Double neutral Higgs production at the LHC

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Based on my following papers

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Phys.Rev.D78, 075002,2008

In Collaboration with

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Renato Guedes Rui Santos

Outline

- Testing the Standard Model Higgs boson
  - -- Higgs mechanism & LHC
  - -- production channels & cross sections
- The 2HDM Higgs Bosons
  - -- Higgs Potential, Yukawa Sector & constraints
  - -- Decoupling Limit.
  - -- Fermiophobic Higgs Limit
  - -- General 2HDM
- Numerical results and discussions
  - -- Higgs signatures.
- Summary

Standard Model: The Higgs Mechanism

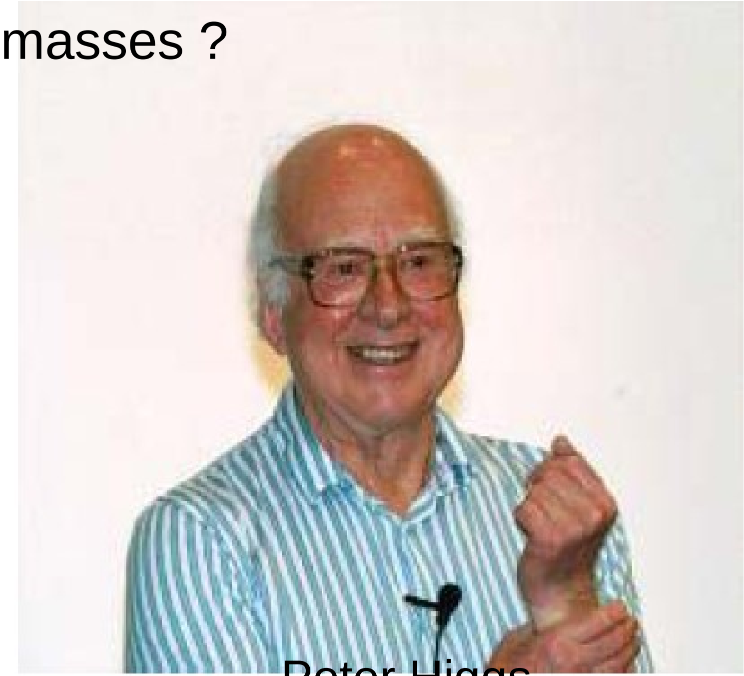
<u>In the Standard Model</u>: The Higgs Mechanism

A most basic question is why particle have masses ?

- The mass mystery could be solved with the “Higgs mechanism”, which predict the existence of new elementry particle “Higgs” (P.Higgs, R.Brout and F.Englert, 1964)

Yes

- Higgs is responsible for mass:
  – it couples to a particle with a strength proportional to its mass
  – heavier particles are more likely to appear in Higgs decays



Peter Higgs

In the Standard Model: The Higgs Mechanism

A most basic question is why particle have masses ?

Peter Higgs

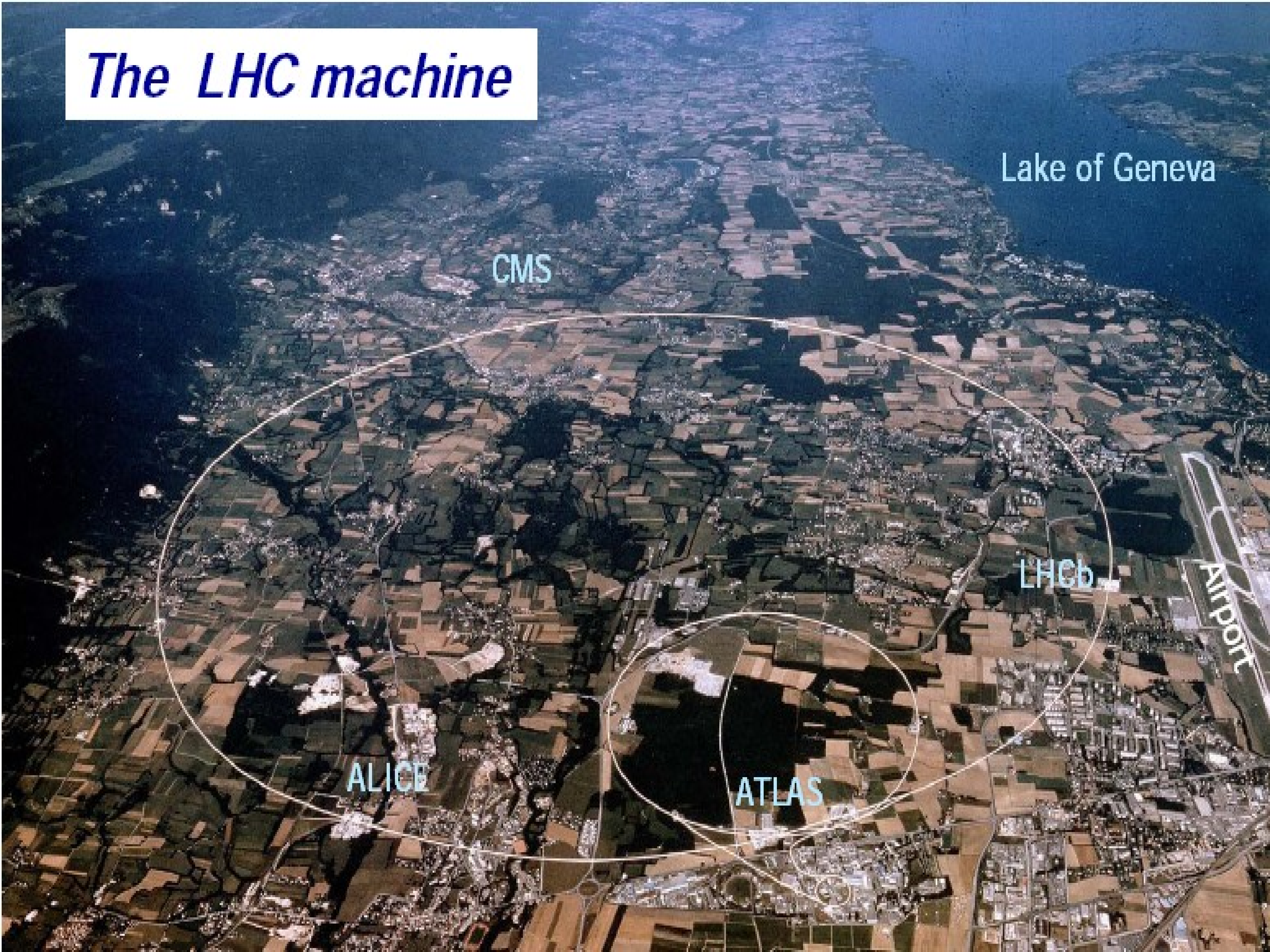
- The mass mystery could be solved with the "Higgs mechanism", which predict the existence of new elementry particle "Higgs" (P.Higgs, R.Brout and F.Englert, 1964)

- Higgs is responsible for mass: Yes

The Higgs (H) particle has been searched for since decades at accelerators, but not yet found…

The LHC will have sufficient energy to produce it for sure, if it exists

The LHC machine

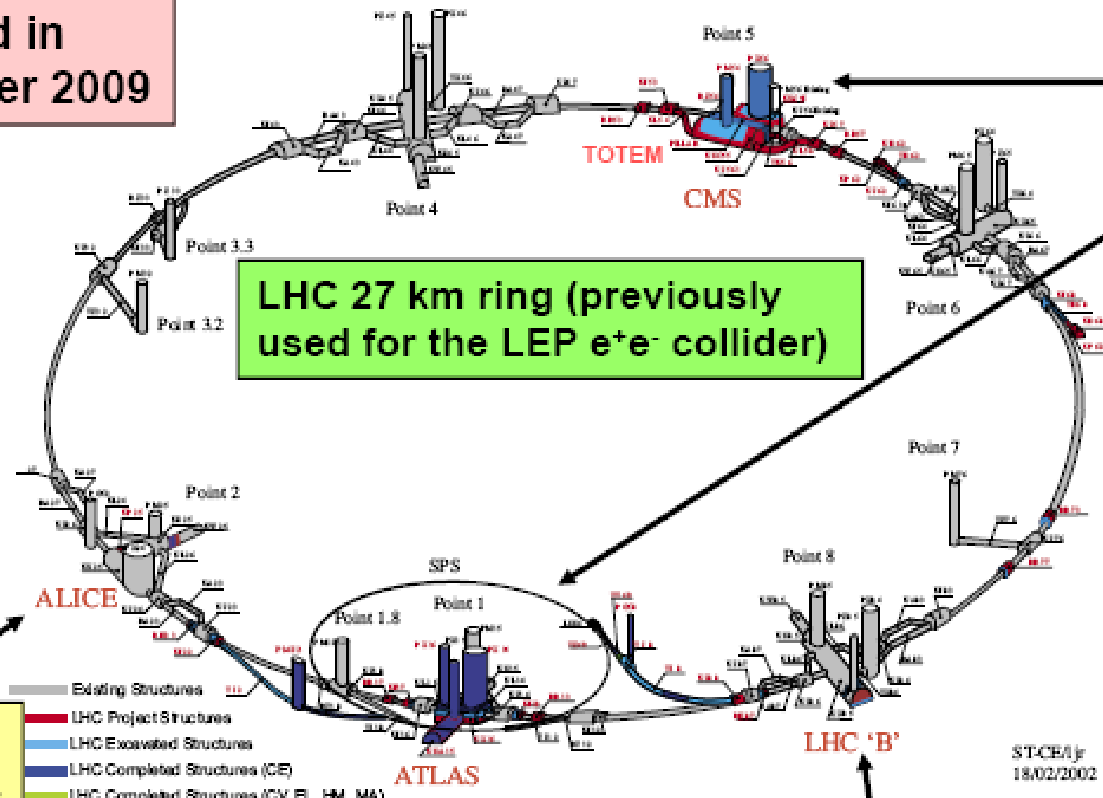


pp $\sqrt{s}$ = 14 TeV $L_{design} = 10^{34}$ cm^{-2} s^{-1} (after 2012/3)

10-14 TeV $L_{initial}$ < few x 10^{33} cm^{-2} s^{-1} (before)

Heavy ions (e.g. Pb-Pb at ~ 1150 TeV)

First collisions: expected in November 2009



ATLAS and CMS: general purpose

LHC 27 km ring (previously used for the LEP e^+e^- collider)

Plus two much smaller experiments with very forward detectors at
Point-1: LHCf
Point-5: Totem

ALICE: Heavy Ions

LHCb: B-physics, CP-violation

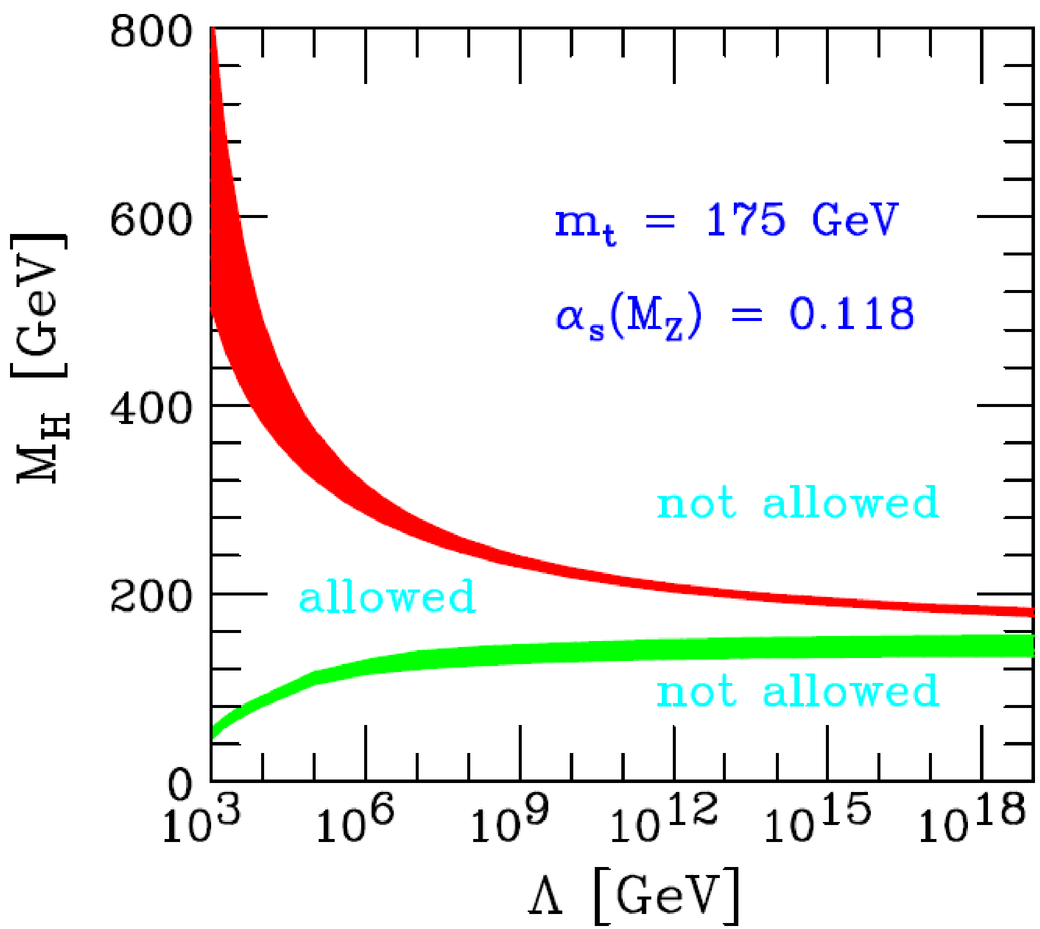
In the Standard Model: The Higgs Mechanism

At TeV scale

$$50\ \text{GeV} \lesssim M_H \lesssim 800\ \text{GeV}$$

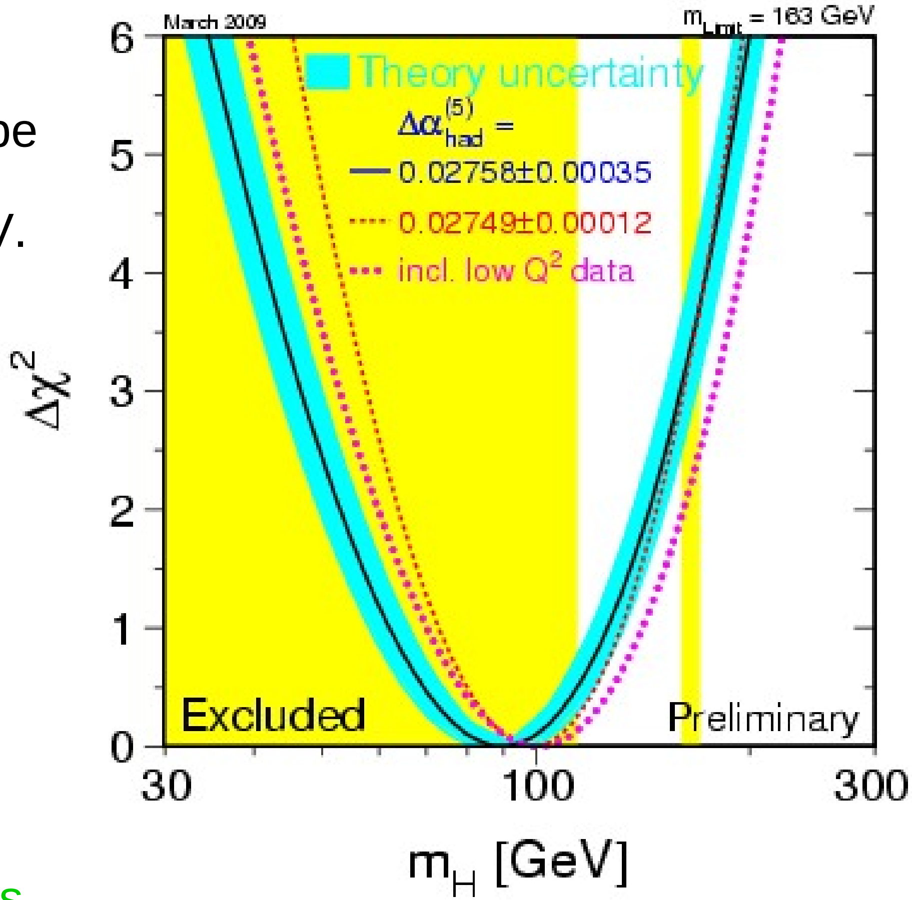
At GUT scale

$$130\ \text{GeV} \lesssim M_H \lesssim 180\ \text{GeV}$$



In the Standard Model: The Higgs Mechanism

March 2009



Delta –chi2 as function of the Higgs bosons mass , assuming the SM to be the correct theory of nature. The preferred value of its mass is 90 GeV.

$$e^+e^- \xrightarrow{Z^*} H_{SM} Z$$

$$\text{with } H_{SM} \to b\bar{b}, \tau^+\tau^-$$

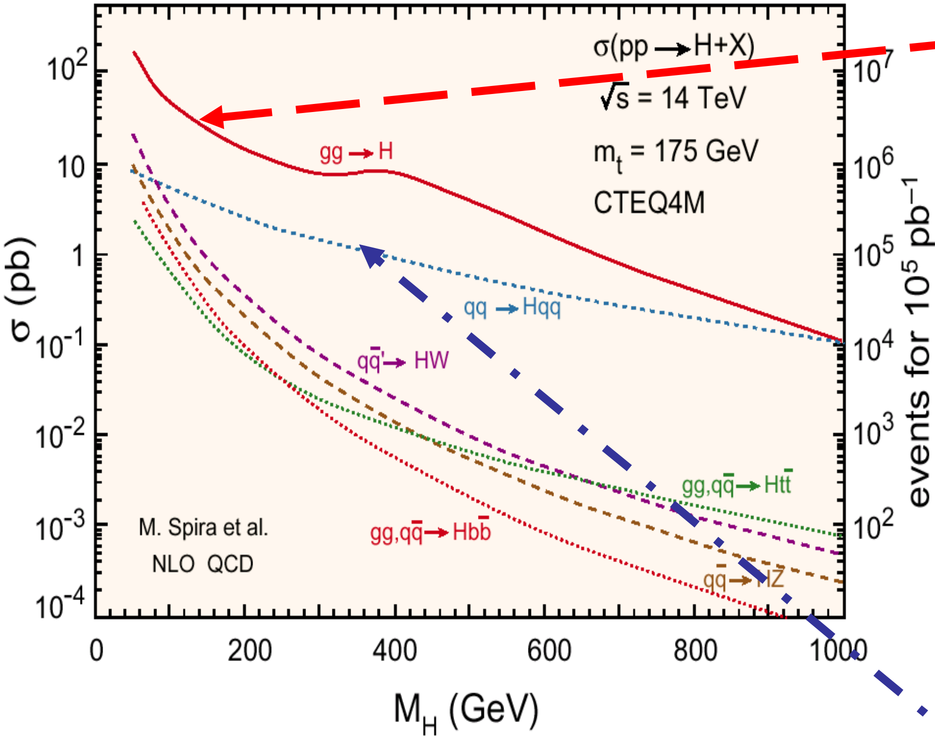
$$\text{and } Z \to q\bar{q}, l^+l^-, \nu\bar{\nu}$$

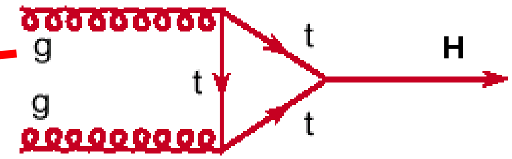
The most recent combined result from Tevatron (CDF, D0) excluding the mass range of 160 GeV to 170 GeV at 95%CL.

$$gg \to H \to W^- W^+ \quad \text{with} \quad 3.fb^{-1}$$

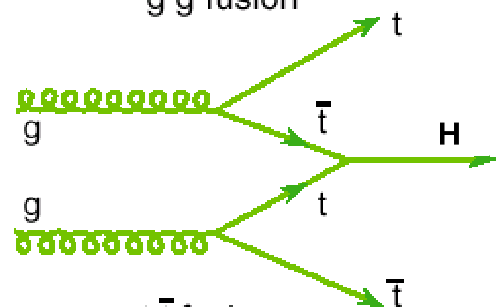
SM Higgs: production @ LHC

SM Higgs: production @ LHC

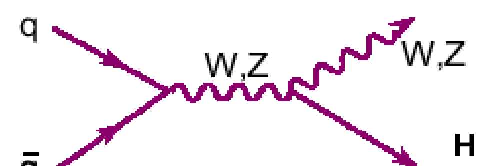




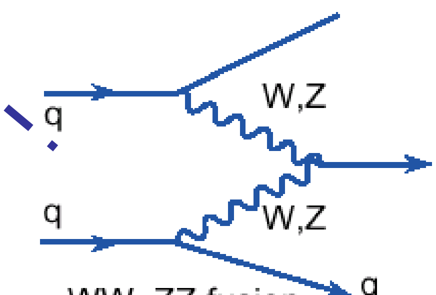
g g fusion



t t̄ fusion



W, Z bremsstrahlung



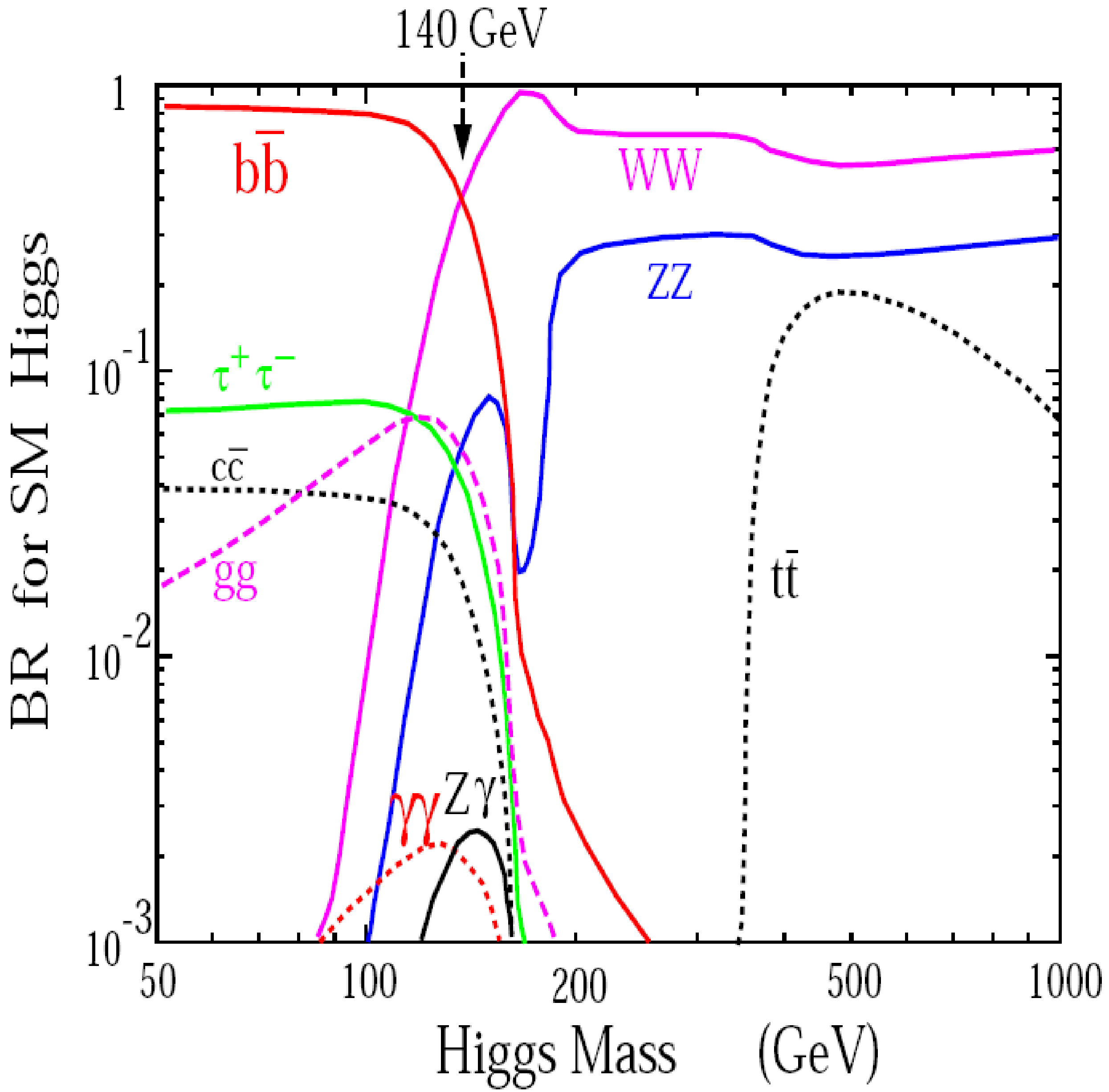
WW, ZZ fusion

gg fusion is more abundant, followed by the vector Boson fusion process

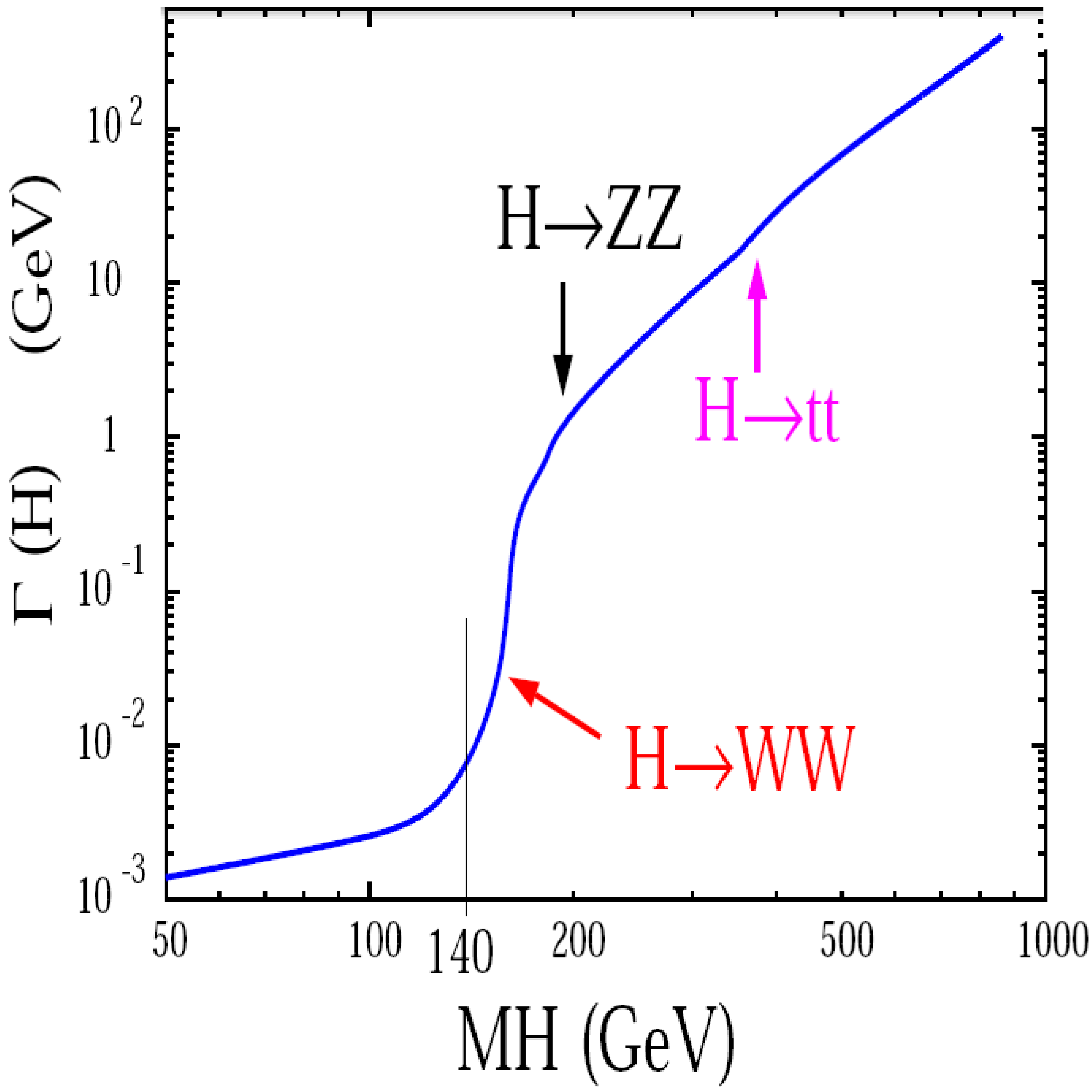
Typical uncertainties on cross-section
- gg 10-20 % (NNLO)
- VBF ~ 5% (NLO)
- WH,ZH ~< 5% (NNLO)
- ttH 10-20 % (NLO)

SM Higgs: Decay

Many channels explored and all mass range is covered



SM Higgs: Width



Beyond the SM

- The Higgs mechanism works well technically.
- Descovering the Higgs boson will be the final cornerstone of the SM

Nevertheless it can't be the ultimate theory:

- The SM cannot explain the origin of the **Higgs boson**
- The SM cannot describe the **neutrino mass**
- The SM cannot tell us what **Dark matter** is?
- …

Even a Higgs boson as predicted by SM my not be Standard

Many more scalar particles may be present

Beyond the Standard Model

Why Two Higgs Doublet Model ?
Motivations

- The simplest extension of the SM by adding one more doublet.

J.F.Gunion, H.E.Haber, “The Higgs Hunter's Guide”

$$\rho = \frac{\sum |v_n|^2 \left[T_n(T_n+1) - Y_n^2 \right]}{2 \sum |v_n|^2 Y_n^2}$$

Experimentally ➡ $\rho \approx 1.001 \pm 0.002$

- The hierarchy of Yukawa couplings
- CP violation explicitly or spontaneously.
- Flavor Changing Neutral Current (FCNC).
- ...

Potential of 2HDM

In the 2HDM, the most general Higg potential compatible with a gauge invariance and CP conservation is given by

$$\begin{aligned}
\mathcal{V}_2 &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \mathrm{h.c.}] \\
&+ \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\
&+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
&+ \left\{ \frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \left[\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)\right] \Phi_1^\dagger \Phi_2 + \mathrm{h.c.} \right\} .
\end{aligned} \tag{2}$$

where $\lambda_{1-4}, m_{11}^2, m_{22}^2 \in \mathbb{R}$ (by the hermicity of the potential),

while in general $\lambda_{5-7}, m_{12}^2 \in \mathbb{C}$.

✓ Z_2 symmetry

S. T. D. Lee, Phys. Rev. D 8 (1973) 1226.

$$\Phi_1 \rightarrow -\Phi_1, \Phi_2 \rightarrow \Phi_2 \quad \text{or} \quad \Phi_1 \rightarrow \Phi_1, \Phi_2 \rightarrow -\Phi_2.$$

$$m_{12}^2 = \lambda_6 = \lambda_7 = 0.$$

Theoretical constraints

- Perturbativity

$$|\lambda_i| \leq 8\pi \ \text{for all} \ i.$$

- Vacuum stability

$$\lambda_1 > 0 \, , \qquad \lambda_2 > 0 \, ,$$
$$\sqrt{\lambda_1 \lambda_2} + \lambda_3 + \min(0, \lambda_4 - |\lambda_5|) > 0 \, .$$

- Unitarity constraints

S.Kanumura , T.Kubato, E. Tkasugi PLB313 (1993)
A.Akeroyd, A. Arhrib, E.Naimi PLB490 (2000)

$$|a_\pm|, |b_\pm|, |c_\pm|, |d_\pm|, |e_{1,2}|, |f_\pm|, |g_{1,2}| < 8\pi$$

Spectrum

- After SSB:

-- Two Higgs CP-even: h, H

-- One Higgs CP-odd: A

-- Two Charged Higgs Bosons

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

Yukawa Sector

V.D. Barger, J. L. Hewett and R. J. N. Philips PRD41: 3421,1990

G. Senjanovic and D. Wyler, PRD 30, 1529 (1984).

$$\mathcal{L}_Y = G^k_{ij}\left(\bar{u} \quad \bar{d}\right)^i_L \phi_k \, d^j_R + \tilde{G}^k_{ij}\left(\bar{u} \quad \bar{d}\right)^i_L \tilde{\phi}_k \, u^j_R + h.c.$$

Yukawa Sector

- The couplings of the Higgs to fermions could be realized in different ways

Models	I	II	III	IV
u	Φ_2	Φ_2	Φ_2	Φ_2
d	Φ_2	Φ_1	Φ_1	Φ_2
ν				
ℓ	Φ_2	Φ_1	Φ_2	Φ_1

	I	II	III	IV
α_{uh}	$-\frac{\cos\alpha}{\sin\beta}$	$-\frac{\cos\alpha}{\sin\beta}$	$-\frac{\cos\alpha}{\sin\beta}$	$-\frac{\cos\alpha}{\sin\beta}$
α_{dh}	$-\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\cos\beta}$	$-\frac{\cos\alpha}{\sin\beta}$
$\alpha_{\ell h}$	$-\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\cos\beta}$	$-\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\cos\beta}$

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 SM (like) LEP 114.4 GeV

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

- $Z \to b\bar{b}$ **and** $B_q\bar{B}_q$

Excludes low TB in all models. Values of low charged Higgd ~ 100 GeV and TB ~ 1 are disfavoured

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

- $B \to \tau\nu$

Excludes high TB just in model II.

- $\tau \to \mu\nu\bar{\nu}$

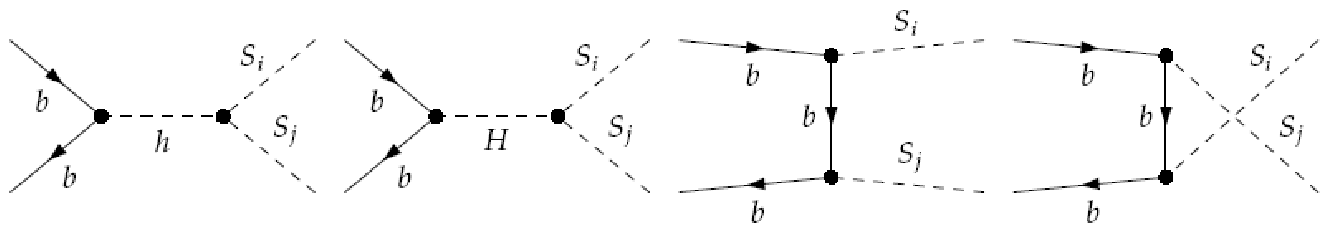
Excludes high TB and low charged Higgs mass just in model II and III

2HDM: cross section

- Our Process

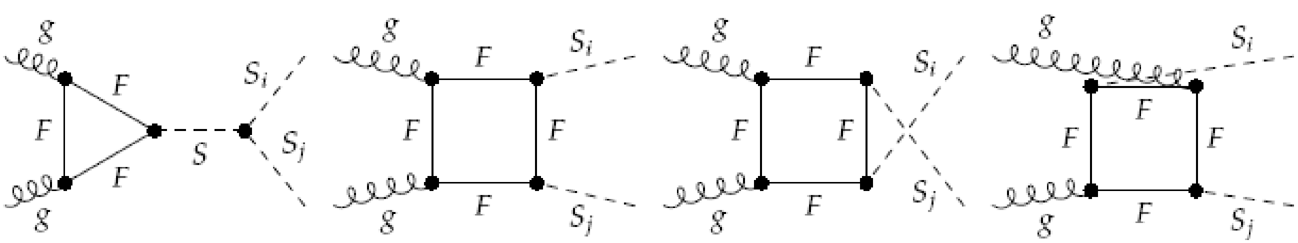
$$pp \to S_i S_j \qquad (S_i S_j = hh, hH, HH)$$

$$q\bar{q} \to S_i S_j$$



(a) (b) (c) (d)

$$gg \to S_i S_j.$$



a b c d

FeynArts, FormCalc and Looptools

www.feynarts.de

2HDM: Decoupling Limit (DL)

Decoupling limit of the 2HDM (1/5)

Scalar masses except the lighter CP-even Higgs become infinite.

$$m_{h^0} \sim \mathcal{O}(v)$$
$$m_{H^0}, m_{A^0}, m_{H^\pm} \sim m_S + \mathcal{O}(v^2/m_S).$$

In this limit $\cos(\beta-\alpha) \to 0$ OR $\alpha \sim \beta - \pi/2$

$$g_{h^0VV} = g_{H_{SM}VV} \quad \text{with} \quad V = Z, W^\pm.$$
$$g_{h^0f\bar{f}} = g_{H_{SM}f\bar{f}} \quad \text{with} \quad f = \text{fermion}.$$

And the triple Higgs couplings

$$\lambda_{h^0h^0h^0} \to \lambda^{SM}_{HHH} = -\frac{3m^2_{h^0}}{v}$$
$$\lambda_{h^0h^0H^0} \to 0.$$

Decoupling limit of the 2HDM (2/5)

S.Kanumura , Y. Okada, E. Senaha, C-P.Yuan PRD 2004

S.Kanumura , S. Kiyoura, Y. Okada, E. Senaha, C-P.Yuan PLB 2002

It has been demonstrated that the one-loop leading contribution from heavy Higgs and top quark the effective coupling can be written as

$$\begin{aligned} \lambda^{effe}_{h^0h^0h^0} &= -\frac{3m_{h^0}^2}{v}\left[1+\frac{m_{H^0}^4}{12\pi^2 m_{h^0}^2 v^2}\left(1+\frac{M^2}{m_{H^0}^2}\right)^3\right. \\ &+ \frac{m_{A^0}^4}{12\pi^2 m_{h^0}^2 v^2}\left(1+\frac{M^2}{m_{A^0}^2}\right)^3 \\ &+ \left.\frac{m_{H^\pm}^4}{6\pi^2 m_{h^0}^2 v^2}\left(1+\frac{M^2}{m_{H^\pm}^2}\right)^3 - \frac{N_c M_t^4}{3\pi^2 m_{h^0}^2 v^2}\right] \end{aligned}$$

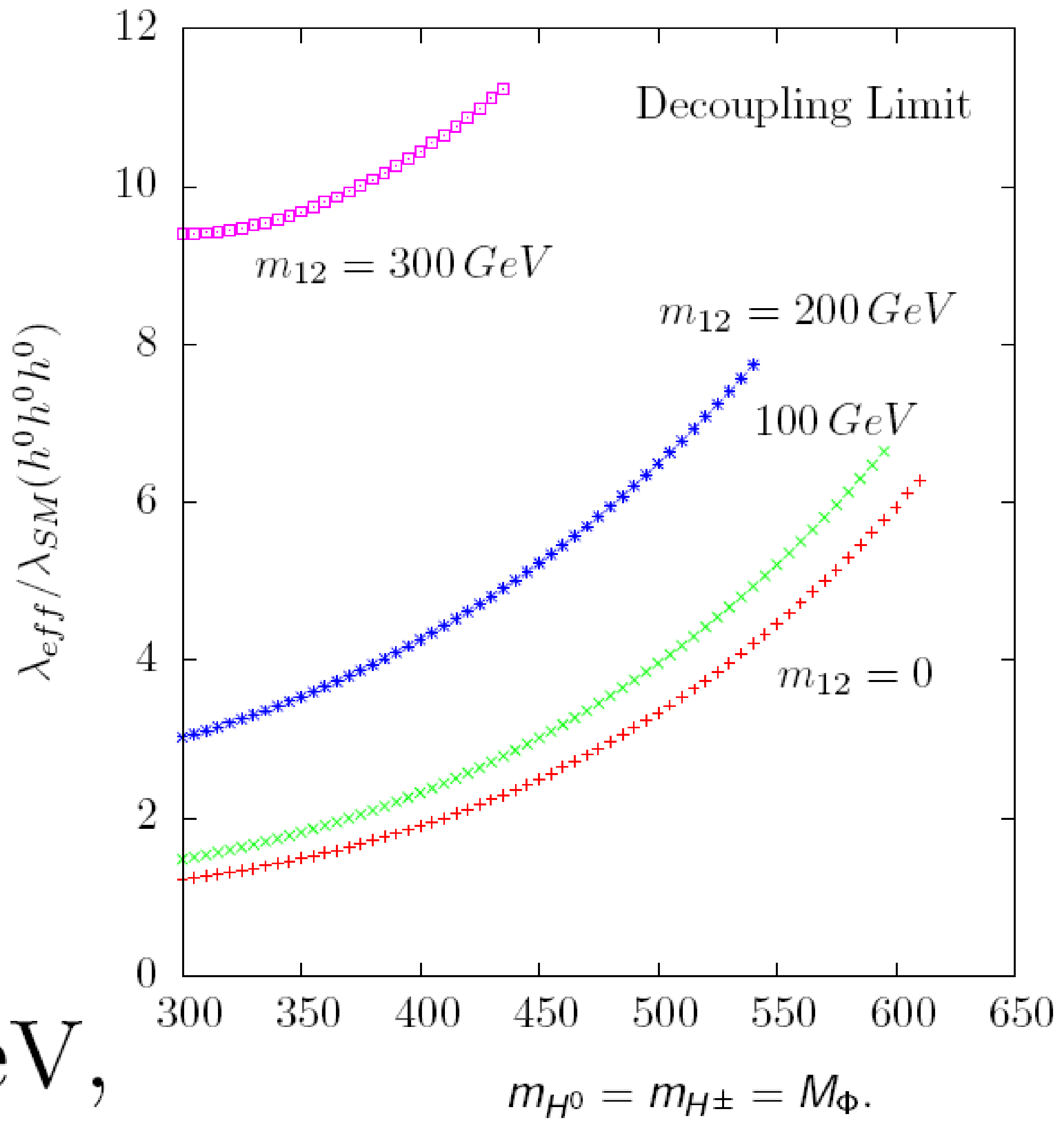
where $M = m_{12}/\sqrt{\sin\beta\cos\beta}$,

Decoupling limit of the 2HDM (3/5)

The effective couplings behaves with the respect to the SM couplings

The deviation from the SM is large due to the non-decoupling effects of the additional heavier Higgs bosons in loops

$$\tan\beta = 1,$$
$$m_{h^0} = 115\ \text{GeV},$$



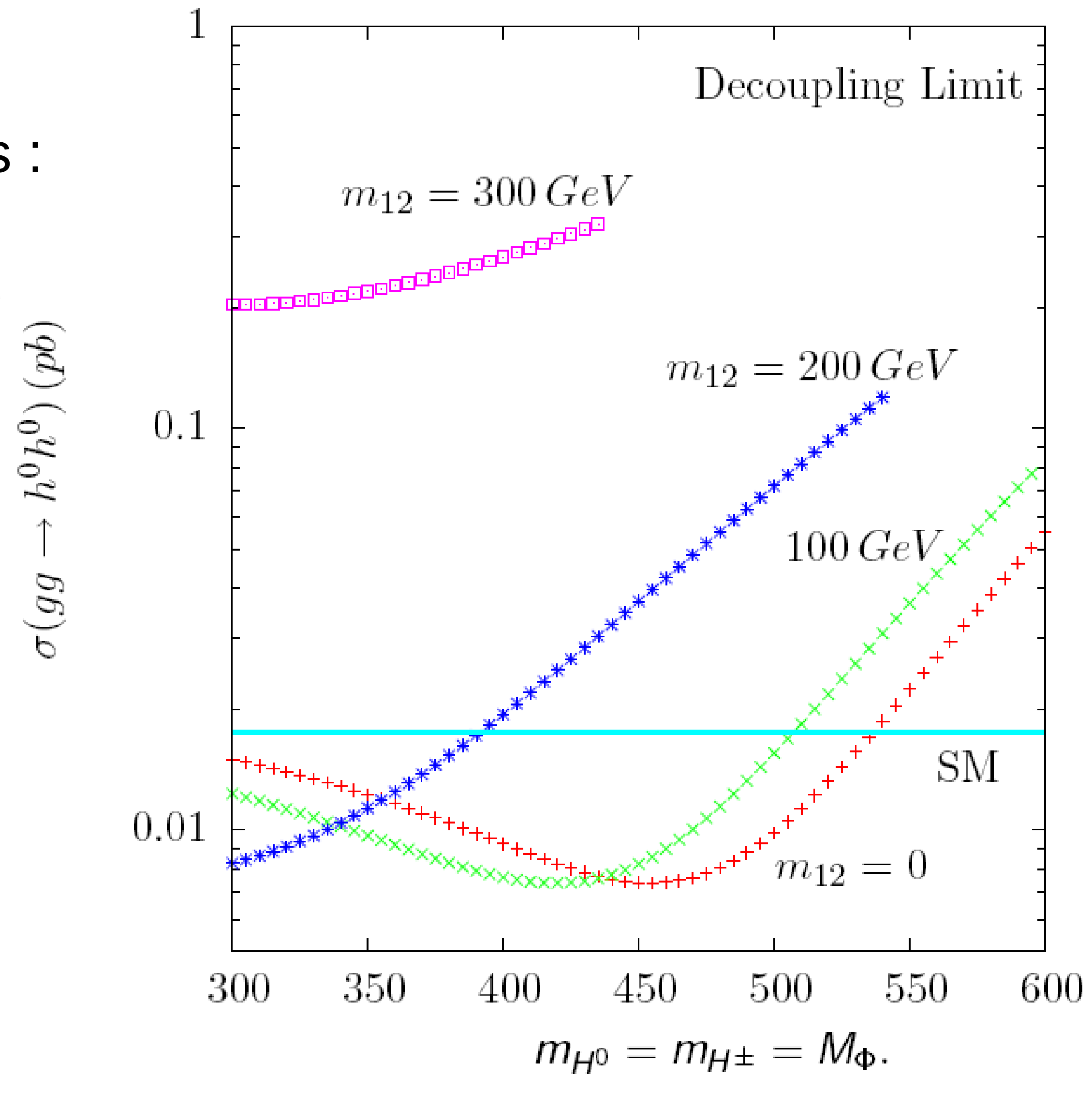
Decoupling limit of the 2HDM (4/5)

Cross section ?

Dependence parameters :

$$M_\Phi, \quad m_{12}, \quad \tan\beta.$$

Large cross section



Decoupling limit of the 2HDM (5/5)

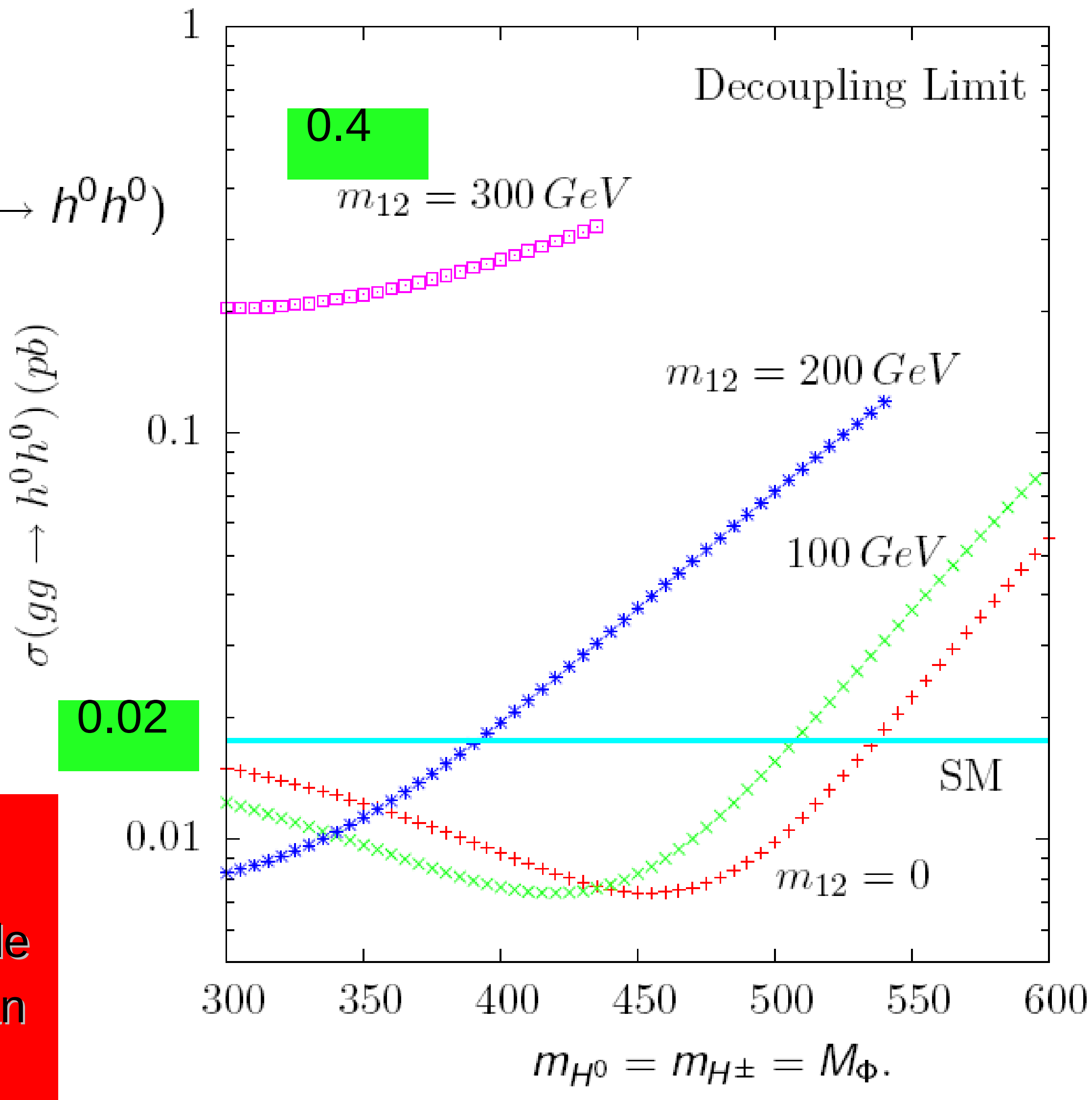
Cross section ?

$$\sigma^{2HDM}(gg \to h^0 h^0) < \sigma^{SM}(gg \to h^0 h^0)$$

How ?

This is because a destructive interference between boxes and vertices.

If m12 is large the box contributions become negligible and non-decoupling effects can be seen already for small M

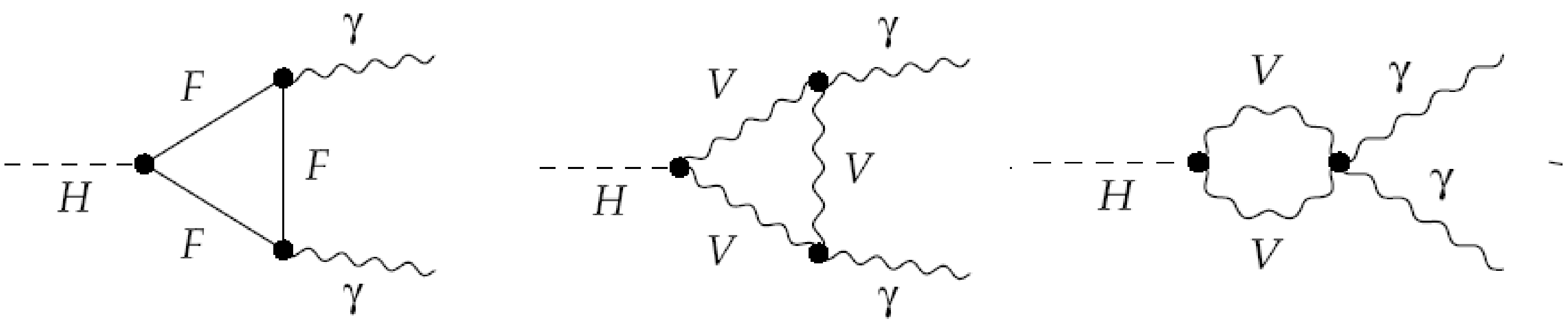


2HDM: Fermiophobic Higgs limit (FB)

Fermiophobic Higgs limit (1/5)

- In the SM:

$$BR(h^0 \to \gamma\gamma) \text{ is below } 0.1\%.$$



By enlarging the coupling $H\gamma\gamma$.

K.Hagiwara, R. Szalapski, D. Zeppenfeld PLB318 (1993)

K. Hagiwara *et al* PRD48(1993)

By reducing the coupling of the Higgs bosons to fermions

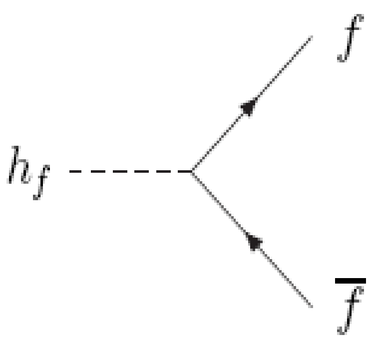
H. Pois, T. J. Weiler and T. C. Yuan, PRD 47 (1993)

A. Stange, W. J. Marciano and S. Willenbrock, PRD49 (1994)

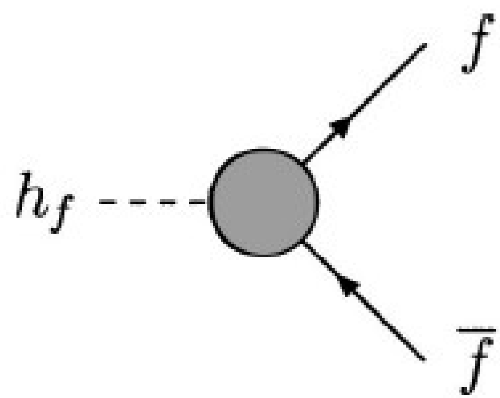
Fermiophobic Higgs limit (1/5)

- Fermiophobic…means you <u>turn off</u> couplings to fermions

  - Can occur in Type-1-doublet Higgs models
    - Type-1 – one doublet couples to fermions, the other to bosons
      - sin(α) for H and cos(α) for h
    - h is therefore "fermiophobic" in the limit $\alpha \to \pi/2$
      - Of course we could have a "fermiophobic" H ($\alpha \to 0$)…but h is lighter so we look there…



$$= \cos\alpha / \sin\beta \sim 0\,.$$



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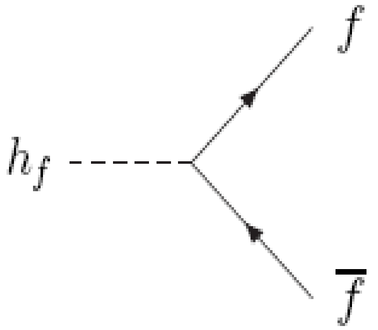
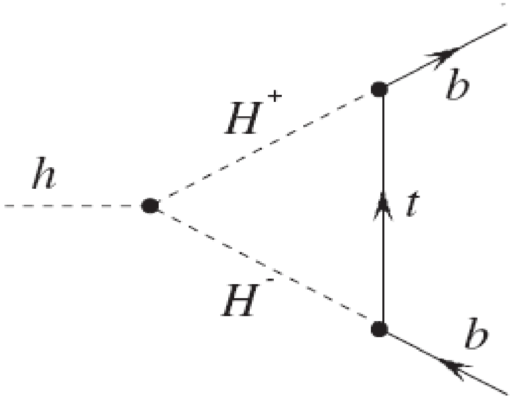


$= \cos\alpha / \sin\beta \sim 0\,.$



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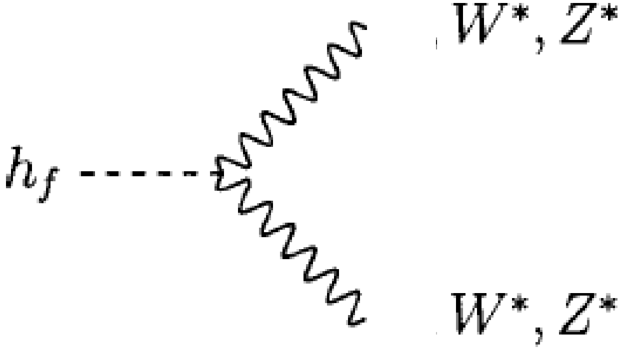
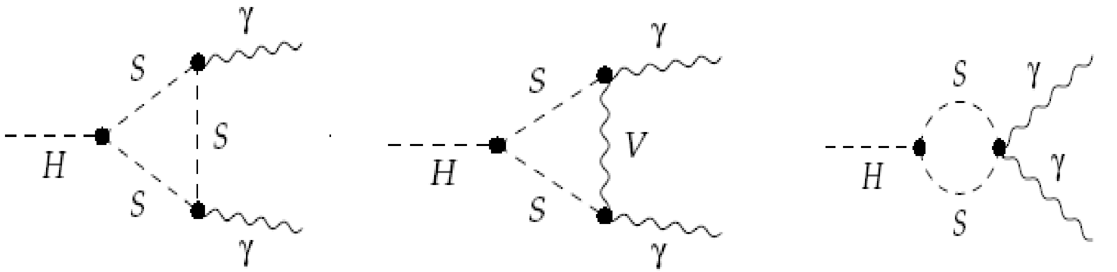


$$h_f VV \sim \sin^2(\beta - \alpha) \rightarrow \cos^2\beta \equiv 1/(1 + \tan^2\beta).$$

Fermiophobic Higgs limit (1/5)



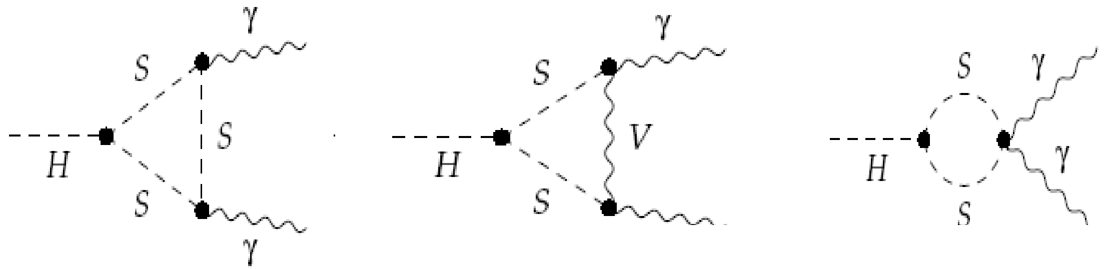
A.G.Akeroyd PRD(2007).

$$\Gamma(h_f \to \gamma\gamma) = \frac{\alpha^2 g^2}{1024\pi^3} \frac{m_{h_f}^3}{m_W^2} |F_0\, \tilde{g}_{h_f H^+ H^-} - F_1 \cos\beta|^2$$

$$\tilde{g}_{h_f H^+ H^-} = -\frac{m_W}{g m_{H^+}^2} g_{h_f H^+ H^-}$$

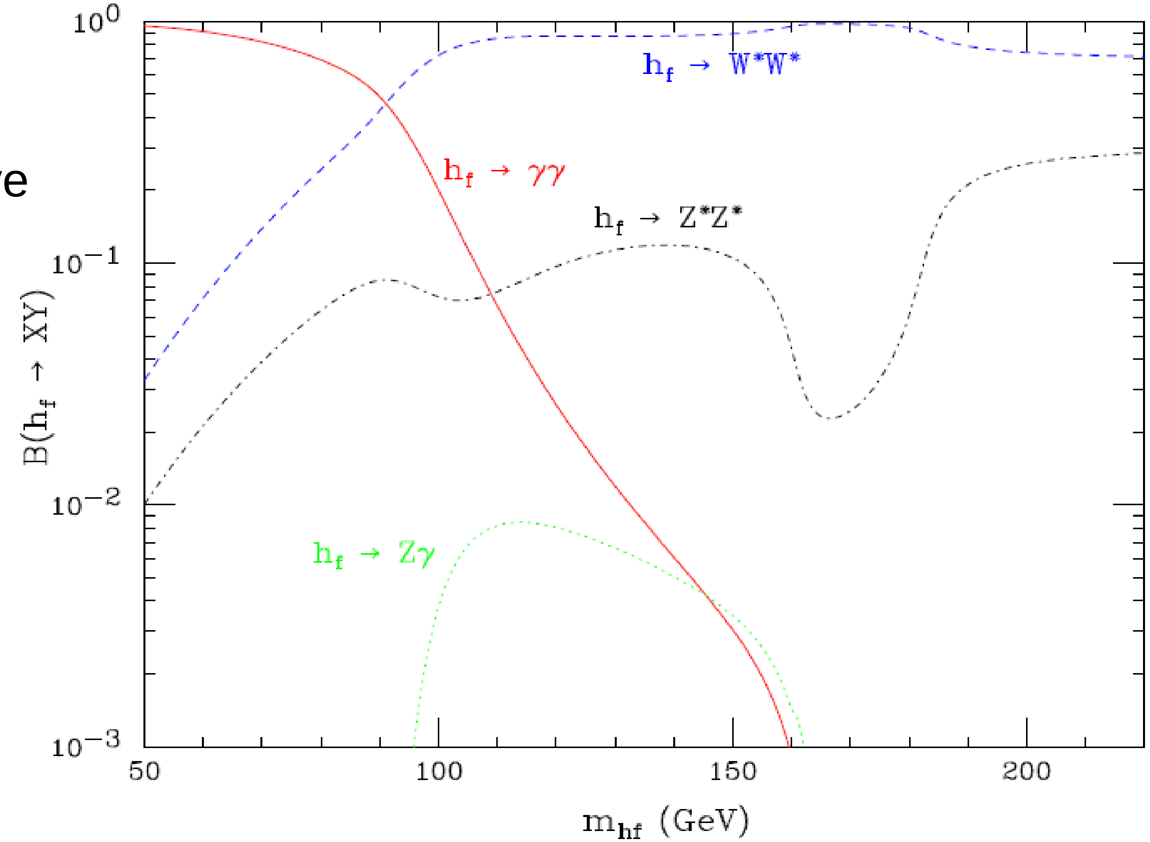
$$g_{h_f H^+ H^-} = c_\beta v \left[2\frac{m_{H^\pm}^2}{v^2} + s_\beta^2 \lambda_1 - (1+s_\beta^2)\frac{m_A^2}{v^2} - (1+s_\beta^2)\lambda_5 \right]$$

Fermiophobic Higgs limit (1/5)



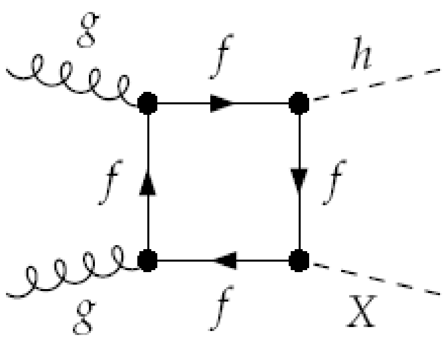
A.G.Akeroyd PRD(2007).

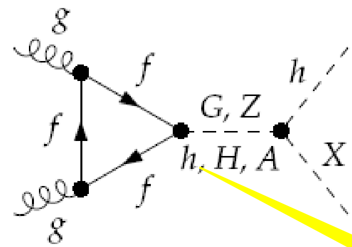
Charged Higgs effect can cause
both constructive and destructive
contribution with W+



Fermiophobic Higgs limit (1/5)

- More…





Ind.of.TB

ffH~1/SB

$$\lambda^{FL}_{Hhh} \propto -m_{12}^2 \sin\beta$$
$$\lambda^{FL}_{HHh} \propto m_{12}^2 \cos\beta$$
$$\lambda^{FL}_{AAh} \propto -2\sin^2\beta\, m_h^2 + m_{12}^2\cos\beta - 4\cos^2\beta\, m_A^2$$
$$\lambda^{FL}_{AGh} = \frac{e\sin\beta}{2 m_W s_W}\left(m_A^2 - m_h^2\right)$$
$$\lambda^{FL}_{hH^\pm H^\mp} \propto 2\sin^3\beta m_h^2 - m_{12}^2\sin\beta - 2\sin 2\beta\cos\beta m_{H^\pm}^2$$

Fermiophobic Higgs limit (2/5)

LHC

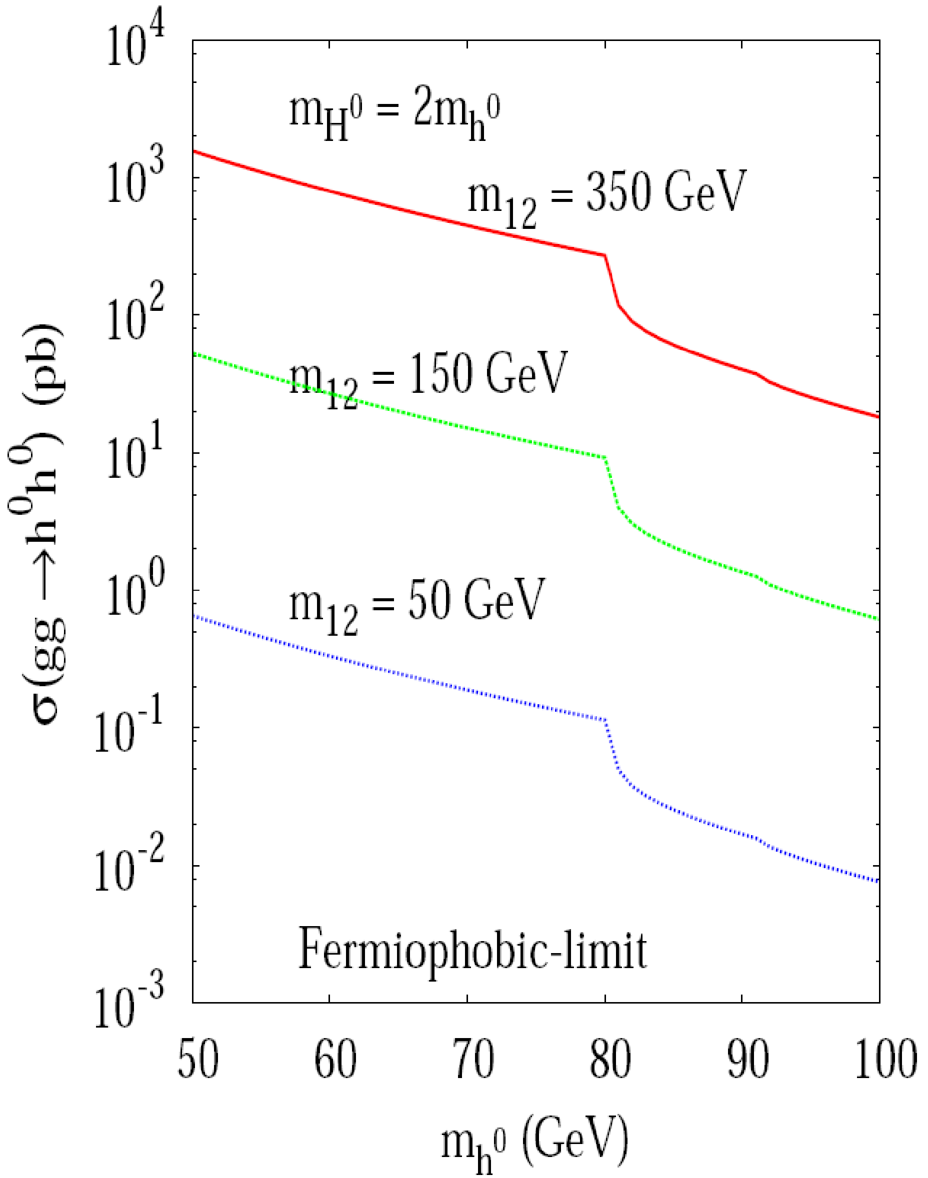
$$\sigma(gg \to h^0 h^0)$$ depend on

$$m_{h^0},\ m_{H^0} \quad \text{and} \quad m_{12}^2.$$

On the resonance

$$m_{H^0} = 2m_{h^0}$$

The cross section is large for light Higgs mass



Fermiophobic Higgs limit (2/5)

LHC

$\sigma(gg \to h^0 h^0)$ depend on

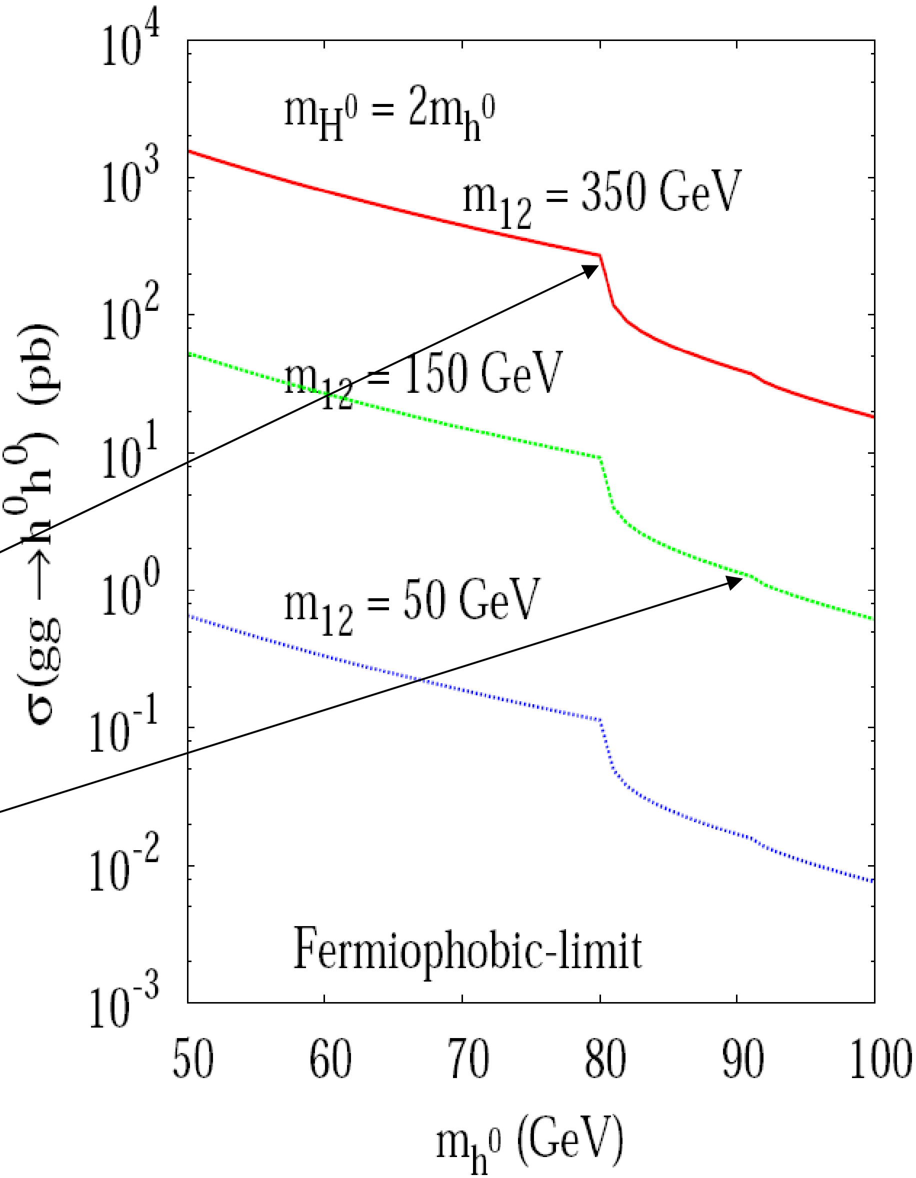
$m_{h^0},\ m_{H^0}\ \ \text{and}\ \ m_{12}^2.$

On the resonance

$$m_{H^0} = 2m_{h^0}$$

$H^0 \to WW$

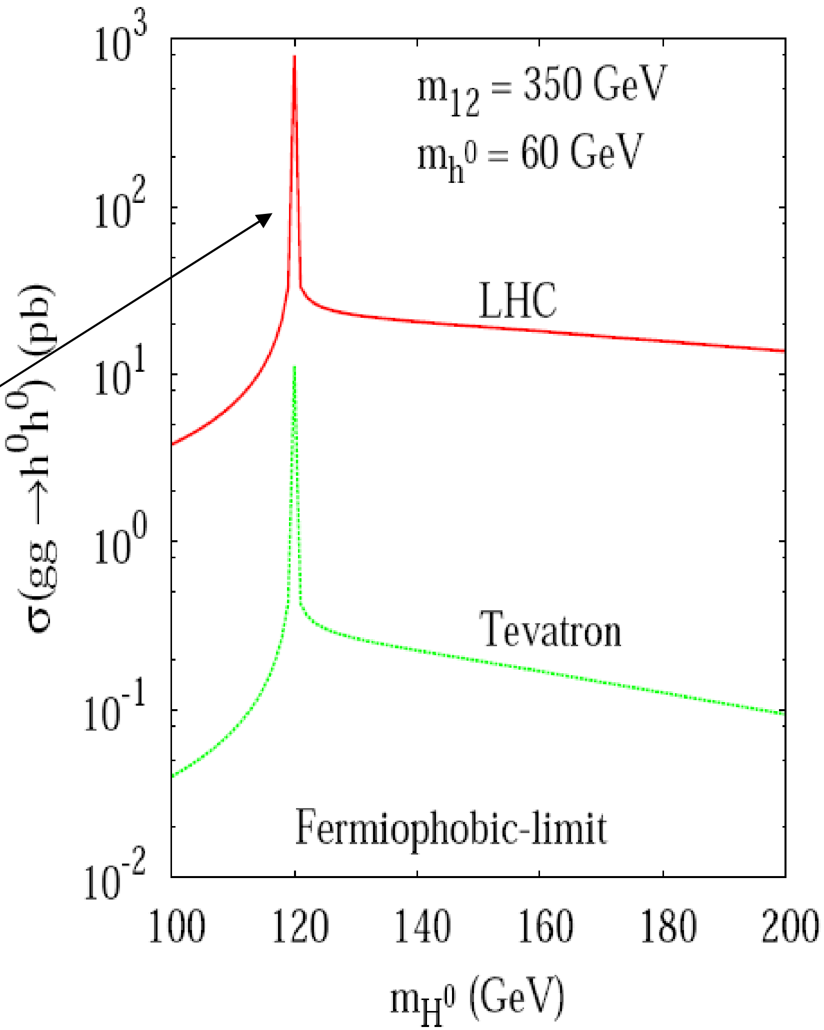
$H^0 \to ZZ$



Fermiophobic Higgs limit (3/5)

pp→ hh as a function of MH

$$H^0 \rightarrow h^0 h^0$$



Peak at MH = 120 GeV is very sharp because the total width of H is very narrow in this region

Fermiophobic Higgs limit (4/5)

pp→ Xh as a function of Mh

pp→Ah can be large and

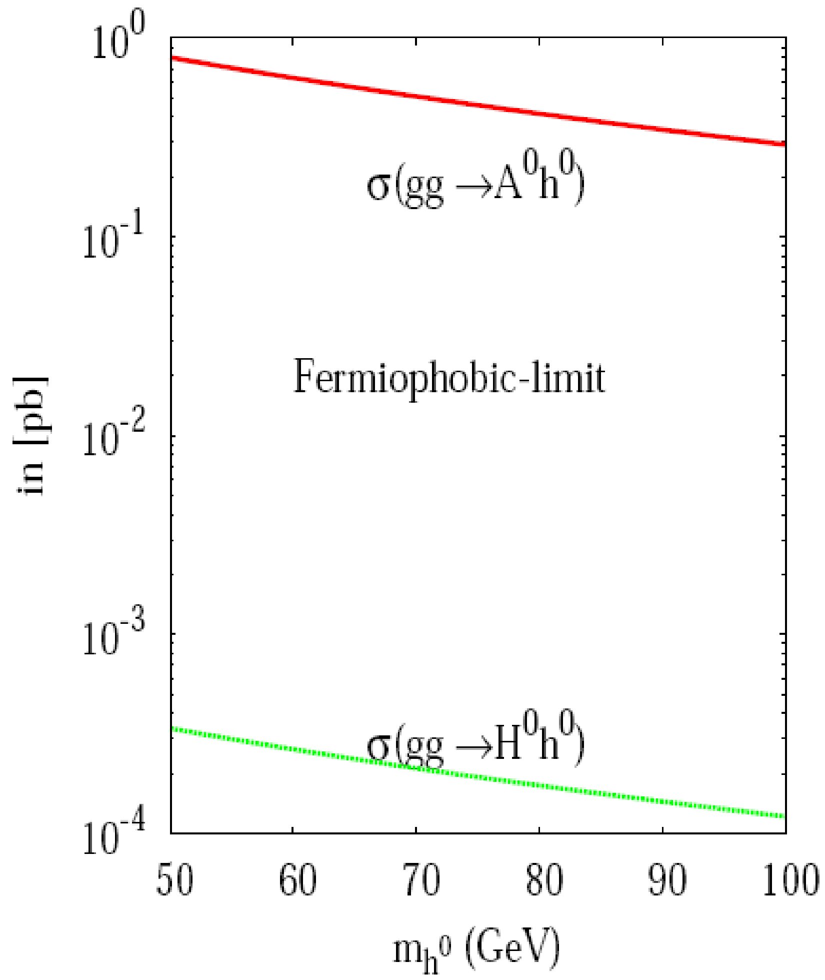
still within the Tevatron reach

pp→Hh is negligible for the most

of the parameter space

$gg \longrightarrow Ah$ Large than

$q\bar{q} \to Z^* \to Ah$



Fermiophobic Higgs limit (5/5)

- ✓ Branching ratios depend mainly with

  $\tan\beta$ $\quad M_h$

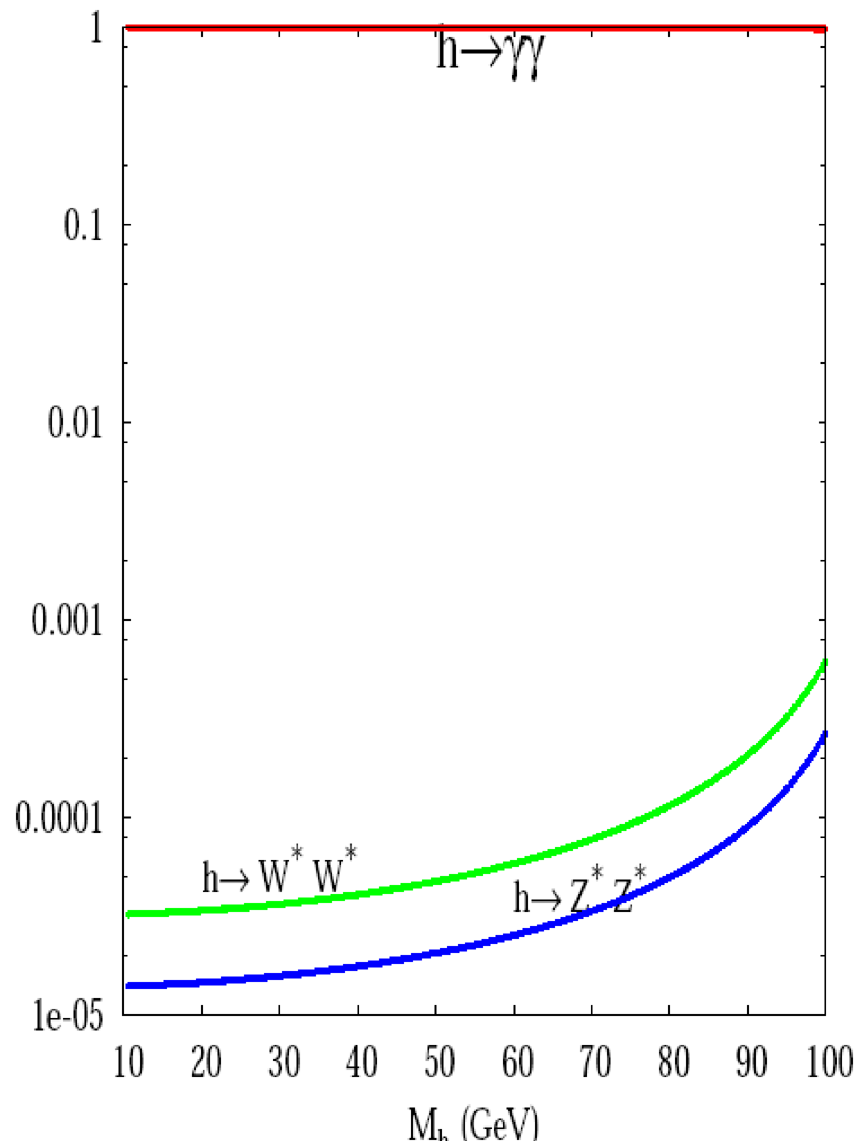
- ✓ For 10 GeV < M_h < 100 GeV

  $$Br(h \to \gamma\gamma) \approx 100\%$$

  and decreases with Mh

$$gg \to hh \to 4\,\gamma$$

$$gg \to hH \to hhh \to 6\,\gamma$$



2HDM: General case

General 2HDM(1/5)

$$gg \to S_i S_j, \text{ where } S = h^0, H^0$$

7 parameters

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

General 2HDM (1/5)

$$gg \to S_i S_j, \text{ where } S = h^0, H^0$$

7 parameters

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

$$\lambda^{2HDM}_{h^0h^0h^0} = \frac{-3e}{m_W s_W s^2_{2\beta}}\left[(c_\beta c^3_\alpha - s_\beta s^3_\alpha) s_{2\beta} m^2_{h^0} + c^2_{\beta-\alpha} c_{\beta+\alpha} m^2_{12}\right]$$

$$\lambda^{2HDM}_{H^0H^0H^0} = \frac{-3e}{m_W s_W s^2_{2\beta}}\left[(c_\beta c^3_\alpha - s_\beta s^3_\alpha) s_{2\beta} m^2_{H^0} + s^2_{\beta-\alpha} s_{\beta+\alpha} m^2_{12}\right]$$

$$\lambda^{2HDM}_{H^0h^0h^0} = -\frac{1}{2}\frac{e c_{\beta-\alpha}}{m_W s_W s^2_{2\beta}}\left[(2m^2_{h^0} + m^2_{H^0}) s_{2\alpha} s_{2\beta} + (3s_{2\alpha} - s_{2\beta}) m^2_{12}\right]$$

$$\lambda^{2HDM}_{H^0H^0h^0} = \frac{1}{2}\frac{e s_{\beta-\alpha}}{m_W s_W s^2_{2\beta}}\left[(m^2_{h^0} + 2m^2_{H^0}) s_{2\alpha} s_{2\beta} + (3s_{2\alpha} + s_{2\beta}) m^2_{12}\right]$$

General 2HDM (1/5)

$$gg \longrightarrow S_i S_j\,, \text{ where } S = h^0, H^0$$

7 parameters $m_{h^0},\quad m_{H^0},\quad m_{A^0},\quad m_{H^\pm},\quad \alpha,\quad \beta\quad m_{12}$

We have scanned the 2HDM parameters space to look for the regions where the cross sections are larger than the SM one.

General 2HDM (2/5)

$(\tan\beta,\ m_{12})$ Plane

$\tan\beta$ Below 5 due to unitarity

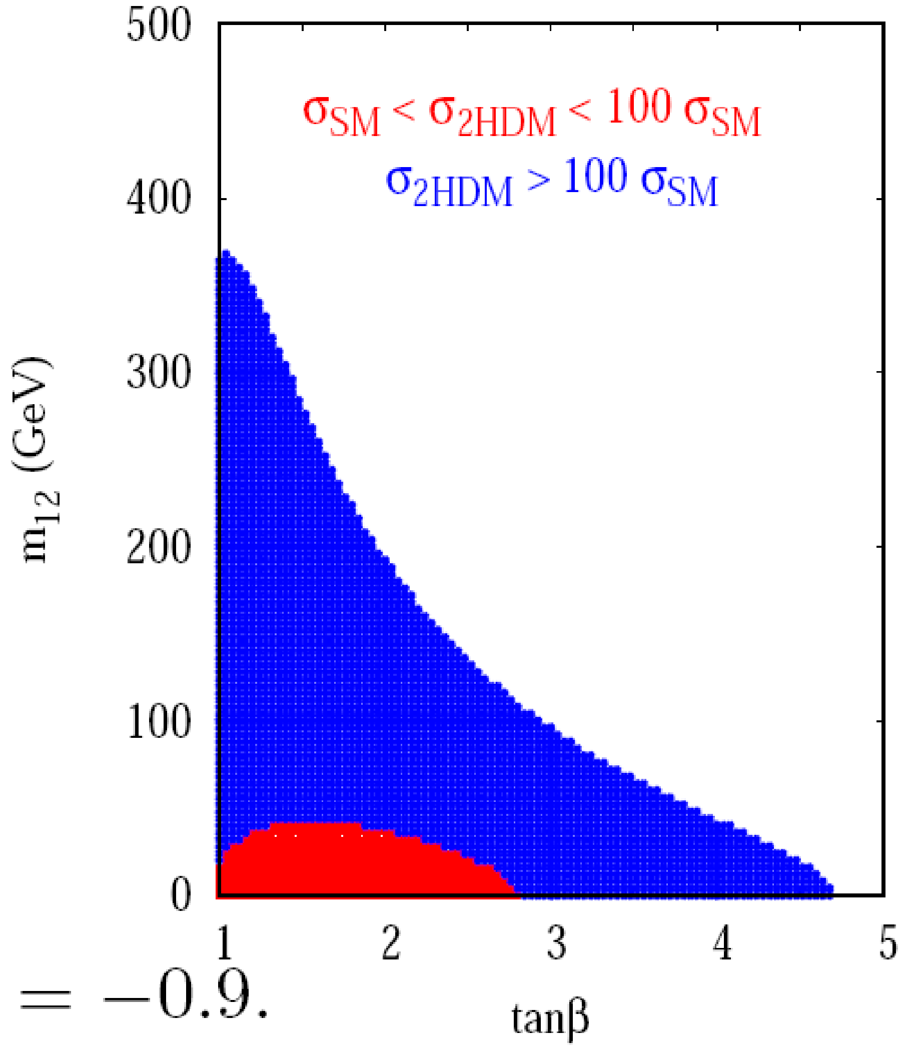
Correlation

m_{12} and $\tan\beta$:

Large values of one of the variables force low values of the other

$h^0 h^0 h^0 \quad H^0 h^0 h^0$

$8 \times \lambda^{SM}_{h^0 h^0 h^0}.$



$m_{H^0} = 250\,GeV$ and $\sin\alpha = -0.9.$

$m_{h^0} = 115$ GeV, $m_{A^0} = 350$ GeV, $m_{H^\pm} = 300$ GeV,

General 2HDM (3/5)

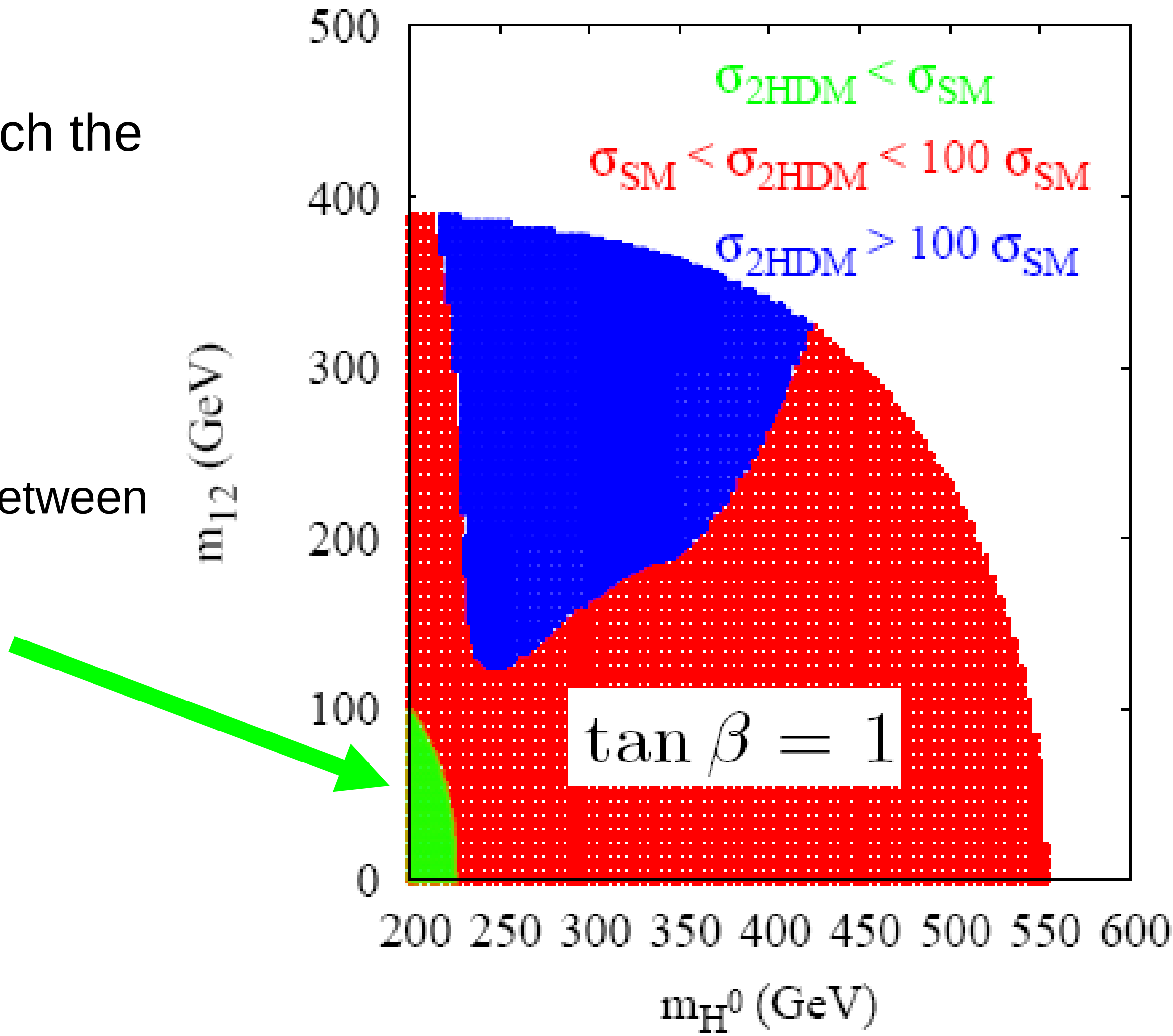
(m_{H^0}, m_{12}) Plane

The cross section reach the maximum when

$$m_{H^0} \approx 2m_{h^0}$$

Destructive contribution between

triangle and boxes



$$\sin\alpha = -0.9$$

$$m_{h^0} = 115\ \text{GeV},\ m_{A^0} = 350\ \text{GeV},\ m_{H^\pm} = 300\ \text{GeV}$$

General 2HDM (4/5)

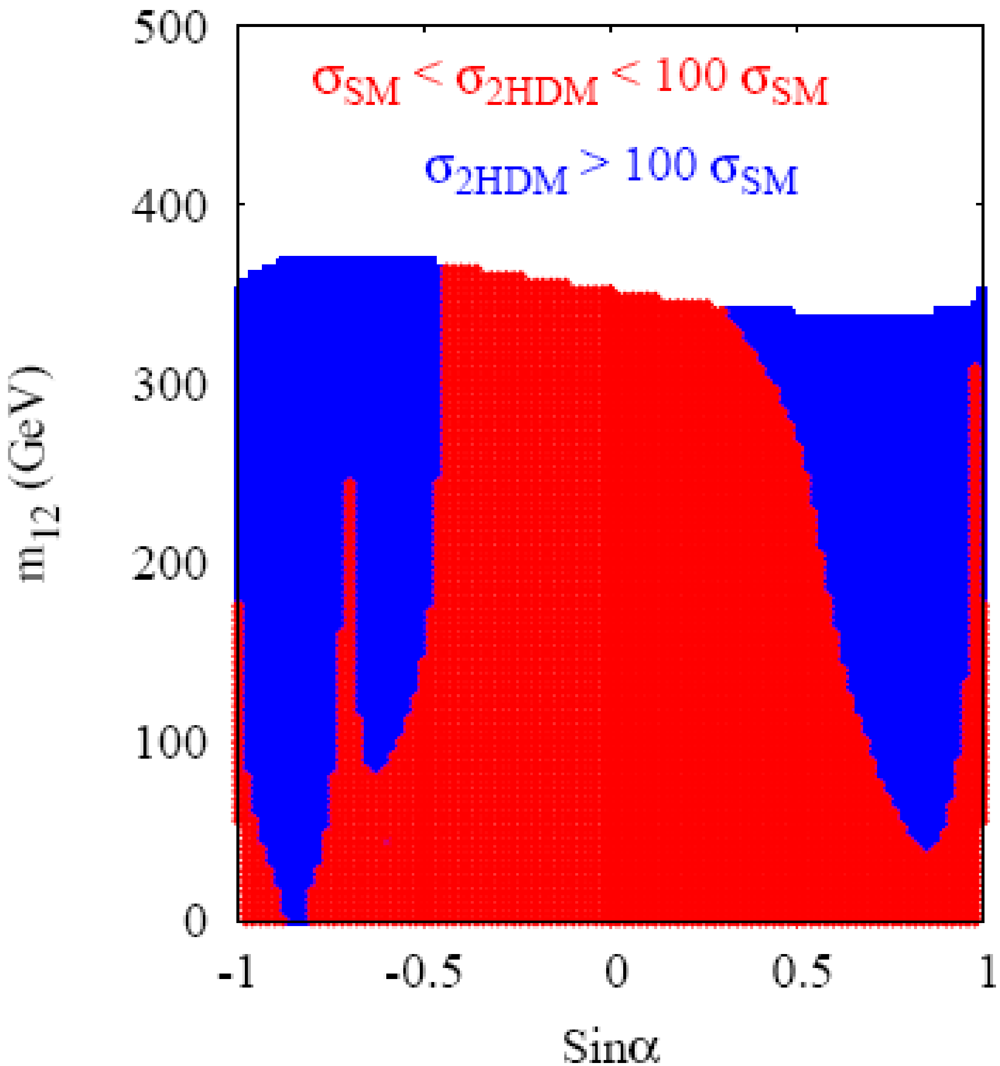
$(\sin\alpha,\ m_{12})$ Plane

$|\sin\alpha|$ maximize

the cross section.

$\tan\beta = 1$

$m_{H^0} = 250\, GeV.$



$m_{h^0} = 115\ \mathrm{GeV},\ m_{A^0} = 350\ \mathrm{GeV},\ m_{H^\pm} = 300\ \mathrm{GeV}$

General 2HDM (5/5)

Before the threshold

The cross section is few pb

And does not depend much

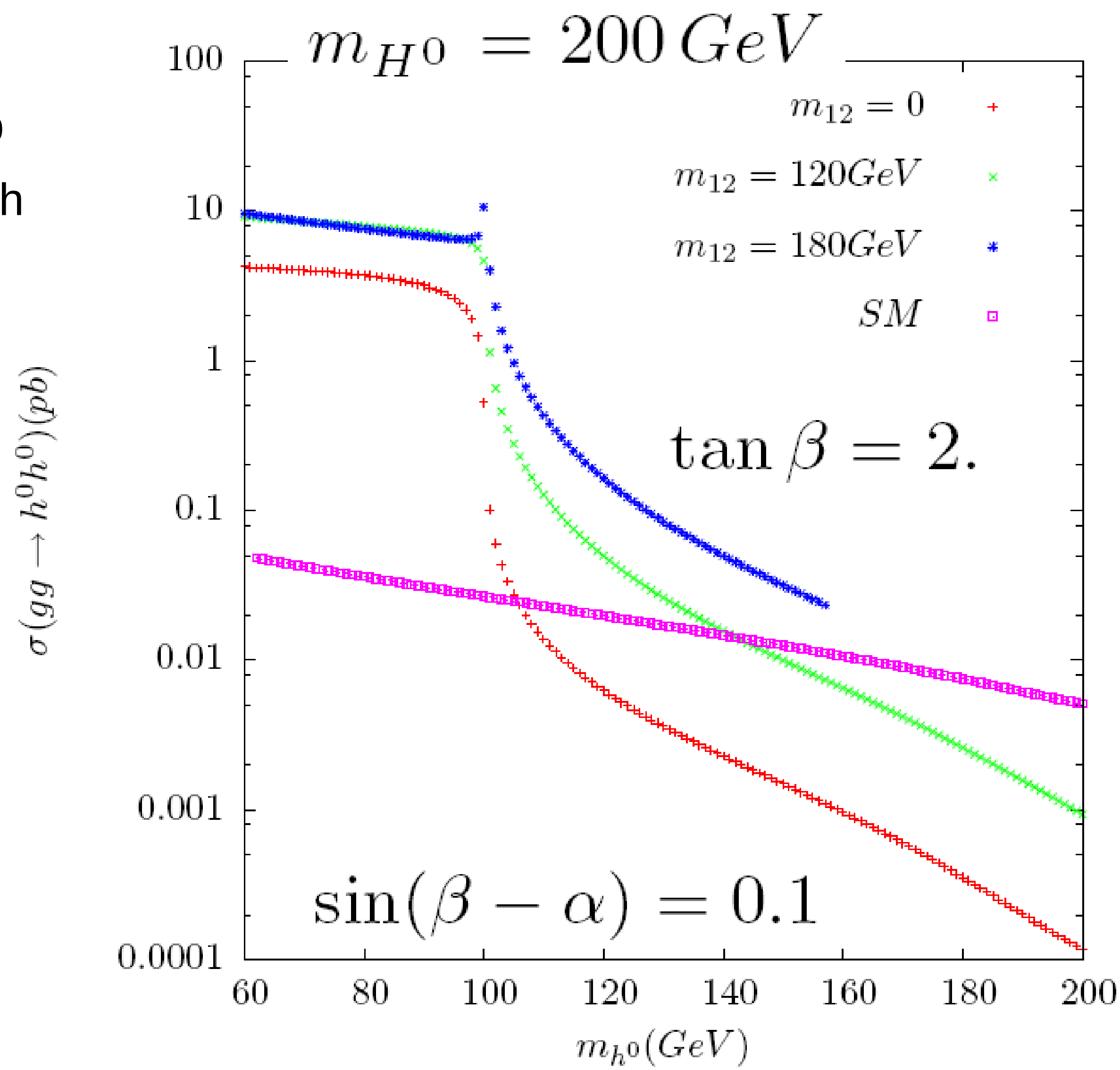
On m12

$\mathrm{Br}(H^0 \to h^0 h^0) \to 100\%.$

$H^0 h^0 h^0$ ↗ $h^0 h^0 h^0$ ↘

Below the threshold

$H^0 \to h^0 h^0$ is closed,



$$m_{A^0} = 320\,GeV,\; m_{H^\pm} = 380\,GeV,$$

<u>2HDM</u>: Higgs signatures

Higgs signatures (type-I)

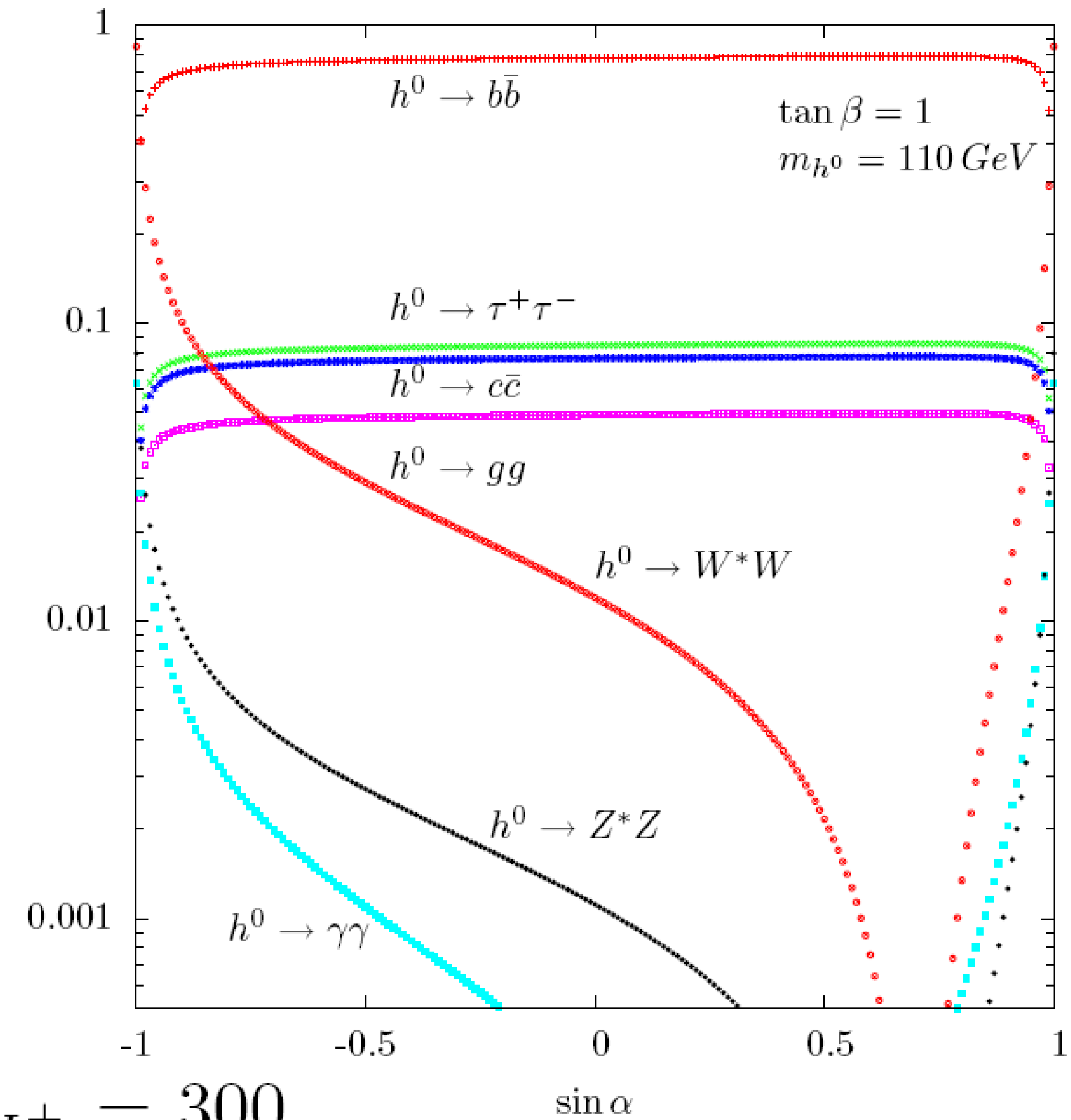
In model type I the lightest

CP-even has the SM signatures

$$h^0 \to b\bar{b},\ \tau^+\tau^-$$

$$\sin\alpha \to \pm 1.$$

$$h^0 \to \gamma\gamma,\ W^*W,\ Z^*Z$$



$$m_{H^0} = m_{A^0} = m_{H^\pm} = 300$$

Higgs signatures (type-II)

$\sin\alpha \to 0.$

$h^0 \to c\bar{c}, gg$

In model II, non-b jets

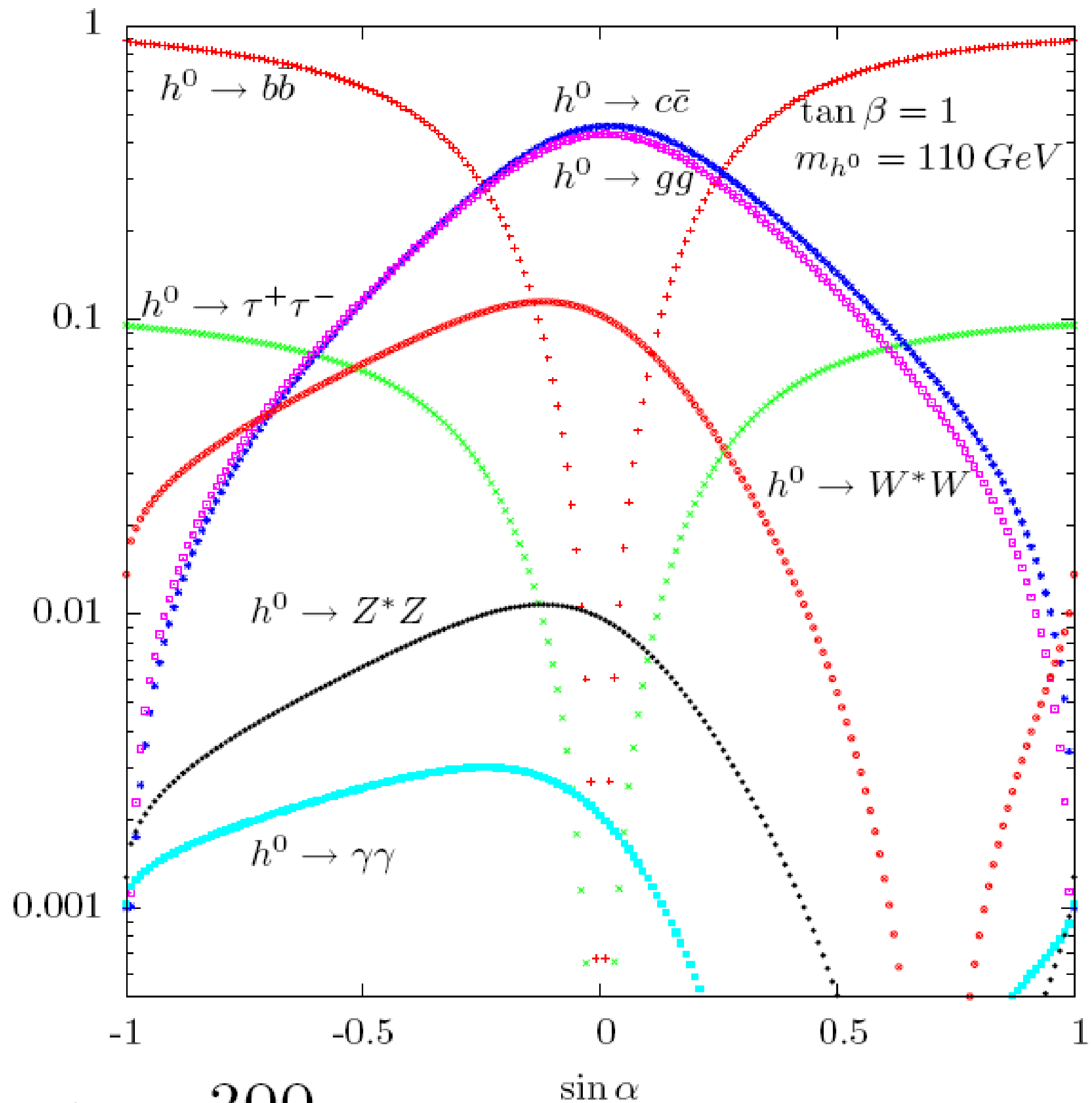
100%.

Dectection of higgs is very hard due to bgd

$\sin\alpha \to 1.$

$h^0 \to b\bar{b}$

$h^0 \to \tau^+\tau^-$



$m_{H^0} = m_{A^0} = m_{H^\pm} = 300$

Higgs signatures (type-III)

$\sin\alpha \to 0.$

$h^0 \to \tau^+\tau^-$

50%.

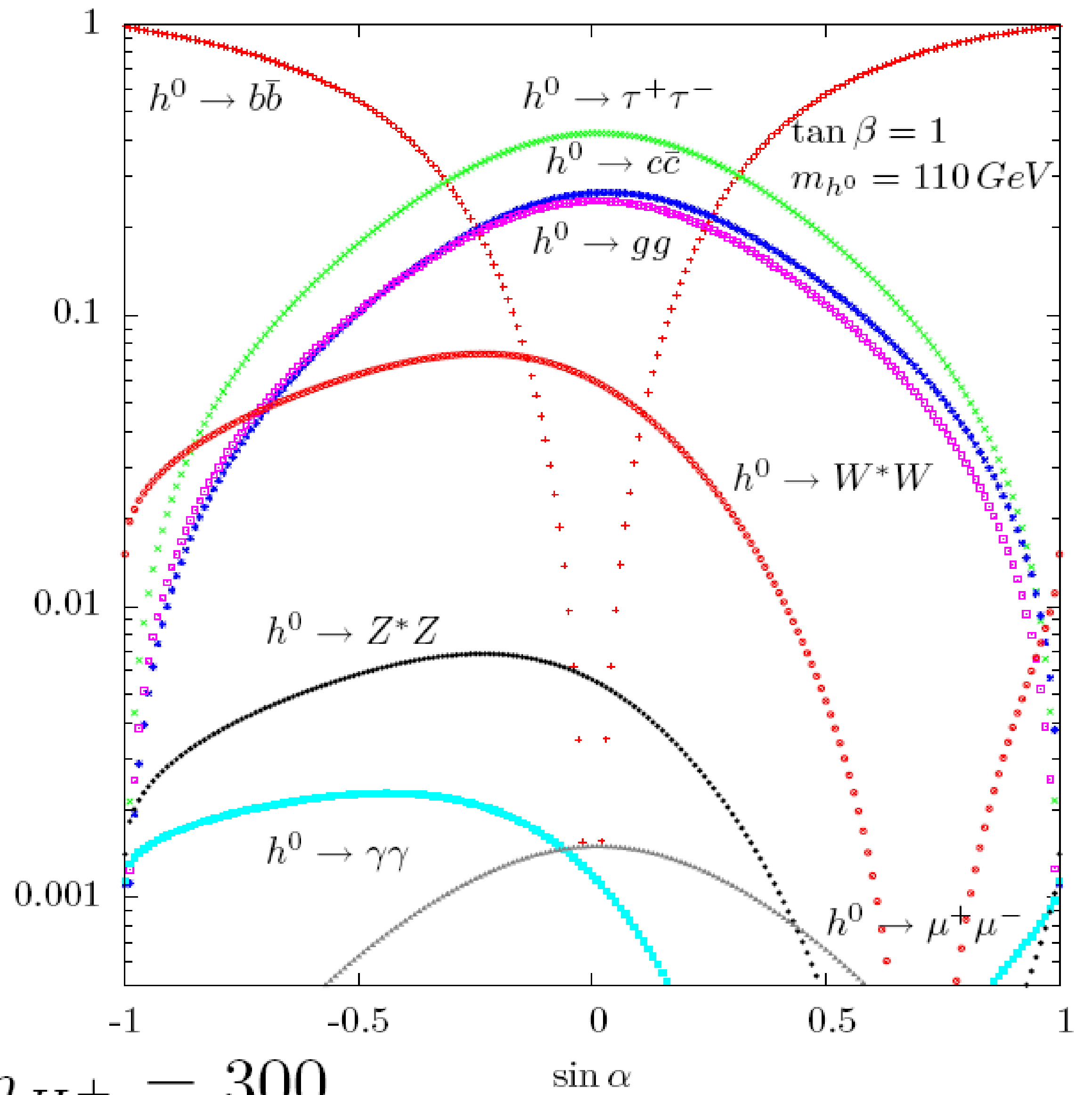
$h^0 \to \mu^+\mu^-$

0.1%.

$\to \tau^+\tau^-\mu^+\mu^-$

$\sin\alpha \to 1.$

$h^0 \to b\bar{b}$



$m_{H^0} = m_{A^0} = m_{H^\pm} = 300$

Higgs signatures (type-IV)

$h^0 \rightarrow b\bar{b}$

dominant decay mode

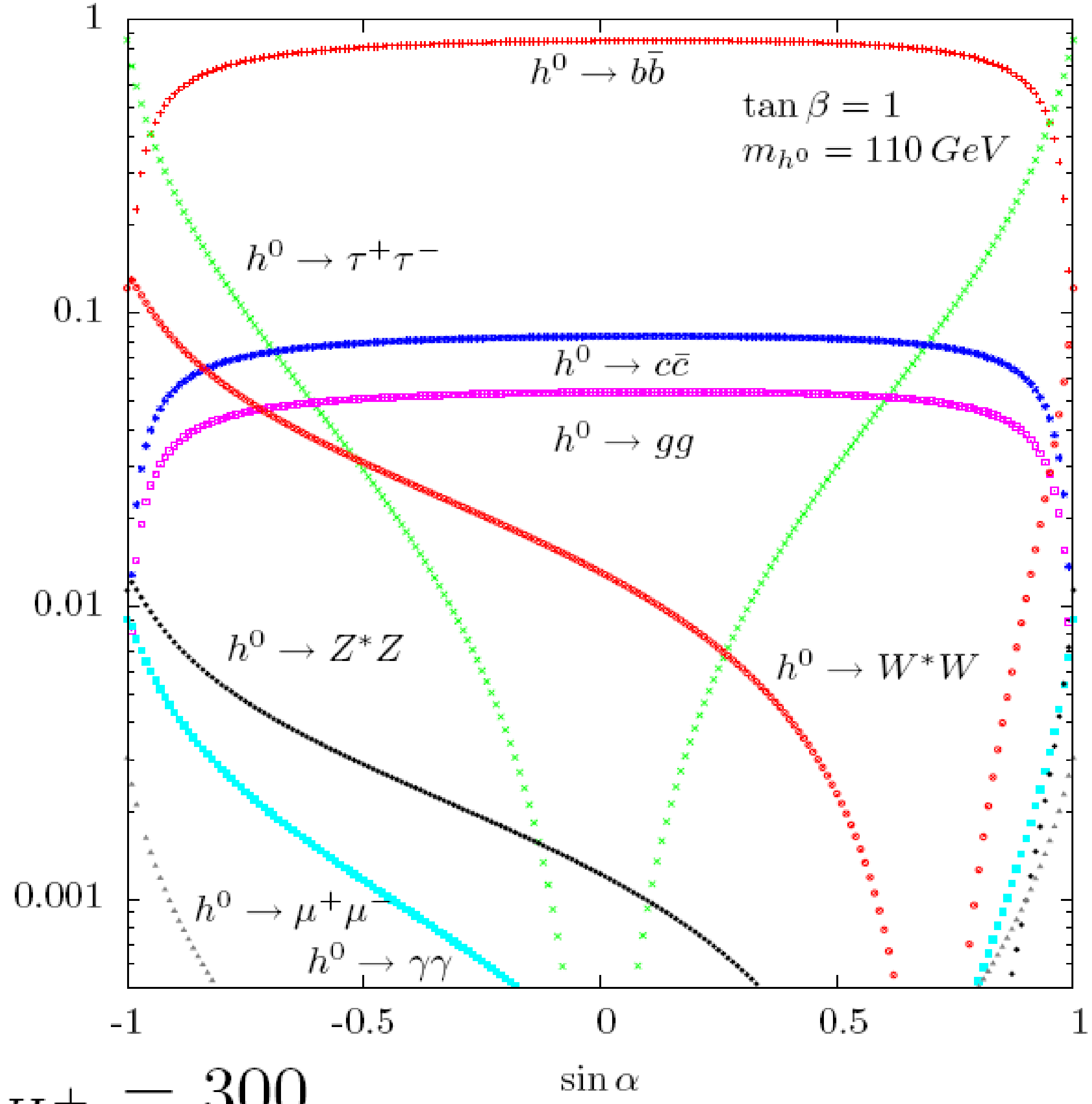
$|\sin\alpha| \approx 1.$

$h^0 \rightarrow \tau^+\tau^-$

70%.

$h^0 \rightarrow \mu^+\mu^-$

0.4%.



$m_{H^0} = m_{A^0} = m_{H^\pm} = 300$

Conclusions

- The 2HDM has a vast region of the parameter space where the cross section is at least as large as the SM cross section

- In the general case, the best scenario need : large m12, large sinalpha and a nice resonance

- In Decoupling limit the cross section is more than one order of magnitude

  -- For large values of m12

  -- Large common mass scale MH.

  Can be extracted $h^0 h^0 h^0$

- We have shown that there are alternative channels to search for FB Higgs with a multi-photon signature.

  -- $gg \to h^0 h^0$ Few pb and can still be discovered at Tevatron.

  -- The two photons search can exclude a FB Higgs.

Thank you

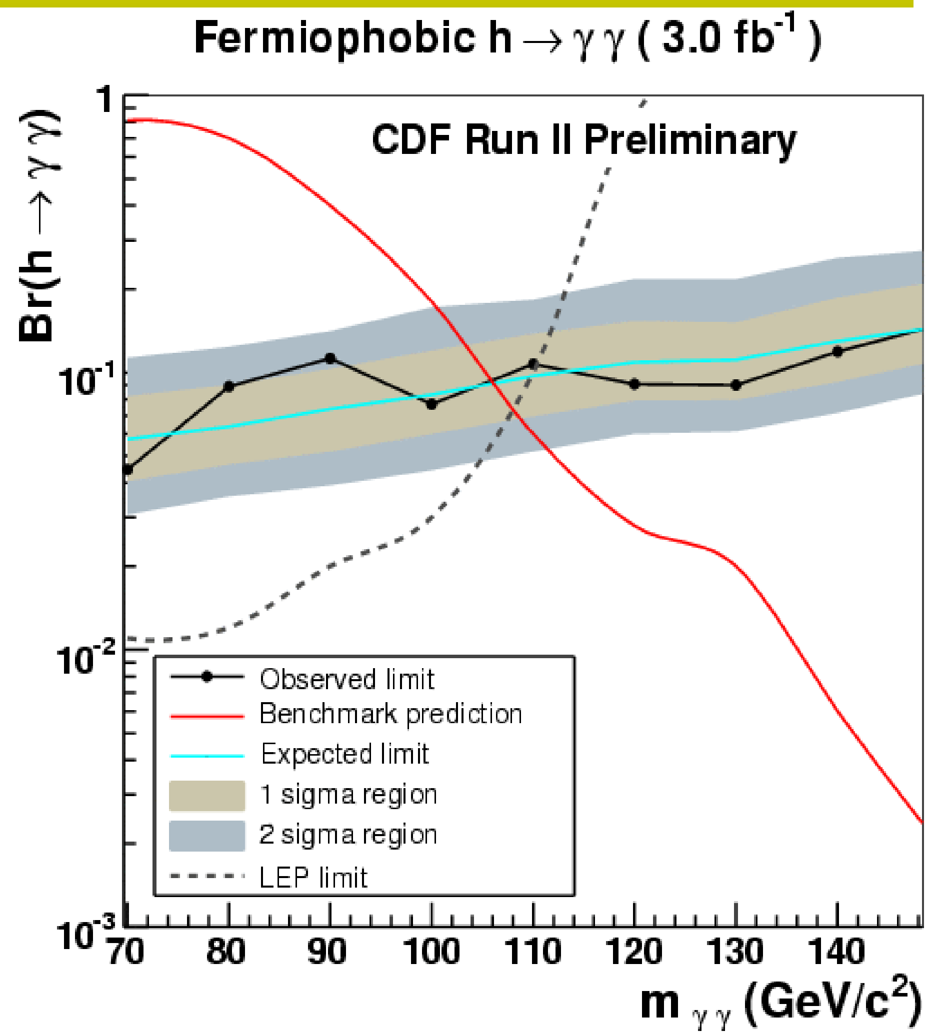
Fermiophobic Higgs limit (2/5)

- Form D0 and CDF:

$m_{h_f} > 78.5\text{GeV}$ *and* 82GeV

$$p\bar{p} \to hV \to \gamma\gamma + X$$

$$p\bar{p} \to VV \to h \to \gamma\gamma + X$$



A lower m_h bound of 100 GeV

Fermiophobic Higgs limit (1/5)

- Form LEP:

$$e^+e^- \to h_f Z \quad \text{with} \quad h_f \to \gamma\gamma$$

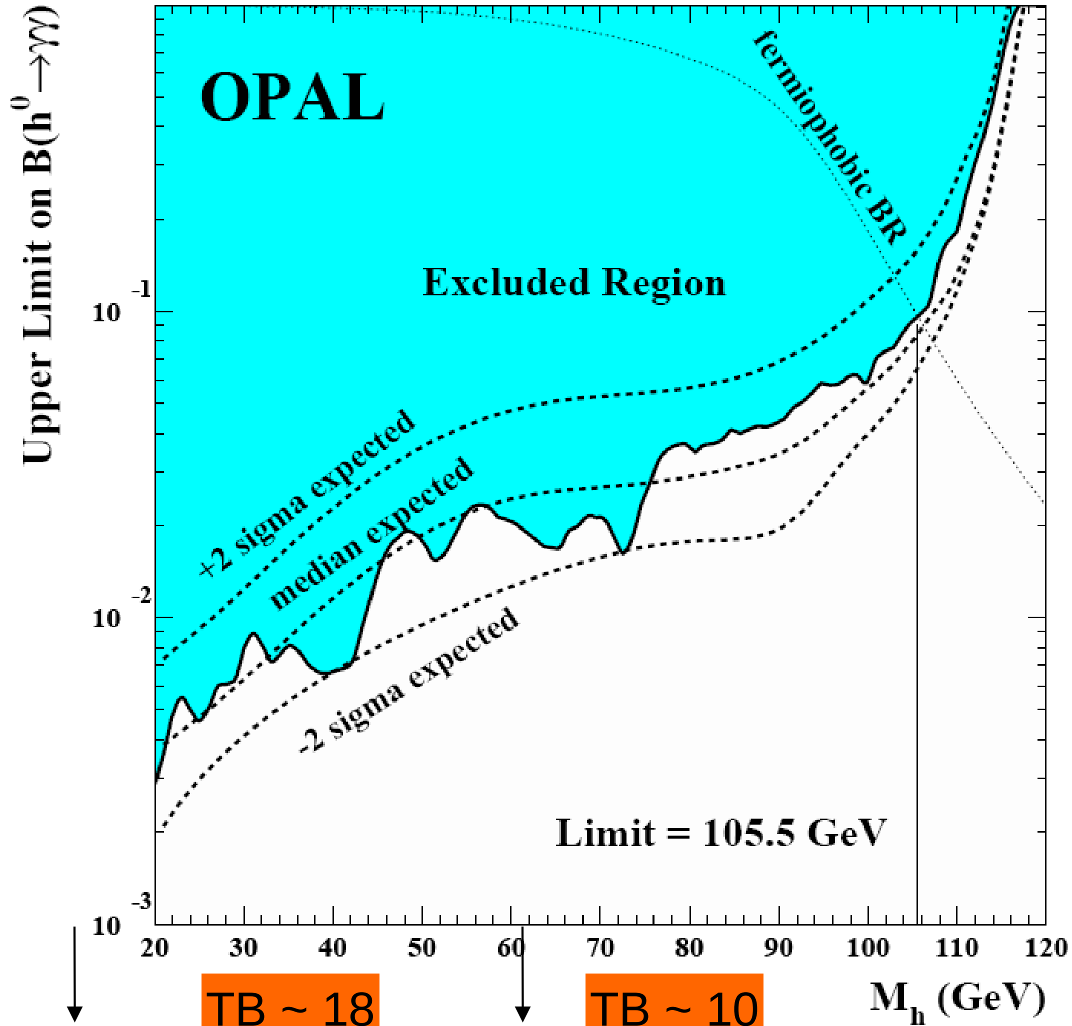
Much higher TB would violate
th Perturbativity cons.

$$e^+e^- \to h_f A^0$$

$$m_{h_f} + m_{A^0} < 160GeV$$

ZZh is suppressed for large TB
and ZZH is the SM-like

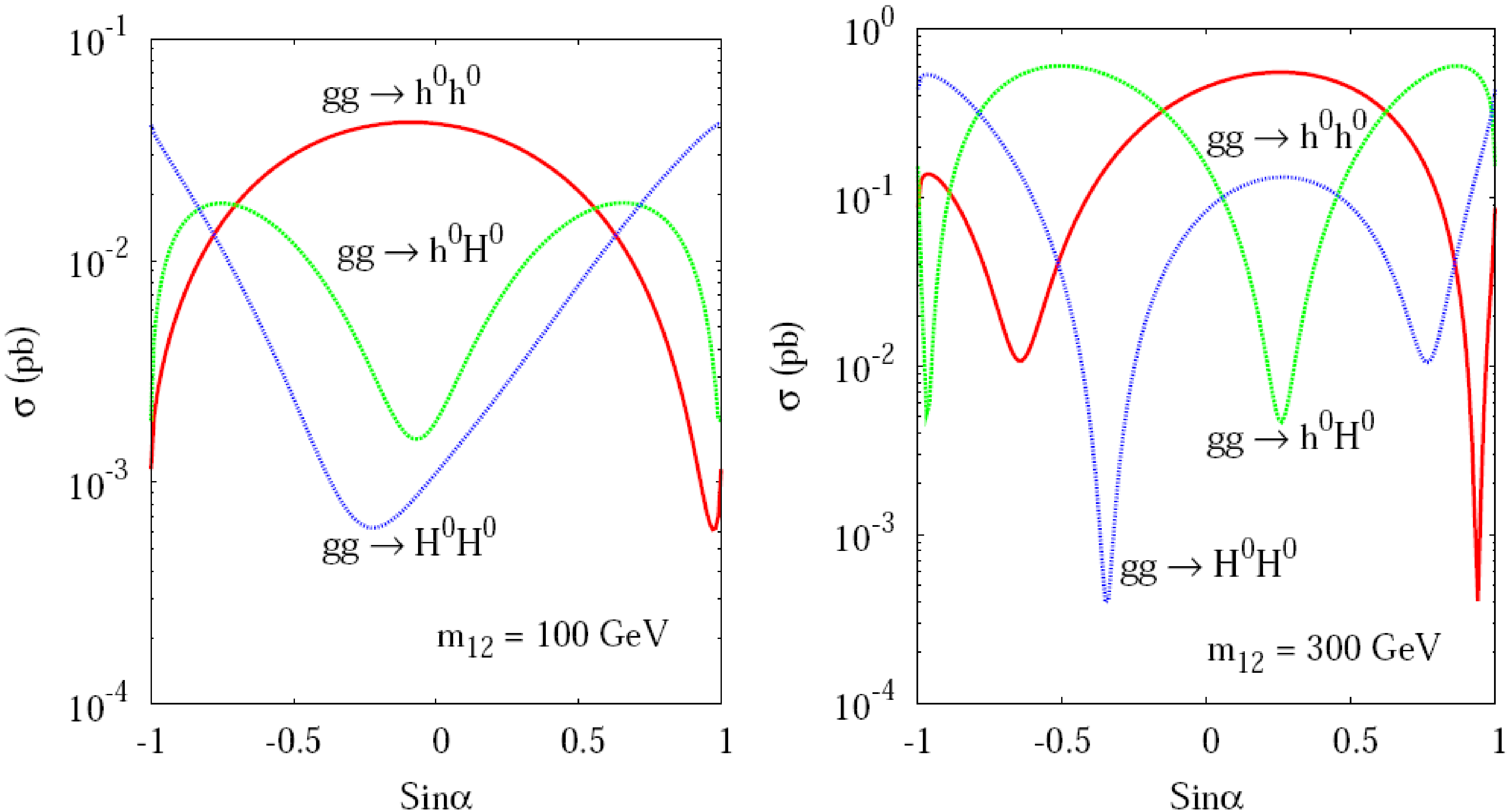
$$m_{h_f} > 100GeV$$



TB ~ 18

TB ~ 10

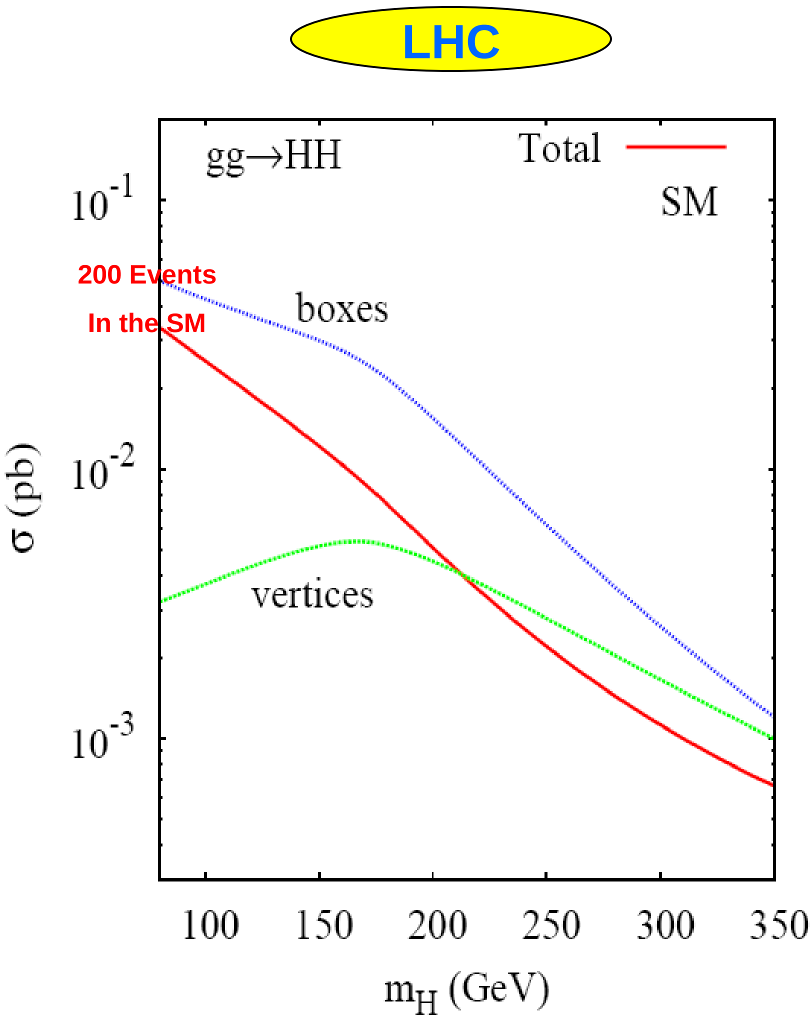
General 2HDM

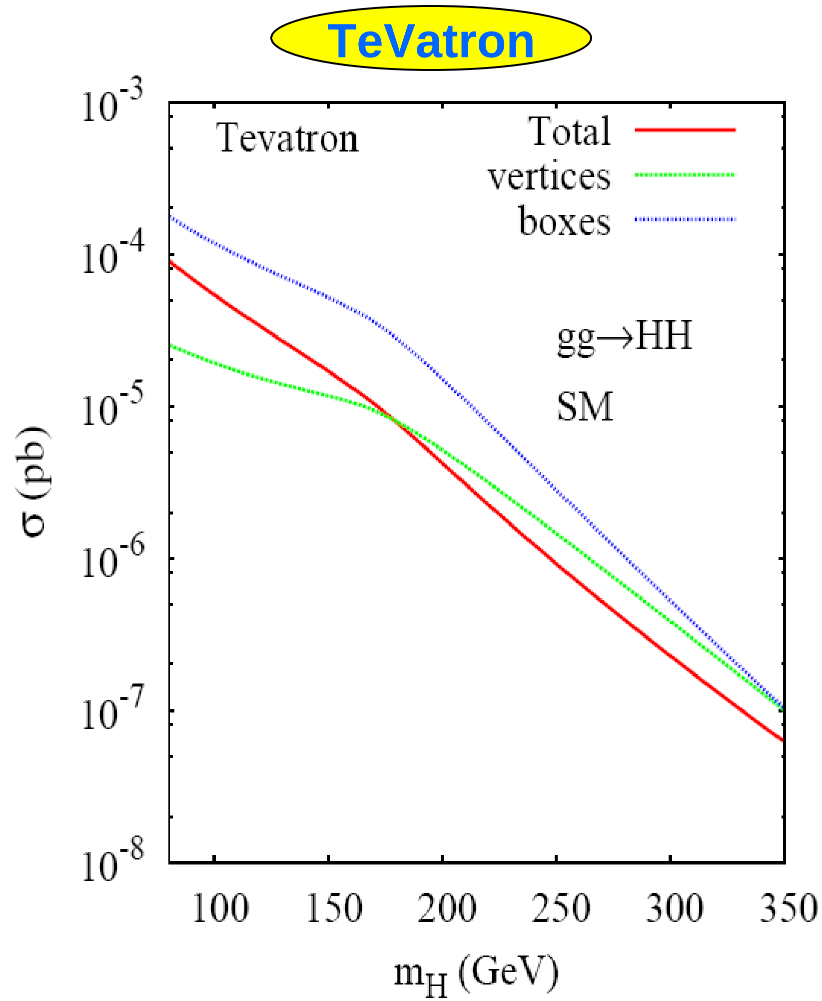


$$m_{H^0} = 200\, GeV$$

$$m_{A^0} = 320\, GeV,\ m_{H^\pm} = 380\, GeV, \qquad \tan\beta = 2.$$

In the SM…pairs production ?

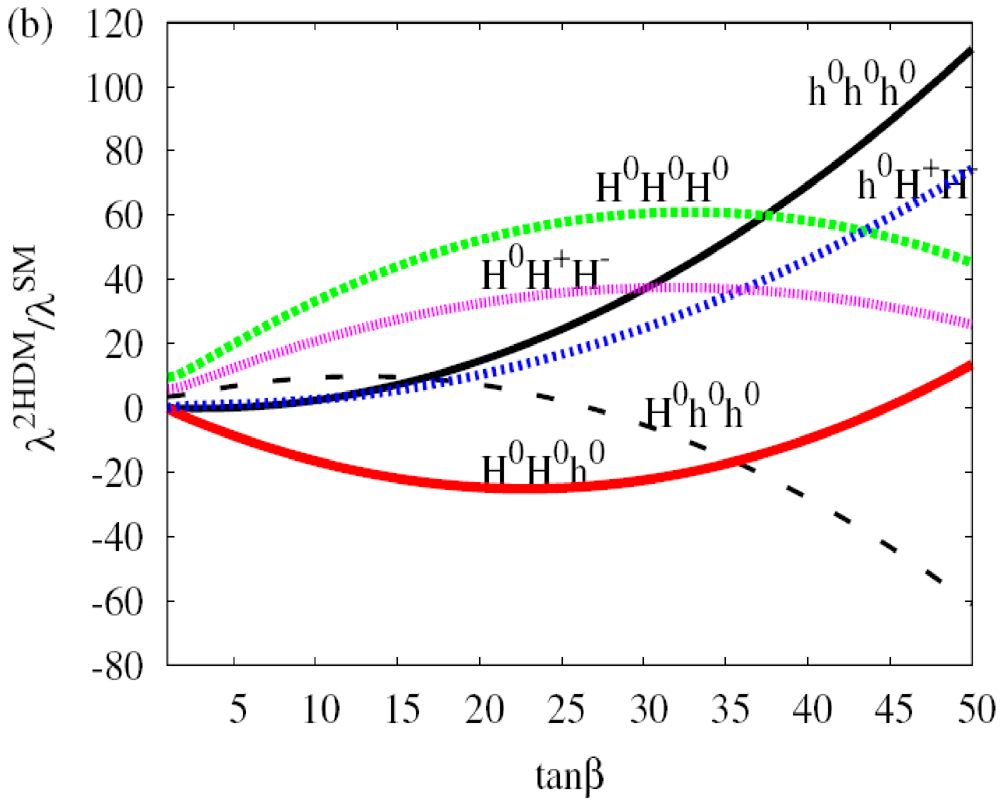




Triple Higgs couplings

A.Arhrib, R.Benbrik and Cheng-Wei Chiang PRD2008.

- The 2HDM tree-level self couplings



All the triple Higgs couplings are enhanced in the large tan beta limit by more than 50 times larger than the SM triple coupling.

Conclusions

- In this work we have shown that there are alternative channels to search for FB Higgs with a multi-photon signature.

- LEP has set a strong limit of $\tan\beta$ or all values of the FB Higgs masses up to 100 GeV.

- $gg \to hh$ does not depend on $\tan\beta$

  $gg \to hA$ $\tan\beta = 10$

  } Will be large

  $gg \to hH$ → Will be negligible

- Dependence with λ_5

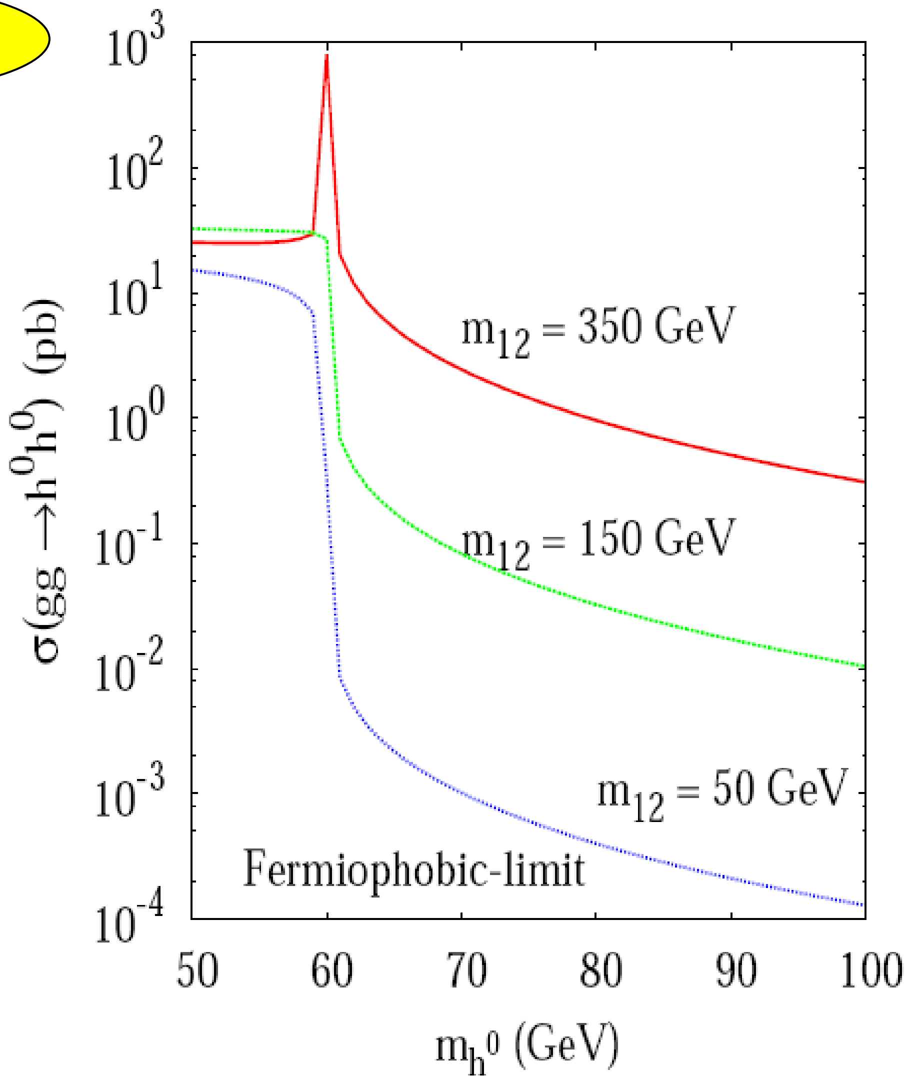
- In vast region of the parameter space of the FB Higgs can be probed at the LHC as well as Tevatron

Fermiophobic Higgs limit (4/5)

LHC

width effect on the cross section

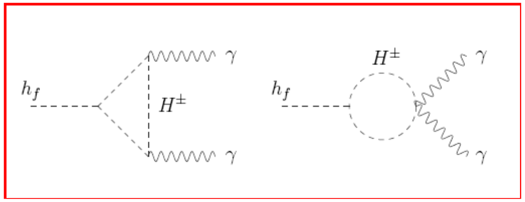
$$H^0 \rightarrow h^0 h^0$$

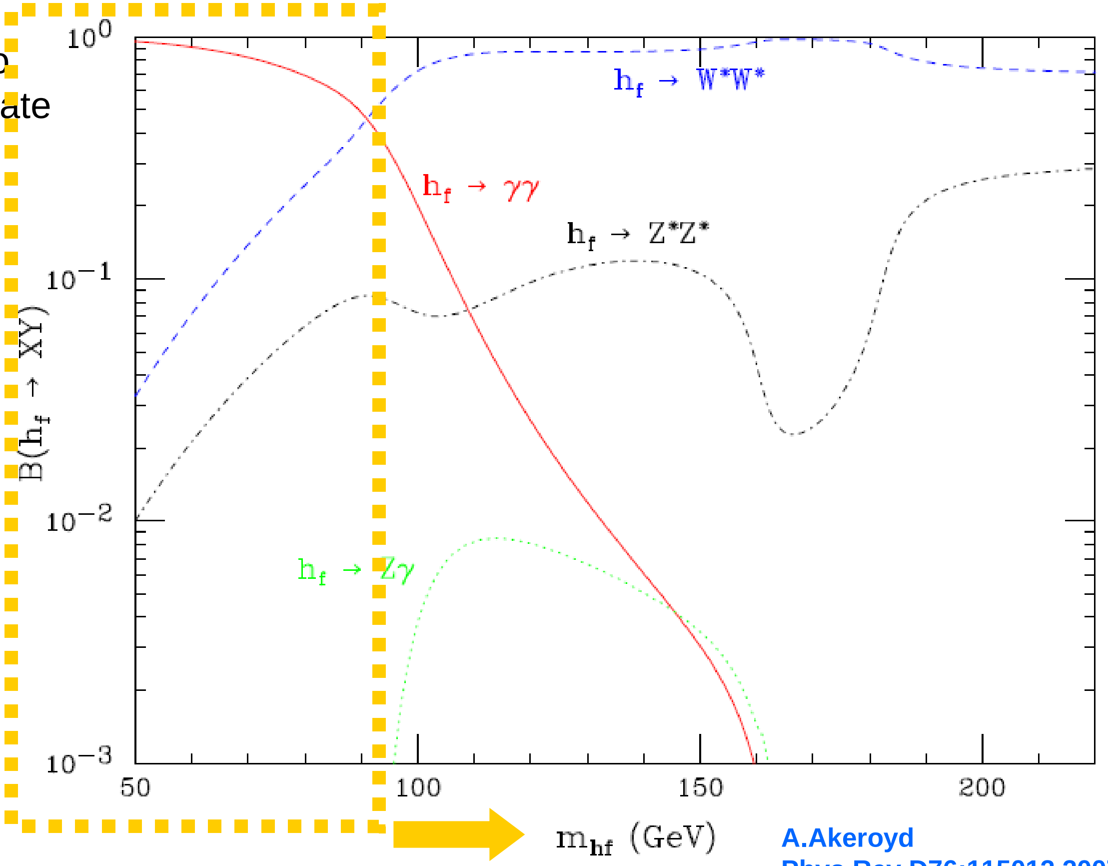


Higgs signatures

- Experimental signatures for the Fb Higgs h and for A

✓ For small Mh the main decay is to 2photons until the WW starts to dominate





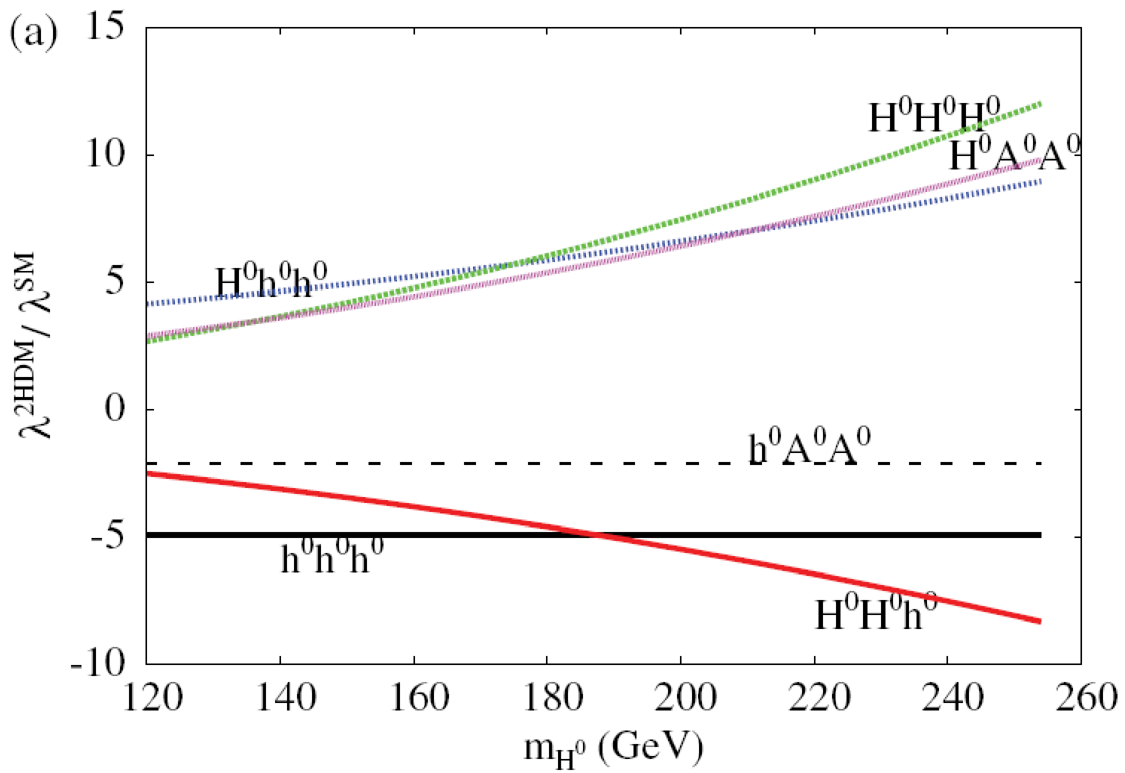
A.Akeroyd
Phys.Rev.D76:115012,2007.

Charged Higgs

Triple Higgs couplings

A.Arhrib, R.Benbrik and Cheng-Wei Chiang
Phys.Rev.D77:115013,2008.

- The 2HDM tree-level self couplings



hAA and hhh have no MH dependence, for the other couplings the variation over MH can change the size by about 1 order of magnitude

$$\lambda^{2HDM}_{h^0h^0h^0} = \frac{-3e}{m_W s_W s^2_{2\beta}}\left[(c_\beta c^3_\alpha - s_\beta s^3_\alpha)s_{2\beta}m^2_{h^0} - c^2_{\beta-\alpha}c_{\beta+\alpha}m^2_{12}\right]$$

$$\lambda^{2HDM}_{H^0H^0H^0} = \frac{-3e}{m_W s_W s^2_{2\beta}}\left[(c_\beta c^3_\alpha - s_\beta s^3_\alpha)s_{2\beta}m^2_{H^0} - s^2_{\beta-\alpha}s_{\beta+\alpha}m^2_{12}\right]$$

$$\lambda^{2HDM}_{H^0h^0h^0} = -\frac{1}{2}\frac{ec_{\beta-\alpha}}{m_W s_W s^2_{2\beta}}\left[(2m^2_{h^0} + m^2_{H^0})s_{2\alpha}s_{2\beta} - (3s_{2\alpha} - s_{2\beta})m^2_{12}\right]$$

$$\lambda^{2HDM}_{H^0H^0h^0} = \frac{1}{2}\frac{es_{\beta-\alpha}}{m_W s_W s^2_{2\beta}}\left[(m^2_{h^0} + 2m^2_{H^0})s_{2\alpha}s_{2\beta} - (3s_{2\alpha} + s_{2\beta})m^2_{12}\right]$$

$$\lambda^{SM}_{h^0h^0h^0} = \frac{-3em^2_{h^0}}{2m_W s_W}$$

Higgs signatures

Triangle topologies in SM and in MSSM

$$gg \to H^0 \to h^0 h^0.$$

In SM

$$gg \to h^0 \to h^0 h^0$$

$$h^0 h^0 \to 2b2\bar{b},\ b\bar{b}\tau^+\tau^-$$

U. Baur, T. Plehn , David L. Rainwater PRD68(2003)

U. J. Dai, J.F. Gunion, R. Vega PLB371 (1996)

$$h^0 h^0 \to b\bar{b}\gamma\gamma$$

U. Baur, T. Plehn , David L. Rainwater PRD69(2004)

Higgs signatures (type-I)

Triangle topologies in SM and in MSSM

$$gg \to H^0 \to h^0 h^0.$$

In SM

$$gg \to h^0 \to h^0 h^0$$

$$h^0 h^0 \to 2b2\bar{b},\ b\bar{b}\tau^+\tau^-$$

U. Baur, T. Plehn , David L. Rainwater PRD68(2003)

U. J. Dai, J.F. Gunion, R. Vega PLB371 (1996)

$$h^0 h^0 \to b\bar{b}\gamma\gamma$$

U. Baur, T. Plehn , David L. Rainwater PRD69(2004)

We will present the profile of the light Higgs boson in all four Yukawa type models....

We are here

Where is Morocco ?

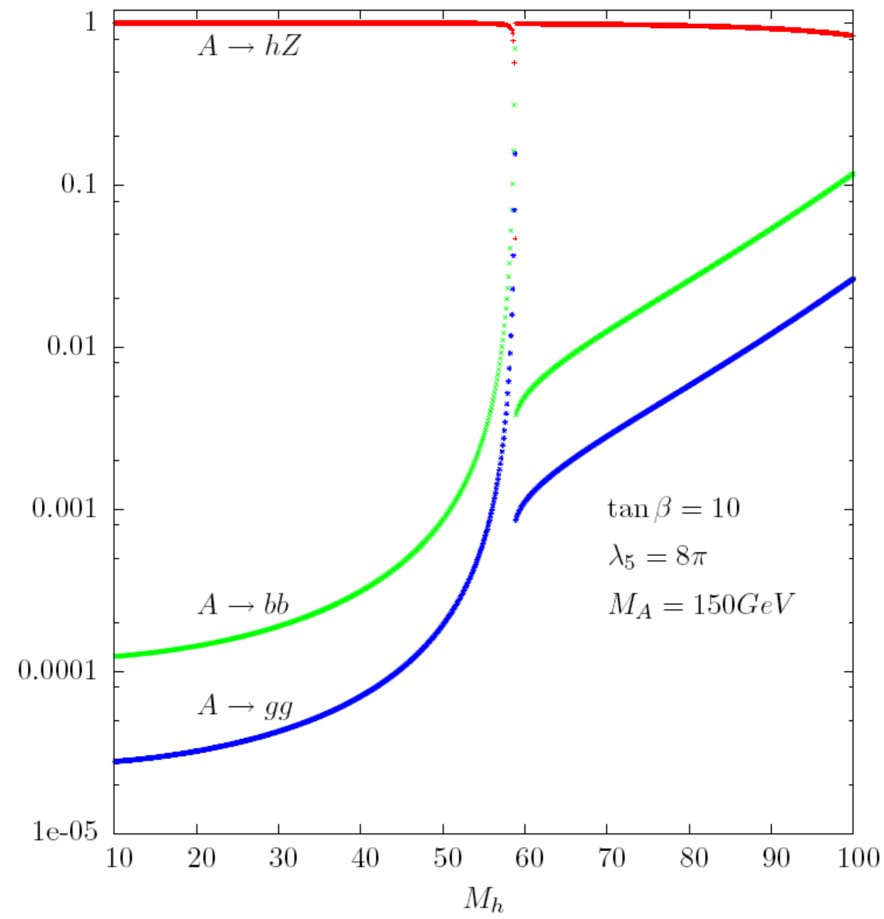
Fermiophobic Higgs limit (6/6)

- Experimental signatures for the Fb Higgs h and for A

if the decay $A \to H^{\mp}W^{\pm}$ is kinematically forbidden.

$$Br(A \to hZ) \approx 100\%$$

$$gg \to hA \to hhZ \to 4\gamma + X.$$



Fermiophobic Higgs limit (6/6)

- Experimental signatures for the Fb Higgs h and for A

- ✓ Branching ratios depend mainly with

$\lambda_5 \quad \tan\beta \quad M_h$

- ✓ For 10 GeV < M_h < 100 GeV

$$Br(h \to \gamma\gamma) \approx 100\%$$

and decreases with Mh

$$\lambda_5 = 0$$

$$\lambda^{FL}_{hH^\pm H^\mp} = \frac{e}{2 m_W s_W \sin 2\beta}\left[2\sin^3\beta m_h^2 - \lambda_5 v^2 \sin\beta - 2\sin 2\beta \cos\beta m^2_{H^\pm}\right]$$

$$gg \to hh \to 4\gamma$$

$$gg \to hH \to hhh \to 6\gamma$$