2HDM Triple Higgs couplings at NLO at the LHC

Applicability of experimental limits from di-Higgs searches

based on arxiv 2212.11242 and 2312.XXXXX

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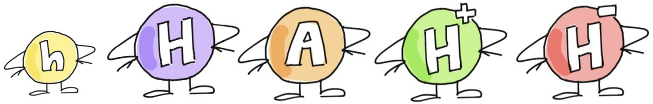
The 2HDM model

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

- Potential:

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

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

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

Higgs self coupling measurements

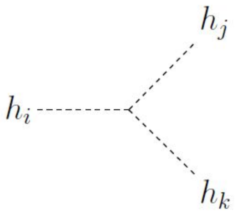
- Motivation: probe of **Higgs potential** and a window to BSM
  [Kanemura, Okada, Senaha: arXiv: 0411354]

- 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 impact the phenomenology

Notation:

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



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

n = number of identical Higgses

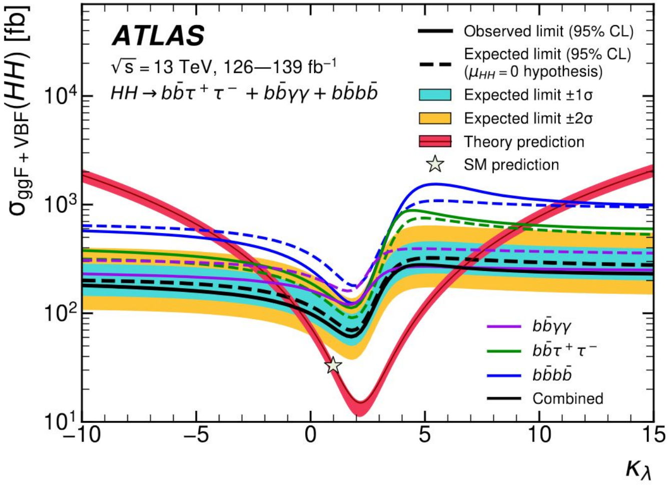
2HDM Type I (tree level):

$\kappa_\lambda = [-0.5, 1.3]$; $\lambda_{hhH} = [-1.7, 1.6]$

[Arco, Heinemeyer, Herrero: arXiv: 2003.12684, 2203.12684]

Experimental status:

- access through Higgs pair production
  [ATLAS: arXiv: 2211.01216]
  $-0.4 < \kappa_\lambda < 6.3$ (95% CL at LHC Run II)
  [CMS: arXiv: 2207.00043]
  $-1.24 < \kappa_\lambda < 6.49$ (95% CL at LHC Run II)



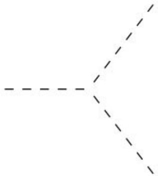
Radiative corrections to the trilinear couplings

- Crucial for first order electroweak phase transition
- We use the effective potential approach and implement an effective coupling in the di-Higgs production

[Coleman, Weinberg: (1973) Physical Review]

$$V_{\text{eff}} = V_{\text{tree}} + V_{\text{CW}} + V_{\text{CT}}$$

$$\lambda^{\text{eff}}_{hhh} = \left.\frac{\partial^3 V_{\text{eff}}}{\partial h^3}\right|_{h=0,\, H=0} =$$



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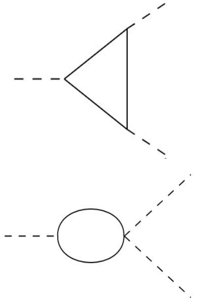

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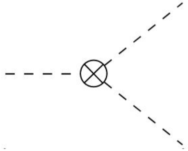


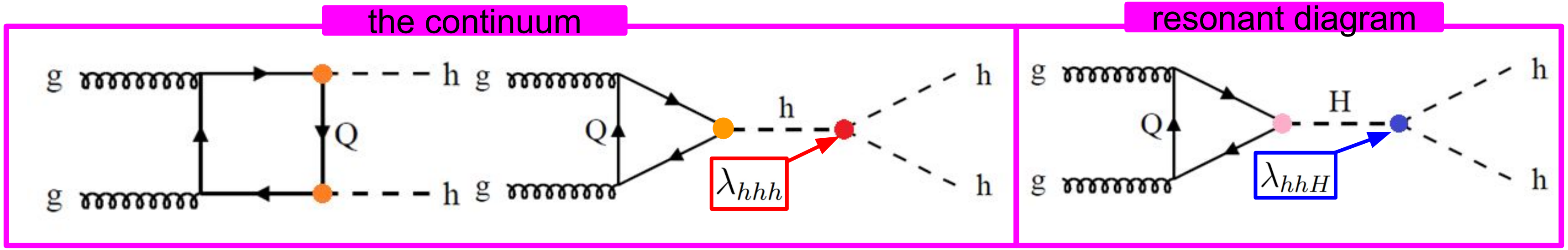
* zero external momentum
* no external leg corrections

- The calculation is done by means of the public code BSMPT: [Basler, Mühlleitner: arXiv: 1803.02846]
- It is performed in the limit of zero external momentum
- Physical masses and mixing angles are renormalized on shell to their tree level value
- An alternative approach would be to compute the corrections diagrammatically: anyH3
  [Bahl, Braathen, Gabelmann, Weiglein: arXiv: 2305.03015]

Di-Higgs production (gg → hh)

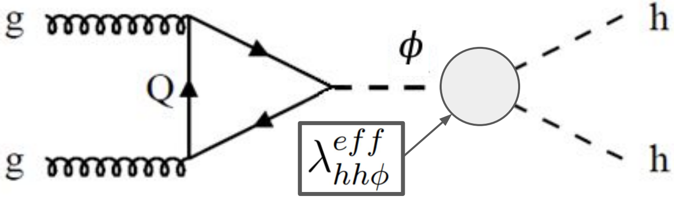
[Plehn, Spira, Zerwas : arXiv: 9603205]

- Dominant process at the LHC **gluon fusion** via quark loop (mostly the top): σ_{SM} ~ 38 fb (NLO QCD)



We include corrections to this process by means of effective trilinear Higgs couplings assuming that the largest contribution comes from this type of diagrams and others can be neglected (eg. double box diagram):

- Is this reasonable? -> modifications of λ_{hhh} are the leading source of deviations of non resonant hh production cross section
[Bahl, Braathen, Weiglein : arXiv: 2202.03453]



Sources of BSM contributions: $\lambda_{hhH}, \lambda_{hhh}$

Di-Higgs production measurements

- Distinction given by experimental data:

Non resonant production

Involves mostly the continuum diagrams (present in the SM)

Targeted to find deviations in κ_λ assuming all other couplings are SM like

$\boldsymbol{\sigma(gg \to hh)}$

HPAIR

[Plehn, Spira, Zerwas : arXiv: 9603205]
[Dawson, Dittmaier, Spira: arXiv:9805244]
[Abouabid, Arhrib, Azevedo, El Falaki, Ferreira, Mühlleitner, Santos: arXiv: 2112.12515]

Resonant production

The heavy Higgs plays an important role in the overall process

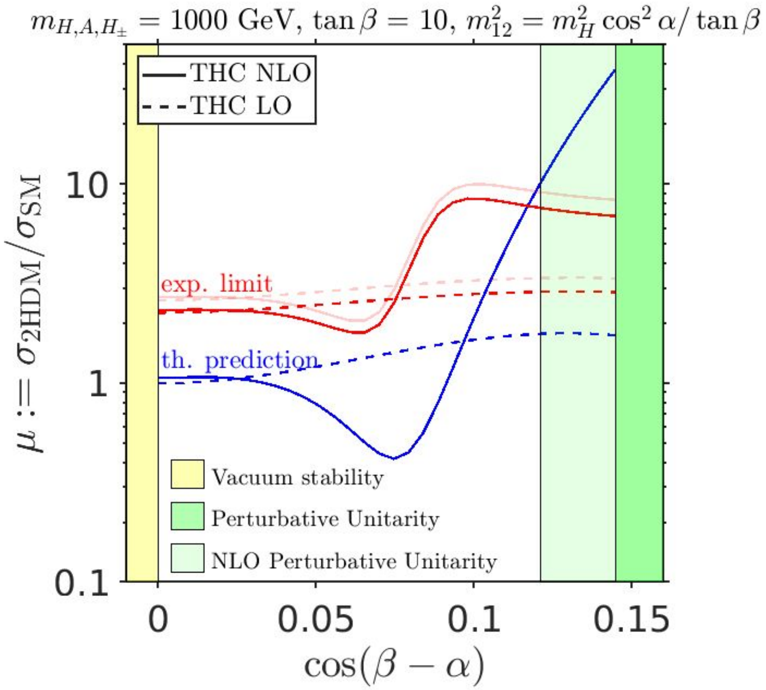
Can be approximated as the production cross section times the branching ratio of the decay to two light Higgses

$\boldsymbol{\sigma(gg \to H)\ BR(H \to hh)}$

SusHi + HDECAY

[Harlander, Liebler, Mantler: arXiv: 1605.03190]
[Djouadi, Kalinowski, Mühlleitner, Spira: arXiv: 1801.09506]

Applicability of non resonant limits



- Allowed regions of the 2HDM parameter space are scanned with the python package thdmTools [Biekötter, Heinemeyer, No, Radchenko, Romacho, Weiglein: arxiv:2309.17431]

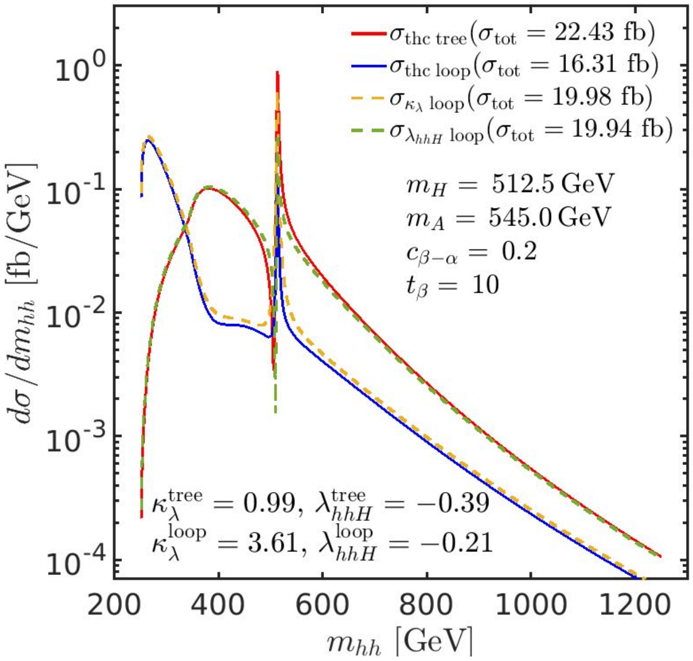
- We show the non resonant Higgs pair production signal strength: theoretically predicted **σ(gg→hh)** with HPAIR at NLO QCD and with (without) corrections to trilinears shown by the solid (dashed) line

- Including loop corrections to trilinear Higgs couplings excludes regions of otherwise allowed parameter space

- Perturbative unitarity bounds are relevant for higher values of cos(β-α), even if you apply "stricter" bounds

Search: [ATLAS: arXiv: 2211.01216]
CMS limits yield a similar bound

Phenomenology of THC in m_{hh} distributions



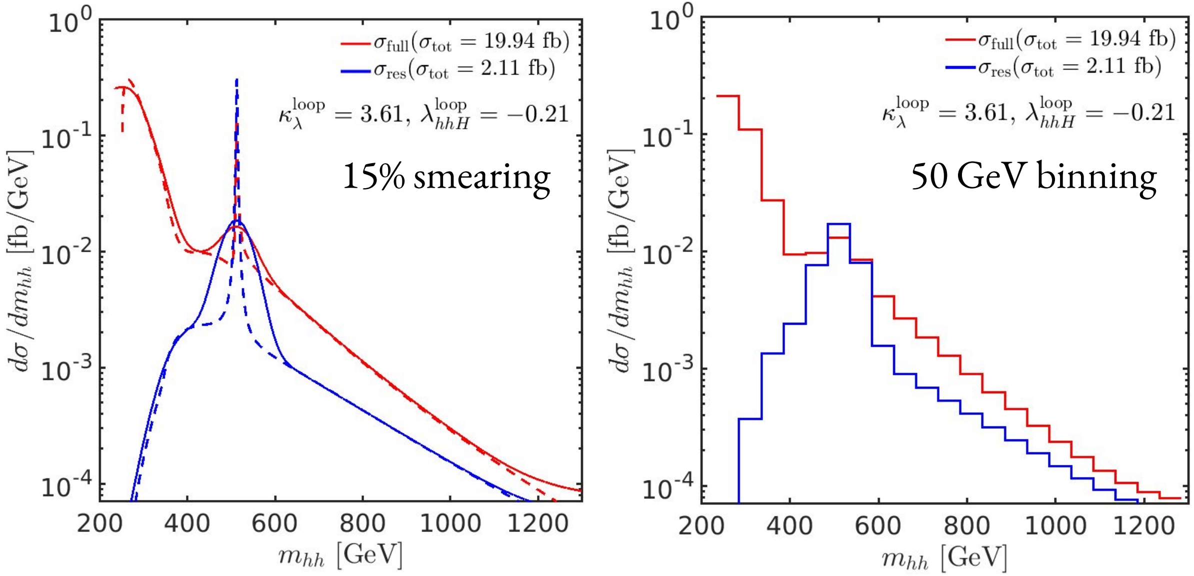
- Resonance located at $m_{hh} \sim m_H$ not very affected by corrections to the λ_{hhH} but large corrections κ_λ modify the dip peak structure substantially

- Larger sensitivity to κ_λ in the low m_{hh} region (because of a cancellation between the box and triangle diagrams in the SM)

- m_{hh} are extremely sensitive to deviations in the trilinears and a precise theoretical prediction is necessary to interpret future results

Experimental challenges: smearing and binning

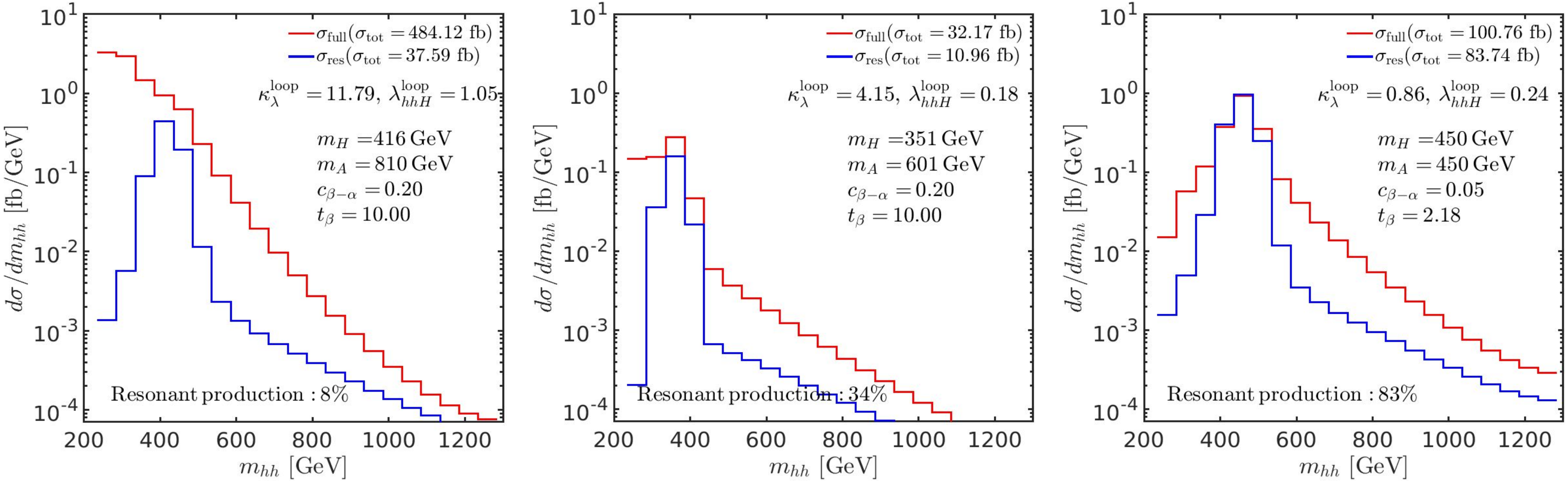
- Differential cross section measurements are affected by the finite resolution of particle detectors → observed spectrum is "**smeared**" → we mimic this effect by introducing *ad hoc* **Gaussian uncertainties** in m_{hh}
- Experimental data is gathered in **bins**



→ Resonant searches dismiss a big contribution at low m_{hh} coming from corrections to κ_λ

Limits from the invariant mass distribution

- Full vs. resonant contributions to the m_{hh} distributions in order of increasing weight of resonant contribution:



<u>exp.limits:</u>

	1st	2nd	3rd
	✘ resonant searches	✓ resonant searches	✓ resonant searches
	✘ non resonant searches	✓ non resonant searches	✘ non resonant searches

- Red curve (full process) is very different from blue curve (only resonant contribution)
- Not including the continuum diagrams makes the prediction at low m_{hh} change by orders of magnitude!

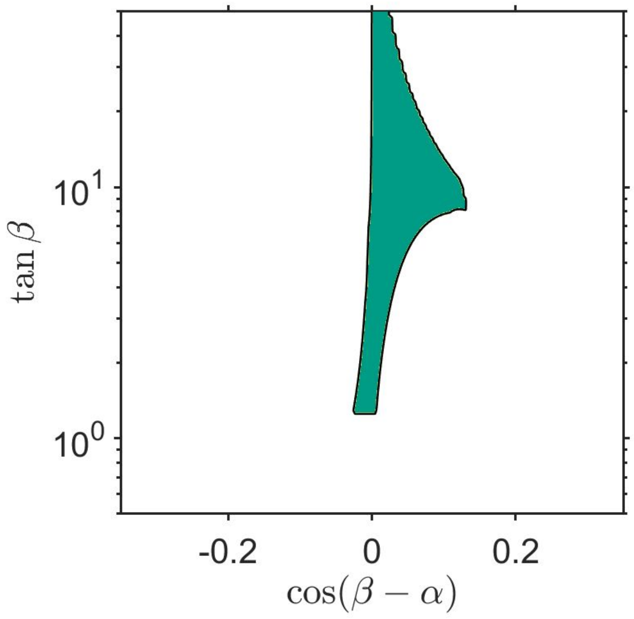
Conclusions

- Sizable **deviations in trilinear Higgs couplings** are allowed by all current constraints and can be embedded in BSM models that have an important **impact on the early universe**
- Contributions of the heavy BSM scalars can be sizable in Higgs pair production
- Including **radiative corrections to the Higgs self interactions** helps to constrain parameter regions of otherwise unconstrained parameter space in the 2HDM applying current experimental bounds on **non-resonant di Higgs production** cross section
- **Invariant mass distributions are drastically** sensitive to deviations in trilinear Higgs couplings from the SM value and a precise theoretical framework is essential to interpret the results
- There are scenarios in simple BSM models where the resonant contribution is completely washed away in the full result and the hypothesis of experimental searches are insufficient to capture their phenomenology

Benchmark planes (updated in 2023) [Arco, Heinemeyer, Herrero: arXiv: 2003.12684, 2203.12684]

We scan the **2HDM** parameter space fixing all but two parameters using **thdmTools** [Biekötter, Heinemeyer, No, Radchenko, Romacho, Weiglein: arxiv:2309.17431]

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



- **EWPO** → checked at two loops using THDM_EWPOS [Hessenberger, Hollik: arXiv: 1607.04610]
- Theoretical:

(N)LO Unitarity: from the 2 → 2 processes scattering amplitude [Cacchio, Chowdhury, Eberhardt, Murphy: arXiv:1609.01290]

Stability: tree level boundedness from below of the potential [Bhattacharyya, Das: arXiv:1507.06424]

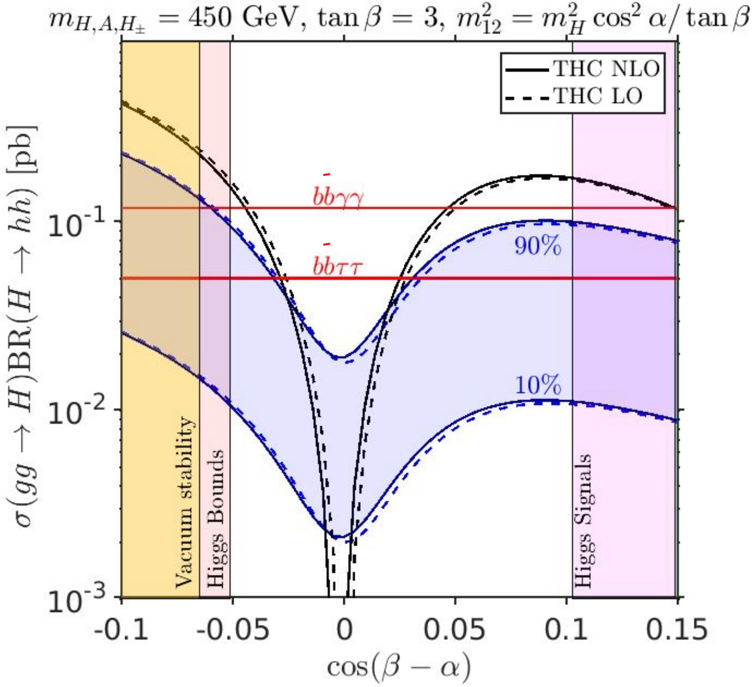
- Collider searches and measurements:

HiggsBounds: experimental limits from direct searches

HiggsSignals: signal strength of the 125 GeV Higgs [HiggsTools Collaboration: arXiv: 2210.09332]

- **Flavour observables** → $B \to X_s\gamma$ and $B_s \to \mu\mu$ (SuperIso) [Mahmoudi: arXiv:0808.3144]

Applicability of resonant limits



- We show the resonant Higgs pair production cross section: **σ(gg→H) BR(H→hh)**

- Most sensitive search is bbττ, also shown bbγγ

- Criterion to apply **resonant** experimental bounds:
σ(gg→H) BR(H→hh) > X σ(gg→hh)
X is arbitrary !

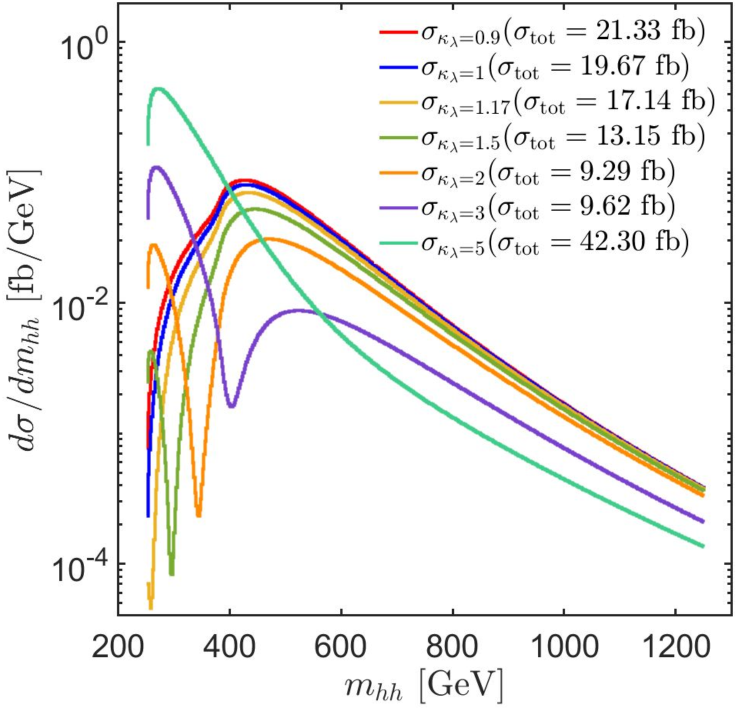
- Hard to interpret the meaning of experimental bounds

Searches: [ATLAS bbττ: arXiv 2112.11876]
[ATLAS bbγγ: arXiv 2209.10910]

Effect of loop corrections to κ_λ in m_{hh}

[Plehn, Spira, Zerwas : arXiv: 9603205]

- 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 κ_λ ~ 2.5)
- The differential cross section also has a minimum for masses of the final system of hh between 200-400 GeV

The reason is a cancellation of the form factors in the continuum diagrams:

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

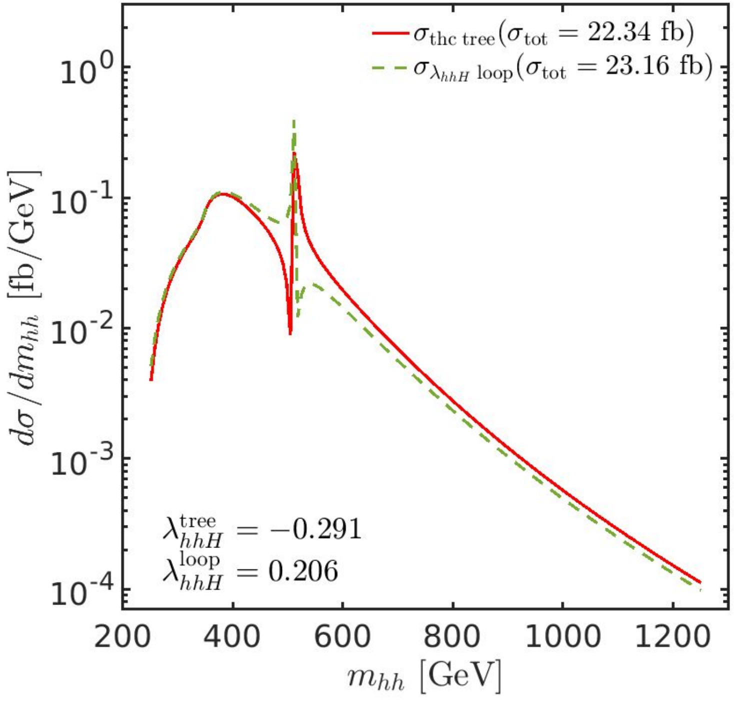
$$C_\triangle \propto \lambda_{hhh}$$

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

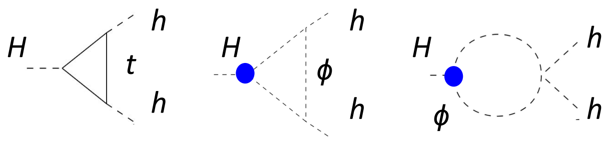
For mhh ~ 2mt ~ 350 GeV the heavy top limit is not valid and the cancellation is reduced

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

- Such a different phenomenology can be induced by the inclusion of loop corrections to the trilinears



- One loop corrections to λ_{hhH} in general are subleading in the allowed regions. However, in scenarios with mass splitting the sign of λ_{hhH} can change.



- $\lambda_{h\phi\phi} \propto (M^2 - m_\phi^2)$ [Braathen, Kanemura: arxiv: 1911.11507]

- Smaller enhancement in the total cross section
- The corrections on λ_{hhH} lead to a completely different phenomenology in invariant mass distributions compared to the tree level coupling

[Arco, Heinemeyer, Mühlleitner, Radchenko: arXiv: 2212.11242]