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Testing the 2HDMS

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Motivation

- Extend the 2HDM to a NMSSM-like Higgs structure (complex singlet and $\mathbb{Z}_3$ symmetry)
- Less constraint parameter compared to super-symmetric models
- Study a light Higgs-boson as a possible explanation for the 96 GeV "excess" at CMS and LEP
- Indirect searches for a light-Higgs via SM-like Higgs coupling modifiers

Outline

- N2HDM
- Theoretical framework of the 2HDMS
- Testing for constraints
- Testing the parameter space
- Summary

Theoretical framework of N2HDM

2HDM model with an additional real singlet field has the Higgs potential:

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

Free parameters:

$$\lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_5,\ \lambda_6,\ \lambda_7,\ \lambda_8,\ m_{12},\ v_S,\ \tan\beta \tag{2}$$

m_{12} softly breaks the $\mathbb{Z}_2$ symmetry

Theoretical framework of the 2HDMS

Two Higgs doublets

$$\Phi_1 = \begin{pmatrix} \chi_1^+ \\ v_1 + \frac{\rho_1 + i\eta_1}{\sqrt{2}} \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \chi_2^+ \\ v_2 + \frac{\rho_2 + i\eta_2}{\sqrt{2}} \end{pmatrix} \tag{3}$$

Additional complex singlet

$$S = v_S + \frac{\rho_S + i\eta_S}{\sqrt{2}} \tag{4}$$

$$\tan\beta = \frac{v_2}{v_1}, \qquad v = \sqrt{v_1^2 + v_2^2} = 174 \text{ GeV} \tag{5}$$

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

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

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

12 free parameters:

$$\lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_1',\ \lambda_2',\ \lambda_3'',\ m_{12},\ \mu_{S1},\ \mu_{12},\ v_S,\ \tan\beta \quad (7)$$

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

Theoretical framework of the 2HDMS

Tree level Higgs mass matrices:

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

$$\begin{aligned}
M^2_{P11} &= (m^2_{12} - \mu_{12} v_S)\tan\beta \\
M^2_{P22} &= (m^2_{12} - \mu_{12} v_S)\cot\beta \\
M^2_{P12} &= -(m^2_{12} - \mu_{12} v_S) \\
M^2_{P13} &= \mu_{12} v \sin\beta \\
M^2_{P23} &= -\mu_{12} v \cos\beta \\
M^2_{P33} &= -\frac{3}{2}\mu_{S1} v_S - \mu_{12}\frac{v^2}{2v_S}\sin 2\beta \\
M^2_{C} &= 2(m^2_{12} - \mu_{12} v_S)\csc 2\beta - \lambda_4 v^2
\end{aligned} \tag{8}$$

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

$$m_{h_{1,2,3}},\ m_{a_{1,2}},\ m_{h^\pm},\ \alpha_1,\ \alpha_2,\ \alpha_3,\ \alpha_4,\ v_S,\ \tan\beta \tag{9}$$

Reduced Couplings

Higgs to fermion couplings:

	$c_{h_i tt}$	$c_{h_i bb}$	$c_{h_i \tau\tau}$
type I	$\frac{R_{i2}}{\sin\beta}$	$\frac{R_{i2}}{\sin\beta}$	$\frac{R_{i2}}{\sin\beta}$
type II	$\frac{R_{i2}}{\sin\beta}$	$\frac{R_{i1}}{\cos\beta}$	$\frac{R_{i1}}{\cos\beta}$
Leptonic	$\frac{R_{i2}}{\sin\beta}$	$\frac{R_{i2}}{\sin\beta}$	$\frac{R_{i1}}{\cos\beta}$
Flipped	$\frac{R_{i2}}{\sin\beta}$	$\frac{R_{i1}}{\cos\beta}$	$\frac{R_{i2}}{\sin\beta}$

Rotation Matrix:

$$R = \begin{pmatrix} c\alpha_1 c\alpha_2 & s\alpha_1 c\alpha_2 & s\alpha_2 \\ -s\alpha_1 c\alpha_3 - c\alpha_1 s\alpha_2 s\alpha_3 & c\alpha_1 c\alpha_3 - s\alpha_1 s\alpha_2 s\alpha_3 & c\alpha_2 s\alpha_3 \\ s\alpha_1 s\alpha_3 - c\alpha_1 s\alpha_2 c\alpha_3 & -s\alpha_1 s\alpha_2 c\alpha_3 - c\alpha_1 s\alpha_3 & c\alpha_2 c\alpha_3 \end{pmatrix} \quad (10)$$

Testing for constraints

Theoretical constraints

- Vaccum stability $\longrightarrow$ `Vevacious` or `Evade` checks
- 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 $m_{h^\pm}$

Tree-level perturbative unitarity

- Ensure perturbativity up to very high scales
- Demand amplitudes of the scalar quartic scalar interactions to be below a value of 8π [J. Horejsi, M. Kladiva,arxiv:hep-ph/0510154]

$$\begin{aligned} \lambda'_{1,2} &< 8\pi \\ \frac{\lambda''_3}{2} &< 8\pi \\ \lambda_{1,2,3} &< 8\pi \\ \lambda_3 \pm \lambda_4 &< 8\pi \\ \frac{1}{2}\left(\lambda_1 + \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_4^2}\right) &< 8\pi \end{aligned} \quad (11)$$

$$\begin{aligned} &64\,(6\lambda_2'^2\lambda_1 + 6\lambda_1'^2\lambda_2 - 9\lambda_3''\lambda_1\lambda_2 - 8\lambda_1'\lambda_2'\lambda_3 + 4\lambda_3''\lambda_3^2 - 4\lambda_1'\lambda_2'\lambda_4 + 4\lambda_3''\lambda_3\lambda_4 + \lambda_3''\lambda_4^2) \\ &+ 16\,(-2\lambda_1'^2 - 2\lambda_2'^2 + 3\lambda_3''\lambda_1 + 3\lambda_3''\lambda_2 + 9\lambda_1\lambda_2 - 4\lambda_3^2 - 4\lambda_3\lambda_4 - \lambda_4^2)\,x \\ &+ (-4\lambda_3'' - 12\lambda_1 - 12\lambda_2)\,x^2 + x^3 \end{aligned} \quad (12)$$

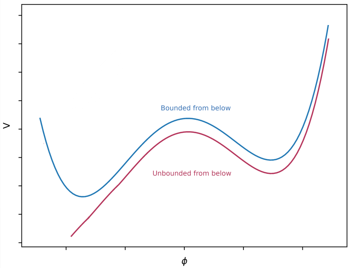
Boundedness from below

- Ensure that the potential remains positive when the field values approach infinity
- The conditions can be found in [K.G.Klimenko, Mat.Fiz.62,87(1985)] and were adapted for the 2HDMS

$$\Omega_1 \cup \Omega_2$$

$$\Omega_1 = \Big\{ \lambda_1, \lambda_2, \lambda_3'' > 0; \sqrt{\lambda_1, \lambda_3''} + \lambda_2' > 0; \sqrt{\lambda_2 \lambda_3''} + \lambda_2' > 0; \sqrt{\lambda_1 \lambda_2} + \lambda_3 + D > 0; \frac{\lambda_1}{\lambda_2}\lambda_2' \geq 0 \Big\}$$

$$\Omega_2 = \Big\{ \lambda_1, \lambda_2, \lambda_3'' > 0; \sqrt{\lambda_2 \lambda_3''} \geq \lambda_2' > -\sqrt{\lambda_2 \lambda_3''}; \sqrt{\lambda_1 \lambda_3''} > \lambda_1' \geq \frac{\lambda_1}{\lambda_2}\lambda_2'; \sqrt{(\lambda_1'^2 - \lambda_1 \lambda_3'')(\lambda_2'^2 - \lambda_2 \lambda_3'')} \geq \lambda_1'^2 \lambda_2'^2 - (D + \lambda_3)\lambda_3'' \Big\},$$



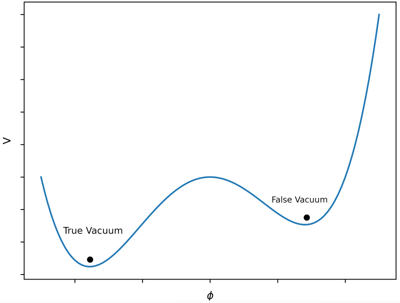
$$D = \begin{cases} \lambda_4 & \text{for } \lambda_4 < 0 \\ 0 & \text{for } \lambda_4 > 0 \end{cases} \qquad (13)$$

Vacuum Stability

- Electroweak (EW) vacuum may be the global minimum (*true vacuum*) or a local minimum (*false vacuum*)
- Parameter point with a local minimum may still be allowed if it is metastable (predicted life-time is greater than age of the universe)
- The decay rate Γ of a metastable state per (spatial) volume V_S is given by

$$\frac{\Gamma}{V_S} = K\, e^{-B} \qquad (14)$$

- The public code `EVADE` finds all tree-level minima via `HOM4PS2` and calculates the bounce action with a straight path approximation.



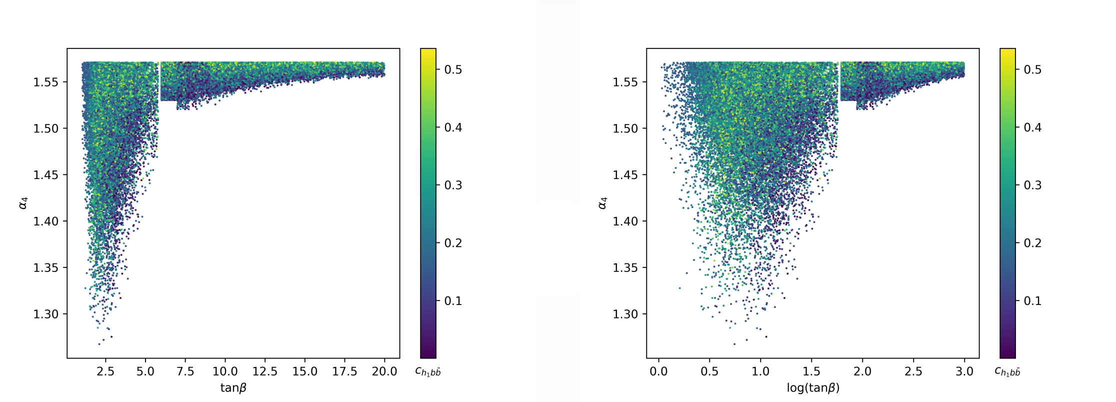
Scan setup

We focus on the Type II Yukawa structure

- Implement the 2HDMS in the SARAH
- Use SPheno to generate the spectra ($\overline{\text{MS}}$ scheme)
- We focus on a light, singlet-like h_1 Higgs-boson $< 100 GeV$
- Scan the parameter space

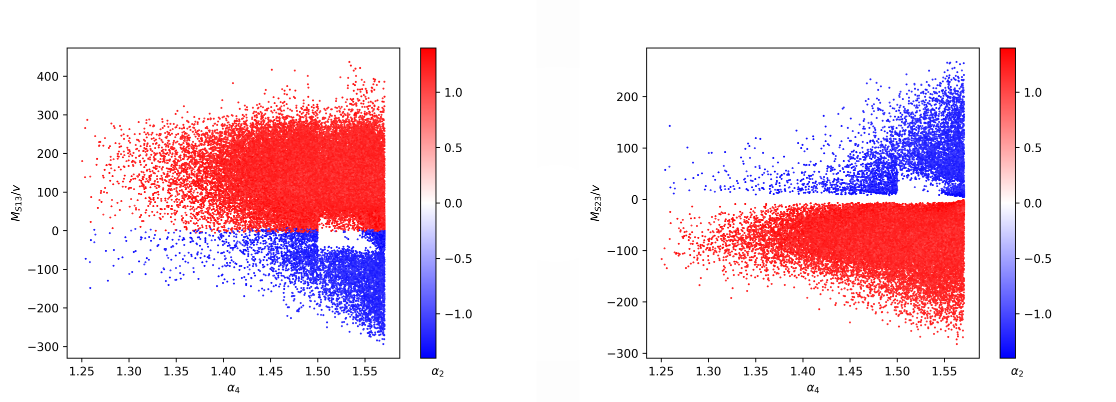
$$
\begin{aligned}
\alpha_1 &\in \{\pm 1.0, \pm 1.57\}, & \alpha_2 &\in \{\pm 0.8, \pm 1.4\}, & \alpha_3 &\in \{\pm 1.0, \pm 1.57\}, \\
\alpha_4 &\in \{1.25, 1.57\} & \tan\beta &\in \{1.0, 50.0\}, & v_S &\in \{200, 2000\}\text{GeV}, \\
m_{h_1} &\in \{80, 93\}\text{GeV}, & m_{h_2} &\in \{110, 126\}\text{GeV}, & m_{a_1} &\in \{200, 500\}\text{GeV} \\
m_{h^\pm} &\in \{650, 2500\}\text{GeV}, & m_{a_2} &\in \{650, 2500\}\text{GeV}, & m_{h_3} &\in \{650, 2500\}\text{GeV}
\end{aligned}
$$

tan$\beta - \alpha_4$



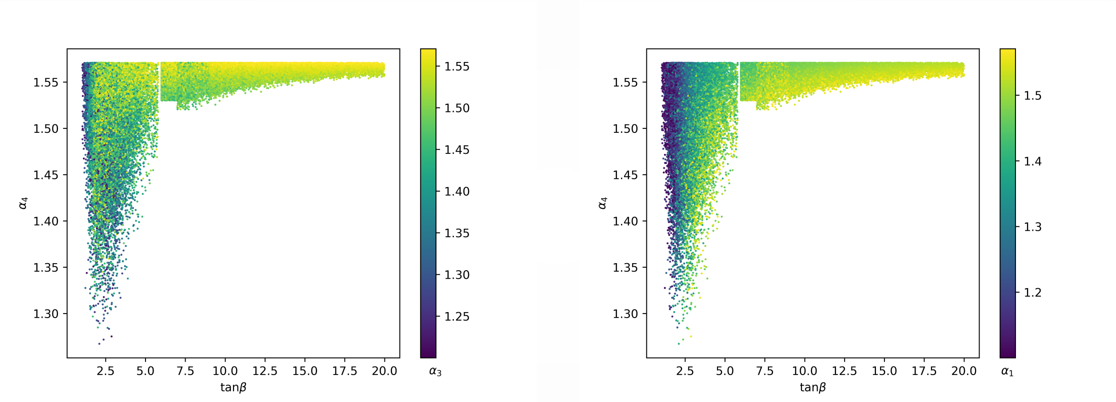
- Larger tanβ can be reached compared to the N2HDM
- Allowed α_4 range depends on tanβ
- Can be understood by looking at the mixing matrices

$\alpha_2 - \alpha_4$



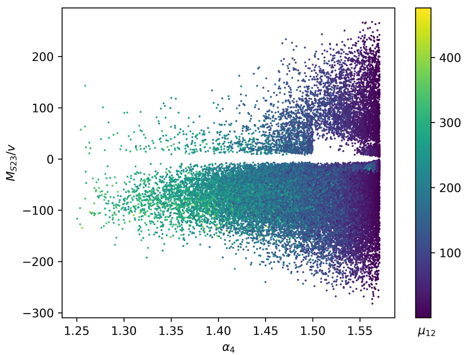
- The sign of α_2 determines the sign of the mixing-matrix elements M_{13} and M_{23}

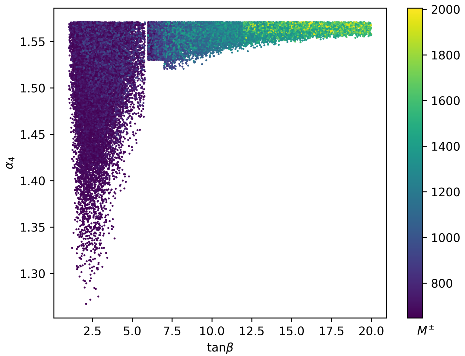
$\alpha_{1/3} - \alpha_4$



- Increasing tanβ shrinks the allowed ranges for α_1 and $\alpha_3 \to \frac{\pi}{2}$

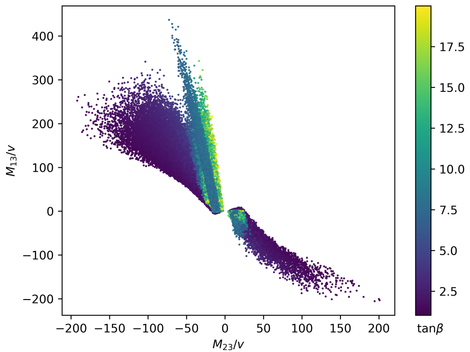
$\alpha_4 - \mu_{12} - M^{\pm}$

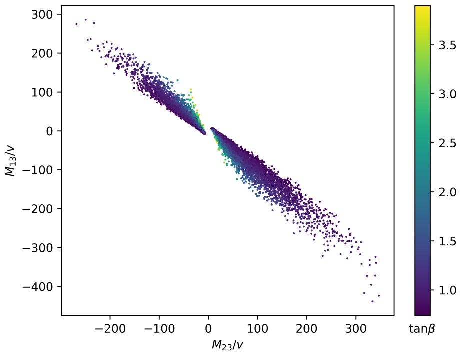




- For $\alpha_4 \to \frac{\pi}{2}$ we get $\mu_{12} \to 0$
- Large tanβ can only be reached with increasing $M^{\pm}$

N2HDM-2HDMS





- Large tanβ allows larger singlet-components of h_1 with small singlet-components of h_2 compared to the N2HDM

Finding a N2HDM limit

Take another look at the tree-level Higgs mass matrices:

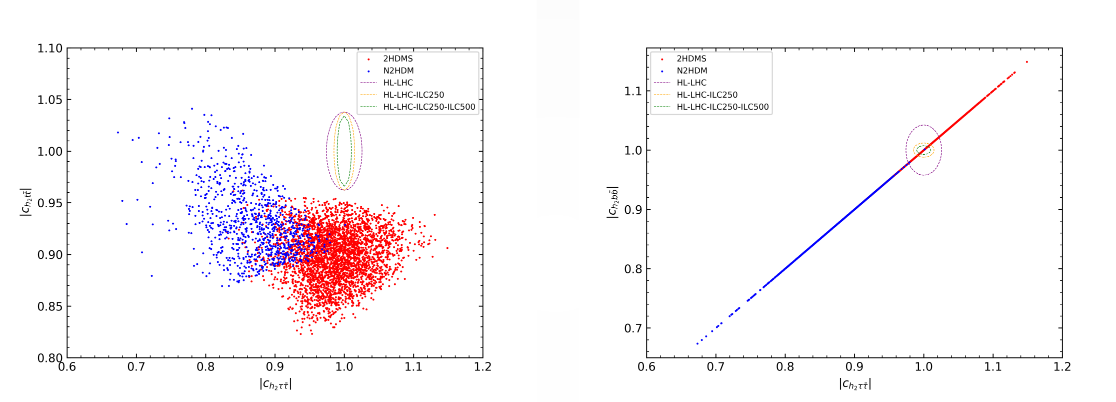
$$
\begin{aligned}
M^2_{S11} &= 2\lambda_1 v^2 \cos^2\beta + (m^2_{12} - \mu_{12} v_S)\tan\beta & M^2_{P11} &= (m^2_{12} - \mu_{12} v_S)\tan\beta \\
M^2_{S22} &= 2\lambda_2 v^2 \sin^2\beta + (m^2_{12} - \mu_{12} v_S)\cot\beta & M^2_{P22} &= (m^2_{12} - \mu_{12} v_S)\cot\beta \\
M^2_{S12} &= (\lambda_3 + \lambda_4) v^2 \sin 2\beta - (m^2_{12} - \mu_{12} v_S) & M^2_{P12} &= -(m^2_{12} - \mu_{12} v_S) \\
M^2_{S13} &= (2\lambda'_1 v_S \cos\beta + \mu_{12}\sin\beta) v & M^2_{P13} &= \mu_{12} v \sin\beta \\
M^2_{S23} &= (2\lambda'_2 v_S \sin\beta + \mu_{12}\cos\beta) v & M^2_{P23} &= -\mu_{12} v \cos\beta \\
M^2_{S33} &= \frac{\mu_{S1}}{2} v_S + \lambda''_3 v_S^2 - \mu_{12}\frac{v^2}{2v_S}\sin 2\beta & M^2_{P33} &= -\frac{3}{2}\mu_{S1} v_S - \mu_{12}\frac{v^2}{2v_S}\sin 2\beta
\end{aligned}
\tag{15}
$$

- N2HDM-like limit can be reached for $\mu_{12} \to 0$ which is realised for $\alpha_4 \to \frac{\pi}{2}$
- Large tanβ values can be reached due to the additional $\mu_{12}\sin(\cos)\beta$ terms in the M_{S13} and M_{S23} elements
- While for the N2HDM $M_{S13} \to 0$ for large tanβ we can maintain large singlet-components for h_1 in the 2HDMS

Future searches

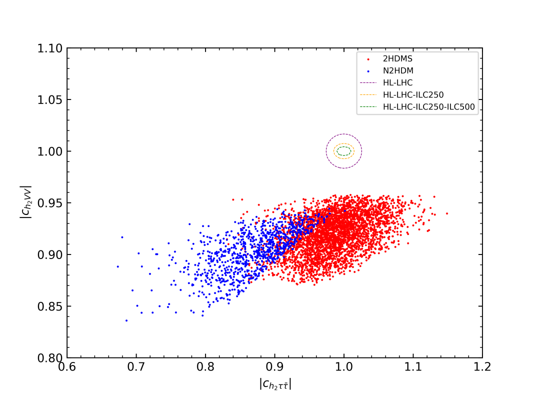
- A light singlet-like light scalar is challenging to directly search for at the LHC (Suppressed coupling to all SM particles, $b\bar{b}$ background)
- Indirect searches via precision measurements of the couplings of the 125 GeV state
- Uncertainties on the measurents of the coupling strengths of the SM-like Higgs boson are still very large
- Tighter constraints are expected after a the 3000 fb^{-1} integrated luminosity at the high-luminosity upgrade (HL-LHC) are reached
- A future linear e^+e^- collider could improve them even further
- A Lepton collider has massively reduced QCD background compared to a hadron collider

Indirect-searches



- The current uncertainties are based on coupling-modifiers (κ-framework)
- Couplings of the SM-like Higgs boson receive a κ_i factor quantifiying the potential deviation from SM predictions
- 1-σ ellipses for the case that no deviation from the Standard model is found

Indirect-searches (II)



- Current uncertainties of up to 40% can be reduced to below 1% for combined HL-LHC and ILC $250 + 500$ GeV constraints

Summary

Work done

- Create theoretical framework and test theoretical constraints to set everything up for phenomenological studies
- Implement constraints to test against experimental results $\rightarrow$ Talk by Cheng Li
- Tested a large portion of the parameter with a light Higgs-boson in mind

Outlook

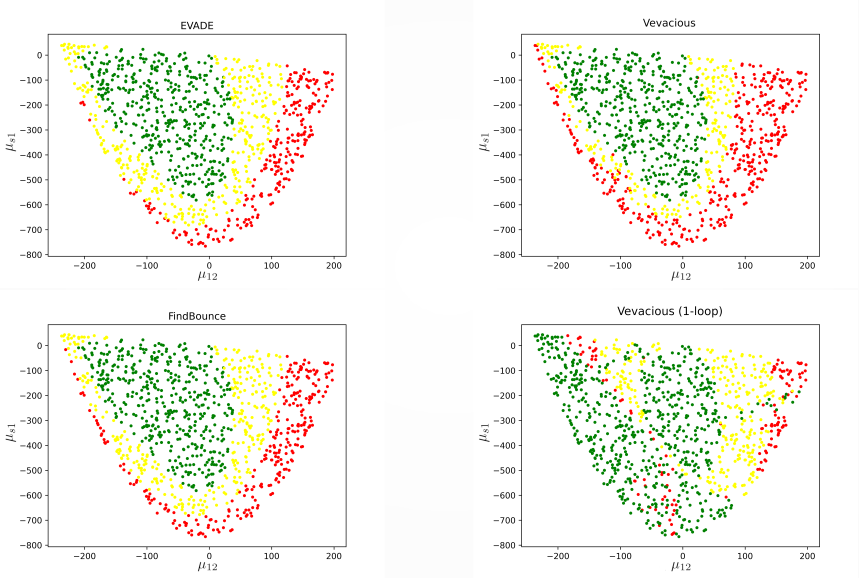
- Further explore differences to the N2HDM
- Evaluation of experimental coupling uncertainties for a light Higgs boson $\rightarrow$ Talk by Cheng Li

Backup

Vacuum Stability (2)

- The straight path approximation with the tree-level potential was found to be sufficient
- We compared the results of the well-known code `Vevacious`, `EVADE` and `EVADE` + `FindBounce`
- We started with a given benchmark point and scanned around the cubic parameters μ_{12} and μ_{S1}

Vacuum Stability (3)



Theoretical framework of the 2HDMS

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

$$\tilde{\mu}^2 = \cos^2\alpha_4 m_{a1}^2 + \sin^2\alpha_4 m_{a2}^2$$
$$\lambda_1 = \frac{1}{2v^2\cos^2\beta}\left[\sum_i m_{h_i}^2 R_{i1}^2 - \tilde{\mu}^2\sin^2\beta\right]$$
$$\lambda_2 = \frac{1}{2v^2\sin^2\beta}\left[\sum_i m_{h_i}^2 R_{i2}^2 - \tilde{\mu}^2\cos^2\beta\right]$$
$$\lambda_3 = \frac{1}{v^2}\left[\frac{1}{\sin 2\beta}\sum_i m_{h_i}^2 R_{i1}R_{i2} + m_{h^\pm}^2 - \tilde{\mu}^2\right]$$
$$\lambda_4 = \frac{\tilde{\mu}^2 - m_{h^\pm}^2}{v^2}$$
$$m_{12}^2 = \mu_{12}v_S + \tilde{\mu}^2\sin\beta\cos\beta$$

$$\mu_{12} = \frac{m_{a1}^2 - m_{a2}^2}{v}\sin\alpha_4\cos\alpha_4$$
$$\lambda_1' = \frac{1}{2v_S v\cos\beta}\left[\sum_i m_{h_i}^2 R_{i1}R_{i3} - \mu_{12}v\sin\beta\right]$$
$$\lambda_2' = \frac{1}{2v_S v\sin\beta}\left[\sum_i m_{h_i}^2 R_{i2}R_{i3} - \mu_{12}v\cos\beta\right]$$
$$\lambda_3'' = \frac{1}{v_S^2}\left[\sum_i m_{h_i}^2 R_{i3}^2 + \mu_{12}\frac{v^2}{2v_S}\sin 2\beta - \frac{\mu_{S1}}{2}v_S\right]$$
$$\mu_{S1} = -\frac{2}{3v_S}\left[\sin^2\alpha_4 m_{a1}^2 + \cos^2\alpha_4 m_{a2}^2 + \frac{v}{2v_S}\sin 2\beta\mu_{12}\right] \tag{16}$$

Resulting mass input parameters:

$$m_{h_{1,2,3}},\ m_{a_{1,2}},\ m_{h^\pm},\ \alpha_1,\ \alpha_2,\ \alpha_3,\ \alpha_4,\ v_S,\ \tan\beta \tag{17}$$

$\mathbb{Z}_2$-Symmetry

- The $\mathbb{Z}_2$-Symmetry extended to the Yukawa sector guarentees the absence of tree-level Flavour Changing Neutral Currents (FCNC).
- Softly broken by the term m_{12}^2
- Transforms as:

$$\phi_1 \to \phi_1, \ \phi_2 \to -\phi_2, \ \phi_S \to \phi_S \tag{18}$$

- Leads to four types of doublet couplings to fermions

	u-type	d-type	leptons
type I	ϕ_2	ϕ_2	ϕ_2
type II	ϕ_2	ϕ_1	ϕ_1
lepton-specific	ϕ_2	ϕ_2	ϕ_1
flipped	ϕ_2	ϕ_1	ϕ_2