BSM triple Higgs couplings at the HL-LHC

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based on arXiv: 2212.11242

Two Higgs Doublet Model

[T. D. Lee (1973) Physical Review , Branco, Ferreira et al: arXiv: 1106.0034]

- **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** ($\Phi_1 \to \Phi_1$; $\Phi_2 \to -\Phi_2$) entails 4 Yukawa types (here only **Type I** analyzed)

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

- Potential:

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

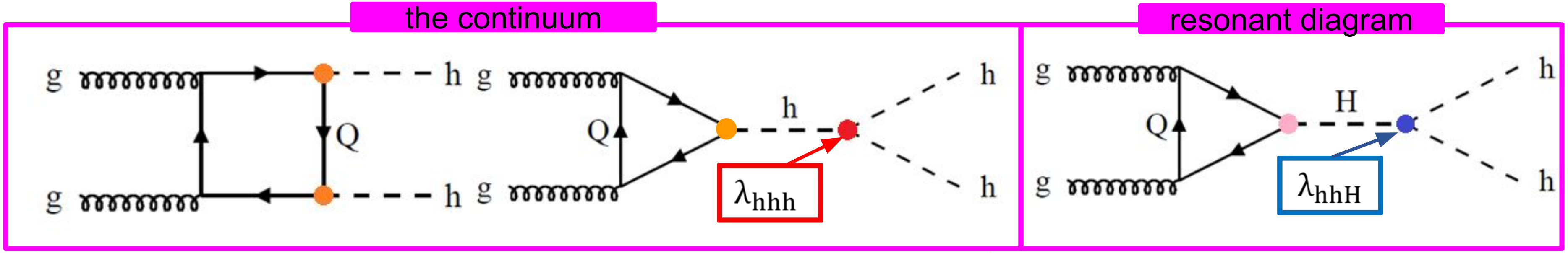
- Free parameters: $m_h,\ m_A,\ m_H,\ m_{H^\pm},\ m_{12}^2, v,\ \cos(\beta-\alpha),\ \tan\beta$

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

- **Phenomenological implications** can originate from:
  - → deviations in **couplings** to fermions, gauge bosons and triple Higgs coupling
  - → contributions of the **heavy scalars** in Higgs production/decay or in loops

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

Dominant process at the LHC → Gluon Fusion



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

Cross section prediction using a modified version of the code **HPAIR** that contains the **2HDM** model.

- Total cross section at NLO QCD in the heavy top limit
- Invariant mass distribution at LO [Abouabid, Arhrib, Azevedo, El Falaki, Ferreira, Mühlleitner, Santos: arXiv: 2112.12515]

Triple Higgs Couplings

[ATLAS-CONF-2022- 050]

Motivation: probe of **Higgs potential** and a window to BSM physics through its relation to:

* origin of EWSB

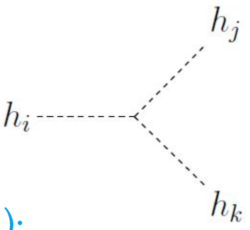
* large THC favour FOEWPT, a necessary condition for EW baryogenesis [Kanemura, Okada, Senaha: arxiv: 0411354, Noble, Perelstein: arXiv: 0711.3018]

Can have **large deviations** from SM predictions in BSM while the couplings to gauge bosons and fermions are very close to the SM values (in agreement with existing constraints)

Improving limits already have important impact on phenomenology

Notation:

$$\kappa_\lambda = \lambda_{hhh}/\lambda^{\mathrm{SM}(0)}_{hhh}$$



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

n = number of identical Higgses

2HDM Type II (tree level):

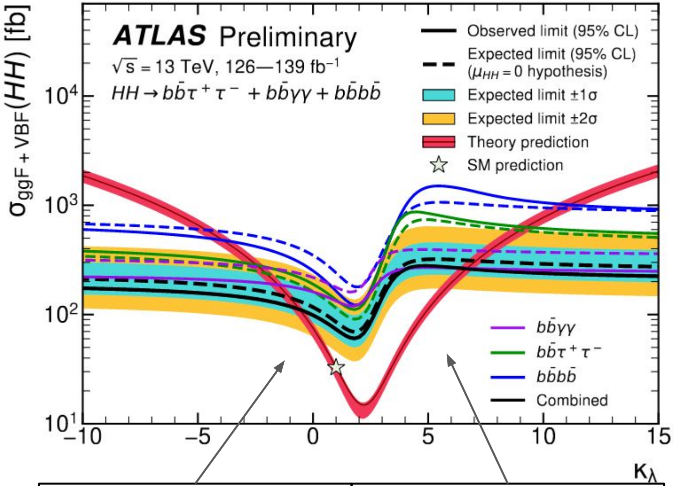
κ_λ = [- 0.5,1.3]; λ_{hhH}= [- 1.7,1.6] [Arco, Heinemeyer, Herrero: arXiv: 2003.12684]

Experimental status:

- access through Higgs pair production

$$\mu_{\mathrm{HH}} \leq 2.4$$

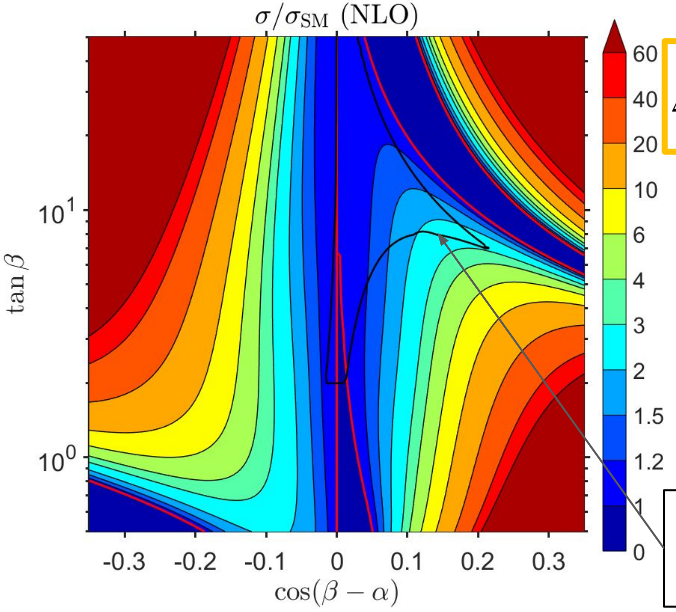
[$-0.4 < \kappa_\lambda < 6.3$] (95% CL at LHC Run II)



Higher cross section for lower values of κ_λ	Higher cross section for high values of κ_λ

Total di-Higgs production cross section

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



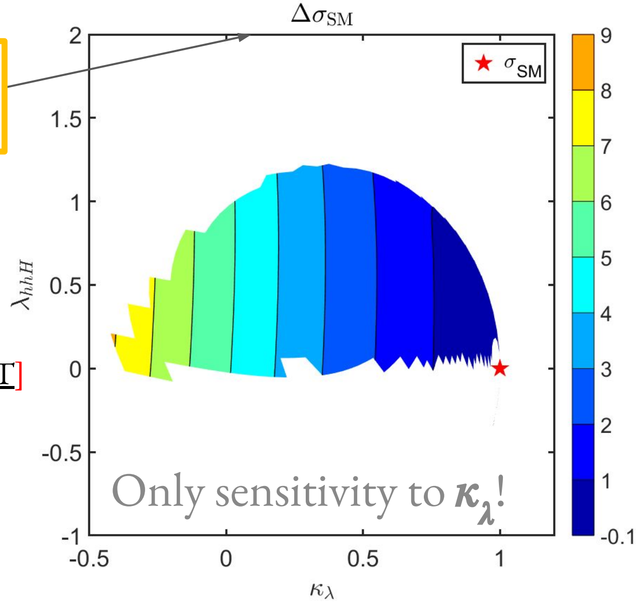
$$\Delta\sigma_{\rm SM} \equiv \frac{\mathbf{xs}_{\rm 2HDM} - \mathbf{xs}_{\rm SM}}{\delta\mathbf{xs}}$$

$$\delta\mathbf{xs} = \mathbf{xs}/4.5$$

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

[FERMILAB-CONF-19-468-E-T]

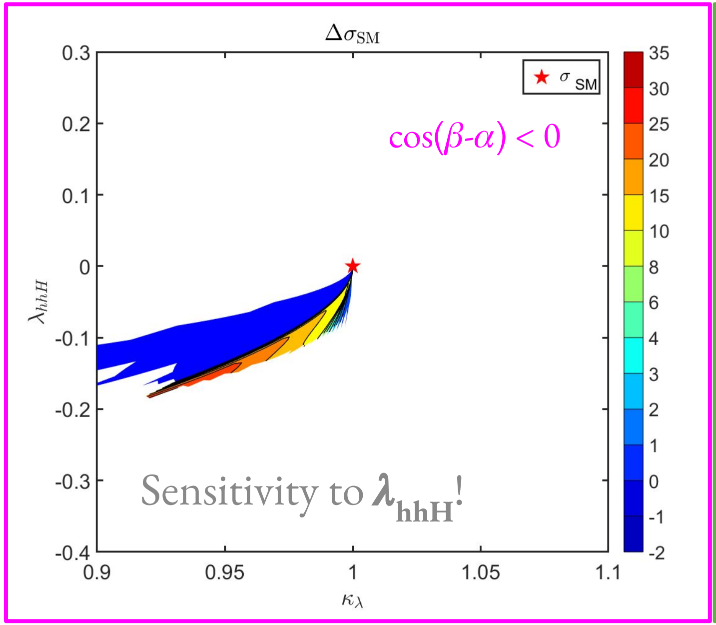
Allowed region inside the black contour!

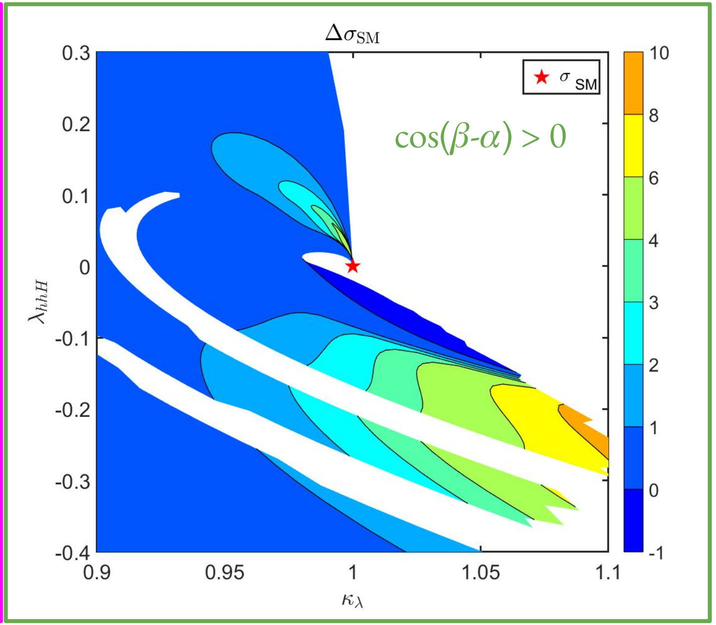


- NLO QCD corrections implemented in HPAIR (in the heavy top quark limit)
- **Largest enhancements** inside the allowed region (black contour) ~ $3\sigma_{SM}$ → due to deviations in $\boldsymbol{\kappa_\lambda}$
- **Expected sensitivity** to the deviation of the xs: up to 8σ away from the SM (above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

BSM Couplings

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





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

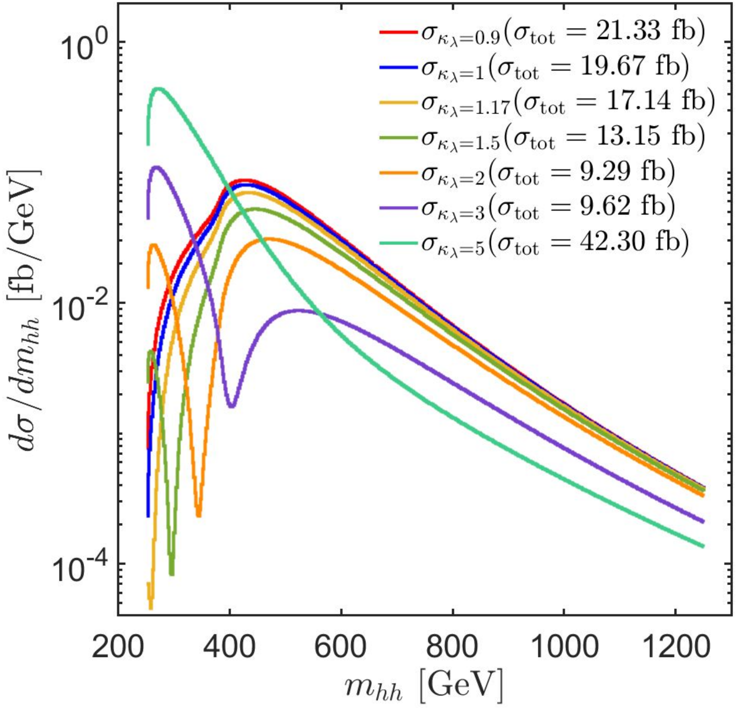
- Very large enhancements for $\cos(\beta\text{-}\alpha) < 0$ up to $8\sigma_{SM}$ that lead to deviations up to 35σ
- Also large enhancements for $\cos(\beta\text{-}\alpha) > 0$ up to $3\sigma_{SM}$ that lead to deviations up to 10σ
- Potential access to the BSM coupling λ_{hhH} is studied for the first time

  -> Need to look for a different observable to find better sensitivity to the THC -> **m_{hh} distributions**

Effect of changes of κ_λ in m_{hh}

Heavy Higgs contribution set to zero

- Changes in the invariant mass distribution in a non resonant scenario with *ad hoc* changes in κ_λ :



- The total cross section features the expected trend (i.e. minimum at $\kappa_\lambda \sim 2.5$)
- Larger sensitivity to κ_λ in the **low m_{hh} region**
- The differential cross section also has a minimum for masses of the final system of hh between 200-400 GeV due to a cancellation of the form factors in the continuum diagrams

$$\sigma \propto |C_\triangle F_\triangle + C_\Box F_\Box|^2$$

$$C_\triangle \propto \lambda_{hhh}$$

In the heavy top limit: $F_\triangle = \frac{2}{3}$; $F_\Box = -\frac{2}{3}$

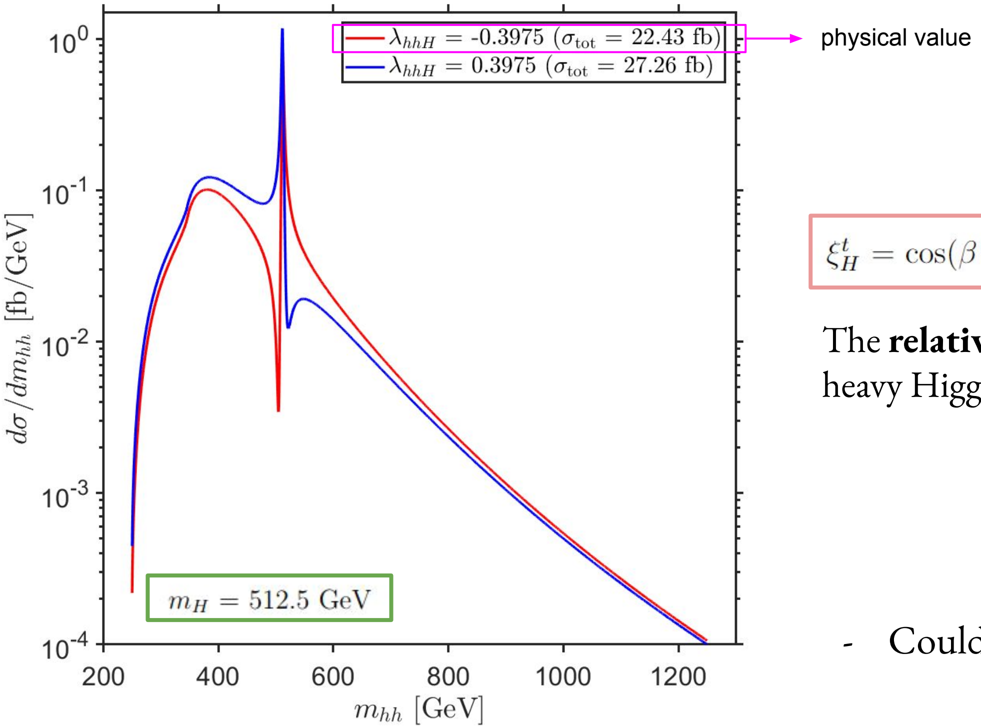
For $m_{hh} \sim 2m_t \sim 350$ GeV the heavy top limit is not valid and the cancellation is reduced

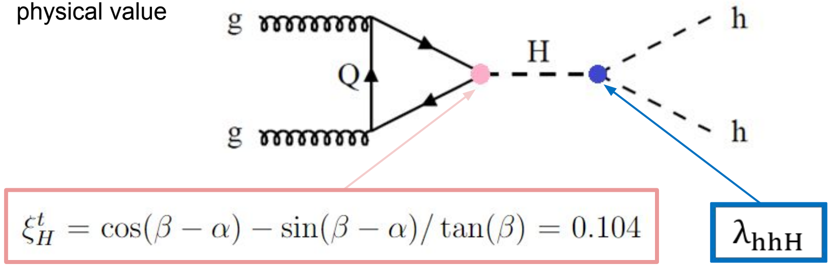
[Plehn, Spira, Zerwas : arXiv: 9603205]

Resonant H-exchange

Effect of changes of λ_{hhH} in m_{hh}

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



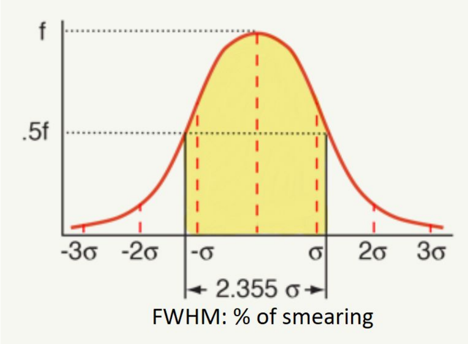


The **relative sign** of the top Yukawa and the BSM coupling to the heavy Higgs gives a **structure** to the resonance:

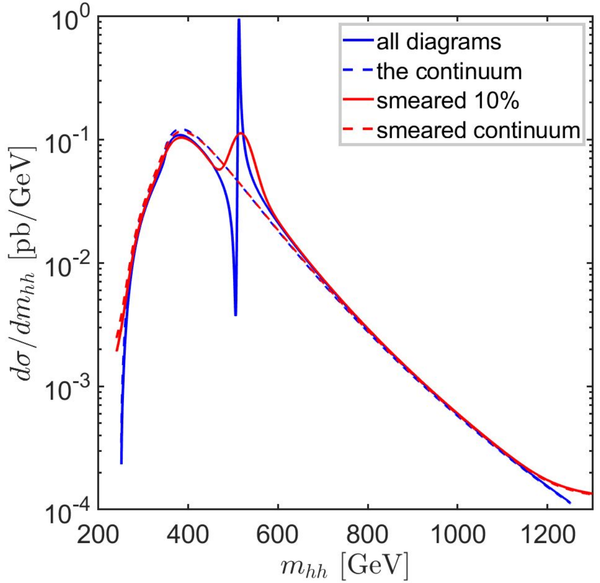
sign $(\lambda_{hhH} \cdot \xi_H^t)$	structure
+	peak-dip
-	dip-peak

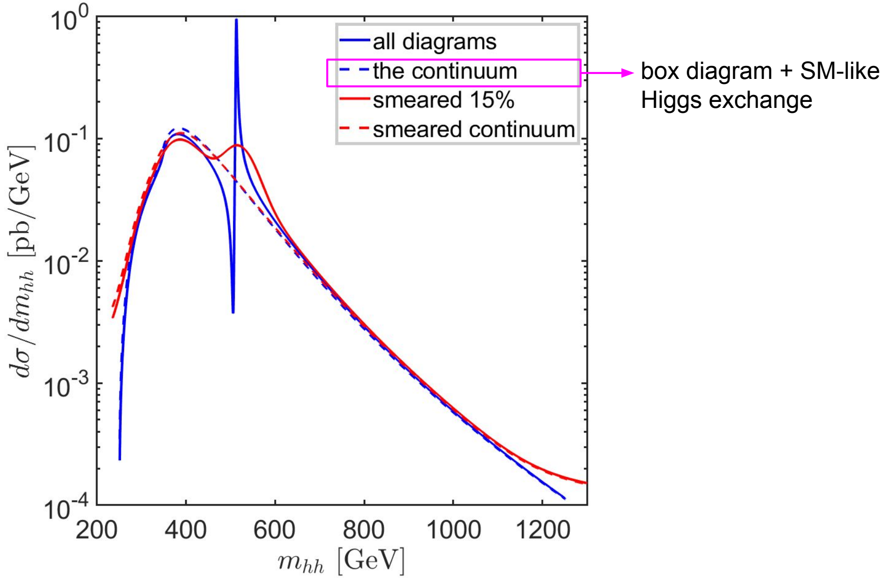
- Could one resolve this effect in an experimental setup?

Experimental challenges: smearing

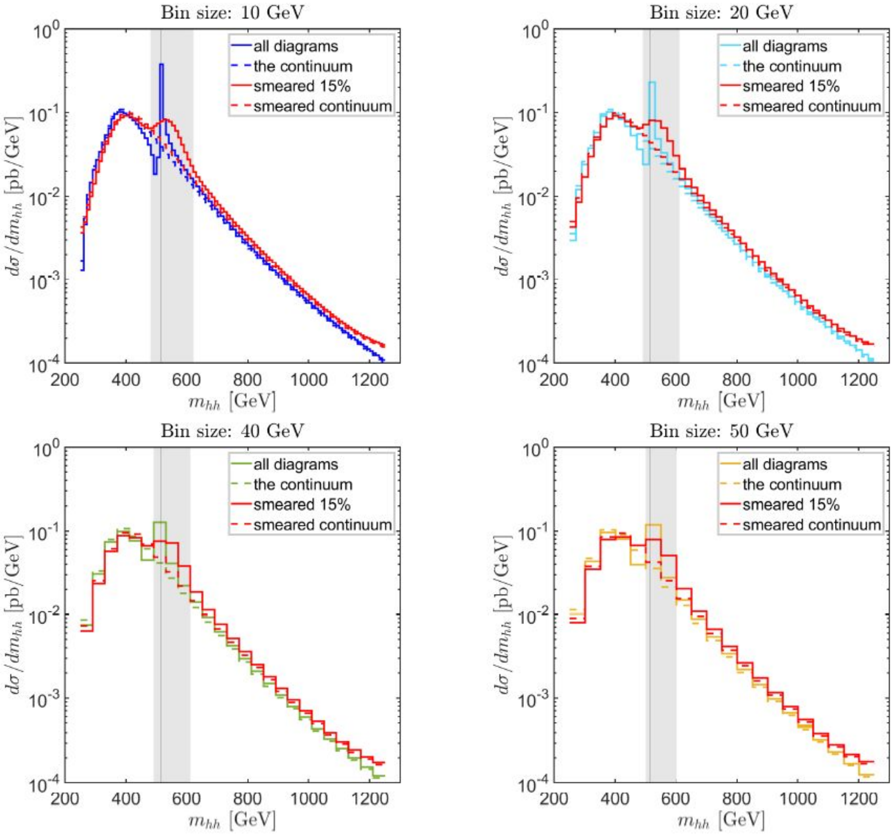


- Differential cross section measurements are affected by the finite resolution of particle detectors → observed spectrum is "**smeared**"
- We try to mimic this effect by artificially smearing the theoretical prediction introducing **Gaussian uncertainties** in the invariant mass





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

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

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

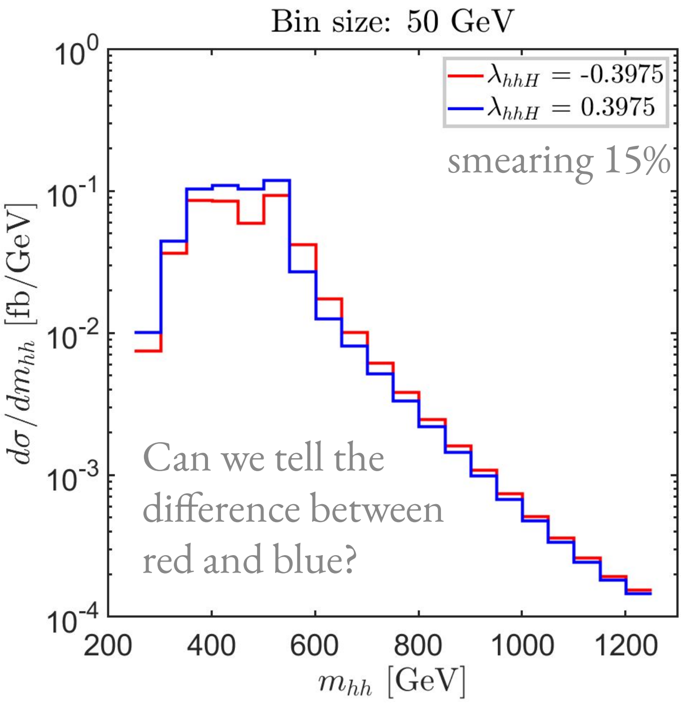
- Window definition:

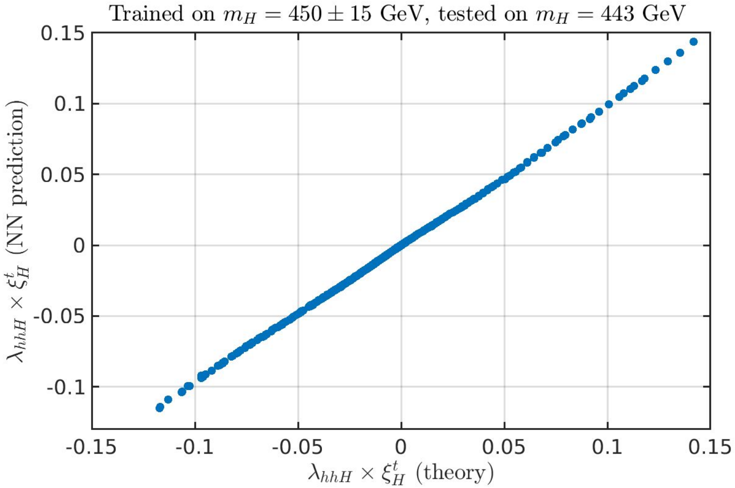
$(N^R - N^C) > (\text{bin size})/50$

→ Smearing dilutes more the resonance than binning

Experimental access to the product $\lambda_{hhH}\xi^t_H$

- We analyze the experimental access to the product of the couplings in the resonant diagram: $\lambda_{hhH}\xi^t_H$
- Strategy: input the data of the m_{hh} distributions for a whole benchmark plane into a fully connected NN





- The mass of the heavy Higgs is a source of uncertainty but it is not an input to the NN
- With enough data sets the prediction for distributions is very accurate

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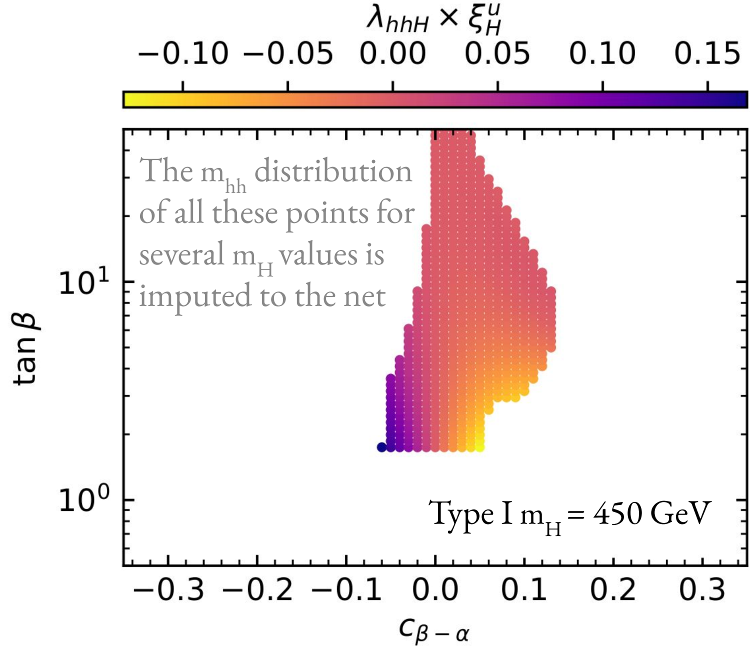

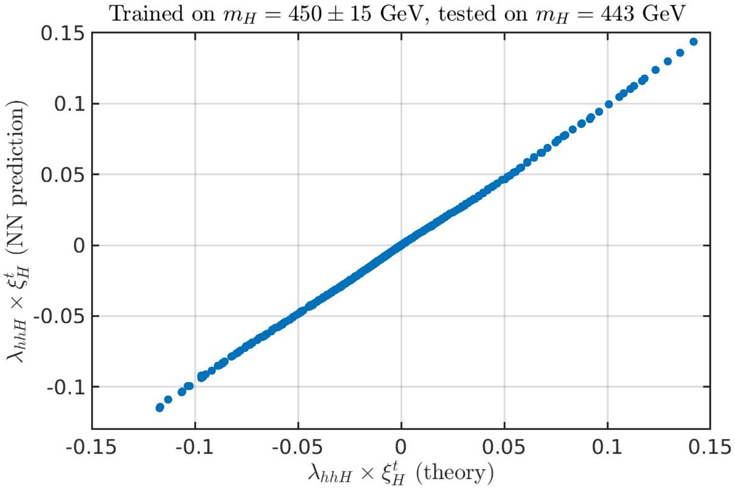

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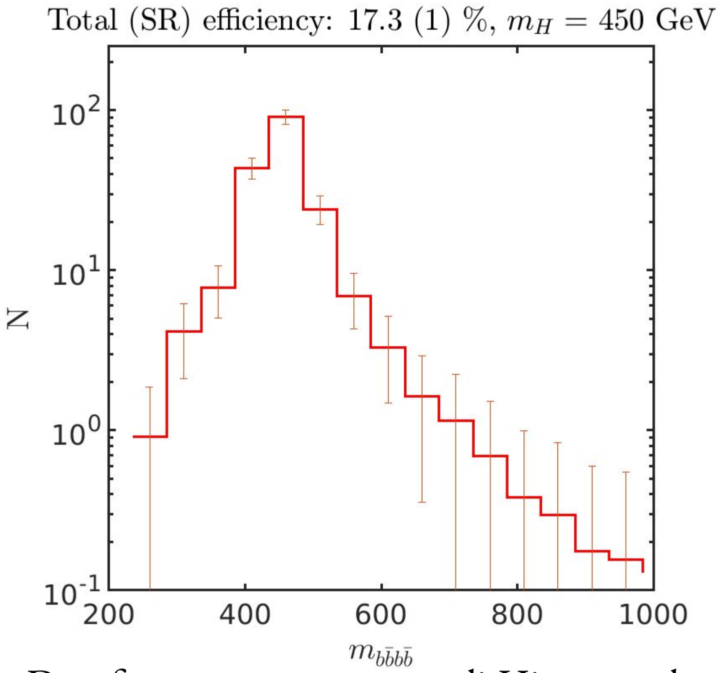
Further experimental uncertainties

We take into account **efficiency rates** of current experiments to estimate the statistical error of the distribution

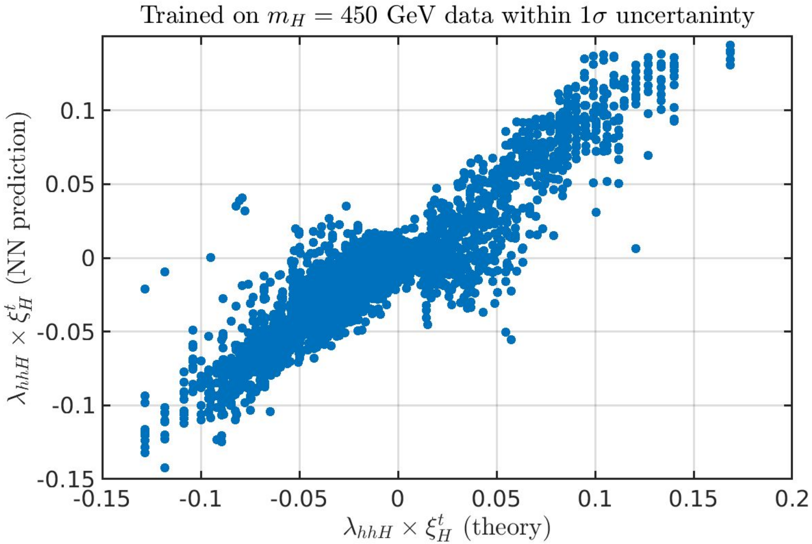


Data from current resonant di-Higgs searches:

[ATLAS: 2202.07288]

$N = \sigma \mathcal{L} \, BR(H \to bb) \, BR(H \to bb) \, \varepsilon$; $\varepsilon = \varepsilon_{TOT} \varepsilon_{SR}$

$\mathcal{L} = 3000 \, fb^{-1}$ ATLAS detector in HL-LHC



- Efficiency rates at HL-LHC will improve, but we neglected theoretical and systematic uncertainties due to lack of projections

Conclusions

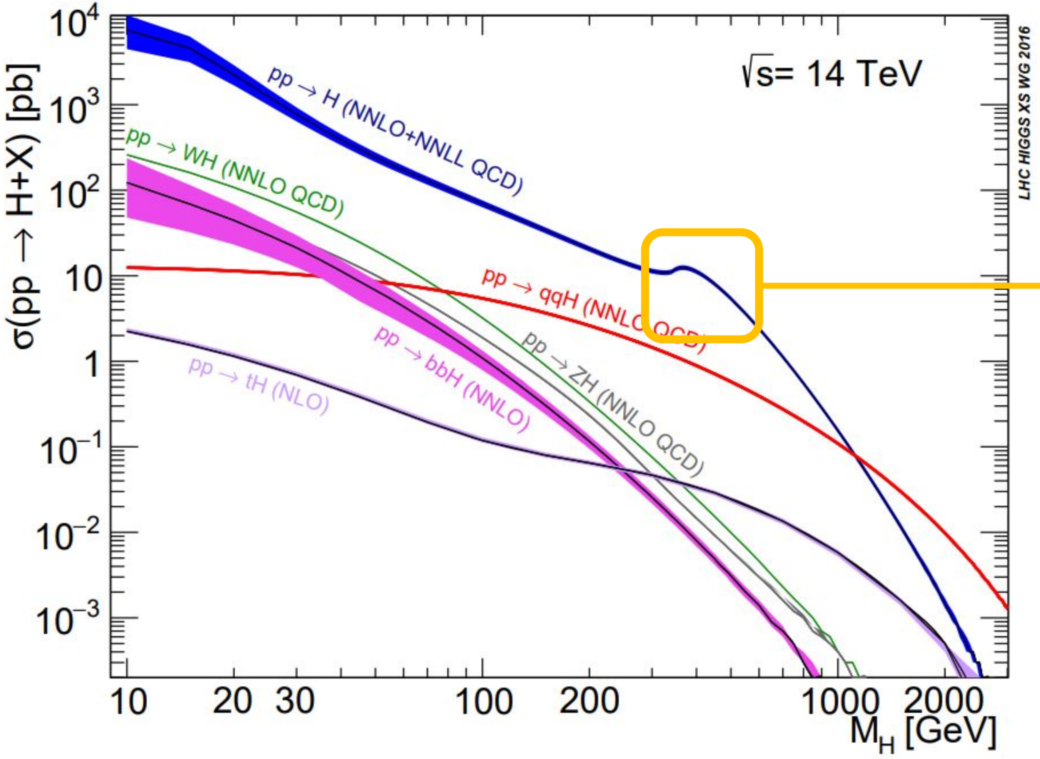
- Deviations in the measured **di-Higgs production cross section** from the SM can originate from:
  1. deviations in $\boldsymbol{\kappa_\lambda}$
  2. additional **'resonant'** contributions

  → 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

- First time that access to λ_{hhH} in HL-LHC has been analyzed → **Invariant mass distributions** give information about **resonant production** that can be embedded in BSM models:
  - relative sign of the couplings → structure of the resonance

  → These effects may be (partially) washed out by limited experimental resolution (**smearing and binning**)
  → Analysis so far indicates that it will be possible to distinguish the structure of the resonance up to some uncertainty, which can be improved depending on the future knowledge of the parameter space and improved detector efficiencies

Backup: Single Higgs production



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

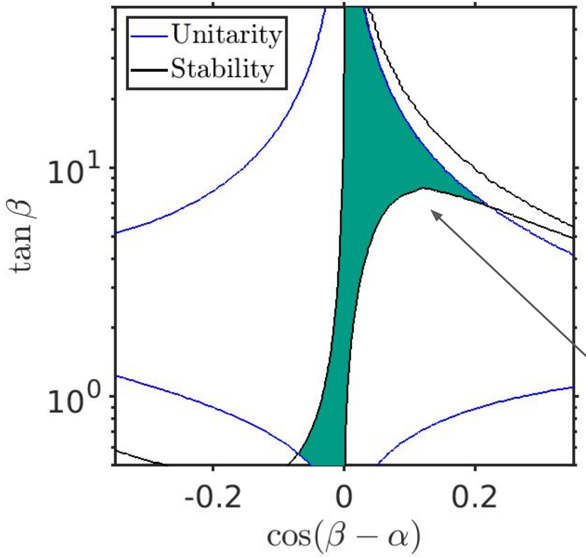
[LHC Higgs Working Group: CERN Yellow Report 4]

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

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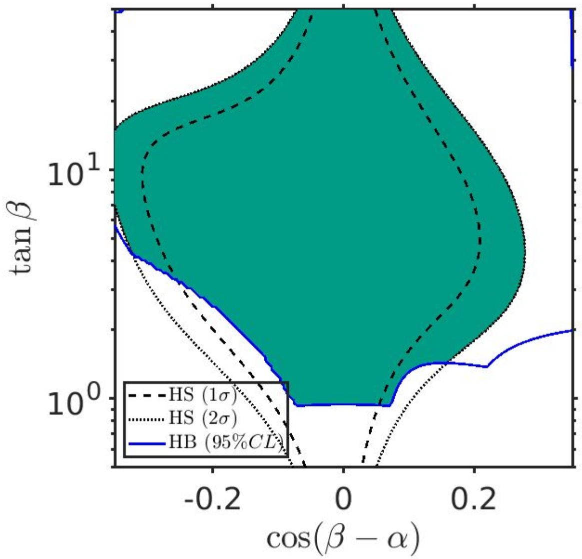

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- Collider searches and measurements:

Higgs Bounds: experimental limits from direct searches

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

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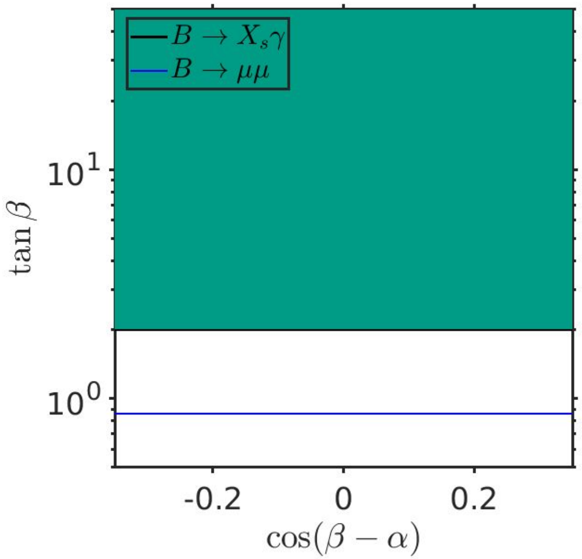

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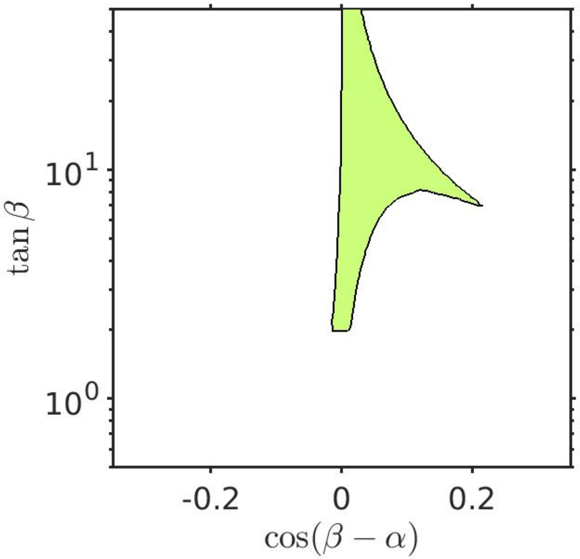

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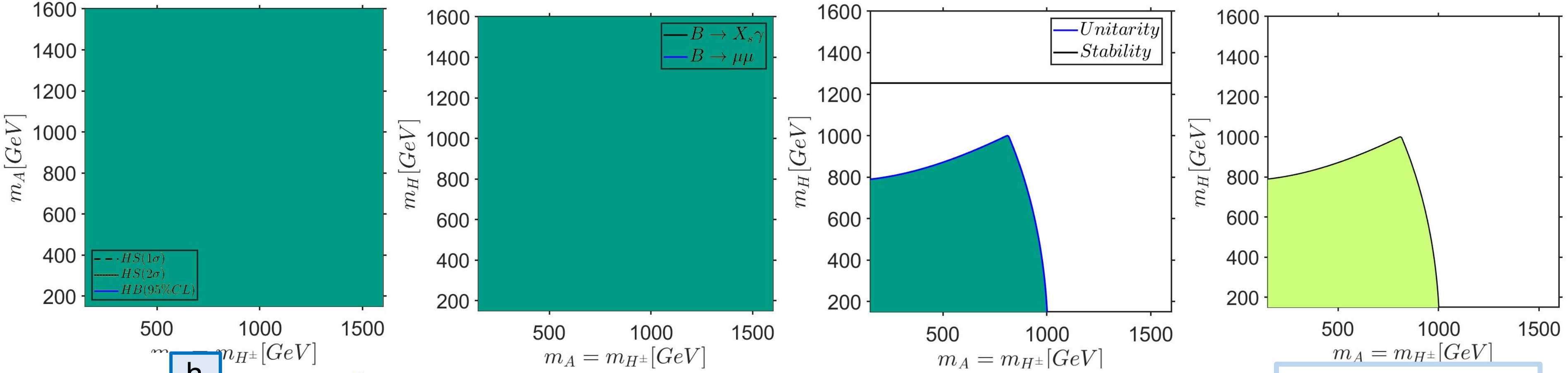
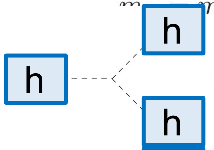
Constraints and Feynman rules

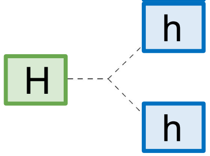
BP: Type I, $\cos(\beta-\alpha) = 0.2$, $\tan\beta = 10$, $m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$





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

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



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

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 BSM couplings:

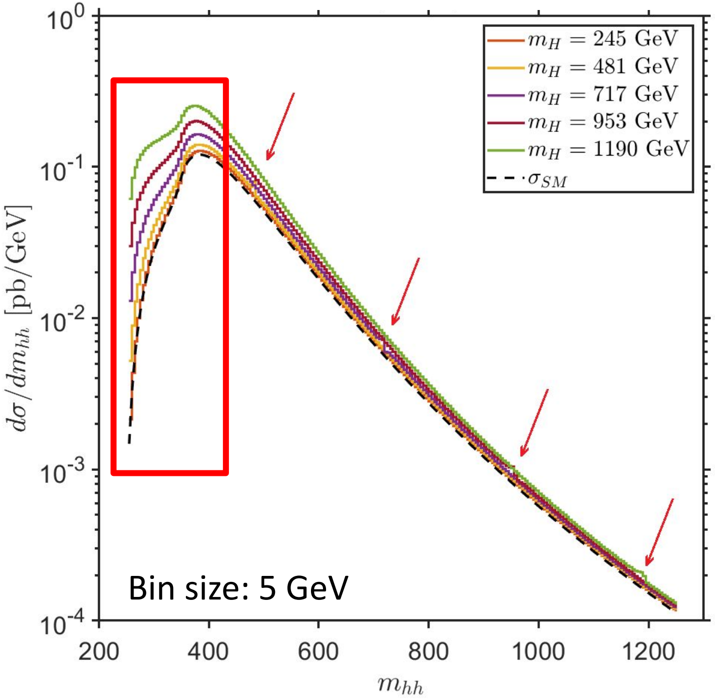
$\kappa_\lambda = 0.97,\ \lambda_{hhH} = 0.05$

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

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

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

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



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

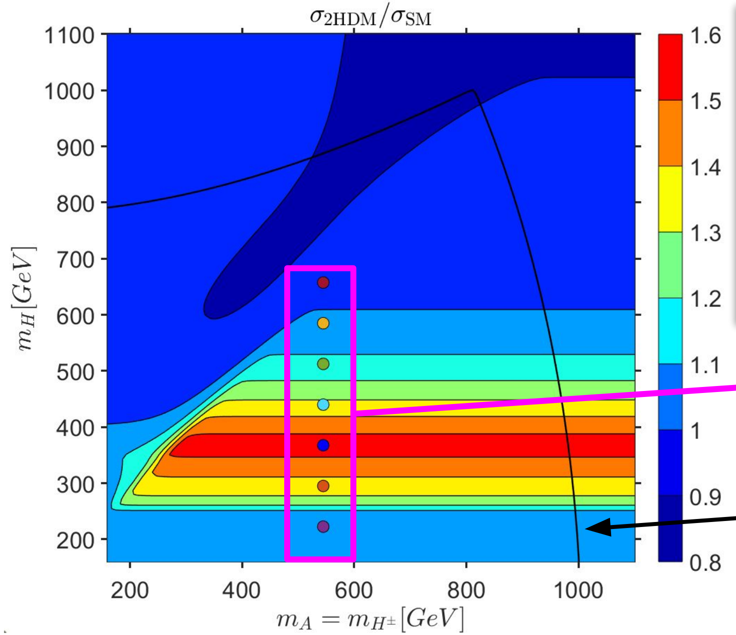
- Resonant contribution very suppressed due to very small top Yukawa $\xi^t_H \sim 10^{-4}$.

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

Effect of the mass of the heavy Higgs

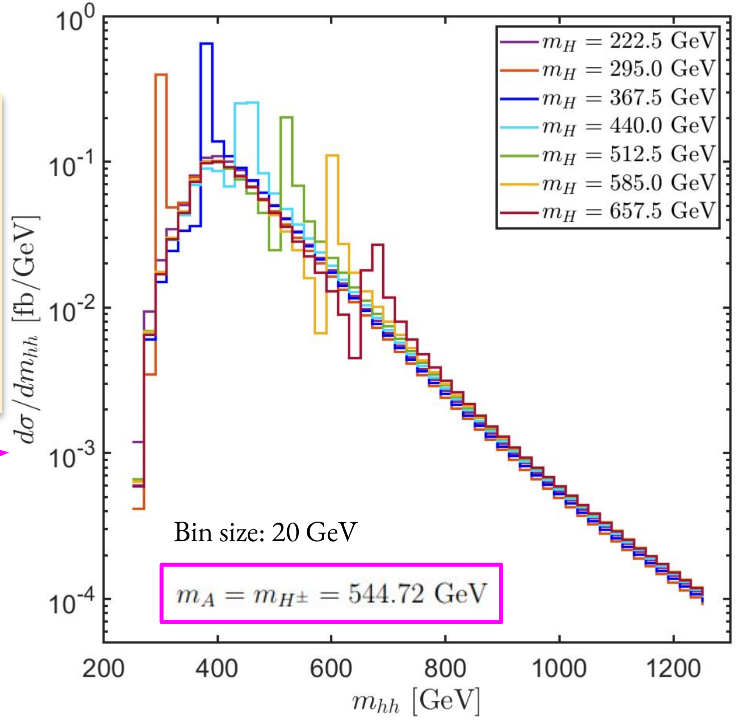
- We vary the mass of the heavy Higgs boson leaving the rest of the parameters of the model fixed.

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.**

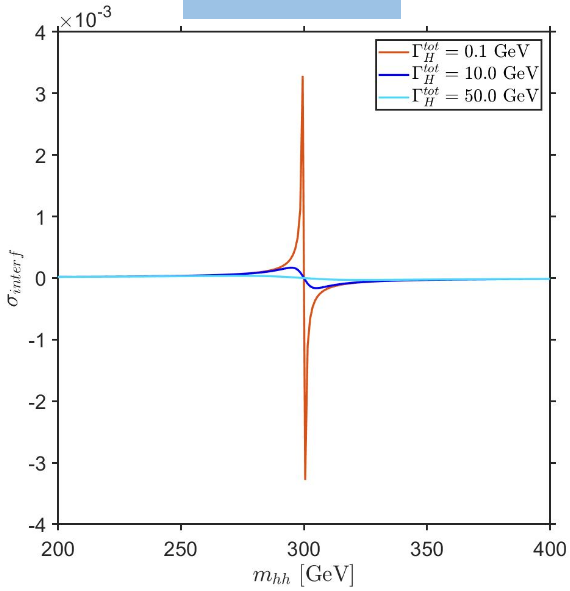
Allowed region inside the black contour.



Effect of the total decay width

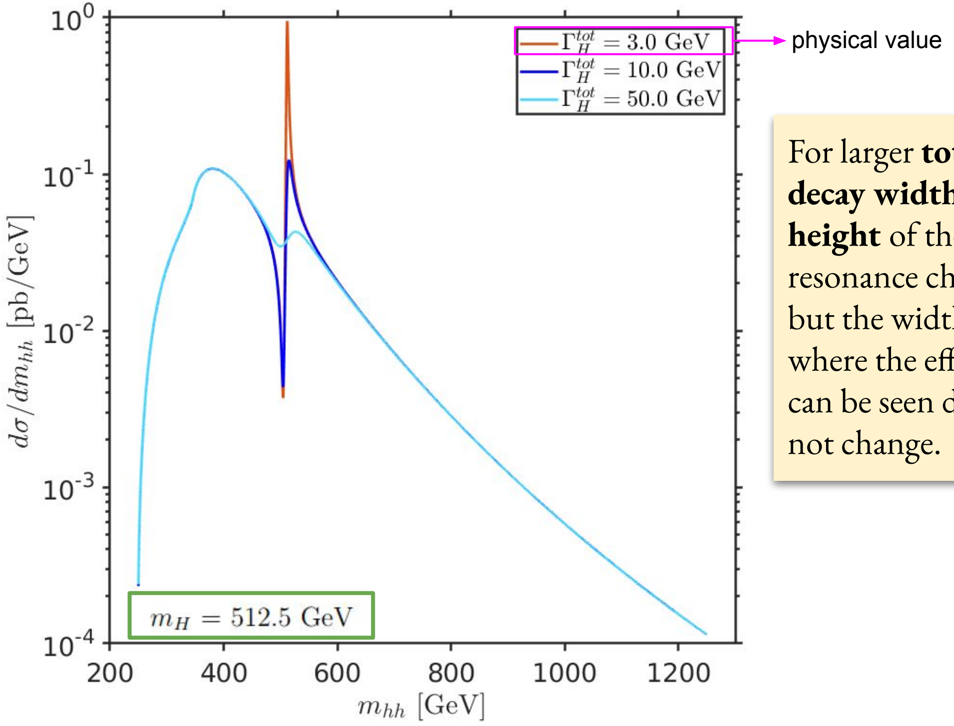
$$\frac{1}{Q^2 - M_{h/H}^2 + i\Gamma_{h/H} M_{h/H}}$$

Toy model



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

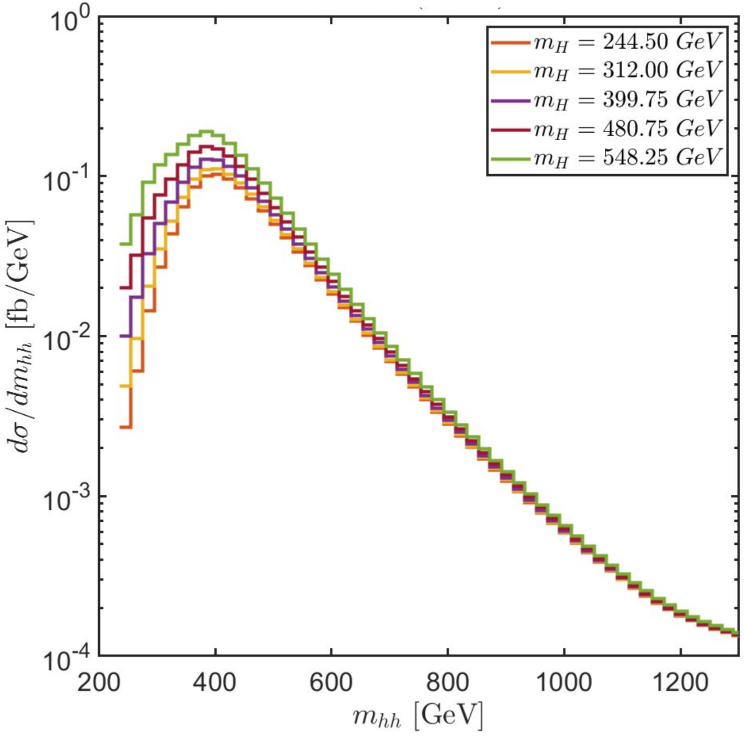
- For the green point of the previous benchmark plane we artificially change the total decay width of the heavy Higgs H:



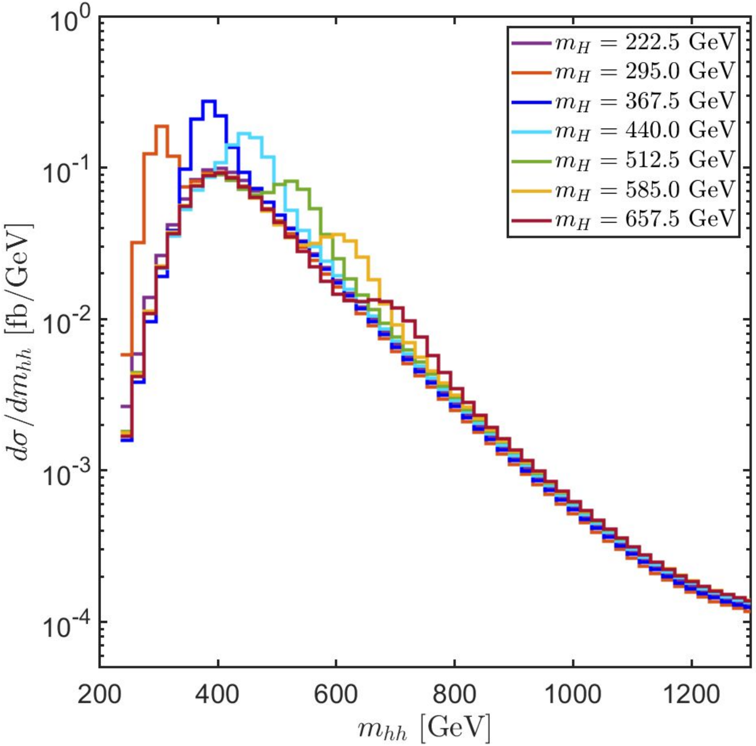
For larger **total decay widths** the **height** of the resonance changes but the width where the effect can be seen does not change.

Smearing applied on the invariant mass distributions

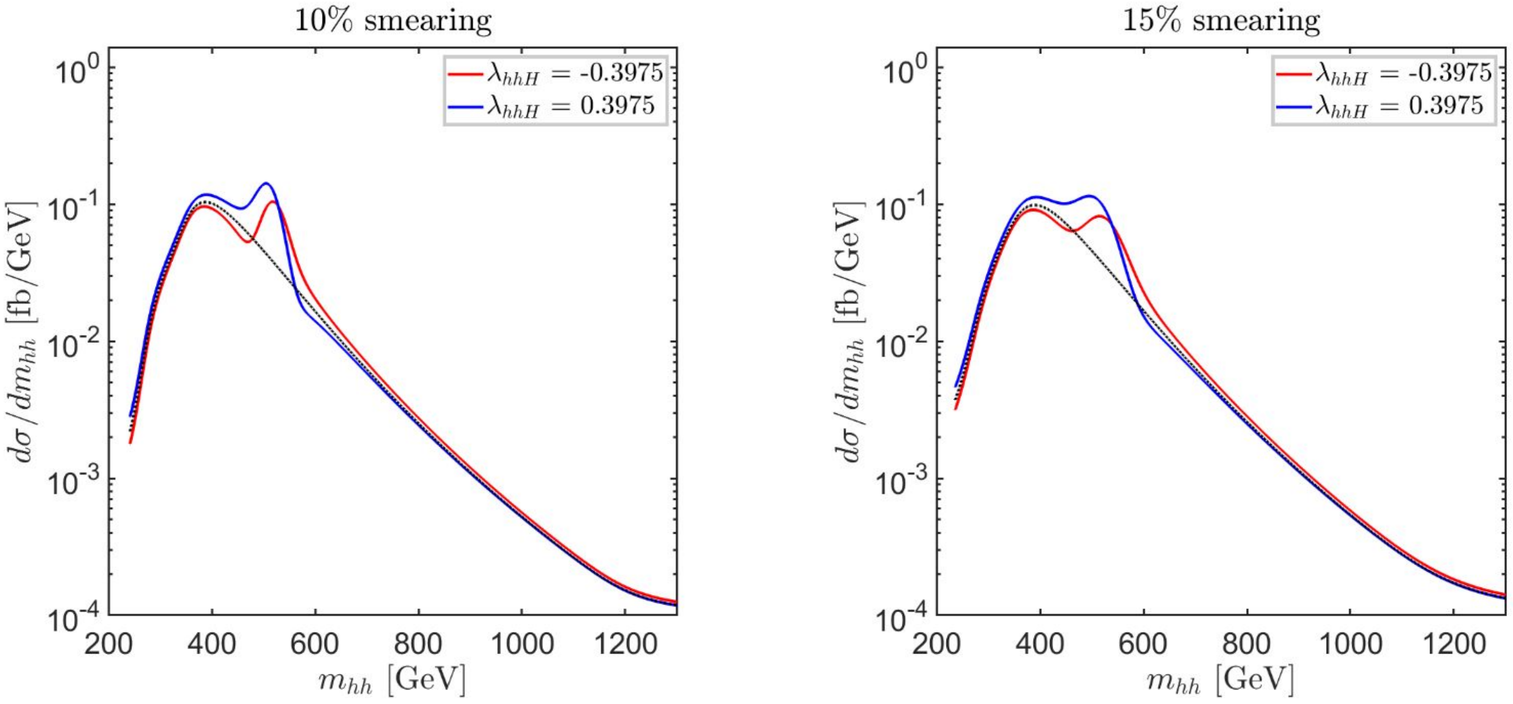
BP: Type I, $\cos(\beta-\alpha)=0.1$, $\tan\beta=10$, $m_{12}^2 = m_H^2\cos^2\alpha/\tan\beta$, $m_H = m_A = m_{H^\pm}$



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



Smearing applied on the structure of the resonance



Binning applied on the structure of the resonance

For 15 % smearing: