BSM Triple Higgs Couplings at the LHC

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based on arXiv: 2212.11242 with Francisco Arco, Sven Heinemeyer and Margarete Mühlleitner

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The 2HDM model

[Santos, Barroso: arXiv: 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: $m_h,\ m_A,\ m_H,\ m_{H^\pm},\ m_{12}^2, v,\ \cos(\beta-\alpha),\ \tan\beta$

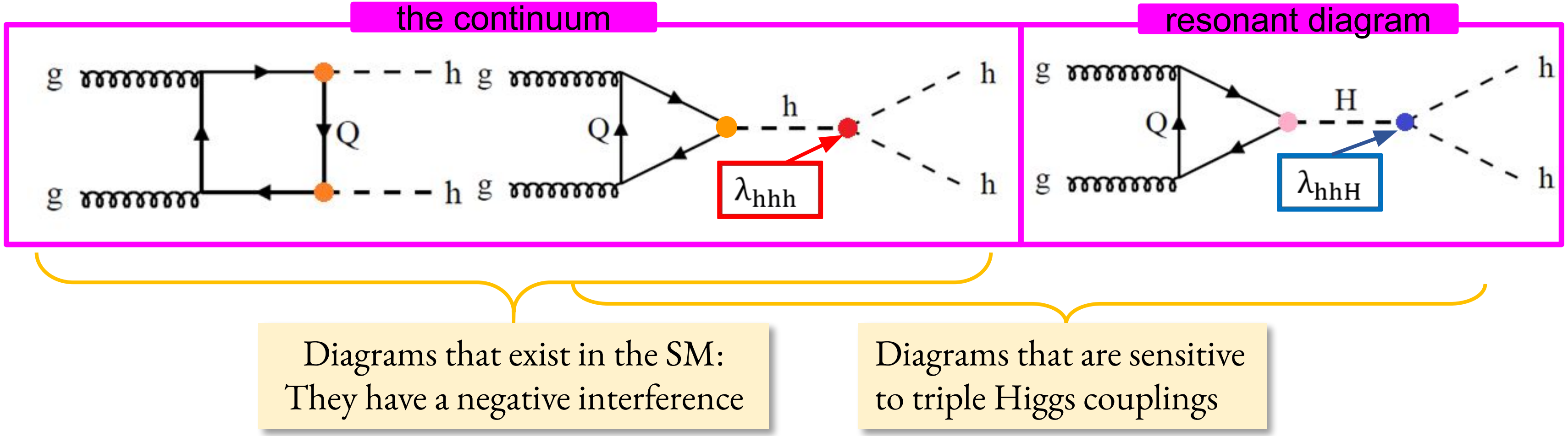
$\tan\beta = v_2/v_1$
$v^2 = v_1^2 + v_2^2 \sim (246\ \text{GeV})^2$

- **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: 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



$\sigma_{SM} \sim$ 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: 2112.12515]

Triple Higgs Couplings

[ATLAS-CONF-2022- 050]

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

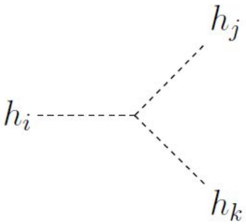
$$\kappa_\lambda = \lambda_{hhh} / \lambda_{hhh}^{SM}$$

[-0.4 < κ_λ < 6.3] (95% CL at LHC Run II)

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

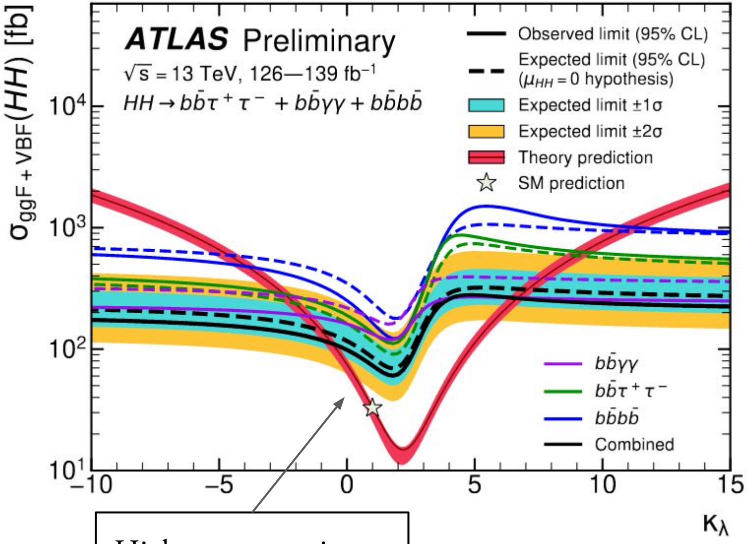
- Higher luminosity needed → what can be expected from HL-LHC?

- Notation:



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

n = number of identical Higgses
All couplings are at tree level



Higher cross section for lower values of κ_λ

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

Type I

κ_λ = [-0.5, 1.3]

λ_{hhH} = [-1.7, 1.6]

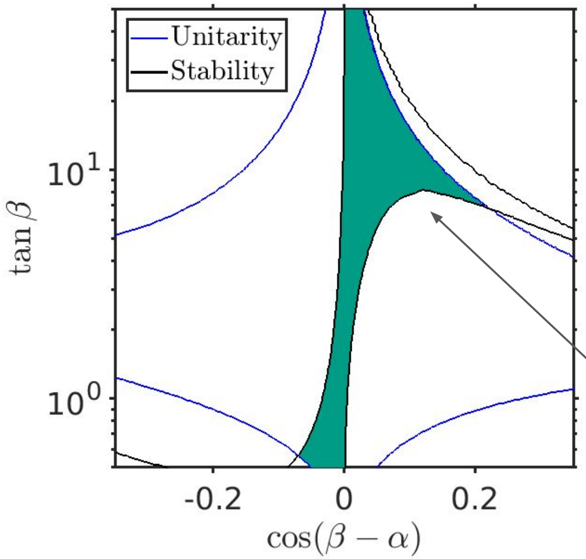
[Arco, Heinemeyer, Herrero: arXiv: 2003.12684]

Benchmark planes

[Arco, Heinemeyer, Herrero: arXiv: 2005.10576]

We scan the 2HDM parameter space fixing all but two parameters and look for large deviations in the trilinear Higgs couplings from the SM in the resulting benchmark planes

$$\text{Type I, } m_H = m_A = m_{H^\pm} = 1000 \text{ GeV, } m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$$



Colored area is allowed!

- **EWPO** → impose a condition on the Higgs boson masses: $(m_{H\pm}-m_H) \sim 0$ and/or $(m_{H\pm}-m_A) \sim 0$
- Theoretical:

Unitarity: from the 2 → 2 processes scattering amplitude
Stability: boundedness from below of the potential

Benchmark planes

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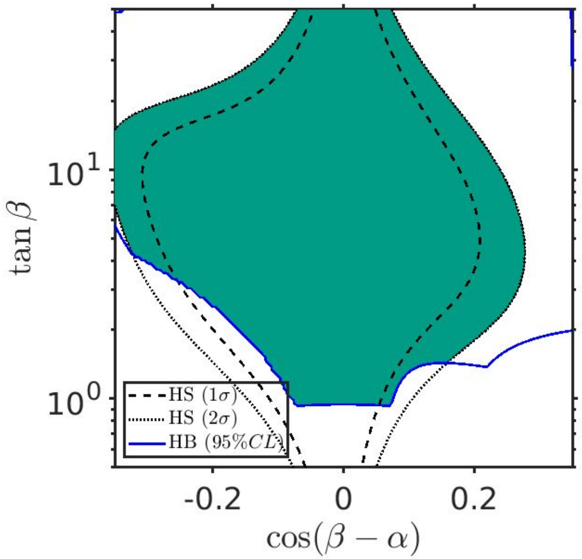

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- Collider searches and measurements:

Higgs Bounds: experimental limits from direct searches

Higgs Signals: consistency with the signal strengths of the 125 GeV Higgs

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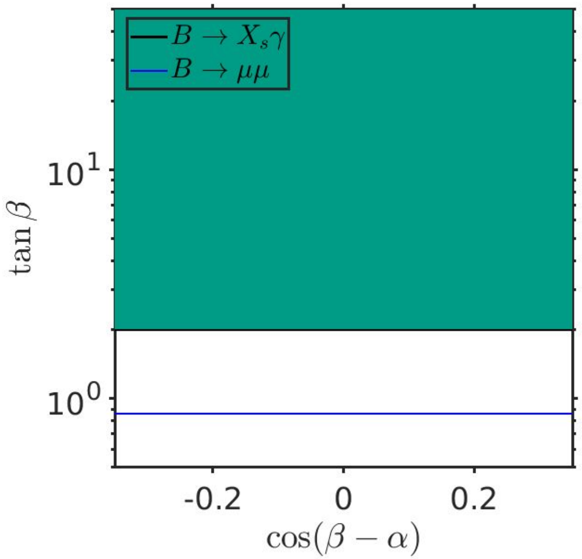

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- **Flavour observables** → $B \to X_S\gamma$ and $B_S \to \mu\mu$ (calculated with SuperIso)

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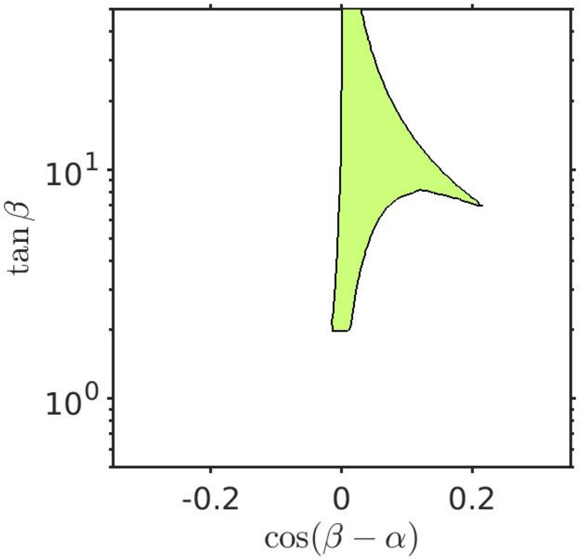

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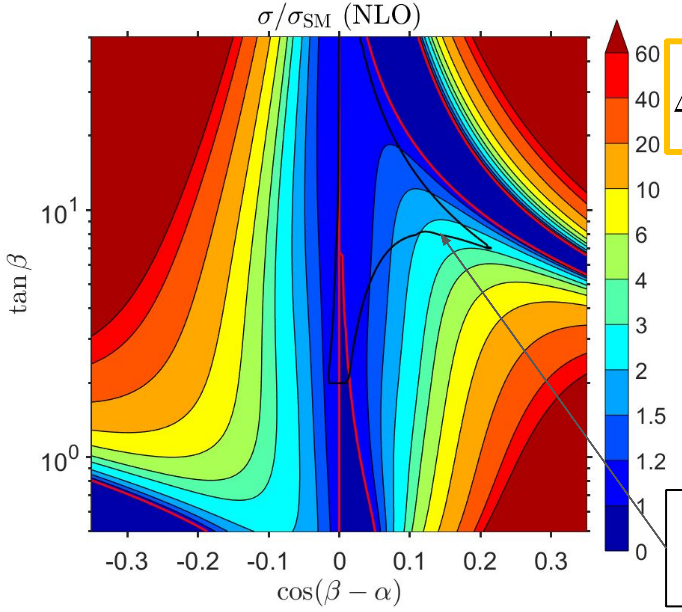
Total di-Higgs production cross section

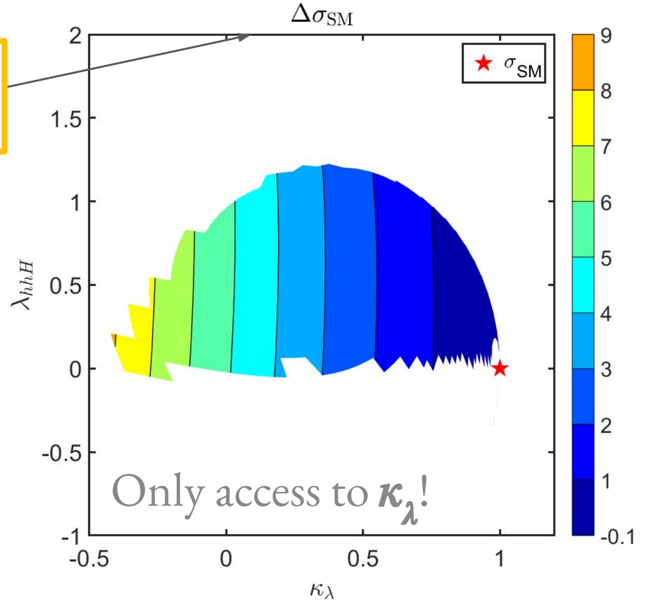
$m_H = m_A = m_{H^\pm} = 1000$ GeV
$m_{12}^2 = (m_H^2 \cos^2\alpha)/\tan\beta$



$$\Delta\sigma_{SM} \equiv \frac{xs_{2HDM} - xs_{SM}}{\delta xs}$$

$$\delta xs = xs/4.5$$

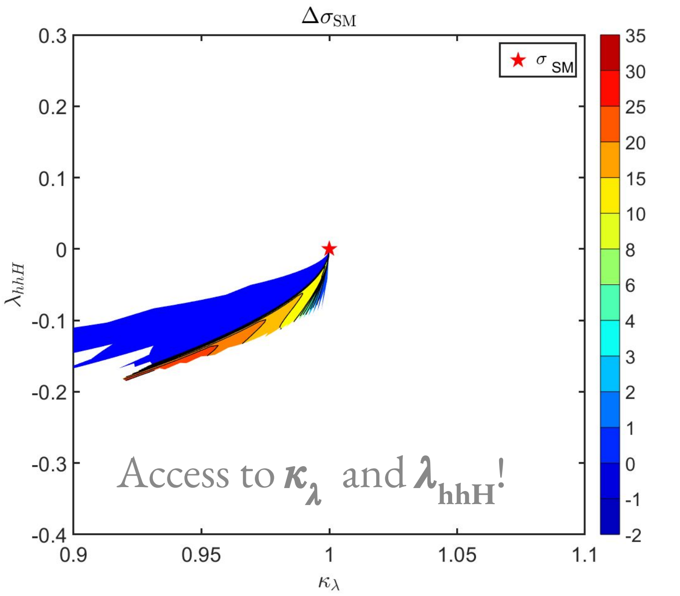
Projected significance in standard deviations of the total di-Higgs production: **4.5σ**

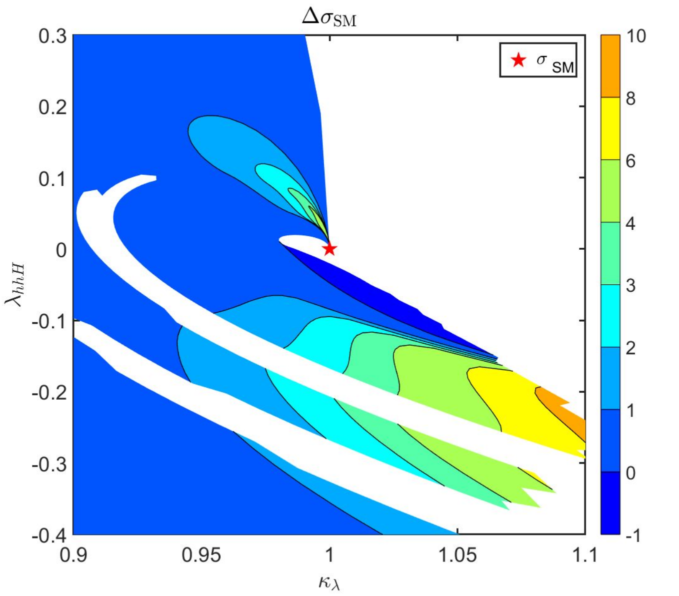


- NLO QCD corrections implemented in HPAIR (in the heavy top quark limit)
- **Largest enhancements** inside the allowed region (black contour) ~ $3\sigma_{SM}$ → due to deviations in κ_λ
- **Expected sensitivity** to the deviation of the xs: up to 8σ away from the SM (above 2σ for $\kappa_\lambda < 0.6$)

$$m_H = m_A = m_{H^\pm}$$
$$m_{12}^2 = (m_H^2 \cos^2\alpha)/\tan\beta$$
$$\tan(\beta) = 10$$

BSM Couplings





This scenario features a resonant enhancement of the cross section, i.e. the largest enhancement is due to the H contribution in the s-channel at m_H~350-450 GeV

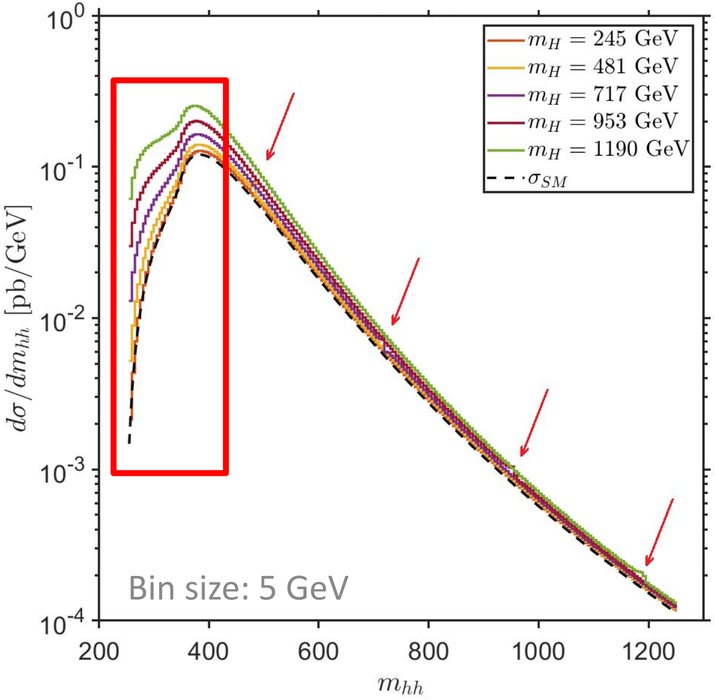
- Very large enhancements for $\cos(\beta\text{-}\alpha) < 0$ up to $8\sigma_{SM}$ that lead to deviations up to 35σ.
- Also large enhancements for $\cos(\beta\text{-}\alpha) < 0$ up to $3\sigma_{SM}$ that lead to deviations up to 10σ.

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

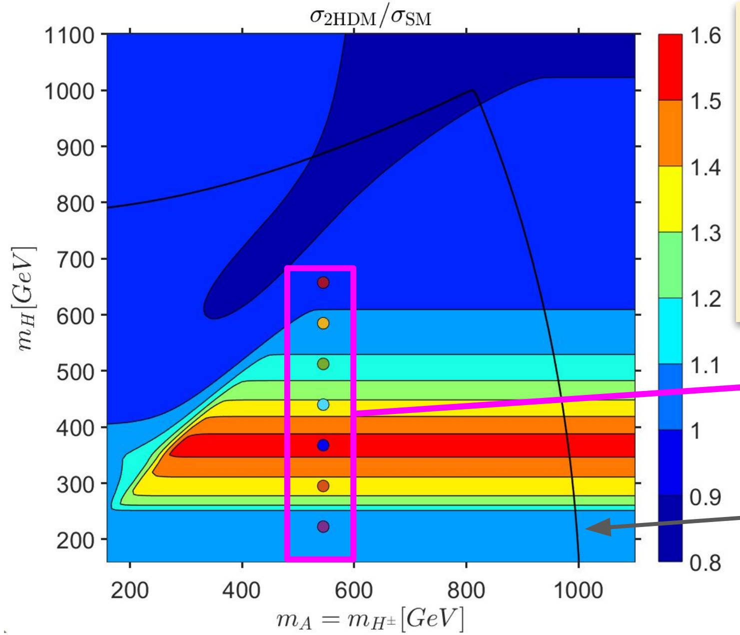
- Resonant contribution very suppressed due to very small top Yukawa $\xi^t_H \sim 10^{-4}$

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

Effect of the mass of the heavy Higgs

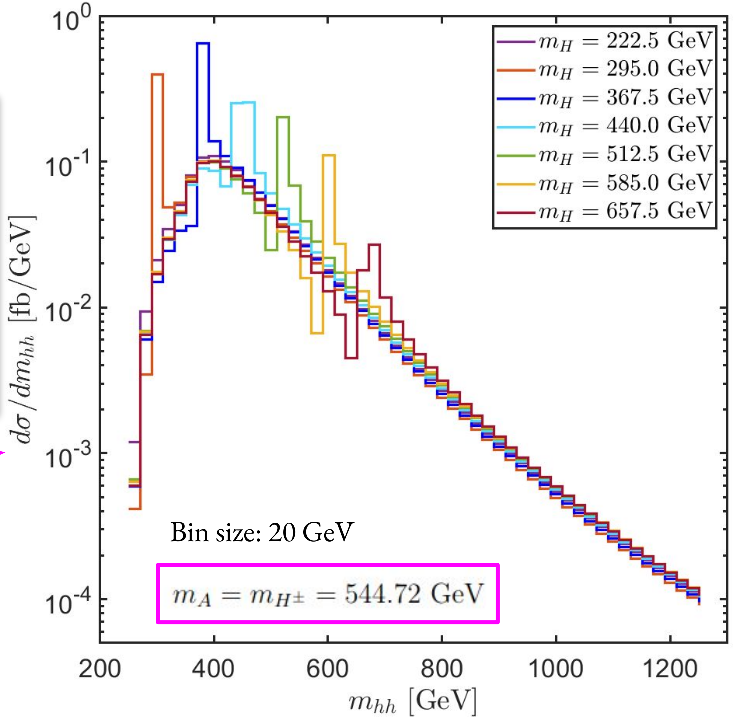
- We vary the mass of the heavy Higgs boson leaving the rest of the parameters of the model fixed.

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**

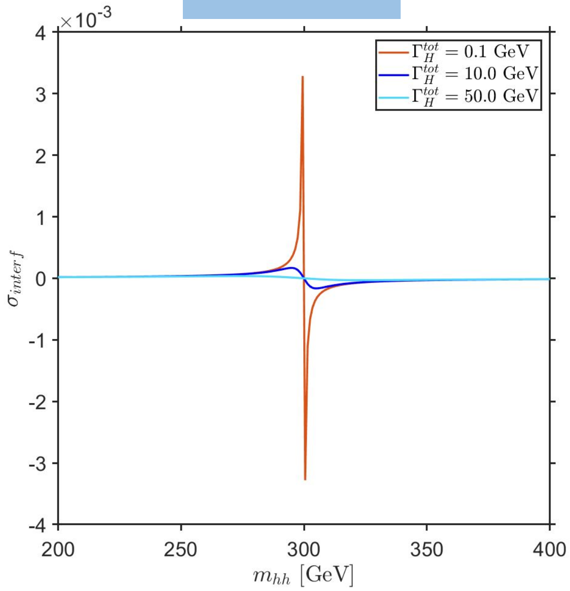
Allowed region inside the black contour.



Effect of the total decay width

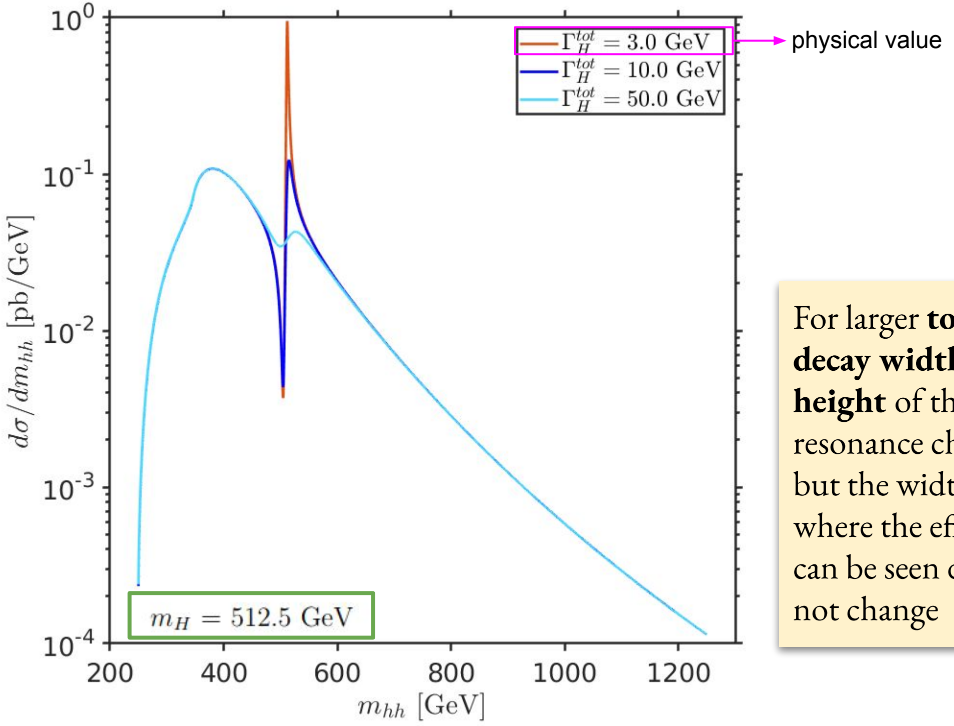
$$\frac{1}{Q^2 - M^2_{h/H} + i\Gamma_{h/H} M_{h/H}}$$

Toy model



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

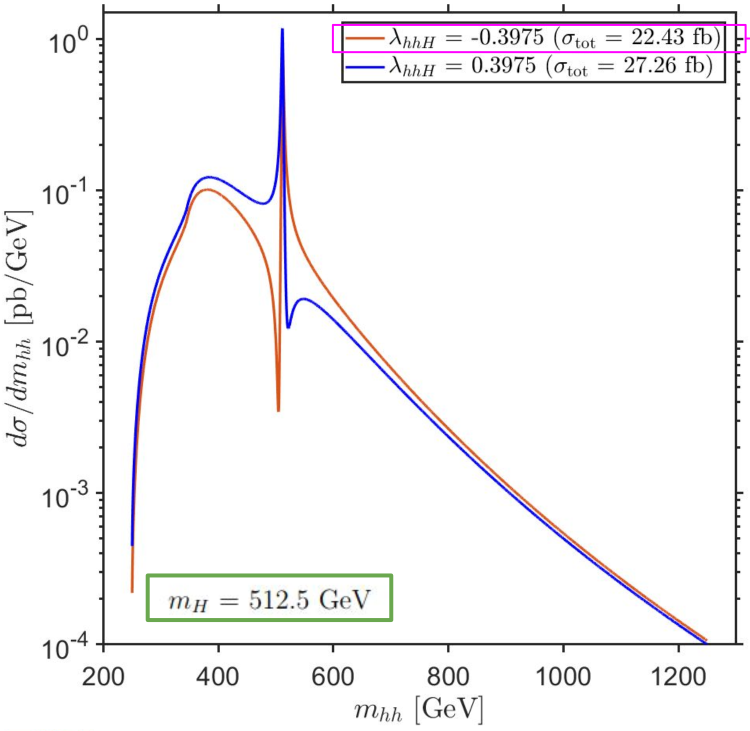
- For the green point of the previous benchmark plane we artificially change the total decay width of the heavy Higgs H:



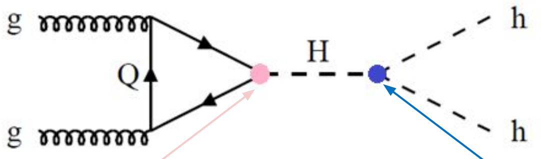
For larger **total decay widths** the **height** of the resonance changes but the width where the effect can be seen does not change

Relative sign of the couplings in the resonance

- 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}

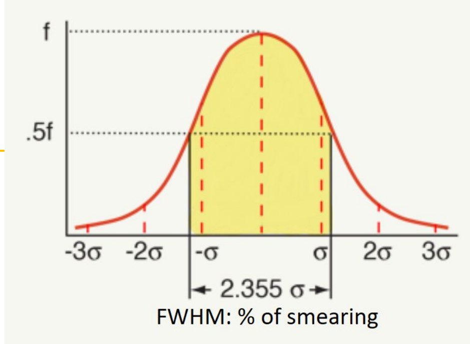
The **relative sign** of the top Yukawa and the BSM coupling to the heavy Higgs gives a **structure** to the resonance:

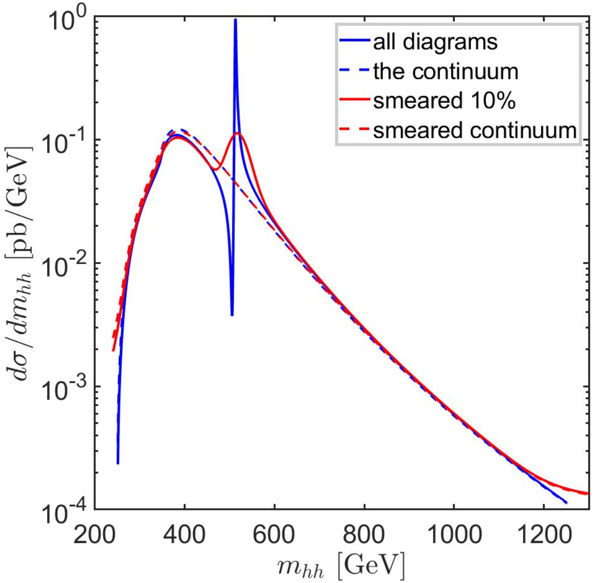
sign $(\lambda_{hhH} \cdot \xi_H^t)$	structure
+	peak-dip
-	dip-peak

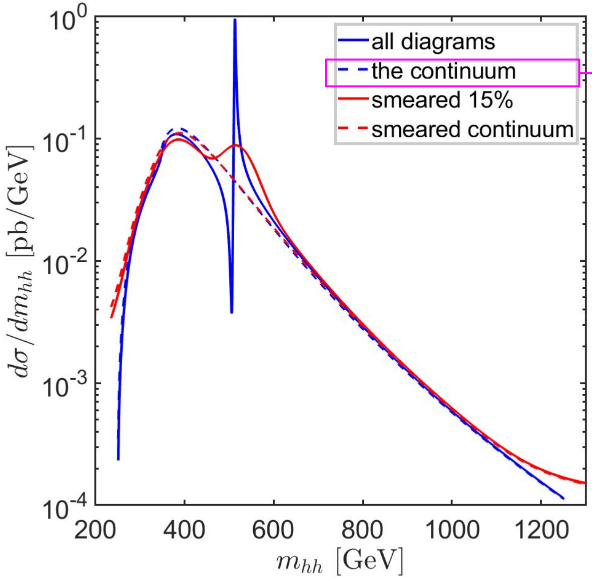
- Will this effect remain in an experimental setup?

Experimental challenges: smearing

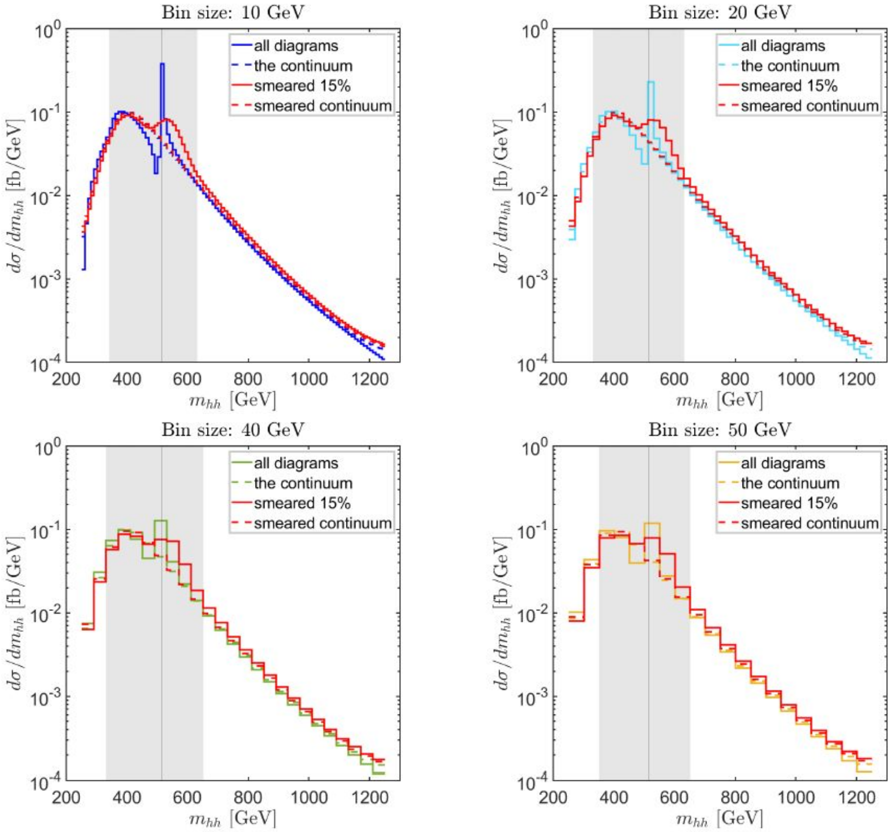
- Differential cross section measurements are affected by the finite resolution of particle detectors → observed spectrum is "**smeared**"
- We try to mimic this effect by artificially smearing the theoretical prediction introducing **Gaussian uncertainties** in the invariant mass







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

$$R := \frac{\sum_i |N_i^R - N_i^C|}{\sqrt{\sum_i N_i^C}}$$

Bin size	R
10 GeV	84.9
20 GeV	86.5
40 GeV	86.8
50 GeV	87.5

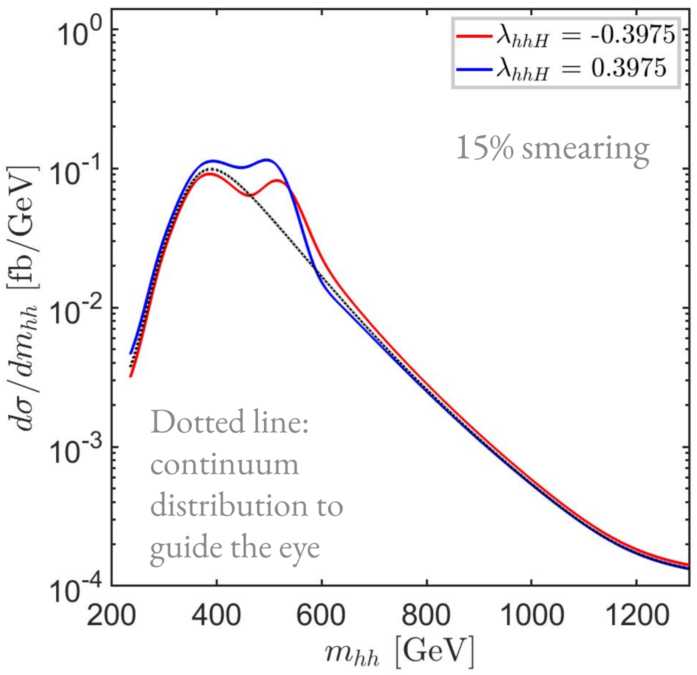
- Window definition:

$|N^R - N^C| >$ (bin size)×20

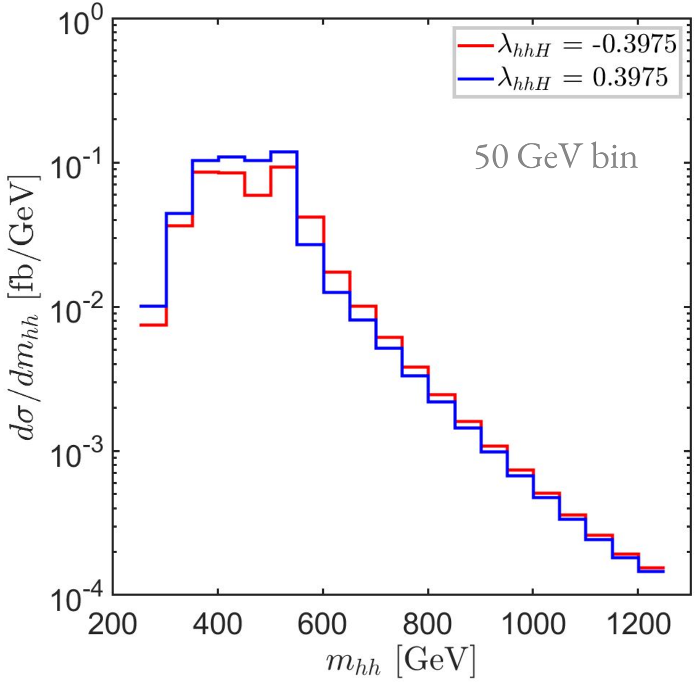
→ Smearing dilutes more the resonance than binning

Relative sign of the couplings in the resonance

Applying smearing:



Applying first smearing and then binning:



The structure of the resonance does not leave a measurable imprint once exp. uncertainties are evaluated

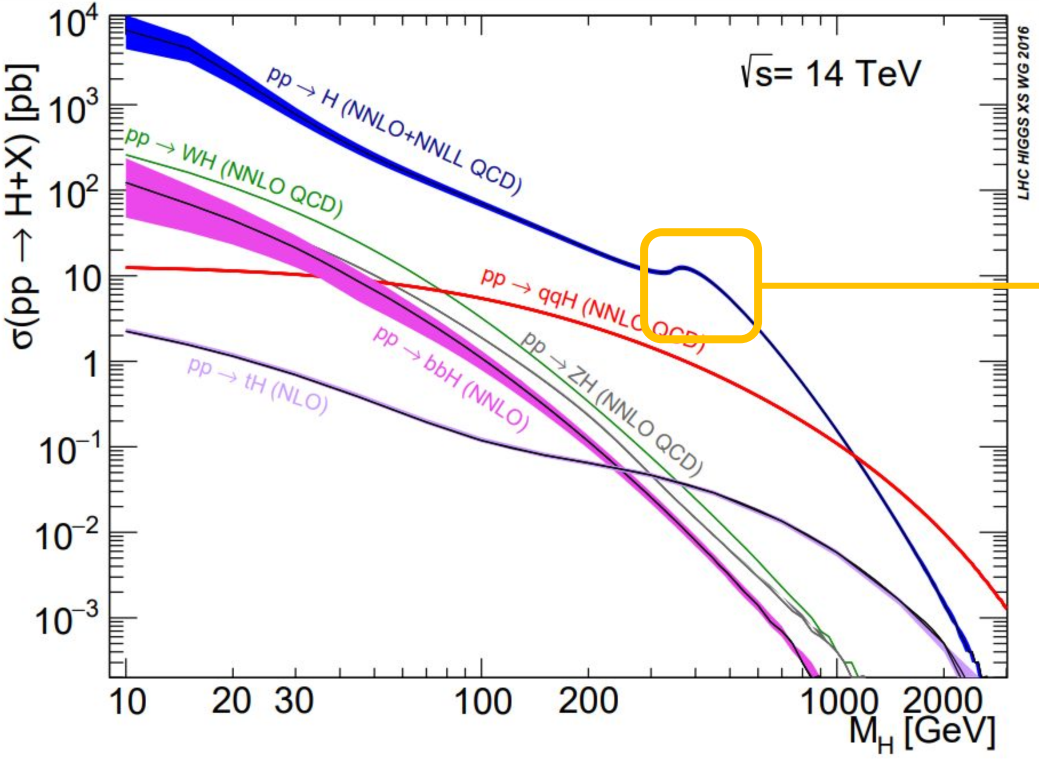
Conclusion

- Differences in the measured **di-Higgs production cross section** can originate from:
    1. deviations in $\boldsymbol{\kappa_\lambda}$
    2. additional **'resonant'** contributions

  → Cannot be disentangled form a measurement of the total cross section alone
  → High sensitivity can be reached at HL-LHC in the regions far from the alignment limit and with heavy scalar masses within 350-450 GeV
- **Invariant mass distributions** give information about **resonant production** that can be embedded in BSM models:
    1. mass of the intermediate Higgs boson → position
    2. total decay width → height of the resonance
    3. relative sign of the couplings → structure of the resonance

  → These effects may be (partially) washed out by experimental precision (**smearing and binning**)
  The relative sensitivity to the coupling λ_{hhH} was analyzed by means of the variable R

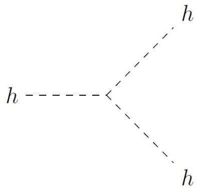
Backup: Single Higgs production



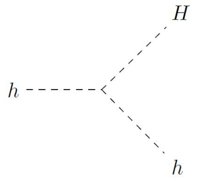
Top pair threshold ⟶ gives a hint on the results for Higgs pair production

[LHC Higgs Working Group: CERN Yellow Report 4]

Feynman rules for 2HDM THC

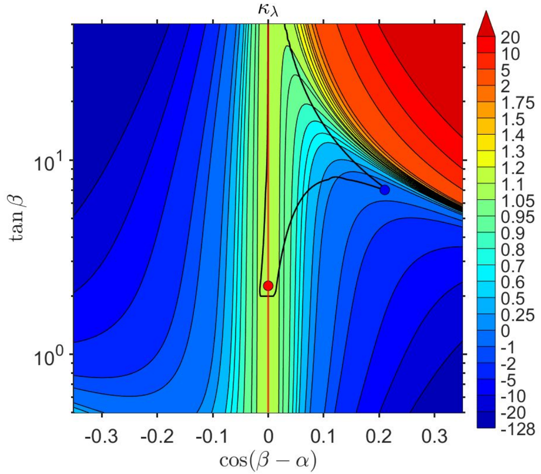


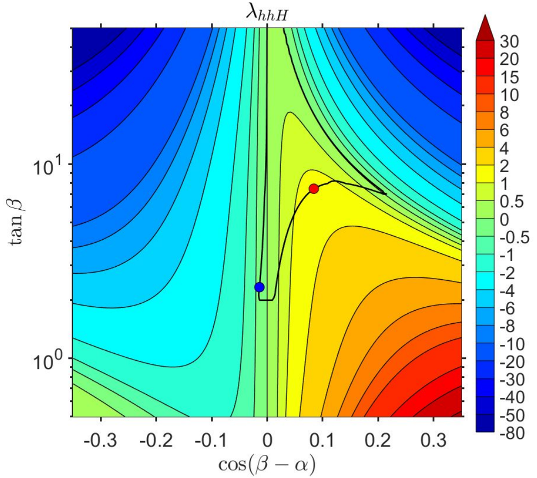
$$\lambda_{hhh} = \frac{1}{2v^2}\left\{m_h^2 s^3_{\beta-\alpha} + \left(3m_h^2 - 2\bar{m}^2\right) c^2_{\beta-\alpha} s_{\beta-\alpha} + 2\cot 2\beta \left(m_h^2 - \bar{m}^2\right) c^3_{\beta-\alpha}\right\}$$



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

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





$\kappa_\lambda \in [-0.4\,,\,1]$

$\lambda_{hhH} \in [-0.3\,,\,1.2]$

Backup: BP

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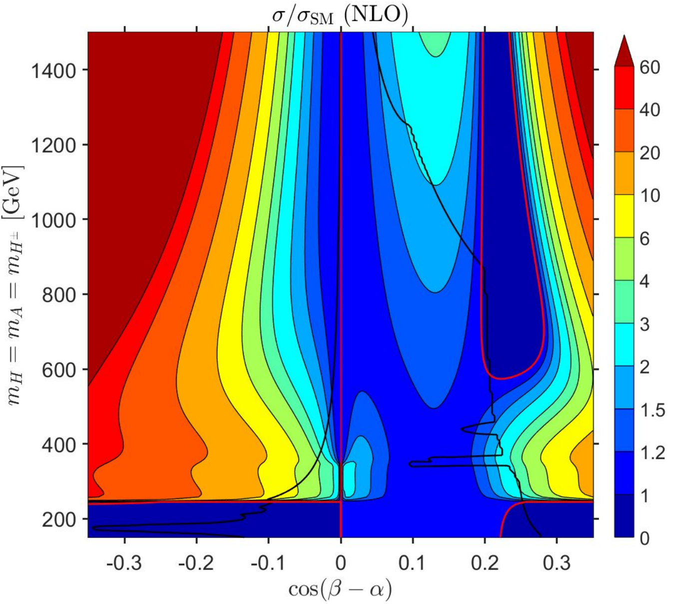
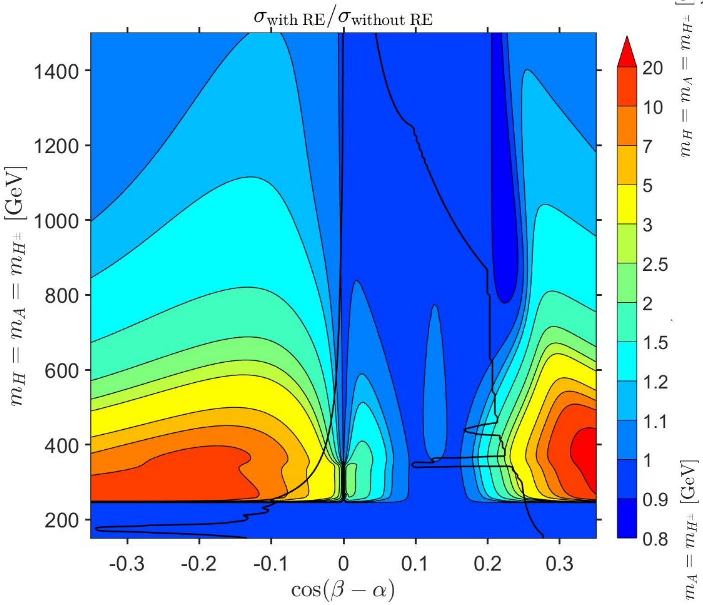
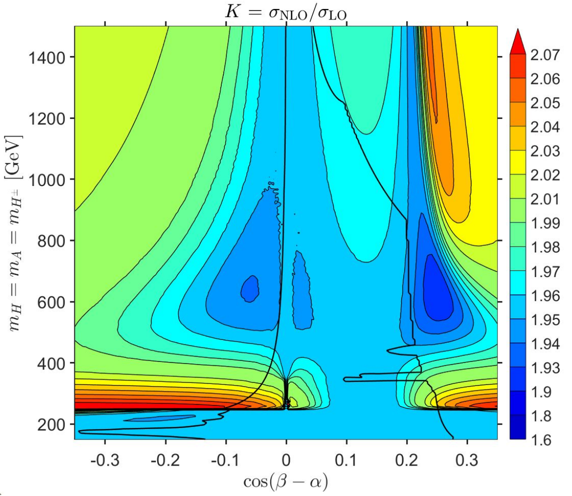
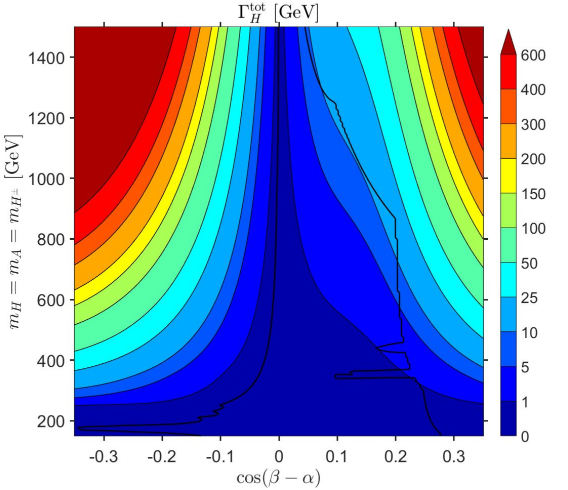






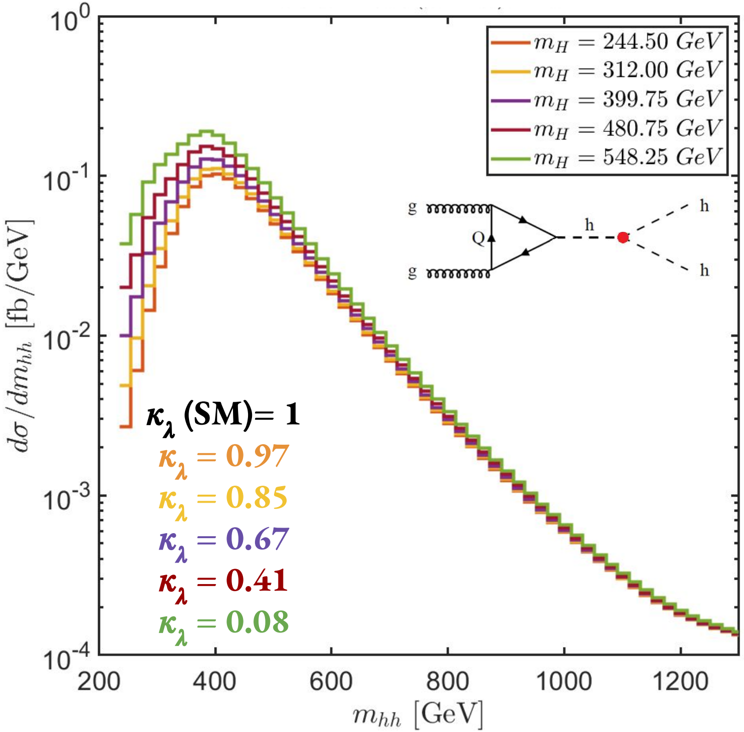


NLO calculation done with HPAIR

- Large enhancements up to $8\sigma_{SM}$ for $m_H \sim 2m_{top}$.
- No enhancement below $m_H \sim 250$ GeV → heavy Higgs is not on shell.
- Dominant contribution of the diagram involving $\boldsymbol{\lambda_{hhH}}$ at $m_H \sim 2m_{top}$.

Smearing applied on the invariant mass distributions

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



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