Vacuum (in)stability in 2HDMS vs N2HDM : A study with EVADE

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Vacuum Stability in multi-Higgs models

- Higgs mechanism in SM relies on stable vacuum, guaranteed at tree-level.
- Higher order corrections can spoil the stability, top quark mass plays a crucial role.
- With extended scalar sectors, the vacuum stability, unlike SM is challenged at tree-level.
- In case of non-supersymmetric extensions of the SM scalar sector, there can be potential charge and CP-breaking minima as well as a second wrong EW vacuum(panic vacuum).

- If there is no stationary point deeper than the EW vacuum, then EW vacuum is *absolutely stable*.

- If there are deeper minima, but the transition time into those is larger than age of universe, EW vacuum is *metastable*, else *unstable*.

- Vacuum structure of 2HDM and its real scalar singlet extension, namely N2HDM, has been studied. *Phys.Lett.B 603 (2004) 219-229, JHEP 09 (2019) 006*

- In 2HDM, any stationary point that is charge or CP breaking is necessarily a saddle point that lies above the normal EW minimum.

- N2HDM, due to addition of an extra scalar degree of freedom, shows quite different vacuum phenomena.

Going beyond N2HDM with 2HDM+complex singlet(2HDMS)

- The objective is to study the vacuum instabilities in 2HDMS.
- A detailed comparison with N2HDM. Is there any diffrence?
  1. Intrinsic diffrence between the vacuum structure of the two models
  2. How much of that difference stands the *test*?

The models

The part of the scalar potential involving the singlet S in N2HDM

$$V_S = \frac{1}{2}m_S^2 S^2 + \frac{1}{8}\lambda_6 S^4 + \frac{1}{2}\lambda_7|\Phi_1|^2 S^2 + \frac{1}{2}\lambda_8|\Phi_2|^2 S^2 \tag{1}$$

and in 2HDMS with complex singlet $S + iP$

$$\begin{aligned} V_S' = &\frac{1}{2}m_S^2 S^2 + \frac{1}{2}m_{S'}^2 P^2 + \frac{1}{8}\lambda_6 S^4 + \frac{1}{8}\lambda_9 P^4 + \frac{1}{8}\lambda_{10} S^2 P^2 \\ &+\frac{1}{2}(\lambda_7|\Phi_1|^2 + \lambda_8|\Phi_2|^2)S^2 + \frac{1}{2}(\lambda_{11}|\Phi_1|^2 + \lambda_{12}|\Phi_2|^2)P^2 \end{aligned} \tag{2}$$

In both cases an extra Z_2 symmetry is imposed on additional singlet

Free parameters in both models

	General basis	Mass-basis
N2HDM	$\lambda_{1,..8}, v_s, m_{12}^2$,tan β, v	$m_{h_{1,..3}}, m_A, m_{H^\pm}, \alpha_{1,..3}, v_s, m_{12}^2$, tan β, v
2HDMS	$\lambda_{1,..12}, v_s, v_p, m_{12}^2$,tan β, v	$m_{h_{1,..4}}, m_A, m_{H^\pm}, \alpha_{1,..6}, v_s, v_p, m_{12}^2$, tan β, v

Possible Vacuua: N2HDM

$$\mathcal{N}_s \to \langle \Phi_1 \rangle_0 = \frac{1}{\sqrt{2}} \left(\begin{array}{c} 0 \\ v_1 \end{array} \right) , \quad \langle \Phi_2 \rangle_0 = \frac{1}{\sqrt{2}} \left(\begin{array}{c} 0 \\ v_2 \end{array} \right) , \quad \langle \Phi_S \rangle_0 = v_s$$

$$\mathcal{CB} \to \langle \Phi_1 \rangle_0 = \frac{1}{\sqrt{2}} \left(\begin{array}{c} 0 \\ c_1 \end{array} \right) , \quad \langle \Phi_2 \rangle_0 = \frac{1}{\sqrt{2}} \left(\begin{array}{c} c_2 \\ c_3 \end{array} \right) , \quad \langle \Phi_S \rangle_0 = 0$$

$$\mathcal{CB}_s \to \langle \Phi_1 \rangle_0 = \frac{1}{\sqrt{2}} \left(\begin{array}{c} 0 \\ c_1 \end{array} \right) , \quad \langle \Phi_2 \rangle_0 = \frac{1}{\sqrt{2}} \left(\begin{array}{c} c_2 \\ c_3 \end{array} \right) , \quad \langle \Phi_S \rangle_0 = s$$

- Similarly $\mathcal{CP}$ and $\mathcal{CP}_s$ can also exist in N2HDM.

Possible Vacuua: 2HDMS

$$\mathcal{N}_{sp} \rightarrow \langle\Phi_1\rangle_0 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad \langle\Phi_2\rangle_0 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix}, \quad \langle\Phi_S\rangle_0 = v_s + iv_p$$

$$\mathcal{CB} \rightarrow \langle\Phi_1\rangle_0 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ c_1 \end{pmatrix}, \quad \langle\Phi_2\rangle_0 = \frac{1}{\sqrt{2}}\begin{pmatrix} c_2 \\ c_3 \end{pmatrix}, \quad \langle\Phi_S\rangle_0 = 0$$

$$\mathcal{CB}_s \rightarrow \langle\Phi_1\rangle_0 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ c_1 \end{pmatrix}, \quad \langle\Phi_2\rangle_0 = \frac{1}{\sqrt{2}}\begin{pmatrix} c_2 \\ c_3 \end{pmatrix}, \quad \langle\Phi_S\rangle_0 = s$$

$$\mathcal{CB}_p \rightarrow \langle\Phi_1\rangle_0 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ c_1 \end{pmatrix}, \quad \langle\Phi_2\rangle_0 = \frac{1}{\sqrt{2}}\begin{pmatrix} c_2 \\ c_3 \end{pmatrix}, \quad \langle\Phi_S\rangle_0 = p$$

$$\mathcal{CB}_{sp} \rightarrow \langle\Phi_1\rangle_0 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ c_1 \end{pmatrix}, \quad \langle\Phi_2\rangle_0 = \frac{1}{\sqrt{2}}\begin{pmatrix} c_2 \\ c_3 \end{pmatrix}, \quad \langle\Phi_S\rangle_0 = s + ip$$

- Similarly, in the CP-breaking sector there can be $\mathcal{CP}$, $\mathcal{CP}_s$, $\mathcal{CP}_p$ and $\mathcal{CP}_{sp}$ type of potentially dangerous vacuua.
- In total there are four extra charge and CP-breaking vacuua in 2HDMS.
- Therefore, the stability of the parameter points should deteriorate in 2HDMS compared to N2HDM.
- There are also "wrong" neutral vacuua present in both N2HDM and 2HDMS. Here too, naturally the number of potentially dangerous vacuua is lot more in 2HDMS.

Comparison in terms of extra model parameters : $\mathcal{N}_{sp}$ in 2HDM vs $\mathcal{N}_s$ in N2HDM

Two *stable* BP's of N2HDM:

	m_{h_1}	m_{h_2}	m_{h_3}	$m_A = m_H^{\pm}$	m_{12}^2	$\tan\beta$	v_s	$\{\alpha_1, \alpha_2, \alpha_3\}$
BP1	95	125	601	621	9529.17	1.37	468.1	{-0.49,0.31,-0.09}
BP2	125	604.5	604.7	624.8	22654	0.91	423.8	{-2.34,-0.001,-1.55}

In the general basis:

	λ_1	λ_2	λ_3	$\lambda_4 = \lambda_5$	λ_6	λ_7	λ_8	m_{12}^2	$\tan\beta$	v_s
BP1	1.43	0.24	12.02	-6.05	2.97	2.11	-0.41	9529.17	1.37	468.1
BP2	5.33	12.41	12.27	-5.7	2.05	3.21	-0.08	22654	0.91	423.8

BP1 accommodates 95 GeV excess with its observed $\mu_{\gamma\gamma}^{\text{CMS}}$. 125 GeV SM Higgs signal strengths are also obeyed by both BP1 and BP2.

Fate in 2HDMS with additional free parameters

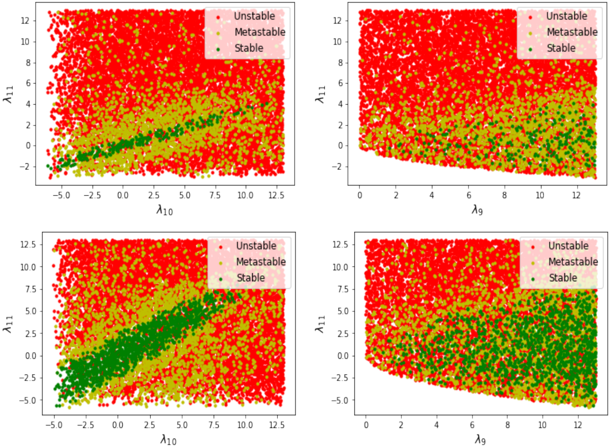


Figure: top : BP1, bottom : BP2

Bounded-from-below condition applied beforehand.

Two *metastable* BP's of N2HDM:

	m_{h_1}	m_{h_2}	m_{h_3}	$m_A = m_H^{\pm}$	m_{12}^2	$\tan\beta$	v_s	$\{\alpha_1, \alpha_2, \alpha_3\}$
BP3	95	125	607.8	628.0	-13222.9	1.48	286.1	{-0.45,0.86,-0.09}
BP4	125	615.78	615.94	635.76	38878.2	1.30	903.86	{0.89,0.026-1.50}

In the general basis:

	λ_1	λ_2	λ_3	$\lambda_4 = \lambda_5$	λ_6	λ_7	λ_8	m_{12}^2	$\tan\beta$	v_s
BP3	12.44	0.58	12.84	-6.99	3.99	6.35	-0.30	-13222.9	1.48	286.1
BP4	8.27	9.18	12.30	-5.35	0.39	1.85	-0.08	38878.2	1.30	903.86

In 2HDMS

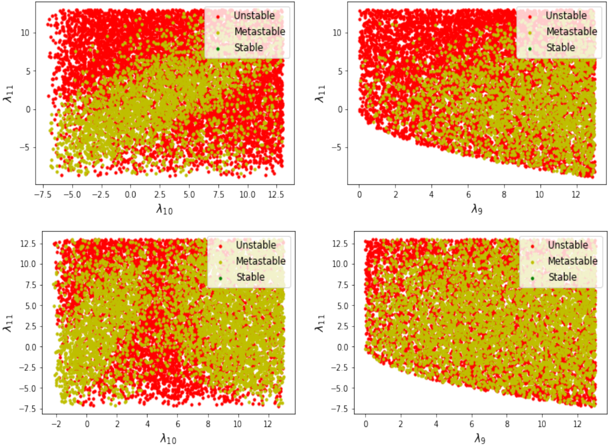


Figure: top : BP3, bottom : BP4

An *unstable* BP of N2HDM:

	m_{h_1}	m_{h_2}	m_{h_3}	$m_A = m_H^{\pm}$	m_{12}^2	$\tan\beta$	v_s	$\{\alpha_1, \alpha_2, \alpha_3\}$
BP5	95	125	614.3	634.3	17856.8	1.82	441.42	{-0.50,0.37,0.05}

In the general basis:

	λ_1	λ_2	λ_3	$\lambda_4 = \lambda_5$	λ_6	λ_7	λ_8	m_{12}^2	$\tan\beta$	v_s
BP5	1.93	0.11	12.72	-5.95	3.36	3.38	0.23	17856.8	1.82	441.42

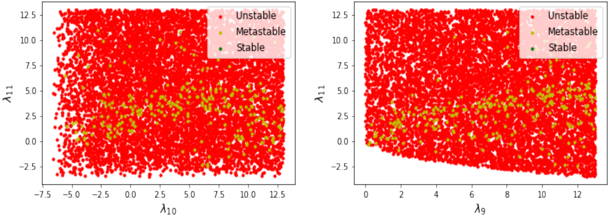


Figure: BP5

	N_s vacuum		N_{sp} vacuum	
N2HDM	stable	meta/unstable	stable	meta/unstable
	↓	↓	↓	↓
2HDMS	stable/meta/unstable	meta/unstable	stable/meta/unstable	stable(fine-tuned)/meta/unstable

Table: The stable and meta/unstable vacuum in N2HDM can can lead to stable or meta/unstable vacuum in 2HDMS depending on the type of vacuum N_s or N_{sp}.

- Stable$\rightarrow$ unstable : larger number of dangerous vacuua in 2HDMS.
- Unstable$\rightarrow$ Stable : not possible in N_s case and extremely finetuned in N_{sp}, also requires large negative values of $\lambda_{10}, \lambda_{11}$ and λ_{12}, disfavored by BFB.

- CAUTION!! The extra parameters of 2HDMS are not really ‘free’.
- Imposing the observed scalar masses and signal strengths already constrains the free parameters of 2HDMS, thereby alleviating the difference between the two models.

Comparison between N2HDM and 2HDMS with couplings in similar range

- We want to check, whether all the differences in the vacuum structure in N2HDM and 2HDMS remain same after all the physical observables are kept at similar values in both cases.
- Since all the couplings of physical scalars to fermions and gauge bosons are functions of mixing matrix elements, we demand all the elements of the 3×3 subspace of the 4×4 mixing matrix elemements of 2HDMS are within $\lesssim 15\%$ of the matrix elements of the 3×3 mixing matrix of N2HDM.

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

$$
\begin{aligned}
R'_{11} &= c_{\alpha_1} c_{\alpha_2} c_{\alpha_4} \\
R'_{12} &= c_{\alpha_2} c_{\alpha_4} s_{\alpha_1} \\
R'_{13} &= c_{\alpha_4} s_{\alpha_2} \\
R'_{14} &= s_{\alpha_4} \\
R'_{21} &= c_{\alpha_5}(-c_{\alpha_3} s_{\alpha_1} - c_{\alpha_1} s_{\alpha_2} s_{\alpha_3}) - c_{\alpha_1} c_{\alpha_2} s_{\alpha_4} s_{\alpha_5} \\
R'_{22} &= c_{\alpha_5}(c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3}) - c_{\alpha_2} s_{\alpha_1} s_{\alpha_4} s_{\alpha_5} \\
R'_{23} &= c_{\alpha_2} c_{\alpha_5} s_{\alpha_3} - s_{\alpha_2} s_{\alpha_4} s_{\alpha_5} \\
R'_{24} &= c_{\alpha_4} s_{\alpha_5} \\
R'_{31} &= c_{\alpha_6}(-c_{\alpha_1} c_{\alpha_3} s_{\alpha_2} + s_{\alpha_1} s_{\alpha_3}) + (-c_{\alpha_1} c_{\alpha_2} c_{\alpha_5} s_{\alpha_4} - (-c_{\alpha_3} s_{\alpha_1} - c_{\alpha_1} s_{\alpha_2} s_{\alpha_3}) s_{\alpha_5}) s_{\alpha_6} \\
R'_{32} &= c_{\alpha_6}(-s_{\alpha_1} c_{\alpha_3} s_{\alpha_2} - c_{\alpha_1} s_{\alpha_3}) + (-s_{\alpha_1} c_{\alpha_2} c_{\alpha_5} s_{\alpha_4} - (-c_{\alpha_3} c_{\alpha_1} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3}) s_{\alpha_5}) s_{\alpha_6} \\
R'_{33} &= c_{\alpha_2} c_{\alpha_3} c_{\alpha_6} + (-c_{\alpha_5} s_{\alpha_2} s_{\alpha_4} - c_{\alpha_2} s_{\alpha_3} s_{\alpha_5}) s_{\alpha_6} \\
R'_{34} &= c_{\alpha_4} c_{\alpha_5} s_{\alpha_6} \\
R'_{41} &= c_{\alpha_6}(-c_{\alpha_1} c_{\alpha_2} c_{\alpha_5} s_{\alpha_4} - (-c_{\alpha_3} s_{\alpha_1} - c_{\alpha_1} s_{\alpha_2} s_{\alpha_3}) s_{\alpha_5}) - (-c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} + s_{\alpha_1} s_{\alpha_3}) s_{\alpha_6} \\
R'_{42} &= c_{\alpha_6}(-s_{\alpha_1} c_{\alpha_2} c_{\alpha_5} s_{\alpha_4} - (c_{\alpha_3} c_{\alpha_1} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3}) s_{\alpha_5}) - (-s_{\alpha_1} s_{\alpha_2} c_{\alpha_3} - c_{\alpha_1} s_{\alpha_3}) s_{\alpha_6} \\
R'_{43} &= c_{\alpha_6}(-c_{\alpha_5} s_{\alpha_2} s_{\alpha_4} - c_{\alpha_2} s_{\alpha_3} s_{\alpha_5}) - c_{\alpha_2} c_{\alpha_3} s_{\alpha_6} \\
R'_{44} &= c_{\alpha_4} c_{\alpha_5} c_{\alpha_6}
\end{aligned}
$$

$$C_{h_i VV} = \cos\beta R^{(\prime)}_{i1} + \sin\beta R^{(\prime)}_{i2},\; C_{h_i t\bar{t}} = \frac{R^{(\prime)}_{i2}}{\sin\beta},\; C_{h_i b\bar{b}} = C_{h_i \tau\bar{\tau}} = \frac{R^{(\prime)}_{i1}}{\cos\beta}$$

- This is a conservative approach and we are confined with small values of extra mixing angles of 2HDMS.
- This ‘difference’ between the two models would definitely enhance with extra heavier scalar mass and larger mixing angles.
- However, we checked that, even with moderately large scalar masses, we can see a ‘difference’ between N2HDM and 2HDMS in terms of vacuum stability of points giving rise to same physical observables($\lesssim$ 15% deviation being allowed).

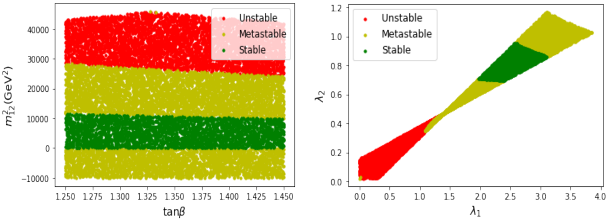


Figure: BP1 in 2HDMS : $\Delta C/C \lesssim 15\% \rightarrow \alpha_4 \approx \alpha_5 \approx \alpha_6 \lesssim 0.2$.

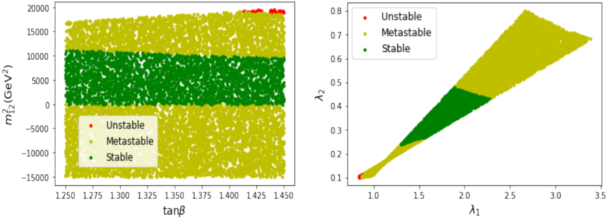


Figure: BP1(Stable in N2HDM) in 2HDMS : $\Delta C/C \lesssim 0.5\%$
$\rightarrow \alpha_4 \approx \alpha_5 \approx \alpha_6 \lesssim 0.05$.

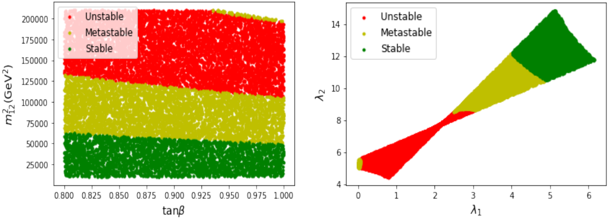


Figure: BP2(Stable in N2HDM) in 2HDMS : $\Delta C/C \lesssim 15\%$
$\rightarrow \alpha_4 \approx \alpha_5 \approx \alpha_6 \lesssim 0.07$.

In this case, even with extremely small mixing angles, I could not get rid of instability. The allowed range of m_{12}^2 itself leads to unstable regions.

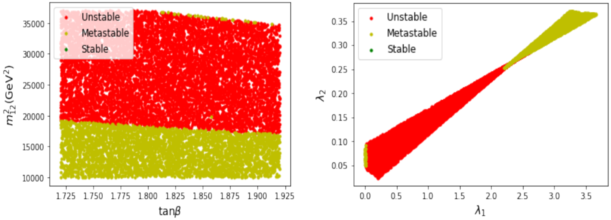


Figure: BP5(Untable in N2HDM) in 2HDMS : $\Delta C/C \lesssim 15\%$
$\rightarrow \alpha_4 \approx \alpha_5 \approx \alpha_6 \lesssim 0.13$.

In all the figures:

- The upper limit on m_{12}^2 from BFB.
- The lower limit on m_{12}^2 from perturbativity.

Impact of tri-linear couplings

- We calculate all the tri-linear couplings (a_{ijk}) at tree-level in both models.
- Demanding they should be in close proximity of each other, in addition puts constraint on the still allowed parameter space of 2HDMS.
- In particular $m_{12}^2, \tan\beta$ and correspondingly all the λ's become further constrained.

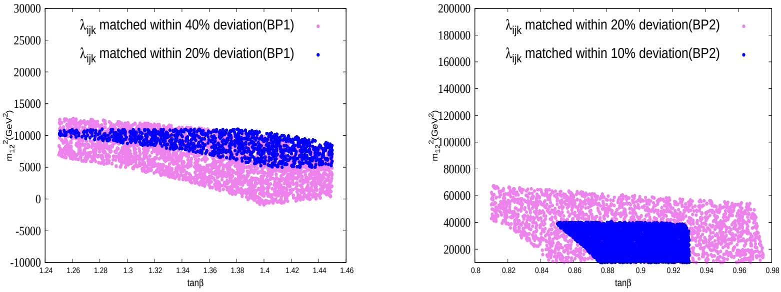


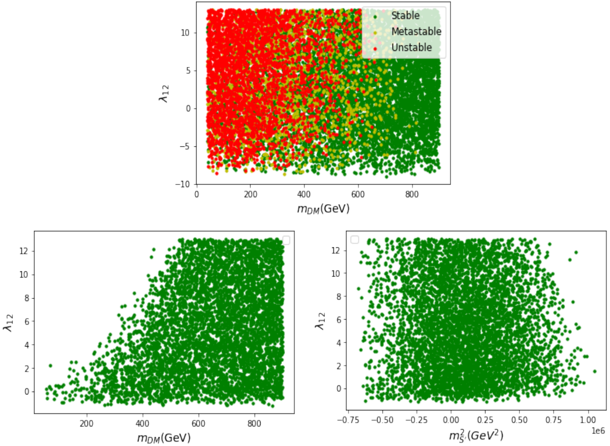
Figure: (left) BP1 in 2HDMS : $\Delta a/a \lesssim$ 40%(20%) for $\alpha_4 \approx \alpha_5 \approx \alpha_6 \approx 0.05$ and (right) BP2 in 2HDMS : $\Delta a/a \lesssim$ 20%(10%) for $\alpha_4 \approx \alpha_5 \approx \alpha_6 \approx 0.07$

Now we become confined within a stable region even in 2DHMS, just like in N2HDM.

Comparison between $\mathcal{N}_s$ vacuum of N2HDM and 2HDMS

- This phase of 2HDMS is the DM phase, unlike N2HDM.
- Here no mixing between the additional scalar sector of 2HDMS with the scalar sector of N2DHM.
- All the couplings (including tri-linear couplings) are same in both models at tree-level.
- Benchmark of N2HDM will map onto 2HDMS.
- Dark sector couplings are completely decoupled from the visible sector phenomenology, can be varied freely.
- This scenario changes at loop level.

Impact of dark sector parameters on vacuum stability of 2HDMS



Figure

Summary and outlook

- There are additional charge and CP-breaking as well as "panic" neutral minima in 2HDMS compared to N2HDM.
- The stability criterion depends strongly on the extra free parameters of 2HDMS.
- The physical observables put strong contraints on 2HDMS parameter space.
- There can still be some difference in the vacuum stability of N2HDM and 2HDMS parameter points even if they lead to the similar masses and fermion and gauge boson couplings of scalars.

- Tri-linear coupling measurement can constrain important parameter m_{12}^2 and thereby determine vacuum stability uniquely, alleviating the purported difference.
- Loop effects can change the outcomes of our analysis completely.
- In case of $\mathcal{N}_s$-type vacuum of 2HDMS, dark sector phenomenology is closely related to vacuum stability and corresponding difference between N2HDM and 2HDMS.

In both N2HDM and 2HDMS
Where

$$\mathcal{V}_{CB} - \mathcal{V}_{Ns} = (\frac{m^2_{H^\pm}}{2v^2})_{Ns}[(v'_2 c_1 - v'_1 c_3)^2 + v'^2_1 c^2_2] - s^2 m^2_{S1} > 0 \quad (3)$$

with

$$m^2_{S1} = m^2_S + \lambda_7 c^2_1 + \lambda_8(c^2_2 + c^2_3) \quad (4)$$

In 2HDMS in addition

$$\mathcal{V}_{CBp} - \mathcal{V}_{Ns} = (\frac{m^2_{H^\pm}}{2v^2})_{Ns}[(v'_2 c_1 - v'_1 c_3)^2 + v'^2_1 c^2_2] + c^2_5 m^2_p - s^2 m^2_{S1} > 0 \quad (5)$$

$m^2_p = m^2_{S'} + \frac{1}{4}\lambda_{10} s^2 + \frac{1}{2}(\lambda_{11} v^2_1 + \lambda_{12} v^2_2)$ is the pseudosccalar DM mass and $m^2_{S1} = m^2_S + \lambda_7 c^2_1 + \lambda_8(c^2_2 + c^2_3) + \frac{1}{4}\lambda_{10} c^2_5$

For N_{sp}-type vacuum of 2HDMS the stability criteria are in addition,

$$\mathcal{V}_{CB} - \mathcal{V}_{N_{sp}} = (\frac{m^2_{H^\pm}}{2v^2})_{N_{sp}}[(v'_2 c_1 - v'_1 c_3)^2 + v'^2_1 c^2_2] - s^2 m^2_{S1} - p^2 m^2_{S2} > 0 \quad (6)$$

Where

$$m^2_{S1} = m^2_S + \lambda_7 c^2_1 + \lambda_8 (c^2_2 + c^2_3) \quad (7)$$

$$m^2_{S2} = m'^2_S + \lambda_{11} c^2_1 + \lambda_{12} (c^2_2 + c^2_3) \quad (8)$$

$$\mathcal{V}_{CBs} - \mathcal{V}_{N_{sp}} = (\frac{m^2_{H^\pm}}{2v^2})_{N_{sp}}[(v'_2 c_1 - v'_1 c_3)^2 + v'^2_1 c^2_2] - p^2 m^2_{S2} > 0 \quad (9)$$

Where

$$m^2_{S2} = m'^2_S + \lambda_{11} c^2_1 + \lambda_{12} (c^2_2 + c^2_3) + \frac{1}{4}\lambda_{10} c^2_4 \quad (10)$$

$$\mathcal{V}_{CBp} - \mathcal{V}_{N_{sp}} = (\frac{m^2_{H^\pm}}{2v^2})_{N_{sp}}[(v'_2 c_1 - v'_1 c_3)^2 + v'^2_1 c^2_2] - s^2 m^2_{S1} > 0 \qquad (11)$$

Where

$$m^2_{S1} = m^2_S + \lambda_7 c^2_1 + \lambda_8 (c^2_2 + c^2_3) + \frac{1}{4}\lambda_{10} c^2_5 \qquad (12)$$