Karlsruhe Institute of Technology

Higgs Pair Production in a Composite 2HDM

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Higgs Pair Production:

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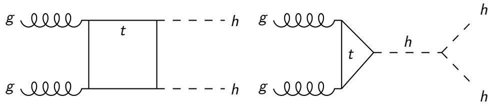

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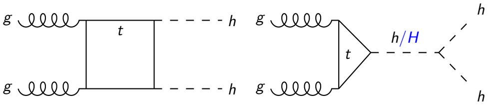

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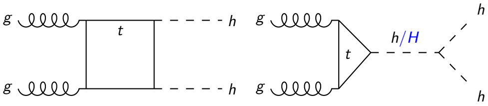

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Composite Models:

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

Illustration by Sandbox Studio, Chicago

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

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- Additional strong sector with $SO(6)$ symmetry: spontaneous breaking $SO(6) \rightarrow SO(4)xSO(2)$
  $\Rightarrow$ Generation of 2HDM-like structure

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- Scalar potential determined by composite parameters

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$\Rightarrow$ Contribution to di-Higgs cross section from **resonance production** as well as **additional top partners in the loop**

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):

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

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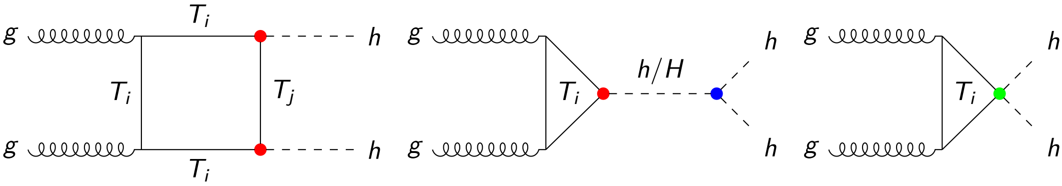
LO Contributions [Plehn, Spira, Zerwas 1996; Gröber, Mühlleitner 2011; Gillioz et al. 2012]

- Di-Higgs production via gluon fusion at LO:



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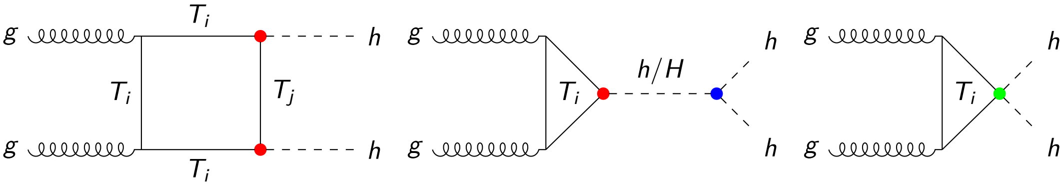

$$C^{hh}_{i,\triangle} = \frac{G_{h\bar{T}_iT_i}\lambda_{hhh}}{\hat{s} - m_h^2 + im_h\Gamma_h} + \frac{G_{H\bar{T}_iT_i}\lambda_{Hhh}}{\hat{s} - m_H^2 + im_H\Gamma_H} + \frac{G_{H\bar{T}_iT_i}\lambda^{(2)}_{Hhh}(2m_h^2 - 2\hat{s})}{\hat{s} - m_H^2 + im_H\Gamma_H} + 2G_{hh\bar{T}_iT_i}$$

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

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

Cross section

- Differential partonic cross section at LO:

$$\frac{\mathrm{d}\hat{\sigma}(gg \to hh)}{\mathrm{d}\hat{t}} = \frac{G_\mathrm{F}^2 \alpha_s^2}{2(2\pi)^3 256} \left[\left| \sum_{i=1}^{9} C_{i,\triangle}^{hh} F_{\triangle}^{hh}(m_i) + \sum_{i=1}^{9} \sum_{j=1}^{9} \left(C_{i,j,\square}^{hh} F_{\square}^{hh}(m_i, m_j) + C_{i,j,\square,5}^{hh} F_{\square,5}^{hh}(m_i, m_j) \right) \right|^2 \right.$$
$$\left. + \left| \sum_{i=1}^{9} \sum_{j=1}^{9} \left(C_{i,j,\square}^{hh} G_{\square}^{hh}(m_i, m_j) + C_{i,j,\square,5}^{hh} G_{\square,5}^{hh}(m_i, m_j) \right) \right|^2 \right]$$

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- Full cross section:

$$\sigma(pp \to hh) = \int_{\tau_0}^{1} \mathrm{d}\tau \frac{\mathrm{d}\mathcal{L}^{gg}}{\mathrm{d}\tau} \int_{\hat{t}_-}^{\hat{t}_+} \frac{\mathrm{d}\hat{\sigma}(gg \to hh, \hat{s} = \tau s)}{\mathrm{d}\hat{t}}, \ \tau_0 = \frac{4m_h^2}{s}, \ \hat{t}_\pm = \frac{-\hat{s}}{2}\left(1 - 2\frac{m_h^2}{\hat{s}} \mp \sqrt{1 - \frac{4m_h^2}{\hat{s}}}\right)$$

Cross section

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

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

$$\Rightarrow K \equiv \frac{\sigma_{\mathrm{NLO}}}{\sigma_{\mathrm{LO}}} \approx 2$$

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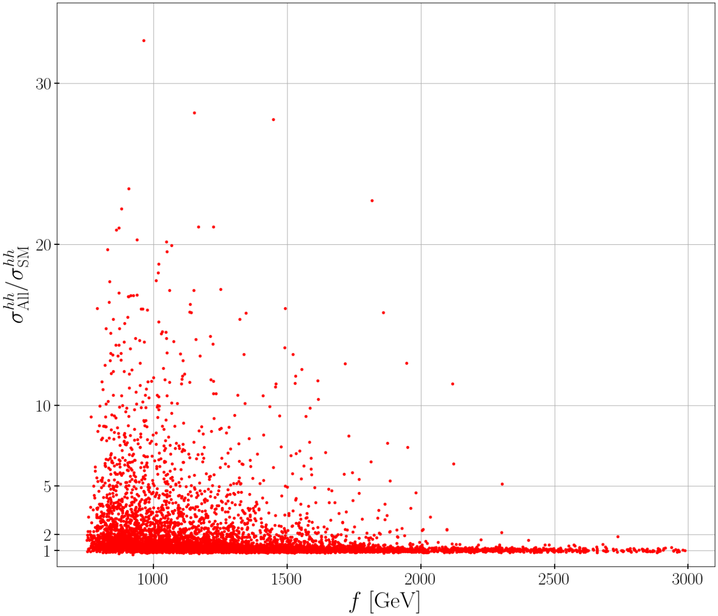
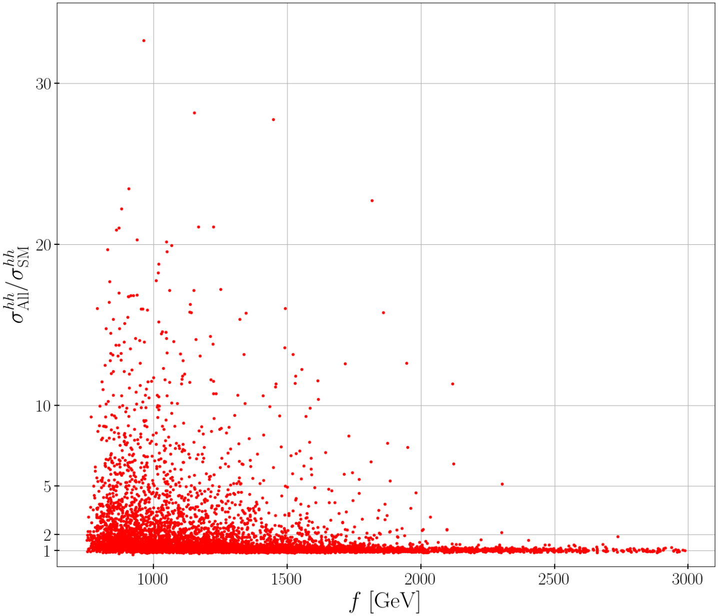
Implementation:

- Parameter points: Checked against constraints from Higgs searches and measurements
- Implementation into HPAIR [Dawson, Dittmaier, Spira 1998]
- Calculation of decay widths with HDECAY [Djouadi, Kalinowski, Spira 1998; + Mühlleitner 2019]

Overall Results



Parameter	Range	
	Lower	Upper
m_H	180 GeV	4840 GeV
$m_{T,8}$	949 GeV	12 794 GeV
$m_{T,1}$	3179 GeV	37 311 GeV
$\lambda_{hhh}/\lambda_{\text{SM}}$	0.83	1.07
$g_{htt}/g_{htt,\text{SM}}$	0.88	1.05
$\sigma/\sigma_{\text{SM}}$	0.75	33



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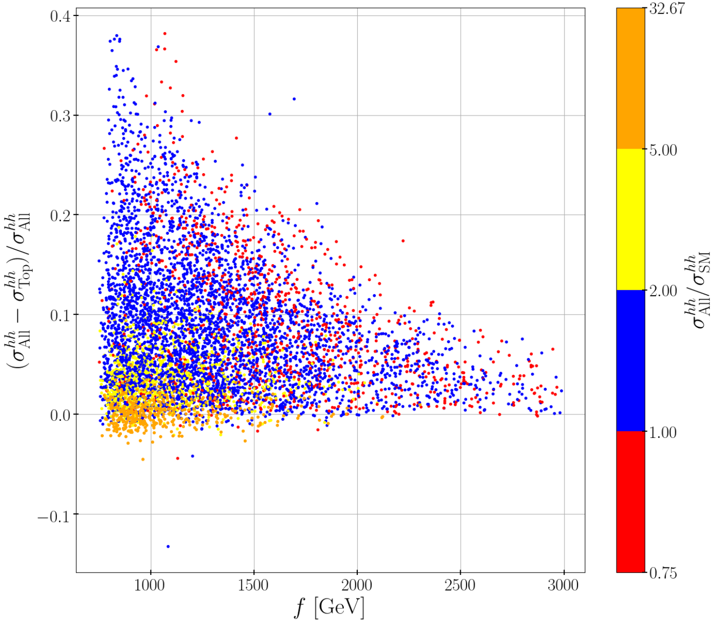

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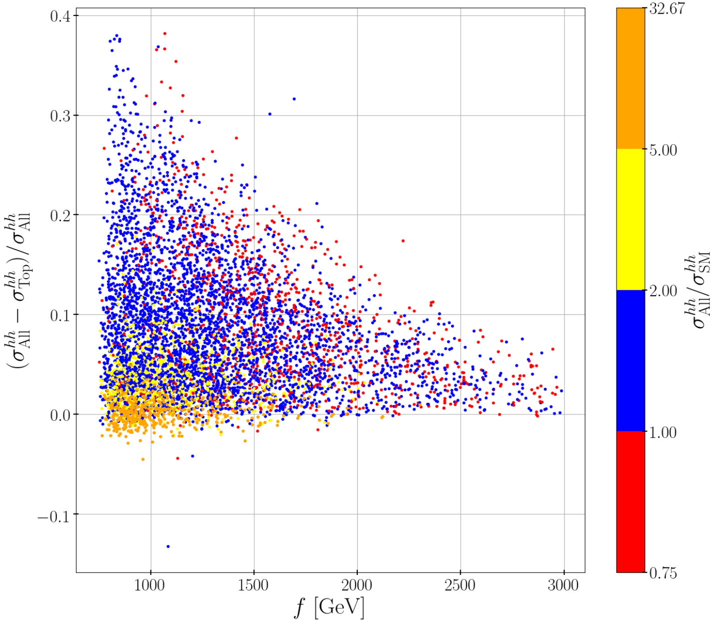

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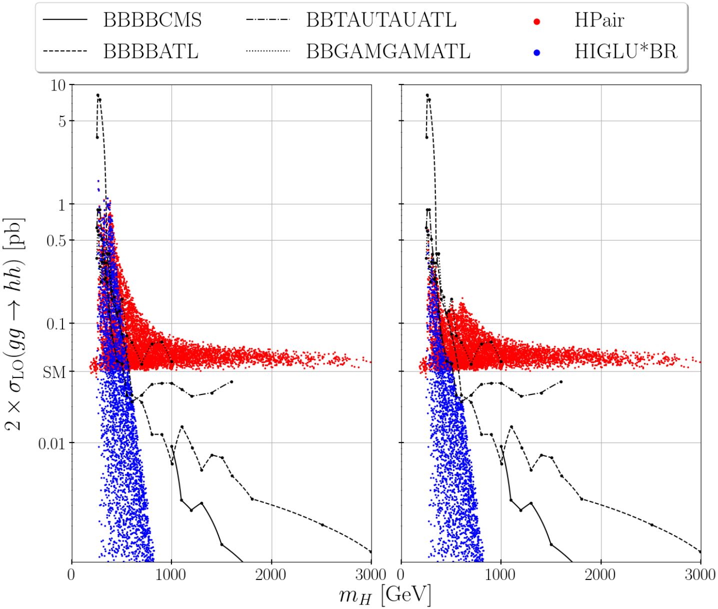
- Resonance enhancement: up to $30 \times \sigma_{\rm SM}$
- Heavy quark contribution: up to 40%
- Resonant case: dominated by top quark
- Non-Resonant case: close to $\sigma_{\rm SM}$ (destructive interference)



Resonant case

- HIGLU*BR [Spira 1995]:
  $\sigma(gg \to H) * \mathrm{BR}(H \to hh)$
- Factor 2: approximate NLO corrections
- HPAIR: All diagrams included
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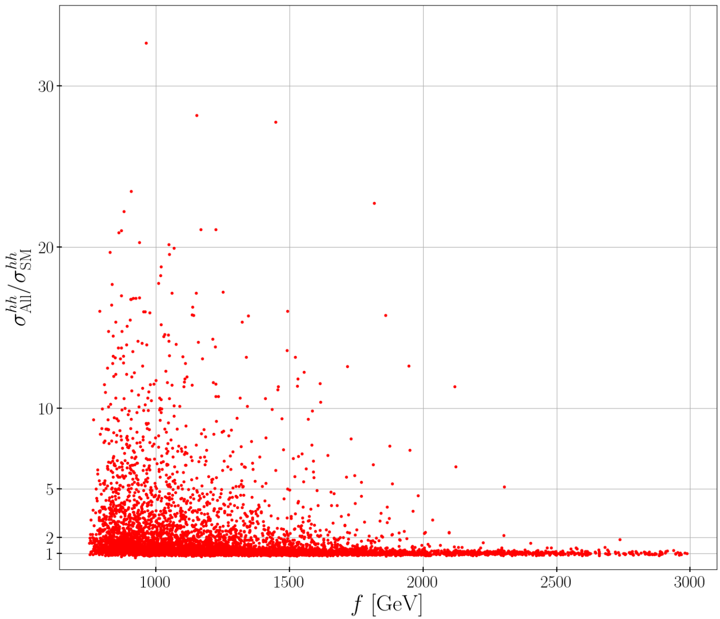

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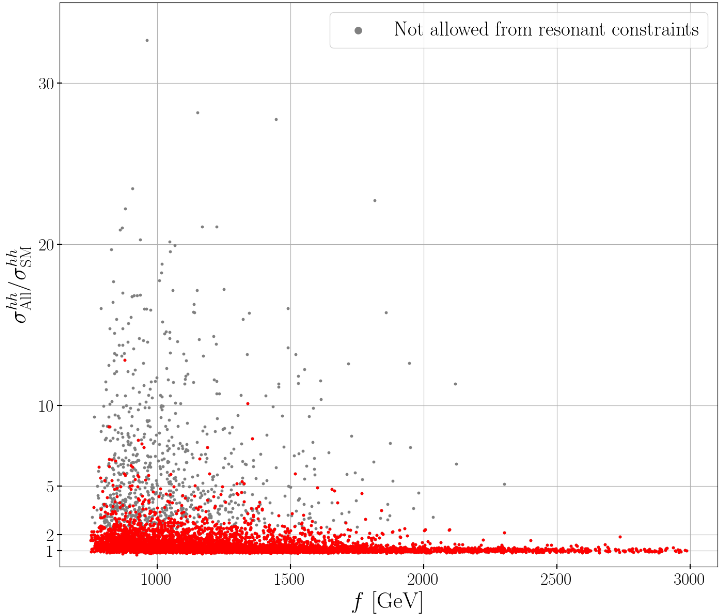

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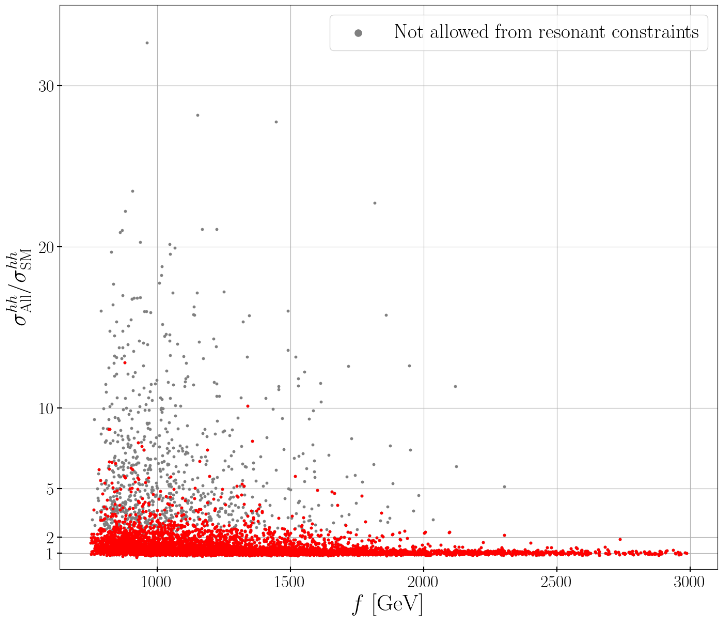

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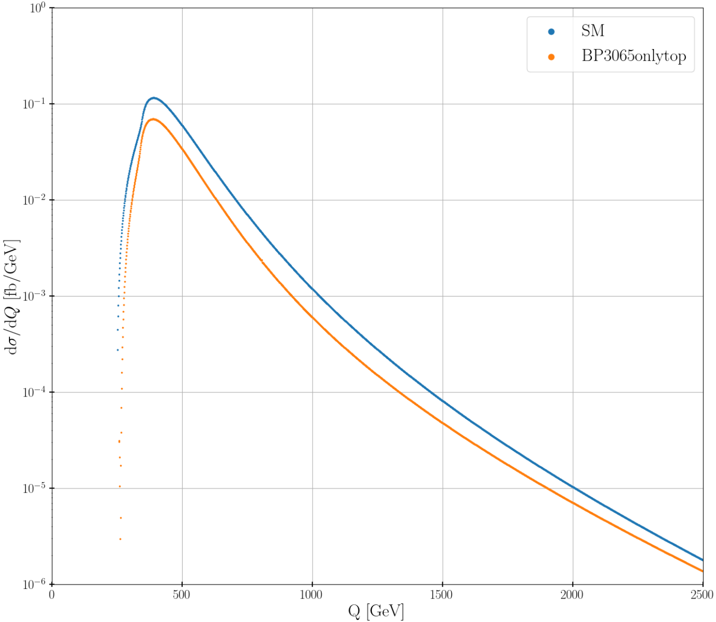
- New maximum: $\sigma_{\rm MAX} = 12.8 \times \sigma_{\rm SM}$ (2HDM: enhancement up to $12 \times \sigma_{\rm SM}$ [Abouabid et al. 2021])



Invariant-mass distribution

- BP3065:

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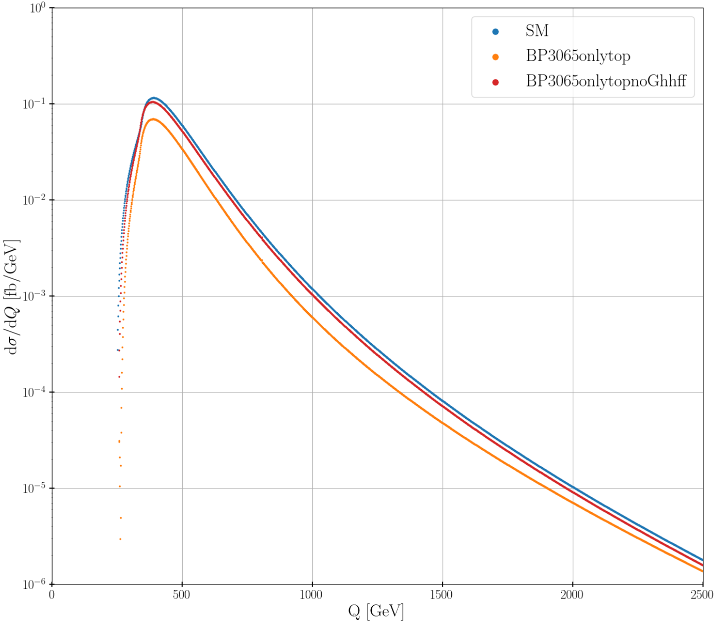

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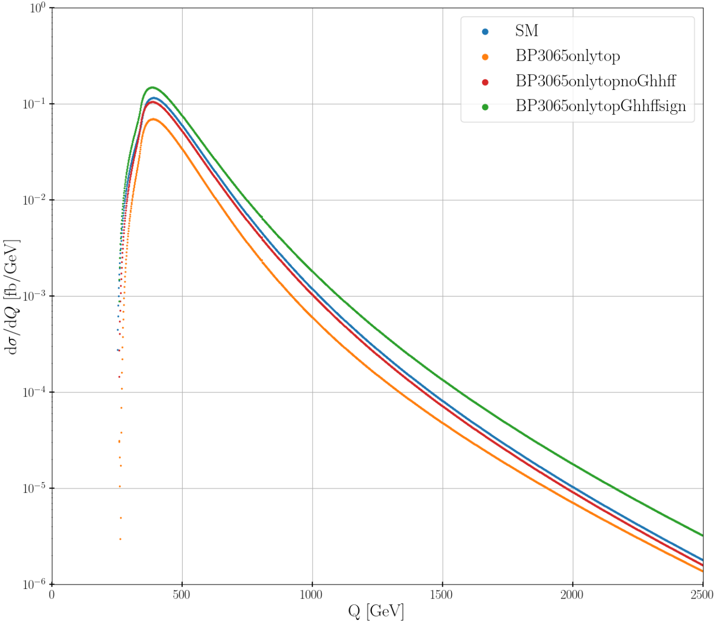

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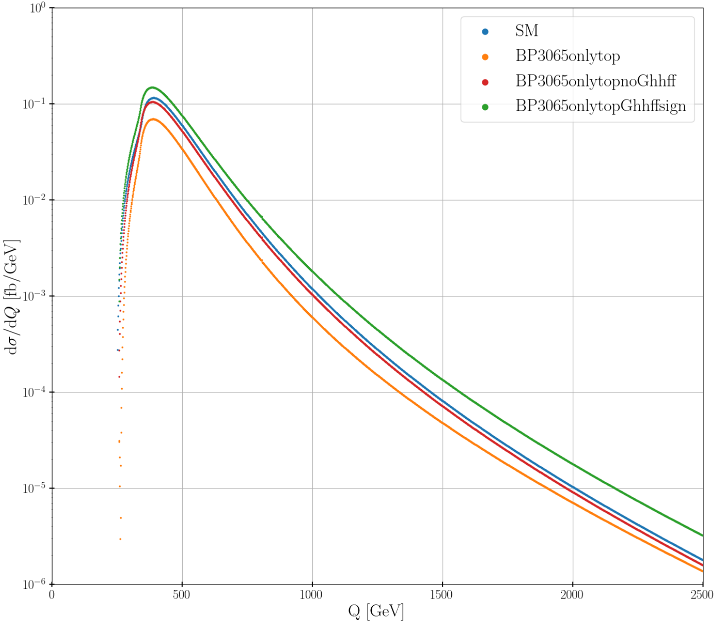

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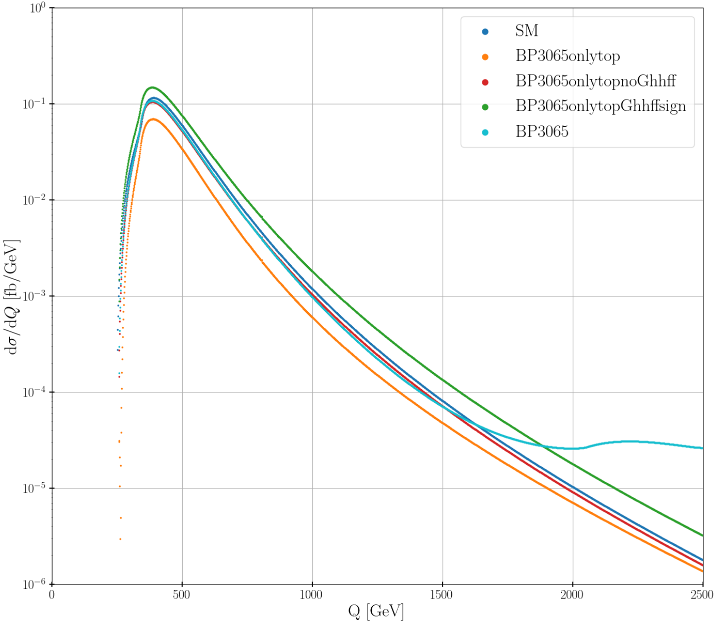
- Quartic coupling G_{hhtt}: destructive interference



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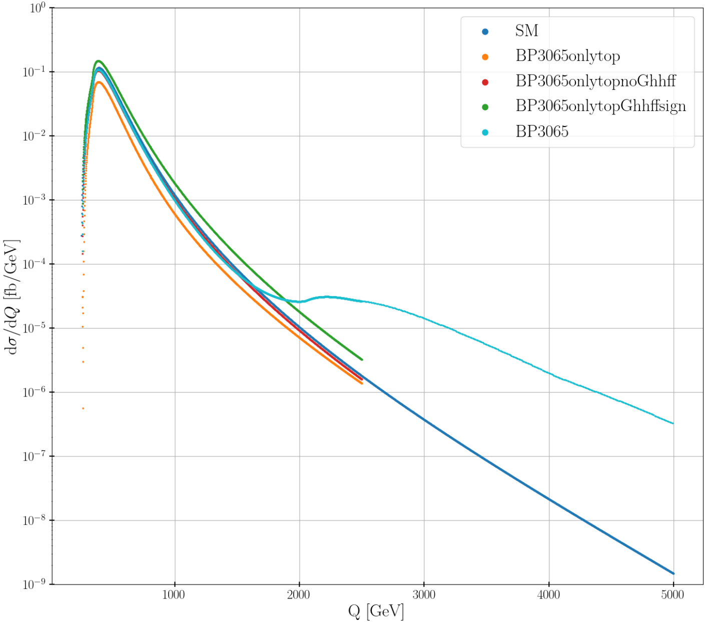
m_H	806 GeV
$m_{T,8}$	1025 GeV
$m_{T,7}$	1153 GeV
$m_{T,6}$	1237 GeV
$\lambda_{hhh}/\lambda_{\text{SM}}$	1.05
$g_{htt}/g_{htt,\text{SM}}$	0.97
$\sigma/\sigma_{\text{SM}}$	0.92

- Quartic coupling G_{hhtt}: destructive interference



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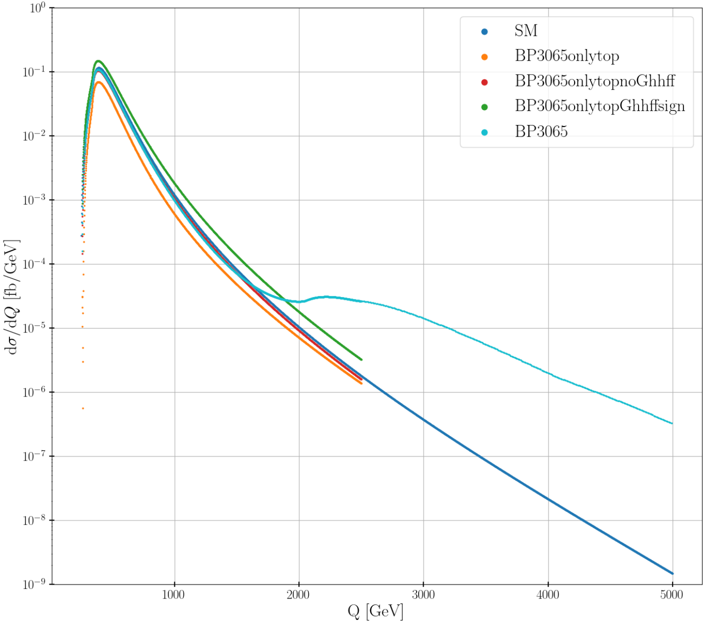

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- Quartic coupling G_{hhtt}: destructive interference
- Heavy quarks: enhancement + "tail effect"

Summary and Outlook

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- Possible **enhancement** of cross section through resonance production and heavy top partners
- **Destructive** interference from G_{hhtt} coupling
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Thank you for your attention!

Literature I

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

Plehn, T., M. Spira, P.M. Zerwas (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 (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. (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.

Gröber, R., M. Mühlleitner, M. Spira (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.

Literature II

Djouadi, A., J. Kalinowski, M. Spira (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.

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

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.

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

More on the Composite 2HDM [De Curtis et al. 2018]

- Full coset structure:

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

- 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 two copies of $G = SO(6) \times U(1)_X$, 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, realises spontaneous symmetry breaking from $G_1 \times G_2$ to diagonal compomenent G
- Σ_2: VEV accounts for breaking to $SO(4) \times SO(2) \times U(1)_X$
- $f^{-2} = f_1^{-2} + f_2^{-2}$

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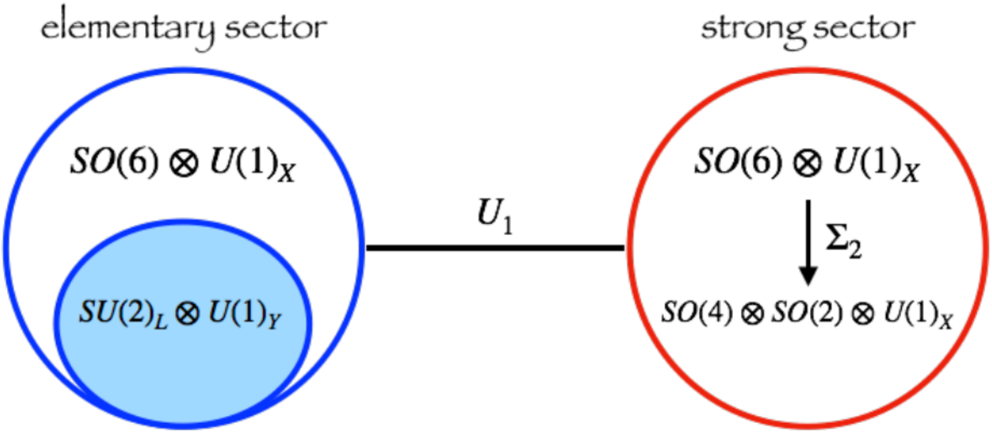

More on the Composite 2HDM [De Curtis et al. 2018]

- 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:
  $$f, \underbrace{Y_1^{12}, Y_2^{12}}_{\text{fermion coupling to resonances}}, \underbrace{\Delta_L^1, \Delta_R^2}_{\text{partial compositeness}}, \underbrace{M_\Psi^{11}, M_\Psi^{22}, M_\Psi^{12}}_{\text{composite fermion mass matrix}}, \underbrace{g_\rho}_{\text{composite gauge coupling}}$$
- 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 the strong sector highly constrains higher-dimensional operators contributing to the Yukawa sector. Flavor alignment is similar to the elementary 2HDM.

A Composite 2HDM

2 Higgs Doublet Model (2HDM):

- SM + additional scalar doublet
- Scalar potential:

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

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- Additional parameters not predetermined

More on LO Calculation [Gillioz et al. 2012]

- Mandelstam:

$$\hat{s} = (p_1 + p_2)^2, \quad \hat{t} = (p_1 + p_3)^2, \quad \hat{u} = (p_2 + p_3)^2 \tag{1}$$

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- 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:

$$A_1 \cdot A_2 = 0, \quad A_1 \cdot A_1 = A_2 \cdot A_2 = 2 \tag{2}$$

More on LO Calculation [Gillioz et al. 2012]

- Triangle amplitude:

$$\mathcal{A}_\triangle = \frac{\alpha_s G_F \sqrt{2}}{4\pi} A_1^{\mu\nu} \epsilon_\mu^a \epsilon_\nu^b \delta_{ab} \sum_{i=1}^{9} C_{i,\triangle}^{hh} F_\triangle(m_i) \tag{3}$$

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- 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:

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

NLO Contribution [Gröber, Mühlleitner, Spira 2016]

- Look at additional contributions:

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

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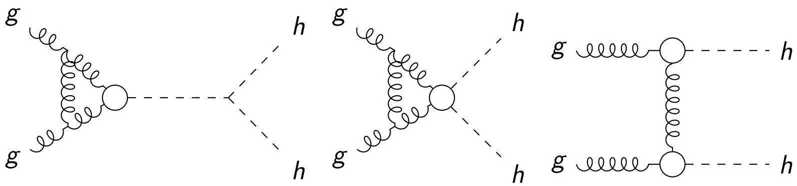

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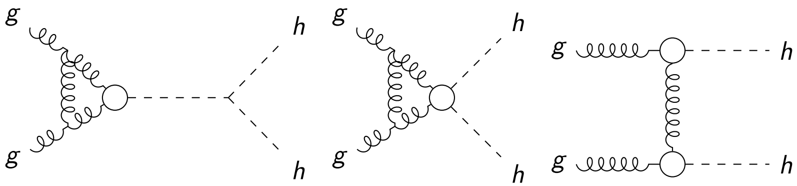

$$\Delta\sigma_{\text{virt}} = \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_0}^{1} \frac{\mathrm{d}\tau \mathcal{L}^{gg}}{\mathrm{d}\tau} \hat{\sigma}_{\text{LO}}(Q^2 = \tau s) C,$$

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

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