[JHEP 06 (2024) 063]

Double Higgs production in composite two Higgs doublet model

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LCWS2024, July 10th

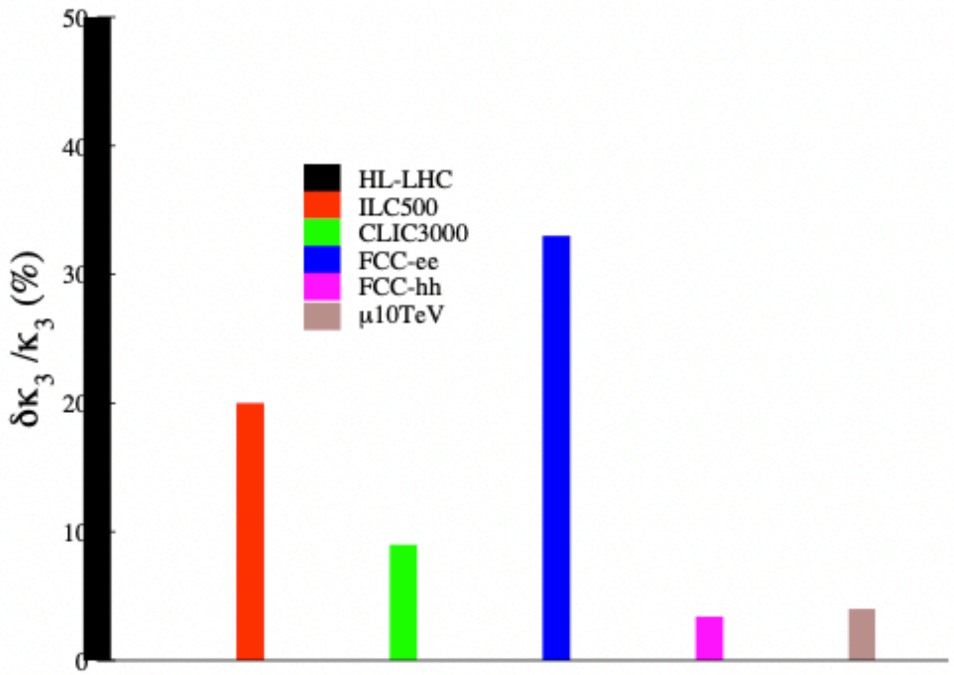
Measurements of the Higgs boson self-coupling

- Current LHC measurements indicate that the properties of the discovered Higgs boson is SM-like.
- However, the Higgs self-coupling is not measured accurately.

ATLAS: $-0.4 < \lambda_{hhh}/\lambda_{hhh}^{\rm SM} < 6.3$ [ATLAS-CONF-2022-050]

CMS: $-1.7 < \lambda_{hhh}/\lambda_{hhh}^{\rm SM} < 8.7$ [Phys.Lett.B 842 (2023) 137531]

- In future experiments, it will be measured with better accuracy.



[Dawson, Meade, Ojalvo, et. al, 2209.07510]

Probe of Higgs sector by Di-Higgs production

- The self-coupling is determined by measuring di-Higgs production $pp \to hh$.
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- Origin of electroweak symmetry breaking
- Structure of the Higgs sector
- Nature of the Higgs boson (Elementary, composite)

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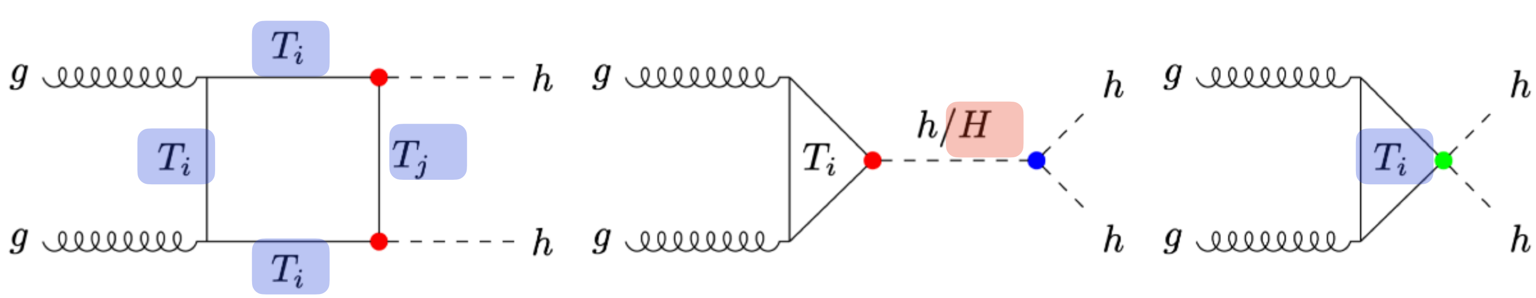
<u>New physics contributions for Di-Higgs producrion:</u>



1. Heavy fermion loop
2. Additional Higgs boson loop

→We focus on Composite Two Higgs doublet model (C2HDM). [S. De Curtis, et al, JHEP 12 (2018) 051]

- How much these new physics effects can enhance $\sigma_{pp\to hh}$?
- How the correlation between $\sigma_{pp\to hh}$ and λ_{hhh} looks like ?

Composite two Higgs doublet model (C2HDM) [1/2]

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

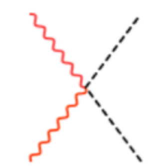
- Symmetry: $\dfrac{\mathcal{G}}{\mathcal{H}} = \dfrac{\mathrm{SO}(6)}{\mathrm{SO}(4)\times\mathrm{SO}(2)},$ Broken generators：8 (=15-7)

  → 8 NGBs (=2HDM d.o.f) $h, G^0, G^\pm, H, A, H^\pm$

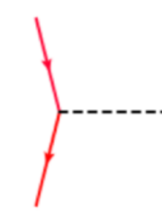
- Lagrangian: $\mathscr{L}_{\mathrm{C2HDM}} = \mathscr{L}_{\mathrm{elementary}} + \mathscr{L}_{\mathrm{mixing}} + \mathscr{L}_{\mathrm{strong}}$

  $= \mathscr{L}_{2HDM} + \mathscr{L}_{d\gtrsim 6}$ (After integrating out heavy resonances)

$\mathscr{L}_{\mathrm{elementary}}$: consists of SM gauge fields and matter fields.

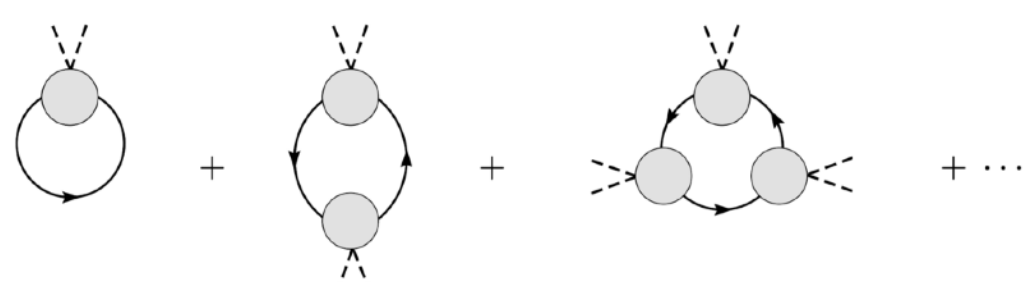


$\mathscr{L}_{\mathrm{strong}}$: contains interaction between NGB and heavy resonance.



$\mathscr{L}_{\mathrm{mix}}$: interaction $\mathscr{L}_{\mathrm{elementary}}$ between $\mathscr{L}_{\mathrm{strong}}$.

Higgs masses and self-coupling are generated through Coleman-Weinberg potential.



The potential is described by the parameters in the composite sector.

Composite two Higgs doublet model (C2HDM) [2/2]

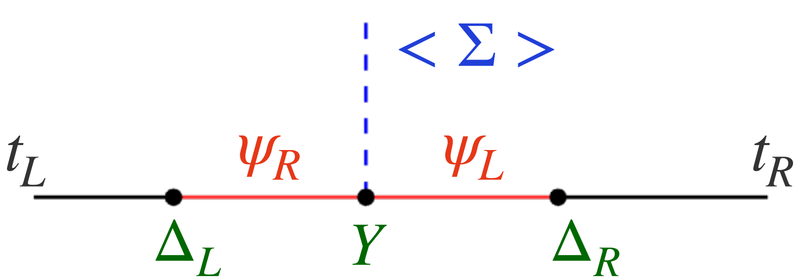
Fermion sector (Σ: NGB fields)

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

$$q^{\mathbf{6}T}_L = \frac{1}{\sqrt{2}}(ib_L, b_L, it_L, -t_L, 0, 0) \qquad q^{\mathbf{6}T}_R = \frac{1}{\sqrt{2}}(0,0,0,0,1,1)t_R$$
$$\psi^T = \frac{1}{\sqrt{2}} = (iB_{-1/3} - iX_{5/3}, B_{-1/3} + X_{5/3}, iT_{2/3} + iX_{2/3}, -T_{2/3} + X_{2/3}, \sqrt{2}\tilde{T}_1, \sqrt{2}\tilde{T}_2)$$

Top partners(4): $T_{2/3}$, $X_{2/3}$, $\tilde{T}_1$, $\tilde{T}_2$ Bottom partners(1): $B_{-1/3}$, Exotic fermion (1): $X_{5/3}$

- SO(6) is explicitly braked by the linear mixing between $q^6_{L/R}$ and $\psi_{L/R}$.
- SM fermion mass terms are generated by the Yukawa interaction and the linear mixing.



$$\sim \frac{\Delta_L \Delta_R}{M^2_\psi}(Y_1 s_\beta + Y_2 c_\beta) v_{\rm SM} \equiv y_t v_{\rm SM}$$

- Two $\psi_{L/R}$ fields are introduced. ➡ 8 heavy top partners contribute to $pp \to hh$.

Di Higgs production cross section

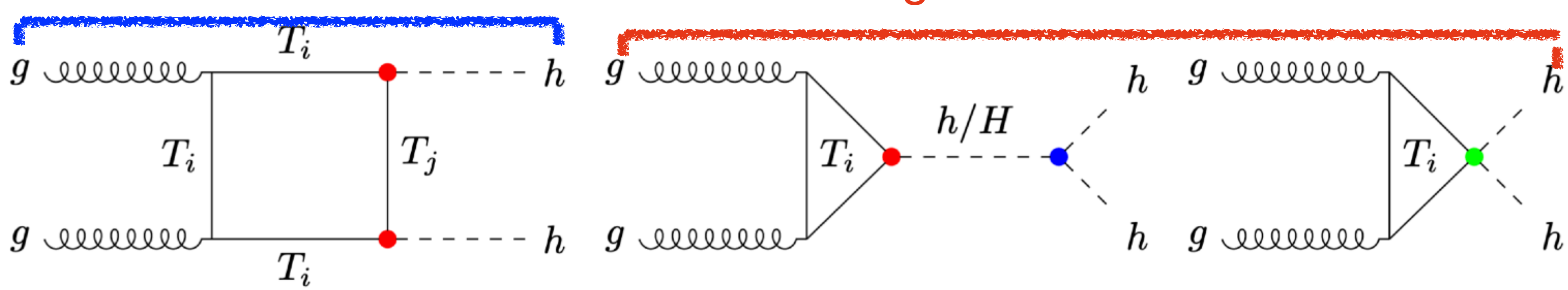
$$
\begin{aligned}
\frac{d\hat{\sigma}(gg \to hh)}{d\hat{t}} =& \frac{\alpha_s^2}{512(2\pi)^3} \\
&\times \Bigg[\Bigg| \sum_{i=1}^{n_q} C_{i,\triangle}^{hh} F_{\triangle}(m_i) + \sum_{i=1}^{n_q}\sum_{j=1}^{n_q} \left(C_{ij,\Box}^{hh} F_{\Box}^{hh}(m_i,m_j) + C_{ij,\Box,5}^{hh} F_{\Box,5}^{hh}(m_i,m_j)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

Spin-0 contributions

Spin-2 contributions

- Feynman diagrams

Box Triangle



box diagrams involve contributions of off-diagonal coupling.

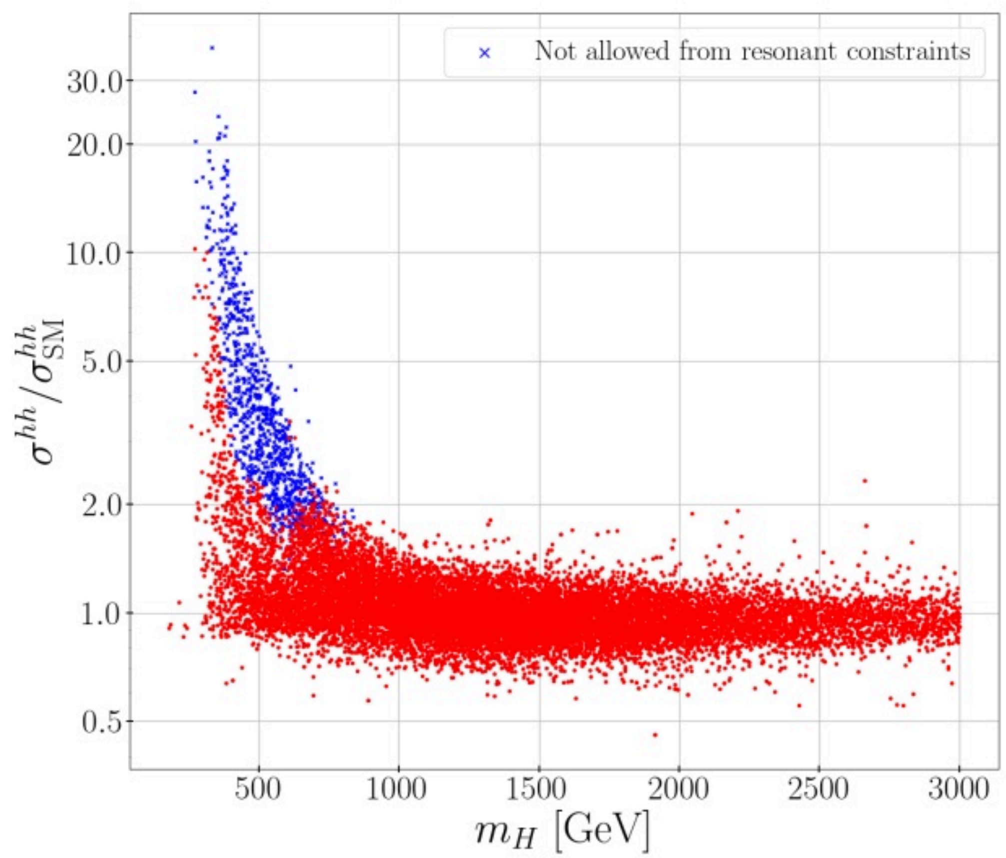
- Heavy mass limit [T. Plehn, M. Spira, P. M. Zerwas, Nucl.Phys.B 479 (1996) 46]

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

Spin-0 contributions is dominant.

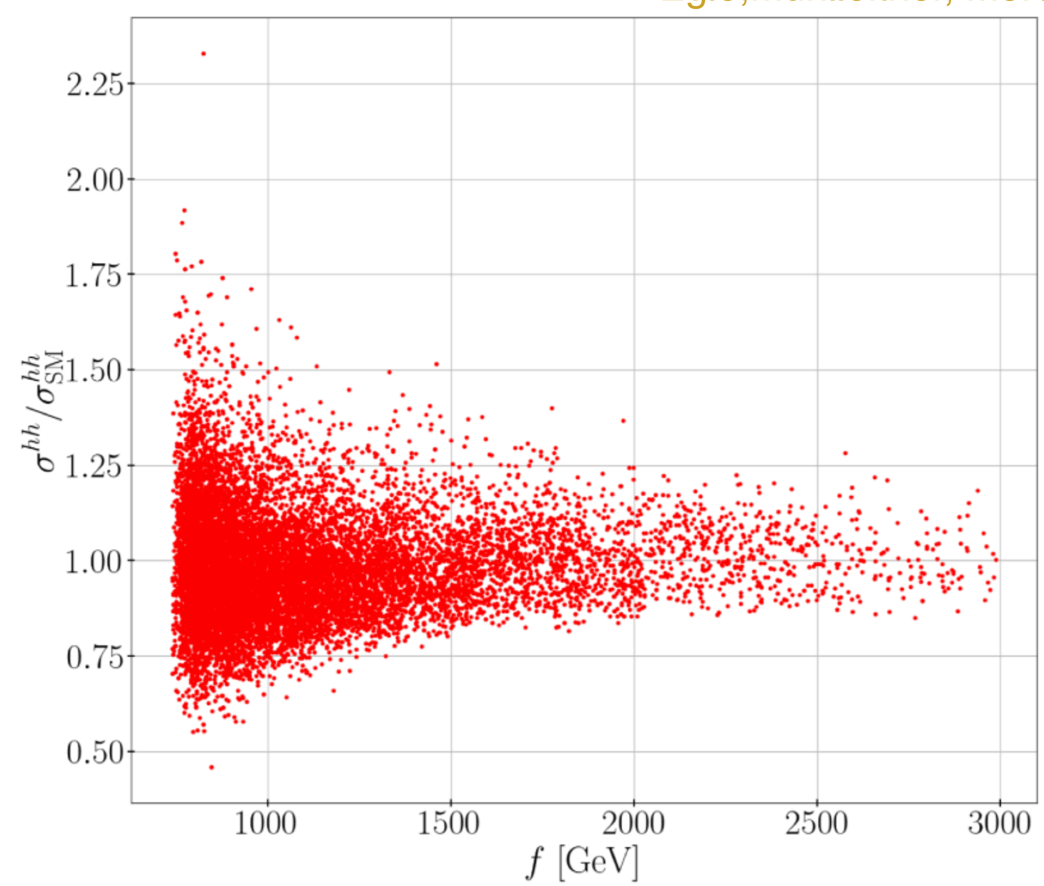
Numerical results: Di-Higgs production cross section

Resonant case



Non-resonant case

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



- two distinct scenarios

Resonant case : $\dfrac{\sigma(gg \to H)\times \mathrm{BR}(H\to hh)}{\sigma(gg\to hh)} > 0.1,$ Non-resonant case : $\dfrac{\sigma(gg \to H)\times \mathrm{BR}(H\to hh)}{\sigma(gg\to hh)} < 0.1$

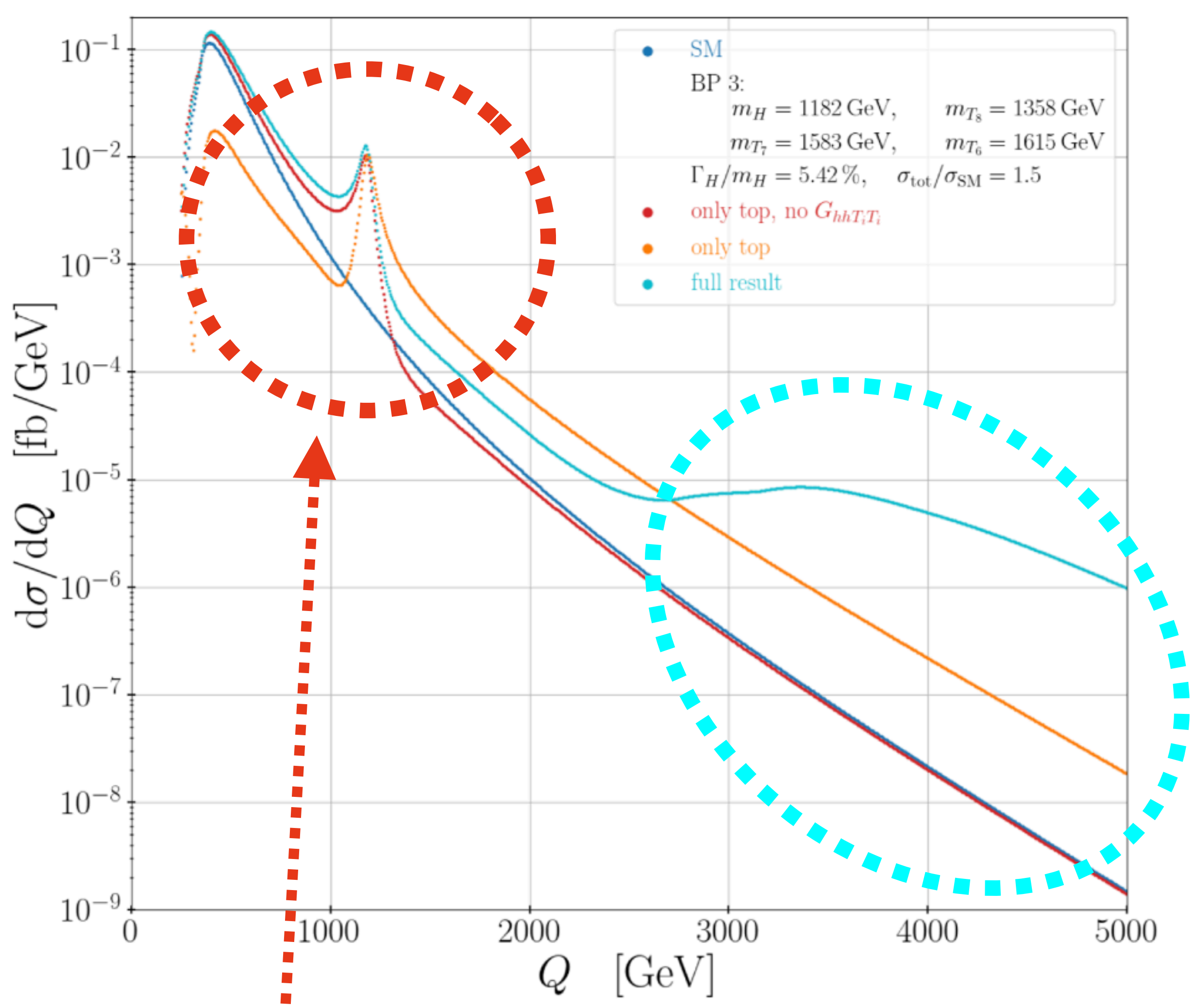
- Constraints : λ_i perturbativity, EW vacuum, H,A,H± direct searches, h couplings $f > 750\mathrm{GeV}$ $(\xi < 0.1)$

→ In resonant case, $\sigma^{hh}/\sigma^{hh}_{\rm SM}$ ~10. In non-resonant case, $\sigma^{hh}/\sigma^{hh}_{\rm SM}$ ~2.3. $\mu_{HH} \lesssim 2.4$ @ATLAS [ATLAS,2211.0121]

Numerical results: Invariant mass distributions

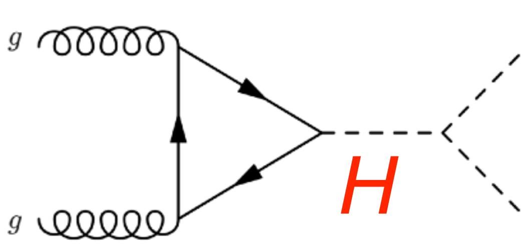
[De Curtis, Delle Rose, Egle,Mühlleitner, Moretti, KS]

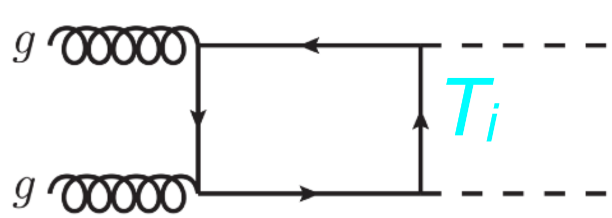
Resonant case



H resonance

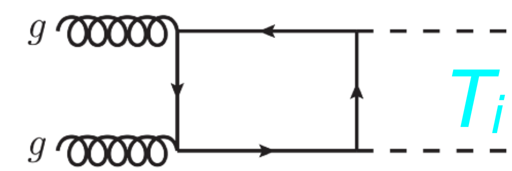
Deviation in Tail

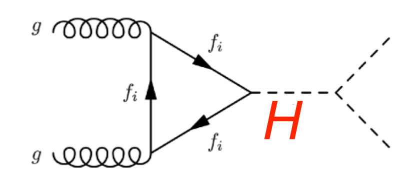


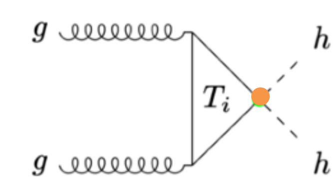


SM

Full

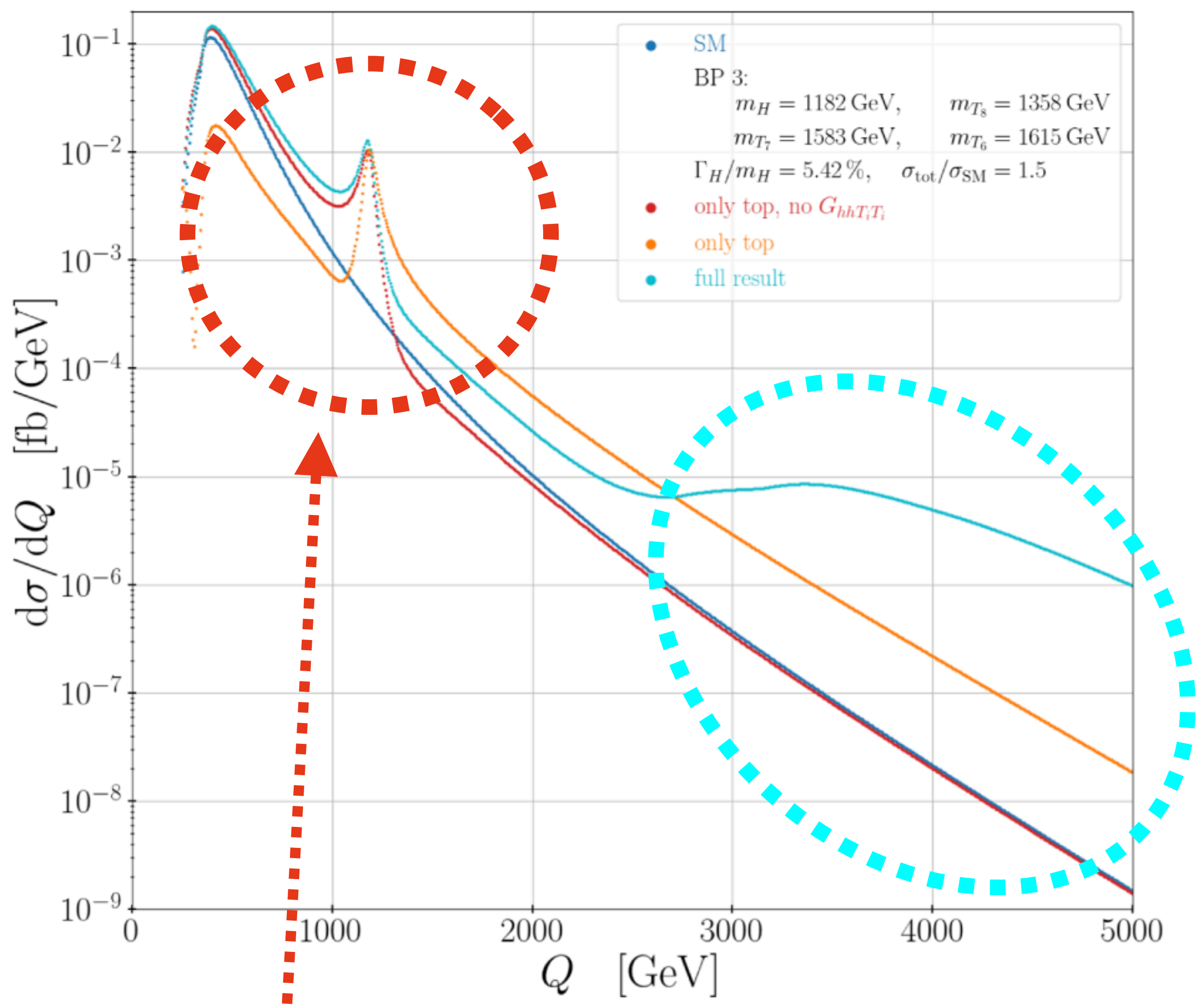






Numerical results: Invariant mass distributions

Resonant case



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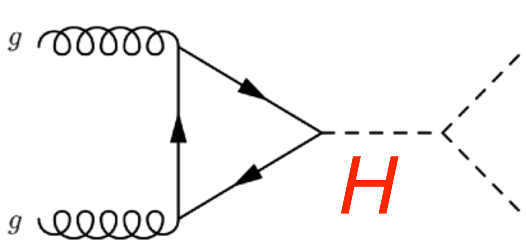
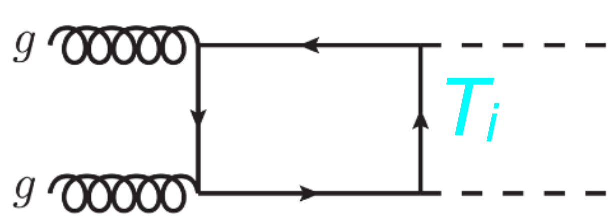
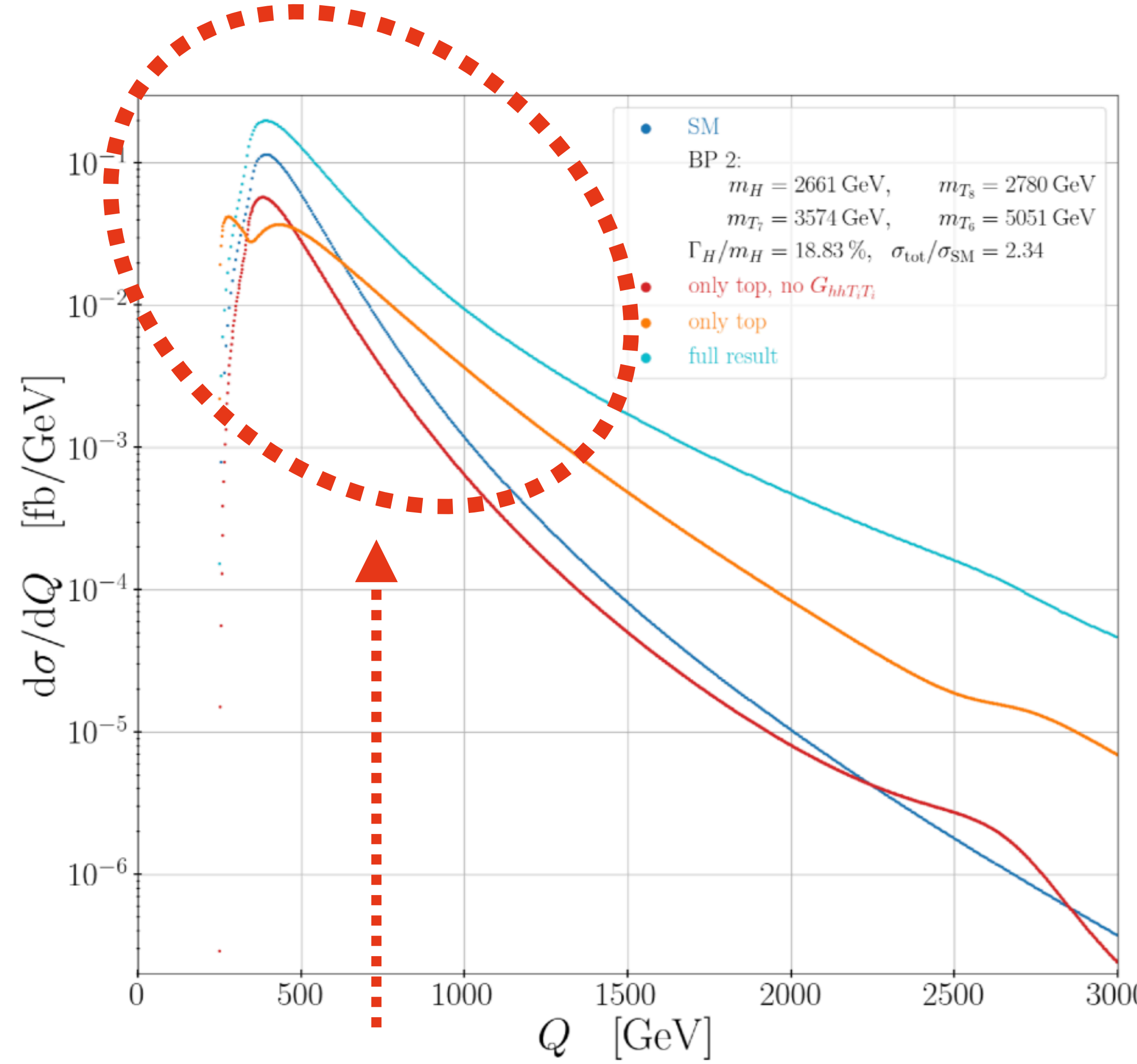


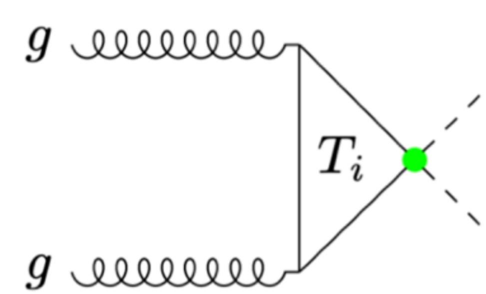


Nonresonant case

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



Deviation in the low mass region

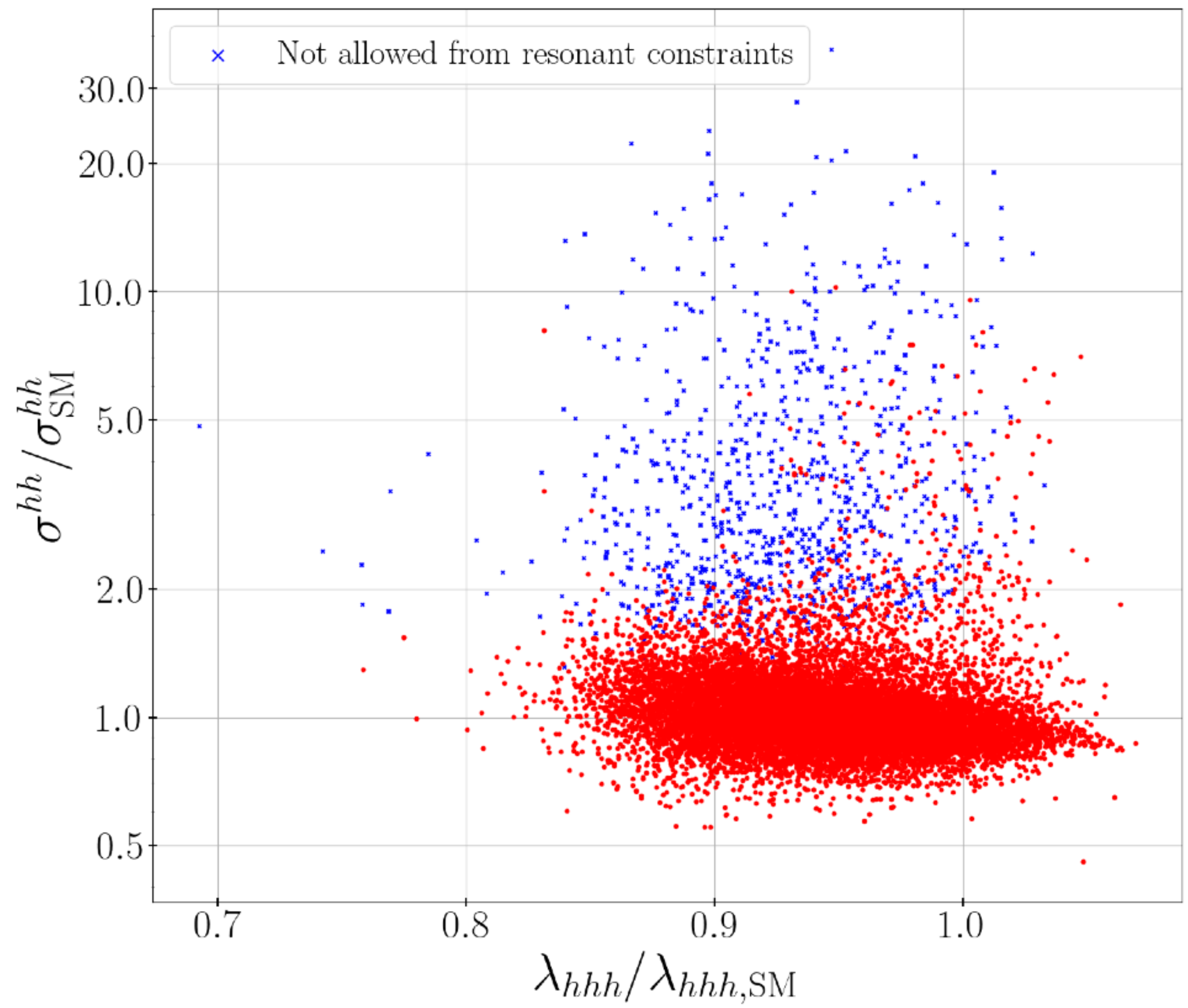


$G_{hhT_iT_i} \sim \mathcal{O}(1)$

(Doesn't suppressed by Q^2)

Correlation between σ_{hh} and λ_{hhh} in C2HDM

[Plot by Felix Egle]



- There is a parameter region where $\sigma^{hh}/\sigma^{hh}_{\rm SM} \sim 1$ but $\lambda_{hhh}/\lambda^{SM}_{hhh} - 1 \sim -20\,\%$.
- In such a parameter region, $\sigma(e^+e^- \to hhZ)$ can deviate from the SM.

→ Even if $\sigma^{hh}/\sigma^{hh}_{\rm SM} \sim 1$, one may be able to survey compositeness by measuring $e^+e^- \to hhZ$ in future colliders.

Summary

- Di Higgs production $pp \to hh$ is an important observable, by which one can explore the structure of the Higgs sector.

- We discussed the new physics effects of the di-Higgs production rate in C2HDM.

- In the resonant case, $\sigma^{hh}/\sigma^{hh}_{\rm SM}$ ~ 10 due to *H* contributions. In the non-resonant case, heavy top-loop contributions are significant ($\sigma^{hh}/\sigma^{hh}_{\rm SM}$~2).

- There is a parameter space where $\sigma_{hh} \sim \sigma_{hh}^{\rm SM}$ but $\lambda_{hhh}/\lambda_{hhh}^{\rm SM} - 1 \simeq -20\,\%$.

Back up

Comparison with elementary 2HDMs

Total cross section $\sigma^{H_1H_1}$

2HDM (Type I): $\sigma_{hh}/\sigma_{hh}^{\rm SM} \sim 12$ [JHEP09(2022)011]

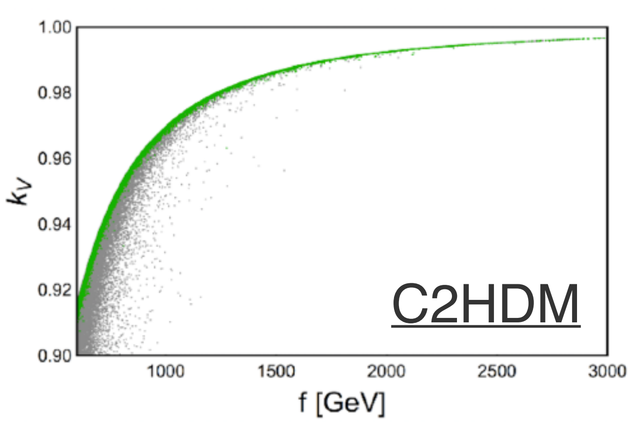
2HDM (Type II): $\sigma_{hh}/\sigma_{hh}^{\rm SM} \sim 2$ [〃]

C2HDM: $\sigma_{hh}/\sigma_{hh}^{\rm SM} \sim 10$

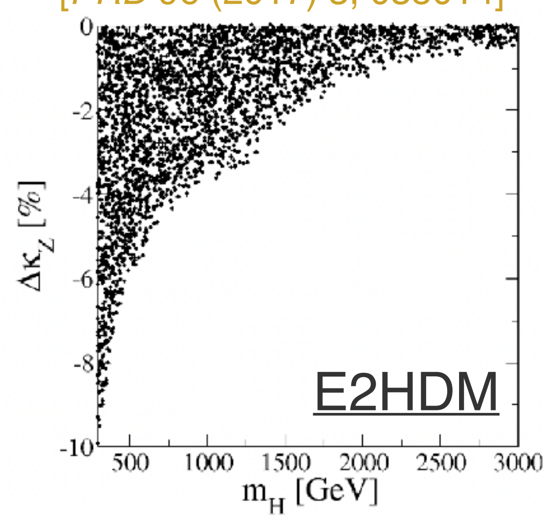
Type II can be separated.

Deviations in h couplings [see also PLB786(2018)189]

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



[*PRD* 96 (2017) 3, 035014]

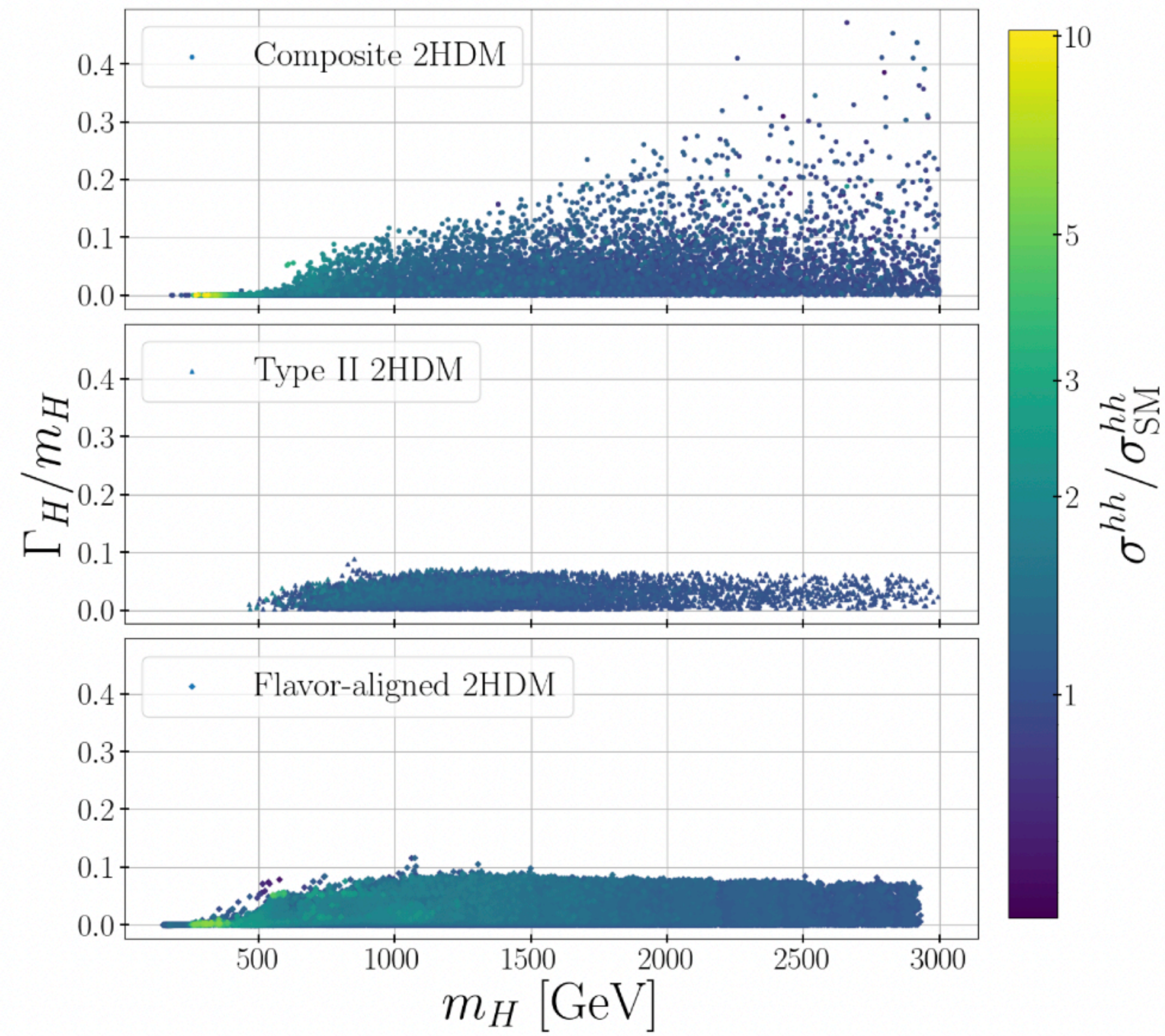


$\kappa_V \sim 1 - v^2/(2f^2)$

$m_H^2 \sim f^2(1+t_\beta^2)/(16\pi^2)$

The correlation between κ_V and m_H is more clear in C2HDM.

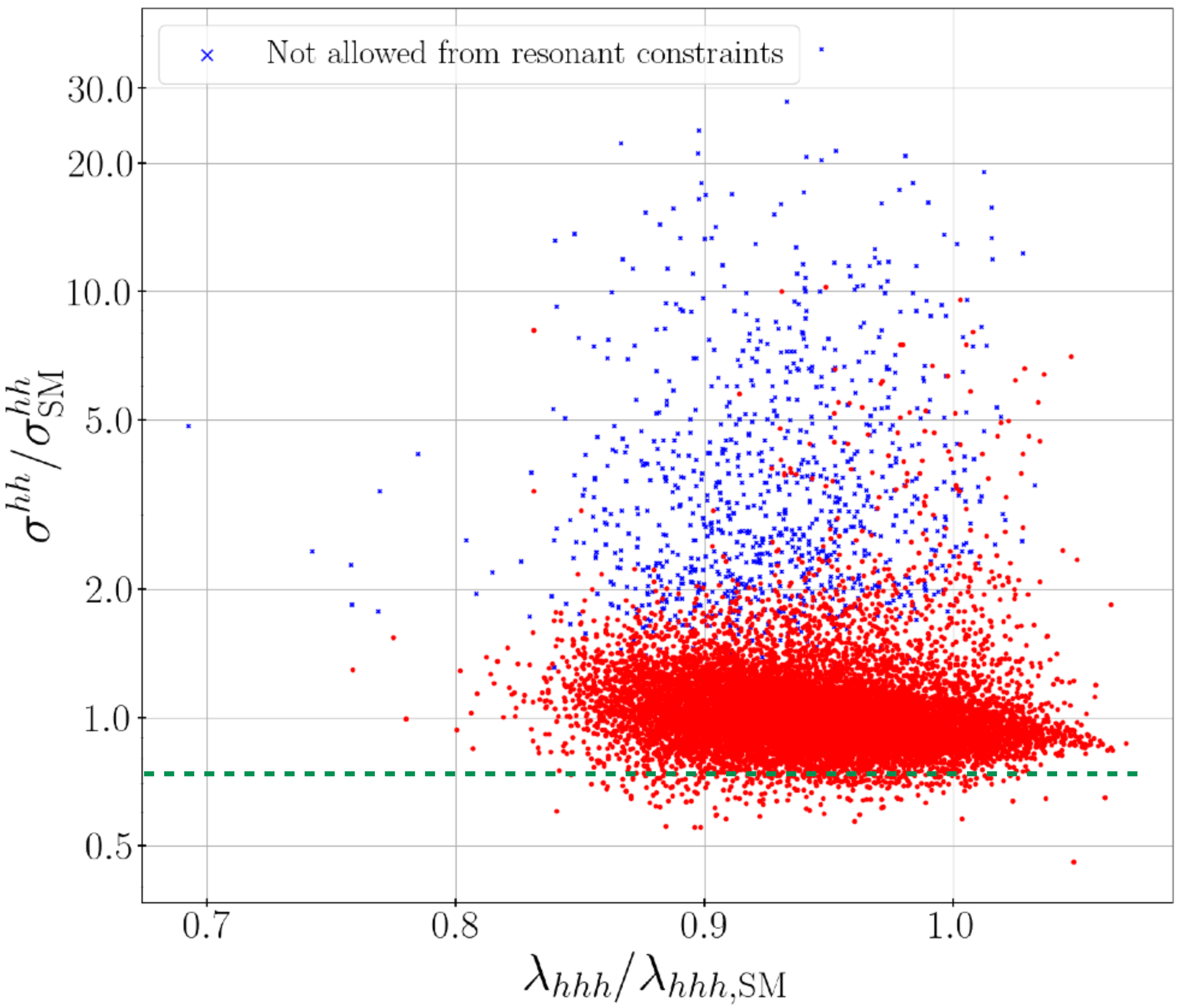
Total width of H [De Curtis, Delle Rose, Egle, Mühlleitner, Moretti, KS]

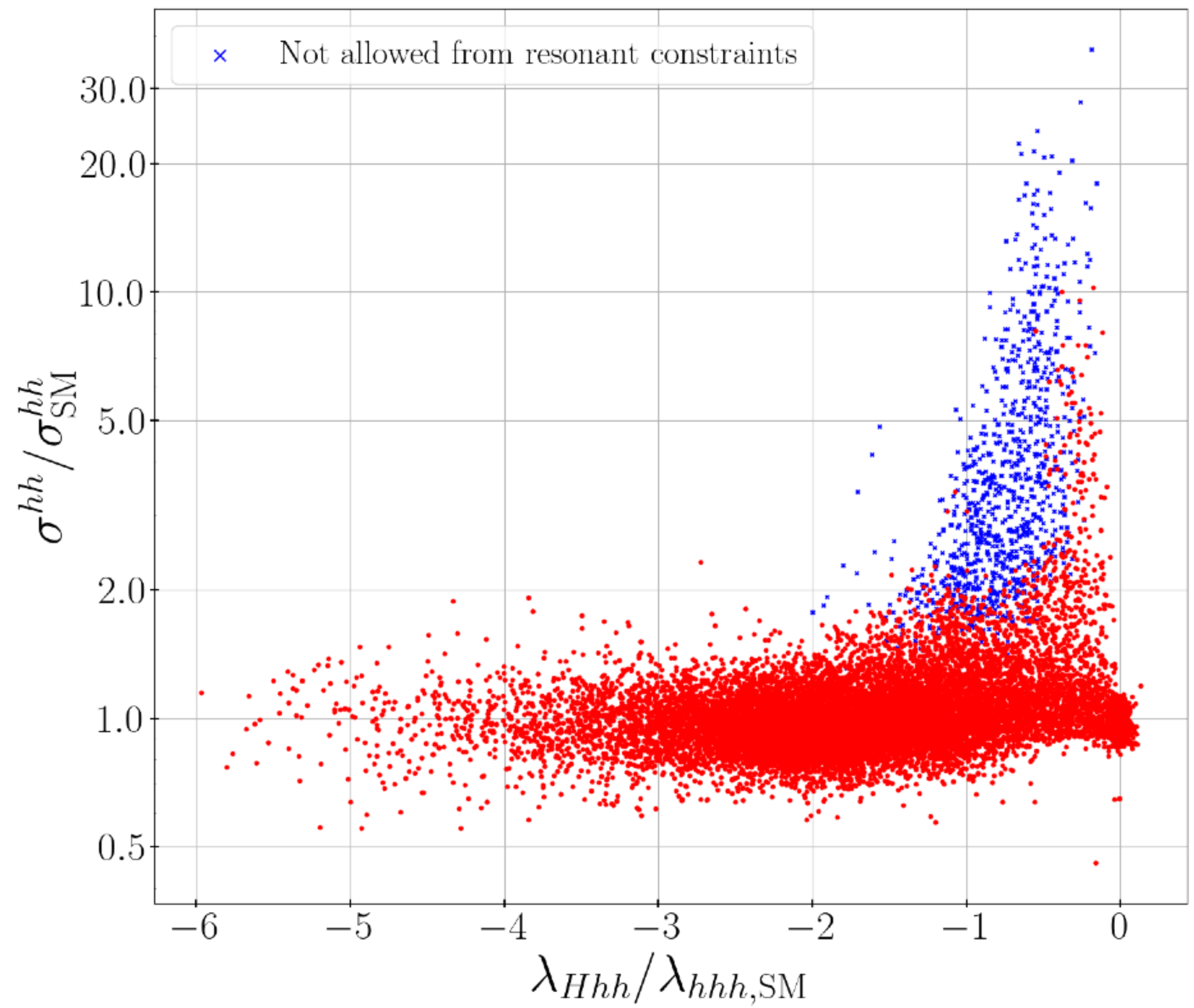


If H is heavy, a new decay mode $H \to tT_i$ opens.

If H is light, the difference appears in σ^{hh} と κ_V . If H is heavy, it appears in Γ_H .

correlation with scalar couplings

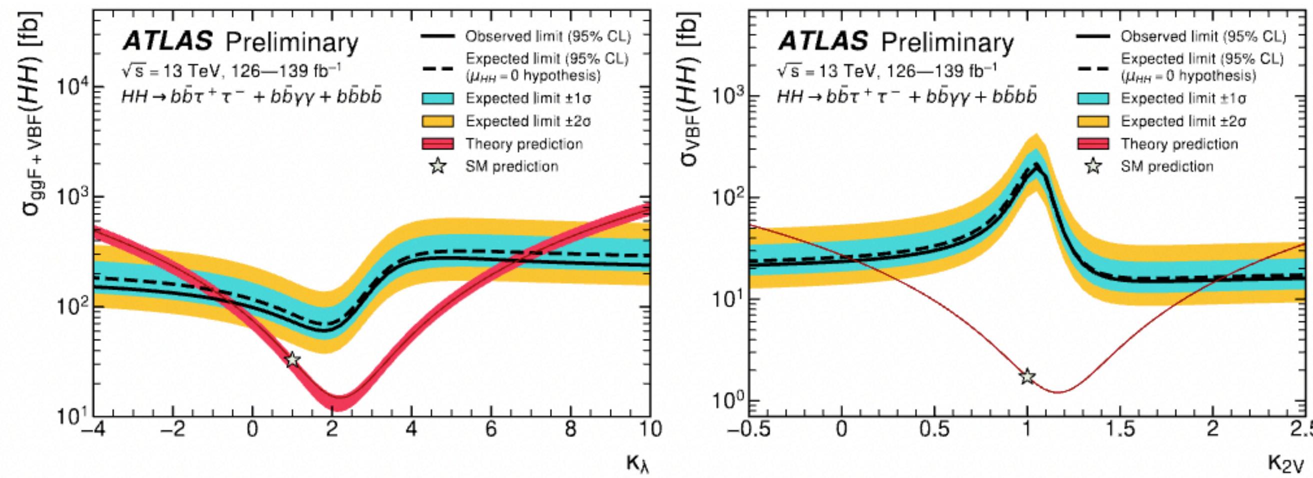




HL-LHC sensitivity
[1902.00134]

hhhとhhVVの測定

[ATLAS-CONF-2022-050]



(a) (b)

Figure 8: Observed and expected 95% CL exclusion limits on (a) the combined ggF HH and VBF HH cross-section as a function of κ_λ and (b) the VBF HH cross-section as a function of κ_{2V}, for the double-Higgs combination. The expected limits assume no HH production or no VBF HH production respectively. The red line shows (a) the theory prediction for the combined ggF HH and VBF HH cross-section as a function of κ_λ where all parameters and couplings are set to their SM values except for κ_λ, and (b) the predicted VBF HH cross-section as a function of κ_{2V}. The band surrounding the red cross-section lines indicates the theoretical uncertainty on the predicted cross section. The uncertainty band in (b) is smaller than the width of the plotted line.

[Phys.Lett.B 842 (2023) 137531]

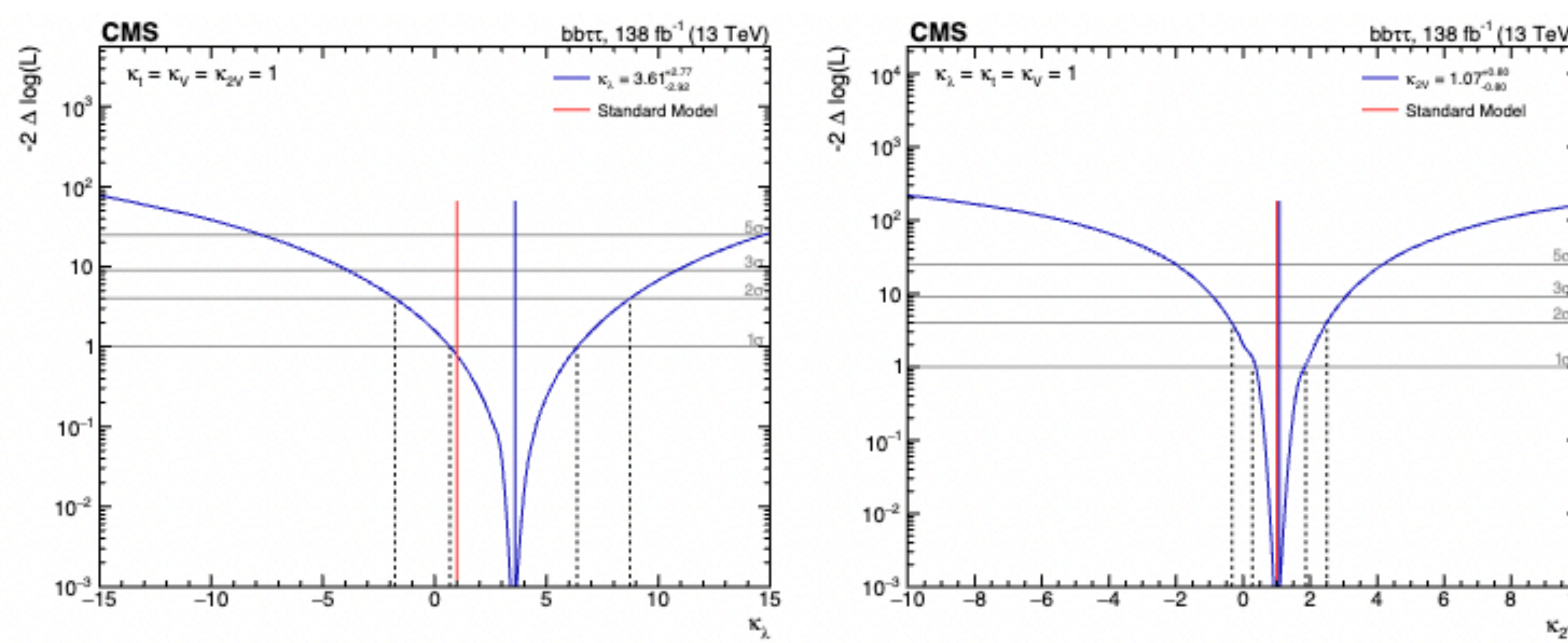


Figure 10: Observed likelihood scan as a function of κ_λ (left) and κ_{2V} (right) for the full 2016–2018 combination. The dashed lines show the intersection with threshold values one and four

Composite two Higgs doublet model (C2HDM) [2/2]

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

ヒッグスセクターに対する制限: [f : composite スケール]

- non-linearities から生じるdim 6 operator

$$\mathscr{L}_{d\geq 6} \supset \frac{c_{ij}\tilde{c}_{kl}}{f^2}(H_i^\dagger \overleftrightarrow{D}_\mu H_j)(H_k^\dagger \overleftrightarrow{D}_\mu H_l) + \text{h.c.},$$

によりTパラメータへ寄与が生じる： $\hat{T} \propto 16 \times \frac{v^2}{f^2} \times \frac{\text{Im}[\langle H_1\rangle^\dagger \langle H_2\rangle]^2}{(|\langle H_1\rangle|^2 + |\langle H_2\rangle|^2)^2}.$ →CP対称性を課す

- Higgs 由来のFCNCが存在する:

$$\mathscr{L}_{\text{2HDM}} \supset Y_u^{ij}\bar{q}_L^i(a_{1u}\tilde{H}_1 + a_{2u}\tilde{H}_2)u_R^j + Y_d^{ij}\bar{q}_L^i(a_{1d}H_1 + a_{2d}H_2)d_R^j + Y_e^{ij}\bar{l}_L^i(a_{1e}H_1 + a_{2e}H_2)e_R^j + \text{h.c.}$$

→ flavor aligned Yukawa 構造 ($Y_1^{ij} \propto Y_2^{ij}$)を考える

ヒッグス質量とヒッグス結合:

[$\xi = v_{\text{SM}}^2/f^2$, $c_f^{H/h} = c_f^{H/h}(\tan\beta, Y_{1,2})$]

$$m_h^2 = c_\theta^2 \mathcal{M}_{11}^2 + s_\theta^2 \mathcal{M}_{22}^2 + s_{2\theta}\mathcal{M}_{12}^2, \quad =125\text{ GeV}$$

$$m_H^2 = s_\theta^2 \mathcal{M}_{11}^2 + c_\theta^2 \mathcal{M}_{22}^2 - s_{2\theta}\mathcal{M}_{12}^2, \quad \sim f^2/(16\pi^2)$$

$$\tan 2\theta = 2\frac{\mathcal{M}_{12}^2}{\mathcal{M}_{11}^2 - \mathcal{M}_{22}^2}. \quad \sim \xi$$

$$\kappa_V = \left(1 - \frac{\xi}{2}\right)\cos\theta$$

$$\kappa_f = (1 + c_f^h \xi)\cos\theta + (\zeta_f + c_H^h \xi)\sin\theta$$

$f \to \infty$で$(m_H, \theta, \kappa_{V/f}) \to (\infty, 0, 1)$

Custdial symmetry

non-linearities　によりdim 6 operatorに以下のようなタームを含む

$$\mathscr{L}_{d\geq 6} \supset \frac{c_{ij}\tilde{c}_{kl}}{f^2}(H_i^\dagger \overleftrightarrow{D}_\mu H_j)(H_k^\dagger \overleftrightarrow{D}_\mu H_l) + \mathrm{h.c.},$$

(これはSp(4)を破る)この寄与によりTパラメータに対するツリーレベルの寄与が生じる

$$\hat{T} \propto 16 \times \frac{v^2}{f^2} \times \frac{\mathrm{Im}[\langle H_1\rangle^\dagger \langle H_2\rangle]^2}{(|\langle H_1\rangle|^2 + |\langle H_2\rangle|^2)^2}.$$

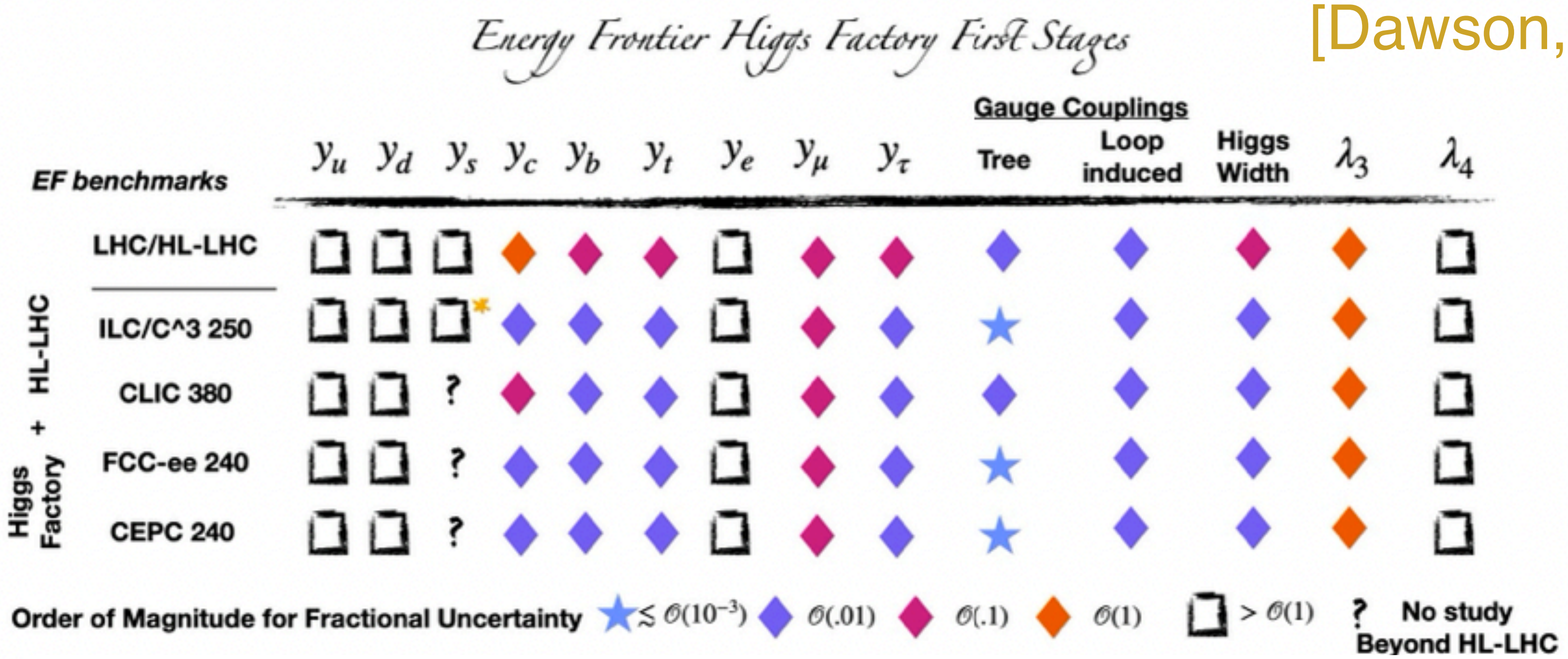
T parameter の制限は以下の対称性があれば回避出来る

1. CP: $\mathrm{Im} < H_i > = 0$

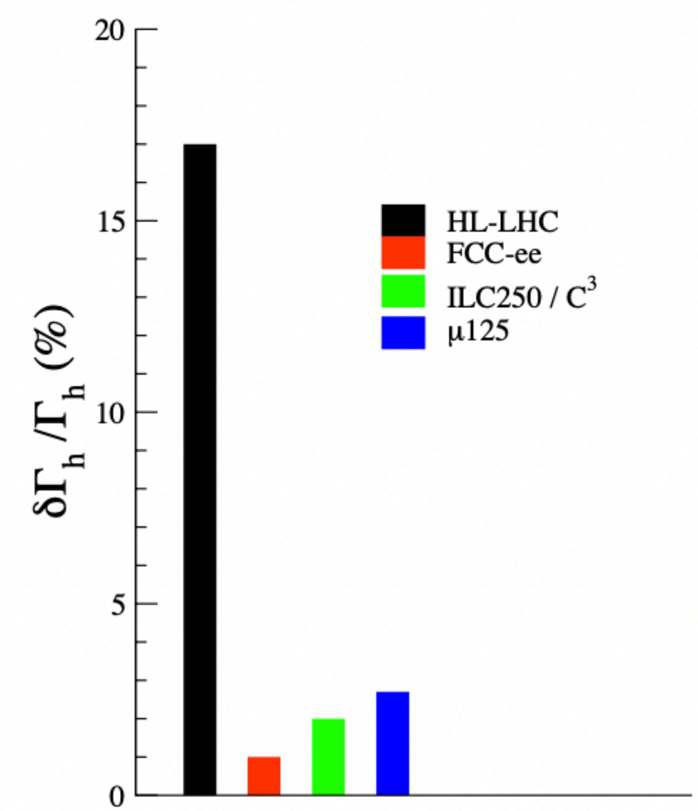
1. C_2 : $< H_1 >$ か $< H_2 >$ が0

Higgs coupling measurements future prospects

[Dawson, Meade, Ojalvo, et. al, 2209.07510]



collider	Indirect-h	hh	combined
HL-LHC [78]	100-200%	50%	50%
$\mathrm{ILC}_{250}/\mathrm{C}^3$-250 [51, 52]	49%	–	49%
$\mathrm{ILC}_{500}/\mathrm{C}^3$-550 [51, 52]	38%	20%	20%
CLIC_{380} [54]	50%	–	50%
CLIC_{1500} [54]	49%	36%	29%
CLIC_{3000} [54]	49%	9%	9%
FCC-ee [55]	33%	–	33%
FCC-ee (4 IPs) [55]	24%	–	24%
FCC-hh [79]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [64]	-	15-30%	15-30%
μ(10 TeV) [64]	-	4%	4%



Effective lagrangian

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

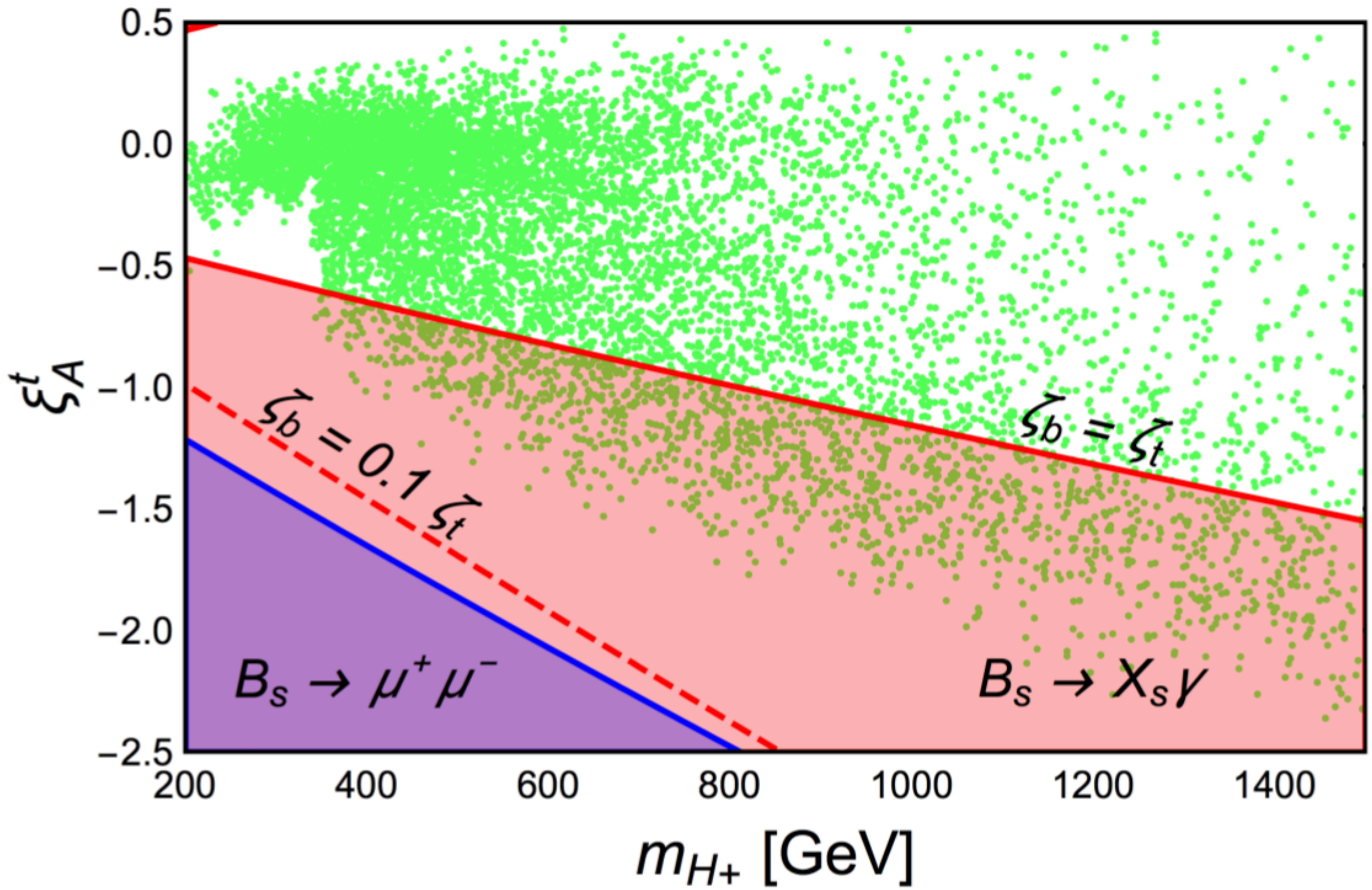
$$\begin{aligned}\mathcal{L}_{\text{Yuk}} =& - G_{h\bar{T}_i T_j}\bar{T}_{Li}T_{Rj}h - G_{H\bar{T}_i T_j}\bar{T}_{Li}T_{Rj}H + \text{h.c.} \\ & - \underbrace{G_{hhT_iT_i}\bar{T}_iT_ih^2} - \underbrace{G_{HHT_iT_i}\bar{T}_iT_iH^2} + \cdots ,\end{aligned}$$

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

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

$$\mathcal{L}^{\rm ferm}_{\rm strong} + \mathcal{L}^{\rm ferm}_{\rm mix} = \bar{\Psi}^I i\not{D}\Psi^I + [-\bar{\Psi}^I_L M^{IJ}_{\Psi}\Psi^J_R - \bar{\Psi}^I_L(Y_1^{IJ}\Sigma + Y_2^{IJ}\Sigma^2)\Psi^J_R$$
$$+(\Delta^I_L \bar{q}^{\mathbf{6}}_L \Psi^I_R + \Delta^I_R \bar{t}^{\mathbf{6}}_R \Psi^I_L)] + \text{h.c.},$$

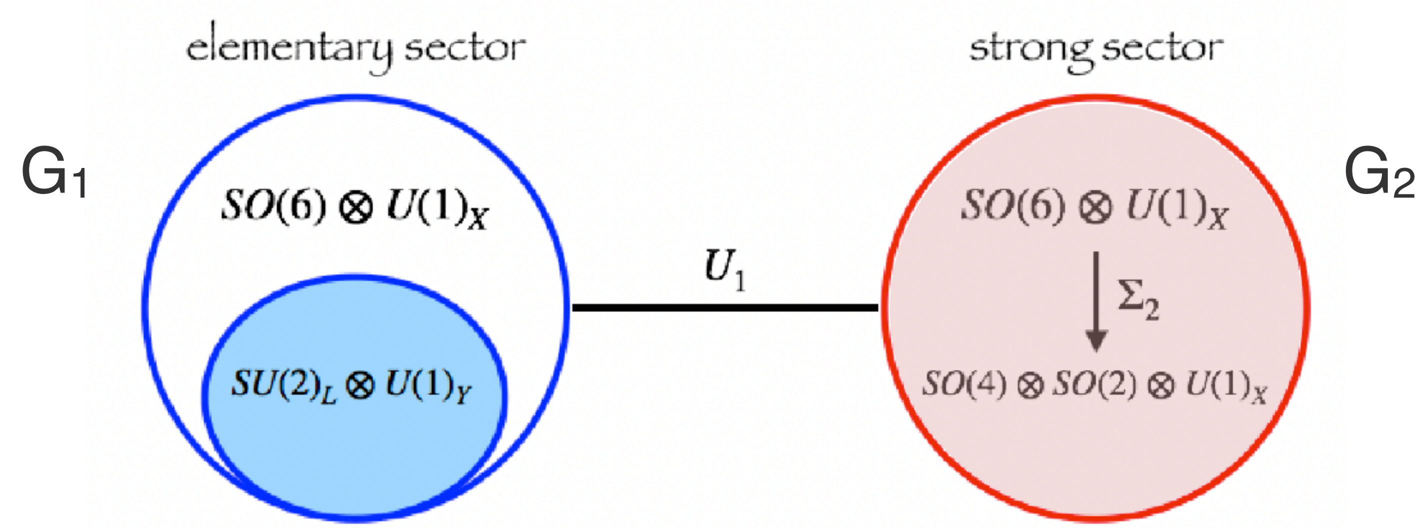
$$\Sigma = U\Sigma_0 U^T$$

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

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

- 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.

2-cite construction in the gauge sector



- G_1 はglobal。SU(2)×U(1)はlocalに格上げされる。G_2 はglobal。
- U_1はリンク場。$SO(6)_L$×$SO(6)_R$を$SO(6)_V$に破る。Σ_2はG2において SO(4)×SO(2)×$U(1)_X$ に破る

$$U_i = \exp i\frac{f}{f_i^2} \qquad \Sigma_2 = U_2\Sigma_0 U_2^T \qquad \Pi \equiv \sqrt{2}\phi_i^{\hat{a}}T_i^{\hat{a}} = -i\begin{pmatrix} 0_{4\times4} & \mathbf{\Phi} \\ -\mathbf{\Phi}^T & 0_{2\times2}\end{pmatrix}, \qquad \Phi_i = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_i^{\hat{2}} + i\phi_i^{\hat{1}} \\ \phi_i^{\hat{4}} - i\phi_i^{\hat{3}}\end{pmatrix}.$$

- covariant derivative

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

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

T^AとT^XはSO(6)と$U(1)^X$の生成子

gauge sector Lagrangian [1/2]

mix

strong

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

$$\boxed{- \frac{1}{4g_A^2}(A^A)_{\mu\nu}(A^A)^{\mu\nu}} - \frac{1}{4g_X^2}X_{\mu\nu}X^{\mu\nu},$$

elementary

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

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

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

ρ_A and ρ_X are spin-1 resonances

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

gauge sector Lagrangian [2/2]

heavy Gauge resonanceをintegrate out すると以下のラグランジアンが得られる。

$$\mathcal{L}^{\mathrm{gauge}}_{\mathrm{Composite}} = -\frac{(P_T)^{\mu\nu}}{2}\Big[q^2\tilde{\Pi}_0(q^2)A^A_\mu A^A_\nu + q^2\tilde{\Pi}_X(q^2)X_\mu X_\nu + f^2\tilde{\Pi}_1(q^2)A^A_\mu A^B_\nu \mathrm{Tr}(\Sigma T^A T^B \Sigma) + f^2\tilde{\Pi}_2(q^2)A^A_\mu A^B_\nu \mathrm{Tr}(T^A \Sigma T^B \Sigma)\Big],$$

$$\Sigma = U_1 \Sigma_2 U_1^T \qquad P^T_{\mu\nu} = \eta_{\mu\nu} - q_\mu q_\nu / q^2$$

Form factors:

$$\tilde{\Pi}_0 = -\frac{m_\rho^2}{g_\rho^2(q^2 - m_\rho^2)}, \qquad \tilde{\Pi}_1 = -\frac{2m_\rho^4(m_{\hat{\rho}}^2 - m_\rho^2)}{f^2 g_\rho^2 (q^2 - m_\rho^2)(q^2 - m_{\hat{\rho}}^2)},$$

$$\tilde{\Pi}_2 = -\tilde{\Pi}_1, \qquad \tilde{\Pi}_X = -\frac{m_{\rho X}^2}{g_{\rho X}^2(q^2 - m_{\rho X}^2)}$$

- W boson とZ boson mass

$$m_W^2 = -\frac{\Pi_W(0)}{4} f^2 \sin^2\frac{v}{f}, \quad m_Z^2 = -\frac{\Pi_W(0)}{4} f^2 \sin^2\frac{v}{f}(1 + \tan^2\theta_W),$$

$$v_{\mathrm{SM}}^2 = f^2 \sin^2\frac{v}{f}, \qquad g^2 = -\Pi_W(0), \quad f^{-2} = f_1^{-2} + f_2^{-2}$$

Scan range of the composite parameters and BPs

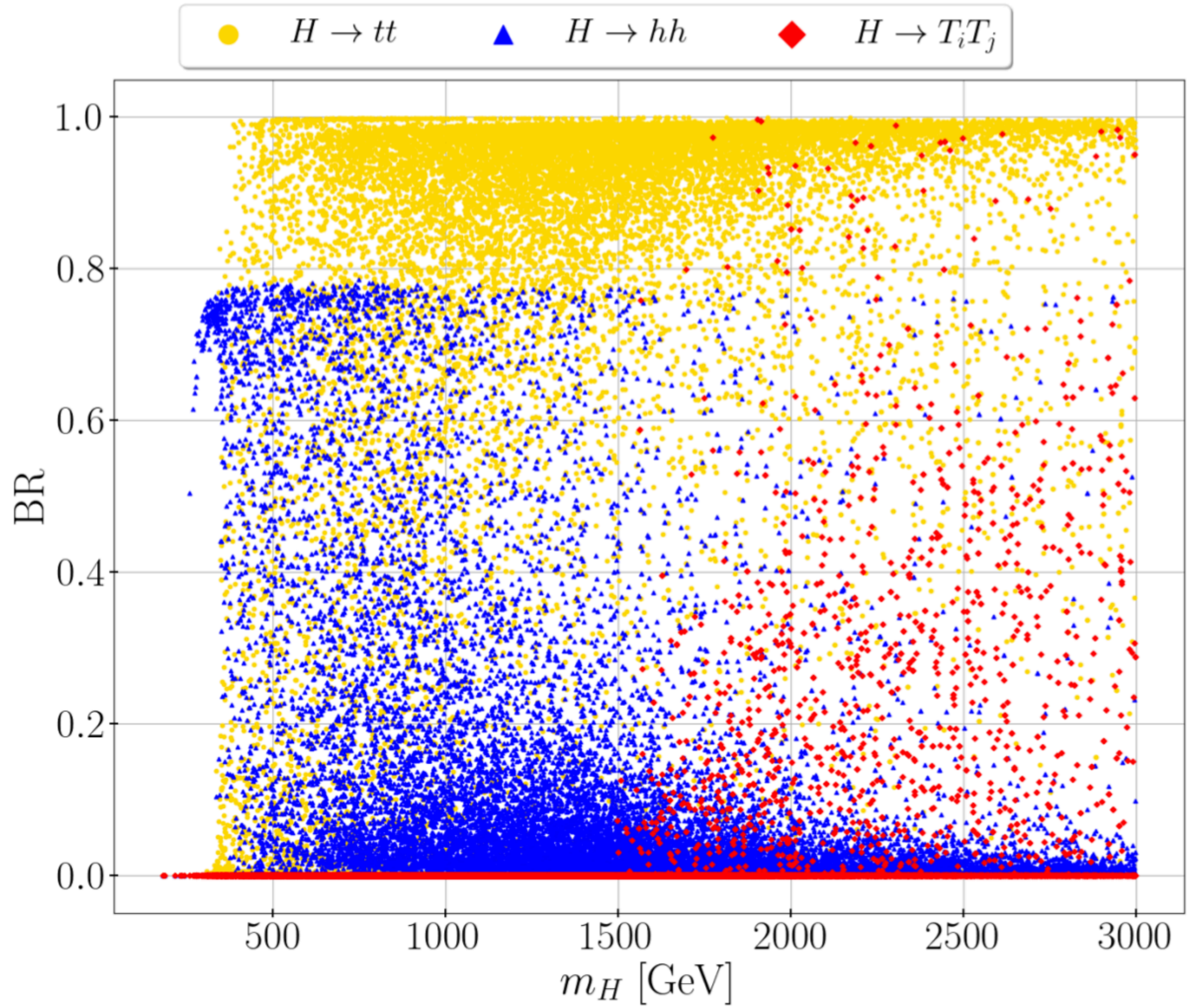
$$f = [700,\ 3000]\ \text{GeV}, \quad g_\rho = [2, 10]$$

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

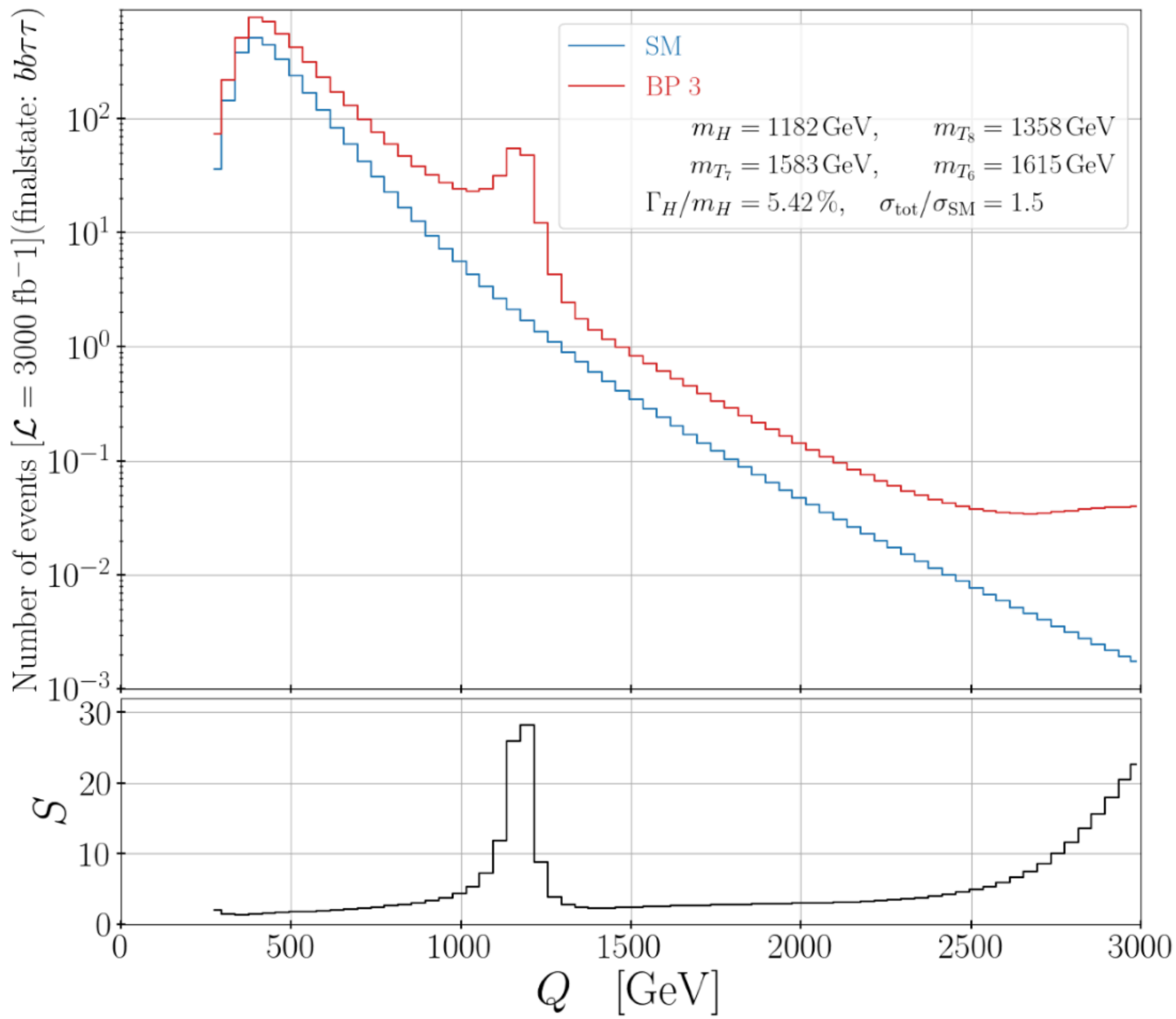
BP	f [GeV]	Δ_L [GeV]	Δ_R [GeV]	Y_1 [GeV]	Y_2 [GeV]	g_ρ
BP 1	1139.21	$\begin{pmatrix} 649.392 \\ -1787.9 \end{pmatrix}$	$\begin{pmatrix} -7244.85 \\ 4633.51 \end{pmatrix}$	$\begin{pmatrix} -406.903 & 421.383 \\ -910.863 & -1651.99 \end{pmatrix}$	$\begin{pmatrix} 3996.82 & 2846.41 \\ 2265.86 & 518.944 \end{pmatrix}$	7.02515
BP 2	821.74	$\begin{pmatrix} 5172.74 \\ -3835.24 \end{pmatrix}$	$\begin{pmatrix} -2850.8 \\ -759.562 \end{pmatrix}$	$\begin{pmatrix} 3194.11 & 2467.64 \\ 2748.76 & 1489.54 \end{pmatrix}$	$\begin{pmatrix} 457.272 & -1135.19 \\ 5946.7 & -3126.3 \end{pmatrix}$	7.87477
BP 3	795.639	$\begin{pmatrix} -168.309 \\ 1137.24 \end{pmatrix}$	$\begin{pmatrix} -2548.98 \\ -2181.22 \end{pmatrix}$	$\begin{pmatrix} -1808.81 & -695.861 \\ 3507.5 & -320.533 \end{pmatrix}$	$\begin{pmatrix} 4348.75 & 399.558 \\ -4182.72 & -1915.42 \end{pmatrix}$	6.7523
BP 4	750.293	$\begin{pmatrix} -1007.88 \\ -1351.26 \end{pmatrix}$	$\begin{pmatrix} 1844.02 \\ 1713.76 \end{pmatrix}$	$\begin{pmatrix} 709.119 & -884.948 \\ -5689.43 & 3420.92 \end{pmatrix}$	$\begin{pmatrix} 2833.62 & -2811.59 \\ 5092.76 & 3134.5 \end{pmatrix}$	8.6289

Table 2: Input values of the BPs analysed in the paper

Branching ratios of the heavy Higgs boson H

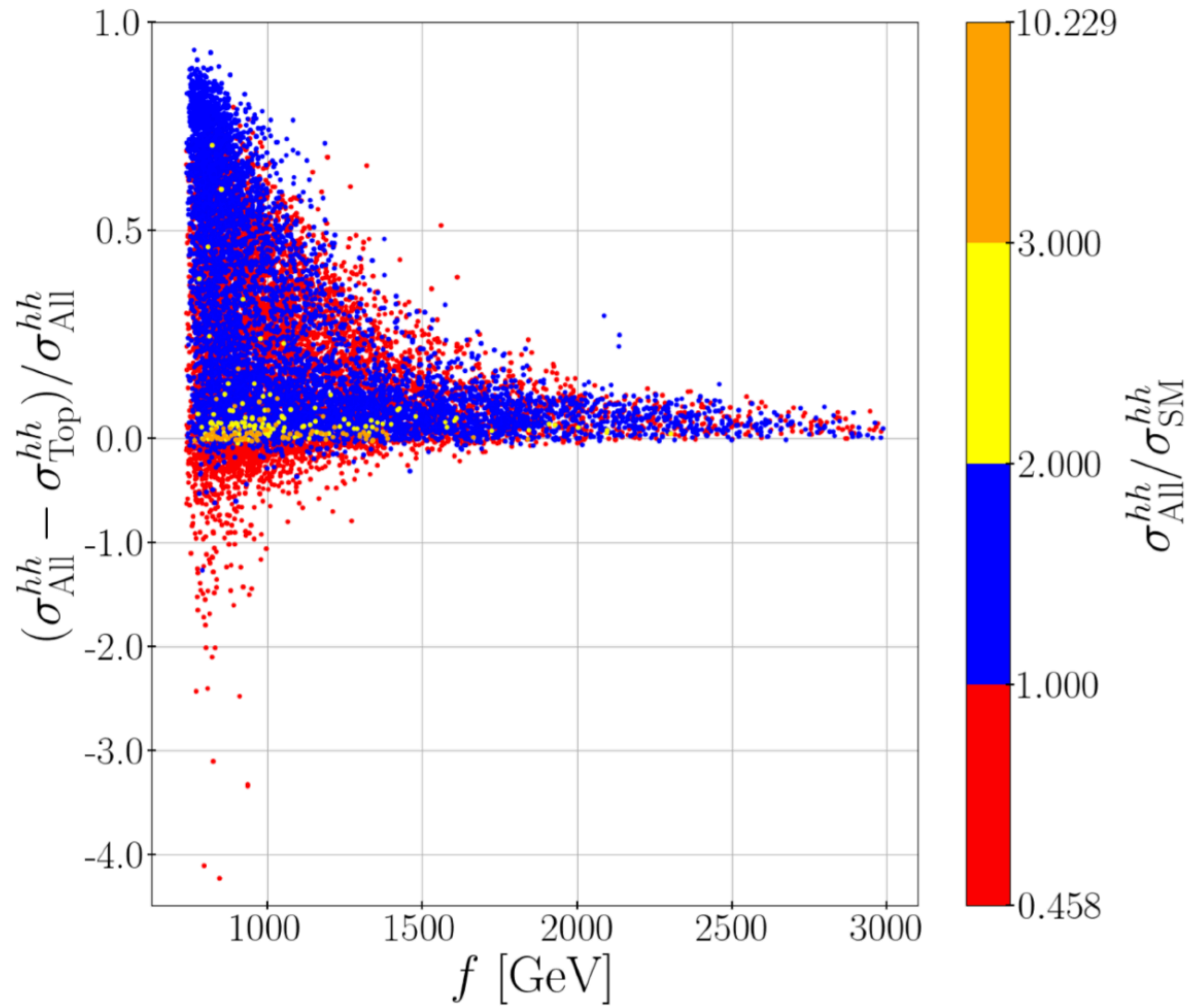


Binned distributions



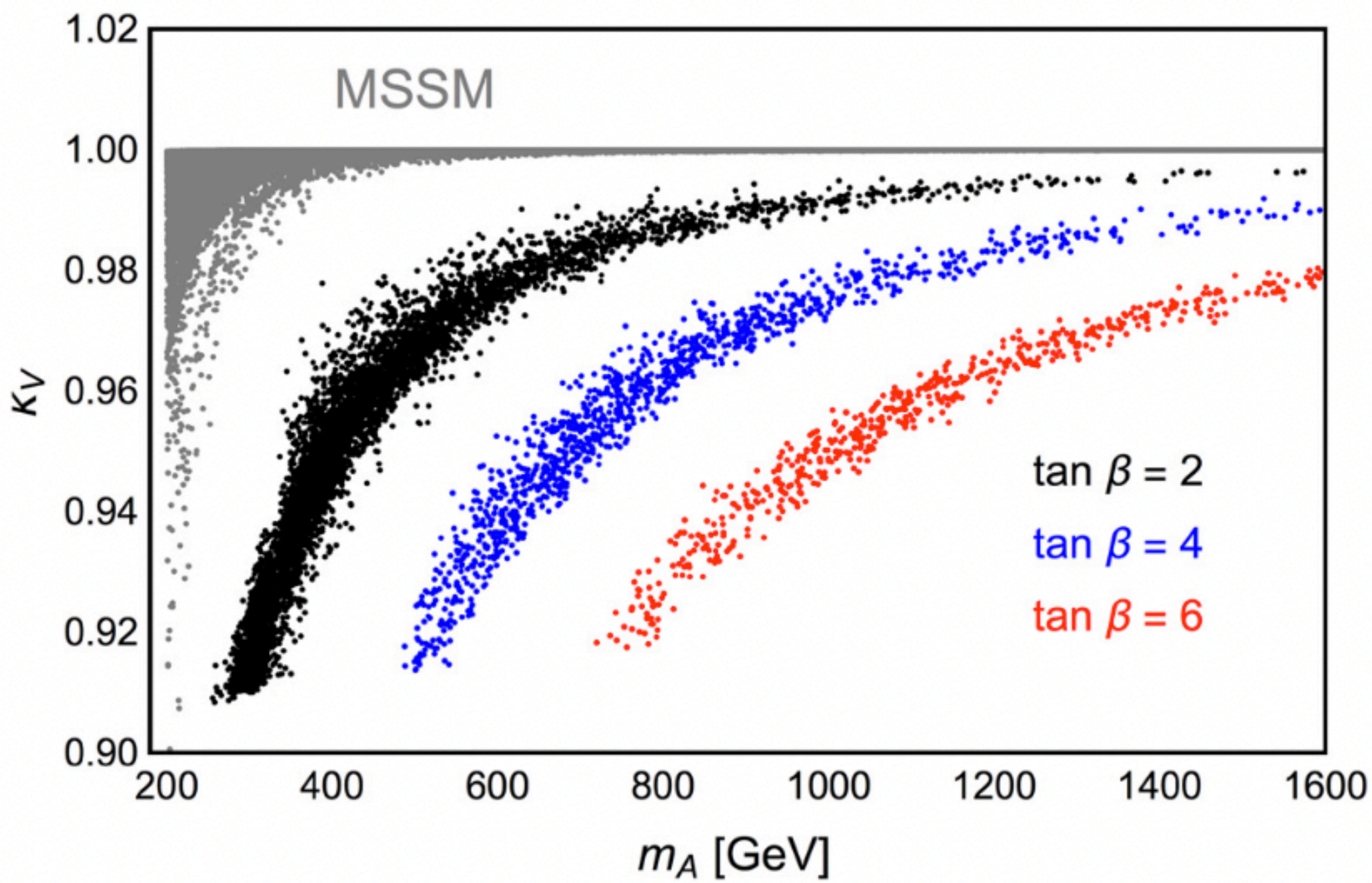
Influence of Heavy top partner loop contributions

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

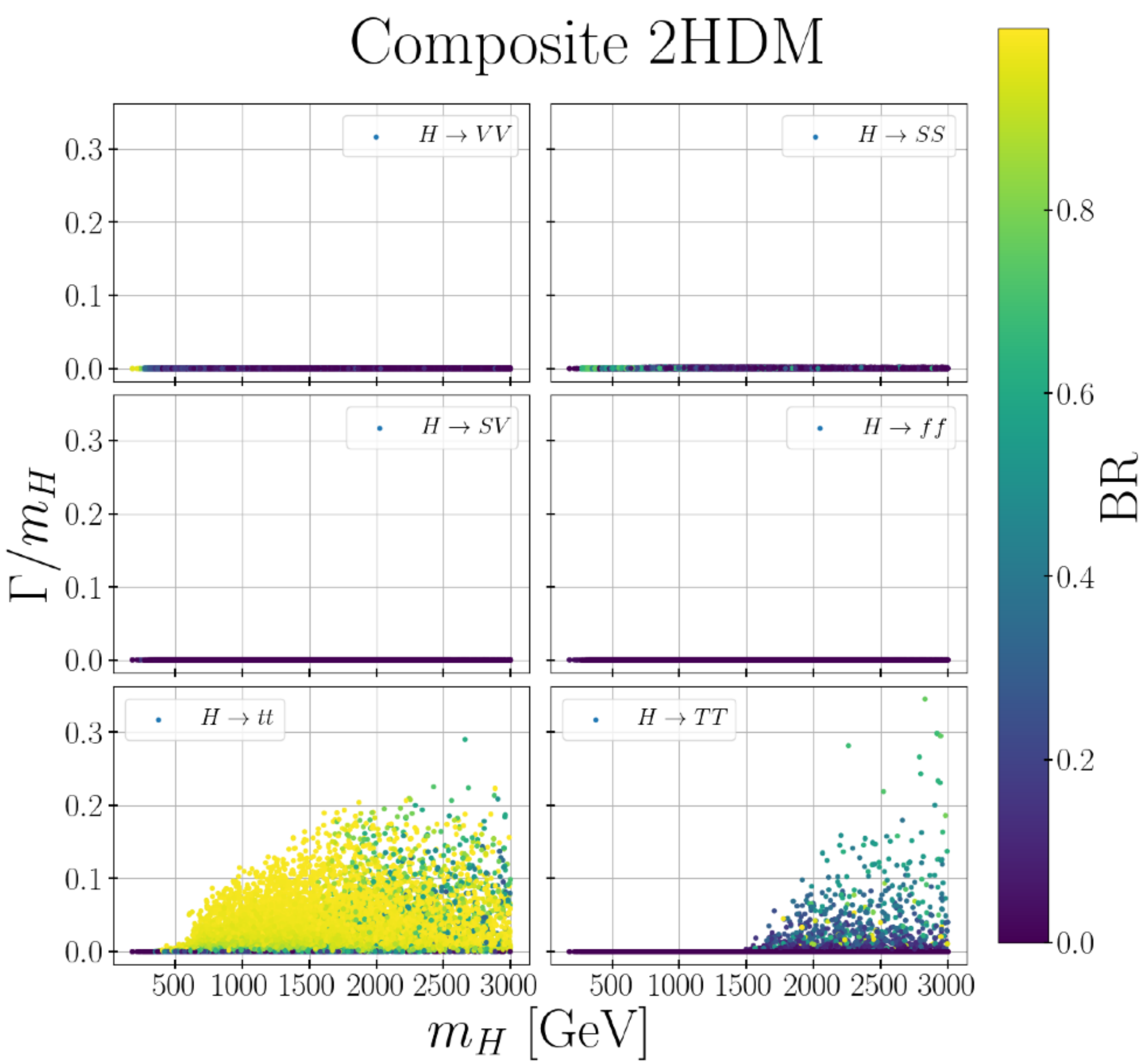


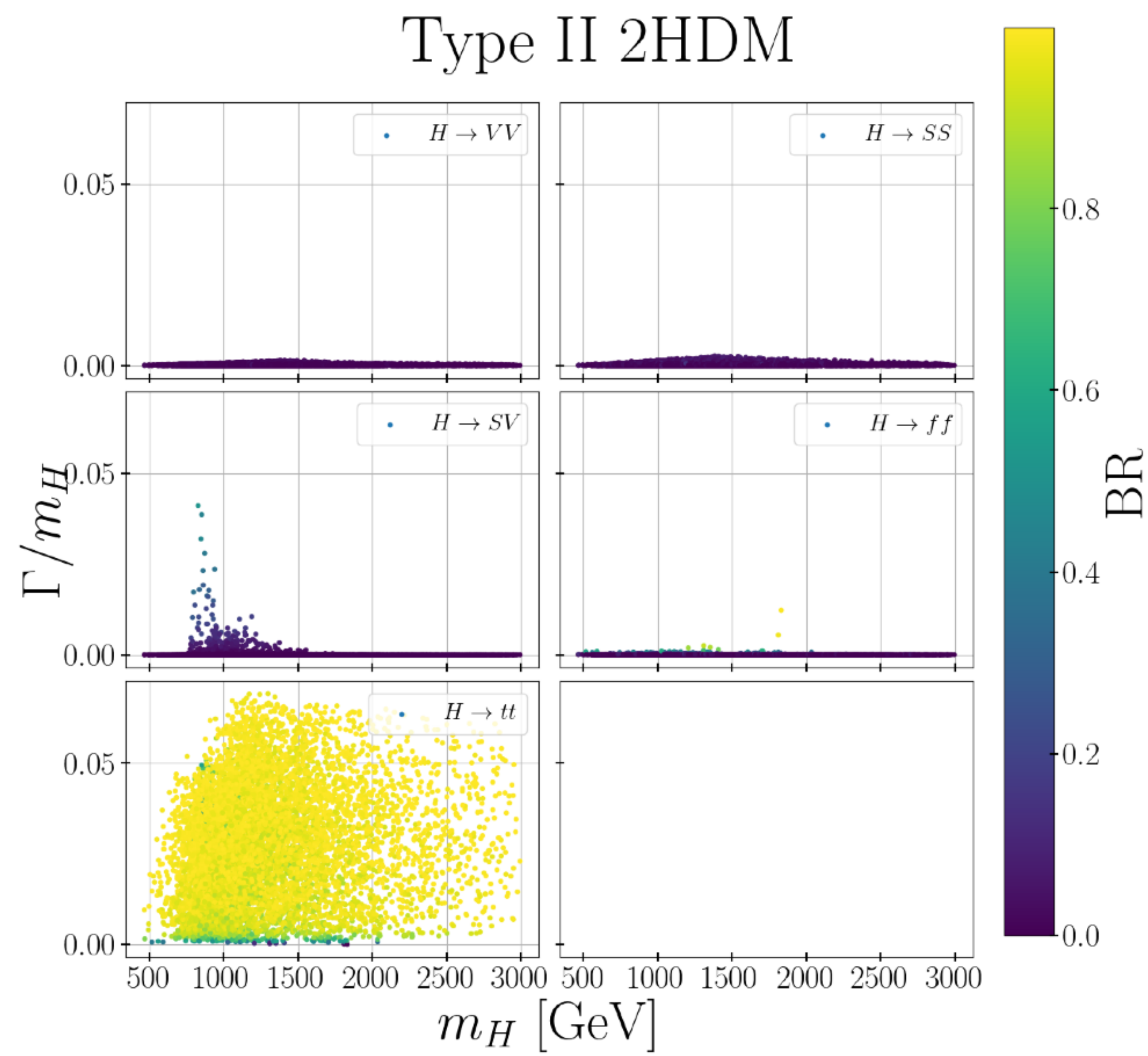
- Heavy top partner gives destractuive and constructive contributions.
- T_i contributions have influence when $\sigma^{hh}/\sigma^{hh}_{SM} \sim 0.5$-2.

MSSMとの比較


MSSM
1.02
1.00
0.98
0.96
0.94
0.92
0.90
κ_V
200
400
600
800
1000
1200
1400
1600
m_A [GeV]
tan β = 2
tan β = 4
tan β = 6

decay rate of H





Form factor decomposition of $gg \to hh$

[E.W.N Glover, J.J. van der BIJ, 1988]

$$\mathcal{M} = \frac{\alpha_s \alpha_w \delta^{ab}}{8 M_W^2} \{ A^{\mu\nu} \, \mathrm{gauge1}(\hat{s}, \hat{t}, \hat{u}) + B^{\mu\nu} \, \mathrm{gauge2}(\hat{s}, \hat{t}, \hat{u}) \} e_\mu^1 e_\nu^2 ,$$

$$A^{\mu\nu} = g^{\mu\nu} - \frac{p_1^\nu p_2^\mu}{p_1 \cdot p_2} ,$$

$$B^{\mu\nu} = g^{\mu\nu} + \frac{m_H^2 p_1^\nu p_2^\mu}{p_T^2 p_1 \cdot p_2} - \frac{2 p_1 \cdot p_3 p_2^\mu p_3^\nu}{p_T^2 p_1 \cdot p_2} - \frac{2 p_2 \cdot p_3 p_1^\nu p_3^\mu}{p_T^2 p_1 \cdot p_2} + \frac{2 p_3^\mu p_3^\nu}{p_T^2} .$$

Noting that $p_{1,2} \cdot \epsilon^{1,2} = 0$, gauge1 and gauge 2 are given by the helicity amplitudes as

$$\mathcal{M}_{+-} = \mathcal{M}_{-+} = -\,\mathrm{gauge1}, \quad \mathcal{M}_{++} = \mathcal{M}_{--} = -\,\mathrm{gauge2},$$

The cross section is calculated as

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{\alpha_w^2 \alpha_s^2}{2^{15} \pi M_W^4 \hat{s}^2} \left(|\mathrm{gauge1}|^2 + |\mathrm{gauge2}|^2 \right) .$$