Impact of Loop Corrections to the Trilinear Higgs Couplings and Interference Effects on Experimental Limits

based on arxiv 2403.14776

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in collaboration with Sven Heinemeyer, Margarete Mühlleitner and Georg Weiglein

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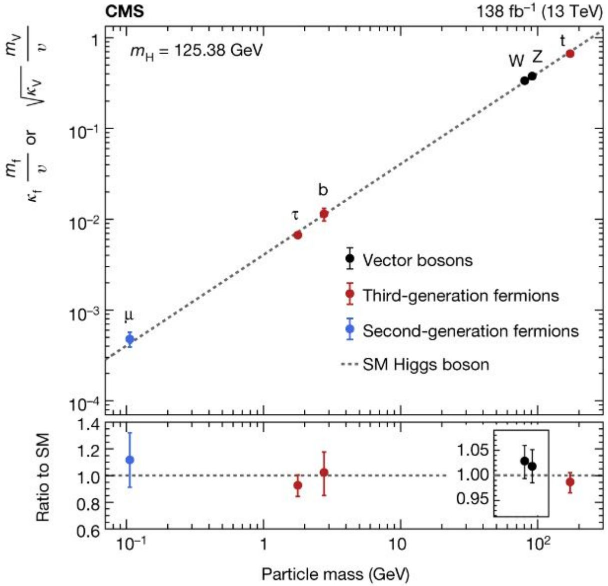
Motivation

Couplings to fermions and bosons: $m_i = \lambda_i\, v/2$

(λ_i are renormalizable parameters that cannot be predicted in the SM)

→ proof of the Brout-Englert-Higgs mechanism 



[Nature 2022]

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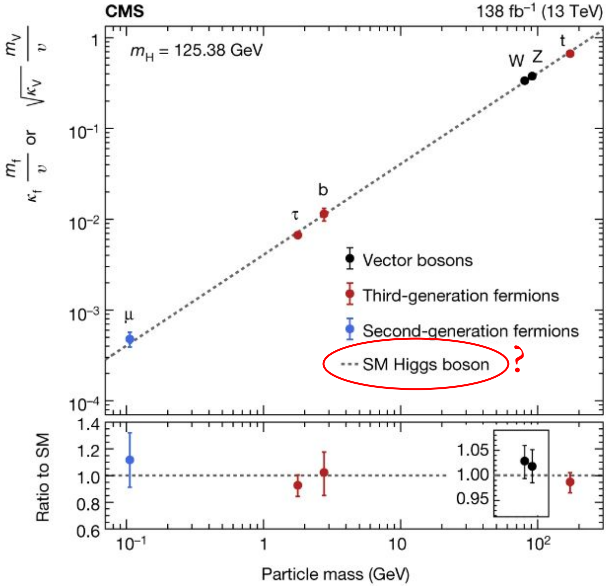

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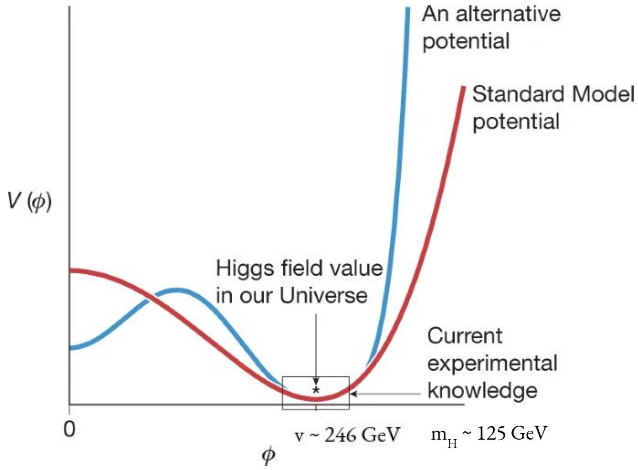

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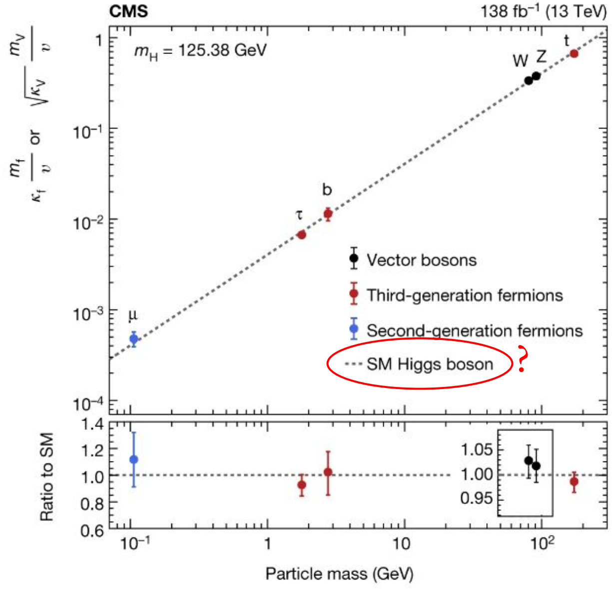

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A potential barrier requires large deviations in the trilinears and is usually related to a **strong first order electroweak phase transition**

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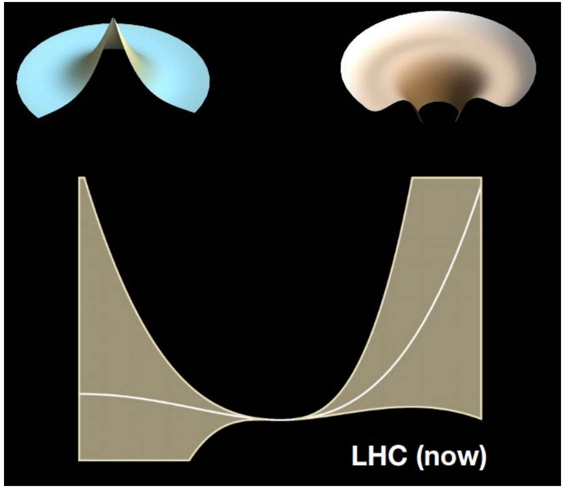

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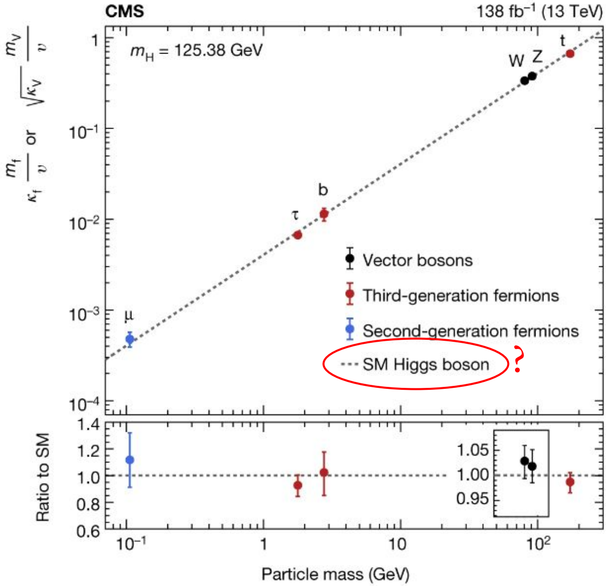

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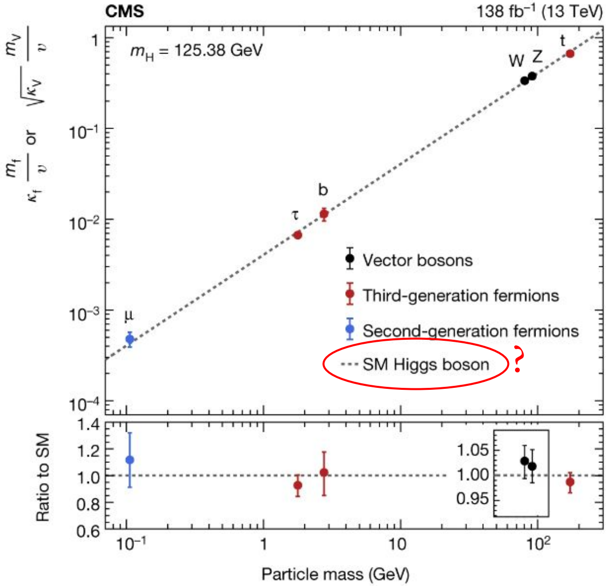

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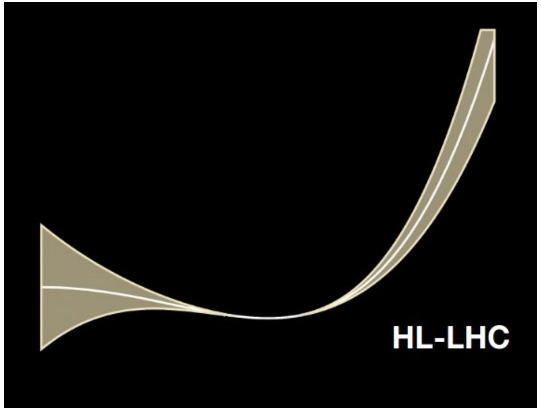

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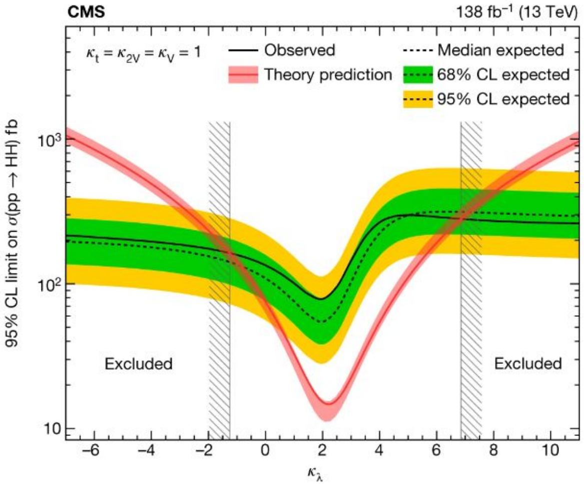
Higgs self coupling measurements

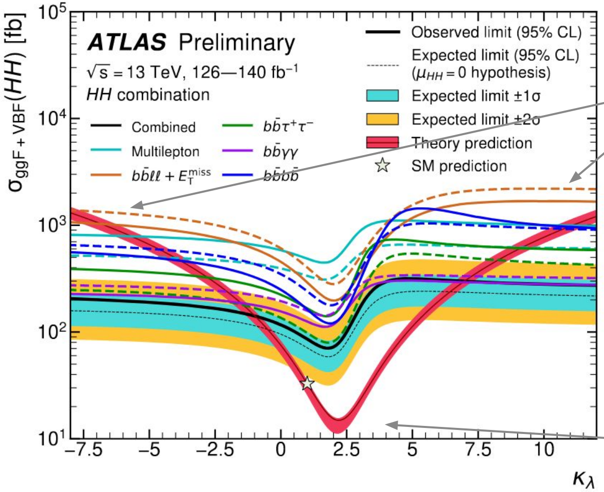
Access through **Higgs pair production -> very rare process** ~ 1 out of 10^9 events in the LHC is a Higgs

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

$\mu_{HH} \leq 2.9$ obs (2.4 exp) at ATLAS (assuming $\kappa_\lambda = 1$) main production process at LHC is **gluon fusion**



[CMS: Nature 2022]



[ATLAS: arXiv: 2211.01216]

Higher (than SM) cross section for low and high values of κ_λ

Lower (than SM) cross section for $1 < \kappa_\lambda < 3.5$ and minimum at $\kappa_\lambda \sim 2.5$

Exp. limits : (95% CL at LHC Run II): CMS $[-1.24 < \kappa_\lambda < 6.49]$; ATLAS $[-1.2 < \kappa_\lambda < 7.2]$;

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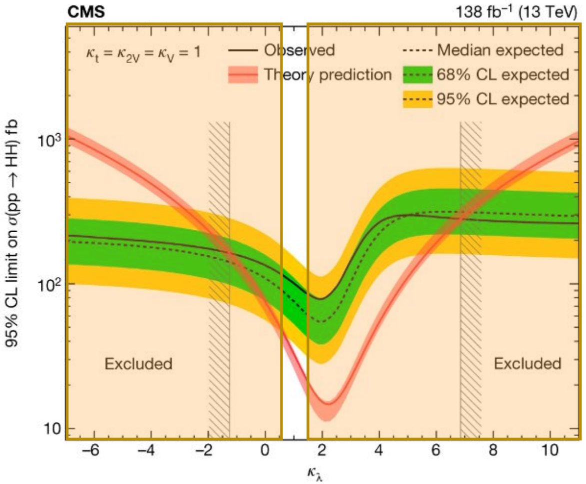

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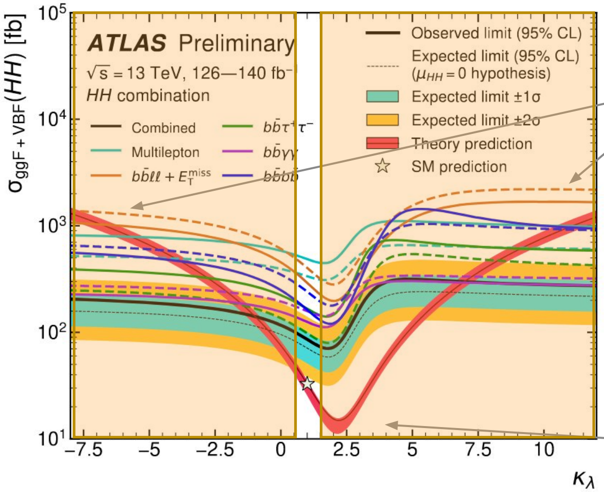

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projections [$0.52 < \kappa_\lambda < 1.5$] [WG2 Report]

;

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

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

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

Phenomenological implications can originate from:

→ deviations in **couplings** of h to fermions, gauge bosons and triple Higgs coupling

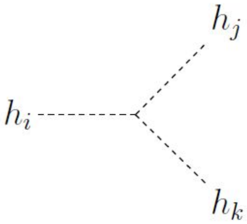
→ contributions of the **heavy scalars** in Higgs production/decay or in loops

Trilinear Higgs couplings in the 2HDM

Can have **large deviations** from SM predictions in BSM while the couplings to gauge bosons and fermions are very close to the SM values, i.e. the alignment limit (in agreement with existing constraints)
$\rightarrow$ Improving limits already have important impact on phenomenology!

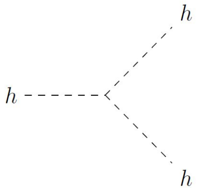
Notation:

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

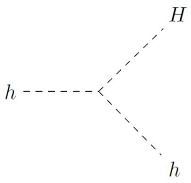


$$= -i\, v\, n!\, \lambda_{h_i h_j h_k}$$

n = number of identical Higgses



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



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

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

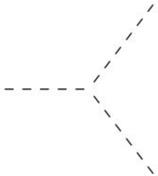
Radiative corrections to the trilinear couplings

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]

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

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



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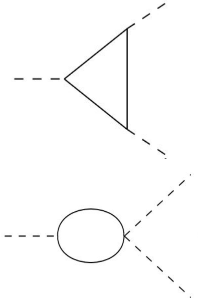

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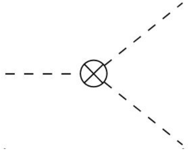
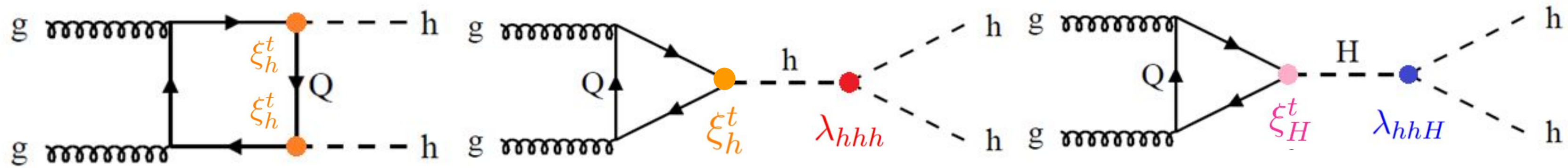


* zero external momentum
* no external leg corrections

The calculation is done by means of the public code BSMPT: [Basler, Biermann, Mühlleitner, Müller, Santos, Viana: arXiv: 2404.19037]
It is performed in the limit of zero external momentum
Physical masses and mixing angles are renormalized in an on shell-like way to their tree level value

Di-Higgs production in the 2HDM

[Plehn, Spira, Zerwas : arXiv: 9603205]
[Dawson, Dittmaier, Spira: arXiv:9805244]

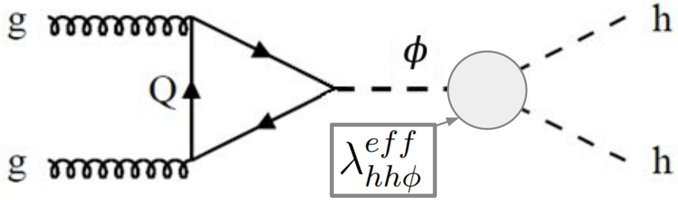


σ_{SM} (HTL) ~ 38 fb (Full NLO) ~ 32 fb

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 the 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]

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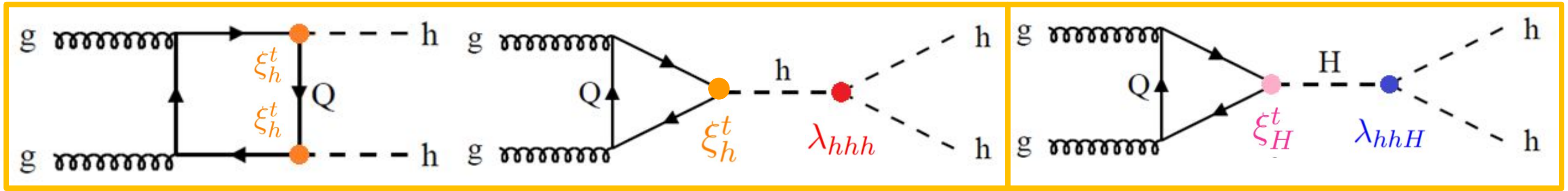

Non-resonant

Resonant

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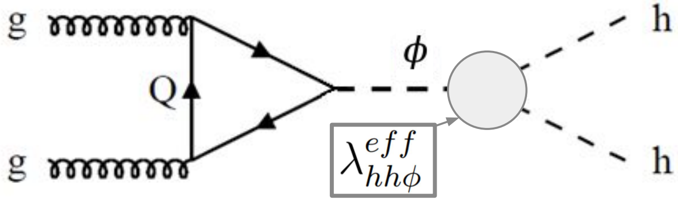

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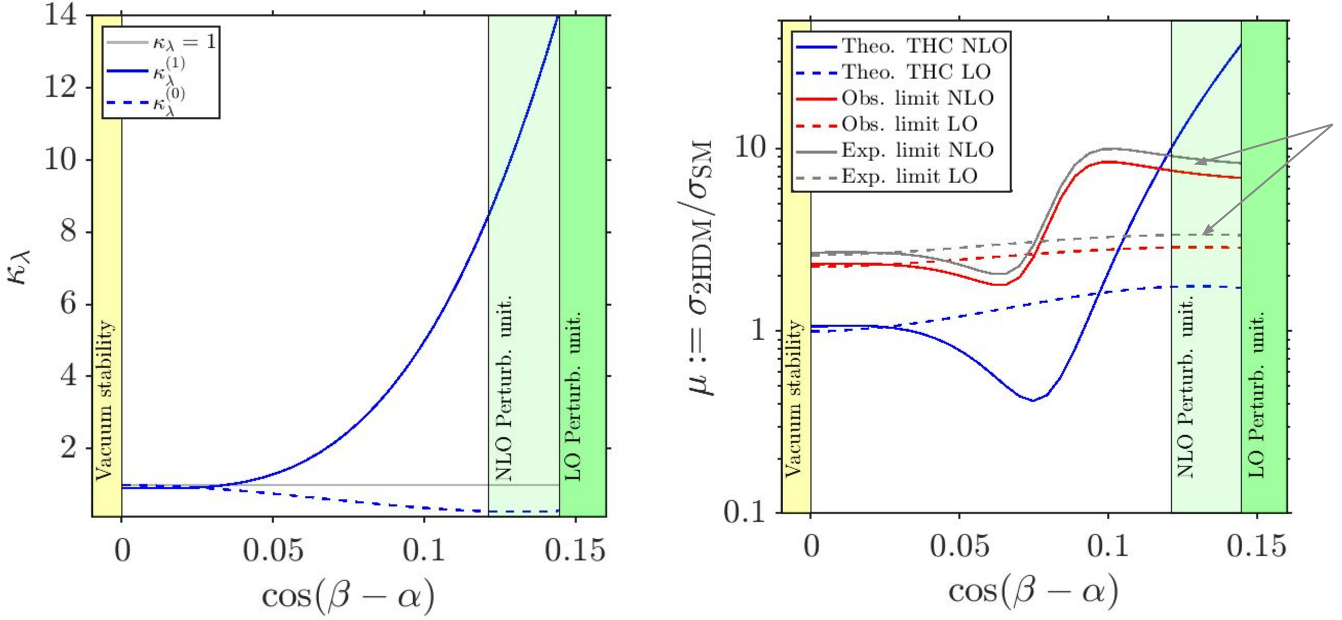
Applicability of non resonant limits

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

$$t_\beta = 10,\ m_H = m_A = m_{H^\pm} = 1000\ \text{GeV},\ m_{12}^2 = m_H^2 c_\alpha^2 / t_\beta$$



Red lines limits on the di Higgs signal strength:

[ATLAS: 2211.01216]

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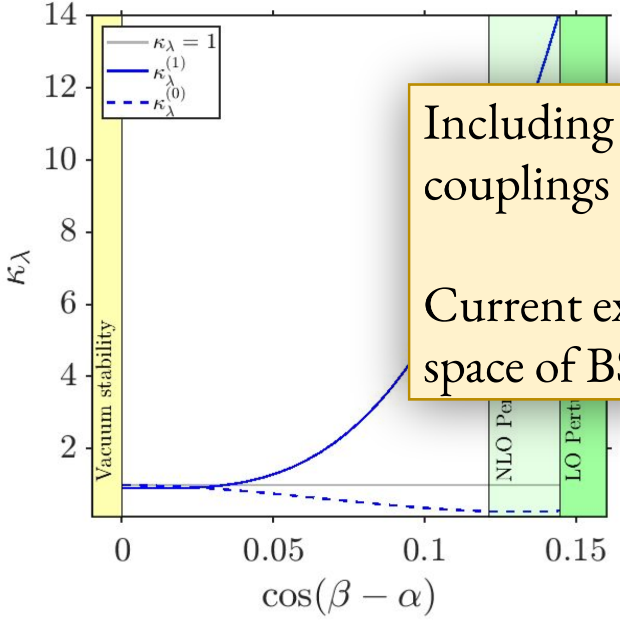

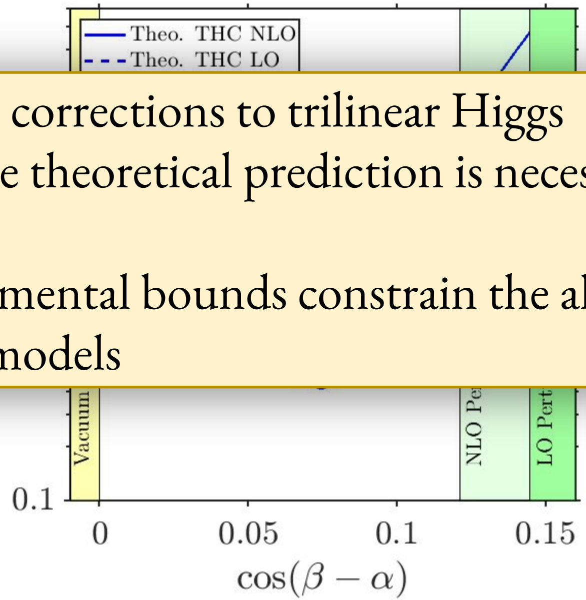

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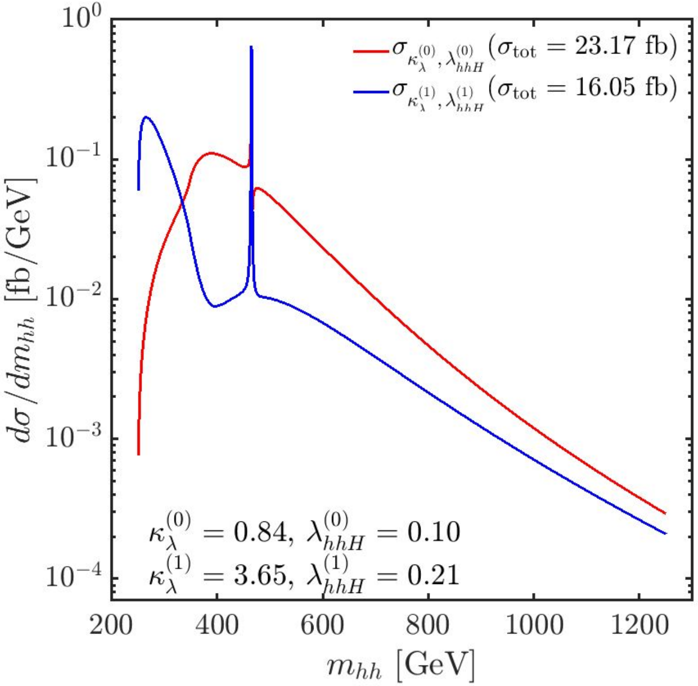
Including loop corrections to trilinear Higgs couplings in the theoretical prediction is necessary

Current experimental bounds constrain the allowed space of BSM models

Effect of loop corrections of THC in m_{hh}

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



$$t_\beta = 10,\ c_{\beta-\alpha} = 0.13\ (s_{\beta-\alpha} > 0)\ m_H = 465\ \text{GeV},$$
$$m_A = m_{H^\pm} = 660\ \text{GeV}\ m_{12}^2 = m_H^2 c_\alpha^2/t_\beta$$

- 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

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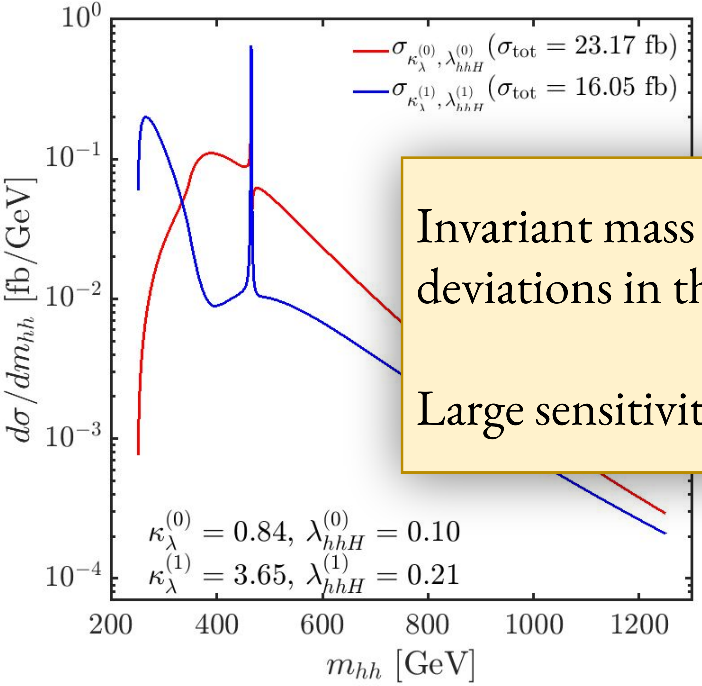

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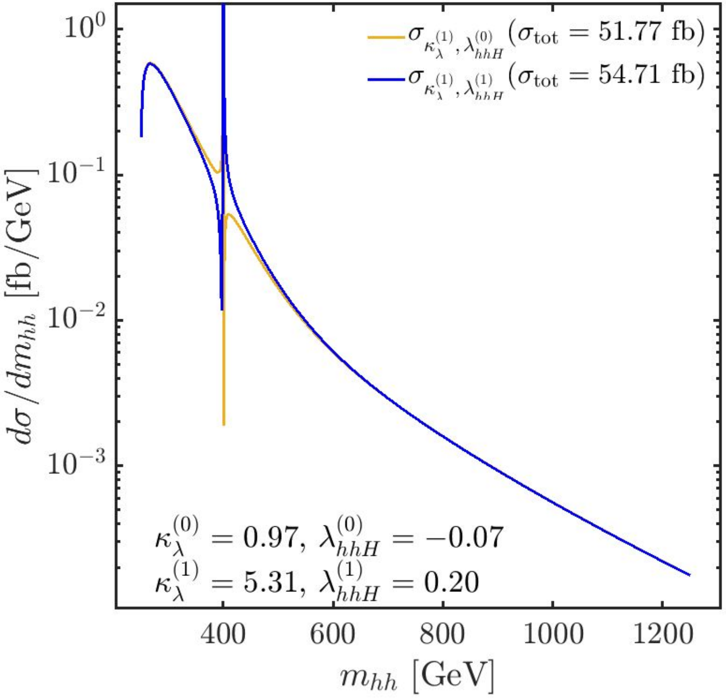
One loop corrections to λ_{hhH} are large in scenarios with mass splittings, even a change in sign is possible



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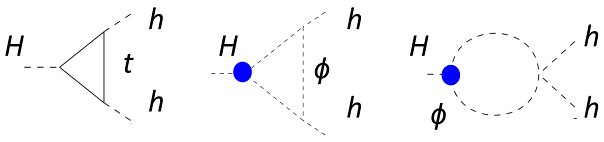

- $\lambda_{h\phi\phi} \propto (M^2 - m_\phi^2)$ [Braathen, Kanemura: arxiv: 1911.11507]

Small enhancement in the total cross section but completely different phenomenology in m_{hh} when corrections to λ_{hhH} are included

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

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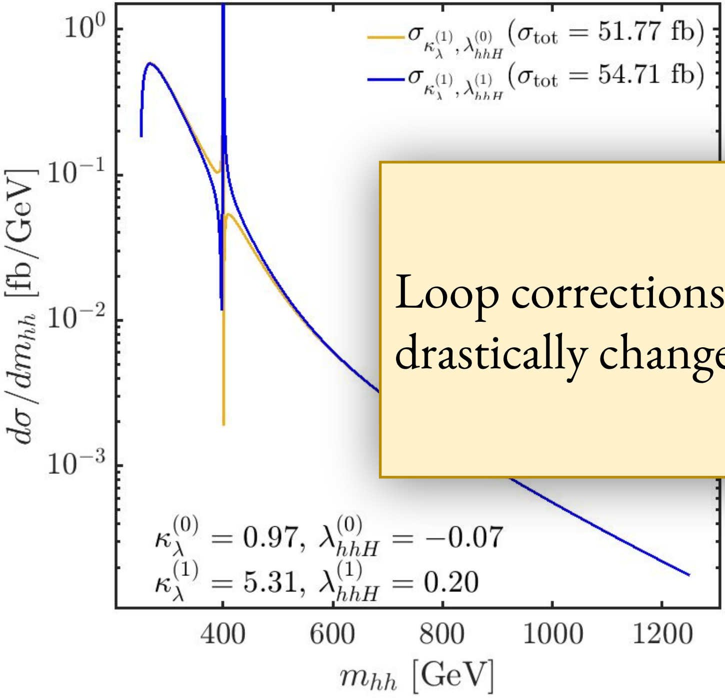

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Loop corrections to the BSM trilinear λ_{hhH} can drastically change the structure of the resonant peak

arxiv: 1911.11507]

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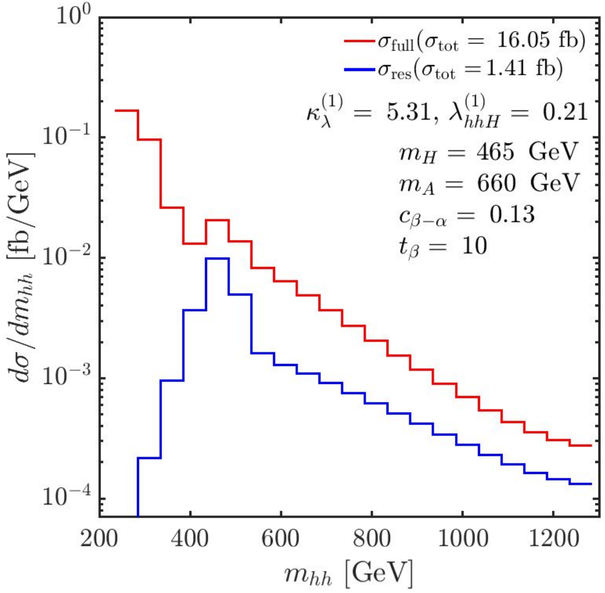
Resonant VS non-resonant m_{hh} distributions

Experimental limits from resonant searches can only be applied in scenarios where the contribution from the continuum diagrams is negligible compared to the resonant diagram

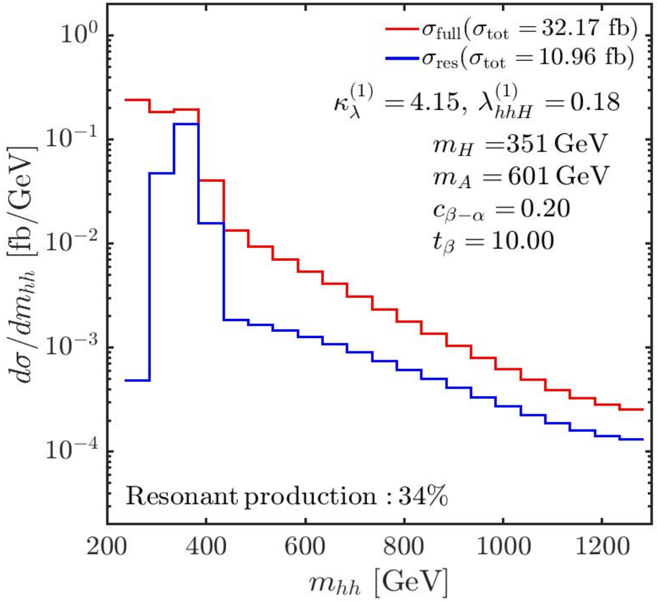


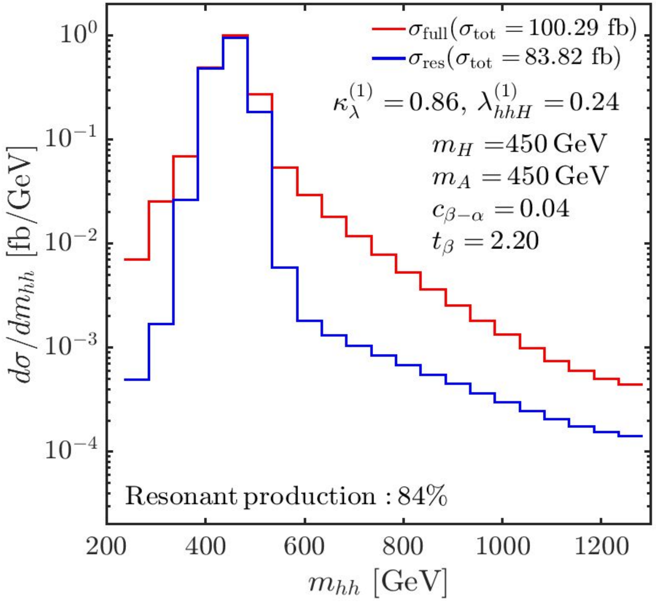
Red curve: full procces
Blue curve: resonance only

15 % smearing
50 GeV binning
applied to account for
experimental uncertainties

Further examples “excluded” by resonant searches

Not including the continuum diagrams makes the prediction at low m_{hh} change by orders of magnitude!
Even when the resonant contribution is very large, the peak is significantly broadened





✘ resonant searches
✓ non resonant searches

Current experimental sensitivity motives a more complex framework where interference effects are taken into account

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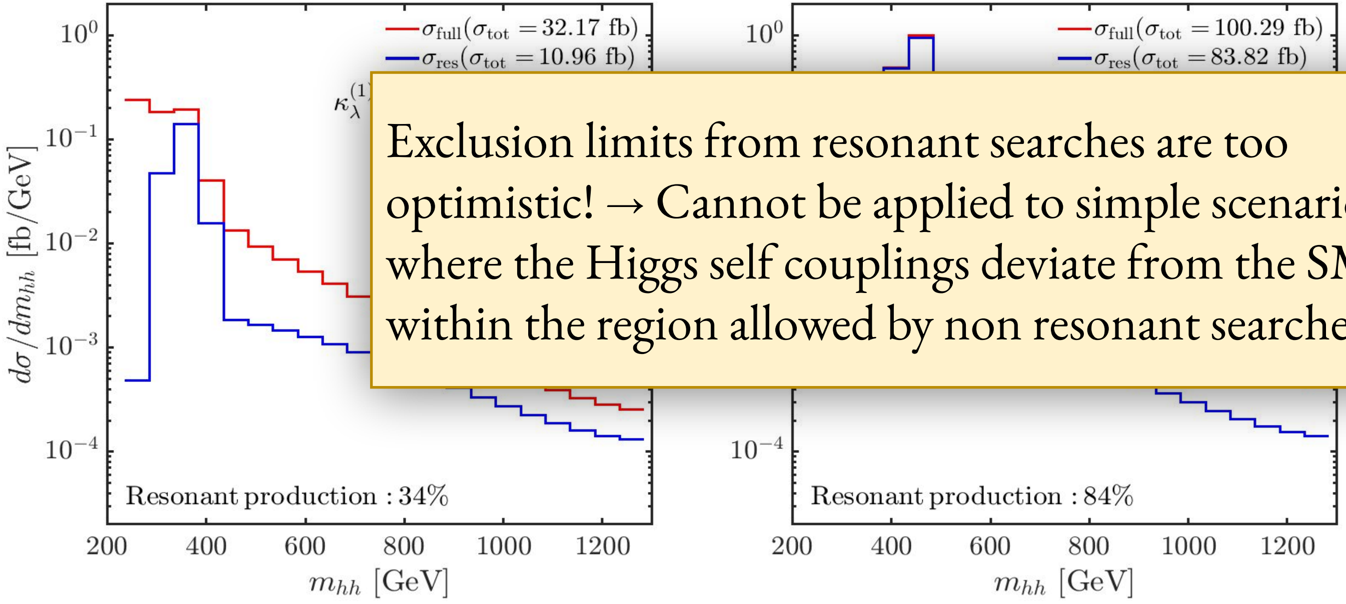

Exclusion limits from resonant searches are too optimistic! → Cannot be applied to simple scenarios where the Higgs self couplings deviate from the SM within the region allowed by non resonant searches

✗ resonant searches
on resonant searches

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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 washed away in the full result and the **hypothesis of experimental searches are insufficient to capture their phenomenology** → joint effort between theory and experiment are needed to define an appropriate framework

thdmTools: a python package to explore the 2HDM

[Biekötter, Heinemeyer, No, KR, Romacho, Weiglein: arxiv:2309.17431]

- **EWPO**: impose a condition on the Higgs boson masses: $(m_{H\pm}-m_H) \sim 0$ and/or $(m_{H\pm}-m_A) \sim 0$
  in our scenarios $m_{H\pm} = m_A$

- Theoretical:

  (N)LO Unitarity: from the $2 \rightarrow 2$ 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**: $B \rightarrow X_S \gamma$ and $B_S \rightarrow \mu\mu$ (SuperIso)
  [Mahmoudi: arXiv:0808.3144]

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

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

* 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:

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

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* Matrix element:

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

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

a,b: color indices

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:

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

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

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

Renormalization conditions in BSMPT

[Basler, Mühlleitner: arXiv: 1803.02846]

* Counterterm potential:

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

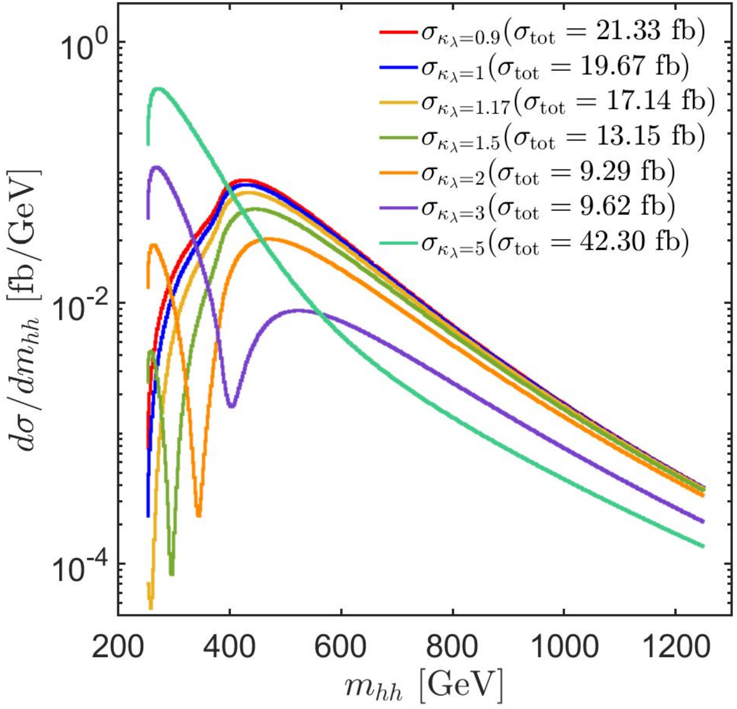
* Renormalization conditions:

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

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