CORFU SUMMER INSTITUTE

21ST HELLENIC SCHOOL AND WORKSHOPS ON ELEMENTARY PARTICLE PHYSICS AND GRAVITY
CORFU, GREECE 2021

Workshop on the Standard Model and Beyond

Some reflexions on hidden features of SM extensions with scalar triplets

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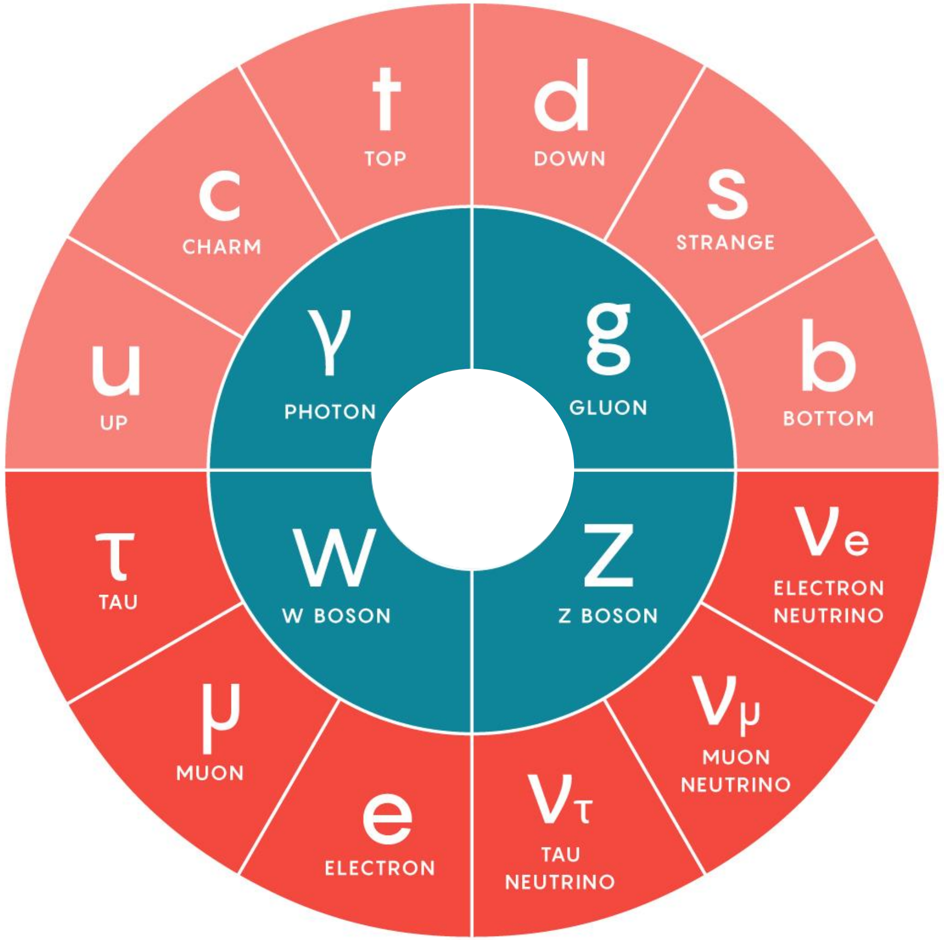
1st September, 2021

The Standard Model of Particle Physics

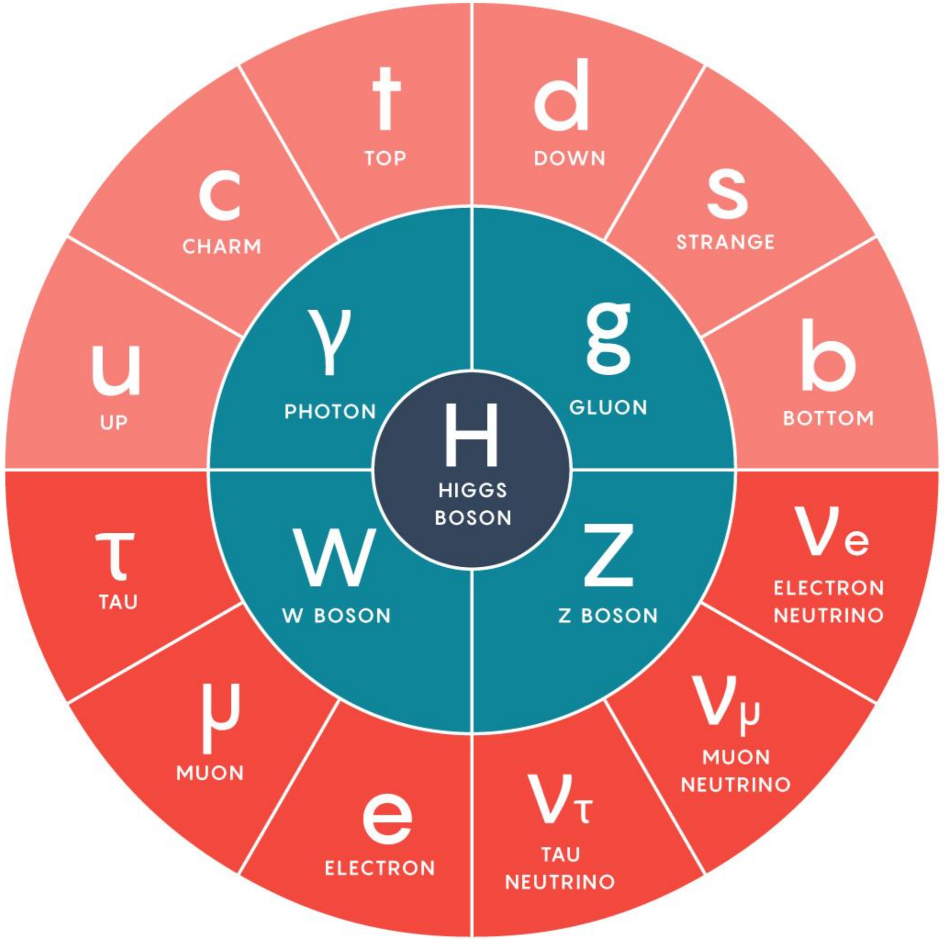
On the 4th July of 2012...

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

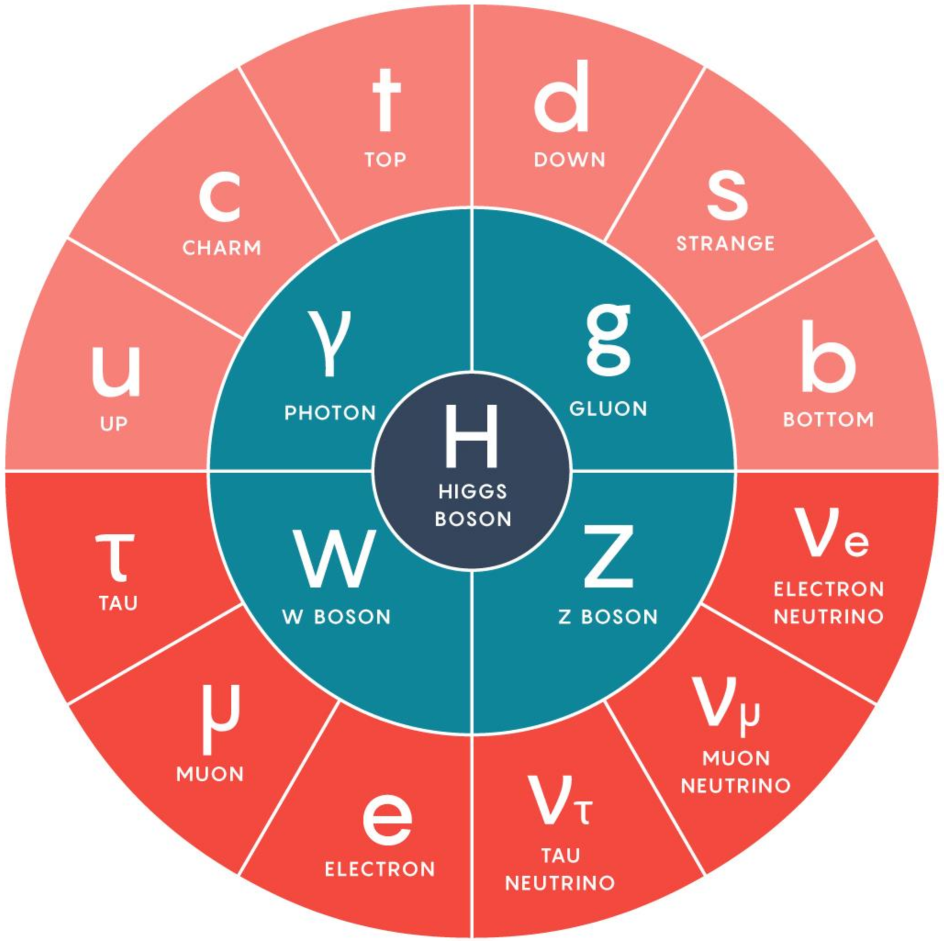
The Standard Model of Particle Physics



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

Multi-Higgs scenario	Higgs-triplet model (HTM)	Two-scalar-triplet model (2STM)
Motivation		
Problem		

Beyond the Standard Model

Scalar triplet extensions of the Standard Model

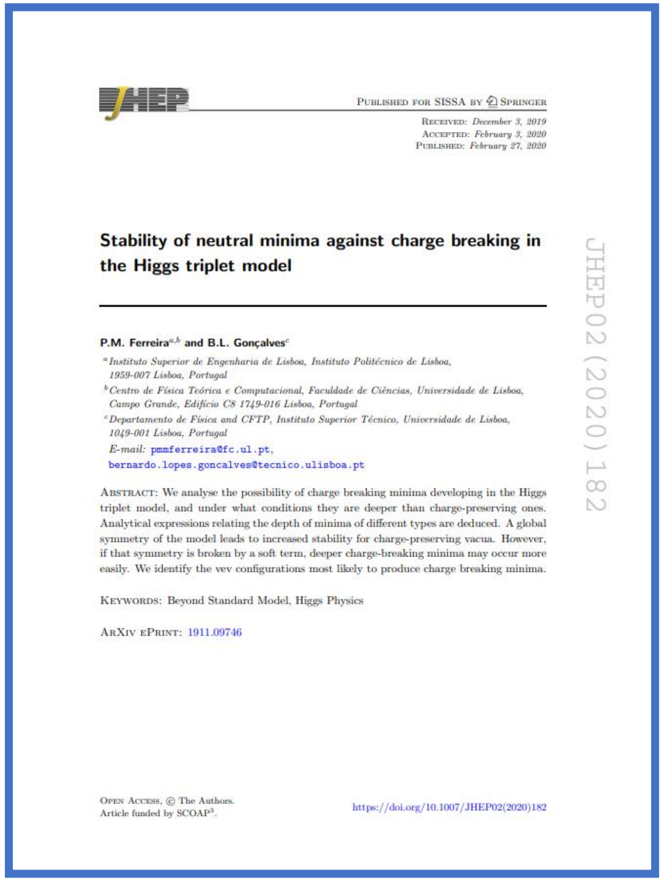
	Higgs-triplet model (HTM)	Two-scalar-triplet model (2STM)
Multi-Higgs scenario	Higgs-triplet model (HTM)	Two-scalar-triplet model (2STM)
Motivation	Neutrino masses in type-II seesaw mechanism	
Problem	Are neutral minima stable against charge breaking?	

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

ARXIV EPRINT: 1911.09746

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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**

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

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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**

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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

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

$$V = m^2\Phi^\dagger\Phi + M^2\mathrm{Tr}(\Delta^\dagger\Delta) + \mu\left(\Phi^T i\tau_2\Delta^\dagger\Phi + \mathrm{h.c.}\right)$$

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

- 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

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

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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

Example

$c_1 \neq 0$

Stability of minima of type N1 against CB1

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

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$\mu = 0$

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

Example

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$\mu = 0$

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Squared mass calculated in minima of type N1

Example

$c_1 \neq 0$

Stability of minima of type N1 against CB1

$$\langle\Phi\rangle_{N1} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_\Phi \end{pmatrix}, \qquad \langle\Delta\rangle_{N1} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ v_\Delta & 0 \end{pmatrix} \qquad \langle\Phi\rangle_{CB1} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ c_1 \end{pmatrix}, \qquad \langle\Delta\rangle_{CB1} = \frac{1}{\sqrt{2}}\begin{pmatrix} -c_3/\sqrt{2} & 0 \\ c_2 & c_3/\sqrt{2} \end{pmatrix}$$

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Squared mass calculated in minima of type N1

STABILITY GUARANTEED

When *N1* is a minimum one always obtains $V_{CB1} - V_{N1} > 0$

Example

$c_1 \neq 0$

Stability of minima of type N1 against CB1

$$\langle\Phi\rangle_{N1} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_\Phi \end{pmatrix}, \qquad \langle\Delta\rangle_{N1} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ v_\Delta & 0 \end{pmatrix} \qquad \langle\Phi\rangle_{CB1} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ c_1 \end{pmatrix}, \qquad \langle\Delta\rangle_{CB1} = \frac{1}{\sqrt{2}}\begin{pmatrix} -c_3/\sqrt{2} & 0 \\ c_2 & c_3/\sqrt{2} \end{pmatrix}$$

$\mu \neq 0$

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

Example

$c_1 \neq 0$

Stability of minima of type N1 against CB1

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

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Example

$c_1 \neq 0$

Stability of minima of type N1 against CB1

$$\langle \Phi \rangle_{N1} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_\Phi \end{pmatrix}, \qquad \langle \Delta \rangle_{N1} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_\Delta & 0 \end{pmatrix} \qquad \langle \Phi \rangle_{CB1} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ c_1 \end{pmatrix}, \qquad \langle \Delta \rangle_{CB1} = \frac{1}{\sqrt{2}} \begin{pmatrix} -c_3/\sqrt{2} & 0 \\ c_2 & c_3/\sqrt{2} \end{pmatrix}$$

$\mu \neq 0$

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

Even if *N1* is a minimum it is not guaranteed that $V_{CB1} - V_{N1} > 0$

STABILITY NOT GUARANTEED

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 $\boxed{c_1 = 0}$

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

$\boxed{c_1 = 0}$ 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

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

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

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

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

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

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

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

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

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

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

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

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

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

Again performing a **bilinear formalism**...

Full analytical conclusions

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**

CB minima $c_1 = 0$

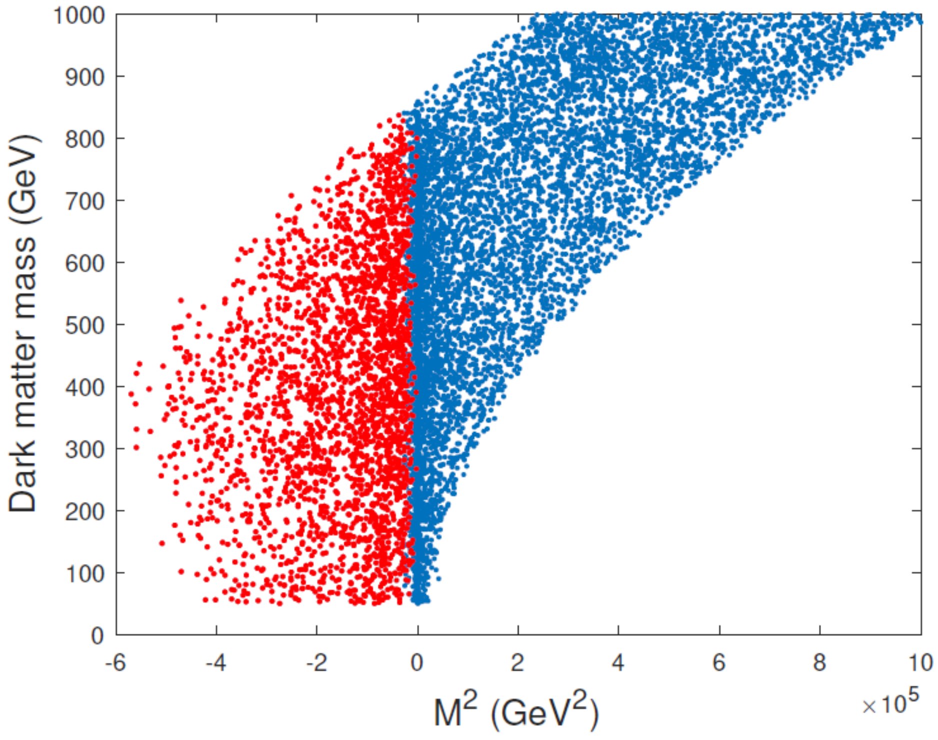
	$\boldsymbol{\mu = 0}$	$\boldsymbol{\mu \neq 0}$
N2 minima	**STABILITY NOT GUARANTEED**	DOES NOT OCCUR
N1 minima	**STABILITY NOT GUARANTEED**	**STABILITY NOT GUARANTEED**

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

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

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



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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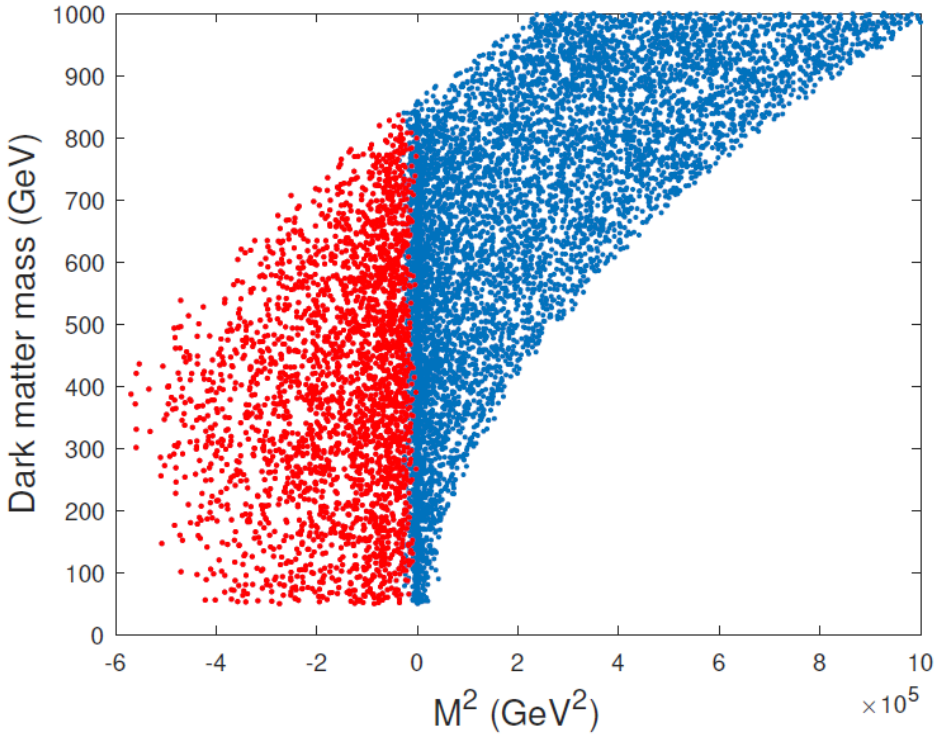

It can be shown analytically that

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 scan without soft-breaking

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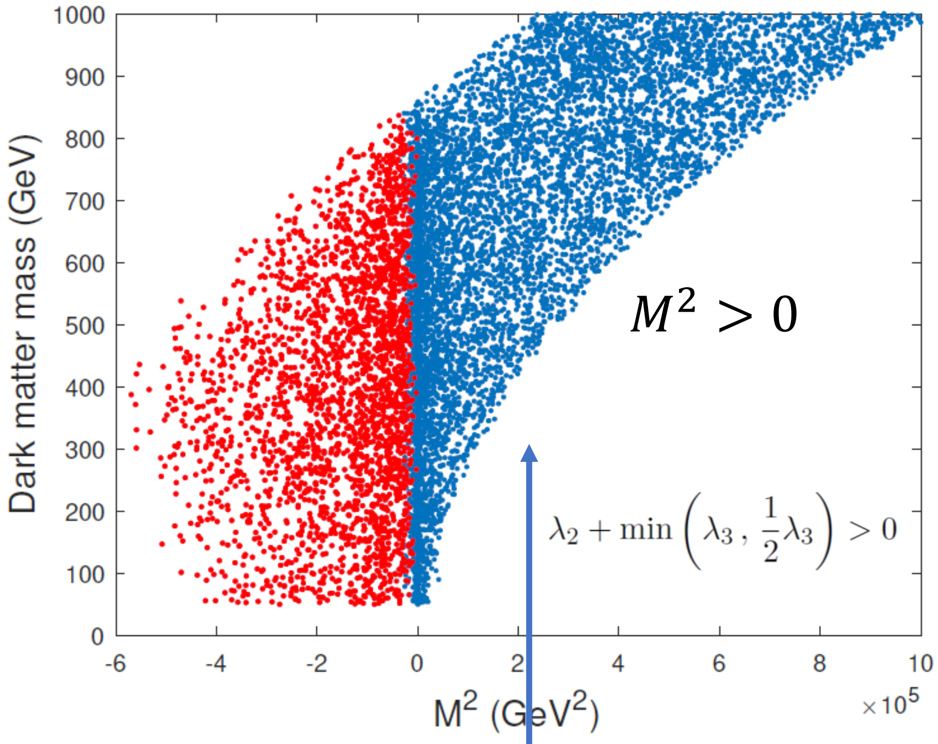
- We have identified the most likely CB vacua as the vev combinations we dubbed CB7 and CB10

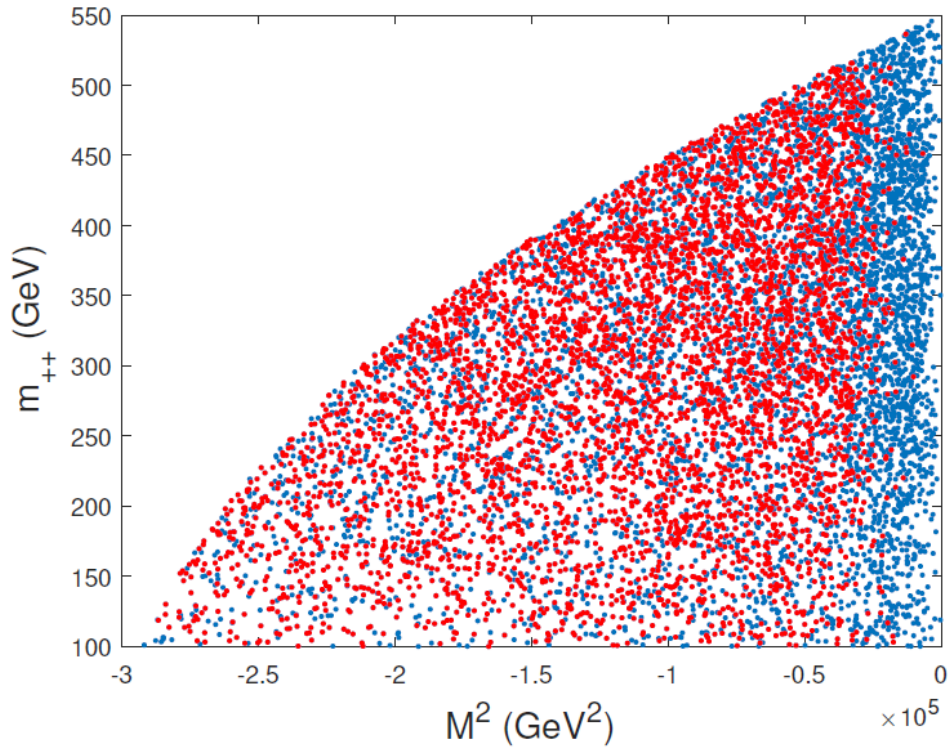


It can be shown analytically that

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 scan with soft-breaking

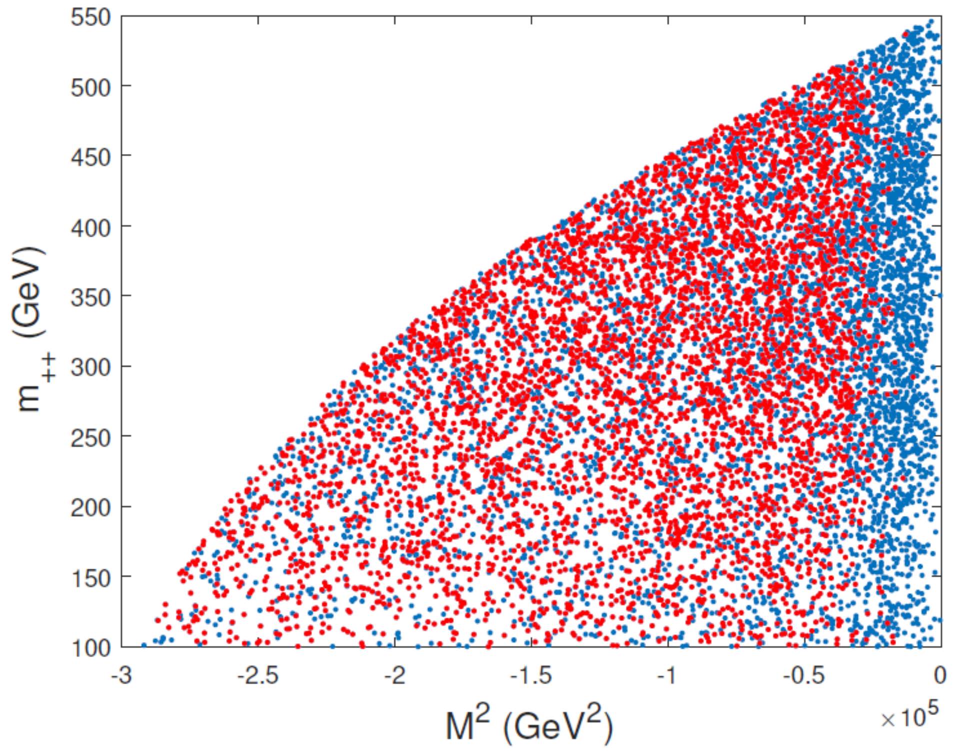
- N2 minima is not possible to occur
- **With a minimum of type N1, there are several possible deeper CB vacua**
- Large percentage of potentially-unstable neutral minima



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

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



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

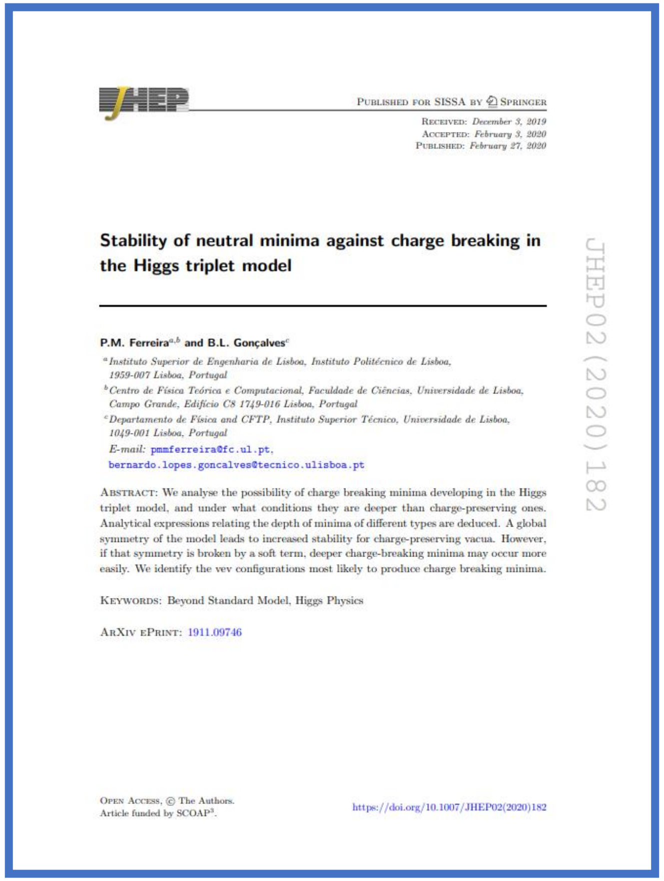
Beyond the Standard Model

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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[c] *Departamento de Física and CFTP, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal*
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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)

Beyond the Standard Model

Scalar triplet extensions of the Standard Model

Multi-Higgs scenario

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?

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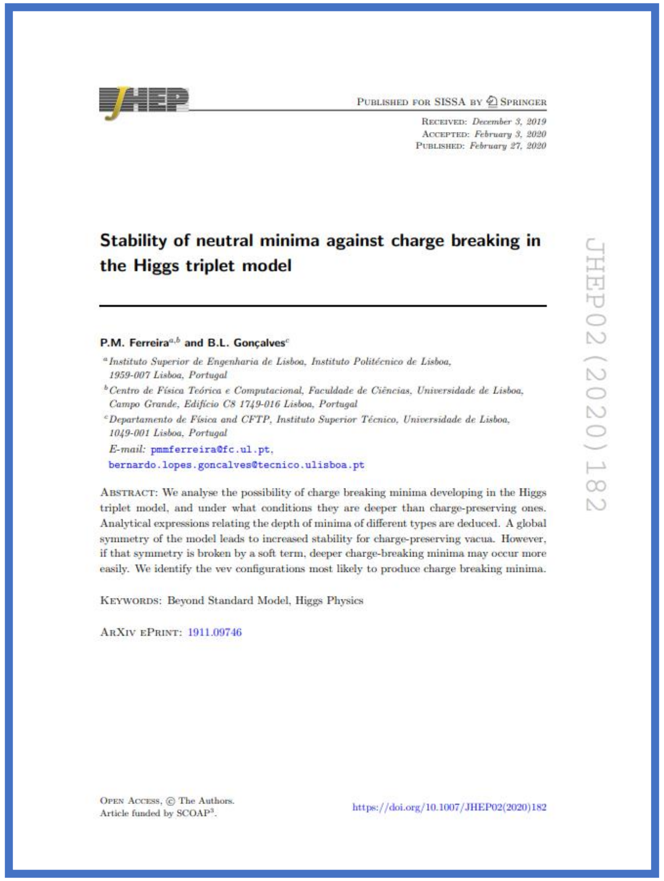
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Two-scalar-triplet model (2STM)

Minimal triplet extension in which spontane... s CP

OUT SOON

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

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Spontaneous CP violation in scalar-triplet models

In the two-scalar-triplet model:

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

$$V = V_{\mathrm{U(1)}} + V_{\mathrm{SB}}$$

U(1)-symmetric

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

$$\Delta_{1,2} \to e^{i\alpha_{1,2}}\Delta_{1,2}$$

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

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

Softly-breaking terms

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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$$\theta_1 \neq \theta_2$$

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

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

Spontaneous CP violation in scalar-triplet models

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SCPV IS POSSIBLE

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SCPV IS POSSIBLE

CP violation can be communicated to the fermion sector

Spontaneous CP violation in scalar-triplet models

In the two-scalar-triplet model:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad + \quad \Delta_{1,2} = \ldots$$

BUT WHAT ABOUT THE SCALAR MASS SPECTRUM?

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

$$\theta_1 \neq \theta_2$$

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

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**

Scalar mass spectrum

CP-conserving scenario

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

Scalar mass spectrum

CP-conserving scenario

- Two Goldstone bosons
- One Higgs-like particle
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CP-violating scenario

- Two Goldstone bosons

...

- One Higgs-like particle

...

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

$|u| < 8$ GeV

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$\Lambda_i \longrightarrow$ combinations of quartic couplings

$|u| < 8$ GeV

- Two Goldstone bosons
- Two light neutral scalars
- One Higgs-like particle

…

CP-violating case

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

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- Two Goldstone bosons
- Two light neutral scalars
- One Higgs-like particle
- Two charged particles at the electroweak scale

...

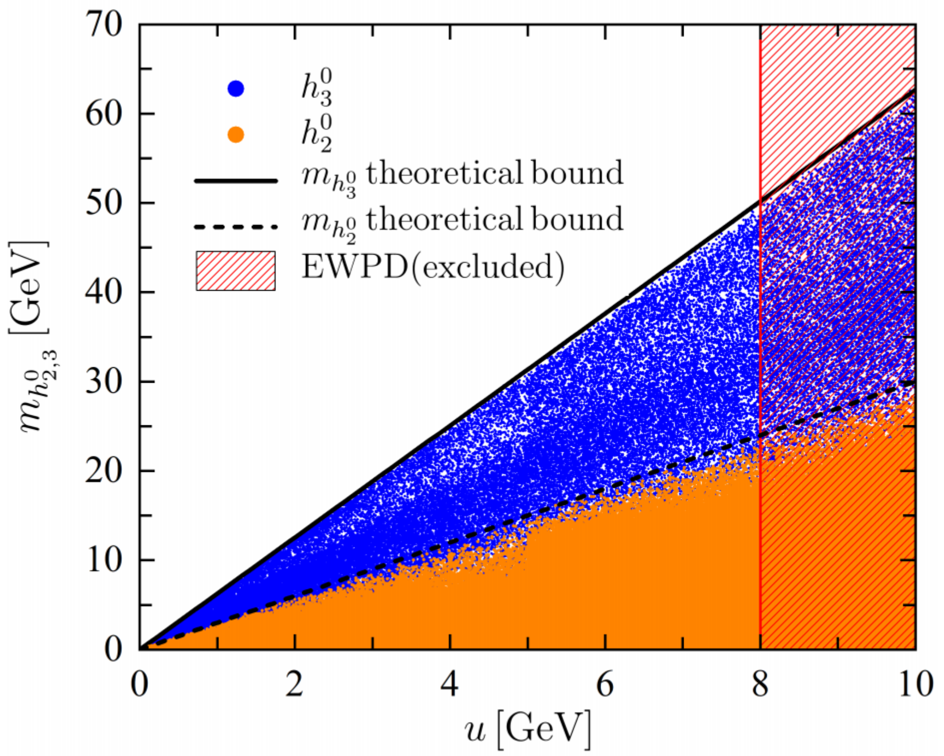
CP-violating case

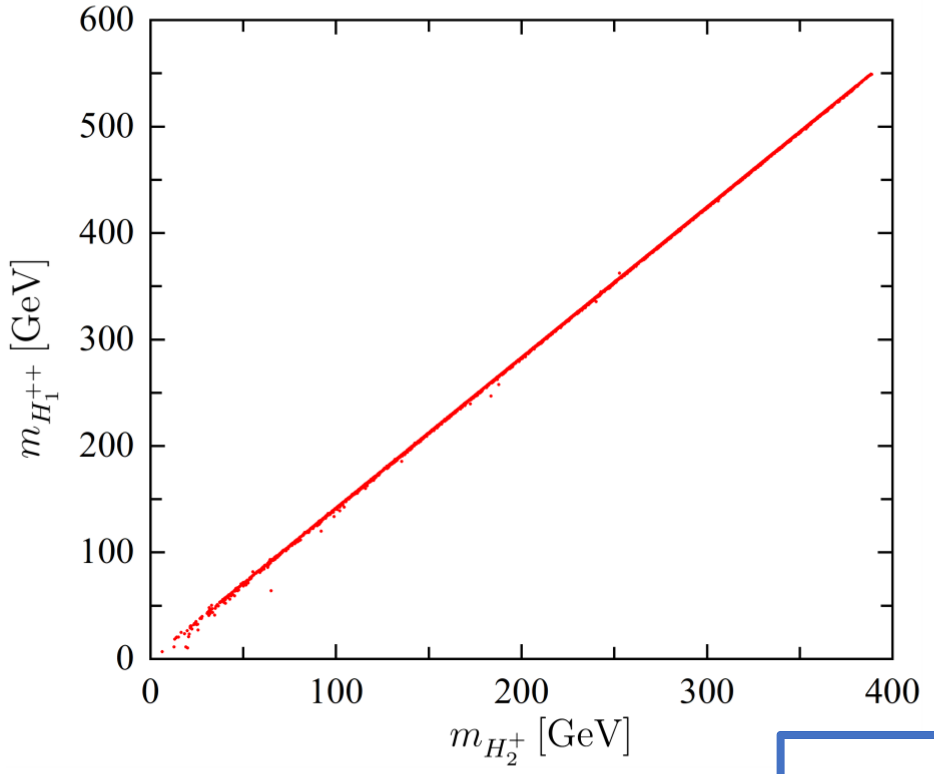
- Two Goldstone bosons
- Two light neutral scalars
- One Higgs-like particle
- Two charged particles at the electroweak scale
- All the remaining particles decouple

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

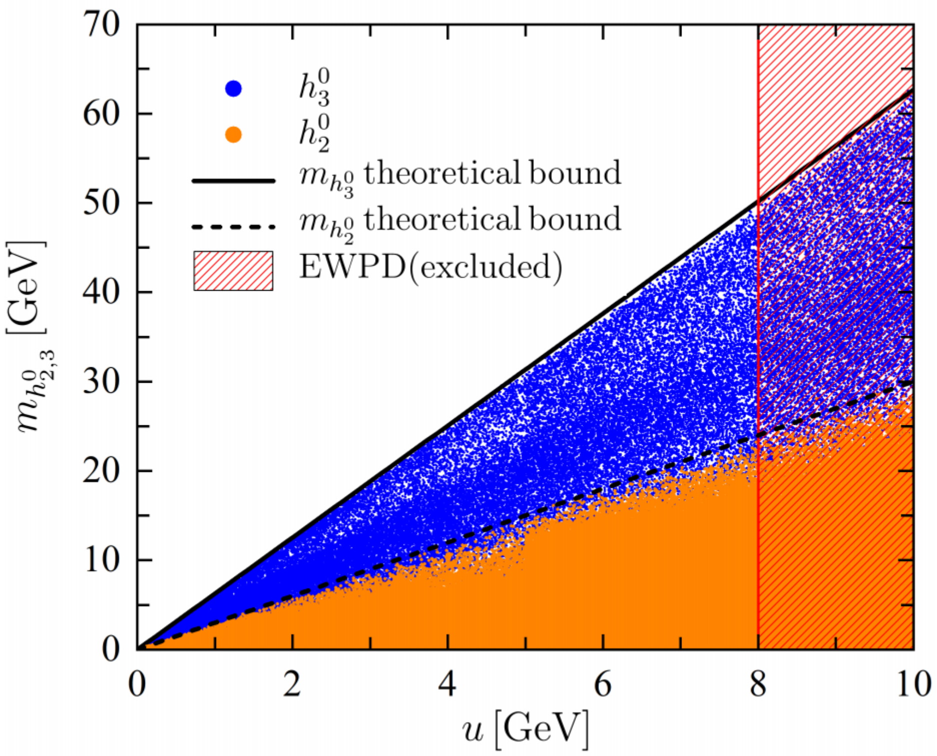


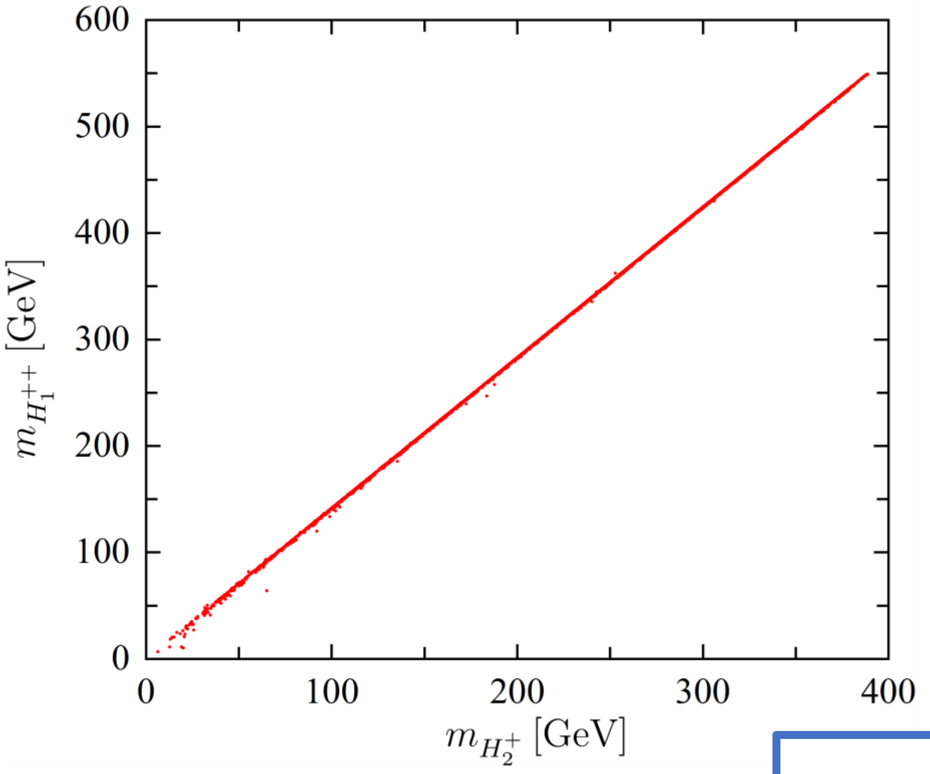


$$m^2_{h^0_{2,3}} \leq \frac{u^2}{2} f(\Lambda, \beta)$$

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

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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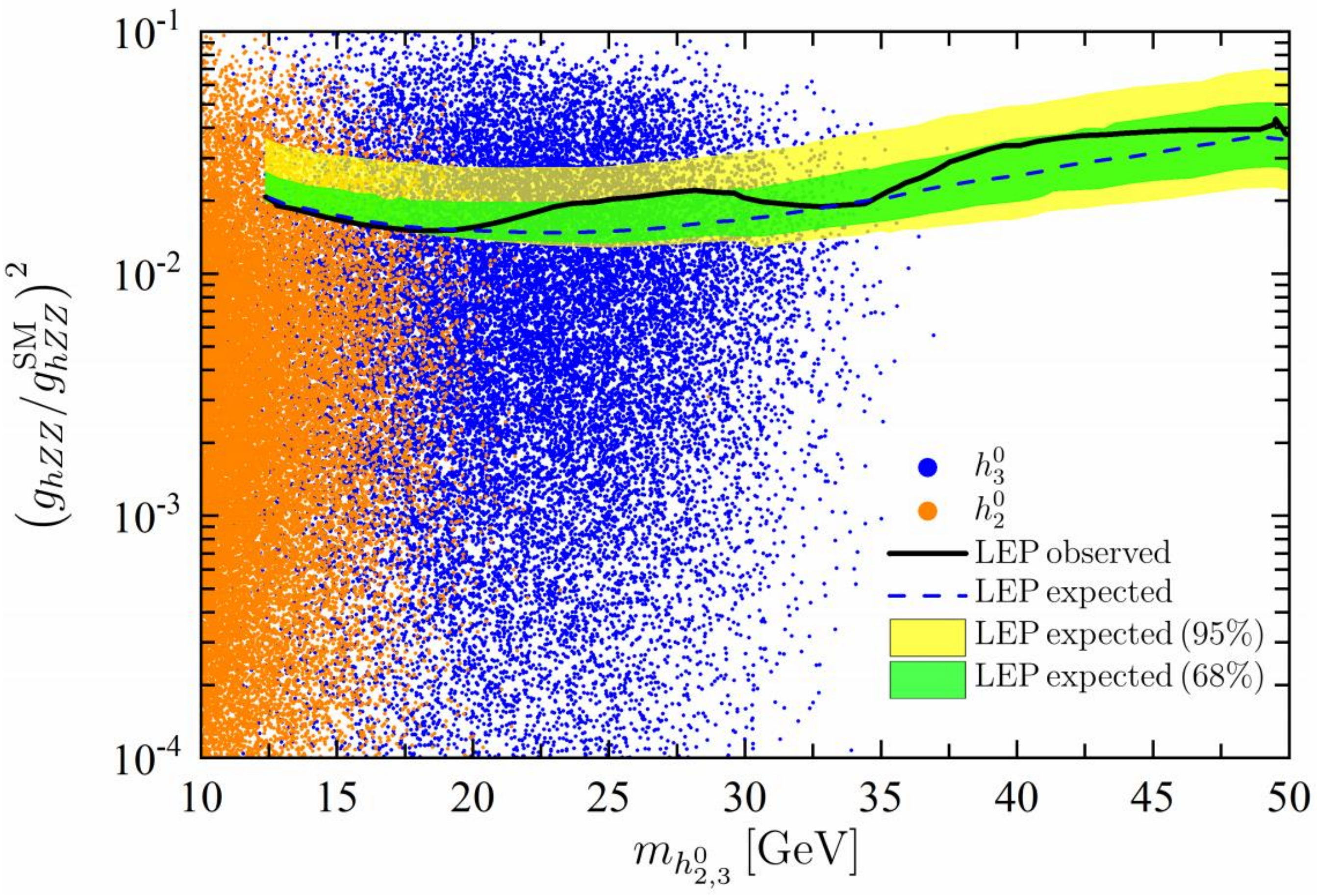

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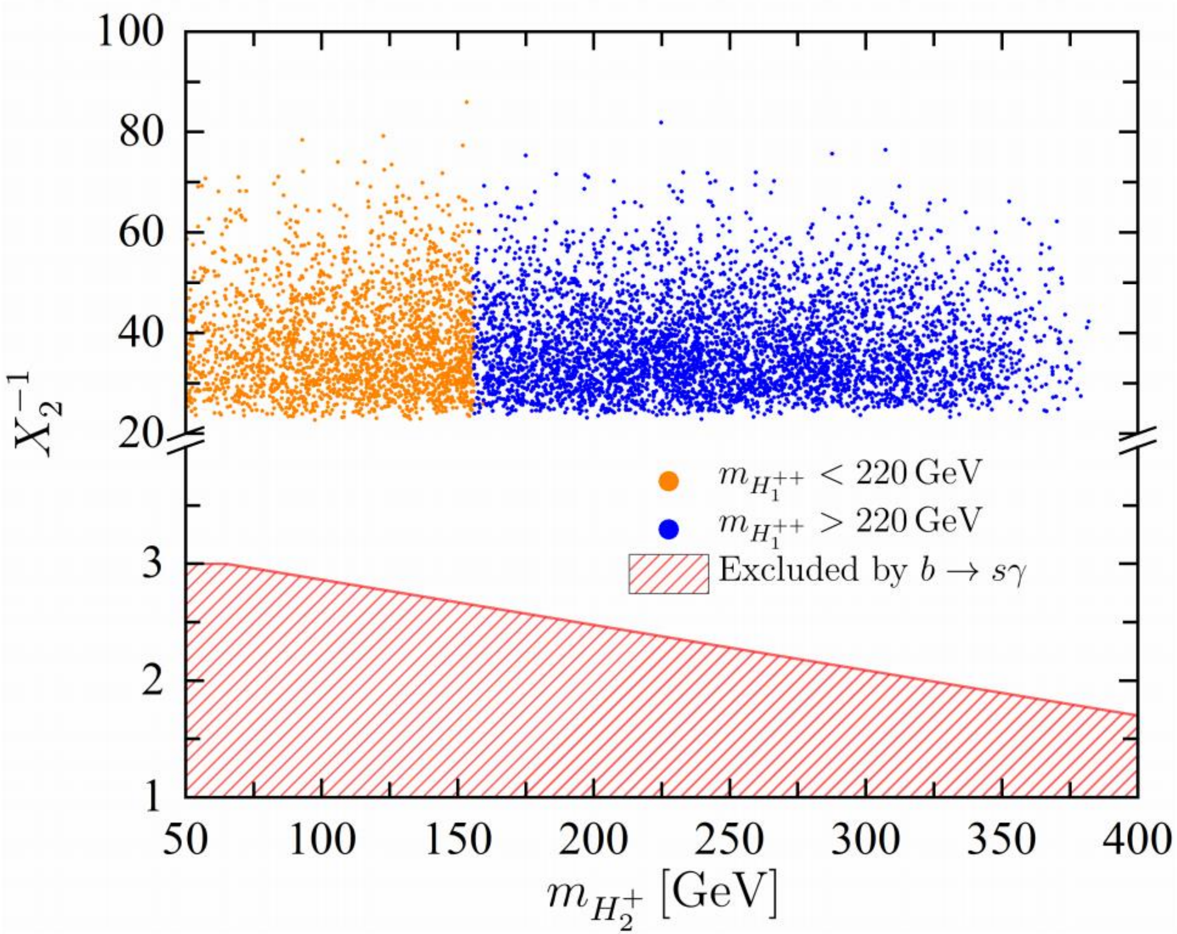

$$\phi^+ = X_1 H_1^+ + X_2 H_2^+ + X_3 H_3^+$$

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?

Conclusions

Scalar triplet extensions of the Standard Model

Multi-Higgs scenario	Higgs-triplet model (HTM)	Two-scalar-triplet model (2STM)
Problem	Are neutral minima stable against charge breaking?	Do we have decoupling in the scalar mass spectrum?

Projects: UIDB/00777/2020, UIDP/00777/2020, UIDB/00618/2020, CERN/FISPAR/0004/2019, CERN/FISPAR/0014/2019
PhD Grant: SFRH/BD/139165/2018

Conclusions

Scalar triplet extensions of the Standard Model

Multi-Higgs scenario	Higgs-triplet model (HTM)	Two-scalar-triplet model (2STM)
Main take-home message	CB global minima can indeed coexist with neutral minima	When SCPV occurs, the 2STM has no decoupling limit

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