2H search at LHC

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Scenario

- LHC has found the Higgs in [120,140] GeV interval (H⇨bb).
- Couplings HVV and Hff measured.
- Not found any trace of SUSY q or g.

What can be said about the Higgs boson found? Is there some space left for non-SM physics in the Higgs sector?

2HDM

2 complex $SU(2)_L, \phi_1, \phi_2$

$$\begin{aligned}V(\phi_1,\phi_2) =& \lambda_1(\phi_1^\dagger\phi_1 - v_1^2)^2 + \lambda_2(\phi_2^\dagger\phi_2 - v_2^2)^2 \\ &+\lambda_3\left[(\phi_1^\dagger\phi_1 - v_1^2) + (\phi_2^\dagger\phi_2 - v_2^2)\right]^2 \\ &+\lambda_4\left[(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2)\right] + \lambda_5\left[(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1)\right] \\ &+\lambda_6\left[Re(\phi_1^\dagger\phi_2) - v_1 v_2 c_\xi\right]^2 \\ &+\lambda_7\left[Im(\phi_1^\dagger\phi_2) - v_1 v_2 s_\xi\right]^2\end{aligned}$$

$$\lambda_i \in R, \quad \lambda_i > 0$$

$$\langle\phi_1\rangle^T = [0 \;\; v_1]$$
$$\langle\phi_2\rangle^T = [0 \;\; v_2 e^{i\xi}]$$

If: $\lambda_6 = \lambda_7 \longrightarrow \lambda|\phi_1^\dagger\phi_2 - v_1 v_2 e^{i\xi}|^2$

then ξ can be rotated away by redefining one of the fields

e.g. Gunion & Haber, Phys. Rev. **D67** (2003) 075019

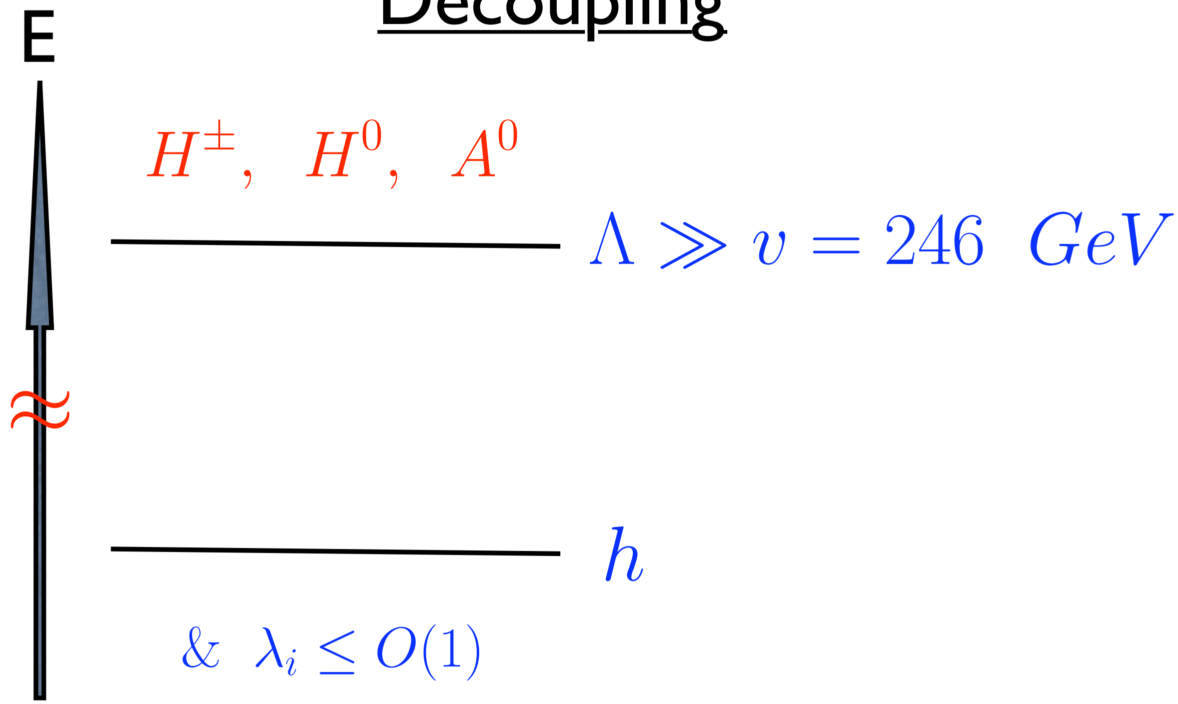
Number of parameters

$H^{\pm}, \quad H^0, \quad h^0$ (CP-even)

A^0 (CP-odd)

- 4 Higgs masses
- mixing angle of H and h: α
- λ's
- $tan(\beta) = \frac{v_2}{v_1}$

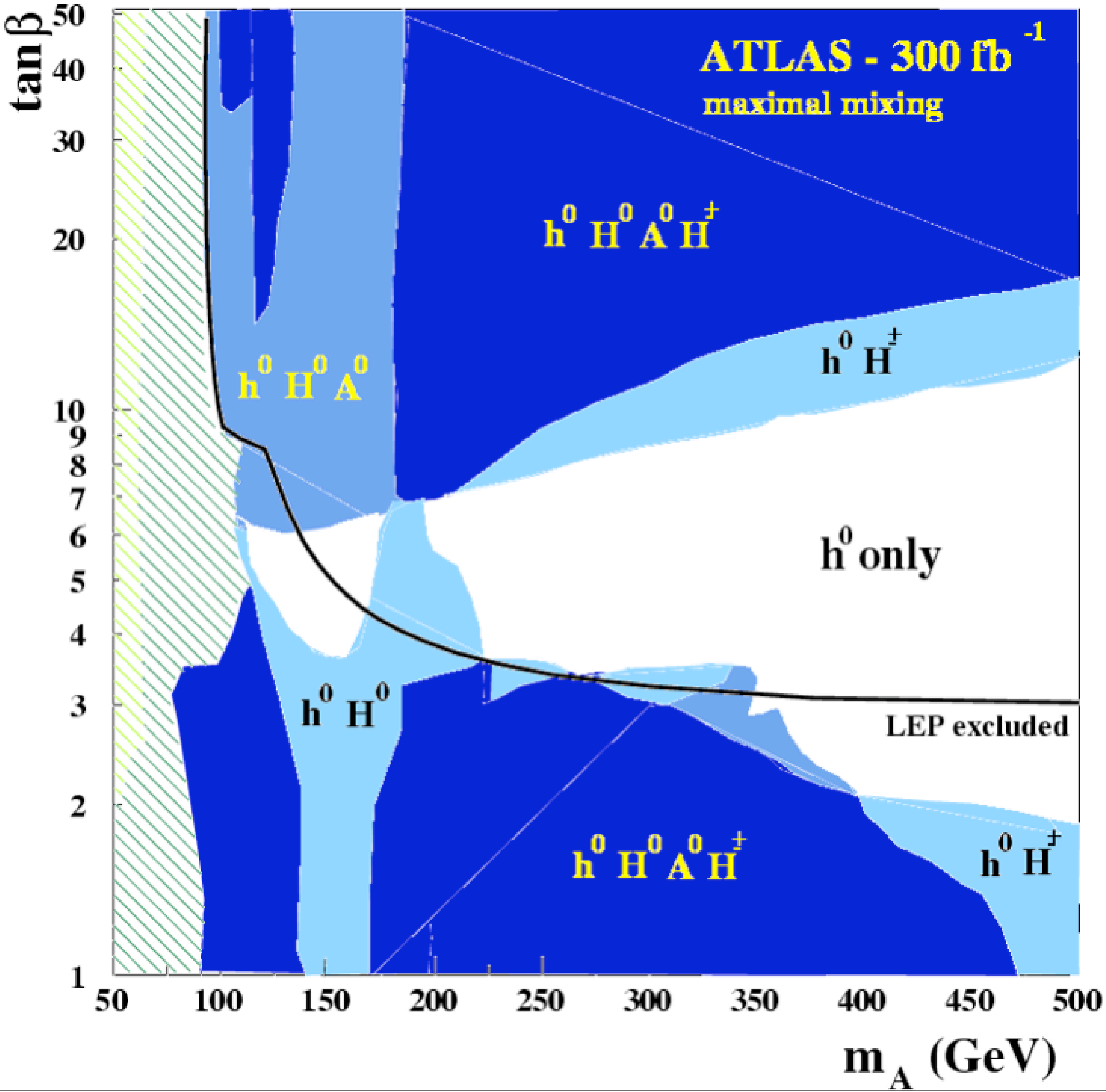
Decoupling



In the decoupling limit the couplings hVV, hff tend to their SM values with deviations $O(v^2/\Lambda^2)$

$$\Lambda \approx m_S = \sqrt{m_A^2 + \tilde{m}}$$

$$m_h \sim O(v)$$



ATLAS - 300 fb -1
maximal mixing
tanβ
50
40
30
20
10
9
8
7
6
5
4
3
2
1
50
100
150
200
250
300
350
400
450
500
m A (GeV)
h0 H0 A0 H±
h0 H0 A0
h0 H±
h0 only
h0 H0
LEP excluded
h0 H0 A0 H±
h0 H±

In the decoupling limit...

$$\frac{g_{hVV}^2}{g_{HVV}^{(0)2}} \sim 1 - \epsilon^2$$

$$\frac{g_{htt}^2}{g_{Htt}^{(0)2}} \sim 1 - 2\epsilon \cdot cot(\beta)$$

$$\frac{\lambda_{3h}^2}{\lambda_{3H}^{(0)2}} \sim 1 - 6\epsilon\frac{\hat{\lambda}}{\lambda}$$

$$\epsilon = \frac{\hat{\lambda} v^2}{m_A^2} \rightarrow 0$$

See Gunion&Haber

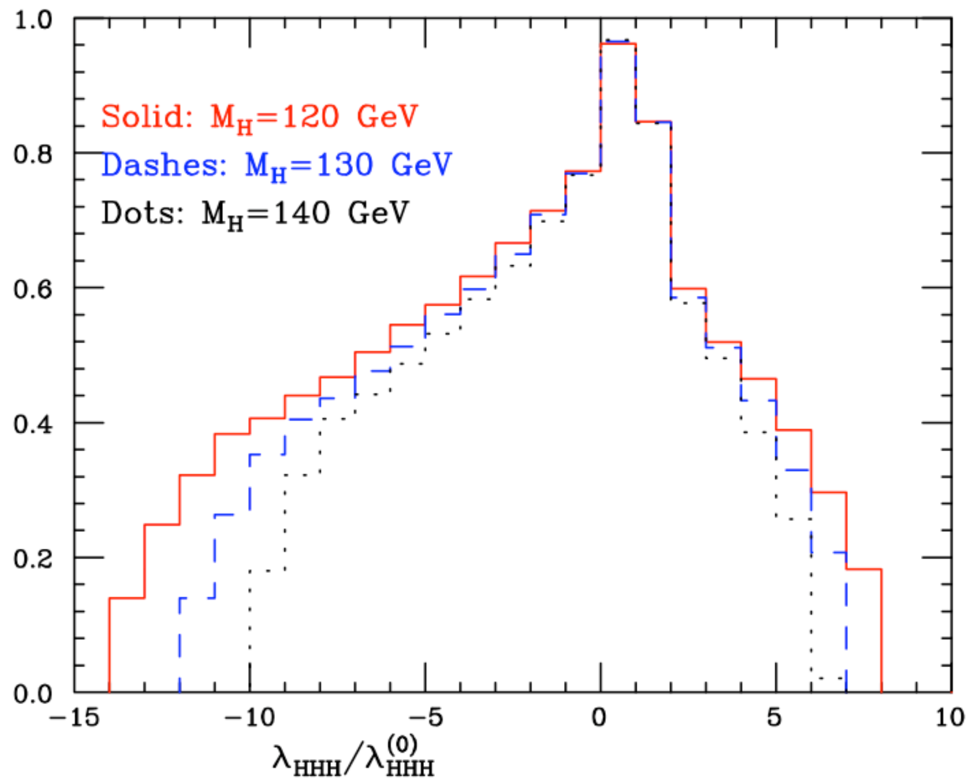
The possibility that this ratio can be large allows the 3Higgs self-couplings to remain large even when the other couplings are converging to SM values.

We examine this possibility by varying:

$$1 < tan(\beta) < 50$$
$$-4\pi < \lambda_i < 4\pi$$

The scan in parameter space was subject to constraints of tree-unitarity and to the requirement that hVV, htt, hbb differ from SM values by no more than 30%, 30%, 70% (below the sensitivity range of LHC direct measurement after 300 1/fb)

- The non-standard Higgs states are heavier than 400 GeV in the indicated range.
- Make sure that small departures of hVV from SM do not lead to any unitarity violating growth of the amplitudes involving them.
- Diagrams involving 3H with the heavy H in the propagators are negligible..
- ..similarly for V2Higgs.
- Hhh, HVV, HQQ weaker than hhh, hVV, hQQ.



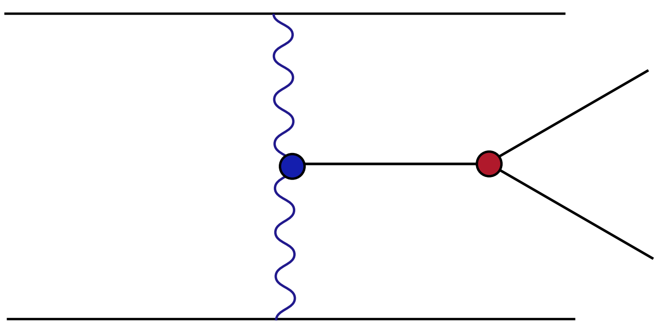
Distribution of the values $\lambda_{3h}/\lambda_{3H}^{(0)}$

Simulating the 2HDM

We simulate the 2HDM using ALPGEN by rescaling $\lambda_{3H}^{(0)}$ in all diagrams where 3Higgs are involved.

$$\lambda_{3H}^{(0)} = -3\frac{M_H^2}{v}\eta$$

This rescaling neglects diagrams involving other fields in 2HDM . We checked that these contributions are numerically negligible. In principle the rescaling breaks gauge inv. e.g. in



The trilinear is rescaled while the gauge is not (is kept fixed to SM).

Anyway, little impact on unitarity.

A full computation is mandatory.

Mangano & al. JHEP **0307** (2003) 001

Channels studied both in SM and 2HDM

$$\cancel{gg \to H\,H}$$ (Gluon fusion)

$$gg, q\bar{q} \to t\bar{t}H\,H$$ (Associated production)

$$qq^{(\prime)} \to qq^{(\prime)}H\,H$$ (VBF)

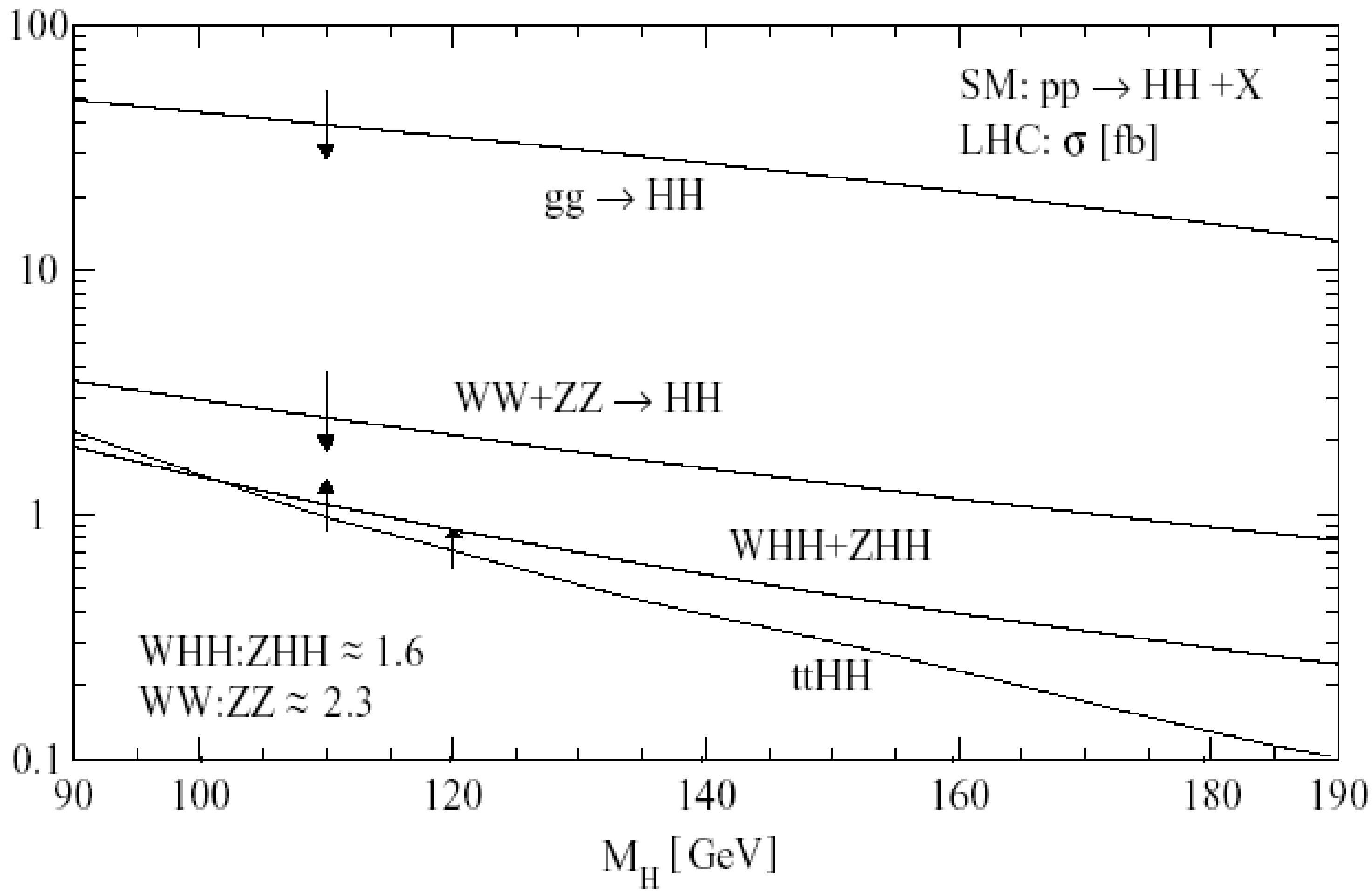
$$q\bar{q}^{(\prime)} \to V\,H\,H$$ (Higgs-strahlung)

$$H \to b\bar{b}$$

Gianotti, Mangano, Virdee, hep-ph/0204087

Additional triggers (with respect to g-fusion) in the studied cases are:

- fwd/bkwd jets in VBF
- leptons/light-jets from V decays and associated production



Djouadi et al. Eur. Phys. J. **C10** (1999) 45

Cross sections for Higgs pair production in the SM. The vertical arrows correspond to a variation of

$\lambda_{3H} \in [1/2, 3/2]\lambda_{3H}^{(0)}$

Signal to Background

One cannot get anything good from a SM study; even at the SLHC one cannot have any statistically significant signal for 2IMH production within SM...but one can find nontrivial limits in the context of 2HDM.

We explore the case where the only low energy trace of a non-SM Higgs sector is a large 3Higgs self-coupling.

Example (SM)

$$VV \to HH$$

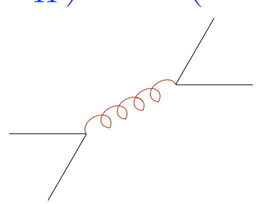
Dominant QCD bkg $b\bar{b}b\bar{b}jj$

$E_\perp > 20\ GeV, \quad \eta_{j_1} > 2.5, \quad \eta_{j_2} < -2.5$

$(m_{b_1,b_2} - M_H)^2 + (m_{b_3,b_4} - M_H)^2 < 2(0.12 M_H)^2$

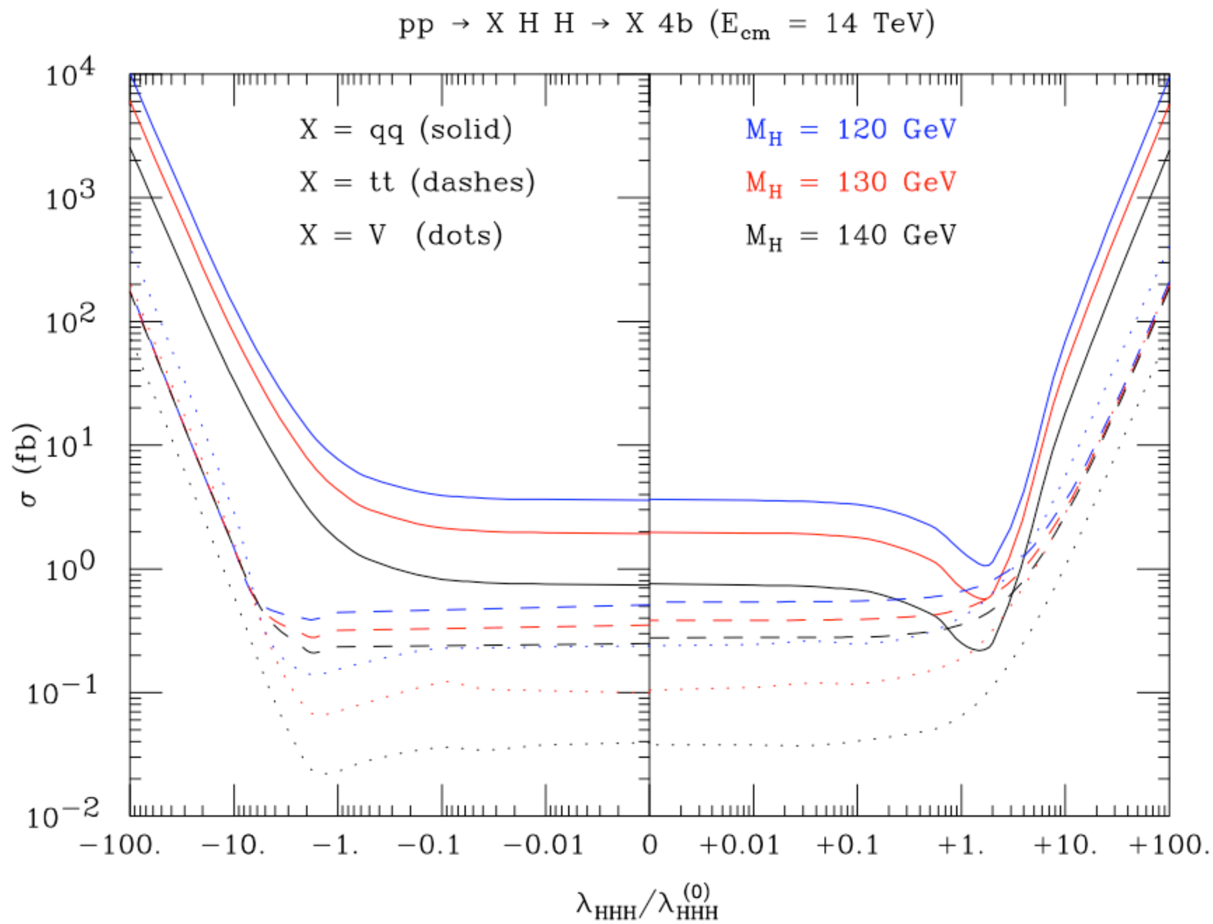
$m_{bb}^{min} > 50\ GeV$

$m_{bb}^{next-to-min} > 100\ GeV$



$S/\sqrt{B} \approx 0.3$

In the allowed range of $r=\lambda_{3h}/\lambda_{3H}^{(0)}$ we can observe xsect enhancement by almost two orders of magnitude. The xsects can be directly related to the production rates of hh in 2HDM.



Dependence of the cross sections on r in the 2HDM

2H visibility at (S)LHC

M_H (GeV)	120		130		140	
LHC, 95%CL	-3.6	6.5	-4.7	7.8	-7.8	11
SLHC, 95%CL	-1.2	3.5	-1.9	4.8	-3.7	6.6
LHC, 3σ	-4.8	7.9	-6.3	9.3	-10	13
SLHC, 3σ	-1.9	4.6	-2.8	5.7	-4.9	7.9
2HDM ($\lambda_{6,7}=0$)	-14	8	-12	7	-10	6
	-4	3	-3.3	2.6	-2.7	2.4
2HDM (general)	-52	51	-44	44	-38	38
	-26	18	-22	15	-19	14

Last two raws: first line = the allowed ranges for a precision of 30%, 30% and 70% in the measurement of the couplings hVV, htt, hbb.
second line = the allowed ranges for a precision of 20%, 20% and 30%.

$$\lambda_{3h}/\lambda_{3H}^{(0)}$$

Summary

- Challenge = Determine whether the observed state is the SM Higgs boson or if it is the lowest lying scalar h of some non-minimal Higgs sectors.

- If the latter, it is likely that the additional scalar states are heavy and the decoupling limit applies. It is possible that these heavier states are not detectable at (S)LHC or at e+e- machines.

- We consider the hypothesis that the only visible trace of the non standard sector is an enhancement of λ3H giving an anomalous visibility of 2IMH final states with respect to SM expectations. Our conclusions are rather model independent since we are not fully implementing the details of 2HDM.

- This study should encourage attempts to look for 2H production at LHC even in the IMH region.

Theorem: In the decoupling limit:

$$cos(\beta - \alpha) \approx O(\frac{v^2}{m_S^2})$$

cos(β−α)	sin(β−α)
HWW, HZZ	hWW, hZZ
ZAh	ZAH
WHh	WHH

AVV , A2γ , H2γ , HVV , ZZA , WWA , HWZ , HWγ
forbidden at tree-level

The Higgs coupling to fermions are model dependent. Here:

$$\phi_1 - D - \ell \quad \phi_2 - U - \nu$$

ttHH signal

The bckg. is: ttbbjj (tag 4b), ttbbbb (tag 6b)

1.5 pb 3.6 fb

$$(E_\perp^{b,j} > 20\ GeV, \quad |\eta^{b,j}| < 2.5, \quad \Delta R_{bb,bj,jj} > 0.4)$$

High b-tagging efficiency mandatory; ϵ^6

$$(\oplus \ \ (m_{bb} - m_H)^2 < (0.12 M_H)^2)$$

$$W \to \ell\nu \quad W \to jj$$

Signal = 0.073 (0.033) [0.011] fb vs. Bckg.= 0.08 fb

Signal and bckg. are expected to be sensitive to the choice of factorization/normalization scale as they originate from QCD induced processes primarily via gluon-PDF.

A data sample could be useful to define QCD normalization.