

2H search at LHC

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Scenario

- LHC has found the Higgs in [120,140] GeV interval ($H \rightarrow b\bar{b}$).
- 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 $SU(2)_L, \phi_1, \phi_2$

$$\begin{aligned} V(\phi_1, \phi_2) = & \lambda_1(\phi_1^\dagger\phi_1 - v_1^2)^2 + \lambda_2(\phi_2^\dagger\phi_2 - v_2^2)^2 \\ & + \lambda_3 \left[(\phi_1^\dagger\phi_1 - v_1^2) + (\phi_2^\dagger\phi_2 - v_2^2) \right]^2 \\ & + \lambda_4 \left[(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) \right] + \lambda_5 \left[(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) \right] \\ & + \lambda_6 \left[\text{Re}(\phi_1^\dagger\phi_2) - v_1v_2c_\xi \right]^2 \\ & + \lambda_7 \left[\text{Im}(\phi_1^\dagger\phi_2) - v_1v_2s_\xi \right]^2 \end{aligned}$$

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

$$\langle \phi_1 \rangle^T = [0 \quad v_1]$$

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

If: $\lambda_6 = \lambda_7 \longrightarrow \lambda |\phi_1^\dagger\phi_2 - v_1v_2e^{i\xi}|^2$

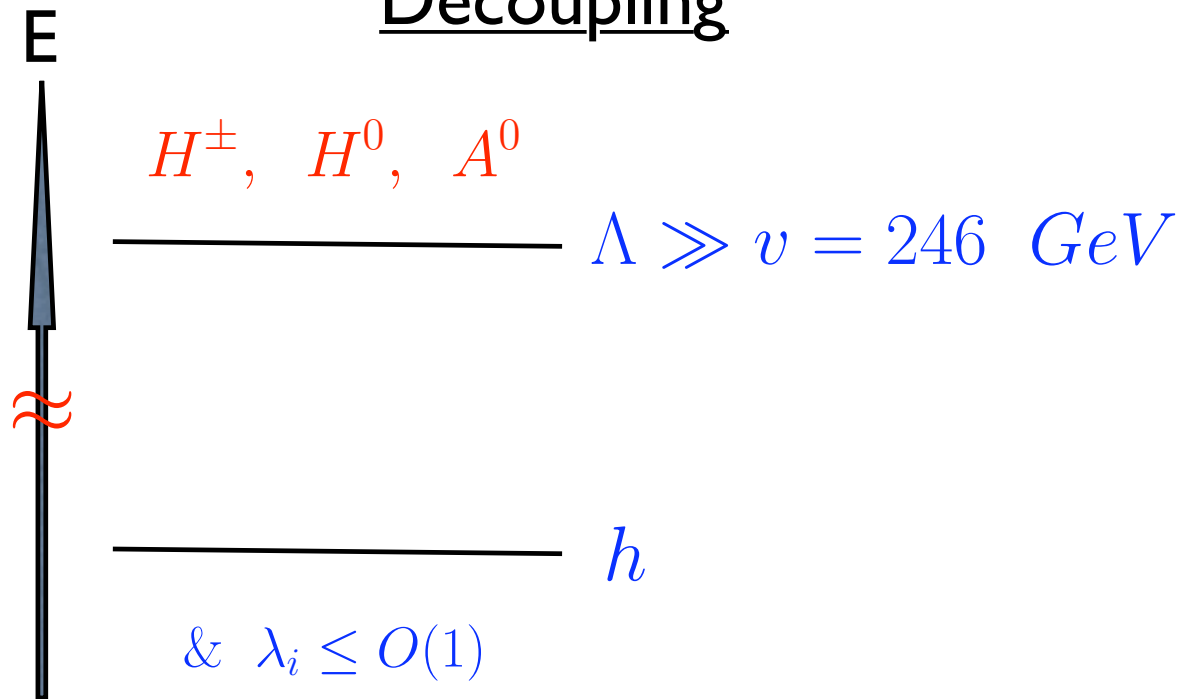
then ξ can be rotated away by redefining one of the fields

Number of parameters

$$\begin{array}{ll} H^\pm, H^0, h^0 & \text{(CP-even)} \\ A^0 & \text{(CP-odd)} \end{array}$$

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

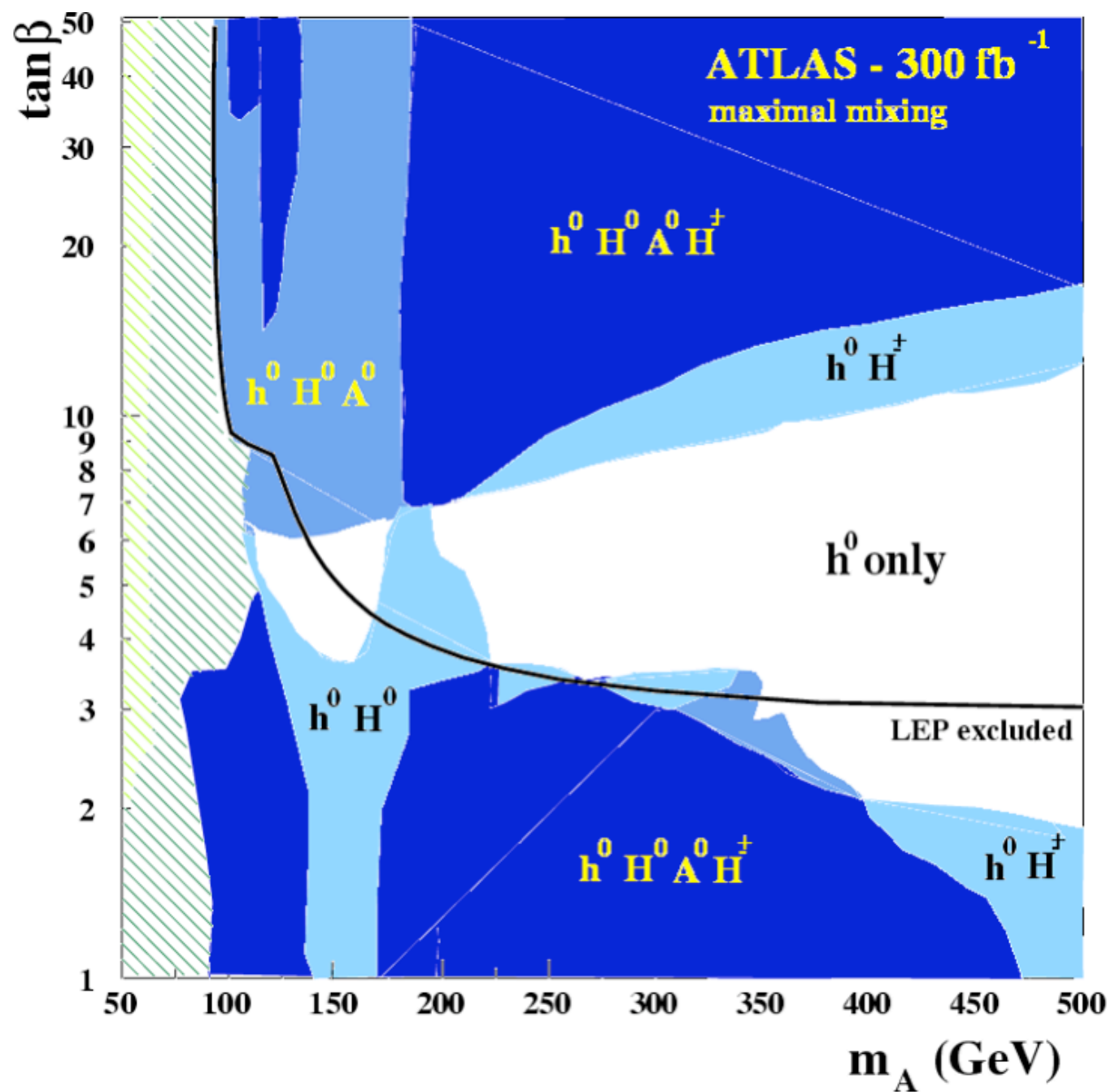
Decoupling



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

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

$$m_h \sim O(v)$$



In the decoupling limit...

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

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

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

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

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.

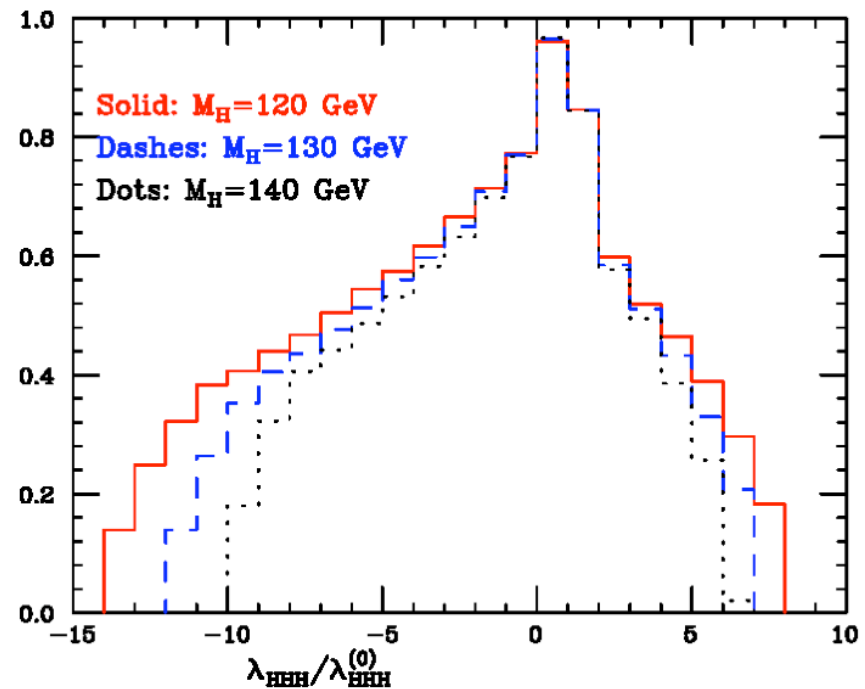
We examine this possibility by varying:

$$1 < \tan(\beta) < 50$$

$$-4\pi < \lambda_i < 4\pi$$

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 I/fb)

- The Higgs states in addition to the lightest ones are heavier than 700 GeV (not detectable) in the indicated range.
- Make sure that the small departure of hVV from SM does not lead to any unitarity violating growth of the amplitudes involving them.
- Diagrams involving 3Higgs with the **heavy** H in the propagators are negligible..
- ..similarly for $V2$ Higgs.
- Hhh , HVV , HQQ weaker than hhh , hVV , hQQ .



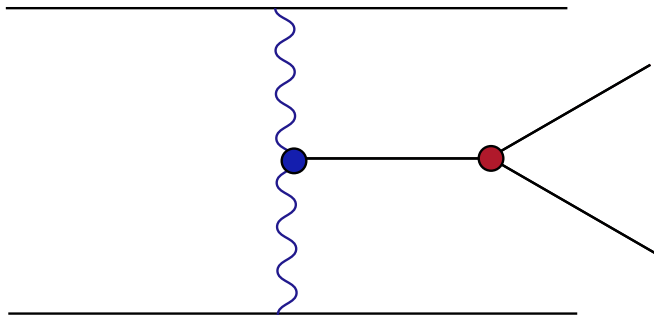
Distribution of the values $\lambda_{3h}/\lambda_{3H}^{(0)}$

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 (not incorporated in ALPGEN). We checked that these contributions are **numerically negligible**. The rescaling **breaks gauge inv.** e.g. in



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

Anyway, little impact on **unitarity**.

Channels studied both in SM and 2HDM

$$~~gg \rightarrow HH~~$$

(Gluon fusion)

$$gg, q\bar{q} \rightarrow t\bar{t}HH$$

(Associated production)

$$qq^{(\prime)} \rightarrow qq^{(\prime)}HH$$

(VBF)

$$q\bar{q}^{(\prime)} \rightarrow VHH$$

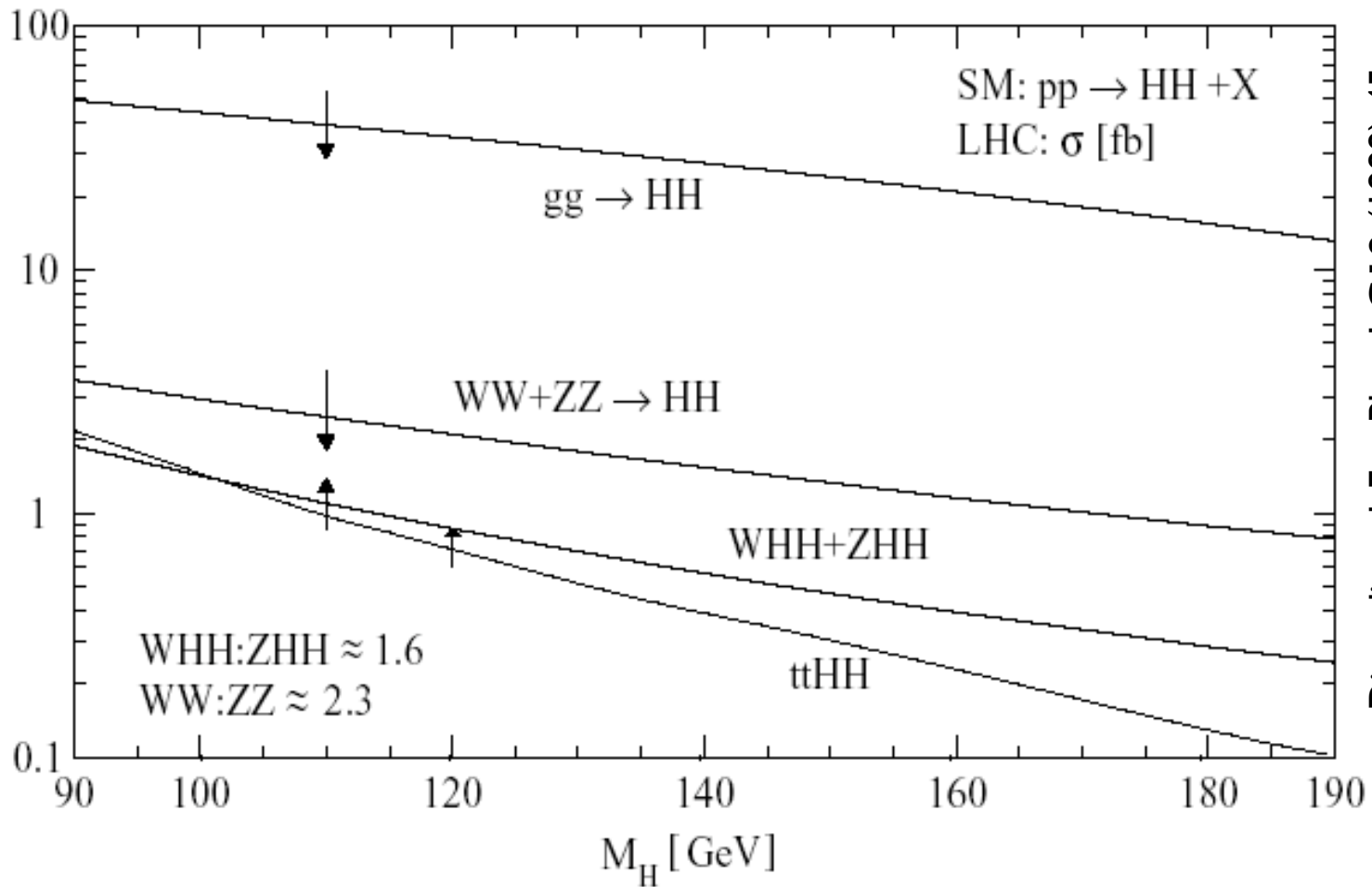
(Higgs-strahlung)

$$H \rightarrow b\bar{b}$$

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)

$$VV \rightarrow HH$$

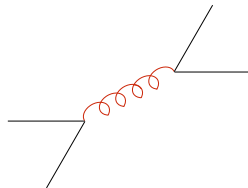
Dominant QCD bkg $b\bar{b}b\bar{b}jj$

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

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

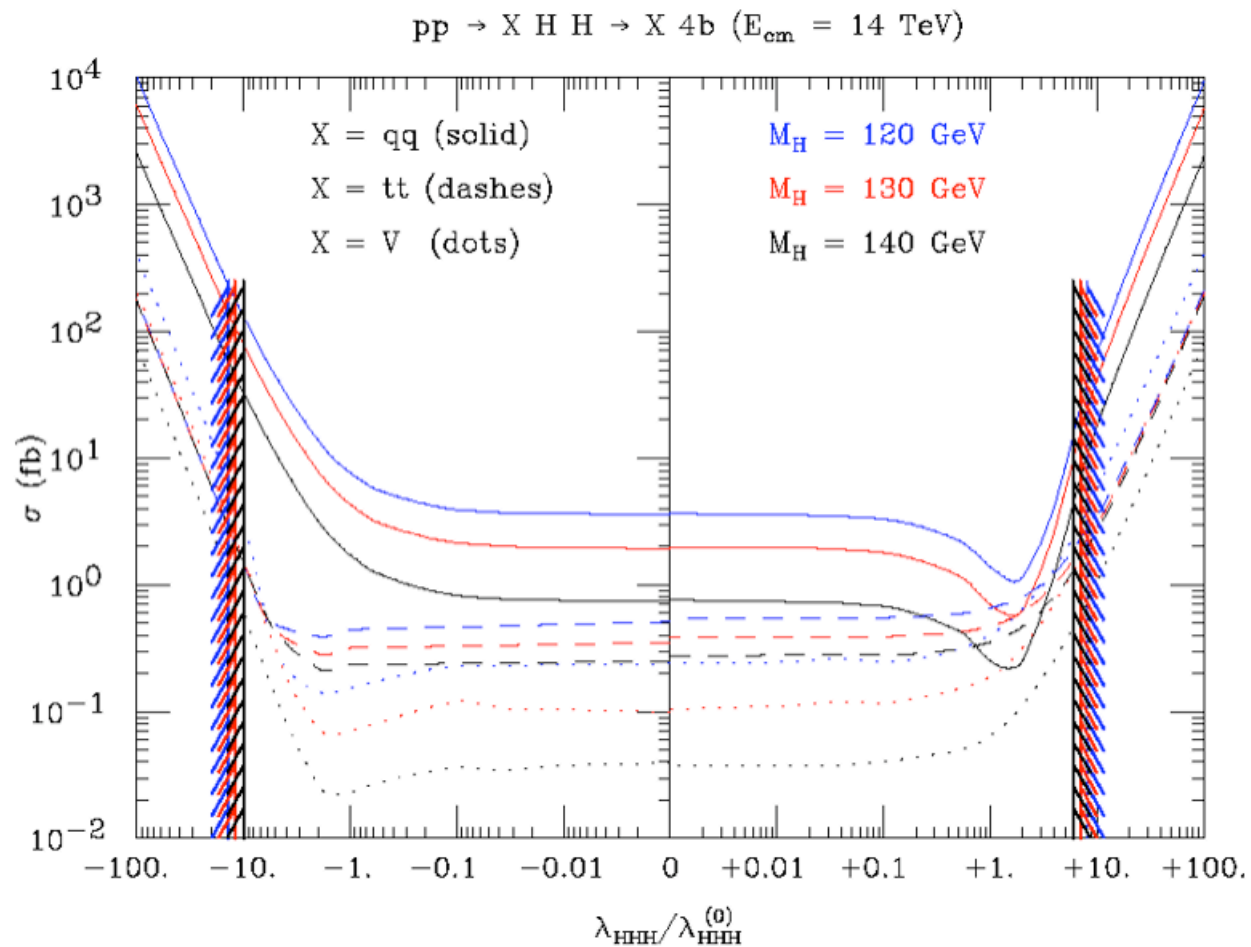
$$m_{bb}^{\min} > 50 \text{ GeV}$$

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



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

In the allowed range of r 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

| $M_H(\text{GeV})$ | 120 | | 130 | | 140 | | |
|--------------------|-----------------|------|-----|------|-----|------|-----|
| excl. @ 95% c.l. | LHC, 95% | -3.6 | 6.2 | -4.7 | 7.5 | -7.8 | 11 |
| | SLHC, 95% | -1.0 | 2.5 | -1.9 | 4.2 | -3.7 | 6.4 |
| probed @ 3σ | LHC, 3σ | -4.8 | 7.6 | -6.3 | 9.1 | -10 | 13 |
| | SLHC, 3σ | -1.9 | 4.0 | -2.7 | 5.3 | -4.9 | 7.7 |
| 2HDM | -14 | 8 | -12 | 7 | -10 | 6 | |

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

Conclusions

- **Challenge**=to 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 $\lambda 3H$** 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:

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

| $\cos(\beta - \alpha)$ | $\sin(\beta - \alpha)$ |
|------------------------|------------------------|
| HWW, HZZ | hWW, hZZ |
| ZAh | ZAH |
| WHh | WHH |

AVV , A2 γ , H2 γ , HVV , ZZA , WWA , HWZ , HW γ
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

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

High b-tagging efficiency mandatory; ϵ^6

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

$$W \rightarrow \ell\nu \quad W \rightarrow jj$$

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.