Invariant mass distribution of di-Higgs production at HL-LHC in the 2HDM

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DESY.

The 2HDM model

[Santos, Barroso: arXiv:hep-ph/9701257]

- **CP conserving** 2HDM with two complex doublets: $\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1+\rho_1+i\eta_1}{\sqrt{2}} \end{pmatrix}, \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2+\rho_2+i\eta_2}{\sqrt{2}} \end{pmatrix}$

- **Softly broken $\mathbb{Z}_2$ symmetry** ($\Phi_1 \rightarrow \Phi_1$; $\Phi_2 \rightarrow -\Phi_2$) entails 4 Yukawa types (Types I and II were analyzed).

h (m_h = 125 GeV), **H** - CP even, **A** - CP odd, **H**$^+$, **H**$^-$

- Potential:

$$V_{2HDM} = m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}((\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2),$$

- Free parameters: $m_h,\ m_A,\ m_H,\ m_{H^\pm},\ m_{12}^2, v,\ \cos(\beta-\alpha),\ \tan\beta$

$$\tan\beta = v_2/v_1$$
$$v^2 = v_1^2 + v_2^2 \sim (246\ \text{GeV})^2$$

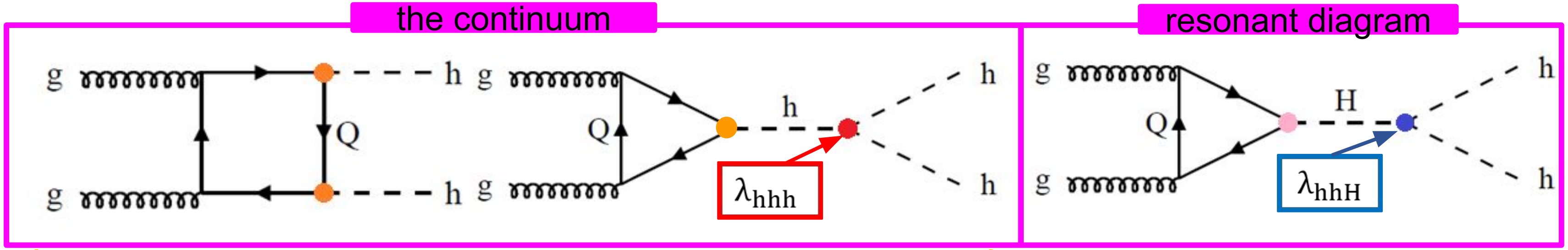
- **Phenomenological implications** can originate from:

  → deviations in **couplings** to fermions and gauge bosons
  → contributions of the **heavy scalars** in the loops

Di-Higgs production ($gg \rightarrow hh$)

[Plehn, Spira, Zerwas : arXiv:hep-ph/9603205]

- Triple Higgs couplings can be accessed through Higgs pair production
- The dominant process at a hadron collider is gluon fusion involving a quark loop



Diagrams that exist in the SM: They have a negative interference

Diagrams that are sensitive to triple Higgs couplings

$\sigma_{SM} \sim$ 38 fb at NLO

- We will study the **invariant mass distribution** of two 125 GeV in the final state
- All calculations were done using a modified version of the code **HPAIR**

[Abouabid, Arhrib, Azevedo, El Falaki, Ferreira, Mühlleitner, Santos: arXiv:hep-ph/2112.12515]

Triple Higgs Couplings

[ATLAS-CONF-2022- 050]

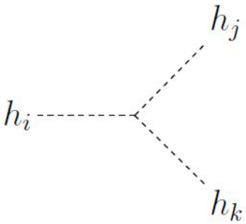
- Can have **large deviations** from SM predictions in BSM:

$$\kappa_\lambda = \lambda_{hhh} / \lambda_{hhh}^{SM}$$

$$\lambda_{hhh}^{SM} = \frac{m_h^2}{2v^2} \cong 0.129$$

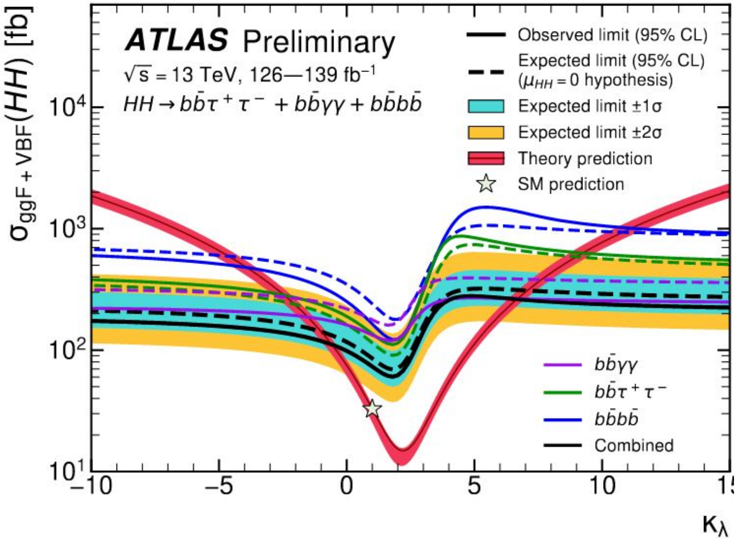
[$-0.4 < \kappa_\lambda < 6.3$] (95% CL at LHC Run II)

- Notation:



$$= -i\, v\, n!\, \lambda_{h_i h_j h_k}$$

n = number of identical Higgses



Type I

κ_λ = [-0.5, 1.3]

λ_{hhH} = [-1.7, 1.6]

[Arco, Heinemeyer, Herrero: arXiv2003.12684]

Large λ's were found: far from the alignment limit and/or for large masses.

Invariant mass distribution: effects of deviations in κ_λ

BP: Type I, $\cos(\beta-\alpha) = 0.1$, $\tan\beta = 10$, $m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$, $m_H = m_A = m_{H^\pm}$

Prediction for SM couplings:

$\kappa_\lambda = 1,\ \lambda_{hhH} = 0$

Prediction for BSM couplings:

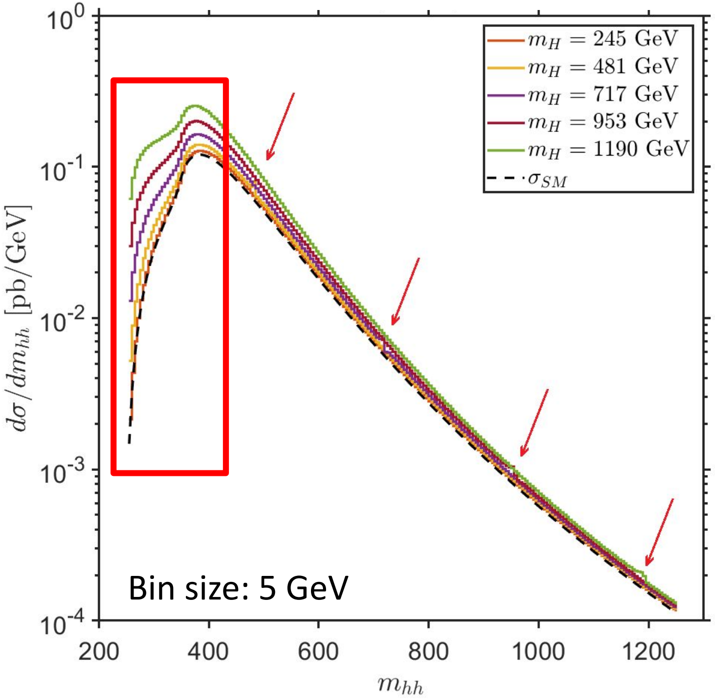
$\kappa_\lambda = 0.97,\ \lambda_{hhH} = 0.05$

$\kappa_\lambda = 0.85,\ \lambda_{hhH} = 0.19$

$\kappa_\lambda = 0.67,\ \lambda_{hhH} = 0.42$

$\kappa_\lambda = 0.41,\ \lambda_{hhH} = 0.74$

$\kappa_\lambda = 0.08,\ \lambda_{hhH} = 1.15$



- Larger sensitivity to κ_λ in the low m_{hh} region

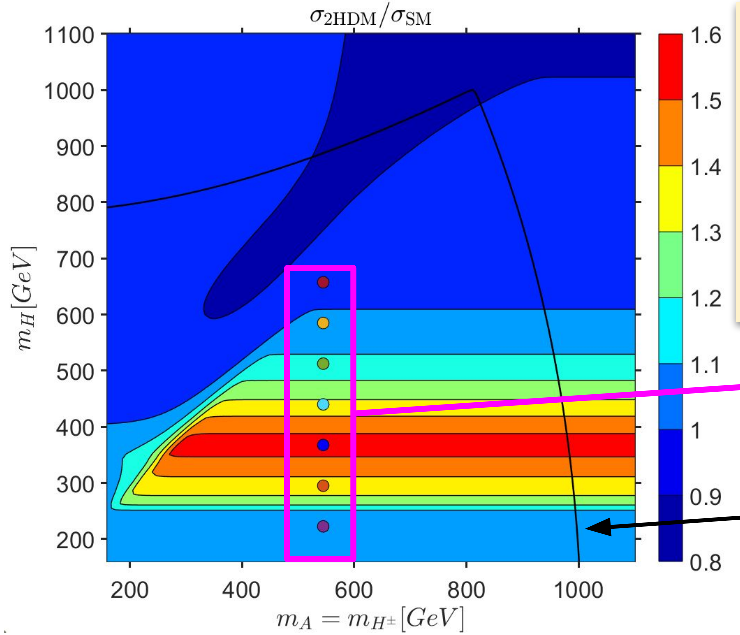
- Resonant contribution very suppressed due to very small top Yukawa $\xi^t_H \sim 10^{-4}$

$\xi_H^t = \cos(\beta-\alpha) - \sin(\beta-\alpha)/\tan(\beta)$

Effect of the mass of the heavy Higgs

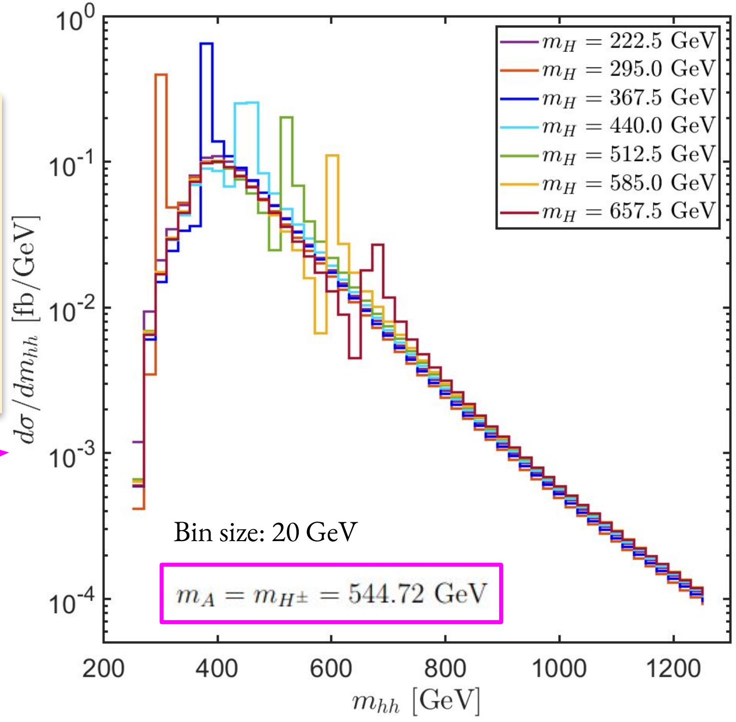
- We vary the mass of the heavy Higgs boson leaving the rest of the parameters of the model fixed.

BP: Type I, $\cos(\beta-\alpha)=0.2$, $\tan\beta=10$, $m_{12}^2=m_H^2\cos^2\alpha/\tan\beta$



Enhancement in the total cross section is resonance dominated. **Location** of the resonance is related to the mass of **H**

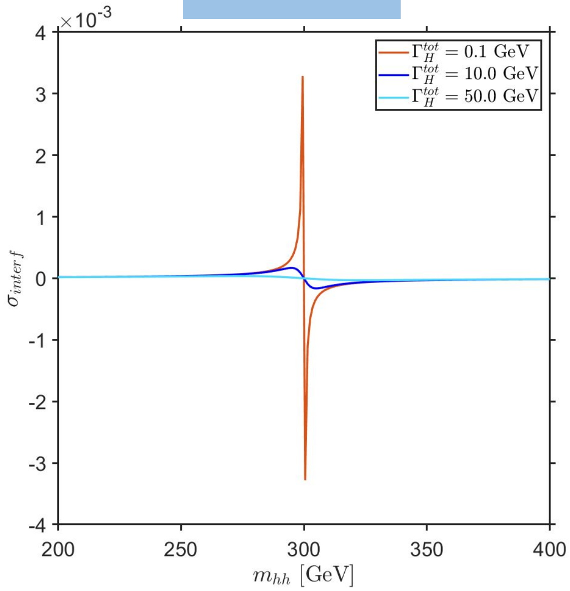
Allowed region inside the black contour.



Effect of the total decay width

$$\frac{1}{Q^2 - M_{h/H}^2 + i\Gamma_{h/H} M_{h/H}}$$

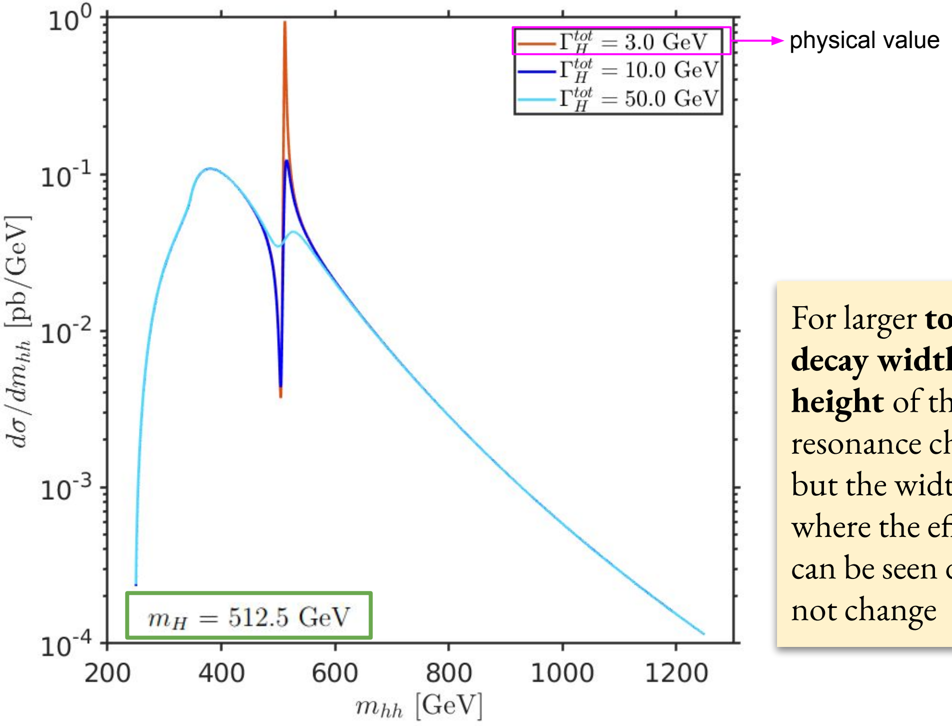
Toy model



$$\sigma_{\text{interf}} \propto \frac{Q^2 - m_H^2}{(Q^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

- For the green point of the previous benchmark plane

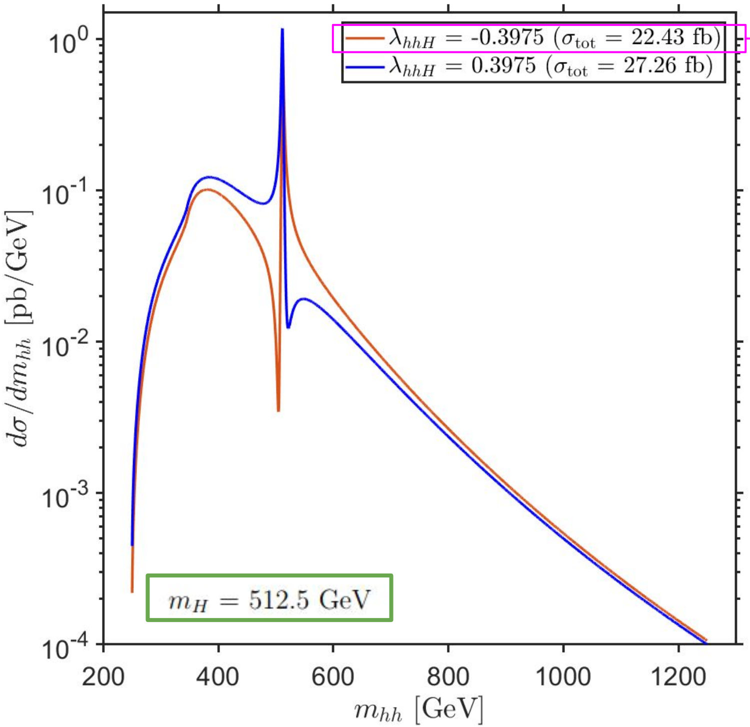
we artificially change the total decay width of the heavy Higgs H:



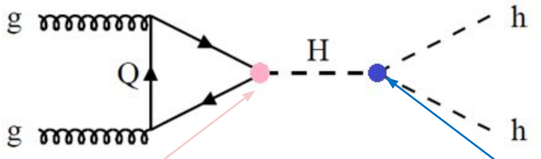
For larger **total decay widths** the **height** of the resonance changes but the width where the effect can be seen does not change

Effect of the couplings

- What is the effect of the couplings involved in the resonant diagram on the invariant mass distributions ?



physical value



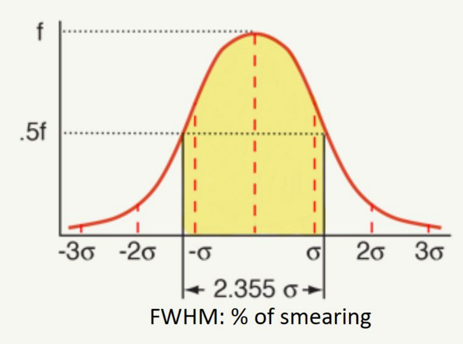
$\xi_H^t = \cos(\beta-\alpha) - \sin(\beta-\alpha)/\tan(\beta) = 0.104$

λ_{hhH}

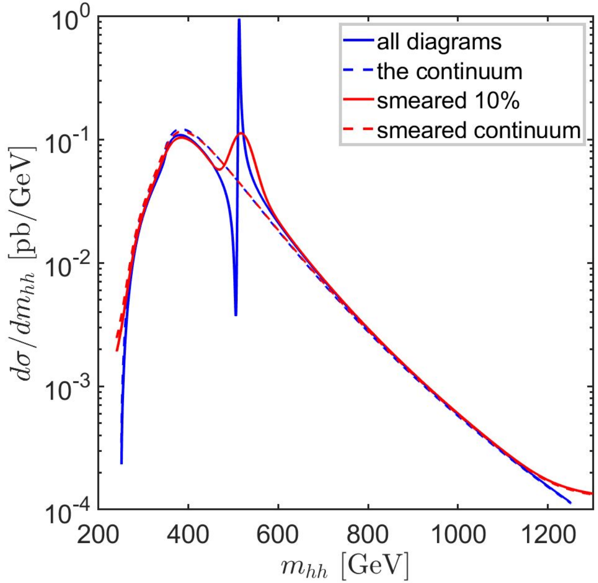
The **relative sign** of the top Yukawa and the BSM coupling to the heavy Higgs gives a **structure** to the resonance:

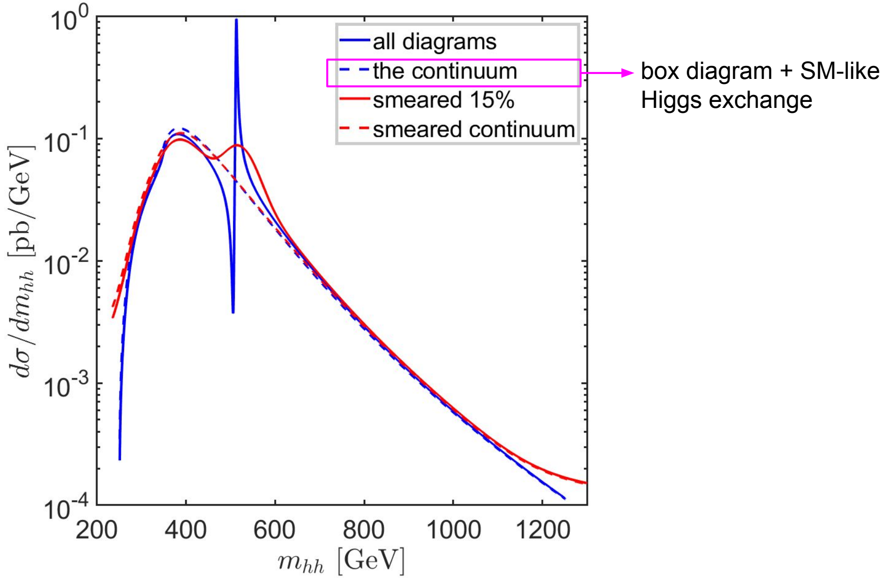
sign $(\lambda_{hhH} \cdot \xi_H^t)$	structure
+	peak-dip
-	dip-peak

Experimental challenges: smearing

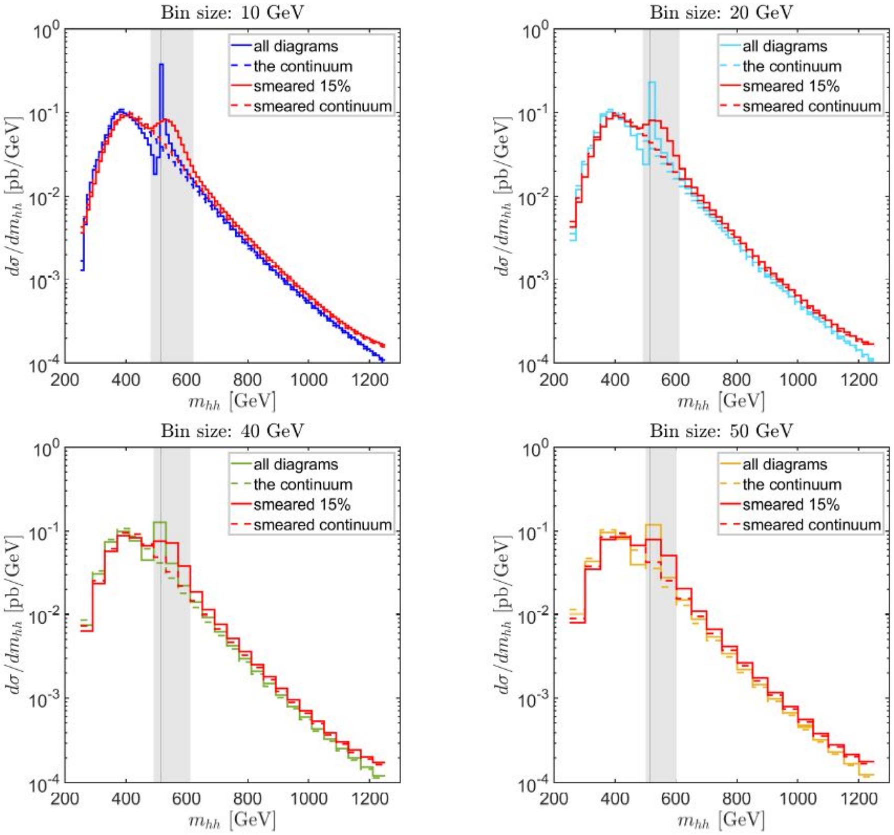


- Differential cross section measurements are affected by the finite resolution of particle detectors → observed spectrum is "**smeared**"
- We try to mimic this effect by artificially smearing the theoretical prediction introducing **Gaussian uncertainties** in the invariant mass





Experimental challenges: binning (15 % smearing)



- We define a value for the 'significance of the signal' according to the excess of the number of events. Assuming: $\mathcal{L} = 6000 \text{ fb}^{-1}$

events below resonant smeared contribution

events below continuum smeared contribution

$$R := \frac{\sum_i (N^R - N^C)}{\sqrt{\sum_i N^C}}$$

Bin size	R
10 GeV	3.79
20 GeV	3.99
40 GeV	3.87
50 GeV	4.04

- Window definition:

$(N^R - N^C) > \text{(bin size)}/50$

→ Smearing dilutes more the resonance than binning

Conclusion

Invariant mass distributions give information about:

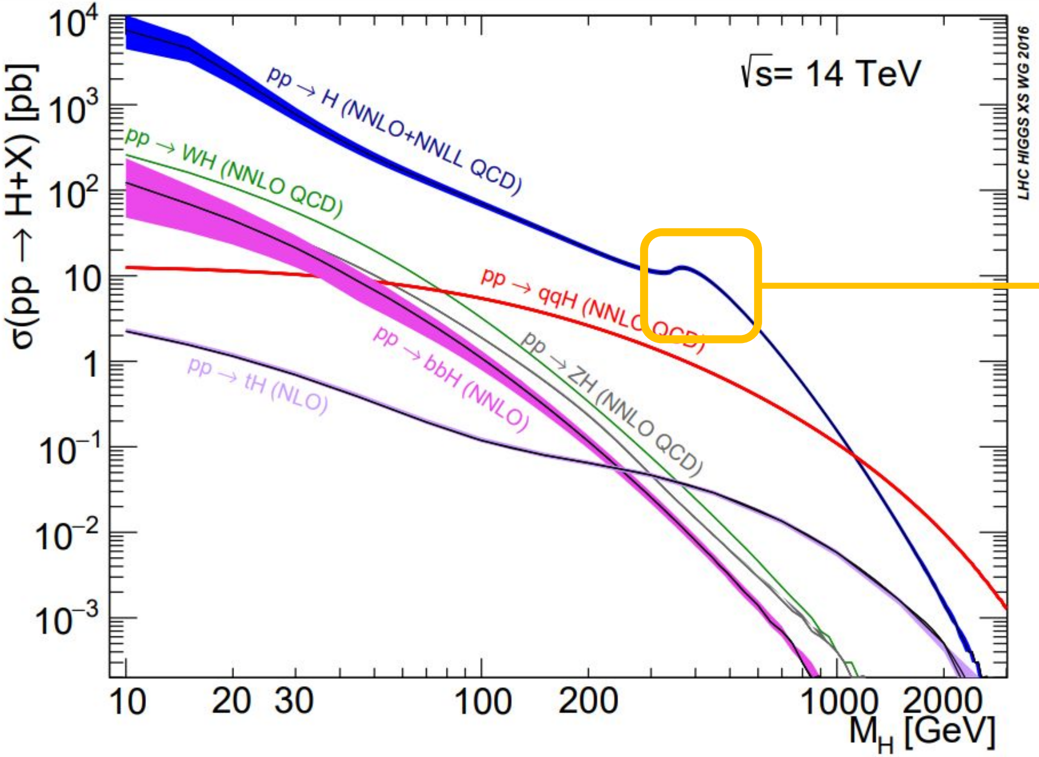
1. Deviations of κ_λ that can be seen in the low m_{hh} threshold

2. **resonant production** that can be embedded in BSM models:

- **mass** of the intermediate Higgs boson → **position** of the resonance
- **total decay width** of the resonance → **height** of the resonance
- relative sign of the **couplings** → **structure** of the resonance

These effects may be (partially) washed out by experimental precision (**smearing**)

Backup: Single Higgs production

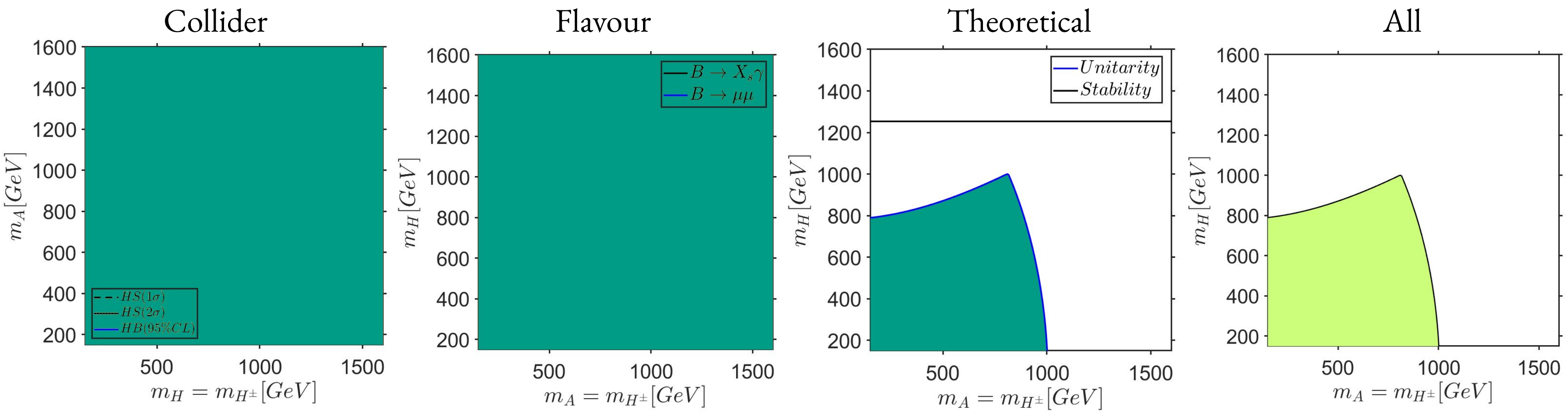


Top pair threshold ⟶ gives a hint on the results for Higgs pair production

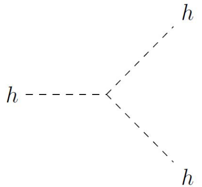
[LHC Higgs Working Group: CERN Yellow Report 4]

Backup: Constraints

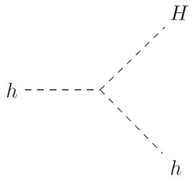
BP: Type I, $\cos(\beta-\alpha)=0.2$, $\tan\beta=10$, $m_{12}^2=m_H^2\cos^2\alpha/\tan\beta$



Backup: Feynman rules for triple Higgs couplings

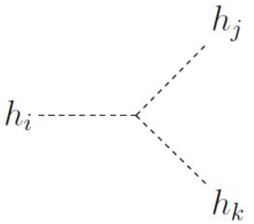


$$\lambda_{hhh} = \frac{1}{2v^2}\left\{m_h^2 s_{\beta-\alpha}^3 + \left(3m_h^2 - 2\bar{m}^2\right) c_{\beta-\alpha}^2 s_{\beta-\alpha} + 2\cot 2\beta \left(m_h^2 - \bar{m}^2\right) c_{\beta-\alpha}^3\right\}$$



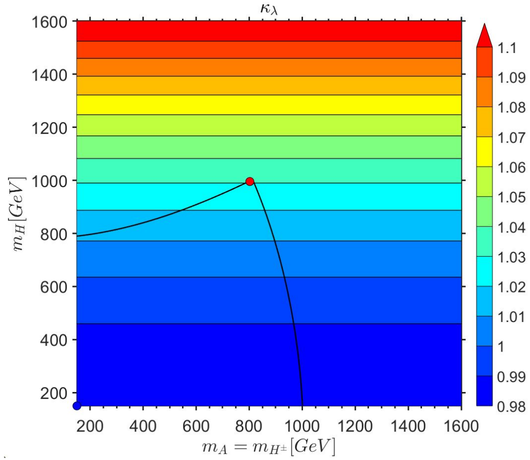
$$\lambda_{hhH} = \frac{-c_{\beta-\alpha}}{2v^2}\left\{\left(2m_h^2 + m_H^2 - 4\bar{m}^2\right) s_{\beta-\alpha}^2 + 2\cot 2\beta \left(2m_h^2 + m_H^2 - 3\bar{m}^2\right) s_{\beta-\alpha} c_{\beta-\alpha} - \left(2m_h^2 + m_H^2 - 2\bar{m}^2\right) c_{\beta-\alpha}^2\right\}.$$

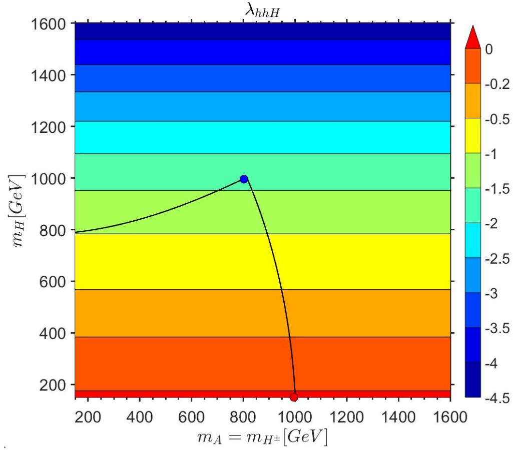
Notation:



$$= -i\, v\, n!\, \lambda_{h_i h_j h_k}$$

n = number of identical Higgses

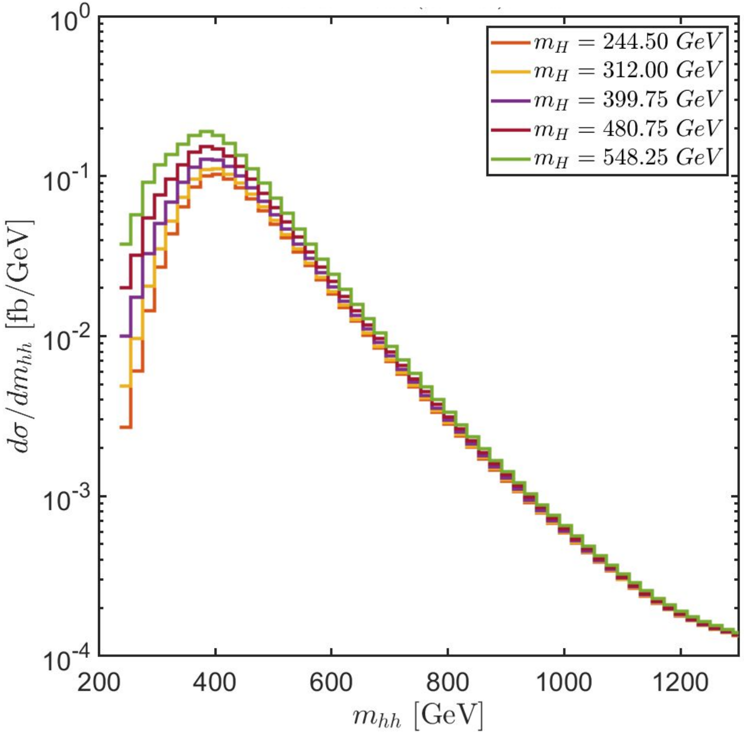




$$\bar{m}^2 = \frac{m_{12}^2}{sin(\beta)cos(\beta)}$$

Smearing applied on the invariant mass distributions

BP: Type I, $\cos(\beta-\alpha) = 0.1$, $\tan\beta = 10$, $m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$, $m_H = m_A = m_{H^\pm}$



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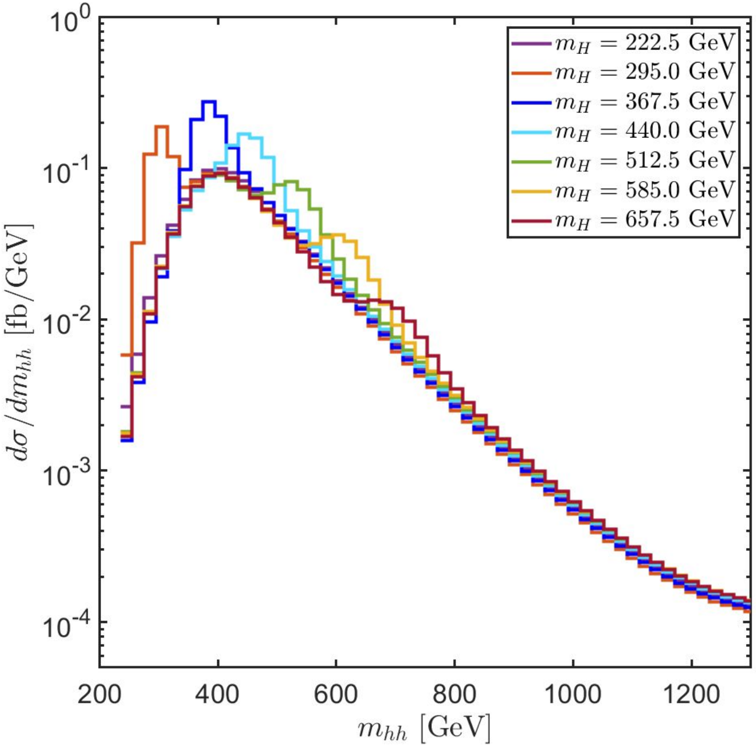
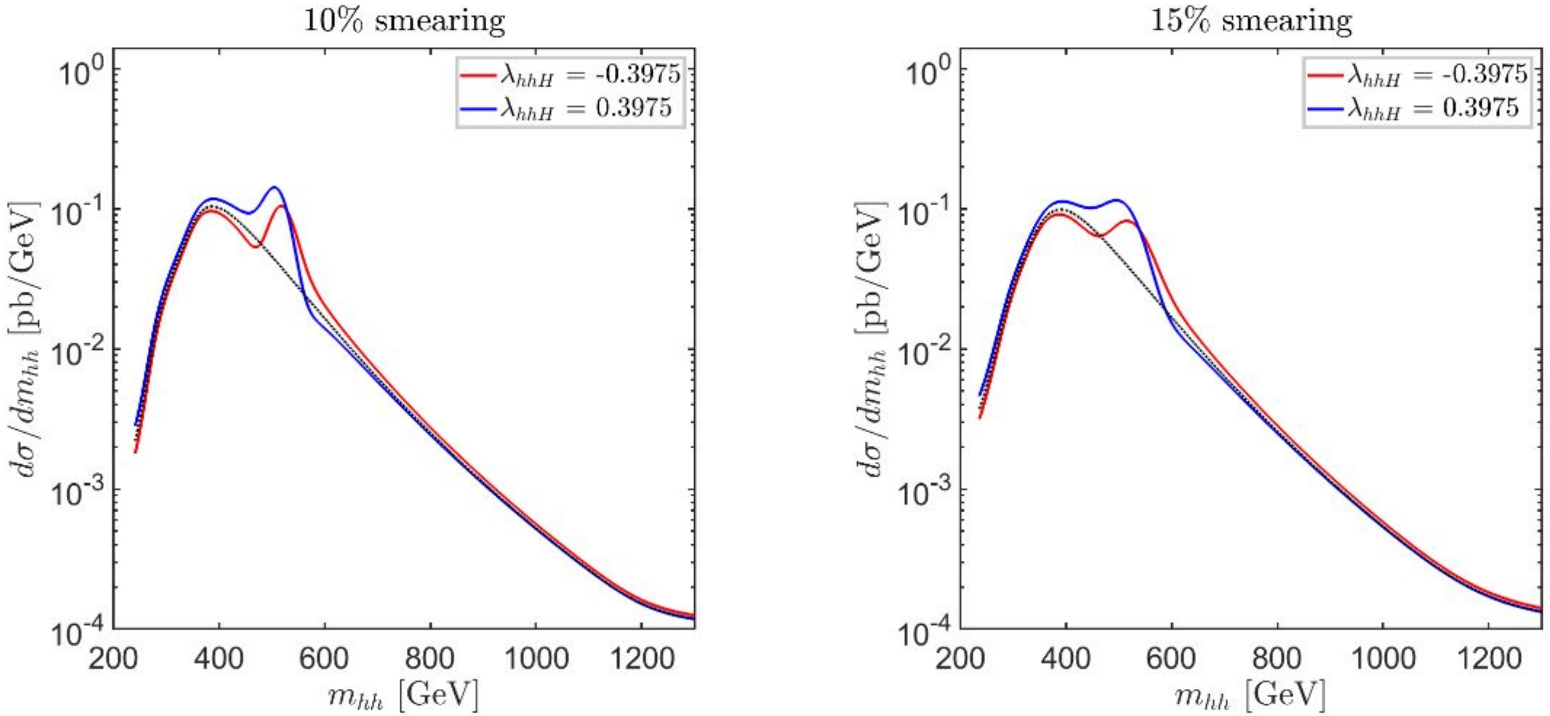
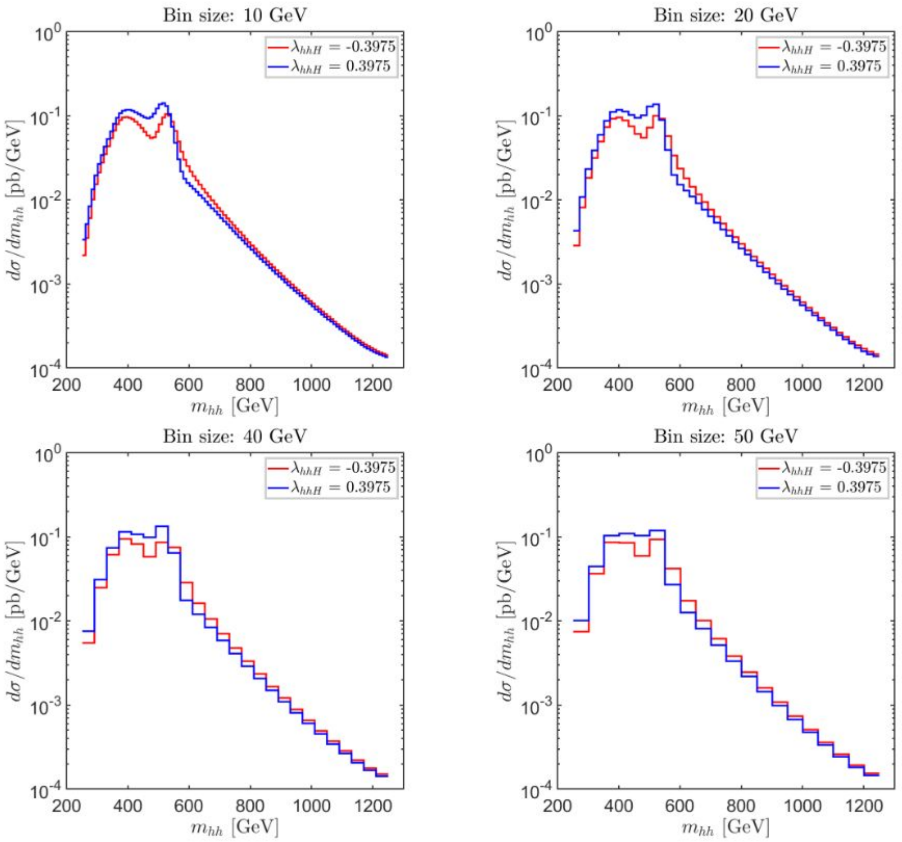


Smearing applied on the structure of the resonance



Binning applied on the structure of the resonance



15 % smearing