New progress of comparing the 2HDMS and N2HDM

2HDM working group

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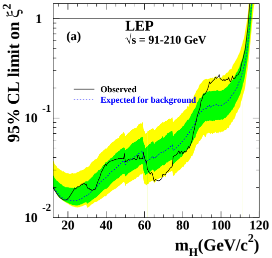
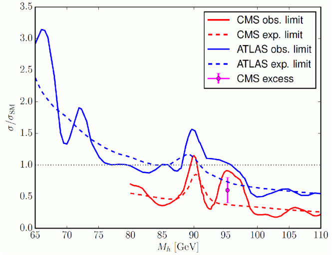
Hamburg, September 9, 2021

Motivation

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

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





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

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

1 Extend the 2HDM to the NMSSM-like Higgs structure (complex singlet and $\mathbb{Z}_3$ symmetry)

2 Interpret the 96 GeV "excess" at LEP and CMS with alternative model

3 Search the 96 GeV Higgs boson at the future colliders (e.g. ILC, CEPC)

Field content 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

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

Convention of vacuum expectation values

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

Symmetry

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

Types of Yukawa couplings:

	type I	type II	lepton-specific	flipped
u-type	Φ_2	Φ_2	Φ_2	Φ_2
d-type	Φ_2	Φ_1	Φ_2	Φ_1
leptons	Φ_2	Φ_1	Φ_1	Φ_2

Field content 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

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

Convention of vacuum expectation values

$$\tan\beta = \frac{v_2}{v_1}, \qquad v = \sqrt{v_1^2 + v_2^2} \approx 246\ \text{GeV} \tag{4}$$

Symmetry

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

Theoretical framework of the 2HDMS

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

$$
\begin{aligned}
V =& m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2 \\
&+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) - m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \\
&+ m_S^2 S^\dagger S + \lambda_1' (S^\dagger S)(\Phi_1^\dagger \Phi_1) + \lambda_2' (S^\dagger S)(\Phi_2^\dagger \Phi_2) \\
&+ \frac{\lambda_3''}{4}(S^\dagger S)^2 + \left(\frac{\mu_{S1}}{6} S^3 + \mu_{12} S \Phi_1^\dagger \Phi_2 + \text{h.c.} \right)
\end{aligned} \tag{5}
$$

12 free parameters:

$$
\lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_1',\ \lambda_2',\ \lambda_3'',\ m_{12},\ \mu_{S1},\ \mu_{12},\ v_S,\ \tan\beta \tag{6}
$$

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.

Mixing angles in the 2HDMS

3 x 3 CP-even rotation matrix:

$$R = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -s_{\alpha_1} c_{\alpha_3} - c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ s_{\alpha_1} s_{\alpha_3} - c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} & -s_{\alpha_1} s_{\alpha_2} c_{\alpha_3} - c_{\alpha_1} s_{a3} & c_{\alpha_2} c_{\alpha_3} \end{pmatrix} \quad (7)$$

Type II Couplings:

$$c_{h_2 tt} \sim \frac{\cos(\alpha_1 \pm \alpha_3)}{\sin\beta} \sin\alpha_2, \; c_{h_2 bb} \sim -\frac{\sin(\alpha_1 \pm \alpha_3)}{\cos\beta} \sin\alpha_2,$$

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

Alignment limit:

$$\sin(\beta - \alpha_1 \mp \alpha_3) \to 1$$

3 x 3 CP-odd rotation matrix:

$$R^A = \begin{pmatrix} -s_\beta c_{\alpha_4} & c_\beta c_{\alpha_4} & s_{\alpha_4} \\ s_\beta s_{\alpha_4} & -c_\beta s_{\alpha_4} & c_{\alpha_4} \\ c_\beta & s_\beta & 0 \end{pmatrix} \quad (8)$$

N2HDM limit for 2HDMS

$$\alpha_4 \to \frac{\pi}{2}$$

96 GeV "excess"

LEP signal strengths:

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

$$\mu_{\text{LEP}} \propto \left(\frac{\tan\alpha_1}{\tan\beta}\right)^2 \tag{9}$$

CMS signal strengths:

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

$$\mu_{\text{CMS}} \propto \cos\alpha_2 \tag{10}$$

Fitting to the ”excess”:

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

Higher $\tan\beta$ region Scan

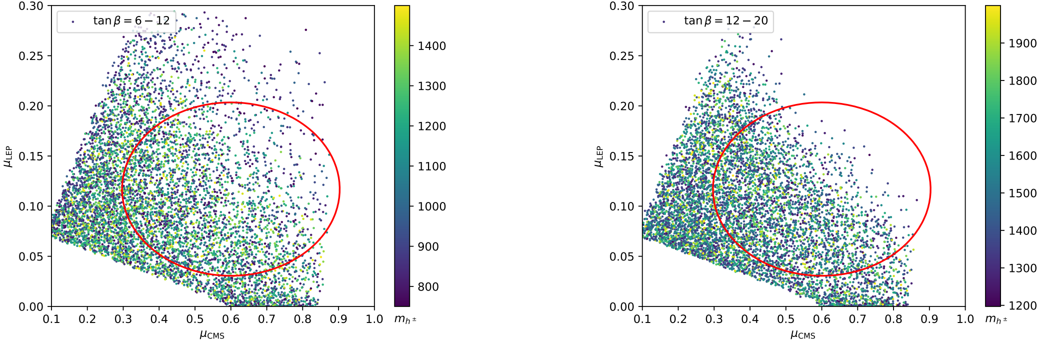
- Parameters with the same scan ranges as the low $\tan\beta$ region scan

$$m_{h_1} \in \{95,\ 99\}\ \text{GeV}, \quad m_{h_2} = 125.1\ \text{GeV}, \quad m_{a_1} \in \{200,\ 500\}\ \text{GeV},$$
$$\frac{\tan\beta}{\tan\alpha_1} \in \{0,1\}, \quad \alpha_2 \in \pm\{0.95,\ 1.3\}, \quad |\sin(\beta - \alpha_1 - |\alpha_3|)| \in \{0.98, 1\}$$
$$v_S \in \{100,\ 2000\}\ \text{GeV}$$

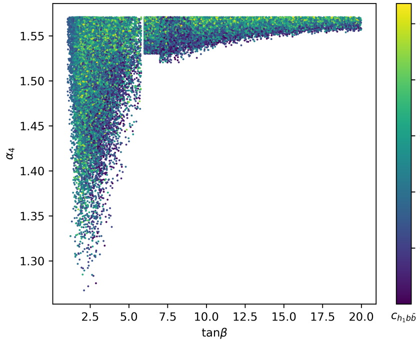
- Parameters with the different scan ranges

$\tan\beta$	α_4	$m_{h_3} \sim m_{a_2} \sim m_{H^\pm}$
$\{6,9\}$	$\{1.35,\ \frac{\pi}{2}\}$	$\{750,\ 1500\}$ GeV
$\{9,12\}$	$\{1.52,\ \frac{\pi}{2}\}$	$\{1000,\ 1500\}$ GeV
$\{12,20\}$	$\{1.54,\ \frac{\pi}{2}\}$	$\{1200,\ 2000\}$ GeV

Results for high tanβ in the 2HDMS



Results for high tanβ in the 2HDMS



- When the tan β goes higher in 2HDMS, α_4 would be more closed to $\frac{\pi}{2}$ because of the perturbative unitarity constraint.
- The 2HDMS would automatically go to the N2HDM limit in higher tan β region

Higher $\tan\beta$ region Scan for N2HDM

> Parameters with the same scan ranges as the low $\tan\beta$ region scan

$$m_{h_1} \in \{95,\ 99\}\ \text{GeV}, \quad m_{h_2} = 125.1\ \text{GeV}, \quad v_S \in \{100,\ 2000\}\ \text{GeV},$$

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

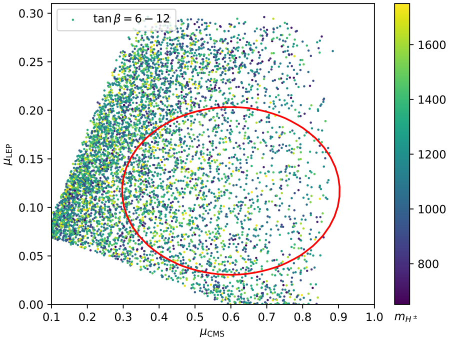
> Parameters with the different scan ranges

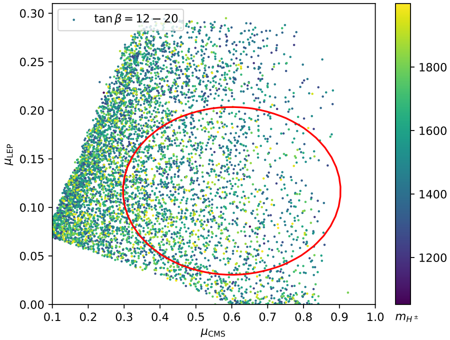
$\tan\beta$	$m_{h_3} \sim m_A \sim m_{H^\pm} \sim \tilde{\mu}$
$\{6, 9\}$	$\{750,\ 1500\}$ GeV
$\{9, 12\}$	$\{1000,\ 1500\}$ GeV
$\{12, 20\}$	$\{1200,\ 2000\}$ GeV

where:

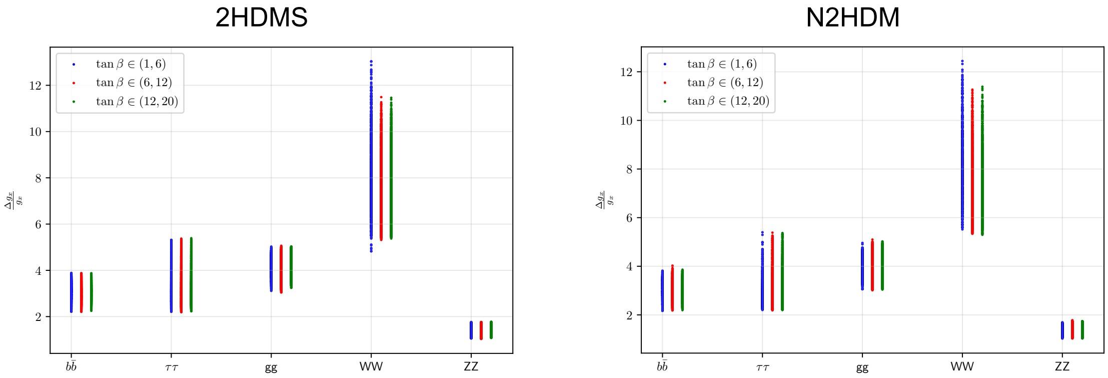
$$\tilde{\mu}^2 = \frac{m_{12}^2}{\sin\beta\cos\beta}$$

Results for high tanβ in the N2HDM





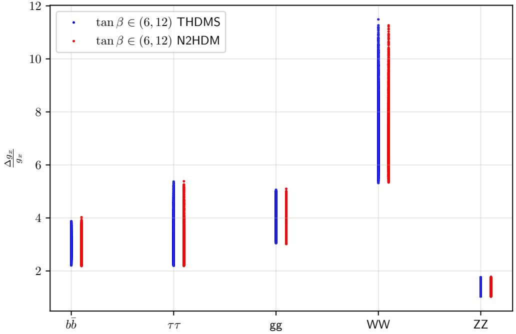
Precision of couplings measurement at the ILC



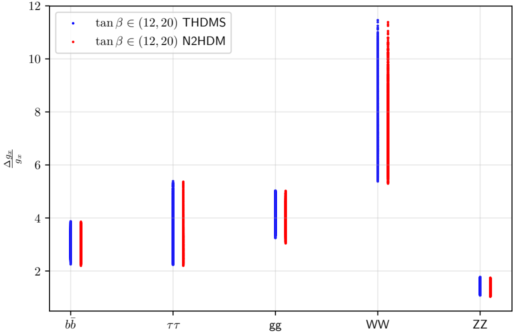
> Comparison between the different tan β region for both models

Precision of couplings measurement at the ILC

$\tan\beta = \{6, 12\}$

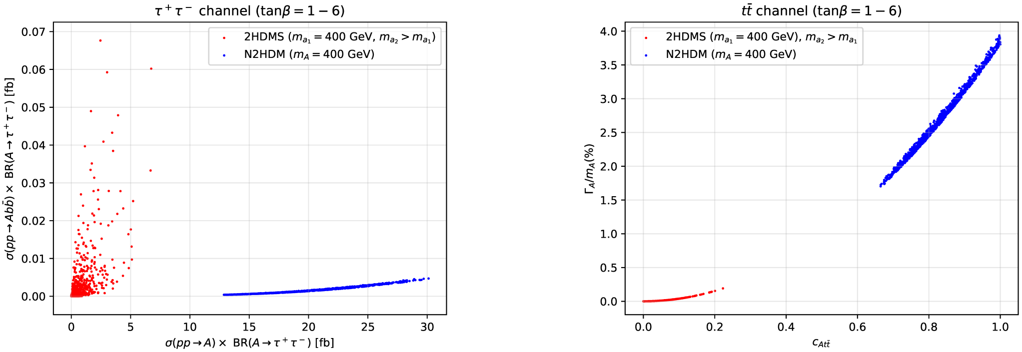


$\tan\beta = \{12, 20\}$



> Comparison between both models for certain $\tan\beta$ region

400 GeV CP-odd Higgs



> In case one can observe a CP-odd Higgs at 400 GeV, one should understand which model it belongs to

> The singlet like a_1 in 2HDMS could be distinguished from the CP-odd Higgs in N2HDM by comparing the $t\bar{t}$ and $\tau^+\tau^-$ production channels.

Summary

Conclusions

- The 2HDMS and N2HDM are equally able to fit the 96 GeV excess for tan$\beta = 1 - 20$
- high tan β region in 2HDMS would be closed to the N2HDM limit and have the same behaviour as N2HDM

Outlook

- Study the CP-odd sector
  - singlet like a_1 is the 400 GeV CP-odd Higgs, but tan β and m_{a_2} are much higher.
  - doublet a_2 is the 400 GeV CP-odd Higgs, but a_1 is a super light hidden sector.
  - doublet a_2 is the 400 GeV CP-odd Higgs, a_1 is a super heavy hidden sector.
- Study the triple-Higgs couplings for both N2HDM and 2HDMS

Thank you!

Contact

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Theoretical framework of the 2HDMS

Higgs mass matrices:

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

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

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

$$
m_{h_{1,2,3}},\ m_{a_{1,2}},\ m_{h^\pm},\ \alpha_1,\ \alpha_2,\ \alpha_3,\ \alpha_4,\ v_S,\ \tan\beta \tag{13}
$$

Testing for constraints

Theoretical constraints

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

Experimental constraints

- LEP, Tevatron & LHC Higgs searches $\longrightarrow$ `HiggsBounds`
- SM Higgs couplings $\longrightarrow$ `HiggsSignals`
- 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 2HDMS 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 $< 100GeV$
- Scan the parameter space

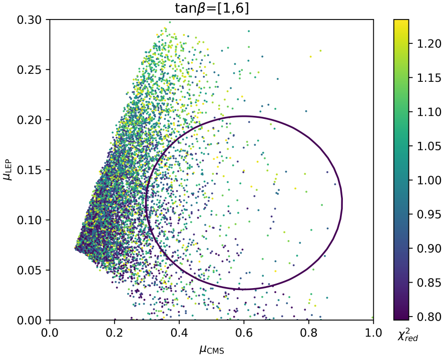
$$m_{h_1} \in \{95,\ 99\}\ \text{GeV}, \quad m_{h_2} = 125.1\ \text{GeV}, \quad m_{h_3} \in \{650,\ 1000\}\ \text{GeV},$$

$$m_{a_1} \in \{200,\ 500\}\ \text{GeV}, \quad m_{a_2} \in \{650,\ 1000\}\ \text{GeV}, \quad m_{H^\pm} \in \{650,\ 1000\}\ \text{GeV},$$

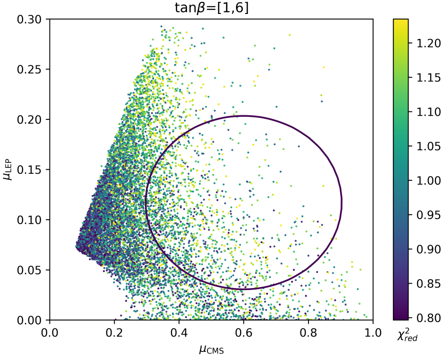
$$\tan\beta \in \{1,\ 6\}, \quad \alpha_4 \in \{1.25,\ \frac{\pi}{2}\}, \quad v_S \in \{100,\ 2000\}\ \text{GeV}$$

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

Results for low tanβ



N2HDM

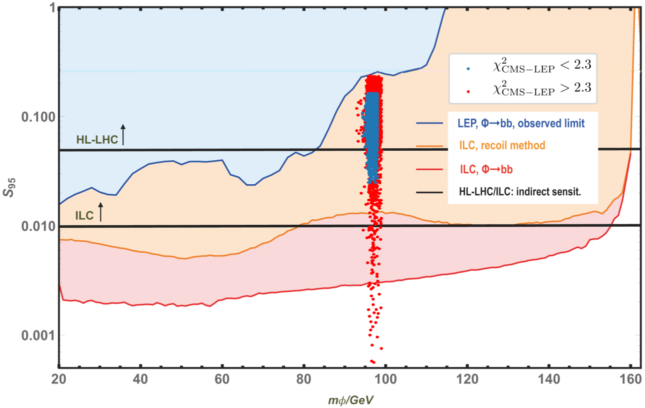


2HDMS

- 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

Predicted detection limits

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

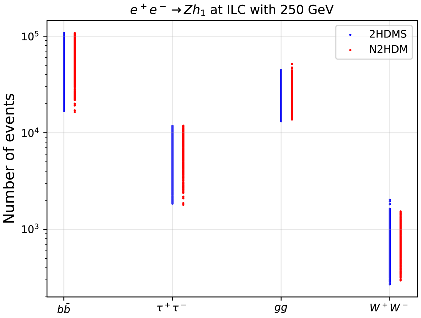


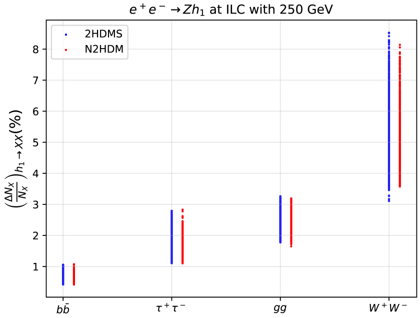
> The light 96 GeV Higgs can be detected at ILC

Observables at the ILC

Method of calculation from [*P. Drechsel et al.*]

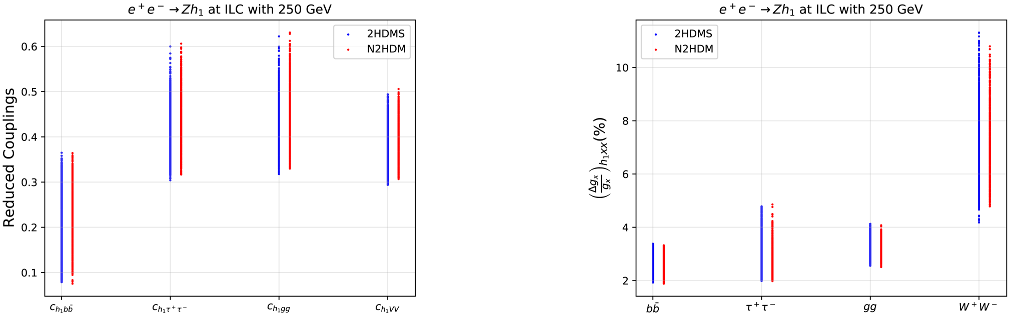
Points with tanβ [1,6]





- 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 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