The 2HDM in light of the recent LHC results

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The 2HDM potential

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

$$\phi_1 \to \phi_1 \qquad \phi_2 \to -\phi_2$$

"Normal" vacuum (CP conserving and non charge breaking)

$$<\Phi_1>_N = \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \qquad <\Phi_2>_N = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

8 + 2 parameters - 2 are fixed by the minimum conditions and one by the W mass $v^2 = v_1^2 + v_2^2$. The remaining 7 are

$$m_h,\ m_H,\ m_A,\ m_{H\pm},\ \tan\beta,\ \sin\alpha \qquad M^2 = \frac{m_{12}^2}{\sin\beta\cos\beta}$$

The 2HDM Lagrangian

- couplings that involve gauge bosons

$$\sin(\beta - \alpha)$$

- couplings that involve fermions

$$\phi_1 \to \phi_1$$
$$\phi_2 \to -\phi_2$$

We extend 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

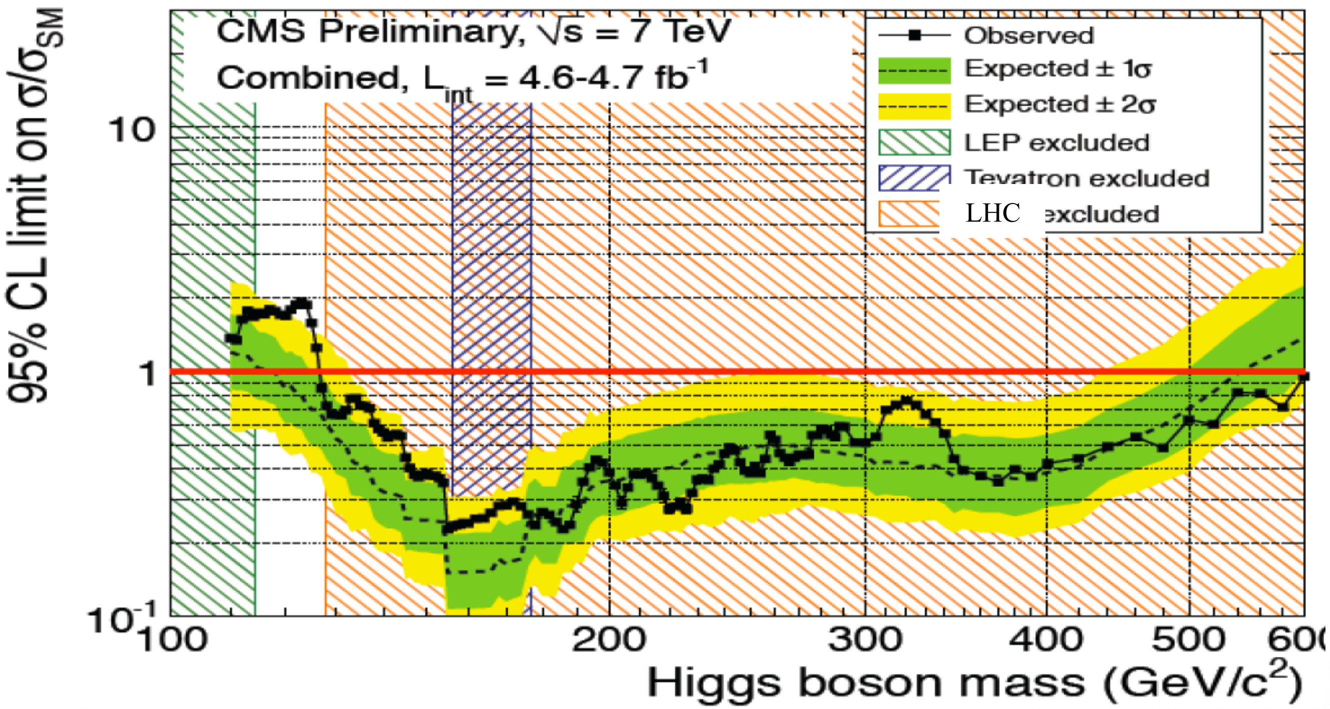
IV = II' = X = Leptonic

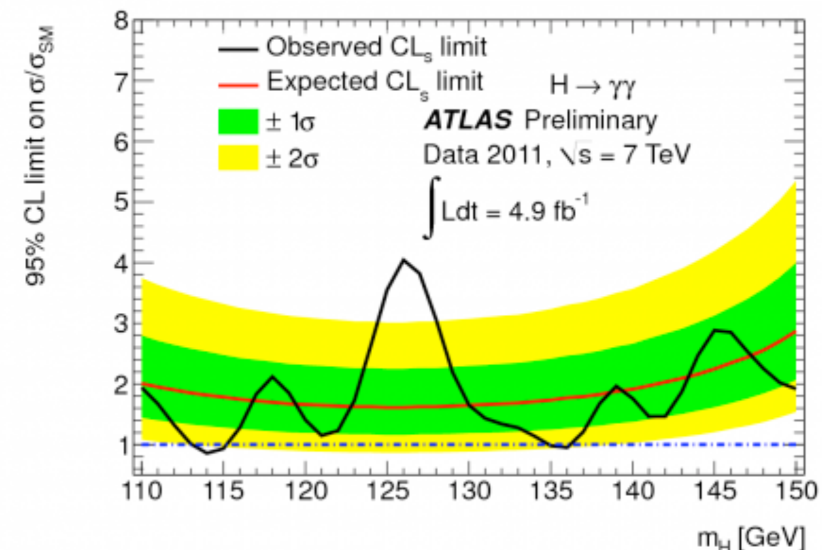
4 models with no FCNC at tree-level

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

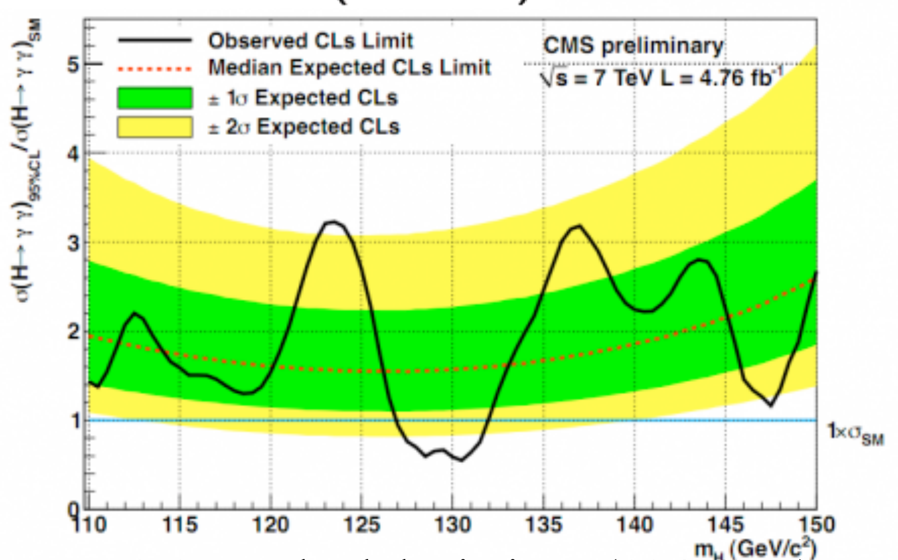
$$\sin\alpha \quad \tan\beta$$

The data - Higgs results LHC@7TeV





2.8 standard deviations (126.5 GeV)
LEE significance is 1.5 standard deviations



3.1 standard deviations (124 GeV)
LEE significance is 1.9 standard deviations

Higgs results LHC@7TeV

- **What do we "know"?**

$$\frac{\sigma^{2HDM}(pp \to h)\, BR^{2HDM}(h \to \gamma\gamma)}{\sigma^{SM}(pp \to h)\, BR^{SM}(h \to \gamma\gamma)} \approx 1$$

$$\frac{\sigma^{2HDM}(pp \to h)\, BR^{2HDM}(h \to VV)}{\sigma^{SM}(pp \to h)\, BR^{SM}(h \to VV)} \approx 1$$

regarding production and decay
to γγ (VV)
2HDM is similar to the SM

- **What will data on new channels tell us?**

$$\frac{\sigma^{2HDM}(pp \to h)\, BR^{2HDM}(h \to \bar{b}b)}{\sigma^{SM}(pp \to h)\, BR^{SM}(h \to \bar{b}b)}$$

$$\frac{\sigma^{2HDM}(pp \to h)\, BR^{2HDM}(h \to \tau^+\tau^-)}{\sigma^{SM}(pp \to h)\, BR^{SM}(h \to \tau^+\tau^-)}$$

how important are
future searches for 2HDM?

The Constraints

Experimental

- **INDIRECT BOUNDS**

All models

$Z \to b\bar{b}$ $\quad B_q \bar{B}_q$

$\tan\beta > 1$

→ Used in all calculations presented.

$$\rho = \frac{M_W^2}{M_Z^2\, c_W^2} = 1$$

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

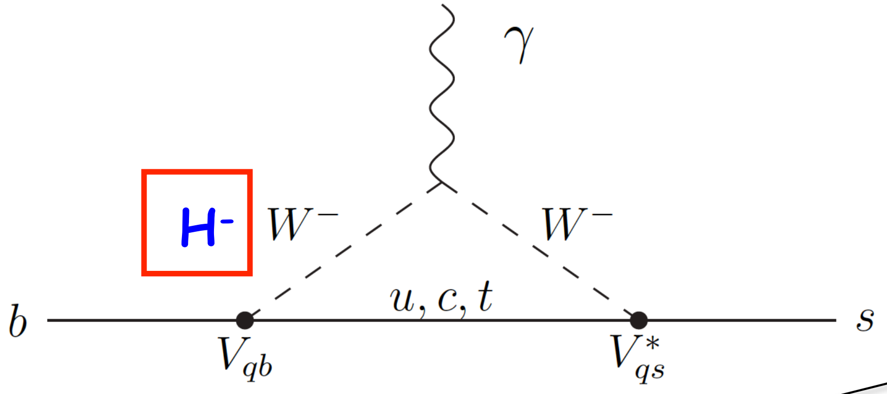
$|\delta\rho| \lesssim 10^{-3}$

Compact spectrum

Experimental

• <u>INDIRECT BOUNDS</u> B factories

$$B \to X_s \gamma$$



Models II and Y $X_i Y_i = 1$

Models I and X $X_i Y_i = 1/\tan^2\beta$

$$\mathcal{L}_Y^{\pm} = (2\sqrt{2}G_F)^{1/2} \sum_{i=2}^{n} (X_i \overline{U}_L V M_D D_R + Y_i \overline{U}_R M_U V D_L + Z_i \overline{N}_L M_E E_R) H_i^+ + \text{h.c.}$$

$$\text{BR}(b \to s\gamma) = C|\eta_2 + G_W(x_t) + (|Y|^2/3) G_W(y_t) + (XY^*) G_H(y_t)|^2,$$

Models II and Y $m_{H^\pm} \gtrsim 300\ GeV$

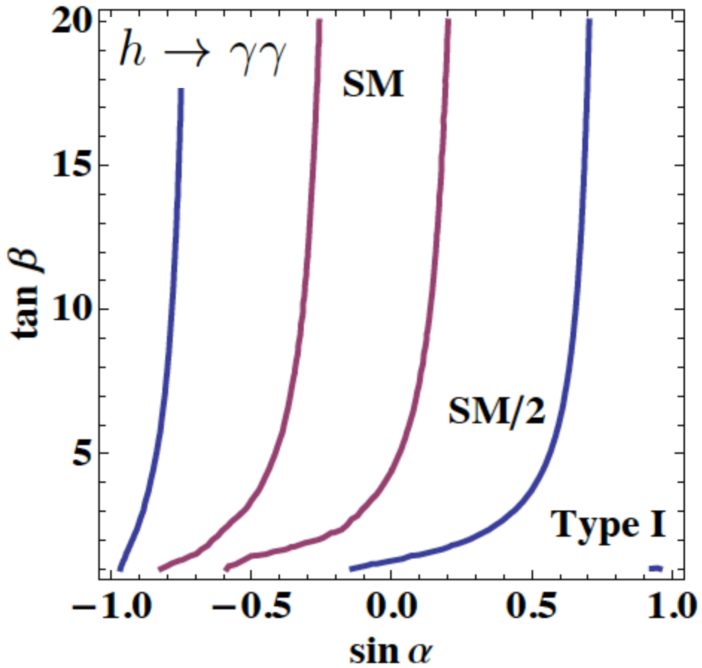
Best available bound on the charged Higgs mass

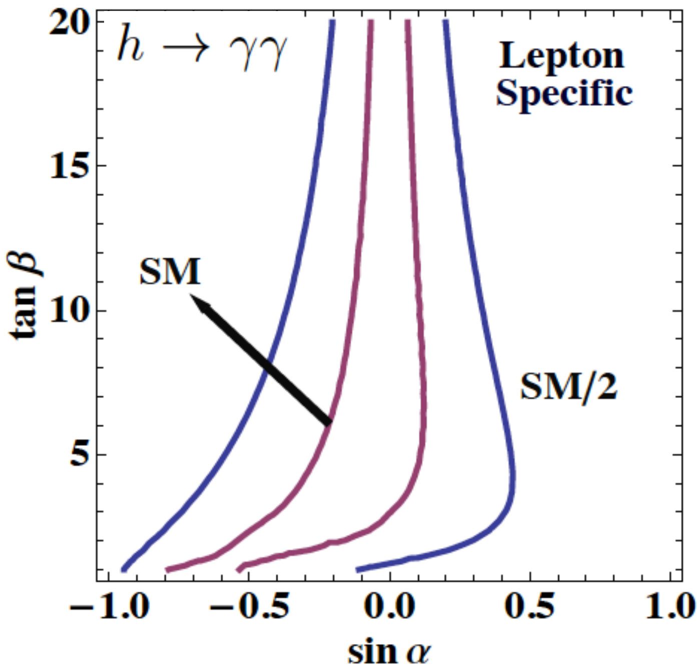
Models I and X $\tan\beta > 1$ $m_{H^\pm} = 100\, GeV$

h or H?

- All results will be presented in the ($\tan\beta$; $\sin\alpha$) plane.
- We started with 7 parameters.
- One of the CP-even Higgs mass is "known" (125 GeV).
- The other CP-even Higgs mass is either irrelevant or benchmarks will be discussed.
- $m_{H\pm} = m_A = 600$ GeV (relevant only h to $\gamma\gamma$ due to charged Higgs loop).
- $M = m_{H\pm} = m_A$ or $M = 0$.

Is it the light CP-even (h)?





$$\frac{\sigma^{2HDM}(pp \to h)\, BR^{2HDM}(h \to \gamma\gamma)}{\sigma^{SM}(pp \to h)\, BR^{SM}(h \to \gamma\gamma)}$$

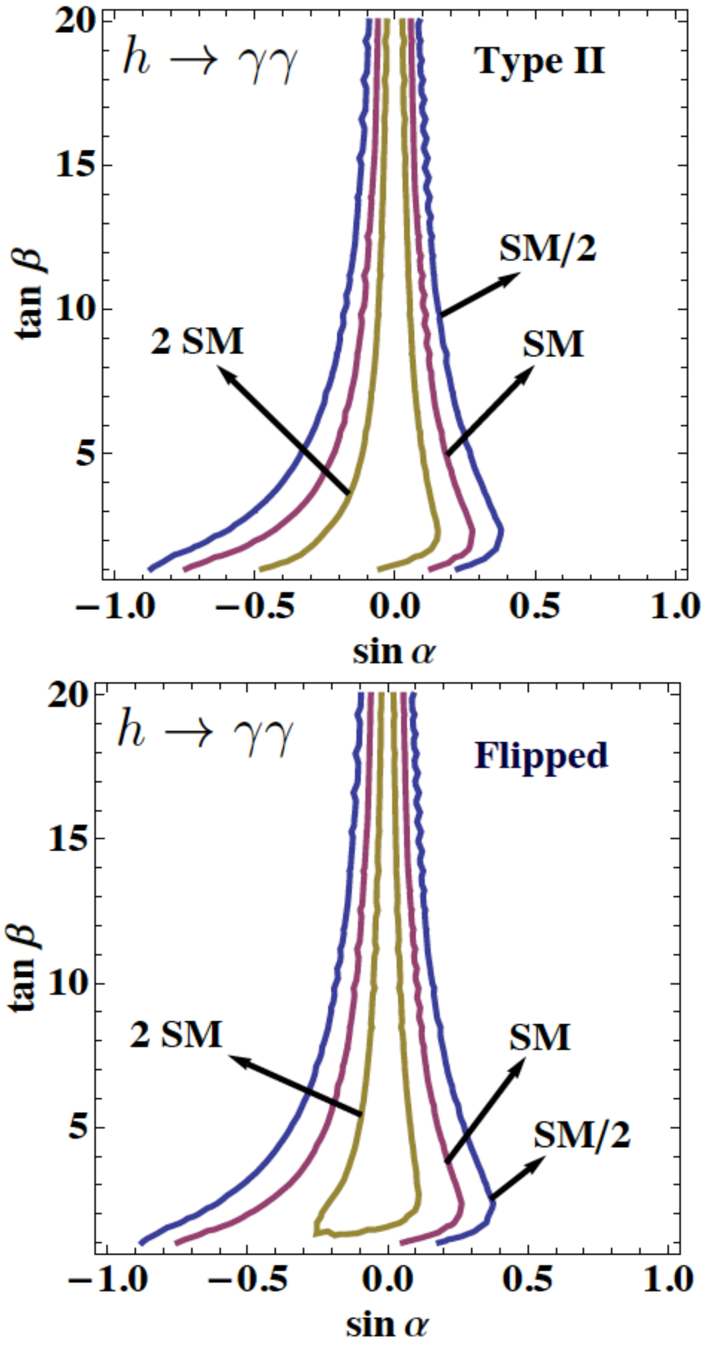
In the quark sector sector I = LS and the cross section ratio is just $\cos^2\alpha/\sin^2\beta$.

In Model I the ratio never reaches 2*SM.

When $\sin\alpha \approx \pm 1$ the Higgs becomes fermiophobic and therefore it is not produced in gluon fusion.

In LS as the total width grows with $\tan\beta$ (due to h to ττ) the allowed region to fit the Higgs shrinks. Again no 2*SM.

Is it the light CP-even?

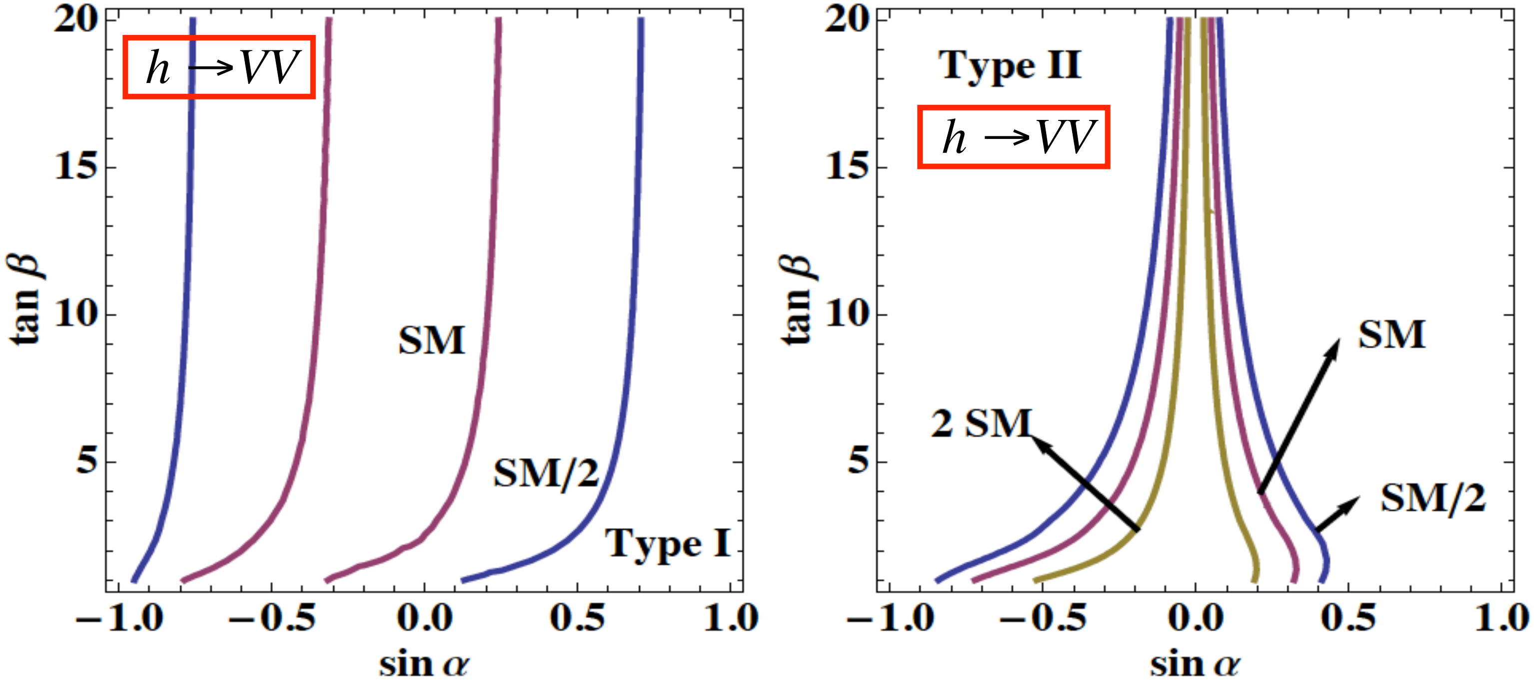


Again, in the quark sector sector II = F
But now the ratio is not just a factor.

The contributions of the b-quark become important and even dominant for large tanβ for both production and decay. <u>This completely changes the picture: we can be above but also below the SM prediction.</u>

For these models, the region of parameter space where we get a number of events close to SM, is more likely to be in the region of <u>small sinα especially for large tanβ</u>.

Is it the light CP-even?



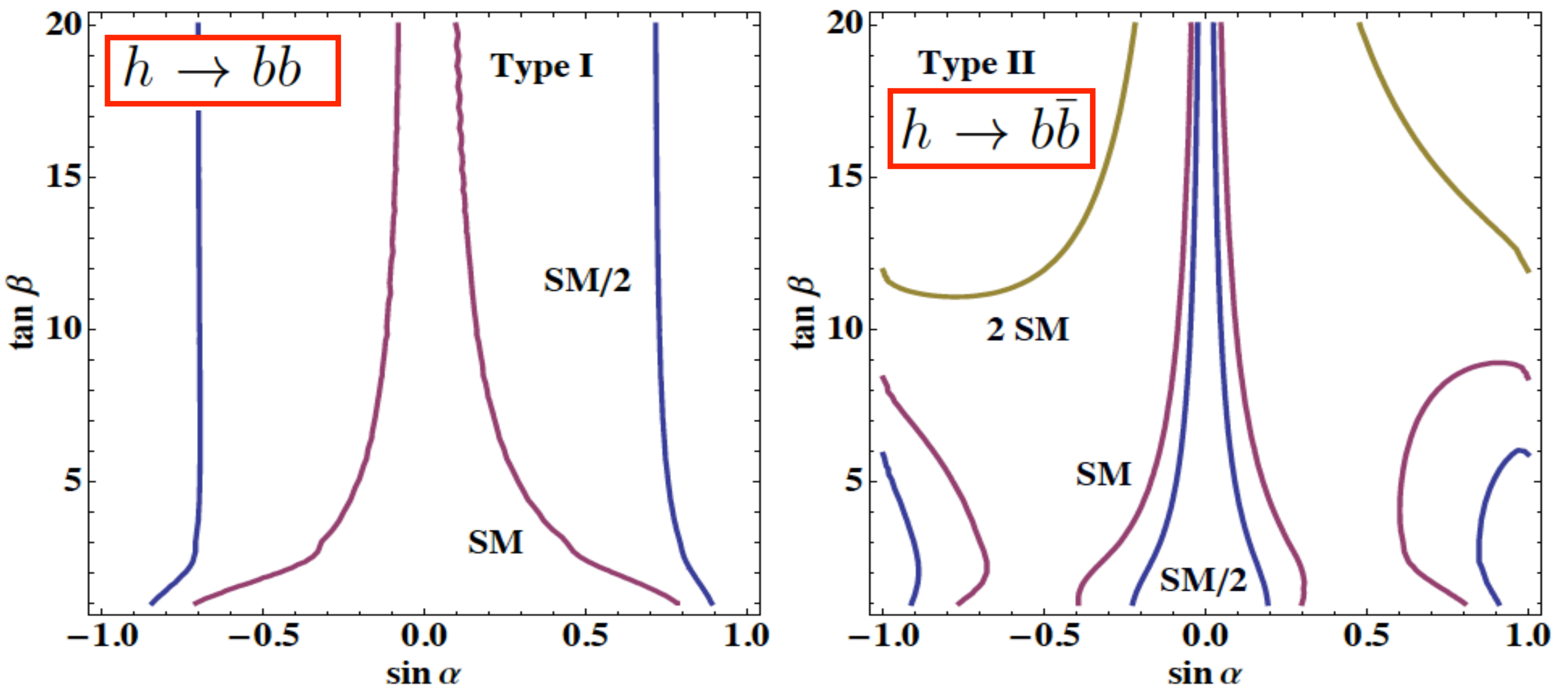
A few events have also been detected in h → WW + ZZ.

Does this information help improving the constraint in the (tanβ; sinα) plane?

Model I and LS - the ratio is never much bigger than 1. Information about this decay is unlikely to prove useful in further constraining the parameter space; but a substantial enhancement would imply physics beyond the 2HDM.

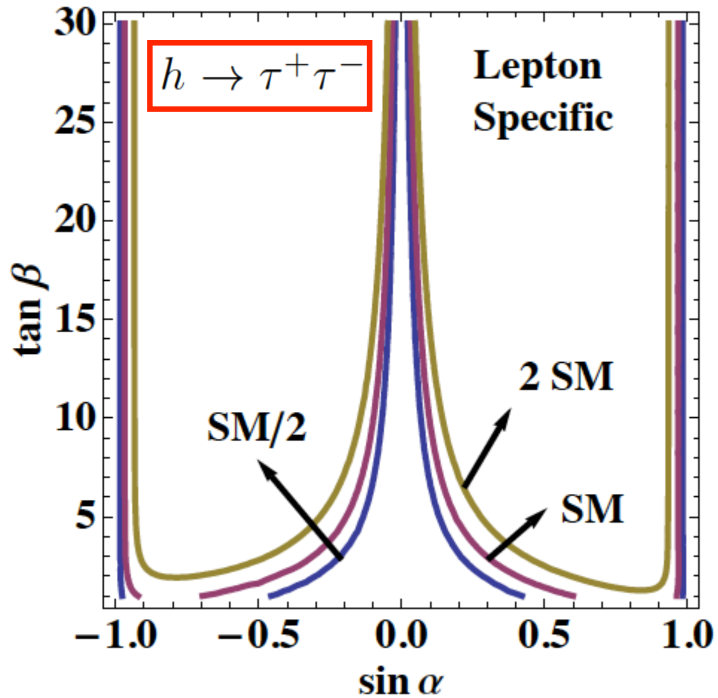
Model II and F – irrelevant unless huge enhancement happens…

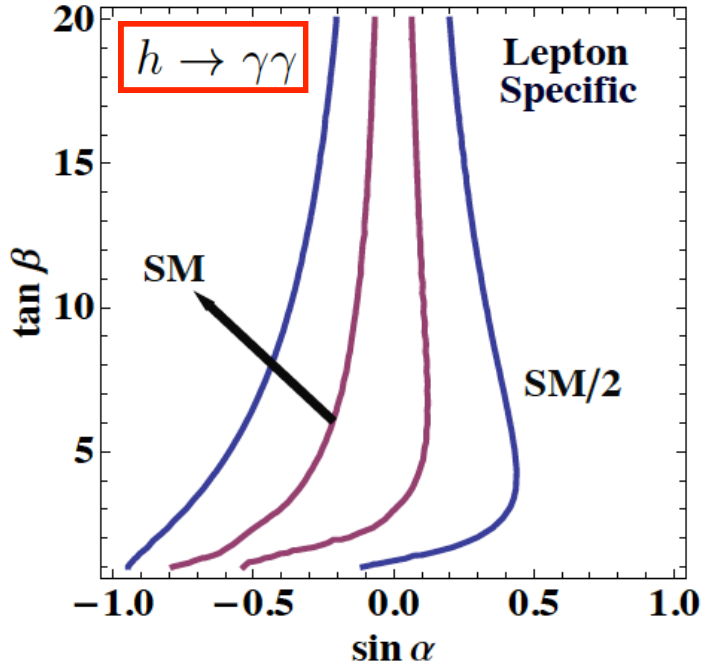
Is it the light CP-even?



We have also analysed the decay h → bb.
For the type I model one sees relatively little variation over much of parameter space. For the type II model, there is a much larger variation. However, if one restricts the parameter space to that allowed by the signal, then the variation is fairly small.
The same happens in the LS and F models.

Is it the light CP-even?





For the LS model the ττ channel gives dramatically different constraints in the (tanβ; sinα) plane.
If one can limit the
rate for h to ττ down to less than twice the SM rate, then the parameter space will be much more severely restricted than implied by other processes.

Is it the light CP-even?

- Data is consistent with the Higgs detected being the lightest CP-even scalar of a 2HDM in all four models.

- With the data to be collected this year and even combining all searches (channels) we will not be able to identify or exclude models unless:

a) Number of gamma events is much above/below SM

b) Number of WW/ZZ events is much above/below SM.

c) Indication of the LS model would be an enhancement in h to $\tau\tau$

Is it the heavy CP-even?

- Hints for a 125 GeV state decaying into two photons. In the context of 2HDMs: h, H or A?

- We now focus on the heavier CP-even scalar, H.

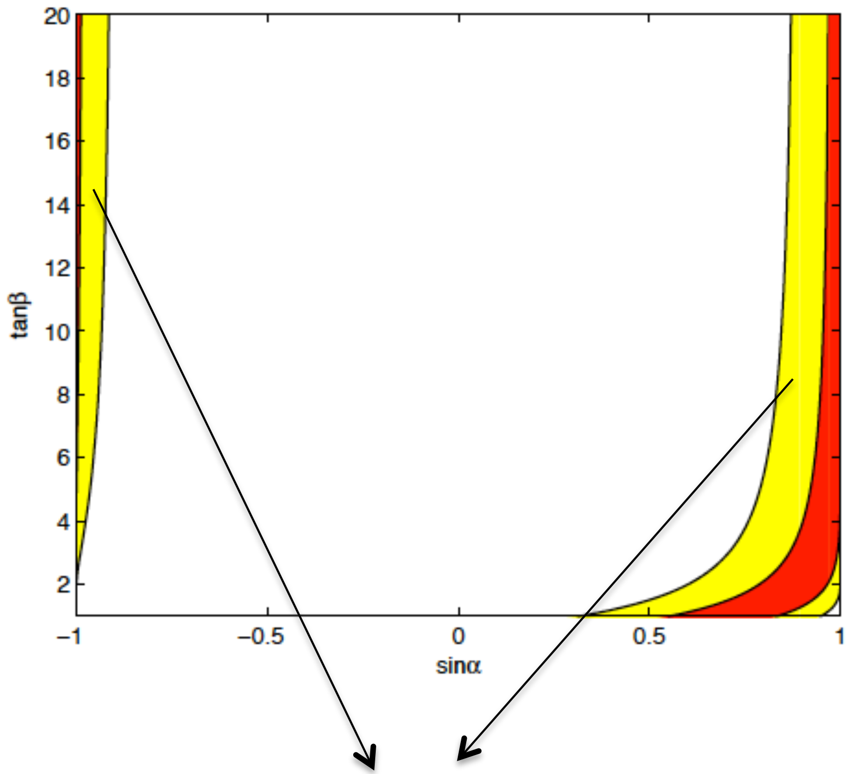
- The lightest scalar h should have, thus far, evaded detection.

- The combined requirements on H and h place stringent limits on the parameter space. We will consider two qualitatively distinct cases.

- Case 1: m_h = 105 GeV and m_H = 125 GeV, thus precluding the decay H to hh.

- Case 2: m_h = 50 GeV and m_H = 125 GeV, implying that H to hh is kinematically allowed.

Is it the heavy CP-even?



LEP constraints

- LEP experiments searched for associated production of a light Higgs up to masses around 115 GeV.

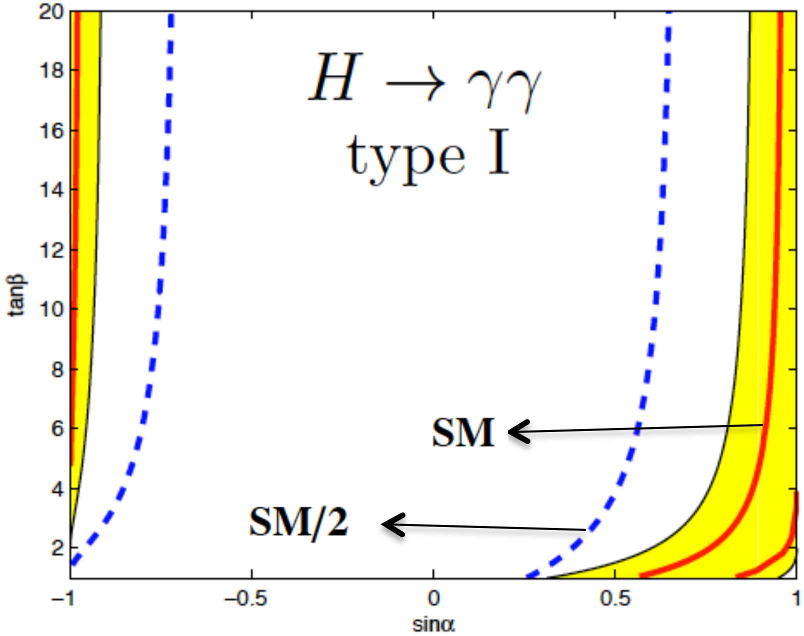
- In 2HDMs, rates with hVV couplings (V = Z;W) are suppressed by $\sin^2(\beta-\alpha)$, which the LEP data constrains to lie below 0.2 for m_h = 105 GeV.

- This implies a very stringent constraint on the ($\sin\alpha$; $\tan\beta$) plane, shown for m_h = 105 GeV (light yellow shaded areas).

- For m_h = 50 GeV, $\sin^2(\beta-\alpha) < 0.04$ leads to even smaller allowed regions, shown in as dark red areas.

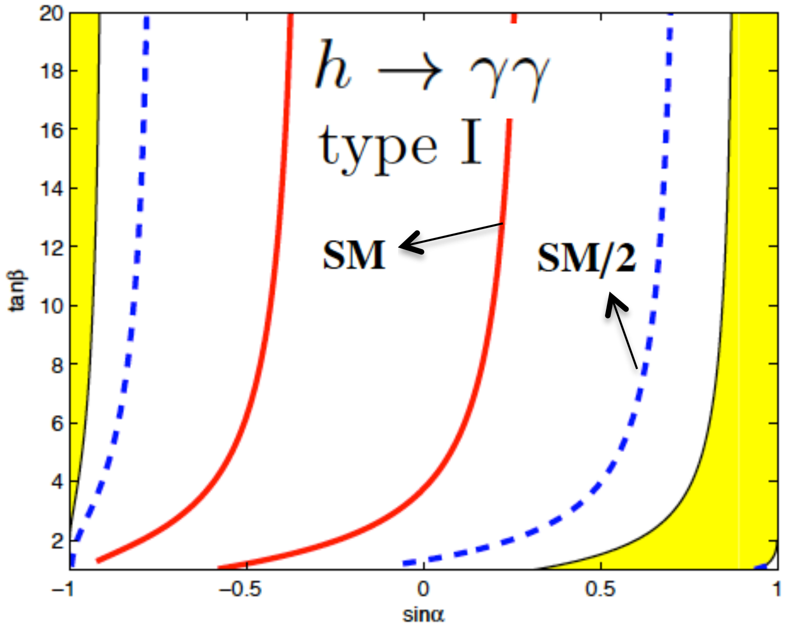
The LEP constraints forces $\sin\alpha$ to be close to ±1, with a severe impact on the observability of the lightest Higgs.

Is it the heavy CP-even?



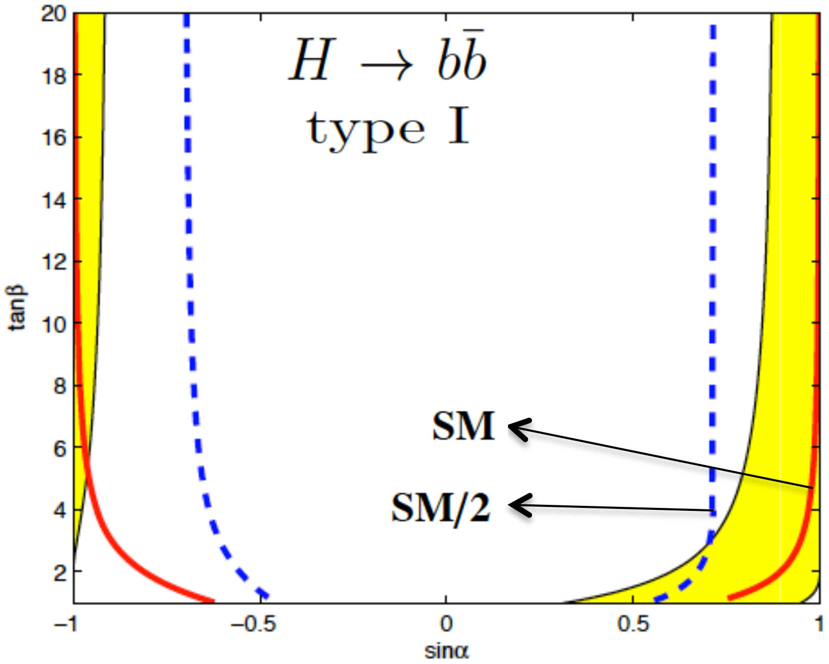
- <u>Case 1</u>: m_h = 105 GeV, m_H = 125 GeV.

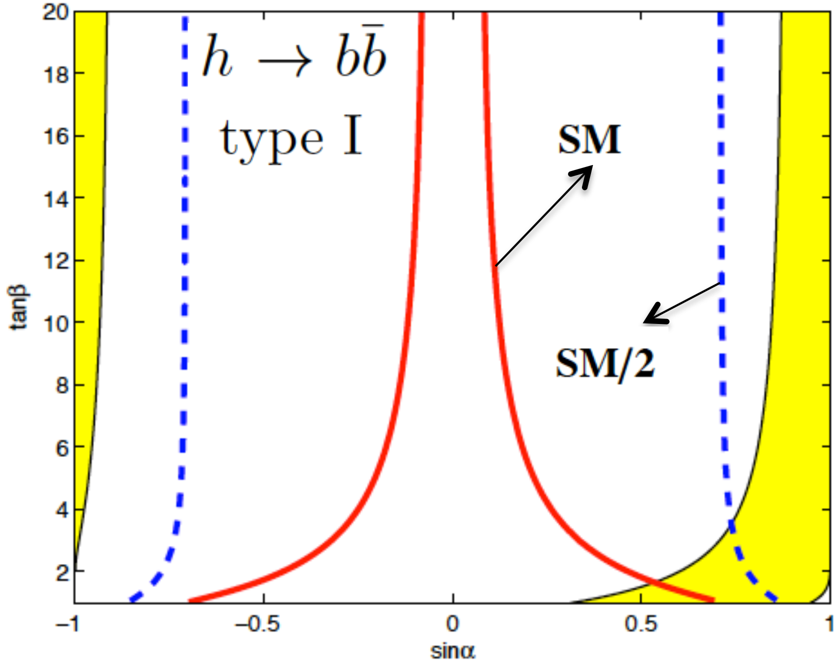
- The decay of the heavy Higgs has to lie <u>very close to its SM value</u>. SM/2 is excluded. This is consistent with its detectability in this channel at the LHC.



- For the light Higgs all values above SM/2 are excluded and therefore for this scenario the <u>lightest Higgs decay into two photons will not be seen at LHC in the near future.</u>

Is it the heavy CP-even?





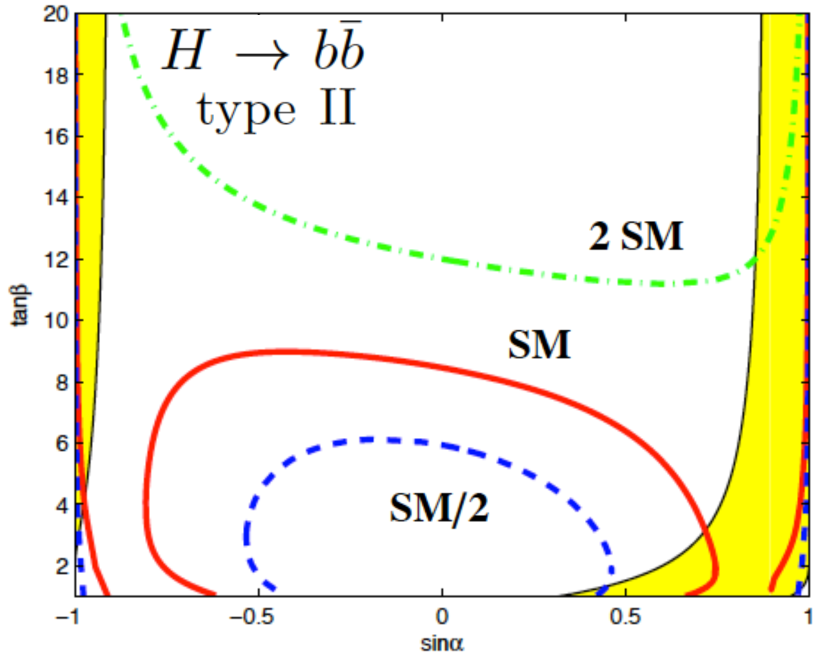
- An interesting situation for type I 2HDM arises in the decays into bb.

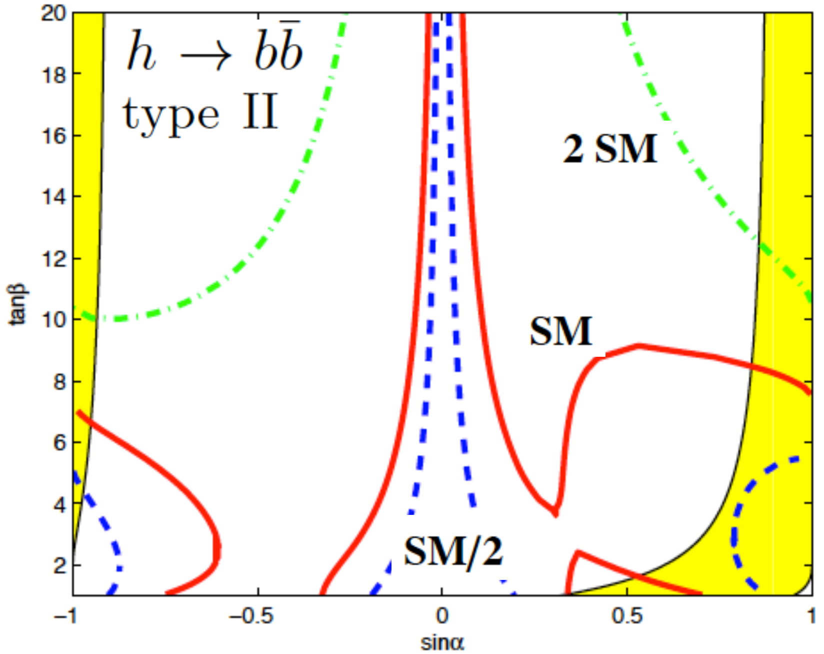
- We find that H can decay into bb, with SM or with SM/2 ratios, in a small region close to (sinα; tanβ) = (0.7; 2).

- This is the same region in which h to bb could have a rate close to the SM one. The same conclusions hold for H to ττ and h to ττ.

- This raises the interesting possibility that the decays into bb and ττ could be sensitive to both the heavy and the light Higgs scalars, while only H can be seen in the γγ and VV channel at the LHC.

Is it the heavy CP-even?



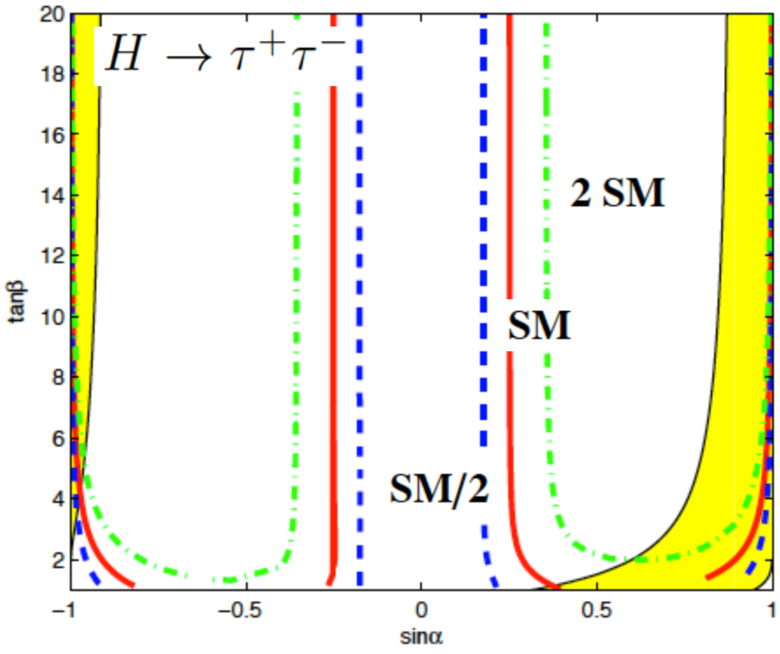


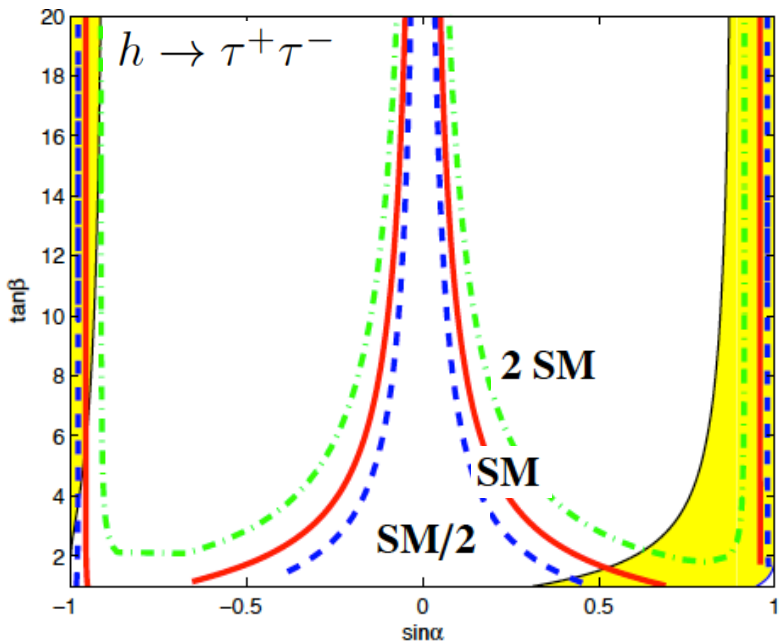
- In model type II and Flipped both the decays to two photons and to VV are similar to type I – the only difference is that values of 2*SM or larger, can be reached. Again h is undetectable in the decays to gauge bosons.

- But the situation may improve with respect to the type I model, concerning bb. We see that both H to bb and h to bb could occur at rates twice the SM rate, for sinα > 0.8 and tanβ > 13.

- Similar behavior is seen in ττ.

Is it the heavy CP-even?





- Next we consider the LS model. As in the type I model, h to two photons is unobservably small, while H may be detected.

- Unlike model I, we see that the decays of both h and H into ττ could be substantially larger than in the SM. Also, they prefer to be close to sinα = ±1.

- The decays into bb have features similar to those for model I. In particular, detection of H to bb at SM rates is possible for large sinα and any value for tanβ , but simultaneous detection of h to bb around SM rates is only possible for low values of tanβ.

Is it the heavy CP-even?

• Case 2: m_h = 50 GeV and m_H = 125 GeV, implying that H to hh is kinematically allowed.

• When H to hh is opened, all other branching ratios are much suppressed and, in particular, H could not even be seen in the γγ channel. This violates our working hypothesis that current LHC hints correspond indeed to H to γγ. As a result, we are interested in regions where λ_{Hhh} is close to zero.

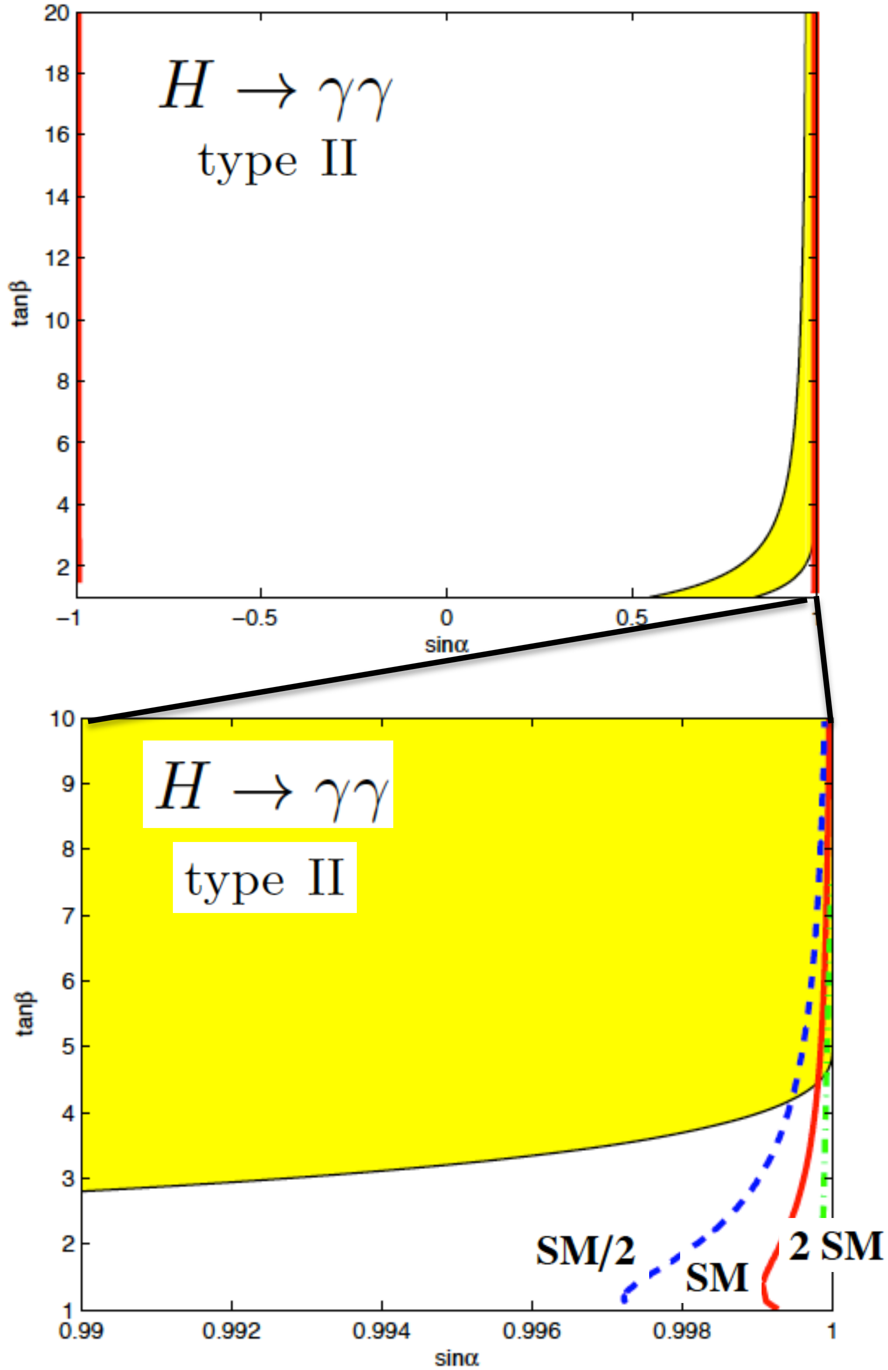
$$\lambda_{Hhh} \propto \frac{\cos(\beta-\alpha)}{\sin(2\beta)} (m_H^2 + 2m_h^2) \sin(2\alpha) \left[1 - x\left(\frac{3}{\sin(2\beta)} - \frac{1}{\sin(2\alpha)}\right)\right]$$

$$x = \frac{2m_{12}^2}{m_H^2 + 2m_h^2}$$

a) Exact Z2: m_{12}= 0.

b) Softly broken Z2: $m_{12} \neq 0$.

Is it the heavy CP-even?



- If m_{12} = 0 λ_{Hhh} is close to zero when sinα = ±1 or 0 but only sinα = ±1 are consistent with the LEP bounds (shown in yellow).

- Only close to sinα = ±1 H may be visible in H to γγ or in any other channel other than H to hh. This a necessary but not a sufficient condition.

- Similar conclusions for the remaining models.

- The results are approximately the same for H to VV .

- <u>Regarding bb and ττ</u>: H might be seen in both decays for type I; it might be seen in bb but not in ττ for LS; it might be seen in ττ but not in bb for the Flipped; and it will not be seen in either for the type II model.

Is it the heavy CP-even?

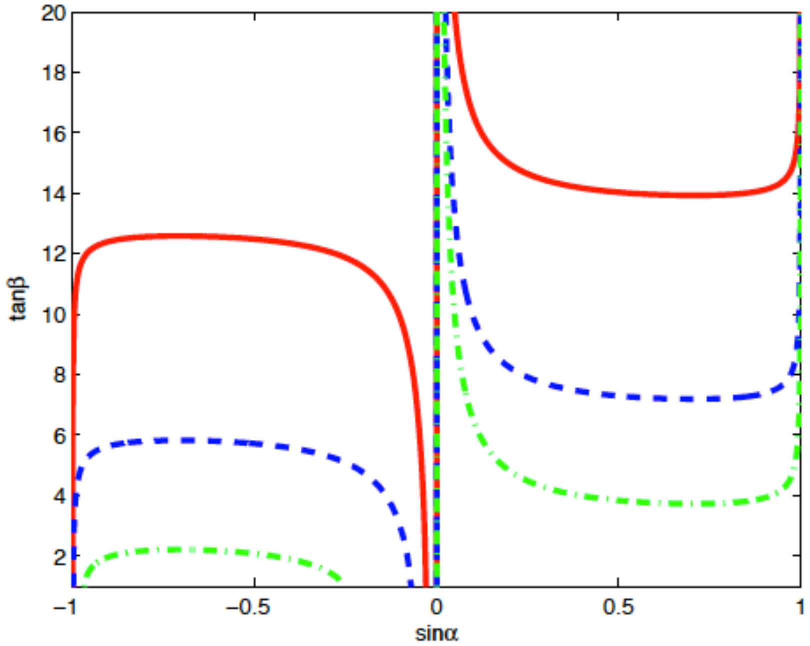
- If $m_{12} = 0$, the $\sin\alpha = \pm 1$ constraint also has a very strong impact on the detectability of the light scalar h.

- To avoid the LEP bound, h is close to gaugephobic. Thus, it cannot be seen in VV, regardless of the specific 2HDM considered.

- We have checked that h to $\gamma\gamma$ and h to bb is undetectable, while h to $\tau\tau$ is only detectable in the LS model.

- Notice that, in the scenario $m_H = 125$ GeV, $m_h = 50$ GeV, and $m_{12} = 0$, the LS model has a very interesting prediction: H may be seen in $\gamma\gamma$, VV, and bb at rates around the SM value, but it will not show up in $\tau\tau$, while h exhibits exactly the opposite features.

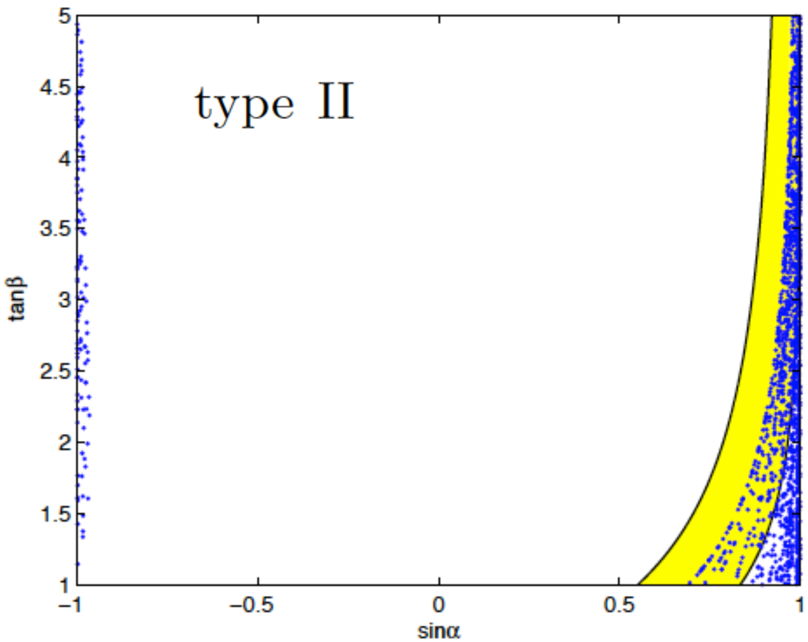
Is it the heavy CP-even?



$$\frac{2m_{12}^2}{m_H^2 + 2m_h^2} = \frac{\sin(2\alpha)\sin(2\beta)}{3\sin(2\alpha) - \sin(2\beta)}$$

- Lines in the (sinα; tanβ) plane where λ_{Hhh} vanishes. A judicious choice of m_{12} guarantees that H to γγ is not swamped by H to hh.

- If $m_{12} \neq 0$ we might have H to γγ at levels consistent with LHC hints in regions away from sinα = ±1.



- This is shown as a scatter plot drawn for the type II model (similar for all other models) and for random choices of m_{12}. One can now cover almost the entire LEP allowed region.

- In this case, the phenomenology is very similar to the m_h = 105 GeV case.

Is it the heavy CP-even?

- Case 1: m_h = 105 GeV, m_H = 125 GeV.

Model /Process	$H \to \gamma\gamma$	$H \to VV$	$H \to \bar{b}b$	$H \to \tau^+\tau^-$
Type I	SM	SM	SM (all $\tan\beta$)	SM (all $\tan\beta$)
Type II	$>$ SM	$>$ SM	$>$ SM (high $\tan\beta$)	$>$ SM (high $\tan\beta$)
Flipped	$>$ SM	$>$ SM	$>$ SM (high $\tan\beta$)	SM (all $\tan\beta$)
LS	SM	SM	SM (all $\tan\beta$)	$>$ SM (all $\tan\beta$)

Model /Process	$h \to \gamma\gamma$	$h \to VV$	$h \to \bar{b}b$	$h \to \tau^+\tau^-$
Type I	No	No	SM (low $\tan\beta$)	SM (low $\tan\beta$)
Type II	No	No	$>$ SM (high $\tan\beta$)	$>$ SM (high $\tan\beta$)
Flipped	No	No	$>$ SM (high $\tan\beta$)	SM (low $\tan\beta$)
LS	No	No	SM (low $\tan\beta$)	$>$ SM (all $\tan\beta$)

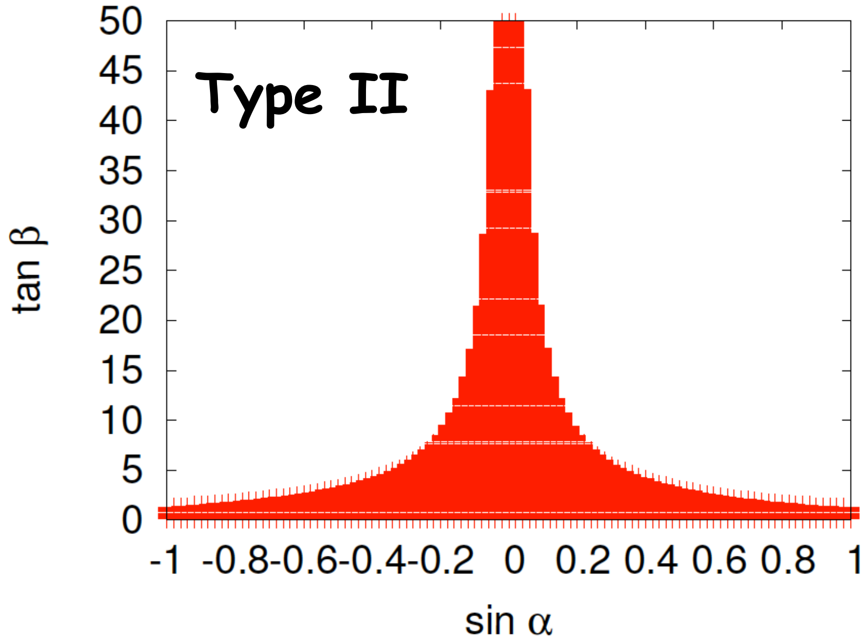
Is it the heavy CP-even?

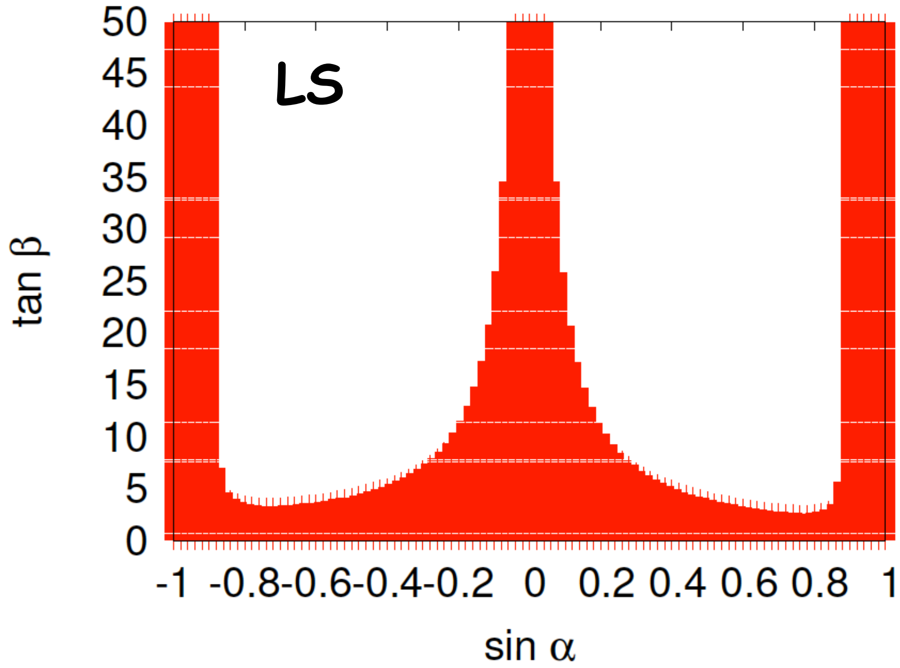
- Case 2 a) m_h = 50 GeV and m_H = 125 GeV, m_{12} = 0.

Model /Process	$H \to \gamma\gamma$	$H \to VV$	$H \to \bar{b}b$	$H \to \tau^+\tau^-$
Type I	SM	SM	Yes	Yes
Type II	$>$ SM	$>$ SM	No	No
Flipped	$>$ SM	$>$ SM	No	Yes
LS	SM	SM	Yes	No

Model /Process	$h \to \gamma\gamma$	$h \to VV$	$h \to \bar{b}b$	$h \to \tau^+\tau^-$
Type I	No	No	No	No
Type II	No	No	No	No
Flipped	No	No	No	No
LS	No	No	No	Yes

Bounds from ττ





- The experimental searches on h to ττ already allow us to set bounds on the 2HDM parameter space

- Type II and LS are the most constrained models due to the large cross section and branching ratio into ττ. Note that in LS, the allowed regions close to sinα = ±1 are not compatible with h being detected in γγ at rates close to the SM rates.

- No bounds on models I and Flipped because either cross section or branching ratio into ττ is too small.

Conclusions

- In a CP-conserving 2HDM with a softly broken Z2 symmetry, both h and H scalars are consistent with the LHC results presented so far.

- More luminosity will probably tell us if the number of $\gamma\gamma$ and VV events is consistent with the SM predictions. A large difference in either $\gamma\gamma$ or VV may be explained by a 2HDM.

- Bounds derived from experimental searches on h to $\tau\tau$ and h to bb may help clarify which types of 2HDM's are allowed (or at least constrain the parameter space).

Workshop on

Multi-Higgs Models

28-31 August 2012

Lisbon - Portugal

This Workshop brings together those interested in the theory and phenomenology of Multi-Higgs models. The program is designed to include talks given by some of the leading experts in the field, and also ample time for discussions and collaboration between researchers. A particular emphasis will be placed on identifying those features of the models which are testable at the LHC.

For registration and/or to propose a talk, send an email to:

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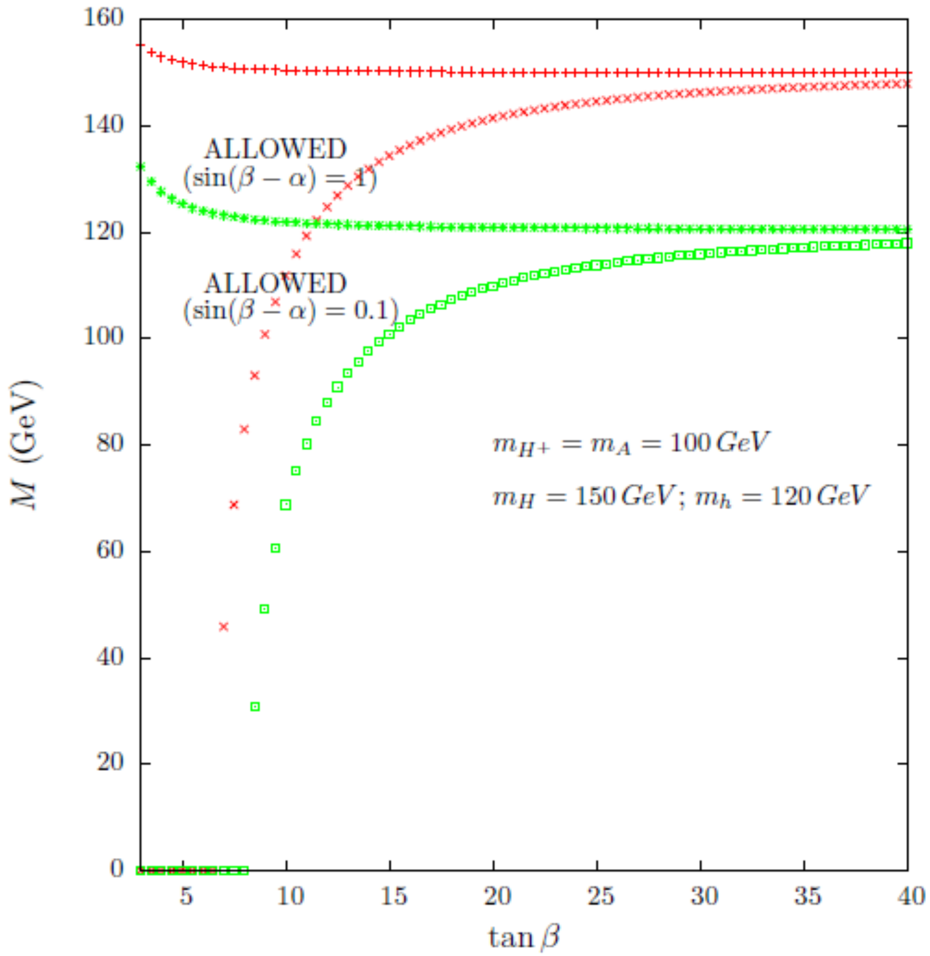
CFTC Centro de Física Teórica e Computacional

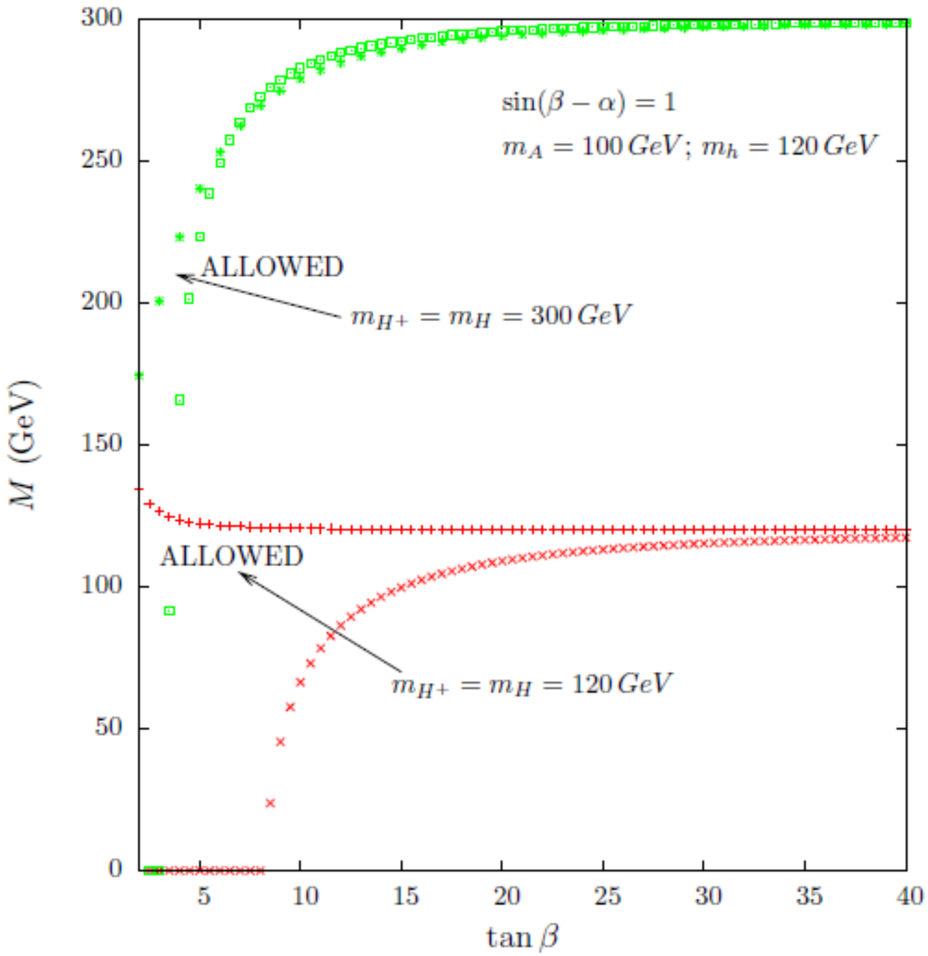
FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

PEOPLE

Theoretical

Remaining parameters are fixed by the theoretical constraints - tree-level vacuum stability (potential is bounded from below at tree-level) and perturbative unitarity.





Is it the heavy CP-even?

- In all four models, decays h to $\gamma\gamma$, WW and ZZ will be unobservable.

- H to hh is kinematically inaccessible. Type I: decays of h and H into bb and $\tau\tau$ can both be observed at a rate similar to SM. Type II and Flipped: decays can both occur at rates twice that of the SM. In LS one can have a huge enhancement in the H to $\tau\tau$ and h to $\tau\tau$ rates.

- H to hh is kinematically allowed, and will generally be large.

  If $m_{12} = 0$, $\sin\alpha = \pm 1$ - h to $\gamma\gamma$, VV and bb is undetectable, while h to $\tau\tau$ is only detectable in the LS model.

  If $m_{12} \neq 0$, the region of parameter-space in which the λ_{Hhh} coupling is suppressed is substantially expanded, and can cover most of the LEP-allowed region (similar results as for case I).