[2310.10471]

Pair production of Higgs boson in composite two Higgs doublet model

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In collaboration with

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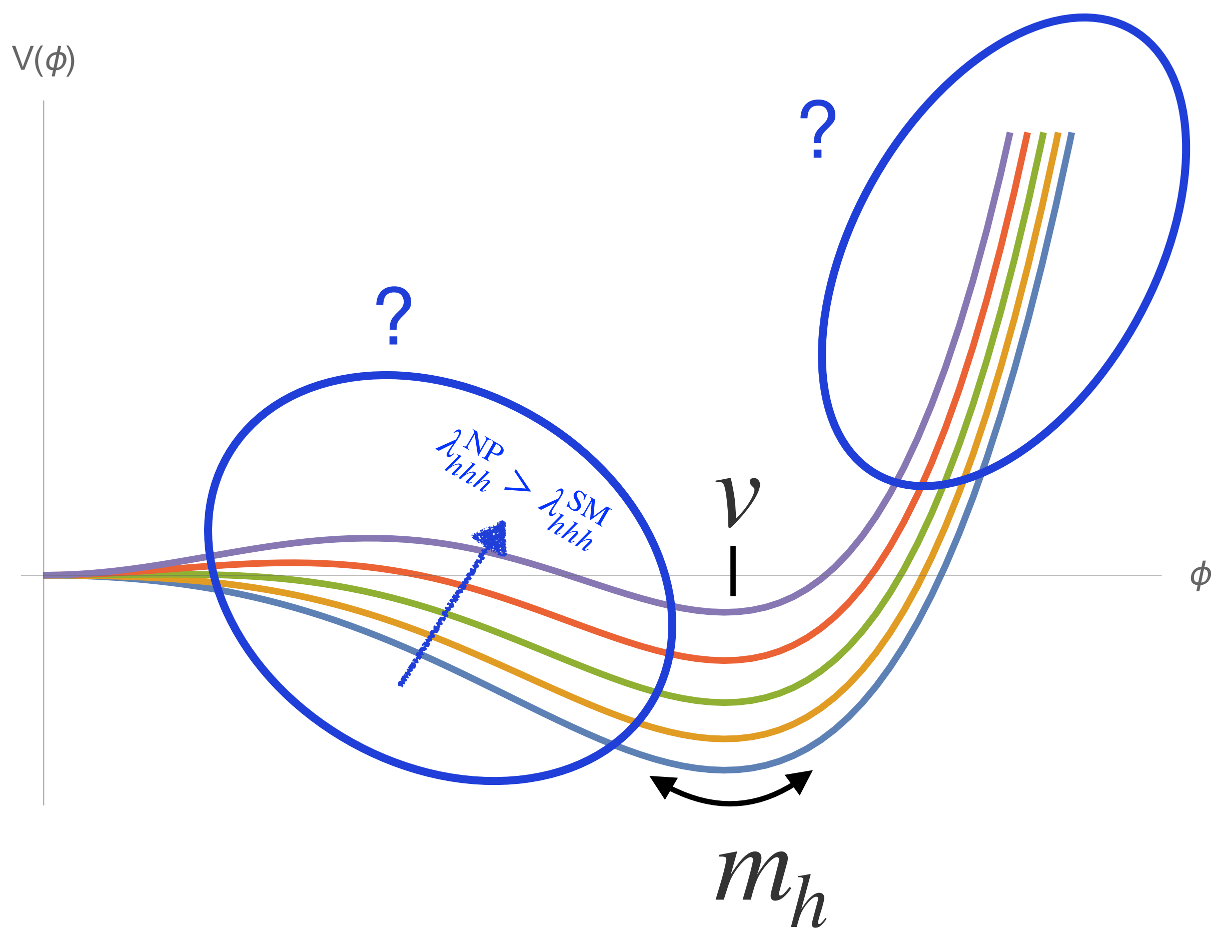
The shape of the Higgs potential is unknown

- After the discovery of the Higgs boson, the properties are measured in LHC experiments.

- What we know currently about the Higgs potential are two things:

  - Position of the EW minimum

  - The curvature of the potential around the minima.



- The hhh coupling is not measured accurately.

$$V(h) = \frac{1}{2}m_h^2h^2 + \lambda_{hhh}h^3 + \lambda_{hhhh}h^4$$

→ The shape of the potential away from the minima is not determined.

Determination of the shape of Higgs potential

Determination of the shape of Higgs potential is a key to find New physics.

- We may restrict the shape of the Higgs sector.

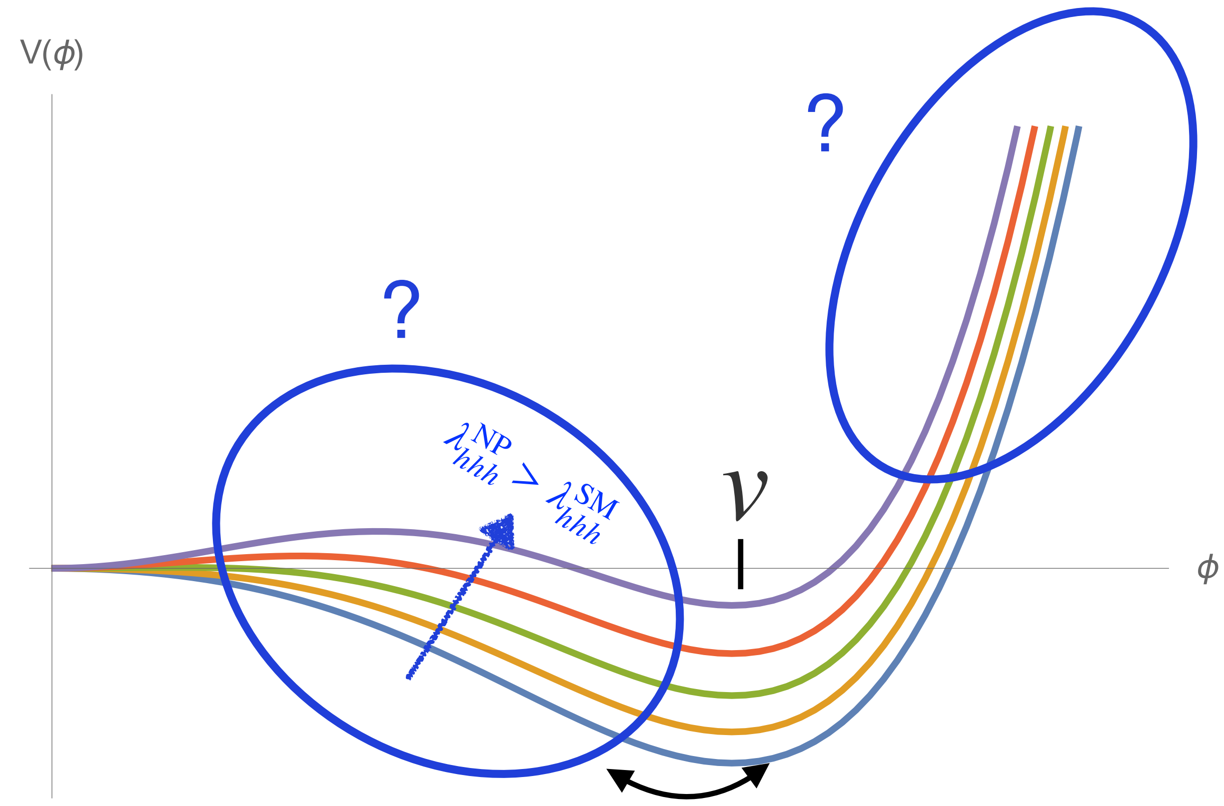
- We may find a clue of a new paradigm beyond SM.

EX.) Models with two Higgs fields

$$\lambda_{hhh}^{\mathrm{E2HDM}} \sim -\frac{m_h^2}{2v} + \frac{m_{12}^2}{v c_\beta s_\beta} c_{\beta-\alpha}^2 \qquad (c_{\beta-\alpha} \ll 1)$$

$$\lambda_{hhh}^{\mathrm{MSSM}} = 3\frac{m_Z^2}{v} c_{2\alpha} s_{\alpha+\beta}$$

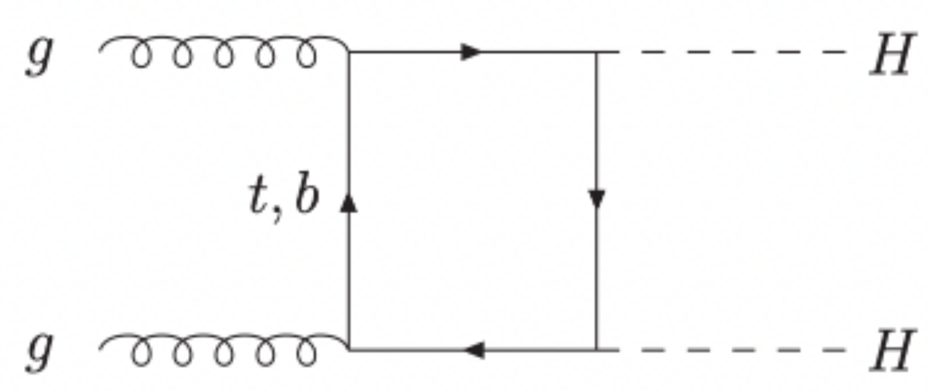
$\lambda_{hhh}^{\mathrm{C2HDM}}$: depends on strong sector

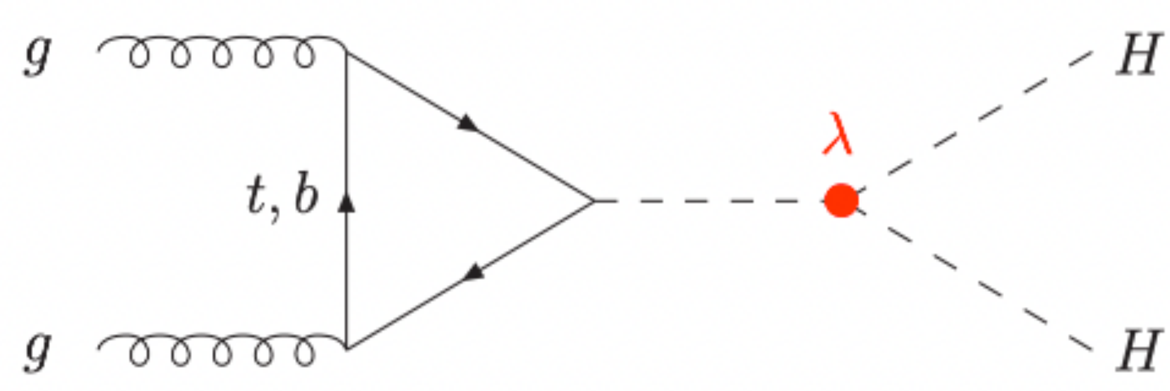


- How EWSB occurs (1st OPT GWs).

Di-Higgs production process

- λ_{hhh} appears in di-Higgs production process. Dominant one is $gg \to hh$

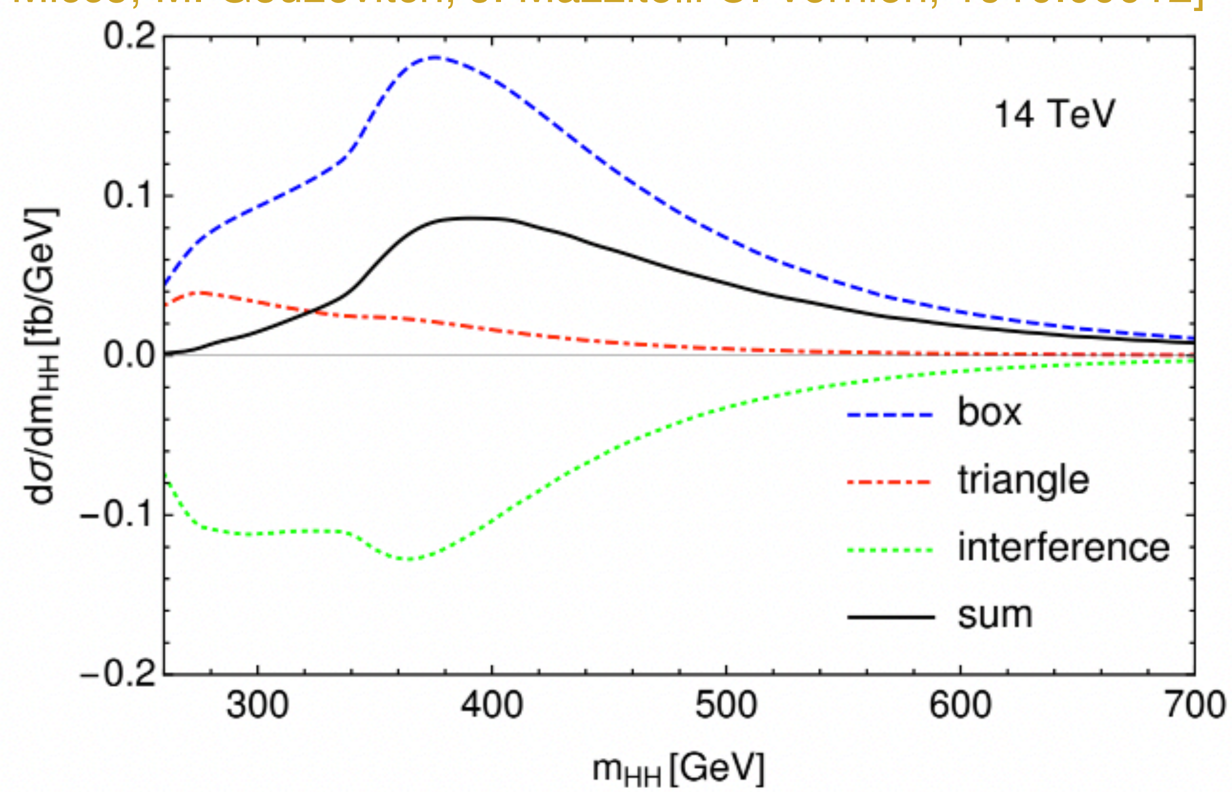




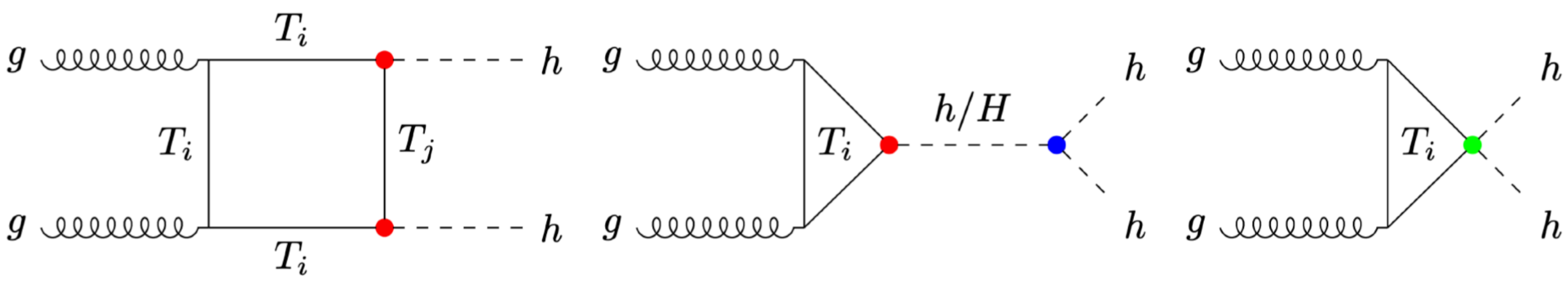
- Through λ_{hhh}, interference can change much.

- Predictions of di-Higgs boson should be prepared in various extended Higgs models to compare experiments such as LHC Run 3 HL-LHC.

[B. Micco, M. Gouzevitch, J. Mazzitelli C. Vernieri, 1910.00012]



Motinvation of this study



- We discuss the theoretical behavior of di-Higgs production cross section in the composite two-Higgs doublet model.

- One has additional vector-like fermion loops (T_i) and heavy CP-even Higgs boson (H) as new physics effects.

- Open questions:

  How match these new physics effects can enhance $\sigma_{pp\to hh}$?

  How the prediction for $\sigma_{pp\to hh}$ can be changed from E2HDM?

Setup: Composite two Higgs doublet model

[S. De Curtis, et al, JHEP 12 (2018) 051]

[See the details in the slide by S. Moretti]

- Group structure: $\dfrac{\mathcal{G}}{\mathcal{H}} = \dfrac{\mathrm{SO}(6)}{\mathrm{SO}(4)\times\mathrm{SO}(2)},$

  8 (=15-7) broken SO(6) generators exist. We have 8 NGBs, which corresponds to Higgs fields in 2HDM.

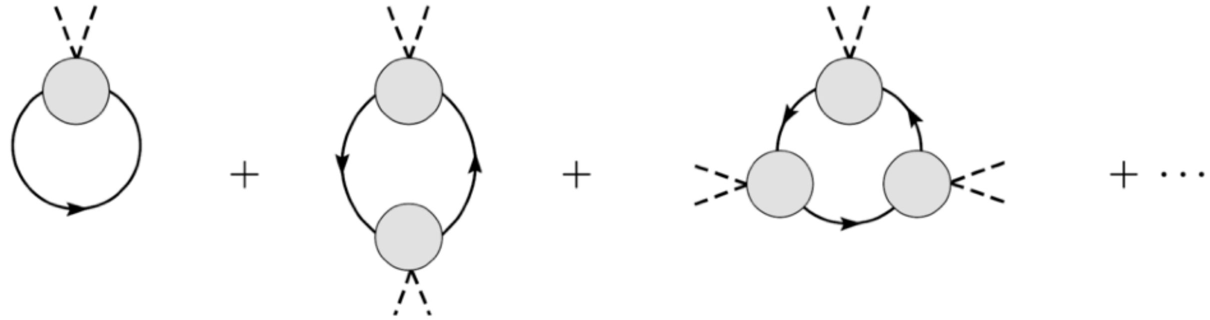
- How is the mass of the Higgs boson generated?

  - The explicit breaking of SO(6) is required.

    For gauge sector, gauging EW subgroup breaks SO(4)×SO(2).

    For fermion sector, explicit breaking terms are introduced

  - The Coleman-Weinberg potential is generated:



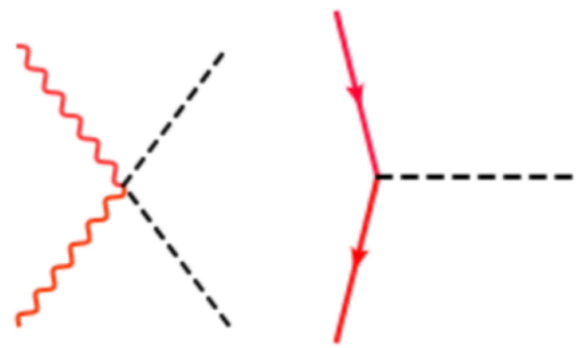
➡ masses and self int.

The potential is governed by composite parameters.

Setup: Composite two Higgs doublet model

$$\mathscr{L}_{\text{C2HDM}} = \mathscr{L}_{\text{elementary}} + \mathscr{L}_{\text{mixing}} + \mathscr{L}_{\text{resonances}}$$

$\mathscr{L}_{\text{resonances}}$: contains NGBs and heavy resonances.
It involves the interactions between them
with suppression 1/f.



$\mathscr{L}_{\text{elementary}}$: constructed by W^a_μ, q_L and q_R .
It involves kinetic terms.

$\mathscr{L}_{\text{mixing}}$: gives int. between $\mathscr{L}_{\text{elementary}}$ and $\mathscr{L}_{\text{ressonance}}$.

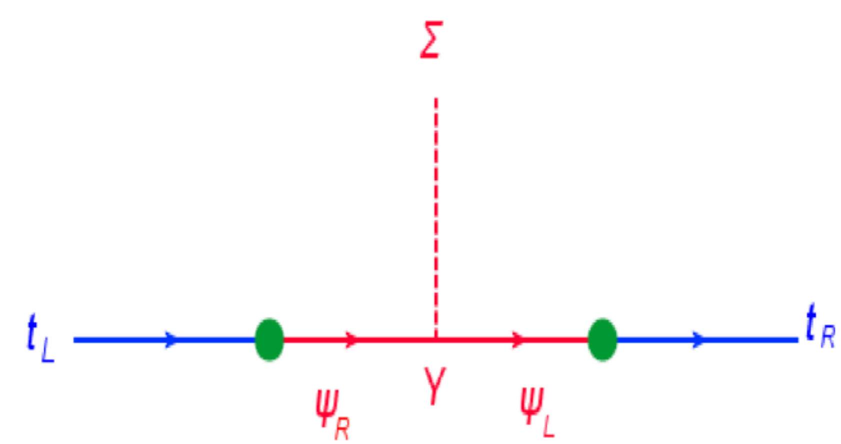
Setup: Composite two Higgs doublet model

$\mathscr{L}_{\rm mixing}$: gives int. between $\mathscr{L}_{\rm elementary}$ and $\mathscr{L}_{\rm ressonance}$.

EX.) fermion sector (U: Higgs field ψ: VL fermion)

$$\mathscr{L}_{\rm mixing} = y_L^{ij} f \bar{q}_L^i U \cdot (\psi^I)^j + \tilde{y}_L^{ij} f \bar{q}_L^i U \cdot (\psi^\alpha)^j + (q_L \to u_R, d_R, l_L, e_R)$$

- It explicitly breaks SO(6).
- It generates Yukawa int. masses of fermions
- We introduces two spices of ψ.



➡ 8 heavy top partners (T_i) are introduced.

Higgs pair production

$$\frac{d\hat{\sigma}(gg \to hh)}{d\hat{t}} = \frac{\alpha_s^2}{512(2\pi)^3}$$

$$\times \left[\left| \sum_{i=1}^{n_q} C_{i,\triangle}^{hh} F_\triangle(m_i) + \sum_{i=1}^{n_q} \sum_{j=1}^{n_q} \left(C_{ij,\Box}^{hh} F_\Box^{hh}(m_i, m_j) + C_{ij,\Box,5}^{hh} F_{\Box,5}^{hh}(m_i, m_j) \right) \right|^2 \right.$$

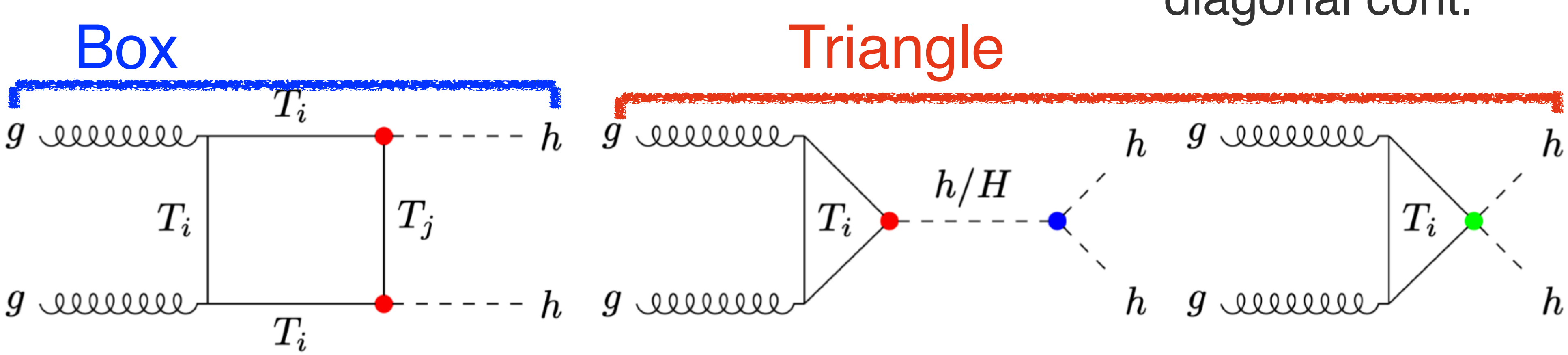
$$\left. + \left| \sum_{i=1}^{n_q} \sum_{j=1}^{n_q} \left(C_{ij,\Box}^{hh} G_\Box^{hh}(m_i, m_j) + C_{ij,\Box,5}^{hh} G_{\Box,5}^{hh}(m_i, m_j) \right) \right|^2 \right],$$

Spin-0 contributions

Spin-2 contributions

- Corresponding diagrams

The box contains off-diagonal cont.



- Heavy mass limit [T. Plehn, M. Spira, P. M. Zerwas, Nucl.Phys.B 479 (1996) 46]

$$F_\triangle \to \frac{s}{m_T}\frac{2}{3}, \quad F_\Box \to -\frac{s}{m_T^2}\frac{2}{3}, \quad G_\Box \to \mathcal{O}\left(\frac{s^2}{m_T^4}\right),$$

Spin-0 cont. is dominant.

Scan analysis

- We scan the composite parameters by applying the following constraints:
  - Correct global EW minimum, m_t
  - Perturbativity for λ_i
  - LHC bounds for $H, A, H^{\pm}$ and h
  - $\sigma_{pp\to hh}$ through resonant seacrh

[calculated by by Felix]

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

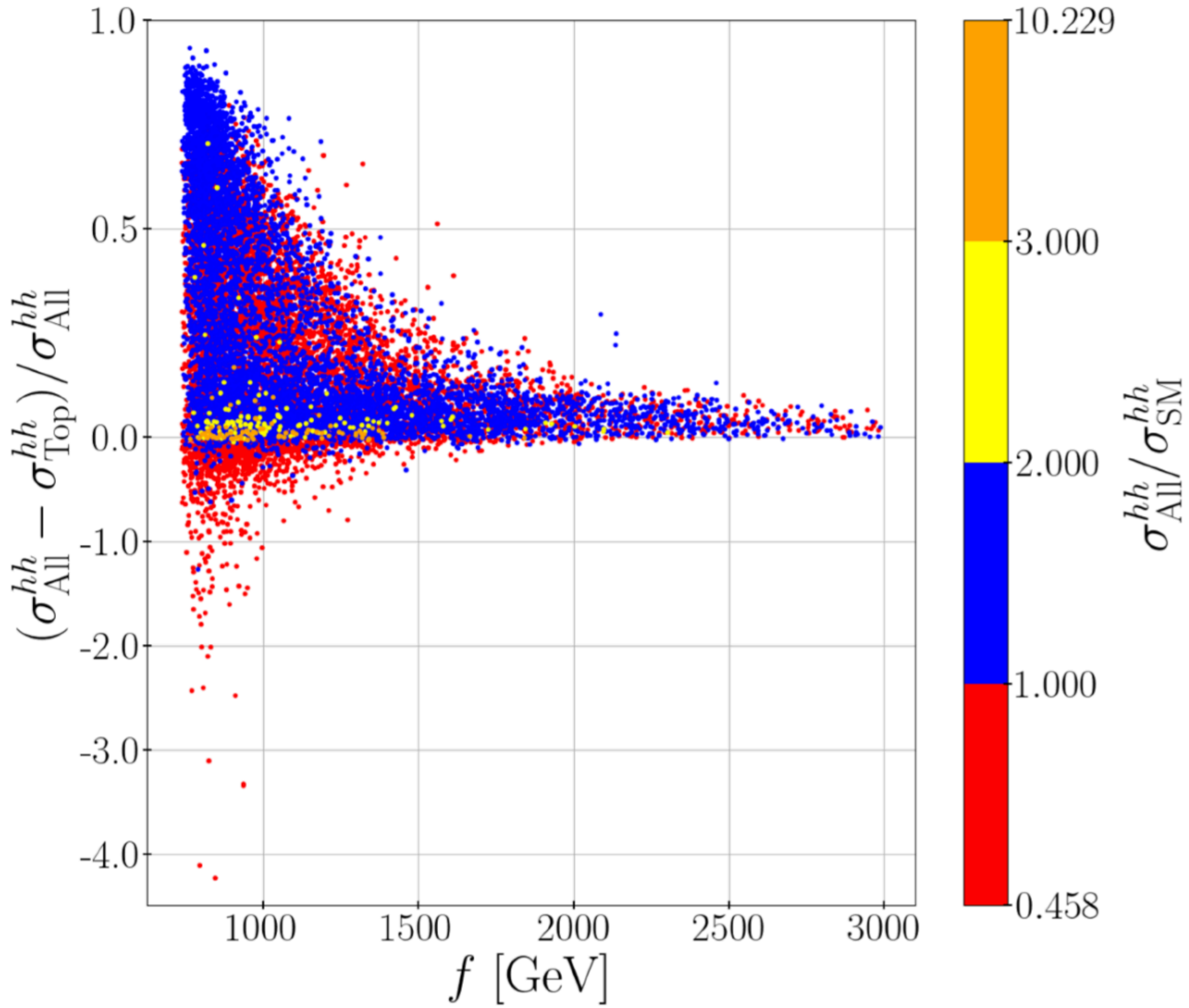
- We consider the two regime:

Resonant case : $\dfrac{\sigma(gg\to H)\times \text{BR}(H\to hh)}{\sigma(gg\to hh)} > 0.1,$ and $\Gamma_H/m_H < 5\,\%$

Nonresonant case : $\dfrac{\sigma(gg\to H)\times \text{BR}(H\to hh)}{\sigma(gg\to hh)} < 0.1$ or $m_H < 2m_h$

Influence of Heavy top partner loop contributions

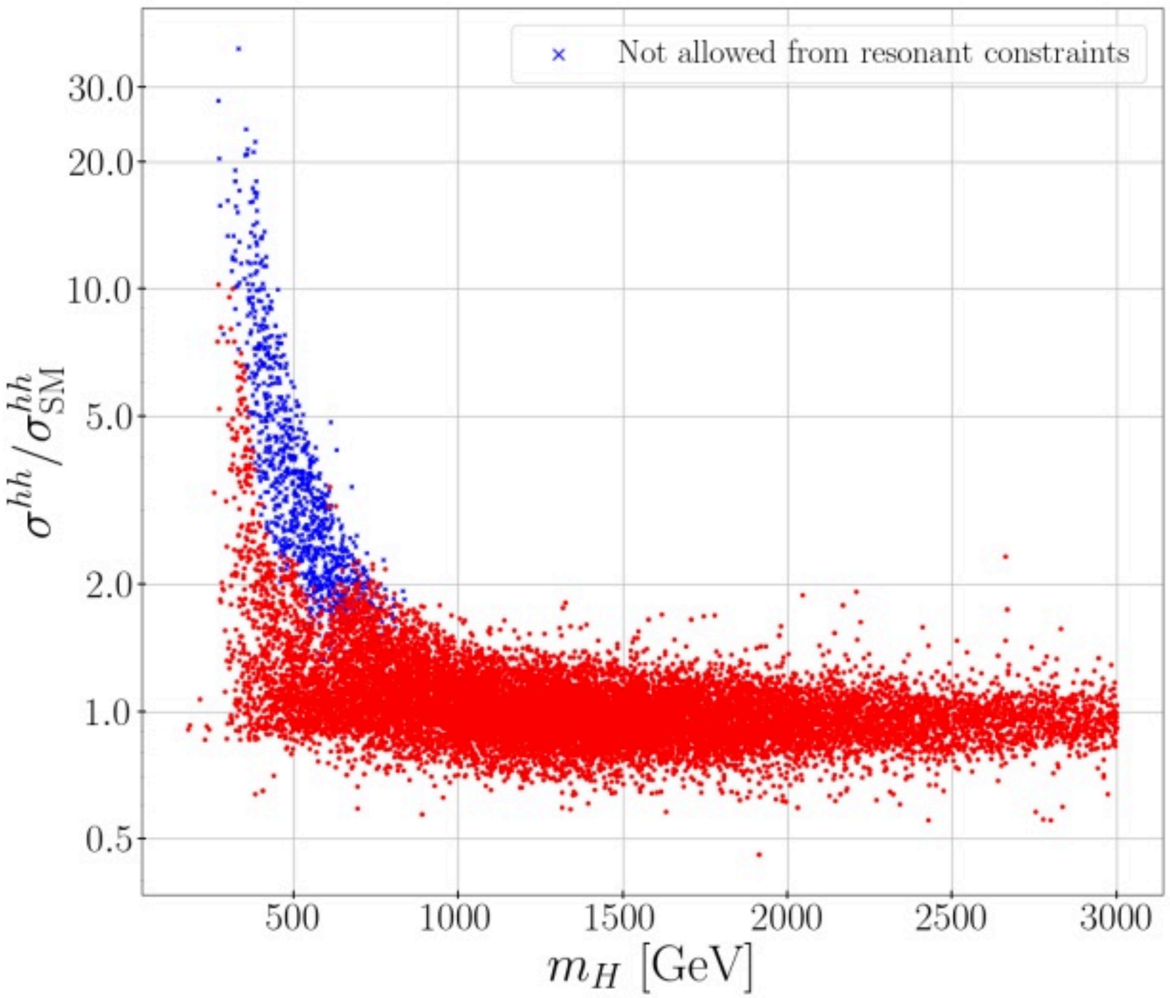
[De Curtis, Delle Rose, Egle,Mühlleitner, Moretti, KS]



- Heavy top partner gives destractuive and constructive contributions.
- T_i contributions have influence when $\sigma^{hh}/\sigma^{hh}_{SM} \sim 0.5\text{-}2$.

Size of σ in resonant and non-resonant cases.

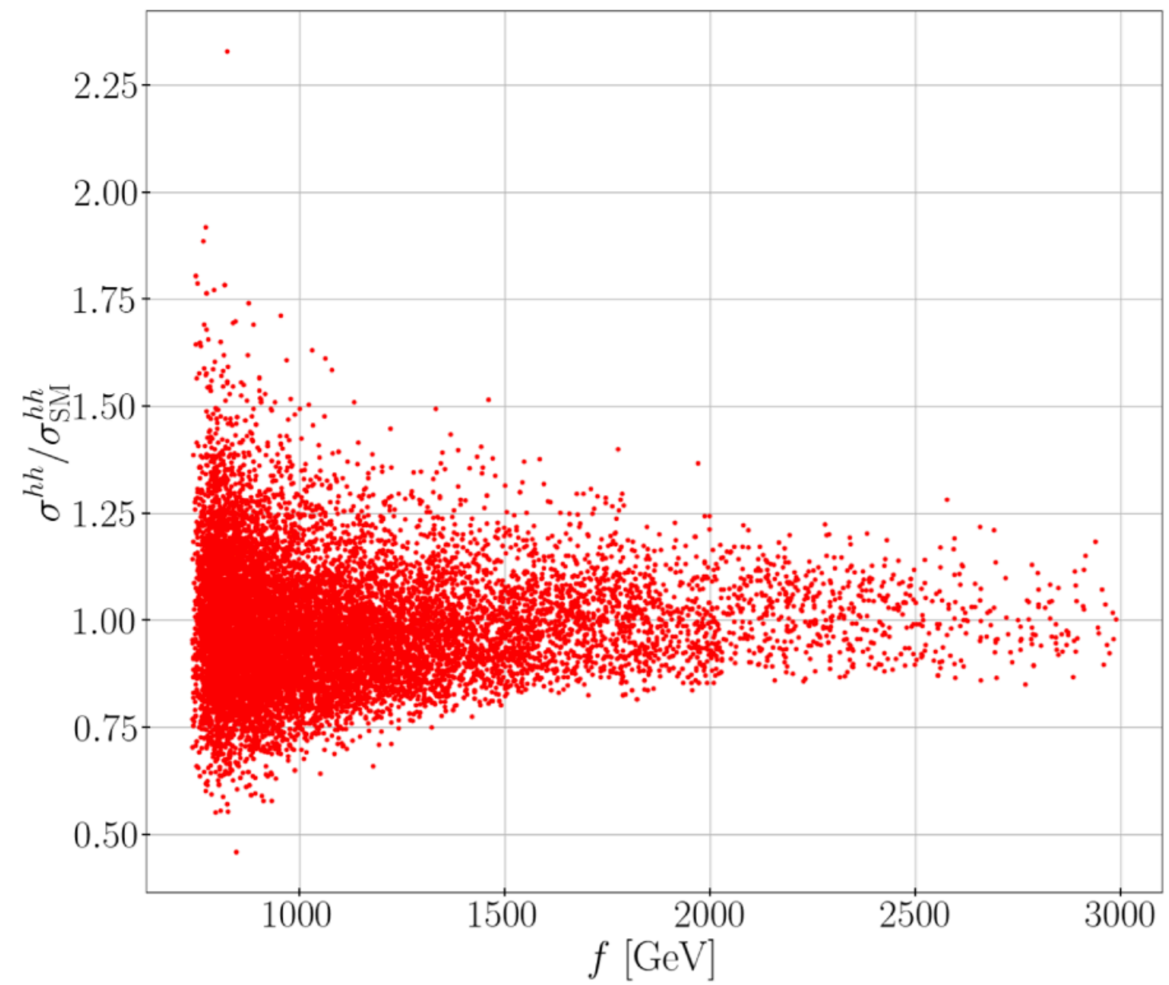
Resonant case



- If $m_H \sim 2m_h$, $\sigma^{hh}/\sigma^{hh}_{SM}$ can be ~10.

Non-resonant case

[De Curtis, Delle Rose, Egle,Mühlleitner, Moretti, KS]



- $\sigma^{hh}/\sigma^{hh}_{SM}$ can reach ~2.3 .

⟷ $\mu_{HH} \lesssim 2.4$ @ATLAS ,139fb[-1]

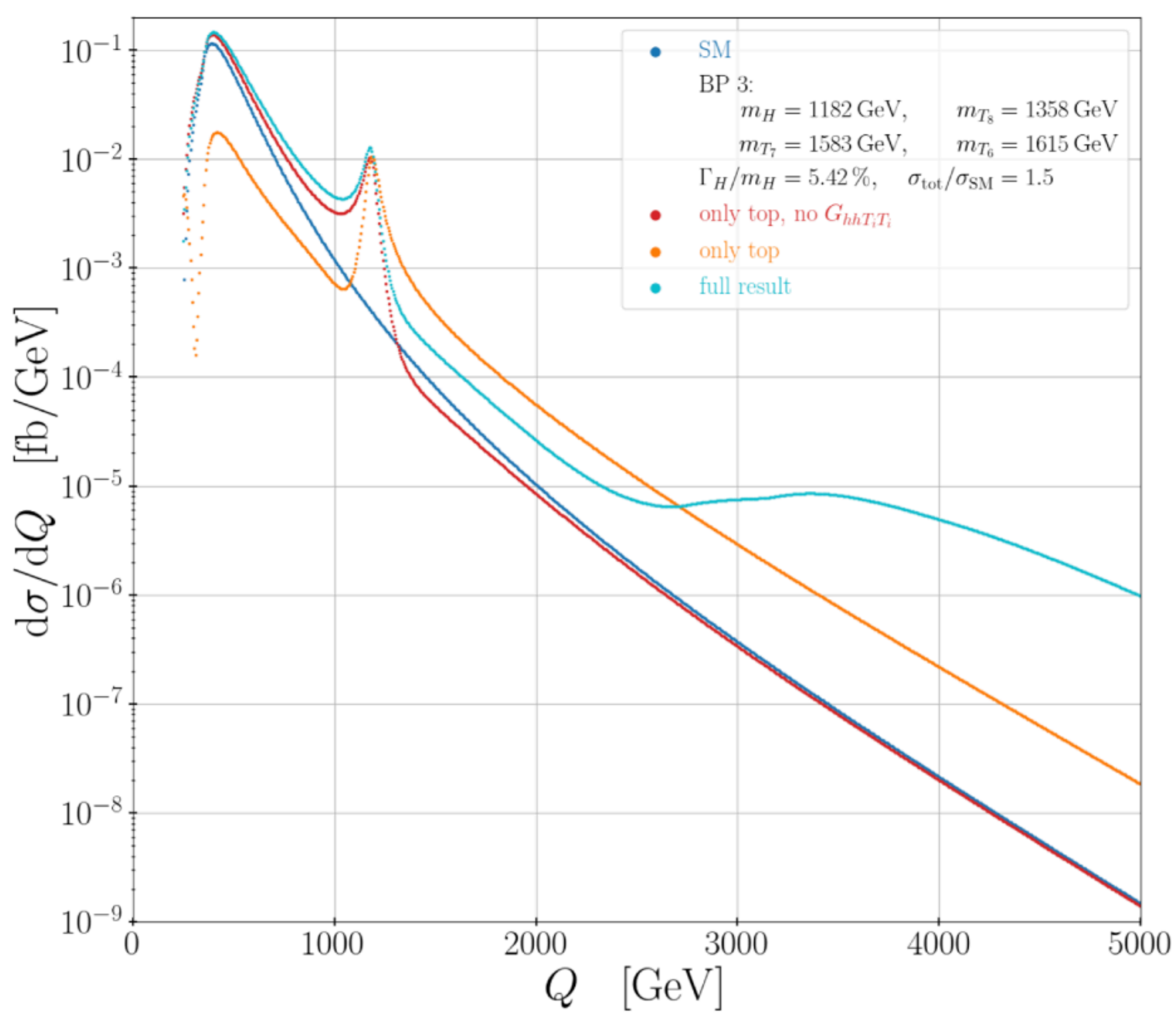
[ATLAS,2211.0121]

Invariant mass distributions

SM result

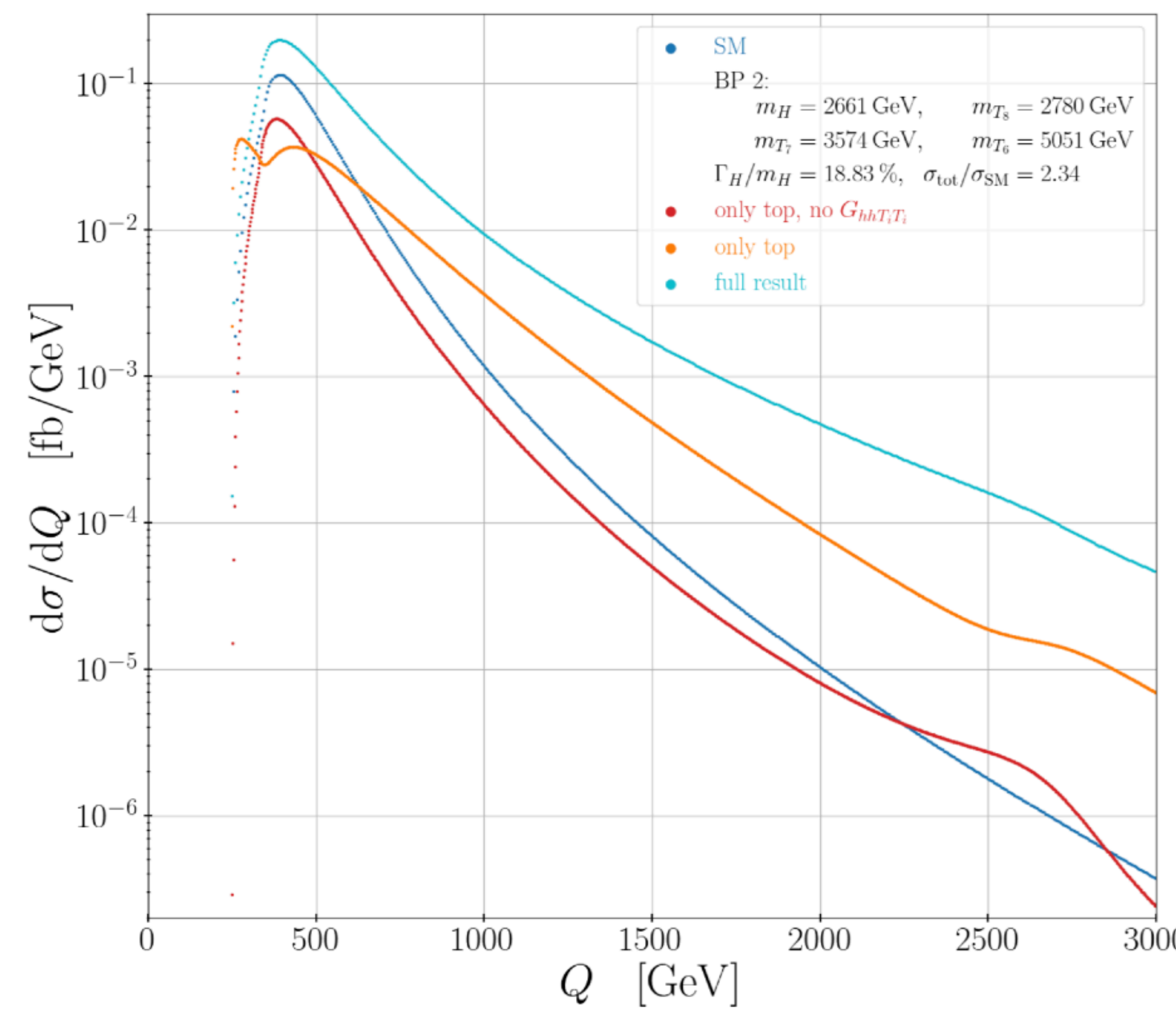
Full result

Resonant case



Nonresonant case

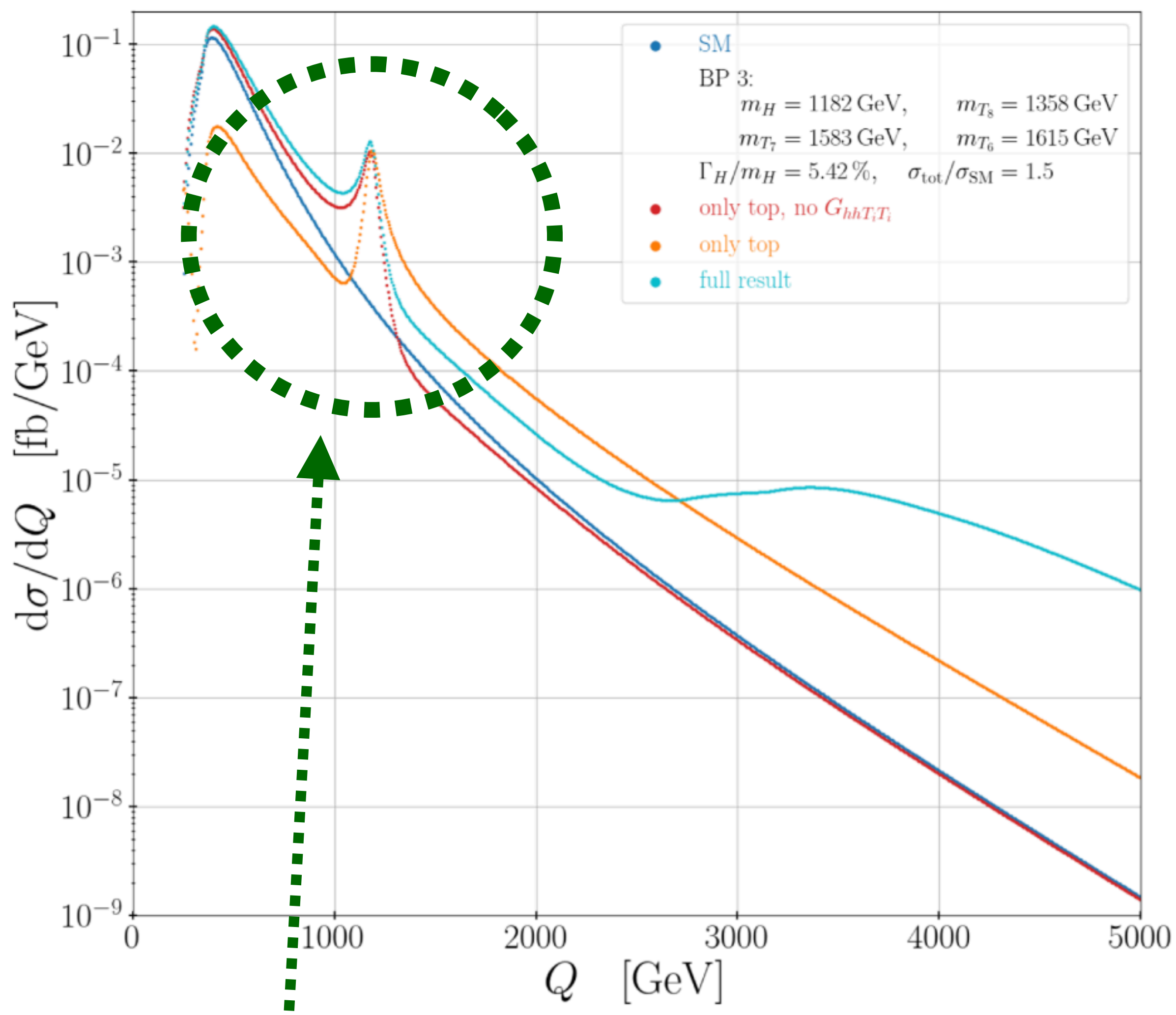
[De Curtis, Delle Rose, Egle,Mühlleitner, Moretti, KS]



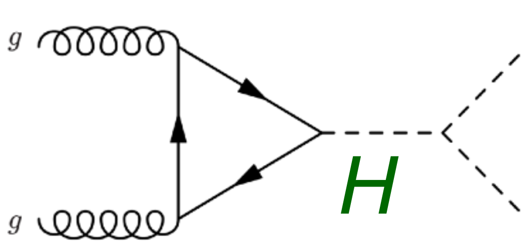
Invariant mass distributions

SM result
Full result

Resonant case



BW distortion



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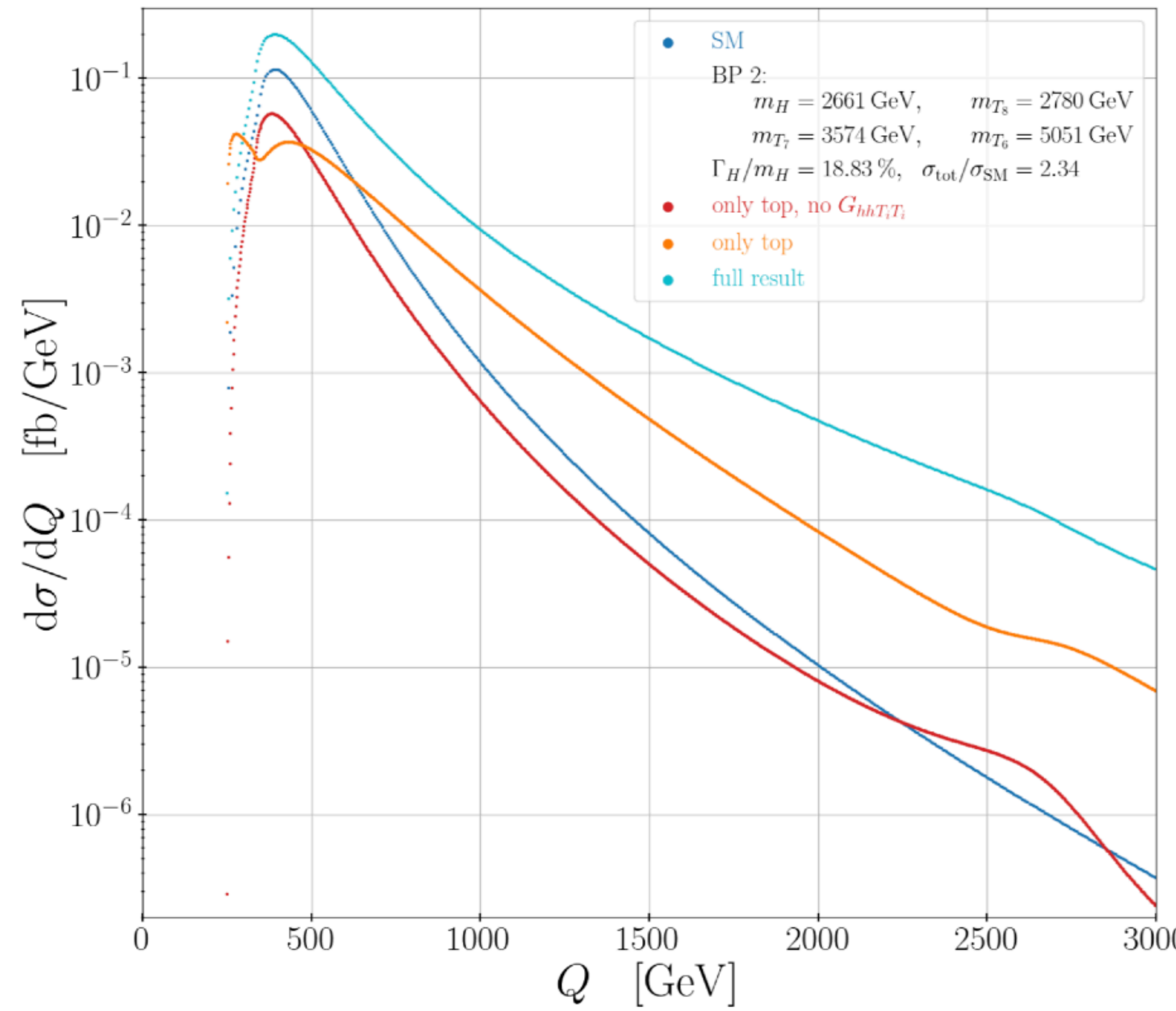

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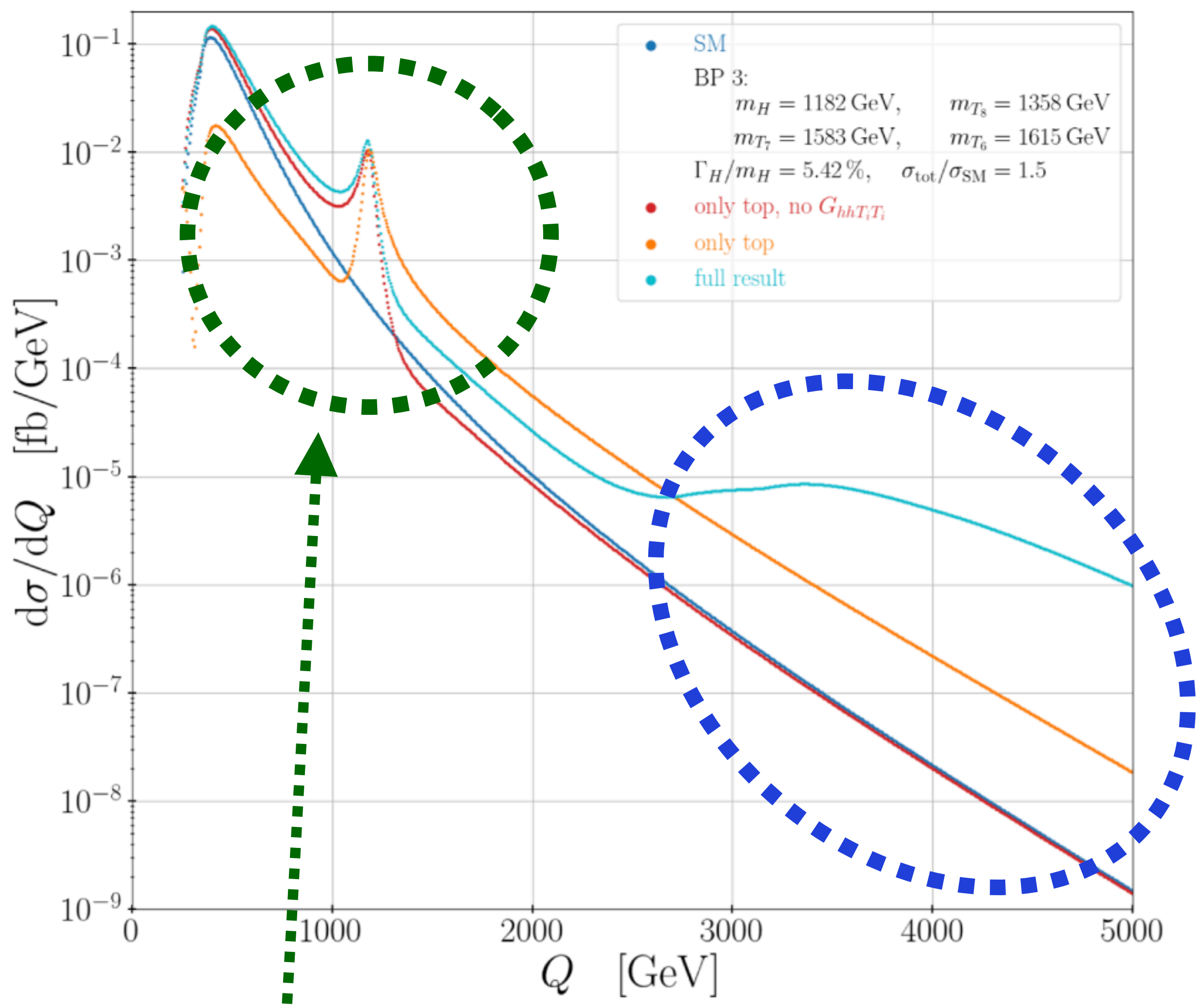
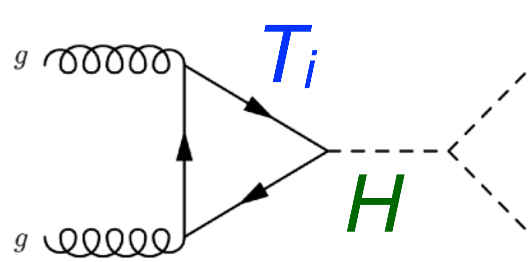
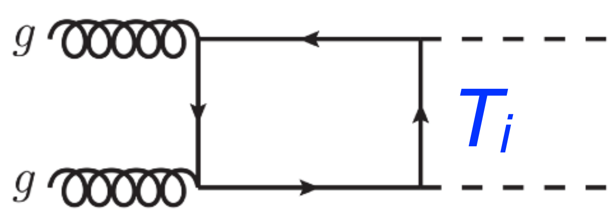


BW distortion

Tail efect





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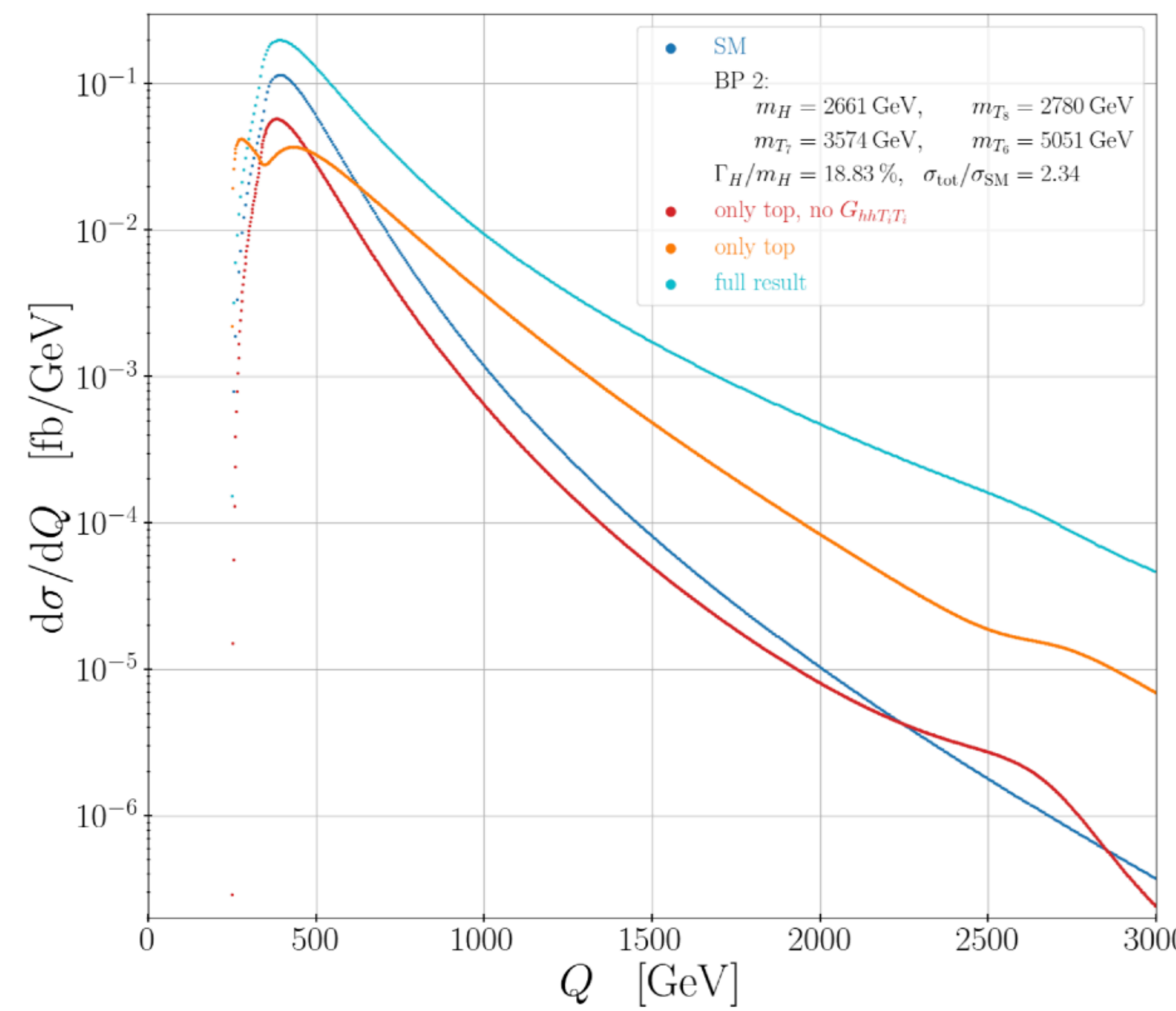

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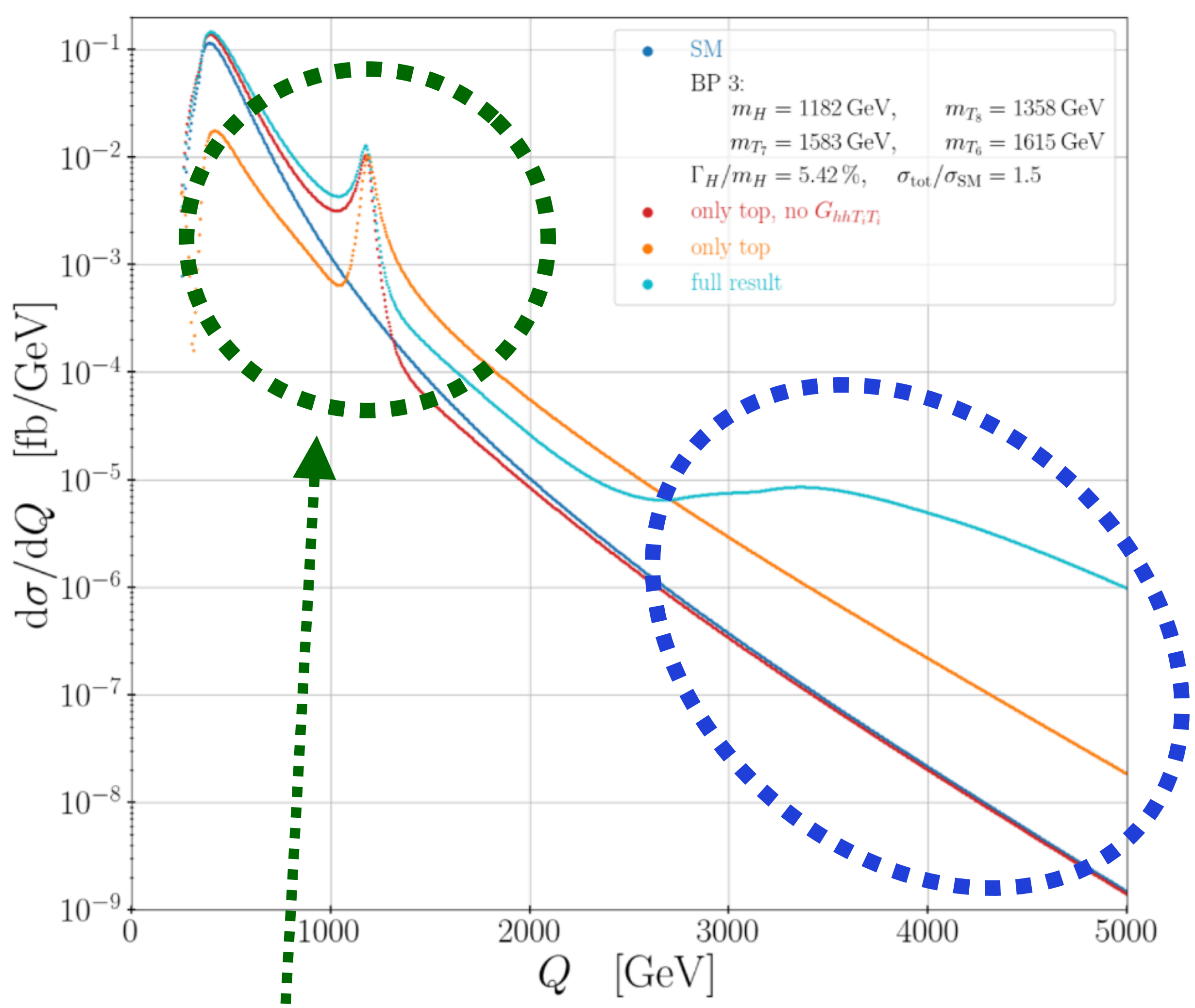

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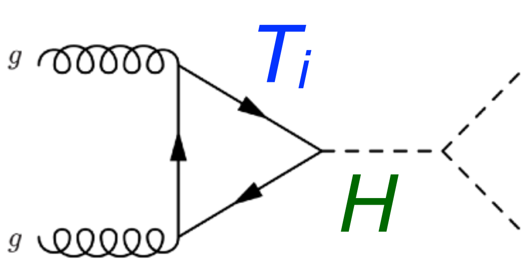
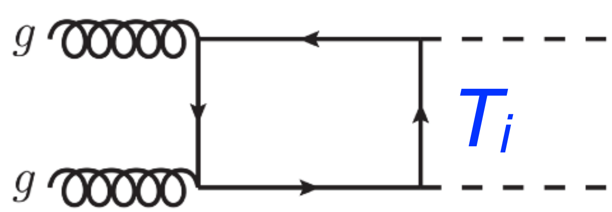
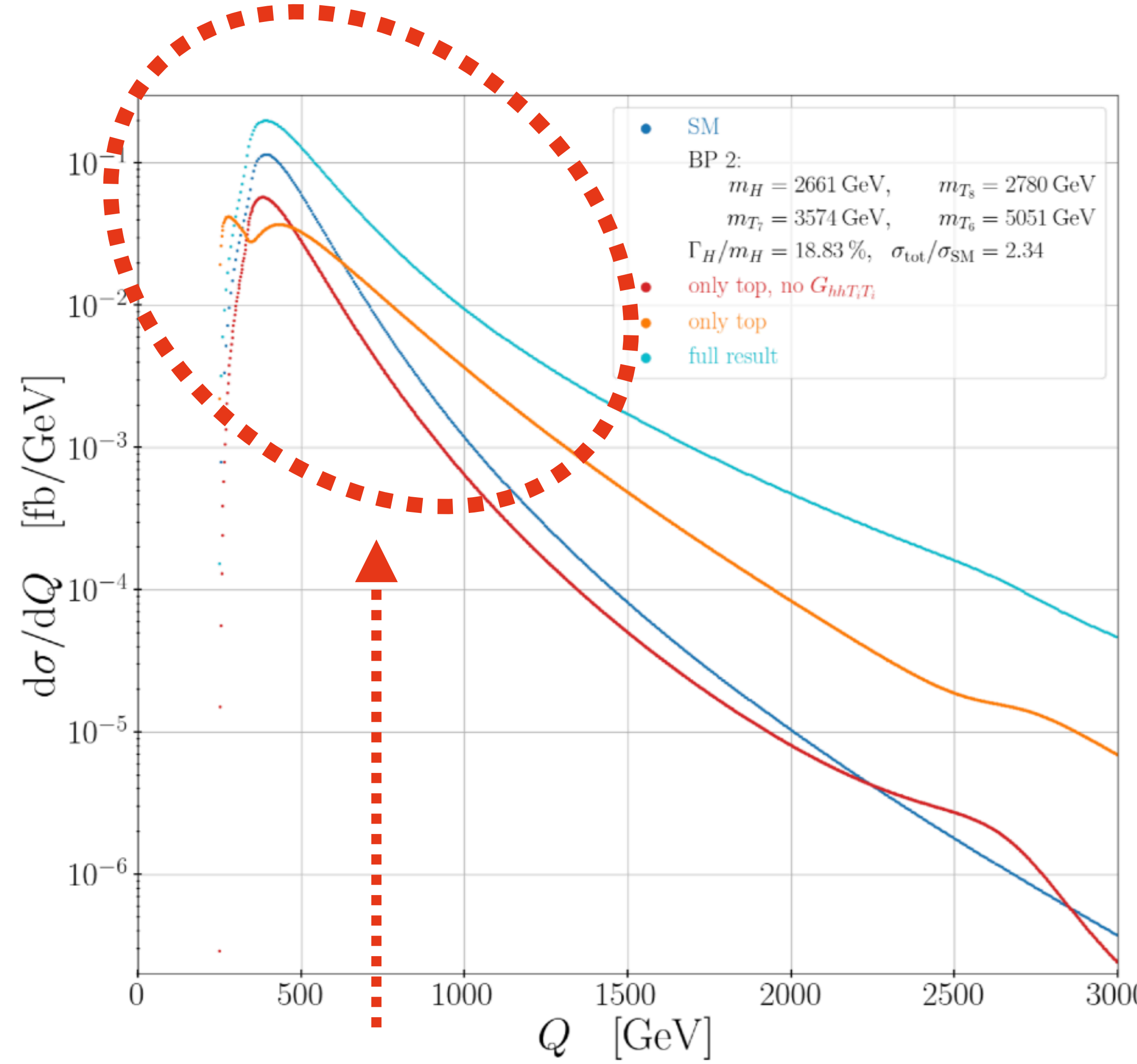


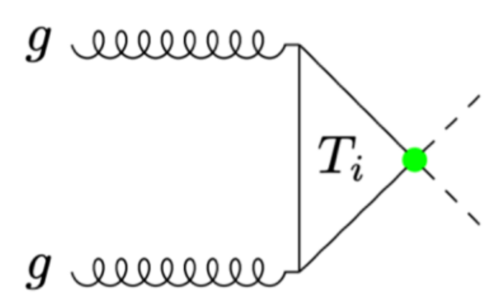


Nonresonant case

[De Curtis, Delle Rose, Egle,Mühlleitner, Moretti, KS]



Enhancement in low mass



Large $G_{hhT_iT_i}$

(dosesn't vanish in $Q \gg v$.)

Comparison with elementary 2HDM

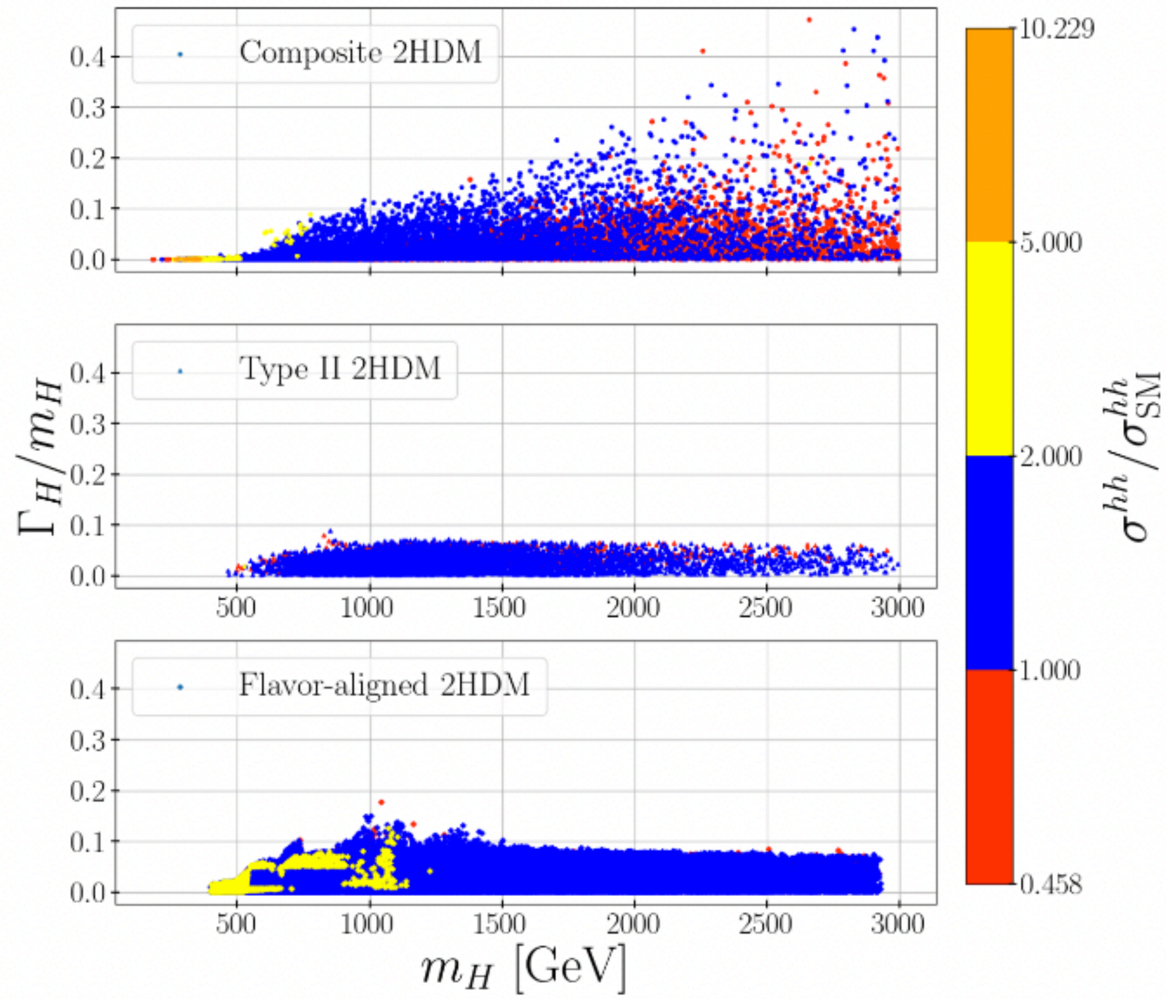
Maximum of $\sigma^{H_1H_1}$

[JHEP09(2022)011]

	H_1	$\frac{\sigma^{H_1H_1}}{\sigma_{SM}}$
R2HDM-I	444	~12
R2HDM-II	81	~ 2

Decay width of H

[De Curtis, Delle Rose, Egle,Mühlleitner, Moretti, KS]



- The maximum of the σ^{hh}_{C2HDM} is close to type-I.
- Γ_H^{C2HDM} glows in $m_H \gg v$ because of $H \to tT_i$.

Comparison with elementary 2HDM

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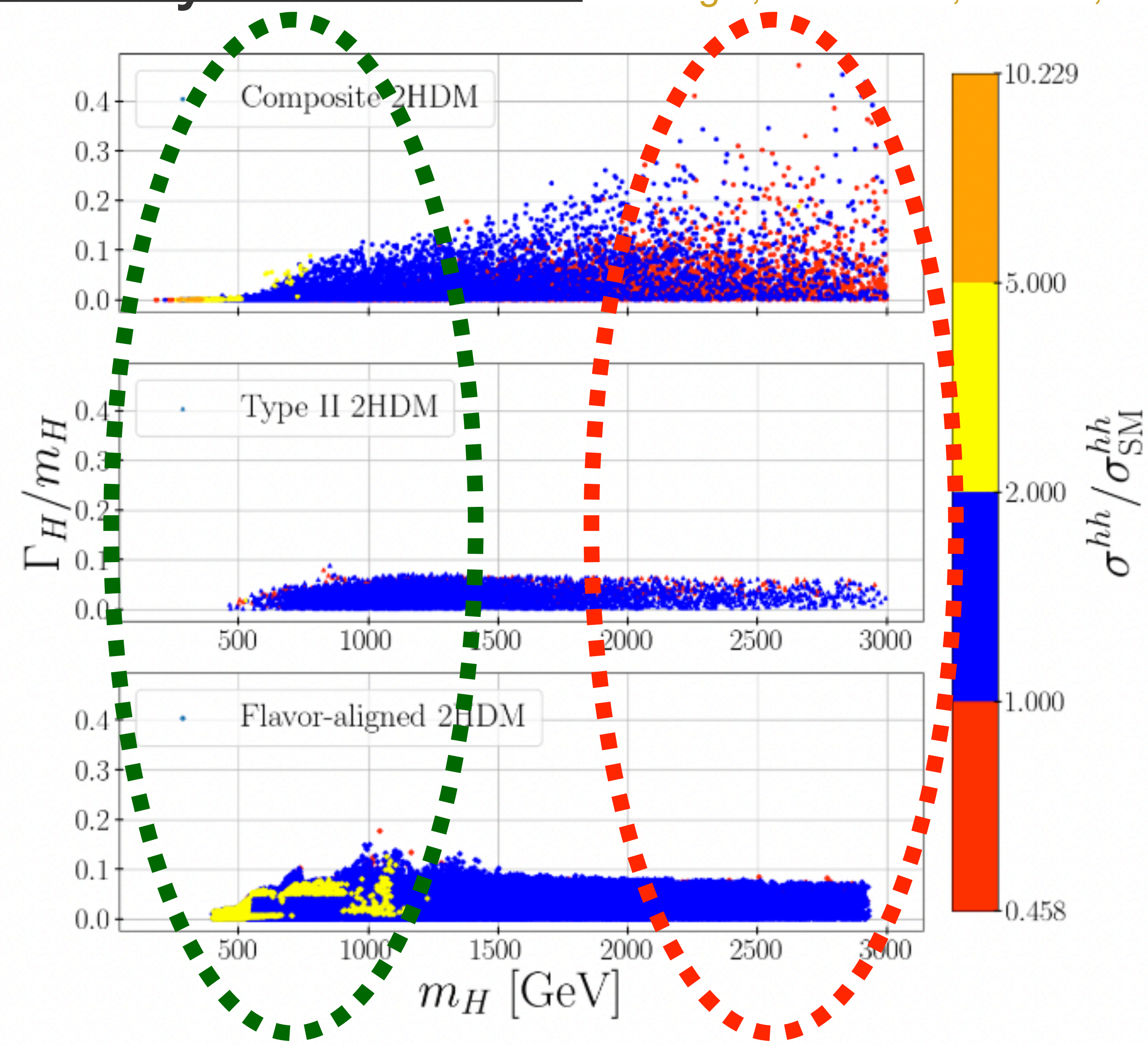


- The maximum of the σ^{hh}_{C2HDM} is close to type-I.
- Γ_H^{C2HDM} glows in $m_H \gg v$ because of $H \to tT_i$.

➡ Difference in σ^{hh} or in Γ_H may distinguish C2HDM from E2HDM

Summary

- We studied di-Higgs production process in C2HDM.
- Heavy CP-even Higgs (H) and heavy top partner (T_i) give additional contributions to the process.
- These two effects are basically complementary. They become important in different parameter spaces.
- By precision measurements of di-Higgs production, one can get a clue to find compositeness.

Back up

Effective lagrangian

For $pp \to hh$, interactions for top and Higgs are only needed.

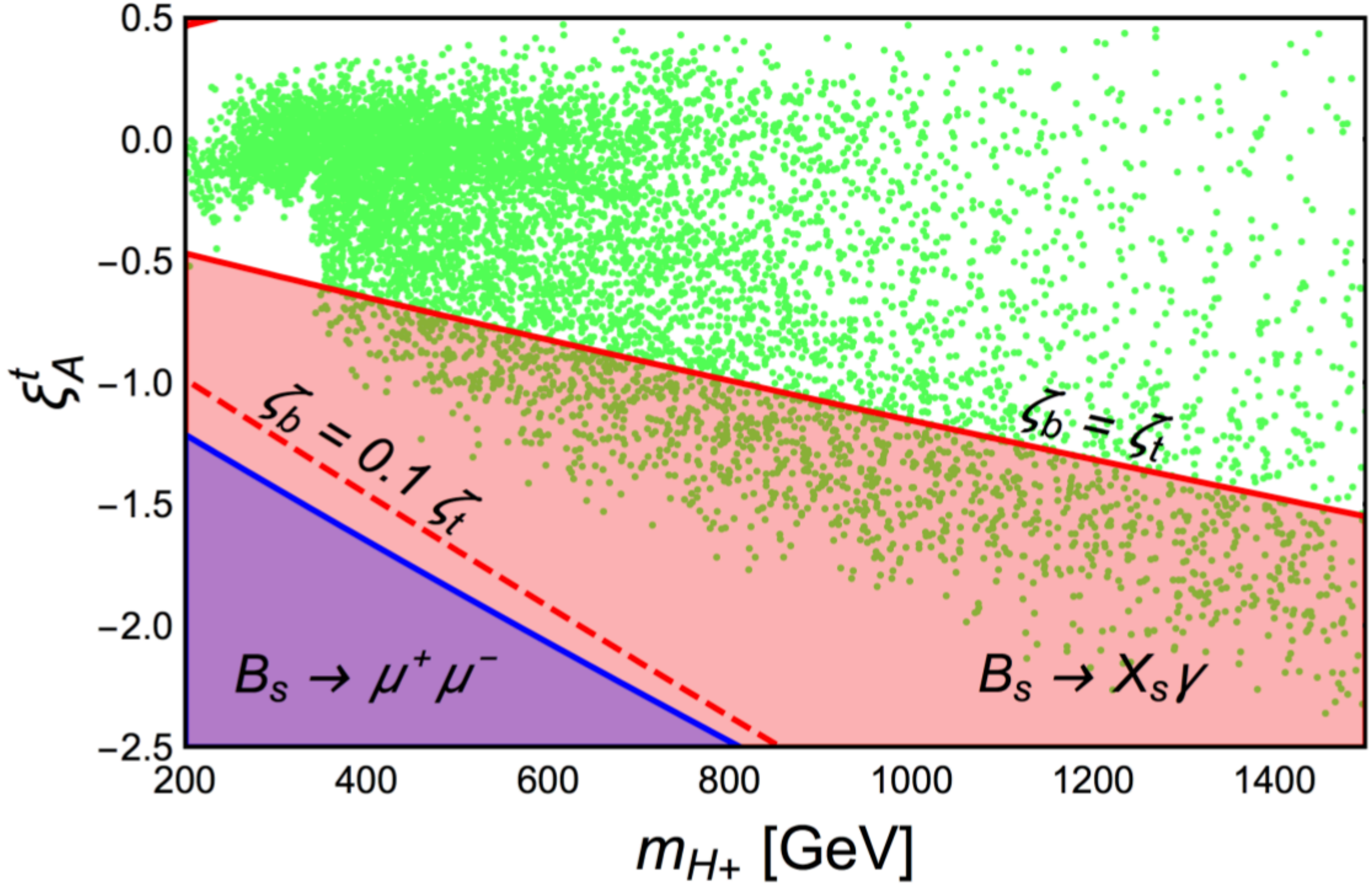
$$\mathcal{L}_{\rm Yuk} = - G_{h\bar{T}_i T_j} \bar{T}_{Li} T_{Rj} h - G_{H\bar{T}_i T_j} \bar{T}_{Li} T_{Rj} H + \text{h.c.}$$
$$- \underbrace{G_{hhT_iT_i} \bar{T}_i T_i h^2} - \underbrace{G_{HHT_iT_i} \bar{T}_i T_i H^2} + \cdots ,$$

$$\mathcal{L}^{\rm int}_{\rm scalar} = - \frac{1}{3!}\lambda_{hhh} h^3 - \frac{1}{2}\lambda^{(1)}_{hhH} h^2 H$$
$$+ \underbrace{\frac{v}{3f^2}(s_\theta\, \partial_\mu h + c_\theta\, \partial_\mu H)(H\partial^\mu h - h\partial^\mu H)} + \cdots ,$$
$$\equiv \lambda^{(2)}_{hhH} hhH + \lambda^{(2)}_{hHH} hHH$$

The couplings G_{hhTT}, G_{HHTT}, $\lambda^{(2)}_{hhH}$, $\lambda^{(2)}_{hHH}$ appears due to nonlinearlities.

b —> s γ constraint

[S. De Curtis, et al, JHEP 12 (2018) 051]



- Green points are allowed by current direct and indirect searches at the LHC.
- By taking $\xi_b = 0.1\xi_t$, the constraint becomes weaker.

Lagrangian of the strong sector for spin-1/2 resonances Ψ_I

$$\mathcal{L}^{\rm ferm}_{\rm strong} + \mathcal{L}^{\rm ferm}_{\rm mix} = \bar{\Psi}^I i \not{D} \Psi^I + [-\bar{\Psi}^I_L M^{IJ}_\Psi \Psi^J_R - \bar{\Psi}^I_L (Y^{IJ}_1 \Sigma + Y^{IJ}_2 \Sigma^2) \Psi^J_R$$
$$+(\Delta^I_L \bar{q}^{\mathbf{6}}_L \Psi^I_R + \Delta^I_R \bar{t}^{\mathbf{6}}_R \Psi^I_L)] + \text{h.c.},$$

$$\Sigma = U \Sigma_0 U^T$$

$$U = e^{i\frac{\Pi}{f}}, \quad \Pi \equiv \sqrt{2}\phi^{\hat{a}}_i T^{\hat{a}}_i = -i \begin{pmatrix} 0_{4\times 4} & \mathbf{\Phi} \\ -\mathbf{\Phi}^T & 0_{2\times 2} \end{pmatrix}, \quad \Phi_i = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^{\hat{2}}_i + i\phi^{\hat{1}}_i \\ \phi^{\hat{4}}_i - i\phi^{\hat{3}}_i \end{pmatrix}.$$

$$q^{\mathbf{6}}_L = \frac{1}{\sqrt{2}} \begin{pmatrix} ib_L \\ b_L \\ it_L \\ -t_L \\ 0 \\ 0 \end{pmatrix}, \qquad t^{\mathbf{6}}_R = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ c_{\theta_t} \\ i s_{\theta_t} \end{pmatrix} t_R, \qquad \Psi = \begin{pmatrix} \psi_4 \\ \psi_2 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} iB_{-1/3} - iX_{5/3} \\ B_{-1/3} + X_{5/3} \\ iT_{2/3} + iX_{2/3} \\ -T_{2/3} + X_{2/3} \\ \sqrt{2}\tilde{T}_1 \\ \sqrt{2}\tilde{T}_2 \end{pmatrix},$$

- To ensure the finiteness of the effective potential, two spices of Ψ_i are needed.
- The mixing angle θ_t is chosen as $\theta_t = 0$ to insure the CP conservation.

Lagrangian of the gauge sector

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

$$D_\mu U_1 = \partial_\mu U_1 - iA_\mu U_1 + iU_1\rho_\mu,$$
$$D_\mu \Sigma_2 = \partial_\mu \Sigma_2 - i[\rho_\mu, \Sigma_2],$$

$$A_\mu \equiv A_\mu^A T^A + X_\mu T^X$$

$$\rho_\mu \equiv \rho_\mu^A T^A + \rho_\mu^X T^X$$

ρ_A and ρ_X are spin-1 resonances

T_A and T_X are geberator of SO(6) and U(1)X

Scan range of the composite parameters

$$f = [700,\ 3000]\ \mathrm{GeV}, \quad g_\rho = [2, 10]$$

$$\Delta^I_{L,R} = [-10, 10] \times f, \quad Y^{IJ}_{1,2} = [-10, 10] \times f$$

Branching ratios of the heavy Higgs boson H