Avoiding Death by Vacuum

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A. Barroso, P.F. , I. Ivanov, R. Santos, J.P. Silva, arXiv:1211.6119

- **LHC hints of the presence of a scalar particle with mass ~125 GeV.**

- **Up to now, all is compatible with the Standard Model (SM) Higgs particle.**

BORING!

Two-Higgs Dublet model, 2HDM (Lee, 1973) : one of the easiest extensions of the SM, with a richer scalar sector. Can help explain the matter-antimatter asymmetry of the universe, provide dark matter candidates, …

G.C. Branco, P.M. Ferreira, L. Lavoura, M. Rebelo, R. Santos, M. Sher, J.P Silva, Physics Reports 716, 1 (2012)

Scalar sector of the 2HDM

Two dublets => **4 neutral scalars (h, H, A) + 1 charged scalar ($H^{\pm}$).**

h

H

} **CP-even scalars**

h, H → γ γ
h, H → ZZ, WW (real or off-shell)
h, H → ff
H → hh (if $m_H > 2m_h$)
…

A - **CP-odd scalar**
(pseudoscalar)

A→ γ γ
~~**A→ ZZ, WW**~~
A→ ff
…

Vaccuum structure more rich => different types of minima possible!

The NORMAL minimum,

$$\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \quad \text{e} \quad \langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

The CHARGE BREAKING (CB) minimum, with

$$\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ v'_1 \end{pmatrix} \quad \text{e} \quad \langle \Phi_2 \rangle = \begin{pmatrix} \alpha \\ v'_2 \end{pmatrix}$$

α has electric charge!

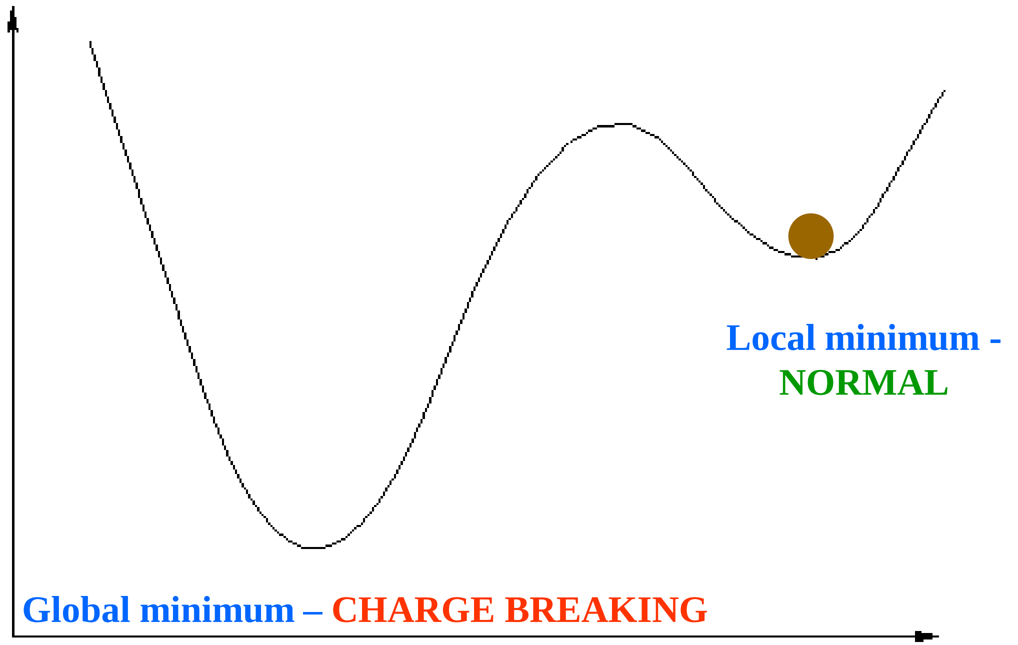
The CP BREAKING minimum, with

$$\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ v'_1 + i\delta \end{pmatrix} \quad \text{e} \quad \langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ v'_2 \end{pmatrix}$$

δ breaks CP!

Would there be any problem if the potential had two of these minima simultaneously?

Answer: there might be, if the CB minimum, for instance, were "deeper" than the normal one (metastable).



$$m_\gamma = 0$$

$$m_\gamma \neq 0 \ !$$

THEOREM: if a Normal Minimum exists, the Global minimum of the theory is Normal - the photon is guaranteed to be massless.

(not so in SUSY, for instance)

Barroso, Ferreira, Santos

$$V_{CB} - V_N = \left(\frac{M^2_{H\pm}}{4v^2}\right)_N \left[(v'_1 v_2 - v'_2 v_1)^2 + \alpha^2 v_2^2\right]$$

$$V_{CP} - V_N = \left(\frac{M^2_{A}}{4v^2}\right)_N \left[(\bar{v}_1 v_2 \cos\theta - \bar{v}_2 v_1)^2 + \bar{v}_1^2 v_2^2 \sin^2\theta\right]$$

If *N* is a minimum, it is the deepest one, and stable against CB or CP

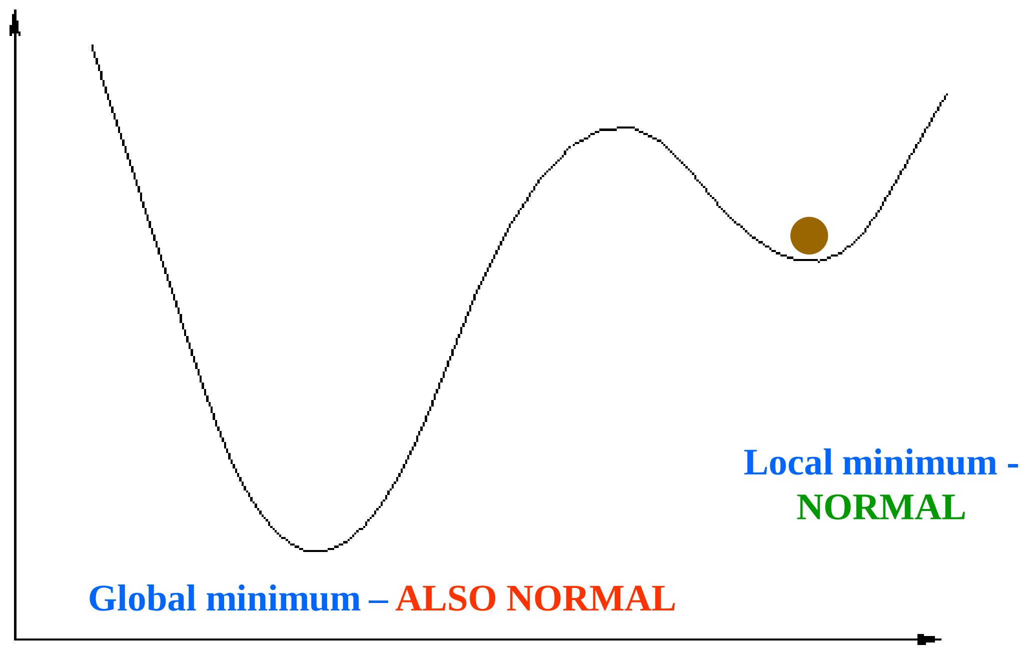
$$V_{N_2} - V_{N_1} = \frac{1}{4}\left[\left(\frac{M^2_{H\pm}}{v^2}\right)_{N_1} - \left(\frac{M^2_{H\pm}}{v^2}\right)_{N_2}\right](v_{1,1}v_{2,2} - v_{2,1}v_{1,2})^2$$

But there is another possibility –

Ivanov

AT MOST TWO NORMAL MINIMA COEXISTING…

So, though our vacuum cannot tunnel to a deper CB or CP minimum, there is another scary prospect…



$$v = 246\, GeV$$
$$m_W = 80\, GeV$$
$$m_t = 173\, GeV$$
$$\ldots$$

$$v \neq 246\, GeV$$
$$m_W \neq 80\, GeV$$
$$m_t \neq 173\, GeV$$
$$\ldots$$

PANIC VACUUM!!

We consider a simple version of the 2HDM: a softly-broken Peccei-Quinn symmetry

$$
\begin{aligned}
V_H &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left[\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1 \right] \\
&+ \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\
&+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1),
\end{aligned}
$$

Coupling to fermions

MODEL I: Only Φ_2 couples to fermions.

MODEL II: Φ_2 couples to up-quarks, Φ_1 to down quarks and leptons.

Theoretical bounds on 2HDM scalar parameters

Potential has to be bounded from below:

$$\lambda_1 \geq 0, \qquad \lambda_2 \geq 0,$$
$$\lambda_3 \geq -\sqrt{\lambda_1\lambda_2}, \qquad \lambda_3 + \lambda_4 - |\lambda_5| \geq -\sqrt{\lambda_1\lambda_2}$$

Theory must respect unitarity:

(for the case under study, $\lambda_5 = 0$)

$$a_\pm = \frac{3}{2}(\lambda_1+\lambda_2) \pm \sqrt{\frac{9}{4}(\lambda_1-\lambda_2)^2 + (2\lambda_3+\lambda_4)^2},$$
$$b_\pm = \frac{1}{2}(\lambda_1+\lambda_2) \pm \frac{1}{2}\sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_4^2},$$
$$c_\pm = \frac{1}{2}(\lambda_1+\lambda_2) \pm \frac{1}{2}\sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_5^2},$$
$$e_1 = \lambda_3 + 2\lambda_4 - 3\lambda_5$$
$$e_2 = \lambda_3 - \lambda_5,$$
$$f_+ = \lambda_3 + 2\lambda_4 + 3\lambda_5,$$
$$f_- = \lambda_3 + \lambda_5,$$
$$f_1 = \lambda_3 + \lambda_4,$$
$$p_1 = \lambda_3 - \lambda_4.$$

$$|a_\pm|, \ |b_\pm|, \ |c_\pm|, \ |f_\pm|, \ |e_{1,2}|, \ |f_1|, \ |p_1| < 8\pi$$

Under what conditions does the 2HDM scalar potential have two normal minima?

If, and only if,

$$m_{11}^2 + k^2 m_{22}^2 < 0$$

$$\sqrt[3]{x^2} + \sqrt[3]{y^2} \leq 1$$

Interior of an astroid

with

$$x = \frac{4\, k\, m_{12}^2}{m_{11}^2 + k^2 m_{22}^2} \frac{\sqrt{\lambda_1 \lambda_2}}{\lambda_{34} - \sqrt{\lambda_1 \lambda_2}}$$

$$y = \frac{m_{11}^2 - k^2 m_{22}^2}{m_{11}^2 + k^2 m_{22}^2} \frac{\sqrt{\lambda_1 \lambda_2} + \lambda_{34}}{\sqrt{\lambda_1 \lambda_2} - \lambda_{34}}$$

and

$$\lambda_{34} = \lambda_3 + \lambda_4$$

$$k = \sqrt[4]{\frac{\lambda_1}{\lambda_2}}$$

I. P. Ivanov, Phys. Rev. D **75**, 035001 (2007) [Erratum-ibid. D **76**, 039902 (2007)] [hep-ph/0609018]; *ibid*, **77**, 015017 (2008).

And out of those two minima,
how can you know whether you are in a panic vacuum?

Let $D = \left(m_{11}^2 - k^2 m_{22}^2\right)\left(\tan\beta - k\right)$ **.** **IF D < 0 PANIC!!!**

. Notice that these discriminants which specify the existence of a second normal minimum N'

ARE ONLY BUILT WITH QUANTITIES OBTAINED IN "OUR" MINIMUM.

Is this at all relevant for phenomenology of the 2HDM?
Must verify what the current data tell us…

• Generate random values for all potential's parameters, such that m_h = 125 GeV (all masses > 90 GeV, < 800 GeV, 1 < tan β < 30).

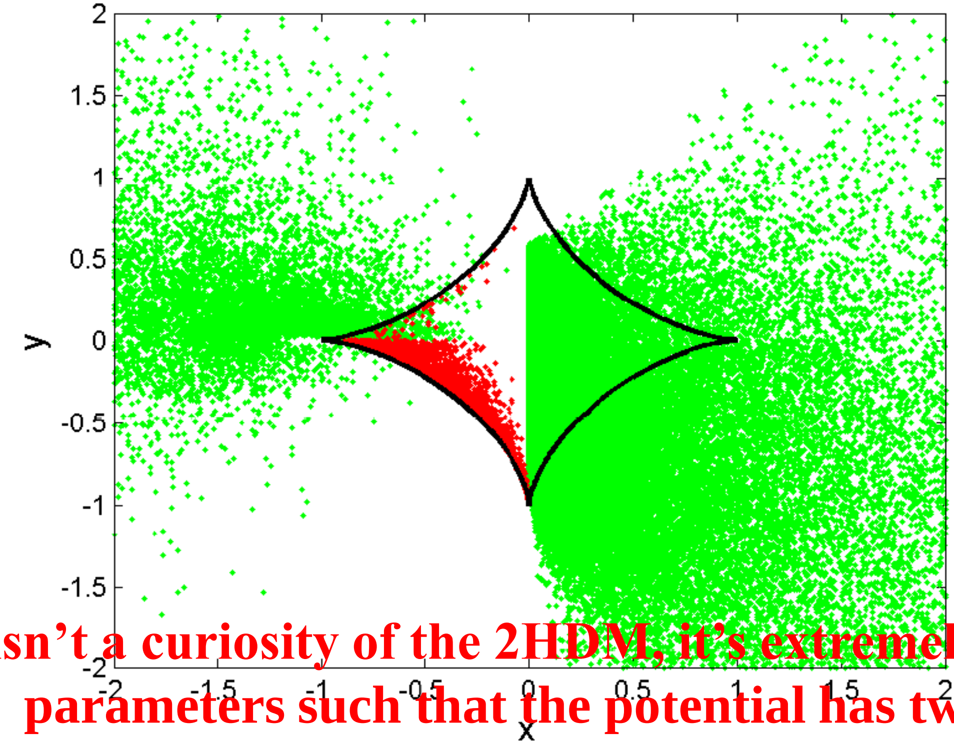
• Ensure the [...] lity, etc).

• Impose *curr*[...] parameter bounds).

• Calculate a[...]

• Compare w[...]

• Serve shake[...]



This isn't a curiosity of the 2HDM, it's extremely simple to choose parameters such that the potential has two minima!!

Inside the astroid: two minima

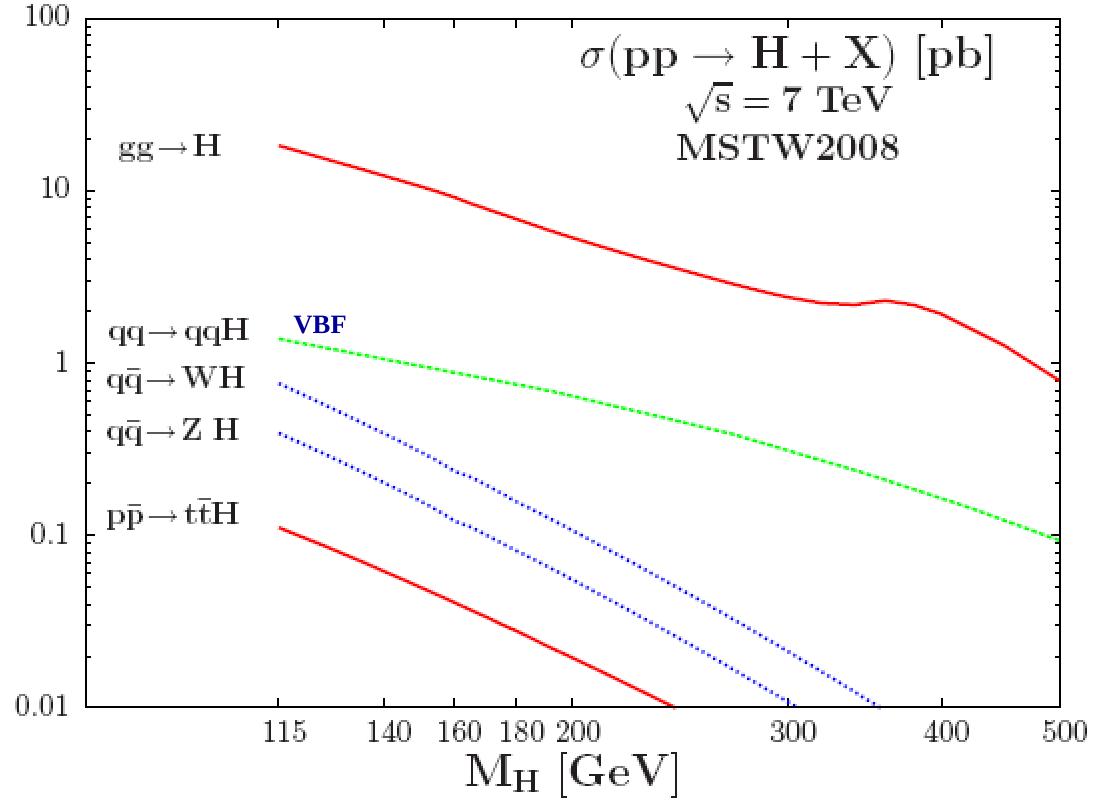
In red: panic vacua points

What we compare to data:

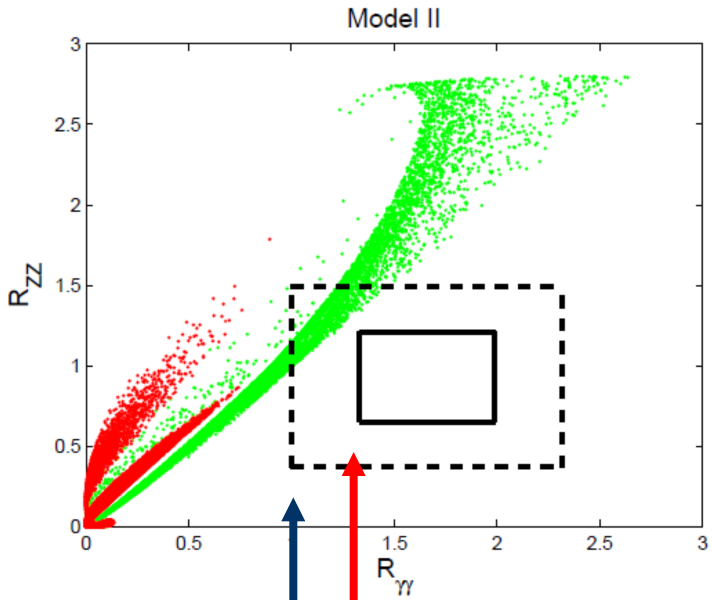
$$R_{XX} = \frac{\sigma^{2HDM}(pp \to h) \times BR^{2HDM}(h \to XX)}{\sigma^{SM}(pp \to h) \times BR^{SM}(h \to XX)}$$

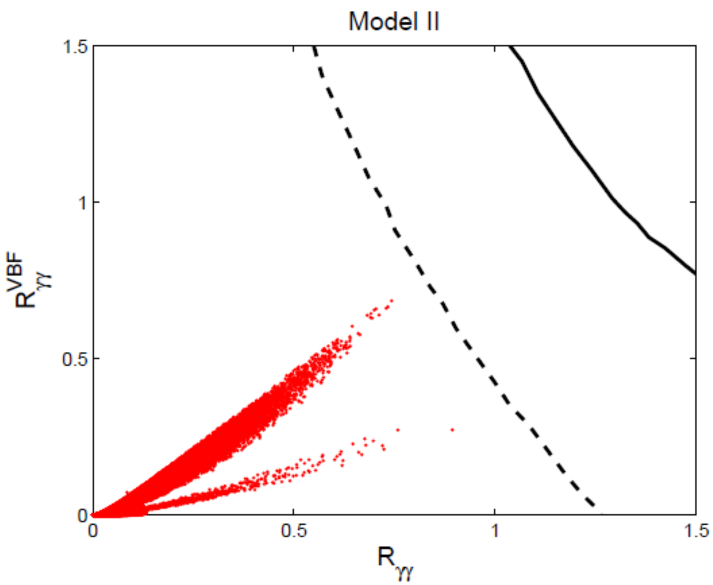
Plenty of different production processes possible at the LHC:

J. Baglio and A. Djouadi, JHEP 03 (2011) 055



So, what does the LHC tell us? Can we sleep at night?





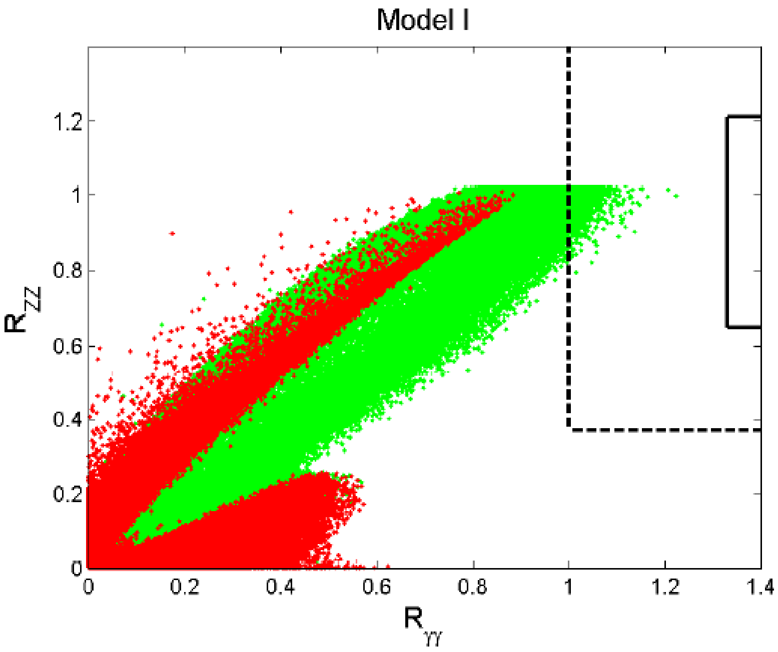
1-σ LHC bounds

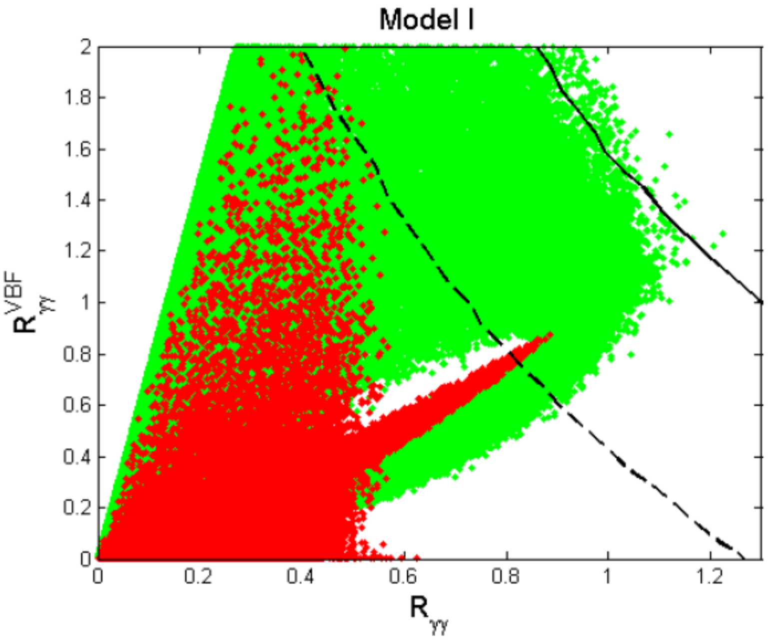
2-σ LHC bounds

Bounds from: Arbey *et al*, JHEP 1209 (2012) 107; ATLAS Coll., PLB 716 (2012) 1

No panic in Model II!!!

What about Model I?





Seems to be doing well in R_{ZZ} and $R_{\gamma\gamma}$, but the 2-σ bounds on the VBF rate still include panic vacua.

So maybe the Mayans were on to something after all…

CONCLUSIONS

- **The 2HDM can have two Normal minima.**

- **This situation occurs for MANY choices of parameters, it is not rare.**

- **There is the possibility that our current vacuum in not the global minimum of the potential.**

- **We have developped extremely simple analytical criteria to determine the nature of our vacuum.**

- **Remarkably, the LHC can already tell us a great deal about this situation, and it seems we can sleep safe…**

- **These bounds should be taken into acount in the study of the 2HDM, just as much as the bounded-from-below ones are.**

$$
\begin{aligned}
m_{12}^2 &= m_A^2\, s_\beta c_\beta, \\
\lambda_1 &= \frac{-s_\beta^2 m_A^2 + c_\alpha^2 m_H^2 + s_\alpha^2 m_h^2}{v^2 c_\beta^2}, \\
\lambda_2 &= \frac{-c_\beta^2 m_A^2 + s_\alpha^2 m_H^2 + c_\alpha^2 m_h^2}{v^2 s_\beta^2}, \\
\lambda_3 &= \frac{2m_{H^\pm}^2 - m_A^2}{v^2} + \frac{s_{2\alpha}(m_H^2 - m_h^2)}{v^2 s_{2\beta}}, \\
\lambda_4 &= \frac{2(m_A^2 - m_{H^\pm}^2)}{v^2},
\end{aligned}
$$