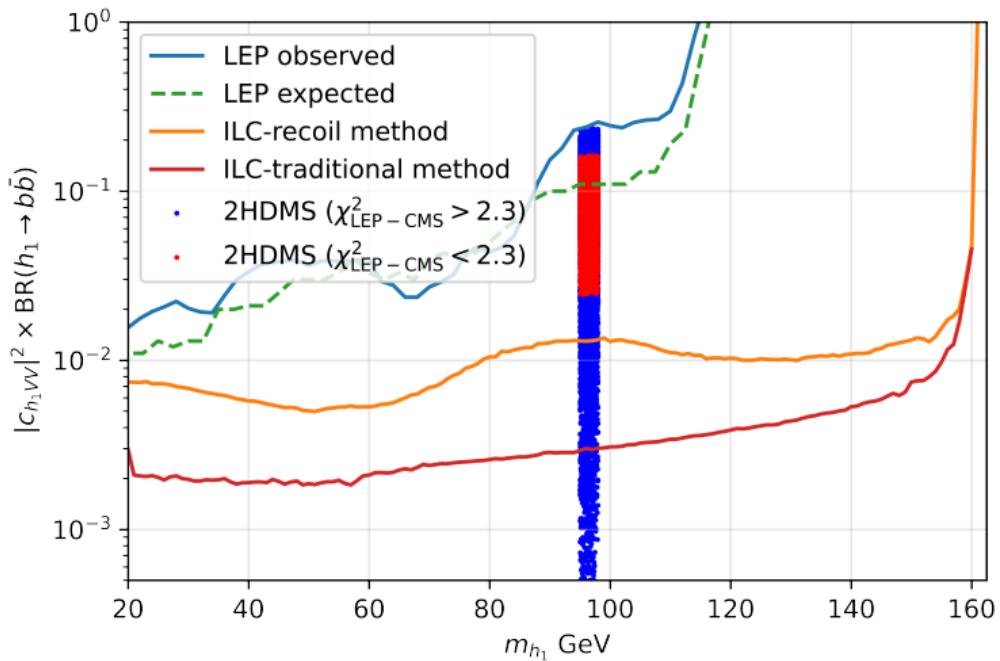
Results for the N2HDM



- > N2HDM analysis for low $\tan\beta$ 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 $\tan\beta$ region as well

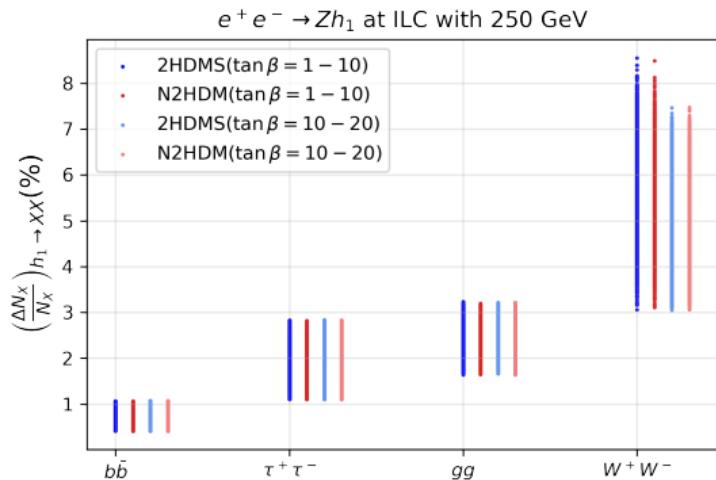
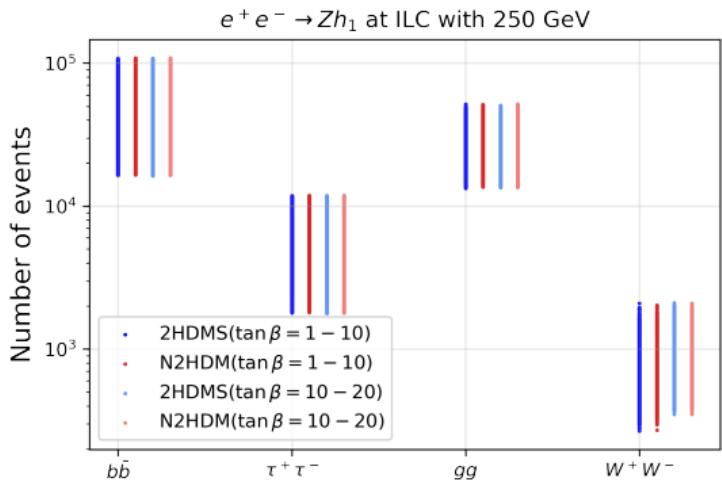
Predicted detection limits at ILC

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 $L = 500 \text{ fb}^{-1}$)
- > The N2HDM result is very similar

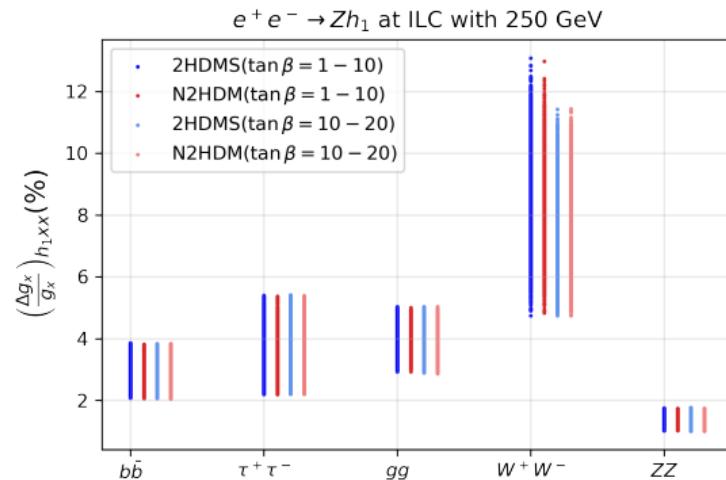
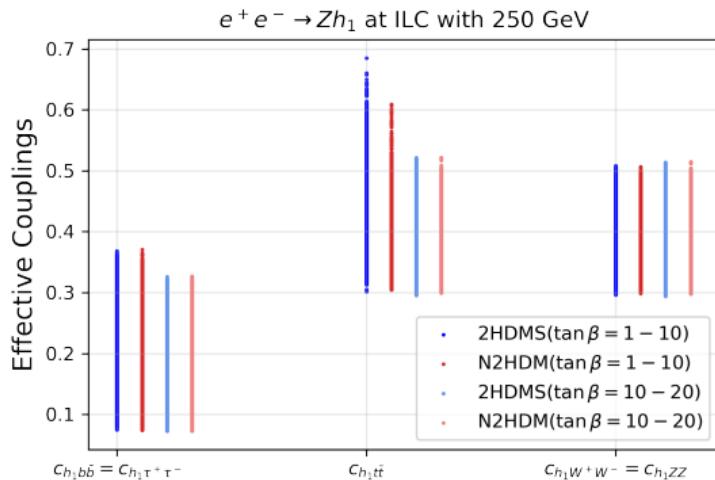
Direct searches at the ILC



- > 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

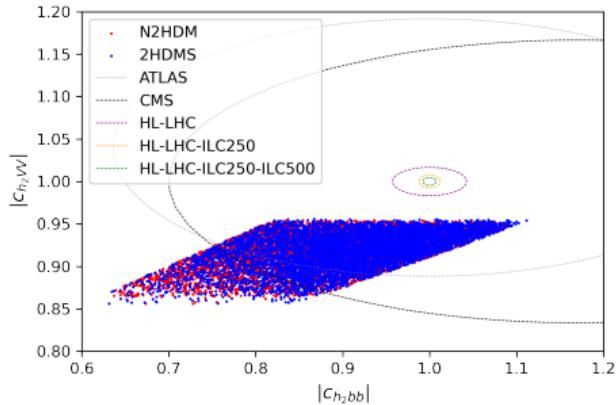
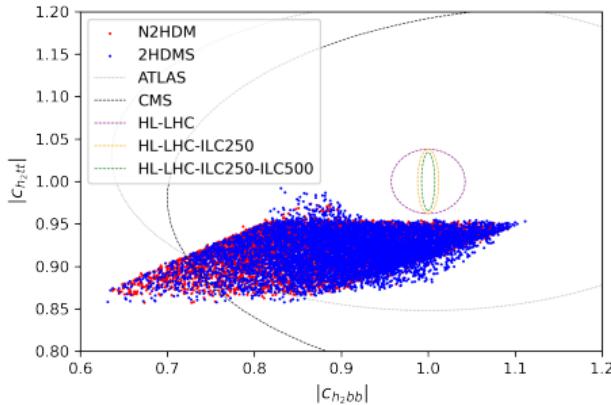
Direct searches at the ILC

- > 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

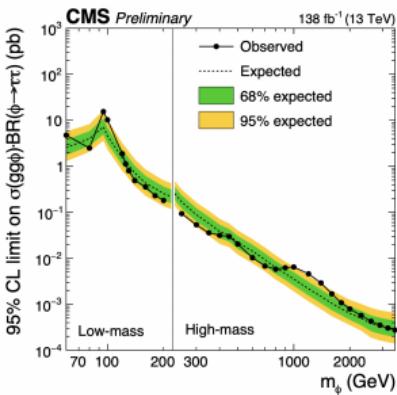
Indirect searches at future colliders



- > 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]



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

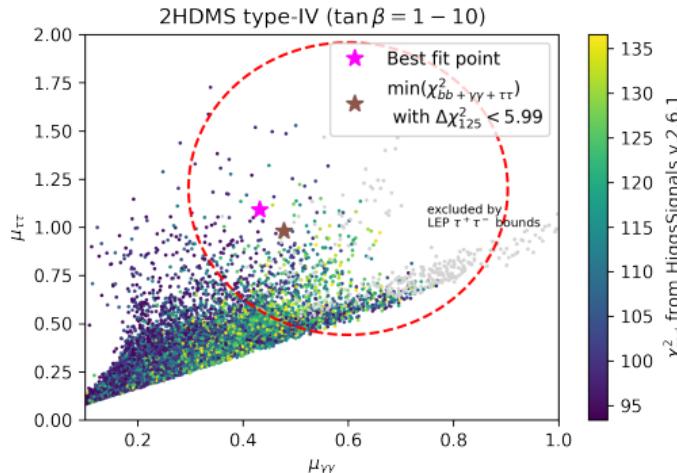
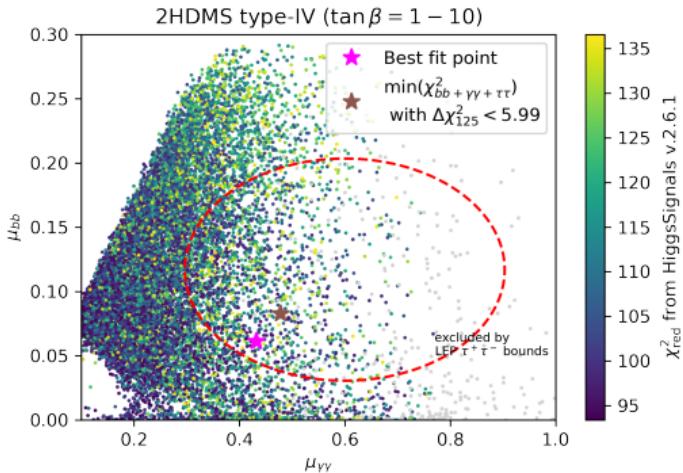
$$\chi^2 = \mu_{\text{LEP}-b\bar{b}} + \mu_{\text{CMS}-\gamma\gamma} + \mu_{\text{CMS}-\tau^+\tau^-} < 3.53 \quad (13)$$

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

[2203.13180]

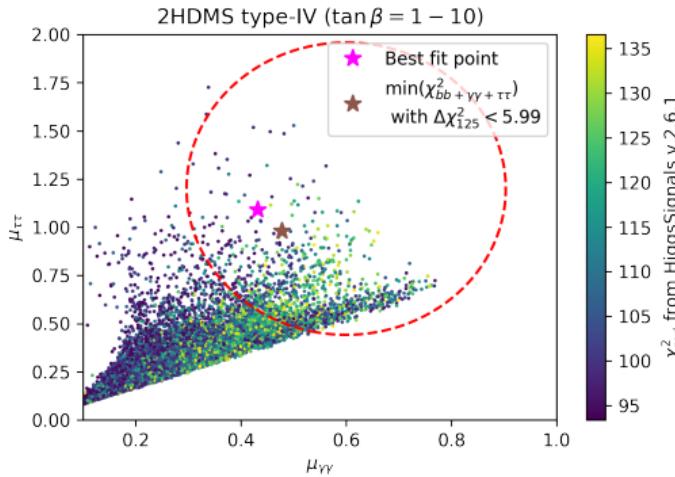
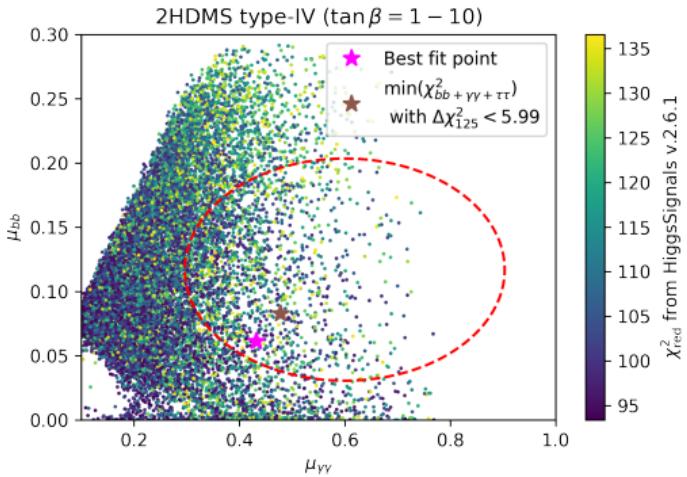


Type-IV 2HDMS



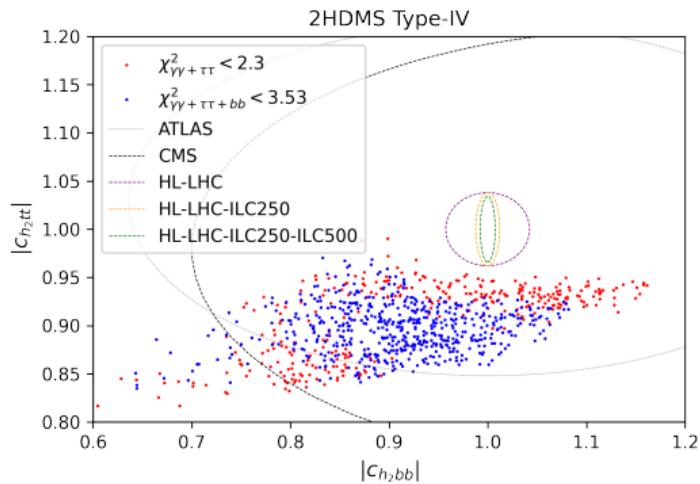
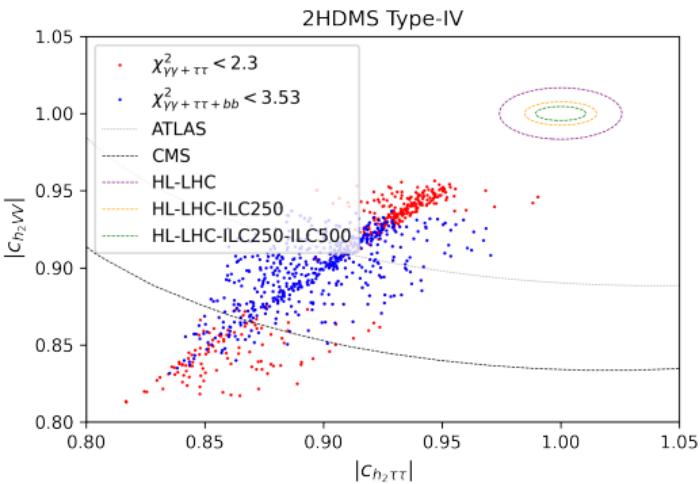
- The current CMS $\tau^+\tau^-$ excess can be accommodated by 2HDMS with Type-IV Yukawa coupling

Type-IV 2HDMS



- 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

Sven Heinemeyer, **Cheng Li**, Florian Lika, Gudrid Moortgat-Pick, Steven Paasch

cheng.li@desy.de



Backup

Higgs mass matrices:

$$M_{S11}^2 = 2\lambda_1 v^2 \cos^2 \beta + (m_{12}^2 - \mu_{12} v_S) \tan \beta$$

$$M_{S22}^2 = 2\lambda_2 v^2 \sin^2 \beta + (m_{12}^2 - \mu_{12} v_S) \cot \beta$$

$$M_{S12}^2 = (\lambda_3 + \lambda_4)v^2 \sin 2\beta - (m_{12}^2 - \mu_{12} v_S)$$

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

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

$$M_{S33}^2 = \frac{\mu_{S1}}{2} v_S + \lambda''_3 v_S^2 - \mu_{12} \frac{v^2}{2v_S} \sin 2\beta$$

$$\begin{aligned} M_{P11}^2 &= (m_{12}^2 - \mu_{12} v_S) \tan \beta \\ M_{P22}^2 &= (m_{12}^2 - \mu_{12} v_S) \cot \beta \\ M_{P12}^2 &= -(m_{12}^2 - \mu_{12} v_S) \\ M_{P13}^2 &= \mu_{12} v \sin \beta \\ M_{P23}^2 &= -\mu_{12} v \cos \beta \end{aligned} \tag{14}$$

$$M_{P33}^2 = -\frac{3}{2}\mu_{S1} v_S - \mu_{12} \frac{v^2}{2v_S} \sin 2\beta$$

$$M_C^2 = 2(m_{12}^2 - \mu_{12} v_S) \csc 2\beta - \lambda_4 v^2$$

Backup

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

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

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

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

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

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

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

$$\lambda'_1 = \frac{1}{2v_S v \cos \beta} \left[\sum_i m_{h_i}^2 R_{i1} R_{i3} - \mu_{12} v \sin \beta \right]$$

$$\lambda'_2 = \frac{1}{2v_S v \sin \beta} \left[\sum_i m_{h_i}^2 R_{i2} R_{i3} - \mu_{12} v \cos \beta \right]$$

$$\lambda''_3 = \frac{1}{v_S^2} \left[\sum_i m_{h_i}^2 R_{i3}^2 + \mu_{12} \frac{v^2}{2v_S} \sin 2\beta - \frac{\mu_{S1}}{2} v_S \right]$$

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

