Beyond Standard Model: From Theory to Experiment (BSM-2021)

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

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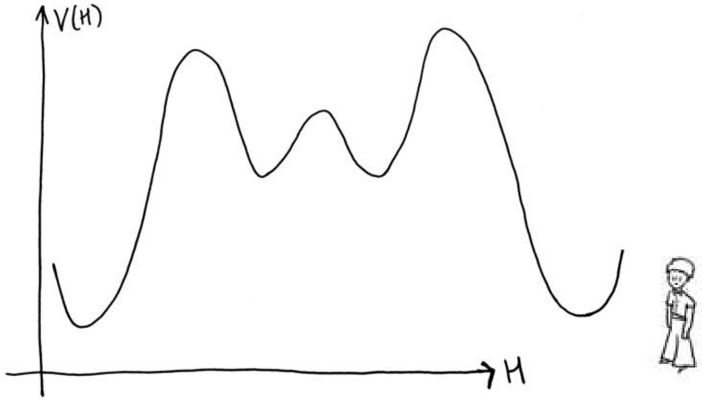

"I showed the grown ups my masterpiece, and I asked them if my drawing scared them."

Fundação para a Ciência e a Tecnologia
TÉCNICO LISBOA
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In collaboration with Pedro M. Ferreira 

Based on: Ferreira, P.M., Gonçalves, B.L. Stability of neutral minima against charge breaking in the Higgs triplet model. *J. High Energ. Phys.* **2020,** 182 (2020). [**arXiv:1911.09746v3 [hep-ph]**]

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The Higgs-triplet model

Beyond SM by expanding its scalar content:

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

The Higgs-triplet model

Beyond SM by expanding its scalar content:

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

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

Beyond SM by expanding its scalar content:

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

MODEL'S MOTIVATION:
- Smallness of neutrino masses (type-II seesaw)
- Dark matter candidates
- Rich phenomenology

The Higgs-triplet model

Beyond SM by expanding its scalar content:

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

DIFFERENT VACUUM POSSIBILITIES:

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

The Higgs-triplet model

Beyond SM by expanding its scalar content:

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

DIFFERENT VACUUM POSSIBILITIES:

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

The Higgs-triplet model

Beyond SM by expanding its scalar content:

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

DIFFERENT VACUUM POSSIBILITIES:

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

Vacua which spontaneously break the electromagnetic symmetry are possible, but clearly **not desirable**!
And the stability of neutral vacua is not guaranteed *a priori*!

The Higgs-triplet model

Beyond SM by expanding its scalar content:

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

DIFFERENT VACUUM POSSIBILITIES:

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

Is it possible to check *analytically* the stability of neutral minima against charge breaking?

The scalar potential

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

Most general gauge invariant scalar potential:

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

Necessary and sufficient bounded-from-below conditions:

$$\lambda_1 > 0\,, \qquad \lambda_2 + \min\left(\lambda_3\,,\, \frac{1}{2}\lambda_3\right) > 0\,,$$
$$\lambda_4 + \min(0\,,\, \lambda_5) + 2\min\left[\sqrt{\lambda_1(\lambda_2+\lambda_3)}\,,\, \sqrt{\lambda_1(\lambda_2+\lambda_3/2)}\right] > 0$$

A. Arhrib *et al.*, The Higgs Potential in the Type II Seesaw Model, Phys. Rev. D 84 (2011) 095005

The scalar potential

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Soft-breaking term

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

The scalar potential

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

Most general gauge invariant scalar potential:

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$$+\lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\mathrm{Tr}\left[(\Delta^\dagger\Delta)^2\right] + \lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi$$

→ Potential **without** soft-breaking term $\mu = 0$ Allows for dark matter particles

→ Potential **with** soft-breaking term $\mu \neq 0$ Helps generate neutrino masses

Normal vacua

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)

Normal vacua

Three possibilities for neutral vacua

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

Neutral minima of greater interest for the **softly broken potential**

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

Neutral minima of greater interest for the **non-softly broken potential**

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

Unphysical neutral minima

Charge-breaking vacua

Six different possibilities

$c_1 \neq 0$ → The doublet can be reduced to a neutral, real component

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

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

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

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

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

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

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

Charged triplet components

Without soft-breaking term

$c_1 \neq 0$

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

G.C. Branco, P.M. Ferreira, L. Lavoura, M.N. Rebelo, M. Sher and J.P. Silva, Theory and phenomenology of two-Higgs-doublet models, Phys. Rept. 516 (2012) 1 and references therein

Without soft-breaking term

$c_1 \neq 0$

Stability of minima of type N2 against charge breaking

Neutral minima of greater interest for the **non-softly broken potential**

$$V_{CB1} - V_{N2} = \frac{1}{4}\left(c_2^2 m_{H,A}^2 + c_3^2 m_+^2\right)$$
$$V_{CB2} - V_{N2} = \frac{1}{4}\left(c_2^2\, m_{H,A}^2 + c_3^2\, m_{++}^2\right)$$
$$V_{CB3} - V_{N2} = \frac{1}{4}\left(c_2^2\, m_{H,A}^2 + c_3^2\, m_+^2 + c_4^2\, m_{++}^2\right)$$
$$V_{CB4} - V_{N2} = \frac{1}{4}\, c_2^2\, m_+^2$$
$$V_{CB5} - V_{N2} = \frac{1}{4}\left(c_2^2\, m_+^2 + c_3^2\, m_{++}^2\right)$$
$$V_{CB6} - V_{N2} = \frac{1}{4}\, c_2^2\, m_{++}^2$$

- When N2 is a minimum on always obtains $V_{CBi} - V_{N2} > 0$
- This conclusion holds even if one considers complex charge breaking vevs
- The stability of N2 against charge breaking is guaranteed

Without soft-breaking term

$c_1 \neq 0$

Stability of minima of type N1 against charge breaking

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

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

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

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

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

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

Without soft-breaking term

$c_1 \neq 0$

Stability of minima of type N1 against charge breaking

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

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

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

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Without soft-breaking term

$c_1 \neq 0$

Stability of minima of type N1 against charge breaking

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

- The simultaneous occurrence of both N1 and CB3 extrema is only possible if $\lambda_3 = \lambda_5 = 0$, which implies $m_{++}^2 = m_+^2 = 0$
- Without these terms in the potential, it becomes possible to perform two independent SU(2) transformations on the doublet and triplet, and thus “rotate away" the charge breaking vevs of the triplet, transforming a seeming CB3 vacuum into the N1 one

Without soft-breaking term

$c_1 \neq 0$

Stability of minima of type N1 against charge breaking

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

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- Without these terms in the potential, it becomes possible to perform two independent SU(2) transformations on the doublet and triplet, and thus “rotate away" the charge breaking vevs of the triplet, transforming a seeming CB3 vacuum into the N1 one

- N1 minima is stable against all CB minima

With soft-breaking term

$c_1 \neq 0$

Stability of minima of type N1 against charge breaking

Neutral minima of greater interest for the **softly broken potential**

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

- If one takes the limit $\mu \to 0$ in this expression (equivalent to making $m_A = 0$) one recovers the non-soft breaking expression

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

With soft-breaking term

$c_1 \neq 0$

Stability of minima of type N1 against charge breaking

Neutral minima of greater interest for the **softly broken potential**

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

- If one takes the limit $\mu \to 0$ in this expression (equivalent to making $m_A = 0$) one recovers the non-soft breaking expression
- Unlike the $\mu = 0$ case, however, now even if $N1$ is a minimum, rendering both m_A^2 and m_+^2 positive, it is no longer guaranteed that $V_{CB1} - V_{N1} > 0$

With soft-breaking term

$c_1 \neq 0$

Stability of minima of type N1 against charge breaking

Neutral minima of greater interest for the **softly broken potential**

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

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

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

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

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

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

Stability against charge breaking

$c_1 \neq 0$

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

- The stability of N2 and N1 against charge breaking seems to be guaranteed

- “Turning on" the soft breaking term in the potential weakens the stability of neutral minima against charge breaking

The case of the vevless doublet

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

$\boxed{c_1 = 0}$ disconnected solution from $c_1 \neq 0$

Charge-breaking vacua

$c_1 = 0$

Six new possibilities

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

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

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

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

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

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

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 $V_{CB11} - V_{N1}$

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 $V_{CB11} - V_{N1}$

Stability against charge breaking

$c_1 = 0$

CB minima $c_1 = 0$

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

- Neutral minima were seemingly CB-stable without soft breaking, but in fact deeper CB vacua with vevless doublet are possible

- For the softly-broken model we had already identied CB vacuum configurations for which deeper CB minima could coexist with neutral ones

Numerical analysis without soft-breaking

- N2 minima stable against N1 minima type
- **N2 not necessarily stable against CB with vevless doublet**

$$V_{N1} - V_{N2} = \frac{1}{4} v_2^2 \, m_{H,A}^2$$

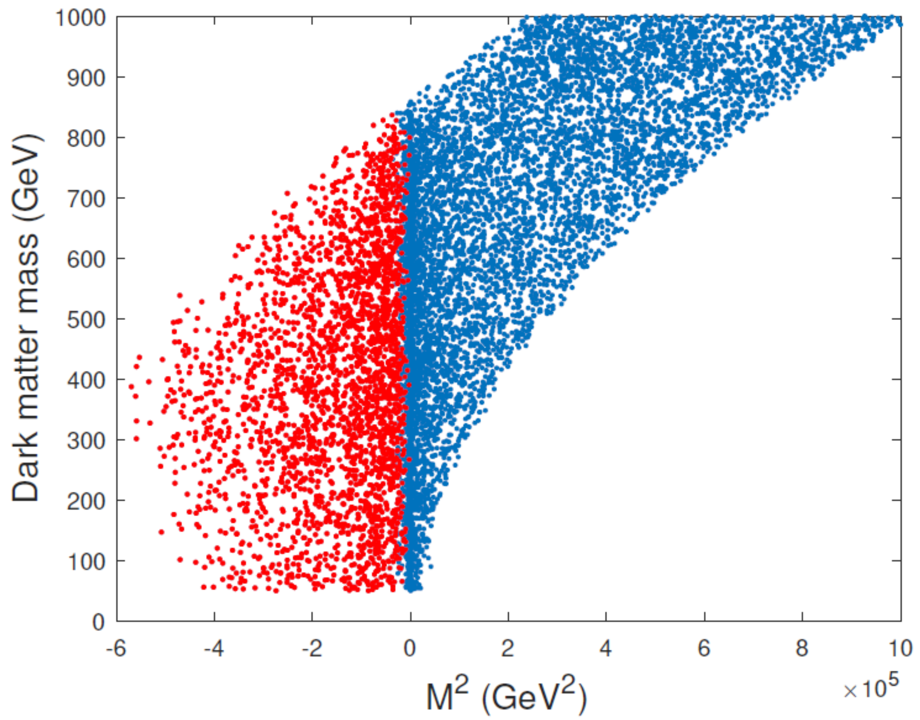


Figure 1. Values of the dark matter particle mass as a function of the quadratic coupling M^2 for a minimum of type $N2$. In blue, all the scanned points; in red, those points for which there exists a CB vacuum (of types $CB7$ or $CB10$) lower than $N2$.

We have identified the most likely CB vacua as the vev combinations we dubbed CB7 and CB10

Numerical analysis without soft-breaking

- N2 minima stable against N1 minima type
- **N2 not necessarily stable against CB with vevless doublet**

$$V_{N1} - V_{N2} = \frac{1}{4} v_2^2 m_{H,A}^2$$

It can be shown analytically that

An $N2$ 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 analysis with soft-breaking

- N2 is not a possible vacuum configuration
- **With a minimum of type N1, there are several possible deeper CB vacua**

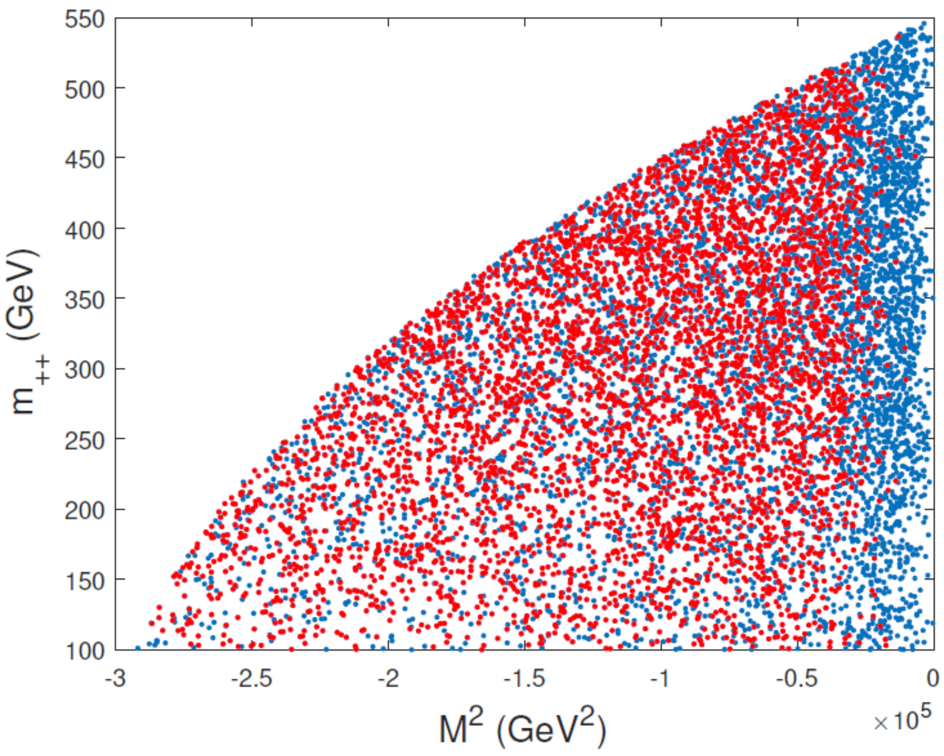
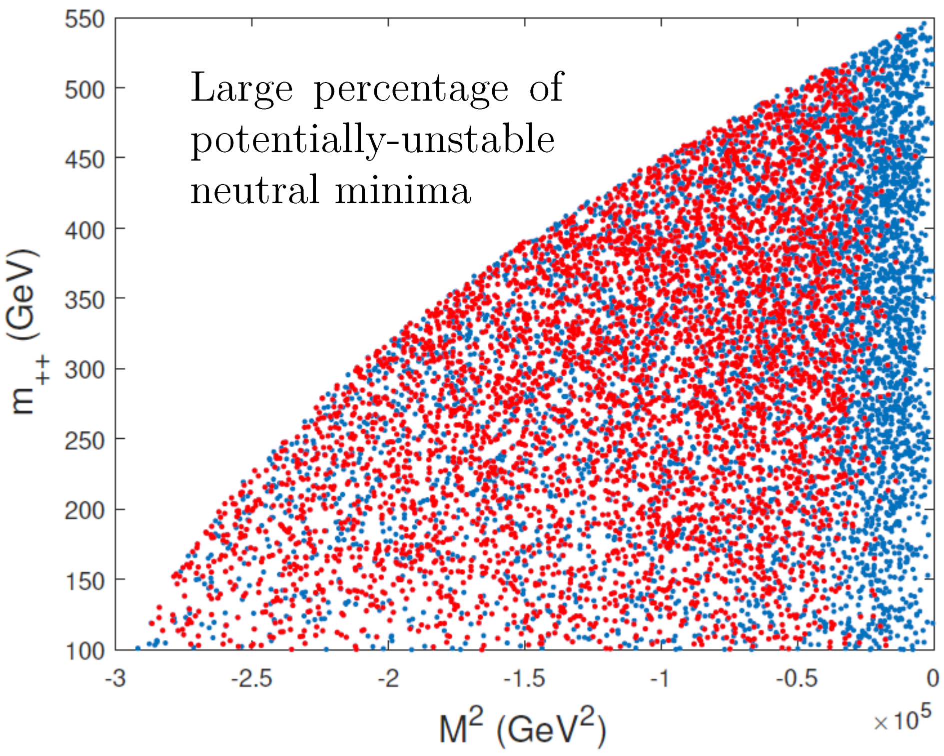


Figure 2. Values of the doubly charged scalar mass a function of the quadratic coupling M^2 for a minimum of type $N1$ in an HTM with softly broken global symmetry. In blue, all the scanned points; in red, those points for which there exists a CB vacuum (of types $CB7$ or $CB10$) lower than $N1$.

Numerical analysis with soft-breaking

- N2 is not a possible vacuum configuration
- **With a minimum of type N1, there are several possible deeper CB vacua**



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Concluding remarks

- Deep analysis of the stability of neutral minima in the Higgs Triplet Model against the possibility of deeper charge breaking minima developing

- We have obtained completely general analytical expressions relating the difference in the depths of the potential at neutral and CB extrema with or without the soft-breaking term, and with or without a vev for the doublet

- 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

- Without the soft-breaking term:

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

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

Thank you!