Avoiding death by vacuum and other 2HDM stories

16 May 2013

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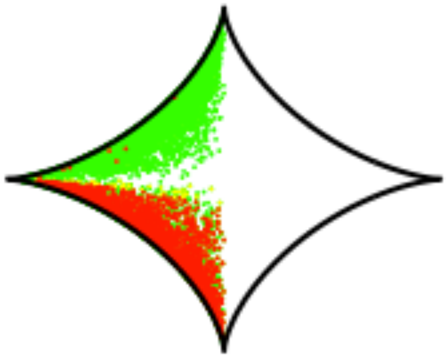
Preface

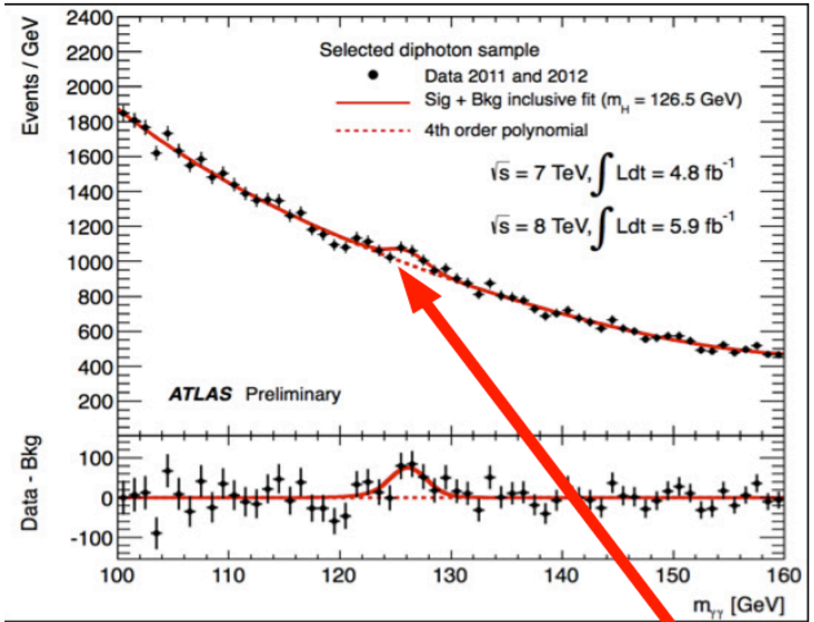
Motivation for Multi-Higgs Models

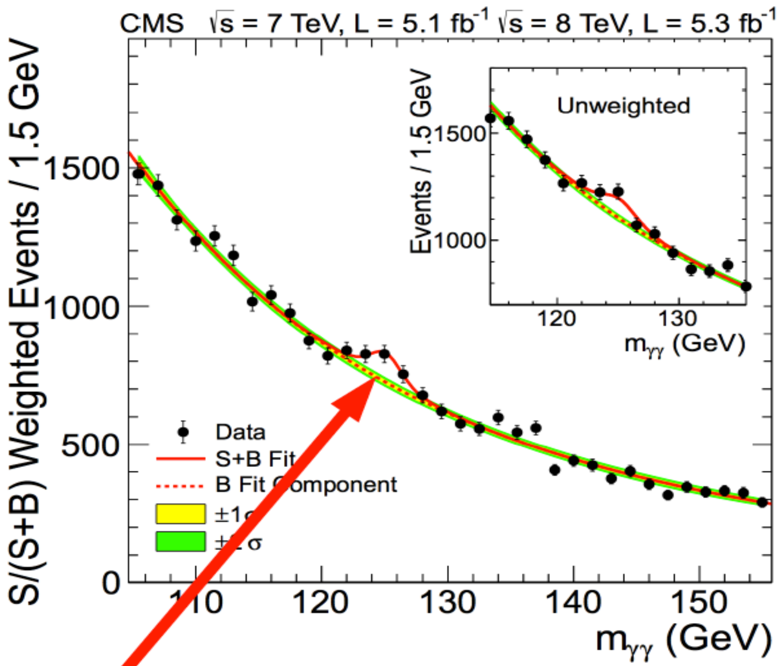
- Simplest extension – SM + 1 singlet; SM + 1 doublet.

- Great fun – dark matter, baryon asymmetry, neutrino oscillations, sophisticated vacuum structure…



LHC

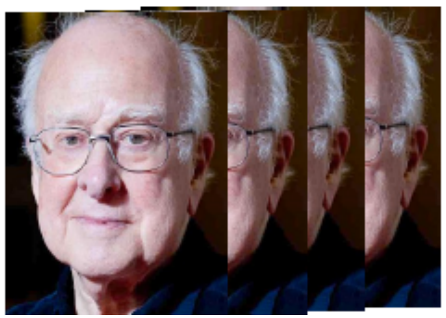




Scalar resonance

stolen from Y. Yamamoto

One Higgs?



Multi-Higgs?

First story

2HDM confronting the LHC data

P.M. Ferreira, R. S., M. Sher, J. P. Silva, PRD85 (2012) 077703.

A. Barroso, P.M. Ferreira, R. S., M. Sher, J. P. Silva, e-Print: arXiv:1304.5225.

The softly broken Z_2 symmetric 2HDM potential

$$\boxed{\begin{aligned} V(\Phi_1,\Phi_2) \;=\;& m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\ +\;& \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}] \end{aligned}}$$

$$\boxed{\phi_1 \to \phi_1 \quad \phi_2 \to -\phi_2}$$

Build your favourite potential: <u>CP conserving</u>, <u>explicit CP breaking</u>, <u>spontaneous CP breaking</u>, by tuning m^2_{12} and λ_5 together with the possible vacuum configurations

- CP CONSERVING (N) $\quad \Phi_1 = \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \;;\; \Phi_2 = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$

- CP BREAKING (CP) $\quad \Phi_1 = \begin{pmatrix} 0 \\ v'_1 + i\delta \end{pmatrix} \;;\; \Phi_2 = \begin{pmatrix} 0 \\ v'_2 \end{pmatrix}$

CP-conserving potential

$$\boxed{\begin{aligned} V(\Phi_1,\Phi_2) \;=\; & m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\ & + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}] \end{aligned}}$$

- m^2_{12} and λ_5 real, vacuum configuration $\boxed{\langle\phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix};\ \langle\phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2\end{pmatrix}}$

7 free parameters + M_W: $m_h,\ m_H,\ m_A,\ m_{H^\pm},\ \tan\beta,\ \alpha,\ M^2 = \frac{m_{12}^2}{\sin\beta\ \cos\beta}$

➡ $\tan\beta = \frac{v_2}{v_1}$ ratio of vacuum expectation values

➡ α rotation angle neutral CP-even sector

2HDM Lagrangian

- scalars-gauge bosons couplings

$$\boxed{g_{SM}\,\sin(\beta-\alpha)}$$

- Yukawa couplings

$$\boxed{\sin\alpha \quad \tan\beta}$$

	I	II	III	IV
leptons (h)	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
down (h)	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$
up (h)	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$
leptons (H)	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$
down (H)	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$
up (H)	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$

III = I' = Y = Flipped

IV = II' = X = Lepton Specific

What are the most relevant theoretical and experimental bounds on the model?

Experimental - not considered

SM - 3.4σ deviation

Type I $\frac{1}{\tan\beta\, m_{H\pm}}$

Type X,Y $\frac{1}{m_{H\pm}}$

For most of the parameter space 2HDM=SM

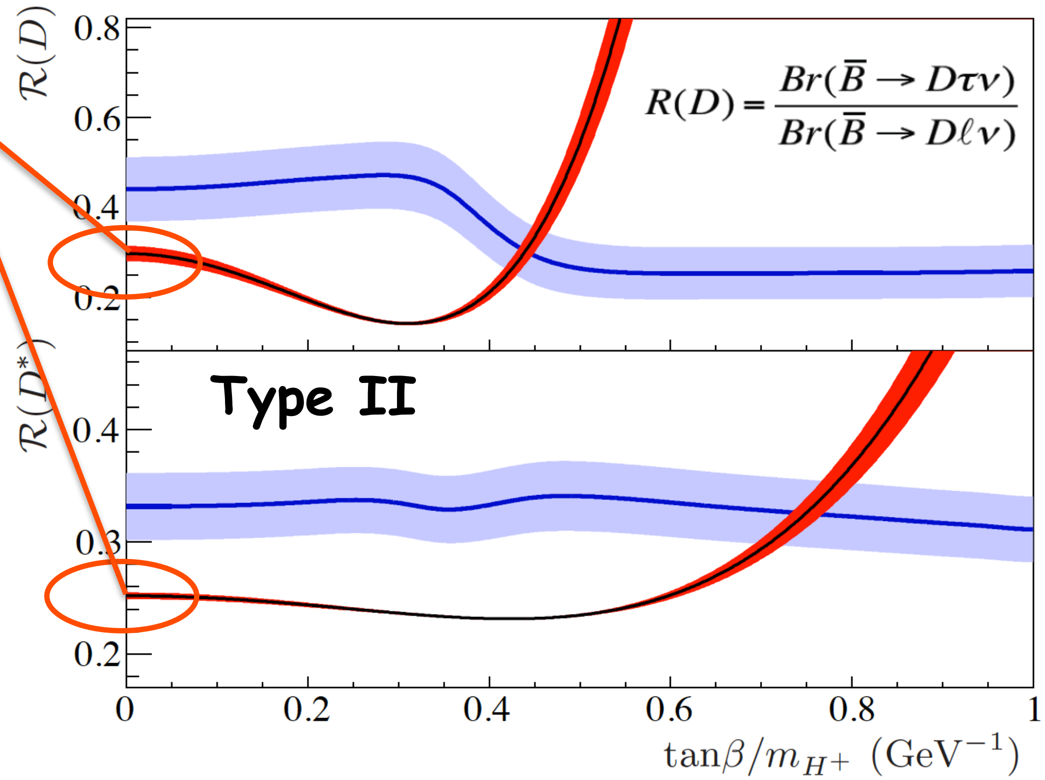


FIG. 2. (Color online) Comparison of the results of this analysis (light gray, blue) with predictions that include a charged Higgs boson of type II 2HDM (dark gray, red). The SM corresponds to $\tan\beta/m_{H+} = 0$.

J.P. Lees et al. [BaBar Collaboration]
Evidence for an excess of B → *$D^{(*)}\tau\nu$ decays*
Phys. Rev. Lett. **109**, 101802 (2012)

Experimental

- **LEP** $\boxed{e^+e^- \to H^+H^-}$

ALEPH, DELPHI, L3 and OPAL Collaborations
The LEP working group for Higgs boson searches[1]

arXiv:1301.6065v1

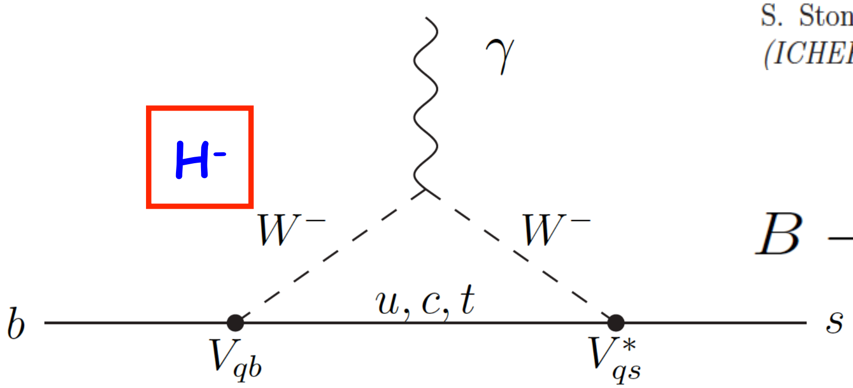
Any $BR(H^+ \to \tau^+\nu)$ $\boxed{m_{H^\pm} \gtrsim 80\ GeV}$

$BR(H^+ \to \tau^+\nu) \approx 1$ $\boxed{m_{H^\pm} \gtrsim 94\ GeV}$ **(Model X)**

- **B factories**

T. Hermann, M. Misiak and M. Steinhauser, JHEP **1211** (2012) 036

S. Stone, Plenary talk at the *International Conference on High Energy Physics (ICHEP 2012)*, Melbourne, Australia, July 4-11th, 2012.



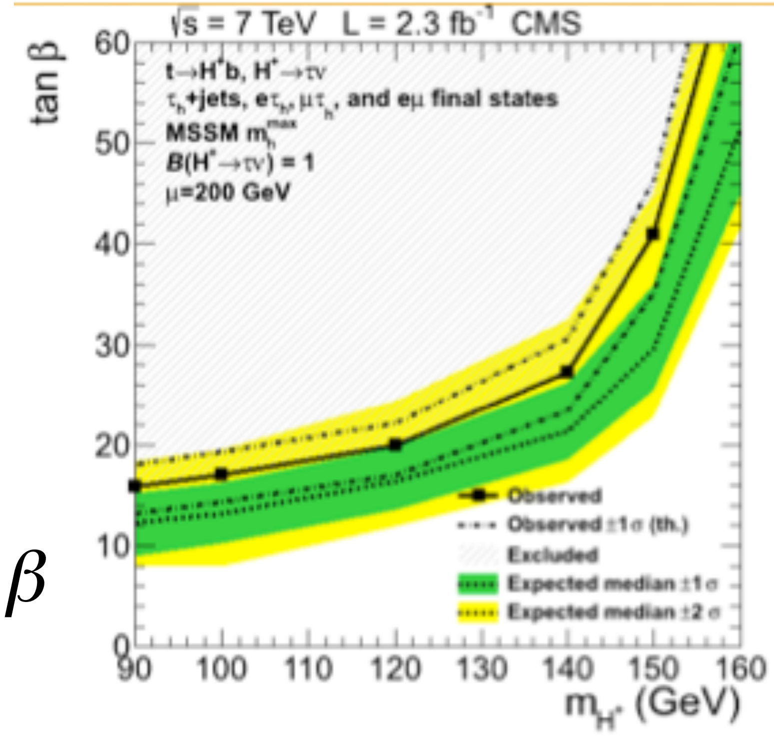
$B \to X_s\gamma$

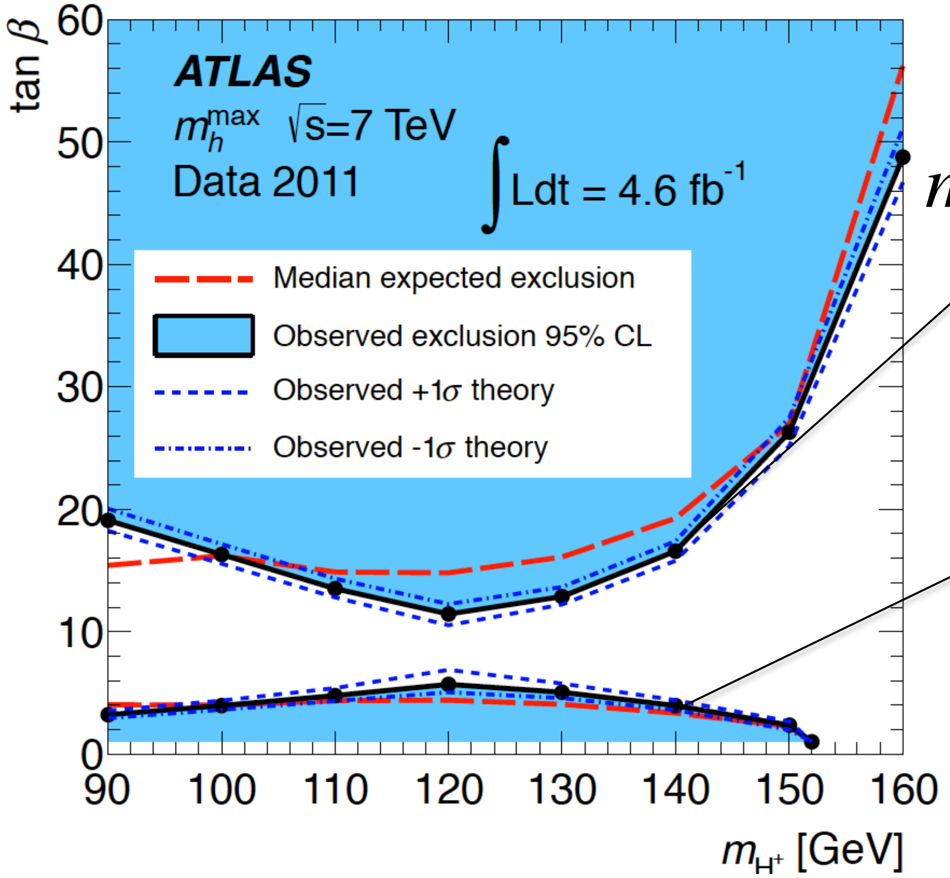
Models II and Y $\boxed{m_{H^\pm} \gtrsim 360\ GeV}$

Best available bound on the charged Higgs mass

Experimental

$$pp \to \bar{t}t \to \bar{b}bW^+H^-$$





$m_b \tan\beta$

$\dfrac{m_t}{\tan\beta}$

Corrected for

$BR(H^- \to \tau\bar{\nu})$

G. Aad *et al.* [ATLAS Collaboration], JHEP **1206** (2012) 039

S. Chatrchyan *et al.* [CMS Collaboration], JHEP **1207** (2012) 143

Experimental

All models

- B_d^0–$\overline{B}_d^0$ and B_s^0–$\overline{B}_s^0$ mixing
- $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$

$$\boxed{\tan\beta \gtrsim 1}$$

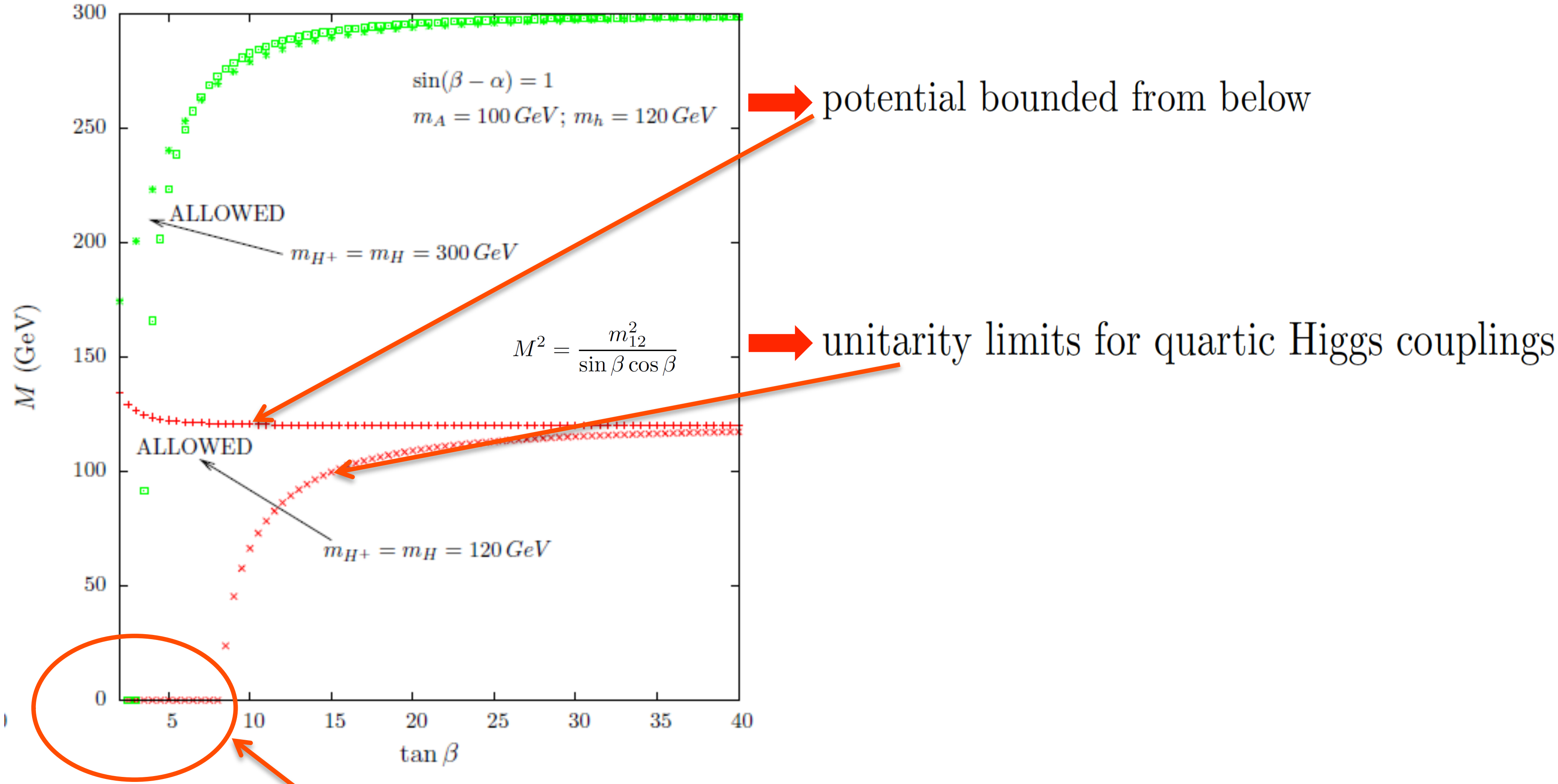
- Precision electroweak constraints

- contributions to S, T and U

$$\begin{cases} m_A = m_{H^\pm} \\ \sin(\beta-\alpha) = 1 \Rightarrow m_{H^\pm} = m_H \\ \sin(\beta-\alpha) = 0 \Rightarrow m_{H^\pm} = m_h \end{cases}$$

- $B^+ \to \tau^+ \nu_\tau$ **Model II only**

Theoretical



No soft breaking term = strong constraint on tanβ

$\boxed{0.18 \lesssim \tan\beta \lesssim 5.59}$

B. Gorczyca, M. Krawczyk, arXiv: 1112.5086

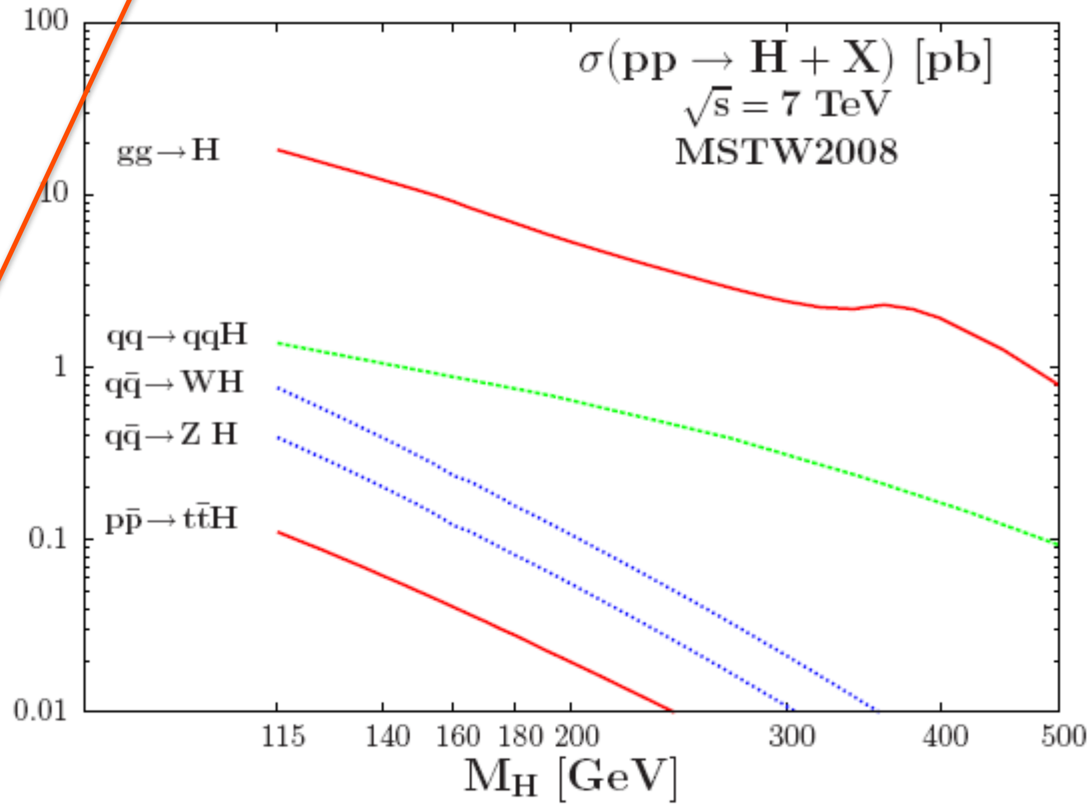
Z_2 symmetric potential

What do we compare to data?

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

The value for each individual production process is multiplied by the corresponding 2HDM factor.

2HDM branching ratios are calculated using our own code. SM BR are calculated with the same code in the SM-like limit.



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

The simplest example is to take model type I and consider that the production occurs only via gluon-gluon fusion

$$\boxed{R_{ZZ} \approx \sin^2(\beta - \alpha)} \quad \text{if} \quad h \to bb \quad \text{dominates}$$

$$R_{ZZ} \to 1 \quad \text{SM - like limit}$$

$$\boxed{R_{\gamma\gamma} = \left(\frac{\cos\alpha}{\sin\beta}\right)^2 \frac{BR^{2HDM}(h \to \gamma\gamma)}{BR^{SM}(h \to \gamma\gamma)}}$$

BR now depends on sinα, tanβ, charged Higgs mass and its coupling to neutral scalars.

In type II even gluon fusion has a different factor in the top and in the bottom loop - with different QCD corrections.

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

Higlu was used for gg and bb@nnlo for bb.

Scan

- Set m_h = 125 GeV.

- Generate random values for potential's parameters such that

$$90\ Gev \leqslant m_{H^\pm},\, m_A \leqslant 900\ GeV$$

$$m_h \leqslant m_H \leqslant 900\ GeV$$

$$-(900)^2\ Gev^2 \leqslant m_{12}^2 \leqslant 900^2\ GeV^2$$

$$1 \leqslant \tan\beta \leqslant 40$$

$$-\frac{\pi}{2} \leqslant \alpha \leqslant \frac{\pi}{2}$$

- Impose all experimental and theoretical constraints previously described.

- Calculate all branching ratios and production rates at the LHC.

- Impose ATLAS and CMS results.

The after Moriond – CMS

$$R_{\gamma\gamma}^{CMS} = 0.78 \pm 0.28 \qquad R_{WW}^{CMS} = 0.76 \pm 0.21$$

$$R_{ZZ}^{CMS} = 0.91 \pm 0.30 \qquad R_{\tau\tau}^{CMS} = 1.1 \pm 0.4$$

The after Moriond – ATLAS

$$R_{\gamma\gamma}^{ATLAS} = 1.65 \pm 0.34 \qquad R_{WW}^{ATLAS} = 1.5 \pm 0.6$$

$$R_{ZZ}^{ATLAS} = 1.7 \pm 0.5 \qquad R_{\tau\tau}^{ATLAS} = 0.7 \pm 0.7$$

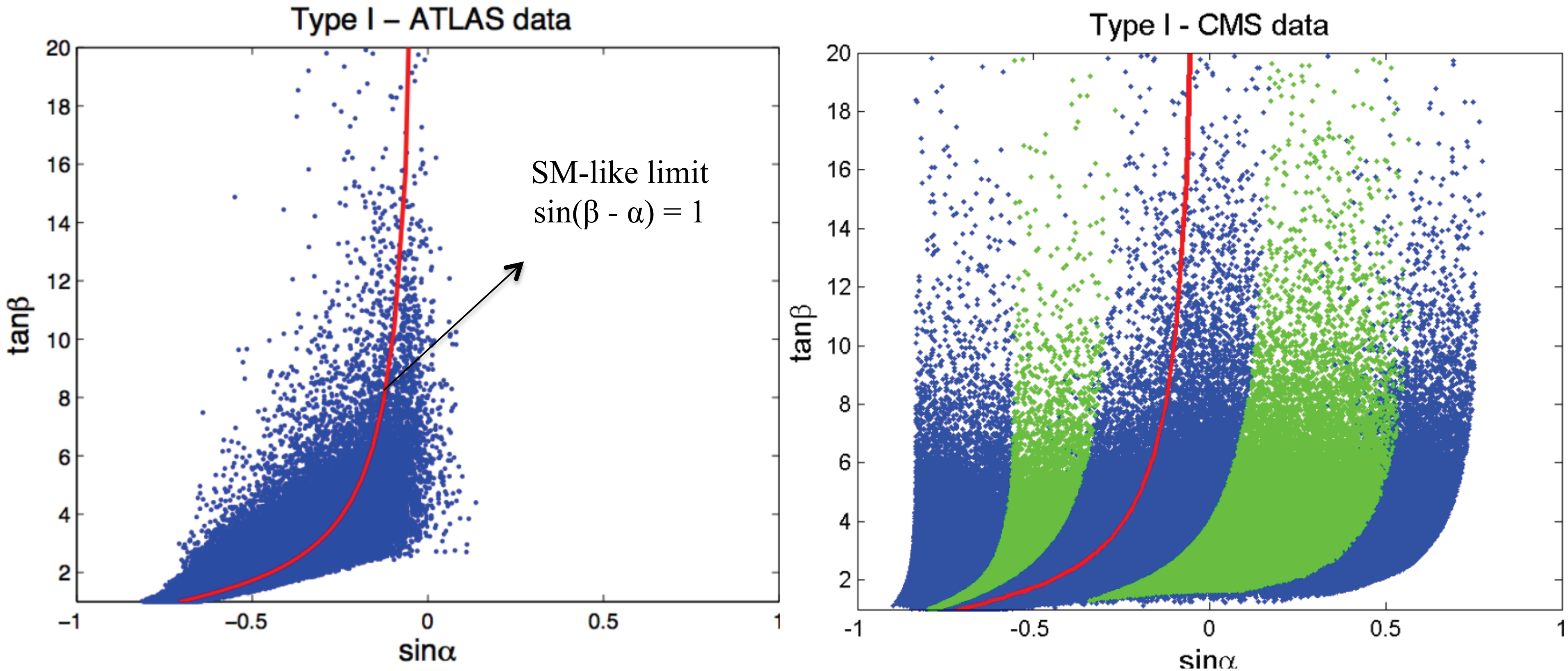
There are some old results with the averaged ATLAS and CMS results where we have used

$$R_{\gamma\gamma} = 1.66 \pm 0.33$$

$$R_{ZZ} = 0.93 \pm 0.28$$

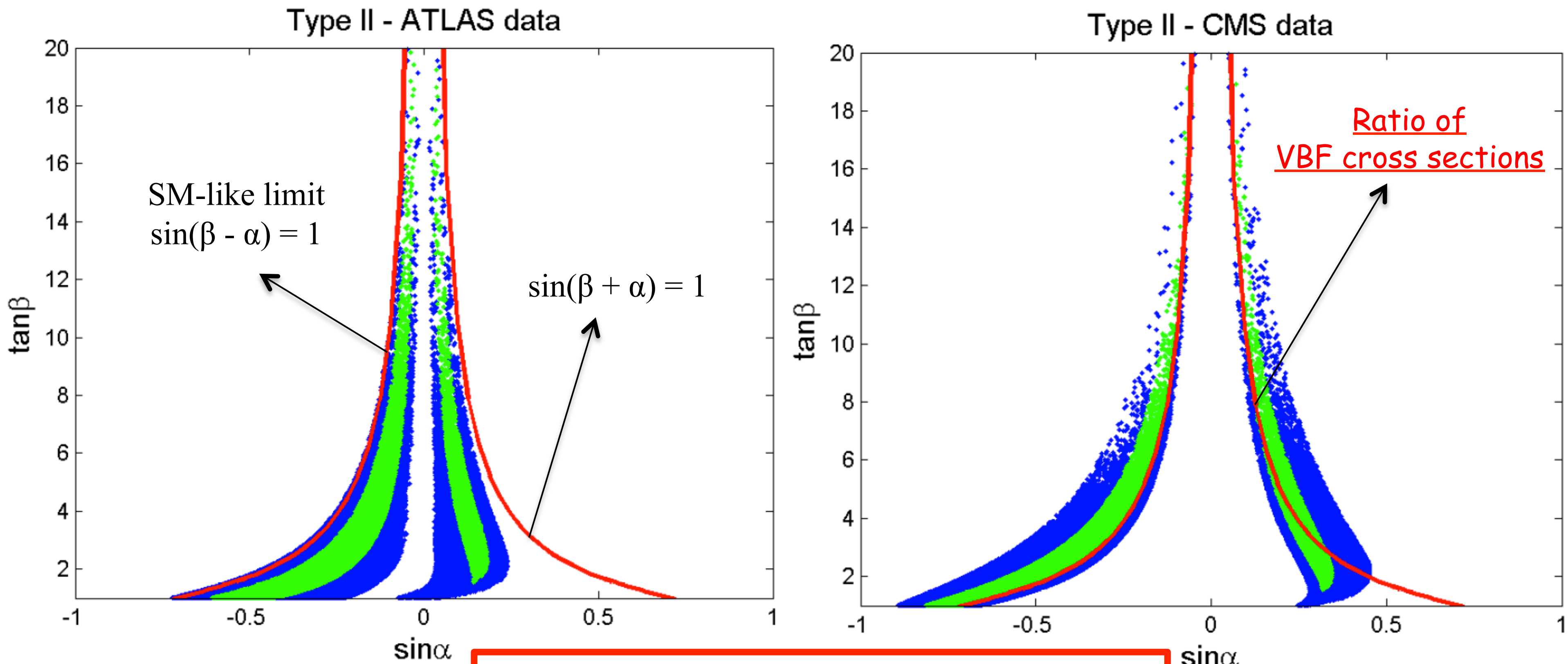
$$R_{\tau\tau} = 0.71 \pm 0.42$$

Arbey, Battaglia, Djouadi, Mahmoudi, arxiv:1211.4004.



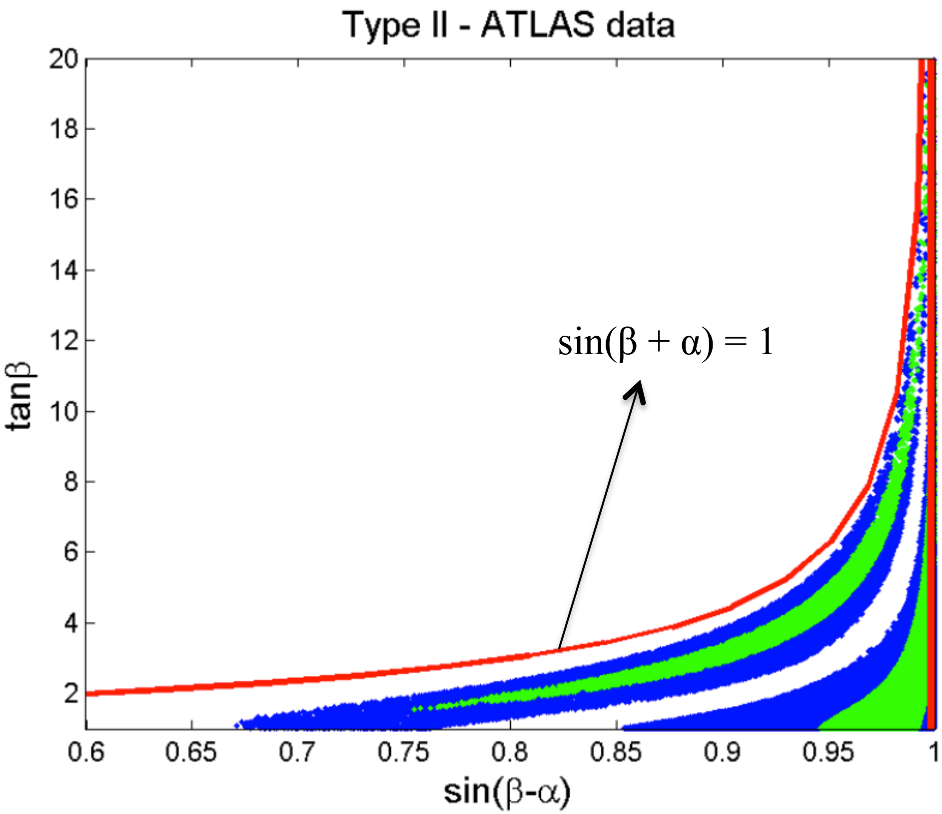
$$R_{ZZ}^{I,approx} = \frac{\cos^2\alpha}{\sin^2\beta}\sin^2(\alpha-\beta)\frac{\sin^2\beta}{\cos^2\alpha} = \sin^2(\alpha-\beta)$$

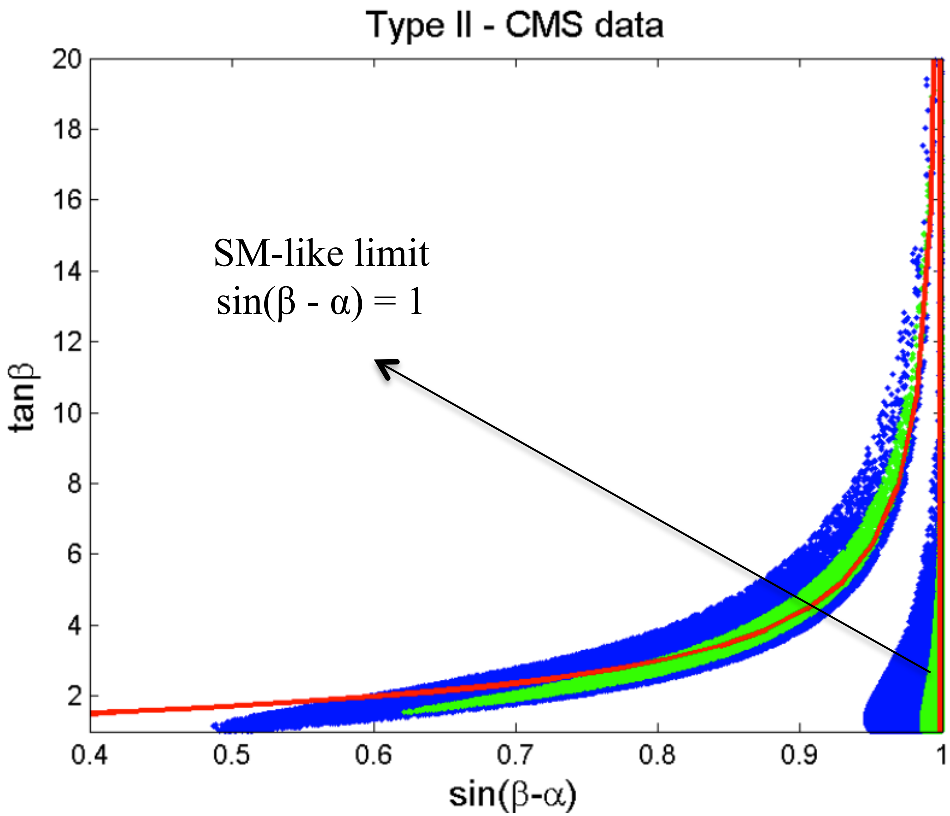
- The function $\sin^2(\beta - \alpha)$ is very sensitive to deviations from 1 – large dispersion.
- For ATLAS R_{ZZ} is above 1 – 1σ (green) excluded; 2σ (blue) allowed.
- For CMS R_{ZZ} is below 1 – 1σ (green) away from SM limit but allowed; 2σ (blue) allowed and with a large dispersion.
- Large positive values of sinα already excluded at 2σ.



$$R_{ZZ}^{II,approx} = \sin^2(\alpha - \beta)\frac{1}{\tan^2\alpha\,\tan^2\beta}$$

- This function is not sensitive to deviations from 1 – small dispersion.
- In both cases we have 1σ (green) and 2σ (blue) allowed regions.
- For CMS they are mostly above the red lines (R's below 1) and for ATLAS they are mostly below the red lines (R's above 1).
- Large positive values of sinα (and the ones close to -1) already excluded at 2σ.

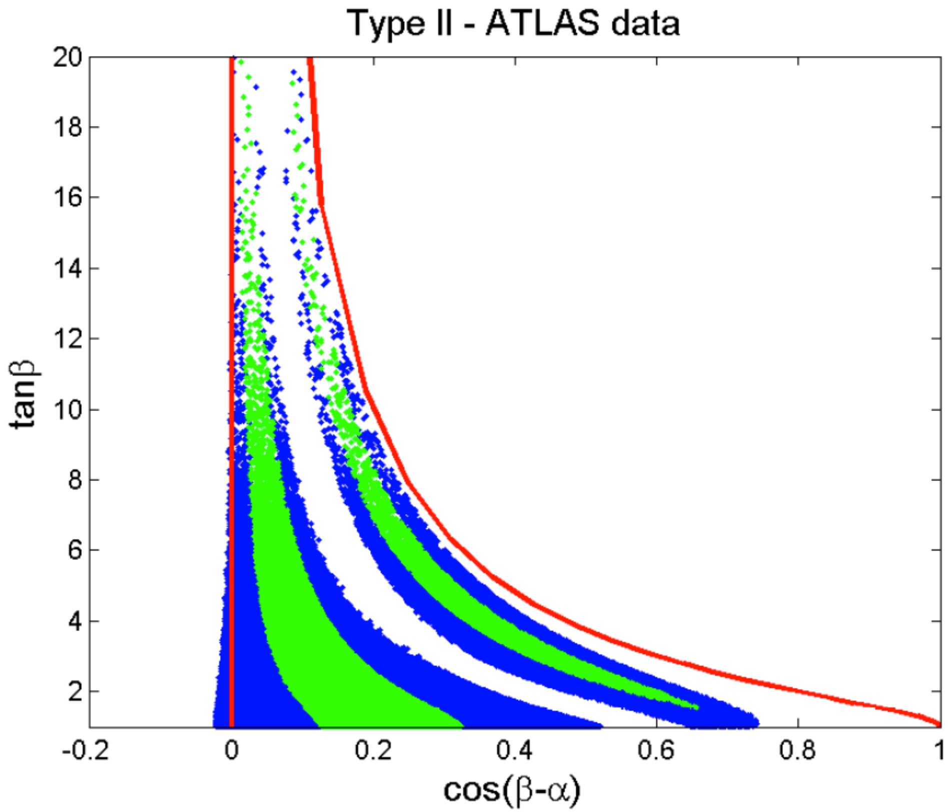


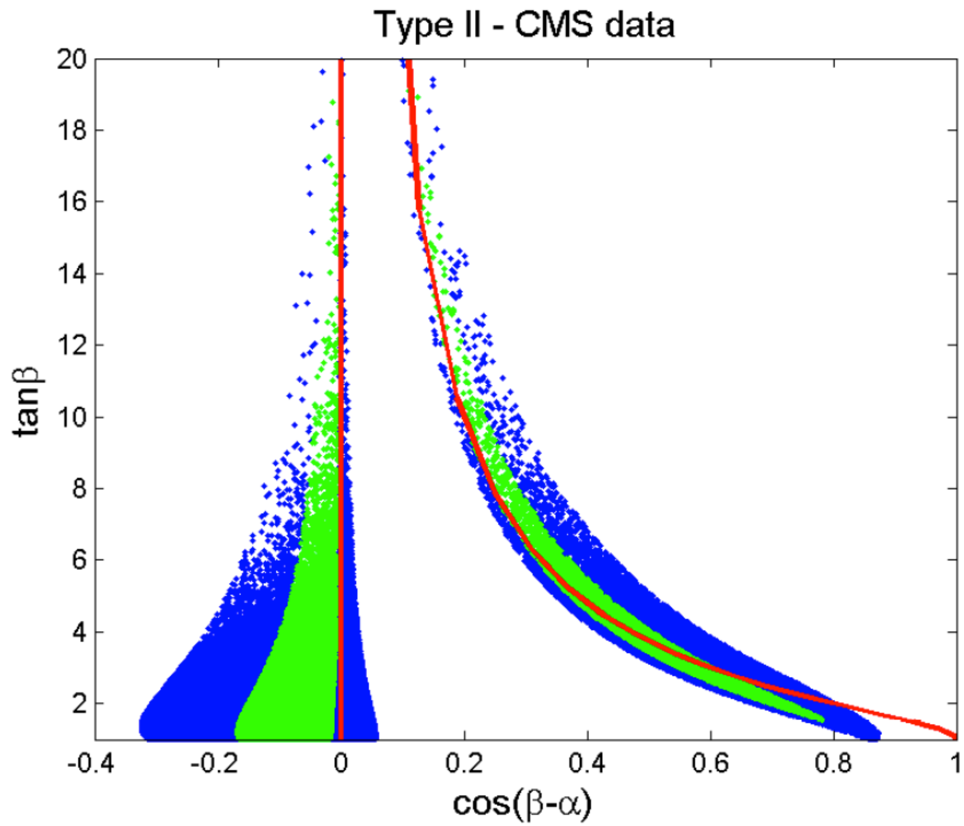


- $\sin(\beta - \alpha) < 0.5$ at 2σ (blue) – <u>deviations of the light Higgs couplings to gauge bosons</u>.

- For $\sin(\beta - \alpha) < 0.8$, $\tan\beta < 4$ – <u>large $\tan\beta$ only close to $\sin(\beta - \alpha) = 1$</u>.

- Again CMS on/above the red lines (R's below 1) and ATLAS below/on the red lines (R's above 1).

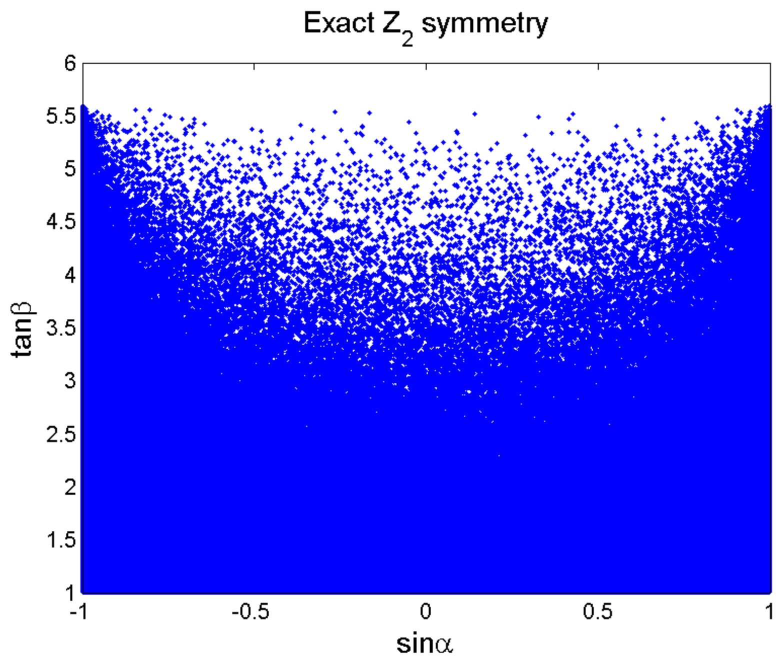




- $-0.4 < \cos(\beta - \alpha) < 0.9$ at 2σ (blue) – <u>deviations of the heavy Higgs couplings to gauge bosons</u>.

- <u>Again large $\tan\beta$ only close to $\cos(\beta - \alpha) = 0$ or $\cos(\beta + \alpha) = 0$</u> .

- And again CMS on/above the red lines (R's below 1) and ATLAS below/on the red lines (R's above 1).

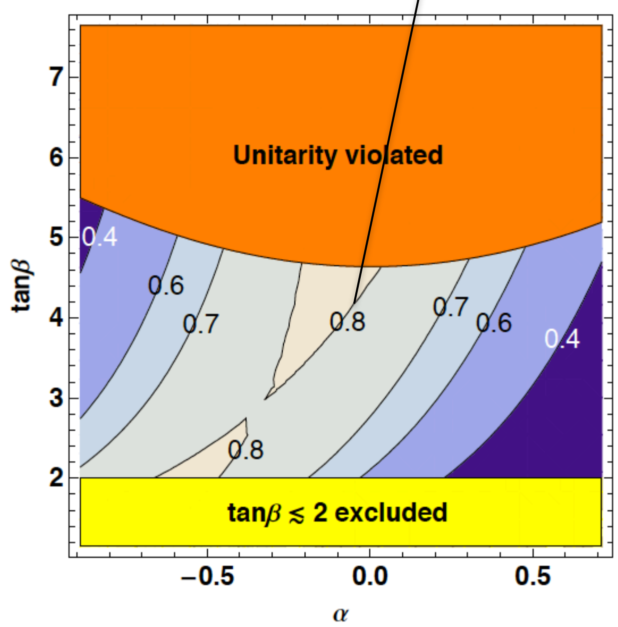


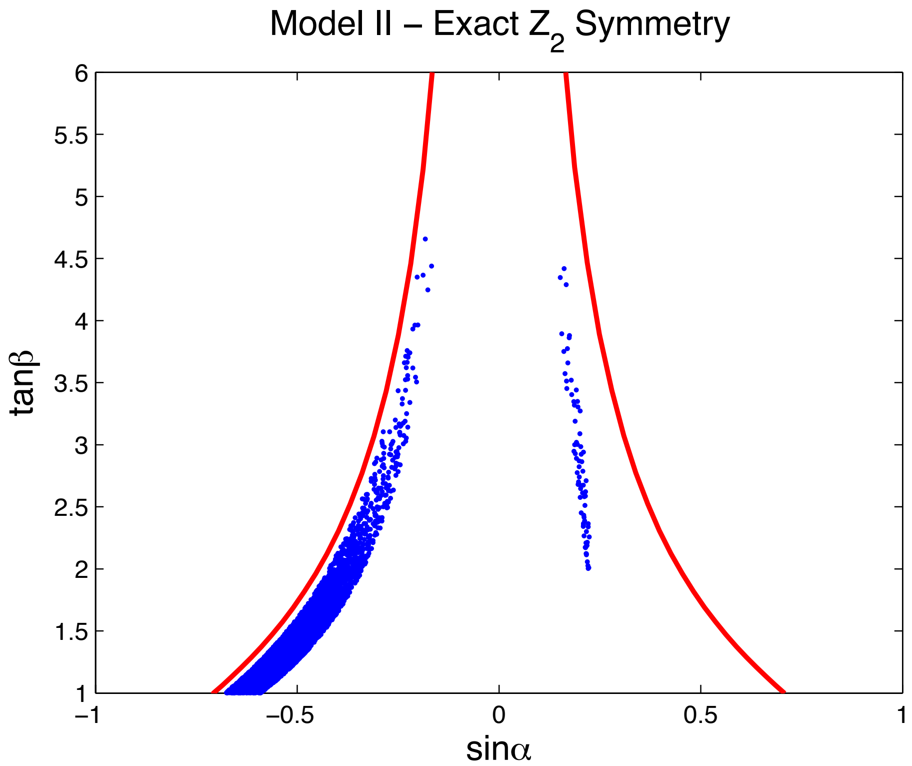
What about the exact Z_2 symmetric scenario?

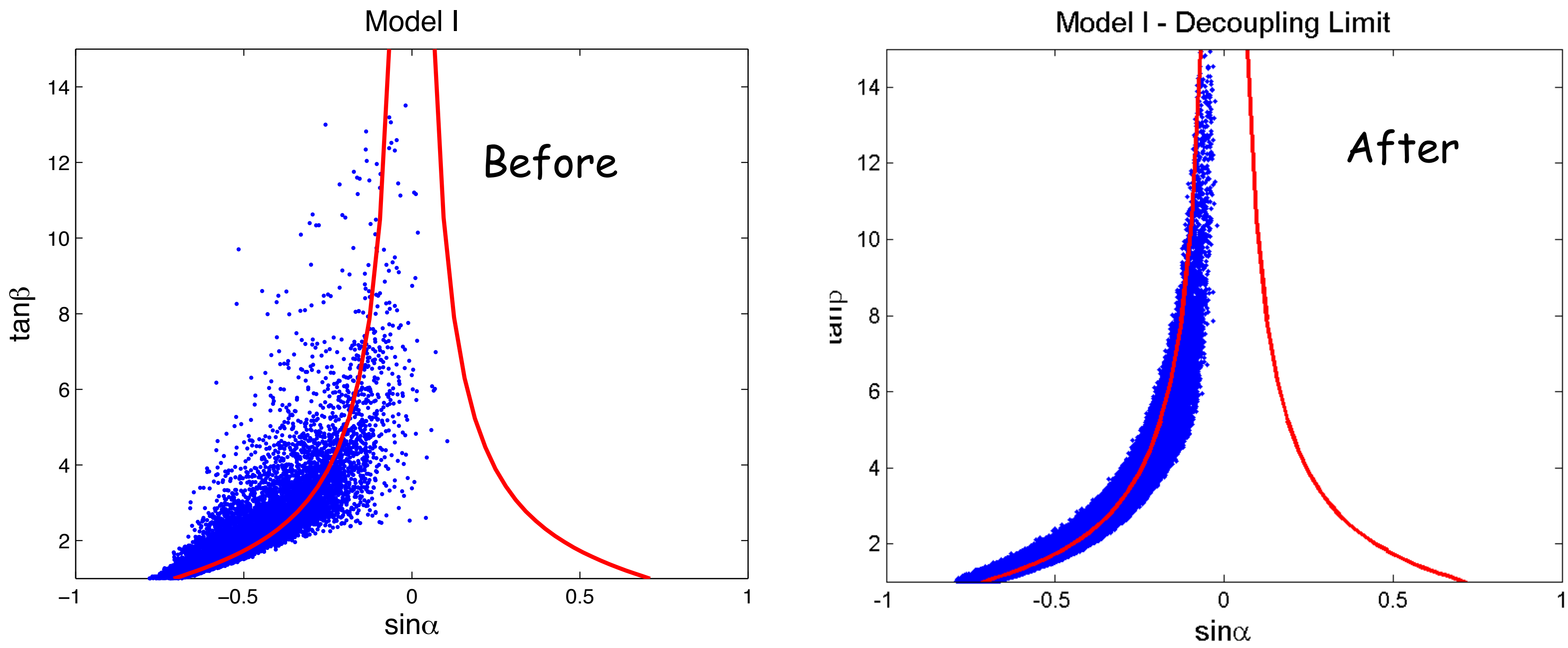
Type I is killed at 2σ

Type II is still allowed at 2σ

Maximum of $R_{\gamma\gamma}$ below 1







Using the combined data pre-Moriond

We then took all masses to be above 600 GeV.

At 1σ everything is excluded.

At 2σ (in blue) the blue regions shrink moving closer to the SM-like limit.

Second story

Is "the scalar" a scalar or a pseudo-scalar?

A. Barroso, P.M. Ferreira, R. S., J. P. Silva, PRD86 (2012) 015022

CP violating 2HDM

- A scalar was found.

- Is is CP-even, CP-odd or a mixture of the two states?

- It is not a pure CP-odd state because it decays to ZZ and WW.

- In a CP-violating 2HDM, a simple limit takes you to the CP-conserving scenario.

- Data can be used to put a bound on the amount of pseudo-scalar contribution.

W. Khater and P. Osland, Nucl. Phys. B 661, 209 (2003).

Parametrisation

- 2 charged, $H^{\pm}$, and 3 neutral, h_1, h_2 and h_3 **3 masses**

- $$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{pmatrix} \qquad R\,\mathcal{M}^2\,R^T = \mathrm{diag}\left(m_1^2, m_2^2, m_3^2\right)$$

$$R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}$$ **3 angles**

- $\mathrm{Re}\left[m_{12}^2\right]$ **soft breaking term**

- $\tan\beta$ **ratio of vacuum expectation values**

- $$m_3^2 = \frac{m_1^2\,R_{13}(R_{12}\tan\beta - R_{11}) + m_2^2\,R_{23}(R_{22}\tan\beta - R_{21})}{R_{33}(R_{31} - R_{32}\tan\beta)}$$

Motivation – which amount of mixture between CP-even and CP-odd states is preferred?

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{pmatrix} \qquad R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}$$

$$\boxed{\begin{array}{l} |s_2| = 0 \;\Rightarrow\; h_1 \text{ is a pure scalar,} \\ |s_2| = 1 \;\Rightarrow\; h_1 \text{ is a pure pseudoscalar} \end{array}}$$

What does LHC data tells about the mixing?

- Set m_{h1} = 125 GeV.

- Generate random values for potential's parameters such that

$$1 \leq \tan\beta \leq 30$$

$$m_{h1} \leq m_{h2} \leq 900\ GeV$$

$$-(1000)^2\ Gev^2 \leq Re(m_{12}^2) \leq 1000^2\ GeV^2$$

$$-\pi/2 < \alpha_1 \leq \pi/2$$

$$-\pi/2 < \alpha_2 \leq \pi/2$$

$$0 \leq \alpha_3 \leq \pi/2$$

- Impose all experimental and theoretical constraints previously described.

- Calculate all branching ratios and production rates at the LHC.

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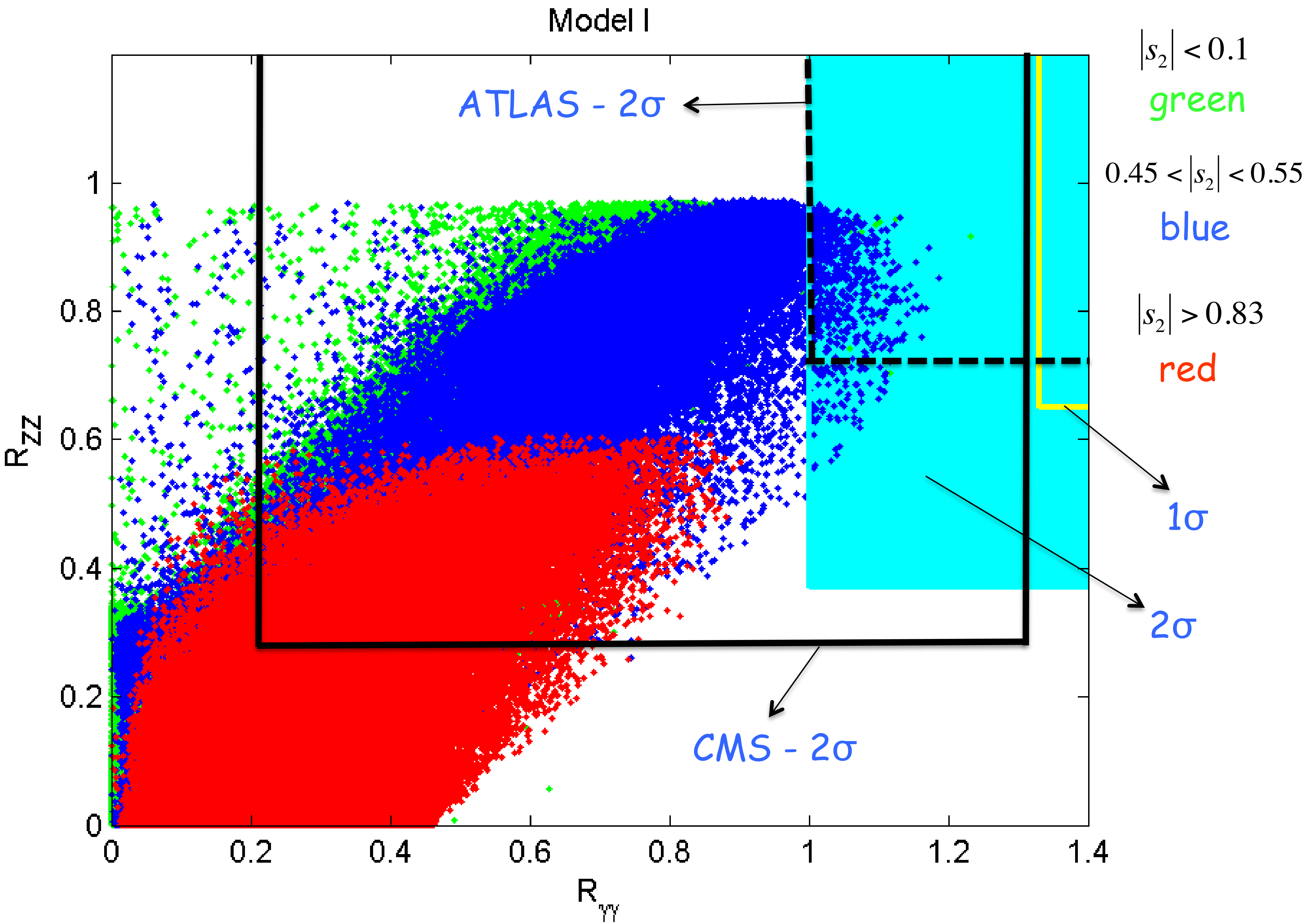
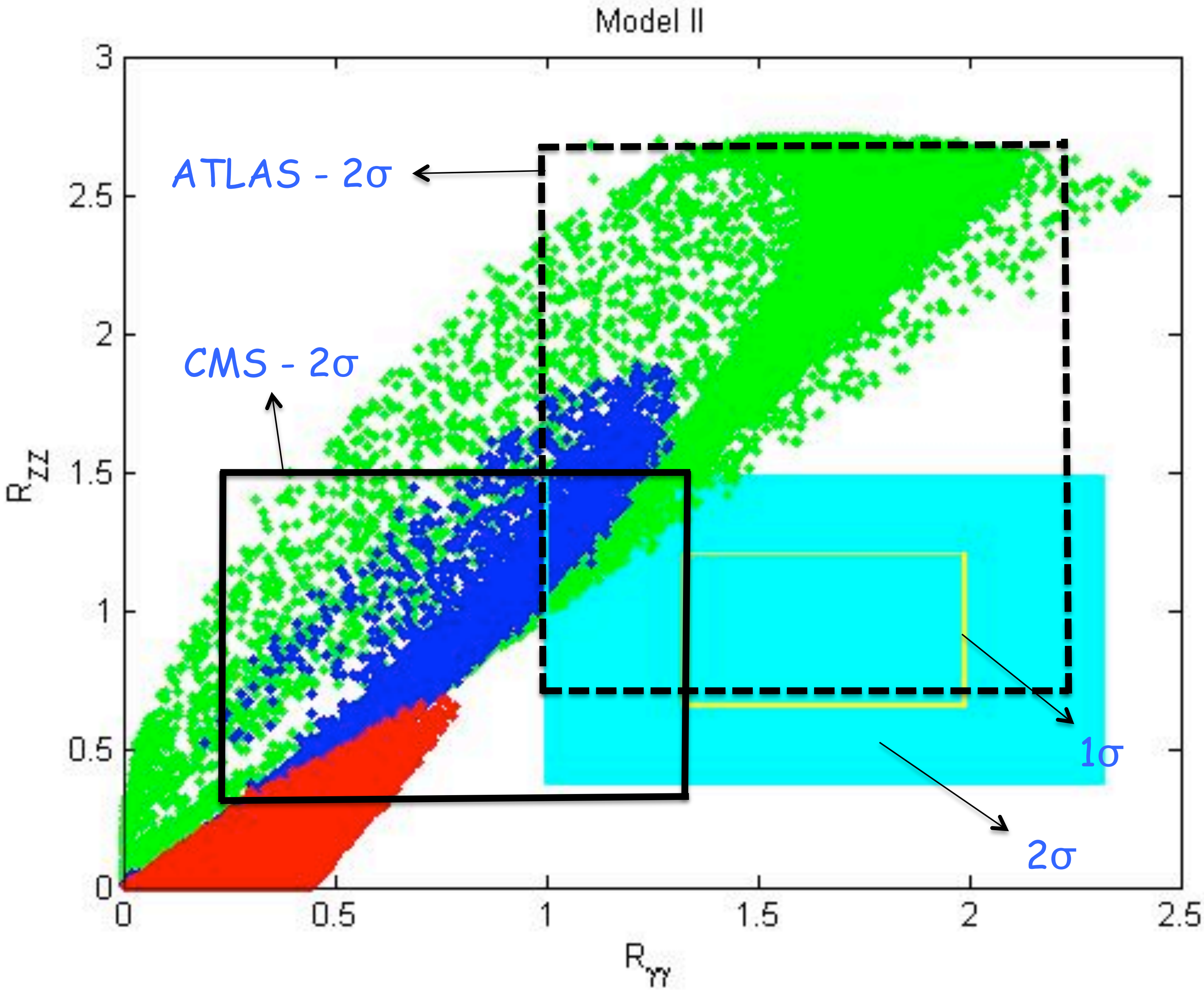

Model I
$|s_2| < 0.1$
green
$0.45 < |s_2| < 0.55$
blue
$|s_2| > 0.83$
red
ATLAS - 2σ
CMS - 2σ
1σ
2σ
R_{ZZ}
$R_{\gamma\gamma}$
0
0.2
0.4
0.6
0.8
1
1.2
1.4



Model II
ATLAS - 2σ
CMS - 2σ
1σ
2σ
R_{ZZ}
$R_{\gamma\gamma}$
0
0.5
1
1.5
2
2.5
3

More mixing means more parameter space to fit the data.

ATLAS (2σ) type I and type II - red regions excluded.

CMS (2σ) type I and type II – part of the red regions are allowed after Moriond.

Blue and green regions are still allowed by both experiments.

<u>With current data no significant difference is found between green and blue regions.</u>

<u>However, (very) large values of $|s_2|$ are excluded.</u>

Third (very short) story

Degenerate states?

P.M. Ferreira, H. E. Haber, R. S., J. P. Silva, Phys. Rev. D.87 (2013) 055009.

Degenerate states?

Is it possible that the "excess" in the h -> $\gamma\gamma$ is due to two 2HDMs degenerate states?

Choices for the degenerate pairs: (h, A), (h, H), or (H,A) or even (h, H, A)

Degenerate Higgs mass of 125 GeV

One of the neutral Higgs boson has SM-like couplings (±20%) to W and Z bosons

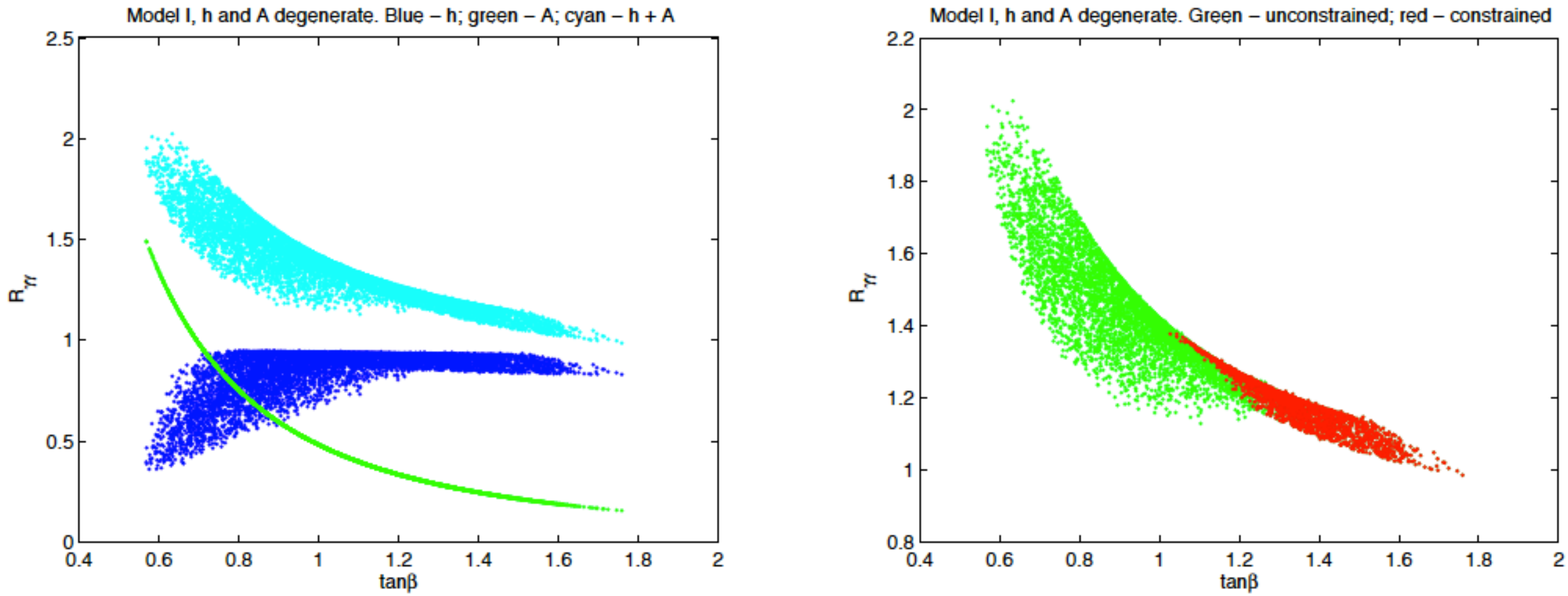
Impose 2HDM constraints

Perform scan focusing on $0.5 < \tan\beta < 2.0$

P.M. Ferreira, H. E. Haber, R. S., J. P. Silva, Phys. Rev. D.87 (2013) 055009.

A. Drozd, B. Grzadkowski, J.F. Gunion and Y. Jiang, 1211.3580

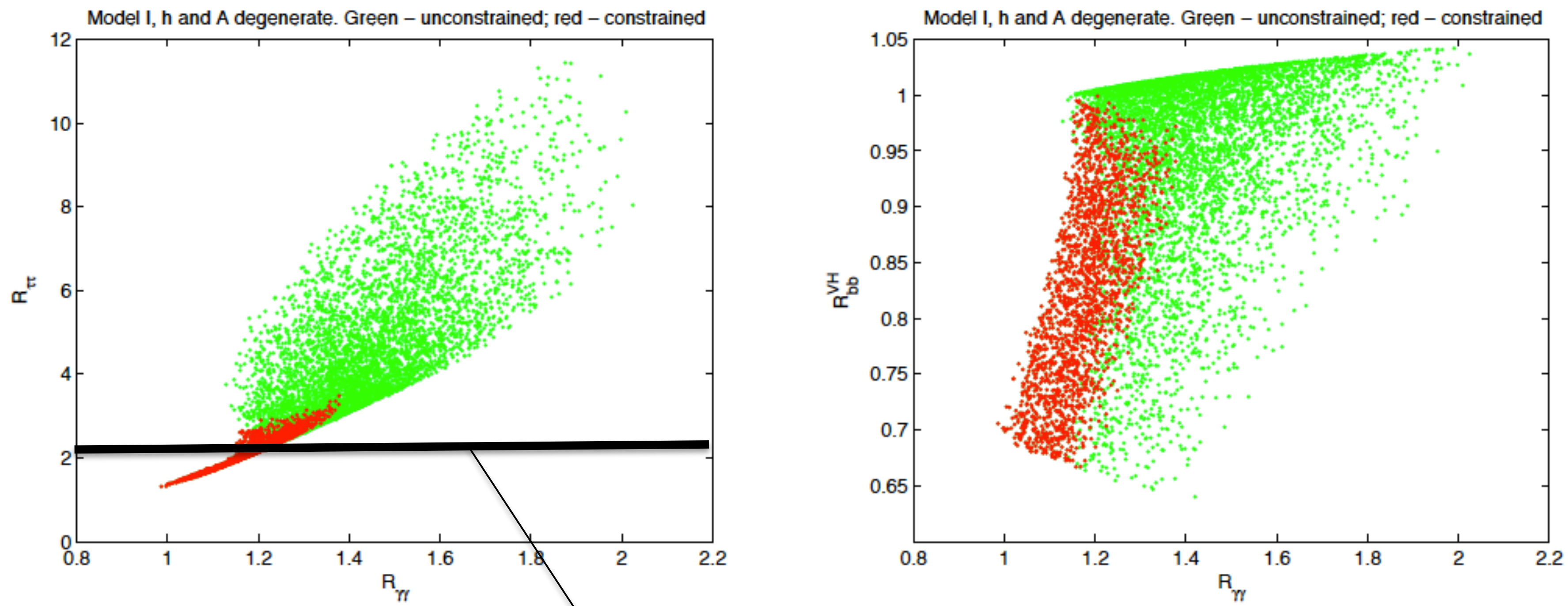
Is it possible that the "excess" in the h -> γγ is due to two 2HDMs degenerate states?



Left panel: $R_{\gamma\gamma}$ as a function of $\tan\beta$ for h (blue), A (green), and the total observable rate (cyan), obtained by summing the rates with intermediate h and A, for the unconstrained scenario.

Right panel: Total rate for $R_{\gamma\gamma}$ as a function of $\tan\beta$ for the constrained (red) and unconstrained (green) scenarios.

If the results on h -> ττ are confirmed all the degenerate scenarios will soon be (are?) excluded



Left panel: Total R_{TT} (h and A summed) as a function of $R_{\gamma\gamma}$ for the constrained (red) and unconstrained (green) scenarios. Right panel: R_{bb}^{VH} (h and A summed) as a function of $R_{\gamma\gamma}$ for the constrained (red) and unconstrained (green) scenarios.

ATLAS and CMS - 2σ

Flavour constraints play an important role.

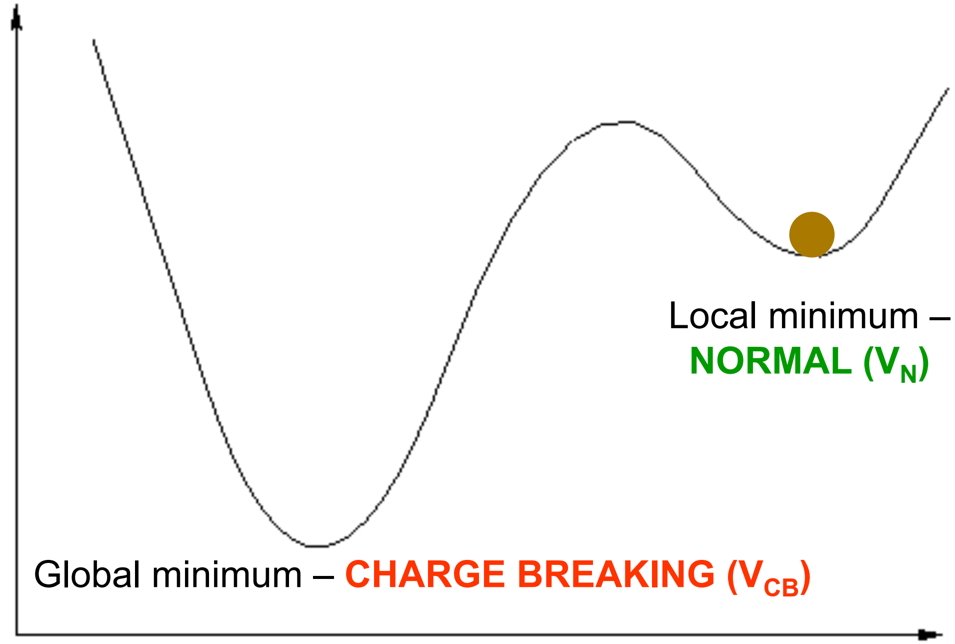
Fourth story

Avoiding death by vacuum in 2HDM

A. Barroso, P.M. Ferreira, I.P. Ivanov, R. S., J. P. Silva, 1211.6119

A. Barroso, P.M. Ferreira, I.P. Ivanov, R. S., 1303.5098

Is it possible to have a charged vacuum (and a massive photon) in the SM)? Is it be possible to break electric charge in the SM? What about CP?



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

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

True facts about SSB in the SM

In the SM we have only one doublet. The most general vacuum configuration can be reduced by an SU(2) rotation to the form

Charged part

$$\Phi_{SM} = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

which by the way also means that no CP-violation can come from the scalar sector (phase can be rotated away).

Charge breaking in 2HDMs

$$\begin{pmatrix} v_2 \\ v_3 \end{pmatrix} \quad \begin{pmatrix} 0 \\ v_1 e^{i\theta} \end{pmatrix}$$

The mass spectrum of the gauge bosons in 2HDM is

$$m_1^2 = m_2^2 = \frac{g^2 v^2}{4}$$

$$m_3^2 = \frac{1}{8}\left[v^2\left(g^2 + g'^2 Y^2\right) + \sqrt{v^4\left(g^2 + g'^2 Y^2\right)^2 - 16\, g^2 g'^2\, v_1^2\, v_2^2 Y^2}\right]$$

$$m_4^2 = \frac{1}{8}\left[v^2\left(g^2 + g'^2 Y^2\right) - \sqrt{v^4\left(g^2 + g'^2 Y^2\right)^2 - 16\, g^2 g'^2\, v_1^2\, v_2^2 Y^2}\right]$$

Look, It's the...
PHOTON?

two ways to recover the photon

$v_1 = 0$ ⇒ SM

$v_2 = 0$ ⇒ Alignment, or else...

… charge is broken!

Charge breaking is possible in the 2HDM. Suppose we live in a 2HDM world. Are we in danger?...

Three minimum field configurations

- ▶ **NORMAL** $\Phi_1 = \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \; ; \; \Phi_2 = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$
- ▶ **CHARGE BREAKING** $\Phi_1 = \begin{pmatrix} 0 \\ v'_1 \end{pmatrix} \; ; \; \Phi_2 = \begin{pmatrix} \alpha \\ v'_2 \end{pmatrix}$
- ▶ **CP BREAKING** $\Phi_1 = \begin{pmatrix} 0 \\ v'_1 + i\delta \end{pmatrix} \; ; \; \Phi_2 = \begin{pmatrix} 0 \\ v'_2 \end{pmatrix}$

True facts about SSB in 2HDMs – the complete epic

1. 2HDM have at most two minima
2. Minima of different nature never coexist
3. Unlike normal minima, CB and CP minima are uniquely determined
4. If a 2HDM has <u>only one</u> normal minimum then this is the absolute minimum – all other SP if they exist are saddle points
5. If a 2HDM has <u>a</u> CP breaking minimum then this is the absolute minimum – all other SP if they exist are saddle points

Regarding vacuum stability, 2HDMs are tree-level stable!

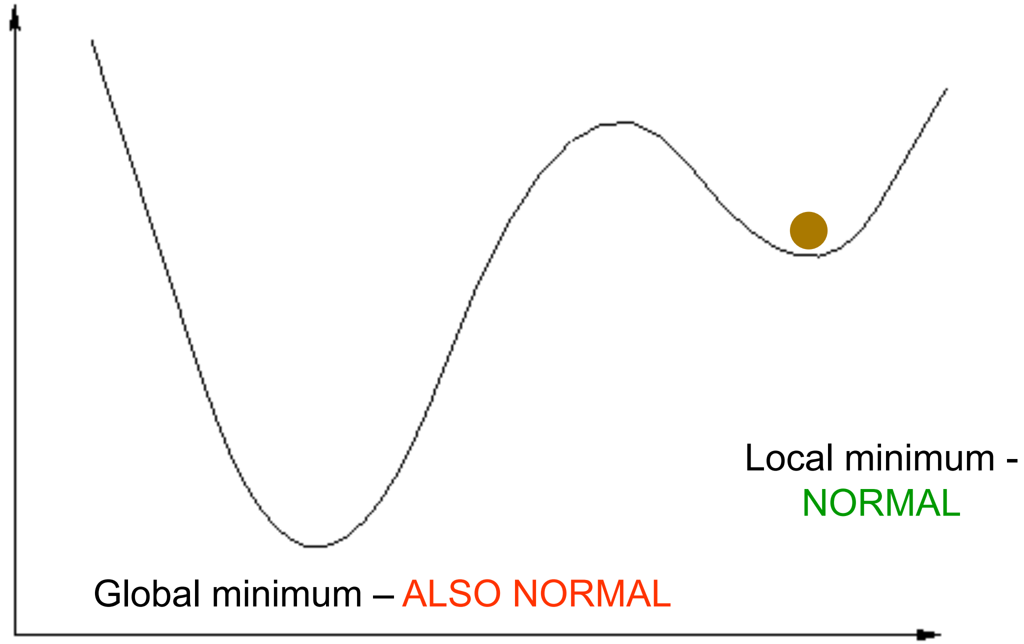
➡ PLB603 (2004), PLB632(2006), PLB652(2007) A. Barroso, P. Ferreira, R.S.

➡ Eur. Phys. J. C48(2006)805 M. Maniatis, A. von Manteuffel, O. Nachtmann and F. Nagel

➡ PRD75(2007)035001, PRD77(2008)15017 I. Ivanov

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!!

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

Necessary conditions:

$$\boxed{\begin{array}{c} m_{11}^2 + k^2\, m_{22}^2 \; < \; 0 \\[2em] \sqrt[3]{x^2} + \sqrt[3]{y^2} \; \leq \; 1 \end{array}}$$

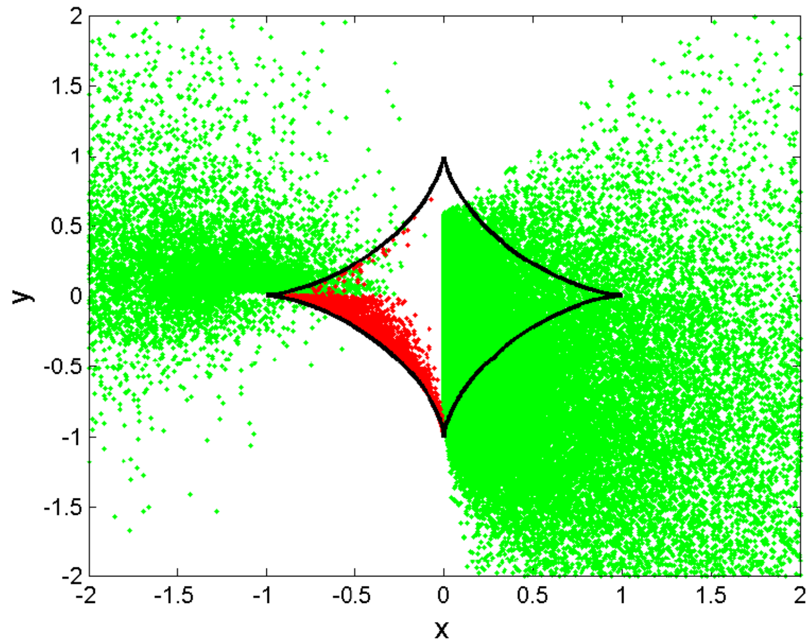
Interior of an astroid

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

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

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

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



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

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

IF D < 0 PANIC!

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

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...

Scan

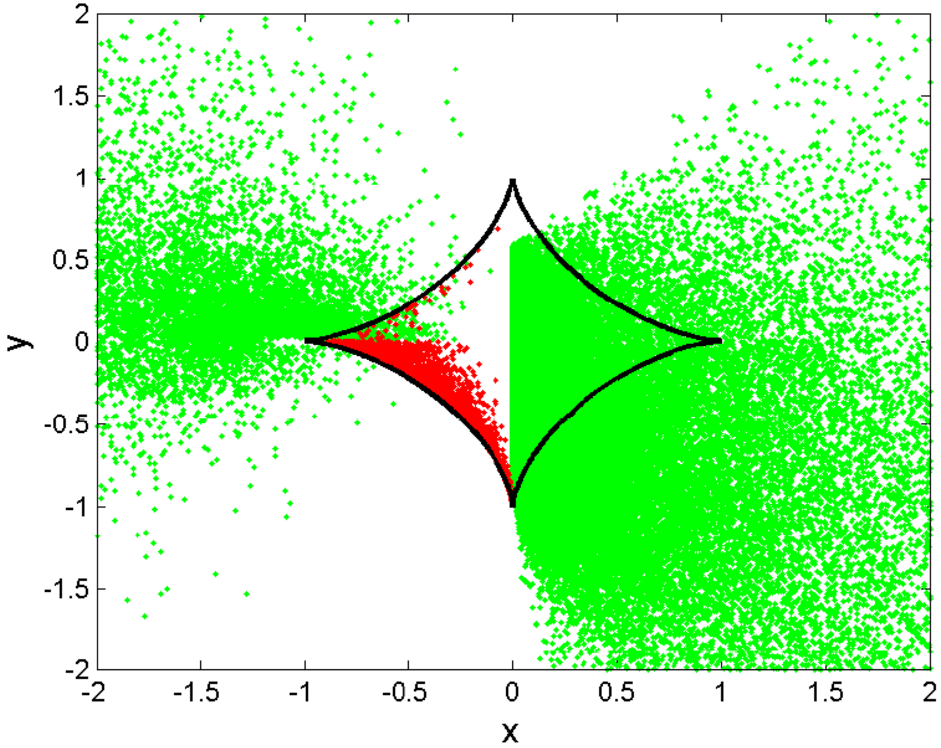
- Generate random values for all potential's parameters, such that m_h = 125 GeV, all remaining masses > 90 GeV, < 800 GeV, $1 < \tan\beta < 30$ and $\sin\alpha$ free.

- Ensure the potential obeys all *theoretical constraints* (unitarity, vacuum stability, etc).

- Impose *current experimental bounds.*

- Calculate all branching ratios and production rates at the LHC.

- Compare with ATLAS and CMS results.

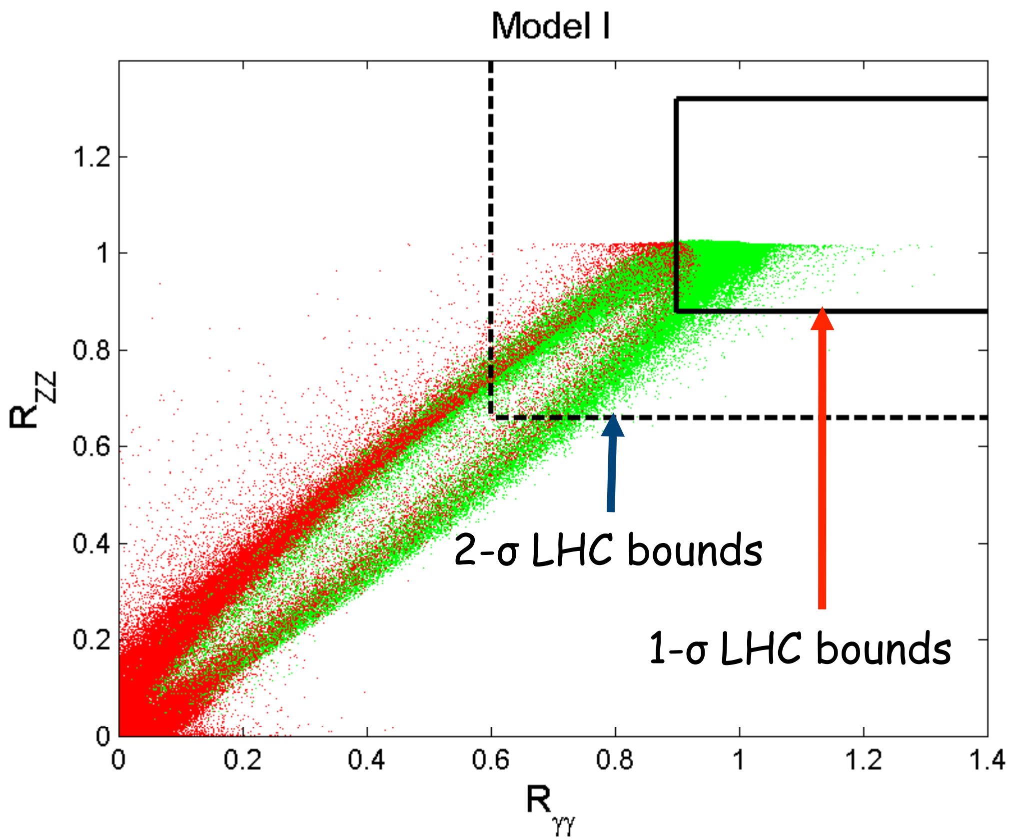


Inside the astroid: two minima
In red: panic vacua points

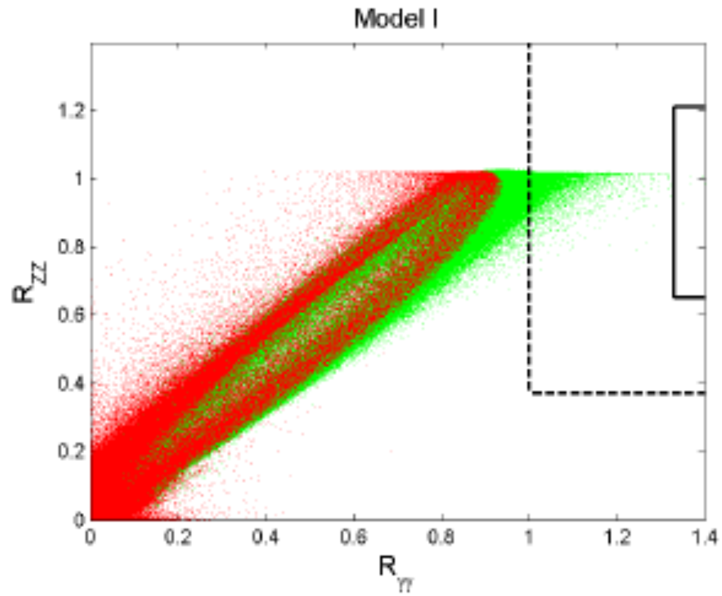
The red points represent choices of 2HDM parameters such that our vacuum, with v = 246 GeV, is NOT the global minimum

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

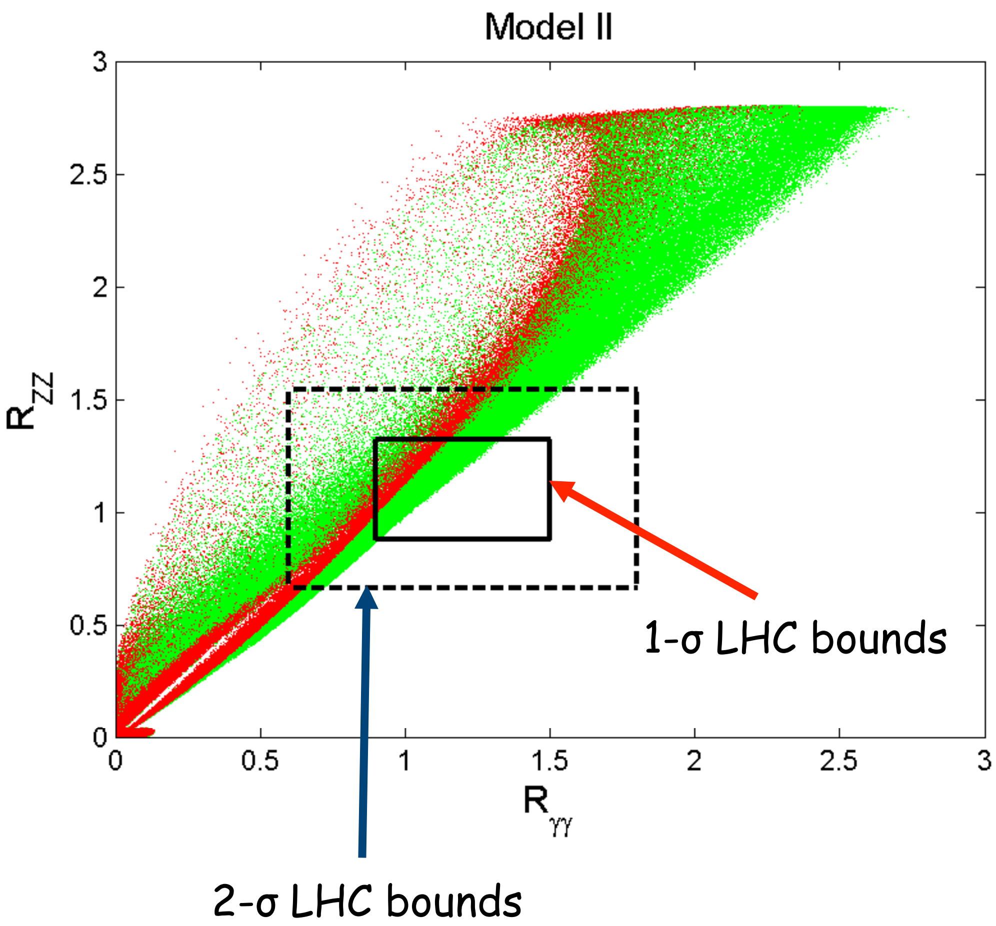
So, what does the LHC tell us? Can we sleep at night?



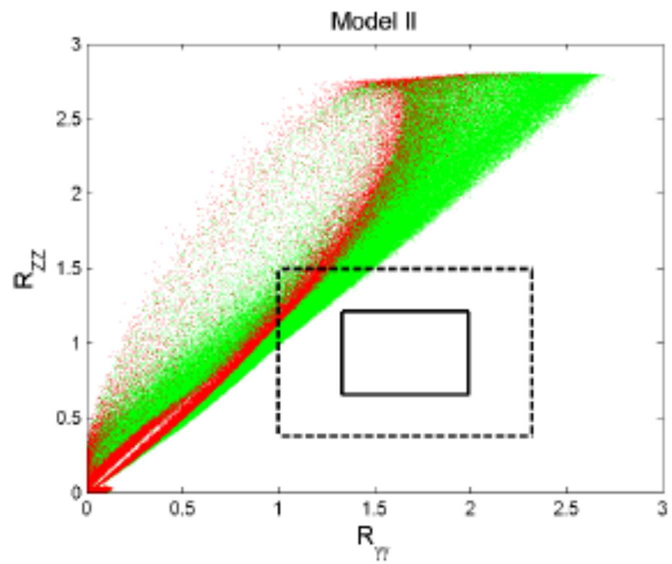
Some panic in Model I
after Moriond!



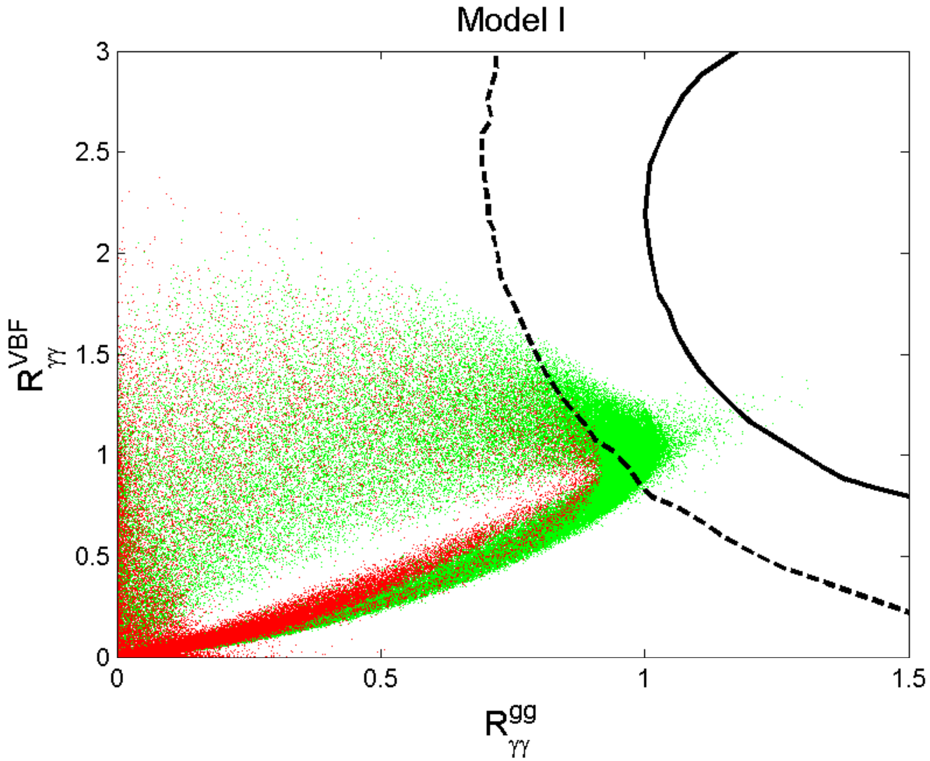
So, what does the LHC tell us? Can we sleep at night?



A lot of panic in Model II after Moriond!

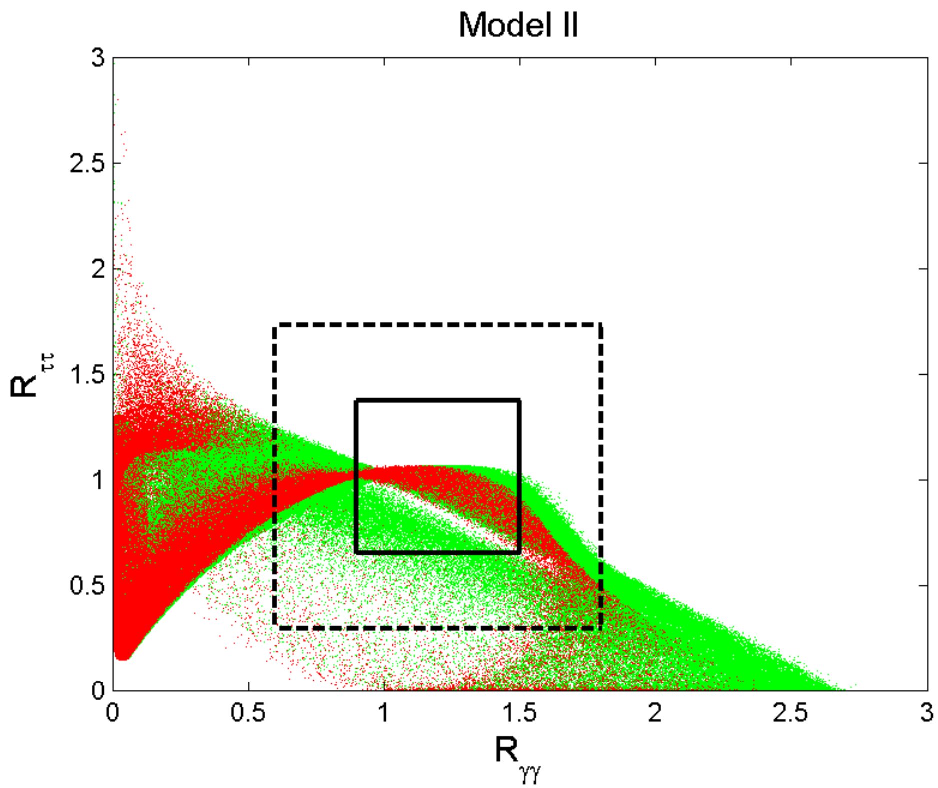


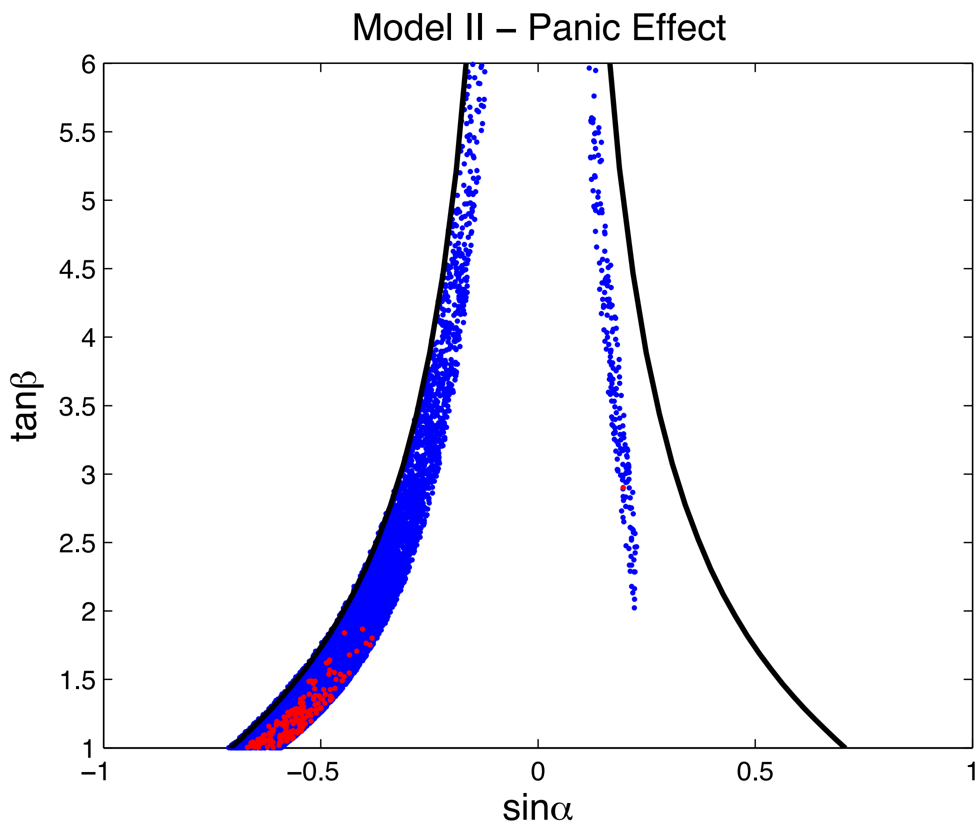
So, what does the LHC tell us? Can we sleep at night?



ATLAS only

A lot of panic in Model II!





In red we present the panic points. Excluding these points goes unnoticed in a scan.

$$\boxed{D = m_{12}^2(m_{11}^2 - k^2 m_{22}^2)(\tan\beta - k) > 0} \qquad k = \sqrt[4]{\frac{\lambda_1}{\lambda_2}}$$

Conclusions

- In the CP-conserving 2HDM the lightest CP-even 125 GeV is being cornered into the SM-like limit although the region near $\sin(\beta+\alpha)=1$ is still allowed in type II.

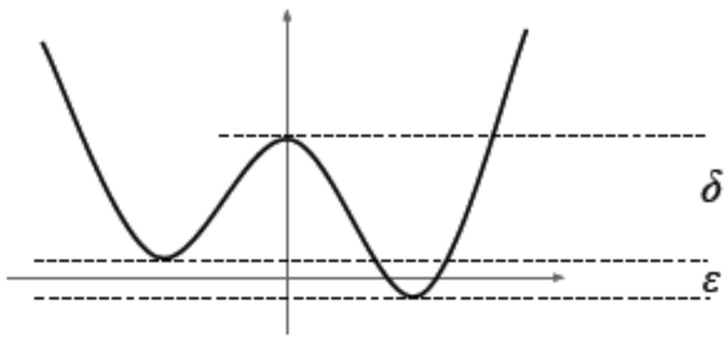
- When all masses but the one from the lightest CP-even scalar are above 600 GeV, the two models are even closer to the SM-like limit. However the $\sin(\beta+\alpha)=1$ region still survives in Type II.

- Data can be used to constrain the amount of scalar-pseudo-scalar mixing. Results are still “weak”.

- Degenerate sates “will soon be killed” by $h \to \tau\tau$ together with flavour constraints.

- Meta-stability bounds have to be used. Panic points are not excluded by data (yet). Sleep safe but keep an eye on the panic vacuum.

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.

Collider physics can give information you thought only cosmology would provide

Epilogue

Feel the gladness of MHM*!
What though the SM which was once so bright
Be now for ever taken from my sight,
Though nothing can bring back the hour
Of splendour in the SM, of glory in one doublet;
We will grieve not, rather find
Strength in what remains behind;
In multi-Higgs models
Which having been must ever be;
In the many scalars that spring
Out of human imagination;
In the faith that looks through death,
In years that bring the philosophic mind.

Wordsworth 1807 Ode – "Slightly" modified and very biased version of Intimations of Immortality from Recollections of Early Childhood

* Multi-Higgs models

BUP