Higgs pair production at the LHC in the 2HDM:

what can we learn from experiment?

Kateryna Radchenko Serdula

in collaboration with Sven Heinemeyer, Margarete Mühlleitner and Georg Weiglein

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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: $\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1+\rho_1+i\eta_1}{\sqrt{2}} \end{pmatrix}, \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2+\rho_2+i\eta_2}{\sqrt{2}} \end{pmatrix}$

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

- **Softly broken $\mathbb{Z}_2$ symmetry** ($\Phi_1 \to \Phi_1$; $\Phi_2 \to -\Phi_2$) entails 4 Yukawa types $\to$ here only **Type I** analyzed

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

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

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

Higgs self coupling measurements

[ATLAS-CONF-2022- 050]

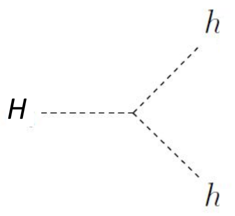
- Motivation: probe of **Higgs potential** and a window to BSM
  [Kanemura, Okada, Senaha: arXiv: 0411354]

- 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:

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



$= - 2iv\,\lambda_{\mathrm{hhH}}$

2HDM Type I (tree level):

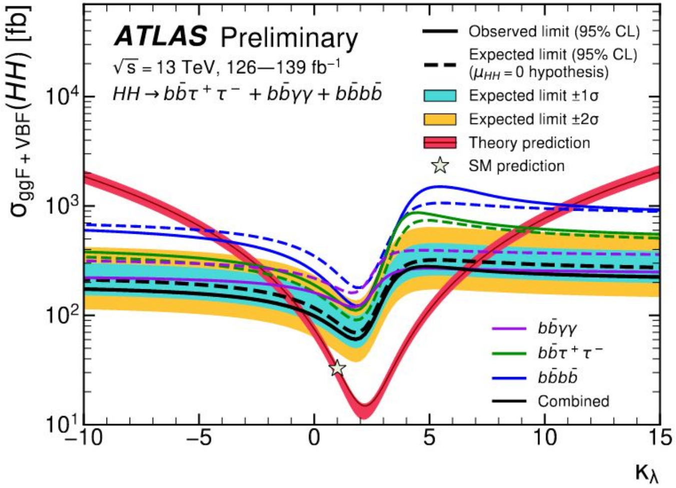
$\kappa_\lambda = [- 0.5,1.3]$; $\lambda_{\mathrm{hhH}} = [- 1.7,1.6]$ [Arco, Heinemeyer, Herrero: arXiv: 2003.12684, 2203.12684]

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)



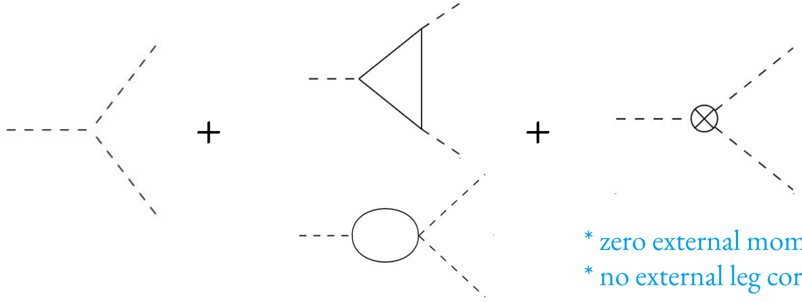
Radiative corrections to the trilinear couplings

- 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]

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

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



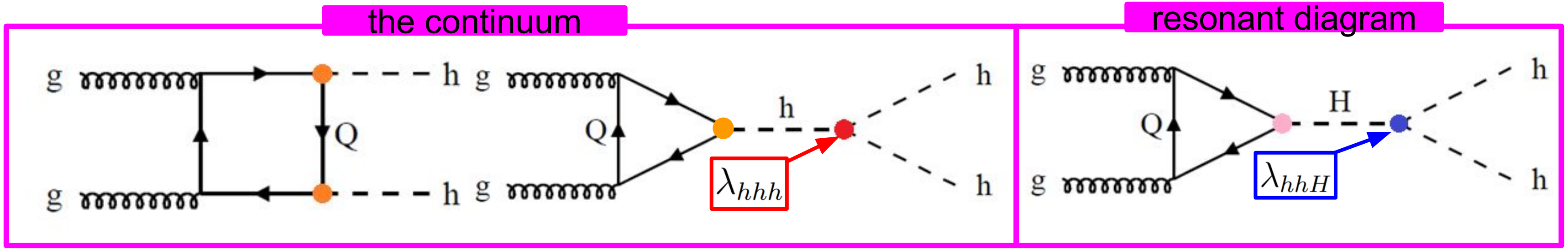
* zero external momentum
* no external leg corrections

- 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]

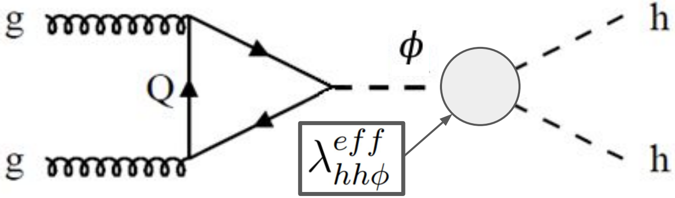
- Dominant process at the LHC **gluon fusion** via quark loop (mostly the top): $\boldsymbol{\sigma}_{SM}$ ~ 38 fb (NLO QCD)



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]

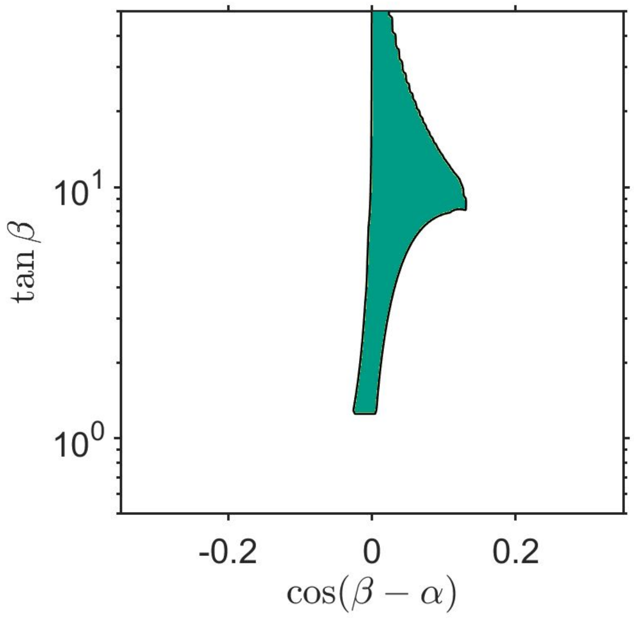


Benchmark planes (updated in 2023)

[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: tbp]

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



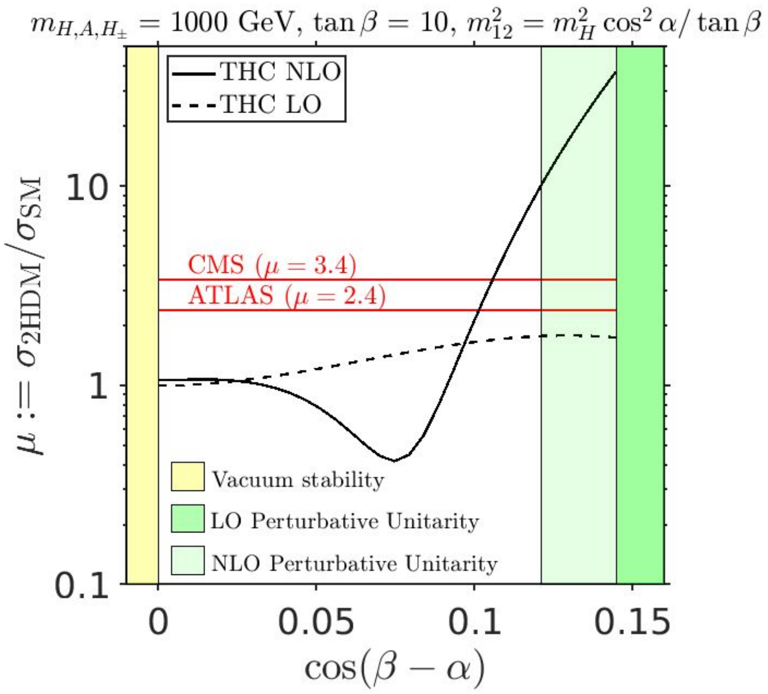
- **EWPO** → checked at two loops using THDM_EWPOS
[Hessenberger, Hollik: arXiv: 1607.04610]
- Theoretical:
(N)LO Unitarity: from the 2 → 2 processes scattering amplitude
[Cacchio, Chowdhury, Eberhardt, Murphy: arXiv:1609.01290]
Stability: tree level boundedness from below of the potential
[Bhattacharyya, Das: arXiv:1507.06424]

- Collider searches and measurements:
Higgs Bounds: experimental limits from direct searches
Higgs Signals: signal strength of the 125 GeV Higgs
[HiggsTools Collaboration: arXiv: 2210.09332]

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

Applicability of non resonant limits

[Abouabid, Arhrib, Azevedo, El Falaki, Ferreira, Mühlleitner, Santos: arXiv: 2112.12515]



- 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

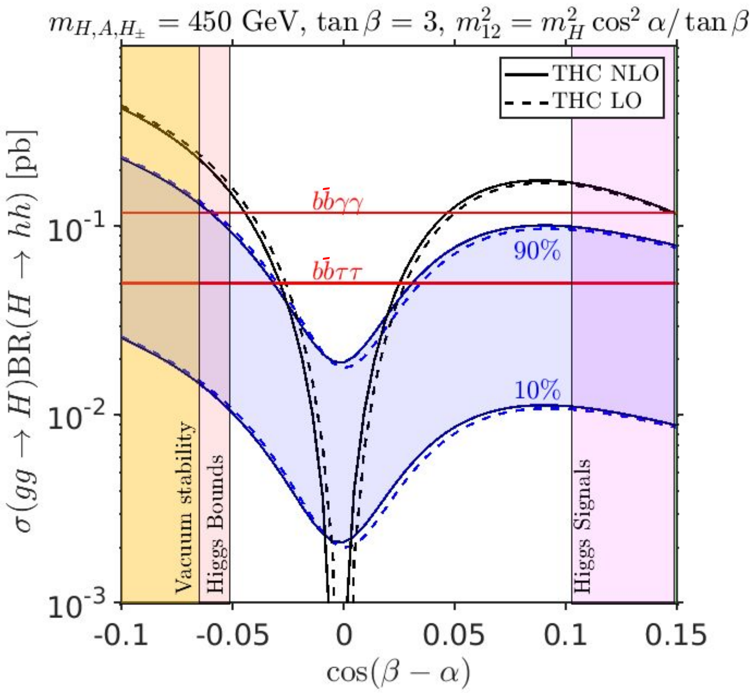
- Including loop corrections to trilinear Higgs couplings excludes regions of otherwise allowed parameter space

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

Searches: [ATLAS-CONF-2022- 05]
[CMS: arXiv: 2207.00043]

Applicability of resonant limits

[Abouabid, Arhrib, Azevedo, El Falaki, Ferreira, Mühlleitner, Santos: arXiv: 2112.12515]



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

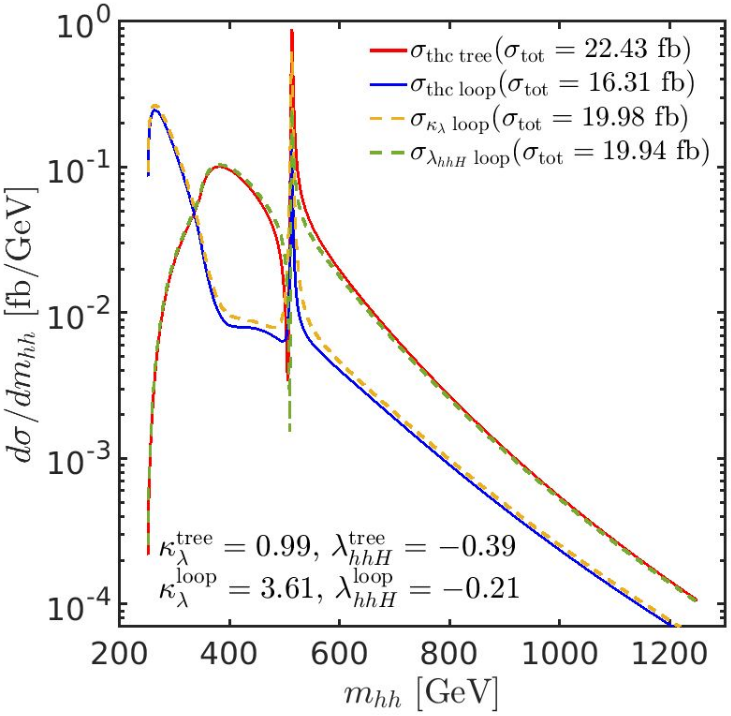
- Most sensitive search is bbττ, also shown bbγγ

- 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]

Phenomenology of THC in m_{hh} distributions



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

- Resonance located at $m_{hh} \sim m_H$ not very affected by corrections to the trilinears

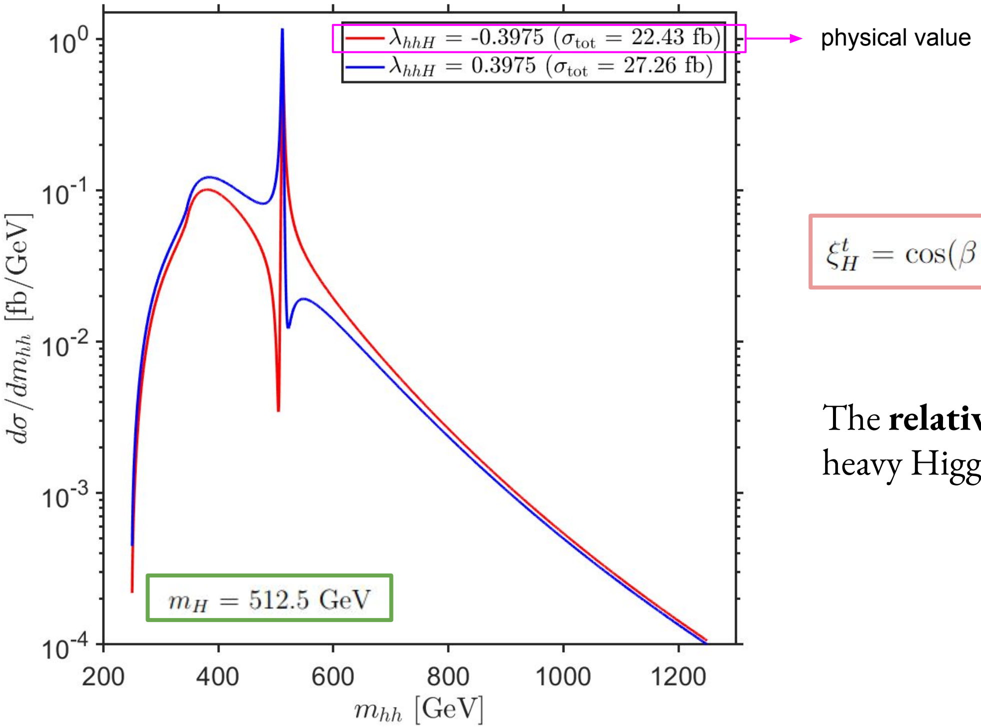
- Larger sensitivity to κ_λ in the low m_{hh} region (because of a cancellation between the box and triangle diagrams in the SM)

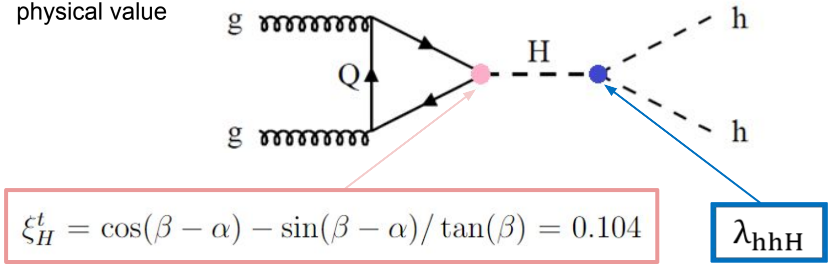
- m_{hh} are extremely sensitive to deviations in the trilinears and a precise theoretical prediction is necessary to interpret future results

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

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

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





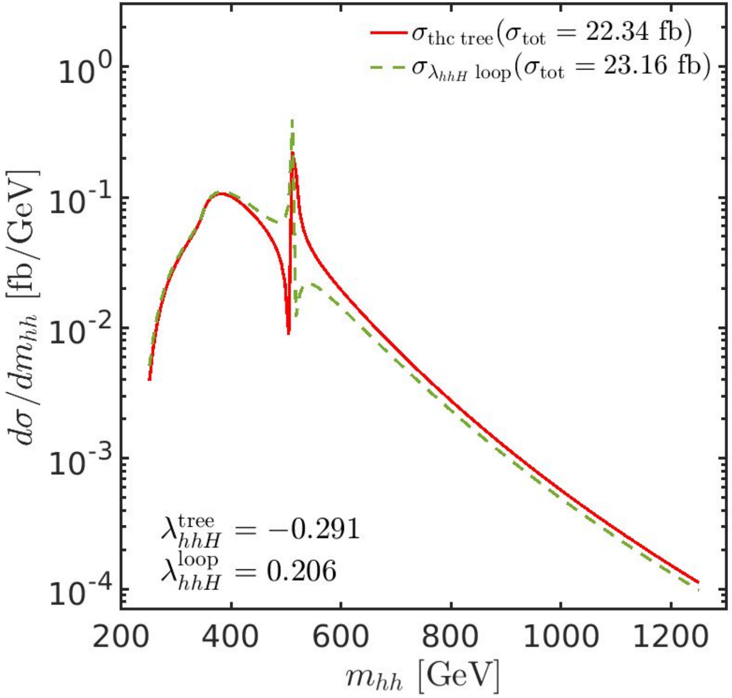
The **relative sign** of the top Yukawa and the BSM coupling to the heavy Higgs gives a **structure** to the resonance:

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

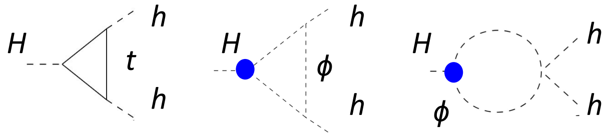
Effect of changes of λ_{hhH} in m_{hh}

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

- 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.



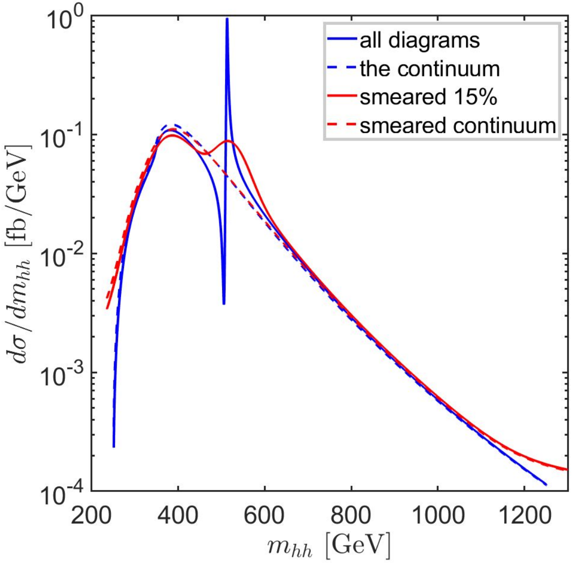
- $\lambda_{h\phi\phi} \propto (M^2 - m_\phi^2)$ [Braathen, Kanemura: arxiv: 1911.11507]

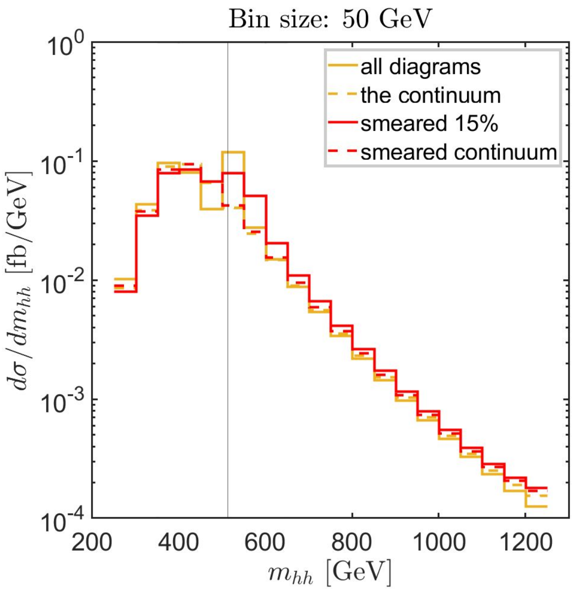
- Smaller enhancement in the total cross section
- The corrections on λ_{hhH} lead to a completely different phenomenology in invariant mass distributions compared to the tree level coupling

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

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**

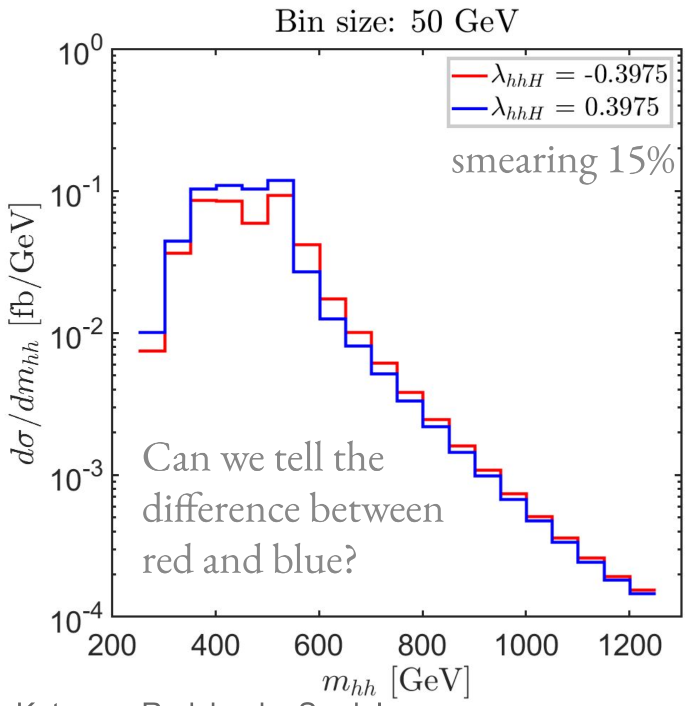


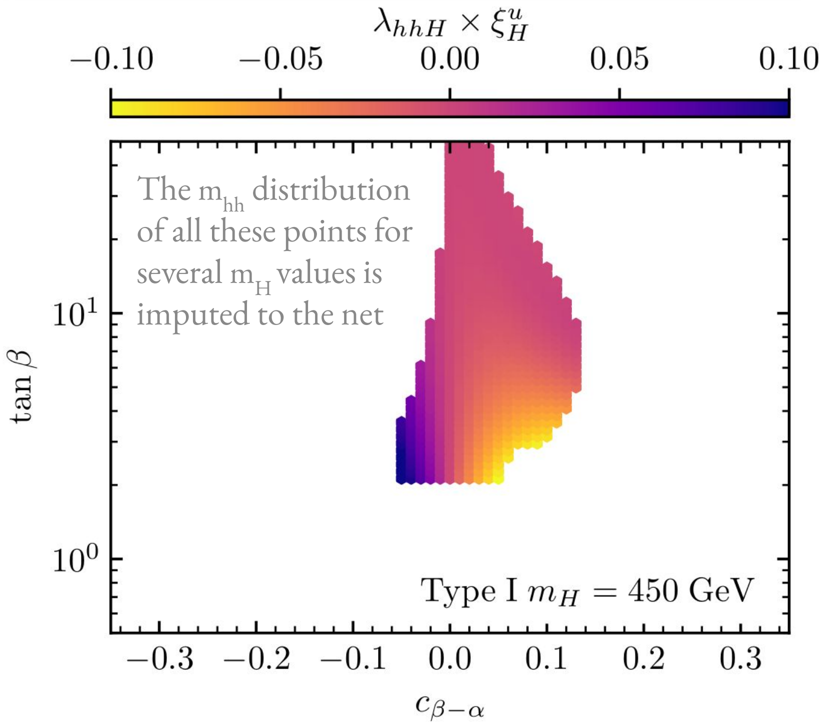


→ Interference substantially washed out by experimental uncertainties [Arco, Heinemeyer, Mühlleitner, Radchenko: arXiv: 2212.11242]

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: $\lambda_{hhH}\xi^{t}_{H}$
- <u>Strategy</u>: input the data of the m_{hh} distributions for a whole benchmark plane into a fully connected NN





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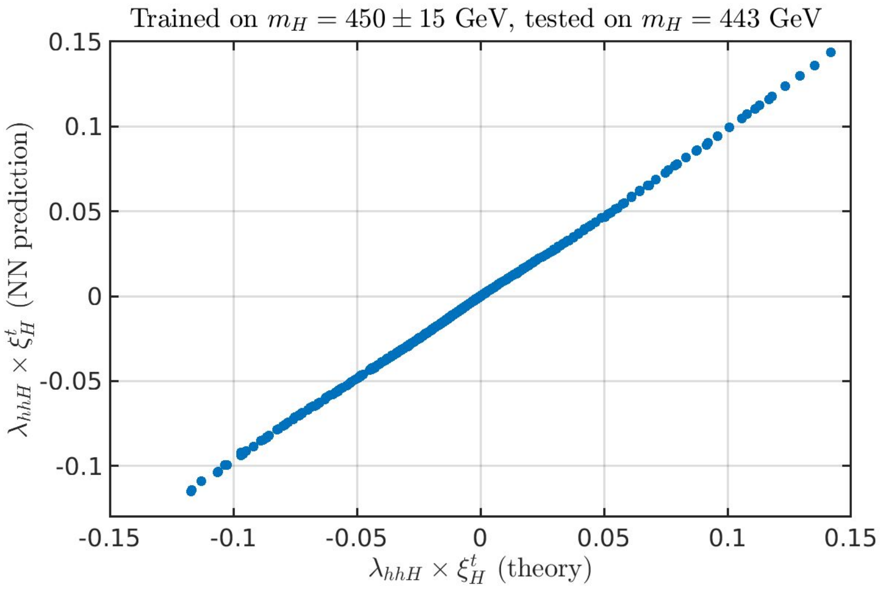
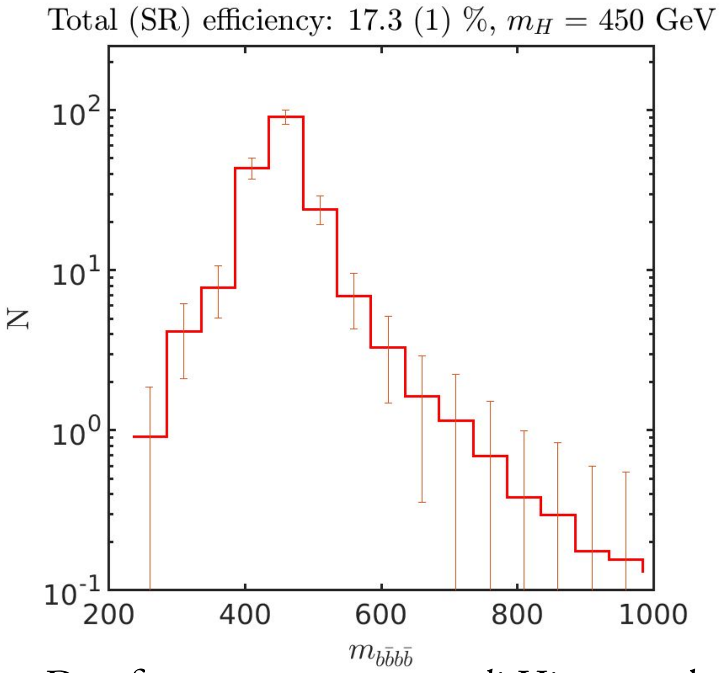


- The mass of the heavy Higgs is a source of uncertainty but it is not an input to the NN
- With enough data sets the prediction for distributions is very accurate

Further experimental uncertainties

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

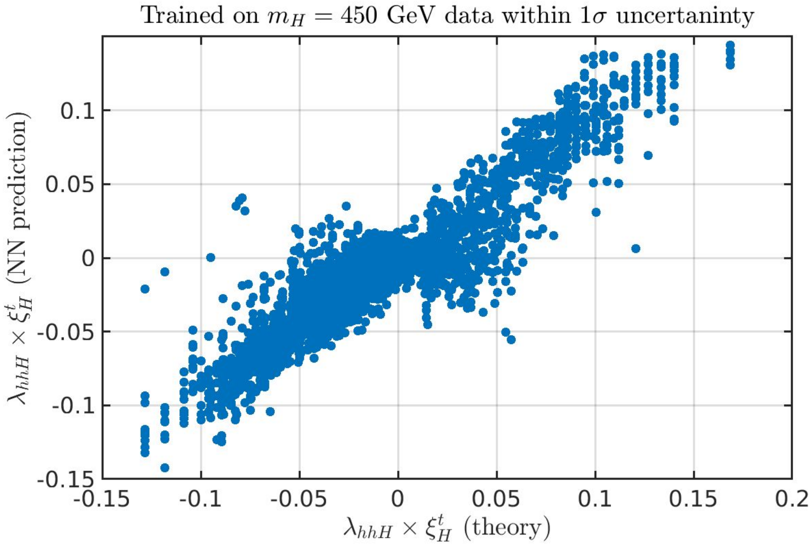


- Data from current resonant di-Higgs searches:

[ATLAS: arXiv: 2202.07288]

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

$\mathcal{L} = 3000\ fb^{-1}$ 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

- 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**

- 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
- Since contributions of the heavy BSM scalars can be sizable in di Higgs production, exchange between theory and experiment must be improved to correctly interpret the results of new resonant Higgs pair production searches

- **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
- Good prospects to sensitivity to the couplings of an extended Higgs sector in the HL phase of the LHC even accounting for experimental uncertainties

Higgs pair production in the 2HDM at tree level

[Plehn, Spira, Zerwas : arXiv: 9603205]

splitting into two spin configurations of the gluons:

spin = 0 spin = 2

$$\frac{d\hat{\sigma}(gg \to HH)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{256(2\pi)^3} \left[\left| \boxed{C_\triangle} \boxed{F_\triangle} + \boxed{C_\Box} \boxed{F_\Box} \right|^2 + \left| \boxed{C_\Box} \boxed{G_\Box} \right|^2 \right]$$

* Generalized coupling constants:

Yukawas

$$C_\triangle = C_\triangle^h + C_\triangle^H \quad ; \quad C_\triangle^{h/H} = \lambda_{H_i H_j (h/H)} \frac{M_Z^2}{\hat{s} - M_{h/H}^2 + i M_{h/H} \Gamma_{h/H}} g_Q^{h/H} \quad ; \quad C_\Box = 1$$

* Triangle form factors:

$$F_\triangle(\tau_t) = \tau_t \left[1 + (1 - \tau_t) f(\tau_t) \right] \quad ; \quad f(\tau) = \begin{cases} \arcsin^2 \dfrac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\dfrac{1}{4} \left[\log \dfrac{1 + \sqrt{1-\tau}}{1 - \sqrt{1-\tau}} - i\pi \right]^2 & \tau < 1 \end{cases}$$

Higgs pair production in the 2HDM at tree level

* Matrix element:

[Plehn, Spira, Zerwas : arXiv: 9603205]

$$\mathcal{M}(g_a g_b \to H_c H_d) = \mathcal{M}^h_\triangle + \mathcal{M}^H_\triangle + \mathcal{M}_\Box$$

$$\mathcal{M}^{h/H}_\triangle = \frac{G_F \alpha_s \hat{s}}{2\sqrt{2}\pi} C^{h/H}_\triangle \; F_\triangle A_{1\,\mu\nu} \; \epsilon^\mu_a \epsilon^\nu_b \; \delta_{ab}$$

$$\mathcal{M}_\Box = \frac{G_F \alpha_s \hat{s}}{2\sqrt{2}\pi} C_\Box \; (F_\Box A_{1\,\mu\nu} + G_\Box A_{2\,\mu\nu}) \; \epsilon^\mu_a \epsilon^\nu_b \; \delta_{ab}$$

a,b: color indices

gluon polarization vectors

* Tensor structure:

$$A_1^{\mu\nu} = \frac{1}{(p_a p_b)} \epsilon^{\mu\nu p_a p_b} \qquad A_2^{\mu\nu} = \frac{p_c^\mu \epsilon^{\nu p_a p_b p_c} + p_c^\nu \epsilon^{\mu p_a p_b p_c} + (p_b p_c)\epsilon^{\mu\nu p_a p_c} + (p_a p_c)\epsilon^{\mu\nu p_b p_c}}{(p_a p_b) p_T^2}$$

* Box form factors:

$$F_\Box = \frac{1}{S^2}\left\{ -2S(S+\rho_c-\rho_d)m_Q^4(D_{abc}+D_{bac}+D_{acb}) + (\rho_c-\rho_d)m_Q^2\left[T_1C_{ac}+U_1C_{bc}+U_2C_{ad}+T_2C_{bd}-(TU-\rho_c\rho_d)m_Q^2D_{acb}\right]\right\}$$

$$G_\Box = \frac{1}{S(TU-\rho_c\rho_d)}\left\{(U^2-\rho_c\rho_d)m_Q^2\left[SC_{ab}+U_1C_{bc}+U_2C_{ad}-SUm_Q^2D_{abc}\right] - (T^2-\rho_c\rho_d)m_Q^2\left[SC_{ab}+T_1C_{ac}+T_2C_{bd}-STm_Q^2D_{bac}\right]\right.$$
$$\left. + \left[(T+U)^2-4\rho_c\rho_d\right](T-U)m_Q^2C_{cd} + 2(T-U)(TU-\rho_c\rho_d)m_Q^4(D_{abc}+D_{bac}+D_{acb})\right\}$$

Renormalization conditions in BSMPT

[Basler, Mühlleitner: arXiv: 1803.02846]

* Counterterm potential:

$$V^{\mathrm{CT}} = \delta m_{11}^2 \Phi_1^\dagger \Phi_1 + \delta m_{22}^2 \Phi_2^\dagger \Phi_2 - \delta m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right) + \frac{\delta\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\delta\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2$$
$$+ \delta\lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \delta\lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \frac{\delta\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \left(\Phi_2^\dagger \Phi_1\right)^2\right]$$
$$+ \delta T_1 \left(\zeta_1 + \omega_1\right) + \delta T_2 \left(\zeta_2 + \omega_2\right) + \delta T_{\mathrm{CP}} \left(\psi_2 + \omega_{\mathrm{CP}}\right) + \delta T_{\mathrm{CB}} \left(\rho_2 + \omega_{\mathrm{CB}}\right) .$$

* On shell renormalization conditions:

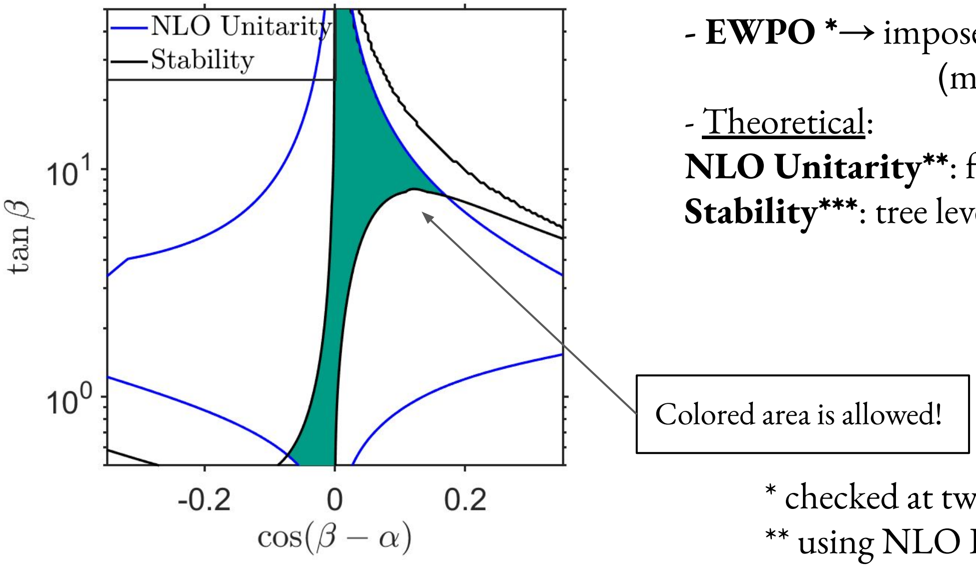
$$\partial_{\phi_i} V^{\mathrm{CT}}\Big|_{\phi=\langle\phi^c\rangle_{T=0}} = - \partial_{\phi_i} V^{\mathrm{CW}}\Big|_{\phi=\langle\phi^c\rangle_{T=0}}$$
$$\partial_{\phi_i}\partial_{\phi_j} V^{\mathrm{CT}}\Big|_{\phi=\langle\phi^c\rangle_{T=0}} = - \partial_{\phi_i}\partial_{\phi_j} V^{\mathrm{CW}}\Big|_{\phi=\langle\phi^c\rangle_{T=0}}$$

Benchmark planes (updated in 2023)

[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

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



- **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:

NLO Unitarity**: from the 2 → 2 processes scattering amplitude

Stability***: tree level boundedness from below of the potential

* checked at two loops with THDM_EWPOS

** using NLO RGE running at high energy limit

*** checked that the EW minimum is global with EVADE

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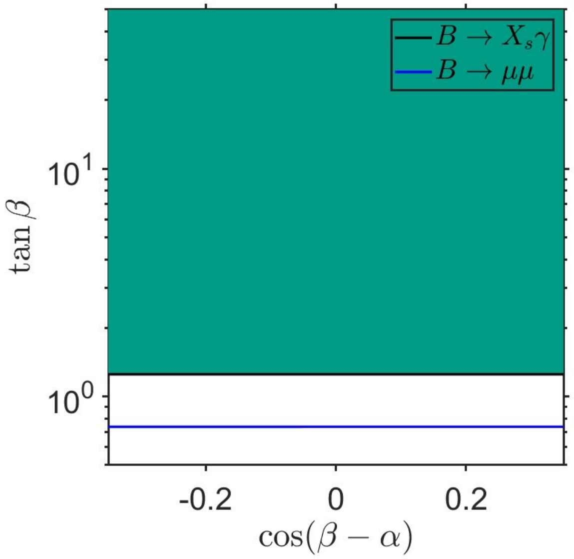

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- Collider searches and measurements:

Higgs Bounds: experimental limits from direct searches

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

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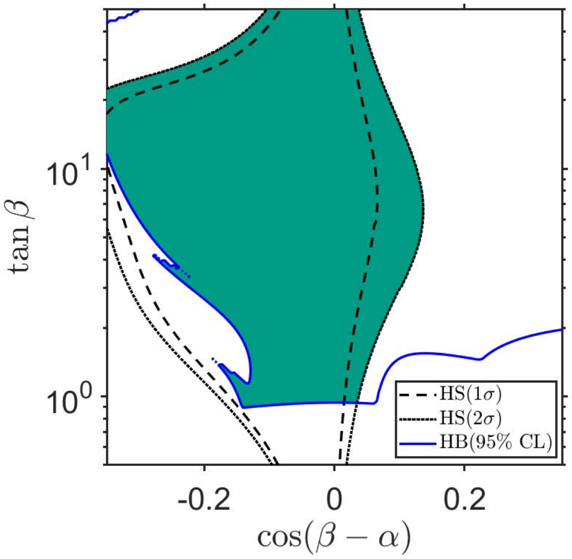

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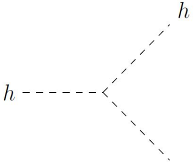
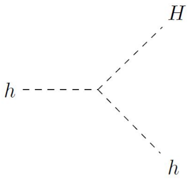
* checked with latest version of HiggsTools

Feynman rules for 2HDM tree level THC

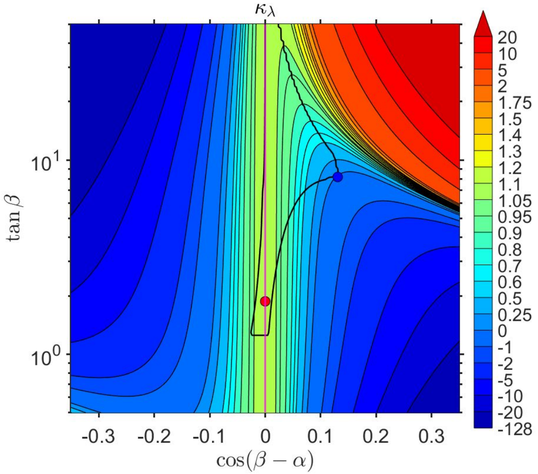


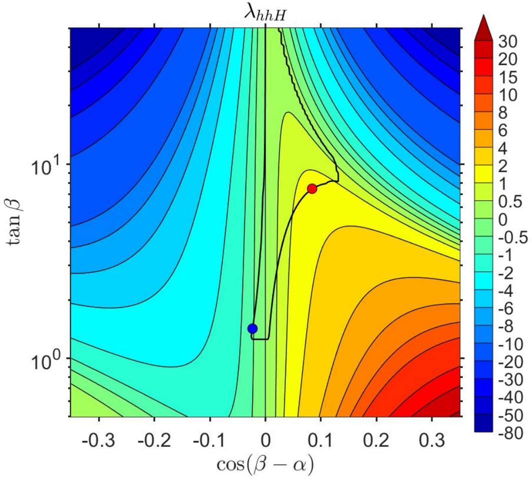
$$\lambda_{hhh} = \frac{1}{2v^2}\left\{m_h^2 s^3_{\beta-\alpha} + \left(3m_h^2 - 2\boxed{\bar{m}^2}\right) c^2_{\beta-\alpha} s_{\beta-\alpha} + 2\cot 2\beta \left(m_h^2 - \boxed{\bar{m}^2}\right) c^3_{\beta-\alpha}\right\}$$



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

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



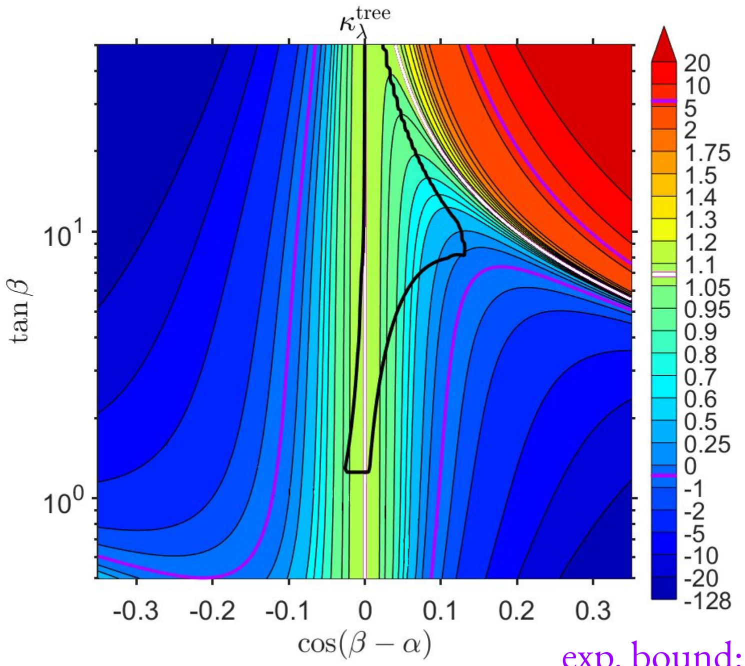


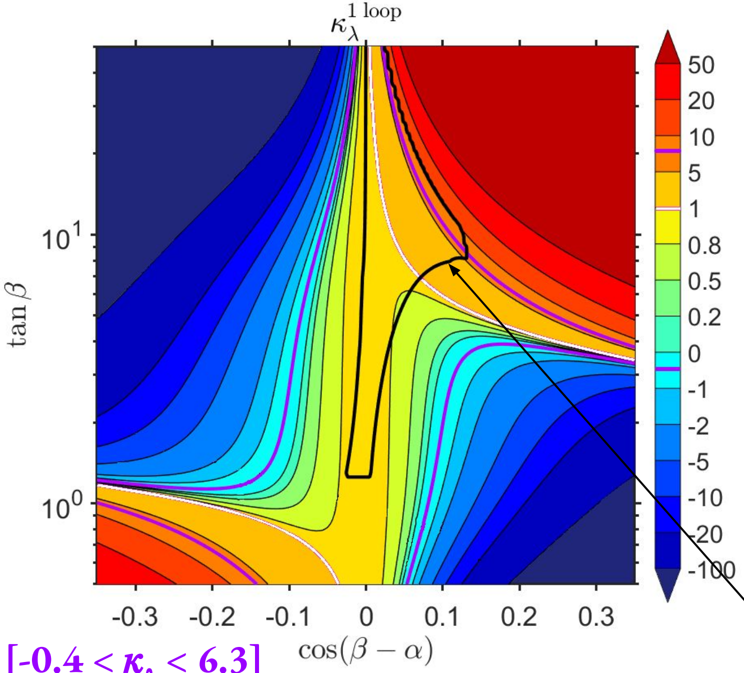
$\kappa_\lambda \in$ [-0.4 , 1]
$\lambda_{\text{hhH}} \in$ [-0.3 , 1.2]

Effect of loop corrections to κ_λ

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

- In this (non resonant) scenario: $0 < \boldsymbol{\kappa_\lambda}^{\text{tree}} < 1$ and $0.7 < \boldsymbol{\kappa_\lambda}^{\text{1 loop}} < 11$





exp. bound: **[-0.4 < $\boldsymbol{\kappa_\lambda}$ < 6.3]**

Current collider experiments already reach the region of otherwise unconstrained parameter space of the 2HDM!

[Bahl, Braathen, Weiglein : arXiv: 2202.03453]

Allowed region inside the black contour

Di-Higgs production measurements

- Distinction given by experimental data:

Non resonant production	Resonant production
Involves mostly the continuum diagrams (present in the SM)	The heavy Higgs plays an important role in the overall process
Targeted to find deviations in κ_λ assuming all other couplings are SM like	Can be approximated as the production cross section times the branching ratio of the decay to two light Higgses
$\boldsymbol{\sigma(gg \to hh)}$	$\boldsymbol{\sigma(gg \to H)\ BR(H \to hh)}$
HPAIR	SusHi + HDECAY

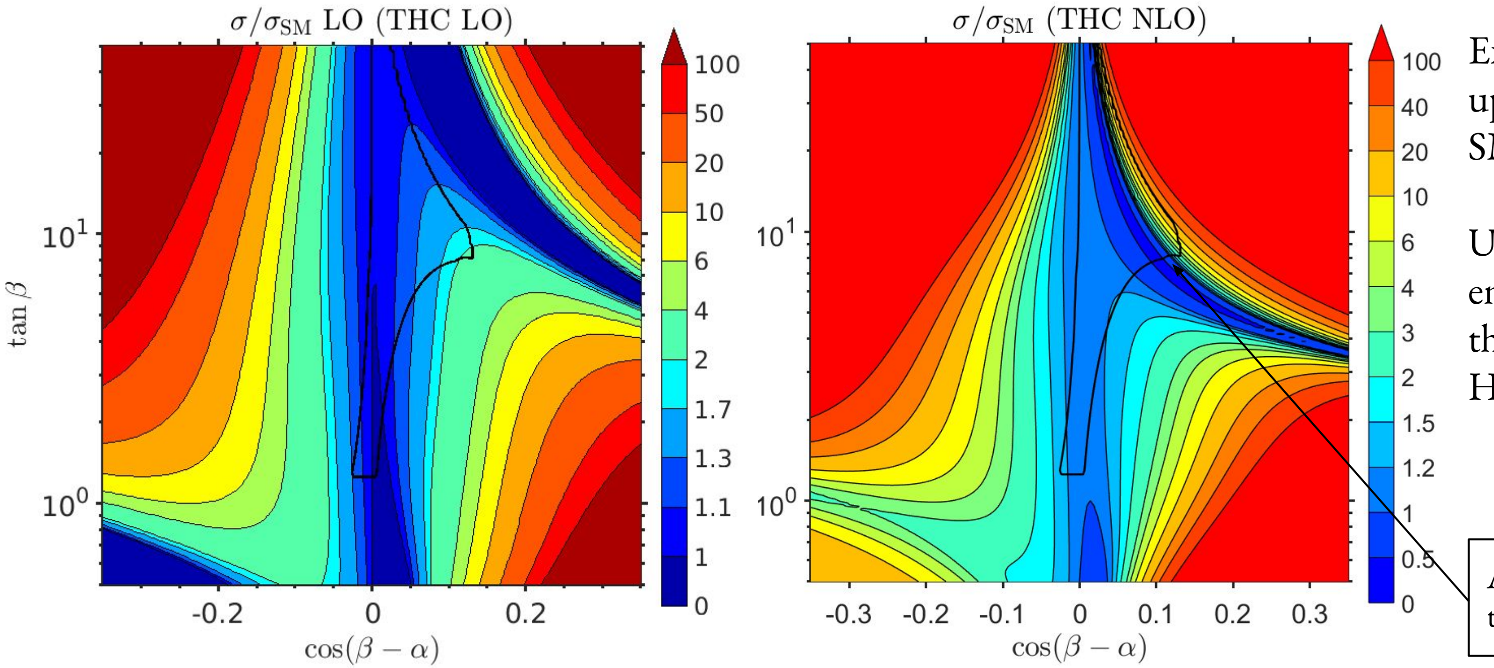
[Plehn, Spira, Zerwas : arXiv: 9603205]
[Dawson, Dittmaier, Spira: arXiv:9805244]
[Abouabid, Arhrib, Azevedo, El Falaki, Ferreira, Mühlleitner, Santos: arXiv: 2112.12515]

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

Impact on Higgs pair production

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

- This example features non resonant Higgs pair production, i.e. the main contribution in the cross section comes from the continuum diagrams, therefore it behaves following the overall trend of $\boldsymbol{\kappa_\lambda}$



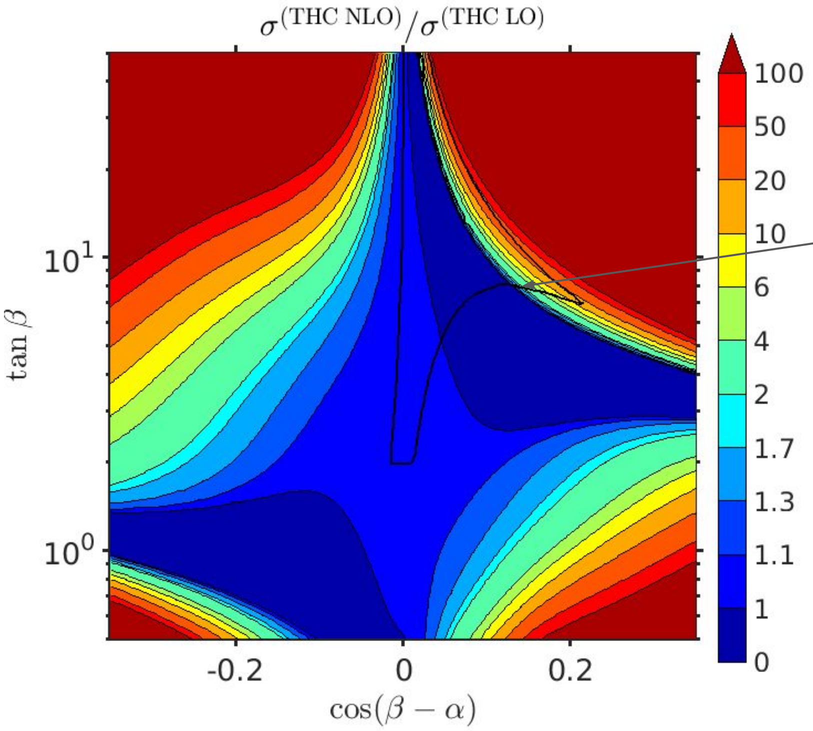
Expected deviations up to 20 times the SM predictions

Up to 10 times enhancement w.r.t the leading order Higgs self coupling

Allowed region inside the black contour

Backup

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

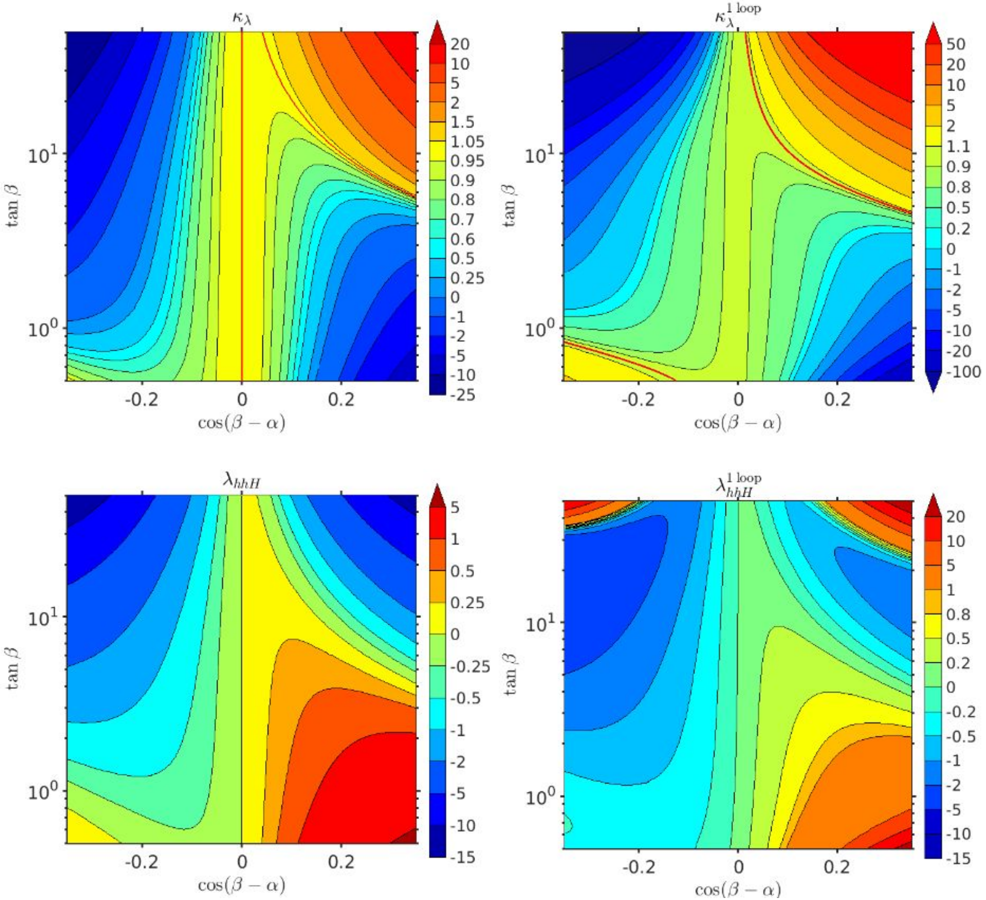


Ratio of the predicted cross section in the non resonant plane scenario with the trilinears at one loop and at tree level

Deviations up to 10 with respect to the prediction with the trilinears at tree level within the allowed region

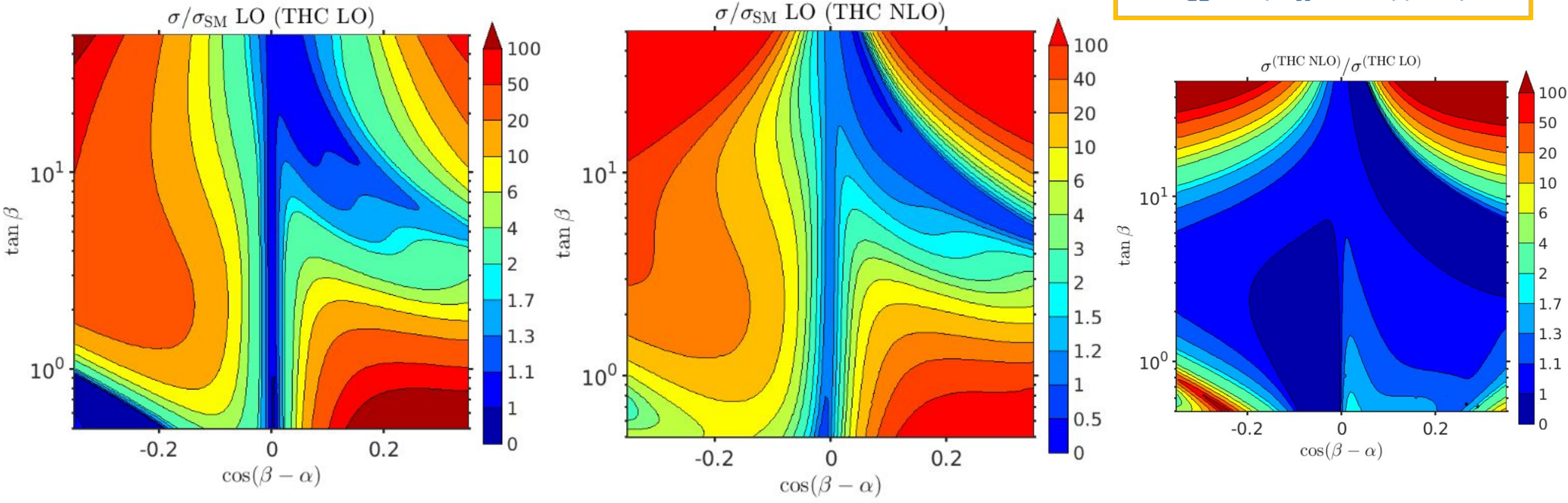
Backup: trilinears in the resonant scenario

$$m_H = m_A = m_{H^\pm} = 450 \quad \text{GeV}$$
$$m_{12}^2 = (m_H^2 \cos^2\alpha)/\tan\beta$$



Backup: cross section in the resonant scenario

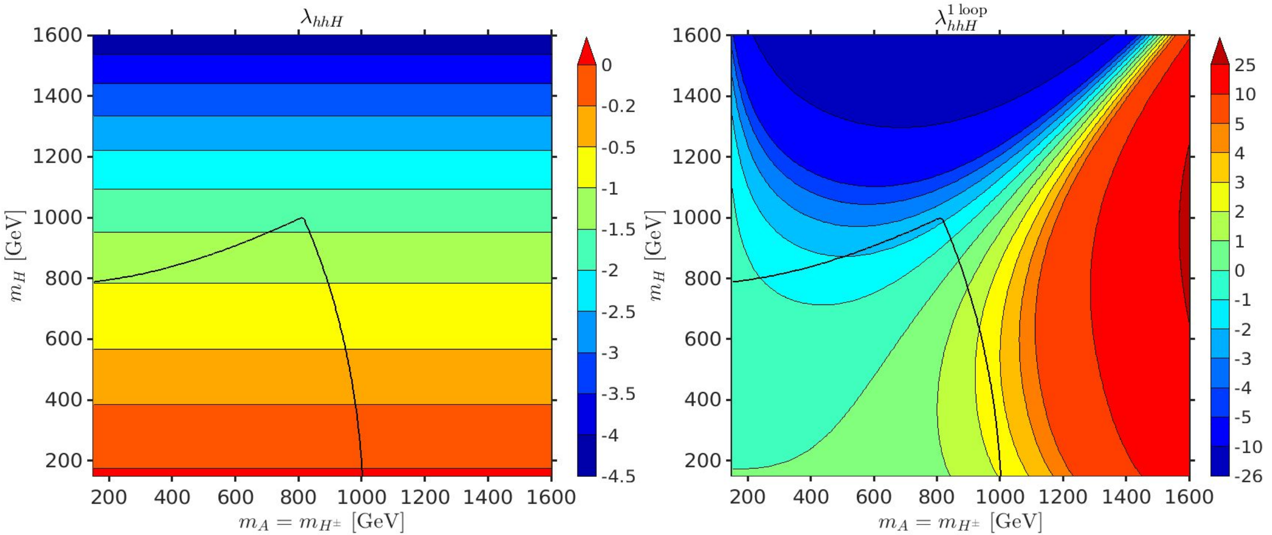
$$m_H = m_A = m_{H^\pm} = 450 \quad \mathrm{GeV}$$
$$m_{12}^2 = (m_H^2 \cos^2\alpha)/\tan\beta$$

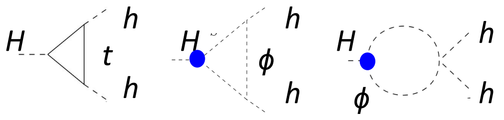


Effect of loop corrections to λ_{hhH}

- In this scenario : $-1.5 < \boldsymbol{\lambda}_{\mathbf{hhH}}^{\mathbf{tree}} < 0$ and $-2.2 < \boldsymbol{\lambda}_{\mathbf{hhH}}^{\mathbf{1\ loop}} < 2.2$
- Loop corrections to λ_{hhH} are subleading in the allowed regions. However, in scenarios with **mass splitting** the **sign of $\boldsymbol{\lambda}_{\mathbf{hhH}}$** can change, leading to a completely different phenomenology in invariant mass distributions

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



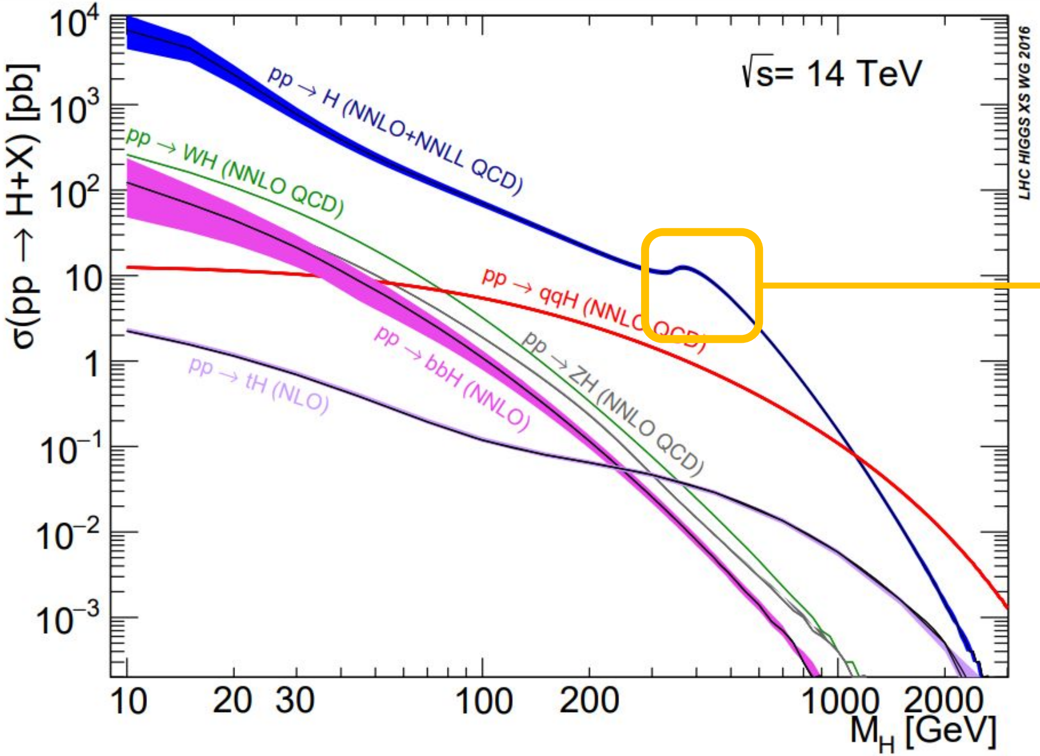


$\lambda_{h\phi\phi} \propto (M^2 - m_\phi^2)$

[Braathen, Kanemura: arxiv: 1911.11507]

- In this benchmark a smaller enhancement in the total cross section is observed due to corrections in the trilinears

Backup



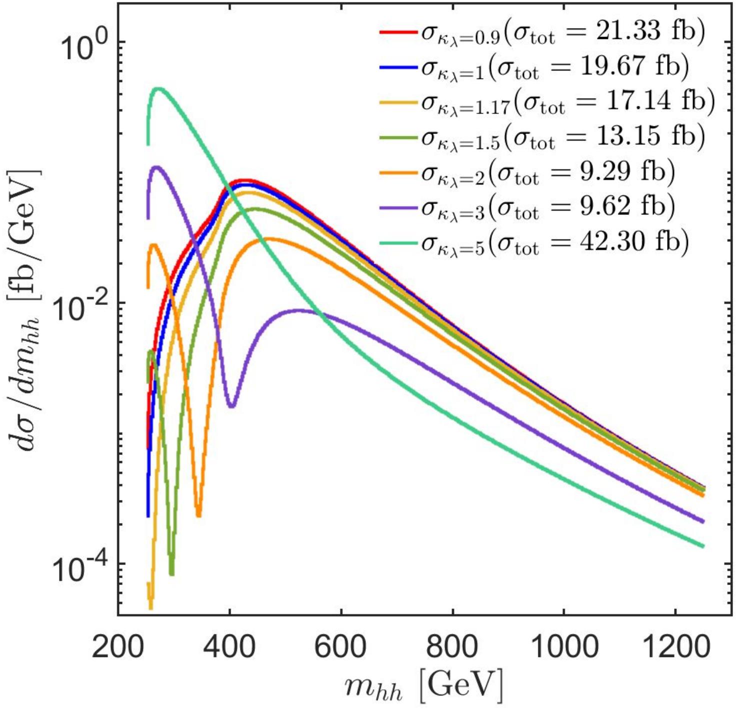
Top pair threshold → gives a hint on the results for Higgs pair production

[LHC Higgs Working Group: CERN Yellow Report 4]

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:

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

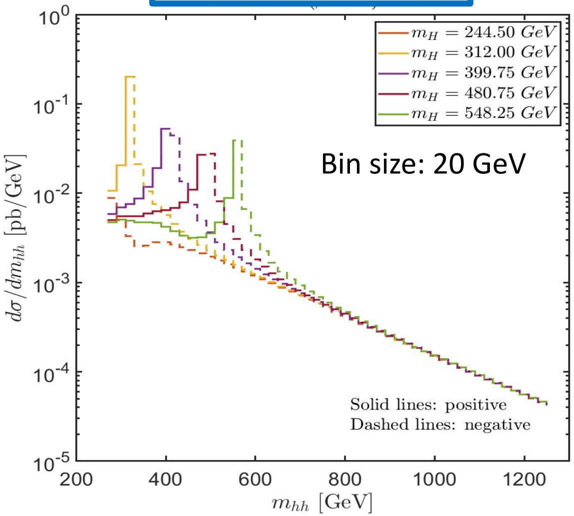
$$C_\triangle \propto \lambda_{hhh}$$

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

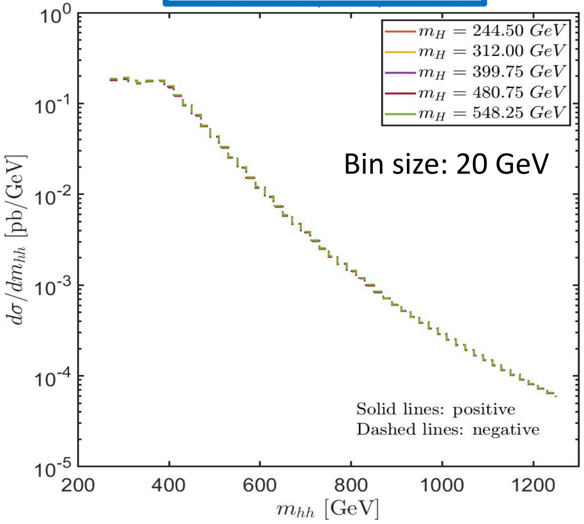
For $m_{hh} \sim 2m_t \sim 350$ GeV the heavy top limit is not valid and the cancellation is reduced

Backup : Interferences

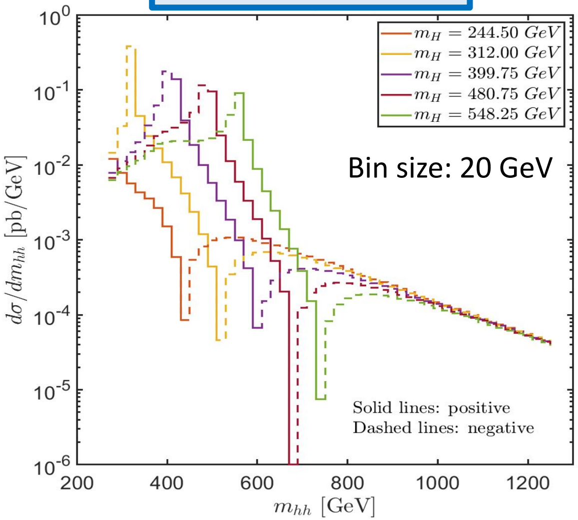
H and h



h and box



H and box



- Negative interference between A and C (SM case)
- Res. Enhancement at m_H = m_{hh} (σ_{interf} changes sign):

Below

B+C: negative
A+C: positive

Above

B+C: positive
A+C: negative

Dip-peak