# Higgs pair production in THDM LHC vs. $\gamma\gamma$ Collider

**LC09 Perugia**

23 September 2009

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# Outline

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

# THDM

THDM = SM + 1 scalar doublet (take the SM fields, add one doublet and write the most general renormalisable Lagrangian compatible with the symmetries).

## Particle content

**SM → 4 degrees of freedom** ⟹ **THDM → 8 degrees of freedom**

1. If we can break all gauge symmetries → 4 NGB + 4 scalar bosons
2. Gauge U(1) conserved but not CP → 3 NGB + 5 scalar bosons (2 charged, $H^{\pm}$, and 3 neutral, $h_1$, $h_2$ and $h_3$)
3. Gauge U(1) and CP conserved → 3 NGB + 5 scalar bosons (2 charged, $H^{\pm}$ , and 3 neutral, h, H and A)

Includes the hit: THE INERT MODEL

4. All gauge symmetries unbroken → 8 scalar bosons
5. Other global symmetries can generate additional NGB.

# "The" THDM potential -DIY

1. Do not touch the gauge and fermion sectors

2. Duplicate the kinetic scalar term – write $\Phi_1$ instead of $\Phi$ in $L_{kin}$, then add another piece with $\Phi_2$ instead of $\Phi$.

3. Don't write the most general Higgs potential. Use a symmetry!

$Z_2$ 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

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

8 + 2 parameters – 2 are fixed by the minimum conditions and one by the W mass $v^2 = v_1^2 + v_2^2$. I choose the remaining 7 as

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

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

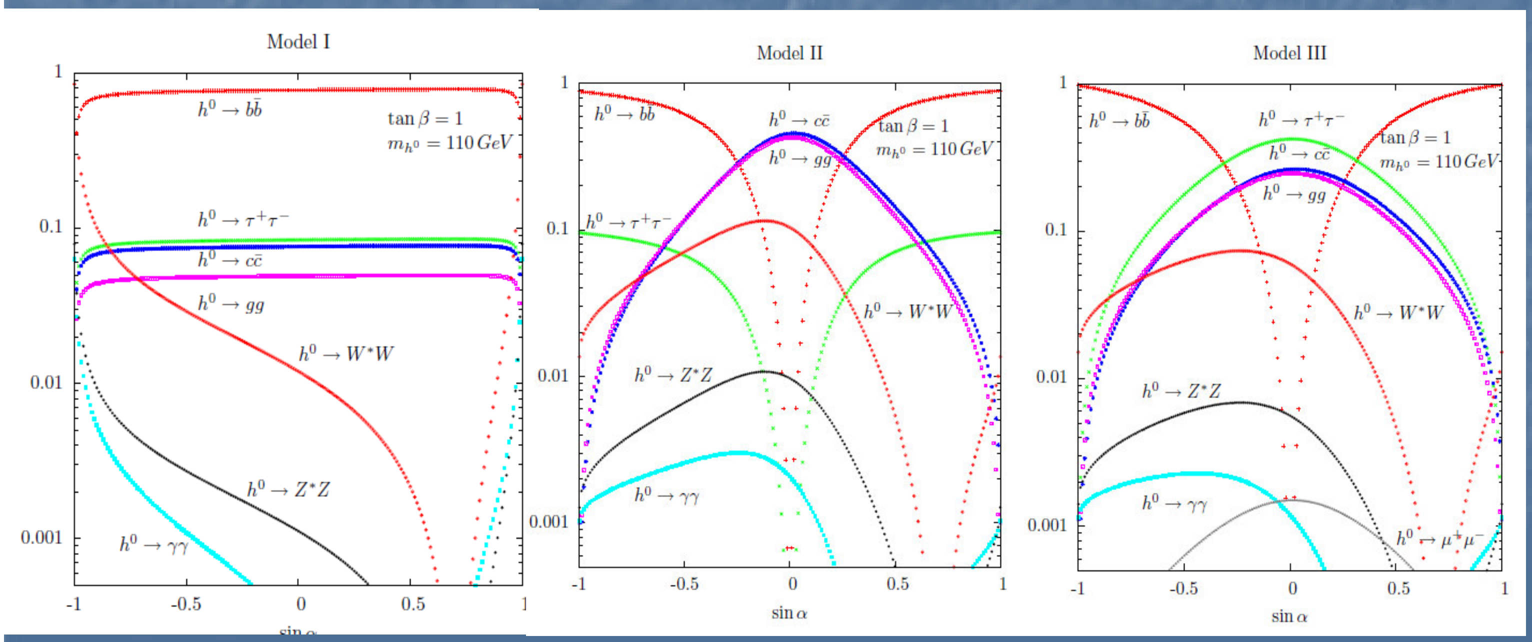
# Yukawa Lagrangian

**4. There are 4 ways to extend the discrete symmetry to the fermions – 4 possible Yukawa Lagrangians (without FCNC at tree-level).**

| | I | II | III | IV |
|---|---|---|---|---|
| up | $\Phi_2$ | $\Phi_2$ | $\Phi_2$ | $\Phi_2$ |
| down | $\Phi_2$ | $\Phi_1$ | $\Phi_1$ | $\Phi_2$ |
| lepton | $\Phi_2$ | $\Phi_1$ | $\Phi_2$ | $\Phi_1$ |

$\Rightarrow$

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




**Couplings to gauge bosons**

**$\cos(\beta - \alpha)$**

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

**5. Serve with branching ratios and cross sections.**

# 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)**

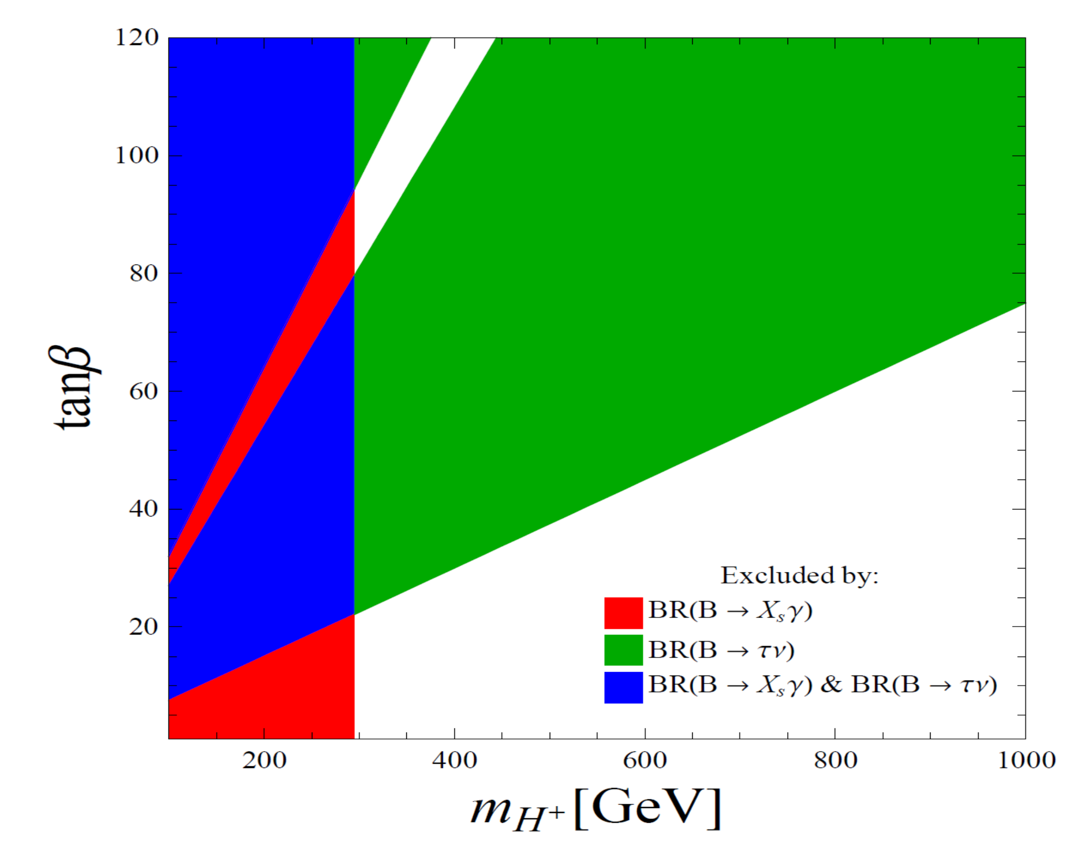
  **SM like – LEP bound 114.4 GeV**

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

- $|\delta\rho| \lesssim 10^{-3}$ **Electroweak precision constraints (all models) – "compact" mass spectrum**

# 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 $\beta$ just in model II**

# Theoretical Constraints

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

  **In a "Normal" minimum, the THDM 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**

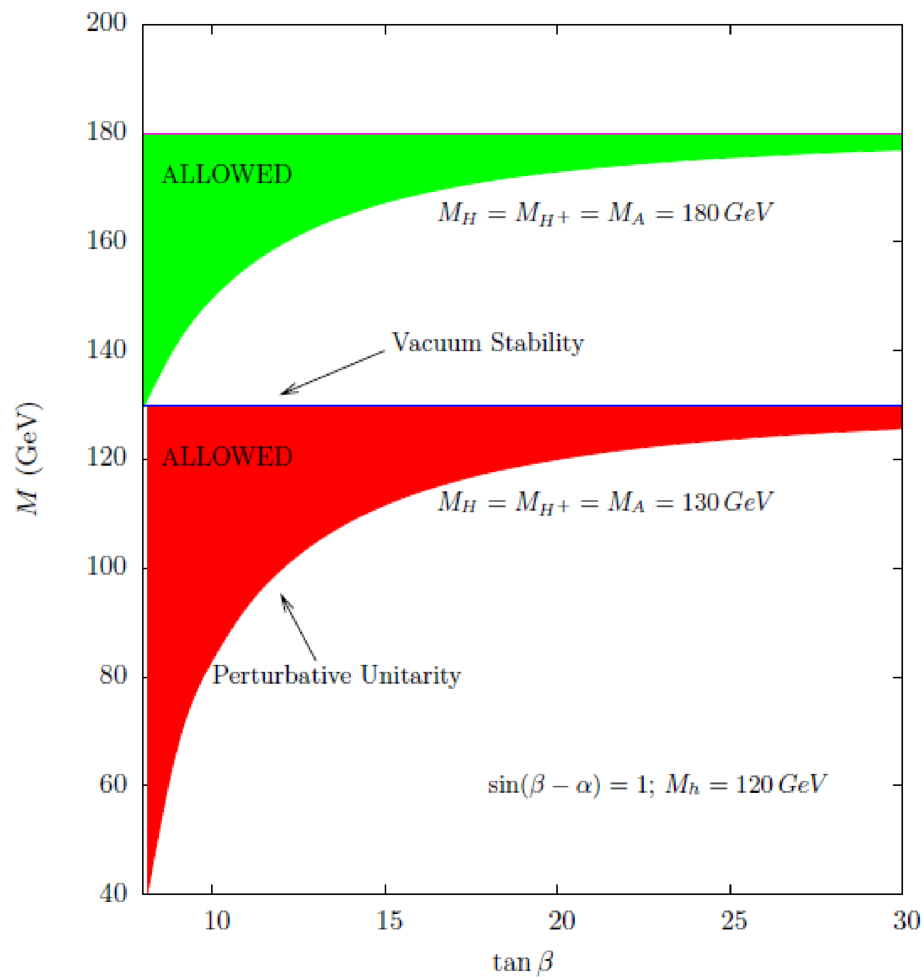
  **Full set of perturbative unitarity conditions – very restrictive – small values of tan $\beta$ (or not) and masses below ≈ 1 TeV.**

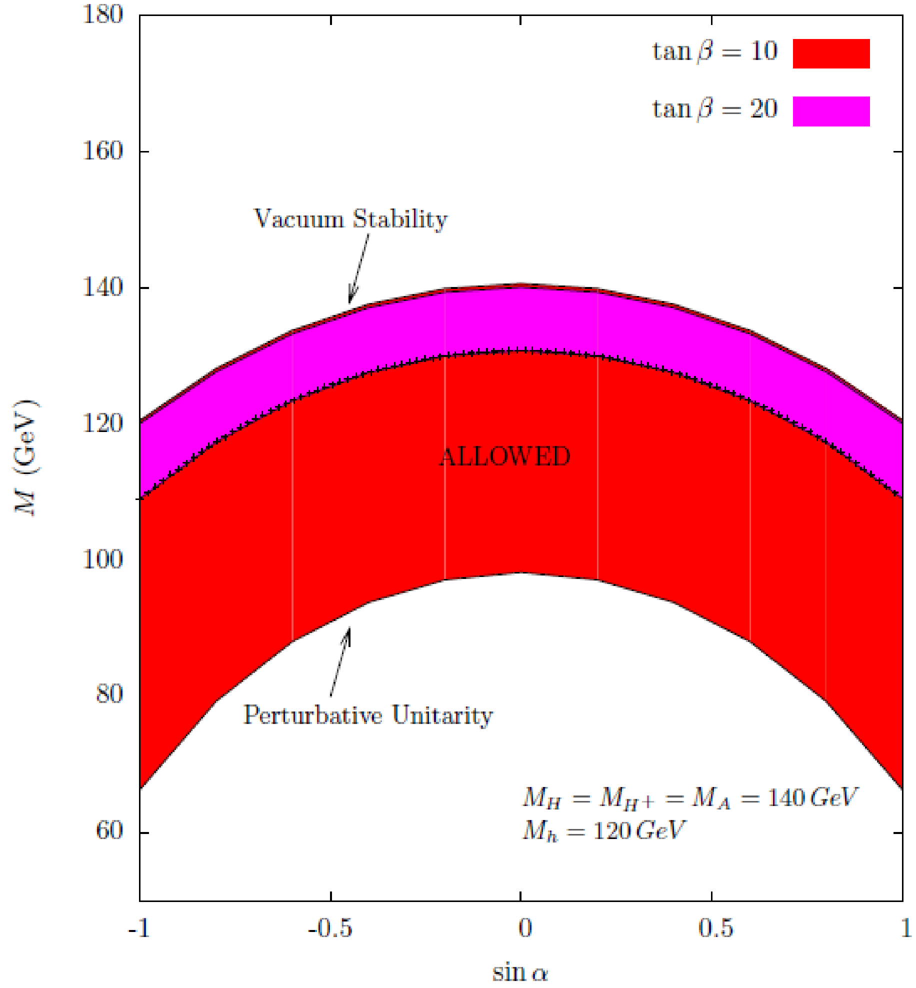
# Theoretical Constraints

$$M^2 > 0$$

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

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



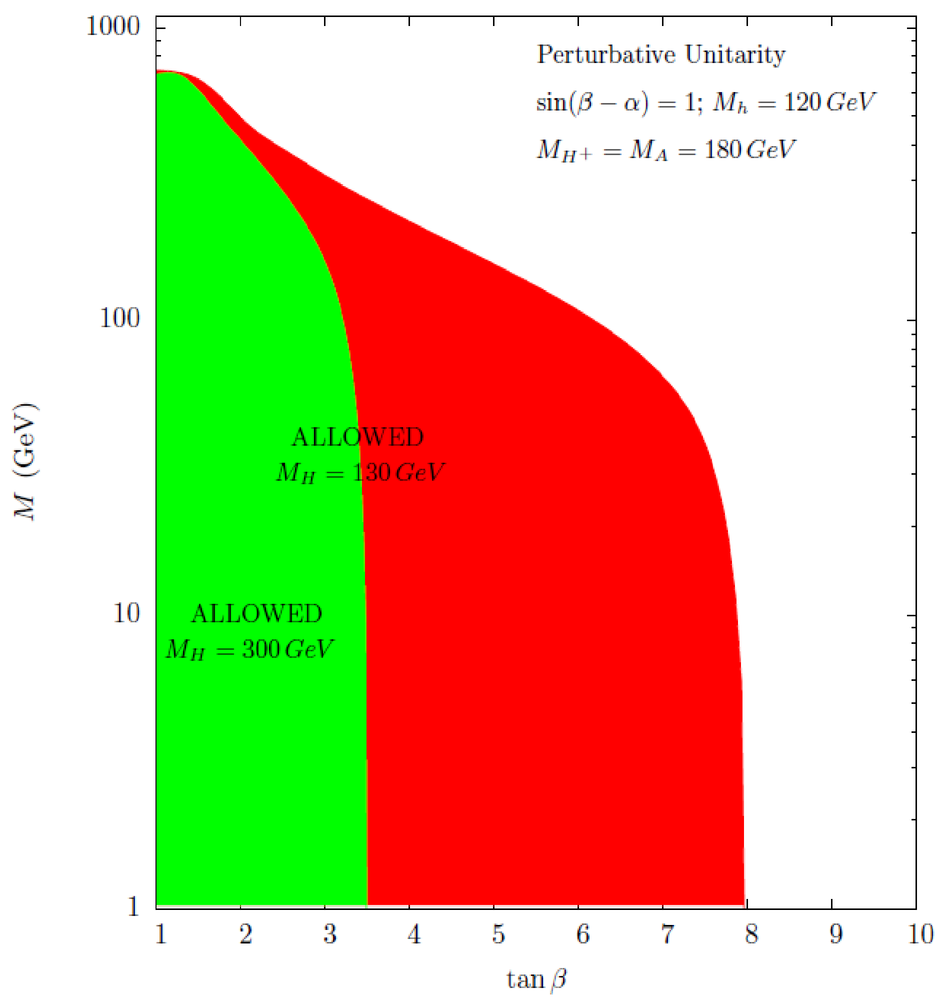



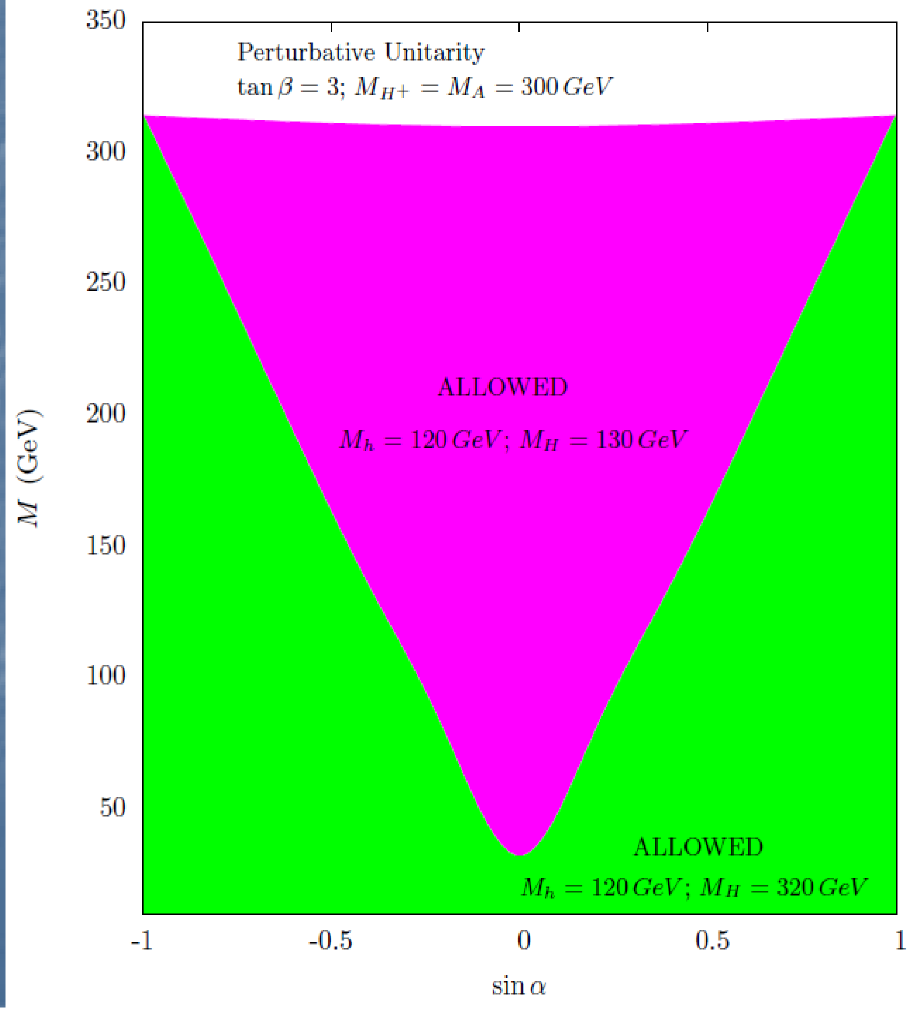
# Theoretical Constraints

$$M^2 < 0$$

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

**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

**$\cos(\beta - \alpha) \approx 0$**

**$\sin(\beta - \alpha) \approx 1$**

- Lightest CP-even Higgs becomes SM-like - the h couplings to the gauge bosons and to the fermions are the same as in the SM

$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \sin(\beta - \alpha) \to 1 \qquad \frac{g_{h\bar{f}f}}{g_{h_{SM}\bar{f}f}} \to 1$$

- $g_{hhh}$ is now the same in the SM and in the THDM (and $g_{Hhh} = 0$)

$$\frac{g_{(hhh)}}{g_{(hhh)_{SM}}} \to 1 \qquad g_{Hhh} \to 0$$

- We take

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

<u>Why?</u>

- Because if we find a Higgs we want to make sure that it is (or maybe not) indeed the SM Higgs boson (look for non-decoupling effects)

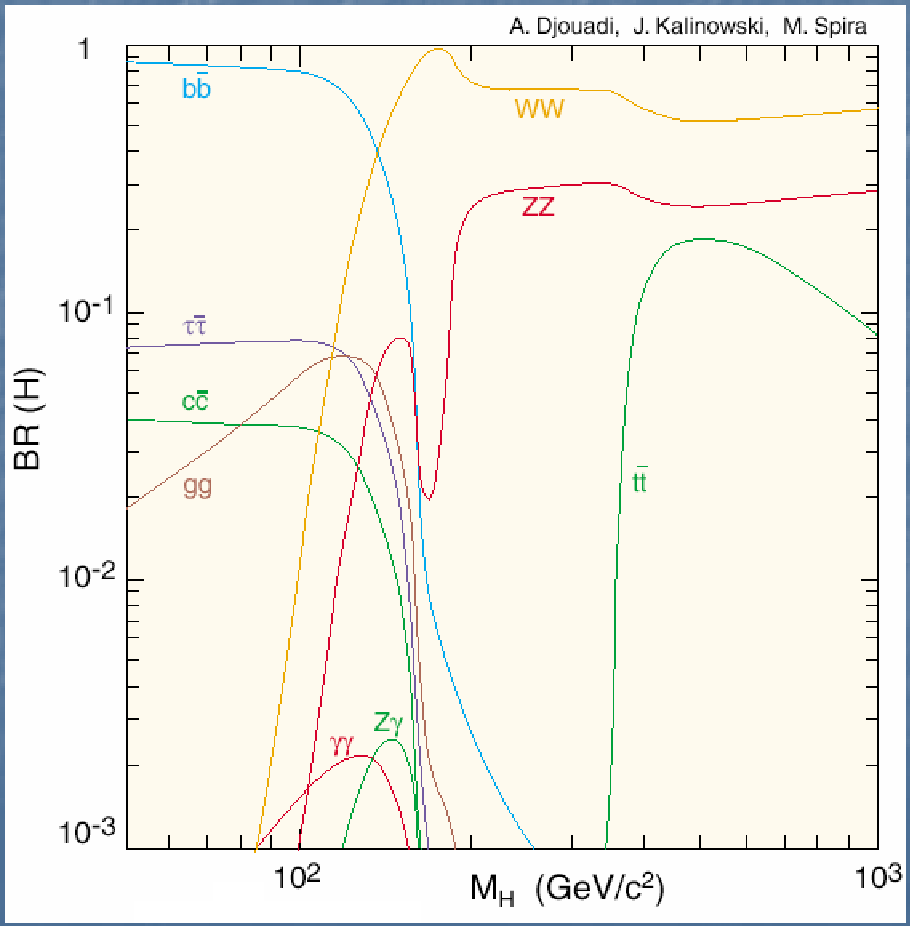
# A SM-like Higgs

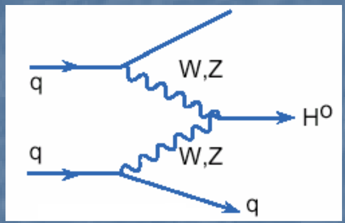
$(g_{hVV})^{SM} \approx (g_{hVV})^{THDM}$

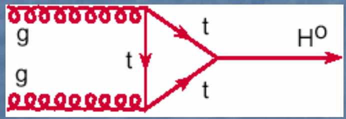
$(g_{hff})^{SM} \approx (g_{hff})^{THDM}$

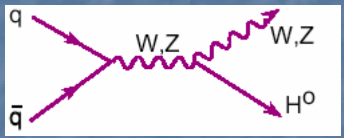
$(g_{hhh})^{SM} \approx (g_{hhh})^{THDM}$

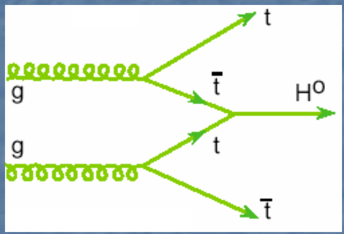
$(g_{Hhh})^{THDM} \approx 0$



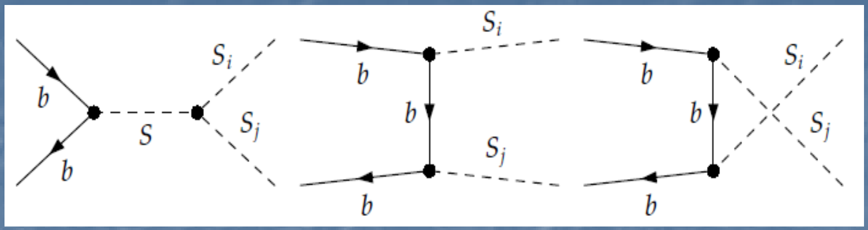



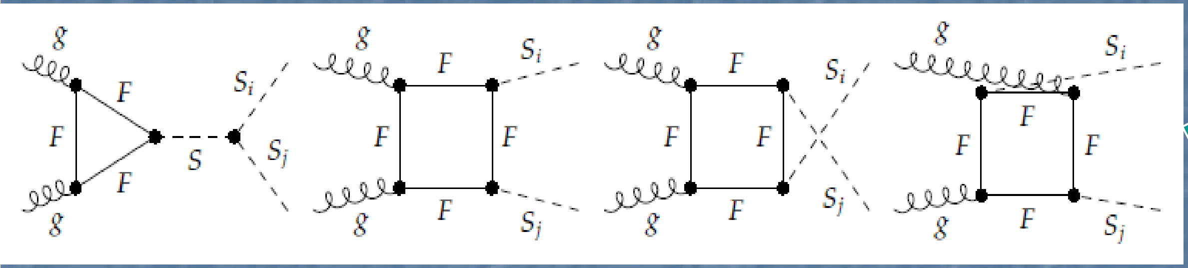




Same couplings, same signatures, same results.

# LHC hh production (pp → hh)




Tree-level contribution




One-loop contribution

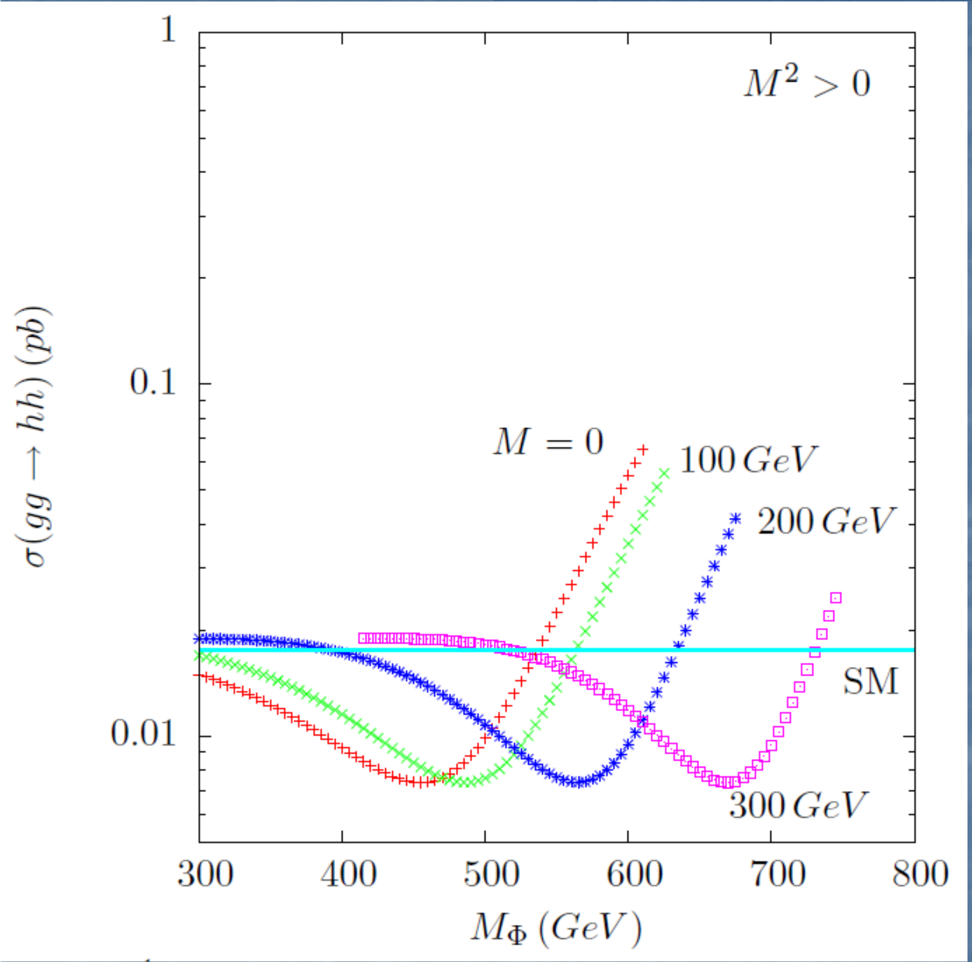
**One loop corrected hhh vertex in the two-Higgs doublet model in the limit $\sin(\beta - \alpha) = 1$**

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

**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 $M^2 > 0$ – small enhancement for heavy $M_\Phi$ and small $M^2$**

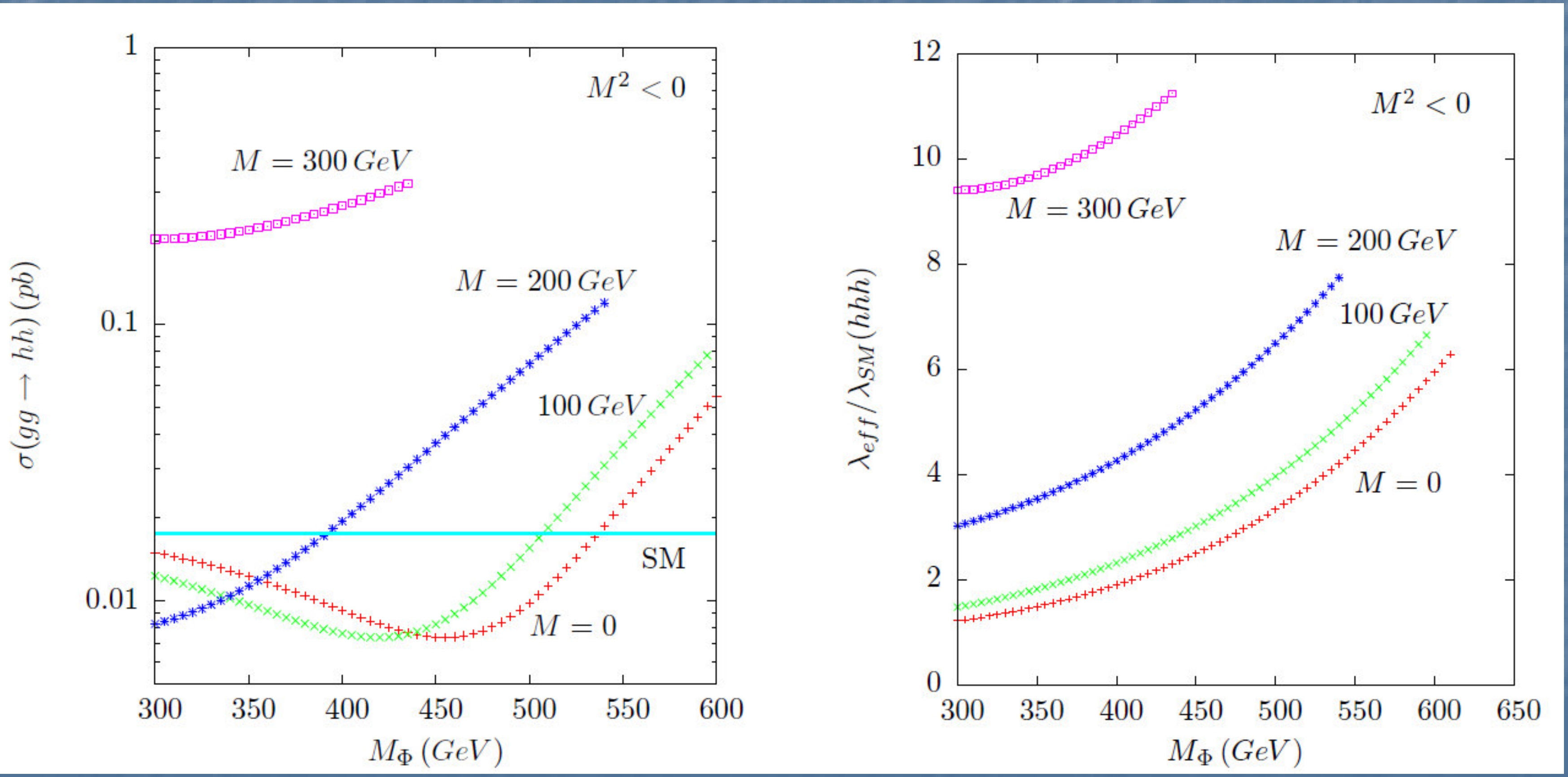
# Non-decoupling effects/ Non-THDM ≈ SM effects

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

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

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

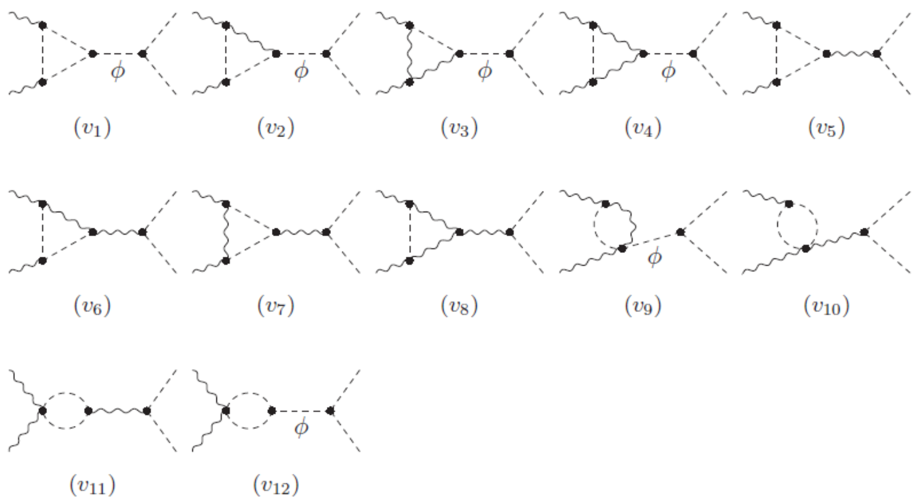
$m_h = 120$ GeV




**Better if $M^2 < 0$ – enhancement all $M_\Phi$ for large $M^2$**

# Photon Collider hh production ($\gamma\gamma \to$ **hh**)

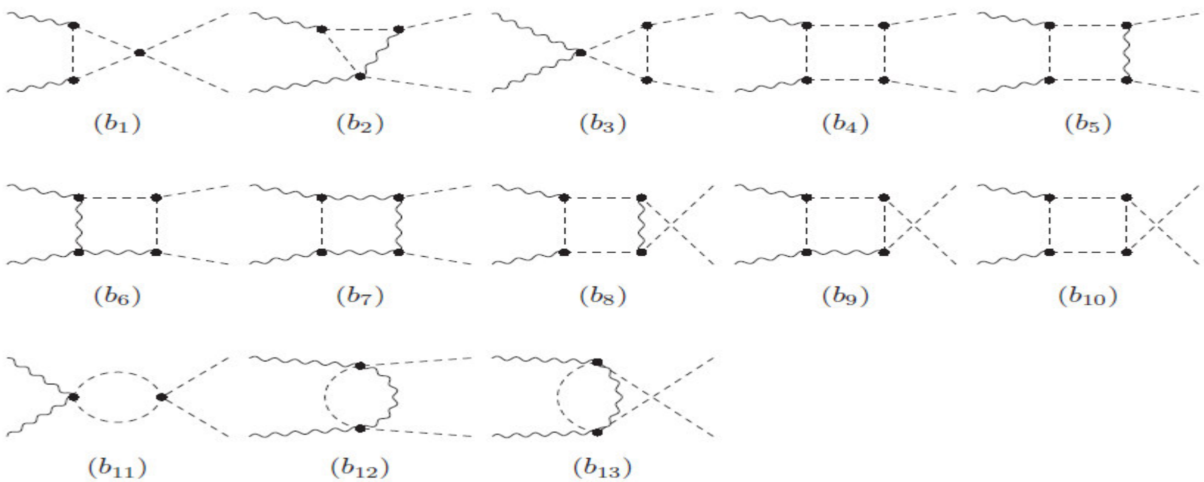
**SM-like contributions (same as before with gluon replaced by photon) plus new and dominant scalar loop contributions**



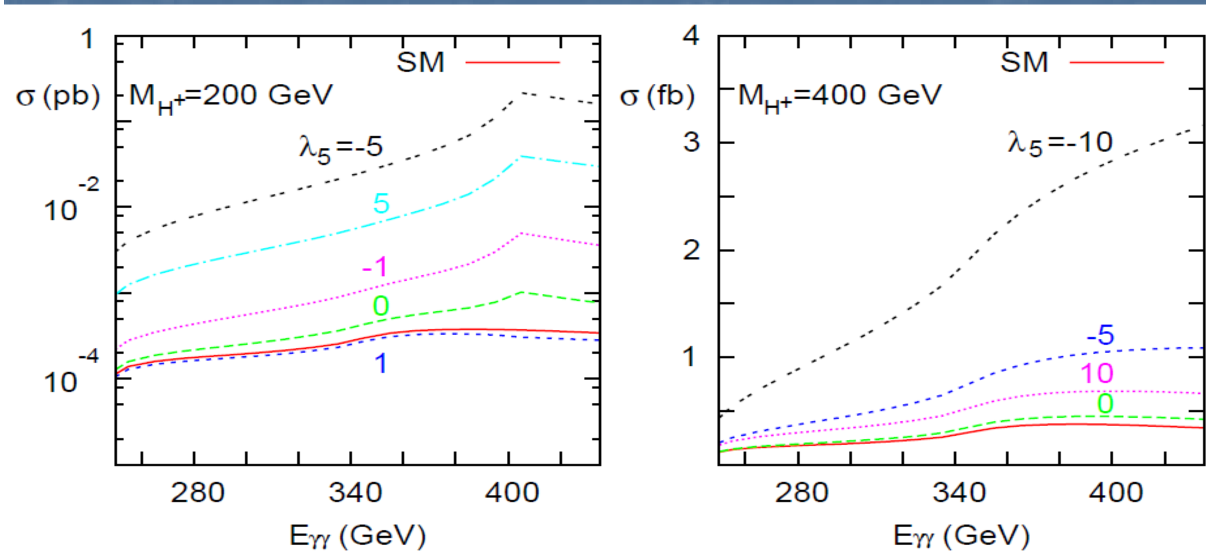
## Contributing scalar couplings

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

**New set of diagrams appear only because of the charged Higgs**



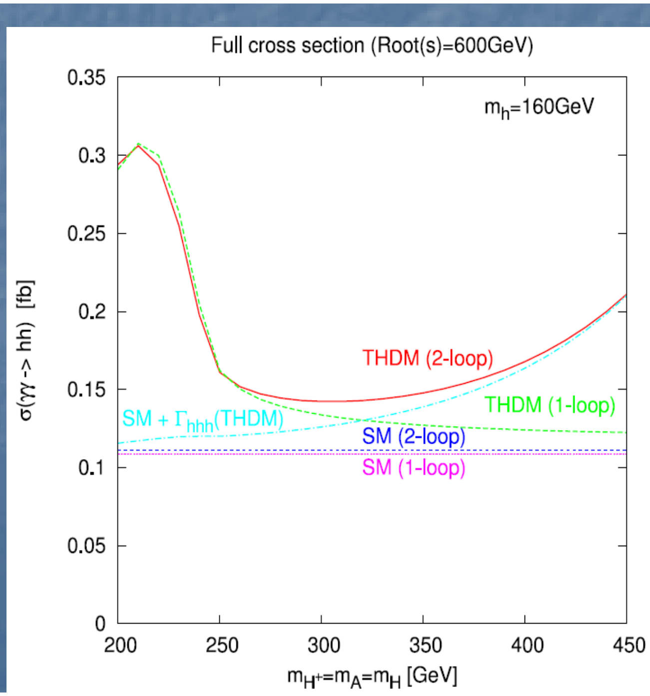
# Photon Collider hh production ($\gamma\gamma \to hh$)




Cornet and Hollik

have looked for effects from

$g_{H^+H^-h}$, $g_{H^+H^-H}$ for $M^2 < 0$ and $M^2 > 0$



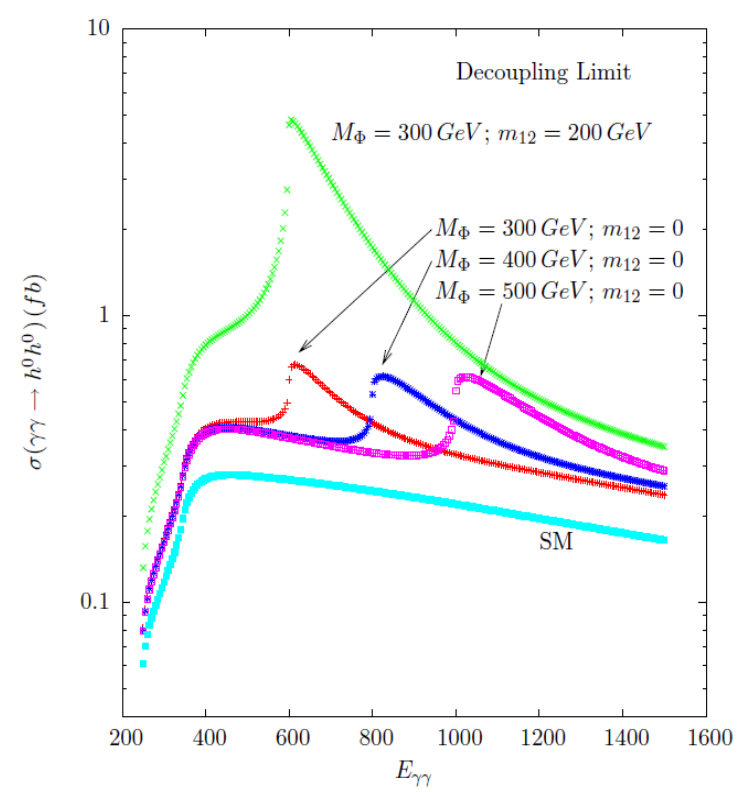

Asakawa et al

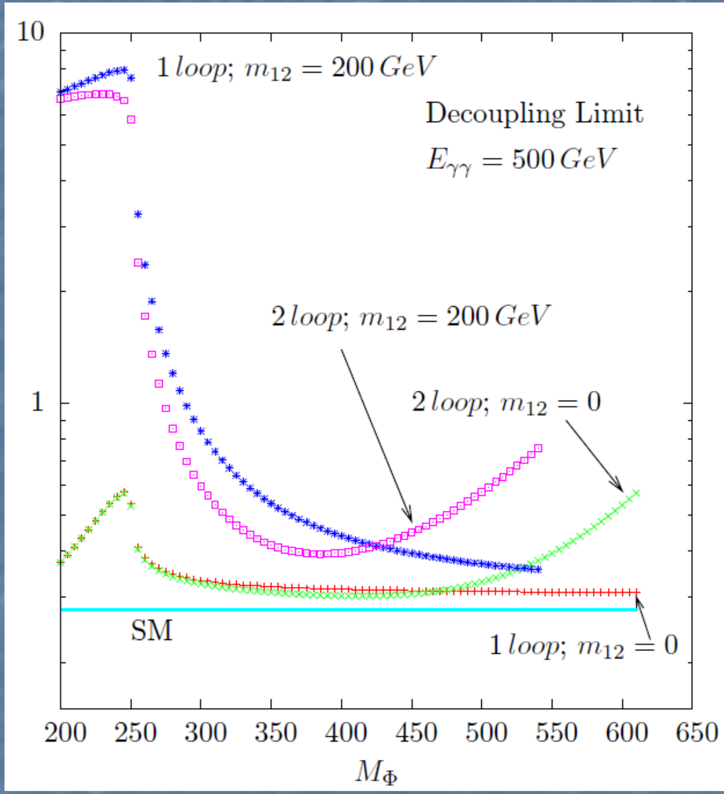
have looked for effects from $g_{H^+H^-h}$, $g_{H^+H^-H}$ and one loop effects (hhh)

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 or just a dark plan to kill the THDM?

**Just to use the word dark**

# Reconstructing the THDM Higgs potential

• Can we use the SM results to find/measure couplings/exclude the lightest CP-even Higgs (≈ 120 GeV) at the LHC?

• LHC - Almost impossible to measure the triple Higgs coupling in the SM for masses below 140 GeV.

• Parton level studies were performed for gg → hh in the SM for the LHC by Baur, Plehn and Rainwater in (other channels M. Moretti et al – best VBF)

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

… 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 THDM Higgs potential

• In some regions of the THDM cross sections can be much larger than the corresponding SM ones. We can use SM analysis to find the regions of the THDM that can be probed with less luminosity. Two of the Baur, Plehn and Rainwater analysis are

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

| | |
|---|---|
| Signal | 0.0106 fb |
| All backgrounds | 0.0186 fb |

To establish a non-zero coupling at 95 % ≈ 600 $fb^{-1}$ are needed

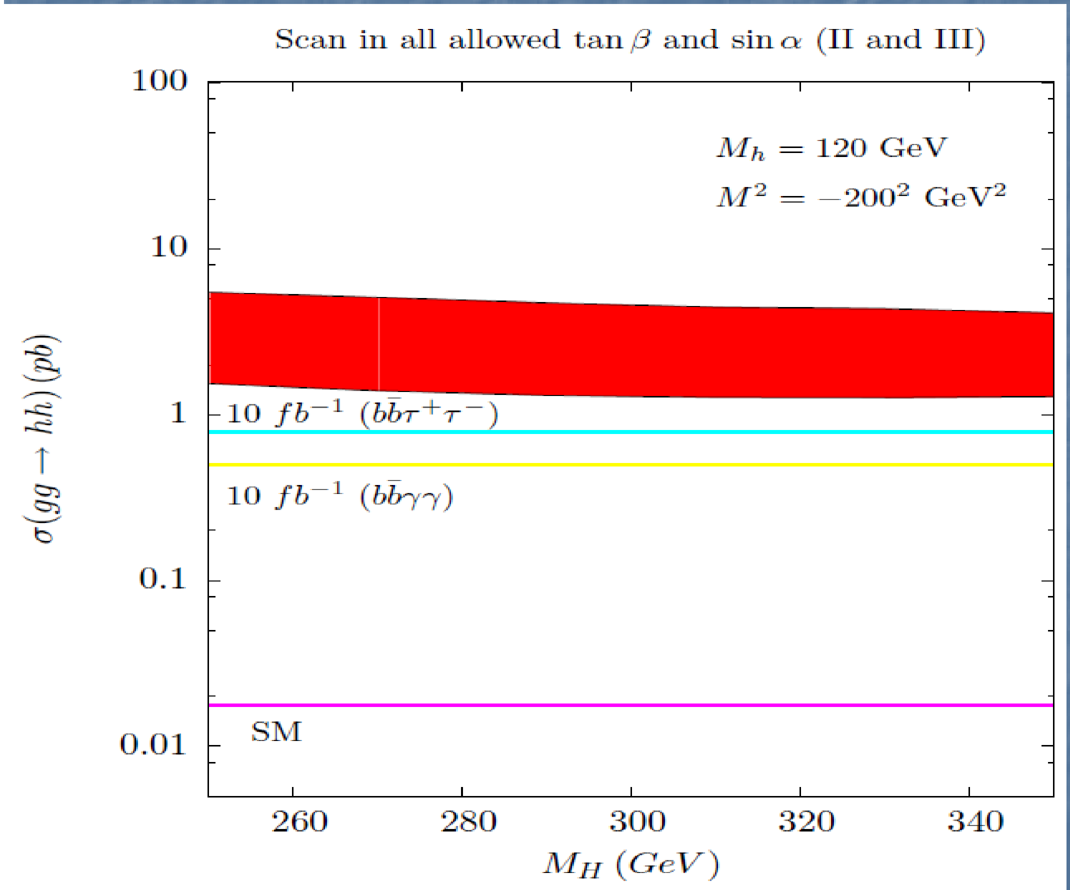
• A hopeless scenario in the SM $gg \rightarrow hh \rightarrow \bar{b}b\tau^+\tau^-$

| | |
|---|---|
| Signal | 0.0066 fb |
| All backgrounds | 0.056 fb |

$M_h$ = 120 GeV

# bbττ vs. bbγγ analysis

- The production process does not depend on $M_{H^+}$ and on $M_A$
  - 5 variables: $M_H$, $M_h$, 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 $M_{H^+}$ .

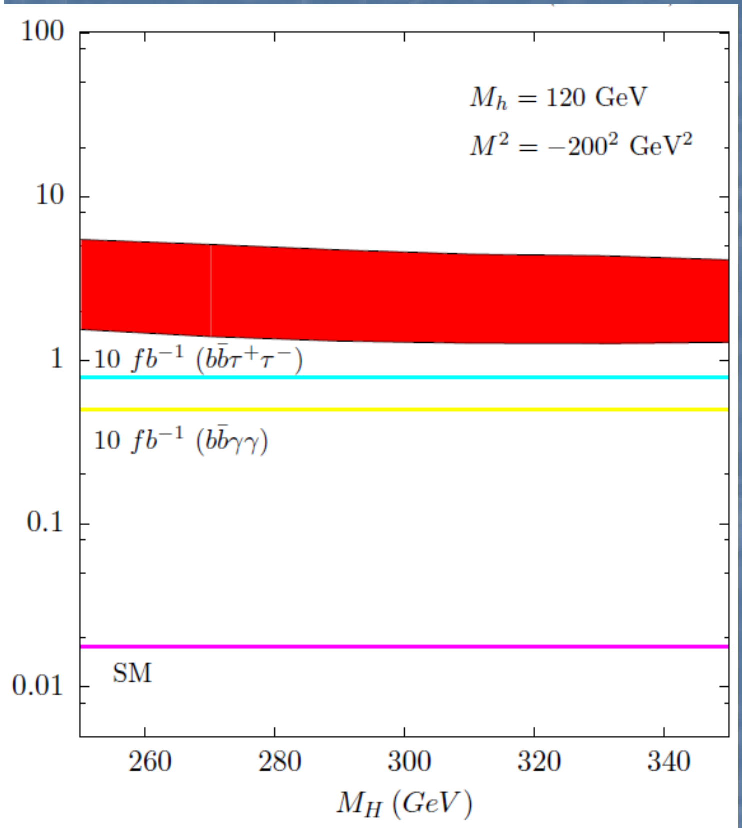
The numbers still have to be scaled by a factor that is Yukawa model dependent.

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

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

# Best of parameter regions probed

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 |

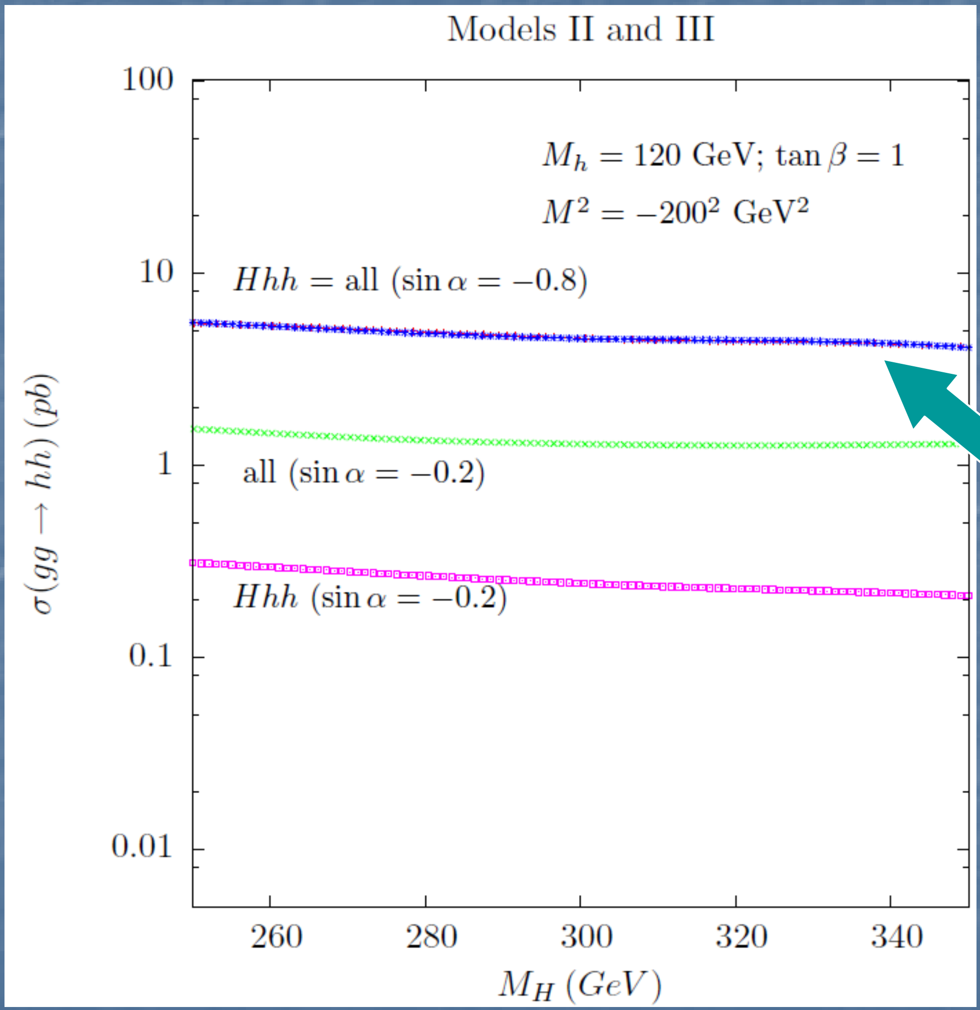
| $\bar{b}b\gamma\gamma$ | I | II | III | IV |
|---|---|---|---|---|
| -1 | - | 0.50 | 0.61 | 0 |
| -0.8 | 1.27 | 0.84 | 0.91 | 1.12 |
| -0.6 | 0.61 | 0.95 | 0.84 | 0.65 |
| -0.4 | 0.35 | 0.86 | 0.55 | 0.40 |
| -0.2 | 0.20 | 0.37 | 0.15 | 0.24 |
| 0 | 0.11 | 0 | 0 | 0.13 |
| 0.2 | 0.04 | 0.07 | 0.03 | 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 |

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

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

The red region can all be probed in Model I

# Measuring any coupling?




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

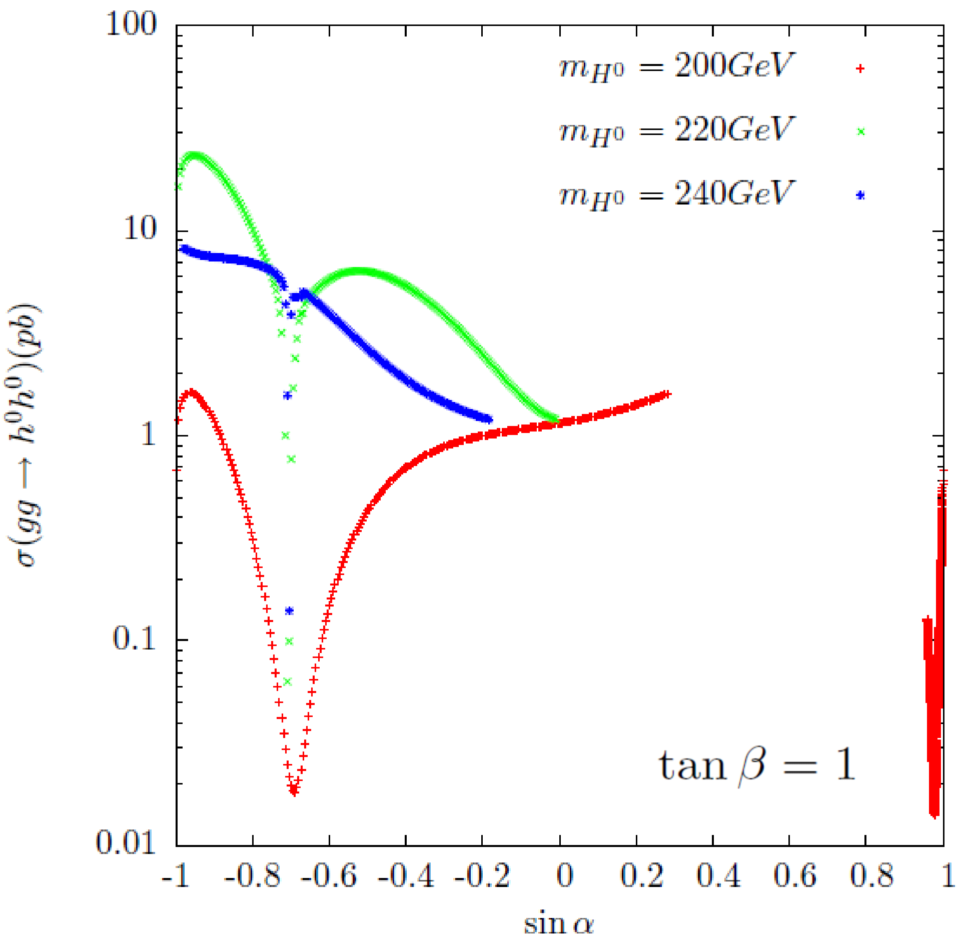
No!

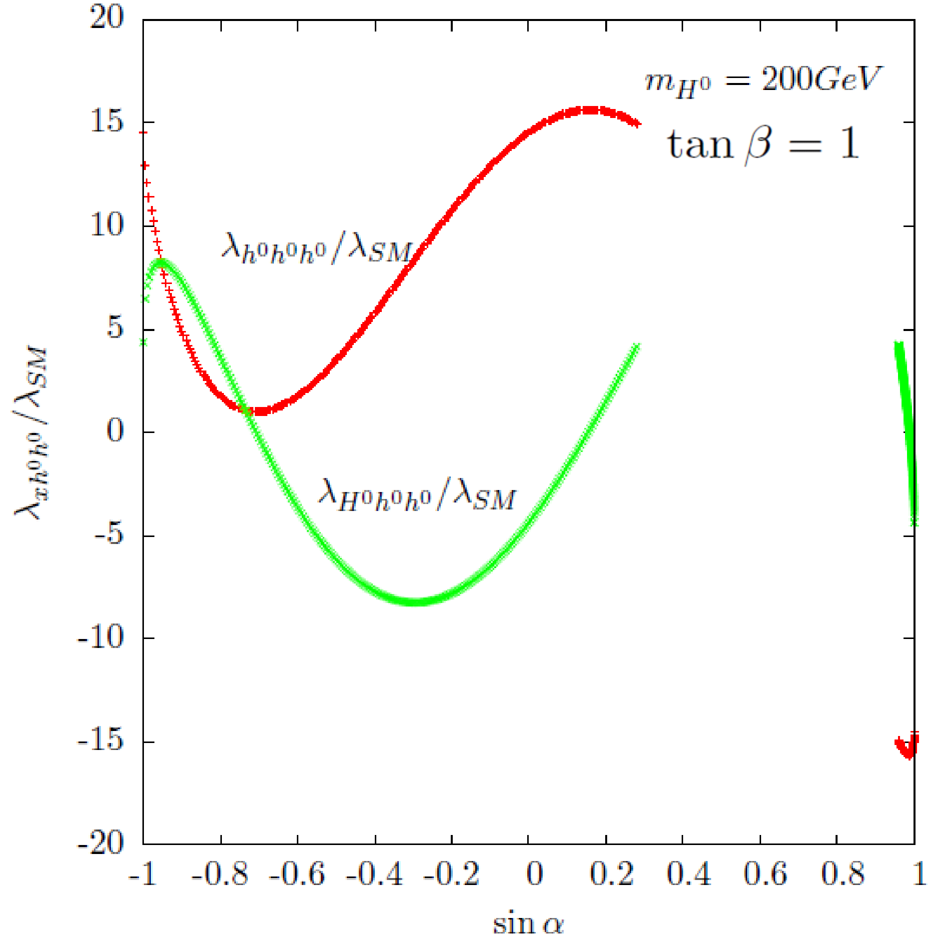
Diagrams with the Hhh coupling dominant

# ...and the reason is

$M_h = 110$ GeV

$M^2 = -(240)^2$ GeV$^2$

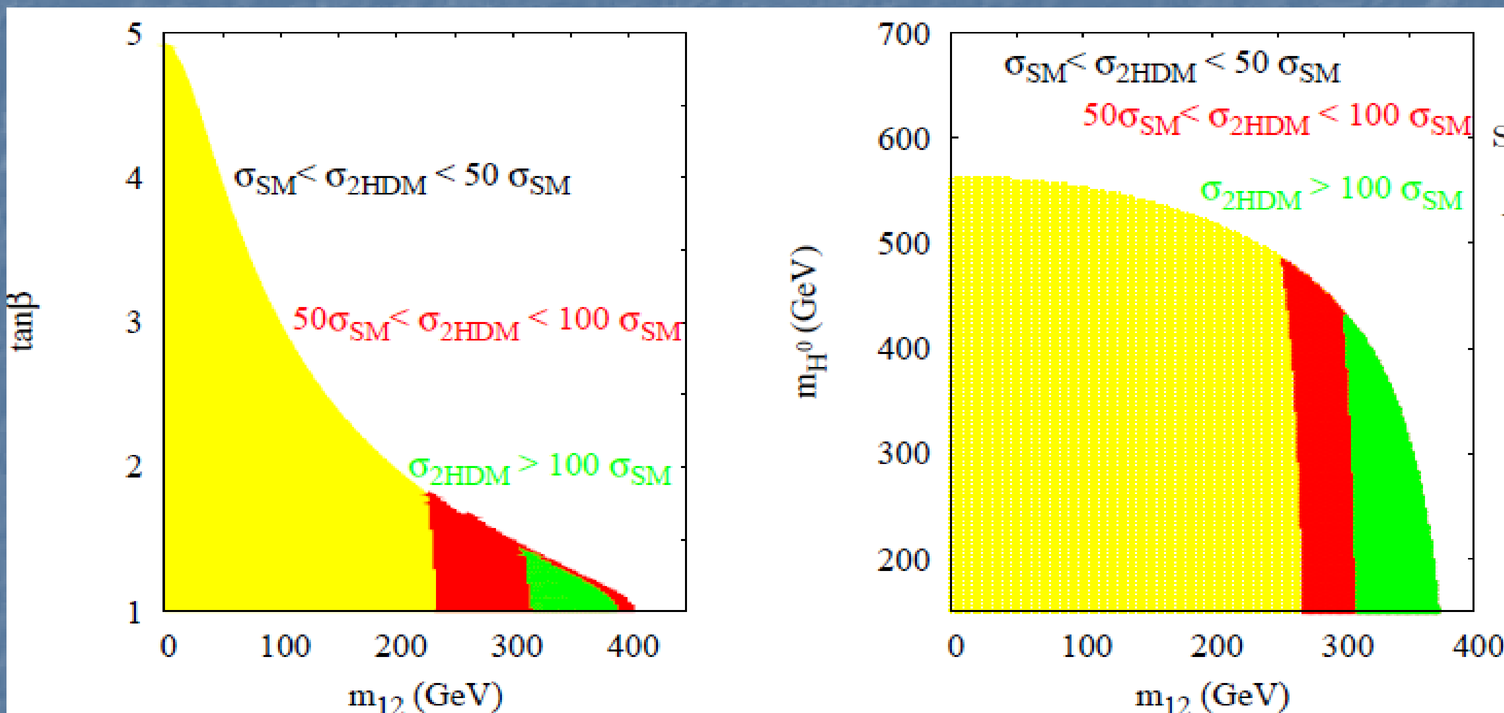



Cross section and couplings as a function of sin α

# Photon Collider

$E_{\gamma\gamma} = 500\ \text{GeV}$ $E_{\gamma\gamma} = 800\ \text{GeV}$




$\sin\alpha = -0.9$

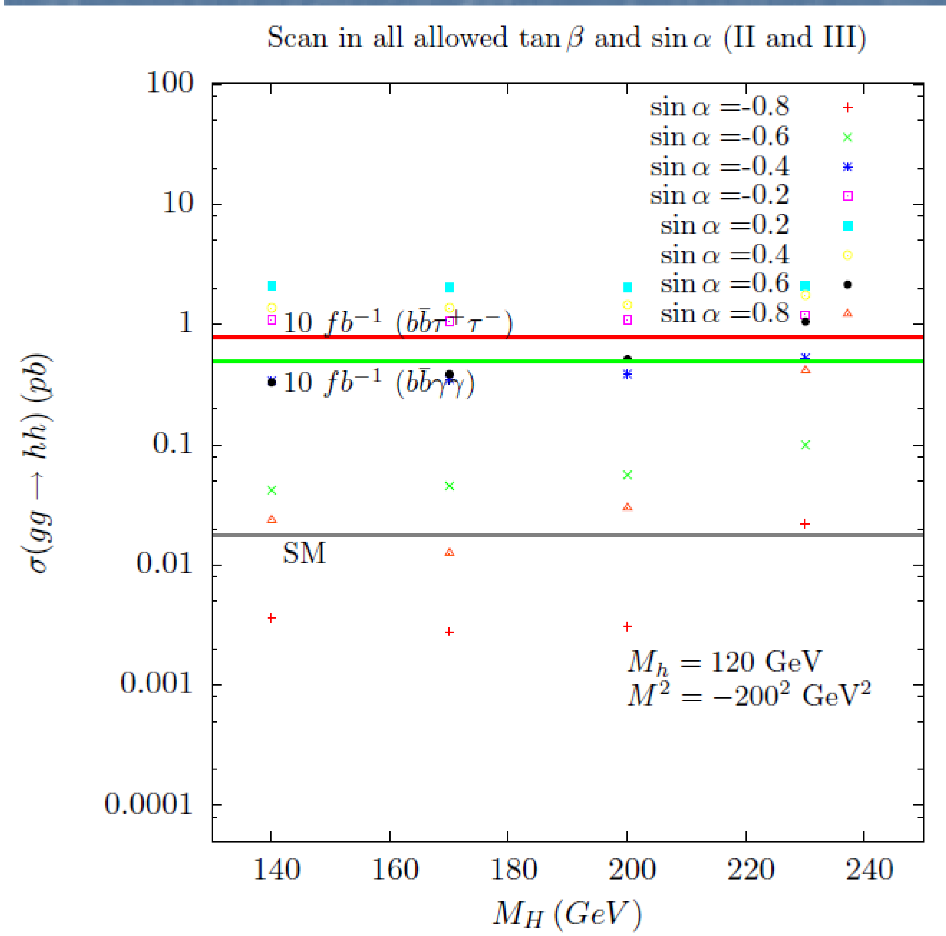
$\tan\beta = 1$

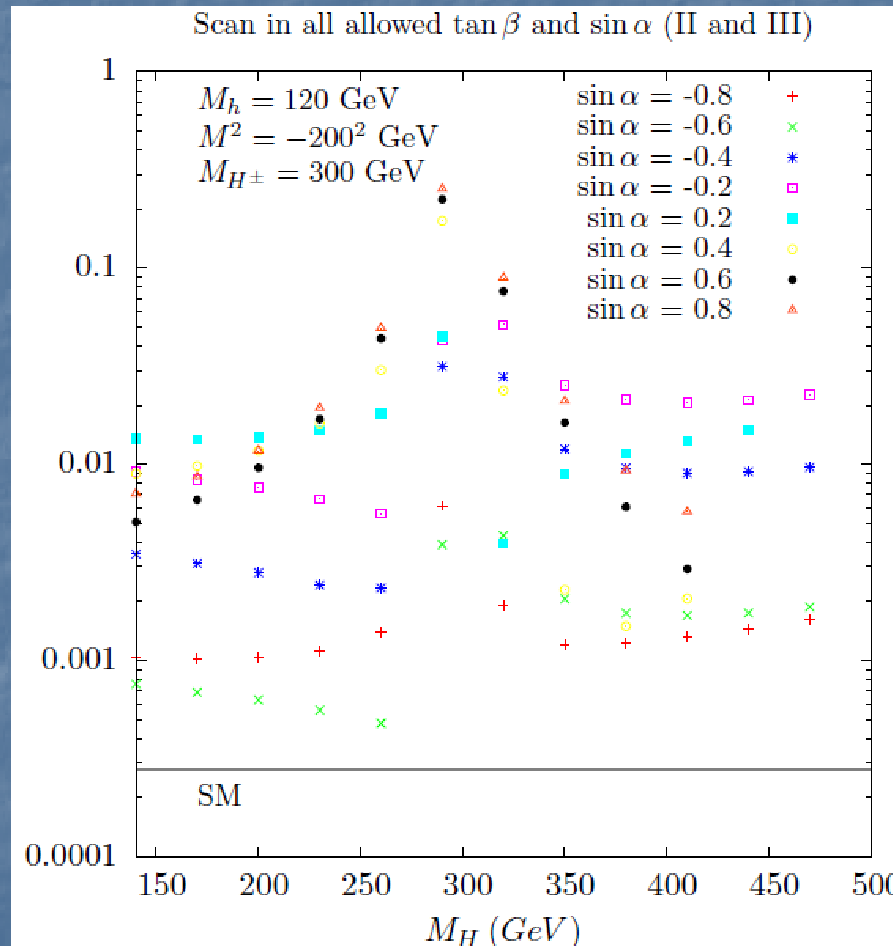
**Scan over sin $\alpha$**

$$m_{h^0} = 115\ \text{GeV}\ m_{A^0} = 270\ \text{GeV}\ m_{H^\pm} = 350\ \text{GeV}$$

# Complementing the LHC?

**pp → hh** | **γγ → hh**




By the end of the LHC some regions of the THDM will remain inaccessible

# Summary

- Can we distinguish the SM from the THDM when $\cos(\beta - \alpha) \approx 0$ ?

$(g_{hVV})^{SM} \approx (g_{hVV})^{THDM}$ ; $(g_{hff})^{SM} \approx (g_{hff})^{THDM}$ ; $(g_{hhh})^{SM} \approx (g_{hhh})^{THDM}$ and $(g_{Hhh})^{THDM} \approx 0$

- LHC – no one loop hhh correction – No!

– with one loop hhh correction

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

- At the LHC non-decoupling effects in pp → hh can only be measured at the <u>two-loop level</u> via radiative corrections to the triple hhh vertex.

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

– with one loop hhh correction – further enhance non DE

- Can we kill the THDM? Which one? 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.

- Some regions could be probed with just a few $fb^{-1}$ and a photon collider will help to complete the picture

Thank you!