Double Higgs production in the CP conserving Two Higgs Doublet Model

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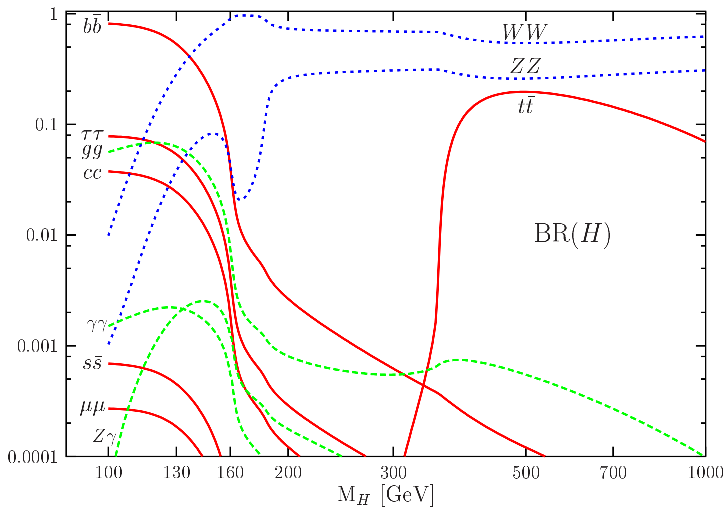
Outline

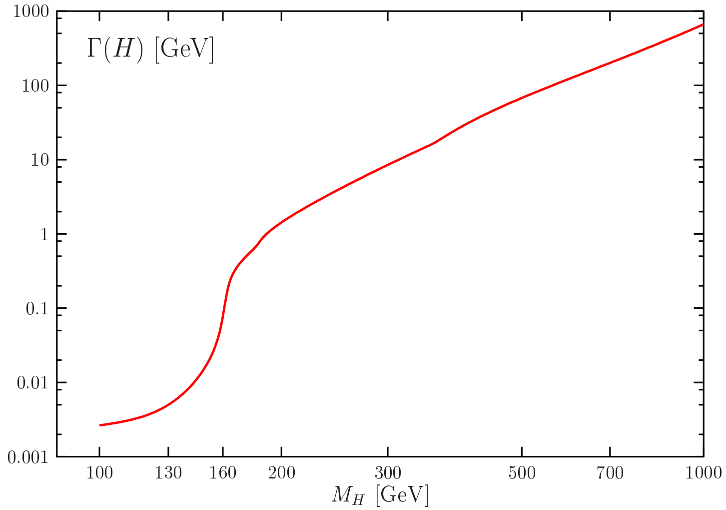
- Higgs production and decays in SM
- Two Higgs Doublets Models (2HDM) and its Decoupling regime
- Triple Higgs coupling from $h^0 \to \gamma\gamma$, $h^0 \to b\bar{b}$
- Triple Higgs couplings from double Higgs production at LHC, ILC and $\gamma\gamma$
- Conclusions

Higgs in SM

- Best fit analysis: $M_H = 84^{+34}_{-26}$ GeV which gives $M_H \lesssim 154$ GeV at 95% CL. (LEP Higgs Working Group).
- LEPII Experiments: $M_H > 114.4$ GeV (LEP), Tevatron exclude $160 \lesssim M_H \lesssim 170$ GeV from $H \to WW$ (S. M. Wang Talk).
- Unitarity constraint: $M_H \lesssim 700$ GeV
- Requiring the SM to be extended up to $\Lambda_{GUT} = 10^{16}$ GeV, one can get $130 \lesssim M_H \lesssim 180$ GeV.
- If the $M_H \gtrsim 200$ GeV, then there should be an additional new ingredient that is relevant at the EWSB scale.

Higgs decays





- At hadron colliders (LHC, Tevatron) the relevant processes are:

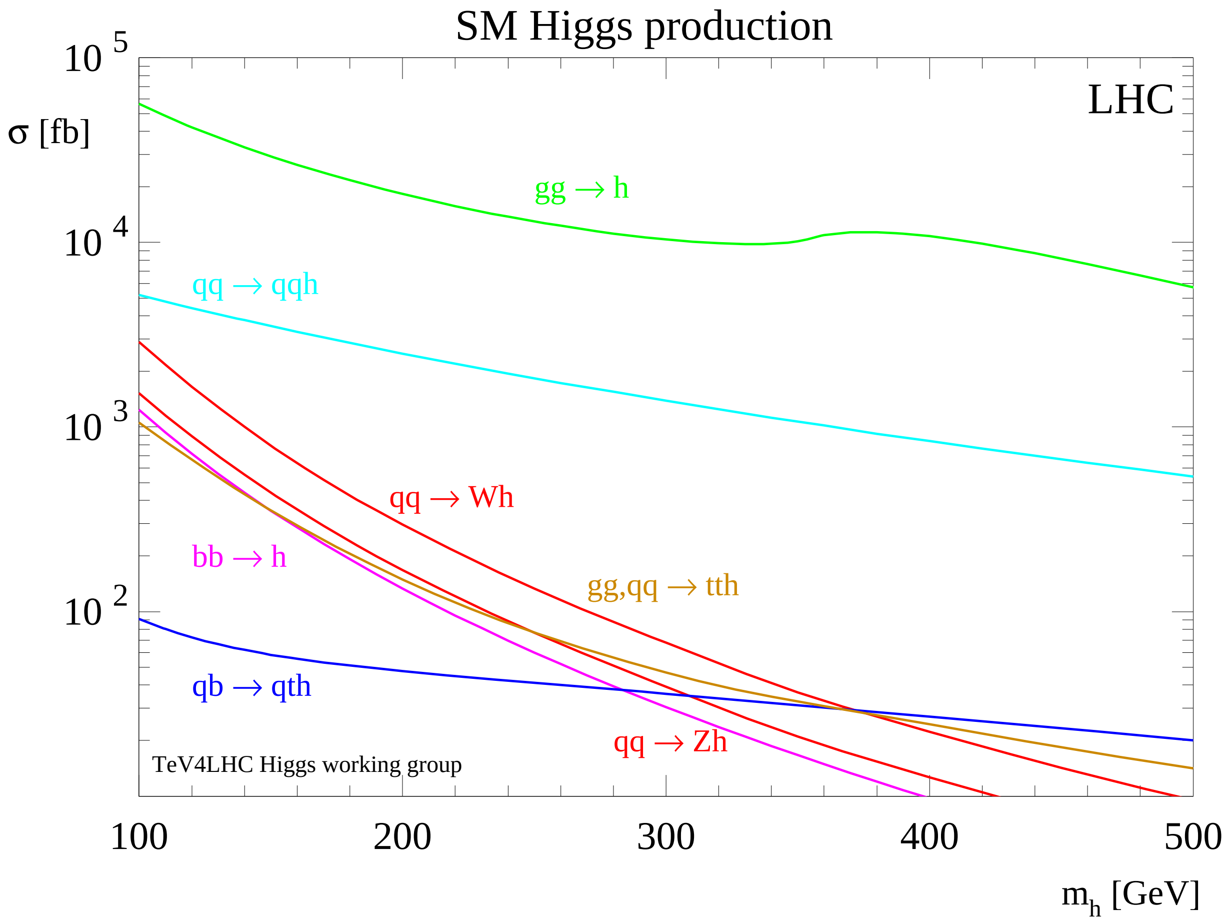
$$gg \to h_{SM} \to \gamma\gamma \quad , \quad gg \to h_{SM} \to VV^*$$

$$qq \to qqV^*V^* \to qqh_{SM} \quad , h_{SM} \to \gamma\gamma, \tau^+\tau^-, VV^*$$

$$gg, qq \to t\bar{t}h_{SM} \quad , \quad h_{SM} \to b\bar{b}, WW^*, WW^*$$

$$qq \to h_{SM}Z \; , \; qq' \to h_{SM}W \quad , \quad h_{SM} \to b\bar{b} (\text{Tevatron})$$

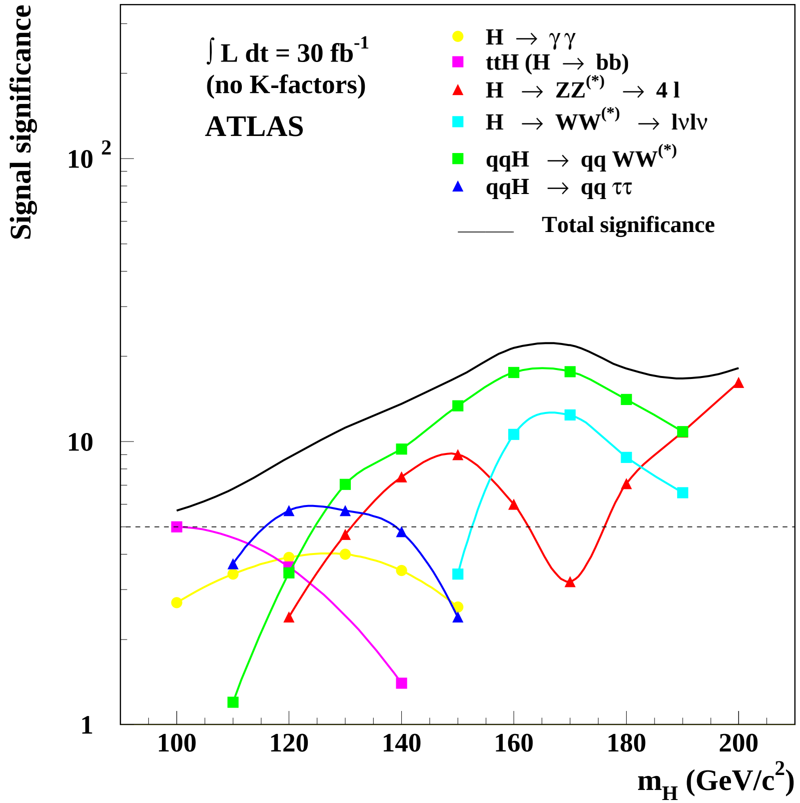
$$gg \to h_{SM}h_{SM} (\text{double Higgs production})$$

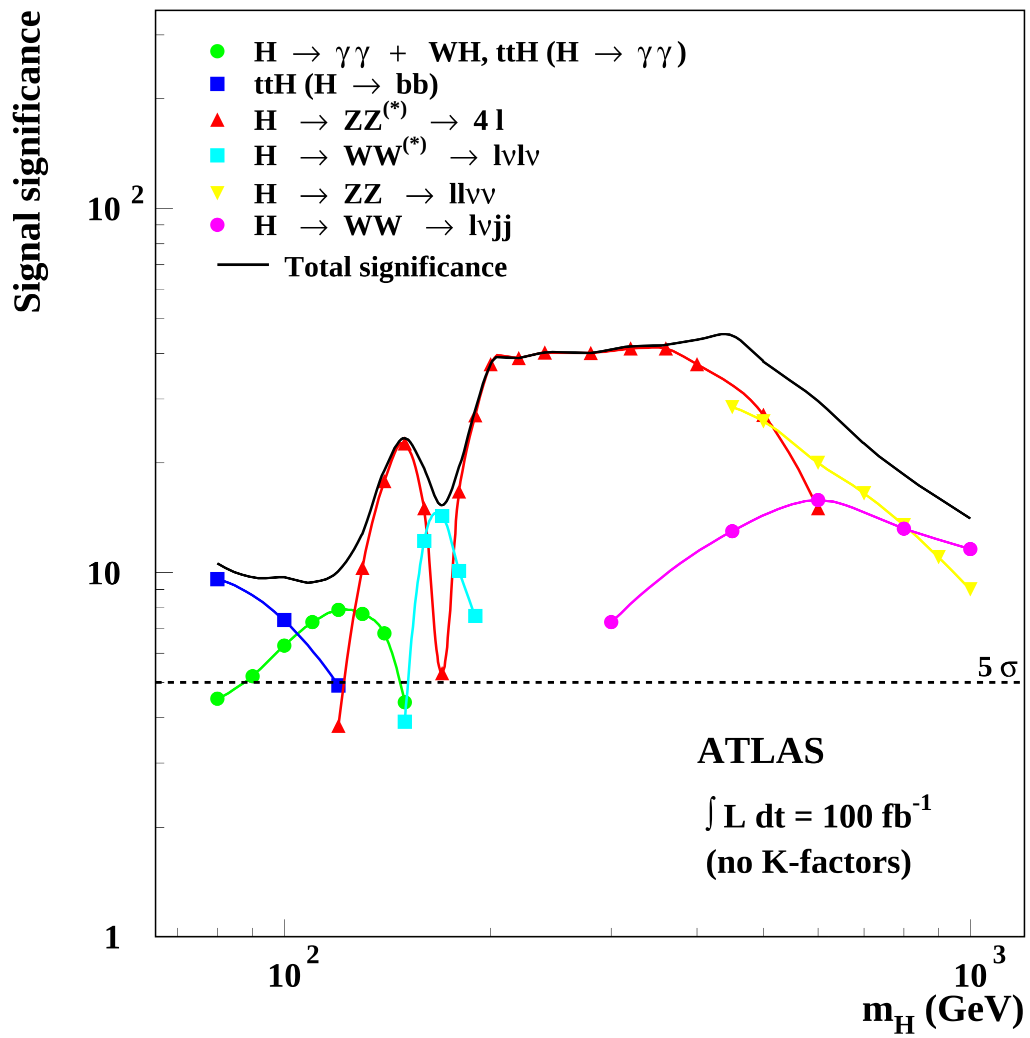


SM Higgs production
LHC
σ [fb]
10^5
10^4
10^3
10^2
gg → h
qq → qqh
qq → Wh
bb → h
gg,qq → tth
qb → qth
qq → Zh
TeV4LHC Higgs working group
100
200
300
400
500
m_h [GeV]

Significance for the experimental detection

Low luminosity





Signal significance
H → γγ + WH, ttH (H → γγ)
ttH (H → bb)
H → ZZ(*) → 4 l
H → WW(*) → lνlν
H → ZZ → llνν
H → WW → lνjj
Total significance
5 σ
ATLAS
∫ L dt = 100 fb-1
(no K-factors)
10 2
10
1
10 2
10 3
mH (GeV)

Extended Higgs sector

- With Extended Higgs sector: 2HDM Φ_1 , Φ_2, CP can be violated either explicitly or spontaneously in Higgs sector T.D.Lee'73
- Some models of dynamical electroweak symmetry breaking yields the 2HDM as their low-energy effective theory. [H. J. He et al, PRD**65**, (2002) hep-ph/0108041].
- Models for phase transition requires 2 Higgs doublets
- Neutrino masses, Dark Matter, BAU
  Zee'80, Ma'06, S. Kanemura and C.S Chen talks

Coupling to fermions

- both Φ_1 and Φ_2 couple to fermions: $M_q = Y^u v_1 + Y^d v_2$: diagonalisation of M_q does not diagonalise similtanousely $Y^{u,d}$: FCNC at tree level: 2HDM-III
- 2HDM-I One doublet couple to gauge boson and the other one couple to fermion (like in SM).
- To avoid FCNC at tree level, We impose Z_2 symmetry (Weinberg Theorem): $\Phi_2 \to -\Phi_2$, $d_{iR} \to -d_{iR}$: 2HDM-II
- 2HDM-X or lepton-specific 2HDM (or Leptophilic Higgs): one doublet generates the masses of the charged leptons and the second one generates the masses of the quarks
  Barnet, Senjanovic, Wolfenstein and Wyler'84, S.Su et al, H.Logan et al, M. Aoki et al'09

$$\begin{aligned} V &= \mu_1^2(\Phi_1^+\Phi_1) + \mu_2^2(\Phi_2^+\Phi_2) + \lambda_1(\Phi_1^+\Phi_1)^2 + \\ & \lambda_2(\Phi_2^+\Phi_2)^2 + \lambda_3(\Phi_1^+\Phi_1)(\Phi_2^+\Phi_2) + \lambda_4|\Phi_1^+\Phi_2|^2 \\ & +\{m_{12}^2(\Phi_1^+\Phi_2) + h.c\} + [\lambda_5(\Phi_1^+\Phi_2)^2 + h.c] \end{aligned}$$

- One can have: Explicit $\not{C}$P if $\Im(m_{12}^4\lambda_5^*) \neq 0$;
- One can have Spontaneous $\not{C}$P if: $|\frac{m_{12}^2}{\lambda_5 v_1 v_2}| < 1$; $< \Phi_1 >= v_1$, $< \Phi_2 >= v_2 e^{i\theta}$
- Five physical scalars (8 d.o.f=5+3): a charged Higgs pair $H^\pm$, two CP-even h^0, H^0 and one CP-odd A^0
- m_A, m_h, m_H, $m_{H\pm}$, α, $\tan\beta = v_1/v_2$ and m_{12}^2 free parameters.

Theoretical constraints:

- $b \to s\gamma$: $m_{H^\pm} > 295$ GeV, $\forall \tan\beta$ in 2HDM-II. No such bound in 2HDM-I [P.Gambino et al, '01,F.Borzumati et al '98].
  In 2HDM-X, light $H^\pm$ is allowed Aoki et al, Logan et al'09
- $\delta\rho \le 10^{-3}$ [(PDG)]: constrain the splitting M_A and $M_{H^\pm}$
- Perturbativity on λ_i: $|\lambda_i| \le 8\pi$
- Potential bounded from bellow: $\lambda_{1,2} > 0$, $\sqrt{\lambda_1\lambda_2} \ge \lambda_3 + \lambda_4 + \lambda_5$
- Unitarity constraints: in 2HDM there is 14 constraints coming from different channel:W^+W^-, ZZ, hh, HH, hH, AA, hA, H^+H^-, hH^+... [S. Kanemura et al '98, A.Akeroyd et al '00]

The decoupling limit of 2HDM

- $\cos(\alpha-\beta) \to 0$ and $m_\Phi = m_{H,H^\pm,A} >> m_Z$:
- The effective theory below M_Φ is described by one Higgs doublet.
- In this limit:

$$h^0VV/(h_{SM}VV) = \sin(\beta-\alpha) \to 1$$

$$h^0b\bar{b}/h_{SM}b\bar{b} = -\frac{\sin\alpha}{\cos\beta} \to 1 \ , \ (h^0\bar{t}t)/h_{SM}t\bar{t} = \frac{\cos\alpha}{\sin\beta} \to 1$$

$$H^0VV \propto \cos(\beta-\alpha) \to 0 \ , \ (hhh)/(hhh)_{SM} \to 1$$

$$h^0H^+H^-, h^0A^0A^0, h^0H^0H^0, H^\pm t\bar{b}... \neq 0$$

- In the decoupling regime, only one Higgs h may be produced. In this case, how to disentangle h from SM Higgs?

A program of precision measurements will begin at LHC and will reach maturity at the ILC :

$$\delta(\Gamma_W)/\Gamma_W \approx 5 - 10\% \ , \ \delta(\Gamma_\tau)/\Gamma_\tau = \delta(\Gamma_\gamma)/\Gamma_\gamma \approx 18\% \text{ at LHC}$$

At Linear Collider(ILC), the situation is much better:

Relative accuracies (in %) on M_H and couplings at ILC $\sqrt{s} = 500$ GeV and $\int \mathcal{L} = 500$ fb^{-1} [hep-ph 0106315]

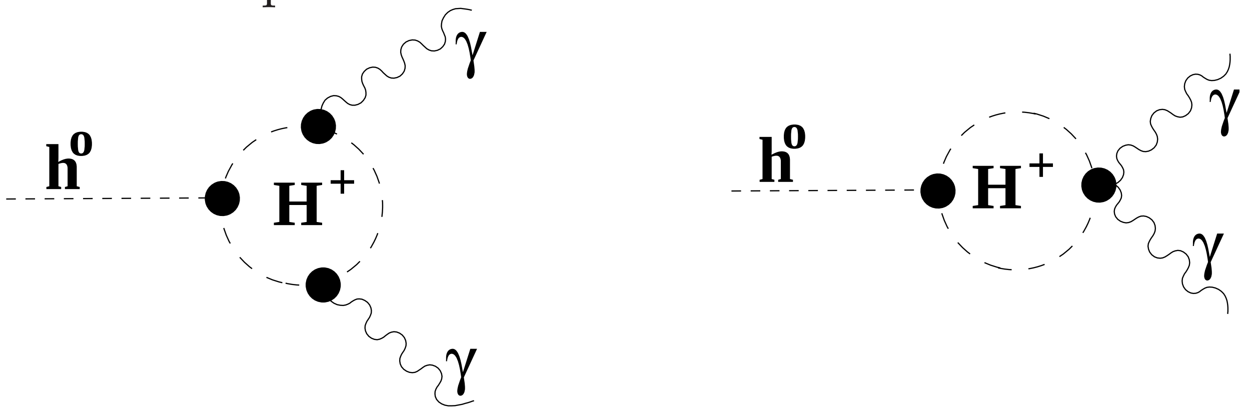
M_H	ΔM_H	g_{HWW}	g_{HZZ}	g_{Htt}	g_{Hbb}	$g_{H\tau\tau}$
120	± 0.033	± 1.2	± 1.2	± 3.0	± 2.2	± 3.3

In $\gamma\gamma$ option of ILC: $\delta\Gamma(H \to \gamma\gamma)/\Gamma(H \to \gamma\gamma) \approx 2\%$ can be achieved (from $\gamma\gamma \to H \to b\bar{b}$).

Non decoupling effects in Higgs decays

A.A, W.Hollik and S.Penaranda PLB'04

- $h^0 \to \gamma\gamma$ is loop-mediated processes since the photon does not couple to neutral particles

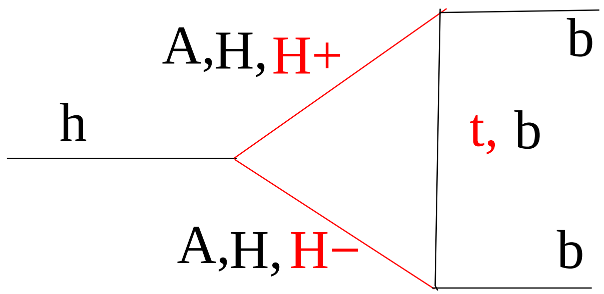


- The only pure 2HDM contribution comes from charged Higgs loops (if $\alpha = \beta - \pi/2$): $h^0 t\bar{t} \approx \frac{c_\alpha}{s_\beta} \approx 1...$

$$g[h^0 H^+ H^-] \approx -\frac{g}{2M_W}\{M_{h^0}^2 + 2(M_{H^\pm}^2 - M_{12}^2)\}$$

The decoupling is achieved when $M_{12} \to \infty$

- $h_0 \to b\bar{b}$, already exists at the tree level because of the Higgs–b Yukawa interaction
- Pure 2HDM one-loop contributions not present in the SM case:



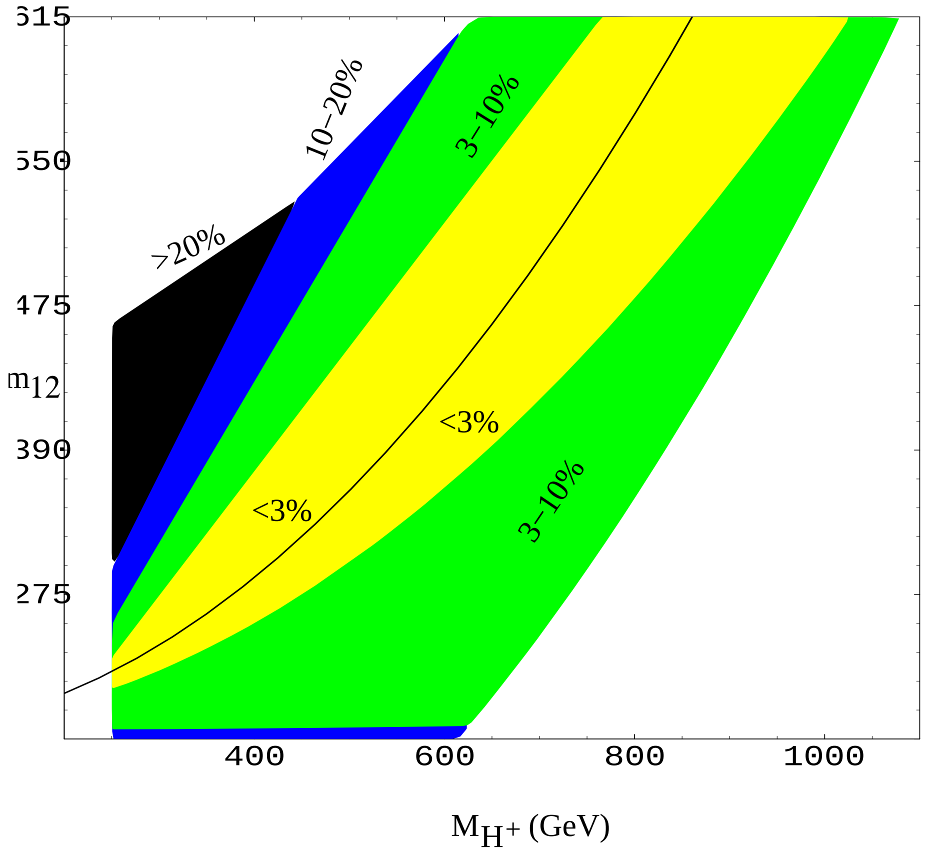
$\alpha \to \beta - \pi/2 \Rightarrow$ only $h^0 H^+ H^-$, $h^0 H^0 H^0$ and $h^0 A^0 A^0$ don't vanish or reduce to their SM values

$$g[h^0 H^+ H^-] \approx -\frac{g}{2M_W}\{M_{h^0}^2 + 2(M_{H^\pm}^2 - M_{12}^2)\}$$

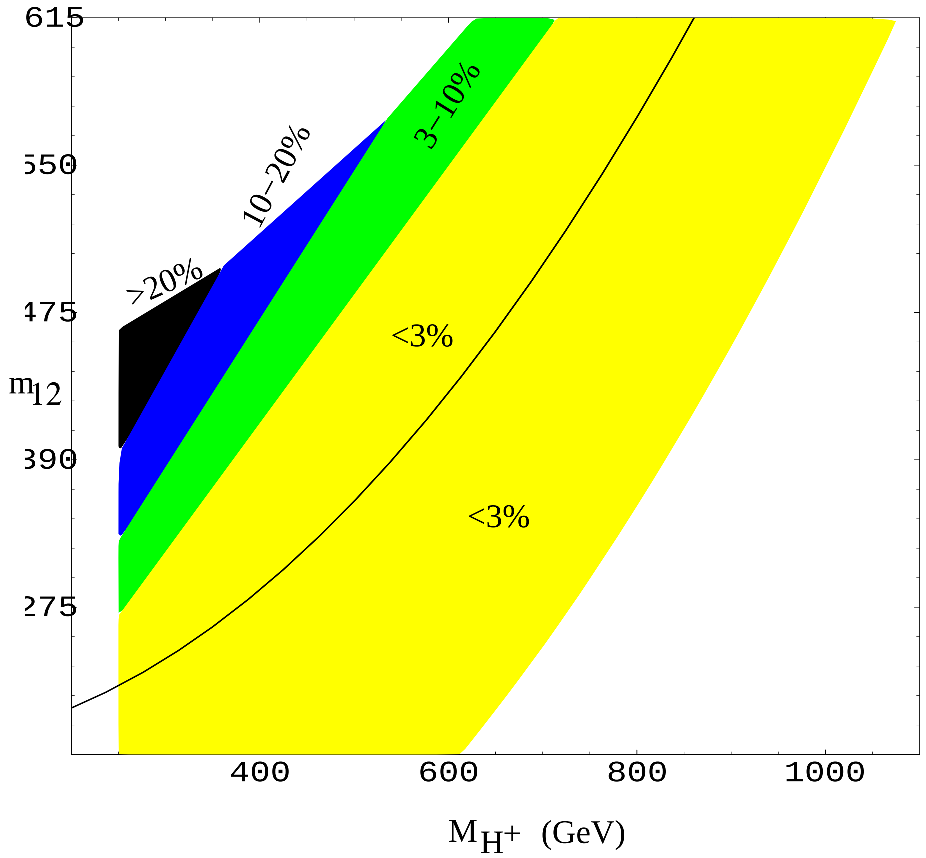
$$g[h^0 H^0 H^0] \approx -\frac{g}{2M_W}\{M_{h^0}^2 + 2(M_{H^0}^2 - M_{12}^2)\}$$

$$g[h^0 A^0 A^0] \approx -\frac{g}{2M_W}\{M_{h^0}^2 + 2(M_{A^0}^2 - M_{12}^2)\}$$

$$h^0 \to \gamma\gamma\text{:}\ \Delta_{\gamma\gamma} = \left|\frac{\Gamma(h\to\gamma\gamma)^{2HDM} - \Gamma(h\to\gamma\gamma)^{SM}}{\Gamma(h\to\gamma\gamma)^{SM}}\right|$$



$h \to b\bar{b}$: $\Delta_{bb} = \left|\frac{\Gamma(h\to bb)^{2HDM} - \Gamma(h\to bb)^{SM}}{\Gamma(h\to bb)^{SM}}\right|$

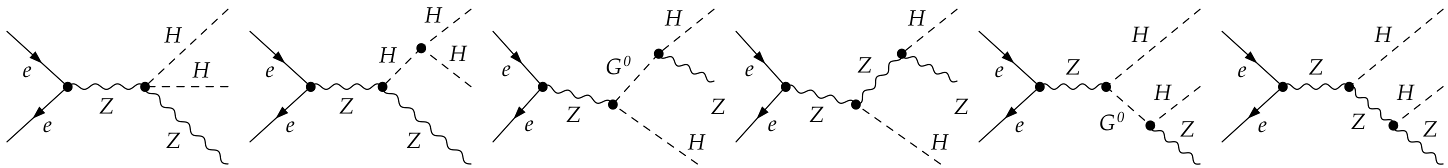


1. Probing triple Higgs couplings in the 2HDM at e^+e^- collider

A.A, R.Benbrik and C.W. Chiang'08

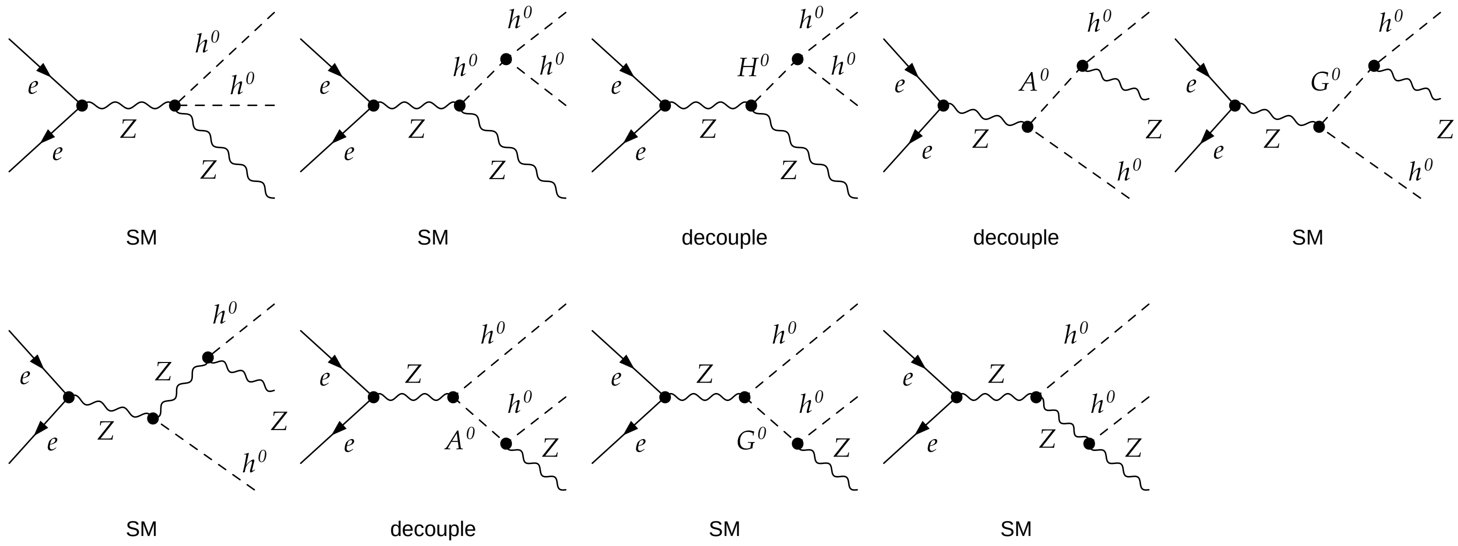
- If the Higgs exist, it will be produced either at Tevatron-II or LHC.
- In order to establish the Higgs mechanism, we need to measure the Higgs couplings to fermions, to gauge boson as well as the self-interaction of Higgs bosons.
- Complementarity of LHC/ILC [G. Weiglein et al, "Physics interplay of the LHC and the ILC," Phys. Rept'06, hep-ph/0410364]
- SM scalar potential can be reconstructed by measuring the triple coupling λ_{hhh} and quartic coupling λ_{hhhh}.
- One can access to λ_{hhh} at ILC from $e^+e^- \to Zhh$

$e^+e^- \to Zhh$ in SM



- In SM, $\sigma(e^+e^- \to Zhh)$ is rather small, for $\sqrt{s}, m_H = 500, 120$ GeV, $\sigma(e^+e^- \to Zhh) = 0.2$ fb
- possible to extract a signal from EW and QCD background $e^+e^- \to Zbb\bar{b}\bar{b}$ by simple kinematics cuts: e.g, invariant masses...
  Much more events are possible if: [D.Miller et al hep-ph/9906395]
  - Very high luminosity
  - Excellent b tagging
  - Beam polarization.

$e \; e \to h^0 \; h^0 \; Z$



In 2HDM we are sensitive to:

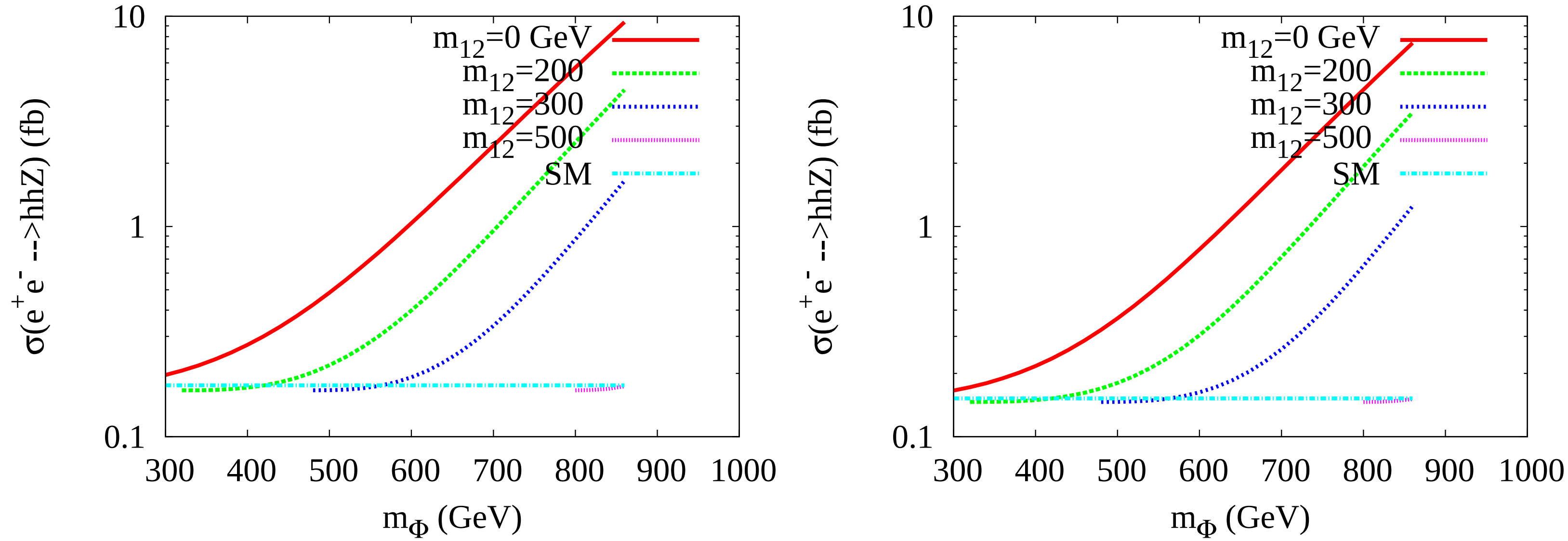
$$hhh = \frac{-3e}{m_W s_W s_{2\beta}^2}\left[(c_\beta c_\alpha^3 - s_\beta s_\alpha^3) s_{2\beta} m_{h^0}^2 - c_{\beta-\alpha}^2 c_{\beta+\alpha} m_{12}^2\right]$$

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

$e^+e^- \to Zhh$ in the decoupling limit: $m_\Phi = m_H = m_A = m_{H^\pm}$

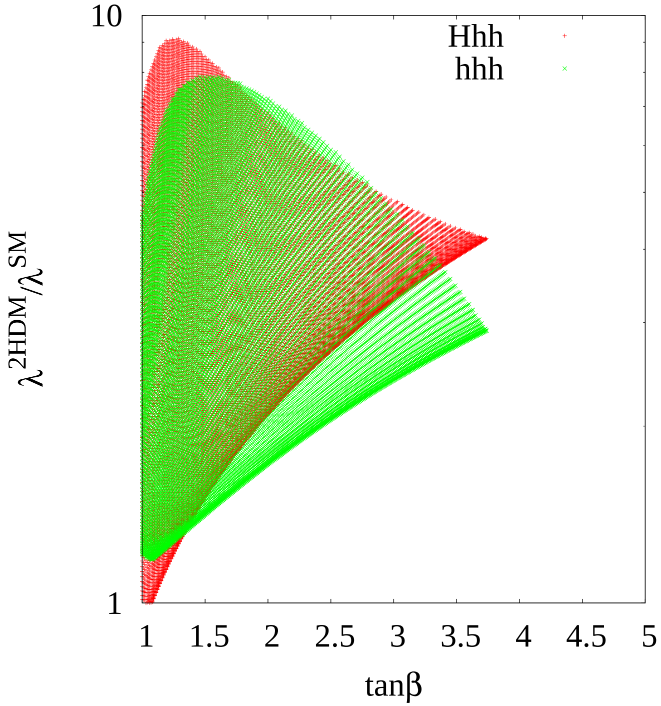
$$hhh_{eff} = \frac{3M_h^2}{v}\left\{1 + \frac{m_\Phi^4}{3\pi^2 m_h^2 v^2}\left(1 - \frac{m_{12}^2}{\sin^2\beta\cos^2\beta m_\Phi^2}\right)^3 - \frac{N_{c_t} m_t^4}{3\pi^2 m_h^2 v^2}\right\},$$

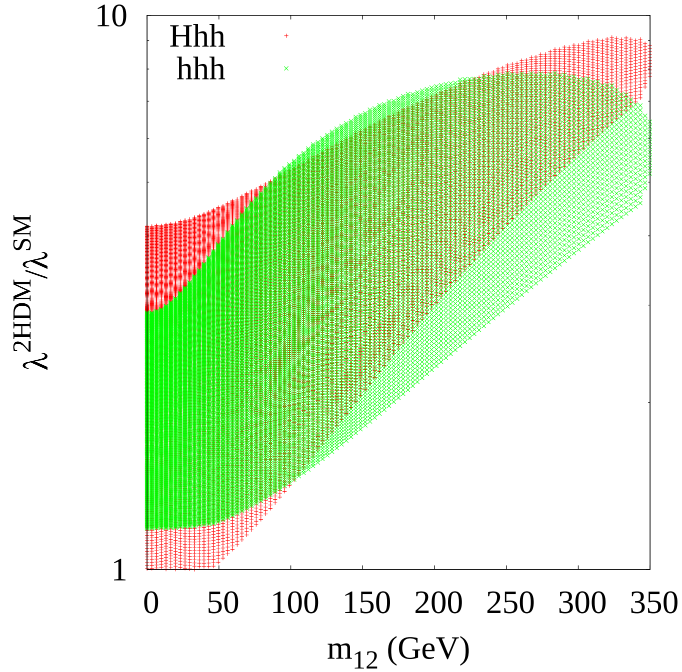
S.Kanemura, E.Senaha, Y.Okada, C.P.Yuan PLB'02



$m_h = 120$ GeV, $\sqrt{s} = 500$ GeV (left) and $\sqrt{s} = 800$ GeV (right).

Away from decoupling limit one can reach 100 fb for $Z\Phi_i\Phi_j$.





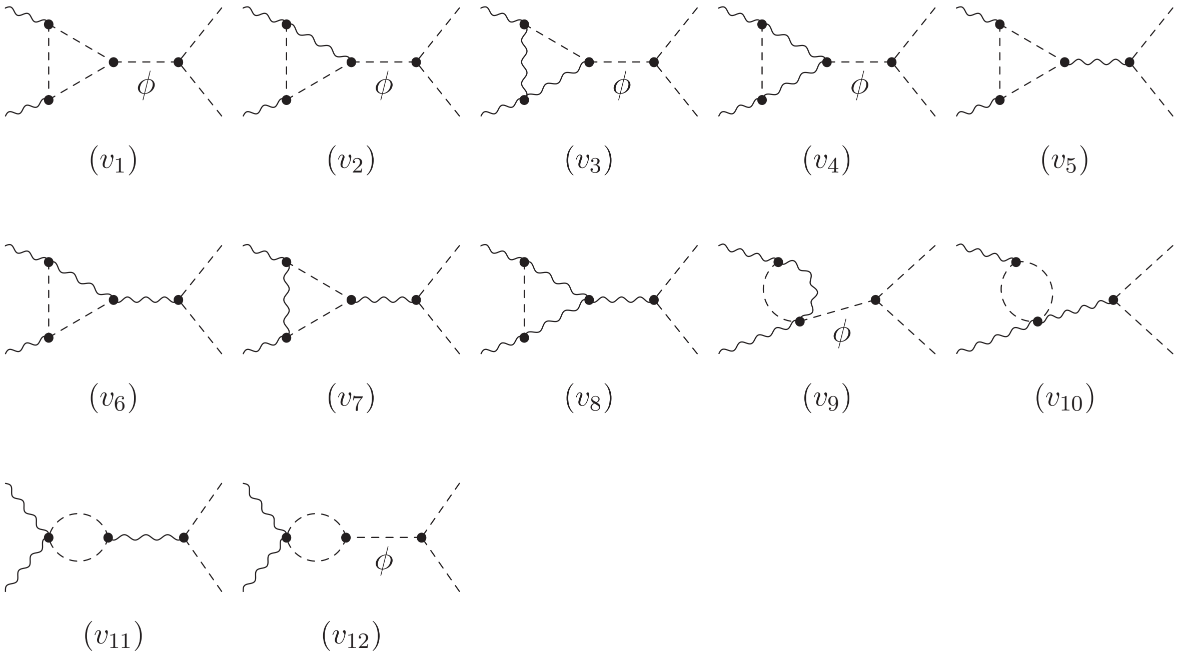
$m_h, M_H, M_A, M_{H\pm} = 120, 300, 350, 300$ GeV, $\sin\alpha = -0.9$,
$1 \lesssim \tan\beta \lesssim 10$, $m_{12} \in [0, 600]$ GeV

Probing triple Higgs couplings in the 2HDM at $\gamma\gamma$ collider

A.A, R.Benbrik and C.H.Chen and R.Santos'09

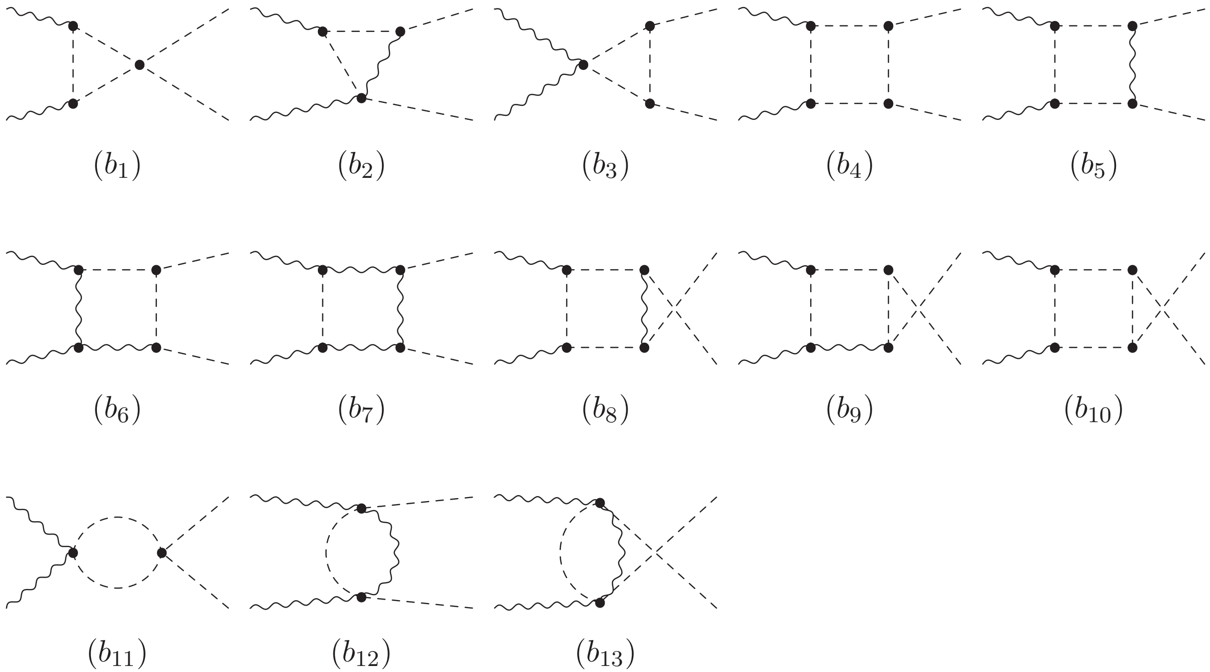
F.Cornet et al PLB'08, E. Asakawa et al PLB'08

- $\gamma\gamma \to hh$ is loop medited, then very sensitive to new physics.
- $\gamma\gamma \to hh$ has more phase space than $e^+e^- \to Zhh$



Just charged Higgs contribution are shown

In 2HDM, scalar loops dominate

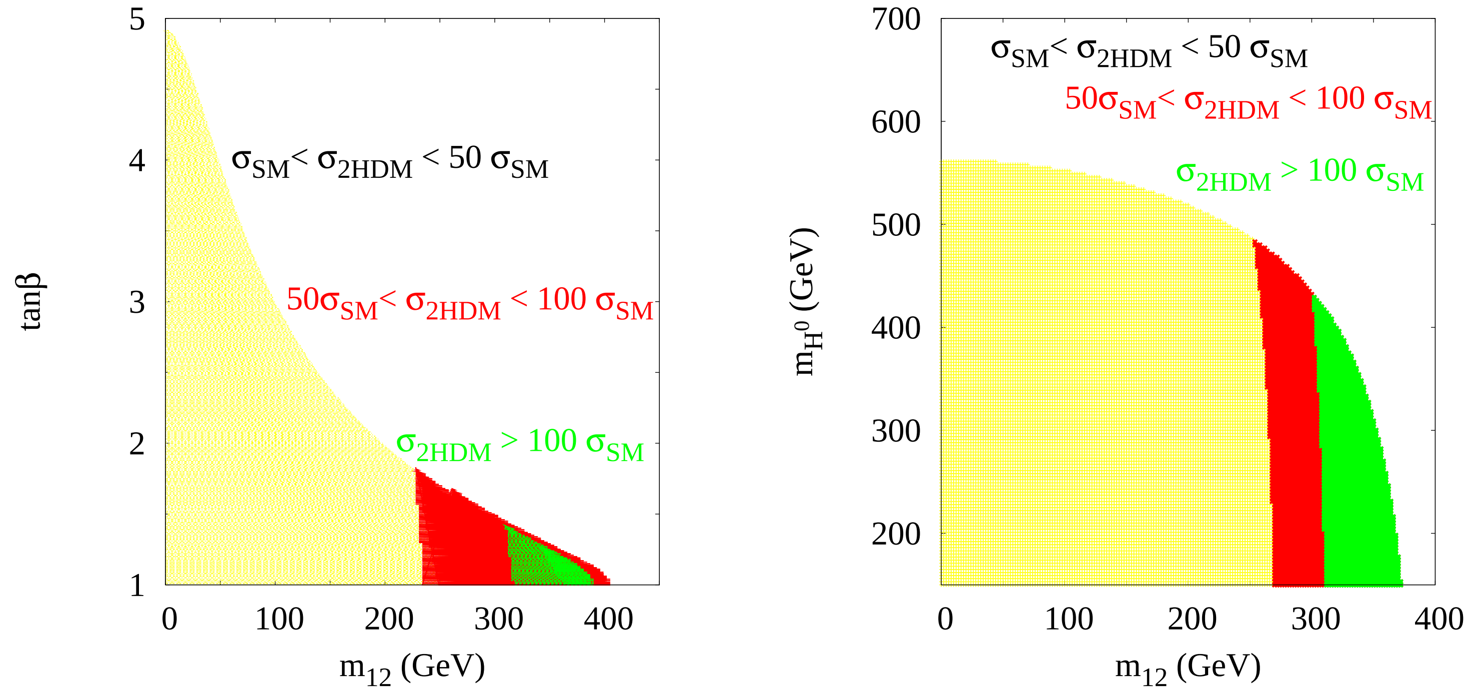


www.FeynArts.de , FormCalc , LoopTools, (T.Hahn)

$\gamma\gamma \to HH$ in SM

Jikia'92, Belusevic'04 and Takahashi'08

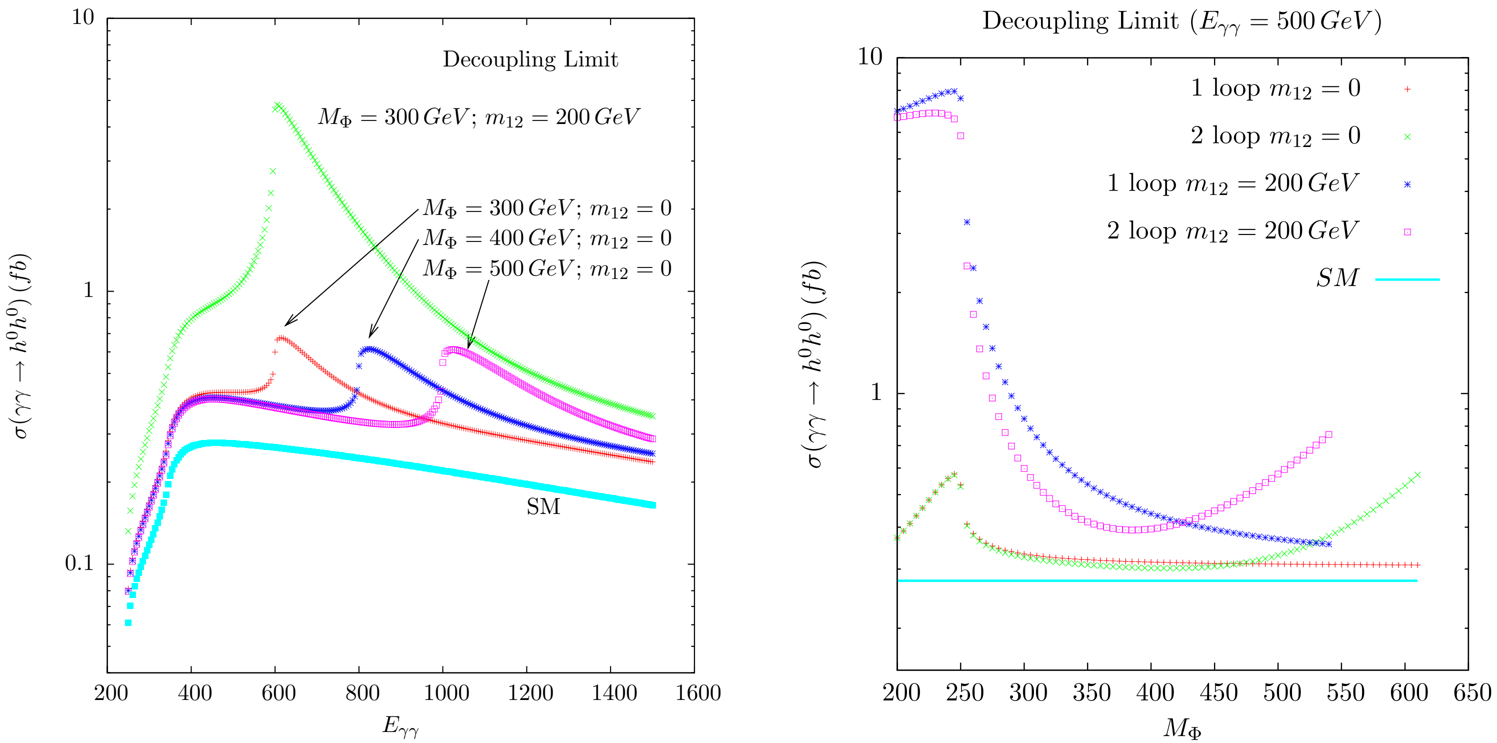
- look for $\gamma\gamma \to HH \to 4b$
- Main background from W^+W^- and from non-resonant four jet final state.
- Select 2 jet and reconstruct Higgs mass, $M(q\bar{q} - MH) < 5$ GeV
- Conclusion: For a center of mass energy of 350 GeV and $m_H = 120$ GeV an integrated luminosity of 450 fb^{-1} would be needed to exclude a zero Higgs boson self-coupling at the 5 σ level.



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

Left $m_{H^0} = 2m_{h^0}$, $E_{\gamma\gamma} = 500$ GeV, $-1 \le \sin\alpha \le 1$, $1 \lesssim \tan\beta \lesssim 10$ and right $\tan\beta = 1$, $\sin\alpha = -0.9$, $E_{\gamma\gamma} = 800$ GeV

Decoupling limit, $m_h = 120$ GeV

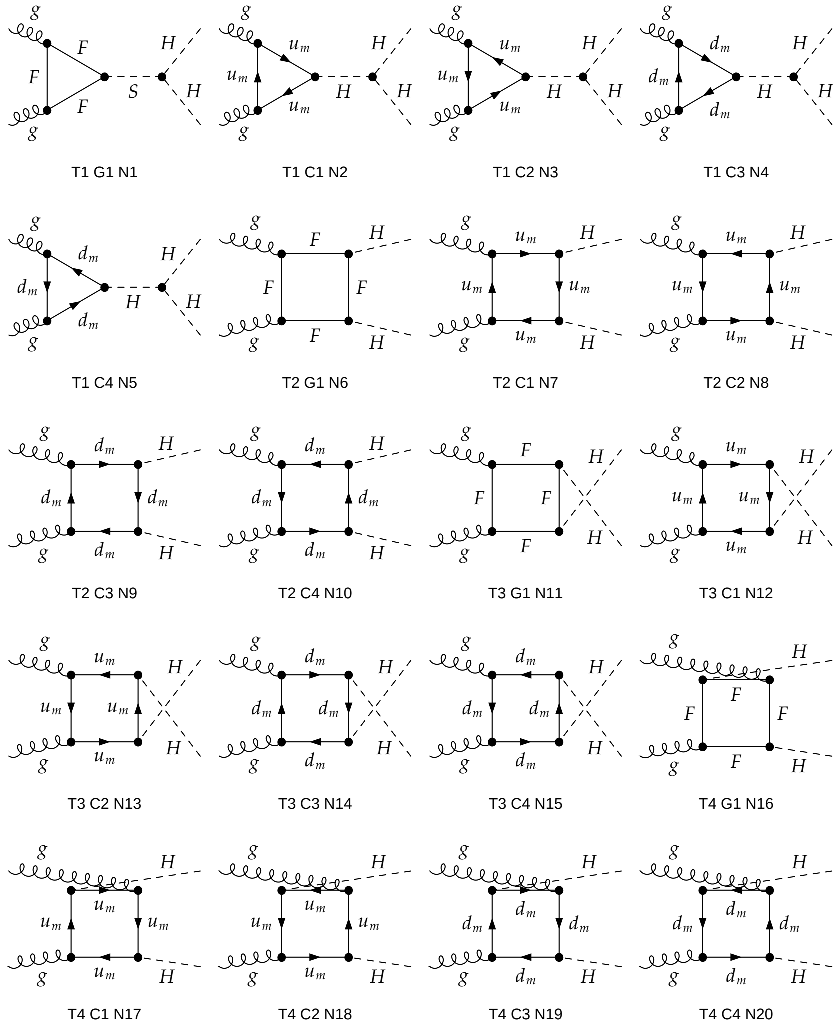


(Left) $\gamma\gamma \to hh$ at LO,

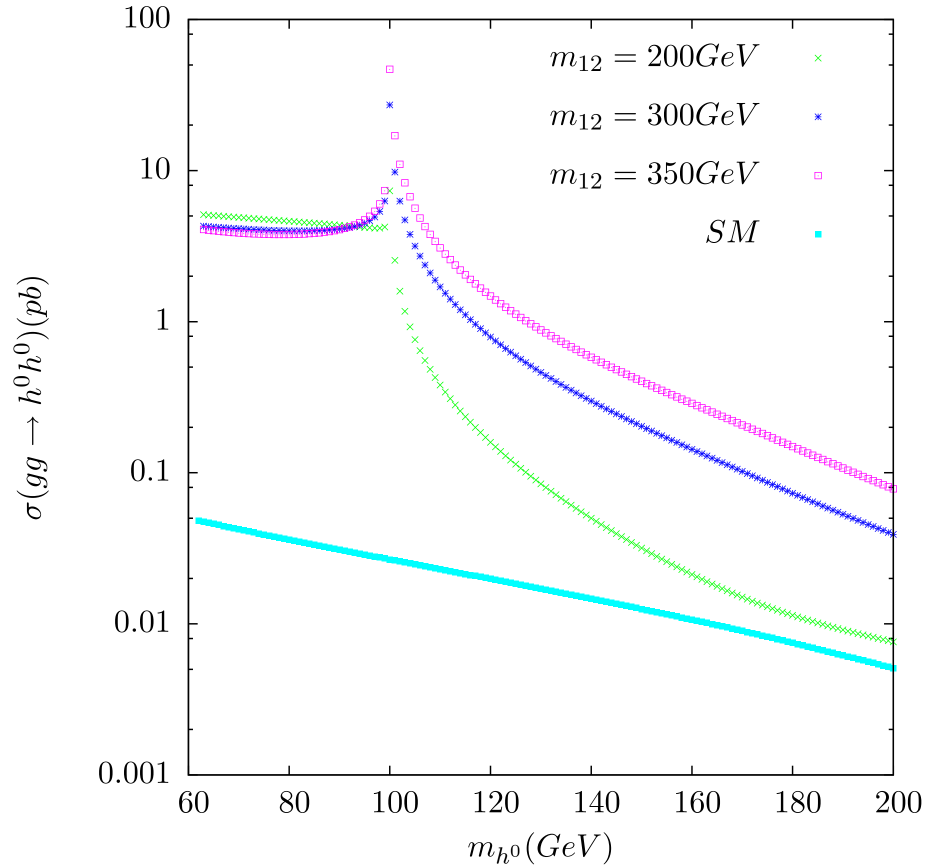
(Right) $\gamma\gamma \to hh$ at LO and LO + High order corrections to hhh

3. Probing triple Higgs couplings in the 2HDM at LHC

(A.A, R.Benbrik, C.H. Chen, R. Guedes and R.Santos'09)

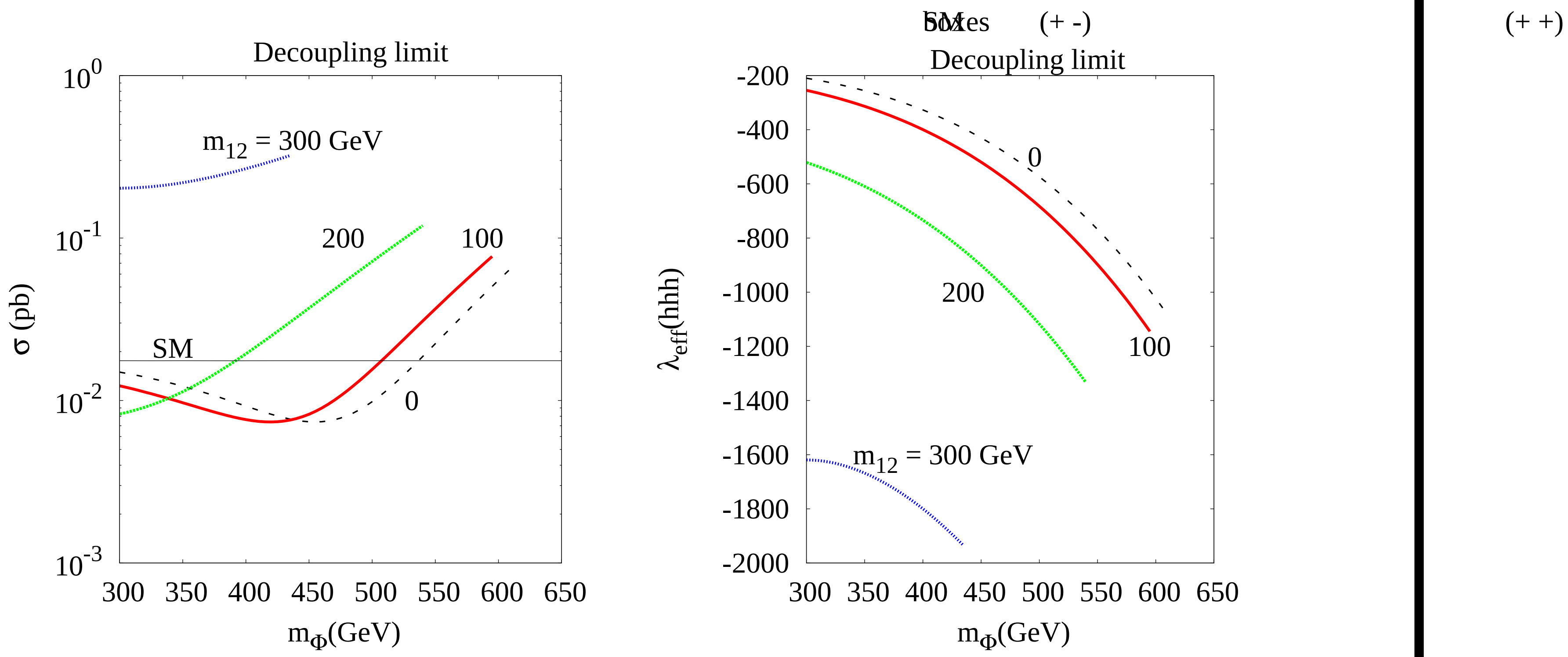


- In SM, the cross section is small $1 \lesssim \sigma(gg \to HH) \lesssim 3$ fb for $120 \lesssim M_H \lesssim 190$ GeV.
- $150 \lesssim M_H \lesssim 200$ GeV, from $gg \to HH \to W^+W^-W^+W^- \to 2l4j$ or $3l2j$, the non vanishing of the triple Higgs coupling of the SM can be established at 95% CL (with 300 fb^{-1}).
- One need VLHC to measure the triple Higgs coupling of the SM with an accuracy of 8-25% at 95% CL. (U. Baur et al '03)
- $M_H \lesssim 140$ GeV, $gg \to HH \to b\bar{b}\gamma\gamma$, look promissing. With 600 fb^{-1} or more, we could make a rough first measurement for $M_H = 120$ GeV (with 6 signal events). (U. Baur et al '04)

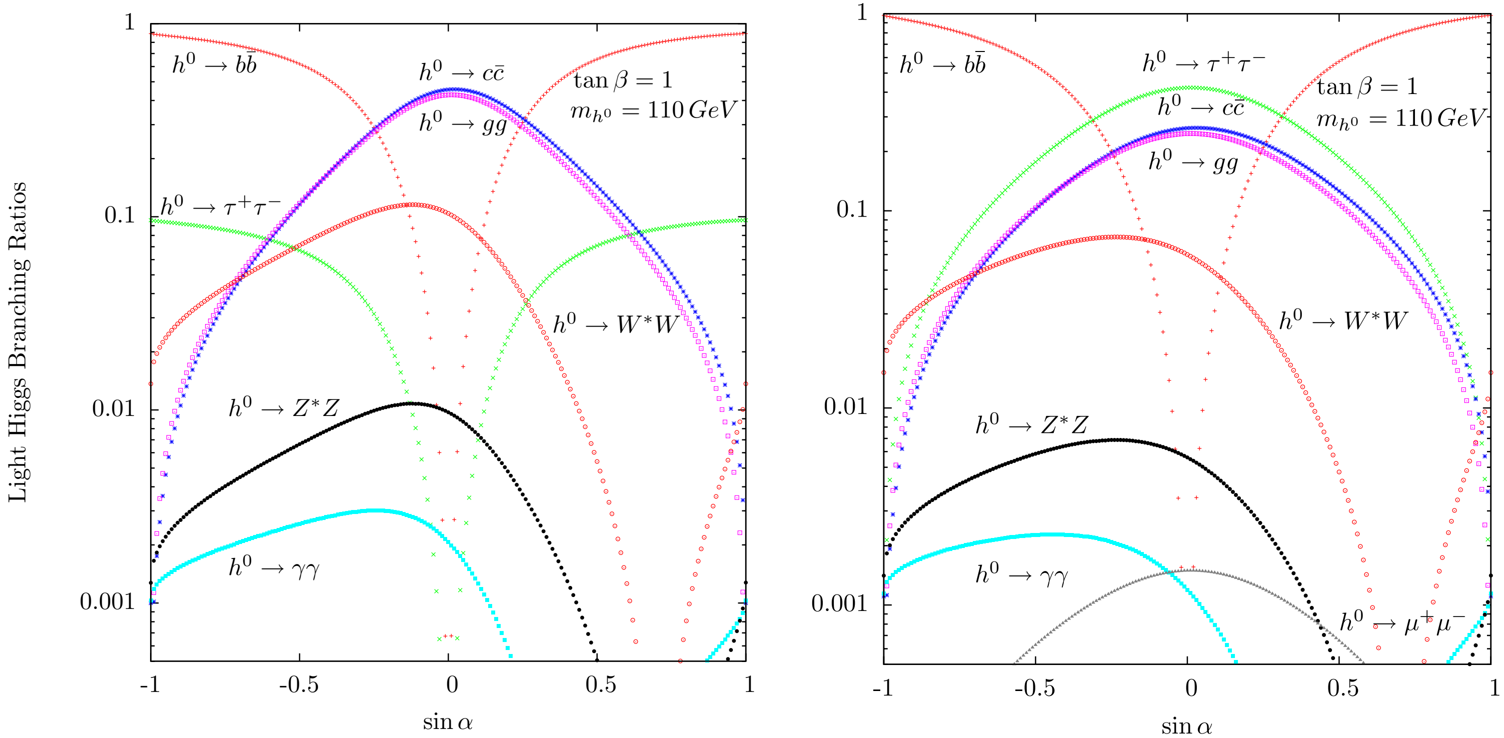


$m_{H^0} = 200GeV$, $m_A = 200GeV$, $m_{H^\pm} = 300GeV$, $\sin\alpha = 0.631$ and $\tan\beta = 1$. ($\sin(\beta - \alpha) = 0.1$)

Decoupling limit



Higgs signatures



Left: 2HDM-II , Right 2HDM-X (leptophilic Higgs)

Conclusions

- LHC will be capable to discover the Higgs bosons and measure its coupling to top quark, τ lepton, W and Z with 10–30% accuracy ($\mathcal{L} = 300 fb^{-1}$).
- At LC, the precision of the measurement is about 1–2%, such precision is needed to distinguish between models.
- In 2HDM, non decoupling effects could be large to be measured both at LHC and ILC and its $\gamma\gamma$ option.
- If 2HDM Higgs masses are not too heavy, their triple self couplings can be accessible at LHC and ILC