Higgs pair production at the HL-LHC in the 2HDM: insight into trilinear Higgs couplings

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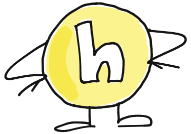
DESY.

1. MOTIVATION

A Higgs boson was discovered in 2012!



What we know:	What we do **not** know:	What we have to explain:
Scalar fields exist Higgs mechanism works	Higgs content Shape of the potential (see Olallas' talk)	Nature of Dark Matter Baryon Asymmetry of the Universe (see Lisa's talk)

OUR GOAL: What can we learn about triple Higgs couplings (and ultimately about the Higgs potential) from measurements at the HL-LHC?

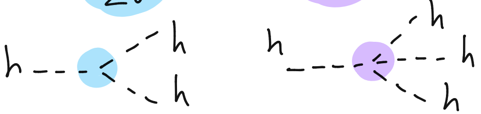
2. WHY TRIPLE HIGGS COUPLINGS?

[ATLAS-CONF-2022- 050]

$$V(\phi) = -\mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2$$

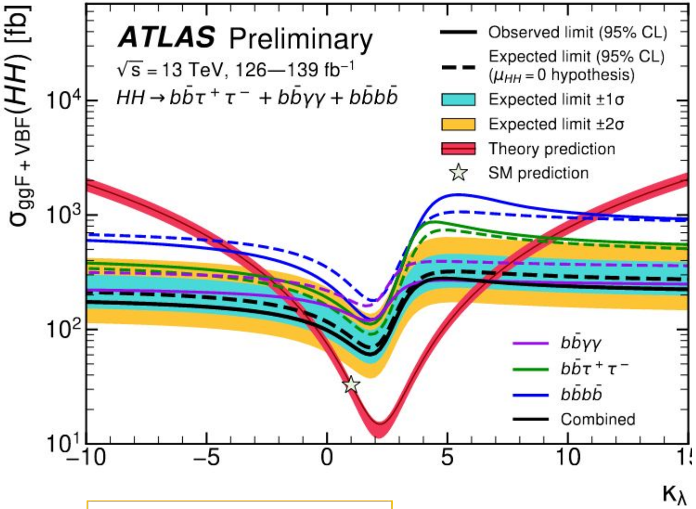
$$V(h) \propto \frac{1}{2}m^2h^2 + \frac{m^2}{2v}h^3 + \frac{m^2}{8v^2}h^4$$

Higgs field   Mass term



Experimental limits established so far:
[-0.4 < λ_{hhh} / $\lambda_{hhh(SM)}$ < 6.3] (95% CL at LHC Run II)

→ New physics around the corner?
→ Higher luminosity at the **HL-LHC** is needed.



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

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

The measurement of Higgs properties and the strength of Higgs self interactions is one of the main goals of the HL-LHC.

3. OUR STRATEGY

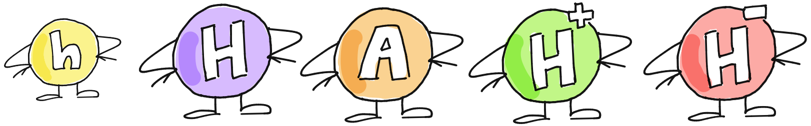
1. Choose a versatile theoretical framework → the **2 Higgs doublet model**
2. Choose a collider → Large Hadron Collider (**LHC**)
3. Where to look for deviations? → choose **observables**:

- Observable 1: total di-Higgs production cross section
  - Sensitivity to BSM triple Higgs couplings: κ_λ, λ_{hhH}
- Observable 2: invariant mass distribution
  - Information about κ_λ
  - Information about resonant production: m_H, Γ_H
  - Experimental challenges

4. THE THEORETICAL FRAMEWORK: 2HDM

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

CP conserving 2HDM with two complex doublets with a softly broken $\mathbb{Z}_2$ symmetry ($\Phi_1 \rightarrow \Phi_1$; $\Phi_2 \rightarrow \Phi_2$)
(only Type I discussed here)



→ Five Higgses!

Pontental: $$V_{2HDM} = m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 - m_3^2 (\Phi_2^\dagger \Phi_1 + \Phi_1^\dagger \Phi_2) + \frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_2^\dagger \Phi_1|^2 + \frac{\lambda_5}{2} \left((\Phi_2^\dagger \Phi_1)^2 + (\Phi_1^\dagger \Phi_2)^2 \right)$$

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

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

→ couplings to fermions and gauge bosons of the SM-like Higgs change.
(we need to be careful that all current data can be reproduced!) [Arco, Heinemeyer, Herrero: arXiv2003.12684]

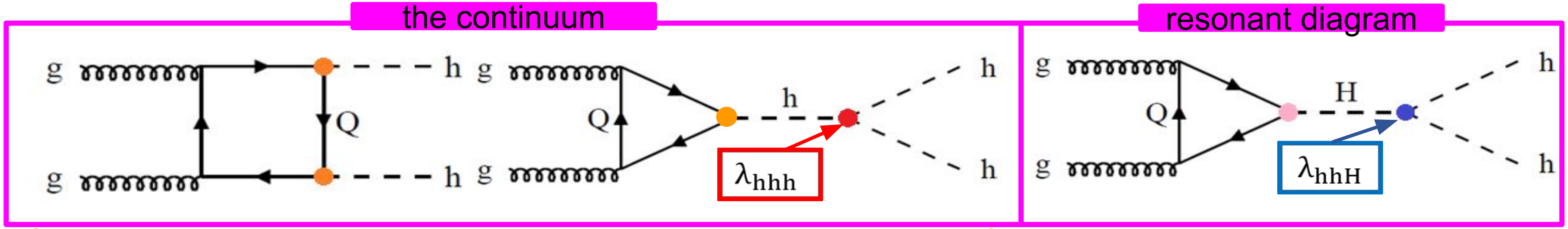
→ many more possibilities for "triple Higgs couplings" (we will look at two: $\kappa_\lambda \in [-0.5, 1.7]$, $\lambda_{hhH} \in [-1.7, 1.6]$)

These lead to **different phenomenology** w.r.t the SM but also the contribution of the **heavy Higgses** in the loops.

5. DI HIGGS PRODUCTION

[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

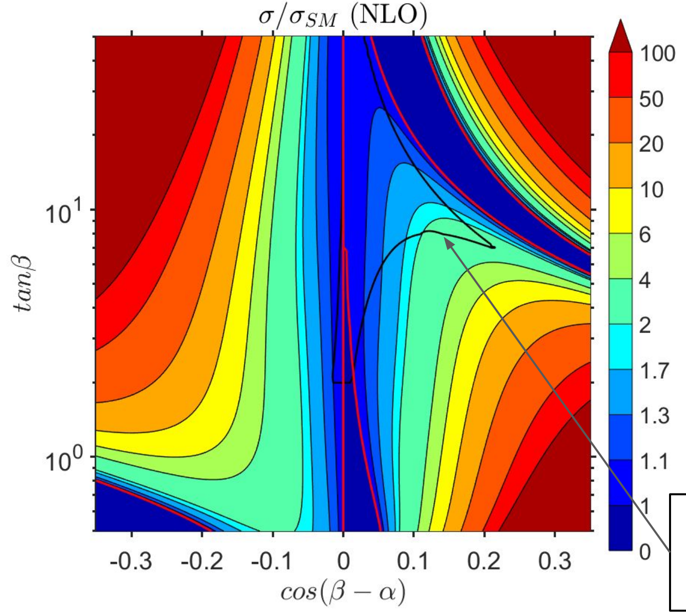
~ 1 out of 10^9 events in the LHC is a Higgs
~ 1 out of 10^{13} events in the LHC is a Higgs pair

→ All calculations were done using a modified version of the code HPAIR

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

6. TOTAL DI-HIGGS PRODUCTION CROSS SECTION

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

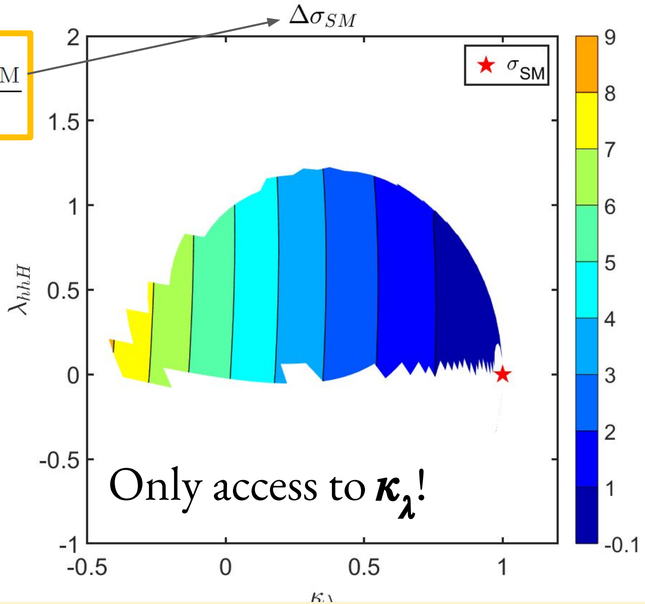


$$\Delta\sigma_{\text{SM}} \equiv \frac{\mathbf{xs}_{\text{2HDM}} - \mathbf{xs}_{\text{SM}}}{\delta\mathbf{xs}}$$

δxs = xs/4.5

projected significance in standard deviation of the total di-Higgs production: **4.5σ**

Allowed region inside the black contour!

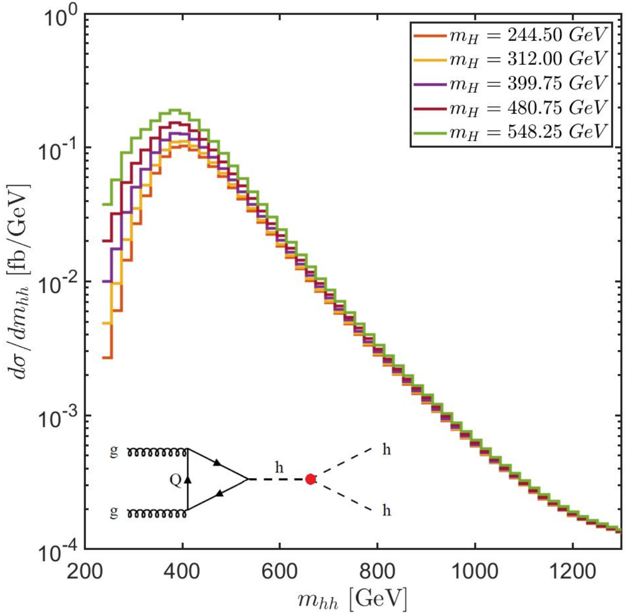


- NLO QCD corrections implemented in HPAIR
- **Largest enhancements** inside the allowed region (black contour) ~ $3\sigma_{\text{SM}}$ → due to deviations in κ_λ
- **Expected sensitivity** to the deviation of the cross section: up to 8σ away from the SM

7. INVARIANT MASS DISTRIBUTION

1) Non-resonant production:

the contribution of the heavy Higgses is negligible:



κ_λ (SM)= 1

$\kappa_\lambda = 0.97$

$\kappa_\lambda = 0.85$

$\kappa_\lambda = 0.67$

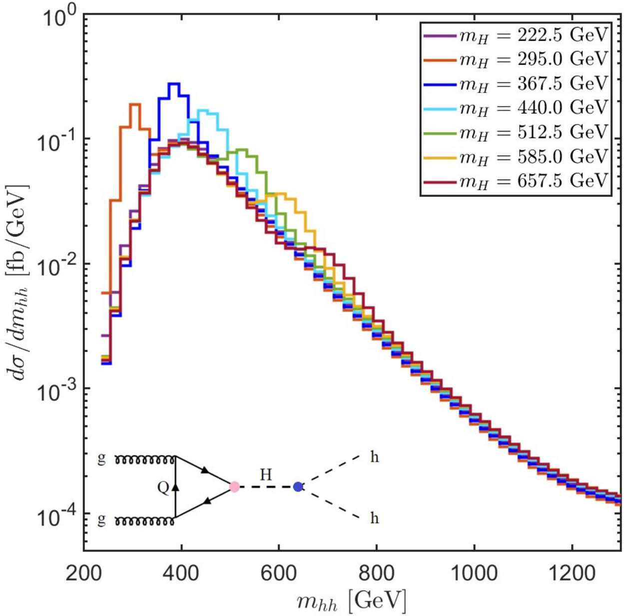
$\kappa_\lambda = 0.41$

$\kappa_\lambda = 0.08$

- Larger sensitivity to deviations in λ_{hhh} in the low m_{hh} region

2) Resonant production:

the contribution of the heavy Higgses is important:



- Sensitivity to the properties of the BSM resonance: m_H, Γ_H

CONCLUSIONS

- Many Beyond the Standard Model theories propose **extended Higgs sectors** and explain some open problems of the Standard Model.

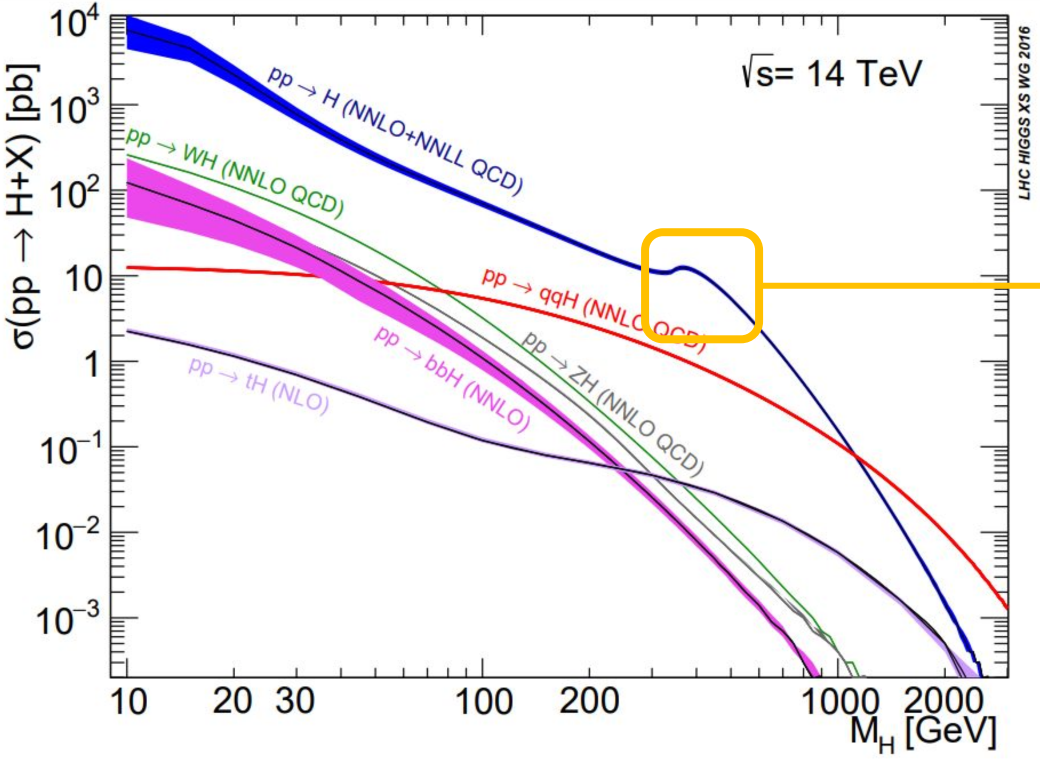
- The next step to establish the Higgs potential is the measurement of **triple Higgs couplings.**

- Deviations of this parameter w.r.t. the Standard Model can affect the **Higgs pair production**.

- Measuring the **total production cross section** is not enough to disentangle the effects from deviations in the Higgs triple self-interactions and contribution of additional particles → **invariant mass distributions** are a complementary and promising avenue.

THANK YOU FOR YOUR ATTENTION!

SINGLE HIGGS PRODUCTION



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

[LHC Higgs Working Group: CERN Yellow Report 4]

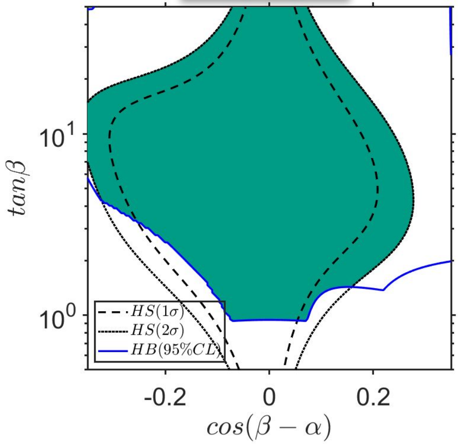
Benchmark planes

[Arco, Heinemeyer, Herrero arXiv2005.10576]

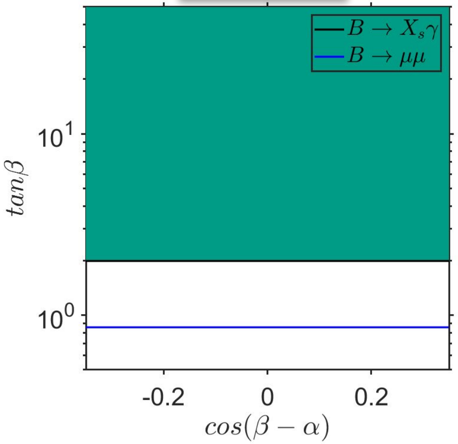
We scan the parameter space fixing all but two paramaters and look for large deviations from the SM in the resulting benchmark planes.

Colored area is allowed

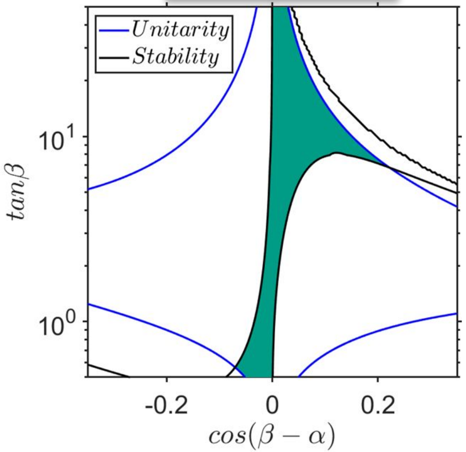
Collider



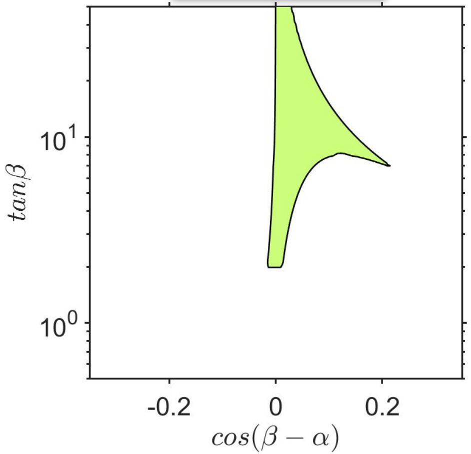
Flavour



Theoretical



Total

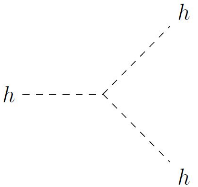


PLANE 1: Type I, $m_H = m_A = m_{H^\pm} = 1000$ GeV , $m_{12}^2 = (m_H^2 \cos^2\alpha)/\tan\beta$
Free parameters: $\cos(\beta-\alpha)$, $\tan(\beta)$

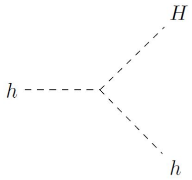
[Ren: arXiv:1706.05980]

→ Special equation for m_{12} that enlarges the area allowed by theoretical constraints.

Feynman rules for 2HDM Triple Higgs Couplings



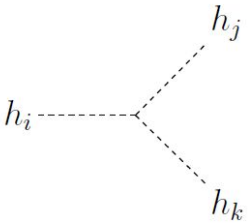
$$\lambda_{hhh} = \frac{1}{2v^2}\left\{m_h^2 s_{\beta-\alpha}^3 + \left(3m_h^2 - 2\bar{m}^2\right) c_{\beta-\alpha}^2 s_{\beta-\alpha} + 2\cot 2\beta \left(m_h^2 - \bar{m}^2\right) c_{\beta-\alpha}^3\right\}$$



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

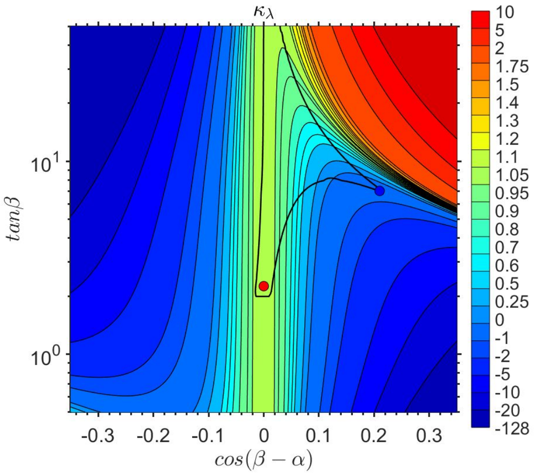
$$\bar{m}^2 = \frac{m_{12}^2}{sin(\beta)cos(\beta)}$$

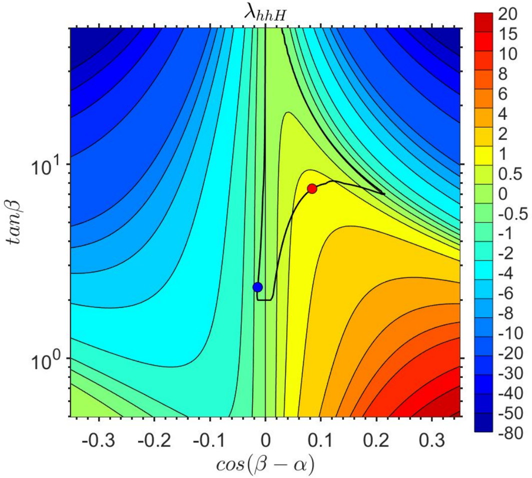
Notation:



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

n = number of identical Higgses



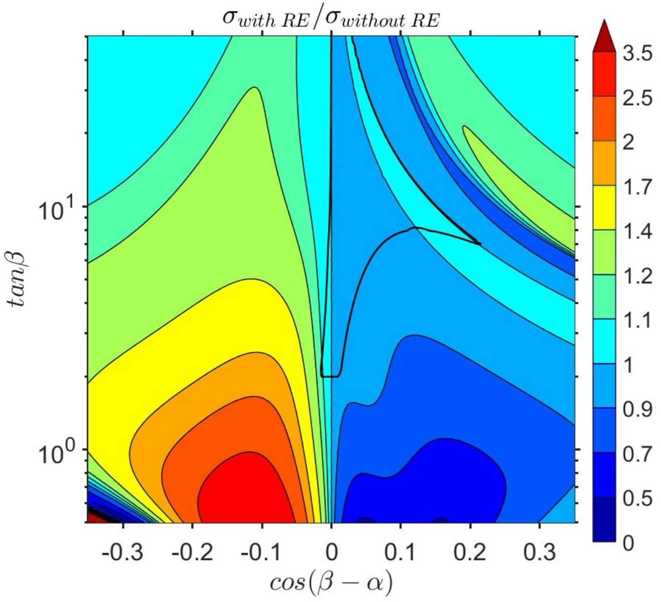


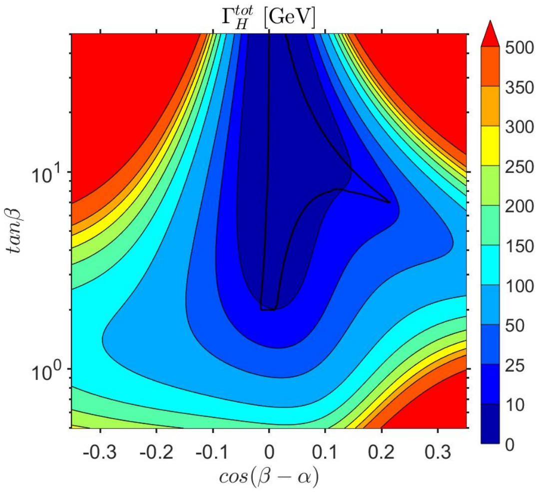
Deviations from the alignment limit:

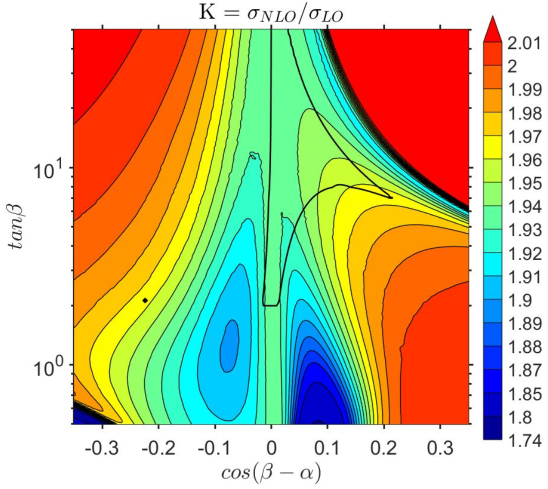
MIN. $\kappa_\lambda \sim -0.4$
$\tan\beta \sim 7$
$\cos(\beta-\alpha) \sim 0.2$

MAX. $\lambda_{hhH} \sim 1.2$
$\tan\beta \sim 7$
$\cos(\beta-\alpha) \sim 0.1$

More about total cross section





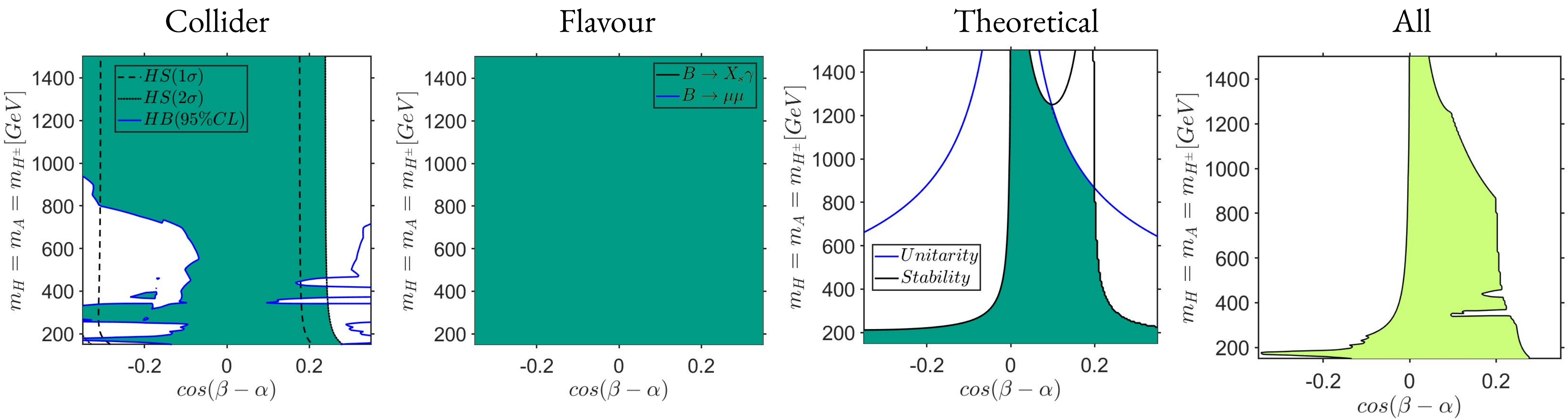


$$m_H = m_A = m_{H^\pm} = 1000\ \text{GeV}$$
$$m_{12}^2 = (m_H^2 \cos^2\alpha)/\tan\beta$$

- Without resonant enhancement → excluding the resonant diagram
- Resonant contribution is negligible in the allowed region
- Total decay width ~ 25 GeV at the tip

Constraints P3

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

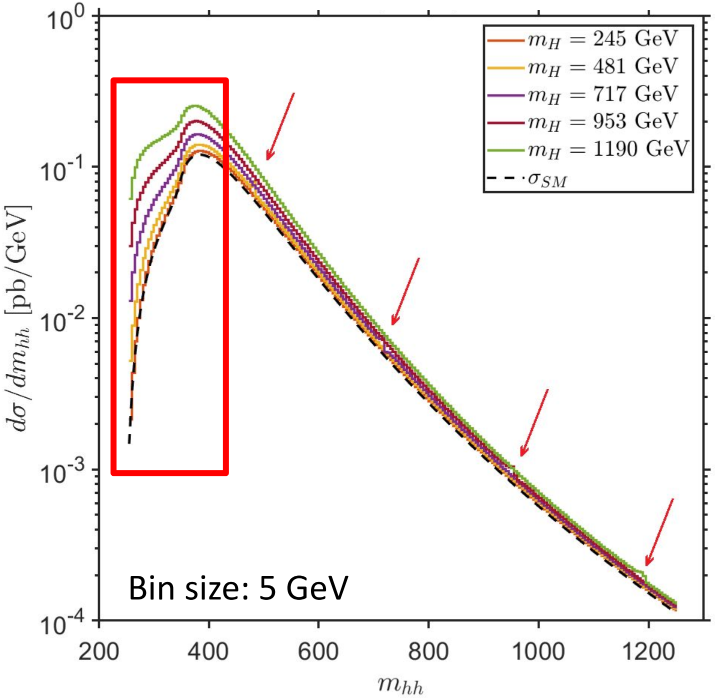


Invariant mass distribution: effects of deviations in κ_λ

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:

$\kappa_\lambda = 0.97$, $\lambda_{hhH} = 0.05$
$\kappa_\lambda = 0.85$, $\lambda_{hhH} = 0.19$
$\kappa_\lambda = 0.67$, $\lambda_{hhH} = 0.42$
$\kappa_\lambda = 0.41$, $\lambda_{hhH} = 0.74$
$\kappa_\lambda = 0.08$, $\lambda_{hhH} = 1.15$



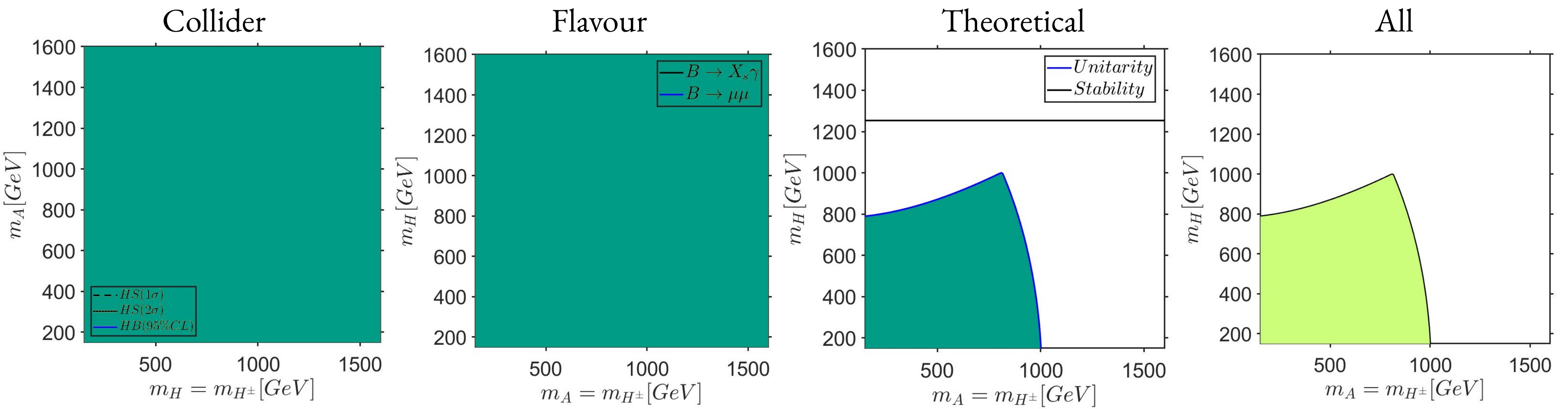
- Larger sensitivity to κ_λ in the low m_{hh} region.

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

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

Constraints P8

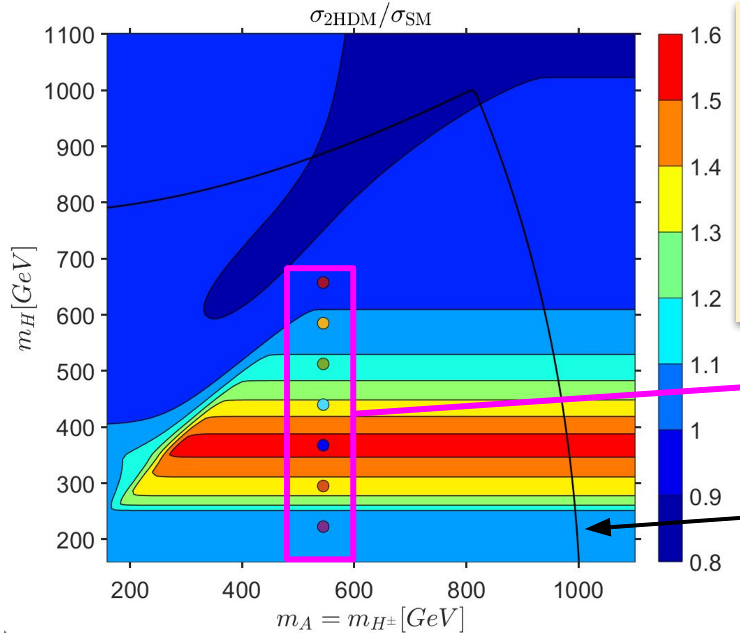
$$\text{BP: Type I, } \cos(\beta-\alpha)=0.2,\ \tan\beta=10,\ m_{12}^2=m_H^2\cos^2\alpha/\tan\beta$$



Effect of the mass of the heavy Higgs

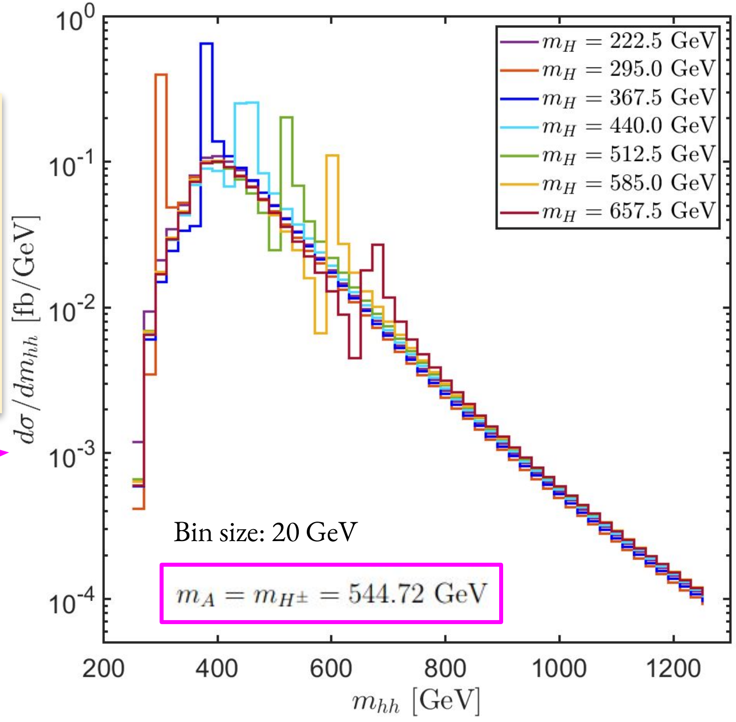
- We vary the mass of the heavy Higgs boson leaving the rest of the parameters of the model fixed.

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.**

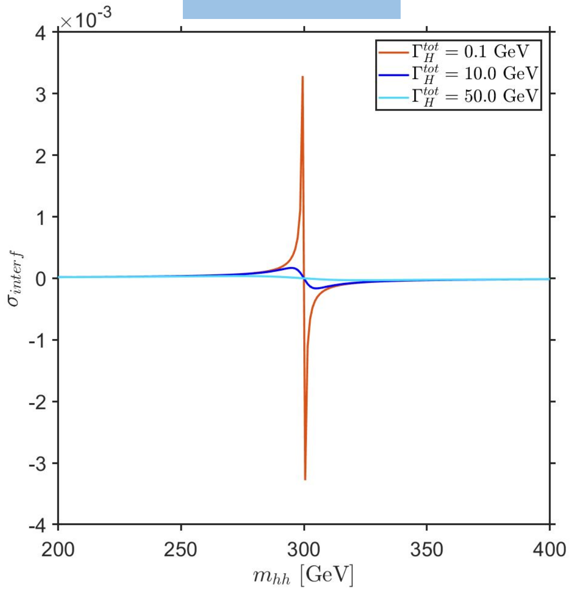
Allowed region inside the black contour.



Effect of the total decay width

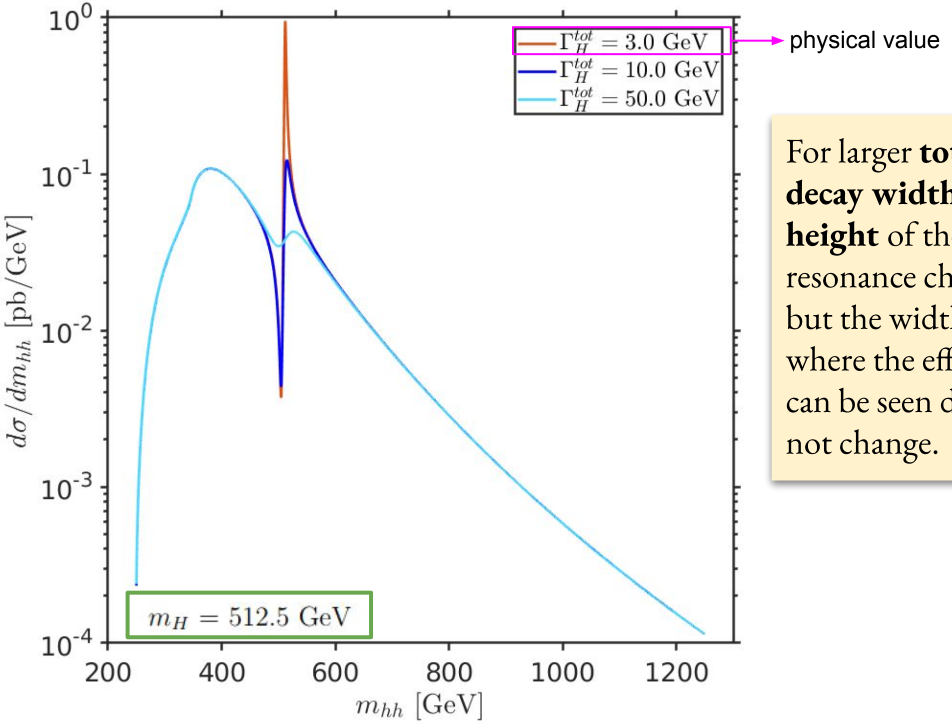
$$\frac{1}{Q^2 - M_{h/H}^2 + i\Gamma_{h/H} M_{h/H}}$$

Toy model



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

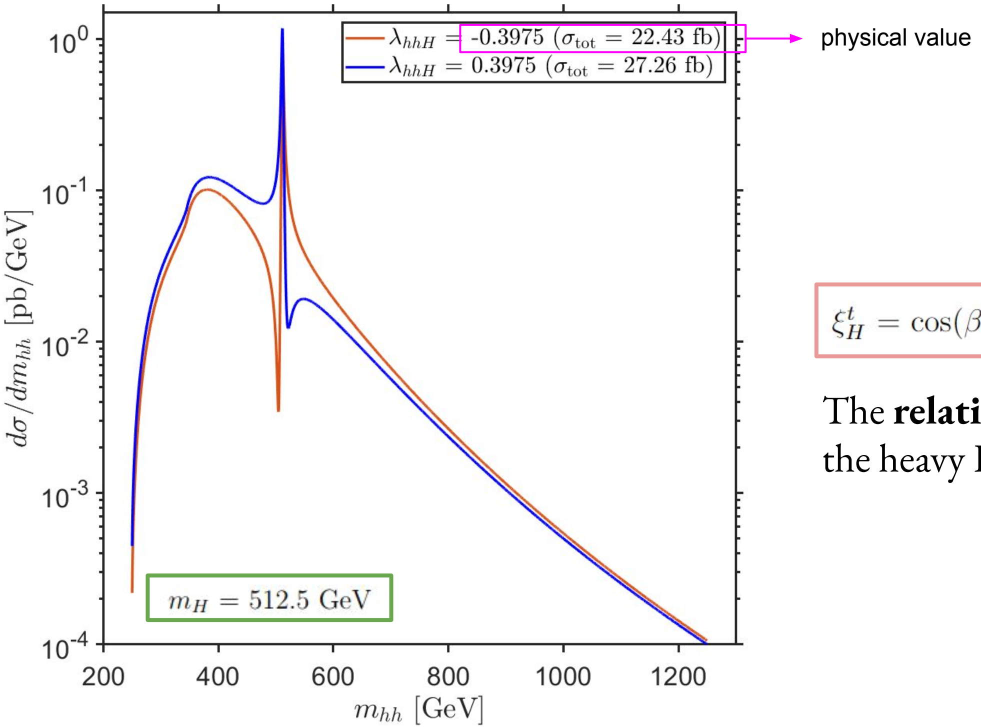
- For the green point of the previous benchmark plane we artificially change the total decay width of the heavy Higgs H:

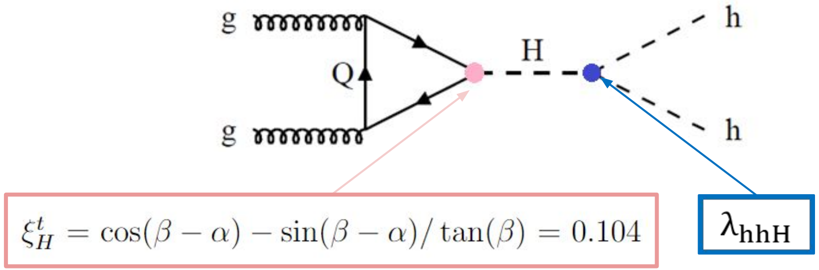


For larger **total decay widths** the **height** of the resonance changes but the width where the effect can be seen does not change.

Effect of the couplings

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

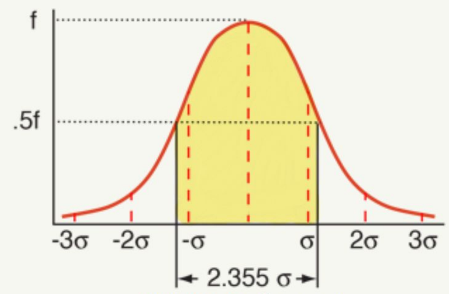




The **relative sign** of the top Yukawa and the BSM coupling to the heavy Higgs gives a **structure** to the resonance:

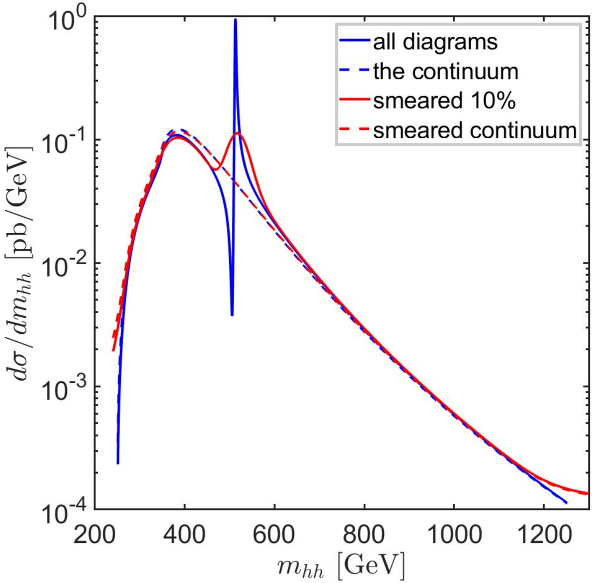
sign ($\lambda_{hhH} \cdot \xi^t_H$)	structure
+	peak-dip
-	dip-peak

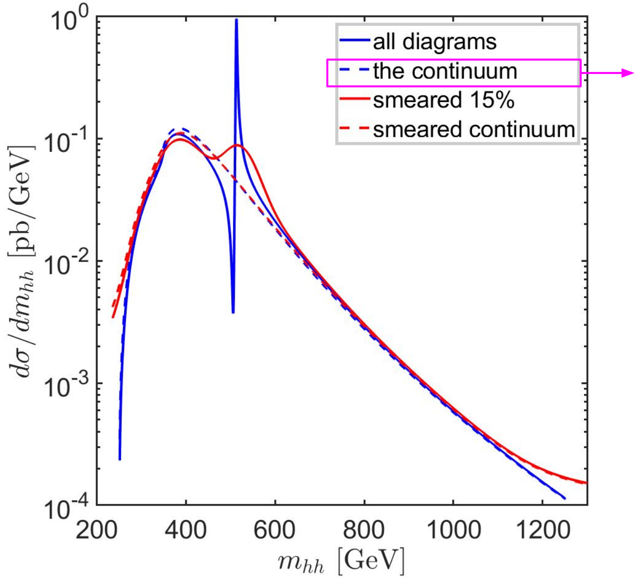
Experimental challenges: smearing



FWHM: % of 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.





box diagram + SM-like Higgs exchange