Higgs Pair Production and Triple Higgs Couplings at the LHC in extended Higgs sectors

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

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

- Potential:

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

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

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

- **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

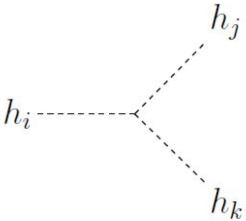
Higks self coupling measurements

[ATLAS-CONF-2022- 050]

- Motivation: probe of **Higgs potential** and a window to BSM physics through its relation to:
  * origin of EWSB
  * thermal history of the universe: large THC favour FOEWPT, a necessary condition for electroweak baryogenesis [Kanemura, Okada, Senaha: arxiv: 0411354], Noble, Perelstein: arXiv: 0711.3018]
  * CP violation and baryogenesis [A. Eichhorn et al.: arxiv: 1711.00019]
  * vacuum stability
- 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:

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



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

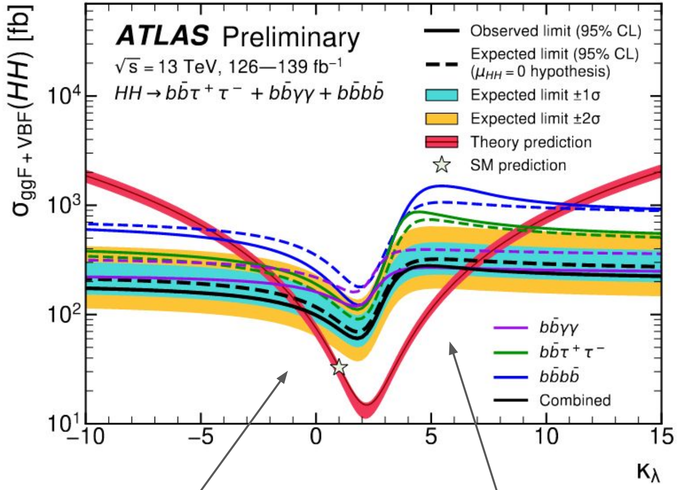
n = number of identical Higgses

Experimental status:

- access through Higgs pair production

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

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



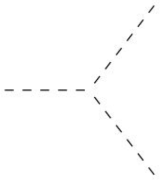
Higher cross section for lower values of κ_λ	Higher cross section for high values of κ_λ

Radiative corrections to the trilinear couplings

- Crucial for FOEWPT
- We use the effective potential approach and implement an effective coupling in the di Higgs production process

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

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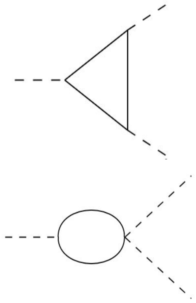
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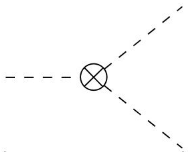


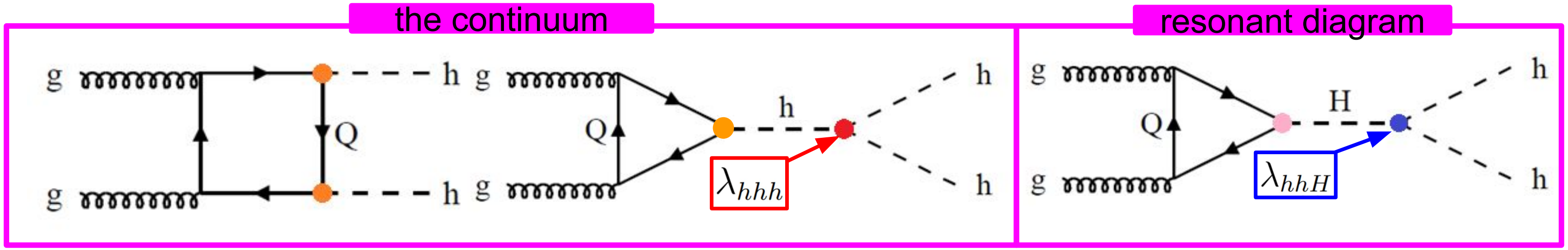
* zero external momentum
* no external leg corrections

- The calculation is done by means of the public code BSMPT
- It is performed in the limit of zero external momentum
- Physical masses and mixing angles are renormalized on shell to their tree level value

[Basler, Mühlleitner: arXiv: 1803.02846]

Di-Higgs production (gg → hh)

[Plehn, Spira, Zerwas : arXiv: 9603205]

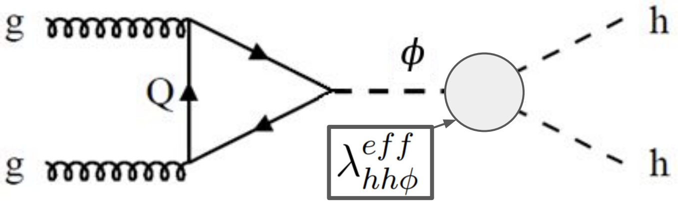


$\sigma_{SM} \sim$ 38 fb at NLO

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]



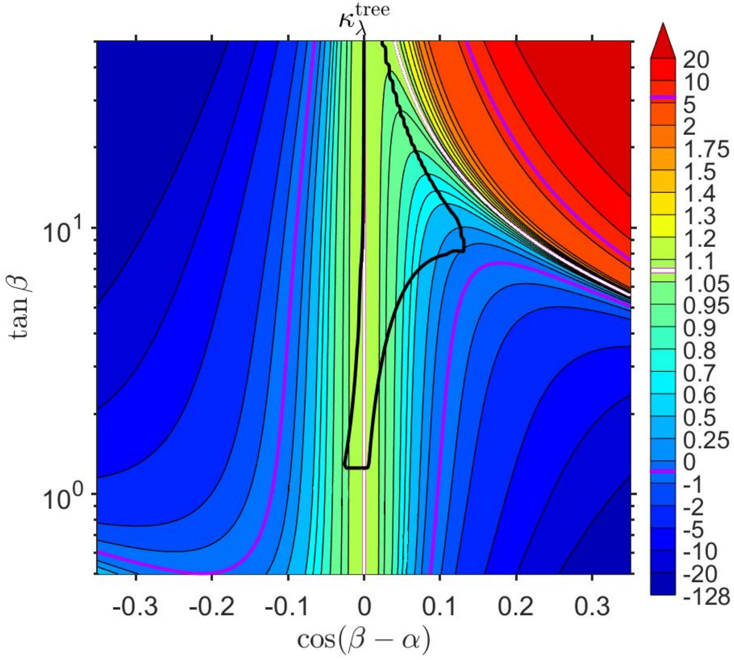
* We use a modified version of the code HPAIR

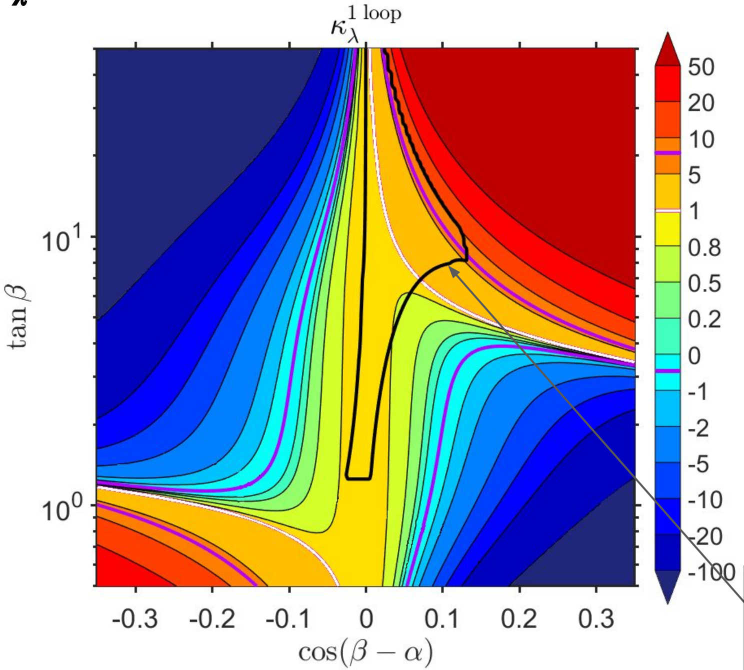
[Abouabid, Arhrib, Azevedo, El Falaki, Ferreira, Mühlleitner, Santos: arXiv: 2112.12515]

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

Effect of loop corrections to κ_λ

- In the 2HDM, deviations of the Higgs self coupling at tree level were found to be: $-0.5 < \boldsymbol{\kappa_\lambda}^{\mathbf{tree}} < 1.3$ (Type I)
  [Arco, Heinemeyer, Herrero: arXiv: 2003.12684, 2203.12684]
- In this scenario: $0 < \boldsymbol{\kappa_\lambda}^{\mathbf{tree}} < 1$ and $0.7 < \boldsymbol{\kappa_\lambda}^{\mathbf{1\ loop}} < 11$





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

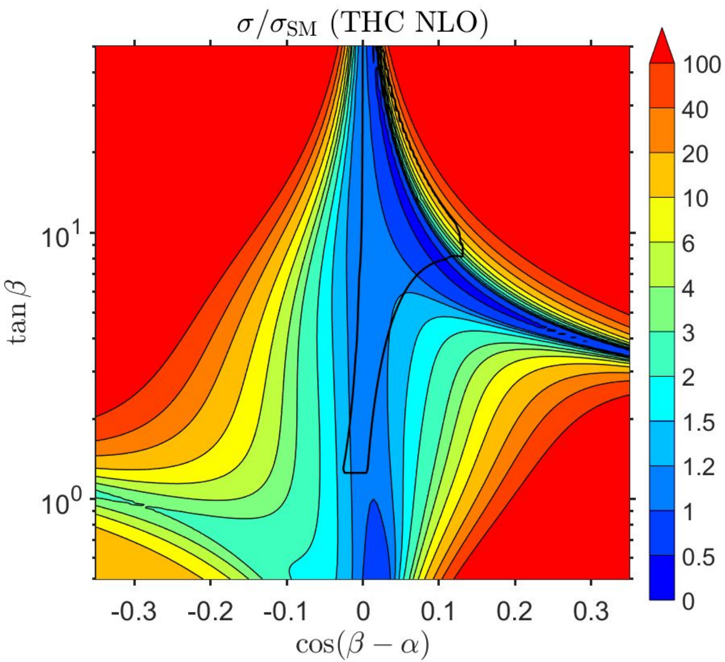
[Bahl, Braathen, Weiglein : arXiv: 2202.03453]

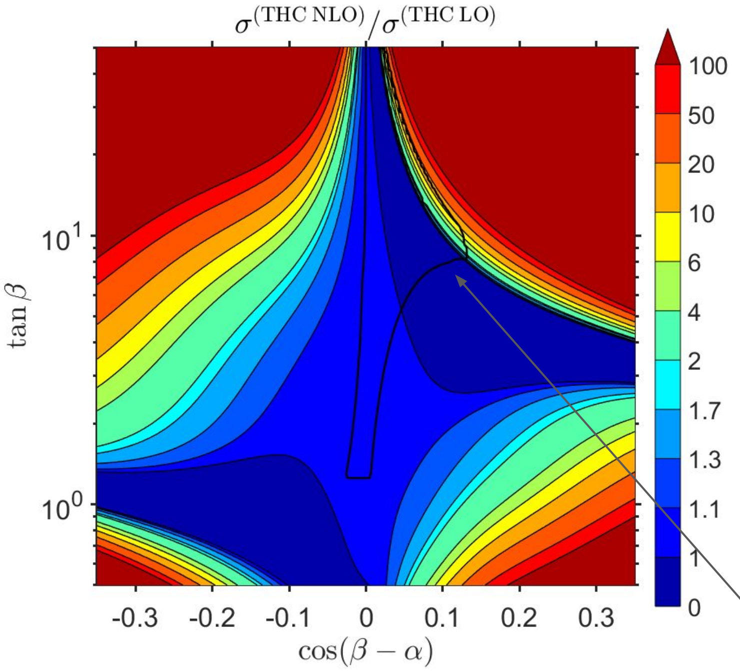
Allowed region inside the black contour

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

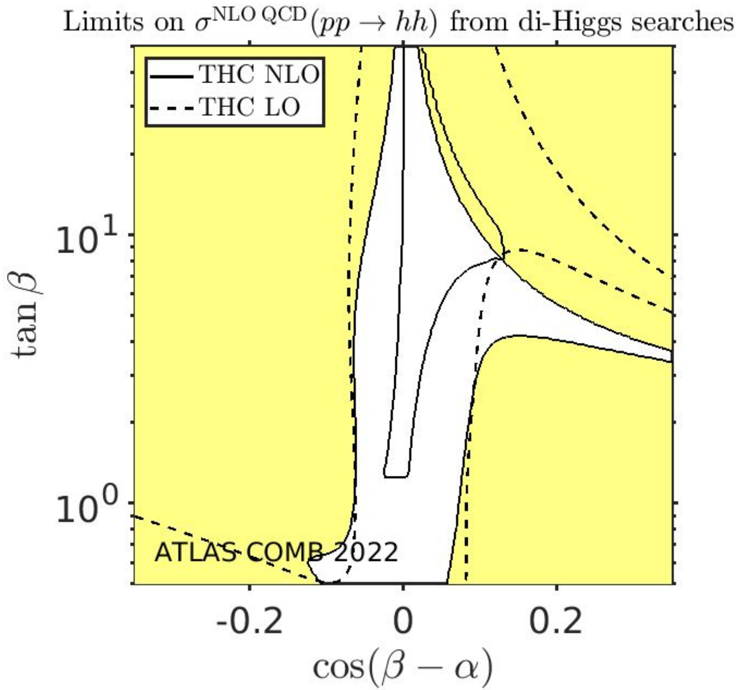
Up to 10 times enhancement w.r.t the leading order Higgs self coupling

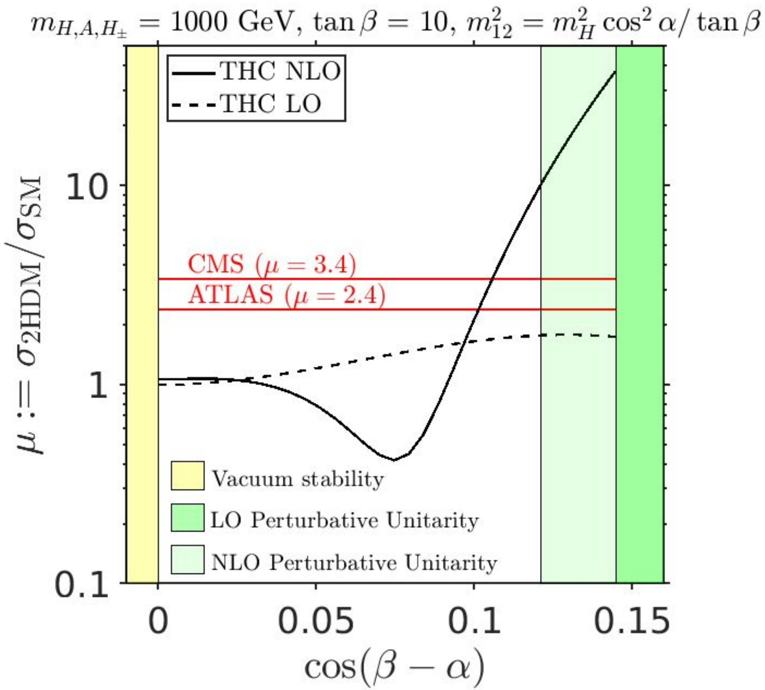
Allowed region inside the black contour

Applicability of non resonant limits

[ATLAS-CONF-2022- 050]

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

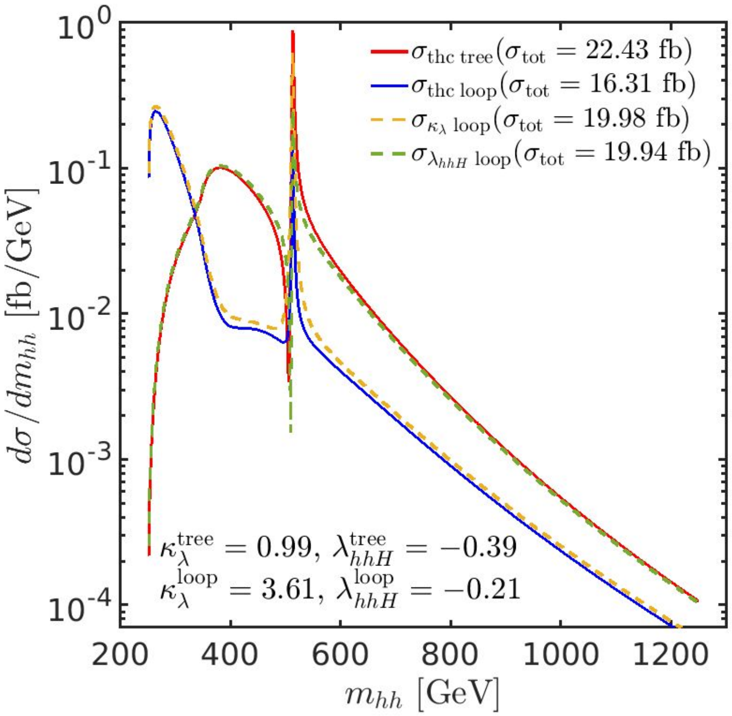




- Including loop corrections to trilinear Higgs couplings excludes regions of otherwise allowed parameter space

Effect of loop corrections of THC in m_{hh}

- Inclusion of loop corrections can drastically change the invariant mass distribution of a particular scenario:



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

- In this case the corrections to λ_{hhH} do not play a significant role

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

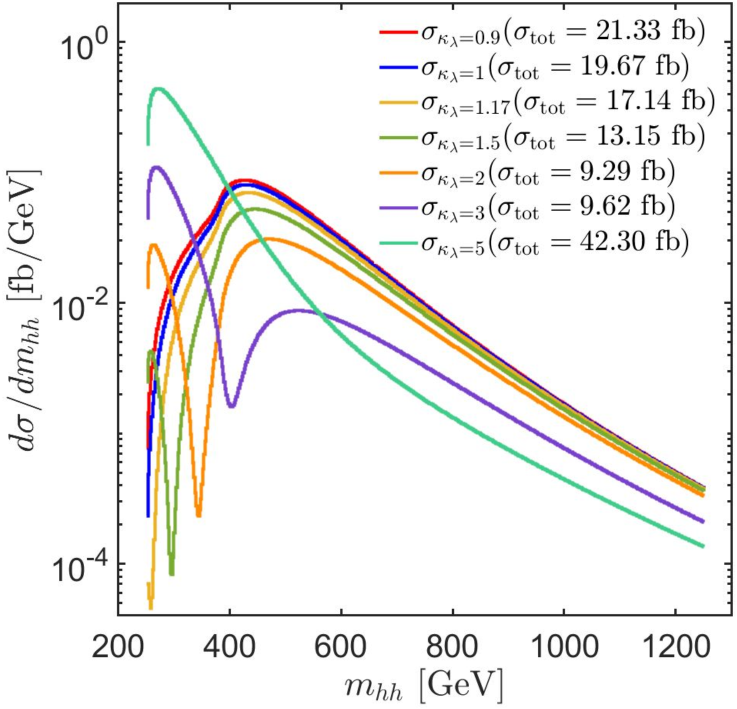
- Drop in the m_{hh} ~ 400 GeV region due to a shift in the cancellation of form factors (see next slide)

- Change in the dip peak structure of the resonance

Effect of loop corrections of THC 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

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

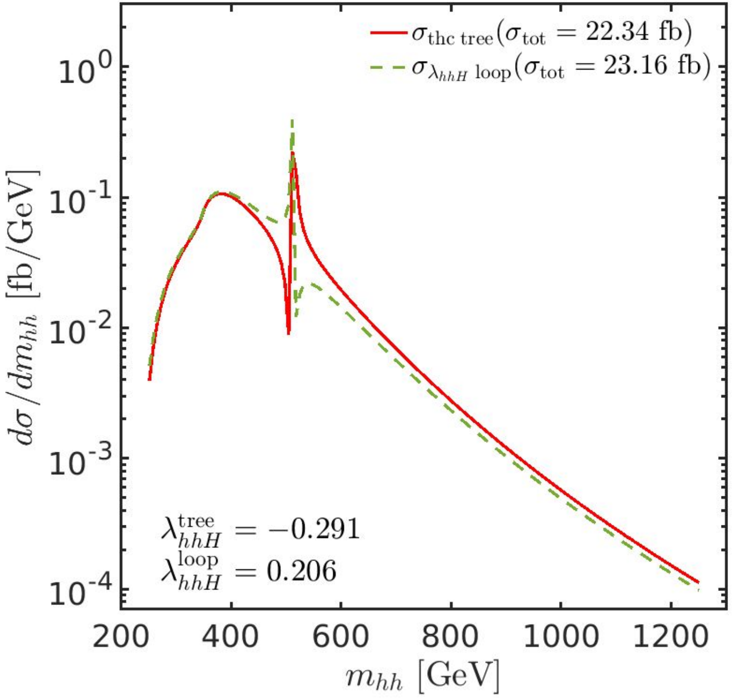
$$C_\triangle \propto \lambda_{hhh}$$

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

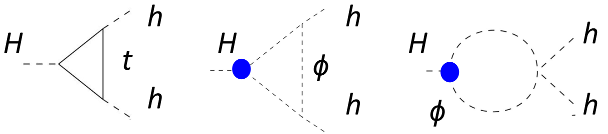
For m_{hh} ~ $2m_t$ ~ 350 GeV the heavy top limit is not valid and the cancellation is reduced

Effect of loop corrections to λ_{hhH}

- In the 2HDM deviations in this coupling from the SM prediction were found to be between -1.7 to 1.6 (Type I)



- 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.



● $\lambda_{h\phi\phi} \propto \sum_{\phi=H,A,H^{\pm}} (M^2 - m_\phi^2)$ [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]

Conclusions

- Sizable **deviations in trilinear Higgs couplings** are allowed by all current constraints. BSM effect could have an important **impact on the early universe**

- Contributions of the heavy BSM scalars can be sizable in di Higgs production

- **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

- Including **radiative corrections to the Higgs self interactions** helps to constrain parameter regions of otherwise unconstrained parameter space in the 2HDM

- Current experimental bounds on **non-resonant di Higgs production** cross section already exclude regions of so far allowed parameter space

- <u>Next step</u>: explore scenarios with a larger resonant contribution in the cross section

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

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

* Triangle form factors:

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

Higgs pair production in the 2HDM at tree level

[Plehn, Spira, Zerwas : arXiv: 9603205]

* Matrix element:

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

a,b: color indices

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

gluon polarization vectors

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

* 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:

$$F_\Box = \frac{1}{S^2}\left\{ -2S(S+\rho_c-\rho_d)m_Q^4(D_{abc}+D_{bac}+D_{acb}) + (\rho_c-\rho_d)m_Q^2\left[T_1 C_{ac} + U_1 C_{bc} + U_2 C_{ad} + T_2 C_{bd} - (TU-\rho_c\rho_d)m_Q^2 D_{acb}\right]\right\}$$

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

$$\left. + \left[(T+U)^2 - 4\rho_c\rho_d\right](T-U)m_Q^2 C_{cd} + 2(T-U)(TU-\rho_c\rho_d)m_Q^4(D_{abc}+D_{bac}+D_{acb})\right\}$$

Renormalization conditions in BSMPT [Basler, Mühlleitner: arXiv: 1803.02846]

* Counterterm potential:

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

* On shell renormalization conditions:

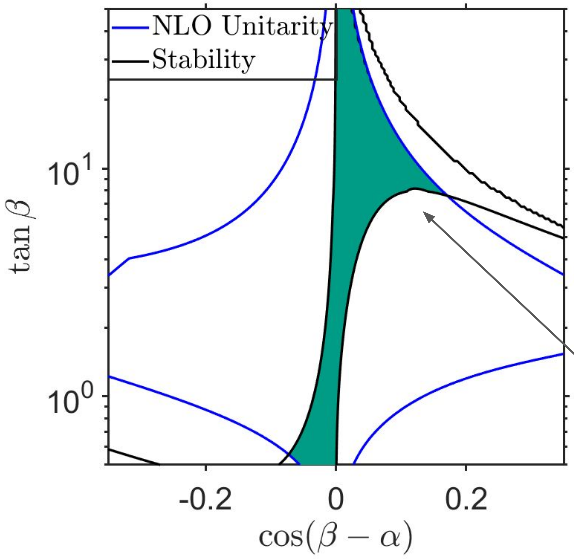
$$
\begin{aligned}
\partial_{\phi_i} V^{\mathrm{CT}}\Big|_{\phi=\langle\phi^c\rangle_{T=0}} &= -\, \partial_{\phi_i} V^{\mathrm{CW}}\Big|_{\phi=\langle\phi^c\rangle_{T=0}} \\
\partial_{\phi_i}\partial_{\phi_j} V^{\mathrm{CT}}\Big|_{\phi=\langle\phi^c\rangle_{T=0}} &= -\, \partial_{\phi_i}\partial_{\phi_j}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

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

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



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:

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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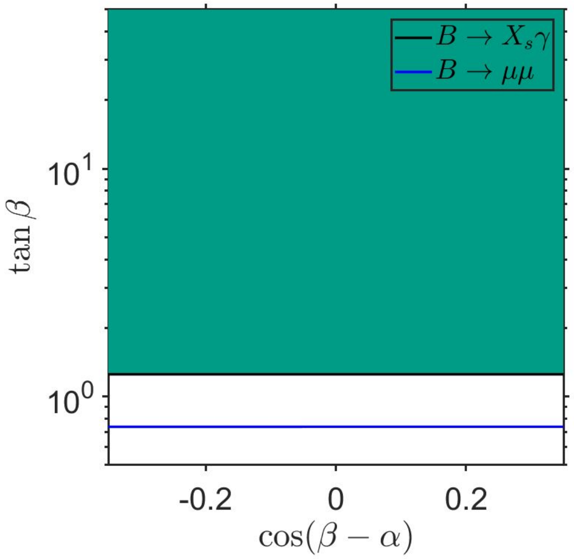

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- Collider searches and measurements:

Higgs Bounds: experimental limits from direct searches
Higgs Signals: consistency with the signal strengths of the 125 GeV Higgs

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

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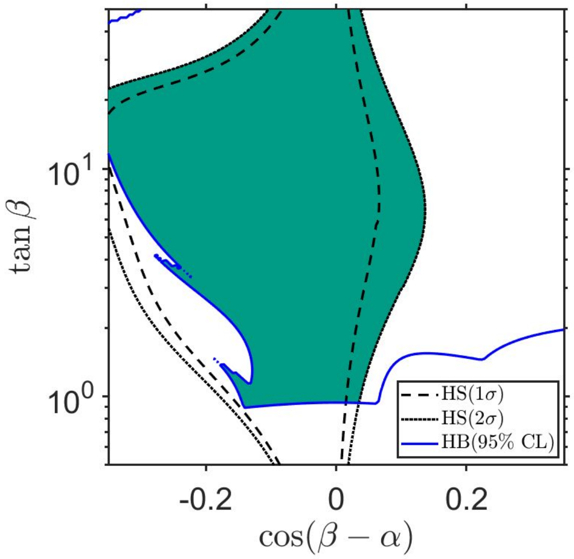

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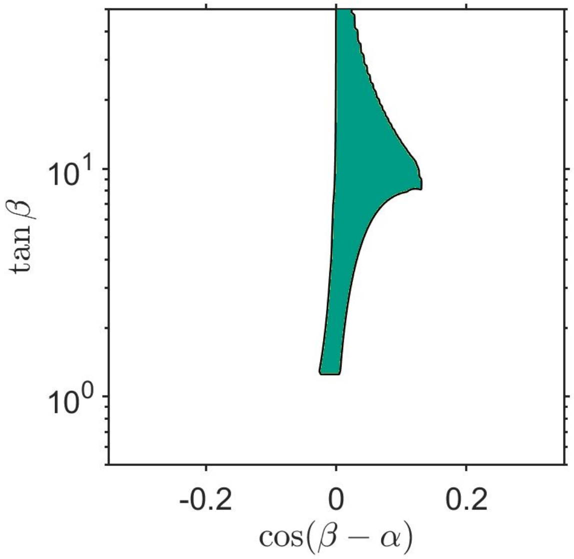

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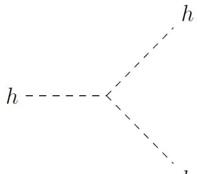
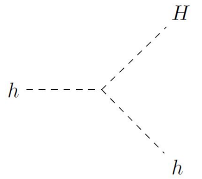
Feynman rules for 2HDM tree level THC

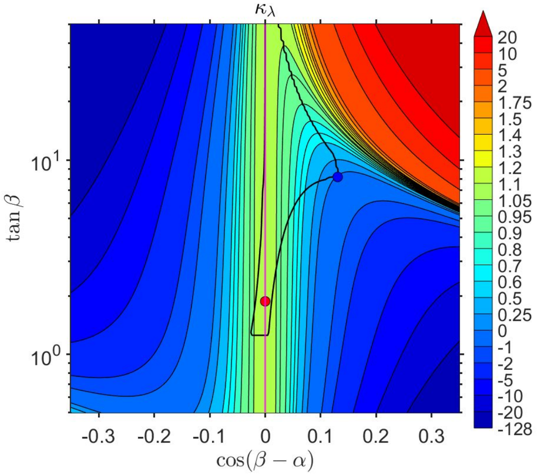


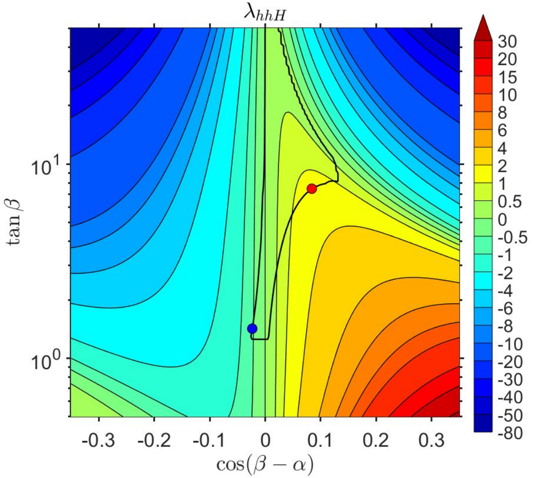
$$\lambda_{hhh} = \frac{1}{2v^2}\left\{m_h^2 s_{\beta-\alpha}^3 + \left(3m_h^2 - 2\boxed{\bar{m}^2}\right) c_{\beta-\alpha}^2 s_{\beta-\alpha} + 2\cot 2\beta \left(m_h^2 - \boxed{\bar{m}^2}\right) c_{\beta-\alpha}^3\right\}$$



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

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



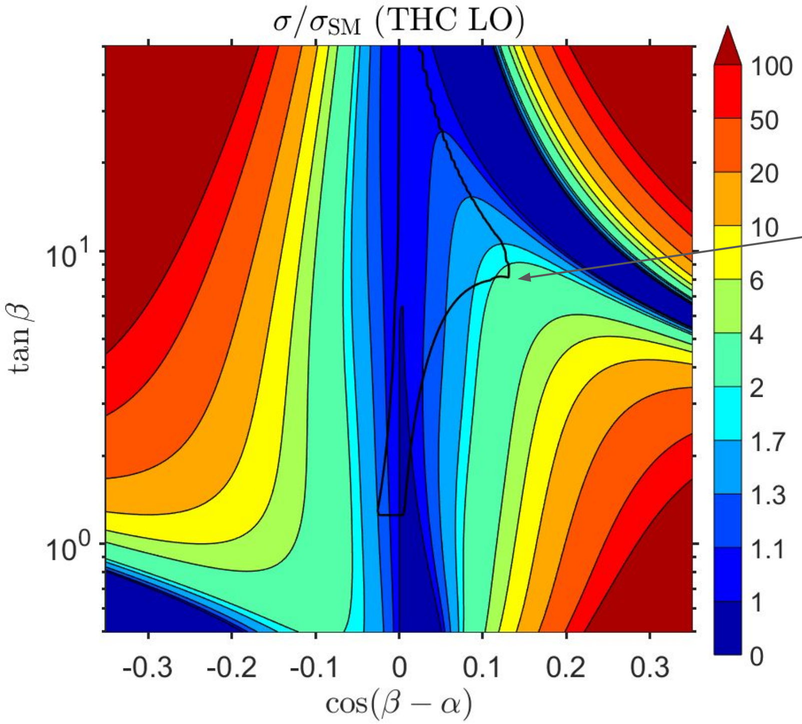


$\kappa_\lambda \in [-0.4\,,\,1]$

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

Backup

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



Prediction of Higgs pair production cross section in the 2HDM with THC at tree level

Deviations up to 3 times the SM value are already expected within the allowed region