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A 96 GeV Higgs Boson in the 2HDMS

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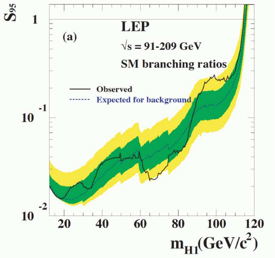
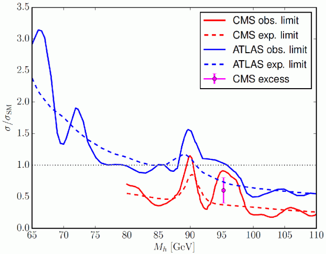
Motivation

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



[T. Stefaniak et al. arxiv.1812.05864]



- Extend the 2HDM to a NMSSM-like Higgs structure (complex singlet and $\mathbb{Z}_3$ symmetry)
- Unified description of the excess at LEP for $e^+e^- \to Z \to Z\phi$ and CMS for $pp \to \phi \to \gamma\gamma$
- Search for a 96 GeV Higgs boson at the future linear colliders (e.g. ILC)

Outline

- N2HDM
- Theoretical framework of the 2HDMS
- 96 GeV excess
- Application at the ILC

Theoretical framework of the N2HDM

Two Higgs doublets

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

Additional complex singlet

$$S = v_S + \rho_S \tag{2}$$

$$\tan\beta = \frac{v_2}{v_1}, \qquad v = \sqrt{v_1^2 + v_2^2} = 246\ \mathrm{GeV} \tag{3}$$

Symmetry

	ϕ_1	ϕ_2	ϕ_S
$\mathbb{Z}_2$	+	-	+
$\mathbb{Z}_2'$	+	+	-

Theoretical framework of the 2HDMS

Two Higgs doublets

$$\Phi_1 = \begin{pmatrix} \chi_1^+ \\ v_1 + \frac{\rho_1 + i\eta_1}{\sqrt{2}} \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \chi_2^+ \\ v_2 + \frac{\rho_2 + i\eta_2}{\sqrt{2}} \end{pmatrix} \tag{4}$$

Additional complex singlet

$$S = v_S + \frac{\rho_S + i\eta_S}{\sqrt{2}} \tag{5}$$

$$\tan\beta = \frac{v_2}{v_1}, \qquad v = \sqrt{v_1^2 + v_2^2} = 174 \text{ GeV} \tag{6}$$

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 the 2HDMS and N2HDM

Higgs potential (S. Baum, N. R. Shah,arXiv:1808.02667):

$$\begin{aligned}V =& m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\ &+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) - m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.} \\ &+ m_S^2 S^\dagger S + \lambda_1'(S^\dagger S)(\Phi_1^\dagger\Phi_1) + \lambda_2'(S^\dagger S)(\Phi_2^\dagger\Phi_2) \\ &+ \frac{\lambda_3''}{4}(S^\dagger S)^2 + \left(\frac{\mu_{S1}}{6}S^3 + \mu_{12}S\Phi_1^\dagger\Phi_2 + \text{h.c.}\right)\end{aligned} \tag{7}$$

12 free parameters:

$$\lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_1',\ \lambda_2',\ \lambda_3'',\ m_{12},\ \mu_{S1},\ \mu_{12},\ v_S,\ \tan\beta \tag{8}$$

where orange terms are similar to the N2HDM and those in red are new in the 2HDMS.
m_{12} softly breaks the $\mathbb{Z}_2$, $\mathbb{Z}_3$ symmetry.

Tree level Higgs mass matrices:

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

$$
\begin{aligned}
M^2_{P11} &= (m^2_{12} - \mu_{12} v_S)\tan\beta \\
M^2_{P22} &= (m^2_{12} - \mu_{12} v_S)\cot\beta \\
M^2_{P12} &= -(m^2_{12} - \mu_{12} v_S) \\
M^2_{P13} &= \mu_{12} v \sin\beta \\
M^2_{P23} &= -\mu_{12} v \cos\beta \\
M^2_{P33} &= -\frac{3}{2}\mu_{S1} v_S - \mu_{12}\frac{v^2}{2v_S}\sin 2\beta \\
M^2_{C} &= 2(m^2_{12} - \mu_{12} v_S)\csc 2\beta - \lambda_4 v^2
\end{aligned}
\tag{9}
$$

Change of basis to express the Potential parameters in terms of the masses and mixing angles

$$
m_{h_{1,2,3}},\ m_{a_{1,2}},\ m_{h^\pm},\ \alpha_1,\ \alpha_2,\ \alpha_3,\ \alpha_4,\ v_S,\ \tan\beta \tag{10}
$$

Mixing angles in the 2HDMS

3 x 3 CP-even rotation matrix:

$$R = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -s_{\alpha_1} c_{\alpha_3} - c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ s_{\alpha_1} s_{\alpha_3} - c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} & -s_{\alpha_1} s_{\alpha_2} c_{\alpha_3} - c_{\alpha_1} s_{a3} & c_{\alpha_2} c_{\alpha_3} \end{pmatrix} \tag{11}$$

3 x 3 CP-odd rotation matrix:

$$R^A = \begin{pmatrix} -s_\beta c_{\alpha_4} & c_\beta c_{\alpha_4} & s_{\alpha_4} \\ s_\beta s_{\alpha_4} & -c_\beta s_{\alpha_4} & c_{\alpha_4} \\ c_\beta & s_\beta & 0 \end{pmatrix} \tag{12}$$

N2HDM limit for $\alpha_4 \to \frac{\pi}{2}$

Couplings in Type II:

$$c_{h_i tt} \sim \frac{R_{i2}}{\sin\beta} \qquad c_{h_i bb} \sim \frac{R_{i1}}{\cos\beta} \qquad c_{h_i \tau\tau} \sim \frac{R_{i1}}{\cos\beta}$$

Testing for constraints

Theoretical constraints

- Vaccum stability $\longrightarrow$ `Evade`
- Boundedness from below
- Tree-level perturbative unitarity

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 $m_{h^\pm}$

Scan setup

We focus on the Type II Yukawa structure

- Implement the 2HDMS in the `SARAH`
- Use `SPheno` to generate the spectra
- We focus on a light, singlet-like h_1 Higgs-boson $< 100 GeV$
- Scan the parameter space

$$
\begin{aligned}
&m_{h_1} \in \{95,\ 99\}\ \text{GeV}, && m_{h_2} = 125.1\ \text{GeV}, && m_{h_3} \in \{650,\ 1000\}\ \text{GeV},\\
&m_{a_1} \in \{200,\ 500\}\ \text{GeV}, && m_{a_2} \in \{650,\ 1000\}\ \text{GeV}, && m_{H^\pm} \in \{650,\ 1000\}\ \text{GeV},\\
&\tan\beta \in \{1,\ 6\}, && \alpha_4 \in \{1.25,\ \frac{\pi}{2}\}, && v_S \in \{100,\ 2000\}\ \text{GeV}\\
&\frac{\tan\beta}{\tan\alpha_1} \in \{0, 1\}, && \alpha_2 \in \pm\{0.95,\ 1.3\}, && |\sin(\beta - \alpha_1 - |\alpha_3|)| \in \{0.98, 1\}
\end{aligned}
$$

96 GeV "excess"

LEP signal strengths:

$$\mu_{\mathsf{LEP}} = \frac{\sigma(e^+e^- \to Zh_1 \to Zb\bar{b})}{\sigma(e^+e^- \to ZH_{\mathsf{SM}} \to Zb\bar{b})} = |c_{h_1VV}|^2 \frac{\mathrm{BR}(h_1 \to b\bar{b})}{\mathrm{BR}_{\mathrm{SM}}(h \to b\bar{b})} = 0.117 \pm 0.057 \quad (13)$$

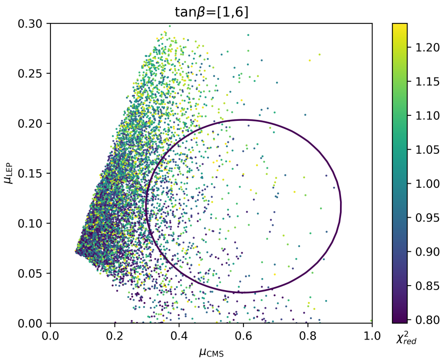
CMS signal strengths:

$$\mu_{\mathsf{CMS}} = \frac{\sigma(pp \to h_1 \to \gamma\gamma)}{\sigma(pp \to H_{\mathsf{SM}} \to \gamma\gamma)} = |c_{h_1tt}|^2 \frac{\mathrm{BR}(h_1 \to \gamma\gamma)}{\mathrm{BR}_{\mathrm{SM}}(h \to \gamma\gamma)} = 0.6 \pm 0.2 \quad (14)$$

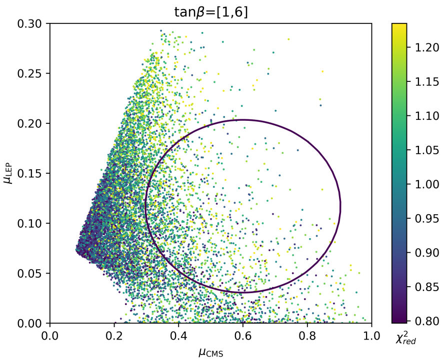
Fitting to the "excess":

$$\chi^2 = \left(\frac{\mu_{\mathrm{LEP}} - 0.117}{0.057}\right)^2 + \left(\frac{\mu_{\mathrm{CMS}} - 0.6}{0.2}\right)^2 < 2.3 \quad (15)$$

Results for low tanβ



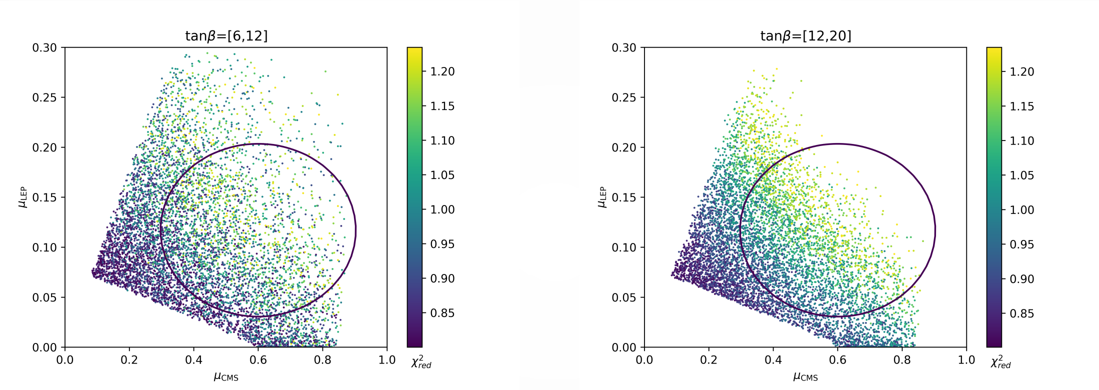
N2HDM



2HDMS

- N2HDM analysis for low tanβ was already carried out in [T. Biekötter et. al, arXiv:1903.11661]
- Both models are equally able to fit the excess

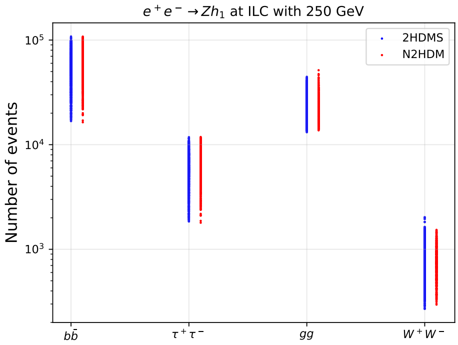
Results for high tanβ in the 2HDMS

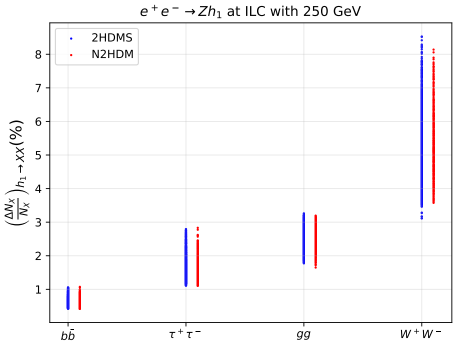


- Higher values for tanβ are easier accessible in the 2HDMS. Scans for higher tanβ in the N2HDM are still running.

Observables at the ILC

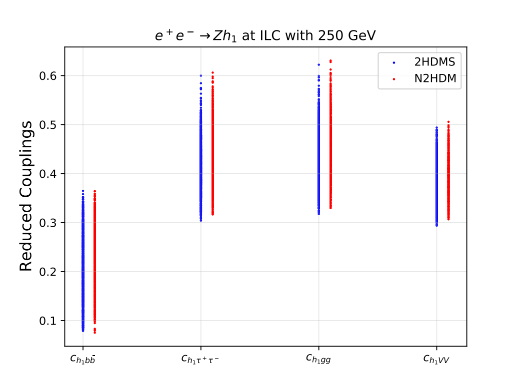
Points with tanβ [1,6]

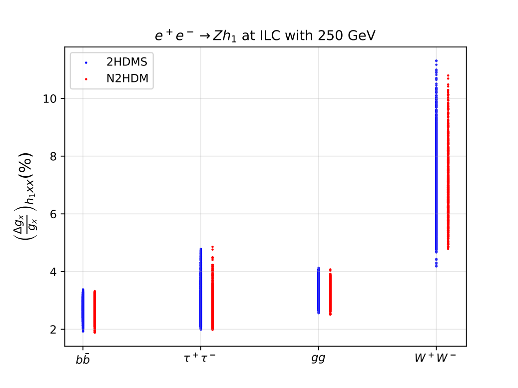




- ILC with $\sqrt{s} = 250$ GeV and an integrated luminosity of $2ab^{-1}$
- Similar number of events for both models with slightly different W^+W^- events in the 2HDMS

Observables at the ILC (II)





- Model prediction for reduced couplings and evaluation of measurement uncertainties at the ILC
- Coupling uncertainties are below 10% at the ILC with similar values for couplings in the tanβ [1,6] range for both models

Summary

Conclusions

- The 2HDMS and N2HDM are equally able to fit the 96 GeV excess in the low tanβ range
- Evaluation of the number of events and coupling measurement precision at the ILC

Outlook

- Study the N2HDM for tan$\beta \geq 6$
- Evaluate the possibility for a experimental distinction of the 2HDMS and N2HDM