Search for leptonic Higgs at the LHC

Workshop on Multi-Higgs Models, Lisboa

18 September 2009

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School of Physics and Astronomy

University of Southampton

In collaboration with
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sorry

Higgs pair production in THDM *

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***see papers for complete list of references references**

Outline

- A Two Higgs Doublet Model
- Constraints
- THDM ≈ SM
- Self-couplings
- Summary

"The" THDM potential

Z_2 symmetry: $\Phi_1 \to -\Phi_1$; $\Phi_2 \to \Phi_2$, softly broken by the m_{12} term

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

"Normal" vacuum (CP conserving and non charge breaking) – if Y = 1

$$< \mathbf{\Phi}_1 >_N = \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \qquad < \mathbf{\Phi}_2 >_N = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

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

$$M_h,\ M_H,\ M_A,\ M_{H^\pm},\ \tan\beta,\ \alpha,\ M^2$$

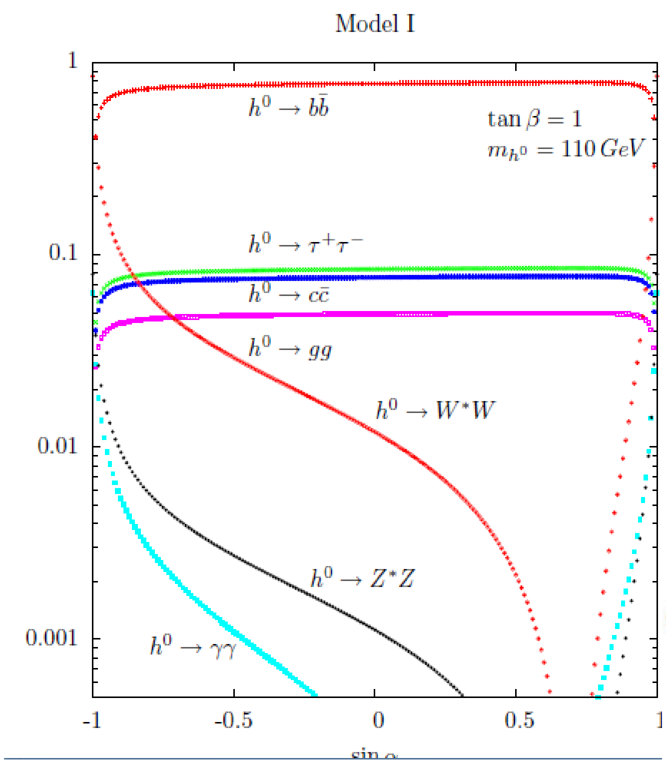
$$M^2 = \frac{m_{12}^2}{\sin\beta\cos\beta}$$

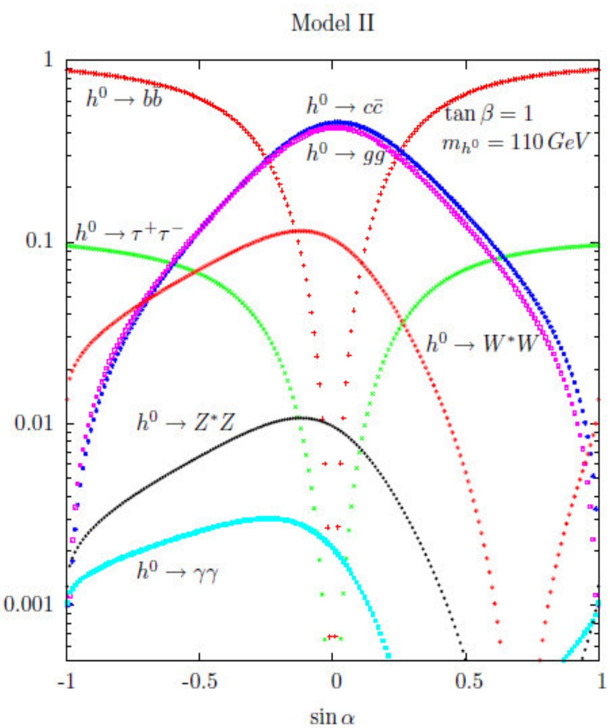
Yukawa Lagrangian

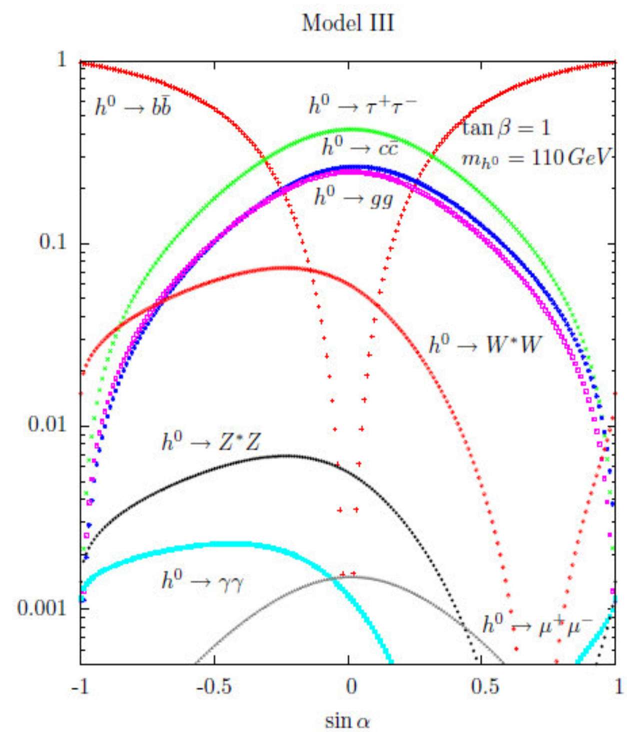
We extend the Z_2 symmetry to the fermions (4 models without FCNC at tree-level).

	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

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







Best of Experimental Constraints I

- **Direct bounds**

  Charged Higgs – LEP 79.3 GeV

  $$B(H^+ \to \tau^+ \nu) + B(H^+ \to c\bar{s}) = 1$$

  Other Higgs – model dependent – h can be very light (angle dependence)

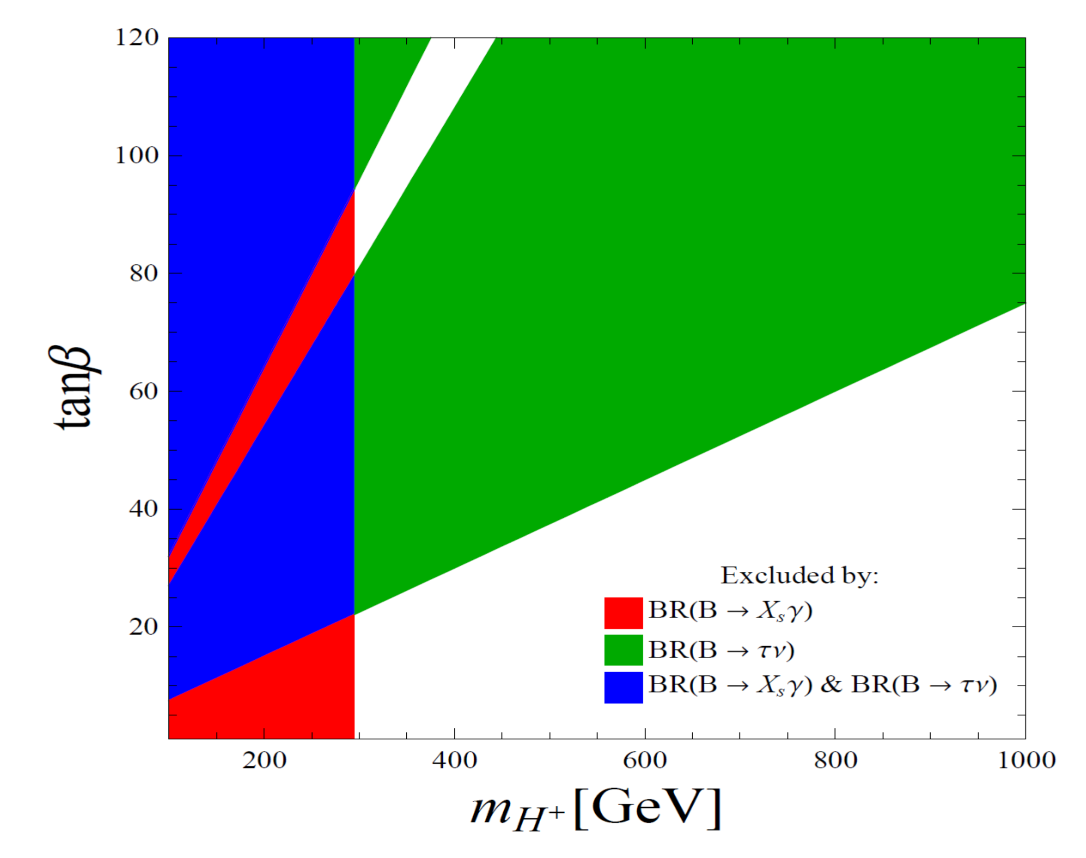
  SM like – LEP bound 114.4 GeV

- $Z \to b\bar{b}$ $B_q \bar{B}_q$ **Excludes low tan β in <u>all models</u>. Light charged Higgs ≈ 100 GeV and tan $\beta \approx 1$ are disfavoured**

- $|\delta\rho| \lesssim 10^{-3}$ **Electroweak precision constraints (<u>all models</u>) – $M_{H^+} \approx M_A$; $M_{H^+} \approx M_H \sin(\beta - \alpha)$; $M_{H^+} \approx M_h \cos(\beta - \alpha)$ or equivalent**

Best of Experimental Constraints II

UT*fit* Collaboration (arXiv:0908.3470)



$B \longrightarrow X_s\gamma$

$m_{H^\pm} \gtrsim 300\ GeV$

Models II and III

$B \longrightarrow \tau\nu$

Excludes high tan β just in model II

Theoretical Constraints

• **Charge and CP breaking – for peace of mind**

In a "Normal" minimum, the 2HDM is naturally protected against charge breaking and against CP breaking.

• **Vacuum stability**

Conditions for the potential to be bounded from below at tree-level – especially important for $M^2 > 0$.

• **Tree-level unitarity**

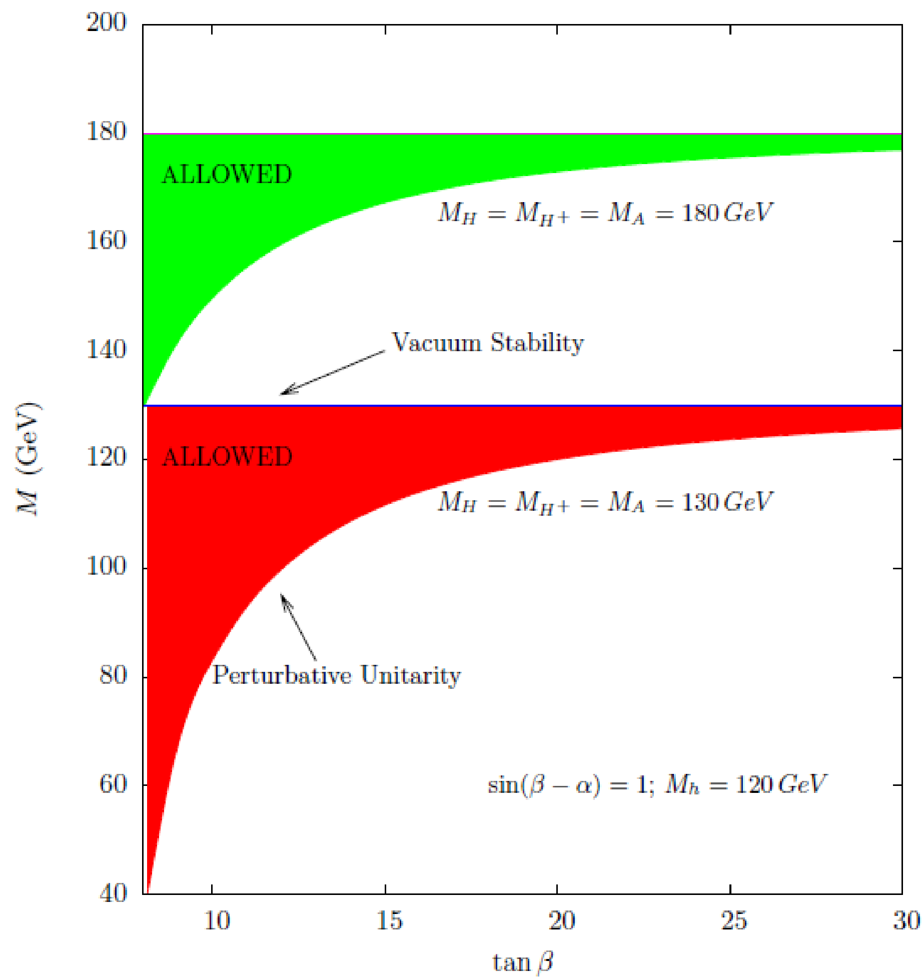
Full set of perturbative unitarity conditions – very restrictive – forces small values of tan β (or not) and masses below ≈ 1 TeV.

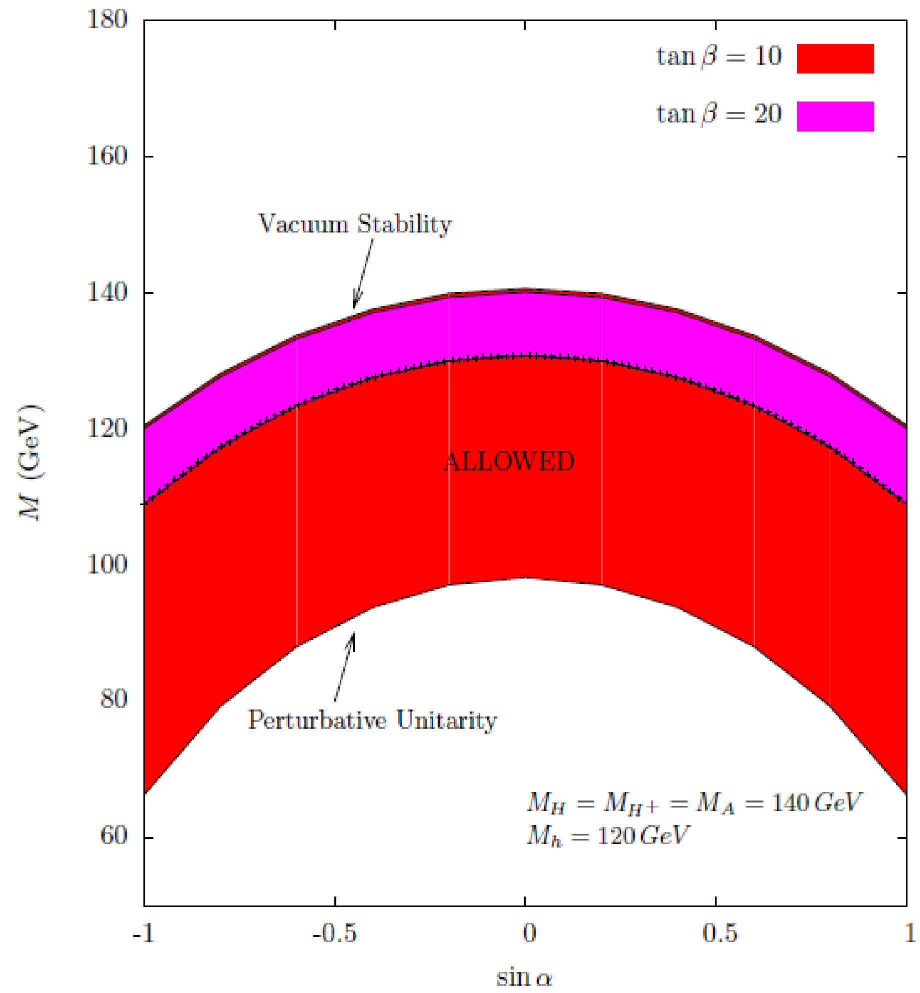
Theoretical Constraints

$$M^2 > 0$$

$$\lambda_1 = \frac{-M^2 \sin^2\beta + M_H^2 \cos^2\alpha + M_h^2 \sin^2\alpha}{v^2 \cos^2\beta} > 0$$

$$0 \le M^2 < M_H^2 \frac{1+\tan^2\beta}{\tan^2\beta}$$



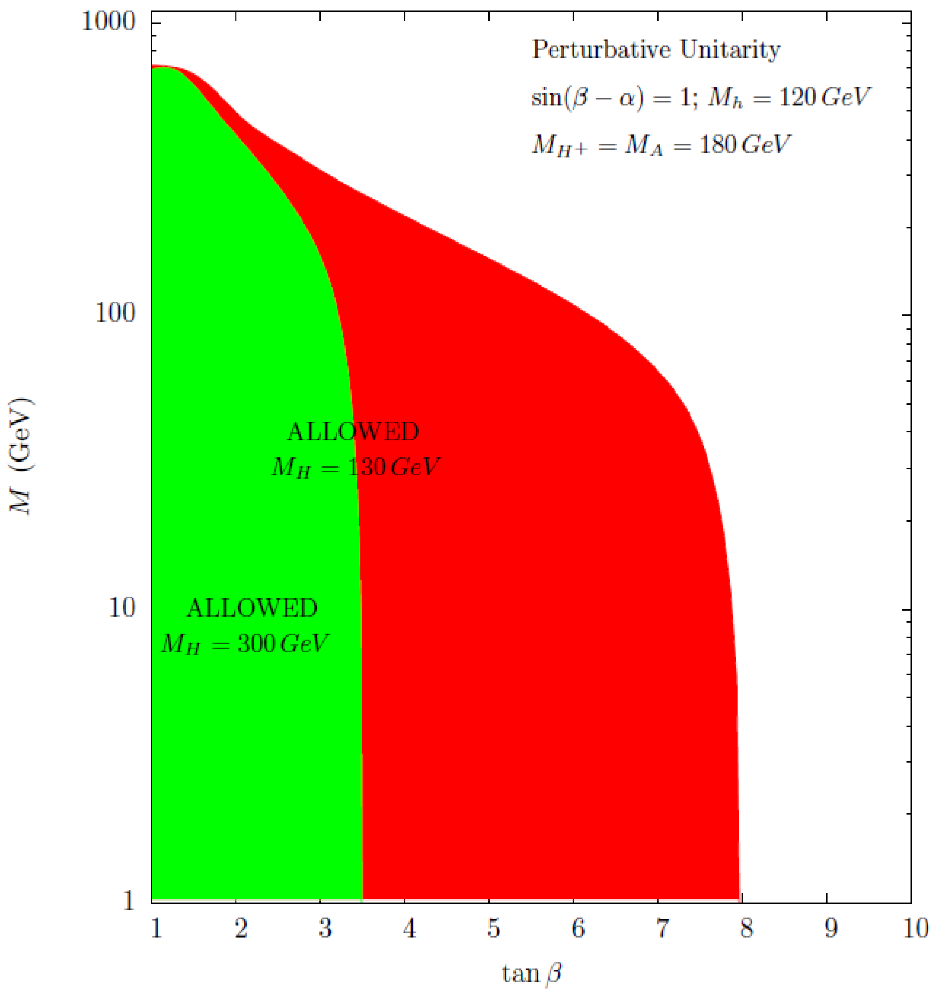


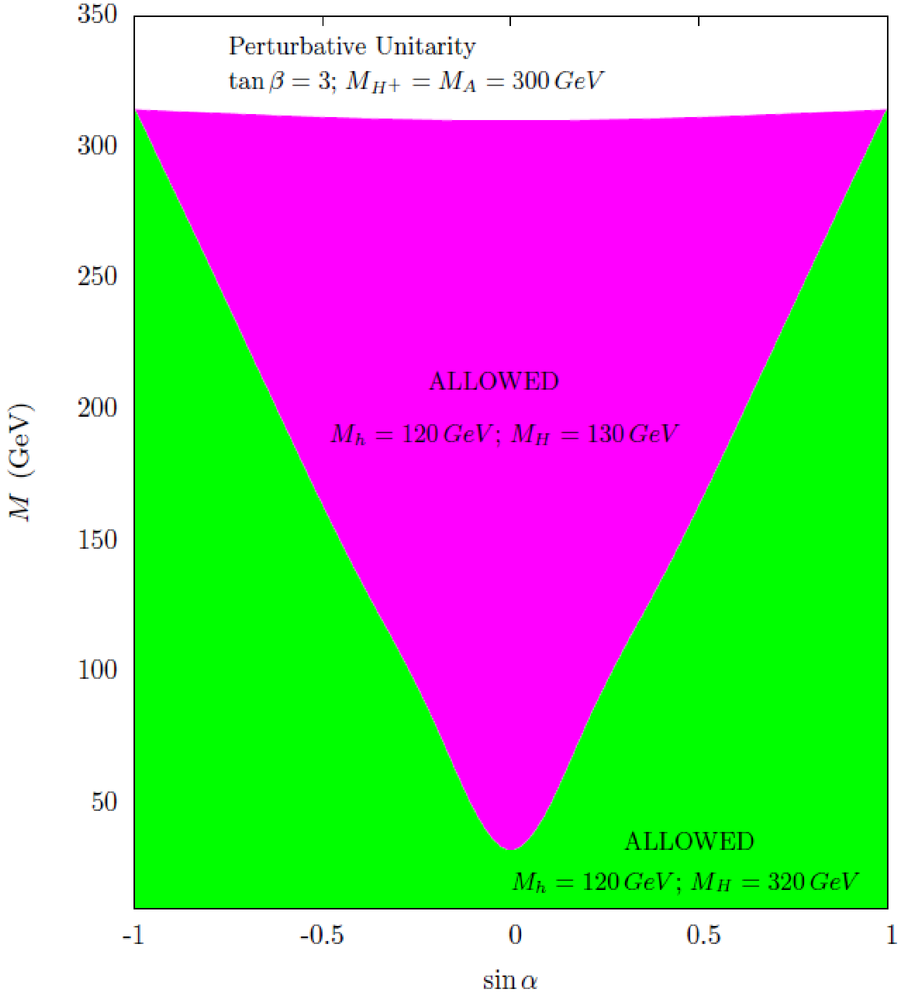
Theoretical Constraints

$$M^2 < 0$$

$$\lambda_1 = \frac{-M^2 \sin^2\beta + M_H^2 \cos^2\alpha + M_h^2 \sin^2\alpha}{v^2 \cos^2\beta} > 0$$

Constraints come almost exclusively from perturbative unitarity.





So

- All Models – Avoid regions where ($\tan\beta$, M_{H+}) < (1, 100 GeV)
  - – Avoid regions where mass spectrum is not compact
  - – Avoid regions with large $\tan\beta$ (unless you have a good reason)
  - – For $M^2 > 0$; $M^2 \leq 2\, M_H^2$

- Model II and III – Add

$$m_{H^\pm} \gtrsim 300\ GeV$$

Terms and conditions apply

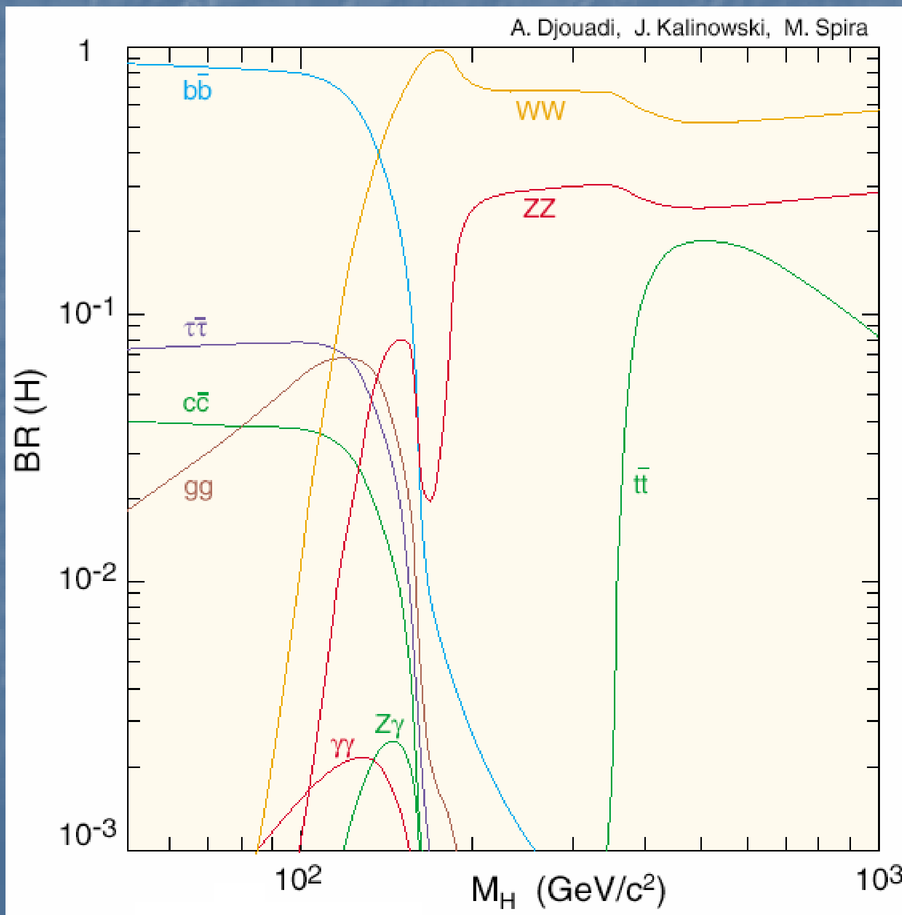
THDM ≈ SM

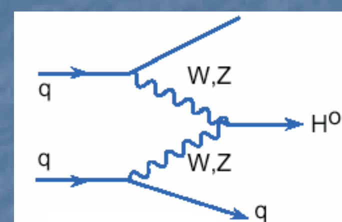
A SM like Higgs

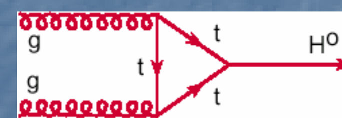
$$\boxed{\begin{aligned}\cos(\beta-\alpha) &\approx 0\\ \sin(\beta-\alpha) &\approx 1\end{aligned}} \Rightarrow$$

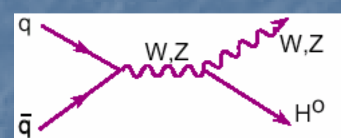
$$(g_{hVV})^{SM} \approx (g_{hVV})^{THDM} \qquad (g_{hhh})^{SM} \approx (g_{hhh})^{THDM}$$

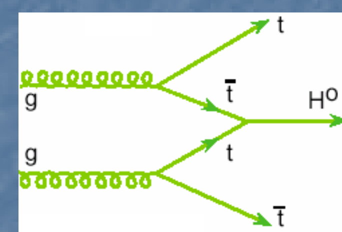
$$(g_{hff})^{SM} \approx (g_{hff})^{THDM} \qquad (g_{Hhh})^{THDM} \approx 0$$





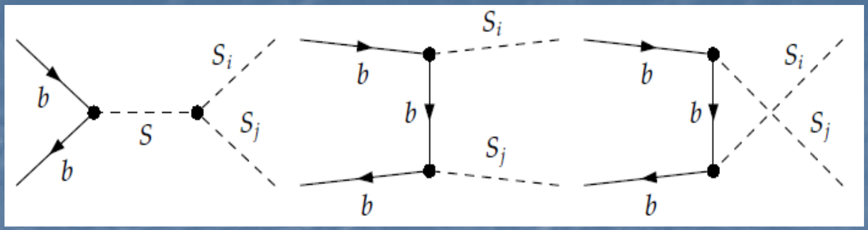




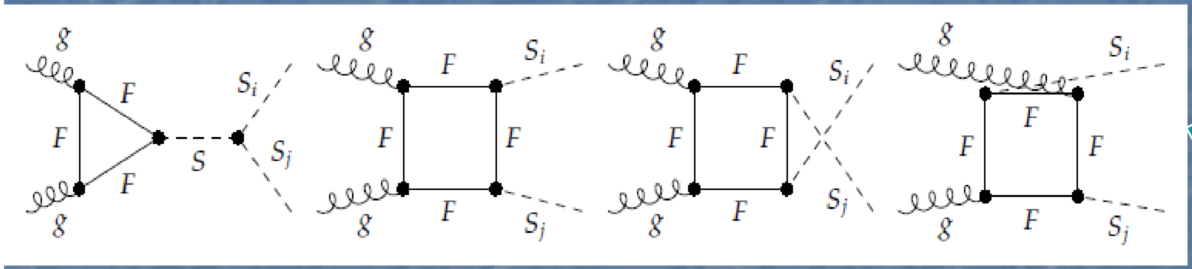


<u>Same couplings, same signatures, same results.</u>

LHC hh production (pp → hh)



Tree-level contribution



One-loop contribution

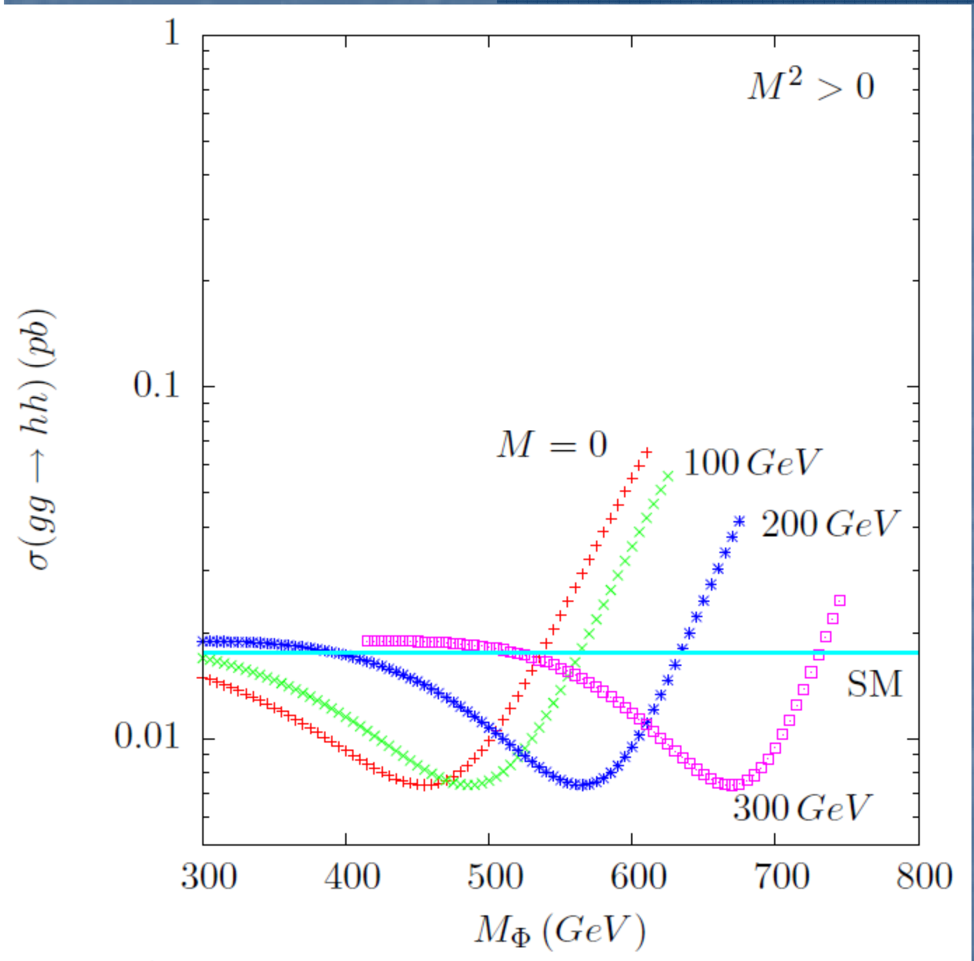
One loop corrected hhh vertex in the two-Higgs doublet model in the limit sin(β – α) = 1

$$\lambda_{hhh}^{eff}(THDM) = \frac{3m_h^2}{v}\left\{1 + \frac{m_H^4}{12\pi^2 m_h^2 v^2}\left(1 - \frac{M^2}{m_H^2}\right)^3 + \frac{m_A^4}{12\pi^2 m_h^2 v^2}\left(1 - \frac{M^2}{m_A^2}\right)^3 + \frac{m_{H\pm}^4}{6\pi^2 m_h^2 v^2}\left(1 - \frac{M^2}{m_{H\pm}^2}\right)^3 - \frac{N_{c_t} m_t^4}{3\pi^2 m_h^2 v^2} + \mathcal{O}\left(\frac{p_i^2 m_\Phi^2}{m_h^2 v^2}, \frac{m_\Phi^2}{v^2}, \frac{p_i^2 m_t^2}{m_h^2 v^2}, \frac{m_t^2}{v^2}\right)\right\},$$

Kanemura, Okada, Senaha, Yuan 04

Non-decoupling effects

$\cos(\beta - \alpha) \approx 0$
$\sin(\beta - \alpha) \approx 1$



$$m_H = m_{H^\pm} = m_A = m_\Phi$$

$$m_h = 120 \text{ GeV}$$

– **Calculation: FeynArts, FormCalc and LoopTools**

– **One-loop corrected hhh included**

– **Theoretical and experimental constraints included**

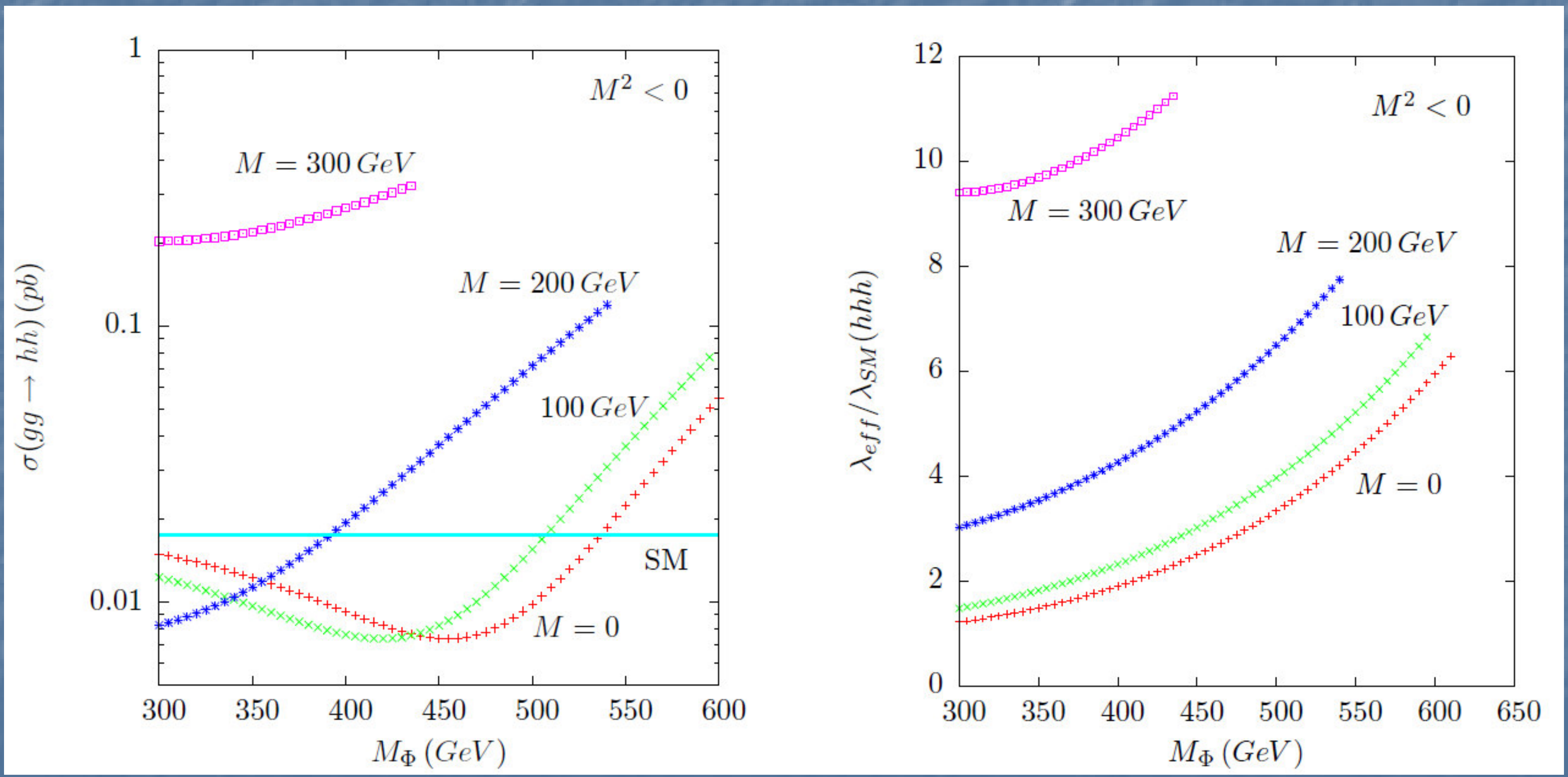
Very hard if $M^2 > 0$

Non-decoupling effects/
Non-THDM ≈ SM effects

$\cos(\beta - \alpha) \approx 0$
$\sin(\beta - \alpha) \approx 1$

$m_H = m_{H^\pm} = m_A = m_\Phi$

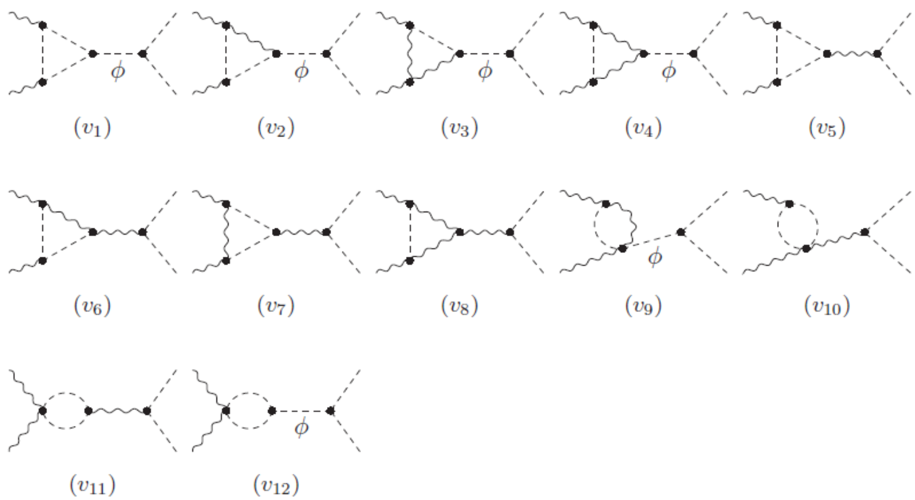
$m_h = 120$ GeV



<u>Better if $M^2 < 0$</u>

Photon Collider hh production ($\gamma\gamma \rightarrow$ **hh**)

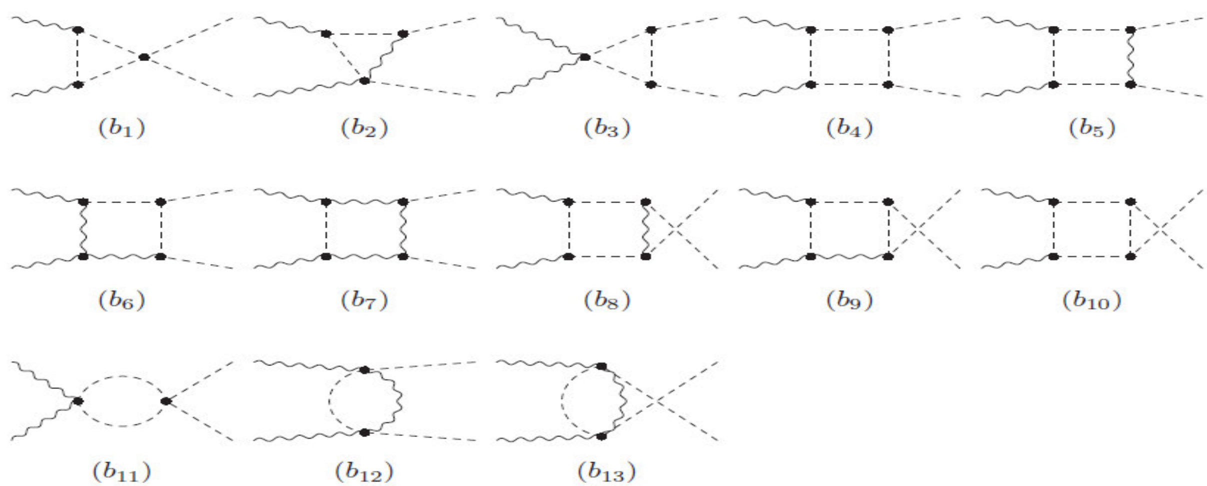
SM like contributions (same as before with gluon replaced by photon) plus new and dominant scalar loop contributions



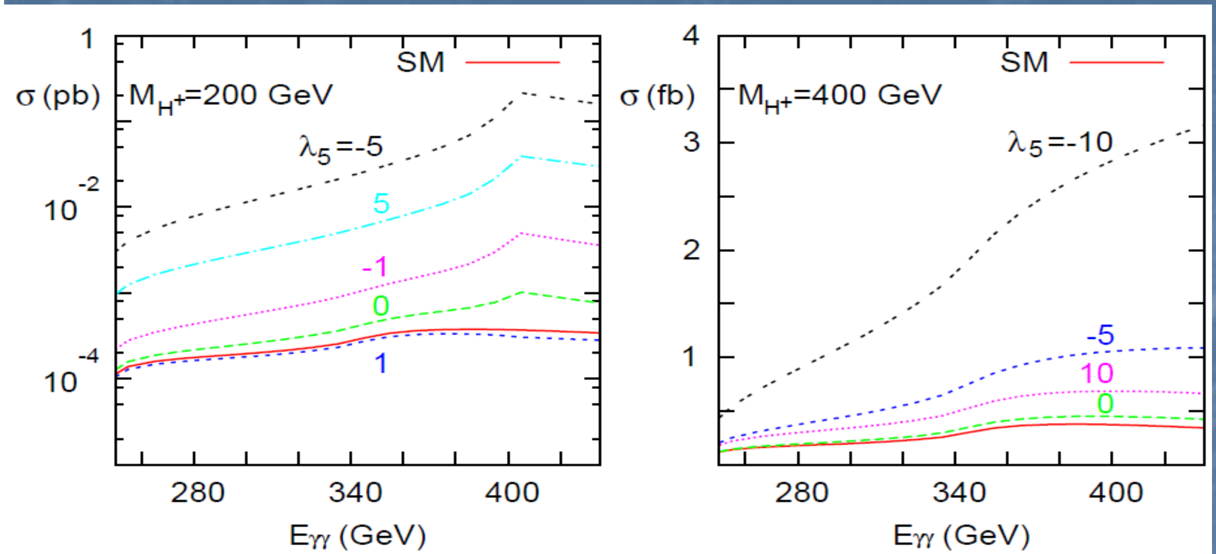
Contributing scalar couplings

- g_{hhh}, g_{Hhh}
- $g_{H^+H^- h\,(h)}$, $g_{H^+H^- H}$ – only in photon collider

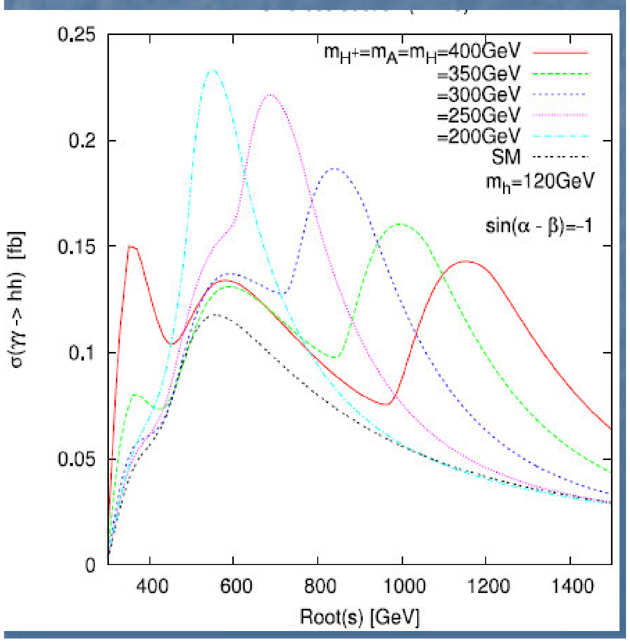
New set of diagrams appear only because of the charged Higgs

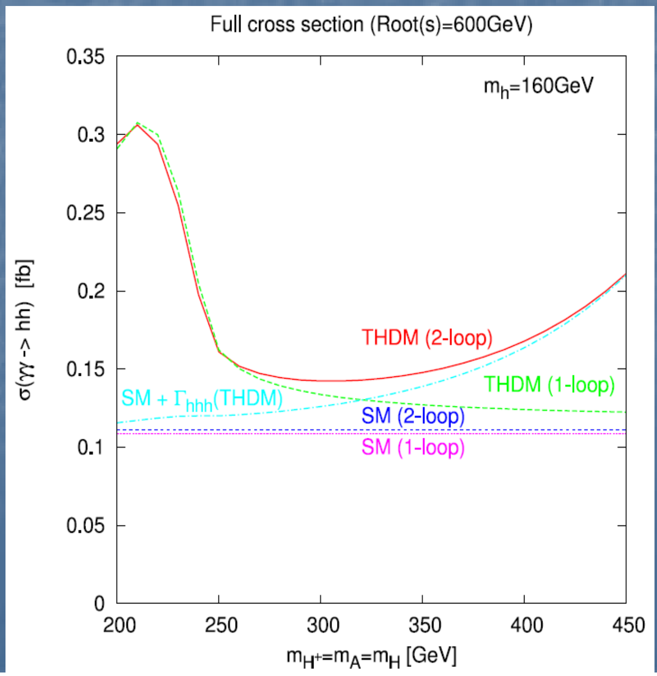


Photon Collider hh production ($\gamma\gamma \rightarrow$ **hh**)



Cornet and Hollik have looked for effects from $g_{H^+H^-h}$, $g_{H^+H^-H}$ for $M^2 < 0$ and $M^2 > 0$



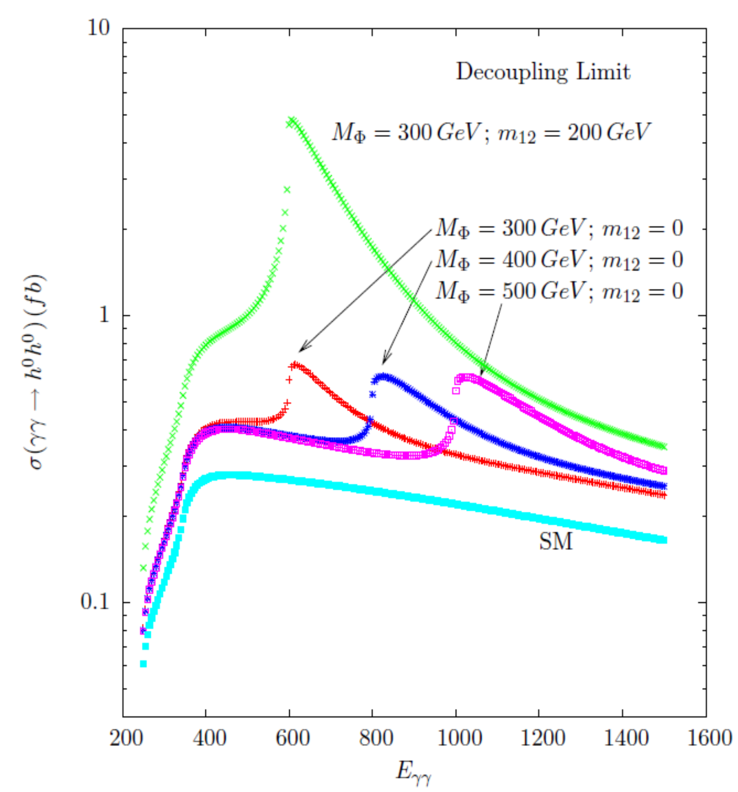


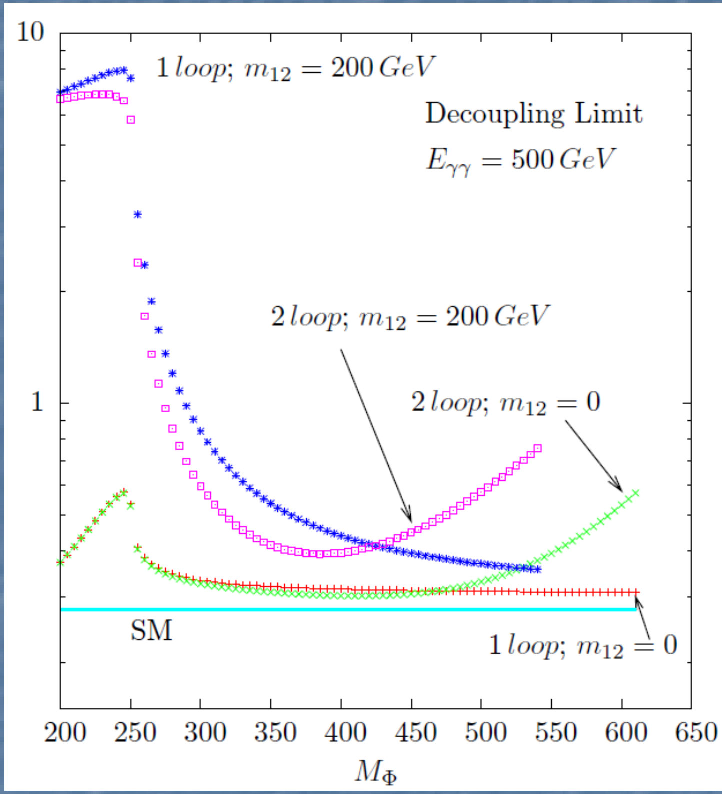
Asakawa et al have looked for effects from $g_{H^+H^-h}$, $g_{H^+H^-H}$ and one loop effects (hhh) for $M^2 > 0$

Non-decoupling effects

$m_H = m_{H^\pm} = m_A = m_\Phi$

$m_h = 120$ GeV





Largest cross sections are obtained for **$M^2 < 0$ including** the one-loop corrected hhh vertex

(Left) $\gamma\gamma \to hh$ at LO,
(Right) $\gamma\gamma \to hh$ at LO and LO + High order corrections to hhh

Self-couplings

Reconstructing the Higgs potential

- Can we use the SM results to find/measure couplings/exclude a light THDM-like Higgs (≈ 120 GeV) at the LHC?

- LHC - Almost impossible to measure the triple Higgs coupling in the SM for masses below 140 GeV;
  Above 140 GeV searches are based on H decaying to VV .

- Parton level studies were performed for gg → hh in the SM for the LHC by Baur, Plehn and Rainwater in

$$gg \to hh \to \bar{b}b\bar{b}b \qquad gg \to hh \to \bar{b}b\tau^+\tau^-$$

… and using rare decays

$$gg \to hh \to \bar{b}b\gamma\gamma \qquad gg \to hh \to \bar{b}b\mu^+\mu^-$$

most promising

Reconstructing the Higgs potential

- In some regions of the THDM the cross section is much larger. We can use the same analysis to find the regions of the THDM that can be probed with less luminosity. We will use two of the Baur, Plehn and Rainwater analysis

- For $gg \longrightarrow hh \longrightarrow \bar{b}b\gamma\gamma$

Signal	0.0106 fb
All backgrounds	0.0186 fb

<u>To establish a non-zero coupling at 95 % ≈ 600 fb^{-1} are needed</u>

- A hopeless scenario in the SM $gg \to hh \to \bar{b}b\tau^+\tau^-$

Signal	0.0066 fb
All backgrounds	0.056 fb

$M_h = 120$ GeV

Reconstructing the Higgs potential

- **The production process does not depend on M_{H+} and on M_A**
  - **only <u>5 variables</u>: M_H, M_h, tanβ, sinα and M .**

- **The branching ratios for h → bb and h → ττ are functions of M_h, tanβ, sinα.**

- **The branching ratio for h → γγ depends on M_h, tanβ, sinα, M and M_{H+} .**

- **The plots shown in the next slides are for the cross sections. The numbers still have to be scaled by a factor that is Yukawa model dependent. For the bbττ final state**

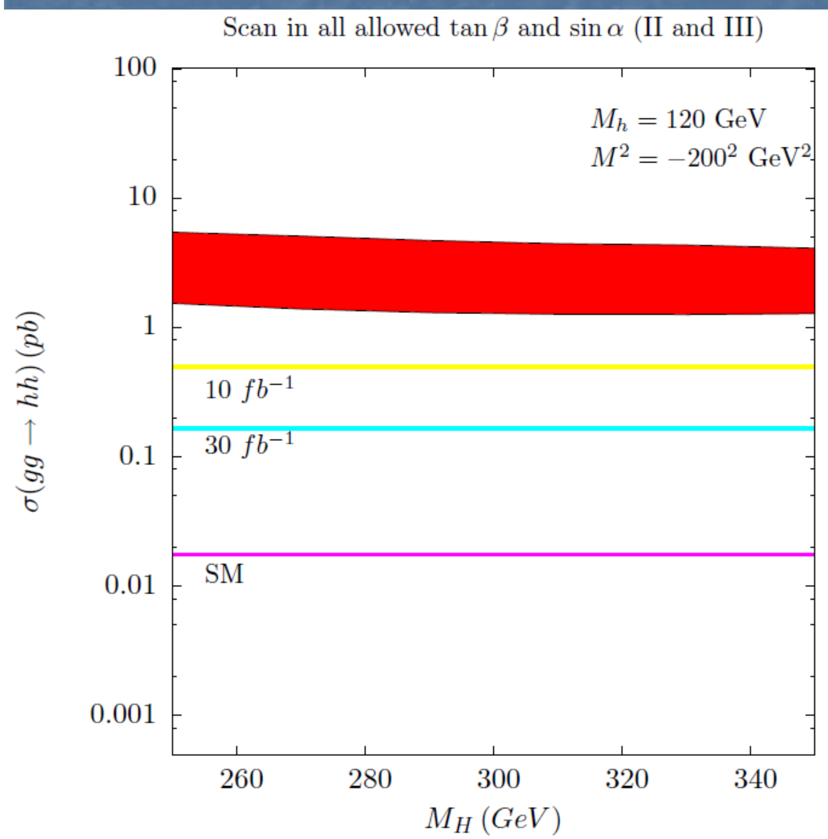
$$\frac{BR(h \to \tau^+\tau^-)_{THDM}\, BR(h \to \bar{b}b)_{THDM}}{BR(h \to \tau^+\tau^-)_{SM}\, BR(h \to \bar{b}b)_{SM}}$$

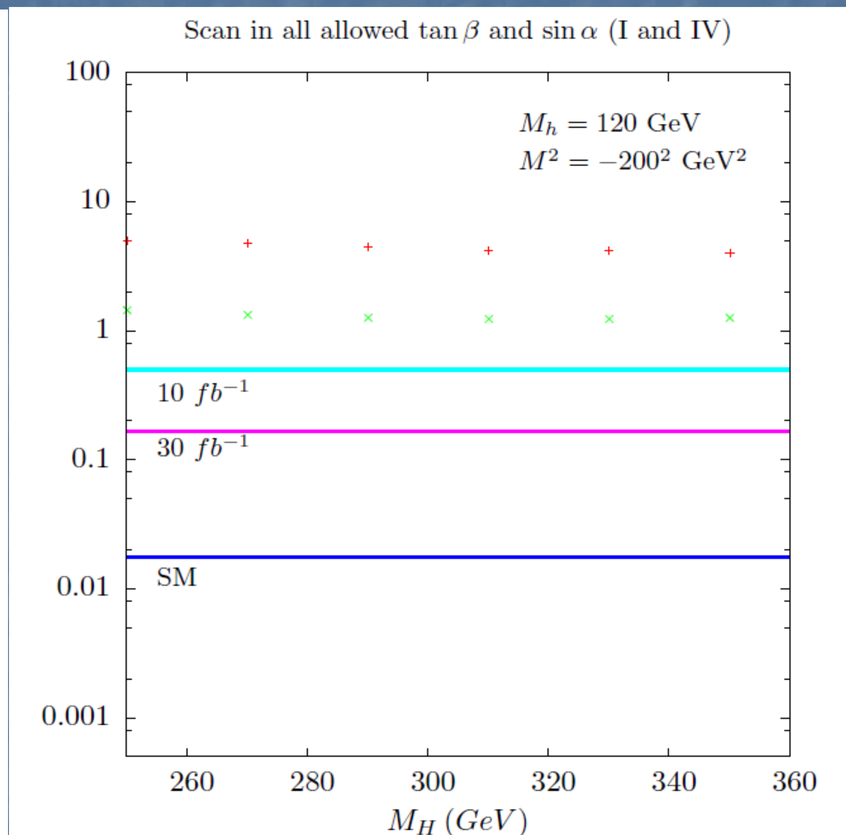
bbγγ analysis

$M_H > 2\,M_h$

and

$M^2 < 0$

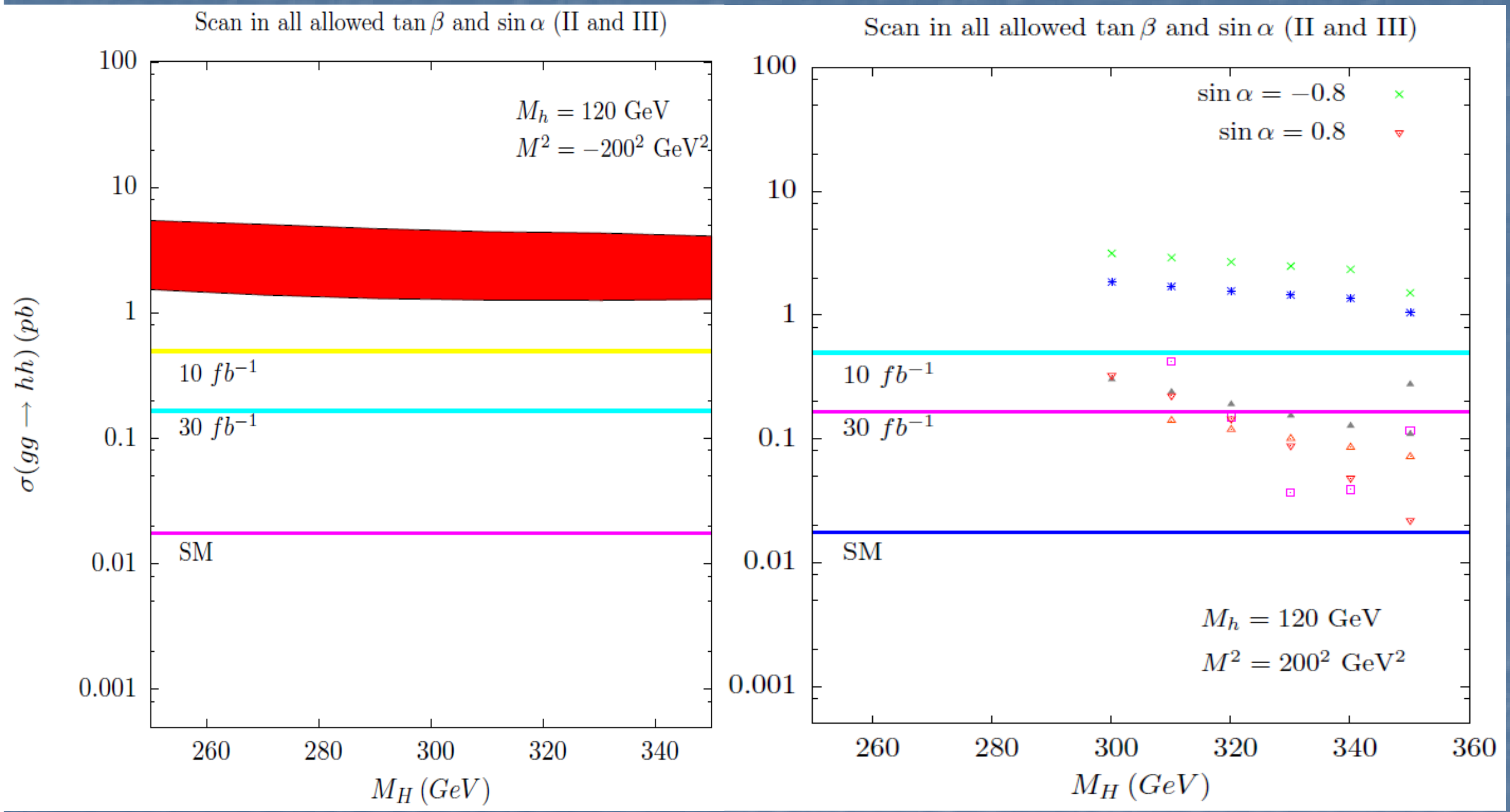




Scan in all values of tanβ and sinα that passed the experimental and theoretical constraints – Models I to IV

bb$\gamma\gamma$ analysis

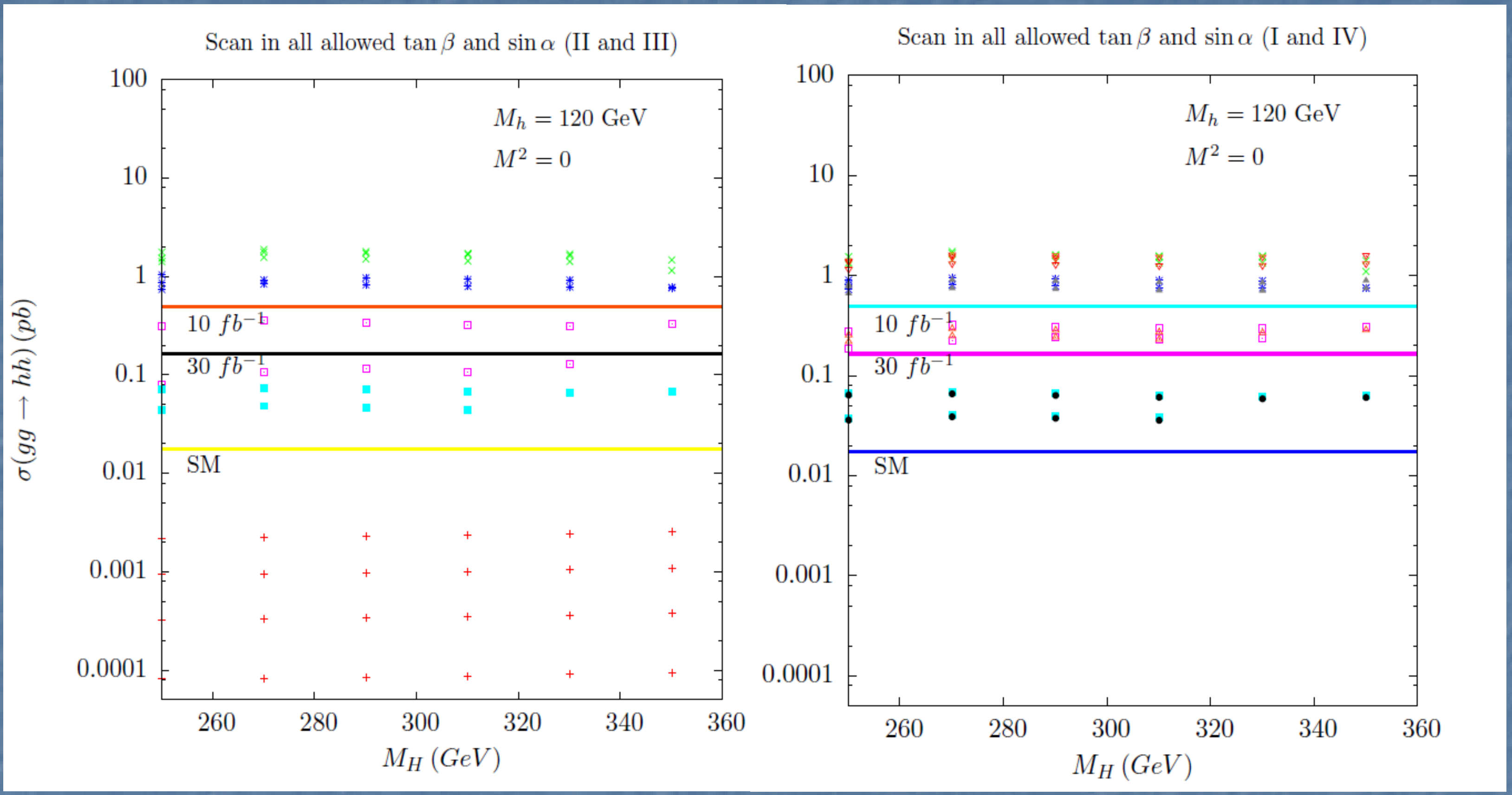
$M_H > 2\, M_h$
and
$M^2 < 0$
Vs.
$M^2 > 0$



Results are better for $M^2 < 0$ than for $M^2 > 0$ – cancellations in the Higgs self-couplings.

bbγγ analysis

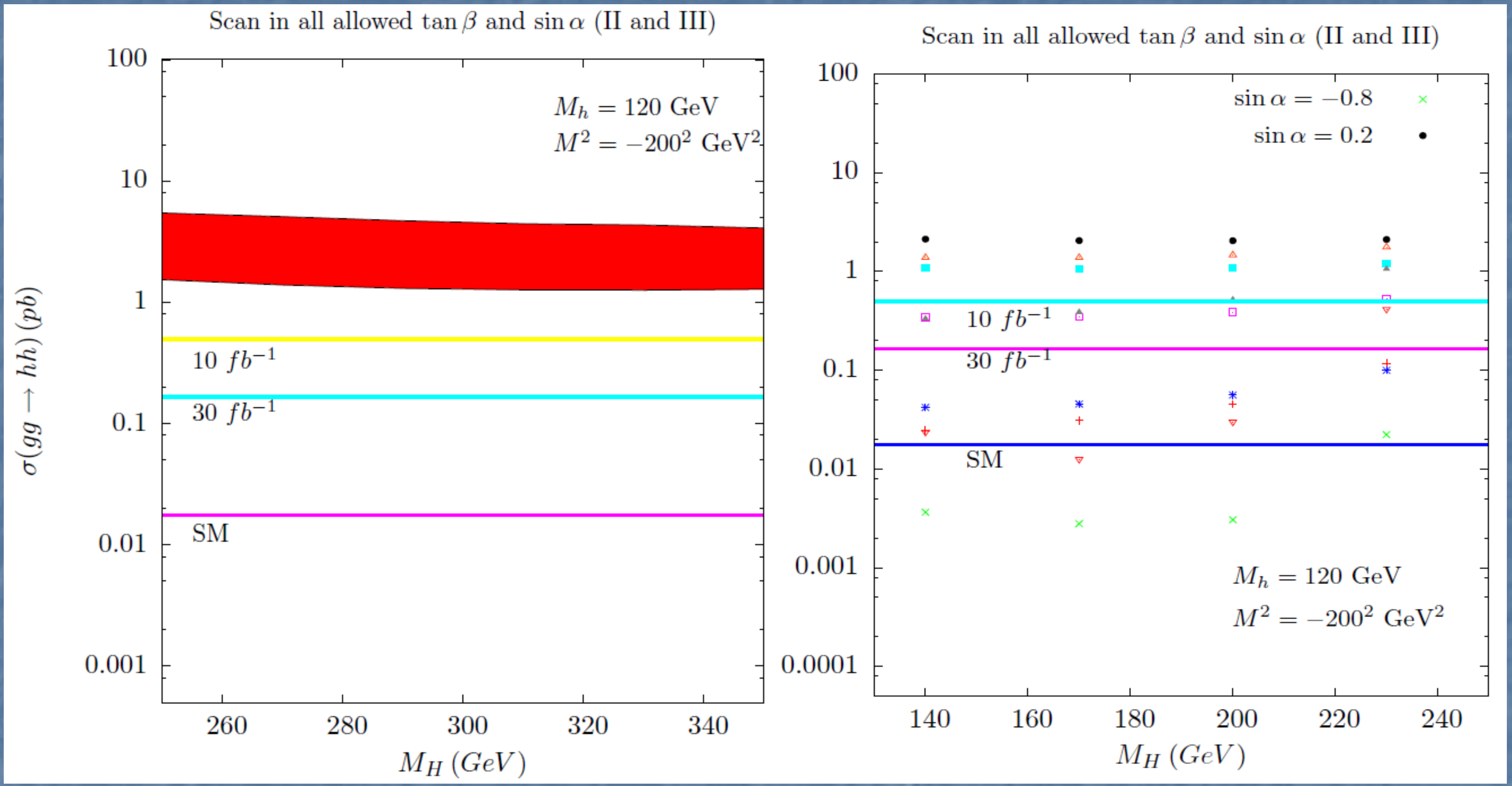
$M_H > 2\ M_h$
and
$M^2 = 0$



Results depend strongly on sinα and M^2 as tanβ is very constrained. Cross sections vary by several orders of magnitude just by changing sinα .

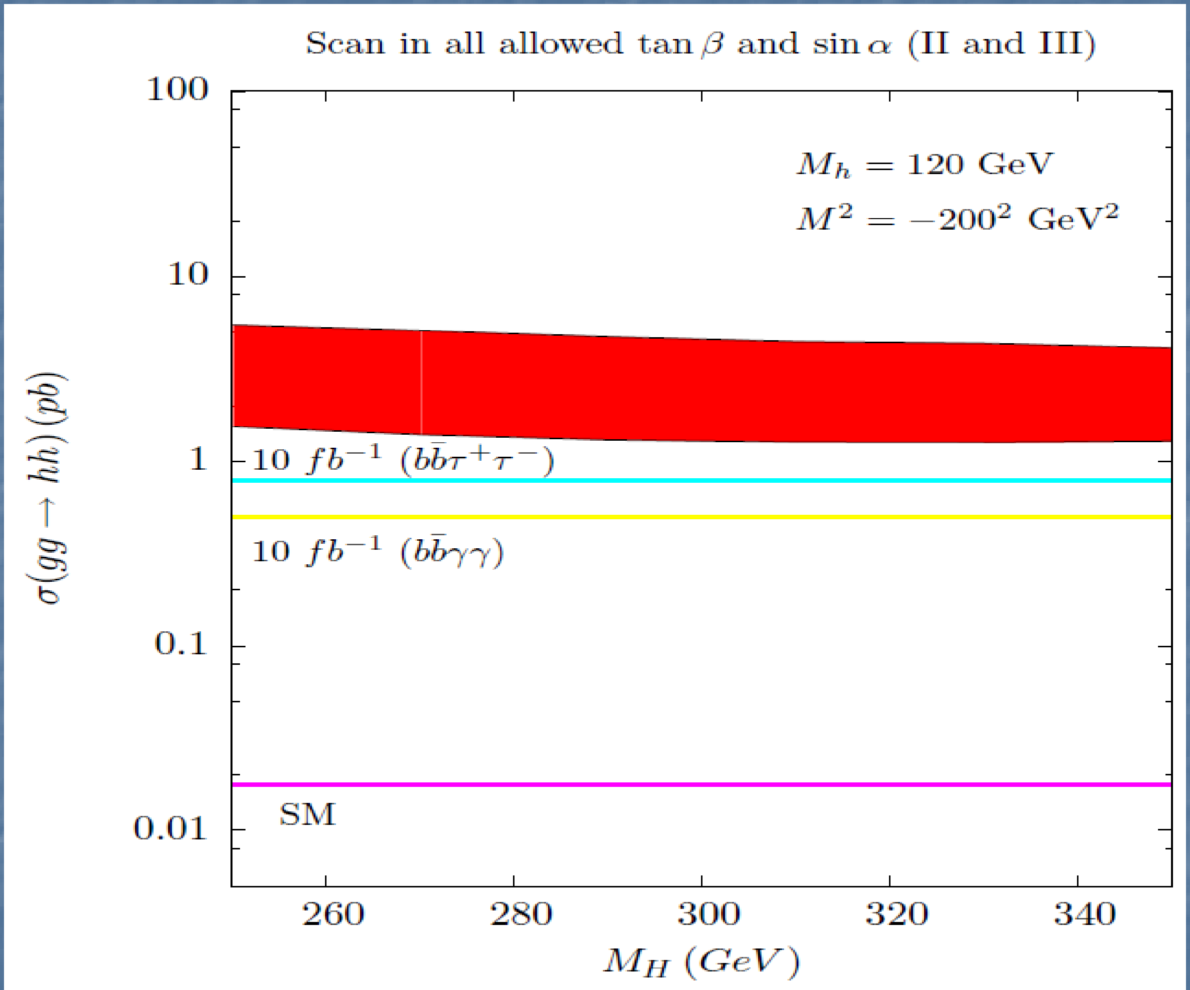
$bb\gamma\gamma$ analysis

$M_H < 2\,M_h$
and
$M^2 < 0$



Below the threshold $M_H < 2\,M_h$, the cross sections are smaller – the enhancement comes only from the couplings.

bbττ analysis



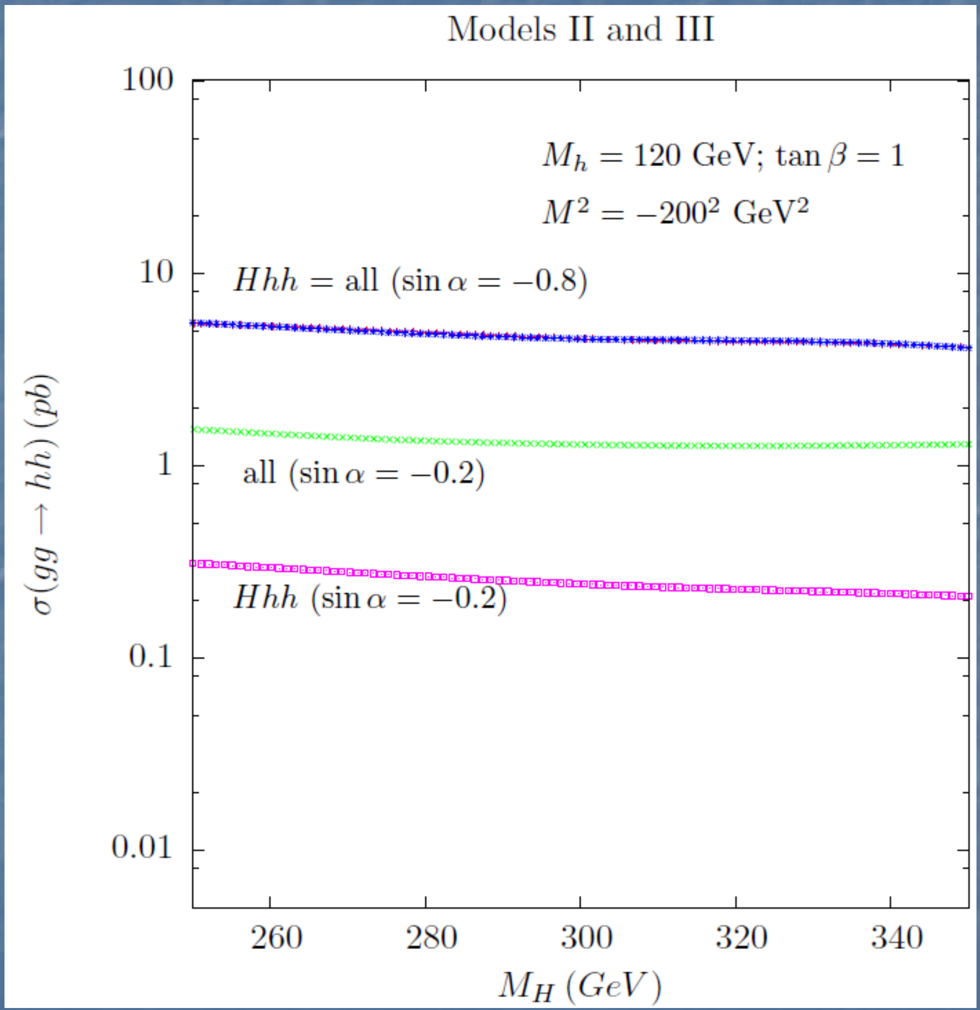
$M_H < 2\,M_h$

and

$M^2 < 0$

Comparison between the two analysis for $M_H < 2\,M_h$, and $M^2 < 0$.

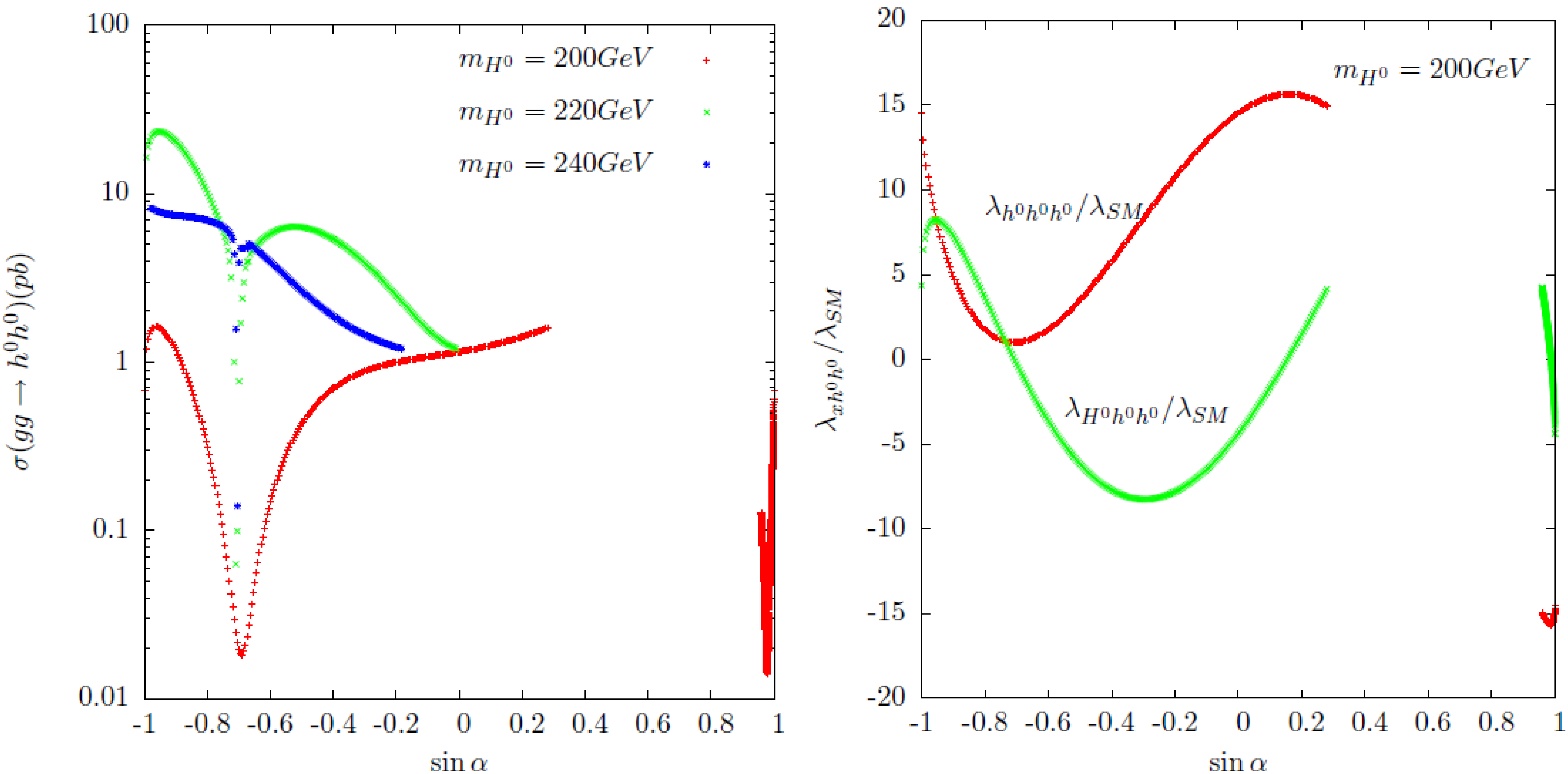
Measuring any coupling?



Is the diagram with the Hhh coupling always the dominant above threshold?

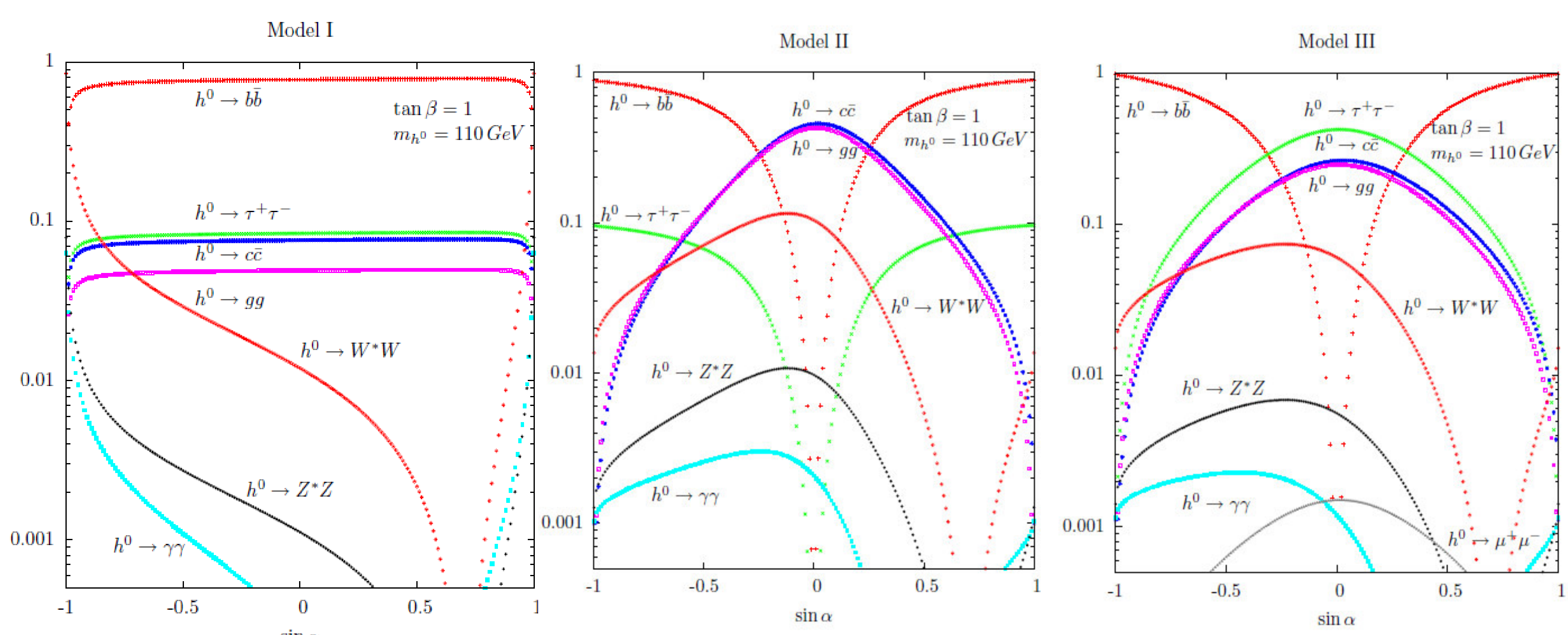
No!

...and the reason is



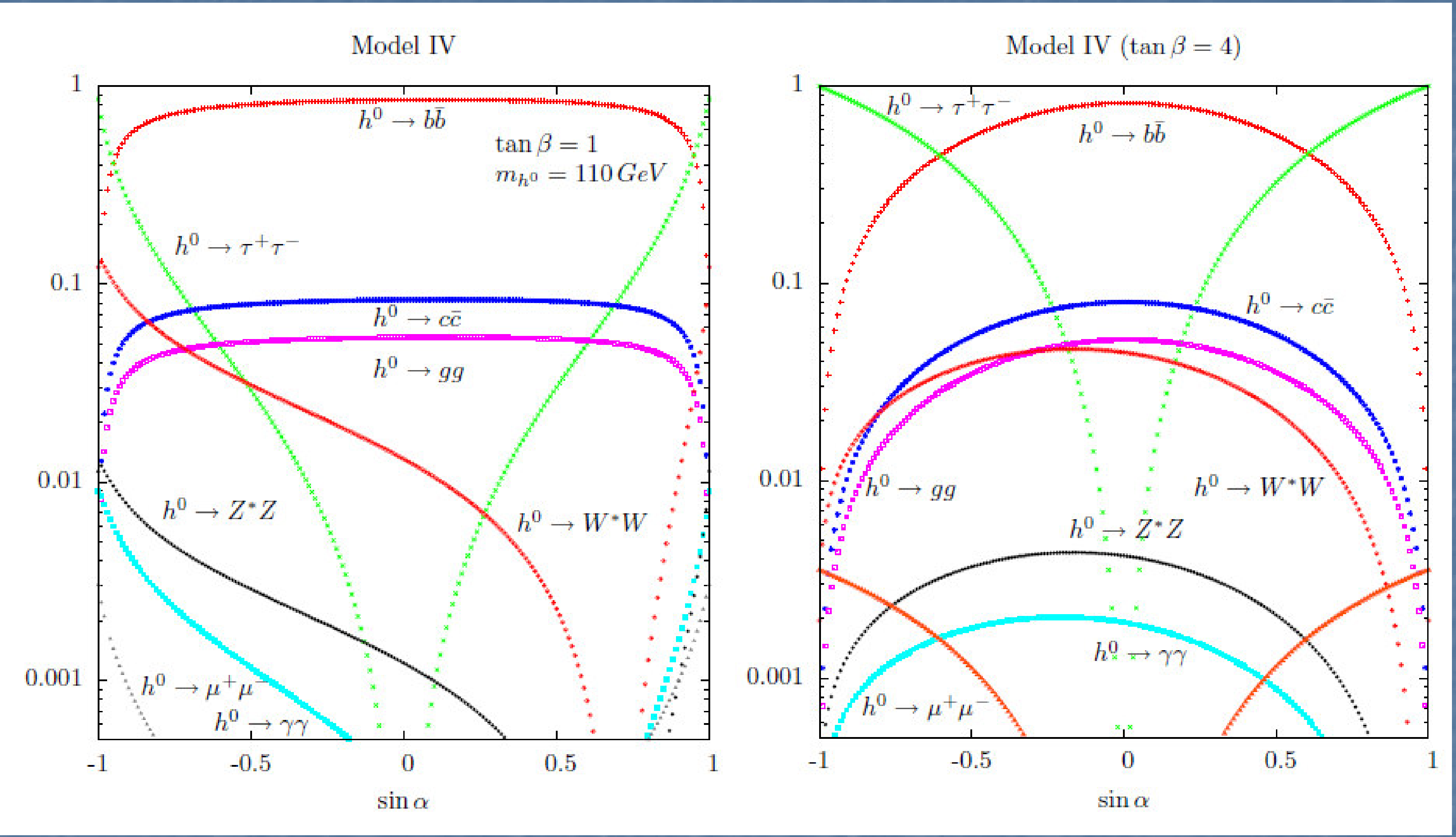
How the couplings behave with sin α

Decays



As tan β grows the bb final state becomes dominant for all sin α values in Model II and $\tau\tau$ dominates in Model III (plots do not change much) .

Decays



For large $\tan\beta$, the decay to leptons becomes dominant in Model IV.

Decays (bbττ analysis)

For sinα = – 0 .95

III – 0.02

IV – 1.30

$$\frac{BR(h \to \tau^+\tau^-)_{THDM}\, BR(h \to \bar{b}b)_{THDM}}{BR(h \to \tau^+\tau^-)_{SM}\, BR(h \to \bar{b}b)_{SM}}$$

tanβ = 1

$\bar{b}b\tau^+\tau^-$	**I**	**II**	**III**	**IV**
-1	1	1.36	0	0
-0.8	1	1.20	0.73	1.57
-0.6	1	0.92	1.44	0.61
-0.4	1	0.49	1.64	0.22
-0.2	1	0.08	0.81	0.05
0	1	0	0	0
0.2	1	0.08	0.81	0.05
0.4	1	0.49	1.64	0.22
0.6	1	0.92	1.44	0.61
0.8	1	1.20	0.73	1.57
1	1	1.36	0	0

tanβ = 3

$\bar{b}b\tau^+\tau^-$	**I**	**II**	**III**	**IV**
-1	1	1.36	0	0
-0.8	1	1.34	0.10	3.10
-0.6	1	1.31	0.30	2.81
-0.4	1	1.19	0.75	1.53
-0.2	1	0.77	1.62	0.42
0	1	0	0	0
0.2	1	0.77	1.62	0.42
0.4	1	1.19	0.75	1.53
0.6	1	1.31	0.30	2.81
0.8	1	1.34	0.10	3.10
1	1	1.36	0	0

For Model I and for this analysis the factor is 1.

Decays (bbγγ analysis)

$$\frac{BR(h\to\gamma\gamma)_{THDM}\, BR(h\to\bar{b}b)_{THDM}}{BR(h\to\gamma\gamma)_{SM}\, BR(h\to\bar{b}b)_{SM}}$$

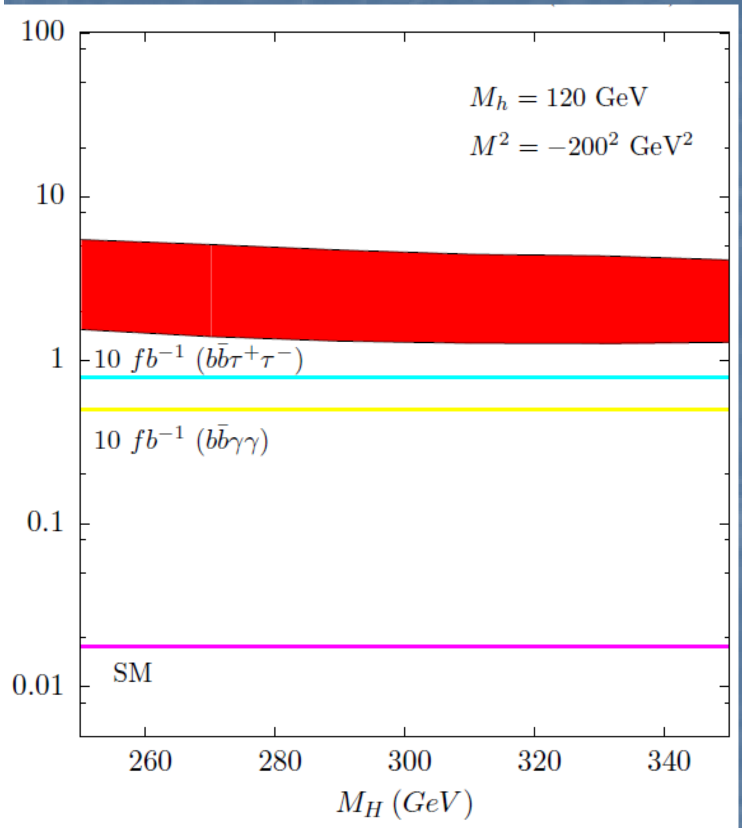
$\tan\beta = 1$

$\bar{b}b\gamma\gamma$	**I**	**II**	**III**	**IV**
-1	-	0.50	0.61	0
-0.8	1.27	0.84	0.91	1.12
-0.6	0.61	0.95	0.84	0.65
-0.4	0.35	0.86	0.55	0.40
-0.2	0.20	0.37	0.15	0.24
0	0.11	0	0	0.13
0.2	0.04	0.07	0.03	0.05
0.4	0.005	0.006	0.004	0.005
0.6	0.02	0.03	0.03	0.02
0.8	0.22	0.16	0.17	0.20
1	0	0.50	0.61	0

$\tan\beta = 2$

$\bar{b}b\gamma\gamma$	**I**	**II**	**III**	**IV**
-1	-	0.52	0.65	0
-0.8	1.37	0.90	0.98	1.20
-0.6	0.65	1.03	0.91	0.71
-0.4	0.38	0.93	0.59	0.43
-0.2	0.22	0.41	0.17	0.26
0	0.12	0	0	0.14
0.2	0.05	0.08	0.03	0.06
0.4	0.006	0.009	0.006	0.007
0.6	0.02	0.03	0.03	0.02
0.8	0.23	0.16	0.18	0.20
1	0	0.52	0.65	0

Best of parameter regions probed



IV	IV
0	0
1.12	1.57
0.65	0.61
0.40	0.22
0.24	0.05
0.13	0
0.05	0.05
0.005	0.22
0.02	0.61
0.20	1.57
0	0

We need more luminosity to probe the regions of low sin α in Model IV. But contrary to models II and III, the two analysis presented are enough to probe the region shown in the plot.

$\tan\beta = 1$

The red region can all be probed in Model I

Summary I

- Model – CP-conserving THDM with 8 parameters in its four Yukawa versions.
- Constraints – parameter space is constrained by all relevant theoretical and experimental constraints.
- Can we distinguish the SM from the THDM when $\cos(\beta - \alpha) \approx 0$

  and $(g_{hVV})^{SM} \approx (g_{hVV})^{THDM}$; $(g_{hff})^{SM} \approx (g_{hff})^{THDM}$; $(g_{hhh})^{SM} \approx (g_{hhh})^{THDM}$

  and $(g_{Hhh})^{THDM} \approx 0$?
- LHC – no one loop hhh correction – No!

  – with one loop hhh correction

$M^2 > 0$	$\longleftrightarrow$	$M^2 < 0$
Harder		**Easier**

- Photon collider – no one loop hhh correction – non DE can come from charged Higgs couplings

  – with one loop hhh correction – more non DE
- Photon collider?

Summary II

• Can we measure any triple couplings? Yes – in some scenarios.

• Can we kill the model? Not easy. But for some Yukawa versions - like Model I – we can probably exclude a very large portion by including other production channels and other decay modes in the gluon fusion process.

$$gg \to hh \to \tau^+\tau^-\tau^+\tau^- \qquad gg \to hh \to \tau^+\tau^-\mu^+\mu^-$$

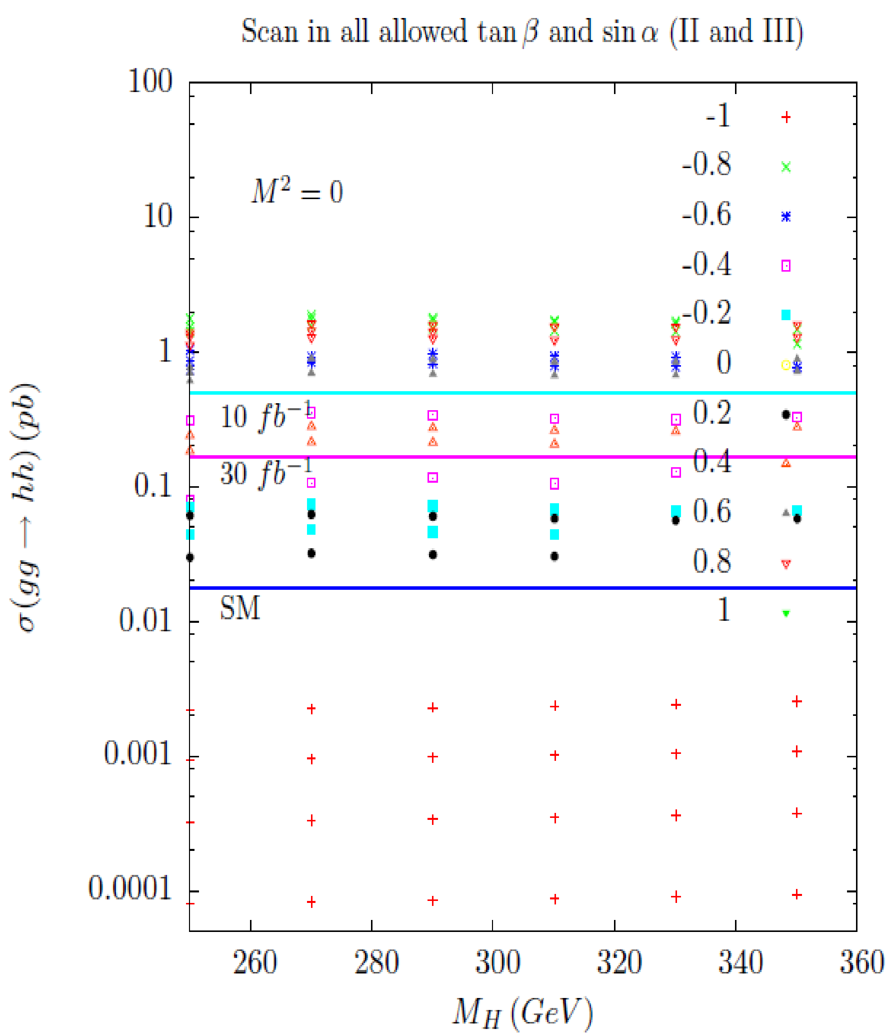
• In the most general case, the best scenarios are the ones with large M^2 (preferably < 0).

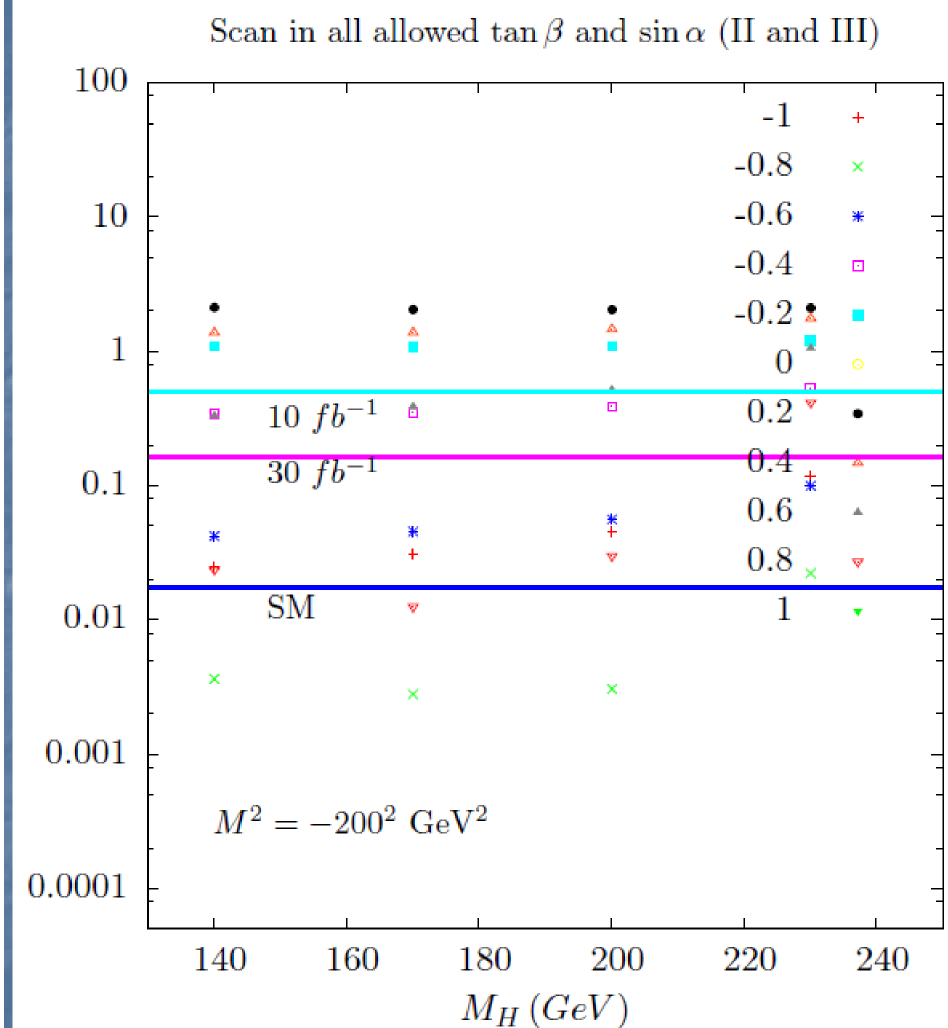
• The combined dependence in $\sin\alpha$, M and $\tan\beta$ is very unorthodox.

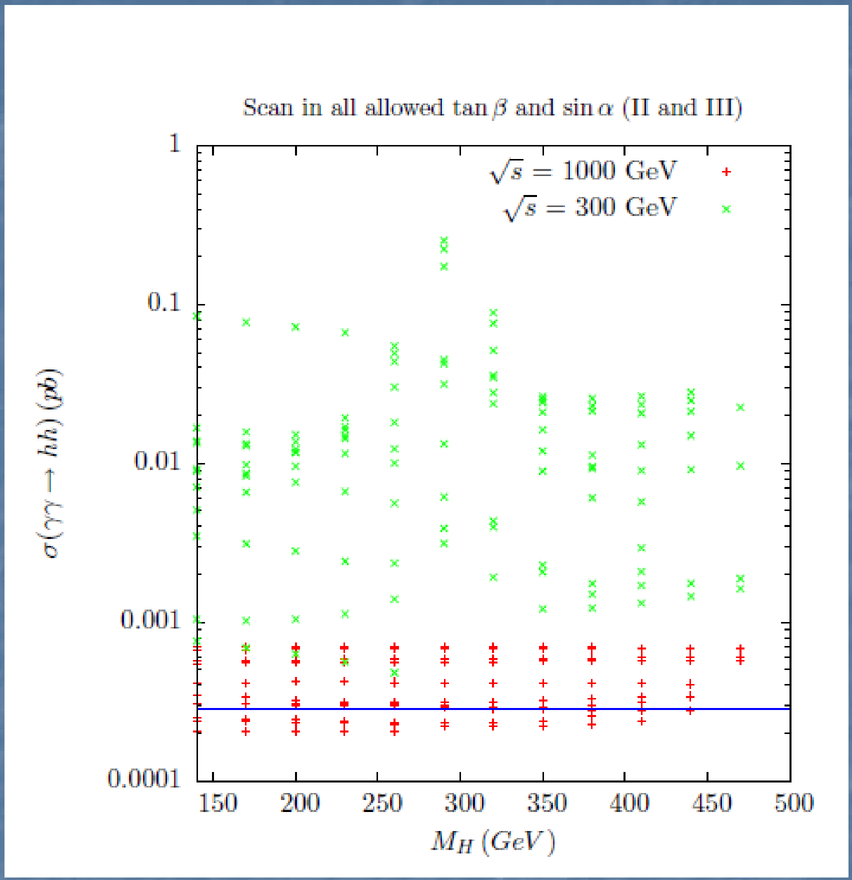
• Some regions could be probed with just a few fb^{-1}

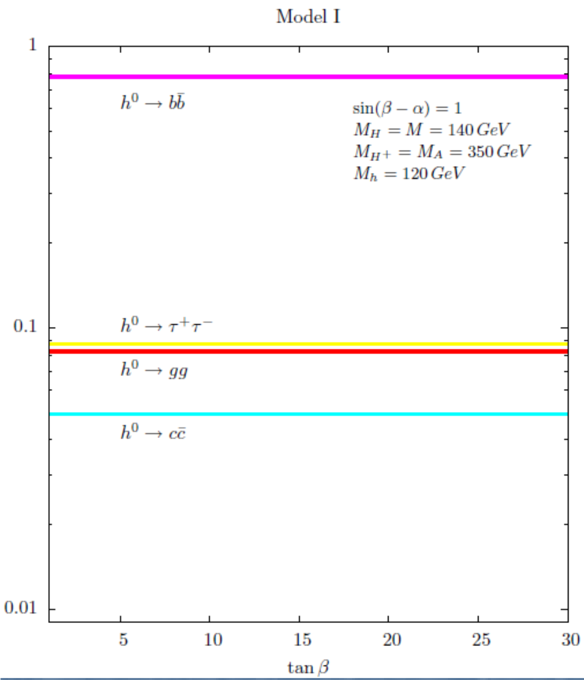
Thank you!

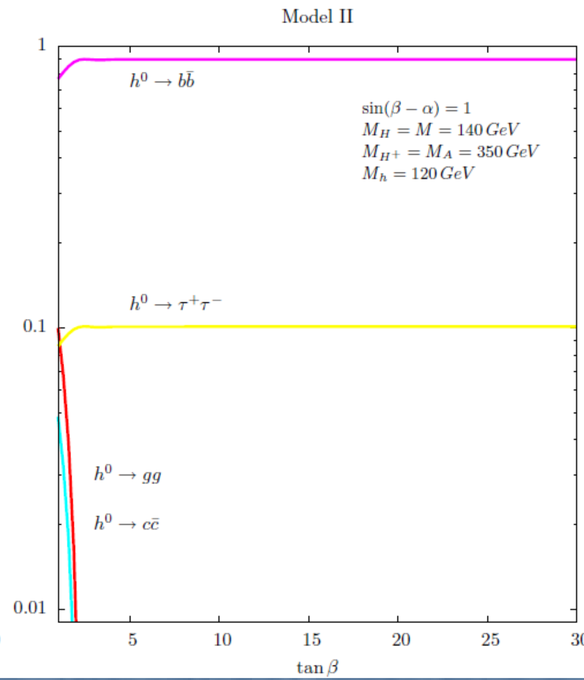
Am I showing these slides?

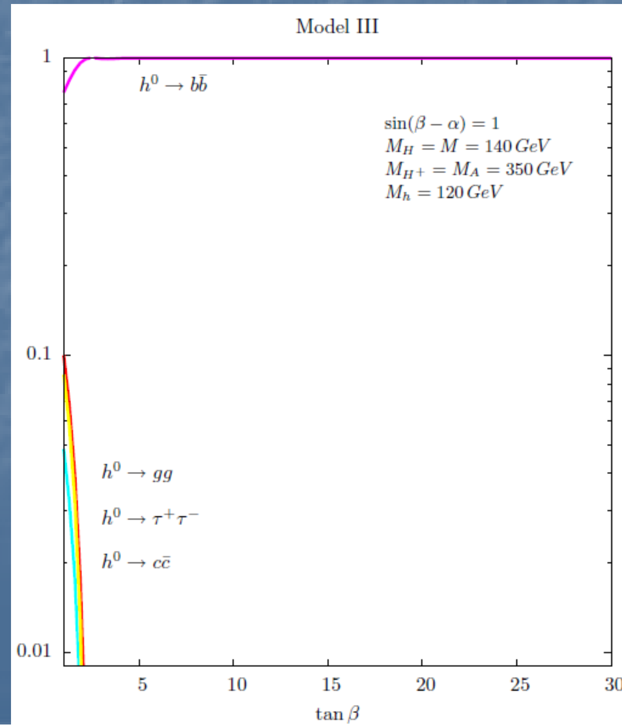

Scan in all allowed tan β and sin α (II and III)
M² = 0
σ(gg → hh) (pb)
M_H (GeV)
10 fb⁻¹
30 fb⁻¹
SM
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

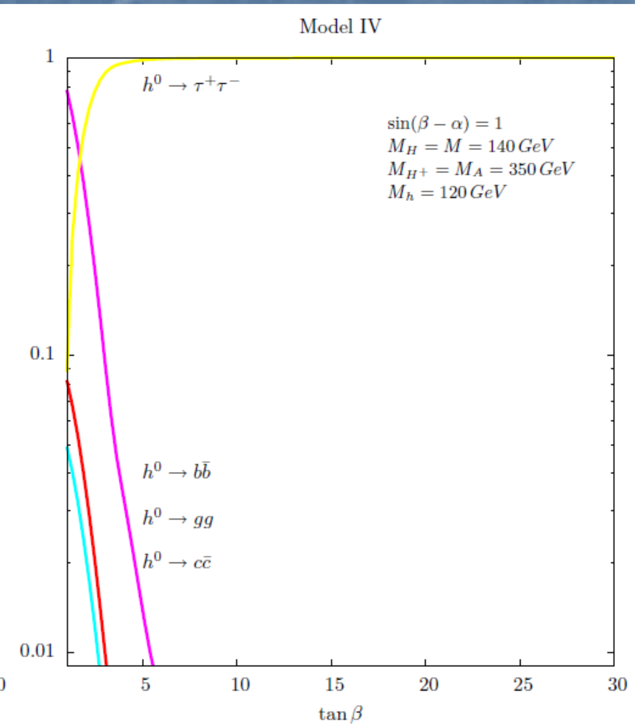

Scan in all allowed tan β and sin α (II and III)
M² = −200² GeV²
M_H (GeV)
10 fb⁻¹
30 fb⁻¹
SM
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1


Scan in all allowed $\tan\beta$ and $\sin\alpha$ (II and III)
$\sqrt{s}$ = 1000 GeV
$\sqrt{s}$ = 300 GeV
$\sigma(\gamma\gamma \to hh)\ (pb)$
$M_H\ (GeV)$
1
0.1
0.01
0.001
0.0001
150
200
250
300
350
400
450
500


Model I
$h^0 \to b\bar{b}$
$h^0 \to \tau^+\tau^-$
$h^0 \to gg$
$h^0 \to c\bar{c}$
$\sin(\beta-\alpha) = 1$
$M_H = M = 140\,GeV$
$M_{H^+} = M_A = 350\,GeV$
$M_h = 120\,GeV$
1
0.1
0.01
5 10 15 20 25 30
$\tan\beta$


Model II
$h^0 \to b\bar{b}$
$h^0 \to \tau^+\tau^-$
$h^0 \to gg$
$h^0 \to c\bar{c}$
$\sin(\beta-\alpha) = 1$
$M_H = M = 140\,GeV$
$M_{H^+} = M_A = 350\,GeV$
$M_h = 120\,GeV$
1
0.1
0.01
5 10 15 20 25 30
$\tan\beta$


Model III
$h^0 \to b\bar{b}$
$h^0 \to gg$
$h^0 \to \tau^+\tau^-$
$h^0 \to c\bar{c}$
$\sin(\beta-\alpha) = 1$
$M_H = M = 140\,GeV$
$M_{H^+} = M_A = 350\,GeV$
$M_h = 120\,GeV$
1
0.1
0.01
5 10 15 20 25 30
$\tan\beta$


Model IV
$h^0 \to \tau^+\tau^-$
$h^0 \to b\bar{b}$
$h^0 \to gg$
$h^0 \to c\bar{c}$
$\sin(\beta-\alpha) = 1$
$M_H = M = 140\,GeV$
$M_{H^+} = M_A = 350\,GeV$
$M_h = 120\,GeV$
1
0.1
0.01
5 10 15 20 25 30
$\tan\beta$

$$\lambda_1 = \frac{1}{v^2\cos^2\beta}\left(-\sin^2\beta M^2 + \sin^2\alpha m_h^2 + \cos^2\alpha m_H^2\right),$$

$$\lambda_2 = \frac{1}{v^2\sin^2\beta}\left(-\cos^2\beta M^2 + \cos^2\alpha m_h^2 + \sin^2\alpha m_H^2\right),$$

$$\lambda_3 = -\frac{M^2}{v^2} + 2\frac{m_{H^\pm}^2}{v^2} + \frac{1}{v^2}\frac{\sin 2\alpha}{\sin 2\beta}(m_H^2 - m_h^2),$$

$$\lambda_4 = \frac{1}{v^2}\left(M^2 + m_A^2 - 2m_{H^\pm}^2\right),$$

$$\lambda_5 = \frac{1}{v^2}\left(M^2 - m_A^2\right).$$

$$m_h^2 = M^2\cos^2(\alpha-\beta) + (\lambda_1\sin^2\alpha\cos^2\beta + \lambda_2\cos^2\alpha\sin^2\beta - \frac{1}{2}\lambda\sin 2\alpha\sin 2\beta)v^2$$

$$m_H^2 = M^2\sin^2(\alpha-\beta) + (\lambda_1\cos^2\alpha\cos^2\beta + \lambda_2\sin^2\alpha\sin^2\beta + \frac{1}{2}\lambda\sin 2\alpha\sin 2\beta)v^2$$

$$m_{H^\pm}^2 = M^2 - \frac{1}{2}(\lambda_4 + \lambda_5)v^2$$

$$m_A^2 = M^2 - \lambda_5 v^2$$