BSM Benchmarks and Interference Effects

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The 22nd workshop of the LHC Higgs Working Group

05.12.2025

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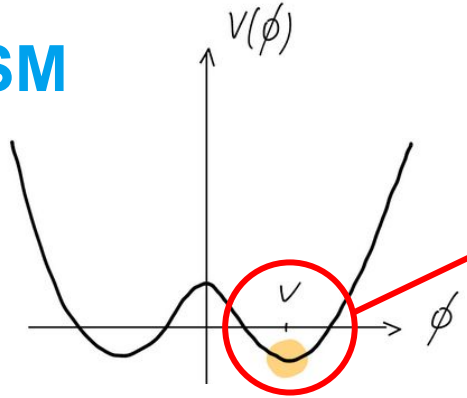
Obra Social Fundación "la Caixa"

Motivation: unravel the scalar potential

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

$$\propto \lambda_{hhh}^{\mathrm{SM}(0)}$$

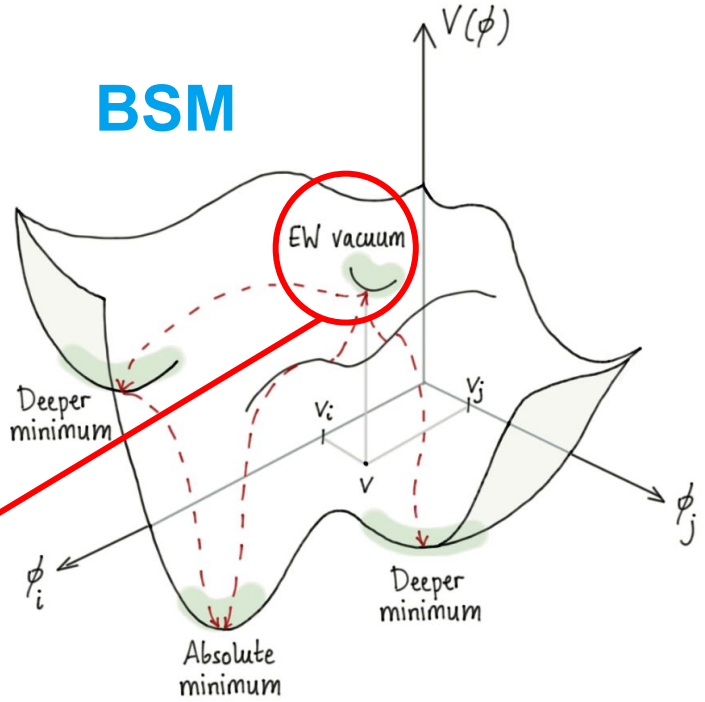
SM



$v \simeq 246\,\mathrm{GeV}$

$m_h \simeq 125\,\mathrm{GeV}$

BSM



Higgs self-coupling measurements

Observable: **Higgs pair production** (at LHC: **gluon fusion**)

Exp. limits :
(95% CL at LHC Run II)

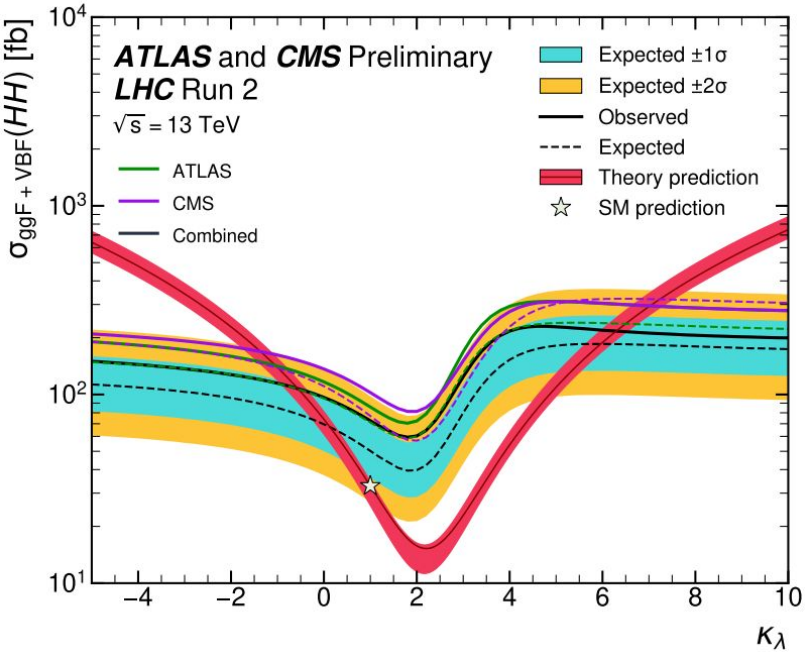
ATLAS and CMS: CONF Note

Obs. $[-0.71 < \kappa_\lambda < 6.1]$

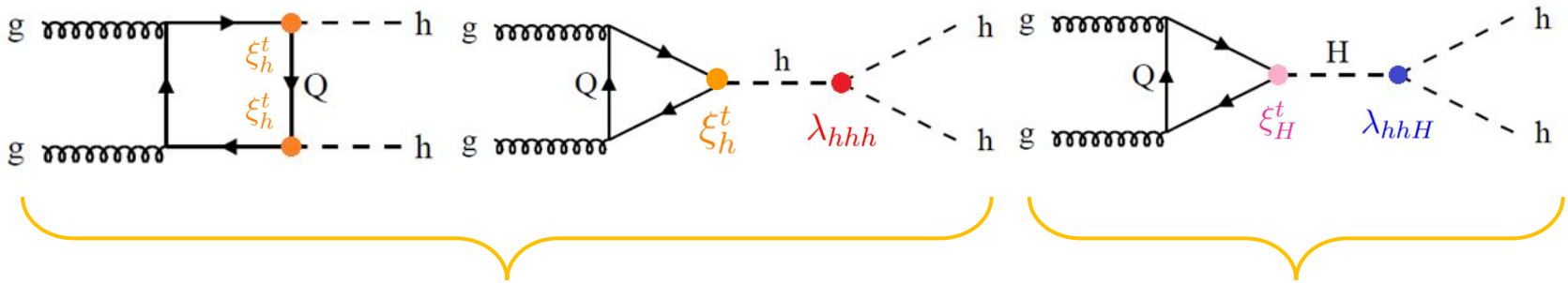
Exp. $[-1.3 < \kappa_\lambda < 6.7]$

Notation:

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



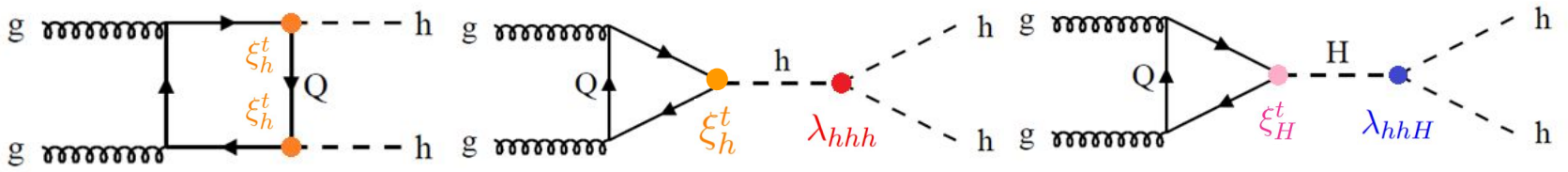
Higgs pair production at the LHC: gluon fusion



- SM-like
- Negative interference (in SM)
- Access to ξ_h^t and λ_{hhh}

- BSM sector
- can be largely enhanced
- BSM couplings: ξ_H^t and λ_{hhH}

Higgs pair production at the LHC: gluon fusion



- SM-like
- Negative interf… (I)
- Access… λ_{hhh}

Non-resonant

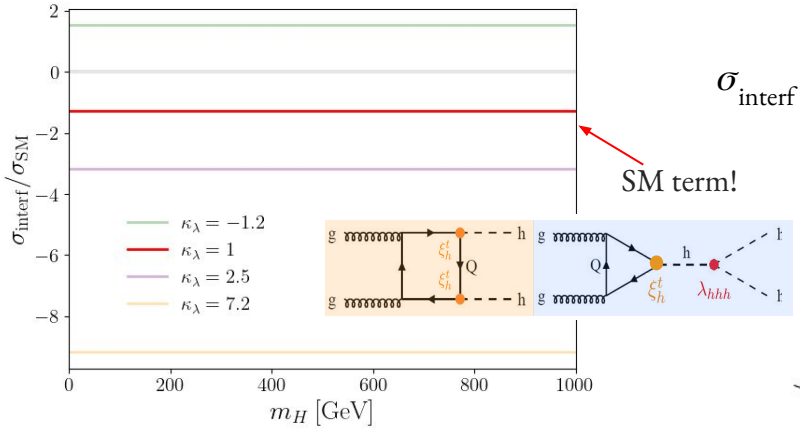
- BSM sector
- can be large…
- BS… ξ_H^t and λ_{hhH}

Resonant

Only considered separately in experimental searches

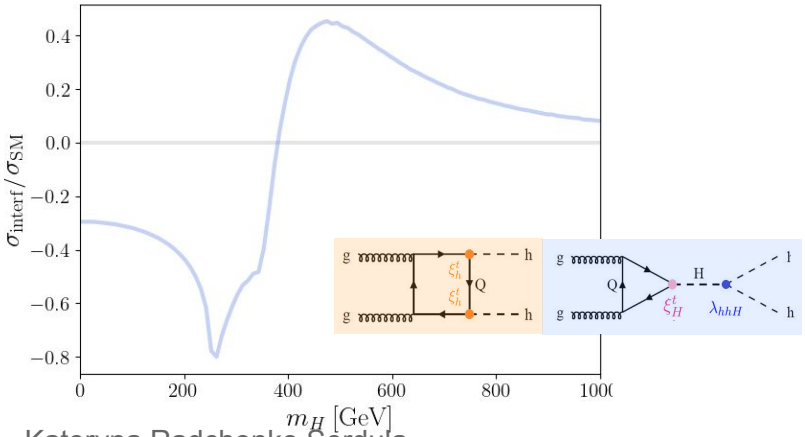
Interference effects

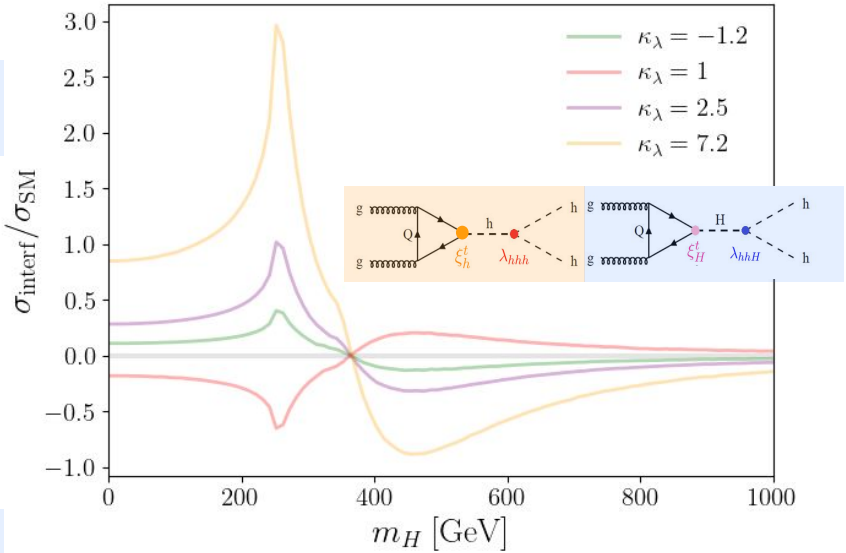
Note! values given for a toy model, actual numbers of the y-axis need to be analyzed in specific BSM models



SM term!

$$\sigma_{\text{interf}} = \left| A + B \right|^2 - \left| A \right|^2 - \left| B \right|^2 = 2\,\text{Re}[A\ B^*]$$





Interference pattern with SM non-resonant diagrams is very different from interference with BSM non-resonant diagrams

Interference effects

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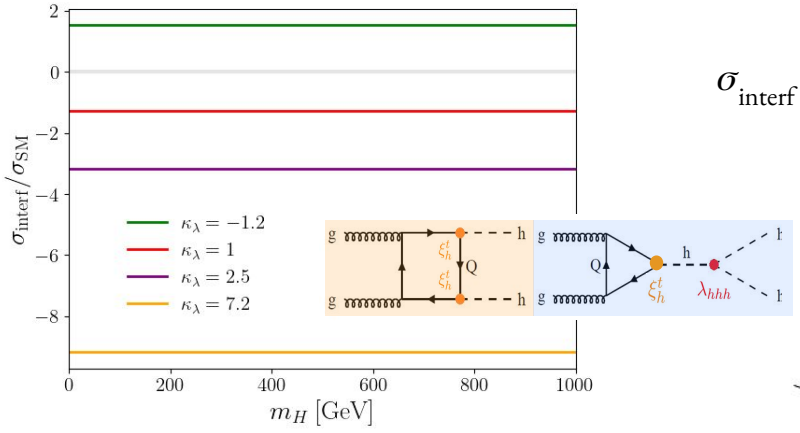

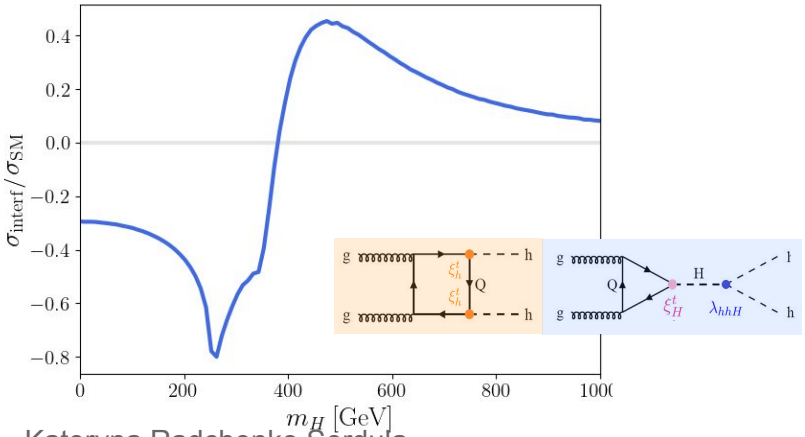

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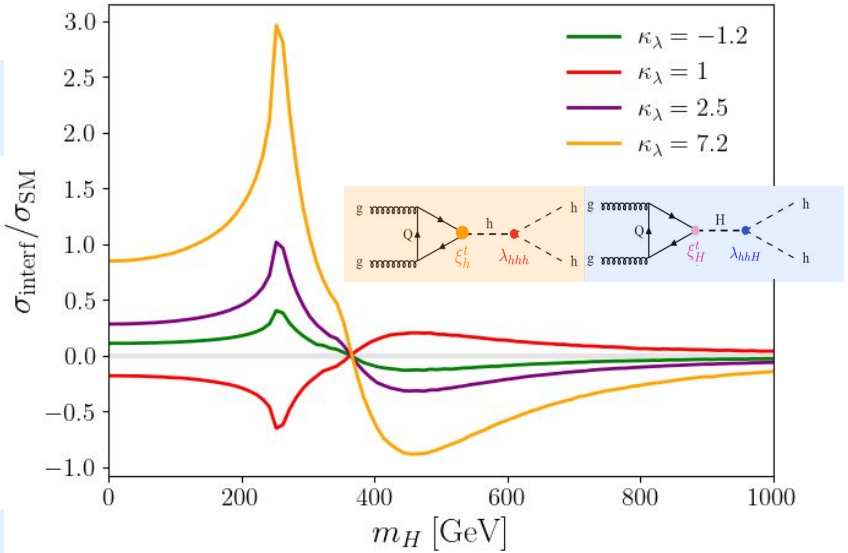
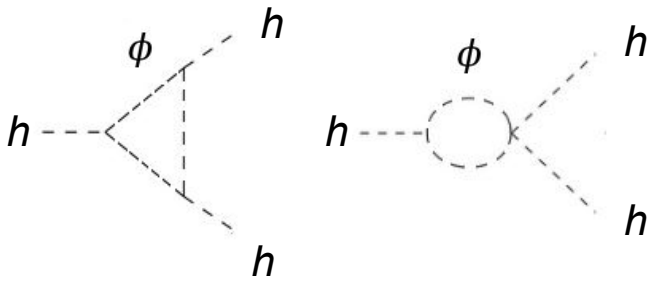


Interference pattern with SM non-resonant diagrams is very different from interference with BSM non-resonant diagrams

Radiative corrections to the trilinear couplings

Large loop effects caused by **heavy New Physics**: ϕ



e.g. in the 2HDM $\phi \in \{A, H, H^{\pm}\}$:

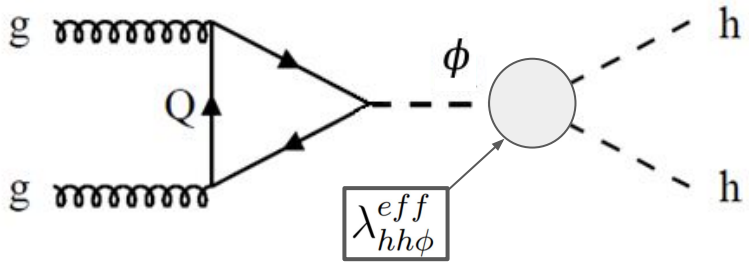
$$g_{hh\phi\phi} = -\frac{2(M^2 - m_\phi^2)}{v^2}$$

Kanemura, Kiyoura, Okada, Senaha, Yuan: arXiv: 0211308
Kanemura, Okada, Senaha, Yuan: arXiv:0408364

(1) Diagrammatically or (2) using effective potential

Trilinear Higgs couplings and di-Higgs production

Loop trilinears = effective trilinear Higgs couplings



Analytical calculation using HPAIR+ BSMPT (1-loop coupling from effective potential)

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

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

Basler, Biermann, Mühlleitner, Müller, Santos, Viana: arXiv: 2404.19037

or

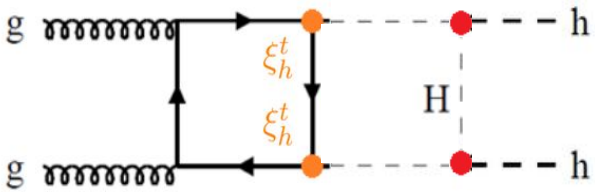
anyHH (diagrammatic 1-loop coupling)

Bahl, Braathen, Gabelmann, Weiglein: arXiv: 2305.03015

Bahl, Braathen, Gabelmann, K.R., Weiglein: TBP

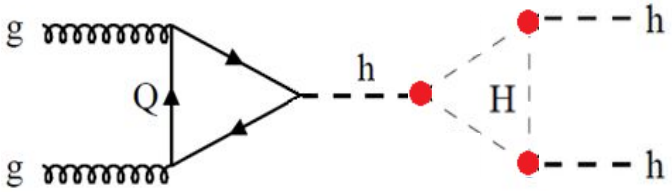
Trilinear Higgs couplings and di-Higgs production

✘ not included



$\propto \mathcal{O}(\xi_H^{t\,2} g_{hhHH}^{\ 2})$

✓ included



$\propto \mathcal{O}(\xi_H^t g_{hhHH}^{\ 3})$

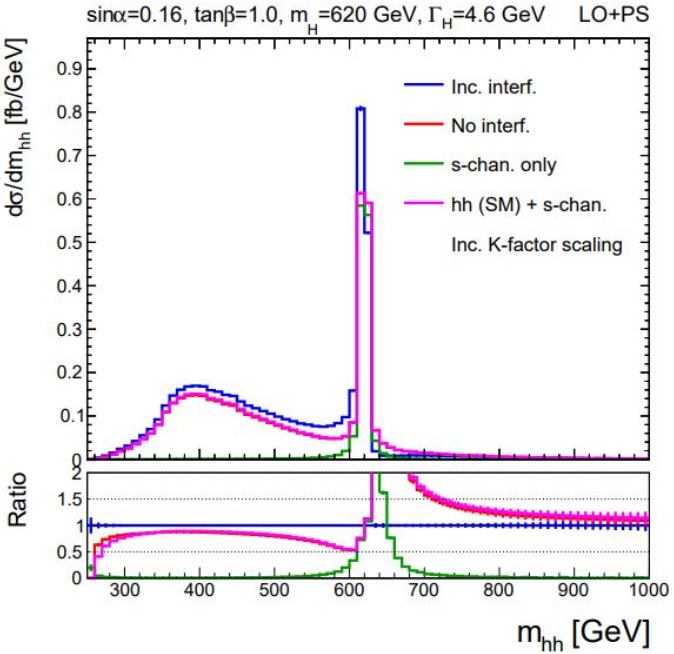
Is this reasonable? → **YES** As long as modifications of λ_{hhh} are large

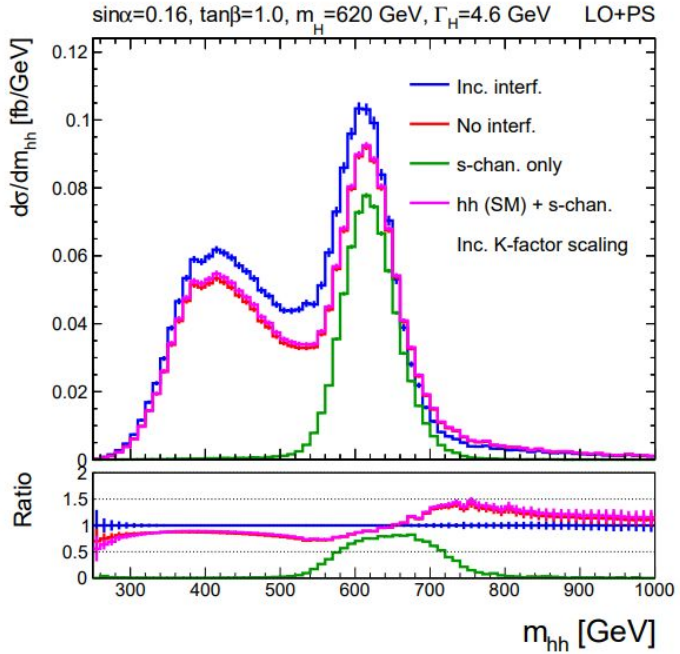
Bahl, Braathen, Weiglein : arXiv: 2202.03453

Examples in BSM frameworks: singlet extension

Feuerstake, Fuchs, Robens, Winterbottom: arXiv: 2409.06651

$$V(\Phi, S) = -m^2\Phi^\dagger\Phi - \mu^2 S^2 + \lambda_1 \left(\Phi^\dagger\Phi\right)^2 + \lambda_2 S^4 + \lambda_3 \Phi^\dagger\Phi S^2$$



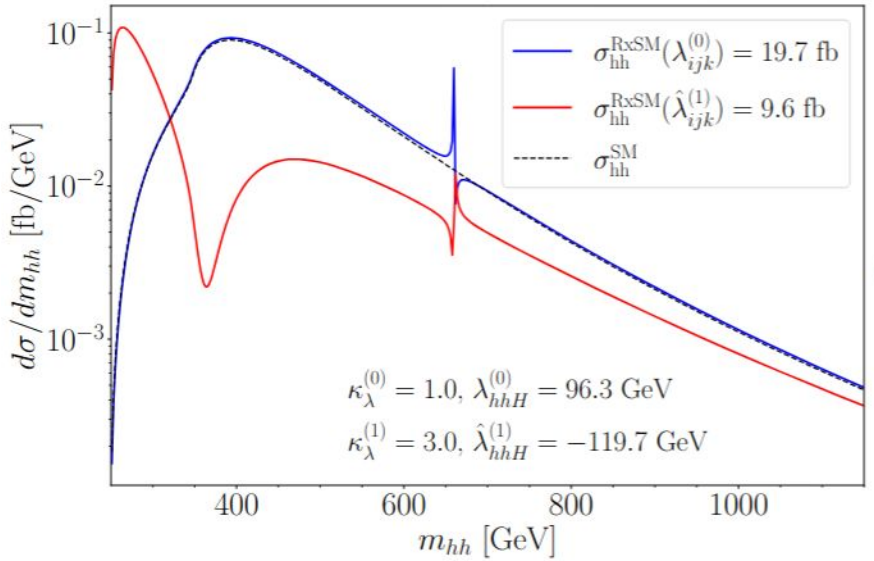


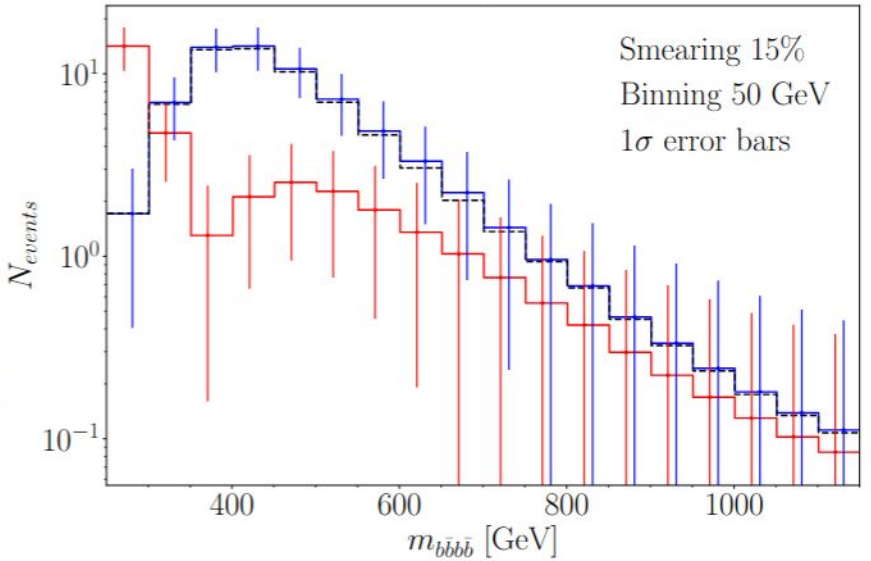
Examples in BSM frameworks: RxSM

Braathen, Heinemeyer, Parra, Verduras: arXiv: 2507.02569

$$V(\Phi, S) = \mu^2(\Phi^\dagger\Phi) + \frac{\lambda}{2}(\Phi^\dagger\Phi)^2 + \kappa_{SH}(\Phi^\dagger\Phi)S + \frac{\lambda_{SH}}{2}(\Phi^\dagger\Phi)S^2 + \frac{M_S^2}{2}S^2 + \frac{\kappa_S}{3}S^3 + \frac{\lambda_S}{2}S^4$$

BP1: $m_H = 659.4$ GeV, $\cos\alpha = 0.99$, $v_S = 56.1$ GeV, $\kappa_S = -880$ GeV, $\kappa_{SH} = -880$ GeV, $Z^{(0)} = 0.3$, $Z^{(1)} = 9.3$

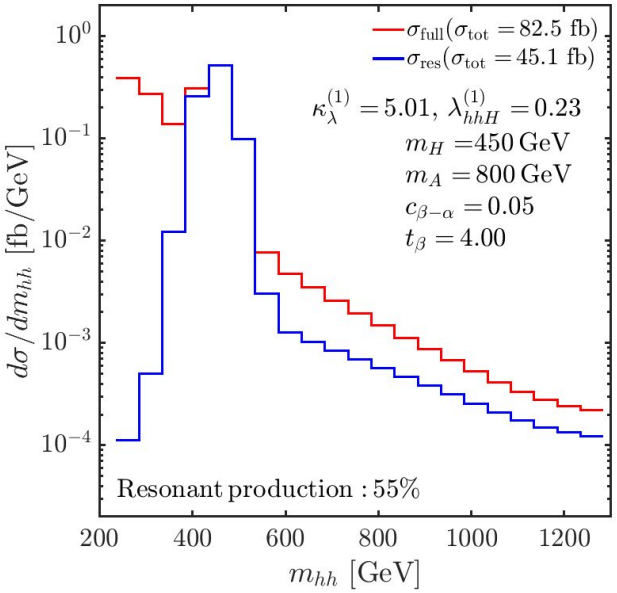


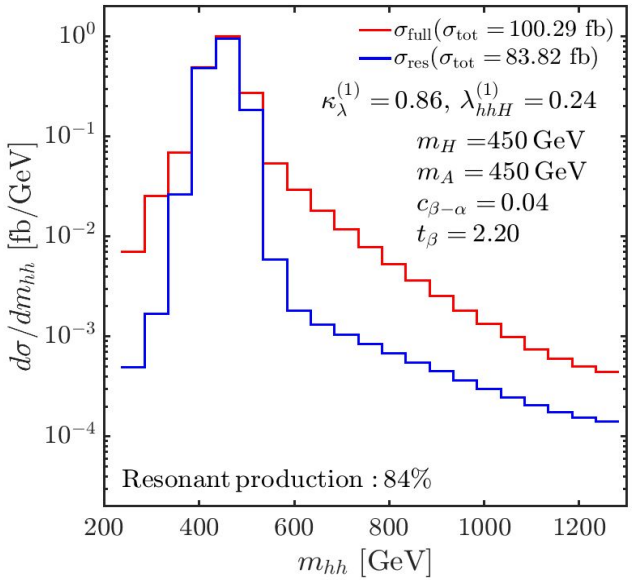


Examples in BSM frameworks: THDM

Heinemeyer, Mühlleitner, K.R., Weiglein: arXiv: 2403.14776

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





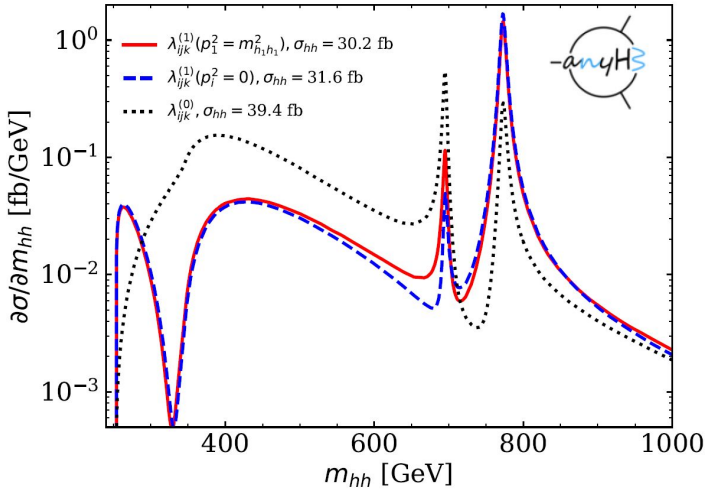
✘ resonant searches $pp \to hh \to b\bar{b}\tau^+\tau^-$ ATLAS: arXiv: 2209.10910

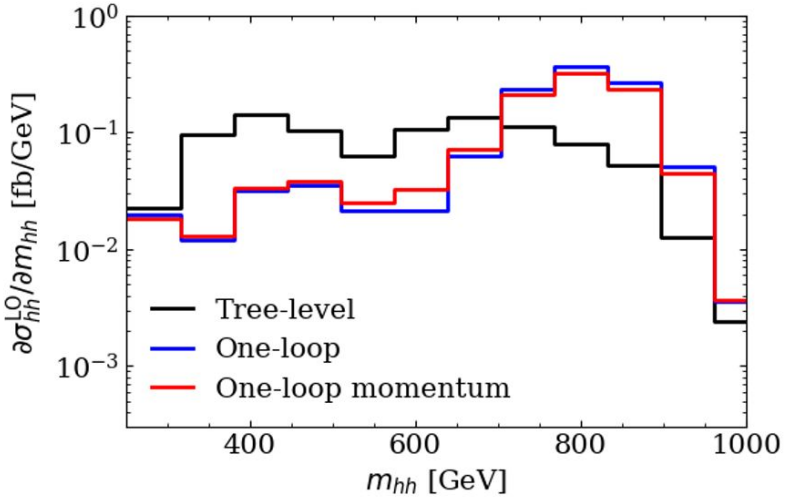
✓ non resonant searches

Examples in BSM frameworks: NTHDM

Bahl, Braathen, Gabelmann, K.R., Weiglein: TBP

$$V_{\text{N2HDM}}(\Phi_1,\Phi_2,S) = V_{\text{2HDM}} + \frac{1}{2}m_S^2 S^2 + \frac{\lambda_6}{8}S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)S^2$$

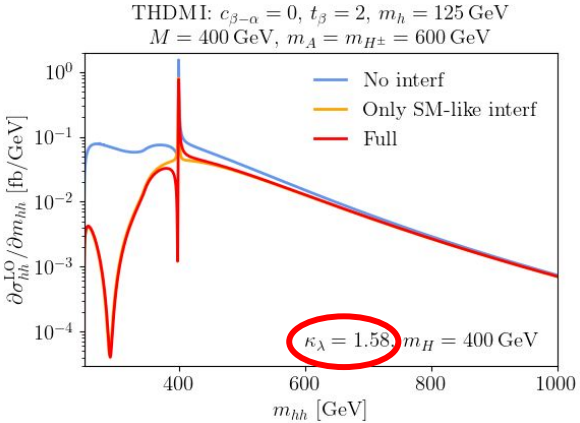


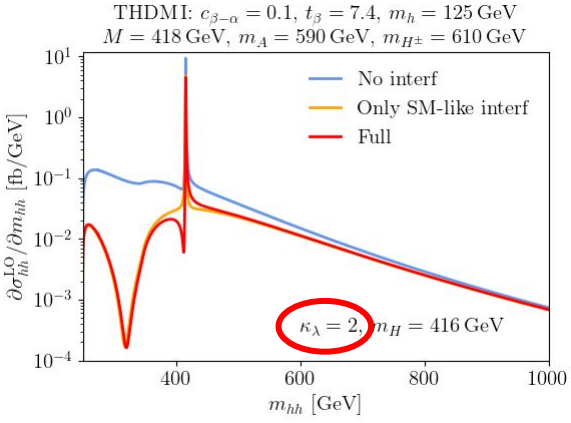


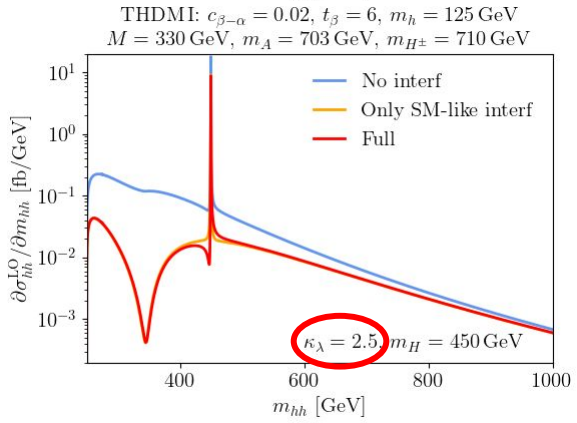
$c_{t,1}$	1.01
$c_{t,2}$	0.42
$c_{t,3}$	-0.47
Γ_1 [MeV]	4.4
Γ_2 [GeV]	5.1
Γ_3 [GeV]	8.2
$\kappa_\lambda^{(0)}$	0.97
$\kappa_\lambda^{(1)}$	2.06
$\lambda^{(0)}_{h_1h_1h_2}$ [GeV]	93.5
$\lambda^{(1)}_{h_1h_1h_2}$ [GeV]	40.3
$\lambda^{(0)}_{h_1h_1h_3}$ [GeV]	160.5
$\lambda^{(1)}_{h_1h_1h_3}$ [GeV]	342.8

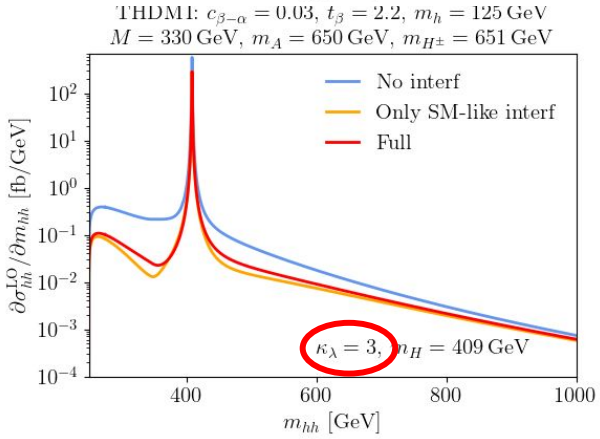
$$\alpha_1 = 1.019, \alpha_2 = -0.076, \alpha_3 = 0.960, M_{h_1} = 125\,\text{GeV}, M_{h_2} = 695\,\text{GeV}, M_{h_3} = 773\,\text{GeV},$$
$$M_A = 673\,\text{GeV}, M_{H^\pm} = 762\,\text{GeV}, M_{12} = 367\,\text{GeV}, \tan\beta = 1.53, v_S = 415.4\,\text{GeV}\,.$$

Quick fix: resonant + non-resonant searches







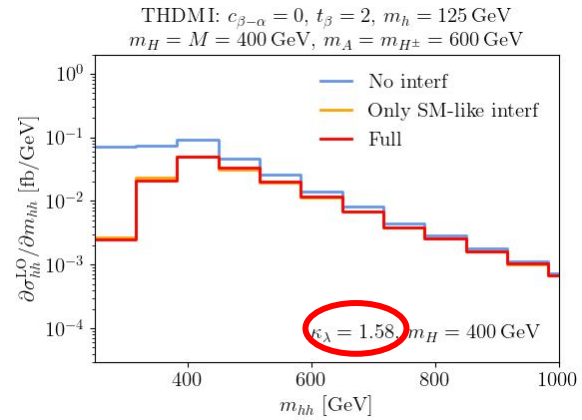


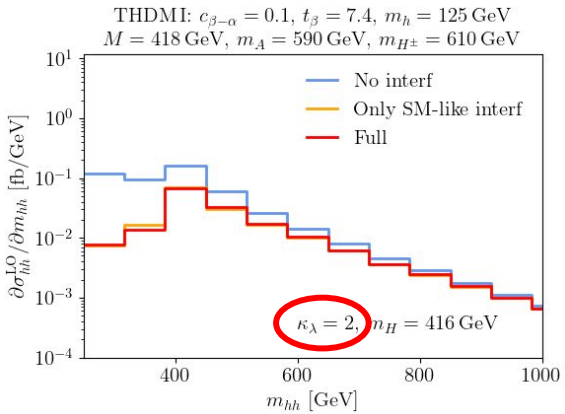
No interference is a very bad approximation

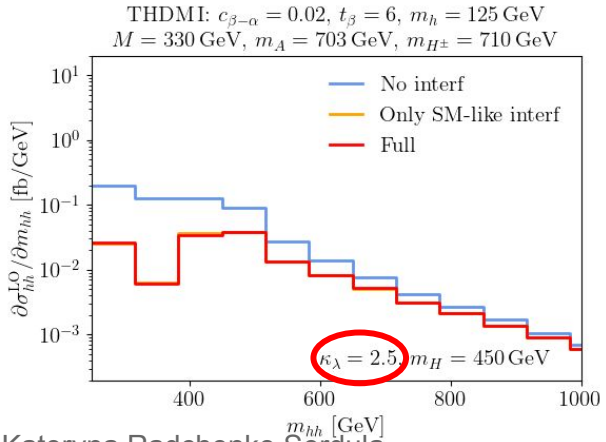
SM-like interference is a good first step for different values of κ_λ

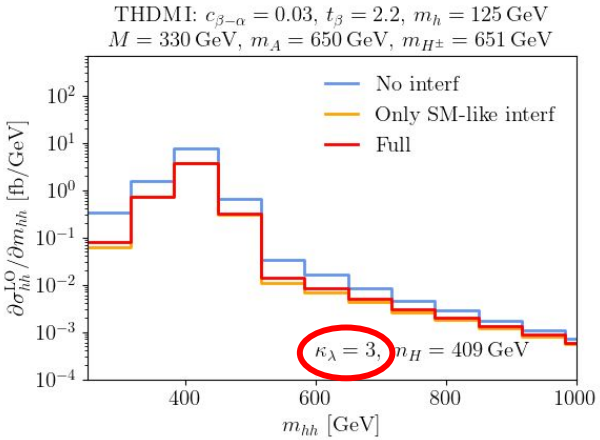
Already good if non-resonant searches were combined with resonant ones for specific benchmark scenarios according to the predicted value of κ_λ

Quick fix: resonant + non-resonant searches





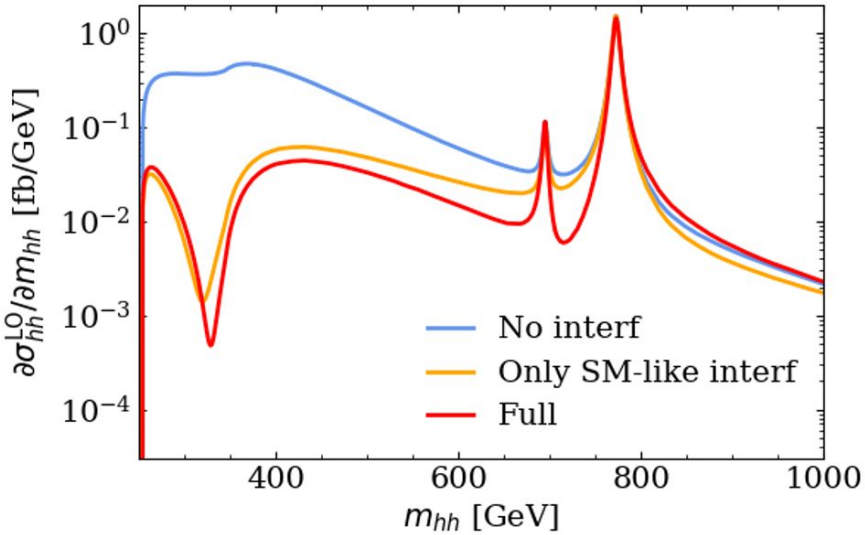


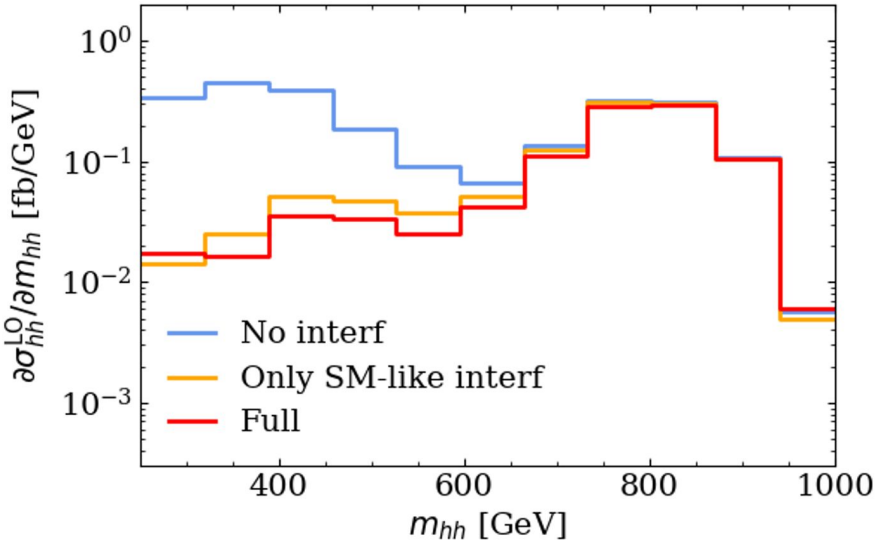


Including 15% smearing and 50 GeV binning confirms previous findings

Quick fix: resonant + non-resonant searches

Seems to work also for models with multiple resonances (NTHDM):





NTHDM $\alpha_1 = 1.019, \alpha_2 = -0.076, \alpha_3 = 0.960, M_{h_1} = 125\,\text{GeV}, M_{h_2} = 695\,\text{GeV}, M_{h_3} = 773\,\text{GeV},$

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Take home messages

It is important to consider **resonant** and **non-resonant** double-Higgs production together.

Loop effects in the **trilinear couplings** modify the interference of the SM-like contribution.

Strategy:

First step: combine resonant with non-resonant results (not including interference between them).

Second step: include all interference terms.

Explore benchmark points in well-motivated BSM (see cited papers and further examples in this talk)

Most importantly, adapt and update the overall analysis framework

Take home messages

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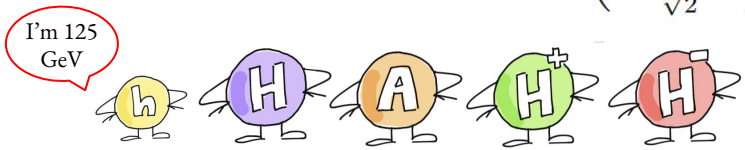
Thank you!

Back up

The 2HDM

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

Potential:

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

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

$\tan\beta = v_2/v_1$

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

$M^2 \equiv m_{12}^2/(s_\beta c_\beta)$

thdmTools: a python package to explore the 2HDM

- **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

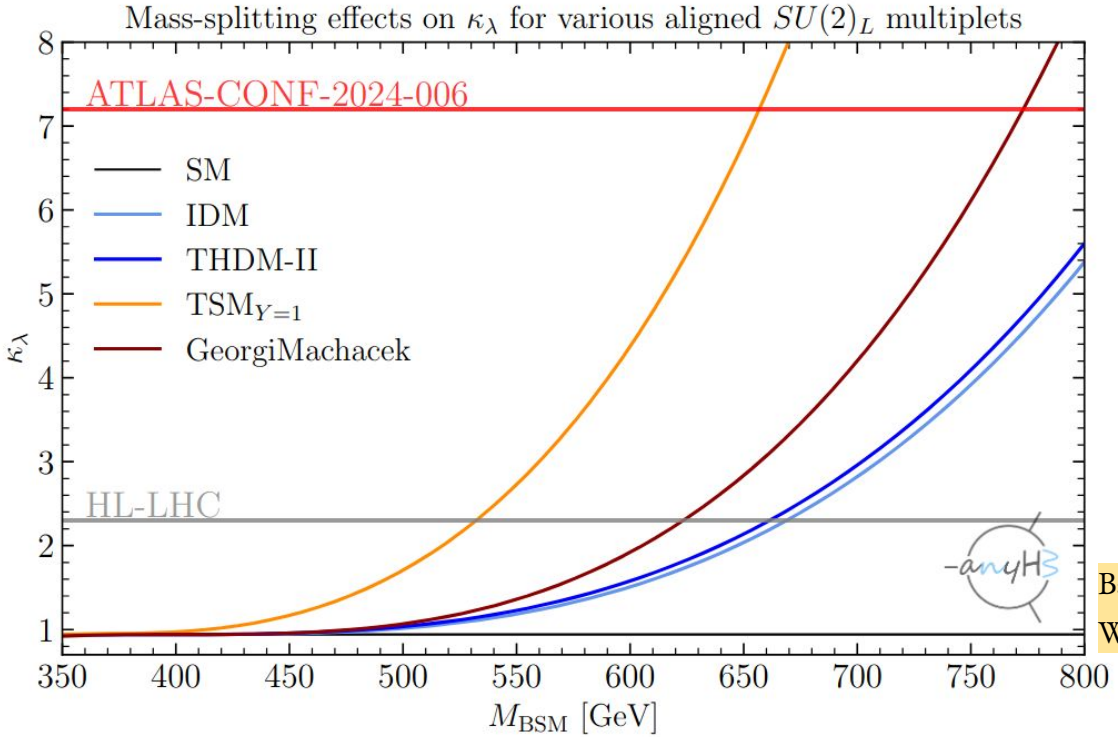
- Collider searches and measurements:
  HiggsBounds: experimental limits from direct searches
  HiggsSignals: signal strength of the 125 GeV Higgs
  HiggsTools Collaboration: arXiv: 2210.09332

- **Flavour observables**: $B \rightarrow X_s\gamma$ and $B_s \rightarrow \mu\mu$ (SuperIso)
  Mahmoudi: arXiv:0808.3144

Allowed regions of the 2HDM parameter space are scanned with the python package **thdmTools**
Biekötter, Heinemeyer, No, K.R., Olea, Weiglein: arxiv:2309.17431

Corrections to the trilinears in BSM models

They play an important role in many BSM models even in the alignment limit (i.e. the other couplings are SM like)



Bahl, Braathen, Gabelmann, Weiglein: arXiv: 2305.03015

Decoupling limit

A cross-check: the decoupling limit

Slide by J. Braathen

- Consider the decoupling limit in several BSM models

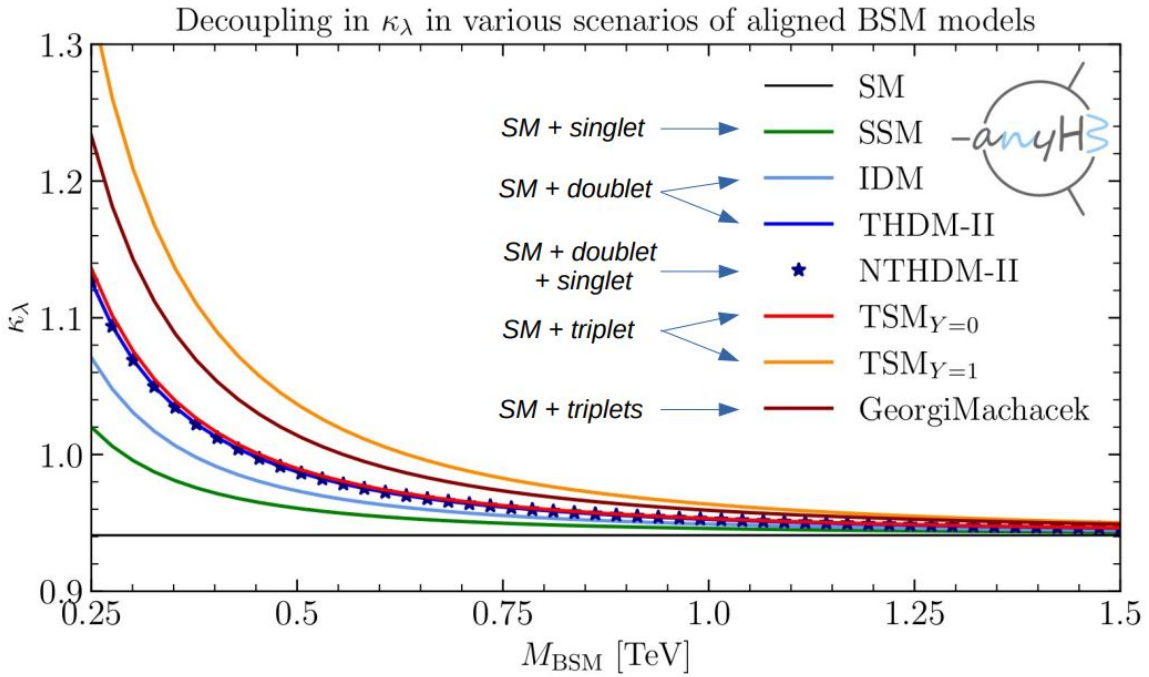
$$M^2_{\rm BSM} = \mathcal{M}^2 + \tilde{\lambda} v^2$$

$\mathcal{M}$: BSM mass scale
$\tilde{\lambda}$: Quartic couplings

- Increase BSM mass scale

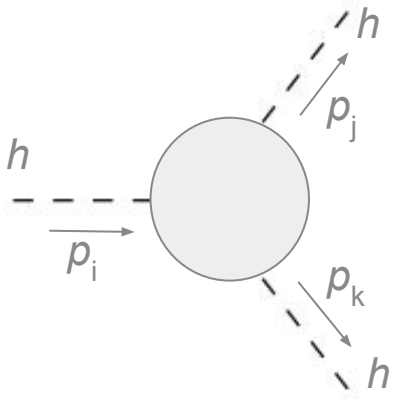
$$\mathcal{M} \to \infty$$

- BSM corrections to should vanish (c.f. decoupling theorem [Appelquist, Carrazone '75])

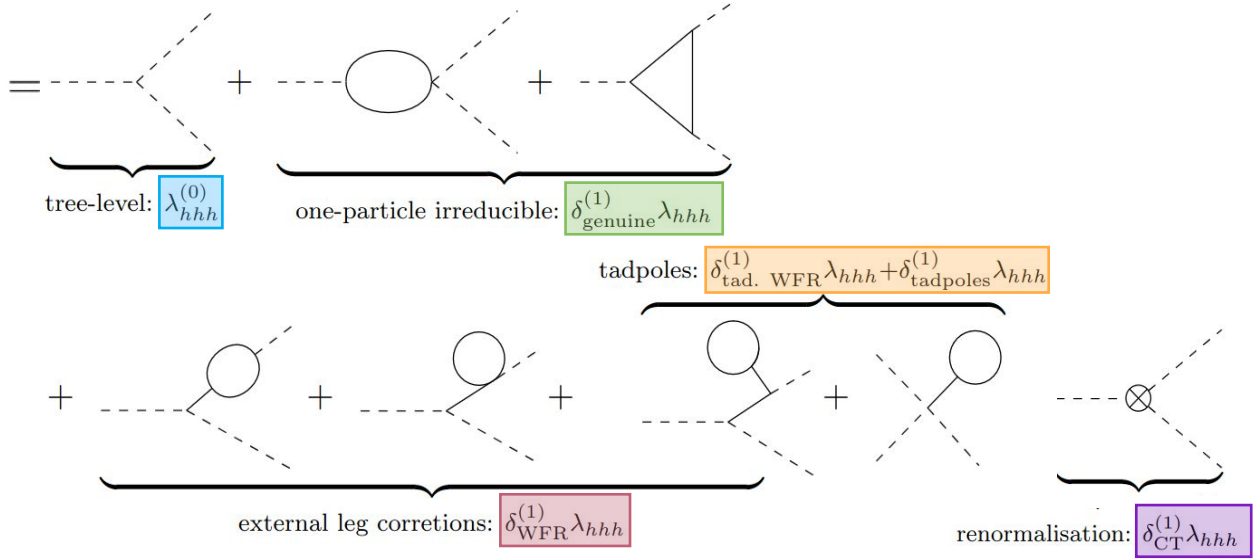


Trilinear Higgs couplings (generic approach)

Trilinear couplings = renormalized three point functions: $\lambda_{hhh} = -\hat{\Gamma}_{hhh}(p_1^2, p_2^2, p_3^2)$



$$= \lambda^{(0)}_{hhh} + \delta^{(1)}_{\text{genuine}}\lambda_{hhh} + \delta^{(1)}_{\text{tadpoles}}\lambda_{hhh} + \delta^{(1)}_{\text{WFR}}\lambda_{hhh} + \delta^{(1)}_{\text{CT}}\lambda_{hhh}$$



note: solid line = generic field

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

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

* Generalized coupling constants:

Yukawas

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

* Triangle form factors:

$$F_\triangle(\tau_t) = \tau_t\left[1 + (1-\tau_t) f(\tau_t)\right] \;\; ; \;\; \tau_t = 4m_t^2/s$$

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

Higgs pair production in the 2HDM at tree level

Plehn, Spira, Zerwas : arXiv: 9603205

* Matrix element:

$$\mathcal{M}\left(g_a g_b \to H_c H_d\right) = \mathcal{M}_{\triangle}^{h} + \mathcal{M}_{\triangle}^{H} + \mathcal{M}_{\square}$$

a,b: color indices

$$\mathcal{M}_{\triangle}^{h/H} = \frac{G_F \alpha_s \hat{s}}{2\sqrt{2}\pi}\, C_{\triangle}^{h/H}\, F_{\triangle} A_{1\mu\nu}\, \epsilon_a^{\mu} \epsilon_b^{\nu}\, \delta_{ab}$$

gluon polarization vectors

$$\mathcal{M}_{\square} = \frac{G_F \alpha_s \hat{s}}{2\sqrt{2}\pi}\, C_{\square}\, \left(F_{\square} A_{1\mu\nu} + G_{\square} A_{2\mu\nu}\right)\, \epsilon_a^{\mu} \epsilon_b^{\nu}\, \delta_{ab}$$

* Tensor structure:

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

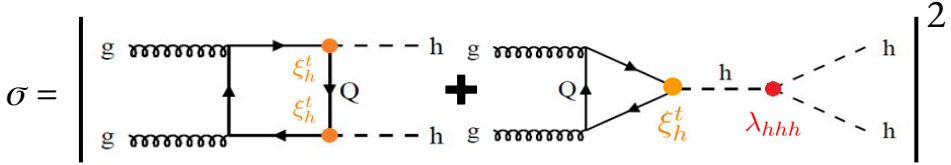
* Box form factors:

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

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

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

Non resonant production

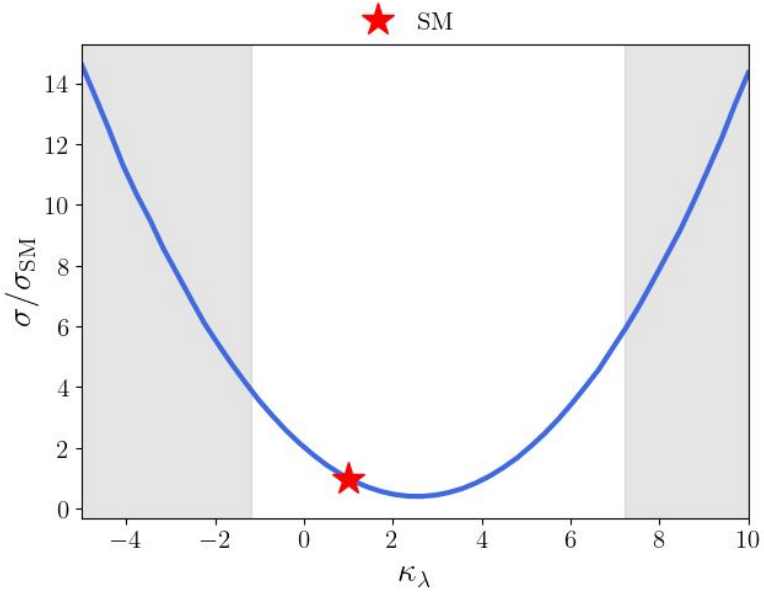


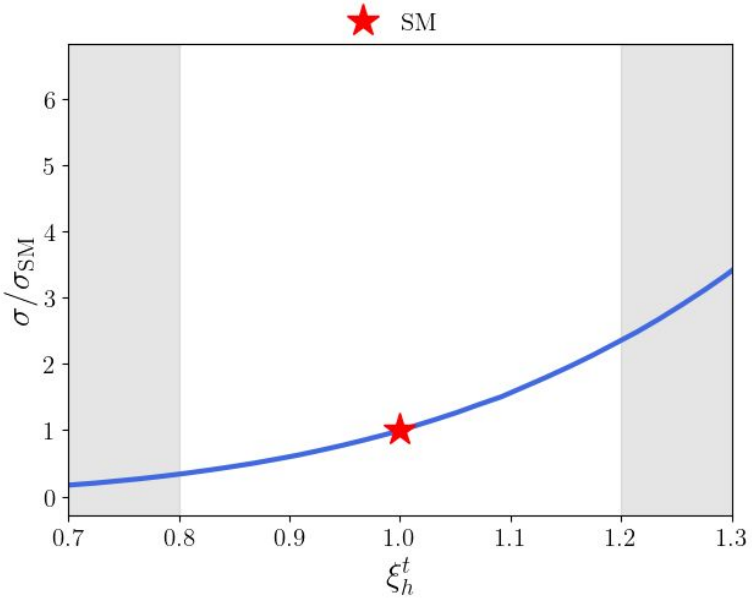
WG4 Twiki

σ_{SM} (NNLO FTapprox) @ 13 TeV = 30.77 fb

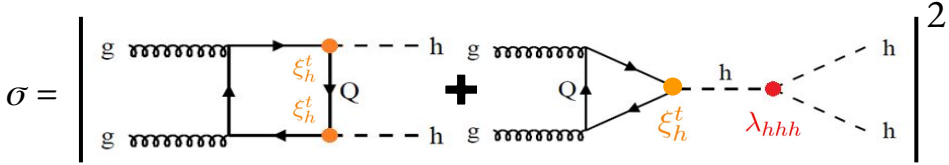
$[-1.2 < \kappa_\lambda < 7.2]$ (2σ CL) ATLAS: arXiv: 2406.09971

$[0.8 < \xi^t_h < 1.2]$(2σ CL) CMS: Nature 2022





Non resonant production: κ_λ



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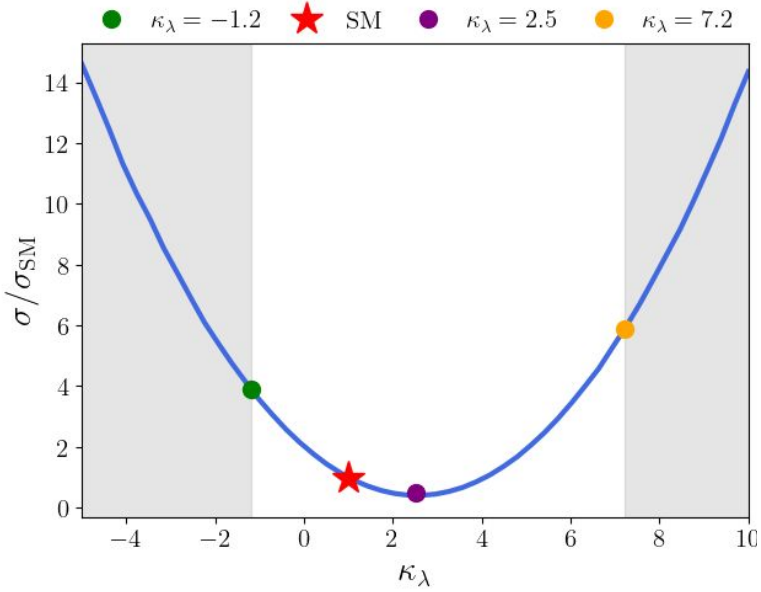
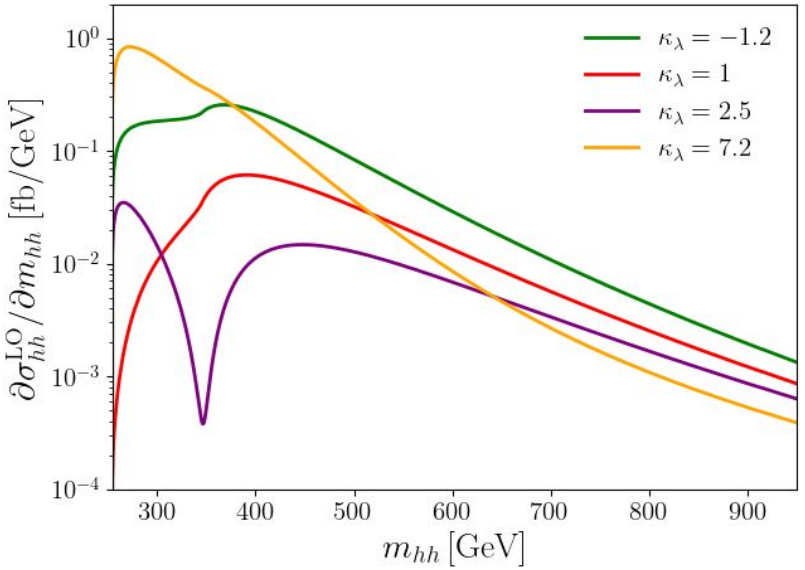
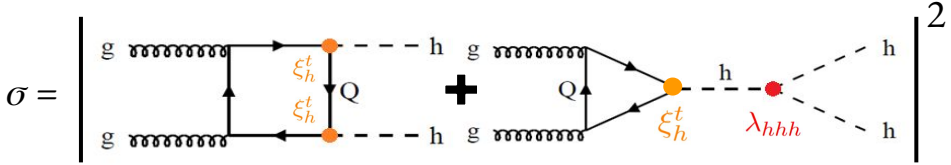




Non resonant production: ξ^t_h

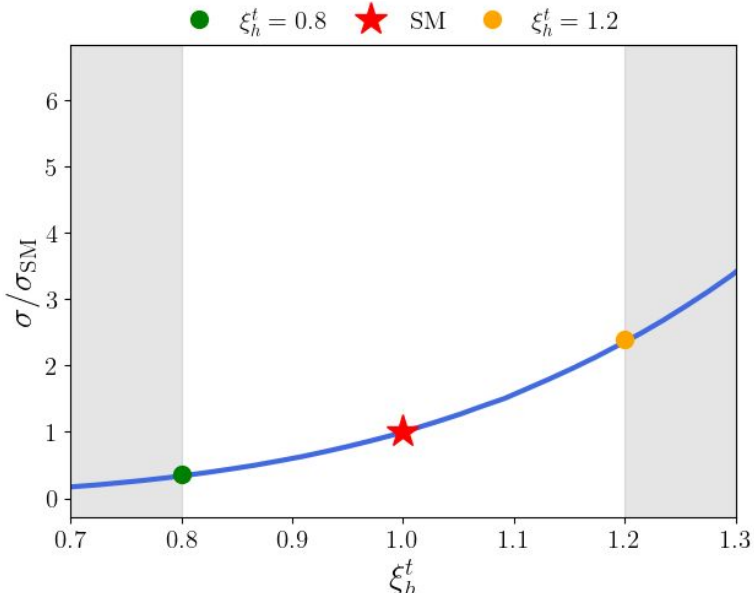


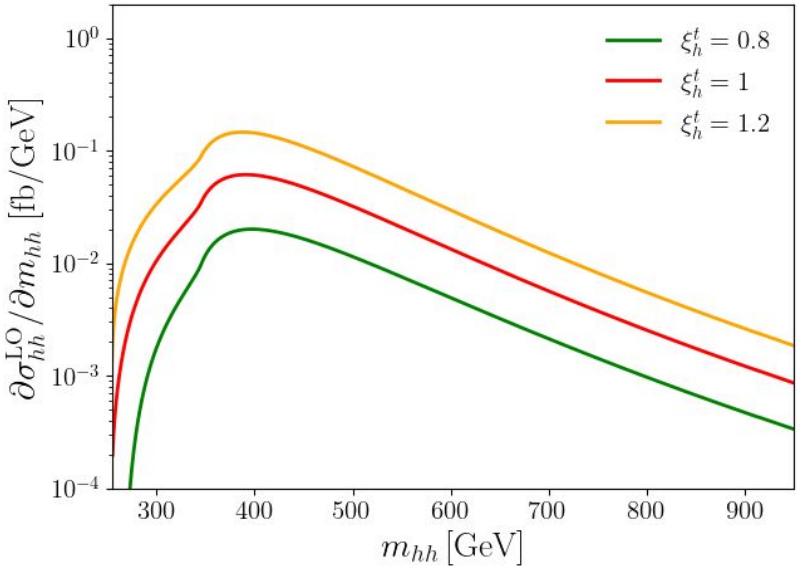
WG4 Twiki

σ_{SM} (NNLO FTapprox) @ 13 TeV = 30.77 fb

$[-1.2 < \kappa_\lambda < 7.2]$ (2σ CL) ATLAS: arXiv: 2406.09971

$[0.8 < \xi^t_h < 1.2]$(2σ CL) CMS: Nature 2022

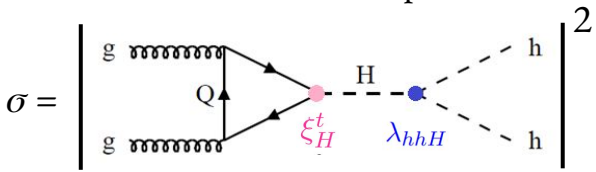




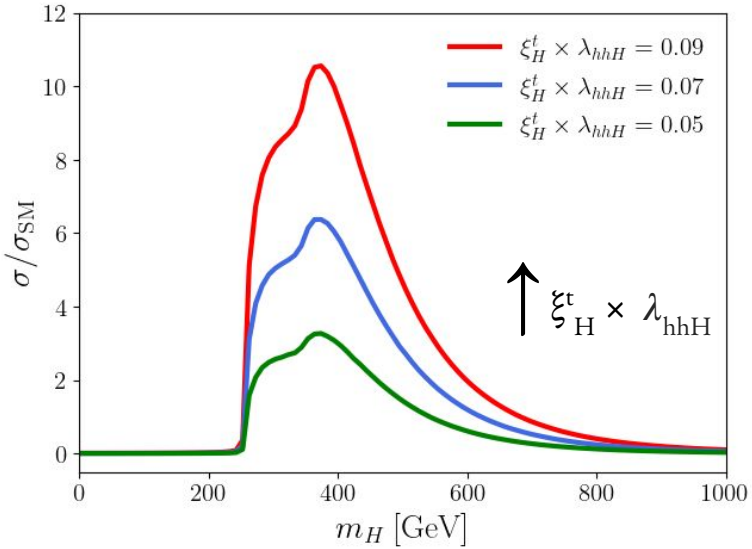
Resonant production

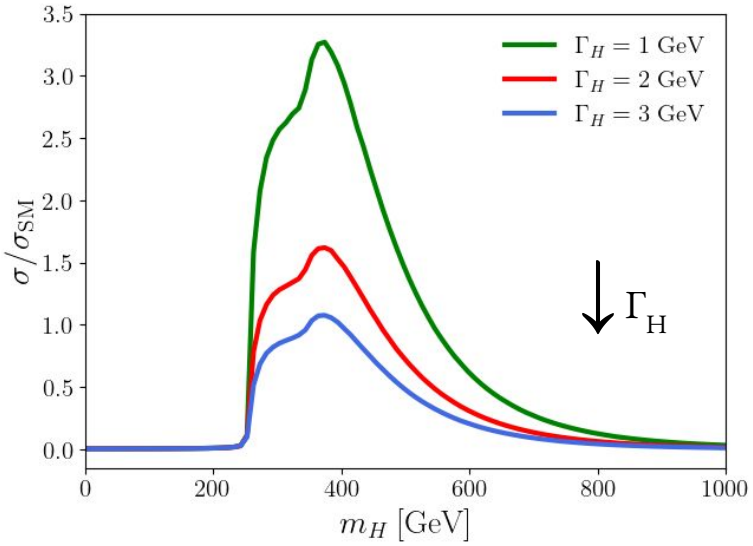
Note! values given for a toy model, actual numbers of the y-axis need to be analyzed in specific BSM models

Conditions to enhance the resonant production and its contribution in the total Higgs pair production process



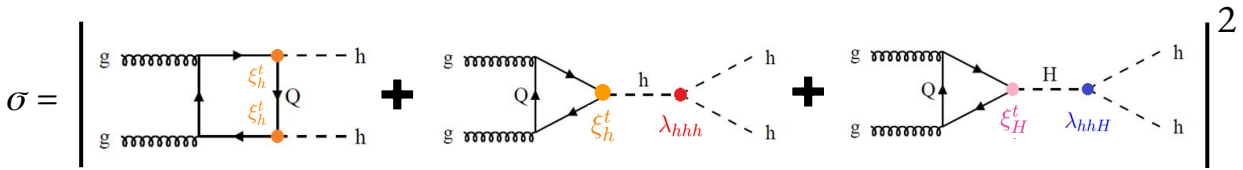
1) m_H above 250 GeV
2) small width: Γ_H
3) large couplings: $\xi^t_H \times \lambda_{hhH}$

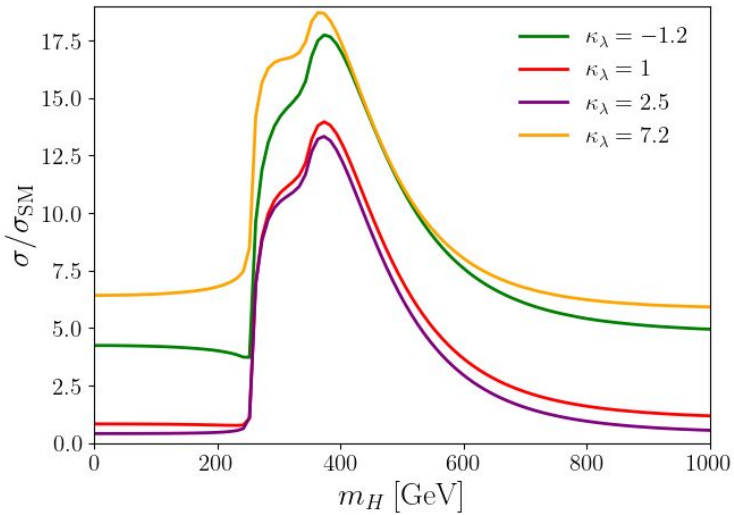


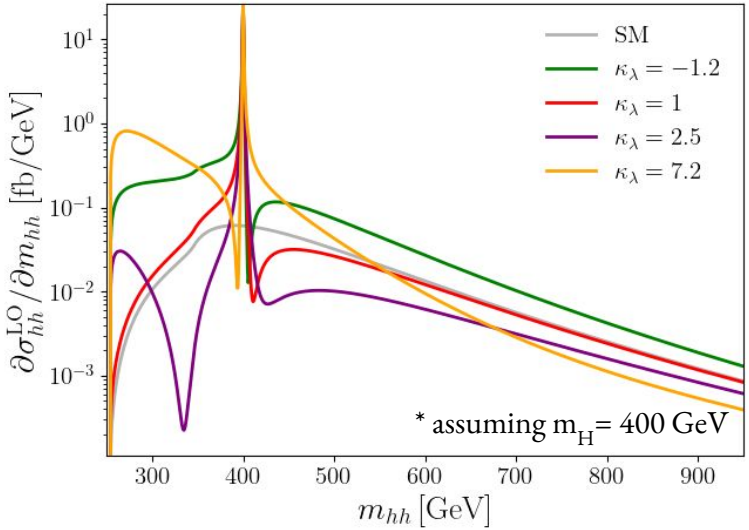


Total Higgs pair production

Note! values given for a toy model, actual numbers of the y-axis need to be analyzed in specific BSM models





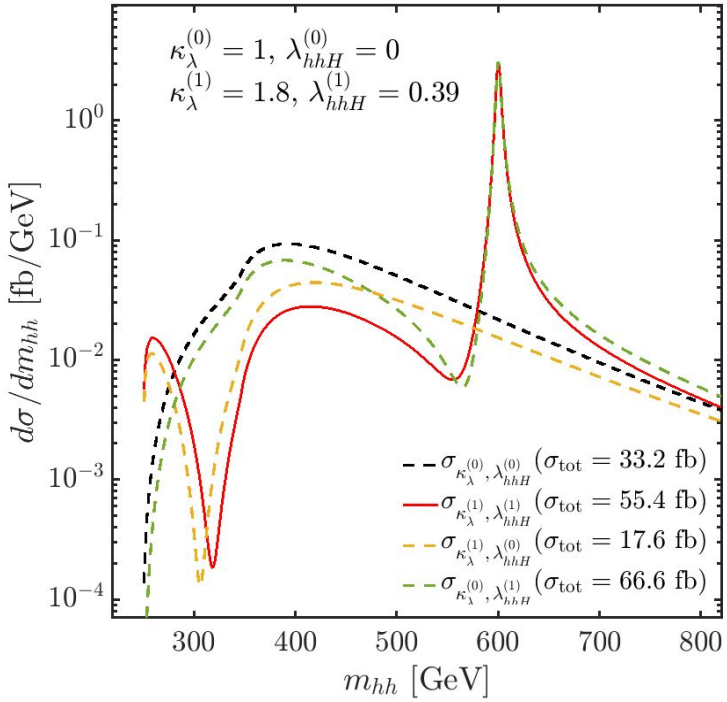


Full process can be enhanced by both deviations in κ_λ and a resonant scalar

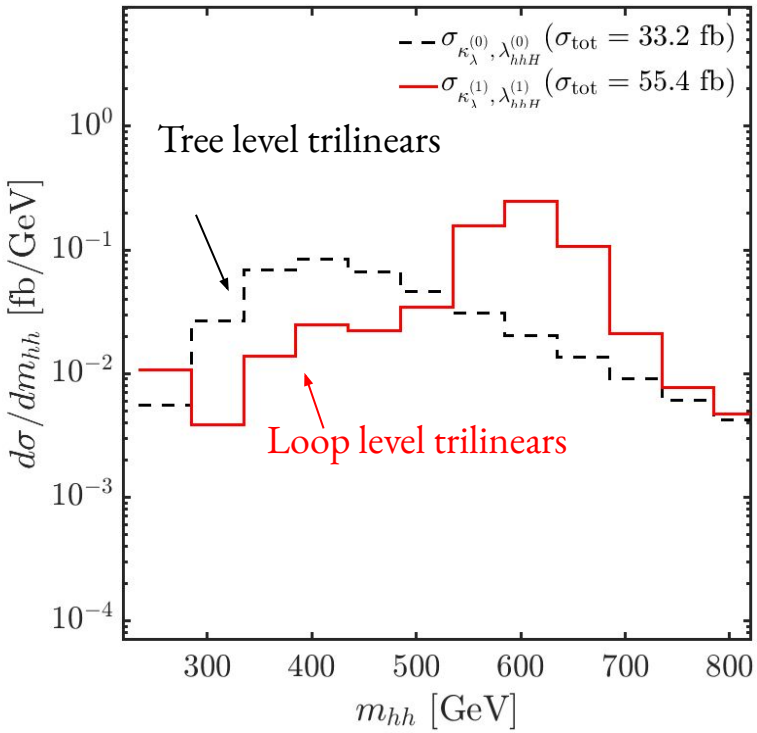
Invariant mass distributions

Bahl, Braathen, Gabelmann, K.R., Weiglein: TBP

$$\tan\beta = 2,\ m_H = m_A = m_{H^\pm} = 600\ \text{GeV},\ M = 400\ \text{GeV},\ \alpha = \beta - \pi/2$$



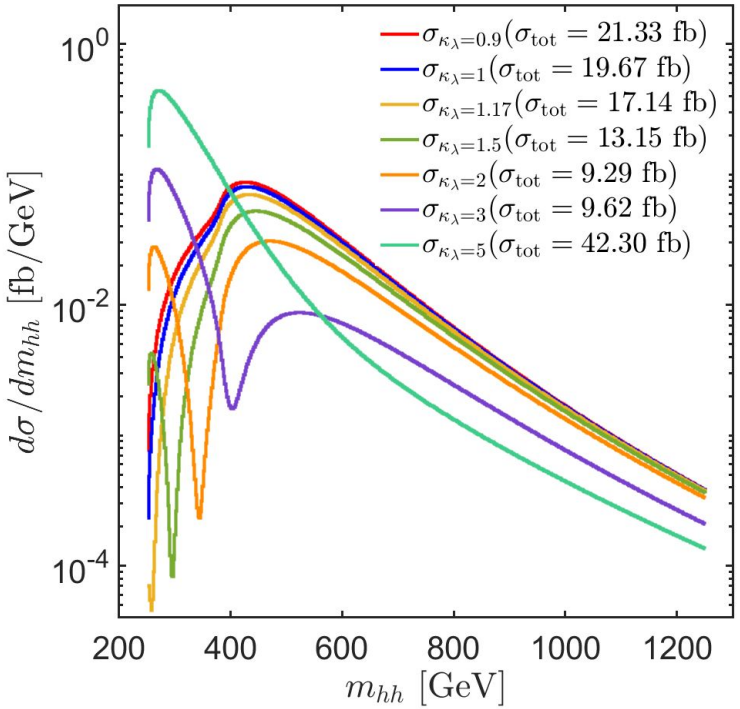
Smeared distribution:



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 $\kappa_\lambda \sim 2.5$)
- 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

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

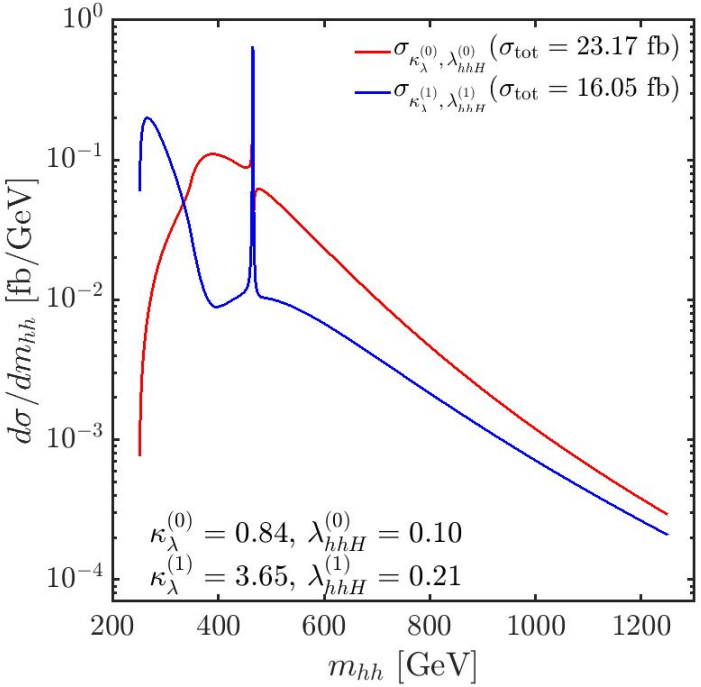
$$C_\triangle \propto \lambda_{hhh}$$

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

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

Effect of loop corrections of THC in m_{hh}

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



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

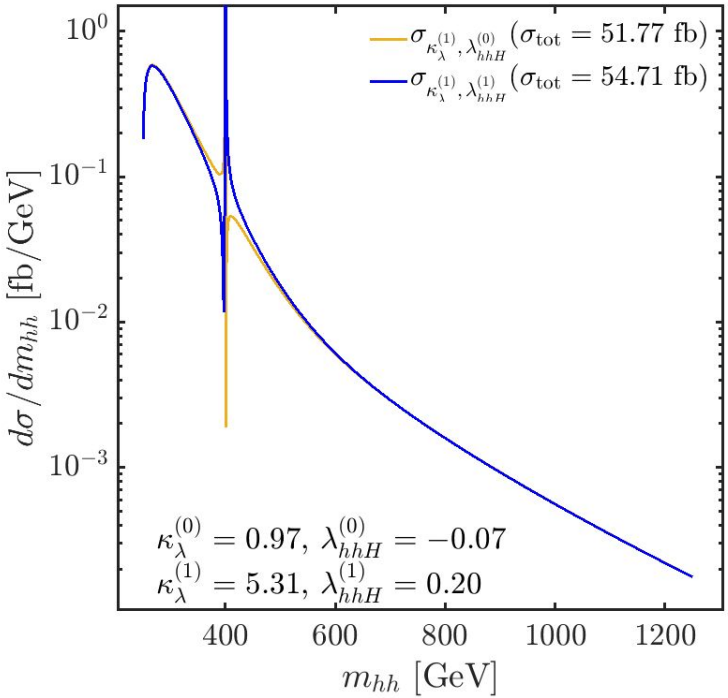
- Larger sensitivity to κ_λ in the low m_{hh} region (because of a cancellation between the box and triangle diagrams in the SM)

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

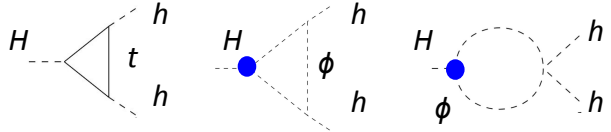
- Change in the dip peak structure of the resonance

Effect of loop corrections to λ_{hhH}

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



$t_\beta = 15,\ c_{\beta-\alpha} = 0.12\ (s_{\beta-\alpha} > 0)\ m_H = 400$ GeV,
$m_A = m_{H^\pm} = 660$ GeV $m_{12}^2 = m_H^2 c_\alpha^2 / t_\beta$



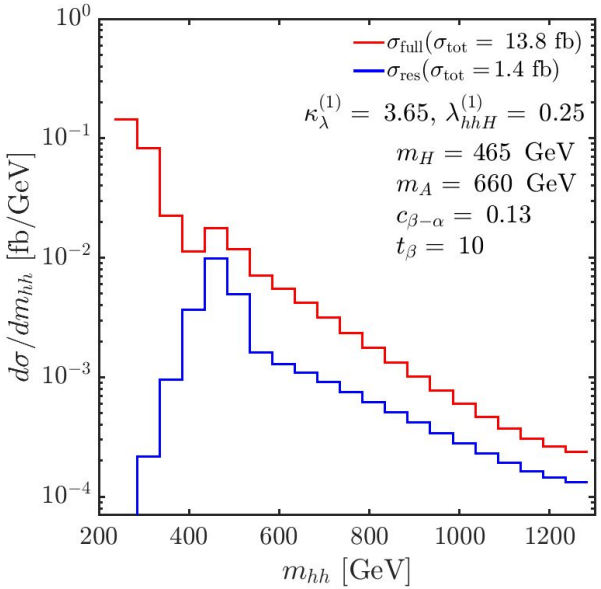
- $\lambda_{h\phi\phi} \propto (M^2 - m_\phi^2)$ Braathen, Kanemura: arxiv: 1911.11507

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]

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