$\gamma\gamma \to hh$ (AA) in 2HDM

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Outline

- A Two Higgs Doublet Model
- Constraints
- Higgs pair production
- Decoupling in the 2HDM
- Summary

A 2HDM – DIY in 8 steps

1. Simplest extension of the SM – write ☞$_1$ instead of ☞ in L_{SM}, then add another piece with ☞$_2$ instead of ☞.

2. Now the Higgs potential. First, write the most general potential compatible with the symmetries. If you got it right, it has 14 independent parameters.

3. At this stage you have tree-level FCNC (bad!). Use a symmetry! By imposing a Z_2 symmetry ☞$_1$ ✸ 📭 ☞$_1$; ☞$_2$ ✸ ☞$_2$ to the Higgs fields and by extending it to the fermions, tree-level FCNC are gone.

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

4. If you want a "normal" vacuum (CP conserving and non charge breaking) just choose the vev as

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

5. We are not done yet. Rotate the fields to the mass eigenstates.

6. You have now 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 for you to choose. My choice is

$$m_{h^0},\ m_{H^0},\ m_{A^0},\ m_{H^\pm},\ \tan\beta,\ \alpha \quad \text{and} \quad m_{12}^2$$

7. Remember the symmetry? There are 4 ways to extend it to the fermions – 4 possible Yukawa Lagrangians (without FCNC at tree-level).

	I	II	III	IV
up	ϕ_2	ϕ_2	ϕ_2	ϕ_2
down	ϕ_2	ϕ_1	ϕ_2	ϕ_1
lepton	ϕ_2	ϕ_1	ϕ_1	ϕ_2

Barger, Hewett, Phillips 89

8. Rotate the remaining fields; serve with branching ratios and cross sections.

- **No major differences in the production process (potential does not change)**
- **There can be differences in the decay**

Experimental Constraints

- **Direct bounds**

  Charged Higgs – LEP   79.3 GeV

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

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

  SM like – LEP bound 114.4 GeV

- $B \longrightarrow X_s \gamma$ **II and III** $\boxed{m_{H^\pm} \gtrsim 295\ GeV}$

- $Z \longrightarrow b\bar{b}$ **and** $B_q \bar{B}_q$ **Excludes low tan β in all models. Values of low charged Higgs $\lesssim$ 100 GeV and tan β $\lesssim$ 1 are disfavoured**

- **Electroweak precision constraints – compact mass spectrum** $\boxed{|\delta\rho| \lesssim 10^{-3}}$

- $B \longrightarrow \tau\nu$ **Excludes high tan β just in model II**

- $\tau \longrightarrow \mu\nu\bar{\nu}$ **Excludes high tan β and low charged Higgs mass just in models II and III**

Theoretical Constraints

• **Tree-level unitarity**

Full set of perturbative unitarity conditions – very restrictive – forces small values of $\tan\beta$ and not too large masses.

Kanemura, Kubota, Takasugi 93;
Akeroyd, Arhrib, Naimi 00.

• **Vacuum stability**

Conditions for the potential to be bounded from below at tree-level – especially important when the soft breaking parameter is large.

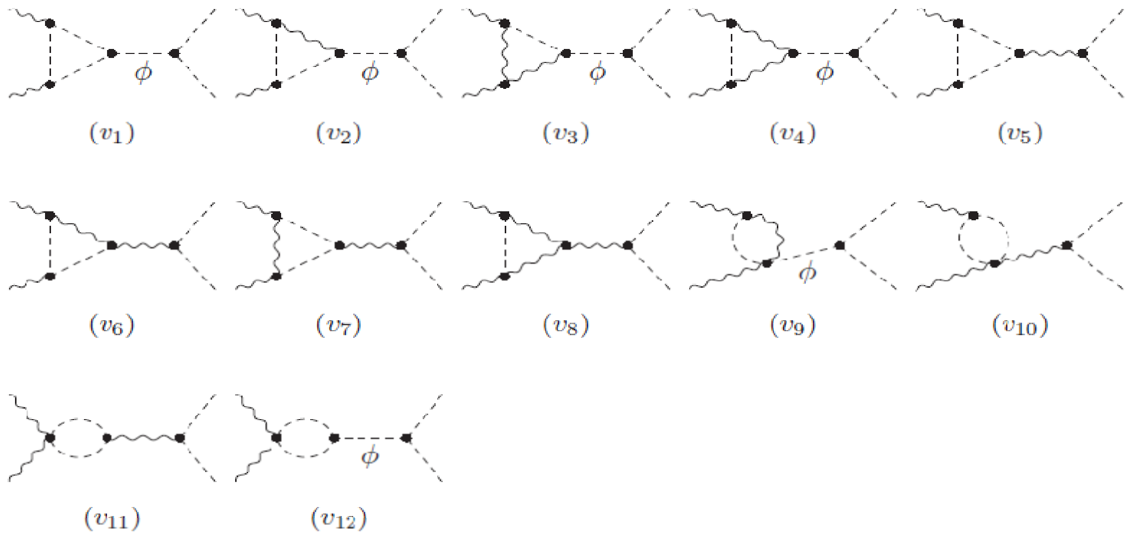
Deshpande and Ma 78.

• **Charge and CP breaking**

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

Barroso, Ferreira, RS 04;
Ivanov 07.

♑♑✹hh and ♑♑✹AA



FeynArts

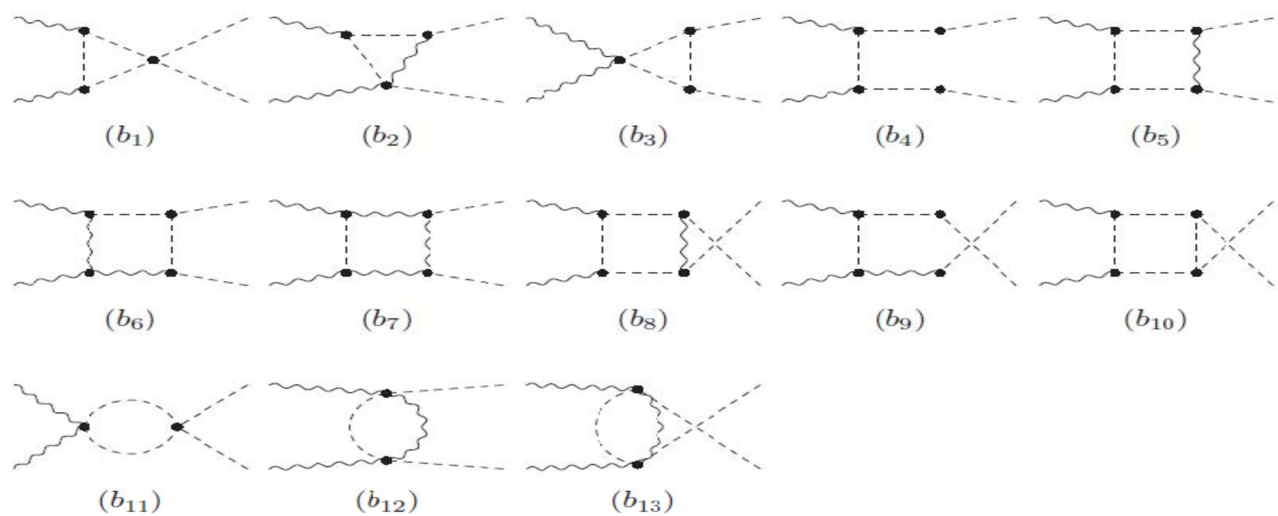
FormCalc

LoopTools

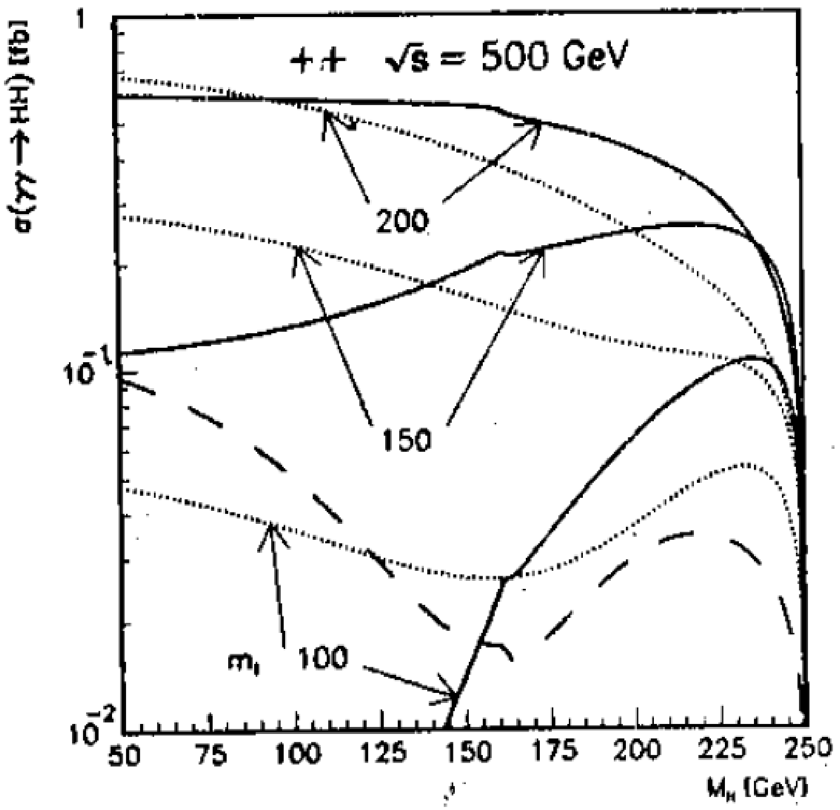
Just the additional contributions are shown.

Scalar loop contributions dominate

Not at the LHC!



Standard Model hhh coupling?



Jikia and Pirogov 92

Belusevic and Jikia 04

Takahashi et al. 08

Nozomi Maeda et al. Next talk!

- BJ study at parton level
- Search for 4 b final state
- Main background from W^+W^- and from non- resonant four jet final state

$$|M(q\bar{q}) - M_H| < 5 \text{ GeV}$$

At least 3 jets originating from b quarks

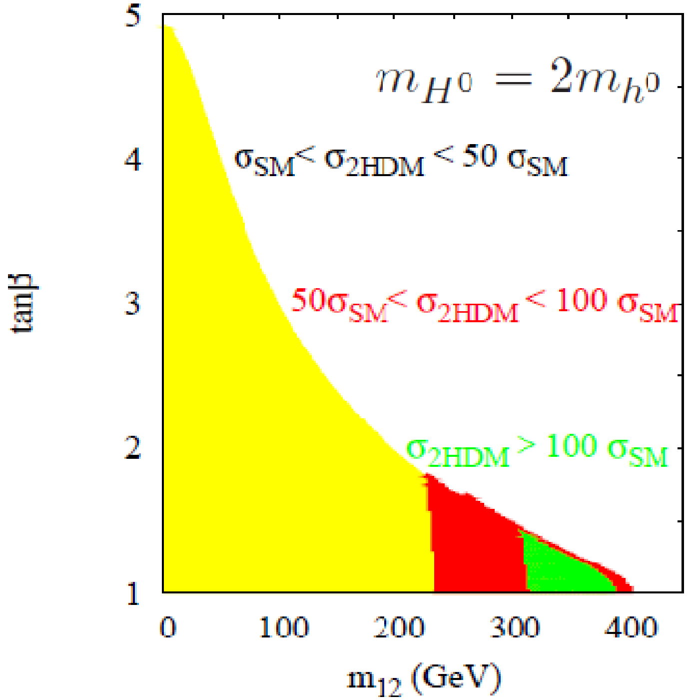
$$|\cos\theta_{q,\bar{q}}| < 0.9$$

Conclusion – For a center of mass energy of 350 GeV and M_H = 120 GeV an integrated luminosity of 450 fb^{-1} would be needed to exclude a zero trilinear Higgs boson self-coupling at the 5 ♦ level.

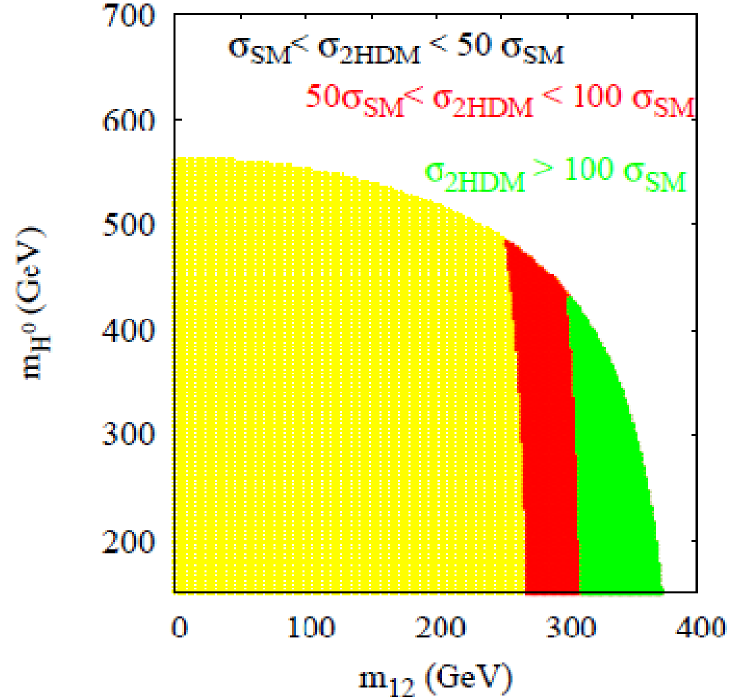
How large?

Allowed regions for $\gamma\gamma \rightarrow h^0 h^0$ in the general 2HDM

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



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



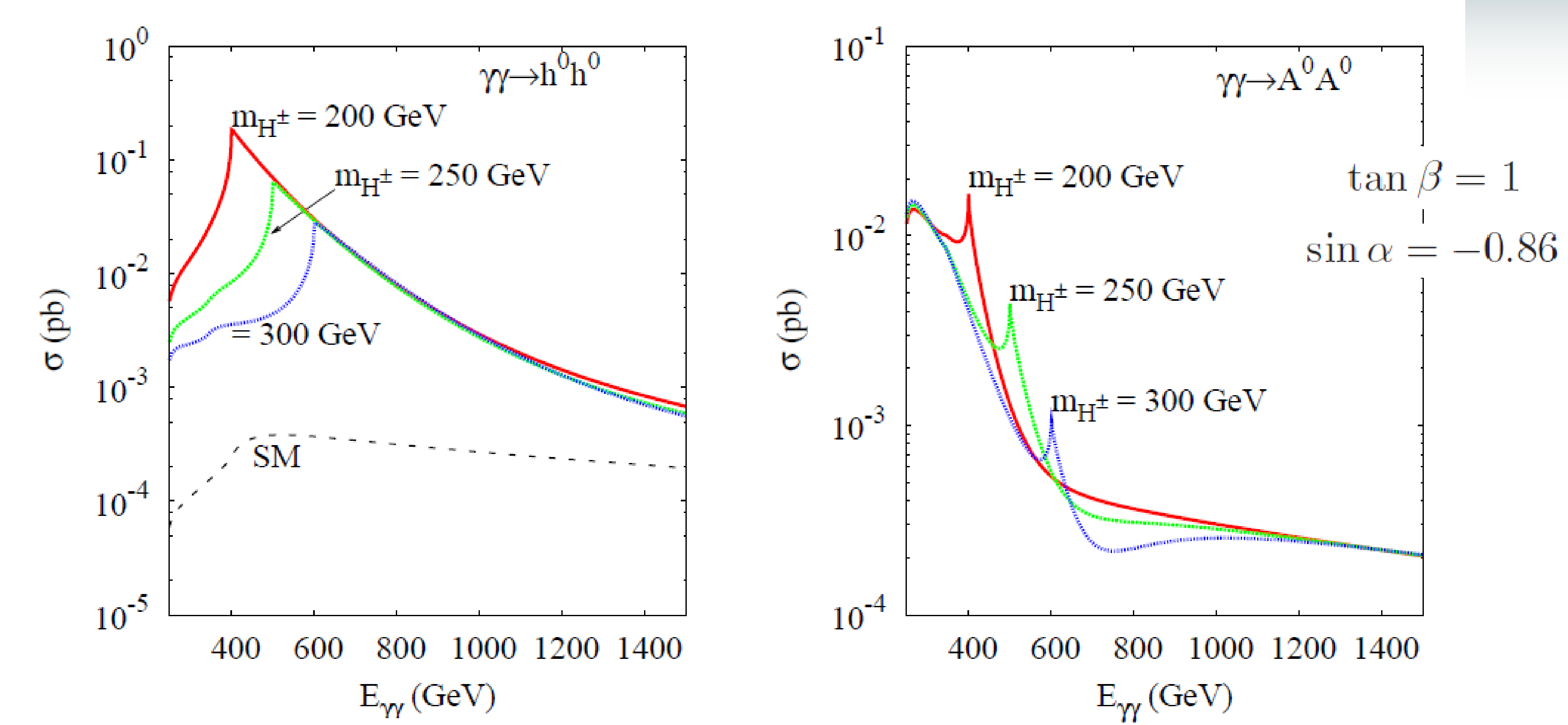
$\tan\beta = 1$

$\sin\alpha = -0.9$

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

Regarding sin ♋, maxima are 🕓 ± 0.9

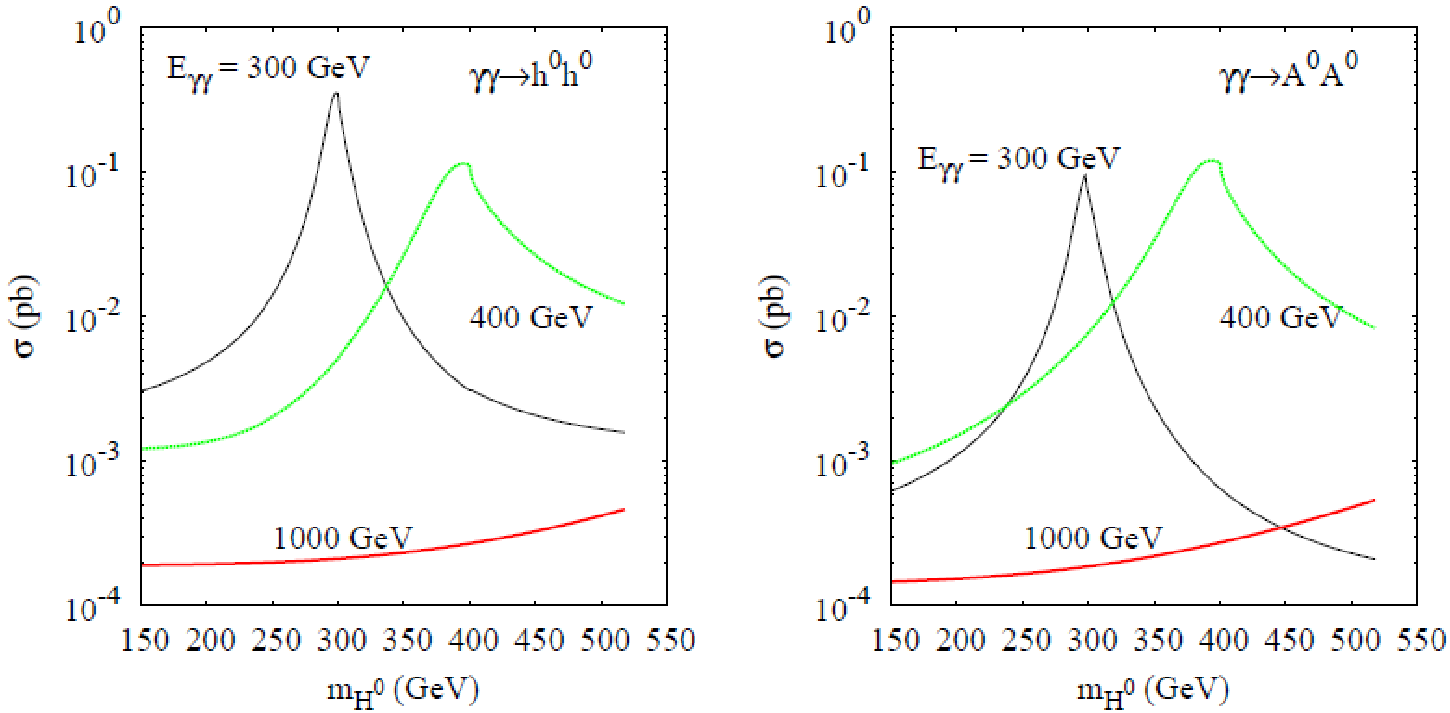
Total cross sections



$$m_{h^0}, m_{H^0}, m_{A^0}, m_{12} = 120, 200, 120, 300 \text{ GeV}$$

Cross section as a function of the center of mass energy for different values of the charged Higgs mass. It is clear that the cross section can be several orders of magnitude above the corresponding SM cross section.

Total cross sections



$m_{h^0}, m_{H^\pm}, m_{A^0}, m_{12} = 120,\ 250,\ 150,\ 200\ GeV$ $\quad \sin\alpha = 0.9$ and $\tan\beta = 1.5$

Cross section as a function of the heavy Higgs mass. Here we see the resonant behaviour (♑♑✸H✸hh) of the cross section.

The decoupling regime of 2HDM

1. What?

- sin(♌ 📫 ♋) 🕓 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
- g_{hhh} is now the same in the SM and in the 2HDM (and $g_{Hhh}= 0$)
- All other Higgs are “heavy” $m_H = m_{H^\pm} = m_A = m_\Phi$

2. Why?

- 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)

♑♑ ✹ hh and non-decoupling effects

Two very recent studies

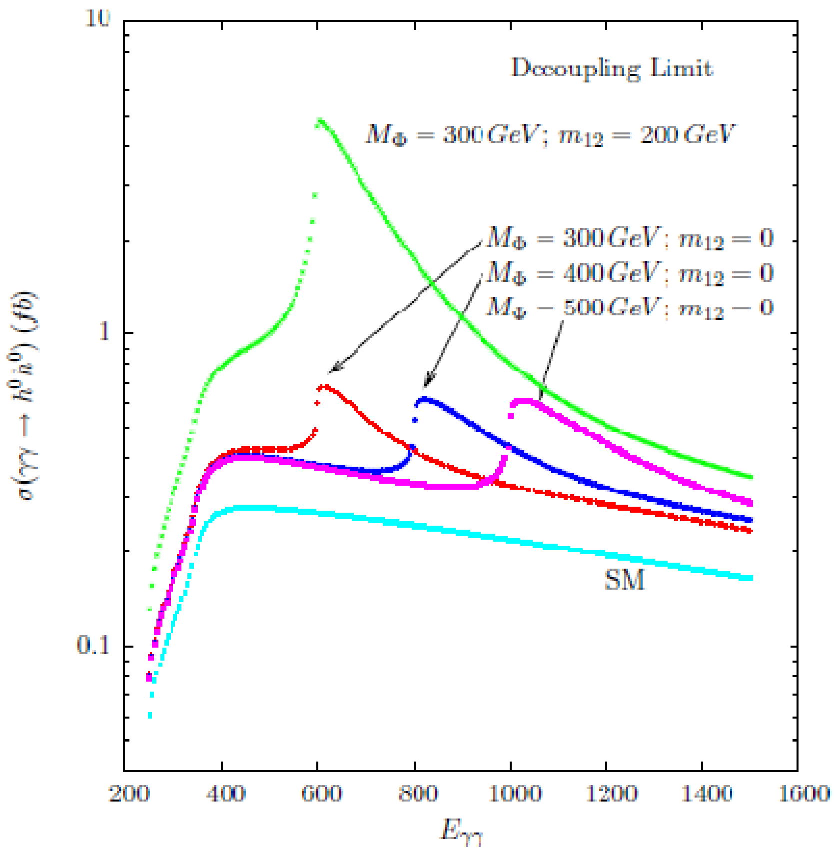
Cornet and Hollik 2008

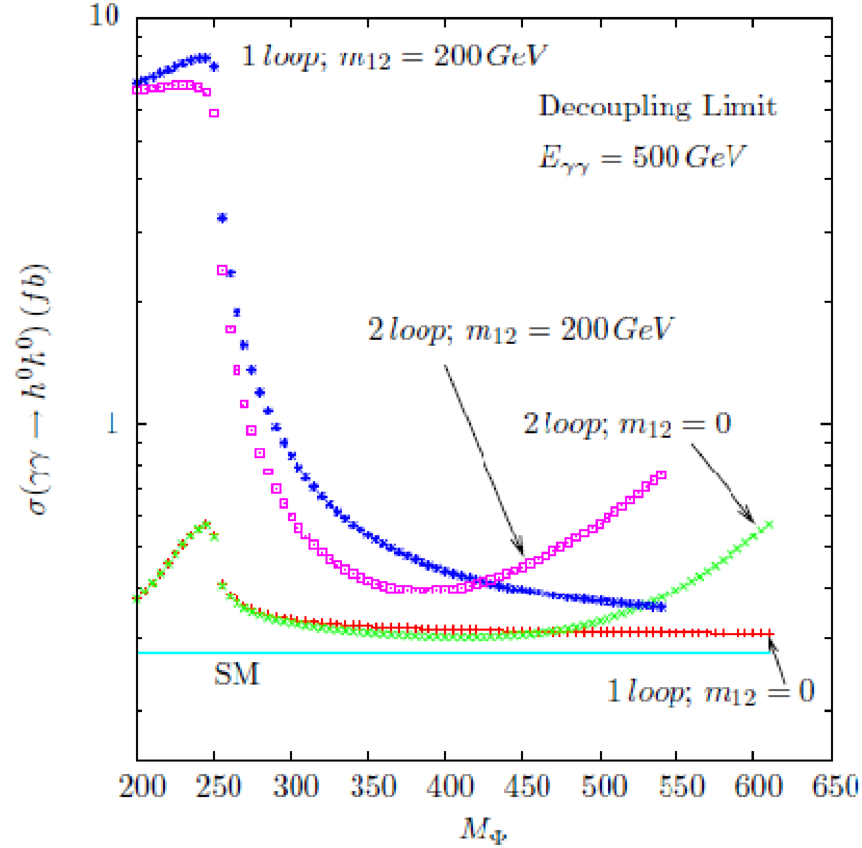
- non decoupling effects at lowest order (one-loop) due mainly to the soft-breaking parameter – low mass (m_Φ) region
- effects are due to the scalar self-interaction hH^+H^-

Asakawa, Harada, Kanemura, Okada and Tsumura 2009

- non decoupling effects from higher order corrections (two-loop) – high mass (m_Φ) region
- originate from one-loop corrections to the scalar self-interactions hhh

Put them together to get



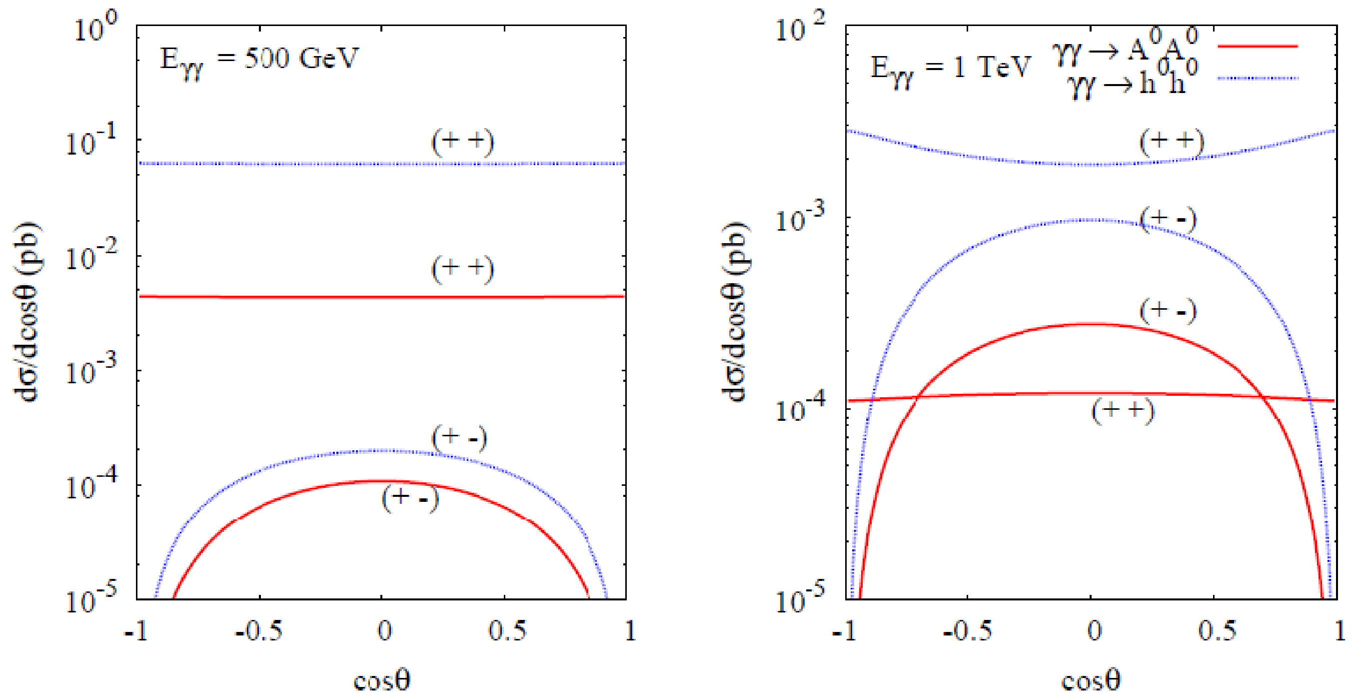


Very good chance to see it happen

Note again that the low mass region can only be probed at a γγ collider

Can we recycle the BJ analysis to bound the 2HDM parameter space?

1. Angular distributions do not change

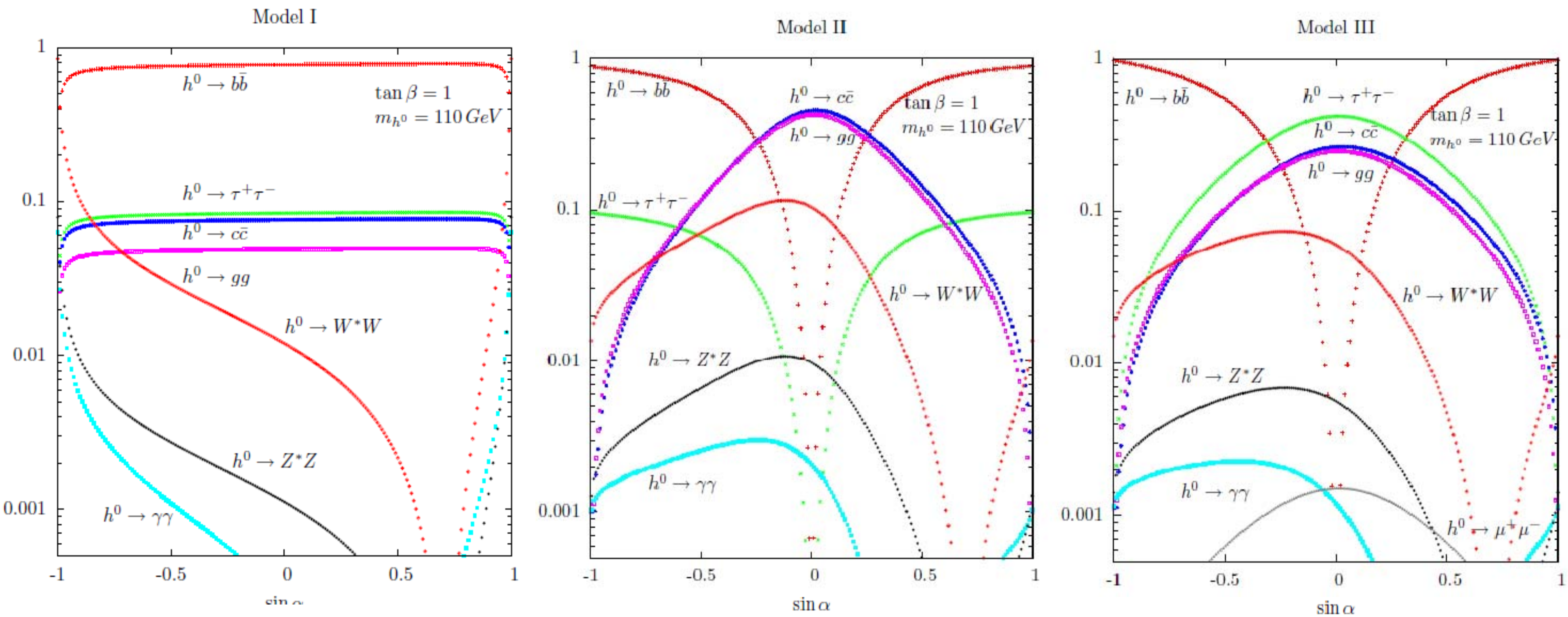


This means we can use the same angular cuts

2. We can still use the invariant mass cut

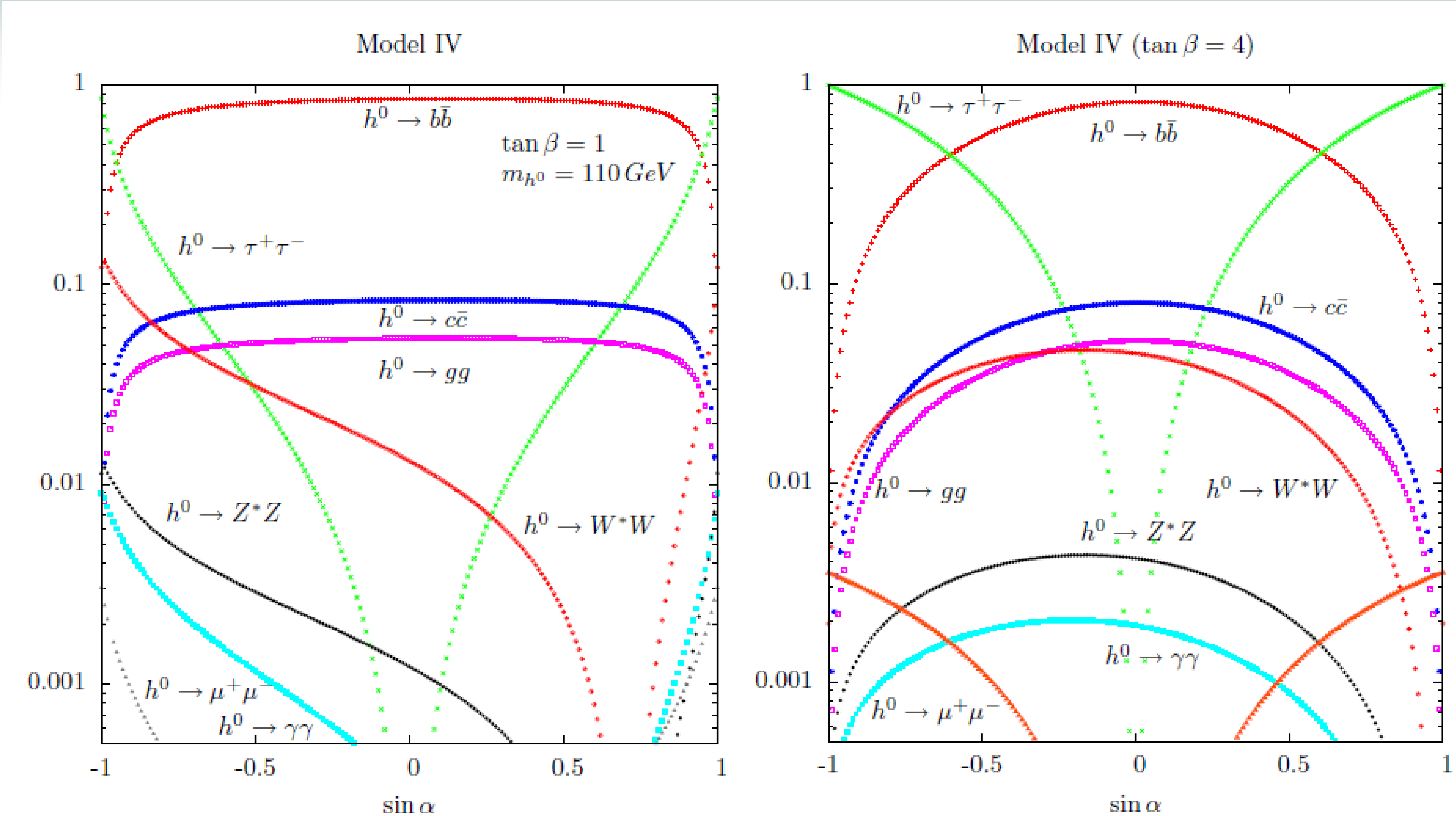
3. Final states?

- **Light Higgs mass (as long as bb dominates)**



Best sin ♋ regions have the same final states for small tan ♌. As tan ♌ grows the bb final state becomes dominant for all sin ♋ values in Model II and ♦♦ dominates in Model III (plots do not change much) .

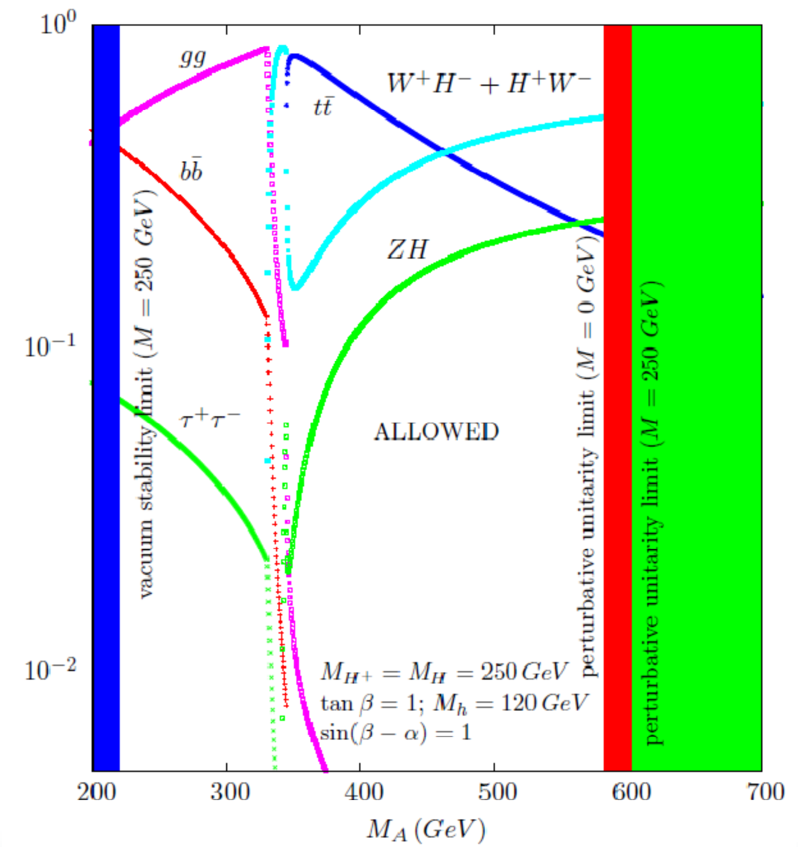
…and in model IV

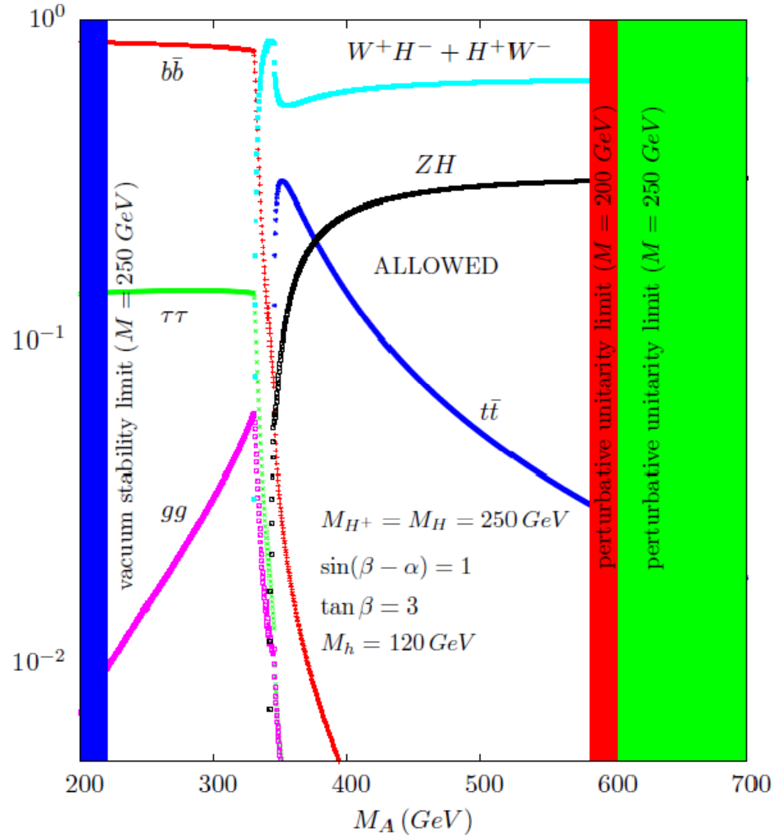


For large tan ♌, the decay to leptons becomes dominant in Model IV. In this case, as for sin ♋ 🕔 0 in the previous plots, the analysis has to be redone.

"A" final states and larger masses

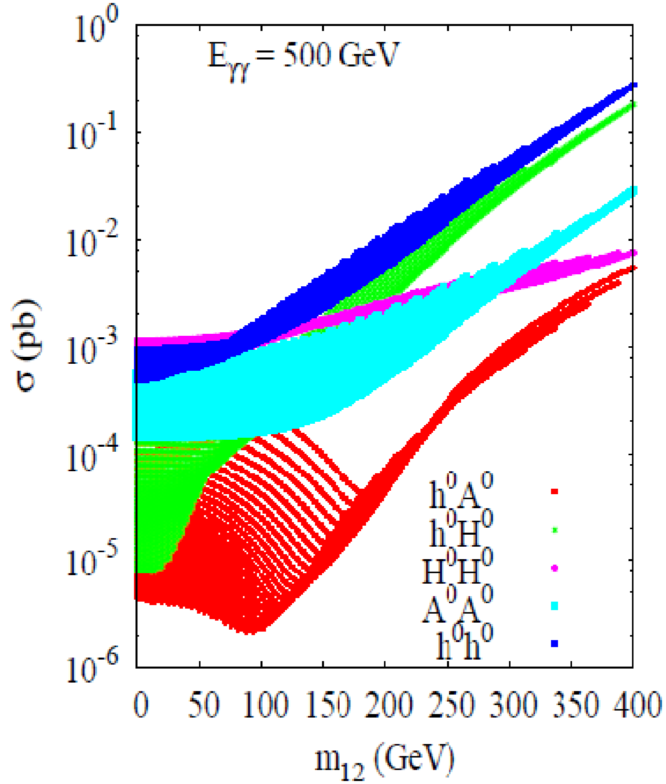
If the A boson is light, a similar situation occurs – final state is either bb or ♦♦ (or two jets). For a heavier A the situation can change dramatically.

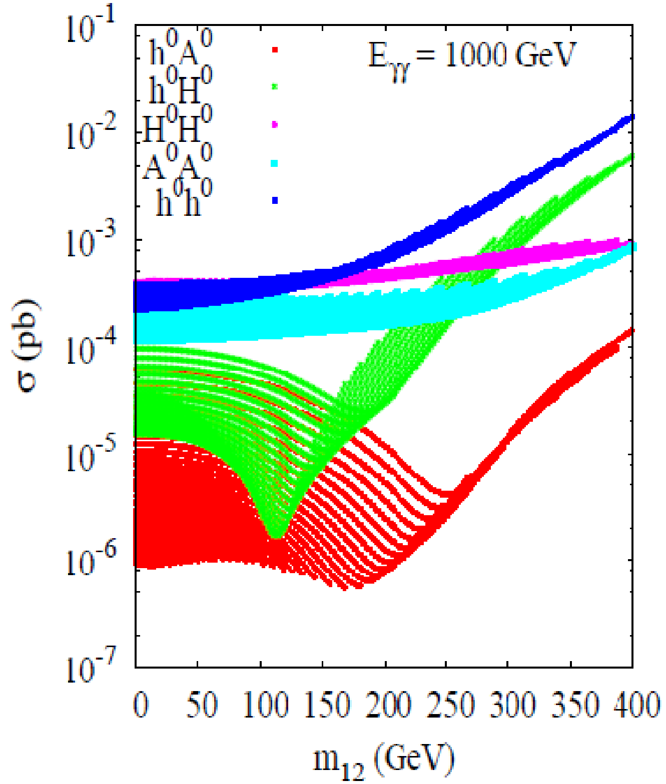




Needs new analysis

What about other production processes?





$m_{h^0}, m_{H^0}, m_{A^0}, m_{H^\pm} = 115, 160, 160, 250$ GeV $\quad \sin\alpha = -0.4$ and $1 \leq \tan\beta \leq 10$.

They all stand a chance

Summary

- Using as reference Belusevic and Jikia's parton level study, the 2HDM has a vast region of the parameter space where the cross section is at least as large as the SM cross section and could therefore be probed in a ♑♑ collider.

- In the general case, the best scenarios need: large tan ♌, large m^2_{12}, low (appropriate) charged Higgs mass, large | sin♋ | and a nice resonance (goes very well with a tuneable CM energy) – in the allowed regions.

- Non-decoupling effects could be large enough to be measured.

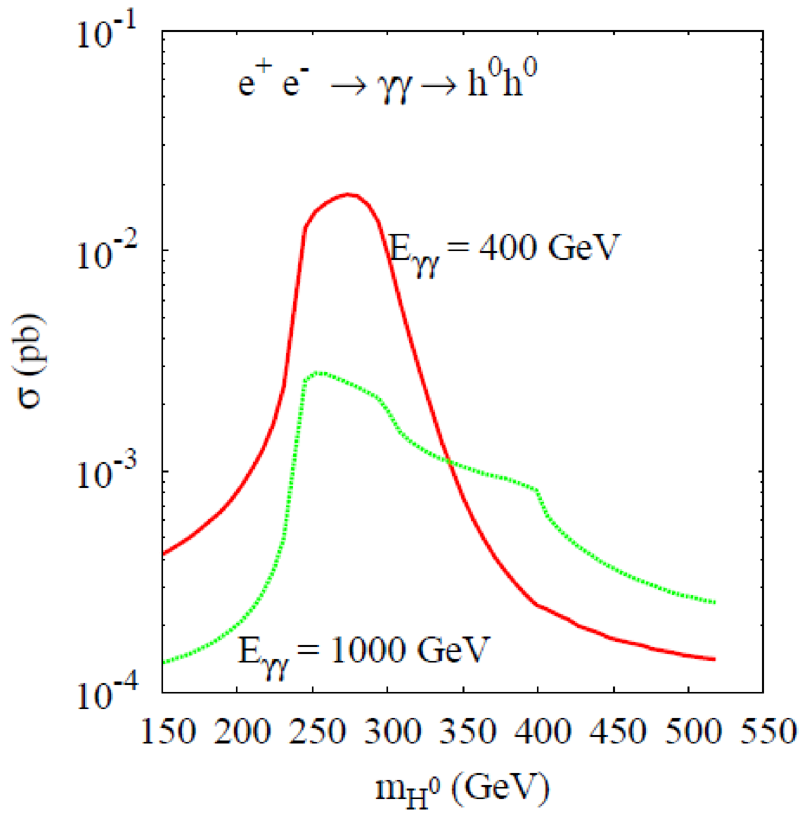
- For larger masses new analysis are needed especially if the decay to other Higgs bosons is kinematically allowed.

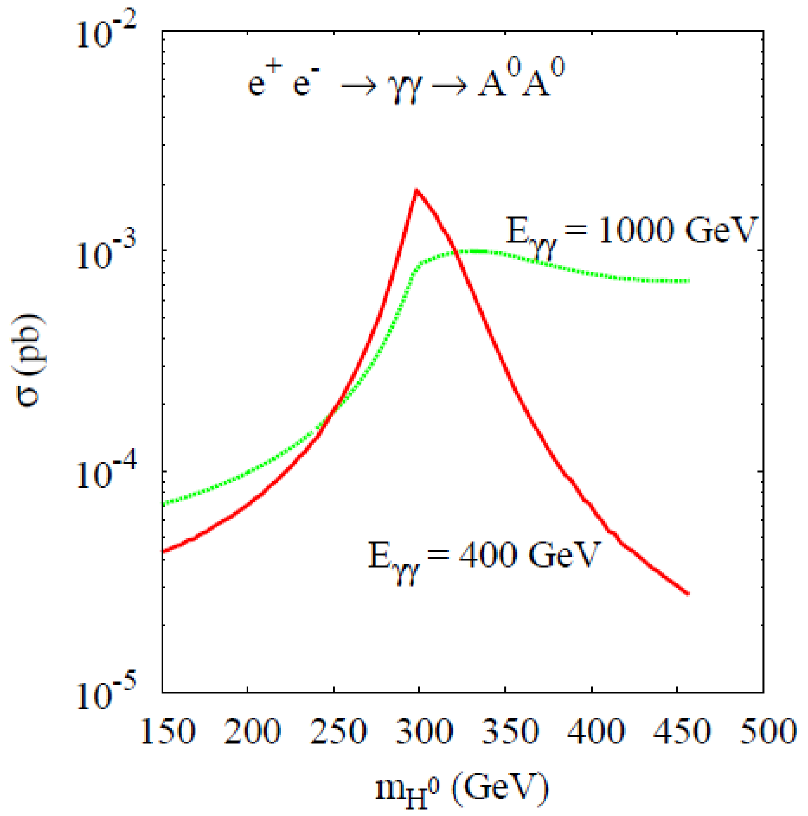
- Other final states with two different scalars are also accessible.

- Don't download the eprint. Resubmission soon!

Thank you!

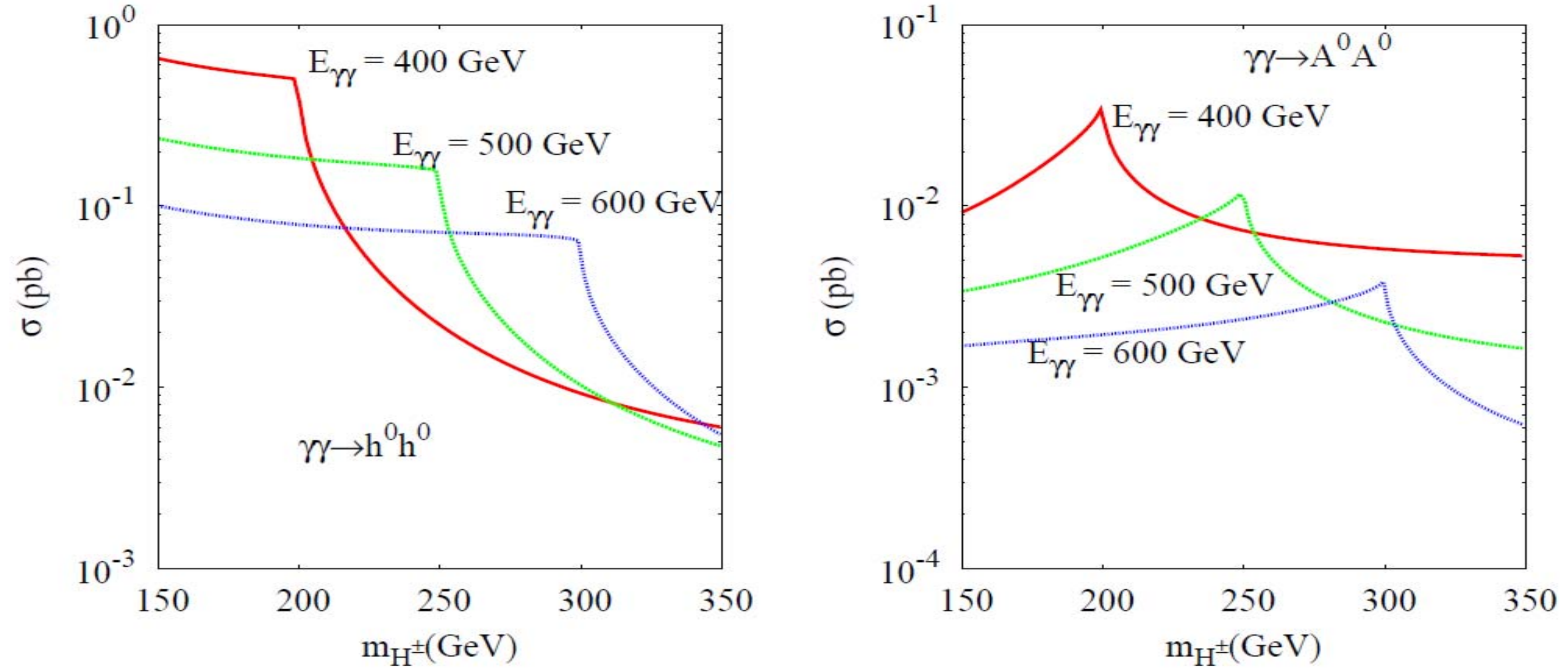
Same as before, but convoluting the photon-photon cross section with the luminosity spectrum taken from the CompAZ library (Zarnecki 03); Ginzburg and Kotkin 00; Telnov http://www.desy.de/~telnov/ggtesla).





Cross section drops by almost one order of magnitude.

Total cross sections



$(m_h,\, m_H,\, m_A,\, m_{12}) = (120,\, 240,\, 270,\, 350)\; GeV \qquad \sin\alpha = -0.9 \quad \tan\beta = 1$

These plots show the optimal relation between the collider energy and the charged Higgs mass.

We are showing plots for the values of sin ♋ and m_{12} that maximize the cross sections.