Higgs Pair Production in a Composite 2HDM [*JHEP* 06 (2024), p. 063, arxiv:2310.10471]

Stefania De Curtis, Luigi Delle Rose, **Felix Egle**, Stefano Moretti, Margarete Mühlleitner, Kodai Sakurai

4th September 2024

Motivation

Composite Models:

Illustration by Sandbox Studio, Chicago

Motivation

Composite Models:

- Alternative approach to explain the Higgs mechanism / electroweak symmetry breaking
- Higgs **not** elementary, but a **composite** pseudo Nambu Goldstone boson (pNGB) (SM analogy: pions)
- Solution to the hierachy problem

Illustration by Sandbox Studio, Chicago

Motivation

Composite Models:

- Alternative approach to explain the Higgs mechanism / electroweak symmetry breaking
- Higgs **not** elementary, but a **composite** pseudo Nambu Goldstone boson (pNGB) (SM analogy: pions)
- Solution to the hierachy problem

Higgs Pair Production:

Illustration by Sandbox Studio, Chicago

Motivation

Composite Models:

- Alternative approach to explain the Higgs mechanism / electroweak symmetry breaking
- Higgs **not** elementary, but a **composite** pseudo Nambu Goldstone boson (pNGB) (SM analogy: pions)
- Solution to the hierachy problem

Higgs Pair Production:

- Measurement of the trilinear Higgs coupling ⇒ Further insight into the Higgs potential
- Goal: Investigation of the impact of the composite sector on Higgs Pair Production

Illustration by Sandbox Studio, Chicago

A Composite 2HDM [De Curtis et al. 2018]

Main features:

A Composite 2HDM [De Curtis et al. 2018]

Main features:

- Additional strong sector with $SO(6)$ symmetry: spontaneous breaking $SO(6) \to SO(4)xSO(2)$
  $\Rightarrow$ Generation of 2HDM-like structure
- **Partial compositeness** of SM fields: Explicit breaking of the symmetry, generation of masses for the scalar sector
- Scalar potential determined by composite parameters

A Composite 2HDM [De Curtis et al. 2018]

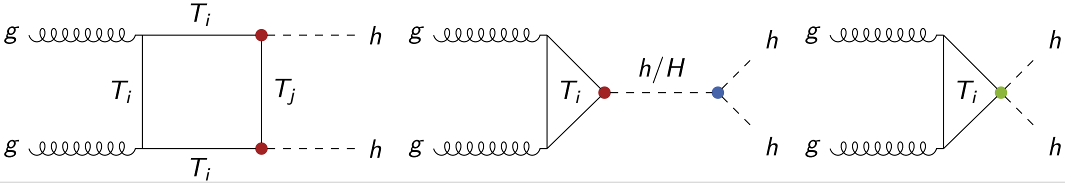
Main features:

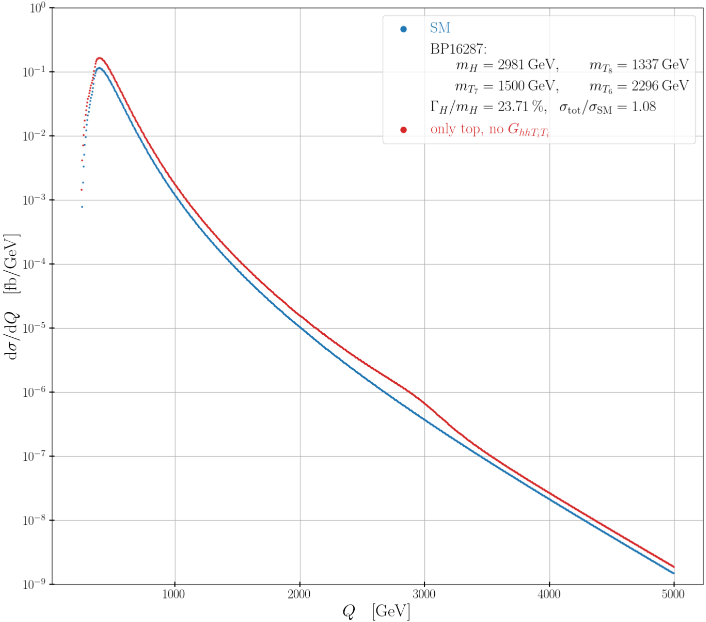
- Additional strong sector with $SO(6)$ symmetry: spontaneous breaking $SO(6) \to SO(4)xSO(2)$
  $\Rightarrow$ Generation of 2HDM-like structure
- **Partial compositeness** of SM fields: Explicit breaking of the symmetry, generation of masses for the scalar sector
- Scalar potential determined by composite parameters
- Incorporate top quark into sextuplet $\Rightarrow$ **8 additional top partners** T_i $(i = 1, .., 9,\ T_9 = t)$
- Obtain effective Lagrangian by integrating out heavy resonances

A Composite 2HDM [De Curtis et al. 2018]

Main features:

- Additional strong sector with $SO(6)$ symmetry: spontaneous breaking $SO(6) \rightarrow SO(4)xSO(2)$
  $\Rightarrow$ Generation of 2HDM-like structure
- **Partial compositeness** of SM fields: Explicit breaking of the symmetry, generation of masses for the scalar sector
- Scalar potential determined by composite parameters
- Incorporate top quark into sextuplet $\Rightarrow$ **8 additional top partners** T_i $(i = 1, .., 9,\ T_9 = t)$
- Obtain effective Lagrangian by integrating out heavy resonances
- **Composite 2HDM: Contribution to di-Higgs cross section from resonant production, additional top partners in the loop as well as new effective couplings**



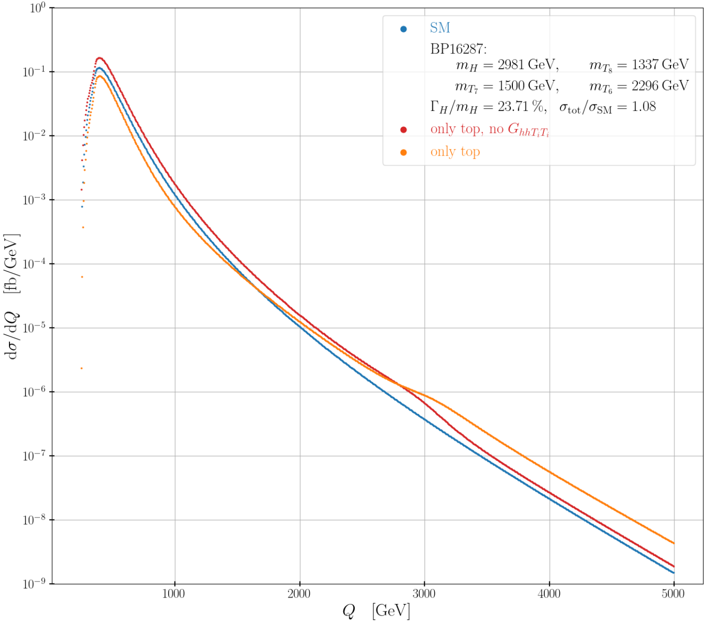


Differential distributions

- BP16287:

f	1140 GeV
$\lambda_{hhh}/\lambda_{SM}$	0.92
$g_{htt}/g_{htt,SM}$	1.07
G_{hhtt}	3.9×10^{-4} 1/GeV

- Red line resembles elementary 2HDM

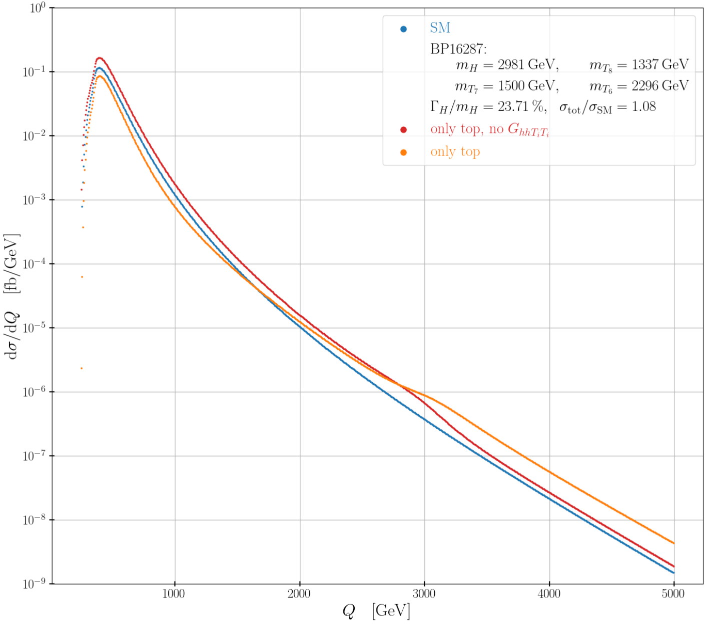


Differential distributions

- BP16287:

f	1140 GeV
$\lambda_{hhh}/\lambda_{\mathrm{SM}}$	0.92
$g_{htt}/g_{htt,\mathrm{SM}}$	1.07
G_{hhtt}	3.9×10^{-4} 1/GeV

- Red line resembles elementary 2HDM

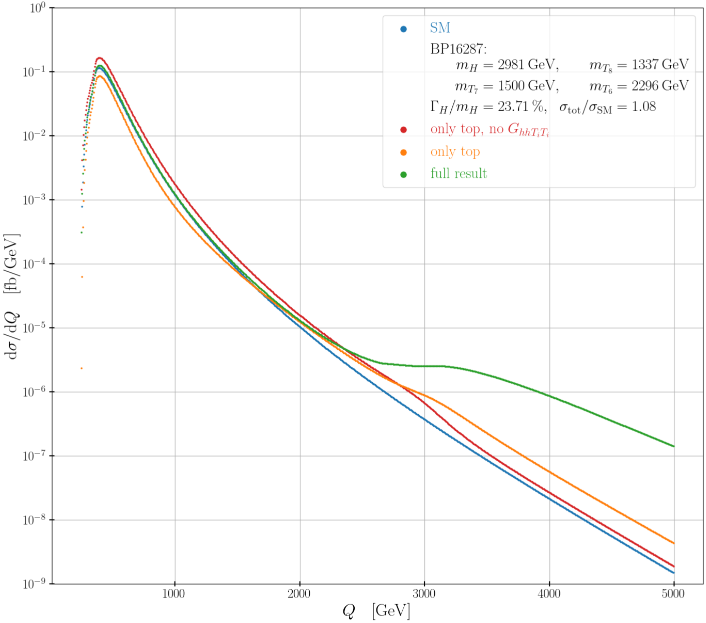


Differential distributions

- BP16287:

f	1140 GeV
$\lambda_{hhh}/\lambda_{\rm SM}$	0.92
$g_{htt}/g_{htt,\rm SM}$	1.07
G_{hhtt}	3.9×10^{-4} 1/GeV

- Red line resembles elementary 2HDM
- G_{hhtt}: destructive interference

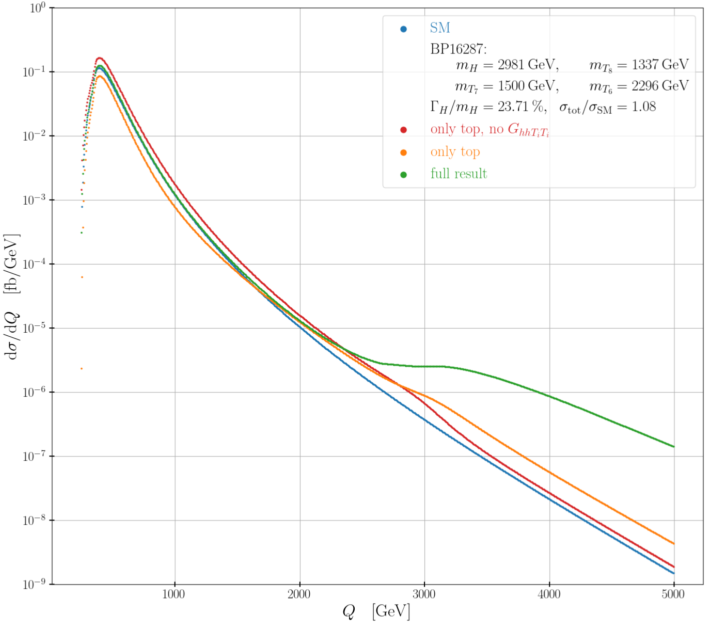


Differential distributions

- BP16287:

f	1140 GeV
$\lambda_{hhh}/\lambda_{SM}$	0.92
$g_{htt}/g_{htt,SM}$	1.07
G_{hhtt}	3.9×10^{-4} 1/GeV

- Red line resembles elementary 2HDM
- G_{hhtt}: destructive interference

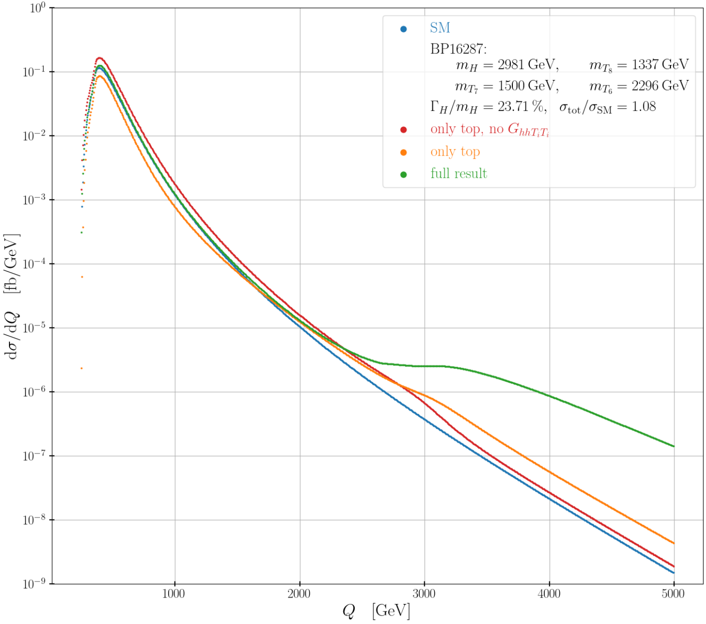


Differential distributions

- BP16287:

f	1140 GeV
$\lambda_{hhh}/\lambda_{\text{SM}}$	0.92
$g_{htt}/g_{htt,\text{SM}}$	1.07
G_{hhtt}	3.9×10^{-4} 1/GeV

- Red line resembles elementary 2HDM
- G_{hhtt}: destructive interference
- Heavy quarks: enhancement + threshold effect

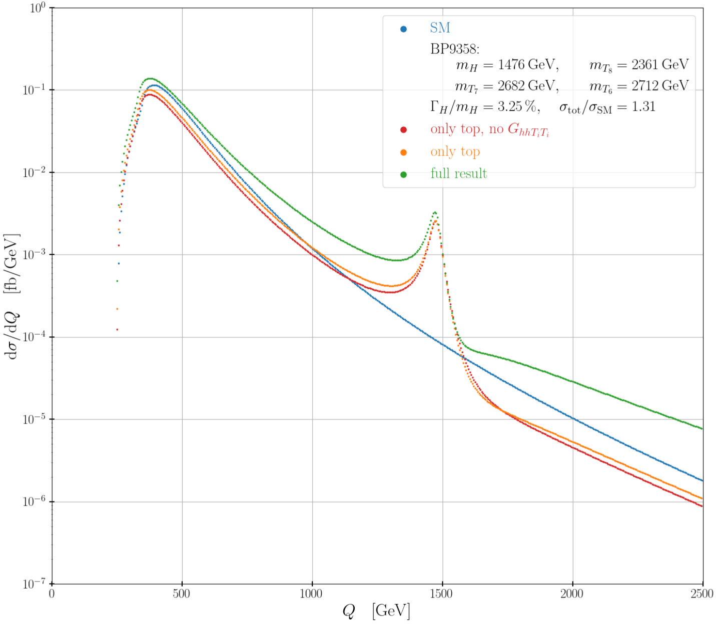


Differential distributions

- BP16287:

f	1140 GeV
$\lambda_{hhh}/\lambda_{\rm SM}$	0.92
$g_{htt}/g_{htt,\rm SM}$	1.07
G_{hhtt}	3.9×10^{-4} 1/GeV

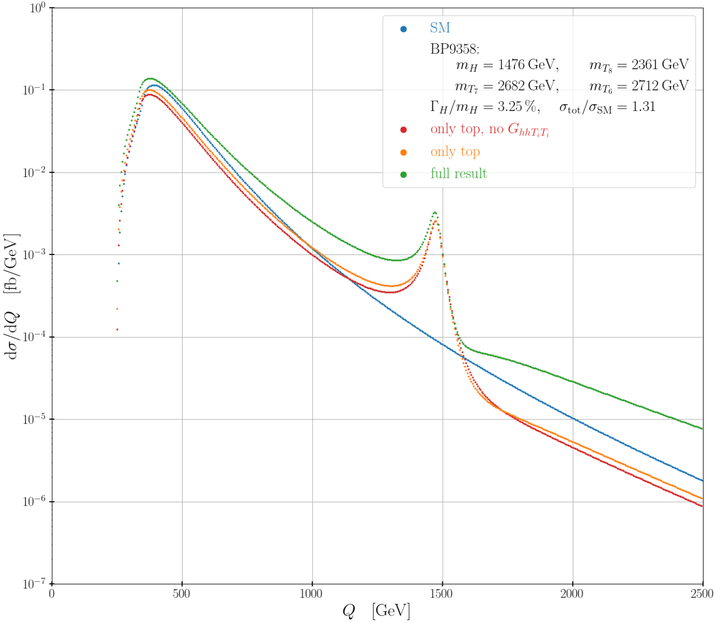
- Red line resembles elementary 2HDM
- G_{hhtt}: destructive interference
- Heavy quarks: enhancement + threshold effect
- Large total width Γ_H



Differential distributions

- BP9358:

f	750 GeV
$\lambda_{hhh}/\lambda_{\text{SM}}$	0.899
$\lambda_{Hhh}/\lambda_{\text{SM}}$	-2.576
$g_{htt}/g_{htt,\text{SM}}$	0.856
$g_{Htt}/g_{htt,\text{SM}}$	-0.864
G_{hhtt}	-6.1×10^{-5} 1/GeV

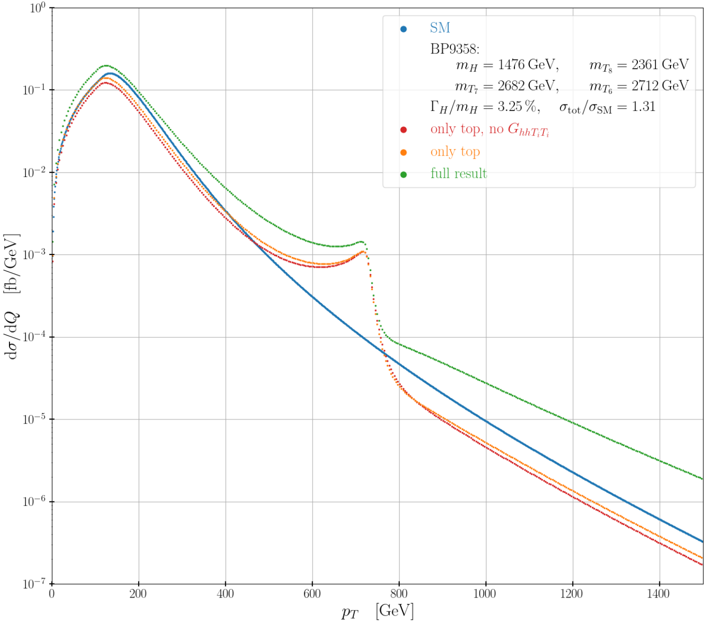


Differential distributions

- BP9358:

f	750 GeV
$\lambda_{hhh}/\lambda_{\rm SM}$	0.899
$\lambda_{Hhh}/\lambda_{\rm SM}$	-2.576
$g_{htt}/g_{htt,\rm SM}$	0.856
$g_{Htt}/g_{htt,\rm SM}$	-0.864
G_{hhtt}	-6.1×10^{-5} 1/GeV

- Here constructive interference from G_{hhtt}
- Interference effects between resonance, heavy Quark contribution and quartic coupling

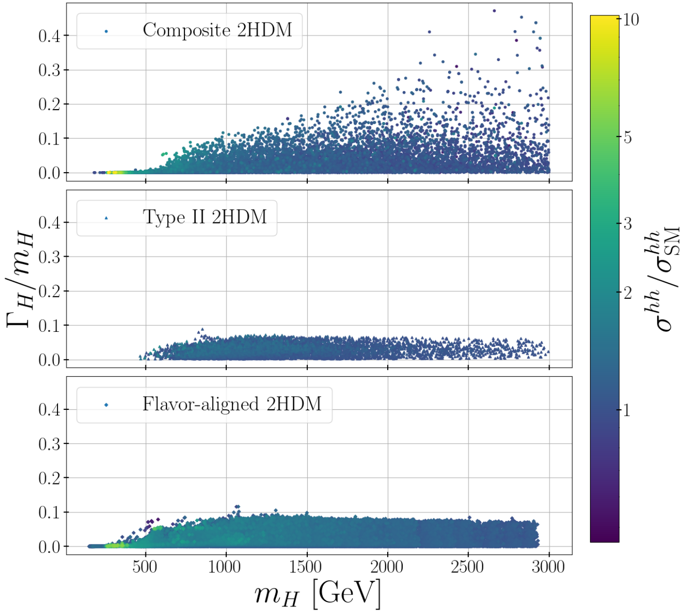


Differential distributions

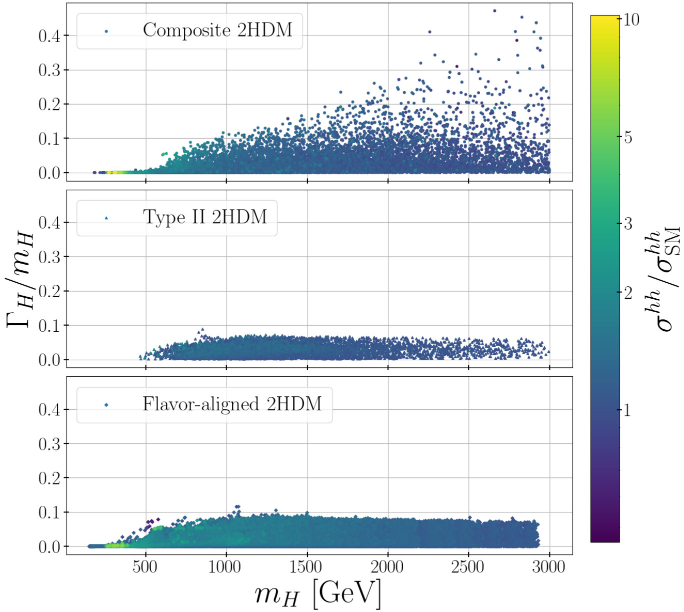
- BP9358:

f	750 GeV
$\lambda_{hhh}/\lambda_{\rm SM}$	0.899
$\lambda_{Hhh}/\lambda_{\rm SM}$	-2.576
$g_{htt}/g_{htt,\rm SM}$	0.856
$g_{Htt}/g_{htt,\rm SM}$	-0.864
G_{hhtt}	-6.1×10^{-5} 1/GeV

- Here constructive interference from G_{hhtt}
- Interference effects between resonance, heavy Quark contribution and quartic coupling



Comparison to elementary 2HDM



Comparison to elementary 2HDM

- Higgs decay to heavy top partners possible in Composite 2HDM for heavy m_H
- Larger Yukawa couplings in composite 2HDM

Summary

- Composite 2HDM allows for **large widths** Γ_H
- Interference effects between resonant production, heavy quark contribution and quartic couplings are important
- Shape of differential distribution can be used to distinguish between the composite 2HDM and an elementary 2HDM

Summary

- Composite 2HDM allows for **large widths** Γ_H
- Interference effects between resonant production, heavy quark contribution and quartic couplings are important
- Shape of differential distribution can be used to distinguish between the composite 2HDM and an elementary 2HDM

Thank you for your attention!

Literature I

De Curtis, Stefania et al. (Dec. 2018). "A concrete composite 2-Higgs doublet model". In: *Journal of High Energy Physics* 2018.12. DOI: 10.1007/jhep12(2018)051.

Ellis, Joshua P. (Jan. 2017). "Ti k Z-Feynman: Feynman diagrams with Ti k Z". In: *Computer Physics Communications* 210, pp. 103–123. ISSN: 0010-4655. DOI: 10.1016/j.cpc.2016.08.019.

Plehn, T., M. Spira, P.M. Zerwas (Nov. 1996). "Pair production of neutral Higgs particles in gluon-gluon collisions". In: *Nuclear Physics B* 479.1-2, pp. 46–64. DOI: 10.1016/0550-3213(96)00418-x.

Gröber, R., M. Mühlleitner (June 2011). "Composite Higgs boson pair production at the LHC". In: *Journal of High Energy Physics* 2011.6. DOI: 10.1007/jhep06(2011)020.

Gillioz, M. et al. (Oct. 2012). "Higgs low-energy theorem (and its corrections) in composite models". In: *Journal of High Energy Physics* 2012.10. DOI: 10.1007/jhep10(2012)004.

Dawson, S., S. Dittmaier, M. Spira (1998). "Two-loop QCD corrections to Higgs-pair production at the LHC". In: DOI: 10.48550/ARXIV.HEP-PH/9806304.

Djouadi, A., J. Kalinowski, M. Spira (Jan. 1998). "HDECAY: a program for Higgs boson decays in the Standard Model and its supersymmetric extension". In: *Computer Physics Communications* 108.1, pp. 56–74. DOI: 10.1016/s0010-4655(97)00123-9.

Literature II

Djouadi, Abdelhak et al. (May 2019). “HDECAY: Twenty++ years after”. In: *Computer Physics Communications* 238, pp. 214–231. DOI: 10.1016/j.cpc.2018.12.010.

Abouabid, Hamza et al. (2021). *Benchmarking Di-Higgs Production in Various Extended Higgs Sector Models*. DOI: 10.48550/ARXIV.2112.12515.

Bechtle, Philip, Daniel Dercks, et al. (Dec. 2020). “HiggsBounds-5: testing Higgs sectors in the LHC 13 TeV Era”. In: *The European Physical Journal C* 80.12. DOI: 10.1140/epjc/s10052-020-08557-9.

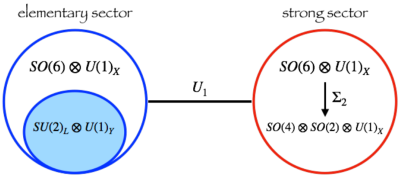
Bechtle, Philip, Sven Heinemeyer, et al. (Feb. 2021). “HiggsSignals-2: probing new physics with precision Higgs measurements in the LHC 13 TeV era”. In: *The European Physical Journal C* 81.2. DOI: 10.1140/epjc/s10052-021-08942-y.

Gröber, R., M. Mühlleitner, M. Spira (June 2016). “Signs of composite Higgs pair production at next-to-leading order”. In: *Journal of High Energy Physics* 2016.6. DOI: 10.1007/jhep06(2016)080.

Spira, M. (1995). *HIGLU: A Program for the Calculation of the Total Higgs Production Cross Section at Hadron Colliders via Gluon Fusion including QCD Corrections*. DOI: 10.48550/ARXIV.HEP-PH/9510347.

A Composite 2HDM [De Curtis et al. 2018]

- $\mathcal{G} = SO(6)$, $\mathcal{H} = SO(4) \times SO(2)$
  $\Rightarrow n = 15 - (6+1) = 8$ NG bosons
- 3 are eaten to give masses to the W and Z bosons, remaining 5: 2HDM-like structure



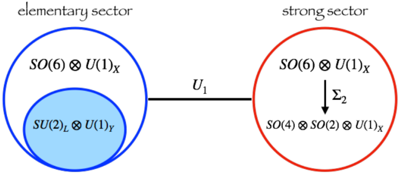
Full coset structure:

$$\frac{\mathcal{G}}{\mathcal{H}} = \frac{SU(3)_c \times SO(6) \times U(1)_X}{SU(3)_c \times SO(4) \times SO(2) \times U(1)_X}$$

A Composite 2HDM [De Curtis et al. 2018]

- Gauge sector Lagrangian:

$$\mathcal{L}^{\text{gauge}}_{\text{C2HDM}} = \frac{f_1^2}{4}\text{Tr}\,|D_\mu U_1|^2 + \frac{f_2^2}{4}\text{Tr}\,|D_\mu \Sigma_2|^2 - \frac{1}{4g_\rho^2}(\rho^A)_{\mu\nu}(\rho^A)^{\mu\nu} - \frac{1}{4g_{\rho X}^2}(\rho^X)_{\mu\nu}(\rho^X)^{\mu\nu} - \frac{1}{4g_A^2}(A^A)_{\mu\nu}(A^A)^{\mu\nu} - \frac{1}{4g_X^2}X_{\mu\nu}X^{\mu\nu}$$



Full coset structure:

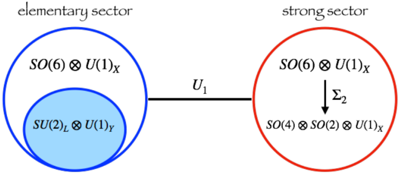
$$\frac{\mathcal{G}}{\mathcal{H}} = \frac{SU(3)_c \times SO(6) \times U(1)_X}{SU(3)_c \times SO(4) \times SO(2) \times U(1)_X}$$

A Composite 2HDM [De Curtis et al. 2018]

- Gauge sector Lagrangian:

$$\mathcal{L}^{\text{gauge}}_{\text{C2HDM}} = \frac{f_1^2}{4}\mathrm{Tr}\,|D_\mu U_1|^2 + \frac{f_2^2}{4}\mathrm{Tr}\,|D_\mu \Sigma_2|^2 - \frac{1}{4g_\rho^2}(\rho^A)_{\mu\nu}(\rho^A)^{\mu\nu} - \frac{1}{4g_{\rho X}^2}(\rho^X)_{\mu\nu}(\rho^X)^{\mu\nu} - \frac{1}{4g_A^2}(A^A)_{\mu\nu}(A^A)^{\mu\nu} - \frac{1}{4g_X^2}X_{\mu\nu}X^{\mu\nu}$$

- $G_1, G_2 = SO(6) \times U(1)_X$
- G_2: local, describes spin-1 resonances through ρ^X and ρ^A ($A \in \mathrm{Adj}(SO(6))$),
- G_1: global with only $SU(2)_L \times U(1)_Y$ local, SM gauge fields embedded



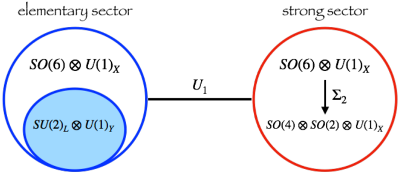
Full coset structure:

$$\frac{\mathcal{G}}{\mathcal{H}} = \frac{SU(3)_c \times SO(6) \times U(1)_X}{SU(3)_c \times SO(4) \times SO(2) \times U(1)_X}$$

A Composite 2HDM [De Curtis et al. 2018]

- Gauge sector Lagrangian:

$$\mathcal{L}^{\text{gauge}}_{\text{C2HDM}} = \frac{f_1^2}{4}\mathrm{Tr}\,|D_\mu U_1|^2 + \frac{f_2^2}{4}\mathrm{Tr}\,|D_\mu \Sigma_2|^2 - \frac{1}{4g_\rho^2}(\rho^A)_{\mu\nu}(\rho^A)^{\mu\nu} - \frac{1}{4g_{\rho X}^2}(\rho^X)_{\mu\nu}(\rho^X)^{\mu\nu} - \frac{1}{4g_A^2}(A^A)_{\mu\nu}(A^A)^{\mu\nu} - \frac{1}{4g_X^2}X_{\mu\nu}X^{\mu\nu}$$



- $G_1, G_2 = SO(6) \times U(1)_X$
- G_2: local, describes spin-1 resonances through ρ^X and ρ^A $(A \in \mathrm{Adj}(SO(6)))$,
- G_1: global with only $SU(2)_L \times U(1)_Y$ local, SM gauge fields embedded
- U_1: link field, realizes spontaneous symmetry breaking from $G_1 \times G_2$ to diagonal component G

Full coset structure:

$$\frac{\mathcal{G}}{\mathcal{H}} = \frac{SU(3)_c \times SO(6) \times U(1)_X}{SU(3)_c \times SO(4) \times SO(2) \times U(1)_X}$$

- Σ_2: VEV accounts for breaking to $SO(4) \times SO(2) \times U(1)_X$
- $f^{-2} = f_1^{-2} + f_2^{-2}$

A Composite 2HDM [De Curtis et al. 2018]

- Fermion Lagrangian, SM fermions embedded into fundamental representation of $SO(6)$:

$$\mathcal{L}_{\text{C2HDM}}^{\text{fermion}} = (\bar{q}_L^{\mathbf{6}}) i \not{D} (q_L^{\mathbf{6}}) + (\bar{t}_R^{\mathbf{6}}) i \not{D} (t_R^{\mathbf{6}}) + \bar{\Psi}^I i \not{D} \Psi^I - \bar{\Psi}^I (M_\Psi)_{IJ} P_R \Psi_J - \bar{\Psi}^I \left[(Y_1)_{IJ} \Sigma_2 + (Y_2)_{IJ} \Sigma_2^2 \right] \Psi^J$$
$$+ (\Delta_L)_I (\bar{q}_L^{\mathbf{6}}) U_1 P_R \Psi^I + (\Delta_R)_I (\bar{t}_R^{\mathbf{6}}) U_1 P_L \Psi^I + \text{h.c.}$$

- q_L,t_R: embedding of top quark, Ψ^I: Additional spin-1/2 resonances

A Composite 2HDM [De Curtis et al. 2018]

- Fermion Lagrangian, SM fermions embedded into fundamental representation of $SO(6)$:

$$\mathcal{L}^{\text{fermion}}_{\text{C2HDM}} = (\bar{q}^{\mathbf{6}}_L) i \not{D} (q^{\mathbf{6}}_L) + (\bar{t}^{\mathbf{6}}_R) i \not{D} (t^{\mathbf{6}}_R) + \bar{\Psi}^I i \not{D} \Psi^I - \bar{\Psi}^I (M_\Psi)_{IJ} P_R \Psi_J - \bar{\Psi}^I \left[(Y_1)_{IJ} \Sigma_2 + (Y_2)_{IJ} \Sigma_2^2 \right] \Psi^J$$
$$+ (\Delta_L)_I (\bar{q}^{\mathbf{6}}_L) U_1 P_R \Psi^I + (\Delta_R)_I (\bar{t}^{\mathbf{6}}_R) U_1 P_L \Psi^I + \text{h.c.}$$

- q_L,t_R: embedding of top quark, Ψ^I: Additional spin-1/2 resonances
- Composite parameters determining the Higgs potential:

$$f, \underbrace{Y_1^{12}, Y_2^{12}}_{\text{fermion coupling to resonances}}, \underbrace{\Delta_L^1, \Delta_R^2}_{\text{partial compositeness}}, \underbrace{M_\Psi^{11}, M_\Psi^{22}, M_\Psi^{12}}_{\text{composite fermion mass matrix}}, \underbrace{g_\rho}_{\text{composite gauge coupling}}$$

A Composite 2HDM [De Curtis et al. 2018]

- Non-linearities in the effective Lagrangian lead to custodial symmetry breaking $\Rightarrow$ need scenarios with additional symmetries (CP invariance, C_2 symmetry) to reduce the effects of the missing custodial symmetry
- Symmetry of strong sector highly constrains higher-dimensional operators contributing to Yukawa sector. Flavor alignment similar to 2HDM.
- Higgs potential obtained from Coleman-Weinberg formalism
- Tuning required for correct EWSB

Generation of parameter points:

- Reconstruction of VEV, Higgs mass and Top mass
- Direct and indirect searches in the scalar sector implemented via `HiggsBounds`/ `HiggsSignals` [Bechtle, Dercks, et al. 2020; Bechtle, Heinemeyer, et al. 2021]
- Flavor constraints from $b \to s\gamma$ and $B_s \to \mu\mu$
- Mass of the heavy tops larger than 1.3 TeV
- UV finiteness of the potential, perturbativity of the quartic couplings
- Points are generated through a MCMC scan

Elementary 2HDM

2 Higgs Doublet Model (2HDM):

- SM + additional scalar doublet
- Scalar potential:

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

Elementary 2HDM

2 Higgs Doublet Model (2HDM):

- SM + additional scalar doublet
- Scalar potential:

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

- Additional parameters not predetermined

A Composite 2HDM [De Curtis et al. 2018]

- Effective Lagrangian (h: 125 GeV Higgs, H: heavy Higgs, T_i: top partners, A: pseudoscalar, ϕ^0: neutral Goldstone boson, f: compositeness scale):

$$\begin{aligned}\mathcal{L}_{\text{yuk}} = &- G_{hT_iT_j}\bar{T}_{L,i}T_{R,j}h - G_{HT_iT_j}\bar{T}_{L,i}T_{R,j}H + iG_{AT_iT_j}\bar{T}_{L,i}T_{R,j}A + \text{h.c.} \\ &- G_{hhT_iT_j}\bar{T}_iT_jh^2 - G_{HHT_iT_j}\bar{T}_iT_jH^2 - G_{AAT_iT_j}\bar{T}_iT_jA^2 \\ &- G_{hHT_iT_j}\bar{T}_iT_jhH + iG_{hAT_iT_j}\bar{T}_i\gamma_5T_jhA + iG_{HAT_iT_j}\bar{T}_i\gamma_5T_jHA + iG_{\phi^0T_iT_j}\bar{T}_i\gamma_5T_j\phi^0\end{aligned}$$

A Composite 2HDM [De Curtis et al. 2018]

- Effective Lagrangian (h: 125 GeV Higgs, H: heavy Higgs, T_i: top partners, A: pseudoscalar, ϕ^0: neutral Goldstone boson, f: compositeness scale):

$$\begin{aligned}\mathcal{L}_{\text{yuk}} = &- G_{hT_iT_j}\bar{T}_{L,i}T_{R,j}h - G_{HT_iT_j}\bar{T}_{L,i}T_{R,j}H + iG_{AT_iT_j}\bar{T}_{L,i}T_{R,j}A + \text{h.c.}\\ &- G_{hhT_iT_j}\bar{T}_iT_jh^2 - G_{HHT_iT_j}\bar{T}_iT_jH^2 - G_{AAT_iT_j}\bar{T}_iT_jA^2\\ &- G_{hHT_iT_j}\bar{T}_iT_jhH + iG_{hAT_iT_j}\bar{T}_i\gamma_5T_jhA + iG_{HAT_iT_j}\bar{T}_i\gamma_5T_jHA + iG_{\phi^0T_iT_j}\bar{T}_i\gamma_5T_j\phi^0\end{aligned}$$

A Composite 2HDM [De Curtis et al. 2018]

- Effective Lagrangian (h: 125 GeV Higgs, H: heavy Higgs, T_i: top partners, A: pseudoscalar, ϕ^0: neutral Goldstone boson, f: compositeness scale):

$$\mathcal{L}_{\text{yuk}} = - G_{hT_iT_j} \bar{T}_{L,i} T_{R,j} h - G_{HT_iT_j} \bar{T}_{L,i} T_{R,j} H + iG_{AT_iT_j} \bar{T}_{L,i} T_{R,j} A + \text{h.c.}$$
$$- G_{hhT_iT_j} \bar{T}_i T_j h^2 - G_{HHT_iT_j} \bar{T}_i T_j H^2 - G_{AAT_iT_j} \bar{T}_i T_j A^2$$
$$- G_{hHT_iT_j} \bar{T}_i T_j hH + iG_{hAT_iT_j} \bar{T}_i \gamma_5 T_j hA + iG_{HAT_iT_j} \bar{T}_i \gamma_5 T_j HA + iG_{\phi^0 T_iT_j} \bar{T}_i \gamma_5 T_j \phi^0$$

A Composite 2HDM [De Curtis et al. 2018]

- Effective Lagrangian (h: 125 GeV Higgs, H: heavy Higgs, T_i: top partners, A: pseudoscalar, ϕ^0: neutral Goldstone boson, f: compositeness scale):

$$\begin{aligned}\mathcal{L}_{\text{yuk}} = &- G_{hT_iT_j}\bar{T}_{L,i}T_{R,j}h - G_{HT_iT_j}\bar{T}_{L,i}T_{R,j}H + iG_{AT_iT_j}\bar{T}_{L,i}T_{R,j}A + \text{h.c.}\\ &- G_{hhT_iT_j}\bar{T}_iT_jh^2 - G_{HHT_iT_j}\bar{T}_iT_jH^2 - G_{AAT_iT_j}\bar{T}_iT_jA^2\\ &- G_{hHT_iT_j}\bar{T}_iT_jhH + iG_{hAT_iT_j}\bar{T}_i\gamma_5T_jhA + iG_{HAT_iT_j}\bar{T}_i\gamma_5T_jHA + iG_{\phi^0T_iT_j}\bar{T}_i\gamma_5T_j\phi^0\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{\text{scalar}} = &-\frac{1}{3!}\lambda_{hhh}h^3 - \frac{1}{2}\lambda_{hhH}h^2H - \frac{1}{2}\lambda_{hHH}hH^2 - \frac{1}{3!}\lambda_{HHH}H^3 - \frac{1}{2}\lambda_{hAA}hA^2 - \frac{1}{2}\lambda_{HAA}HA^2\\ &- \lambda_{\phi^0hA}\phi^0hA - \lambda_{\phi^0HA}\phi^0HA\\ &+ \frac{v}{3f^2}\left(h_2\partial_\mu h_1 - h_1\partial_\mu h_2\right)\partial^\mu h_2 + \frac{v}{3f^2}\left(2A\partial_\mu\phi^0\partial^\mu h_2 - \phi^0\partial_\mu A\partial^\mu h_2 - h_2\partial_\mu A\partial^\mu\phi^0\right)\end{aligned}$$

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} c_\theta & -s_\theta \\ s_\theta & c_\theta \end{pmatrix}\begin{pmatrix} h \\ H \end{pmatrix}$$

A Composite 2HDM [De Curtis et al. 2018]

- Effective Lagrangian (h: 125 GeV Higgs, H: heavy Higgs, T_i: top partners, A: pseudoscalar, ϕ^0: neutral Goldstone boson, f: compositeness scale):

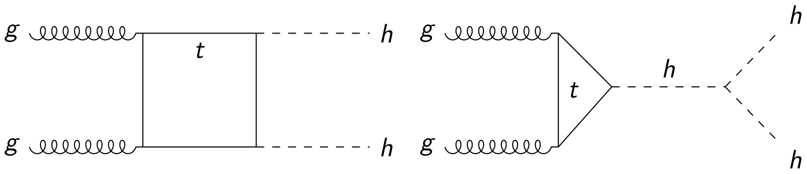
$$\begin{aligned}\mathcal{L}_{\text{yuk}} = &- G_{hT_iT_j}\bar{T}_{L,i}T_{R,j}h - G_{HT_iT_j}\bar{T}_{L,i}T_{R,j}H + iG_{AT_iT_j}\bar{T}_{L,i}T_{R,j}A + \text{h.c.}\\ &- G_{hhT_iT_j}\bar{T}_iT_jh^2 - G_{HHT_iT_j}\bar{T}_iT_jH^2 - G_{AAT_iT_j}\bar{T}_iT_jA^2\\ &- G_{hHT_iT_j}\bar{T}_iT_jhH + iG_{hAT_iT_j}\bar{T}_i\gamma_5T_jhA + iG_{HAT_iT_j}\bar{T}_i\gamma_5T_jHA + iG_{\phi^0T_iT_j}\bar{T}_i\gamma_5T_j\phi^0\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{\text{scalar}} = &-\frac{1}{3!}\lambda_{hhh}h^3 - \frac{1}{2}\lambda_{hhH}h^2H - \frac{1}{2}\lambda_{hHH}hH^2 - \frac{1}{3!}\lambda_{HHH}H^3 - \frac{1}{2}\lambda_{hAA}hA^2 - \frac{1}{2}\lambda_{HAA}HA^2\\ &- \lambda_{\phi^0hA}\phi^0hA - \lambda_{\phi^0HA}\phi^0HA\\ &+ \underbrace{\frac{v}{3f^2}\left(h_2\partial_\mu h_1 - h_1\partial_\mu h_2\right)\partial^\mu h_2}_{\lambda^{(2)}} + \frac{v}{3f^2}\left(2A\partial_\mu\phi^0\partial^\mu h_2 - \phi^0\partial_\mu A\partial^\mu h_2 - h_2\partial_\mu A\partial^\mu\phi^0\right)\end{aligned}$$

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} c_\theta & -s_\theta \\ s_\theta & c_\theta \end{pmatrix}\begin{pmatrix} h \\ H \end{pmatrix}$$

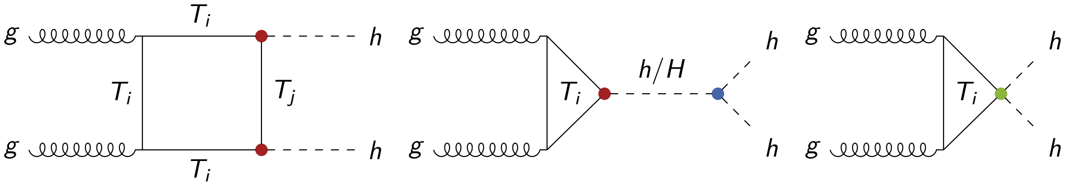
Higgs Pair Production [Plehn, Spira, Zerwas 1996; Gröber, Mühlleitner 2011; Gillioz et al. 2012]

- **SM**:



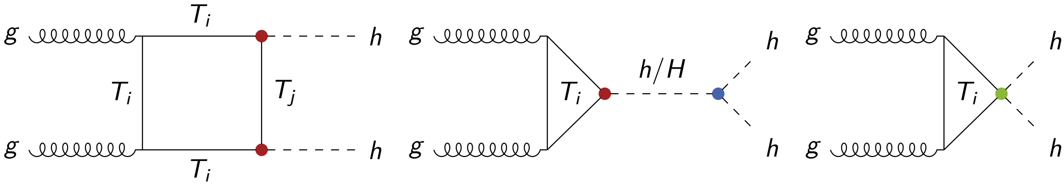
Higgs Pair Production [Plehn, Spira, Zerwas 1996; Gröber, Mühlleitner 2011; Gillioz et al. 2012]

- **Composite 2HDM: Contribution to di-Higgs cross section from resonant production, additional top partners in the loop as well as new effective couplings.**



Higgs Pair Production [Plehn, Spira, Zerwas 1996; Gröber, Mühlleitner 2011; Gillioz et al. 2012]

- **Composite 2HDM: Contribution to di-Higgs cross section from resonant production, additional top partners in the loop as well as new effective couplings.**



$$C^{hh}_{i,\triangle} = \frac{G_{h\bar{T}_iT_i}\lambda_{hhh}}{\hat{s}-m_h^2+im_h\Gamma_h} + \frac{G_{H\bar{T}_iT_i}\lambda_{Hhh}}{\hat{s}-m_H^2+im_H\Gamma_H} + \frac{G_{H\bar{T}_iT_i}\lambda^{(2)}_{Hhh}(2m_h^2-2\hat{s})}{\hat{s}-m_H^2+im_H\Gamma_H} + 2G_{hh\bar{T}_iT_i}$$

$$C^{hh}_{i,j,\Box} = g_{h\bar{T}_iT_j}g_{h\bar{T}_iT_j}, \qquad C^{hh}_{i,j,\Box,5} = -g_{h\bar{T}_iT_j,5}g_{h\bar{T}_iT_j,5}$$

$$g_{h\bar{T}_iT_j} = \frac{1}{2}\left(G_{h\bar{T}_iT_j} + G_{h\bar{T}_jT_i}\right), \qquad g_{h\bar{T}_iT_j,5} = \frac{1}{2}\left(G_{h\bar{T}_iT_j} - G_{h\bar{T}_jT_i}\right)$$

Cross section [Plehn, Spira, Zerwas 1996; Gröber, Mühlleitner 2011; Gillioz et al. 2012]

- Differential partonic cross section at LO:

$$\frac{\mathrm{d}\hat{\sigma}(gg \to hh)}{\mathrm{d}\hat{t}} = \frac{\alpha_s^2}{(2\pi)^3 512} \left[\left| \sum_{i=1}^{9} C_{i,\triangle}^{hh} F_{\triangle}^{hh}(m_i) + \sum_{i=1}^{9} \sum_{j=1}^{9} \left(C_{i,j,\square}^{hh} F_{\square}^{hh}(m_i, m_j) + C_{i,j,\square,5}^{hh} F_{\square,5}^{hh}(m_i, m_j) \right) \right|^2 \right.$$
$$\left. + \left| \sum_{i=1}^{9} \sum_{j=1}^{9} \left(C_{i,j,\square}^{hh} G_{\square}^{hh}(m_i, m_j) + C_{i,j,\square,5}^{hh} G_{\square,5}^{hh}(m_i, m_j) \right) \right|^2 \right]$$

Cross section [Plehn, Spira, Zerwas 1996; Gröber, Mühlleitner 2011; Gillioz et al. 2012]

- Differential partonic cross section at LO:

$$\frac{\mathrm{d}\hat{\sigma}(gg \to hh)}{\mathrm{d}\hat{t}} = \frac{\alpha_s^2}{(2\pi)^3 512} \left[\left| \sum_{i=1}^{9} C^{hh}_{i,\triangle} F^{hh}_{\triangle}(m_i) + \sum_{i=1}^{9} \sum_{j=1}^{9} \left(C^{hh}_{i,j,\Box} F^{hh}_{\Box}(m_i, m_j) + C^{hh}_{i,j,\Box,5} F^{hh}_{\Box,5}(m_i, m_j) \right) \right|^2 \right.$$
$$\left. + \left| \sum_{i=1}^{9} \sum_{j=1}^{9} \left(C^{hh}_{i,j,\Box} G^{hh}_{\Box}(m_i, m_j) + C^{hh}_{i,j,\Box,5} G^{hh}_{\Box,5}(m_i, m_j) \right) \right|^2 \right]$$

Implementation:

- Generation of set of parameter points obeying several theoretical and experimental constraints (details see appendix)
- Implementation into HPAIR [Dawson, Dittmaier, Spira 1998], including p_T distributions
- Calculation of decay widths with HDECAY [Djouadi, Kalinowski, Spira 1998; + Mühlleitner 2019]

More on LO Calculation [Plehn, Spira, Zerwas 1996; Gröber, Mühlleitner 2011; Gillioz et al. 2012]

- Mandelstam:

$$\hat{s} = (p_1 + p_2)^2, \quad \hat{t} = (p_1 + p_3)^2, \quad \hat{u} = (p_2 + p_3)^2$$

More on LO Calculation [Plehn, Spira, Zerwas 1996; Gröber, Mühlleitner 2011; Gillioz et al. 2012]

- Mandelstam:

$$\hat{s} = (p_1 + p_2)^2, \quad \hat{t} = (p_1 + p_3)^2, \quad \hat{u} = (p_2 + p_3)^2$$

- Projectors:

$$A_1^{\mu\nu} = g^{\mu\nu} - \frac{p_1^\nu p_2^\mu}{(p_1 \cdot p_2)},$$
$$A_2^{\mu\nu} = g^{\mu\nu} + \frac{p_3^2 p_1^\nu p_2^\mu}{p_T^2 (p_1 \cdot p_2)} - \frac{2(p_3 \cdot p_2) p_1^\nu p_3^\mu}{p_T^2 (p_1 \cdot p_2)} - \frac{2(p_3 \cdot p_1) p_3^\nu p_2^\mu}{p_T^2 (p_1 \cdot p_2)} + \frac{2 p_3^\mu p_3^\nu}{p_T^2},$$
$$p_T^2 = 2\frac{(p_1 \cdot p_3)(p_2 \cdot p_3)}{(p_1 \cdot p_2)} - p_3^2.$$

- It follows:

$$A_1 \cdot A_2 = 0, \quad A_1 \cdot A_1 = A_2 \cdot A_2 = 2$$

More on LO Calculation [Plehn, Spira, Zerwas 1996; Gröber, Mühlleitner 2011; Gillioz et al. 2012]

- Triangle amplitude:

$$\mathcal{A}_\triangle = \frac{\alpha_s G_F \sqrt{2}}{4\pi} A_1^{\mu\nu} \epsilon_\mu^a \epsilon_\nu^b \delta_{ab} \sum_{i=1}^{9} C_{i,\triangle}^{hh} F_\triangle(m_i)$$

More on LO Calculation [Plehn, Spira, Zerwas 1996; Gröber, Mühlleitner 2011; Gillioz et al. 2012]

- Triangle amplitude:

$$\mathcal{A}_\triangle = \frac{\alpha_s G_F \sqrt{2}}{4\pi} A_1^{\mu\nu} \epsilon_\mu^a \epsilon_\nu^b \delta_{ab} \sum_{i=1}^{9} C_{i,\triangle}^{hh} F_\triangle(m_i)$$

- Box amplitude:

$$\mathcal{A}_\square = \frac{\alpha_s G_F \sqrt{2}}{4\pi} \epsilon_\mu^a \epsilon_\nu^b \delta_{ab} \sum_{i=1}^{9} \sum_{j=1}^{9} \Big[A_1^{\mu\nu} \left(C_{i,j,\square}^{hh} F_\square(m_i, m_j) + C_{i,j,\square,5}^{hh} F_{\square,5}(m_i, m_j) \right) + A_2^{\mu\nu} \left(C_{i,j,\square}^{hh} G_\square(m_i, m_j) + C_{i,j,\square,5}^{hh} G_{\square,5}(m_i, m_j) \right) \Big]$$

- Total:

$$\mathcal{A}(gg \to hh) = \mathcal{A}_\triangle + \mathcal{A}_\square$$

Cross section [Plehn, Spira, Zerwas 1996; Gröber, Mühlleitner 2011; Gillioz et al. 2012]

- Full partonic cross section:

$$\hat{\sigma}(gg \to hh) = \int_{\hat{t_-}}^{\hat{t_+}} \frac{\mathrm{d}\hat{\sigma}(gg \to hh)}{\mathrm{d}\hat{t}}, \quad \hat{t}_\pm = \frac{-\hat{s}}{2}\left(1 - 2\frac{m_h^2}{\hat{s}} \mp \sqrt{1 - \frac{4m_h^2}{\hat{s}}}\right)$$

- Hadronic cross section:

$$\sigma(pp \to gg \to hh) = \int_{\tau_0}^{1} \mathrm{d}\tau \frac{\mathrm{d}\mathcal{L}^{gg}}{\mathrm{d}\tau} \hat{\sigma}(\hat{s} = \tau s) \quad (\tau_0 = \frac{4m_h^2}{s})$$

- Cross section at NLO [Dawson, Dittmaier, Spira 1998; Gröber, Mühlleitner, Spira 2016]:

$$\sigma_{\mathrm{NLO}}(pp \to hh + X) = \sigma_{\mathsf{LO}} + \Delta\sigma_{\mathsf{virt}} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{q\bar{q}}$$
$$\Rightarrow K \equiv \frac{\sigma_{\mathrm{NLO}}}{\sigma_{\mathrm{LO}}} \approx 2$$

NLO Contribution [Dawson, Dittmaier, Spira 1998; Gröber, Mühlleitner, Spira 2016]

- Look at additional contributions:

$$\sigma_{\mathrm{NLO}}(pp \to hh + X) = \sigma_{\mathsf{LO}} + \Delta\sigma_{\mathsf{virt}} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{q\bar{q}}$$

NLO Contribution [Dawson, Dittmaier, Spira 1998; Gröber, Mühlleitner, Spira 2016]

- Look at additional contributions:

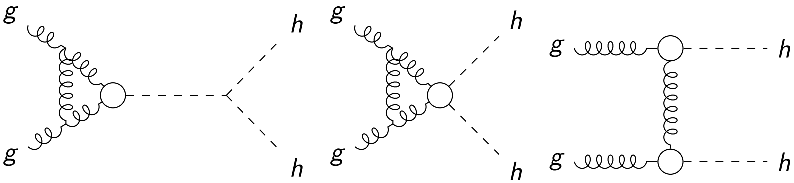
$$\sigma_{\mathrm{NLO}}(pp \to hh + X) = \sigma_{\mathrm{LO}} + \Delta\sigma_{\mathrm{virt}} + \underbrace{\Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{q\bar{q}}}_{\sigma_{\mathrm{LO}}\text{ factorizes out}}$$

NLO Contribution [Dawson, Dittmaier, Spira 1998; Gröber, Mühlleitner, Spira 2016]

- Look at additional contributions:

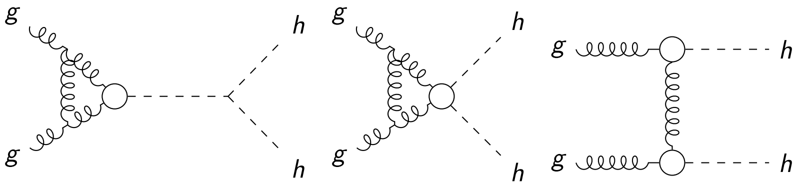
$$\sigma_{\mathrm{NLO}}(pp \to hh + X) = \sigma_{\mathrm{LO}} + \Delta\sigma_{\mathrm{virt}} + \underbrace{\Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{q\bar{q}}}_{\sigma_{\mathrm{LO}} \text{ factorizes out}}$$

- $\Delta\sigma_{\mathrm{virt}}$:



NLO Contribution [Dawson, Dittmaier, Spira 1998; Gröber, Mühlleitner, Spira 2016]

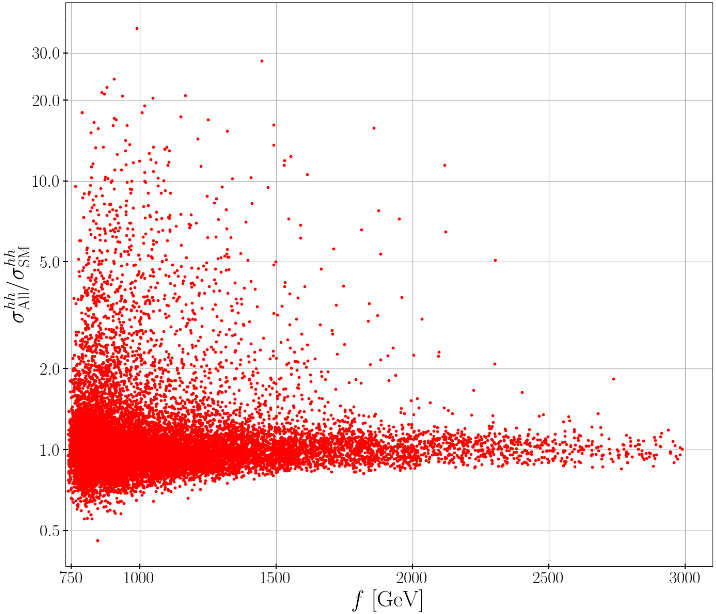
- $\Delta\sigma_{\text{virt}}$:



$$\Delta\sigma_{\text{virt}} = \frac{\alpha_s(\mu_R)}{\pi}\int_{\tau_0}^{1}\frac{\mathrm{d}\tau\,\mathcal{L}^{gg}}{\mathrm{d}\tau}\hat{\sigma}_{\text{LO}}(Q^2=\tau s)C,$$

$$C = \pi^2 + \frac{11}{2} + \frac{33-2N_F}{6}\log\frac{\mu_R^2}{Q^2} + \text{Re}\frac{\int_{\hat{t}_-}^{\hat{t}_+}\mathrm{d}\hat{t}\,\frac{4}{9}(g_{hgg}^{\text{eff}})^2\left[F_1 - \frac{p_T^2}{2\hat{t}\hat{u}}(Q^2-2m_h^2)F_2\right]}{\int_{\hat{t}_-}^{\hat{t}_+}\mathrm{d}\hat{t}\,\left[|F_1|^2+|F_2|^2\right]},$$

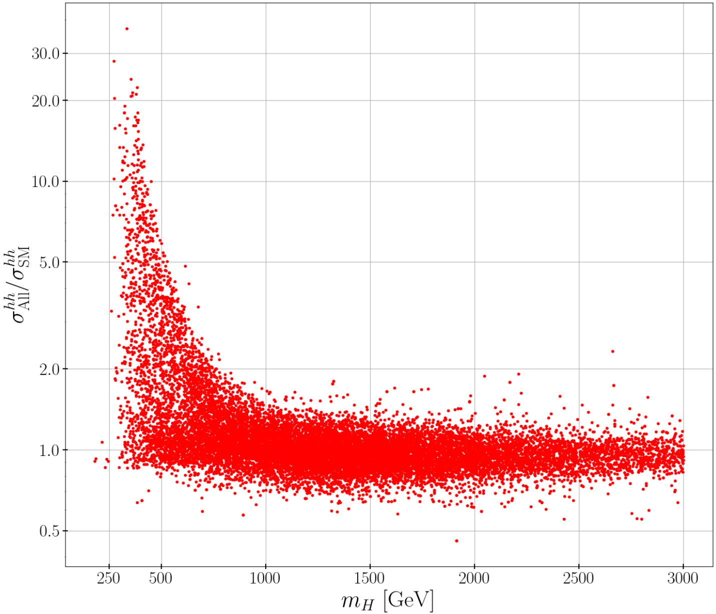
$$p_T^2 = \frac{(\hat{t}-m_h^2)(\hat{u}-m_h^2)}{Q^2} - m_h^2, \quad g_{hgg}^{\text{eff}} = \sum_{i=1}^{9}\frac{g_{h\bar{T}_i T_i}v}{m_{T_i}}$$



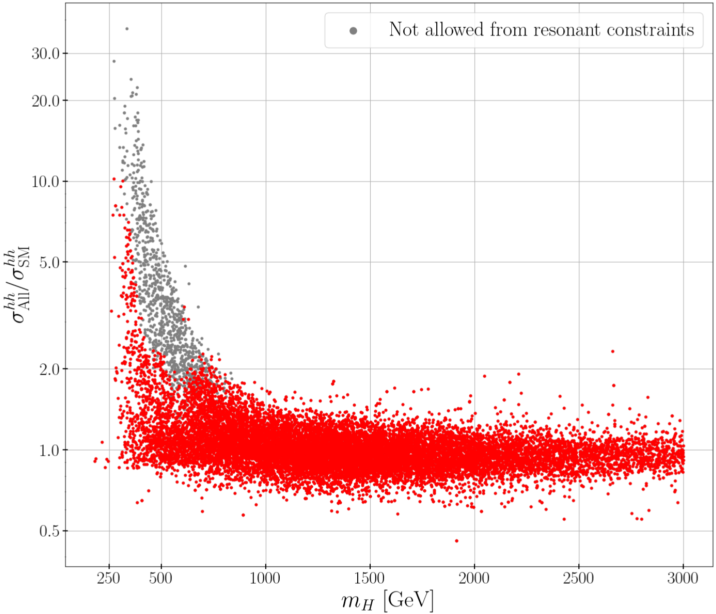
Overall Results

Parameter	Range	
	Lower	Upper
m_H	180 GeV	3 TeV
$m_{T,8}$	1300 GeV	23 TeV
$m_{T,1}$	2700 TeV	80 TeV
$\lambda_{hhh}/\lambda_{\rm SM}$	0.7	1.07
$g_{htt}/g_{htt,\rm SM}$	0.73	1.33
$\sigma/\sigma_{\rm SM}$	0.46	37

Overall Results



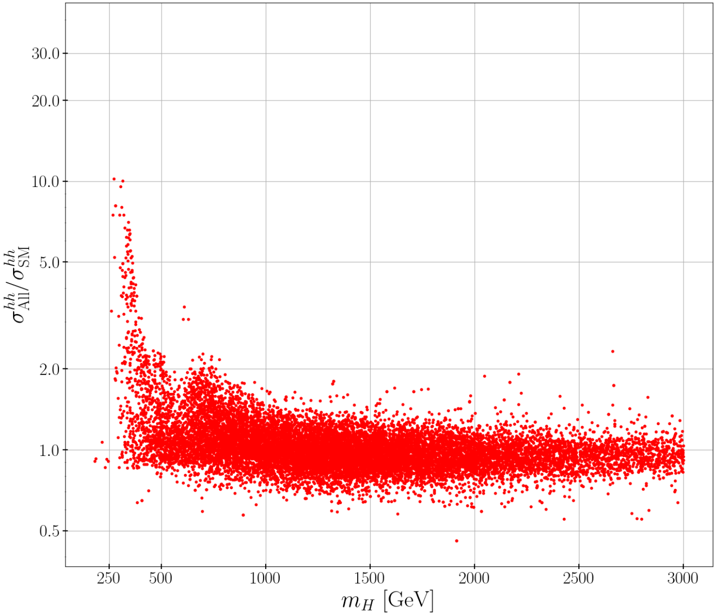
Parameter	Range	
	Lower	Upper
m_H	180 GeV	3 TeV
$m_{T,8}$	1300 GeV	23 TeV
$m_{T,1}$	2700 TeV	80 TeV
$\lambda_{hhh}/\lambda_{\text{SM}}$	0.7	1.07
$g_{htt}/g_{htt,\text{SM}}$	0.73	1.33
$\sigma/\sigma_{\text{SM}}$	0.46	37



Overall Results

Parameter	Range	
	Lower	Upper
m_H	180 GeV	3 TeV
$m_{T,8}$	1300 GeV	23 TeV
$m_{T,1}$	2700 TeV	80 TeV
$\lambda_{hhh}/\lambda_{\mathrm{SM}}$	0.7	1.07
$g_{htt}/g_{htt,\mathrm{SM}}$	0.73	1.33
$\sigma/\sigma_{\mathrm{SM}}$	0.46	37

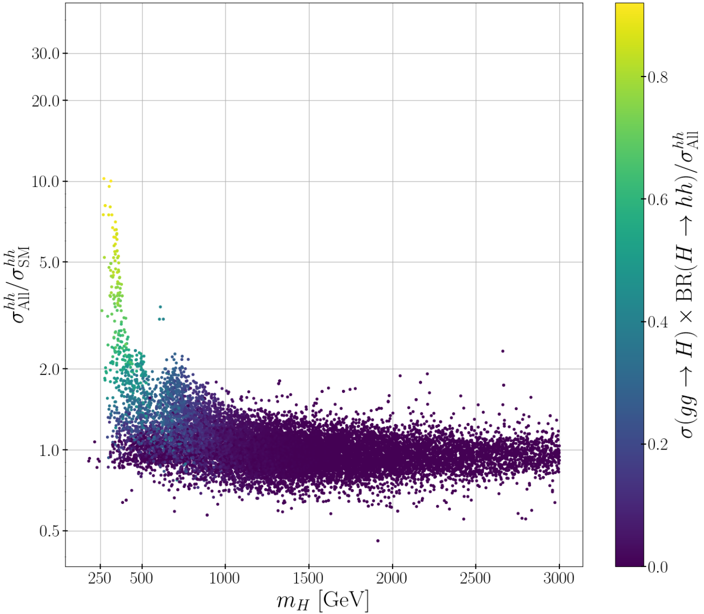
- Applying resonant constraints: $\sigma_{\mathrm{MAX}} \approx 10 \times \sigma_{\mathrm{SM}}$ (similiar to 2HDM [Abouabid et al. 2021])



Overall Results

Parameter	Range	
	Lower	Upper
m_H	180 GeV	3 TeV
$m_{T,8}$	1300 GeV	23 TeV
$m_{T,1}$	2700 TeV	80 TeV
$\lambda_{hhh}/\lambda_{\text{SM}}$	0.7	1.07
$g_{htt}/g_{htt,\text{SM}}$	0.73	1.33
$\sigma/\sigma_{\text{SM}}$	0.46	37

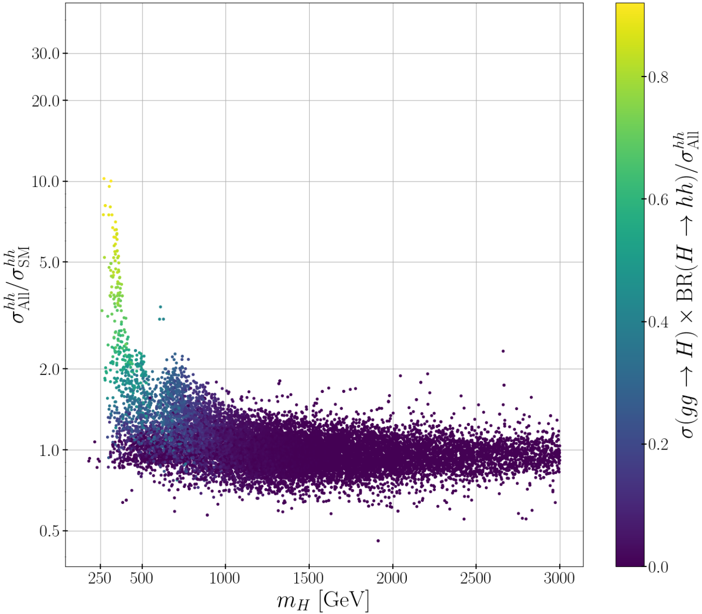
- Applying resonant constraints: $\sigma_{\text{MAX}} \approx 10 \times \sigma_{\text{SM}}$ (similiar to 2HDM [Abouabid et al. 2021])



Overall Results

Parameter	Range	
	Lower	Upper
m_H	180 GeV	3 TeV
$m_{T,8}$	1300 GeV	23 TeV
$m_{T,1}$	2700 TeV	80 TeV
$\lambda_{hhh}/\lambda_{\text{SM}}$	0.7	1.07
$g_{htt}/g_{htt,\text{SM}}$	0.73	1.33
$\sigma/\sigma_{\text{SM}}$	0.46	37

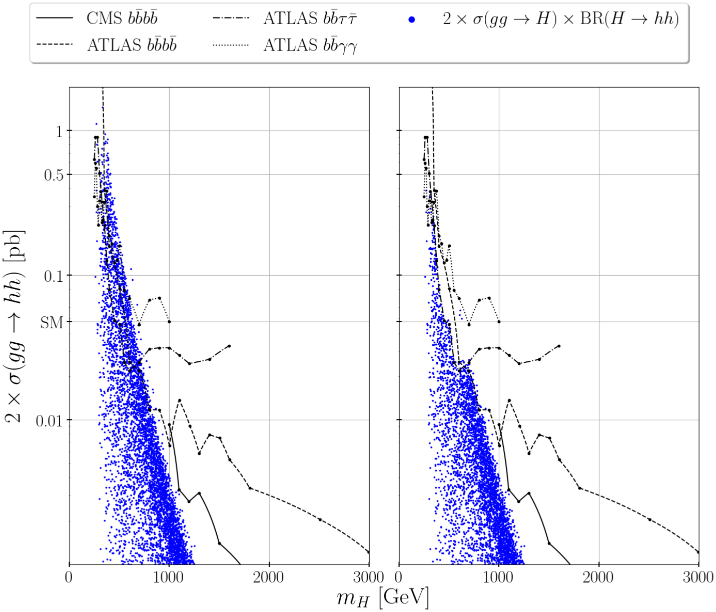
- Applying resonant constraints: $\sigma_{\text{MAX}} \approx 10 \times \sigma_{\text{SM}}$ (similiar to 2HDM [Abouabid et al. 2021])



Overall Results

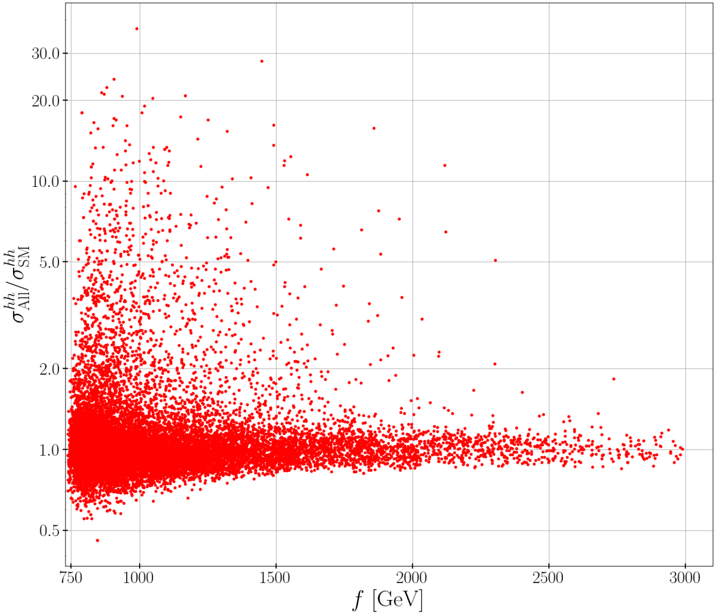
Parameter	Range	
	Lower	Upper
m_H	180 GeV	3 TeV
$m_{T,8}$	1300 GeV	23 TeV
$m_{T,1}$	2700 TeV	80 TeV
$\lambda_{hhh}/\lambda_{\text{SM}}$	0.7	1.07
$g_{htt}/g_{htt,\text{SM}}$	0.73	1.33
$\sigma/\sigma_{\text{SM}}$	0.46	37

- Applying resonant constraints: $\sigma_{\text{MAX}} \approx 10 \times \sigma_{\text{SM}}$ (similiar to 2HDM [Abouabid et al. 2021])
- 3 regions:
  - Resonant case: resonant production
  - Non-resonant case: heavy Quarks and quartic coupling
  - Intermediate region: Interference between all contributions



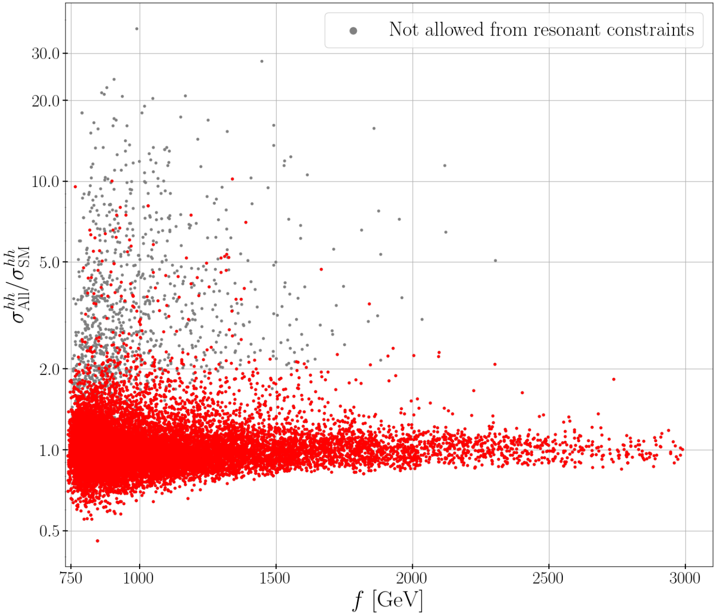
Resonant case

- HIGLU*BR [Spira 1995]: $\sigma(gg \to H) * \mathrm{BR}(H \to hh)$
- Factor 2: approximate NLO corrections
- HPAIR: All diagrams included
- Experimental data from: [CMS-PAS-B2G-20-004,ATLAS-CONF-2021-016,ATLAS-CONF-2021-030,ATLAS-CONF-2021-035]
- Similar approach as [Abouabid et al. 2021]



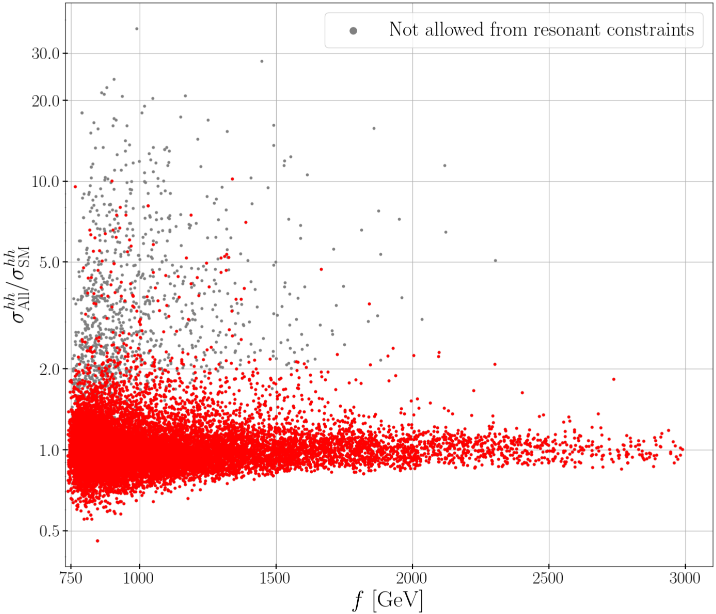
Resonant case

- HIGLU*BR [Spira 1995]: $\sigma(gg \to H) * \mathrm{BR}(H \to hh)$
- Factor 2: approximate NLO corrections
- HPAIR: All diagrams included
- Experimental data from: [CMS-PAS-B2G-20-004,ATLAS-CONF-2021-016,ATLAS-CONF-2021-030,ATLAS-CONF-2021-035]]
- Similar approach as [Abouabid et al. 2021]]



Resonant case

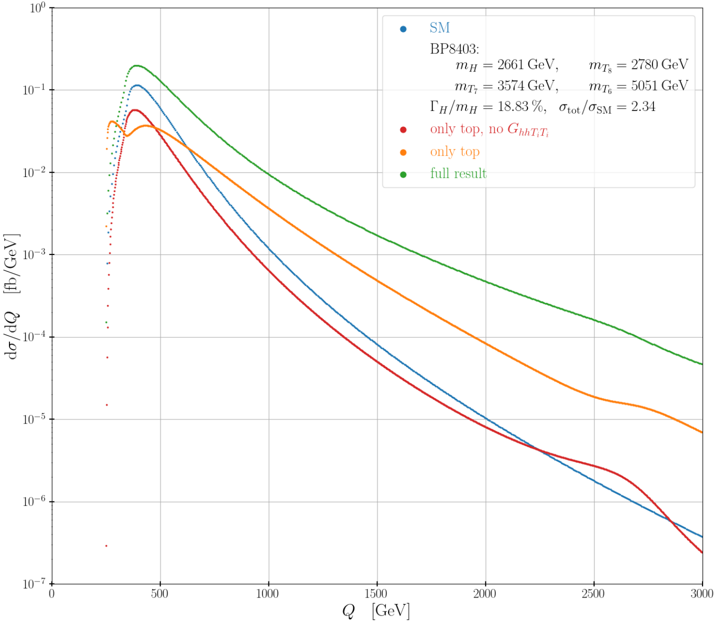
- HIGLU*BR [Spira 1995]: $\sigma(gg \to H) * \text{BR}(H \to hh)$
- Factor 2: approximate NLO corrections
- HPAIR: All diagrams included
- Experimental data from: [CMS-PAS-B2G-20-004,ATLAS-CONF-2021-016,ATLAS-CONF-2021-030,ATLAS-CONF-2021-035]]
- Similar approach as [Abouabid et al. 2021]]



Resonant case

- HIGLU*BR [Spira 1995]: $\sigma(gg \to H) * \mathrm{BR}(H \to hh)$
- Factor 2: approximate NLO corrections
- HPAIR: All diagrams included
- Experimental data from: [CMS-PAS-B2G-20-004,ATLAS-CONF-2021-016,ATLAS-CONF-2021-030,ATLAS-CONF-2021-035]]
- Similar approach as [Abouabid et al. 2021]]

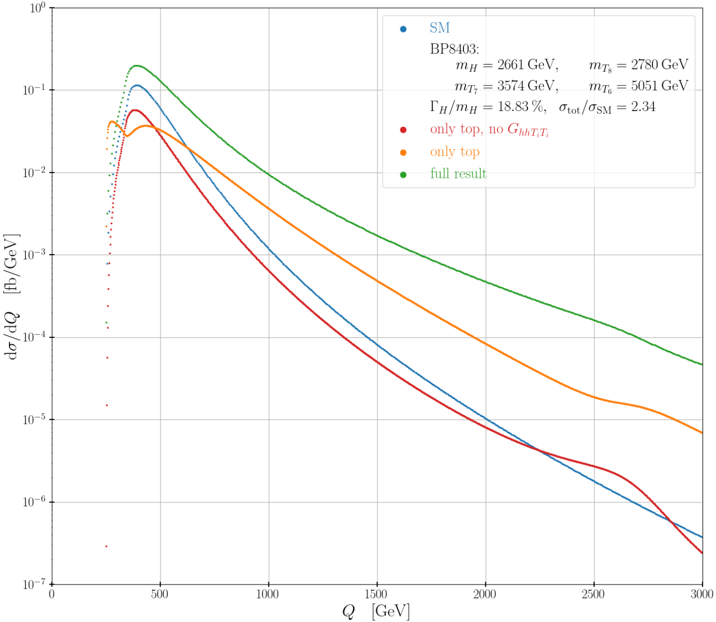
- New maximum: $\sigma_{\mathrm{MAX}} \approx 10 \times \sigma_{\mathrm{SM}}$ (2HDM: enhancement up to $12 \times \sigma_{\mathrm{SM}}$ [Abouabid et al. 2021]])



Invariant-mass distribution

- BP8403:

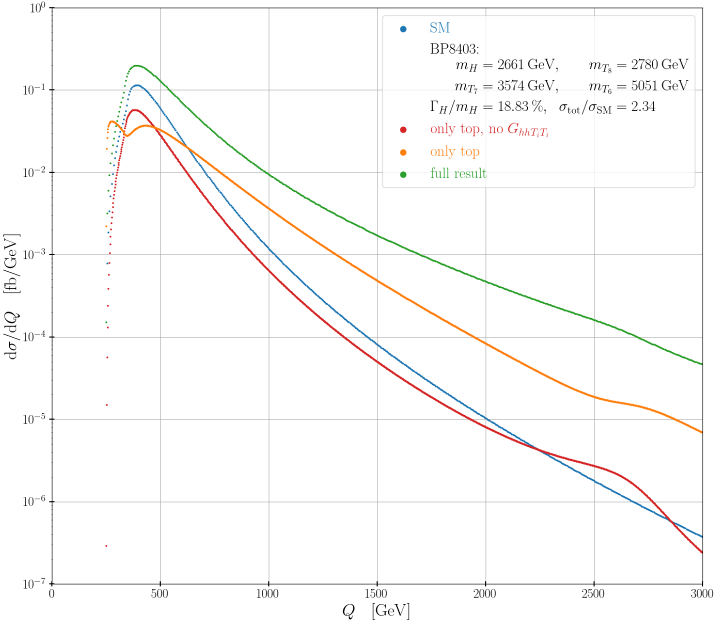
f	822 GeV
$\lambda_{hhh}/\lambda_{SM}$	0.96
$\lambda_{Hhh}/\lambda_{SM}$	-2.73
$g_{htt}/g_{htt,SM}$	0.81
$g_{Htt}/g_{htt,SM}$	-2.2



Invariant-mass distribution

- BP8403:

f	822 GeV
$\lambda_{hhh}/\lambda_{SM}$	0.96
$\lambda_{Hhh}/\lambda_{SM}$	-2.73
$g_{htt}/g_{htt,SM}$	0.81
$g_{Htt}/g_{htt,SM}$	-2.2

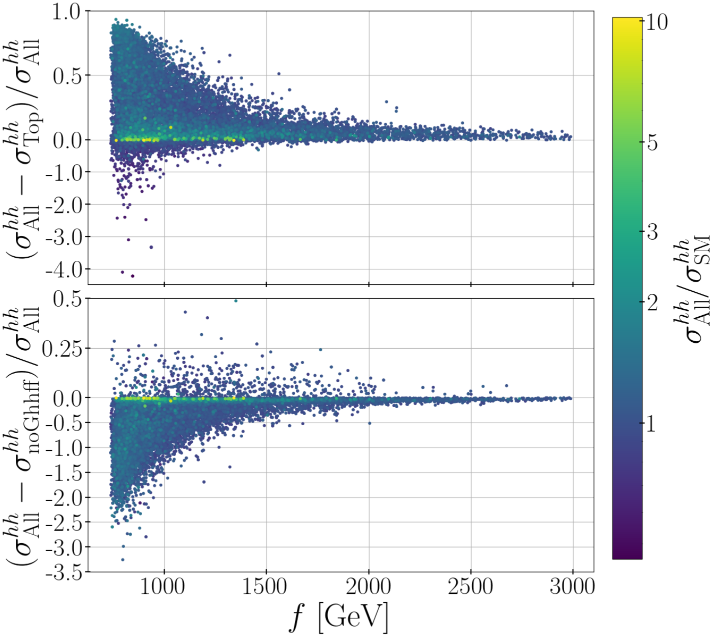


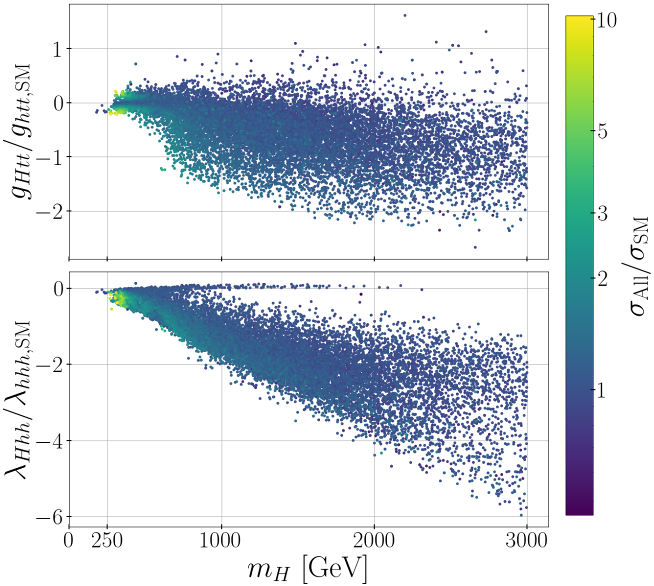
Invariant-mass distribution

- BP8403:

f	822 GeV
$\lambda_{hhh}/\lambda_{\text{SM}}$	0.96
$\lambda_{Hhh}/\lambda_{\text{SM}}$	-2.73
$g_{htt}/g_{htt,\text{SM}}$	0.81
$g_{Htt}/g_{htt,\text{SM}}$	-2.2

- $G_{hhT_iT_i}$ coupling dominant for large Q values


$(\sigma^{hh}_{\mathrm{All}} - \sigma^{hh}_{\mathrm{Top}})/\sigma^{hh}_{\mathrm{All}}$
$(\sigma^{hh}_{\mathrm{All}} - \sigma^{hh}_{\mathrm{noGhhff}})/\sigma^{hh}_{\mathrm{All}}$
f [GeV]
$\sigma^{hh}_{\mathrm{All}}/\sigma^{hh}_{\mathrm{SM}}$
1.0
0.5
0.0
-1.0
-2.0
-3.0
-4.0
0.25
-0.5
-1.5
-2.5
-3.5
1000
1500
2000
2500
3000
10
5
3
2
1



$g_{Htt}/g_{htt,\mathrm{SM}}$
1
0
−1
−2
$\lambda_{Hhh}/\lambda_{hhh,\mathrm{SM}}$
0
−2
−4
−6
0
250
1000
2000
3000
m_H [GeV]
10
5
3
2
1
$\sigma_{\mathrm{All}}/\sigma_{\mathrm{SM}}$