Avoiding Death by Vacuum

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A. Barroso, P.F. , I. Ivanov, R. Santos, J.P. Silva, arXiv:1211.6119
A. Barroso, P.F. , I. Ivanov, R. Santos, arXiv:1302.XXXX

- **LHC discovered a new particle (a scalar?) 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)

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!

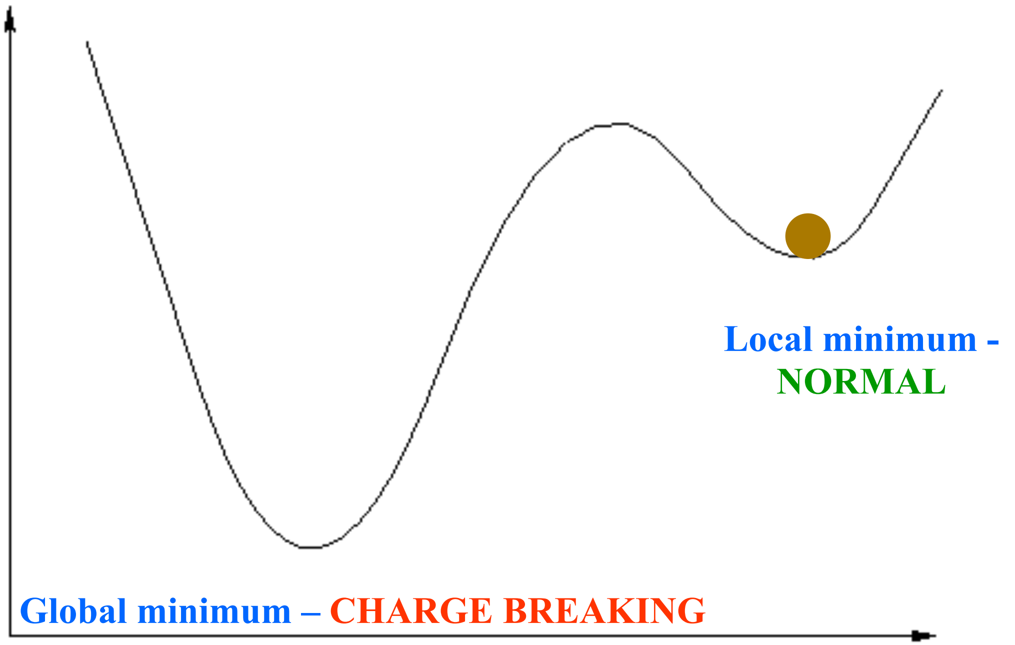
The CP BREAKING minimum, with

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

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).



$$\sout{m_\gamma = 0}$$

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

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

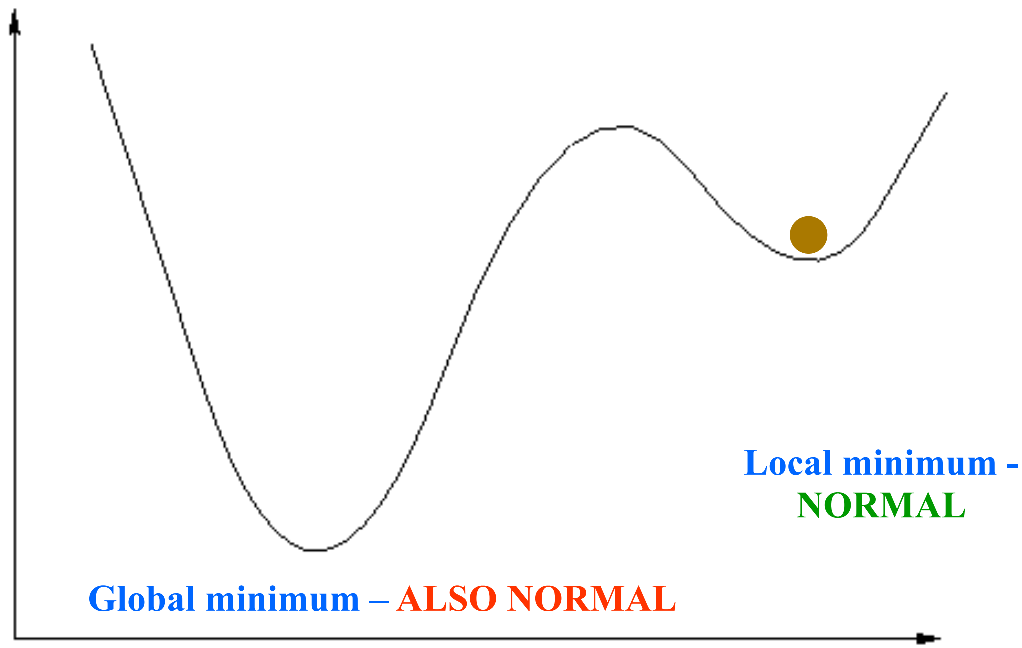
$$V_{N_2} - V_{N_1} = \frac{1}{4}\left[\left(\frac{M^2_{H^\pm}}{v^2}\right)_{N_1} - \left(\frac{M^2_{H^\pm}}{v^2}\right)_{N_2}\right](v_{1,1}v_{2,2} - v_{2,1}v_{1,2})^2$$

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!!

Cannot occur for SUSY, models with exact U(1) or Z_2 symmetries
(exception – *INERT MODEL*! See Maria's talk!)

Can occur if there is soft symmetry breaking!
(or for potentials with only CP symmetry, or no symmetry at all)

We consider, to begin, 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, $\lambda_5 = 0$)

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

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

S. Kanemura, T. Kubota and E. Takasugi, Phys. Lett. B **313** (1993) 155 [arXiv:hep-ph/9303263].
A. G. Akeroyd, A. Arhrib and E. -M. Naimi, Phys. Lett. B **490**, 119 (2000) [hep-ph/0006035].

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

Necessary condition:

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

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

← **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).

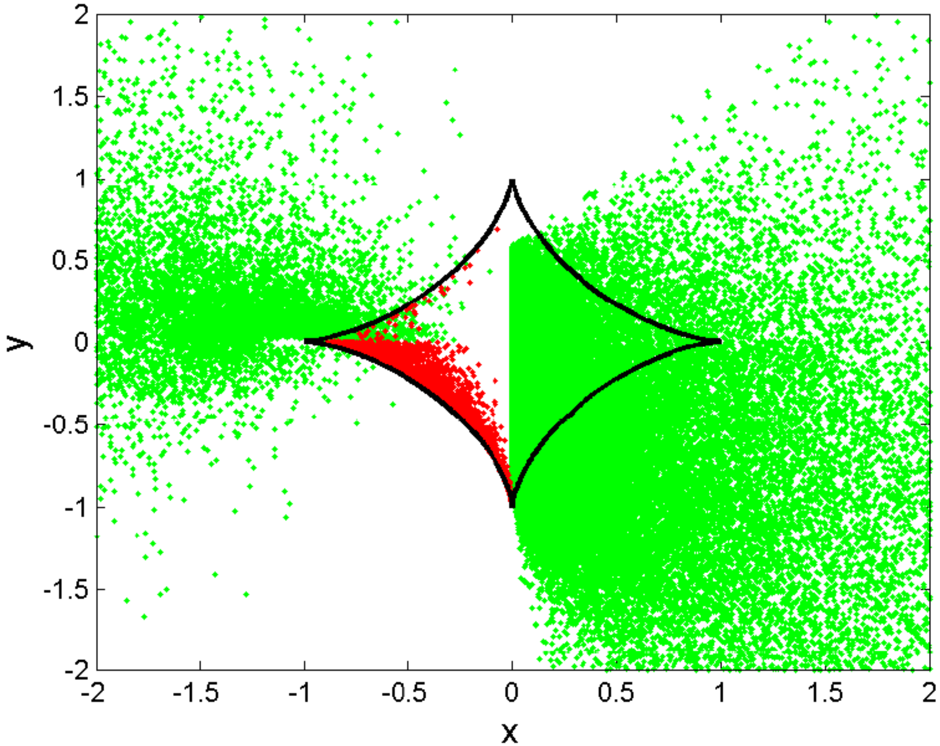
• Impose *curr*

parameter bounds).

• Calculate a

• Compare w

• Serve shake



This

e to choose

na!!

Inside the astroid: two minima

In red: panic vacua points

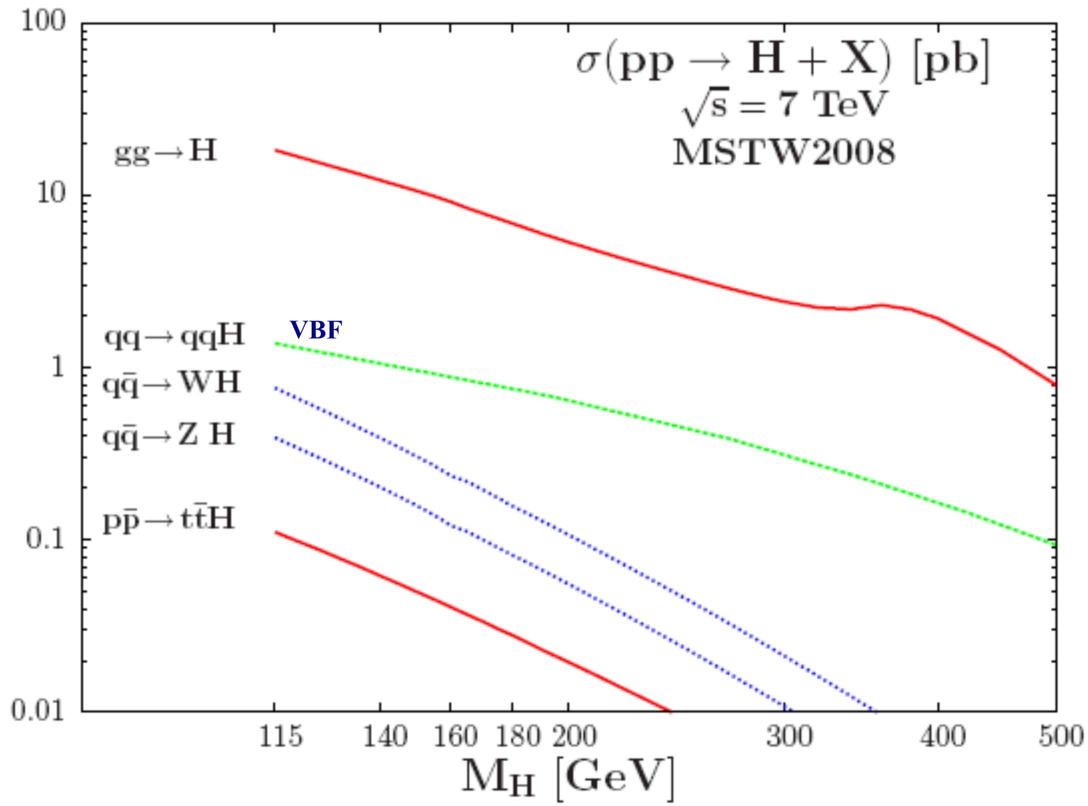
The red points represent choices of 2HDM parameters such that our vacuum, with v = 246 GeV, is NOT the global minimum.

What we compare to data:

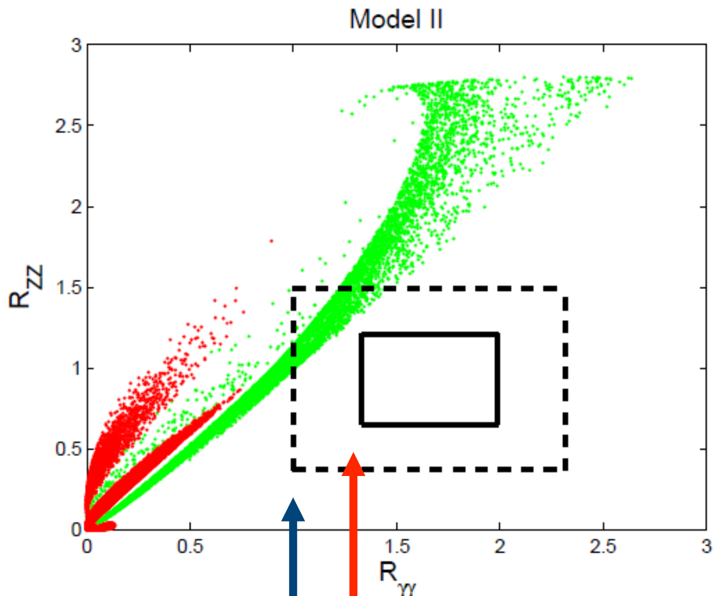
$$R_{XX} = \frac{\sigma^{2HDM}(pp \to h) \times BR^{2HDM}(h \to XX)}{\sigma^{SM}(pp \to h) \times BR^{SM}(h \to XX)}$$

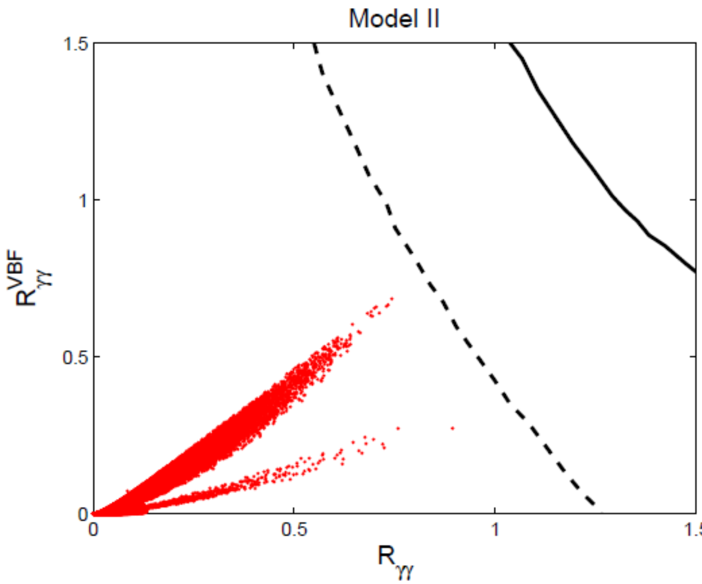
Plenty of different production processes possible at the LHC:

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



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





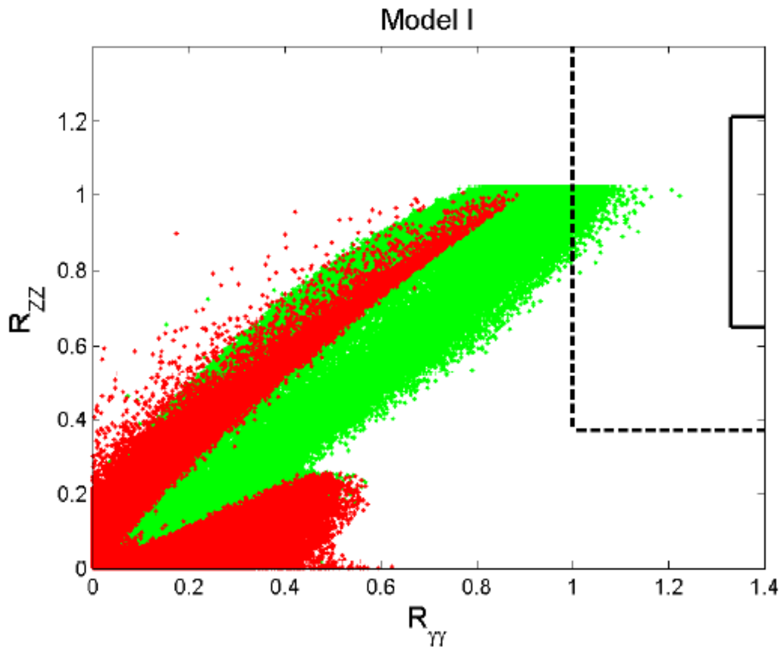
1-σ LHC bounds

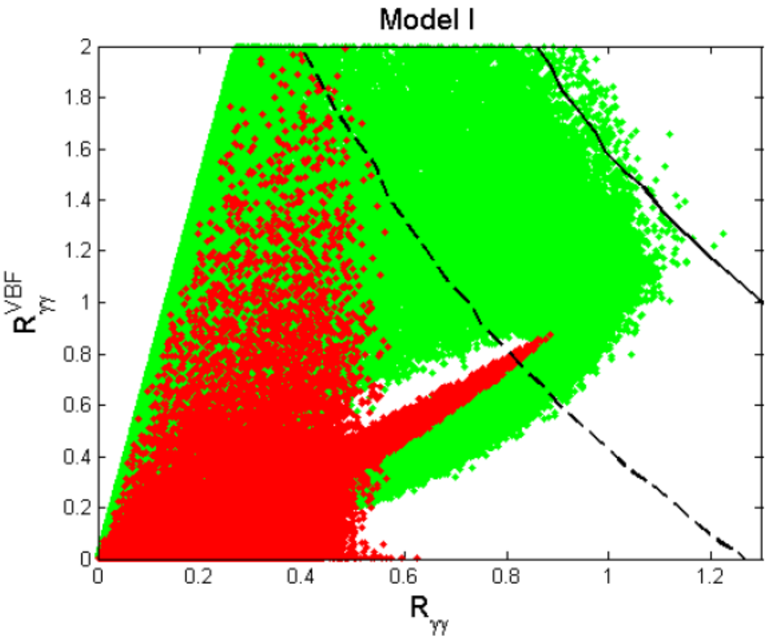
2-σ LHC bounds

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…

More interesting 2HDM: a softly-broken Z_2 symmetry

- **Extremely simple "panic" conditions may be obtained for more general models.**

- **For the case of the Z model, the discriminant becomes**
  (simple generalization of the previous one)

$$D = m_{12}^2(m_{11}^2 - k^2 m_{22}^2)(\tan\beta - k)$$

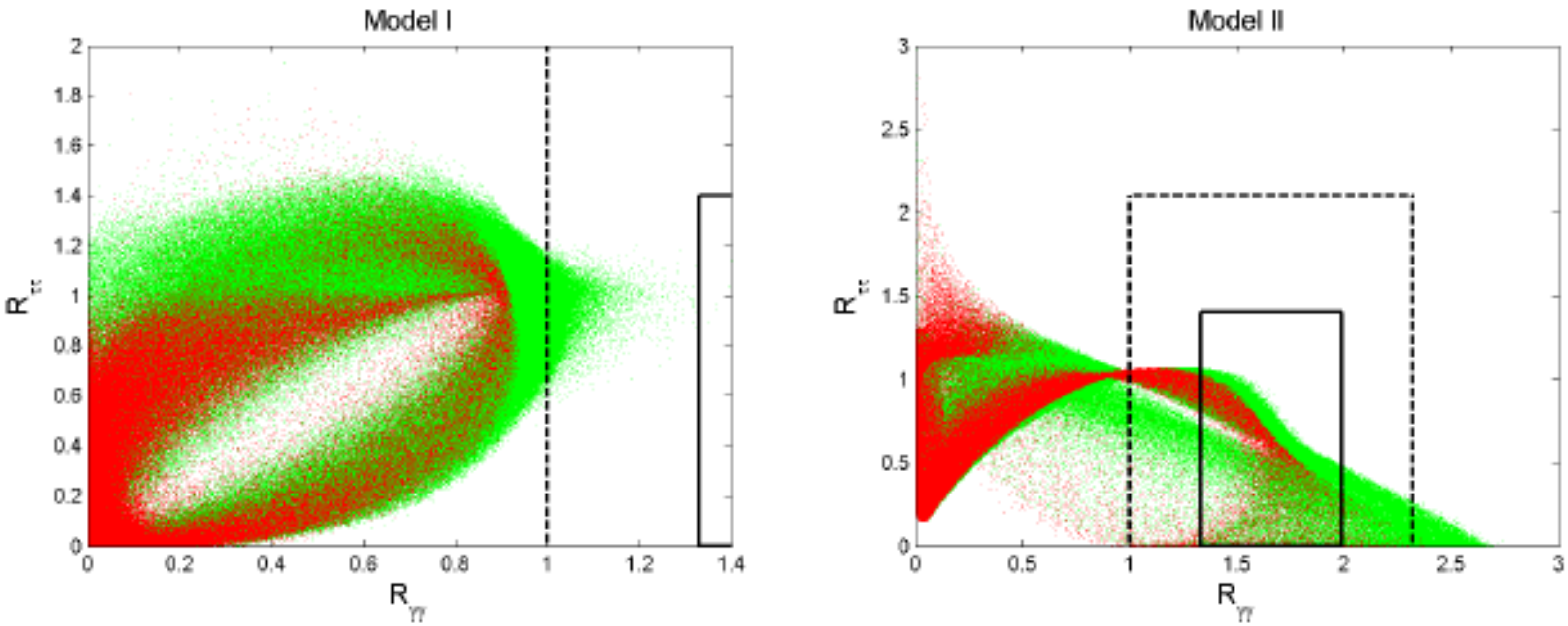
with $k = \sqrt[4]{\frac{\lambda_1}{\lambda_2}}$

Our vacuum is the global minimum of the 2HDM potential

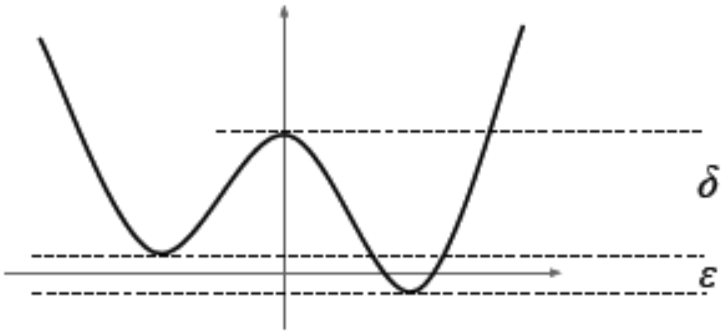
if, and only if,

D > 0

Parameters which give panic vacua can have important phenomenological consequences in this model!



Cosmological vacuum lifetime estimates



Should we worry about a deeper minimum?

What if the tunnelling time is bigger than the age of the universe?

- **Very tricky calculation, full of assumptions.**
- **Usual criterion:** **if $\delta/\varepsilon >\sim 1$, the tunnelling time is big and the vacuum is safe.**
- **Calculations show vast majority of panic vacua *NOT SAFE*.**

S. R. Coleman, "The Fate of the False Vacuum. 1. Semiclassical Theory," Phys. Rev. D **15**, 2929 (1977) [Erratum-ibid. D **16**, 1248 (1977)].

V. A. Rubakov, "Classical theory of gauge fields," Princeton, USA: Univ. Pr. (2002) 444 p.

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. Some versions of the 2HDM seem to be panic-free, given LHC data – but not all!**

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

$$D = m_{12}^2(m_{11}^2 - k^2 m_{22}^2)(\tan\beta - k) \quad > 0$$

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