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Some reflexions on hidden features of SM extensions with scalar triplets

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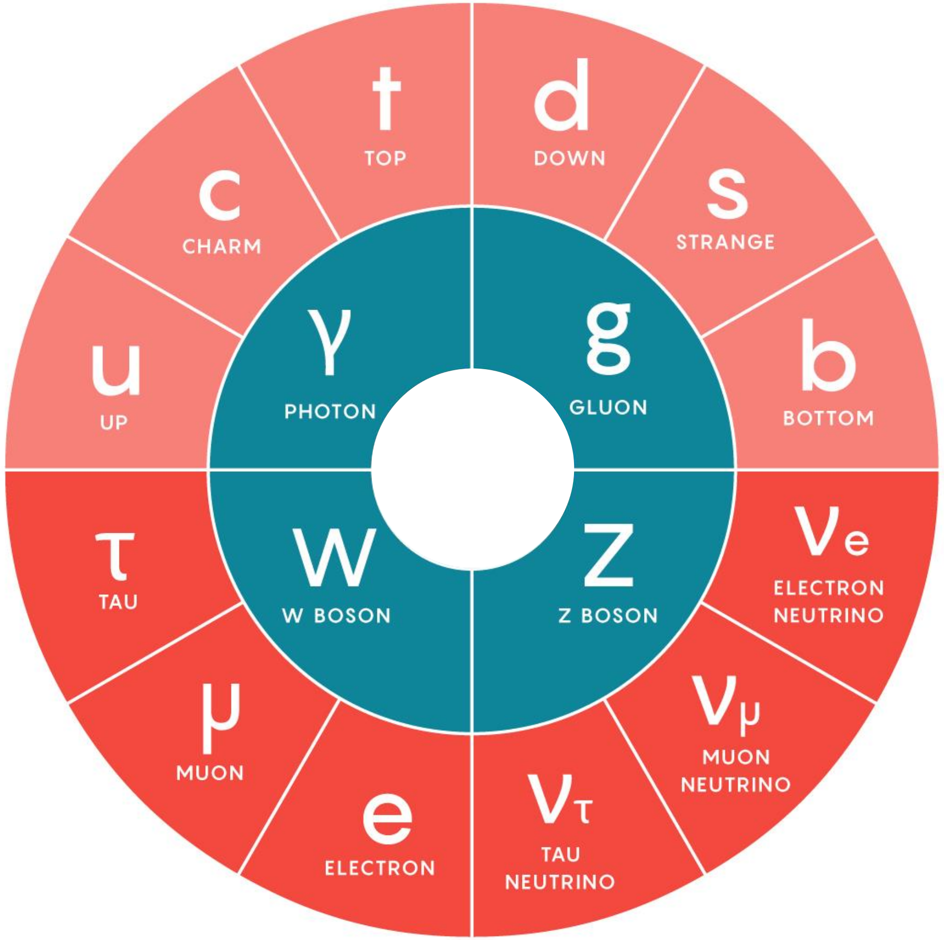
The Standard Model of Particle Physics

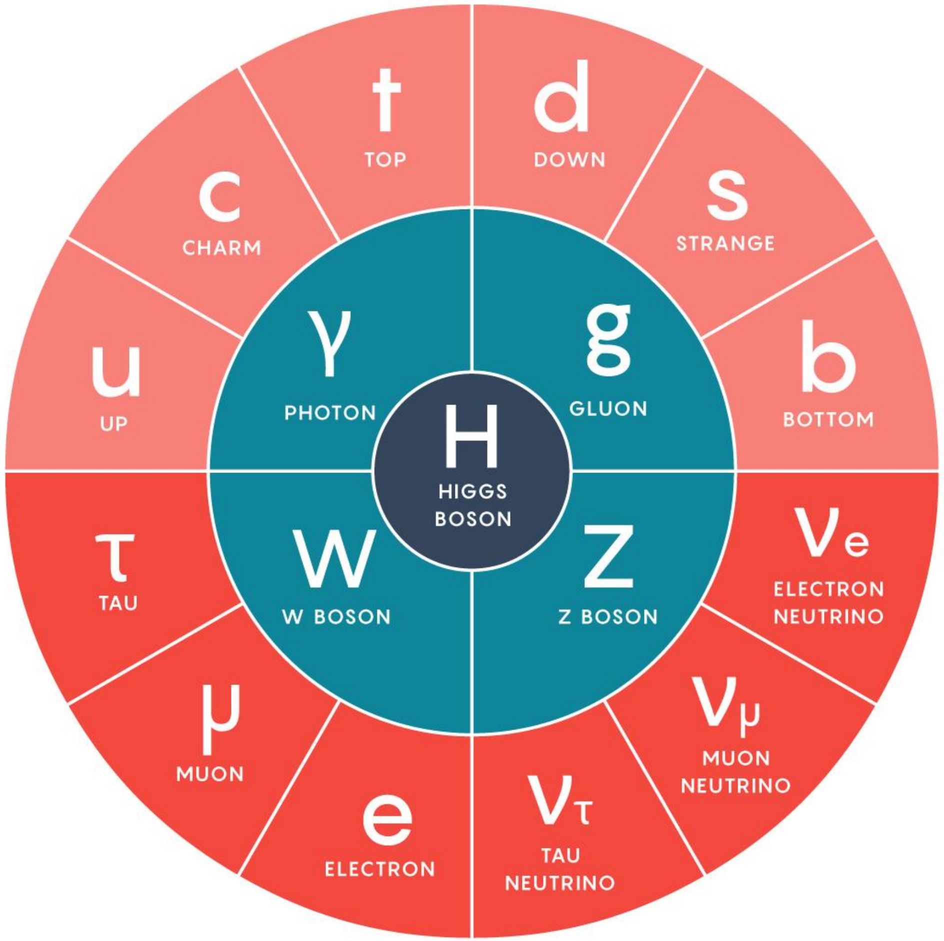
On the 4th July of 2012...

The discovery of a Higgs-like particle is announced at CERN

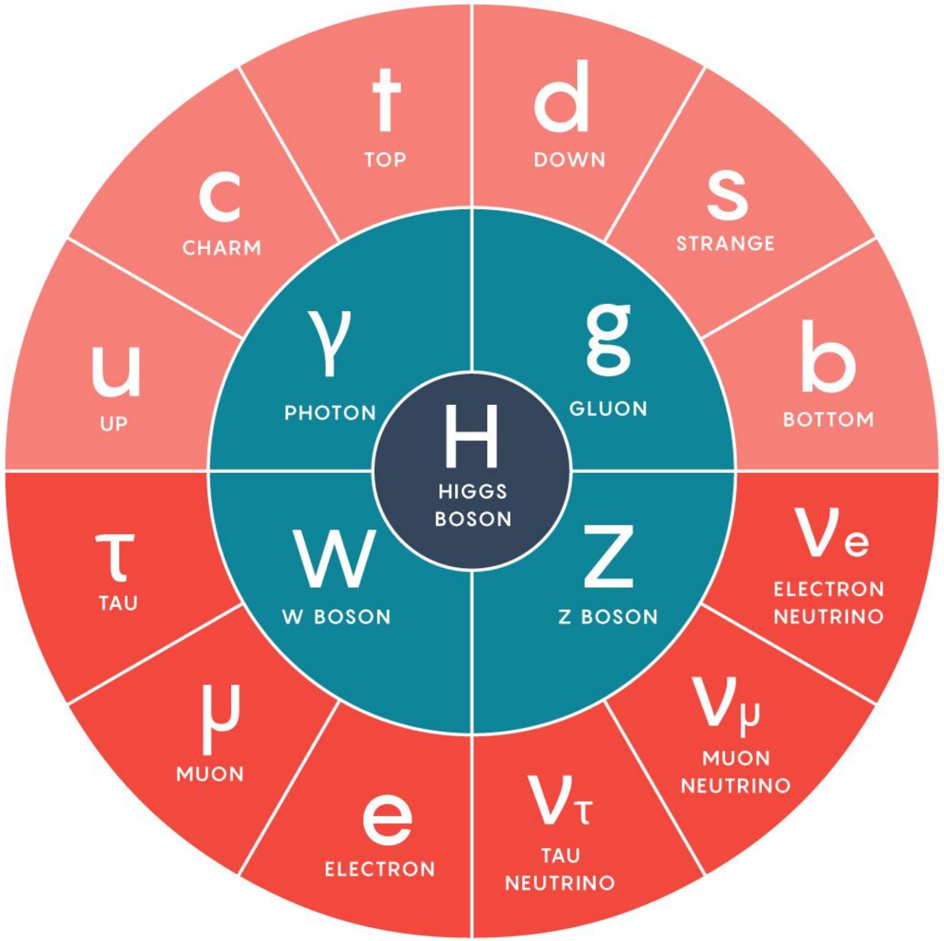
The Standard Model of Particle Physics



The Standard Model of Particle Physics



The Standard Model of Particle Physics



However, this is not the whole story...

Beyond the Standard Model

Scalar triplet extensions of the Standard Model

	Higgs-triplet model (HTM)	Two-scalar-triplet model (2STM)
Multi-Higgs scenario	Higgs-triplet model (HTM)	Two-scalar-triplet model (2STM)
Motivation	Neutrino masses in type-II seesaw mechanism	
Problem	Are neutral minima stable against charge breaking?	

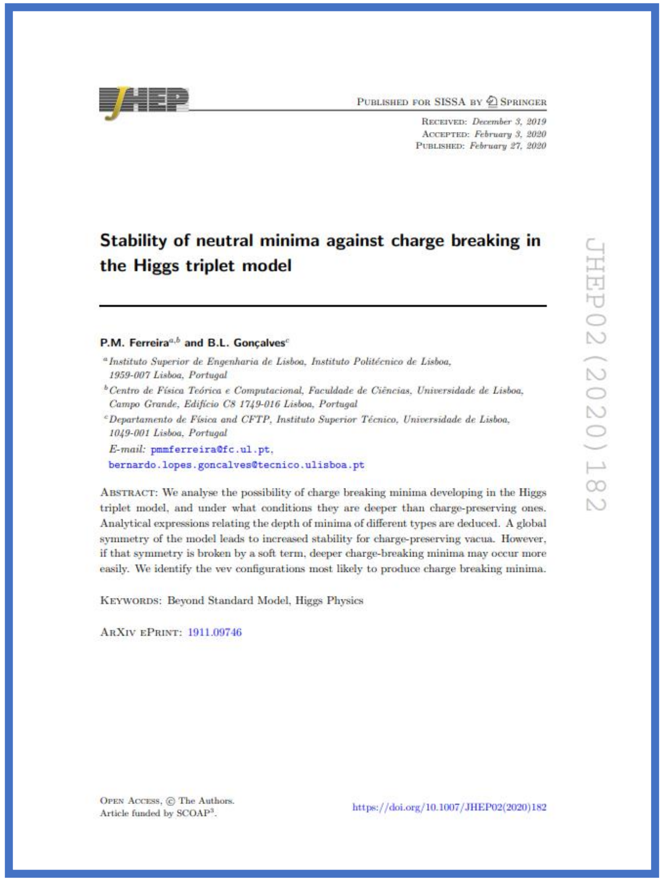
Beyond the Standard Model

Scalar triplet extensions of the Standard Model

Multi-Higgs scenario

Motivation

Problem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Stability of neutral minima against charge breaking in the Higgs triplet model

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ABSTRACT: We analyse the possibility of charge breaking minima developing in the Higgs triplet model, and under what conditions they are deeper than charge-preserving ones. Analytical expressions relating the depth of minima of different types are deduced. A global symmetry of the model leads to increased stability for charge-preserving vacua. However, if that symmetry is broken by a soft term, deeper charge-breaking minima may occur more easily. We identify the vev configurations most likely to produce charge breaking minima.

KEYWORDS: Beyond Standard Model, Higgs Physics

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Two-scalar-triplet model (2STM)

The Higgs-Triplet Model

All SM fields, with the **addition of an SU(2) scalar triplet**

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad + \quad \Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

RICHER PARTICLE SPECTRUM:

- Two CP-even scalars, h and H
- One pseudoscalar, A
- One charged scalar, H^+
- One doubly charged scalar, H^{++}

The Higgs-Triplet Model

All SM fields, with the **addition of an SU(2) scalar triplet**

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad + \quad \Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

MODEL'S MOTIVATION:

- Smallness of neutrino masses (type-II seesaw)
- Dark matter candidates
- Rich phenomenology

The Higgs-Triplet Model

All SM fields, with the **addition of an SU(2) scalar triplet**

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad + \quad \Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

DIFFERENT VACUUM POSSIBILITIES:

- CP-breaking vacua
- Charge-breaking (CB) vacua
- Normal (N) vacua

The Higgs-Triplet Model

All SM fields, with the **addition of an SU(2) scalar triplet**

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} + \Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

DIFFERENT VACUUM POSSIBILITIES:

- ~~CP-breaking vacua~~ **NOT POSSIBLE!**
- Charge-breaking (CB) vacua
- Normal (N) vacua

The Higgs-Triplet Model

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$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} + \quad \Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

DIFFERENT VACUUM POSSIBILITIES:

- ~~CP-breaking vacua~~ **NOT POSSIBLE!**
- Charge-breaking (CB) vacua
- Normal (N) vacua

Are neutral minima stable against charge breaking in the Higgs triplet model?

The Higgs-Triplet Model

Most general gauge invariant scalar potential

Soft-breaking term

$$\Phi \rightarrow e^{i\theta}\Phi$$

$$V = m^2\Phi^\dagger\Phi + M^2\mathrm{Tr}(\Delta^\dagger\Delta) + \mu\left(\Phi^T i\tau_2\Delta^\dagger\Phi + \mathrm{h.c.}\right)$$
$$+\lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\mathrm{Tr}\left[(\Delta^\dagger\Delta)^2\right] + \lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi$$

- Potential **without** soft-breaking term $\mu = 0$ Allows for dark matter particles
- Potential **with** soft-breaking term $\mu \neq 0$ Helps generate neutrino masses

The Higgs-Triplet Model

Three possibilities for neutral vacua

$$\langle\Phi\rangle_{N1} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_\Phi \end{pmatrix}, \qquad \langle\Delta\rangle_{N1} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ v_\Delta & 0 \end{pmatrix}$$

- Can occur whether the soft breaking term is present or not
- If such term is not present, we get a massless axion

$$\langle\Phi\rangle_{N2} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}, \qquad \langle\Delta\rangle_{N2} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}$$

- Only occurs when the soft breaking term is not present
- Good dark matter candidates

$$\langle\Phi\rangle_{N3} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \qquad \langle\Delta\rangle_{N3} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ v_\Delta & 0 \end{pmatrix}$$

- Can occur whether the soft breaking term is present or not
- Unphysical vacuum type (massless quarks)

The Higgs-Triplet Model

$c_1 \neq 0$

Three possibilities for neutral vacua

$$\langle\Phi\rangle_{N1} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_\Phi \end{pmatrix}, \qquad \langle\Delta\rangle_{N1} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ v_\Delta & 0 \end{pmatrix}$$

$$\langle\Phi\rangle_{N2} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}, \qquad \langle\Delta\rangle_{N2} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}$$

$$\langle\Phi\rangle_{N3} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \qquad \langle\Delta\rangle_{N3} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ v_\Delta & 0 \end{pmatrix}$$

Six different possibilities for CB vacua

$$\langle\Phi\rangle_{CB1} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ c_1 \end{pmatrix}, \qquad \langle\Delta\rangle_{CB1} = \frac{1}{\sqrt{2}}\begin{pmatrix} -c_3/\sqrt{2} & 0 \\ c_2 & c_3/\sqrt{2} \end{pmatrix}$$

$$\langle\Phi\rangle_{CB2} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ c_1 \end{pmatrix}, \qquad \langle\Delta\rangle_{CB2} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & c_3 \\ c_2 & 0 \end{pmatrix}$$

$$\langle\Phi\rangle_{CB3} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ c_1 \end{pmatrix}, \qquad \langle\Delta\rangle_{CB3} = \frac{1}{\sqrt{2}}\begin{pmatrix} c_3/\sqrt{2} & c_4 \\ c_2 & -c_3/\sqrt{2} \end{pmatrix}$$

$$\langle\Phi\rangle_{CB4} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ c_1 \end{pmatrix}, \qquad \langle\Delta\rangle_{CB4} = \frac{1}{\sqrt{2}}\begin{pmatrix} c_2/\sqrt{2} & 0 \\ 0 & -c_2/\sqrt{2} \end{pmatrix}$$

$$\langle\Phi\rangle_{CB5} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ c_1 \end{pmatrix}, \qquad \langle\Delta\rangle_{CB5} = \frac{1}{\sqrt{2}}\begin{pmatrix} c_2/\sqrt{2} & c_3 \\ 0 & -c_2/\sqrt{2} \end{pmatrix}$$

$$\langle\Phi\rangle_{CB6} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ c_1 \end{pmatrix}, \qquad \langle\Delta\rangle_{CB6} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & c_2 \\ 0 & 0 \end{pmatrix}$$

The Higgs-Triplet Model

$c_1 \neq 0$

Using a **bilinear formalism similar to the one developed for the 2HDM**, it is possible to find analytical formulae relating the depth of the potential at different extrema of the potential

Stability without soft-breaking

$c_1 \neq 0$

Stability of minima of type N2 against charge breaking

Stability of minima of type N1 against charge breaking

Stability without soft-breaking

$c_1 \neq 0$

Stability of minima of type N2 against charge breaking

$$V_{CB1} - V_{N2} = \frac{1}{4}\left(c_2^2 m_{H,A}^2 + c_3^2 m_+^2\right)$$

$$V_{CB2} - V_{N2} = \frac{1}{4}\left(c_2^2\, m_{H,A}^2 + c_3^2\, m_{++}^2\right)$$

$$V_{CB3} - V_{N2} = \frac{1}{4}\left(c_2^2\, m_{H,A}^2 + c_3^2\, m_+^2 + c_4^2\, m_{++}^2\right)$$

$$V_{CB4} - V_{N2} = \frac{1}{4}\, c_2^2\, m_+^2$$

$$V_{CB5} - V_{N2} = \frac{1}{4}\left(c_2^2\, m_+^2 + c_3^2\, m_{++}^2\right)$$

$$V_{CB6} - V_{N2} = \frac{1}{4}\, c_2^2\, m_{++}^2$$

Stability of minima of type N1 against charge breaking

Stability without soft-breaking

$c_1 \neq 0$

Stability of minima of type N2 against charge breaking

$$V_{CB1} - V_{N2} = \frac{1}{4}\left(c_2^2 m_{H,A}^2 + c_3^2 m_+^2\right)$$

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$$V_{CB3} - V_{N2} = \frac{1}{4}\left(c_2^2\, m_{H,A}^2 + c_3^2\, m_+^2 + c_4^2\, m_{++}^2\right)$$

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$$V_{CB6} - V_{N2} = \frac{1}{4}\, c_2^2\, m_{++}^2$$

Stability of minima of type N1 against charge breaking

$$V_{CB1} - V_{N1} = \frac{c_3^2\, m_+^2}{4\left(1 + \frac{2v_\Delta^2}{v_\Phi^2}\right)}$$

$$V_{CB2} - V_{N1} = \frac{1}{4}\, c_3^2\, m_{++}^2$$

$$V_{CB3} - V_{N1} = \frac{m_+^2\, c_3^2}{4\left(1 + \frac{2\, v_\Delta^2}{v_\Phi^2}\right)} + \frac{1}{4}\, c_4^2\, m_{++}^2 - \frac{1}{8}\lambda_3 v_\Delta^2 \frac{c_3^2 c_4}{c_2}$$

$$V_{CB4} - V_{N1} = \frac{c_1^2\, m_+^2}{4\left(2 + \frac{v_\Phi^2}{v_\Delta^2}\right)} + \frac{1}{8}\, c_2^2\, m_{++}^2$$

$$V_{CB5} - V_{N1} = \frac{c_1^2\, m_+^2}{4\left(2 + \frac{v_\Phi^2}{v_\Delta^2}\right)} + \frac{1}{8}\, c_2^2\, m_{++}^2 + \frac{c_3^2\, m_+^2}{2\left(1 + \frac{2v_\Delta^2}{v_\Phi^2}\right)}$$

$$V_{CB6} - V_{N1} = \frac{c_1^2\, m_+^2}{2\left(2 + \frac{v_\Phi^2}{v_\Delta^2}\right)} + \frac{c_2^2\, m_+^2}{2\left(1 + \frac{2v_\Delta^2}{v_\Phi^2}\right)}$$

Stability without soft-breaking

$c_1 \neq 0$

Stability of minima of type N2 against charge breaking

$$V_{CB1} - V_{N2} = \frac{1}{4}\left(c_2^2 m_{H,A}^2 + c_3^2 m_+^2\right)$$

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$$V_{CB3} - V_{N2} = \frac{1}{4}\left(c_2^2\, m_{H,A}^2 + c_3^2\, m_+^2 + c_4^2\, m_{++}^2\right)$$

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$$V_{CB5} - V_{N2} = \frac{1}{4}\left(c_2^2\, m_+^2 + c_3^2\, m_{++}^2\right)$$

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Stability of minima of type N1 against charge breaking

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$$V_{CB2} - V_{N1} = \frac{1}{4}\, c_3^2\, m_{++}^2$$

$$V_{CB3} - V_{N1} = \frac{m_+^2\, c_3^2}{4\left(1 + \frac{2\, v_\Delta^2}{v_\Phi^2}\right)} + \frac{1}{4}\, c_4^2\, m_{++}^2 - \frac{1}{8}\lambda_3 v_\Delta^2 \frac{c_3^2 c_4}{c_2}$$

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$$V_{CB6} - V_{N1} = \frac{c_1^2\, m_+^2}{2\left(2 + \frac{v_\Phi^2}{v_\Delta^2}\right)} + \frac{c_2^2\, m_+^2}{2\left(1 + \frac{2v_\Delta^2}{v_\Phi^2}\right)}$$

Stability without soft-breaking

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$$V_{CB1} - V_{N2} = \frac{1}{4}\left(c_2^2 m_{H,A}^2 + c_3^2 m_+^2\right)$$

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$$V_{CB4} - V_{N2} = \frac{1}{4}\, c_2^2\, m_+^2$$

$$V_{CB5} - V_{N2} = \frac{1}{4}\left(c_2^2\, m_+^2 + c_3^2\, m_{++}^2\right)$$

$$V_{CB6} - V_{N2} = \frac{1}{4}\, c_2^2\, m_{++}^2$$

Stability of minima of type N1 against charge breaking

$$V_{CB1} - V_{N1} = \frac{c_3^2\, m_+^2}{4\left(1 + \frac{2 v_\Delta^2}{v_\Phi^2}\right)}$$

$$V_{CB2} - V_{N1} = \frac{1}{4}\, c_3^2\, m_{++}^2$$

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$$= \frac{c_1^2\, m_+^2}{4\left(2 + \frac{v_\Phi^2}{v_\Delta^2}\right)} + \frac{1}{8}\, c_2^2\, m_{++}^2 + \frac{c_3^2\, m_+^2}{2\left(1 + \frac{2 v_\Delta^2}{v_\Phi^2}\right)}$$

$$V_{CB6} - V_{N1} = \frac{c_1^2\, m_+^2}{2\left(2 + \frac{v_\Phi^2}{v_\Delta^2}\right)} + \frac{c_2^2\, m_+^2}{2\left(1 + \frac{2 v_\Delta^2}{v_\Phi^2}\right)}$$

STABILITY GUARANTEED

Stability with soft-breaking

$c_1 \neq 0$

Stability of minima of type N1 against charge breaking

Stability with soft-breaking

$c_1 \neq 0$

Stability of minima of type N1 against charge breaking

$$V_{CB1} - V_{N1} = \frac{m_A^2}{4\left(1+\frac{4\,v_\Delta^2}{v_\Phi^2}\right)}(c_2 - v_\Delta)^2\left(1 - \frac{v_\Delta}{c_2}\frac{c_1^2}{v_\Phi^2}\right) + \frac{m_+^2\,c_3^2}{4\left(1+\frac{2\,v_\Delta^2}{v_\Phi^2}\right)}$$

$$V_{CB2} - V_{N1} = \frac{m_A^2}{4\left(1+\frac{4\,v_\Delta^2}{v_\Phi^2}\right)}(c_2 - v_\Delta)^2\left(1 - \frac{v_\Delta}{c_2}\frac{c_1^2}{v_\Phi^2}\right) + \frac{1}{4}c_3^2\,m_{++}^2$$

$$V_{CB3} - V_{N1} = \frac{m_A^2}{4\left(1+\frac{4\,v_\Delta^2}{v_\Phi^2}\right)}(c_2 - v_\Delta)^2\left(1 - \frac{v_\Delta}{c_2}\frac{c_1^2}{v_\Phi^2}\right) + \frac{m_+^2\,c_3^2}{4\left(1+\frac{2\,v_\Delta^2}{v_\Phi^2}\right)} + \frac{1}{4}c_4^2\,m_{++}^2 - \frac{1}{8}\lambda_3 v_\Delta^2\frac{c_3^2 c_4}{c_2}$$

$$V_{CB4} - V_{N1} = \frac{m_A^2}{4\left(1+\frac{4\,v_\Delta^2}{v_\Phi^2}\right)}\left(\frac{c_2^2}{2} + v_\Delta^2 + c_1^2\frac{v_\Delta^2}{v_\Phi^2}\right) + \frac{1}{8}c_2^2 m_{++}^2 + \frac{v_\Delta^2}{v_\Phi^2}\frac{c_1^2\,m_+^2}{4\left(1+\frac{2\,v_\Delta^2}{v_\Phi^2}\right)}$$

$$V_{CB5} - V_{N1} = \frac{m_A^2}{4\left(1+\frac{4\,v_\Delta^2}{v_\Phi^2}\right)}\left(\frac{c_2^2}{2} + v_\Delta^2 + c_1^2\frac{v_\Delta^2}{v_\Phi^2} - c_3^2\right) + \frac{1}{8}c_2^2 m_{++}^2 + \frac{m_+^2}{4\left(1+\frac{2\,v_\Delta^2}{v_\Phi^2}\right)}\left(c_1^2\frac{v_\Delta^2}{v_\Phi^2} + 2\,c_3^2\right)$$

$$V_{CB6} - V_{N1} = \frac{m_A^2}{4\left(1+\frac{4\,v_\Delta^2}{v_\Phi^2}\right)}(v_\Delta^2 - c_2^2) + \frac{m_+^2}{2\left(1+\frac{2\,v_\Delta^2}{v_\Phi^2}\right)}\left(c_1^2\frac{v_\Delta^2}{v_\Phi^2} + c_2^2\right)$$

Stability with soft-breaking

$c_1 \neq 0$

Stability of minima of type N1 against charge breaking

$$V_{CB1} - V_{N1} = \frac{m_A^2}{4\left(1 + \frac{4\,v_\Delta^2}{v_\Phi^2}\right)} (c_2 - v_\Delta)^2 \left(1 - \frac{v_\Delta}{c_2}\frac{c_1^2}{v_\Phi^2}\right) + \frac{m_+^2\, c_3^2}{4\left(1 + \frac{2\,v_\Delta^2}{v_\Phi^2}\right)}$$

$$V_{CB2} - V_{N1} = \frac{m_A^2}{4\left(1 + \frac{4\,v_\Delta^2}{v_\Phi^2}\right)} (c_2 - v_\Delta)^2 \left(1 - \frac{v_\Delta}{c_2}\frac{c_1^2}{v_\Phi^2}\right) + \frac{1}{4} c_3^2\, m_{++}^2$$

$$V_{CB3} - V_{N1} = \frac{m_A^2}{4\left(1 + \frac{4\,v_\Delta^2}{v_\Phi^2}\right)} (c_2 - v_\Delta)^2 \left(1 - \frac{v_\Delta}{c_2}\frac{c_1^2}{v_\Phi^2}\right) + \frac{m_+^2\, c_3^2}{4\left(1 + \frac{2\,v_\Delta^2}{v_\Phi^2}\right)} + \frac{1}{4} c_4^2\, m_{++}^2 - \frac{1}{8}\lambda_3 v_\Delta^2 \frac{c_3^2 c_4}{c_2}$$

$$V_{CB4} - V_{N1} = \frac{m_A^2}{4\left(1 + \frac{4\,v_\Delta^2}{v_\Phi^2}\right)} \left(\frac{c_2^2}{2} + v_\Delta^2 + c_1^2 \frac{v_\Delta^2}{v_\Phi^2}\right) + \frac{1}{8} c_2^2 m_{++}^2 + \frac{v_\Delta^2}{v_\Phi^2} \frac{c_1^2\, m_+^2}{4\left(1 + \frac{2\,v_\Delta^2}{v_\Phi^2}\right)}$$

$$V_{CB5} - V_{N1} = \frac{m_A^2}{4\left(1 + \frac{4\,v_\Delta^2}{v_\Phi^2}\right)} \left(\frac{c_2^2}{2} + v_\Delta^2 + c_1^2 \frac{v_\Delta^2}{v_\Phi^2} - c_3^2\right) + \frac{1}{8} c_2^2 m_{++}^2 + \frac{m_+^2}{4\left(1 + \frac{2\,v_\Delta^2}{v_\Phi^2}\right)} \left(c_1^2 \frac{v_\Delta^2}{v_\Phi^2} + 2\,c_3^2\right)$$

$$V_{CB6} - V_{N1} = \frac{m_A^2}{4\left(1 + \frac{4\,v_\Delta^2}{v_\Phi^2}\right)} (v_\Delta^2 - c_2^2) + \frac{m_+^2}{2\left(1 + \frac{2\,v_\Delta^2}{v_\Phi^2}\right)} \left(c_1^2 \frac{v_\Delta^2}{v_\Phi^2} + c_2^2\right)$$

Stability with soft-breaking

$c_1 \neq 0$

Stability of minima of type N1 against charge breaking

$$V_{CB1} - V_{N1} = \frac{m_A^2}{4\left(1 + \frac{4\,v_\Delta^2}{v_\Phi^2}\right)} (c_2 - v_\Delta)^2 \left(1 - \frac{v_\Delta}{c_2}\frac{c_1^2}{v_\Phi^2}\right) + \frac{m_+^2\, c_3^2}{4\left(1 + \frac{2\,v_\Delta^2}{v_\Phi^2}\right)}$$

$$V_{CB2} - V_{N1} = \frac{m_A^2}{4\left(1 + \frac{4\,v_\Delta^2}{v_\Phi^2}\right)} (c_2 - v_\Delta)^2 \left(1 - \frac{v_\Delta}{c_2}\frac{c_1^2}{v_\Phi^2}\right) + \frac{1}{4} c_3^2\, m_{++}^2$$

$$V_{CB3} - V_{N1} = \frac{m_A^2}{4\left(1 + \frac{4\,[illegible]}{[illegible]}\right)} [illegible] + -\frac{1}{8}\lambda_3 v_\Delta^2 \frac{c_3^2 c_4}{c_2}$$

$$V_{CB4} - V_{N1} = \frac{m_A^2}{4\left(1 + \frac{4\,[illegible]}{v_\Phi^2}\right)} [illegible] \frac{[illegible]}{4\left(1 + \frac{2\,v_\Delta^2}{v_\Phi^2}\right)}$$

STABILITY NOT GUARANTEED

$$V_{CB5} - V_{N1} = \frac{m_A^2}{4\left(1 + \frac{4\,v_\Delta^2}{v_\Phi^2}\right)} \left(\frac{c_2^2}{2} + v_\Delta^2 + c_1^2 \frac{v_\Delta^2}{v_\Phi^2} - c_3^2\right) + \frac{1}{8} c_2^2 m_{++}^2 + \frac{m_+^2}{4\left(1 + \frac{2\,v_\Delta^2}{v_\Phi^2}\right)} \left(c_1^2 \frac{v_\Delta^2}{v_\Phi^2} + 2\,c_3^2\right)$$

$$V_{CB6} - V_{N1} = \frac{m_A^2}{4\left(1 + \frac{4\,v_\Delta^2}{v_\Phi^2}\right)} (v_\Delta^2 - c_2^2) + \frac{m_+^2}{2\left(1 + \frac{2\,v_\Delta^2}{v_\Phi^2}\right)} \left(c_1^2 \frac{v_\Delta^2}{v_\Phi^2} + c_2^2\right)$$

Stability so far...

$c_1 \neq 0$

CB minima $c_1 \neq 0$

	$\boldsymbol{\mu = 0}$	$\boldsymbol{\mu \neq 0}$
N2 minima	STABILITY GUARANTEED	DOES NOT OCCUR
N1 minima	STABILITY GUARANTEED	STABILITY NOT GUARANTEED

The case of the vevless doublet

$c_1 = 0$

$$\frac{\partial V}{\partial c_1} = c_1 \left[m^2 + \lambda_1 c_1^2 + \frac{\lambda_4}{2}(c_2^2 + c_3^2 + c_4^2) + \frac{\lambda_5}{2}(2c_2^2 + c_3^2) \right] = 0$$

→ $c_1 = 0$ disconnected solution from $c_1 \neq 0$

The case of the vevless doublet

$c_1 = 0$

Three possibilities for neutral vacua

$$\langle\Phi\rangle_{N1} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_\Phi \end{pmatrix}, \qquad \langle\Delta\rangle_{N1} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ v_\Delta & 0 \end{pmatrix}$$

$$\langle\Phi\rangle_{N2} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}, \qquad \langle\Delta\rangle_{N2} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}$$

$$\langle\Phi\rangle_{N3} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \qquad \langle\Delta\rangle_{N3} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ v_\Delta & 0 \end{pmatrix}$$

Six new possibilities for CB vacua

$$\langle\Phi\rangle_{CB7} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \qquad \langle\Delta\rangle_{CB7} = \frac{1}{\sqrt{2}}\begin{pmatrix} c_3/\sqrt{2} & c_2 \\ c_2 & -c_3/\sqrt{2} \end{pmatrix}$$

$$\langle\Phi\rangle_{CB8} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \qquad \langle\Delta\rangle_{CB8} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & c_2 \\ c_2 & 0 \end{pmatrix}$$

$$\langle\Phi\rangle_{CB9} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \qquad \langle\Delta\rangle_{CB9} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & -c_2 \\ c_2 & 0 \end{pmatrix}$$

$$\langle\Phi\rangle_{CB10} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \qquad \langle\Delta\rangle_{CB10} = \frac{1}{\sqrt{2}}\begin{pmatrix} c_3/\sqrt{2} & -c_3^2/2c_2 \\ c_2 & -c_3/\sqrt{2} \end{pmatrix}$$

$$\langle\Phi\rangle_{CB11} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \qquad \langle\Delta\rangle_{CB11} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & c_4 \\ 0 & 0 \end{pmatrix}$$

$$\langle\Phi\rangle_{CB12} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \qquad \langle\Delta\rangle_{CB12} = \frac{1}{\sqrt{2}}\begin{pmatrix} c_3/\sqrt{2} & 0 \\ 0 & -c_3/\sqrt{2} \end{pmatrix}$$

Stability without soft-breaking

$c_1 = 0$

Stability of minima of type N1 against charge breaking

$$V_{CB7} - V_{N1} = \frac{v_\Phi^2}{v_\Delta^2}\frac{m_h^2 m_H^2}{16(\lambda_2+\lambda_3)} - \lambda_3 \frac{[2(\lambda_2+\lambda_3)v_\Delta^2 + (\lambda_4+\lambda_5)v_\Phi^2]^2}{16(\lambda_2+\lambda_3)(2\lambda_2+\lambda_3)}$$

$$V_{CB10} - V_{N1} = \frac{v_\Phi^2}{v_\Delta^2}\frac{m_h^2 m_H^2}{16(\lambda_2+\lambda_3)}$$

Stability of minima of type N2 against charge breaking

$$V_{CB7} - V_{N2} = \frac{1}{4}\left(\frac{m^4}{\lambda_1} - \frac{M^4}{\lambda_2 + \frac{1}{2}\lambda_3}\right)$$

$$V_{CB10} - V_{N2} = \frac{1}{4}\left(\frac{m^4}{\lambda_1} - \frac{M^4}{\lambda_2 + \lambda_3}\right)$$

The expressions for $V_{CB7} - V_{N1}$ hold for $CB8$, $CB9$ and $CB12$, while the second one also holds for $V_{CB11} - V_{N1}$

Stability with soft-breaking

$c_1 = 0$

Stability of minima of type N1 against charge breaking

$$V_{CB7} - V_{N1} = \frac{v_\Phi^2}{v_\Delta^2}\frac{m_h^2 m_H^2}{16(\lambda_2+\lambda_3)} - \frac{\lambda_1}{8(\lambda_2+\lambda_3)}\frac{m_A^2}{1+\frac{4v_\Delta^2}{v_\Phi^2}}\frac{v_\Phi^4}{v_\Delta^2} - \lambda_3\frac{[2(\lambda_2+\lambda_3)v_\Delta^2+(\lambda_4+\lambda_5)v_\Phi^2]^2}{16(\lambda_2+\lambda_3)(2\lambda_2+\lambda_3)}$$

$$+\frac{\lambda_3}{2(2\lambda_2+\lambda_3)}\frac{m_A^2}{1+\frac{4v_\Delta^2}{v_\Phi^2}}\left[v_\Delta^2+\frac{\lambda_4+\lambda_5}{2(\lambda_2+\lambda_3)}v_\Phi^2 - \frac{1}{2(\lambda_2+\lambda_3)}\frac{m_A^2}{1+\frac{4v_\Delta^2}{v_\Phi^2}}\right]$$

$$V_{CB10} - V_{N1} = \frac{v_\Phi^2}{v_\Delta^2}\frac{m_h^2 m_H^2}{16(\lambda_2+\lambda_3)} - \frac{\lambda_1}{8(\lambda_2+\lambda_3)}\frac{m_A^2}{1+\frac{4v_\Delta^2}{v_\Phi^2}}\frac{v_\Phi^4}{v_\Delta^2}$$

The expressions for $V_{CB7} - V_{N1}$ hold for $CB8$, $CB9$ and $CB12$, while the second one also holds for $V_{CB11} - V_{N1}$

Full analytical conclusions

CB minima $c_1 \neq 0$

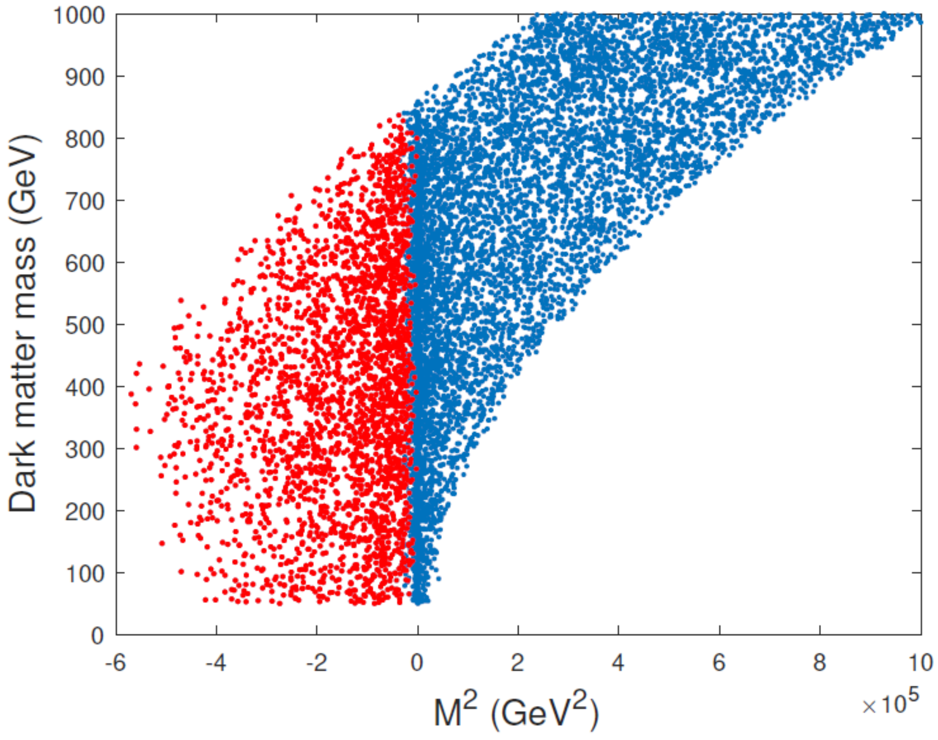
	$\mu = 0$	$\mu \neq 0$
N2 minima	**STABILITY GUARANTEED**	DOES NOT OCCUR
N1 minima	**STABILITY GUARANTEED**	**STABILITY NOT GUARANTEED**

CB minima $c_1 = 0$

	$\mu = 0$	$\mu \neq 0$
N2 minima	**STABILITY NOT GUARANTEED**	DOES NOT OCCUR
N1 minima	**STABILITY NOT GUARANTEED**	**STABILITY NOT GUARANTEED**

Numerical scan without soft-breaking

- N2 minima is stable against N1 minima type
- **N2 not necessarily stable against CB with vevless doublet**
- We have identified the most likely CB vacua as the vev combinations we dubbed CB7 and CB10



In blue, all scanned points for a minimum of type N2; in red, those points for which there exists a CB vacuum (CB7 or CB10) lower than N2

Numerical scan without soft-breaking

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- **N2 not necessarily stable against CB with vevless doublet**
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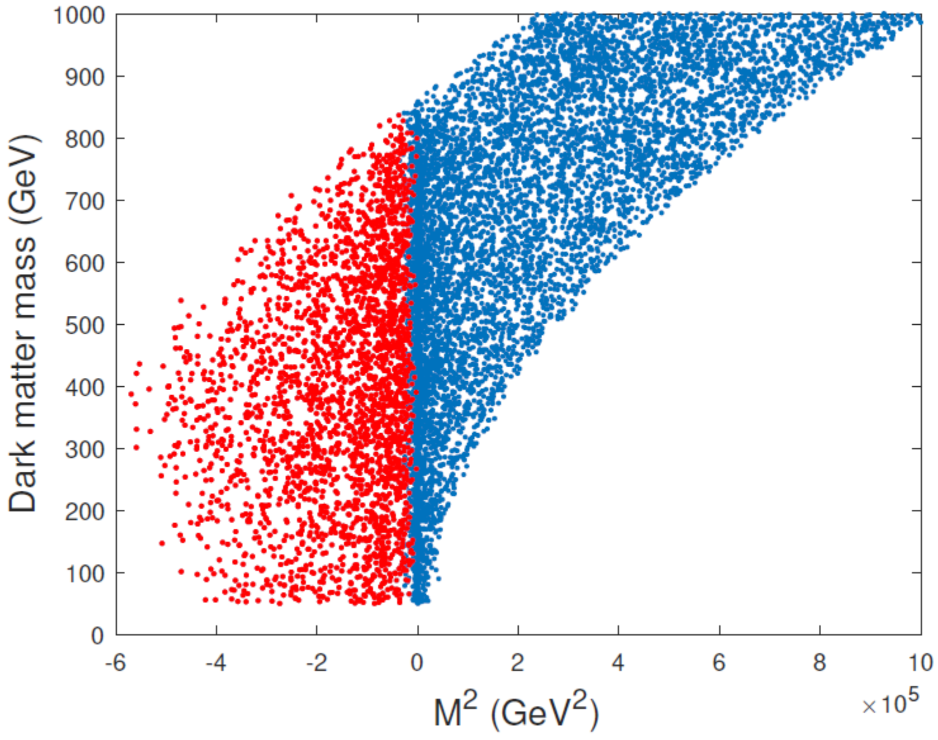
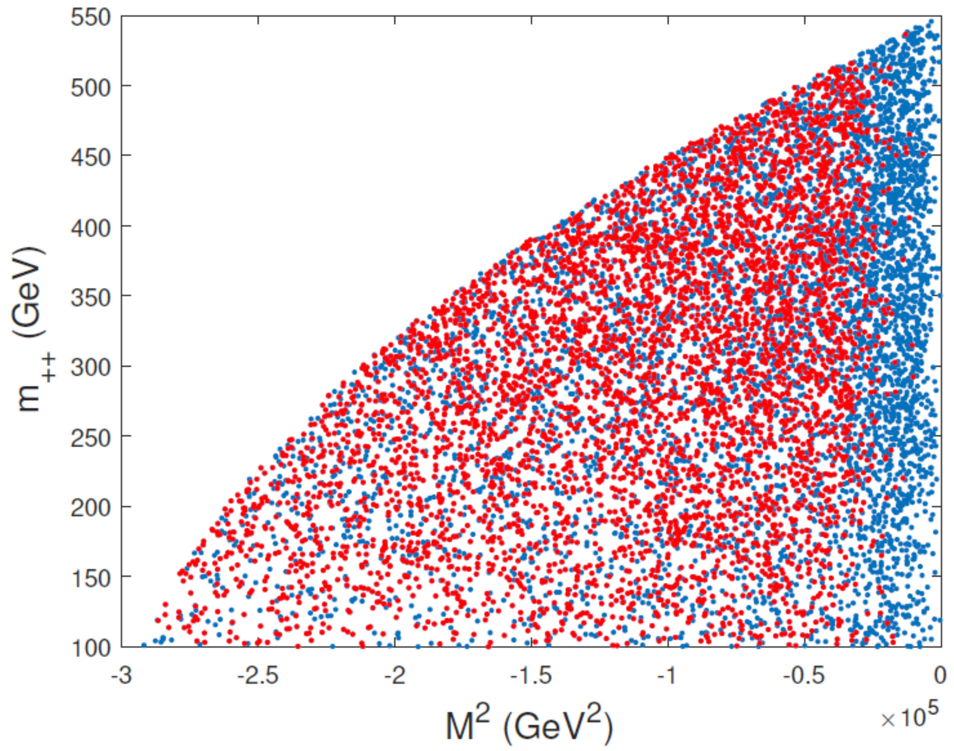


It can be shown analytically that

$$\text{An } N2 \text{ minimum is stable against charge breaking iff } M^2 > -\sqrt{\min\left(\lambda_2 + \frac{1}{2}\lambda_3\,,\,\lambda_2+\lambda_3\right)}\,\frac{m_h v}{\sqrt{2}}$$

Numerical scan with soft-breaking

- N2 minima is not possible to occur
- **With a minimum of type N1, there are several possible deeper CB vacua**
- Large percentage of potentially-unstable neutral minima



In blue, all scanned points for a minimum of type N1; in red, those points for which there exists a CB vacuum (CB7 or CB10) lower than N1

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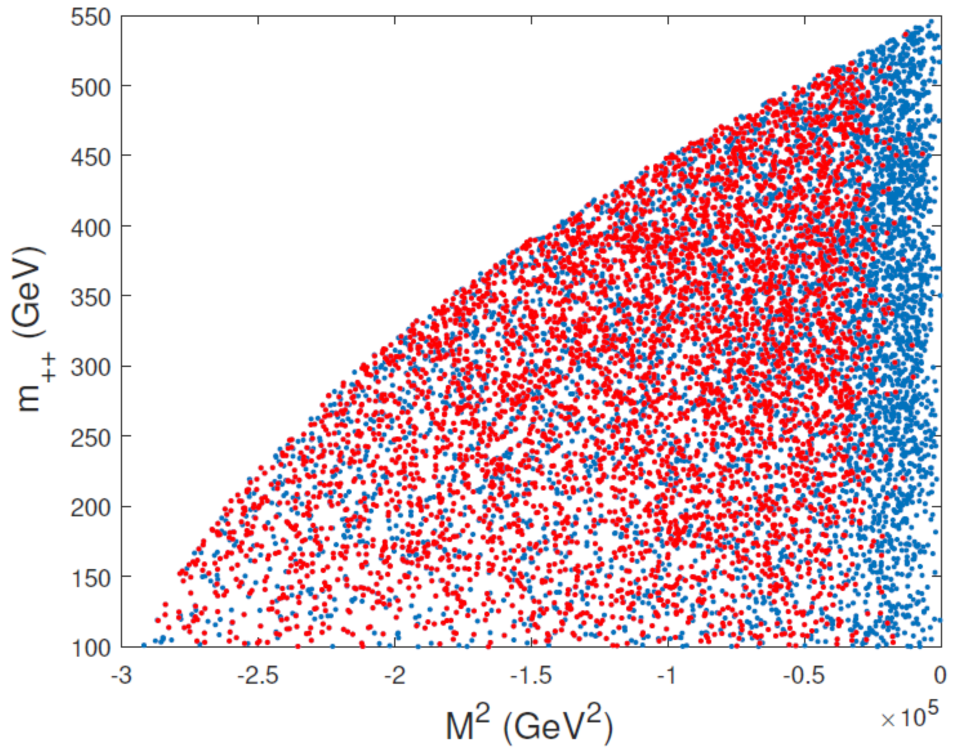


SOME REMARKS

- We found that for roughly 26% (48%) of the parameter space found for the globally symmetric (softly broken) potential neutral minima had deeper charge breaking ones

- CB global minima can indeed coexist, in some cases fairly frequently, with neutral minima

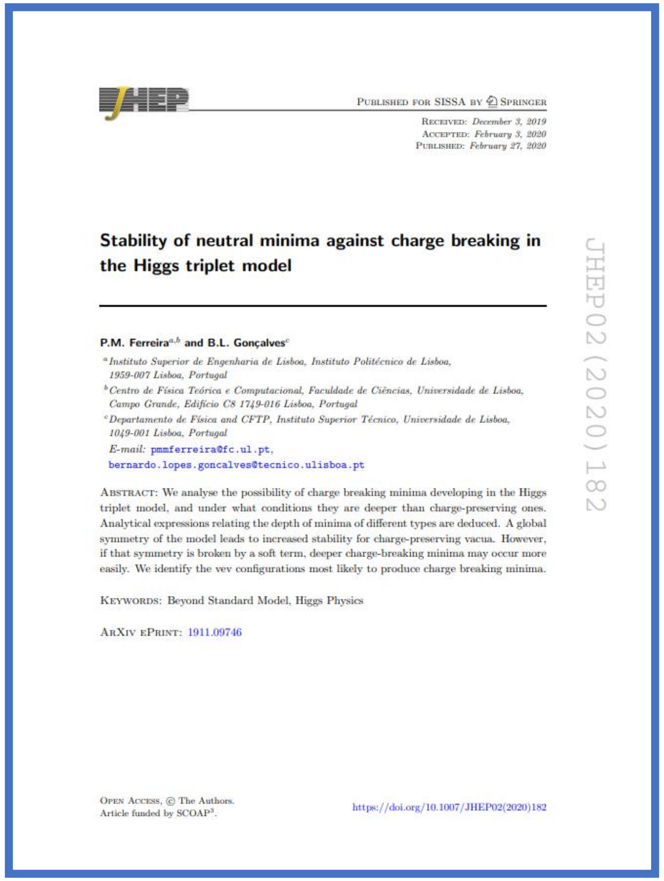
Beyond the Standard Model

Scalar triplet extensions of the Standard Model

Multi-Higgs scenario

Motivation

Problem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Stability of neutral minima against charge breaking in the Higgs triplet model

P.M. Ferreira[a,b] and B.L. Gonçalves[c]

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Abstract: We analyse the possibility of charge breaking minima developing in the Higgs triplet model, and under what conditions they are deeper than charge-preserving ones. Analytical expressions relating the depth of minima of different types are deduced. A global symmetry of the model leads to increased stability for charge-preserving vacua. However, if that symmetry is broken by a soft term, deeper charge-breaking minima may occur more easily. We identify the vev configurations most likely to produce charge breaking minima.

Keywords: Beyond Standard Model, Higgs Physics

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Two-scalar-triplet model (2STM)

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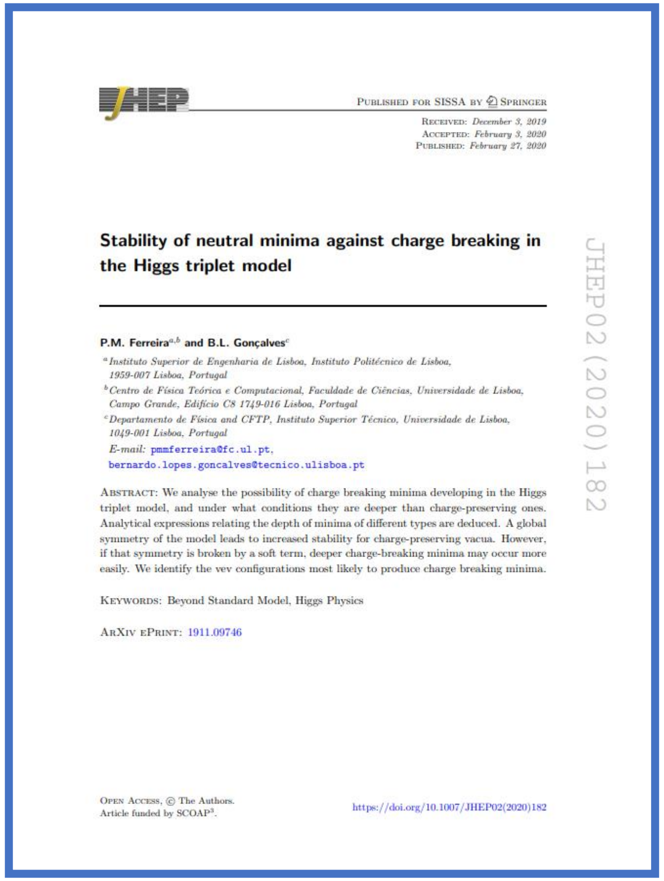

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Two-scalar-triplet model (2STM)

Motivation

Minimal triplet extension in which spontaneous CP violation occurs

Problem

Do we have decoupling in the scalar mass spectrum?

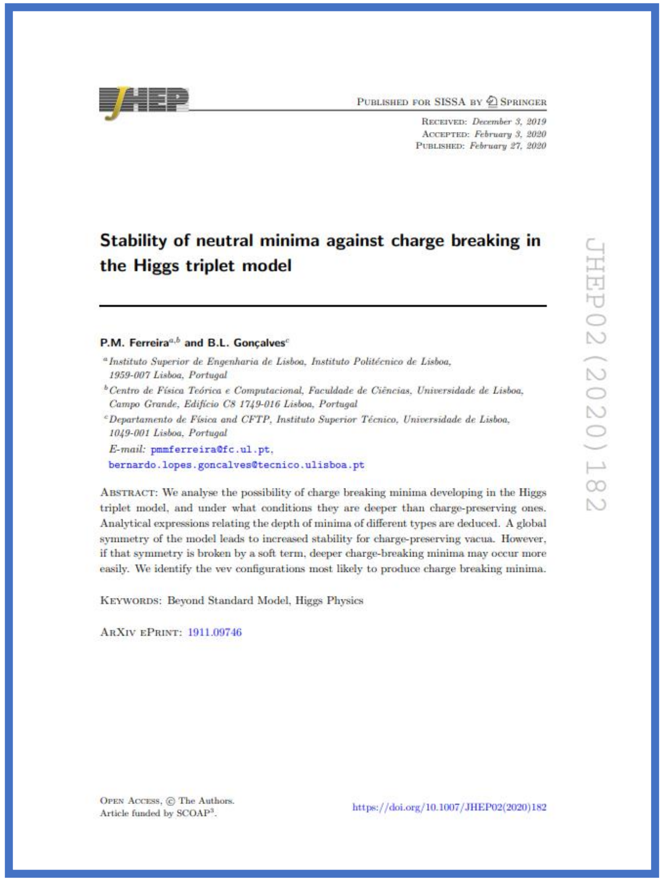
Beyond the Standard Model

Scalar triplet extensions of the Standard Model

Multi-Higgs scenario

Motivation

Problem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Two-scalar-triplet model (2STM)

Minimal triplet extension in which spontane s CP

OUT SOON

Do e have decoupling in the scalar mass spectrum?

Spontaneous CP violation in scalar-triplet models

In the Higgs-triplet model:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad + \quad \Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$$

Spontaneous CP violation in scalar-triplet models

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$$\langle \phi^0 \rangle = \frac{v}{\sqrt{2}} \, , \; \langle \delta^0 \rangle = \frac{u e^{i\theta}}{\sqrt{2}} \longrightarrow \boxed{\mu \, v u \sin\theta = 0}$$

Spontaneous CP violation in scalar-triplet models

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NO SCPV

Spontaneous CP violation in scalar-triplet models

In the two-scalar-triplet model:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad + \quad \Delta_{1,2} = \begin{pmatrix} \delta^+_{1,2}/\sqrt{2} & \delta^{++}_{1,2} \\ \delta^0_{1,2} & -\delta^+_{1,2}/\sqrt{2} \end{pmatrix}$$

$$\begin{aligned} V_{\mathrm{U}(1)} = & \, m^2\Phi^\dagger\Phi + M_{11}^2\mathrm{Tr}(\Delta_1^\dagger\Delta_1) + M_{22}^2\mathrm{Tr}(\Delta_2^\dagger\Delta_2) + \lambda_0(\Phi^\dagger\Phi)^2 \\ & + \lambda_1[\mathrm{Tr}(\Delta_1^\dagger\Delta_1)]^2 + \lambda_2[\mathrm{Tr}(\Delta_2^\dagger\Delta_2)]^2 + \lambda_{21}\mathrm{Tr}(\Delta_2^\dagger\Delta_2)\mathrm{Tr}(\Delta_1^\dagger\Delta_1) + \lambda_{12}\mathrm{Tr}(\Delta_1^\dagger\Delta_2)\mathrm{Tr}(\Delta_2^\dagger\Delta_1) \\ & + \tilde{\lambda}_1\mathrm{Tr}[(\Delta_1^\dagger\Delta_1)^2] + \tilde{\lambda}_2\mathrm{Tr}[(\Delta_2^\dagger\Delta_2)^2] + \tilde{\lambda}_{21}\mathrm{Tr}(\Delta_2^\dagger\Delta_2\Delta_1^\dagger\Delta_1) + \tilde{\lambda}_{12}\mathrm{Tr}(\Delta_1^\dagger\Delta_2\Delta_2^\dagger\Delta_1) \\ & + \lambda_1'\mathrm{Tr}(\Delta_1^\dagger\Delta_1)\Phi^\dagger\Phi + \lambda_2'\mathrm{Tr}(\Delta_2^\dagger\Delta_2)\Phi^\dagger\Phi + \hat{\lambda}_1\Phi^\dagger\Delta_1\Delta_1^\dagger\Phi + \hat{\lambda}_2\Phi^\dagger\Delta_2\Delta_2^\dagger\Phi \end{aligned}$$

$+$

$$V_{\mathrm{SB}} = M_{12}^2[\mathrm{Tr}(\Delta_1^\dagger\Delta_2) + \mathrm{Tr}(\Delta_2^\dagger\Delta_1)] + (\mu_1\Phi^T\mathrm{i}\tau_2\Delta_1^\dagger\Phi + \mu_2\Phi^T\mathrm{i}\tau_2\Delta_2^\dagger\Phi + \mathrm{H.c.})$$

Spontaneous CP violation in scalar-triplet models

In the two-scalar-triplet model:

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$$\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \;,\; \langle\Delta_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ u_1 e^{i\theta_1} & 0 \end{pmatrix} \;,\; \langle\Delta_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ u_2 e^{i\theta_2} & 0 \end{pmatrix}$$

$$\theta_1 \neq \theta_2$$

Spontaneous CP violation in scalar-triplet models

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$$\theta_1 \neq \theta_2$$

$$u_1 = u\, c_\beta$$
$$u_2 = u\, s_\beta$$
$$\tan\beta = u_2/u_1$$

$$uv\left(\mu_1 c_\beta s_{\theta_1} + \mu_2 s_\beta s_{\theta_2}\right) = 0$$

Spontaneous CP violation in scalar-triplet models

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SCPV IS POSSIBLE

Spontaneous CP violation in scalar-triplet models

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SCPV IS POSSIBLE

CP violation can be communicated to the fermion sector

Spontaneous CP violation in scalar-triplet models

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$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad + \quad \Delta_{1,2} = \begin{pmatrix} \delta^+_{1,2}/\sqrt{2} & \delta^{++} \\ \ldots & \ldots/\sqrt{2} \end{pmatrix}$$

BUT WHAT ABOUT THE SCALAR MASS SPECTRUM?

$$\langle\Phi\rangle = \frac{1}{\sqrt{\ldots}} \ldots \quad \frac{1}{\sqrt{2}}\begin{pmatrix} \ldots & 0 \\ u_1 e^{i\theta_1} & 0 \end{pmatrix}, \quad \langle\Delta_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ u_2 e^{i\theta_2} & 0 \end{pmatrix}$$

$$\theta_1 \neq \theta_2$$

$$uv\left(\mu_1 c_\beta s_{\theta_1} + \mu_2 s_\beta s_{\theta_2}\right) = 0$$

SCPV IS POSSIBLE

CP violation can be communicated to the fermion sector

Scalar mass spectrum

Using **results from matrix theory**, it is possible to find analytical results, exact or up to a good approximation, regarding the eigenvalues of the mass matrices, thus the scalar masses

- **Six neutral scalars**
- **Three charged scalars**
- **Two doubly-charged scalars**

CP-conserving case

$$m^2_{h^0_2} \simeq 2\lambda_0 v^2 - 2\sqrt{2}u\bar{\mu}\,, \quad \bar{\mu} = \mu_1 c_\beta + \mu_2 s_\beta$$

$$m^2_{h^0_{3,4}} \simeq m^2_{h^0_{5,6}} \simeq -\frac{M^2_{12}}{s_{2\beta}} + \frac{\sqrt{2}}{2}\frac{v^2\bar{\mu}}{us_{2\beta}} \pm \sqrt{\frac{v^2}{u^2 s_{2\beta}}\left(-\mu_1\mu_2 v^2 + \sqrt{2}M^2_{12}u\bar{\mu}\right) + \left(-\frac{M^2_{12}}{s_{2\beta}} + \frac{\sqrt{2}}{2}\frac{v^2\bar{\mu}}{us_{2\beta}}\right)^2}$$

$$m^2_{h^0_3} \approx m^2_{h^0_4} \approx m^2_{H^+_2} \approx m^2_{H^{++}_1} \quad , \quad m^2_{h^0_5} \approx m^2_{h^0_6} \approx m^2_{H^+_3} \approx m^2_{H^{++}_2}$$

- Two Goldstone bosons
- One Higgs-like particle
- All the remaining particles decouple

CP-violating case

CP-violating case

This result is exact!

$$m^2_{h^0_{2,3}} \leq \frac{u^2}{2}\left[\Lambda_3+\Lambda_5+(\Lambda_3-\Lambda_5)c_{2\beta} \pm \sqrt{[\Lambda_3+\Lambda_5+(\Lambda_3-\Lambda_5)c_{2\beta}]^2+(\Lambda_4^2-4\Lambda_3\Lambda_5)\,s^2_{2\beta}}\right]$$

Λ_i ⟶ combinations of quartic couplings

CP-violating case

This result is exact!

$$m^2_{h^0_{2,3}} \leq \frac{u^2}{2}\left[\Lambda_3 + \Lambda_5 + (\Lambda_3 - \Lambda_5)c_{2\beta} \pm \sqrt{[\Lambda_3 + \Lambda_5 + (\Lambda_3 - \Lambda_5)c_{2\beta}]^2 + (\Lambda_4^2 - 4\Lambda_3\Lambda_5)\, s^2_{2\beta}}\right]$$

Λ_i ⟶ combinations of quartic couplings

Two light neutral scalars!

CP-violating case

$$M_\Delta^2 \equiv \frac{\mu_1}{\sqrt{2}u} v^2$$

$$m_{h_4^0}^2 \simeq 2\lambda_1 v^2 + 2\sqrt{2}\,\mu_1 u c_\beta \frac{s_{\theta_1-\theta_2}}{s_{\theta_2}}$$

$$m_{h_5^0}^2 \simeq m_{h_6^0}^2 \simeq -\frac{s_{\theta_2}}{s_{\theta_1-\theta_2}} \left[f_1(\beta,\theta_1,\theta_2) + f_2(\beta)\right] M_\Delta^2$$

$$m_{H_2^+}^2 \simeq \frac{m_{H_1^{++}}^2}{2} \simeq -\frac{1}{4} \frac{\hat{\lambda}_1 f_1(\beta,\theta_1,\theta_2) + \hat{\lambda}_2 f_2(\beta)}{f_1(\beta,\theta_1,\theta_2) + f_2(\beta)} v^2$$

$$m_{H_3^+}^2 \simeq m_{H_2^{++}}^2 \simeq -\frac{s_{\theta_2}}{s_{\theta_1-\theta_2}} \left[f_1(\beta,\theta_1,\theta_2) + f_2(\beta)\right] M_\Delta^2$$

CP-violating case

$$M_\Delta^2 \equiv \frac{\mu_1}{\sqrt{2}u} v^2$$

$$m_{h_4^0}^2 \simeq 2\lambda_1 v^2 + 2\sqrt{2}\,\mu_1 u c_\beta \frac{s_{\theta_1-\theta_2}}{s_{\theta_2}}$$

Higgs-like

$$m_{h_5^0}^2 \simeq m_{h_6^0}^2 \simeq -\frac{s_{\theta_2}}{s_{\theta_1-\theta_2}} \left[f_1(\beta,\theta_1,\theta_2) + f_2(\beta)\right] M_\Delta^2$$

$$m_{H_2^+}^2 \simeq \frac{m_{H_1^{++}}^2}{2} \simeq -\frac{1}{4}\frac{\hat{\lambda}_1 f_1(\beta,\theta_1,\theta_2) + \hat{\lambda}_2 f_2(\beta)}{f_1(\beta,\theta_1,\theta_2) + f_2(\beta)} v^2$$

$$m_{H_3^+}^2 \simeq m_{H_2^{++}}^2 \simeq -\frac{s_{\theta_2}}{s_{\theta_1-\theta_2}} \left[f_1(\beta,\theta_1,\theta_2) + f_2(\beta)\right] M_\Delta^2$$

CP-violating case

$$M_\Delta^2 \equiv \frac{\mu_1}{\sqrt{2}u} v^2$$

$$m^2_{h_4^0} \simeq 2\lambda_1 v^2 + 2\sqrt{2}\,\mu_1 u c_\beta \frac{s_{\theta_1-\theta_2}}{s_{\theta_2}}$$

Higgs-like

$$m^2_{h_5^0} \simeq m^2_{h_6^0} \simeq -\frac{s_{\theta_2}}{s_{\theta_1-\theta_2}} \left[f_1(\beta,\theta_1,\theta_2) + f_2(\beta)\right] M_\Delta^2$$

Decoupled

$$m^2_{H_2^+} \simeq \frac{m^2_{H_1^{++}}}{2} \simeq -\frac{1}{4}\frac{\hat\lambda_1 f_1(\beta,\theta_1,\theta_2) + \hat\lambda_2 f_2(\beta)}{f_1(\beta,\theta_1,\theta_2) + f_2(\beta)} v^2$$

$$m^2_{H_3^+} \simeq m^2_{H_2^{++}} \simeq -\frac{s_{\theta_2}}{s_{\theta_1-\theta_2}} \left[f_1(\beta,\theta_1,\theta_2) + f_2(\beta)\right] M_\Delta^2$$

Decoupled

CP-violating case

$$M_\Delta^2 \equiv \frac{\mu_1}{\sqrt{2}u} v^2$$

$$m_{h_4^0}^2 \simeq 2\lambda_1 v^2 + 2\sqrt{2}\,\mu_1 u c_\beta \frac{s_{\theta_1-\theta_2}}{s_{\theta_2}}$$

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Decoupled

$$m_{H_2^+}^2 \simeq \frac{m_{H_1^{++}}^2}{2} \simeq -\frac{1}{4}\frac{\hat\lambda_1 f_1(\beta,\theta_1,\theta_2) + \hat\lambda_2 f_2(\beta)}{f_1(\beta,\theta_1,\theta_2) + f_2(\beta)} v^2$$

Electroweak!

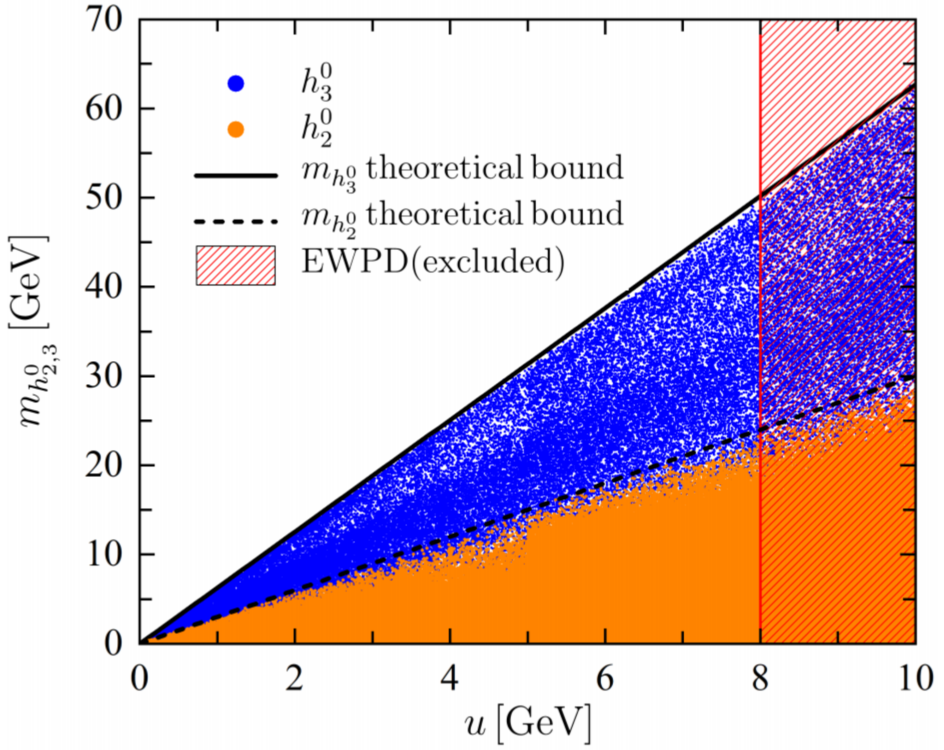
$$m_{H_3^+}^2 \simeq m_{H_2^{++}}^2 \simeq -\frac{s_{\theta_2}}{s_{\theta_1-\theta_2}} \left[f_1(\beta,\theta_1,\theta_2) + f_2(\beta)\right] M_\Delta^2$$

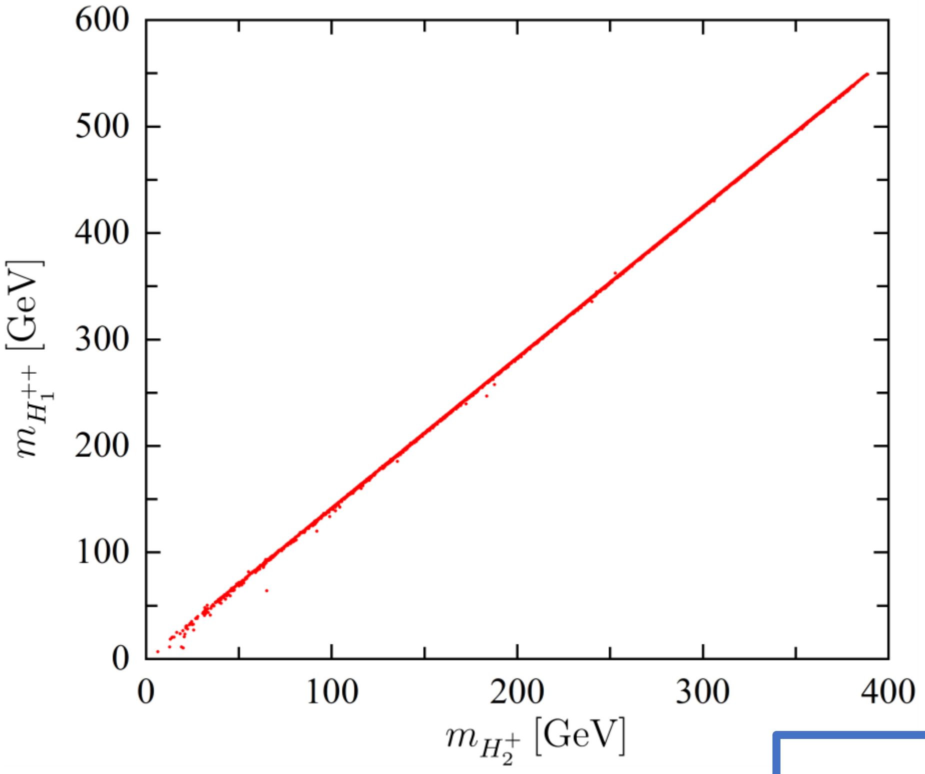
Decoupled

Full analytical conclusions

Mass spectrum		CP-Conserving	CP-Violating
Neutral	h_1^0	Massless - Goldstone boson	
	h_2^0	SM Higgs-like	Light
	h_3^0	Decoupled	
	h_4^0		SM Higgs-like
	h_5^0	Decoupled	Decoupled
	h_6^0		
Singly-charged	H_1^+	Massless - Goldstone boson	
	H_2^+	Decoupled	Electroweak
	H_3^+	Decoupled	Decoupled
Doubly-charged	H_1^{++}	Decoupled	Electroweak
	H_2^{++}	Decoupled	Decoupled

Numerical scan

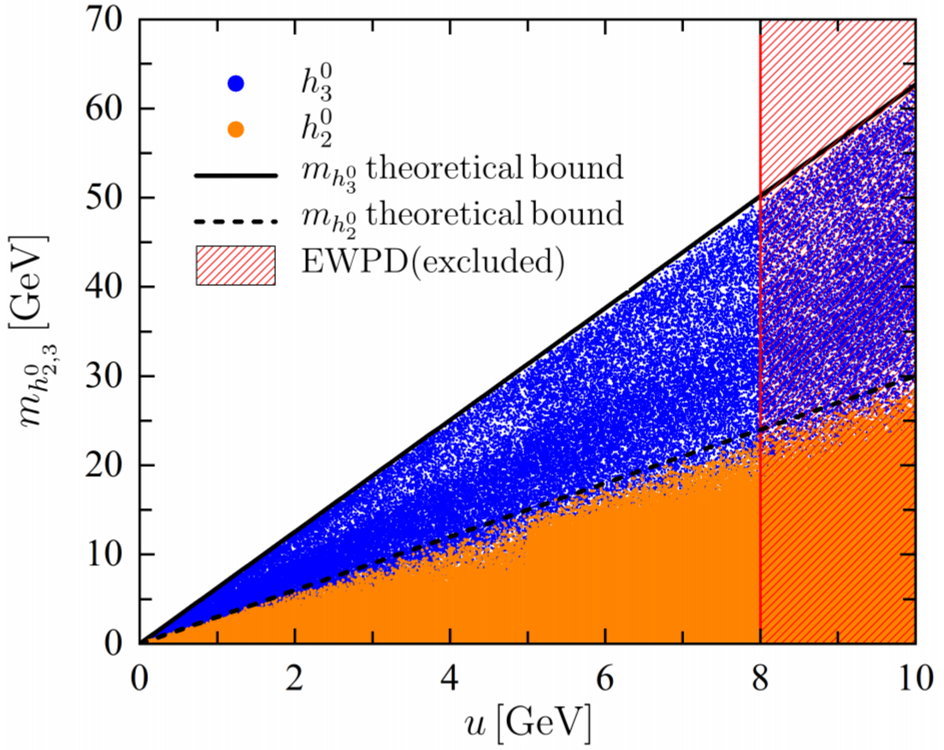


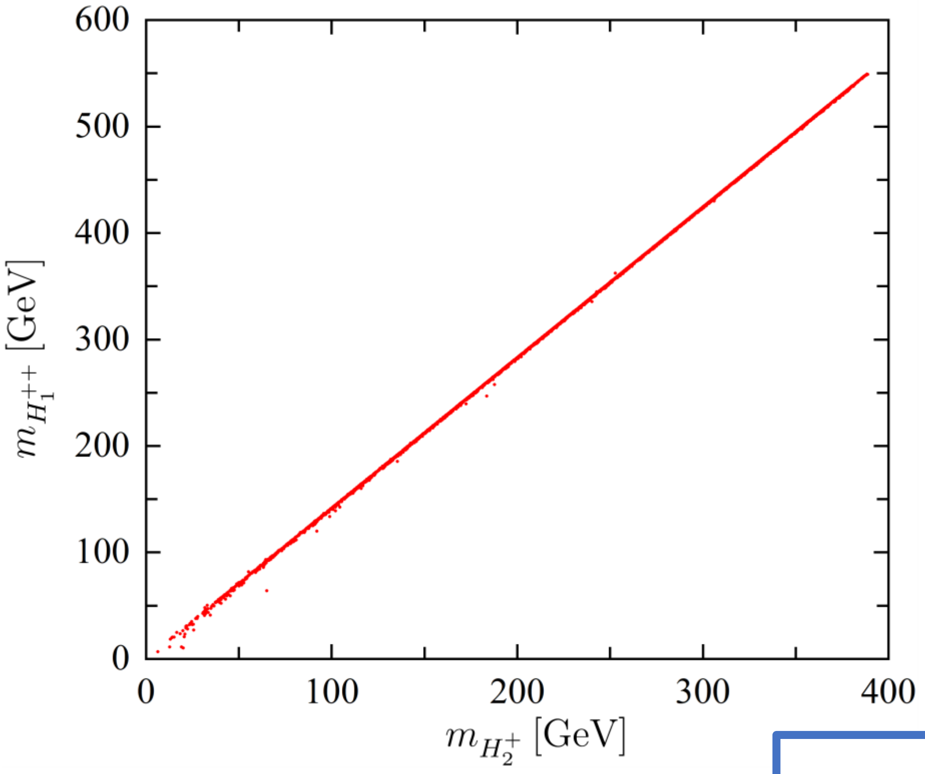


$$m^2_{h^0_{2,3}} \leq \frac{u^2}{2} f(\Lambda, \beta)$$

$$m^2_{H_2^+} \simeq \frac{m^2_{H_1^{++}}}{2}$$

Numerical scan





$$m^2_{h^0_{2,3}} \leq \frac{u^2}{2}\, f(\Lambda, \beta)$$

Analytical results confirmed!

$$m^2_{H_2^+} \simeq \frac{m^2_{H_1^{++}}}{2}$$

Numerical scan

Could such scalars have evaded detection?

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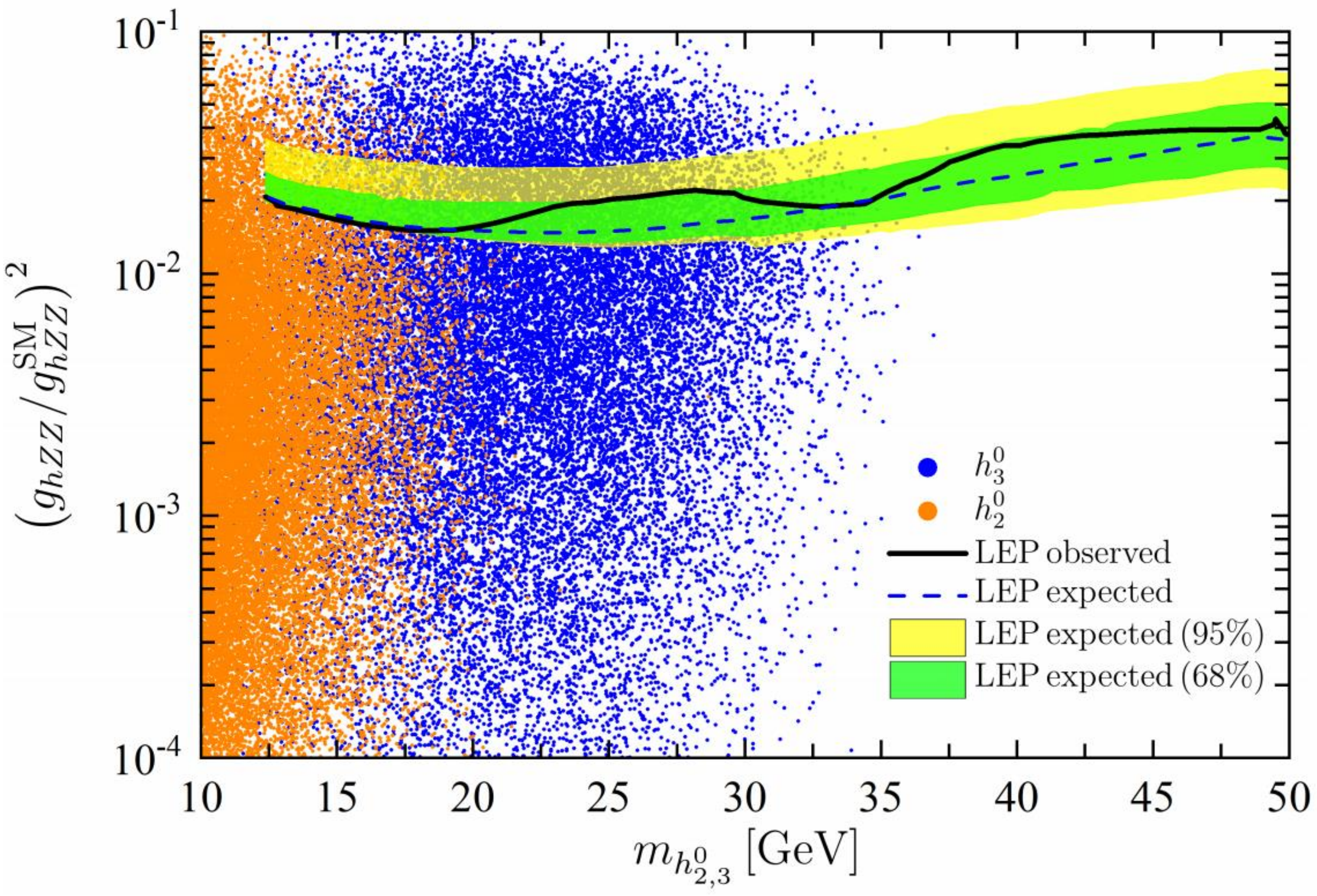
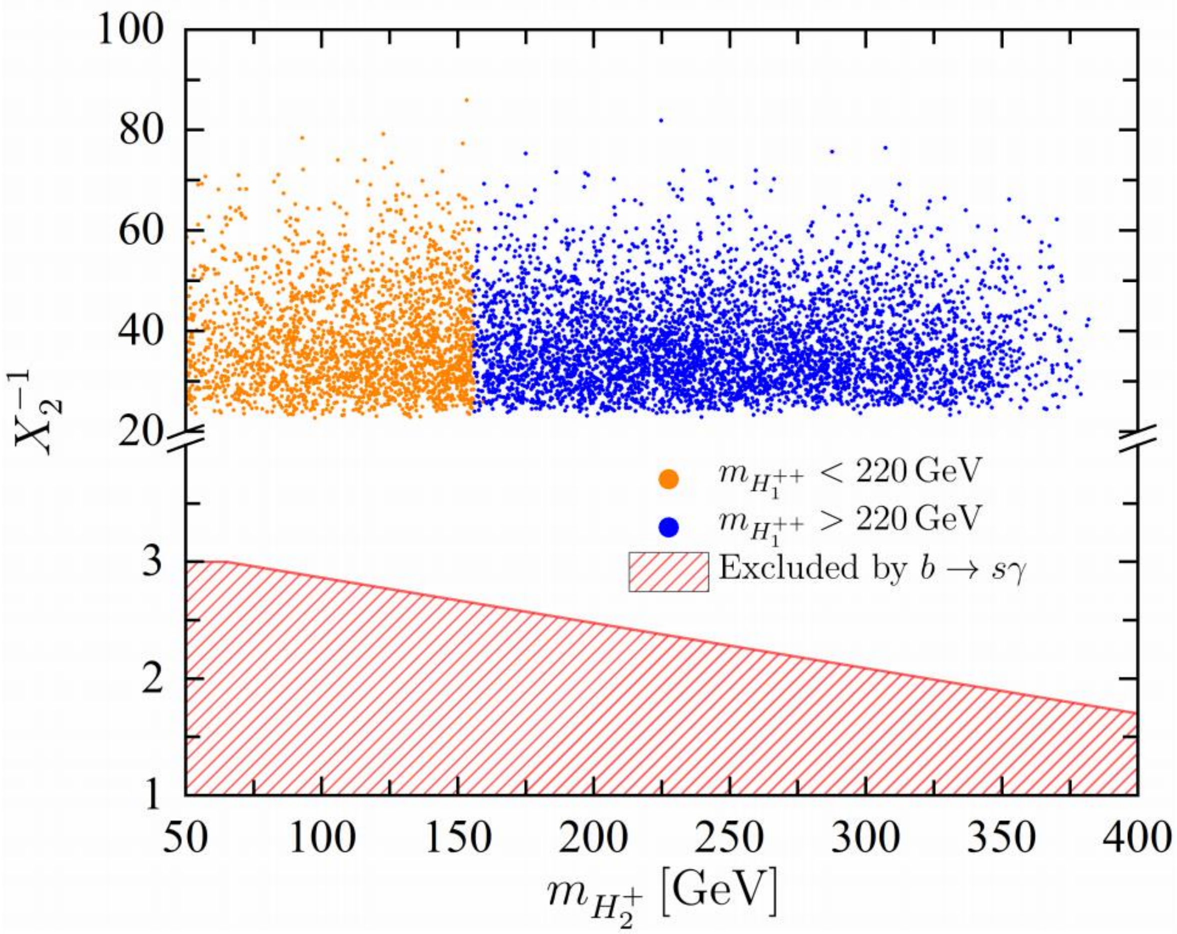


Numerical scan

Could such scalars have evaded detection?



$$\phi^+ = X_1 H_1^+ + X_2 H_2^+ + X_3 H_3^+$$

Some remarks

BUT...

- Lepton-flavour-violation processes can impose a lower bound on the triplet's vev u
- Can one simultaneously explain neutrino masses and leptonic CP violation via SCPV in the 2STM?
- Is this true for any number of triplets?