Higgs Pair Production in a Composite 2HDM

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Introduction

Composite Higgs Models

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

Illustration by Sandbox Studio, Chicago

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Higgs Pair Production

- Measurement of the trilinear Higgs coupling $\lambda \Rightarrow$ 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 2-Higgs-Doublet Model (2HDM) [De Curtis et al. 2018]

Main Features

- **Additional strong sector** with $SO(6)$ symmetry: spontaneous breaking $SO(6) \to SO(4) \times SO(2)$
  $\Rightarrow$ Generation of 2HDM-like structure
- **Partial compositeness** of SM fields: Explicit breaking of the symmetry
- **8 additional top partners** T_i ($i = 1, ..., 9$, $T_9 =$top quark)
- Obtain effective Lagrangian by integrating out heavy resonances

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Remarks

- Yukawa sector: resembles flavor-aligned 2HDM
- Higgs potential generated at loop level
- Need to reconstruct SM parameters (VEV, Higgs mass, top mass, ...)

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

Effective Lagrangian

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

Notation

- h: 125 GeV Higgs, H: heavy Higgs, A: pseudoscalar, ϕ^0: neutral Goldstone boson
- T_i: top partners
- f: composite scale

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

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

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

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$$+ \underbrace{\frac{v}{3f^2}\left(h_2\partial_\mu h_1 - h_1\partial_\mu h_2\right)\partial^\mu h_2}_{\lambda^{(2)}} + \frac{v}{3f^2}\left(2A\partial_\mu\phi^0\partial^\mu h_2 - \phi^0\partial_\mu A\partial^\mu h_2 - h_2\partial_\mu A\partial^\mu\phi^0\right)$$

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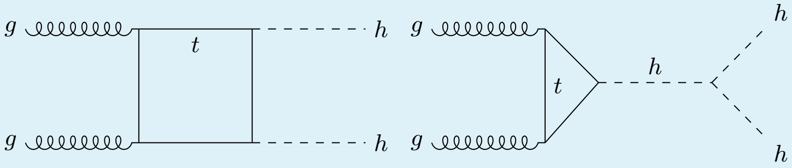
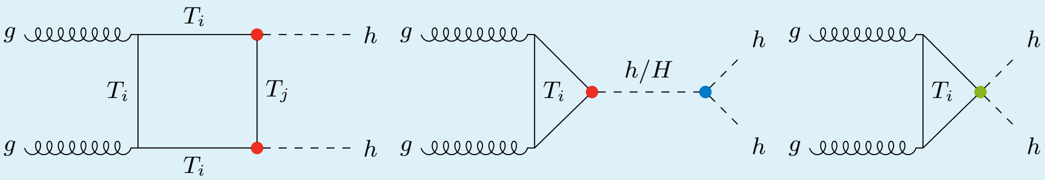
Higgs Pair Production [Plehn, M. Spira, and Zerwas 1996; R. Grober and M. Muhlleitner 2011; Gillioz et al. 2012]

- **SM**:



Higgs Pair Production [Plehn, M. Spira, and Zerwas 1996; R. Grober and M. Muhlleitner 2011; Gillioz et al. 2012]

> **Contribution to di-Higgs cross section from resonant production, additional top partners in the loops as well as new effective couplings**



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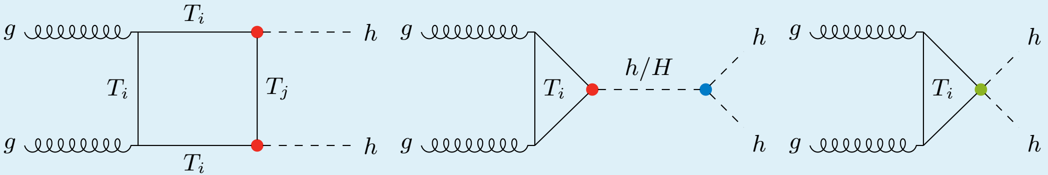

$$C^{hh}_{i,\triangle} = \frac{G_{h\bar{T}_iT_i}\lambda_{hhh}}{\hat{s}-m_h^2+im_h\Gamma_h} + \frac{G_{H\bar{T}_iT_i}\lambda_{Hhh}}{\hat{s}-m_H^2+im_H\Gamma_H} + \frac{G_{H\bar{T}_iT_i}\lambda^{(2)}_{Hhh}(2m_h^2-2\hat{s})}{\hat{s}-m_H^2+im_H\Gamma_H} + 2G_{hh\bar{T}_iT_i}$$

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

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

Calculation and Setup

Differential Partonic Cross Section [Plehn, M. Spira, and Zerwas 1996; R. Grober and M. Muhlleitner 2011; Gillioz et al. 2012]

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

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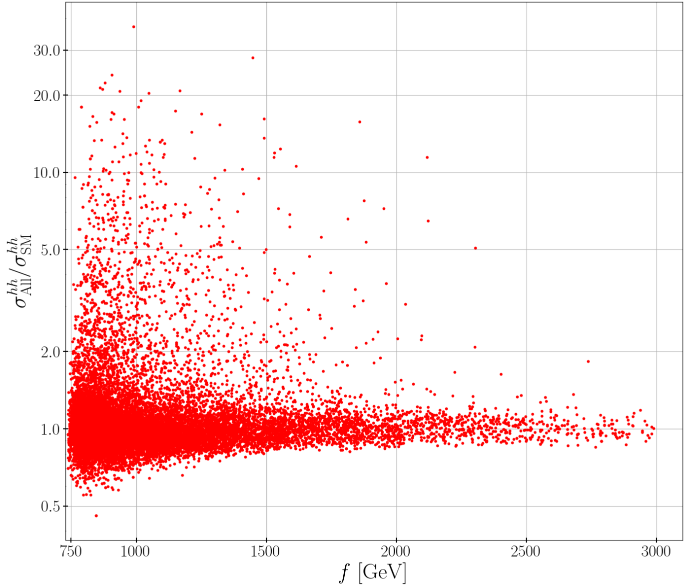
Generation of Parameter Points

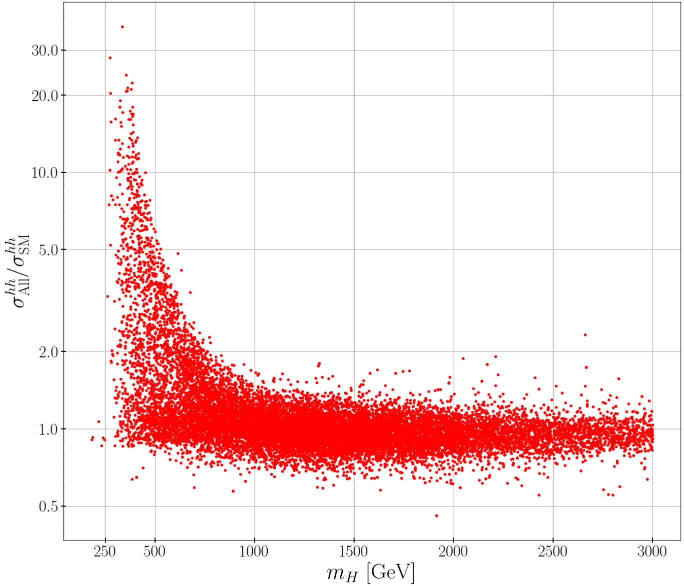
- Scan in composite parameters
- Reconstruction of VEV, Higgs mass and top mass
- Perturbativity constraints
- Higgs searches and measurements implemented via `HiggsBounds`/ `HiggsSignals` [P. Bechtle, S. Heinemeyer, et al. 2010, 2011, 2014, 2015, 2020, 2021]
- Flavour constraints from $b \to s\gamma$ and $B_s \to \mu\mu$
- Mass of the heavy tops larger than 1.3 TeV [ATLAS 2023]



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

Remarks



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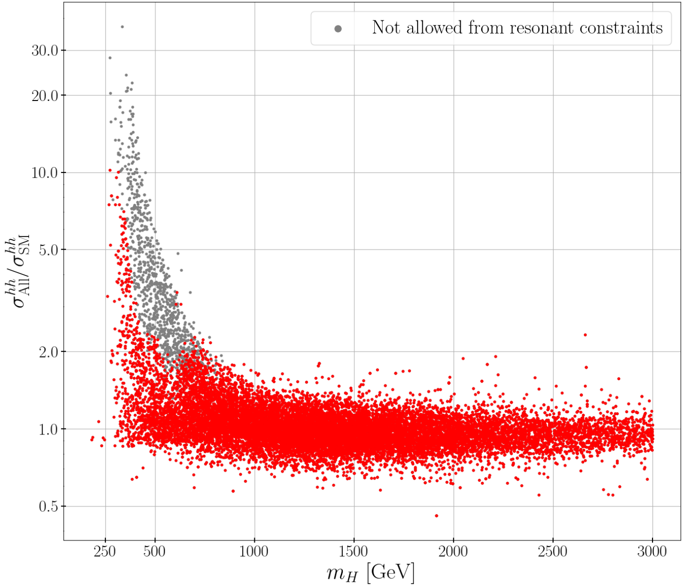

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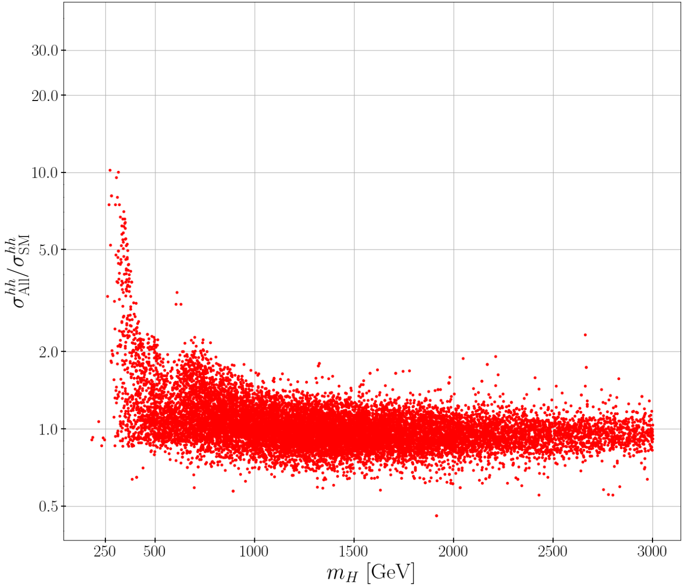

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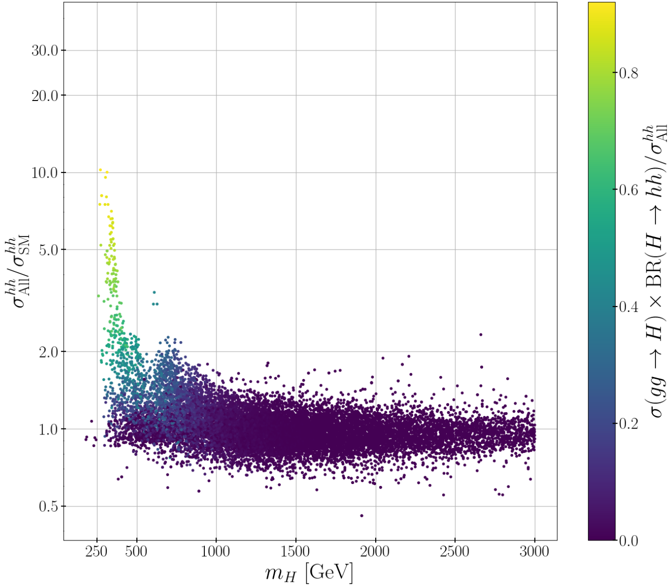

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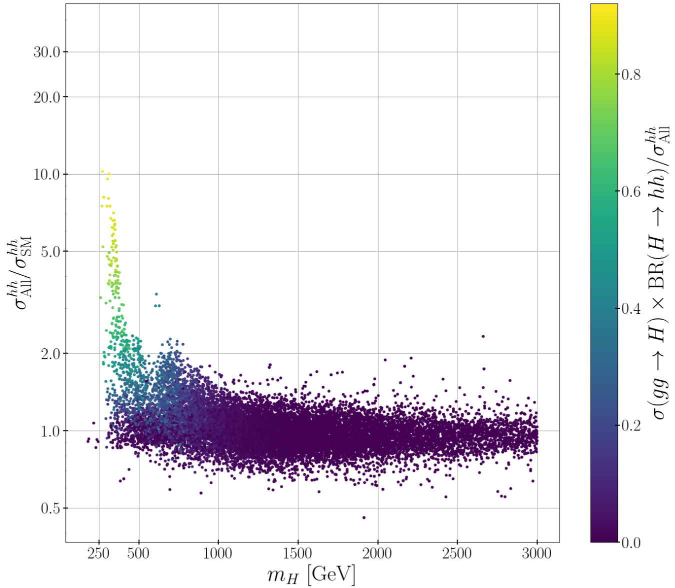

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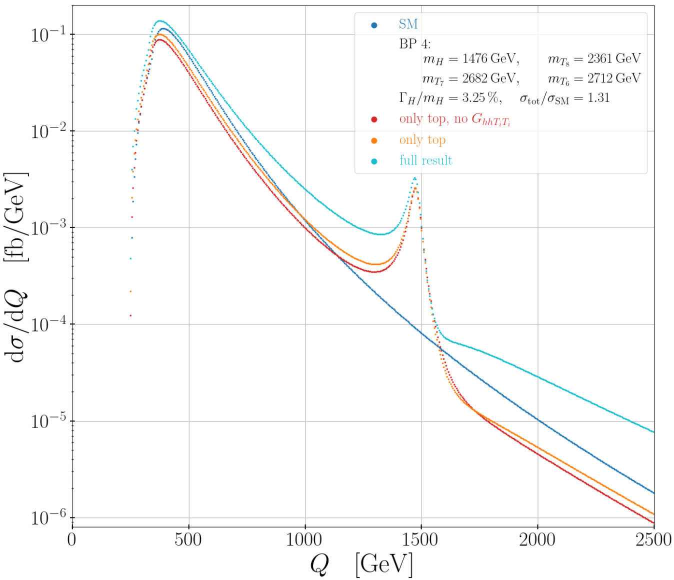
Remarks

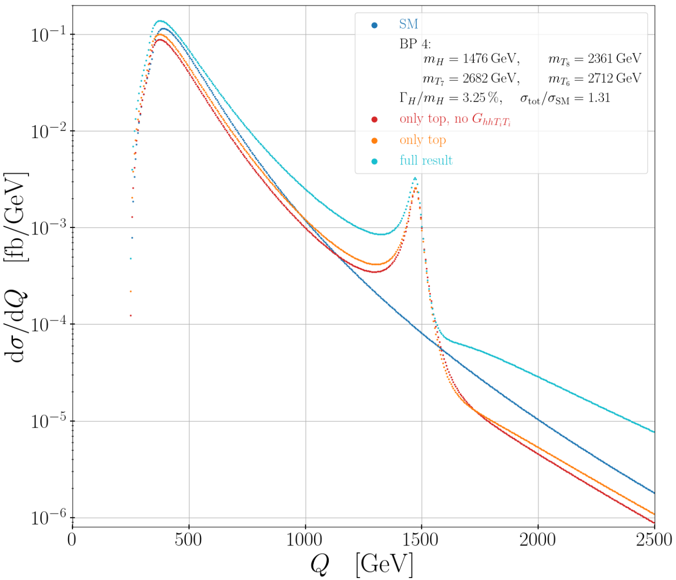
- Applying resonant constraints: $\sigma_{\mathrm{MAX}} \approx 10 \times \sigma_{\mathrm{SM}}$ (similiar to 2HDM [Abouabid et al. 2022])
- Resonant case: resonant production
- Non-resonant case: Impact of heavy top partners and effective couplings
- Interference between all contributions



Differential Distributions

> BP4 parameters:

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



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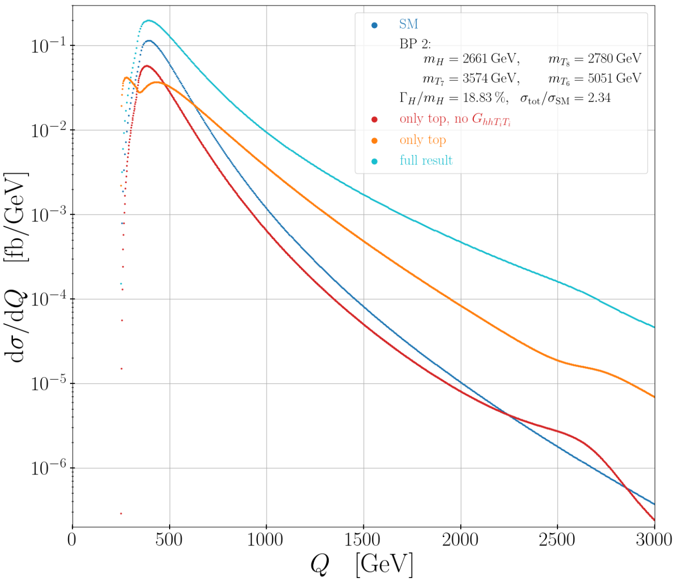
Remarks

- Resonance visible at $m_H = 1476$ GeV
- Red line: 2HDM without composite sector
- Interference effects between **resonance**, **heavy quark contribution** and **effective quartic coupling**

Differential Distributions

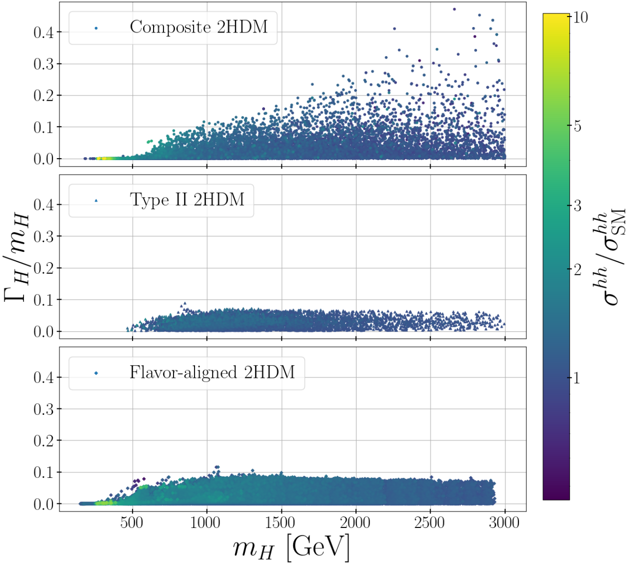
- BP2 parameters:

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_{hhtt}	1.2×10^{-3} 1/GeV



Remarks

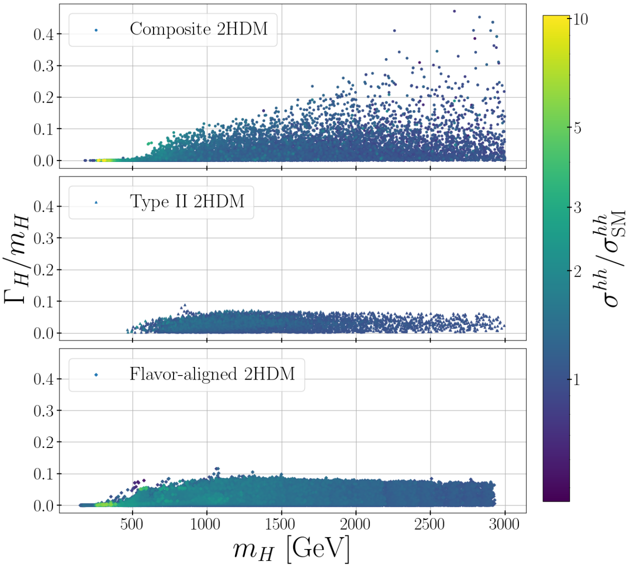
- $G_{hhT_iT_i}$ coupling dominant for large Q values



Comparison to other 2HDM Realizations

2HDM Realizations

> Type II-2HDM, Flavor-aligned 2HDM: SM + additional Higgs doublet, distinct Yukawa structures



Comparison to other 2HDM Realizations

2HDM Realizations

- Type II-2HDM, Flavor-aligned 2HDM: SM + additional Higgs doublet, distinct Yukawa structures

Remarks

- Large total width Γ_H in composite 2HDM due to:
  - Higgs decay to heavy top partners possible in Composite 2HDM for heavy m_H
  - Larger Yukawa couplings in composite 2HDM

Conclusion

Summary

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

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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. ISSN: 1029-8479. DOI: 10.1007/jhep12(2018)051.
- Plehn, T., M. Spira, and P. M. Zerwas (1996). "Pair production of neutral Higgs particles in gluon-gluon collisions". In: Nucl. Phys. B 479. [Erratum: Nucl.Phys.B 531, 655–655 (1998)], pp. 46–64. DOI: 10.1016/0550-3213(96)00418-X. arXiv: hep-ph/9603205.
- Grober, R. and M. Muhlleitner (2011). "Composite Higgs Boson Pair Production at the LHC". In: JHEP 06, p. 020. DOI: 10.1007/JHEP06(2011)020. arXiv: 1012.1562 [hep-ph].
- Gillioz, M. et al. (2012). "Higgs Low-Energy Theorem (and its corrections) in Composite Models". In: JHEP 10, p. 004. DOI: 10.1007/JHEP10(2012)004. arXiv: 1206.7120 [hep-ph].
- Bechtle, P. et al. (2010). "HiggsBounds: Confronting arbitrary Higgs sectors with exclusion bounds from LEP and the Tevatron". In: Computer Physics Communications 181.1, pp. 138–167. ISSN: 0010-4655. DOI: 10.1016/j.cpc.2009.09.003.
- — (Dec. 2011). "HiggsBounds 2.0.0: Confronting neutral and charged Higgs sector predictions with exclusion bounds from LEP and the Tevatron". In: Computer Physics Communications 182.12, pp. 2605–2631. ISSN: 0010-4655. DOI: 10.1016/j.cpc.2011.07.015.

Literature II

- Bechtle, Philip, Oliver Brein, et al. (Mar. 2014). “HiggsBounds-4: improved tests of extended Higgs sectors against exclusion bounds from LEP, the Tevatron and the LHC”. In: The European Physical Journal C 74.3. ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-013-2693-2.
- Bechtle, Philip, Sven Heinemeyer, Oscar Stål, et al. (Sept. 2015). “Applying exclusion likelihoods from LHC searches to extended Higgs sectors”. In: The European Physical Journal C 75.9. ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-015-3650-z.
- 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. ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-020-08557-9.
- Aad, G. et al. (Aug. 2023). “Search for pair-produced vector-like top and bottom partners in events with large missing transverse momentum in pp collisions with the ATLAS detector”. In: The European Physical Journal C 83.8. ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-023-11790-7.
- Abouabid, Hamza et al. (Sept. 2022). “Benchmarking di-Higgs production in various extended Higgs sector models”. In: Journal of High Energy Physics 2022.9. ISSN: 1029-8479. DOI: 10.1007/jhep09(2022)011.

Literature III

- Bechtle, Philip, Sven Heinemeyer, Tobias Klingl, 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. ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-021-08942-y.
- Spira, M. (n.d.). HPAIR. http://tiger.web.psi.ch/proglist.html.
- Djouadi, A., J. Kalinowski, and M. Spira (1998). “HDECAY: A Program for Higgs boson decays in the standard model and its supersymmetric extension”. In: Comput. Phys. Commun. 108, pp. 56–74. DOI: 10.1016/S0010-4655(97)00123-9. arXiv: hep-ph/9704448.
- Djouadi, Abdelhak et al. (2019). “HDECAY: Twenty$_{++}$ years after”. In: Comput. Phys. Commun. 238, pp. 214–231. DOI: 10.1016/j.cpc.2018.12.010. arXiv: 1801.09506 [hep-ph].
- Dawson, S., S. Dittmaier, and M. Spira (Nov. 1998). “Neutral Higgs-boson pair production at hadron colliders: QCD corrections”. In: Physical Review D 58.11. ISSN: 1089-4918. DOI: 10.1103/physrevd.58.115012.
- Grober, Ramona, Margarete Muhlleitner, and Michael Spira (2016). “Signs of Composite Higgs Pair Production at Next-to-Leading Order”. In: JHEP 06, p. 080. DOI: 10.1007/JHEP06(2016)080. arXiv: 1602.05851 [hep-ph].

Literature IV

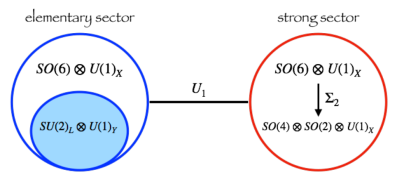
Spira, M. (1995). HIGLU: A Program for the Calculation of the Total Higgs Production Cross Section at Hadron Colliders via Gluon Fusion including QCD Corrections. arXiv: hep-ph/9510347 [hep-ph].

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

Degrees of Freedom

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

Composite Symmetry 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]

Composite Gauge Lagrangian

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

> $G_1, G_2 = SO(6) \times U(1)_X$

> G_2: local, describes spin-1 resonances through ρ^X and ρ^A ($A \in \text{Adj}(SO(6))$),

> 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

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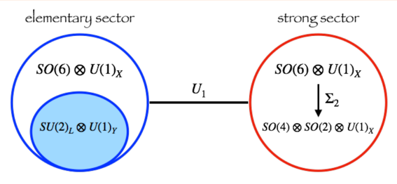

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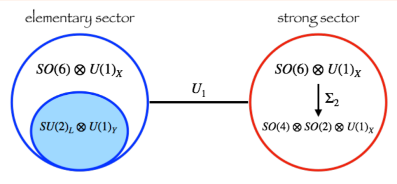

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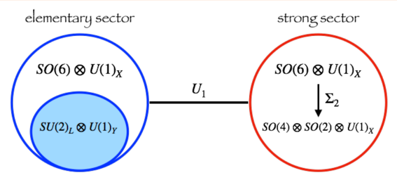

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- Σ_2: VEV accounts for breaking to $SO(4) \times SO(2) \times U(1)_X$
- $f^{-2} = f_1^{-2} + f_2^{-2}$

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

Composite Fermion Lagrangian

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

- SM fermions embedded into fundamental representation of $SO(6)$
- q_L,t_R: embedding of top quark, Ψ^I: Additional spin-1/2 resonances

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

Composite Fermion Lagrangian

$$\mathcal{L}_{\text{C2HDM}}^{\text{fermion}} = (\bar{q}_L^{\mathbf{6}}) i \not{D} (q_L^{\mathbf{6}}) + (\bar{t}_R^{\mathbf{6}}) i \not{D} (t_R^{\mathbf{6}}) + \bar{\Psi}^I i \not{D} \Psi^I - \bar{\Psi}^I (M_\Psi)_{IJ} P_R \Psi_J - \bar{\Psi}^I \left[(Y_1)_{IJ} \Sigma_2 + (Y_2)_{IJ} \Sigma_2^2 \right] \Psi^J$$
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- SM fermions embedded into fundamental representation of $SO(6)$
- q_L,t_R: embedding of top quark, Ψ^I: Additional spin-1/2 resonances
- Composite parameters determining the Higgs potential:

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

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

Remarks

- Non-linearities in the effective Lagrangian lead to custodial symmetry breaking $\Rightarrow$ need scenarios with additional symmetries (CP invariance, C_2 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

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

Generation of Parameter Points

- Reconstruction of VEV, Higgs mass and top mass
- Direct and indirect searches in the scalar sector implemented via `HiggsBounds`/ `HiggsSignals` [Philip Bechtle, Dercks, et al. 2020; Philip Bechtle, Heinemeyer, Klingl, 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

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

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$$+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left(\frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right)$$

- Additional parameters not predetermined

Differential Partonic Cross Section [Plehn, M. Spira, and Zerwas 1996; R. Grober and M. Muhlleitner 2011; Gillioz et al. 2012]

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

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Implementation

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

More on LO Calculation [Plehn, M. Spira, and Zerwas 1996; R. Grober and M. Muhlleitner 2011; Gillioz et al. 2012]

Definitions

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

$$A_1^{\mu\nu} = g^{\mu\nu} - \frac{p_1^\nu p_2^\mu}{(p_1 \cdot p_2)},$$

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

$$p_T^2 = 2 \frac{(p_1 \cdot p_3)(p_2 \cdot p_3)}{(p_1 \cdot p_2)} - p_3^2.$$

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

More on LO Calculation [Plehn, M. Spira, and Zerwas 1996; R. Grober and M. Muhlleitner 2011; Gillioz et al. 2012]

Di-Higgs Amplitudes

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

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

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

Cross section [Plehn, M. Spira, and Zerwas 1996; R. Grober and M. Muhlleitner 2011; Gillioz et al. 2012]

Di-Higgs 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:

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

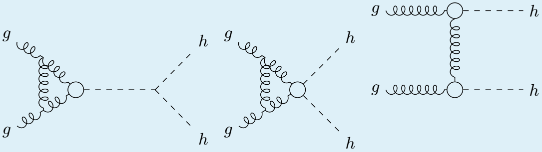
- Cross section at NLO [Dawson, Dittmaier, and M. Spira 1998; Ramona Grober, Margarete Muhlleitner, and Michael Spira 2016]:

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

NLO Correction [Dawson, Dittmaier, and M. Spira 1998; Ramona Grober, Margarete Muhlleitner, and Michael Spira 2016]

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

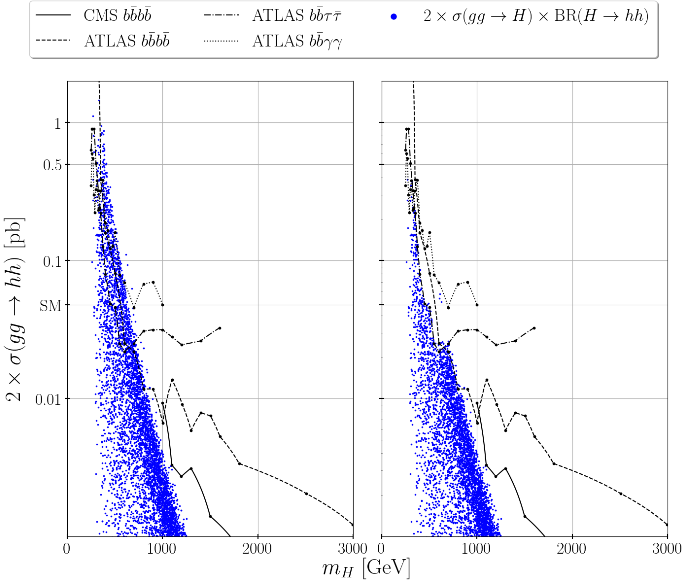
$\Delta\sigma_{\text{virt}} =$



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

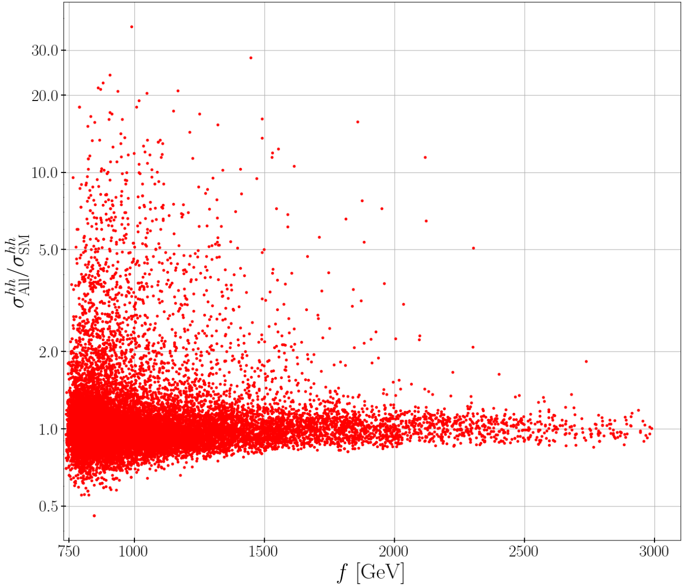
$$C = \pi^2 + \frac{11}{2} + \frac{33 - 2N_F}{6} \log \frac{\mu_R^2}{Q^2} + \text{Re} \frac{\int_{\hat{t}_-}^{\hat{t}_+} \mathrm{d}\hat{t} \, \frac{4}{9} (g_{hgg}^{\text{eff}})^2 \left[F_1 - \frac{p_T^2}{2\hat{t}\hat{u}} (Q^2 - 2m_h^2) F_2 \right]}{\int_{\hat{t}_-}^{\hat{t}_+} \mathrm{d}\hat{t} \left[|F_1|^2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

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



Resonant case

- HIGLU*BR [M. 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. 2022]



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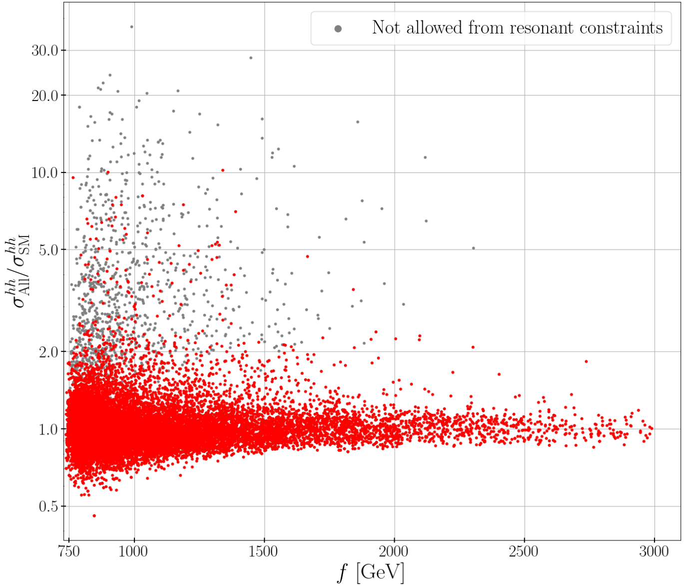

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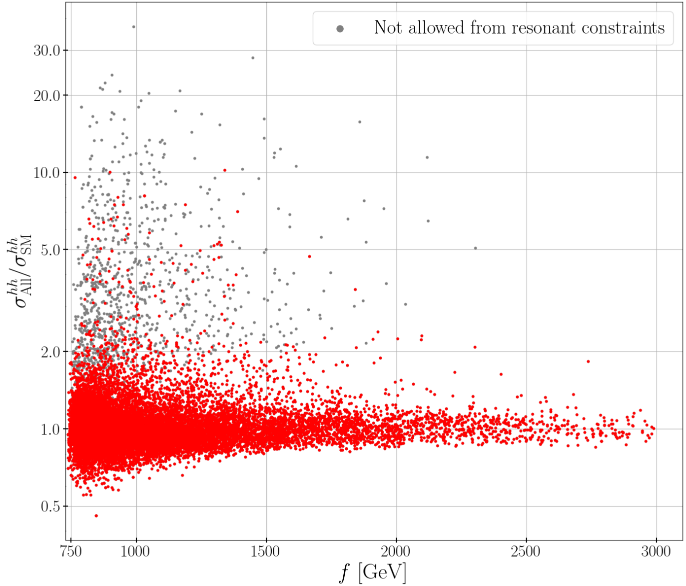

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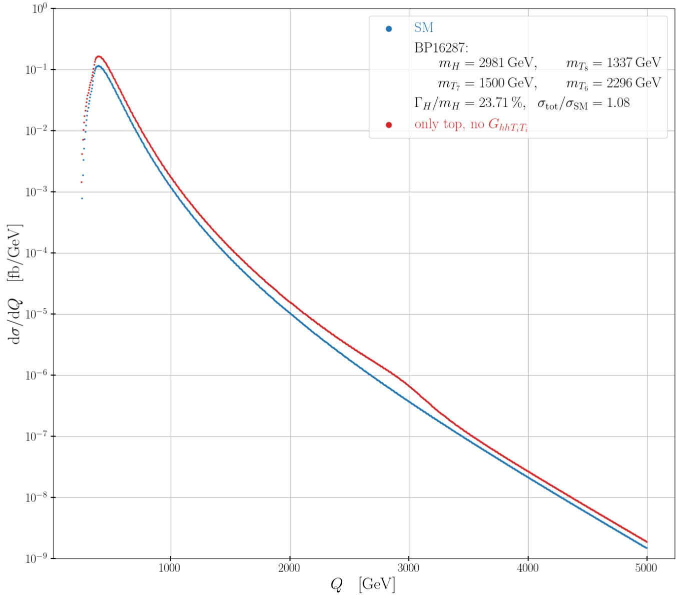
- New maximum: $\sigma_{\text{MAX}} \approx 10 \times \sigma_{\text{SM}}$ (2HDM: enhancement up to $12 \times \sigma_{\text{SM}}$ [Abouabid et al. 2022])



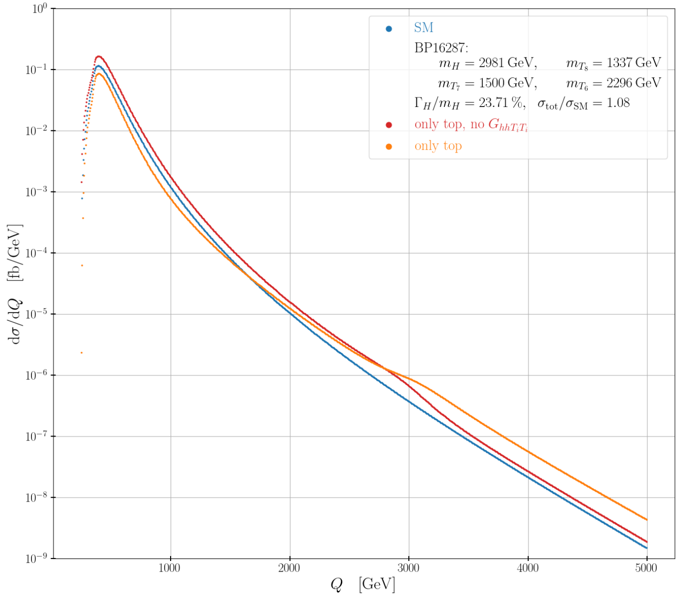
Differential Distributions

> `BP16287` parameters:

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

Remarks

> Red line resembles elementary 2HDM



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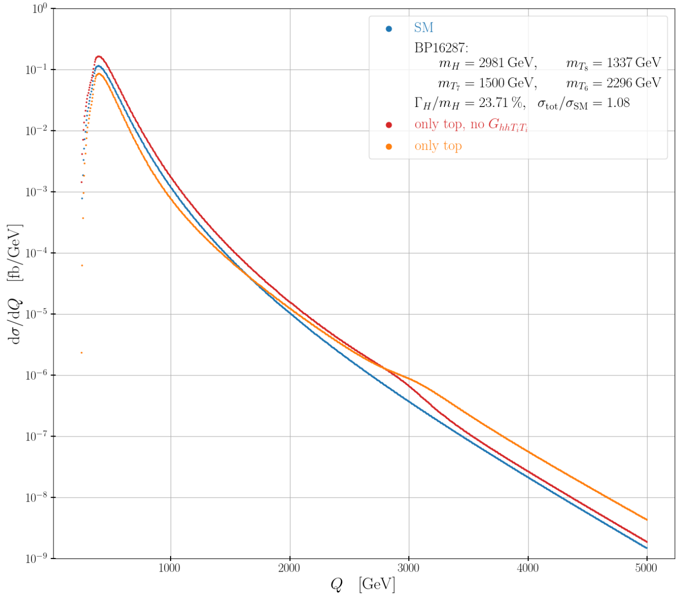

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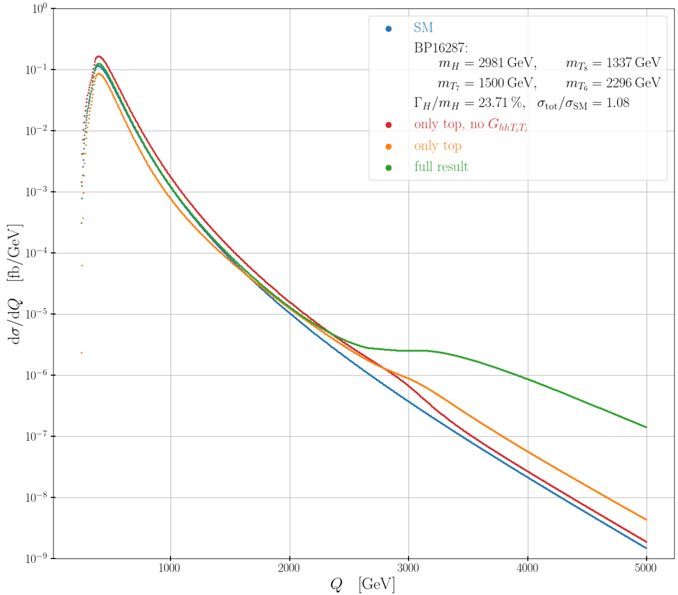
> G_{hhtt}: destructive interference



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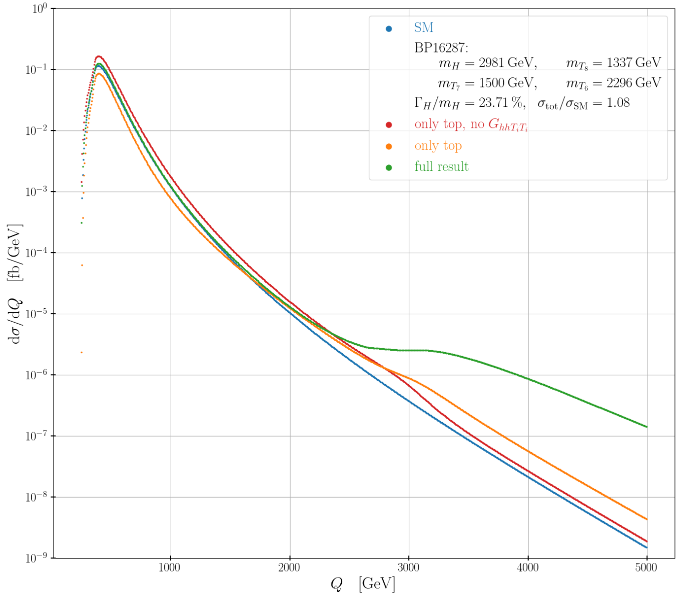
> G_{hhtt}: destructive interference



Differential Distributions

> BP16287 parameters:

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

Remarks

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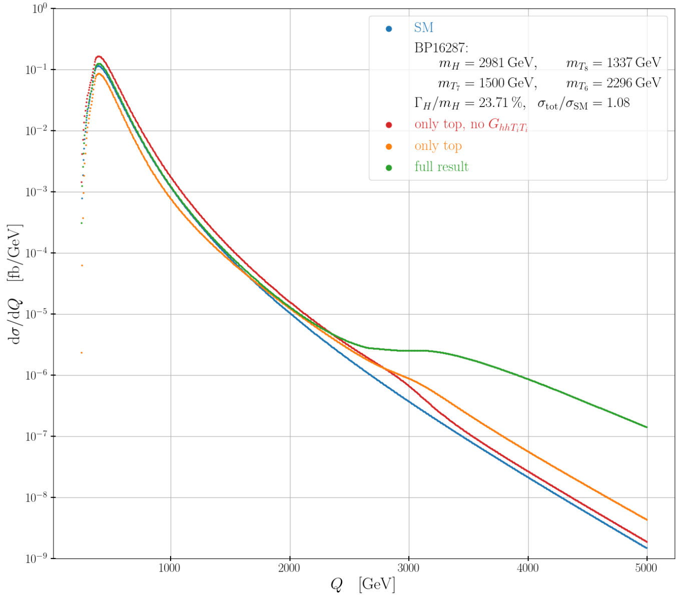
- G_{hhtt}: destructive interference
- Heavy quarks: enhancement + threshold effect



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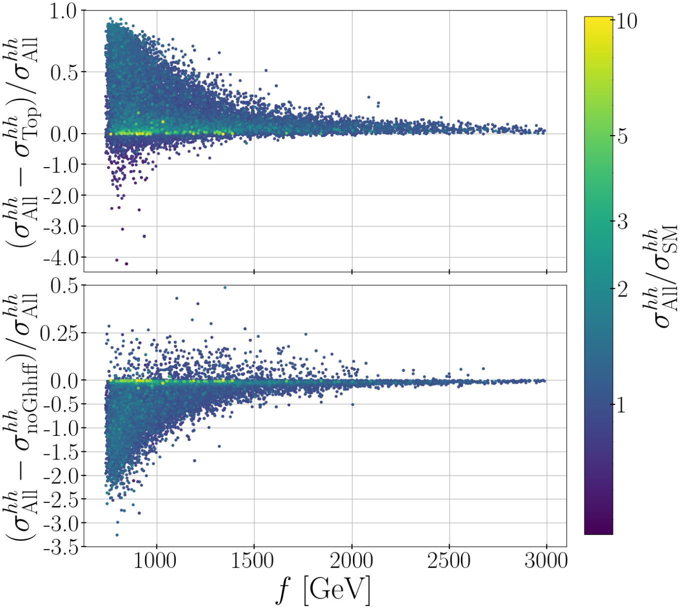
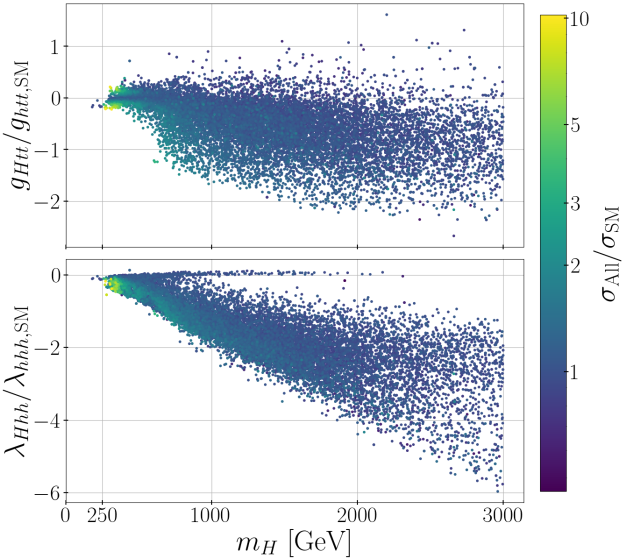
> Large total width Γ_H



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



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