2HDM at the LHC – the story so far

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PREFACE

The 2HDM Models,the constraints and the scalar

The softly broken Z_2 symmetric 2HDM potential

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

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

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

- CP CONSERVING (N) $\quad \Phi_1 = \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \; ; \; \Phi_2 = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$
- CHARGE BREAKING (CB) $\quad \Phi_1 = \begin{pmatrix} 0 \\ v'_1 \end{pmatrix} \; ; \; \Phi_2 = \begin{pmatrix} \alpha \\ v'_2 \end{pmatrix}$
- 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 and explicit CP-violating

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

- m^2_{12} and λ_5 real, vacuum configuration (CP-conserving)

$$\boxed{\langle\phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix};\ \langle\phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2\end{pmatrix}}$$

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

- m^2_{12} and λ_5 complex, vacuum configuration (explicit CP-violating)

$$\boxed{\langle\phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix};\ \langle\phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2\end{pmatrix}}$$

I. Ginzburg, M. Krawczyk and P. Osland, hep-ph/ 0211371.

8 free parameters + M_W: $m_1,\ m_2,\ \boxed{m_3,}\ m_{H\pm},\ \tan\beta,\ \alpha_{1,2,3},\ Re(m_{12}^2)$

Common features

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

Extending the Z_2 symmetry to the fermions – 4 independent Yukawa Lagrangians

	I	II	III	IV
up	Φ_2	Φ_2	Φ_2	Φ_2
down	Φ_2	Φ_1	Φ_1	Φ_2
lepton	Φ_2	Φ_1	Φ_2	Φ_1

III = I' = Y = Flipped

IV = II' = X = Leptonic

➡ **same charged Higgs-fermions couplings**

➡ **three neutral scalars**

2HDM Lagrangian (CP conserving to CP-violating potential)

- scalars-gauge bosons couplings

$$\boxed{g_{SM}\sin(\beta-\alpha)} \;\rightarrow\; \boxed{g_{SM}(c_\beta R_{11}+s_\beta R_{12})}$$

to CP-violating

- Yukawa couplings

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

$$\boxed{R=\begin{pmatrix} c_1c_2 & s_1c_2 & s_2 \\ -(c_1s_2s_3+s_1c_3) & c_1c_3-s_1s_2s_3 & c_2s_3 \\ -c_1s_2c_3+s_1s_3 & -(c_1s_3+s_1s_2c_3) & c_2c_3 \end{pmatrix}}$$

	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)	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$

to CP-violating

	Type I	Type II	Lepton Specific	Flipped
Up	$\frac{R_{12}}{s_\beta}-ic_\beta\frac{R_{13}}{s_\beta}$	$\frac{R_{12}}{s_\beta}-ic_\beta\frac{R_{13}}{s_\beta}$	$\frac{R_{12}}{s_\beta}-ic_\beta\frac{R_{13}}{s_\beta}$	$\frac{R_{12}}{s_\beta}-ic_\beta\frac{R_{13}}{s_\beta}$
Down	$\frac{R_{12}}{s_\beta}+ic_\beta\frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta}-is_\beta\frac{R_{13}}{c_\beta}$	$\frac{R_{12}}{s_\beta}+ic_\beta\frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta}-is_\beta\frac{R_{13}}{c_\beta}$
Leptons	$\frac{R_{12}}{s_\beta}+ic_\beta\frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta}-is_\beta\frac{R_{13}}{c_\beta}$	$\frac{R_{11}}{c_\beta}-is_\beta\frac{R_{13}}{c_\beta}$	$\frac{R_{12}}{s_\beta}+ic_\beta\frac{R_{13}}{s_\beta}$

The Constraints

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

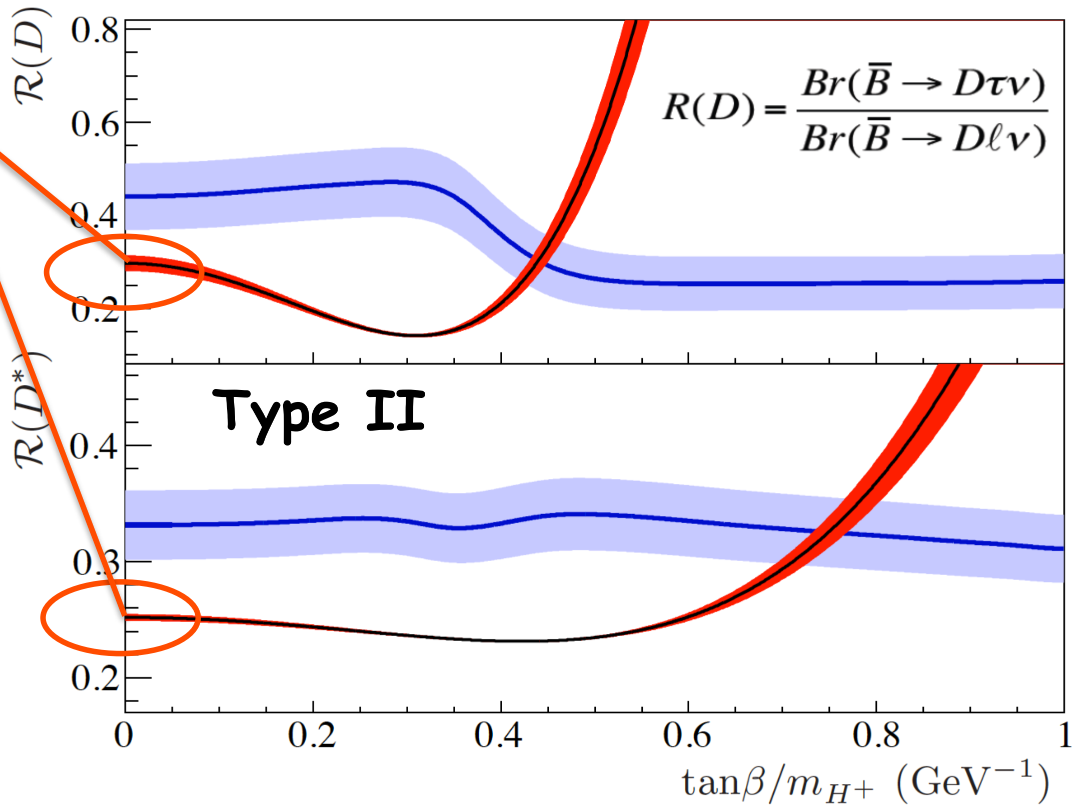


FIG. 2. (Color online) Comparison of the results of this analysis (light gray, blue) with predictions that include a charged Higgs boson of type II 2HDM (dark gray, red). The SM corresponds to $\tan\beta/m_{H^+} = 0$.

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

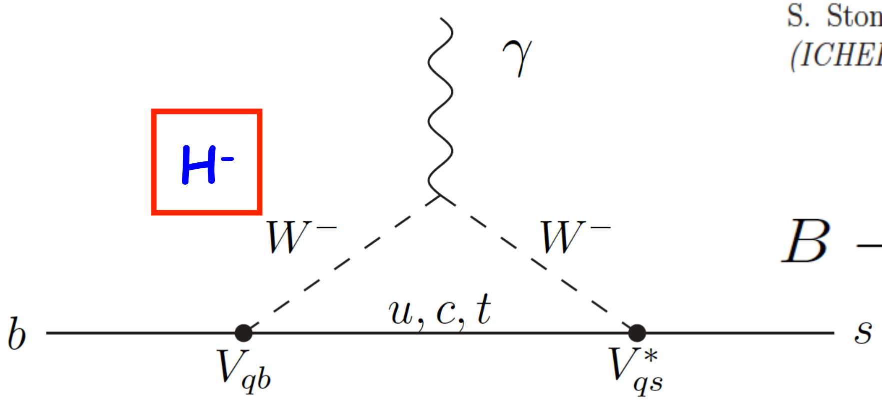
Any $BR(H^+ \to \tau^+\nu)$ $\boxed{m_{H^\pm} \gtrsim 80\ GeV}$

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

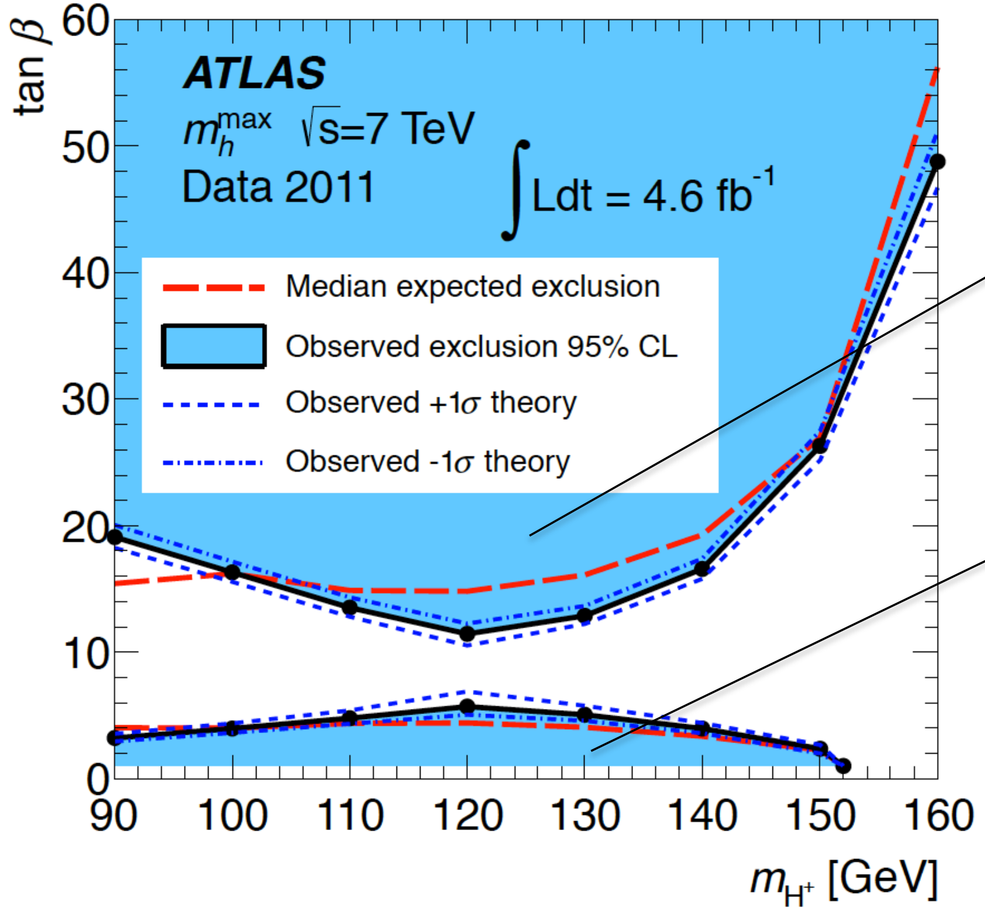


$B \to X_s\gamma$

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

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

Models I and X

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
- $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$

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

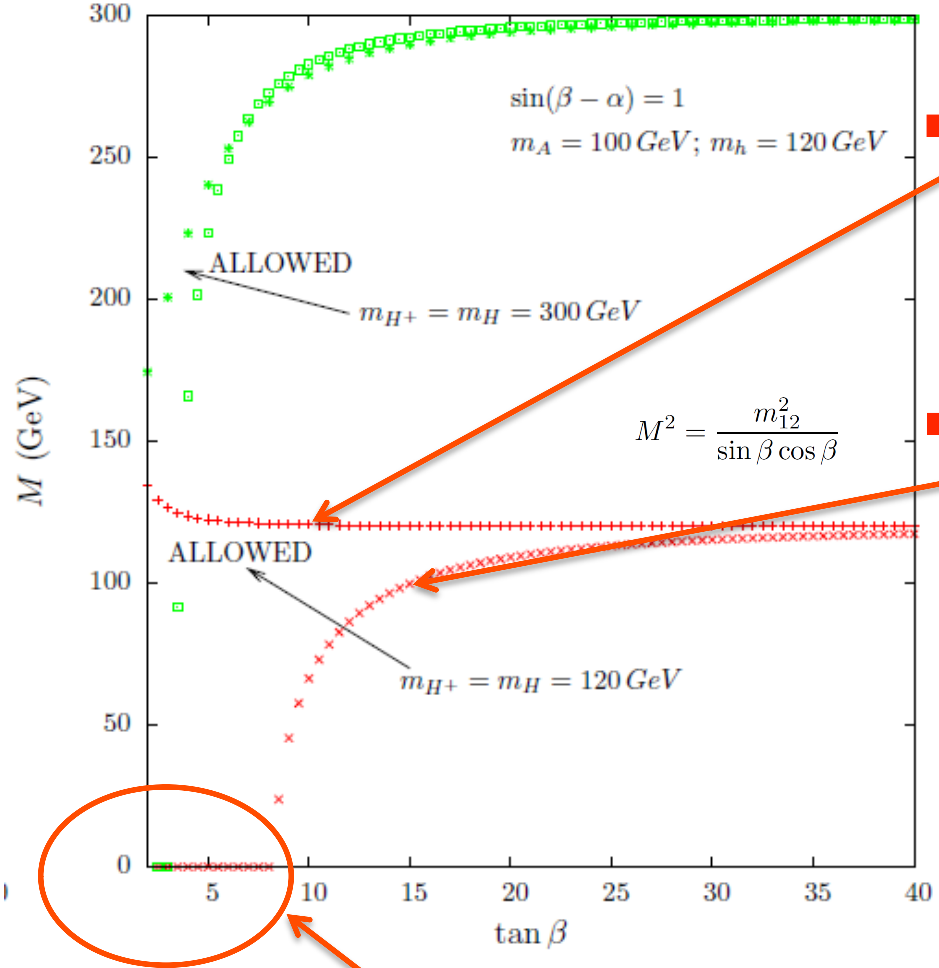
- Precision electroweak constraints

  - 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



potential bounded from below

unitarity limits for quartic Higgs couplings

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

Theoretical

If a 2HDM has only one normal minimum then this is the absolute minimum – all other SP if they exist are saddle points

But it can have (at most) two normal minima – in some cases it can generate a panic vacuum

Pedro Ferreira's talk

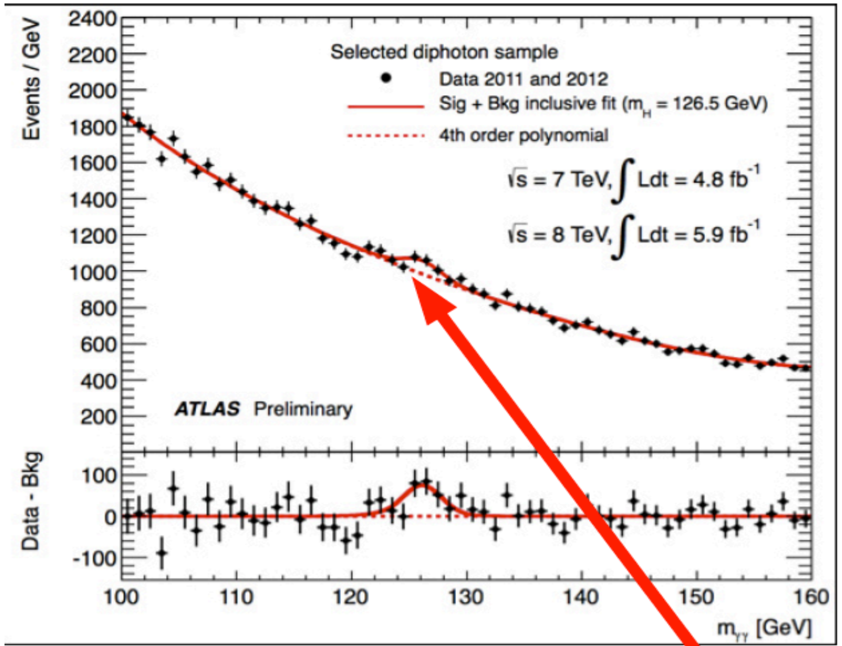
➡ How to avoid the panic vacuum

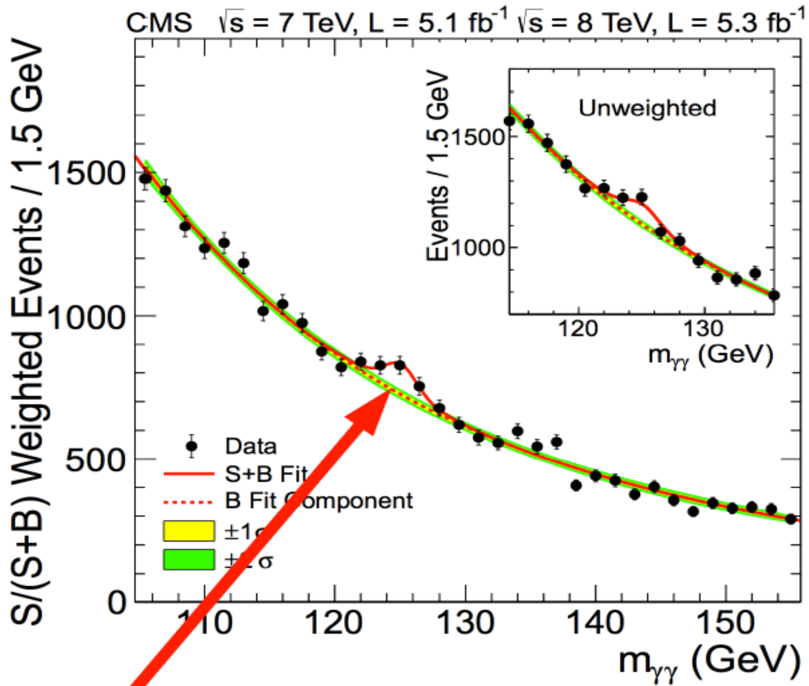
➡ $$\boxed{D = m_{12}^2(m_{11}^2 - k^2 m_{22}^2)(\tan\beta - k) > 0}$$

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

The scalar and the 2HDM

LHC





Scalar!

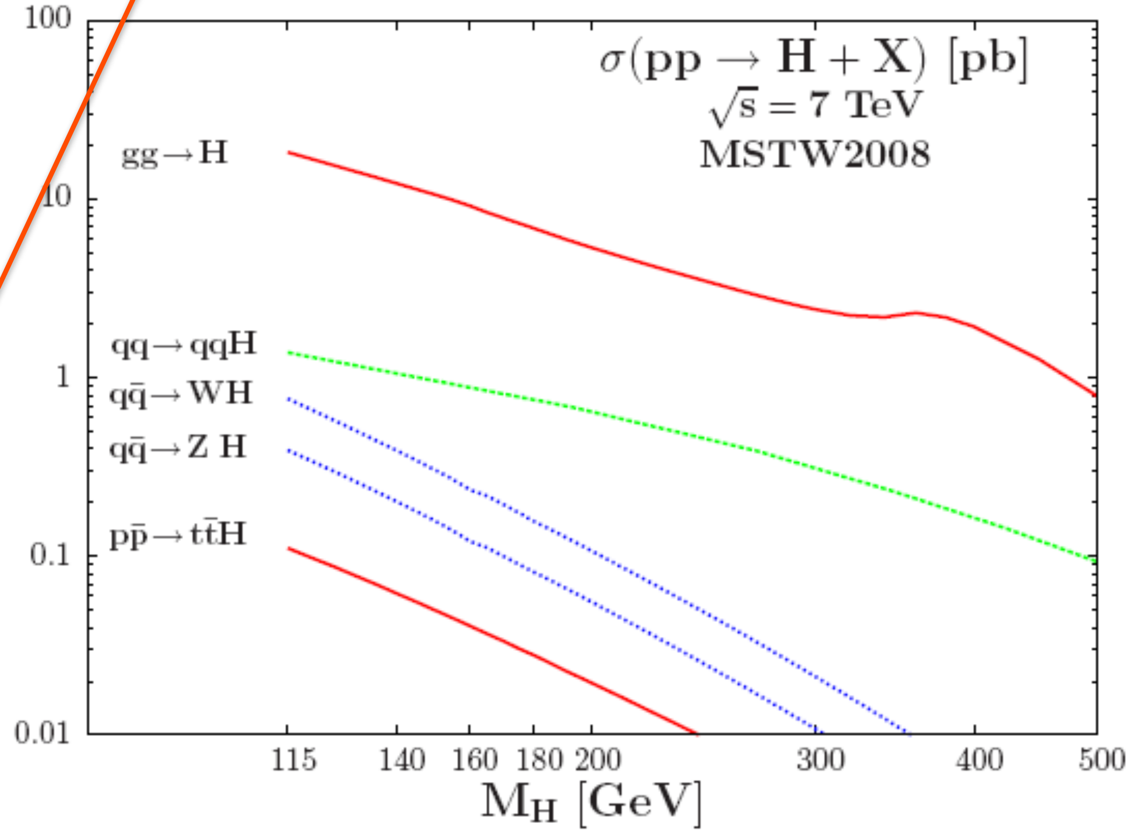
From a 2HDM?

What do we compare to data?

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

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

$$\boxed{R_{ZZ} \approx \sin^2(\beta - \alpha)}$$

if $h \to bb$ 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.

1st story

The lightest scalar in the CP conserving model

- Set m_h = 125 GeV.

- Generate random values for potential's parameters such that

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

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

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

$$1 \leqslant \tan\beta \leqslant 40$$
$$-\frac{\pi}{2} \leqslant \alpha \leqslant \frac{\pi}{2}$$

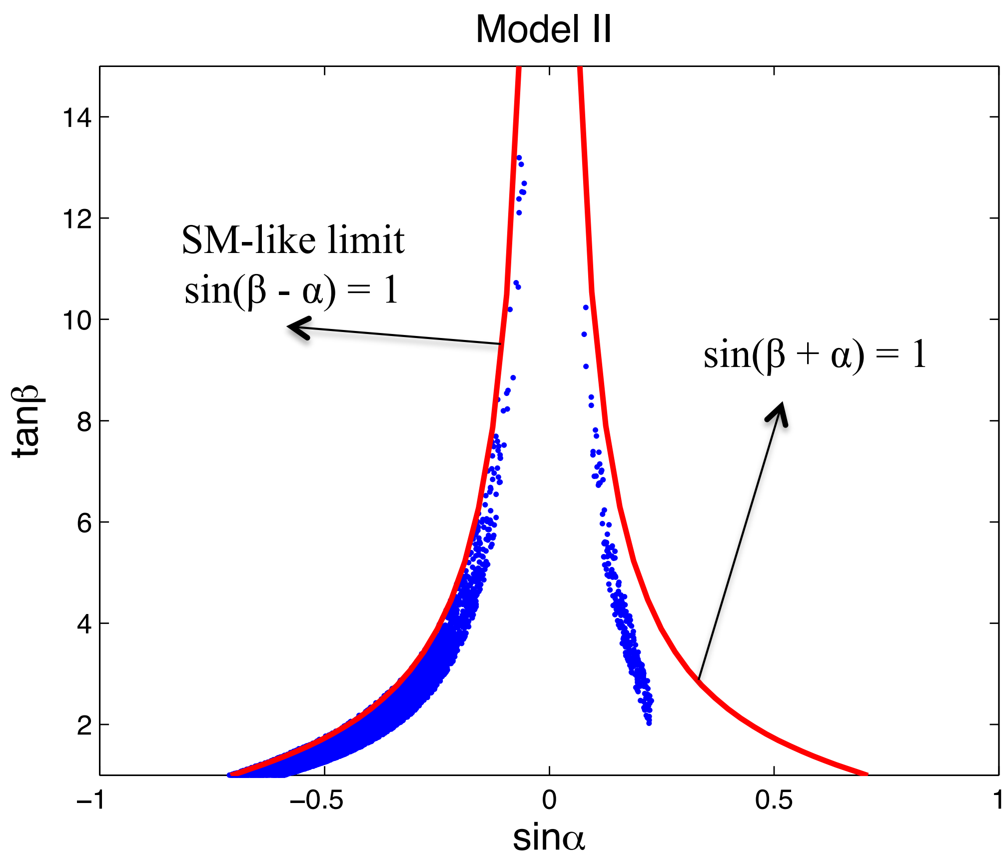
- Impose all experimental and theoretical constraints previously described.

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

- Impose averaged ATLAS and CMS results. We have used

$$\mu_{\gamma\gamma} = 1.66 \pm 0.33$$
$$\mu_{ZZ} = 0.93 \pm 0.28$$
$$\mu_{\tau\tau} = 0.71 \pm 0.42$$

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



At 1σ everything is excluded.

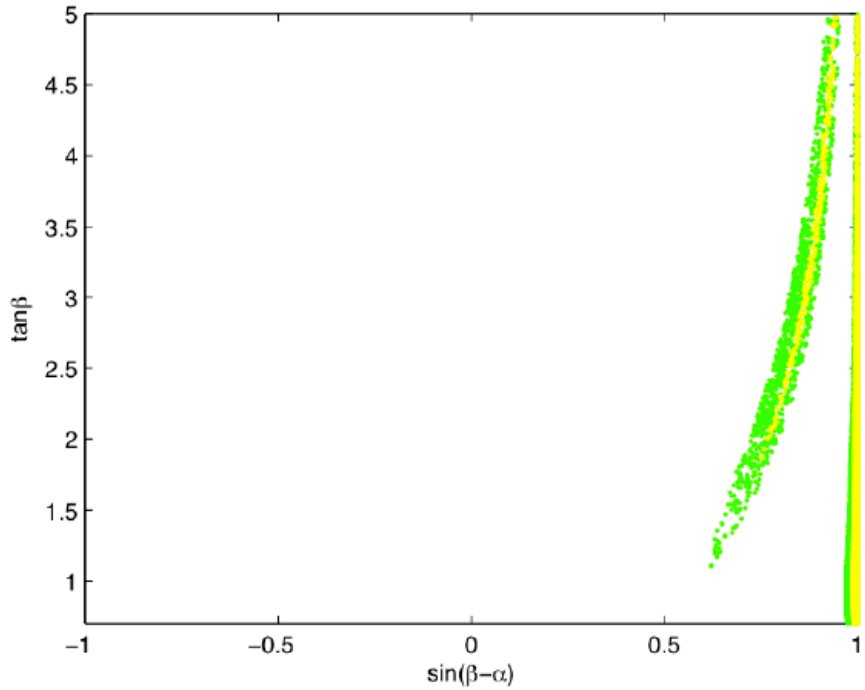
At 2σ (in blue) two regions are still allowed:

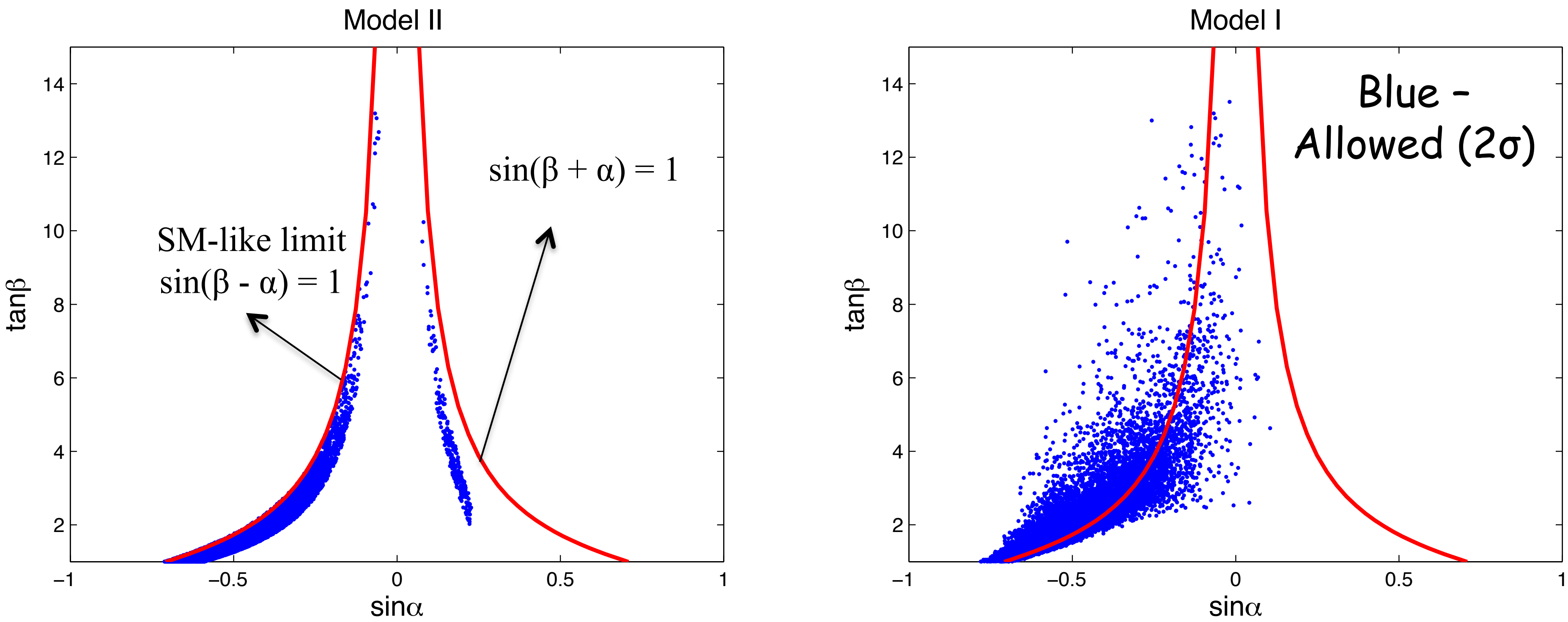
- The region just below the SM-like limit
- The region just below the limit sin(β+α) = 1

Same plot now as a function of sin(β-α)

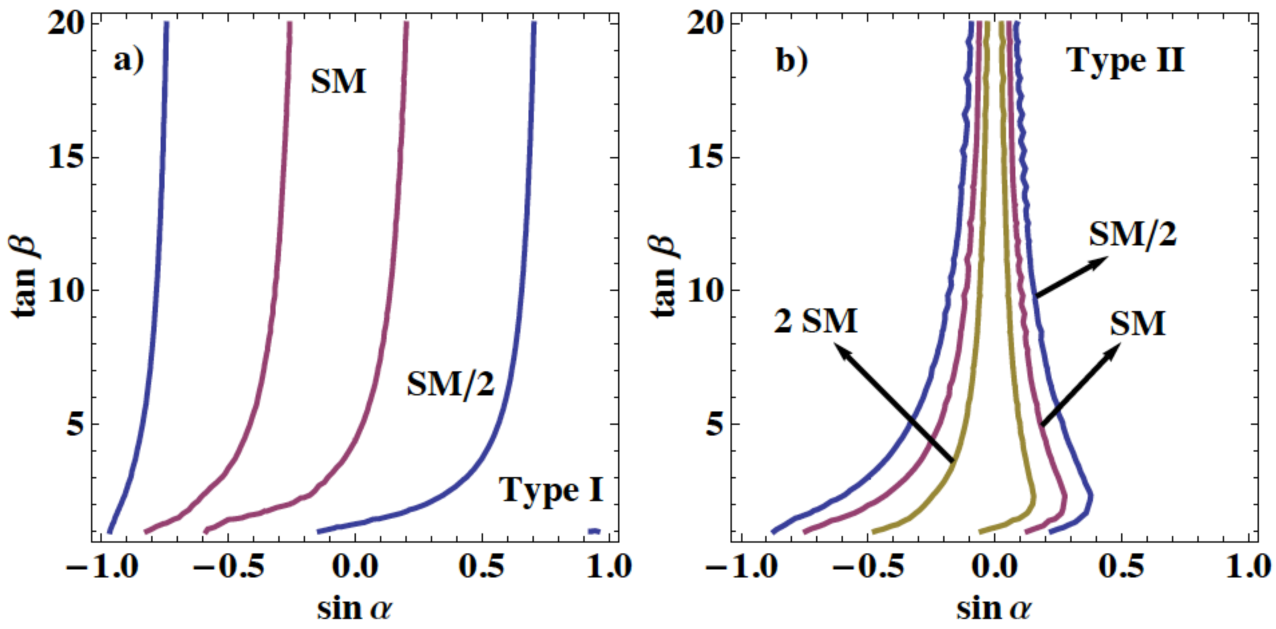
At 2σ (in yellow) and 3σ (in green)

Note that if tanβ >> 1
sin(β-α) ≅ sin(β+α) ≅ cos(α)

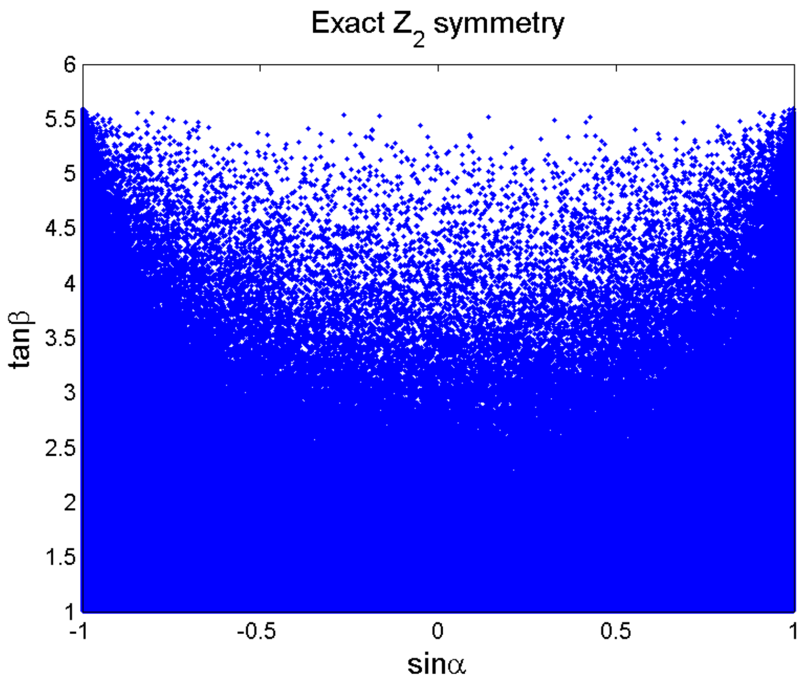




Comparison between type I and type II



Predictions for type I and type II for h -> γγ



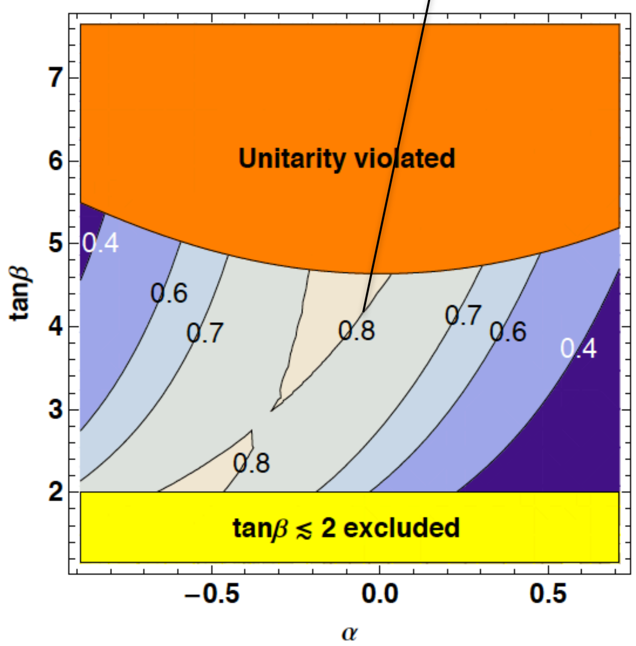
What about the exact Z_2 symmetric scenario?

$0.18 \lesssim \tan\beta \lesssim 5.59$ B. Gorczyca, M. Krawczyk

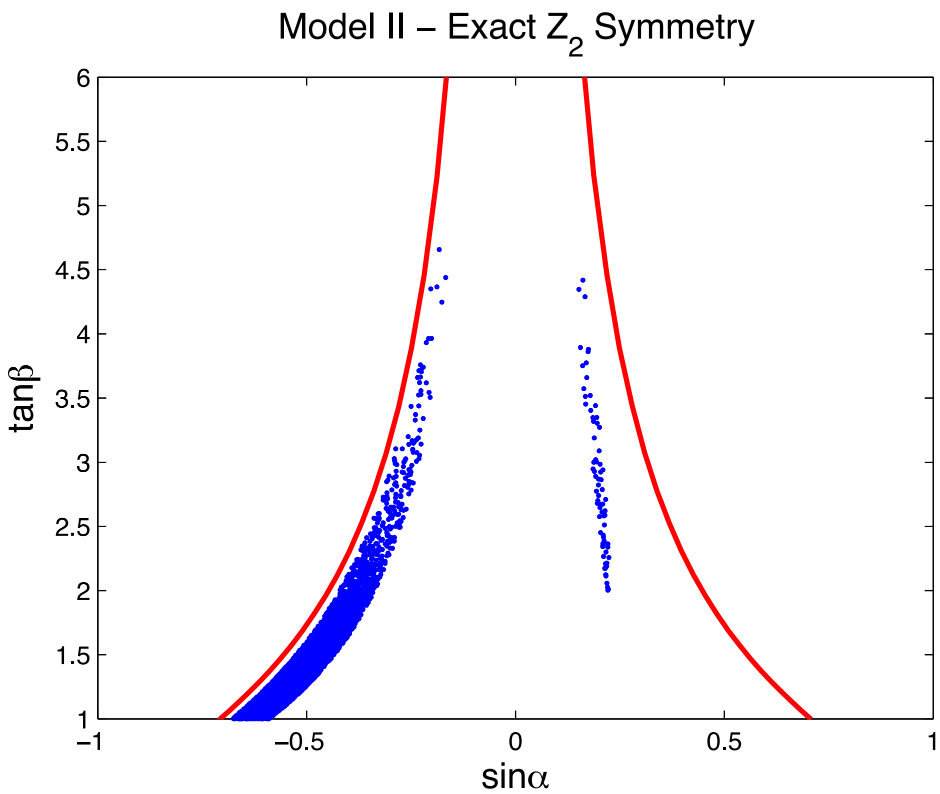
Type I is killed at 2σ

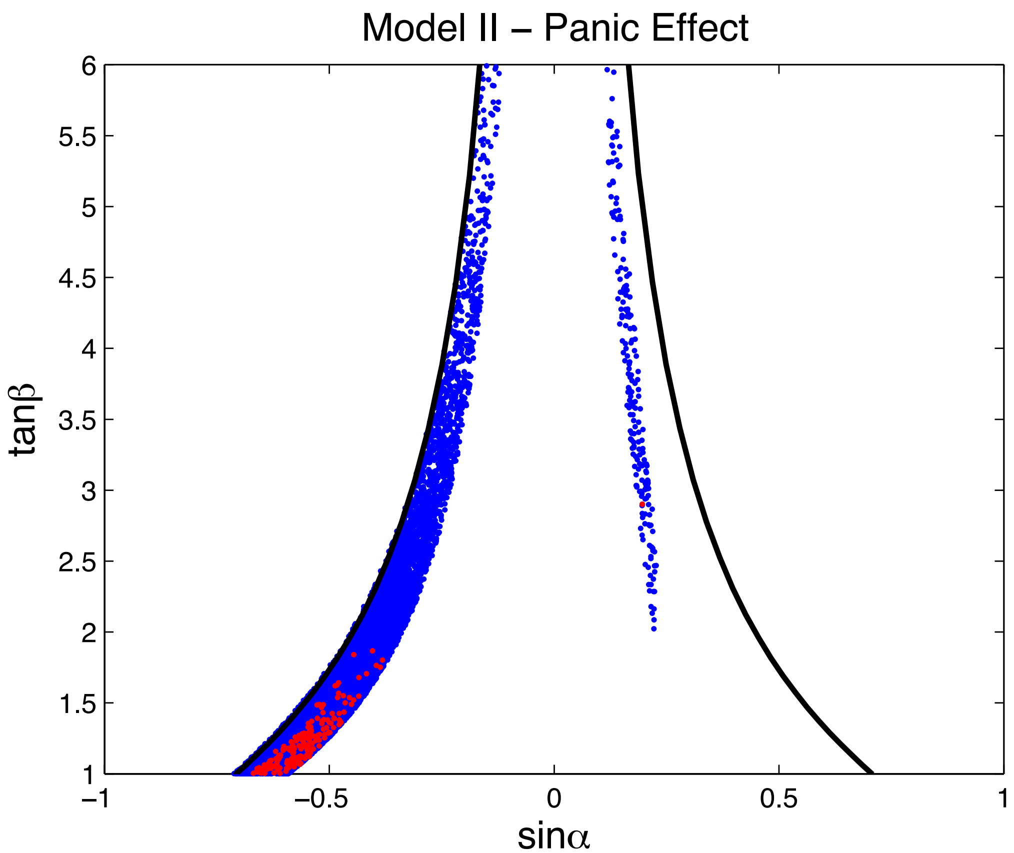
Type II is still allowed at 2σ

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



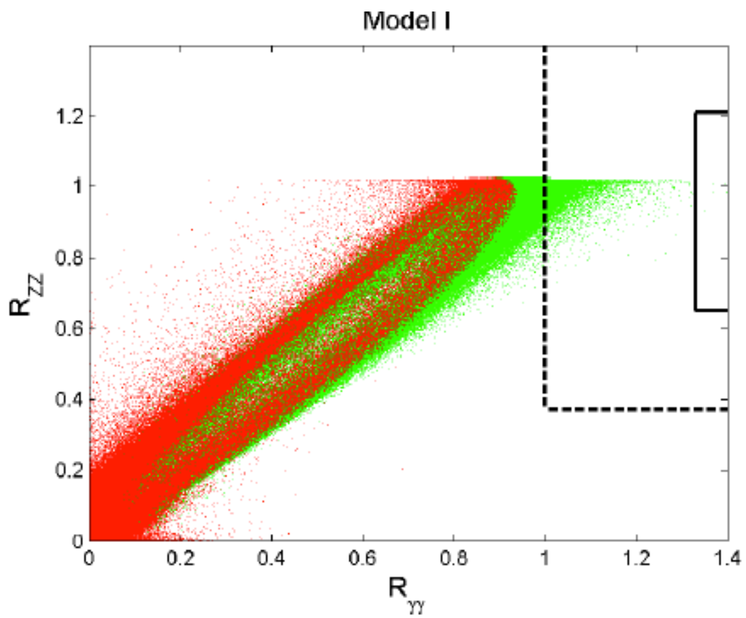
P. Posch
PLB696
(2011) 447.





Panic points – the ones where two normal minima coexist and where the "bad" minimum is below the "good" one.

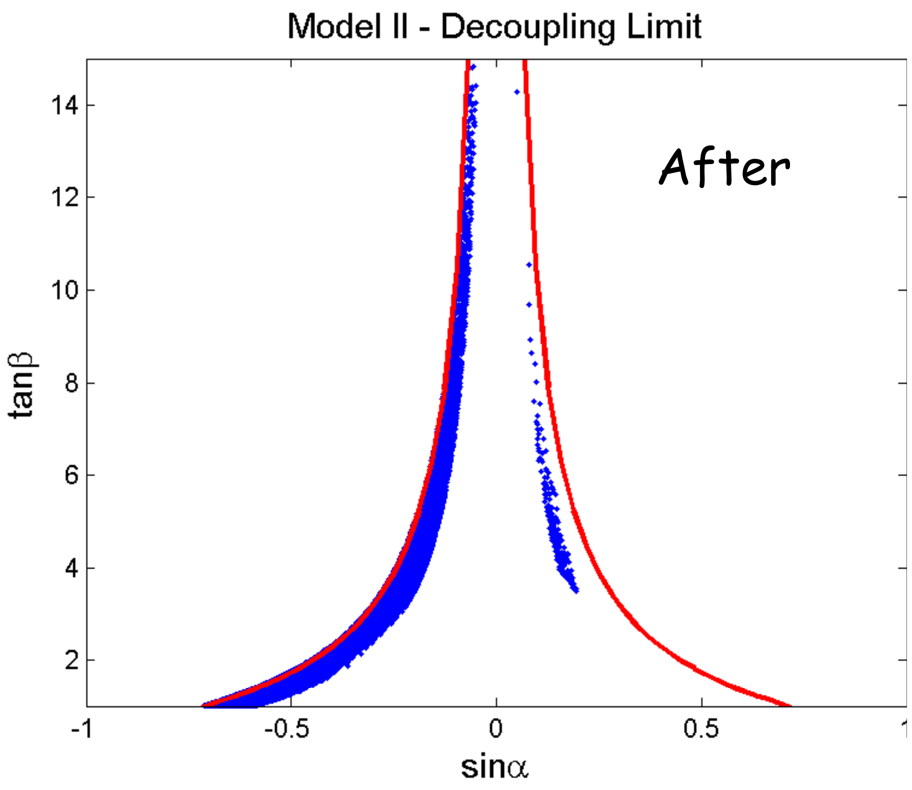
In red we present the panic points. Excluding these points goes unnoticed in a scan.

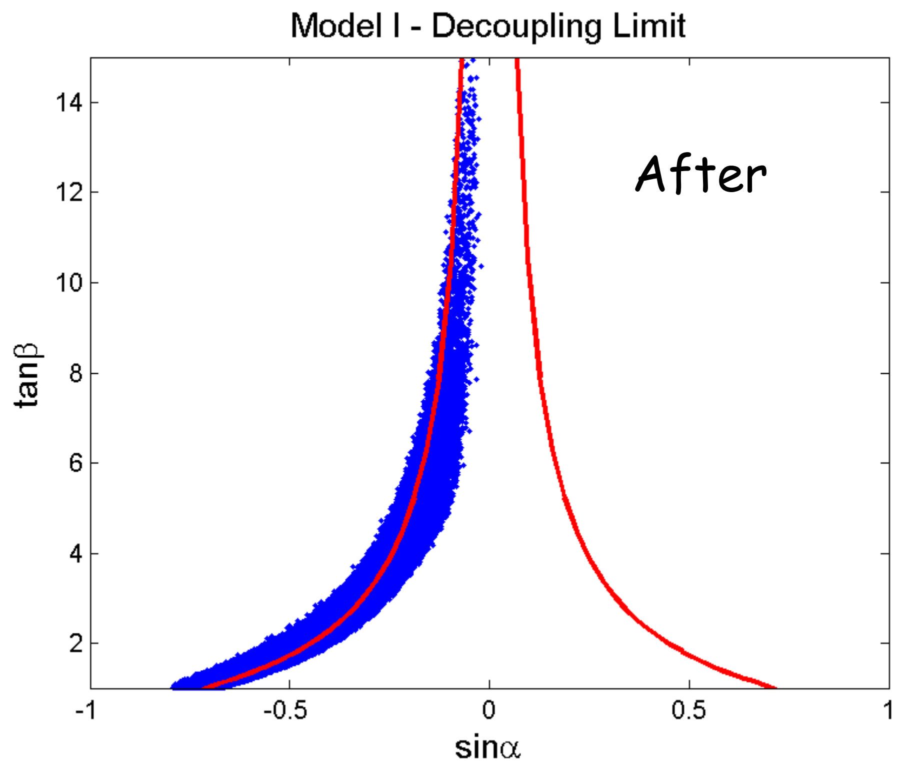


$$\boxed{D = m_{12}^2(m_{11}^2 - k^2 m_{22}^2)(\tan\beta - k) > 0}$$

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

In type I the LHC already allow us to exclude these points at 2σ.

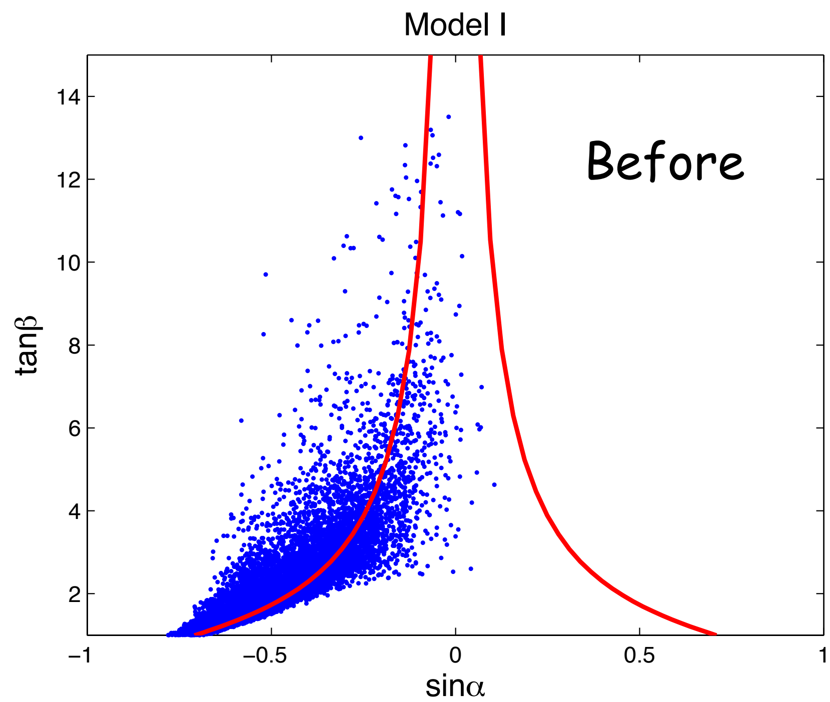


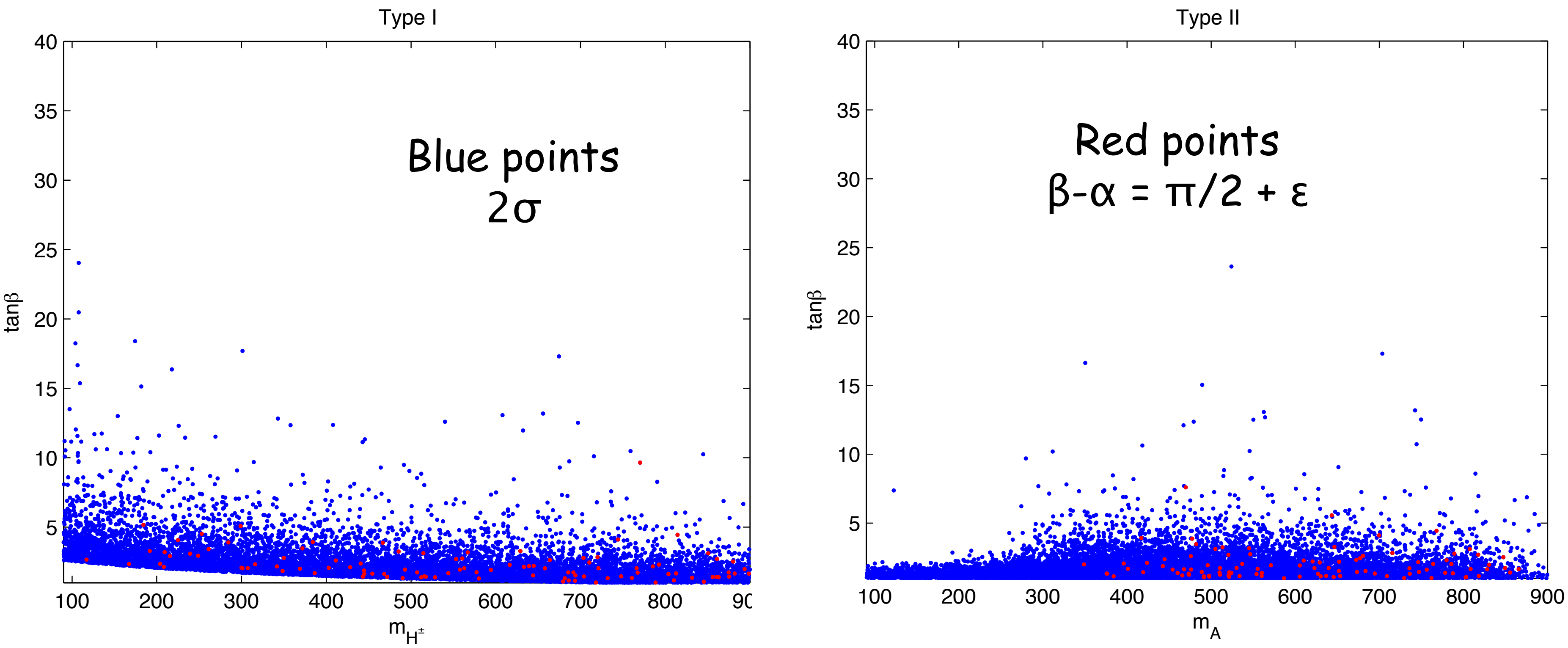


We then took all masses to be above 600 GeV.

At 1σ everything is excluded.

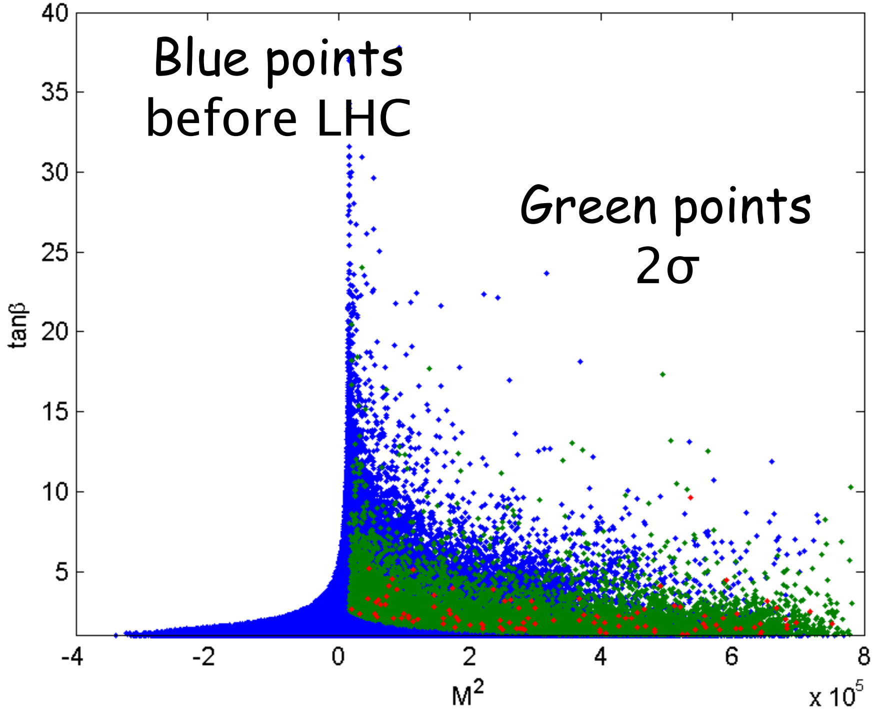
At 2σ (in blue) the blue regions shrink moving closer to the SM-like limit.

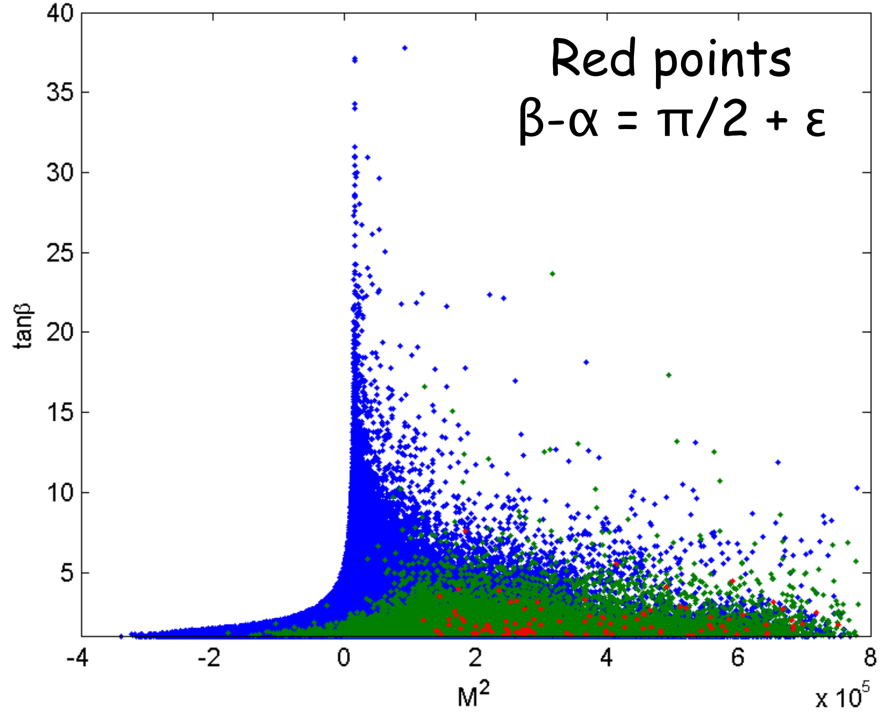




Are we nearly there yet? No, there are still no constraints on the masses.

Same is true for the other masses except for the bound on the charged Higgs mass in type II.





$$M^2 = \frac{m_{12}^2}{\sin\beta\ \cos\beta}$$

Again no special trend is observed for type II. In type I values of positive M^2 seem to be preferred. We saw that the exact Z_2 type I was excluded at 2σ. Now we see that negative M^2 is also excluded.

This is related to the h -> γγ constraint.

2^{nd} story

The lightest scalar in the CP violating model

- Set m_{h1} = 125 GeV.

- Generate random values for potential's parameters such that

$$1 \le \tan\beta \le 30$$

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

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

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

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

$$0 \le \alpha_3 \le \pi/2$$

- Impose all experimental and theoretical constraints previously described.

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

- Impose combined ATLAS and CMS results,

$$\mu_{\gamma\gamma} = 1.66 \pm 0.33$$
$$\mu_{ZZ} = 0.93 \pm 0.28$$
$$\mu_{\tau\tau} = 0.71 \pm 0.42$$

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**

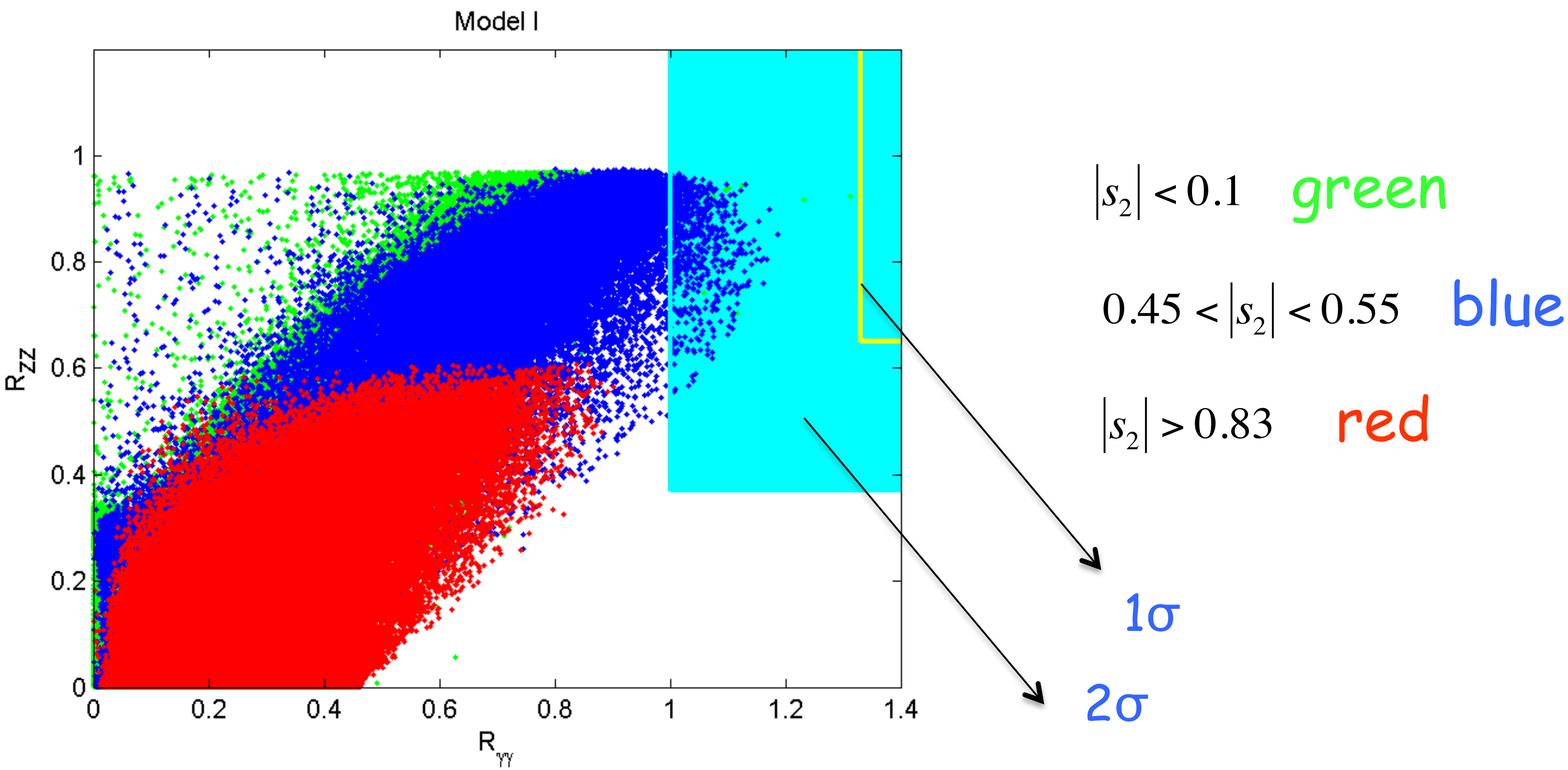
➡ $$m_3^2 = \frac{m_1^2\,R_{13}(R_{12}\tan\beta - R_{11}) + m_2^2\,R_{23}(R_{22}\tan\beta - R_{21})}{R_{33}(R_{31} - R_{32}\tan\beta)}$$

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

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

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

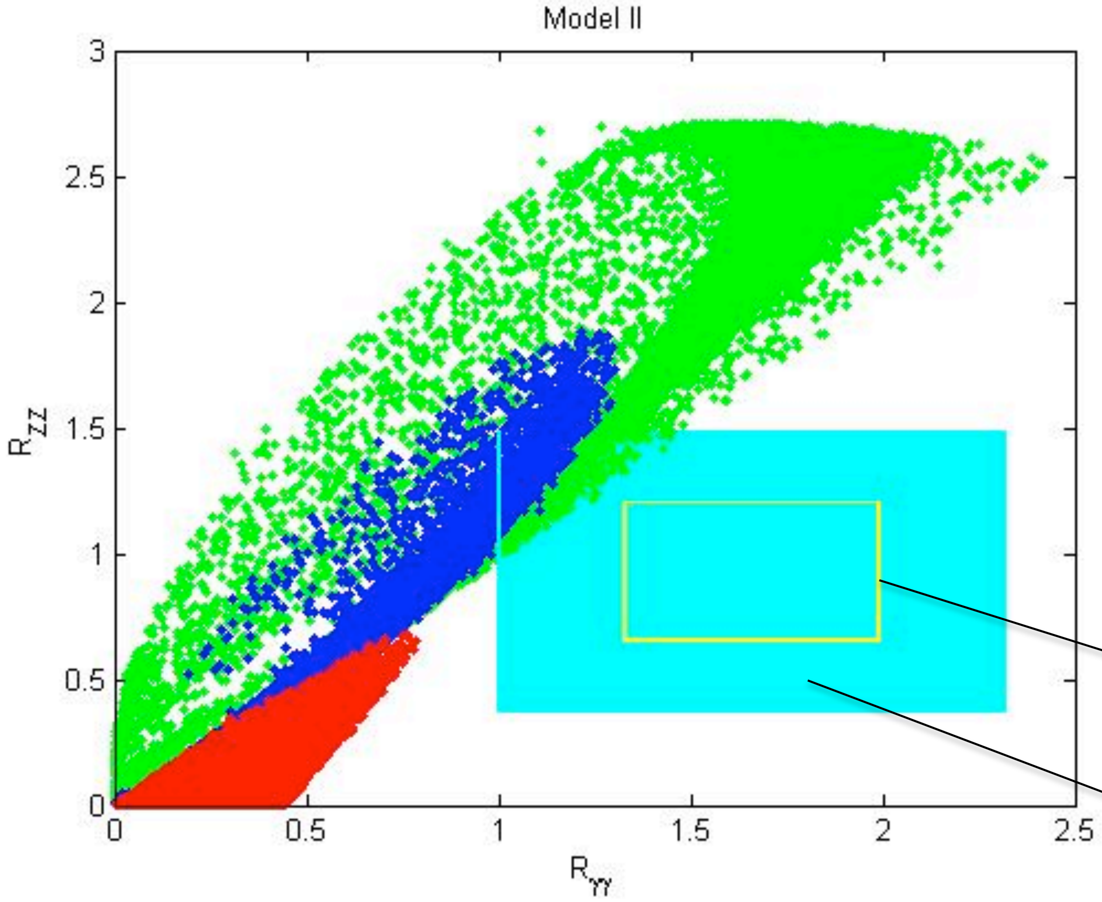
What does LHC data tells about the mixing?



More mixing means more parameter space to fit the data.

In type I everything is excluded at 1σ. At 2σ the red region is excluded while blue and green regions are still allowed.

With current data no significant difference is found between green and blue regions.



$|s_2| < 0.1$ green

$0.45 < |s_2| < 0.55$ blue

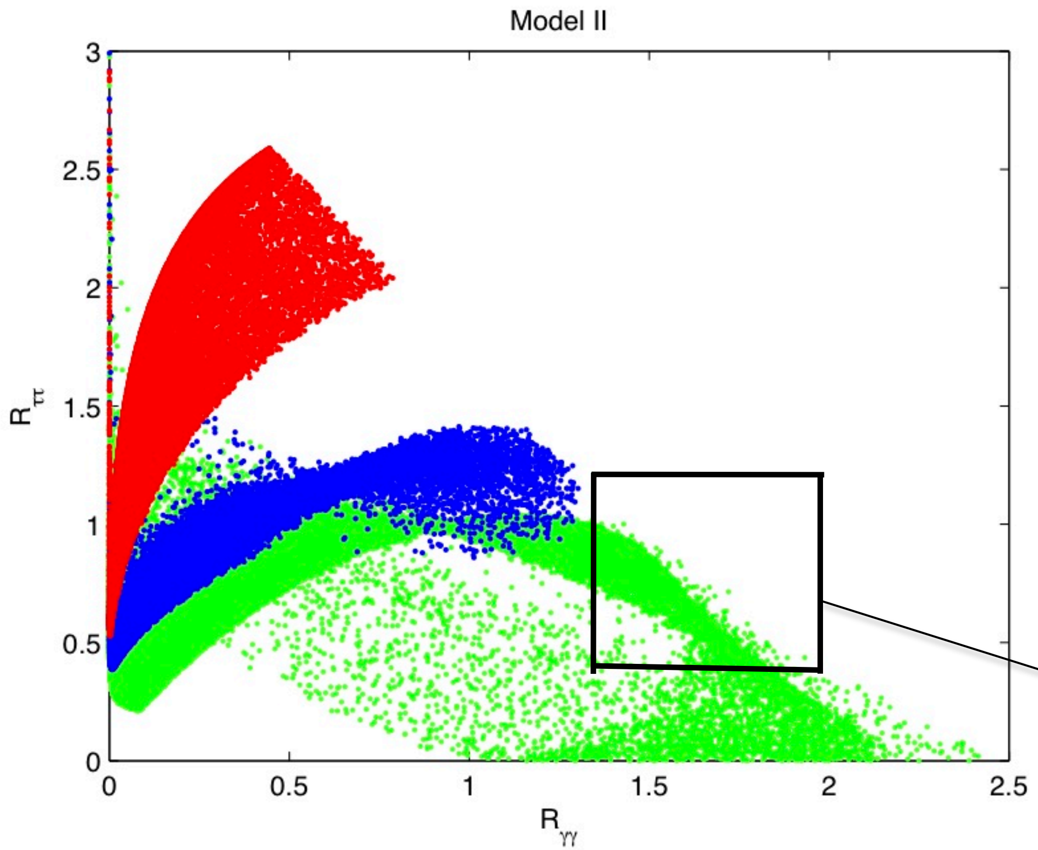
$|s_2| > 0.83$ red

1σ

2σ

Again, in type II everything is excluded at 1σ. At 2σ the red region is excluded while blue and green regions are still allowed.

<u>No significant difference is found between green and blue regions.</u>



$|s_2| < 0.1$ green

$0.45 < |s_2| < 0.55$ blue

$|s_2| > 0.83$ red

1σ

Other channels still do not provide information to distinguish blue and green regions.

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

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. The models are excluded at 1σ for the combined average.

• In the CP-violating version of the model presented, mixing that includes a large component of "pseudo-scalar" are already excluded by the combined 2σ results from the LHC. We can put a bound on the amount of pseudo-scalar mixing.