Gauged Two Higgs Doublet Model
— Constraints & Phenomenology —

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Presented at the 5th Workshop on
Dark Matter, Dark Energy and Matter-Antimatter Asymmetry
Dec. 28, 2018 - Dec. 31, 2018
NCTS, Hsinchu & Fo Guang Shan, Kaohsiung
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Based on

- Wei-Chih Huang, Y. L. Sming Tsai, TCY, arXiv:1512.00229, JHEP04(2016)019
- Wei-Chih Huang, Y. L. Sming Tsai, TCY, arXiv:1512.07268, NPB909 (2016) 122-134
- Wei-Chih Huang, Hiroyuki Ishida, Chih-Ting Lu, Y. L. Sming Tsai, TCY, arXiv:1708.02355, EPJC78(2018) no.8, 613
- Adelssalem Arhrib, Wei-Chih Huang, Raymundo Ramos, Y. L. Sming Tsai, TCY, arXiv:1806.05632, PRD98(2018) no.9,095006
- Chuan-Ren Chen, Yu-Xiang Lin, Van Que Tran, TCY, arXiv:1810.04837
- Cheng-Tse Huang, Raymundo Ramos, Van Que Tran, Sming Tsai, TCY, in preparation

Introduction

- Dark matter (DM) & neutrino masses → BSM
- 2 Higgs doublet model (2HDM) are very popular. For example,
  - In MSSM, 2 Higgs doublets are needed due to holomorphic nature of the superpotential as well as anomaly cancellation.
  - With its additional CP phases, general 2HDM is a prototype model to discuss matter-antimatter asymmetry in the universe.
- Inert Higgs Doublet Model (IHDM) (Deshpande and Ma, '78) can provide dark matter candidate, with a discrete Z_2 symmetry imposed. No FCNC at tree level too!
- Scalar singlet as DM: Silveria & Zee ('85), McDonald ('94), Burgess *et al* ('01), He *et al* ('09). Also based on Z_2.
- However Wilczek and Krauss ('89) had argued that global symmetry (discrete or continuous) can be violated by gravitation processes like black hole evaporation or wormhole tunneling. Suggested discrete gauge symmetry.
- We embed the two Higgs doublets into a fundamental representation of a new gauge group $SU(2)_H$. Accidental Z_2 symmetry emerges.

Some Highlights of G2HDM

- New gauge group $SU(2)_H \otimes U(1)_X$
- Anomaly free and renormalizable
- Symmetry breaking of $SU(2)_L$ is triggered or induced by $SU(2)_H$ breaking
- One of the Higgs doublet (H_2) can be inert and may play some role of dark matter, whose stability is protected by gauge invariance
- Accidental Z_2 symmetry in which all SM particles are even
- Unlike Left-Right symmetric models, the complex vector fields $W'^{(p,m)}$ are electrically neutral
- No tree level FCNC in the Higgs couplings
- *etc*

Outline

- Introduction
- The Model
  - Particle Content
  - Higgs Potential & Symmetry Breaking
  - Yukawa Couplings
  - Mass Spectra
- Constraints
  - Theoretical (Perturbative Unitarity, Vacuum Stability)
  - Phenomenological (EWPT, Higgs Physics, Dark Matter)
- Phenomenology
  - Double Higgs Production at LHC
- Summary & Outlook

Particle Content

	Matter Fields	$SU(3)_C$	$SU(2)_L$	$SU(2)_H$	$U(1)_Y$	$U(1)_X$
Scalars	$H = (H_1 \;\; H_2)^{\rm T}$	1	2	2	1/2	1
	Δ_H	1	1	3	0	0
	Φ_H	1	1	2	0	1
Fermions	$Q_L = (u_L \;\; d_L)^{\rm T}$	3	2	1	1/6	0
	$U_R = \left(u_R \;\; u_R^H\right)^{\rm T}$	3	1	2	2/3	1
	$D_R = \left(d_R^H \;\; d_R\right)^{\rm T}$	3	1	2	$-1/3$	-1
	u_L^H	3	1	1	2/3	0
	d_L^H	3	1	1	$-1/3$	0
	$L_L = (\nu_L \;\; e_L)^{\rm T}$	1	2	1	$-1/2$	0
	$N_R = \left(\nu_R \;\; \nu_R^H\right)^{\rm T}$	1	1	2	0	1
	$E_R = \left(e_R^H \;\; e_R\right)^{\rm T}$	1	1	2	-1	-1
	ν_L^H	1	1	1	0	0
	e_L^H	1	1	1	-1	0

TABLE I: Matter content and their quantum number assignments in G2HDM.

- H_1 and H_2 are grouped into a $SU(2)_H$ doublet. H_1 is the SM one.
- Three VEVs of H_1, $\mathbf{\Phi}_H$, Δ_H provide symmetry breaking and provide masses
- $SU(2)_L$ doublet fermions are singlet under $SU(2)_H$
- $SU(2)_L$ singlet fermions are grouped with new heavy fermions to form $SU(2)_H$ doublets

Higgs Potential (I)

$$H = \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

$$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left\{(H_1^\dagger H_2)^2 + \text{h.c.}\right\} .$$

(IHDM)

$$V_T = V(H) + V(\Phi_H) + V(\Delta_H) + V_{\text{mix}}(H, \Delta_H, \Phi_H),$$

(G2HDM)

$$\begin{aligned} V(H) &= \mu_H^2 (H^{\alpha i} H_{\alpha i}) + \lambda_H (H^{\alpha i} H_{\alpha i})^2 \\ &\quad + \frac{1}{2}\lambda'_H \epsilon_{\alpha\beta}\epsilon^{\gamma\delta}(H^{\alpha i} H_{\gamma i})(H^{\beta j} H_{\delta j}), \\ &= \mu_H^2 (H_1^\dagger H_1 + H_2^\dagger H_2) + \lambda_H (H_1^\dagger H_1 + H_2^\dagger H_2)^2 \\ &\quad + \lambda'_H(-H_1^\dagger H_1 H_2^\dagger H_2 + H_1^\dagger H_2 H_2^\dagger H_1), \end{aligned}$$

$$\begin{aligned} V(\Phi_H) &= \mu_\Phi^2 \Phi_H^\dagger \Phi_H + \lambda_\Phi (\Phi_H^\dagger \Phi_H)^2, \\ &= \mu_\Phi^2 (\Phi_1^* \Phi_1 + \Phi_2^* \Phi_2) + \lambda_\Phi (\Phi_1^* \Phi_1 + \Phi_2^* \Phi_2)^2, \end{aligned}$$

$$\Delta_H = \begin{pmatrix} \Delta_3/2 & \Delta_p/\sqrt{2} \\ \Delta_m/\sqrt{2} & -\Delta_3/2 \end{pmatrix} = \Delta_H^\dagger \quad \text{with}$$

$$\Delta_m = (\Delta_p)^* \quad \text{and} \quad (\Delta_3)^* = \Delta_3;$$

$$\begin{aligned} V(\Delta_H) &= -\mu_\Delta^2 \text{Tr}(\Delta_H^2) + \lambda_\Delta (\text{Tr}(\Delta_H^2))^2, \\ &= -\mu_\Delta^2 \left(\frac{1}{2}\Delta_3^2 + \Delta_p\Delta_m\right) + \lambda_\Delta \left(\frac{1}{2}\Delta_3^2 + \Delta_p\Delta_m\right)^2, \end{aligned}$$

Higgs Potential (II)

$$V_{\rm mix}(H, \Delta_H, \Phi_H)$$
$$= +M_{H\Delta}(H^\dagger \Delta_H H) - M_{\Phi\Delta}(\Phi_H^\dagger \Delta_H \Phi_H)$$
$$+ \lambda_{H\Phi}(H^\dagger H)(\Phi_H^\dagger \Phi_H) + \lambda'_{H\Phi}(H^\dagger \Phi_H)(\Phi_H^\dagger H)$$
$$+ \lambda_{H\Delta}(H^\dagger H)\mathrm{Tr}(\Delta_H^2) + \lambda_{\Phi\Delta}(\Phi_H^\dagger \Phi_H)\mathrm{Tr}(\Delta_H^2).$$

- Six new parameters from $V_{\rm mix}$!
- Note that terms like

$$(H^\dagger \Phi_H)(\Phi_H^T \epsilon H) \text{ and } \Phi_H^T \epsilon \Delta_H \Phi_H$$

are invariant under $SU(2)_H$ but forbidden by $U(1)_X$!

Accidental Discrete Symmetry

$$H = \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}, \Phi_H = \begin{pmatrix} G_H^p \\ \Phi_{H0} \end{pmatrix}, \Delta_H = \begin{pmatrix} \frac{\Delta_0}{2} & \frac{\Delta_p}{\sqrt{2}} \\ \frac{\Delta_m}{\sqrt{2}} & -\frac{\Delta_0}{2} \end{pmatrix}$$

- The scalar potential contained all possible renormalizable terms has the following accidental Z_2 symmetry, which is not put in by hand.

$$H_1 \to H_1, \Phi_{H,0} \to \Phi_{H,0}, \Delta_0 \to \Delta_0$$

$$H_2 \to -H_2, G_H^{p,m} \to -G_H^{p,m}, \Delta_{p,m} \to -\Delta_{p,m}$$

- Thus we can have either inert Higgs doublet or Goldstone boson or triplet as scalar dark matter candidate in the model!

Symmetry Breaking (I)

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+h}{\sqrt{2}} + i\frac{G^0}{\sqrt{2}} \end{pmatrix} \qquad \Phi_H = \begin{pmatrix} G_H^p \\ \frac{v_\Phi+\phi_2}{\sqrt{2}} + i\frac{G_H^0}{\sqrt{2}} \end{pmatrix} \qquad \Delta_H = \begin{pmatrix} \frac{-v_\Delta+\delta_3}{2} & \frac{1}{\sqrt{2}}\Delta_p \\ \frac{1}{\sqrt{2}}\Delta_m & \frac{v_\Delta-\delta_3}{2} \end{pmatrix}$$

Quadratic terms for H_1 and H_2

$$\mu_H^2 - \frac{1}{2}M_{H\Delta}\cdot v_\Delta + \frac{1}{2}\lambda_{H\Delta}\cdot v_\Delta^2 + \frac{1}{2}\lambda_{H\Phi}\cdot v_\Phi^2,$$

← Can be negative even for a positive μ_H^2

$$\mu_H^2 + \frac{1}{2}M_{H\Delta}\cdot v_\Delta + \frac{1}{2}\lambda_{H\Delta}\cdot v_\Delta^2 + \frac{1}{2}(\lambda_{H\Phi}+\lambda'_{H\Phi})\cdot v_\Phi^2,$$

$M_{H\Delta,\Phi\Delta}, \lambda_{H\Delta,\Phi\Delta}, \lambda'_{H\Phi}$
can be either positive or negative

Quadratic terms for $\mathbf{\Phi}_1$ and $\mathbf{\Phi}_2$

$$\mu_\Phi^2 + \frac{1}{2}M_{\Phi\Delta}\cdot v_\Delta + \frac{1}{2}\lambda_{\Phi\Delta}\cdot v_\Delta^2 + \frac{1}{2}(\lambda_{H\Phi}+\lambda'_{H\Phi})\cdot v^2,$$

$$\mu_\Phi^2 - \frac{1}{2}M_{\Phi\Delta}\cdot v_\Delta + \frac{1}{2}\lambda_{\Phi\Delta}\cdot v_\Delta^2 + \frac{1}{2}\lambda_{H\Phi}\cdot v^2,$$

← Can be negative even for a positive μ_Φ^2

Symmetry Breaking (II)

$$V(v, v_\Delta, v_\Phi) = \frac{1}{4}\left[\lambda_H v^4 + \lambda_\Phi v_\Phi^4 + \lambda_\Delta v_\Delta^4 + 2\left(\mu_H^2 v^2 + \mu_\Phi^2 v_\Phi^2 - \mu_\Delta^2 v_\Delta^2\right)\right.$$
$$\left. - \left(M_{H\Delta} v^2 + M_{\Phi\Delta} v_\Phi^2\right) v_\Delta + \lambda_{H\Phi} v^2 v_\Phi^2 + \lambda_{H\Delta} v^2 v_\Delta^2 + \lambda_{\Phi\Delta} v_\Phi^2 v_\Delta^2\right]$$

Minimization:

$$v \cdot \left(2\lambda_H v^2 + 2\mu_H^2 - M_{H\Delta} v_\Delta + \lambda_{H\Phi} v_\Phi^2 + \lambda_{H\Delta} v_\Delta^2\right) = 0\ ,$$
$$v_\Phi \cdot \left(2\lambda_\Phi v_\Phi^2 + 2\mu_\Phi^2 - M_{\Phi\Delta} v_\Delta + \lambda_{H\Phi} v^2 + \lambda_{\Phi\Delta} v_\Delta^2\right) = 0\ ,$$
$$4\lambda_\Delta v_\Delta^3 - 4\mu_\Delta^2 v_\Delta - M_{H\Delta} v^2 - M_{\Phi\Delta} v_\Phi^2 + 2v_\Delta\left(\lambda_{H\Delta} v^2 + \lambda_{\Phi\Delta} v_\Phi^2\right) = 0\ .$$

$v^2(v_\Delta)$:
$$v^2 = \frac{(2\lambda_\Phi \lambda_{H\Delta} - \lambda_{H\Phi}\lambda_{\Phi\Delta}) v_\Delta^2 + (\lambda_{H\Phi} M_{\Phi\Delta} - 2\lambda_\Phi M_{H\Delta}) v_\Delta + 2(2\lambda_\Phi \mu_H^2 - \lambda_{H\Phi}\mu_\Phi^2)}{\lambda_{H\Phi}^2 - 4\lambda_H\lambda_\Phi}\ , \tag{A.1}$$

$v_\Phi^2(v_\Delta)$:
$$v_\Phi^2 = \frac{(2\lambda_H \lambda_{\Phi\Delta} - \lambda_{H\Phi}\lambda_{H\Delta}) v_\Delta^2 + (\lambda_{H\Phi} M_{H\Delta} - 2\lambda_H M_{\Phi\Delta}) v_\Delta + 2(2\lambda_H \mu_\Phi^2 - \lambda_{H\Phi}\mu_H^2)}{\lambda_{H\Phi}^2 - 4\lambda_H\lambda_\Phi}\ . \tag{A.2}$$

Yukawa Couplings (I)

- We pair the SM $SU(2)_L$ singlet fermions with heavy fermions to form $SU(2)_H$ doublets. SM fermions obtain masses through $\langle H_1 \rangle$

SM

$$\mathcal{L}_{\rm Yuk} \supset +y_d \bar{Q}_L \left(d_R^H H_2 - d_R H_1 \right) - y_u \bar{Q}_L \left(u_R \tilde{H}_1 + u_R^H \tilde{H}_2 \right) + y_e \bar{L}_L \left(e_R^H H_2 - e_R H_1 \right) - y_\nu \bar{L}_L \left(\nu_R \tilde{H}_1 + \nu_R^H \tilde{H}_2 \right) + \text{H.c.},$$

- Additional terms involve H_2 couples between SM fermions and heavy fermions with the same SM Yukawa couplings!
  Since H_2 has no VEV, this implies absence of FCNC interaction for SM fermions!
  (Natural flavor conservation: Weinberg & Glashow, '77; Paschos, '77
  Minimal flavor violation: G. D'Ambrosio, G. F. Giudice, G. Isidori, A. Strumia '02)

- The second doublet H_2 is inert — it could be DM candidate if it is lighter than all heavy fermions, scalars, and gauge bosons.

- SM neutrinos get Dirac masses.

Yukawa Couplings (II)

- To give masses to the new heavy fermions, we add their left-handed partners to couple to a $SU(2)_H$ scalar doublet $\mathbf{\Phi}_H=(\mathbf{\Phi}_1\ \mathbf{\Phi}_2)^T$

$$\mathcal{L}_{\text{Yuk}} \supset -y'_d \overline{d_L^H}\left(d_R^H \Phi_2 - d_R \Phi_1\right) - y'_u \overline{u_L^H}\left(u_R \Phi_1^* + u_R^H \Phi_2^*\right)$$
$$- y'_e \overline{e_L^H}\left(e_R^H \Phi_2 - e_R \Phi_1\right) - y'_\nu \overline{\nu_L^H}\left(\nu_R \Phi_1^* + \nu_R^H \Phi_2^*\right) + \text{H.c.}.$$

- H_1 does not couple to heavy fermions. So the SM Higgs signal strengths are not affected by the new fermions if mixing effects are turned off.

- $U(1)_X$ prevents Yukawa couplings that may give rise to mixings among SM fermions and heavy fermions. For example,

$$\overline{u_L^H} U_R \epsilon \Phi_H \sim \overline{u_L^H}(u_R \Phi_2 - u_R^H \Phi_1), \cdots$$

- Majorana mass term is also possible for the heavy neutrinos.

$$\overline{\nu_L^{Hc}} \nu_L^H$$

Scalar Mass Spectrum (I)

- Expand the scalar fields around the vacua

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+h}{\sqrt{2}} + i\frac{G^0}{\sqrt{2}} \end{pmatrix}, \; H_2 = \begin{pmatrix} H^+ \\ H_2^0 \end{pmatrix}, \; \Phi_H = \begin{pmatrix} G_H^p \\ \frac{v_\Phi + \phi_2}{\sqrt{2}} + i\frac{G_H^0}{\sqrt{2}} \end{pmatrix}, \; \Delta_H = \begin{pmatrix} \frac{-v_\Delta + \delta_3}{2} & \frac{1}{\sqrt{2}}\Delta_p \\ \frac{1}{\sqrt{2}}\Delta_m & \frac{v_\Delta - \delta_3}{2} \end{pmatrix}$$

$$\Phi_{\text{Goldstone}} \equiv \{G^0, G^\pm, G_H^0, G_H^{p,m}\}$$

$$\Phi_{\text{Physical}} \equiv \{h, H^\pm, H_2^0, H_2^{0*}, \delta_3, \Delta_{p,m}\}$$

- We have 8 generators for the electroweak gauge group but 6 Goldstone bosons. We left with 2 unbroken generators associated with the two massless photon and dark photon. The two unbroken generators are

$$Q = T_L^3 + Y \qquad\qquad Q_D = 4\cos^2\theta_W T_L^3 - 4\sin^2\theta_W Y + 2T_H^3 + X$$

Scalar Mass Spectrum (II) $S = \{h, \phi_2, \delta_3\}$

$$\mathcal{M}_0^2 = \begin{pmatrix} 2\lambda_H v^2 & \lambda_{H\Phi} v v_\Phi & \frac{v}{2}\left(M_{H\Delta} - 2\lambda_{H\Delta} v_\Delta\right) \\ \lambda_{H\Phi} v v_\Phi & 2\lambda_\Phi v_\Phi^2 & \frac{v_\Phi}{2}\left(M_{\Phi\Delta} - 2\lambda_{\Phi\Delta} v_\Delta\right) \\ \frac{v}{2}\left(M_{H\Delta} - 2\lambda_{H\Delta} v_\Delta\right) & \frac{v_\Phi}{2}\left(M_{\Phi\Delta} - 2\lambda_{\Phi\Delta} v_\Delta\right) & \frac{1}{4v_\Delta}\left(8\lambda_\Delta v_\Delta^3 + M_{H\Delta} v^2 + M_{\Phi\Delta} v_\Phi^2\right) \end{pmatrix}$$

- The 125 GeV Higgs is now a mixture of $\{h, \phi_2, \delta_3\}$

$$h_1 = O_{11} h + O_{21} \phi_2 + O_{31} \delta_3,$$

- However, the mixing is constrained to be quite small, suppressed by v/v_Φ as $v \sim 246$ GeV and $v_\Phi \geq 10$ TeV due to LEP Z-Z′ mixing constraint (More on this later)!

Scalar Mass Spectrum (III)

$G = \{G_H^p, H_2^{0*}, \Delta_p\}$

$$\mathcal{M}_0'^2 = \begin{pmatrix} M_{\Phi\Delta}v_\Delta + \frac{1}{2}\lambda'_{H\Phi}v^2 & \frac{1}{2}\lambda'_{H\Phi}vv_\Phi & -\frac{1}{2}M_{\Phi\Delta}v_\Phi \\ \frac{1}{2}\lambda'_{H\Phi}vv_\Phi & M_{H\Delta}v_\Delta + \frac{1}{2}\lambda'_{H\Phi}v_\Phi^2 & \frac{1}{2}M_{H\Delta}v \\ -\frac{1}{2}M_{\Phi\Delta}v_\Phi & \frac{1}{2}M_{H\Delta}v & \frac{1}{4v_\Delta}\left(M_{H\Delta}v^2 + M_{\Phi\Delta}v_\Phi^2\right) \end{pmatrix}$$

- The above mass matrix has zero determinant!
- The zero eigenvalue state is the Goldstone boson absorbed by the longitudinal component of the gauge bosons of SU(2)$_H$ $W_H'^{(p,m)}$, a vector dark matter candidate.
- The other two eigenstates correspond to a dark Higgs $\tilde{\Delta}$ and a scalar dark matter candidate D.

$$\tilde{\Delta} = O_{13}^D G_H^p + O_{23}^D H_2^{0*} + O_{33}^D \Delta_p \text{ (Heavier)}$$

$$D = O_{12}^D G_H^p + O_{22}^D H_2^{0*} + O_{32}^D \Delta_p \text{ (Lighter)}$$

Scalar Mass Spectrum (IV)

- The rest

Goldstone Bosons: (Longitudinal components of $W^{\pm}$, Z,Z')

$$m^2_{G^\pm} = m^2_{G^0} = m^2_{G^0_H} = 0$$

Physical Charged Higgs:

$$m^2_{H^\pm} = M_{H\Delta} v_\Delta - \frac{1}{2}\lambda'_H v^2 + \frac{1}{2}\lambda'_{H\Phi} v^2_\Phi,$$

Different from IHDM!

Neutral Gauge Bosons Z_1, Z_2, Z_3 (I)

In the basis $\{B, W^3, W'^3, X\}$:

$$\mathcal{M}^2_{\text{gauge}} = \begin{pmatrix} \frac{g'^2 v^2}{4} + \cancel{M_Y^2} & -\frac{g' g\, v^2}{4} & \frac{g' g_H v^2}{4} & \frac{g' g_X v^2}{2} + \cancel{M_X M_Y} \\ -\frac{g' g\, v^2}{4} & \frac{g^2 v^2}{4} & -\frac{g g_H v^2}{4} & -\frac{g g_X v^2}{2} \\ \frac{g' g_H v^2}{4} & -\frac{g g_H v^2}{4} & \frac{g_H^2 \left(v^2 + v_\Phi^2\right)}{4} & \frac{g_H g_X \left(v^2 - v_\Phi^2\right)}{2} \\ \frac{g' g_X v^2}{2} + \cancel{M_X M_Y} & -\frac{g g_X v^2}{2} & \frac{g_H g_X \left(v^2 - v_\Phi^2\right)}{2} & g_X^2 \left(v^2 + v_\Phi^2\right) + M_X^2 \end{pmatrix}$$

M_X, M_Y are Stueckelberg masses

Ruegg & Ruiz-Altaba, '04

SM with nonzero M_Y! The theory is well defined!

Feldman, Kors, Liu, Nath, '05-'07

StSM with both M_X and M_Y nonzero!

$$|\epsilon| = |M_Y/M_X| \leq 0.061\sqrt{1 - (M_Z/M_X)^2}$$

Neutral Gauge Bosons Z_1,Z_2,Z_3 (II)

Set $M_Y = 0$!

$$\mathcal{O}^{4\times4}_{M_Y=0} = \begin{pmatrix} c_W & -s_W & 0 & 0 \\ s_W & c_W & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & & & \\ 0 & & \mathcal{O} & \\ 0 & & & \end{pmatrix}, \quad \longrightarrow \quad (\gamma, Z^{\rm SM}, W'^3, X)$$

$$\mathcal{O}^{4\times4}_{\rm SM}\mathcal{M}^2_{\rm gauge}\mathcal{O}^{4\times4}_{\rm SM} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \frac{v^2\left(g^2+g'^2\right)}{4} & -\frac{g_H v^2\sqrt{g^2+g'^2}}{4} & -\frac{g_X v^2\sqrt{g^2+g'^2}}{2} \\ 0 & -\frac{g_H v^2\sqrt{g^2+g'^2}}{4} & \frac{g_H^2\left(v^2+v_\Phi^2\right)}{4} & \frac{g_X g_H\left(v^2-v_\Phi^2\right)}{2} \\ 0 & -\frac{g_X v^2\sqrt{g^2+g'^2}}{2} & \frac{g_X g_H\left(v^2-v_\Phi^2\right)}{2} & g_X^2(v^2+v_\Phi^2)+M_X^2 \end{pmatrix}$$

$$(\mathcal{O}^{4\times4})^T\mathcal{M}^2_{\rm gauge}\mathcal{O}^{4\times4} = {\rm diag}(0, M^2_{Z_1}, M^2_{Z_2}, M^2_{Z_3}),$$

$$(Z_1, Z_2, Z_3)^T = \mathcal{O}^T\cdot(Z^{SM}, W'^3, X)^T.$$

Dark $W'^{(p,m)}$

- Unlike LR model, W′ doesn't mix with $SU(2)_L$ W!

- All three VEVs entered in the W′ mass!

$$m^2_{W'(p,m)} = \frac{1}{4} g_H^2 \left(v^2 + v_\Phi^2 + 4 v_\Delta^2 \right)$$

- Candidate for dark matter in G2HDM. (In progress)

W.-C. Huang, H. Ishida, C.-T. Tu, Y.-L. S. Tsai and T. C. Yuan, EPJC (2018) 78:613

Drell-Yan Constraints

$$Z' = W'_3$$

Z'' is super heavy and decoupled!

Spectrum A:

$$m_{L^H(\nu^H)} = 2m_D$$

Spectrum B:

$$m_{Q^H} = m_{L^H(\nu^H)} = 2m_D$$

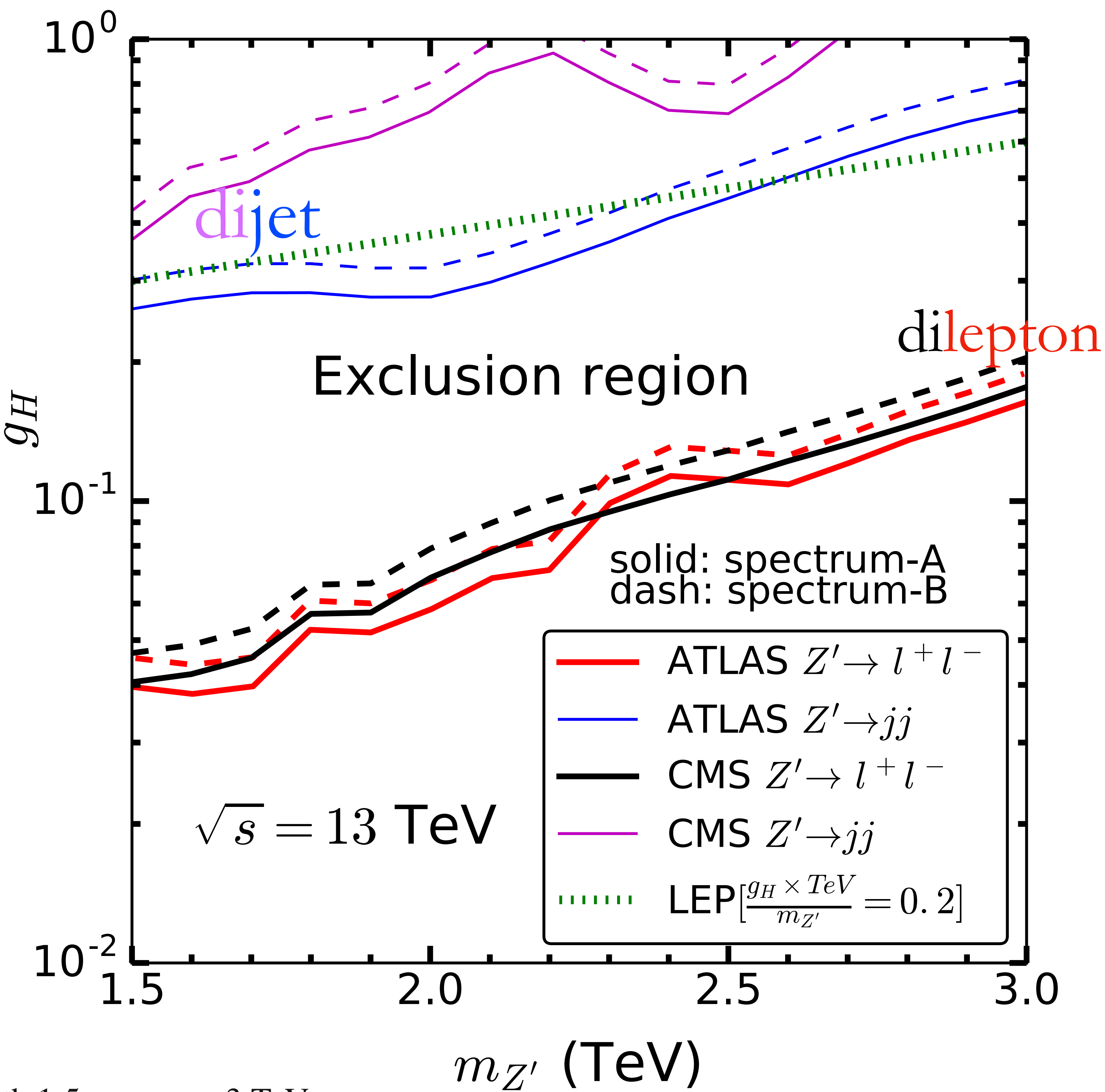


Table 2 Branching ratios for different decay modes of Z' with $1.5 \le m_{Z'} \le 3$ TeV

Z'	$BR(Q\overline{Q})(\%)$	$BR(L^+L^-)$ (%)	$BR(\nu\overline{\nu})$ (%)	$BR(Q^H\overline{Q^H})$ (%)	$BR(L^H\overline{L^H})$ (%)	$BR(\nu^H\overline{\nu^H})$ (%)
Spectrum A	66.52	11.13	11.13	–	5.61	5.61
Spectrum B	49.84	8.31	8.31	25.14	4.20	4.20

Here Q denotes 6 quark flavors (u, d, c, s, t, b) and L (ν) represents 3 lepton flavors $(e\ (\nu_e), \mu\ (\nu_\mu), \tau\ (\nu_\tau))$

Constraints on the Gauge Sector

1. LEP Z-pole observables
2. LEP-II constraints on contact interactions
3. Constraints from Electroweak Zjj production at LHC

Parameter Scan

$$\frac{M_X}{\text{TeV}} : \begin{cases} [0.1 : 10] & (\text{heavy } M_X) \\ [10^{-6} : 0.08] & (\text{light } M_X) \end{cases} .$$

$$10^{-8} \leq g_H \leq g_2^{\mathtt{SM}}$$

$$10^{-8} \leq g_X \leq g_1^{\mathtt{SM}}$$

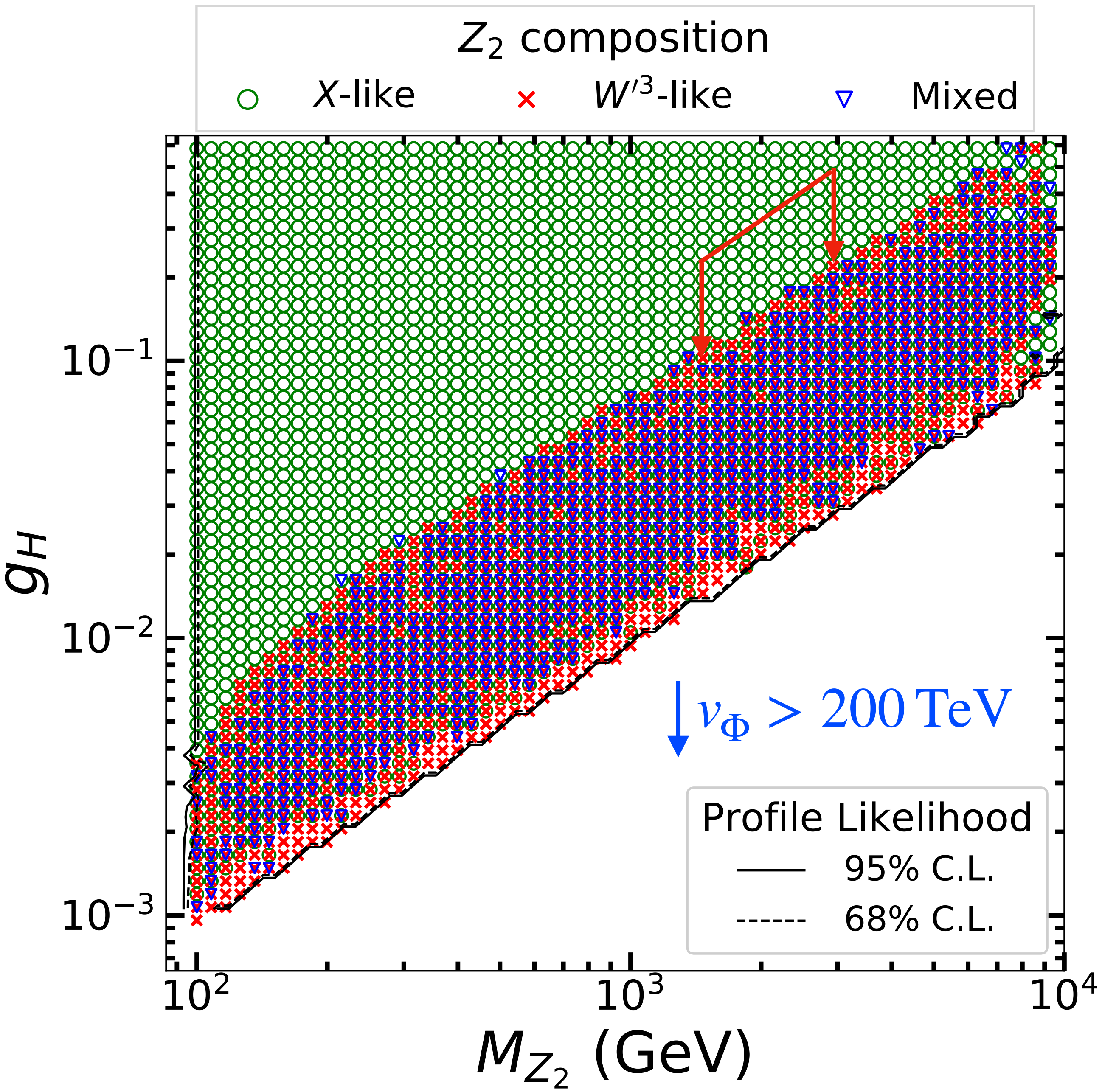
$$5 \text{ TeV} \leq v_\Phi \leq 200 \text{ TeV}$$

$$M_Y = 0.$$

Cheng-Tse Huang, Raymundo Ramos, Van Que Tran, Y. L. Sming Tsai, TCY, in preparation

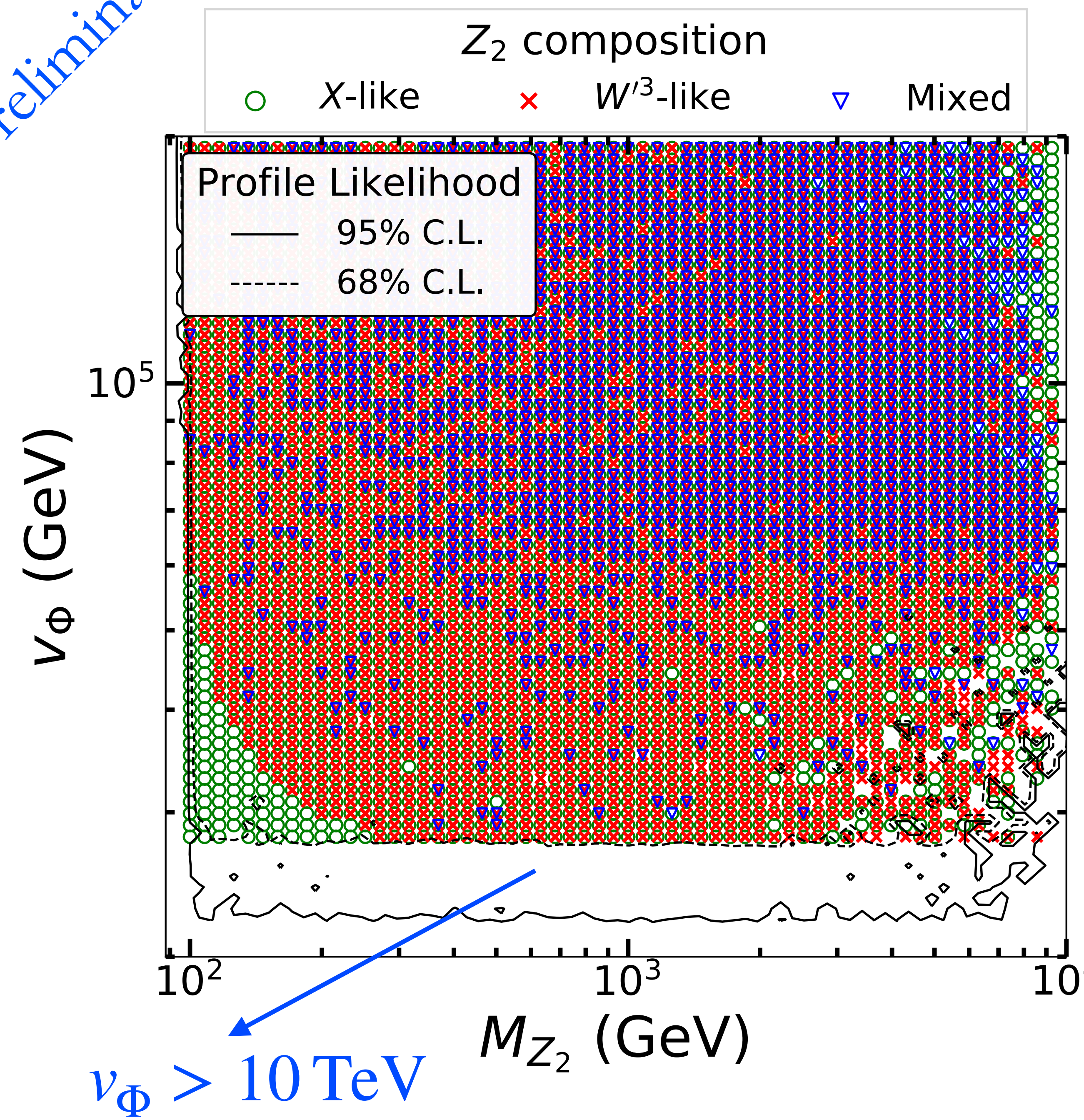
Heavy M_X

$Z_1 \sim 91.1876$ GeV



(a)

Preliminary



(b)

Dark Matter in G2HDM

See Sming Tsai's talk for details.

- Accidental Z_2:

$$\{\text{All SM particles, } h_2,\ h_3,\ Z',\ Z'' \text{ are even.}\}$$

$$\{D, \tilde{\Delta}, H^{\pm}, W'^{(p,m)}, \nu^H, l^H, q^H\} \text{are odd} .$$

- DM Candidates:

$$\{D, \nu^H, W'^{(p,m)}\}$$

Stability: Wei-chih's operator analysis

Yu-Xiang Lin, Raymundo Ramos, Chrisna Seyto Nugroho, *et al.* work in progress.

Theoretical and Phenomenological Constraints (Scalar Sector)

- Vacuum Stability (VS)
  - Scalar potential should be bounded from below
- Perturbative Unitarity (PU)
  - Scattering amplitudes in the scalar sector
- Higgs Physics (HP)
  - Diphoton signal strength of the 128 GeV Higgs

Reference:
Adelssalem Arhrib, Wei-Chih Huang, Raymundo Ramos, Y. L. Sming Tsai, TCY, arXiv:1806.05632, PRD98(2018) no.9, 095006

Scalar Potential (Quartic terms)

- Due to gauge symmetry, the potential depends only on these combinations.

$$x \equiv H^\dagger H,$$

$$y \equiv \Phi_H^\dagger \Phi_H,$$

$$z \equiv \mathrm{Tr}(\Delta_H^\dagger \Delta_H),$$

$$\xi \equiv \frac{(H^\dagger \Phi_H)(\Phi_H^\dagger H)}{(H^\dagger H)(\Phi_H^\dagger \Phi_H)},$$

$$\eta \equiv \frac{(-H_1^\dagger H_1 H_2^\dagger H_2 + H_1^\dagger H_2 H_2^\dagger H_1)}{(H^\dagger H)^2}.$$

$$0 \le \xi \le 1,\ -\frac{1}{4} \le \eta \le 0,\ \eta \ge \xi(\xi - 1)$$

- The quartic terms in the potential is then a quadratic form.

$$V_4 = \begin{pmatrix} x & y & z \end{pmatrix} \cdot \mathbf{Q}(\xi,\eta) \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix},$$

$$\mathbf{Q}(\xi,\eta) = \begin{pmatrix} \tilde{\lambda}_H(\eta) & \frac{1}{2}\tilde{\lambda}_{H\Phi}(\xi) & \frac{1}{2}\lambda_{H\Delta} \\ \frac{1}{2}\tilde{\lambda}_{H\Phi}(\xi) & \lambda_\Phi & \frac{1}{2}\lambda_{\Phi\Delta} \\ \frac{1}{2}\lambda_{H\Delta} & \frac{1}{2}\lambda_{\Phi\Delta} & \lambda_\Delta \end{pmatrix},$$

and $\tilde{\lambda}_H(\eta) \equiv \lambda_H + \eta\lambda'_H$, $\tilde{\lambda}_{H\Phi}(\xi) \equiv \lambda_{H\Phi} + \xi\lambda'_{H\Phi}$.

Copositivity

References:

A. Arhrib *et. al.*, PRD 84, 095005 (2011)

K. Kannike, EPJC 72, 2093 (2012); 76, 324 (2016); 78, 355(E) (2018)

(A)

$$\tilde{\lambda}_H(\eta) \geq 0, \qquad \lambda_\Phi \geq 0, \qquad \lambda_\Delta \geq 0,$$

(B)

$$\Lambda_{H\Phi}(\xi,\eta) \equiv \tilde{\lambda}_{H\Phi}(\xi) + 2\sqrt{\tilde{\lambda}_H(\eta)\lambda_\Phi} \geq 0,$$

$$\Lambda_{H\Delta}(\eta) \equiv \lambda_{H\Delta} + 2\sqrt{\tilde{\lambda}_H(\eta)\lambda_\Delta} \geq 0,$$

$$\Lambda_{\Phi\Delta} \equiv \lambda_{\Phi\Delta} + 2\sqrt{\lambda_\Phi\lambda_\Delta} \geq 0,$$

$$\tilde{\lambda}_H(\eta) = \lambda_H + \eta\lambda'_H$$

$$\tilde{\lambda}_{H\Phi}(\xi) = \lambda_{H\Phi} + \xi\lambda'_{H\Phi}$$

$$0 \leq \xi \leq 1, \ -\frac{1}{4} \leq \eta \leq 0; \ \eta \geq \xi(\xi - 1)$$

(C)

$$\Lambda_{H\Phi\Delta}(\xi,\eta) \equiv \sqrt{\tilde{\lambda}_H(\eta)\lambda_\Phi\lambda_\Delta} + \frac{1}{2}(\tilde{\lambda}_{H\Phi}(\xi)\sqrt{\lambda_\Delta} + \lambda_{H\Delta}\sqrt{\lambda_\Phi} + \lambda_{\Phi\Delta}\sqrt{\tilde{\lambda}_H(\eta)}) + \frac{1}{2}\sqrt{\Lambda_{H\Phi}(\xi,\eta)\Lambda_{H\Delta}(\eta)\Lambda_{\Phi\Delta}} \geq 0$$

Scalar Bosons Scattering Amplitudes

- $2 \to 2$ processes

$$\left\{\frac{hh}{\sqrt{2}}, \frac{G^0G^0}{\sqrt{2}}, G^+G^-, H_2^{0*}H_2^0, H^+H^-, \frac{\phi_2\phi_2}{\sqrt{2}}, \frac{G_H^0G_H^0}{\sqrt{2}}, G_H^pG_H^m, \frac{\delta_3\delta_3}{\sqrt{2}}, \Delta_p\Delta_m\right\}$$

$$\mathcal{M}_1 = \begin{pmatrix}
3\lambda_H & \lambda_H & \frac{2}{\sqrt{2}}\lambda_H & \frac{2}{\sqrt{2}}\lambda_H & \frac{2}{\sqrt{2}}\tilde{\lambda}_H & \frac{1}{2}\lambda_{H\Phi} & \frac{1}{2}\lambda_{H\Phi} & \frac{1}{\sqrt{2}}\tilde{\lambda}_{H\Phi} & \frac{1}{2}\lambda_{H\Delta} & \frac{1}{\sqrt{2}}\lambda_{H\Delta} \\
\lambda_H & 3\lambda_H & \frac{2}{\sqrt{2}}\lambda_H & \frac{2}{\sqrt{2}}\lambda_H & \frac{2}{\sqrt{2}}\tilde{\lambda}_H & \frac{1}{2}\lambda_{H\Phi} & \frac{1}{2}\lambda_{H\Phi} & \frac{1}{\sqrt{2}}\tilde{\lambda}_{H\Phi} & \frac{1}{2}\lambda_{H\Delta} & \frac{1}{\sqrt{2}}\lambda_{H\Delta} \\
\frac{2}{\sqrt{2}}\lambda_H & \frac{2}{\sqrt{2}}\lambda_H & 4\lambda_H & 2\tilde{\lambda}_H & 2\lambda_H & \frac{1}{\sqrt{2}}\lambda_{H\Phi} & \frac{1}{\sqrt{2}}\lambda_{H\Phi} & \tilde{\lambda}_{H\Phi} & \frac{1}{\sqrt{2}}\lambda_{H\Delta} & \lambda_{H\Delta} \\
\frac{2}{\sqrt{2}}\lambda_H & \frac{2}{\sqrt{2}}\lambda_H & 2\tilde{\lambda}_H & 4\lambda_H & 2\lambda_H & \frac{1}{\sqrt{2}}\tilde{\lambda}_{H\Phi} & \frac{1}{\sqrt{2}}\tilde{\lambda}_{H\Phi} & \lambda_{H\Phi} & \frac{1}{\sqrt{2}}\lambda_{H\Delta} & \lambda_{H\Delta} \\
\frac{2}{\sqrt{2}}\tilde{\lambda}_H & \frac{2}{\sqrt{2}}\tilde{\lambda}_H & 2\lambda_H & 2\lambda_H & 4\lambda_H & \frac{1}{\sqrt{2}}\tilde{\lambda}_{H\Phi} & \frac{1}{\sqrt{2}}\tilde{\lambda}_{H\Phi} & \lambda_{H\Phi} & \frac{1}{\sqrt{2}}\lambda_{H\Delta} & \lambda_{H\Delta} \\
\frac{1}{2}\lambda_{H\Phi} & \frac{1}{2}\lambda_{H\Phi} & \frac{1}{\sqrt{2}}\lambda_{H\Phi} & \frac{1}{\sqrt{2}}\tilde{\lambda}_{H\Phi} & \frac{1}{\sqrt{2}}\tilde{\lambda}_{H\Phi} & 3\lambda_\Phi & \lambda_\Phi & \frac{2}{\sqrt{2}}\lambda_\Phi & \frac{1}{2}\lambda_{\Phi\Delta} & \frac{1}{\sqrt{2}}\lambda_{\Phi\Delta} \\
\frac{1}{2}\lambda_{H\Phi} & \frac{1}{2}\lambda_{H\Phi} & \frac{1}{\sqrt{2}}\lambda_{H\Phi} & \frac{1}{\sqrt{2}}\tilde{\lambda}_{H\Phi} & \frac{1}{\sqrt{2}}\tilde{\lambda}_{H\Phi} & \lambda_\Phi & 3\lambda_\Phi & \frac{2}{\sqrt{2}}\lambda_\Phi & \frac{1}{2}\lambda_{\Phi\Delta} & \frac{1}{\sqrt{2}}\lambda_{\Phi\Delta} \\
\frac{1}{\sqrt{2}}\tilde{\lambda}_{H\Phi} & \frac{1}{\sqrt{2}}\tilde{\lambda}_{H\Phi} & \tilde{\lambda}_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Phi} & \frac{2}{\sqrt{2}}\lambda_\Phi & \frac{2}{\sqrt{2}}\lambda_\Phi & 4\lambda_\Phi & \frac{1}{\sqrt{2}}\lambda_{\Phi\Delta} & \lambda_{\Phi\Delta} \\
\frac{1}{2}\lambda_{H\Delta} & \frac{1}{2}\lambda_{H\Delta} & \frac{1}{\sqrt{2}}\lambda_{H\Delta} & \frac{1}{\sqrt{2}}\lambda_{H\Delta} & \frac{1}{\sqrt{2}}\lambda_{H\Delta} & \frac{1}{2}\lambda_{\Phi\Delta} & \frac{1}{2}\lambda_{\Phi\Delta} & \frac{1}{\sqrt{2}}\lambda_{\Phi\Delta} & 3\lambda_\Delta & \frac{2}{\sqrt{2}}\lambda_\Delta \\
\frac{1}{\sqrt{2}}\lambda_{H\Delta} & \frac{1}{\sqrt{2}}\lambda_{H\Delta} & \lambda_{H\Delta} & \lambda_{H\Delta} & \lambda_{H\Delta} & \frac{1}{\sqrt{2}}\lambda_{\Phi\Delta} & \frac{1}{\sqrt{2}}\lambda_{\Phi\Delta} & \lambda_{\Phi\Delta} & \frac{2}{\sqrt{2}}\lambda_\Delta & 4\lambda_\Delta
\end{pmatrix},$$

$$\tilde{\lambda}_H \equiv \lambda_H - \lambda'_H/2, \tilde{\lambda}_{H\Phi} \equiv \lambda_{H\Phi} + \lambda'_{H\Phi}$$

- Unitarity constraints: $|\lambda_i(\mathcal{M}_1)| \leq 8\pi$

Scalar Bosons Scattering Amplitudes

- There are also 12 other groups of $2 \to 2$ processes
- The perturbative unitarity constraints can be summarized as

$$
\begin{aligned}
(\mathrm{I}) &\Rightarrow & |\lambda_i(\mathcal{M}_1)| \le 8\pi, \quad \forall \;\; i = (1, \ldots, 10), \\
(\mathrm{II})\text{–}(\mathrm{VIII}) &\Rightarrow & |\lambda_H| \le 4\pi, |\lambda'_H| \le 8\sqrt{2}\pi, |2\lambda_H \pm \lambda'_H| \le 8\pi, |\lambda_\Phi| \le 4\pi, |\lambda_\Delta| \le 4\pi, \\
(\mathrm{IX}), (\mathrm{X}), (\mathrm{XI}) &\Rightarrow & |\lambda_{H\Phi}| \le 8\pi, |\tilde{\lambda}_{H\Phi}| = |\lambda_{H\Phi} + \lambda'_{H\Phi}| \le 8\pi, |\lambda'_{H\Phi}| \le 8\sqrt{2}\pi, \\
(\mathrm{XII}), (\mathrm{XIII}) &\Rightarrow & |\lambda_{H\Delta}| \le 8\pi, |\lambda_{\Phi\Delta}| \le 8\pi.
\end{aligned}
$$

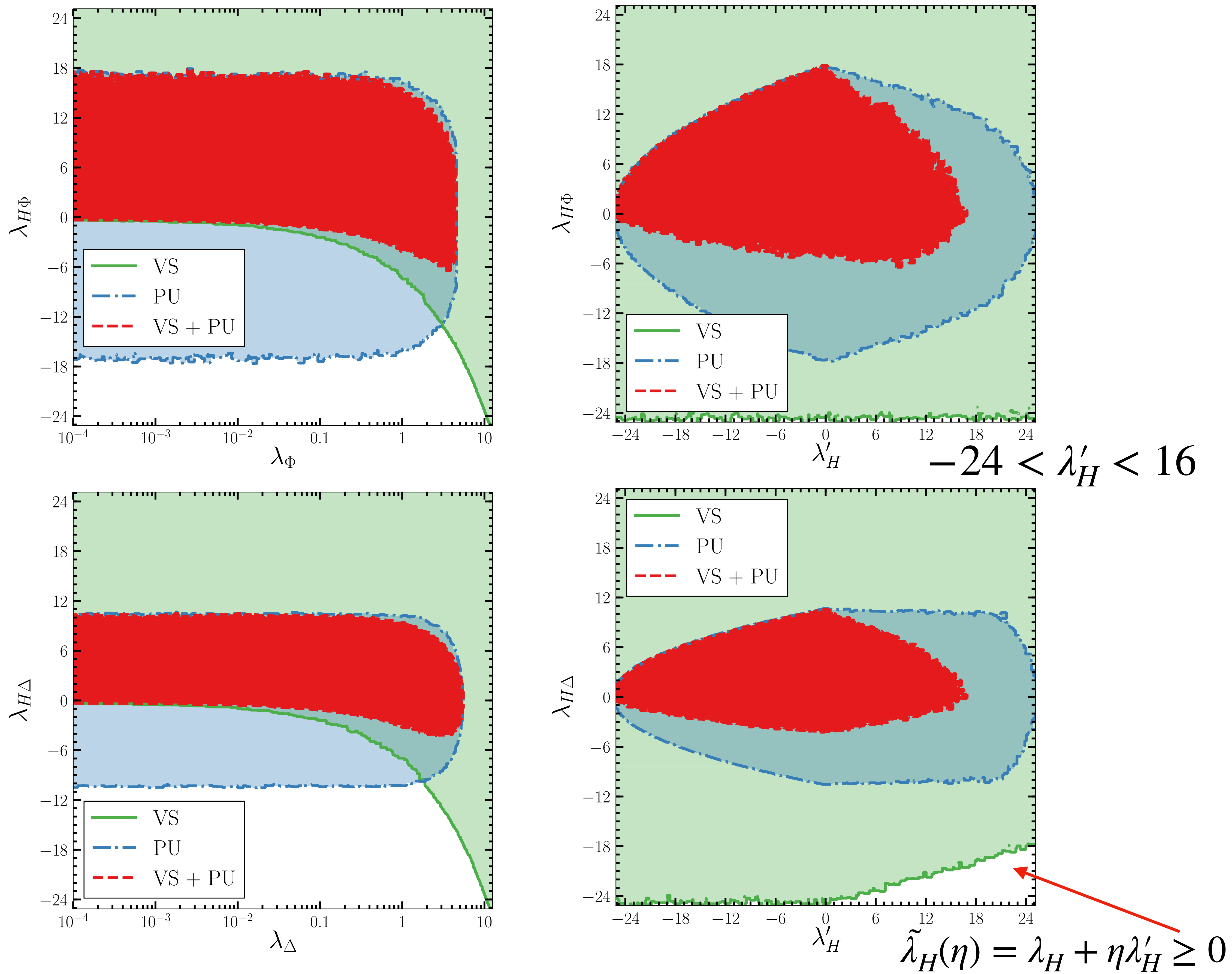
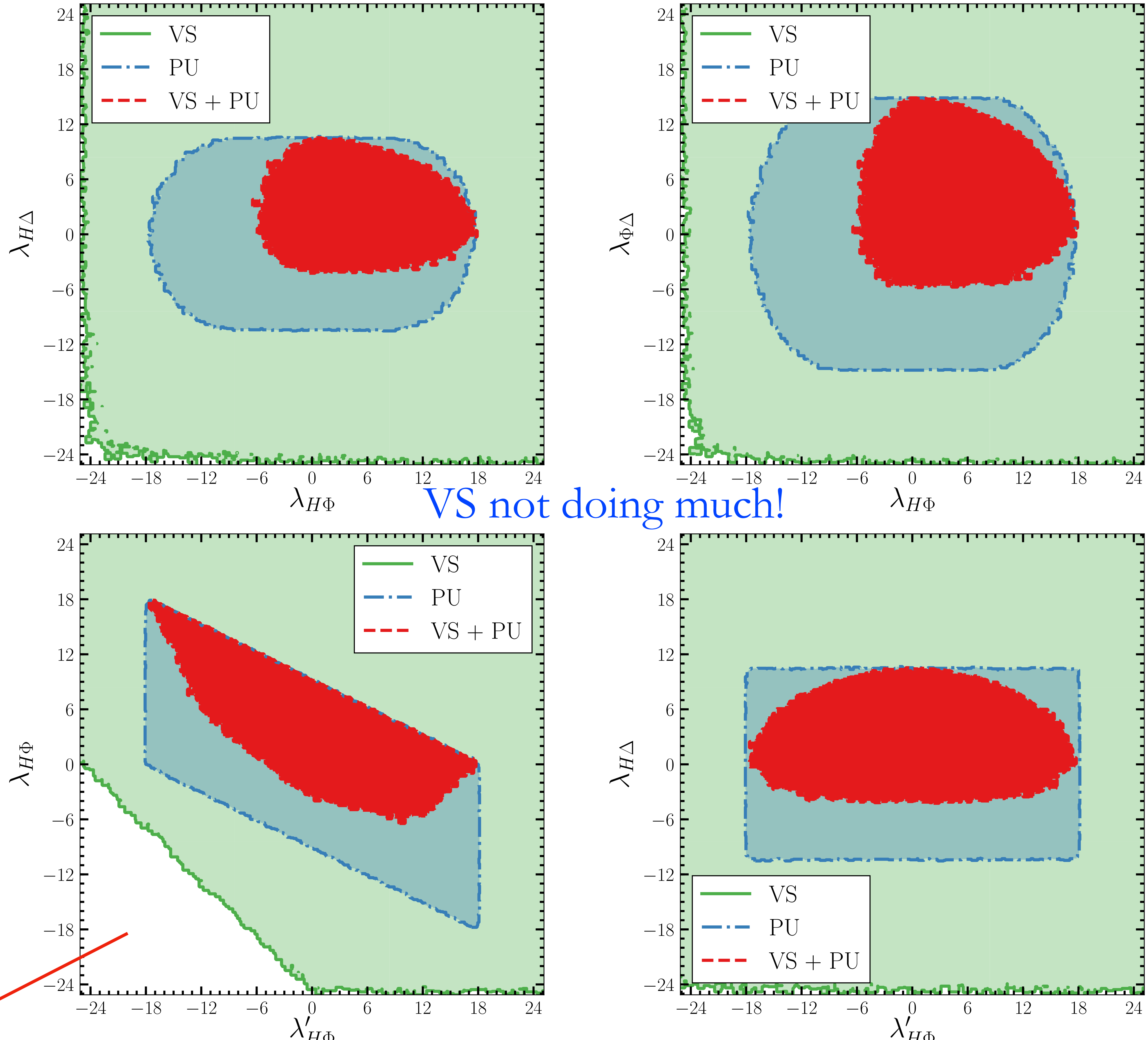


FIG. 1. Allowed regions of the parameter space by the VS, PU and (VS + PU) constraints projected onto the $(\lambda_\Phi, \lambda_{H\Phi})$, $(\lambda_\Delta, \lambda_{H\Delta})$, $(\lambda'_H, \lambda_{H\Phi})$ and $(\lambda'_H, \lambda_{H\Delta})$ planes.



$\tilde{\lambda}_{H\Phi}(\xi) = \lambda_{H\Phi} + \xi\lambda'_{H\Phi}$ can't be too negative!

FIG. 2. Allowed regions of the parameter space by the VS, PU and (VS + PU) constraints projected onto the planes of $(\lambda_{H\Phi}, \lambda_{H\Delta})$, $(\lambda'_{H\Phi}, \lambda_{H\Phi})$, $(\lambda_{H\Phi}, \lambda_{\Phi\Delta})$ and $(\lambda'_{H\Phi}, \lambda_{H\Delta})$.

Higgs Phenomenology

- Mixing Effects: $h_1 = O_{11}h + O_{21}\phi_2 + O_{31}\delta_3,$ $m_{h_1} = 125.09 \pm 0.24$ GeV

- Signal Strength: $\mu^{\gamma\gamma}_{\rm ggH} = \frac{\Gamma^{\rm SM}_h}{\Gamma_{h_1}} \frac{\Gamma(h_1 \to gg)\Gamma(h_1 \to \gamma\gamma)}{\Gamma^{\rm SM}(h \to gg)\Gamma^{\rm SM}(h \to \gamma\gamma)},$ $\mu^{\gamma\gamma}_{ggH} = 0.81^{+0.19}_{-0.18}$

$$\Gamma(h_1 \to \gamma\gamma) = \frac{G_F \alpha^2 m^3_{h_1} O^2_{11}}{128\sqrt{2}\pi^3}\Big| A_1(\tau_{W^\pm}) + \sum_f N_C Q^2_f A_{1/2}(\tau_f)$$

Charged Higgs $$+ \mathcal{C}_h \frac{\tilde{\lambda}_H v^2}{m^2_{H^\pm}} A_0(\tau_{H^\pm})$$

$$\mathcal{C}_h = 1 + \frac{O_{21}}{O_{11}} \frac{(\lambda_{H\Phi} + \lambda'_{H\Phi})v_\Phi}{2\tilde{\lambda}_H v} - \frac{O_{31}}{O_{11}} \frac{2\lambda_{H\Delta}v_\Delta + M_{H\Delta}}{4\tilde{\lambda}_H v},$$

Heavy Fermions $$+ \frac{O_{21}}{O_{11}} \frac{v}{v_\Phi} \sum_F N_C Q^2_F A_{1/2}(\tau_F)\Big|^2,$$

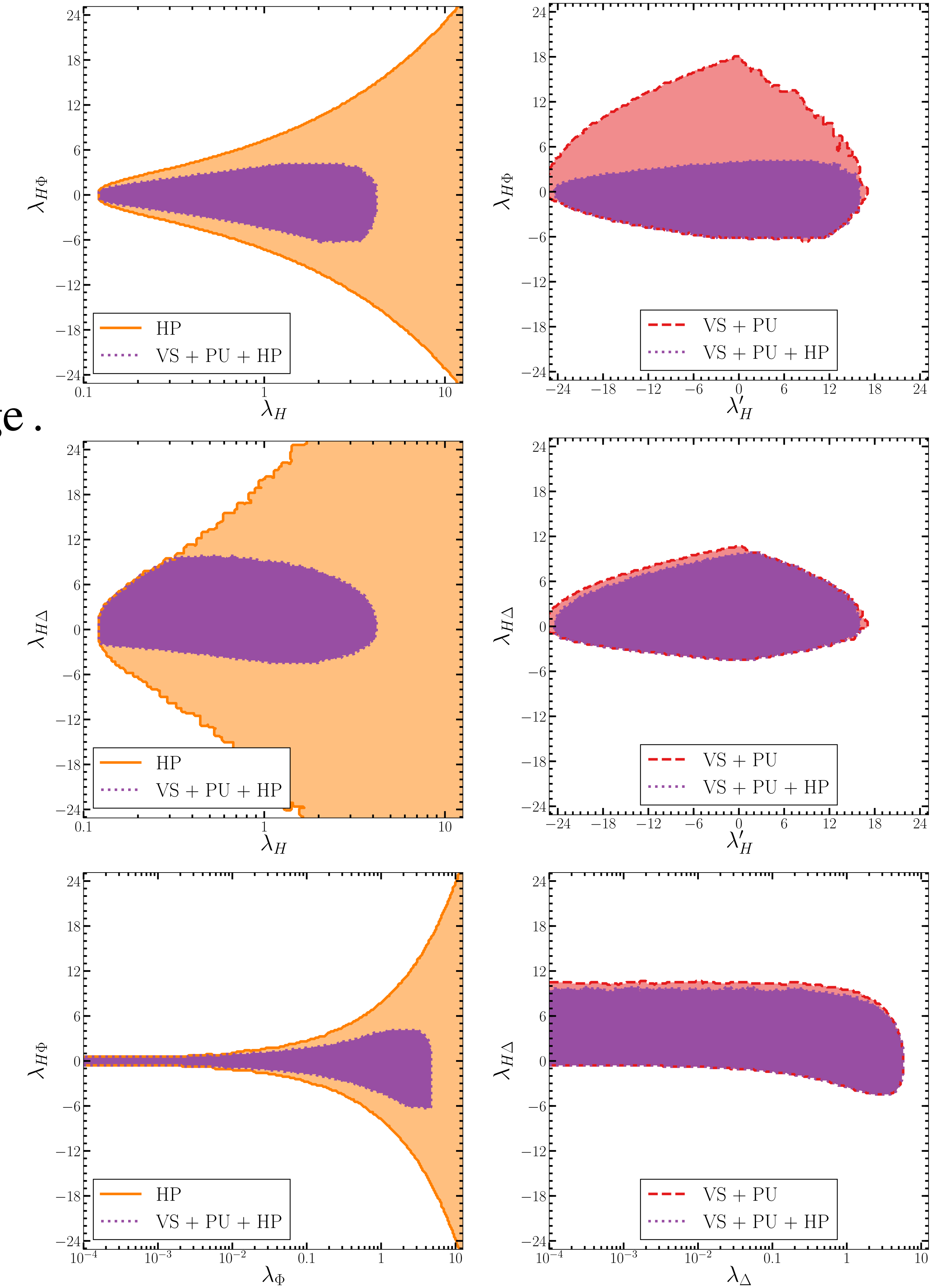
$$\Gamma(h_1 \to gg) = \frac{\alpha^2_s m^3_{h_1} O^2_{11}}{72 v^2 \pi^3}\Big| \sum_f \frac{3}{4} A_{1/2}(\tau_f)$$

$$+ \frac{O_{21}}{O_{11}} \frac{v}{v_\Phi} \sum_F \frac{3}{4} A_{1/2}(\tau_F)\Big|^2.$$

λ_H has an allowed range .

$0.13 < \lambda_H < 4.00$

λ'_H is still loosely constrained .



$\lambda_\Phi < 4.19$

$\lambda_\Delta < 5.03$

FIG. 3. Allowed regions of the parameter space by the HP, (VS + PU) and (VS + PU + HP) constraints projected onto the planes of $(\lambda_H, \lambda_{H\Phi})$, $(\lambda_H, \lambda_{H\Delta})$, $(\lambda_\Phi, \lambda_{H\Phi})$, $(\lambda'_H, \lambda_{H\Phi})$, $(\lambda'_H, \lambda_{H\Delta})$ and $(\lambda_\Delta, \lambda_{H\Delta})$.

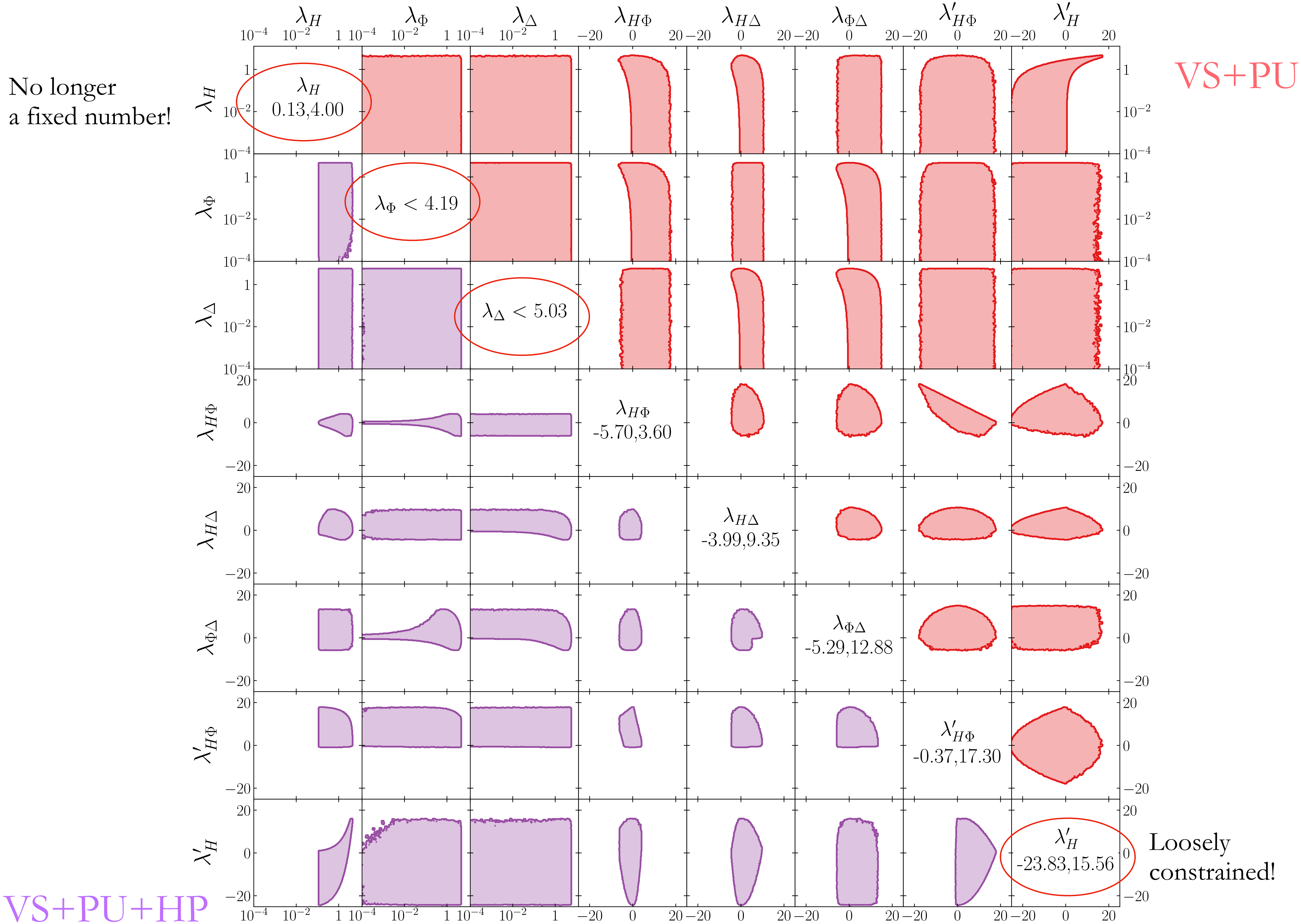


FIG. 9. A summary of the parameter space allowed by the theoretical and phenomenological constraints. The red regions show the results from the theoretical constraints (VS + PU) of Sec. III. The magenta regions are constrained by Higgs physics as well as the theoretical constraints (HP + VS + PU), as discussed in Sec. IV.

Phenomenology

- Double Higgs Production

Ref: Chuan-Ren Chen, Yu-Xiang Lin, Van Que Tran, TCY, arXiv:1810.04837

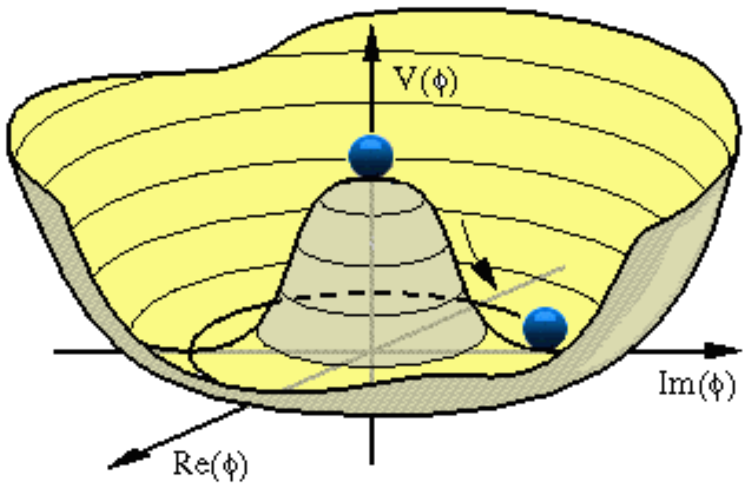
Higgs discovery at LHC, $m_h \simeq 125$ GeV

$$V_{\rm SM} = \frac{m_h^2}{2} h^2 + \lambda_{\rm SM} v h^3 + \frac{\kappa_{\rm SM}}{4} h^4, \quad \lambda_{\rm SM} = \kappa_{\rm SM} = \frac{m_h^2}{2v^2} \simeq 0.13$$

The Higgs self coupling is a key parameter that can help us reconstructing the shape of the Higgs potential.

➠ How EWSB really happens

➠ Whether there is an extended Higgs sector



[Slides from VQ Tran]

However, it is a challenging measurement for the SM due to its small production cross section

$$\sigma(pp \to h)_{\rm SM} = \mathcal{O}(45\,{\rm pb})$$ easy

$$\Big\downarrow \frac{1}{1300}$$

$$\sigma(pp \to hh)_{\rm SM} = \mathcal{O}(35\,{\rm fb})$$ hard

$$\Big\downarrow \frac{1}{350}$$

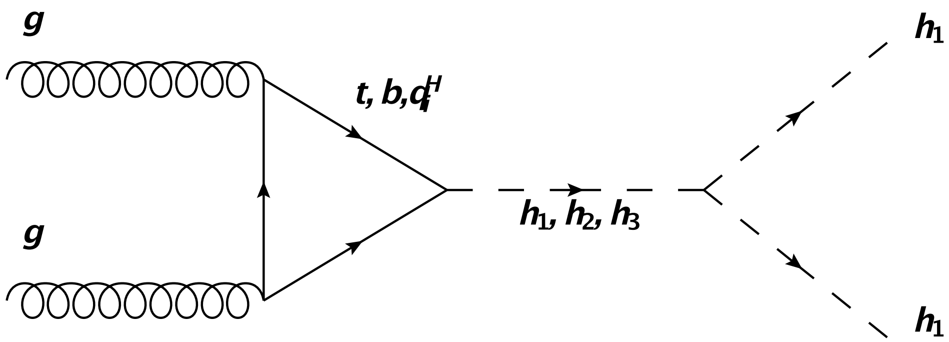
$$\sigma(pp \to 3h)_{\rm SM} = \mathcal{O}(0.1\,{\rm fb})$$ no way

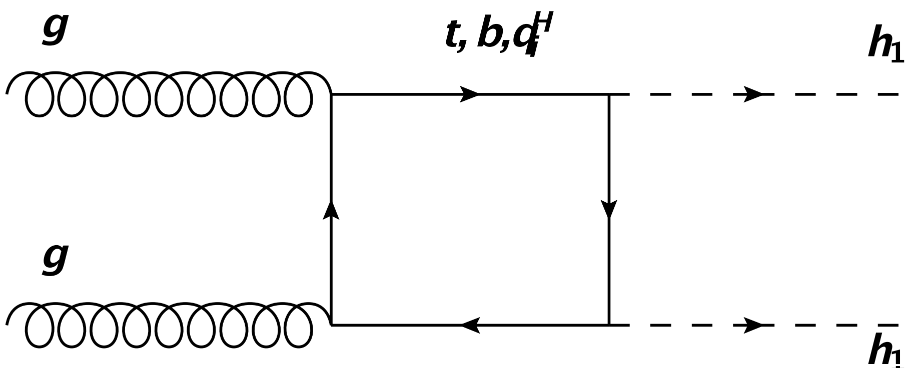
[Slides from VQ Tran]

BSM physics can easily affect the Higgs pair production cross section through:

1. Modification in the quark Yukawa couplings;
2. Modification in the trilinear Higgs self-coupling;
3. New colored particles running in triangle and box loops;
4. Existence of new heavy scalars decaying into Higgs pairs.

➢ (1)—(3) belong to the non-resonance effect, while (4) belongs to the resonance effect.

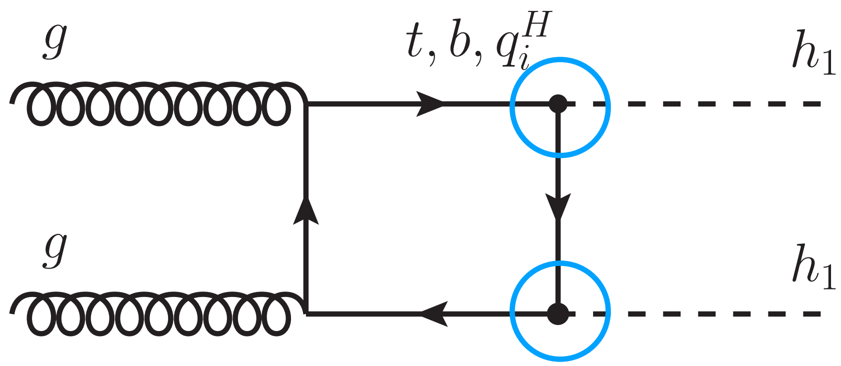




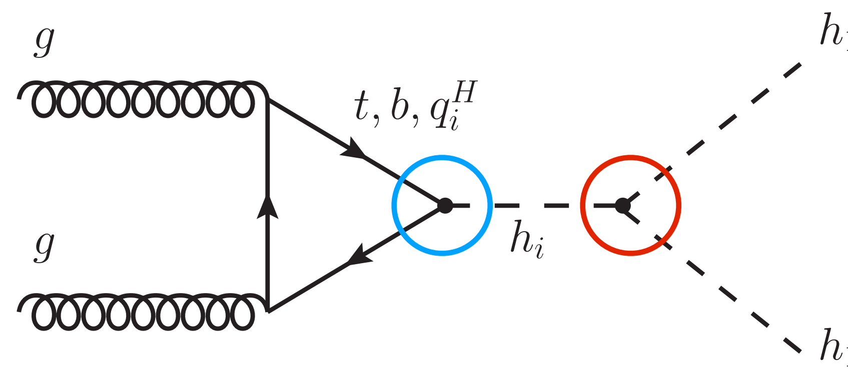
G2HDM has all these ingredients!

[Slides from VQ Tran]

Double Higgs Production in G2HDM



(a)



(b)

$$g_{qqh_i} = O^H_{1i}\,\frac{m_q}{v}\,,$$

$$g_{q^H q^H h_i} = O^H_{2i}\,\frac{m_{q^H}}{v_\Phi}\,,$$

$$\begin{aligned}
g_{h_1h_1h_1} = {} & 6\Big(\lambda_H\, v\,(O^H_{11})^3 + \lambda_\Phi\, v_\Phi\,(O^H_{21})^3 - \lambda_\Delta\, v_\Delta\,(O^H_{31})^3\Big)\\
& + \frac{3}{2}\Big(\,(M_{H\Delta} - 2\lambda_{H\Delta}\, v_\Delta)\,(O^H_{11})^2\, O^H_{31} + (M_{\Phi\Delta} - 2\lambda_{\Phi\Delta}\, v_\Delta)\,(O^H_{21})^2\, O^H_{31}\Big)\\
& + 3(\lambda_{H\Phi})\,\left(v\, O^H_{11}\,(O^H_{21})^2 + v_\Phi (O^H_{11})^2\, O^H_{21}\right)\\
& + 3\Big(\lambda_{H\Delta}\, v\, O^H_{11}\,(O^H_{31})^2 + \lambda_{\Phi\Delta}\, v_\Phi\, O^H_{21}\,(O^H_{31})^2\Big)\,,
\end{aligned}$$

$$\begin{aligned}
g_{h_2h_1h_1} = {} & 6\Big(\lambda_H\, v\,(O^H_{11})^2 O^H_{12} + \lambda_\Phi\, v_\Phi\,(O^H_{21})^2 O^H_{22} - \lambda_\Delta\, v_\Delta\,(O^H_{31})^2 O^H_{32}\Big)\\
& + \frac{1}{2} M_{H\Delta} O^H_{11}\,(O^H_{11} O^H_{32} + 2 O^H_{12} O^H_{31}) + \frac{1}{2} M_{\Phi\Delta} O^H_{21}\,(O^H_{21} O^H_{32} + 2 O^H_{22} O^H_{31})\\
& + \lambda_{H\Delta}\Big[v\Big((O^H_{31})^2 O^H_{12} + 2 O^H_{11} O^H_{31} O^H_{32}\Big) - v_\Delta\Big((O^H_{11})^2 O^H_{32} + 2 O^H_{11} O^H_{12} O^H_{31}\Big)\Big]\\
& + \lambda_{\Phi\Delta}\Big[v_\Phi\Big((O^H_{31})^2 O^H_{22} + 2 O^H_{21} O^H_{31} O^H_{32}\Big) - v_\Delta\Big((O^H_{21})^2 O^H_{32} + 2 O^H_{21} O^H_{22} O^H_{31}\Big)\Big]\\
& + (\lambda_{H\Phi})\Big[v\Big((O^H_{21})^2 O^H_{12} + 2 O^H_{11} O^H_{21} O^H_{22}\Big) + v_\Phi\Big(O^H_{11}(O^H_{11} O^H_{22} + 2 O^H_{12} O^H_{21})\Big)\Big]\,,
\end{aligned}$$

Parameter Scan

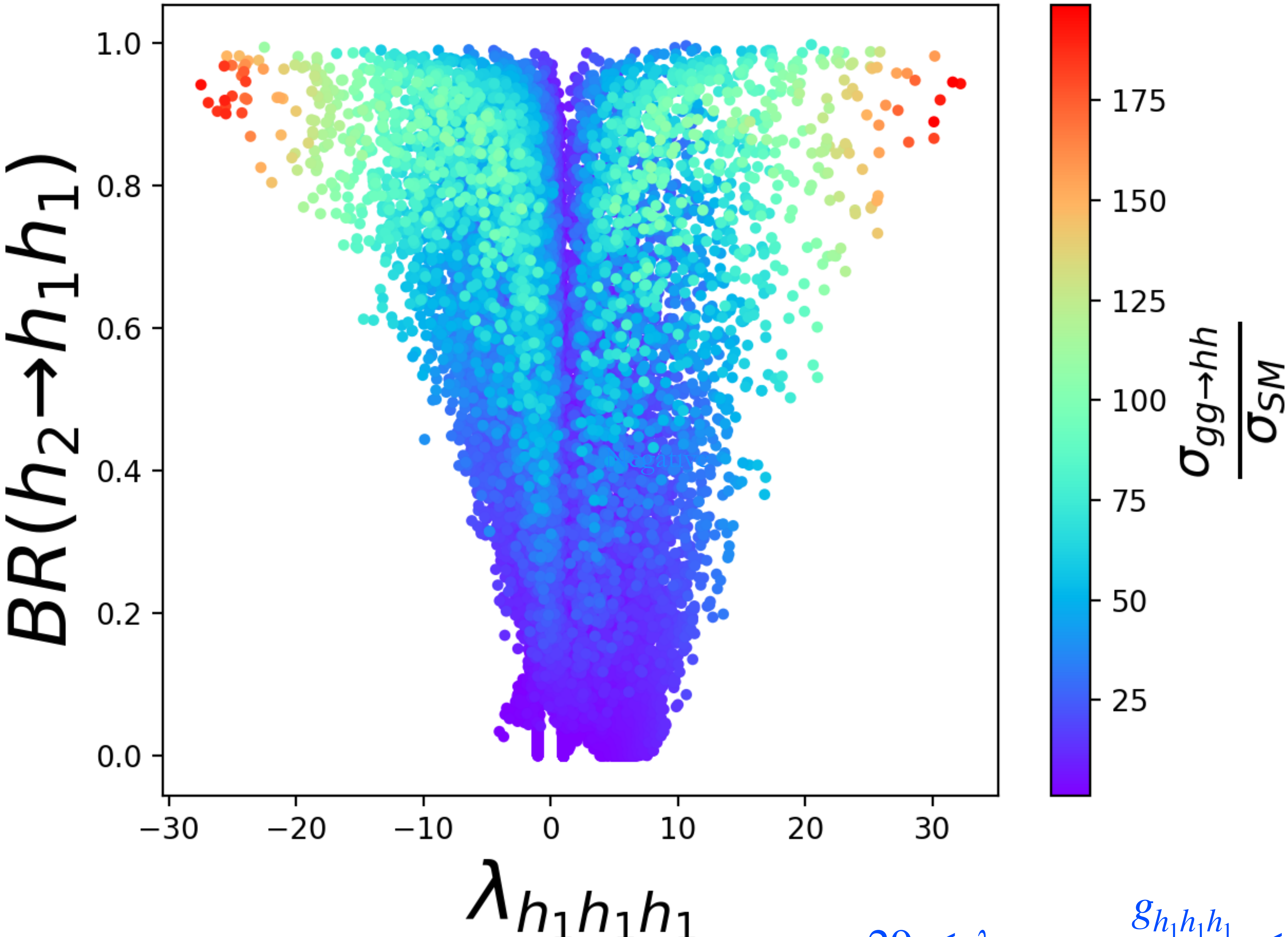
- All the lambdas satisfy PU+VS+HP constraints discussed before.
- For the double Higgs phenomenology, we will scan

$$0.1\,\mathrm{GeV} < v_\Delta < 4\,\mathrm{TeV}\,,$$
$$30\,\mathrm{TeV} < v_\Phi < 100\,\mathrm{TeV}\,,$$
$$-3\,\mathrm{TeV} < M_{H\Delta} < 3\,\mathrm{TeV}\,,$$
$$0 < M_{\Phi\Delta} < 15\,\mathrm{GeV}\,.$$

- Constraints from direct Z' resonance search at ATLAS and CMS.
- All masses of the heavy fermions are set to be 3 TeV.

$$h_2 \to h_1 h_1 \quad \text{(On-shell decay)}$$
$$h_1 \nrightarrow DD \quad \text{(Kinematically forbidden)}$$

- Note: Effects from the heaviest dark Higgs h_3 are neglected.



$$-29 \leq \lambda_{h_1 h_1 h_1} \equiv \frac{g_{h_1 h_1 h_1}}{\lambda_{\rm SM}} \leq 32$$

Negative values provide constructive interferences!

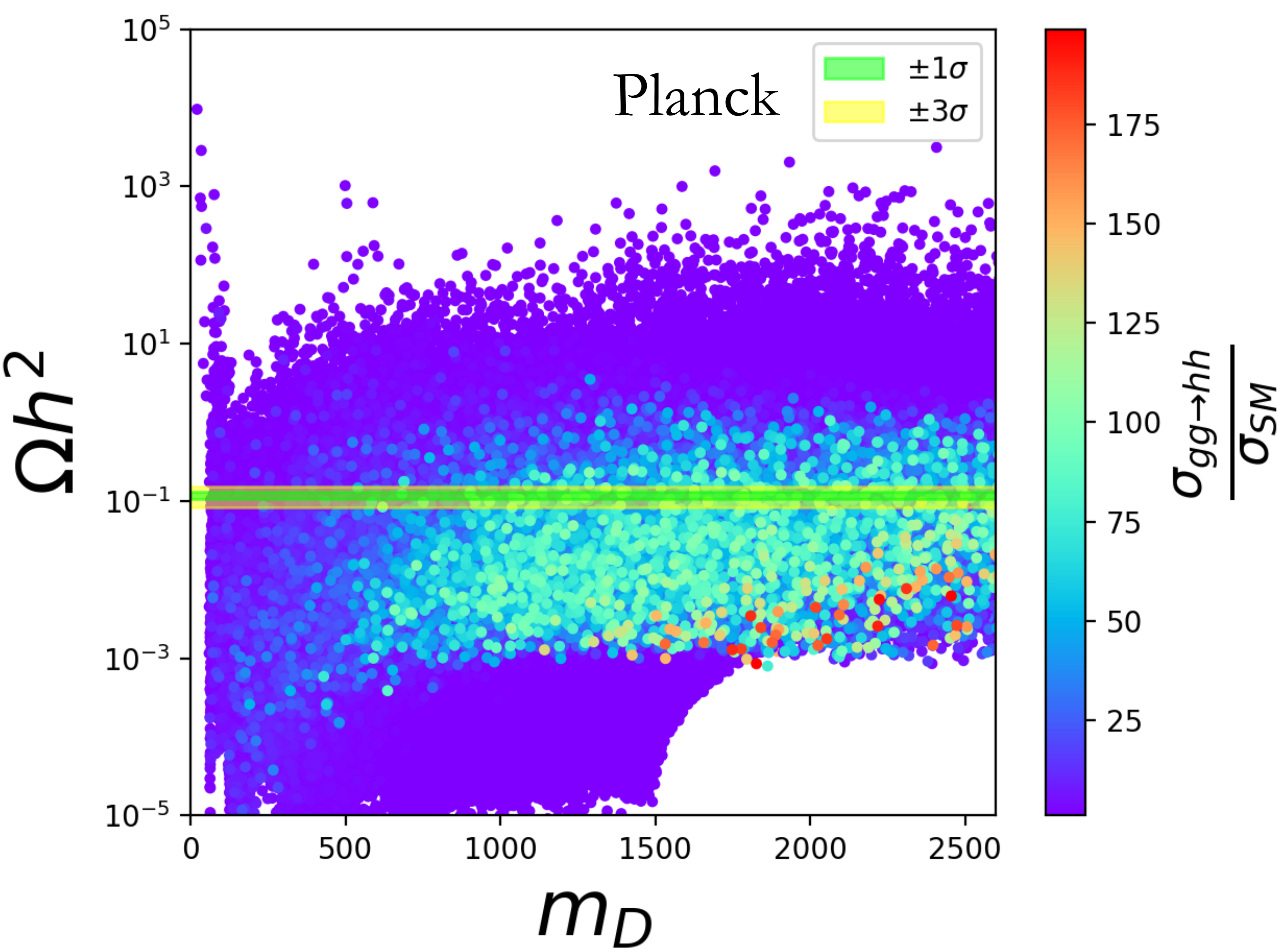
Correlations with Dark Matter Physics

- Relic Density

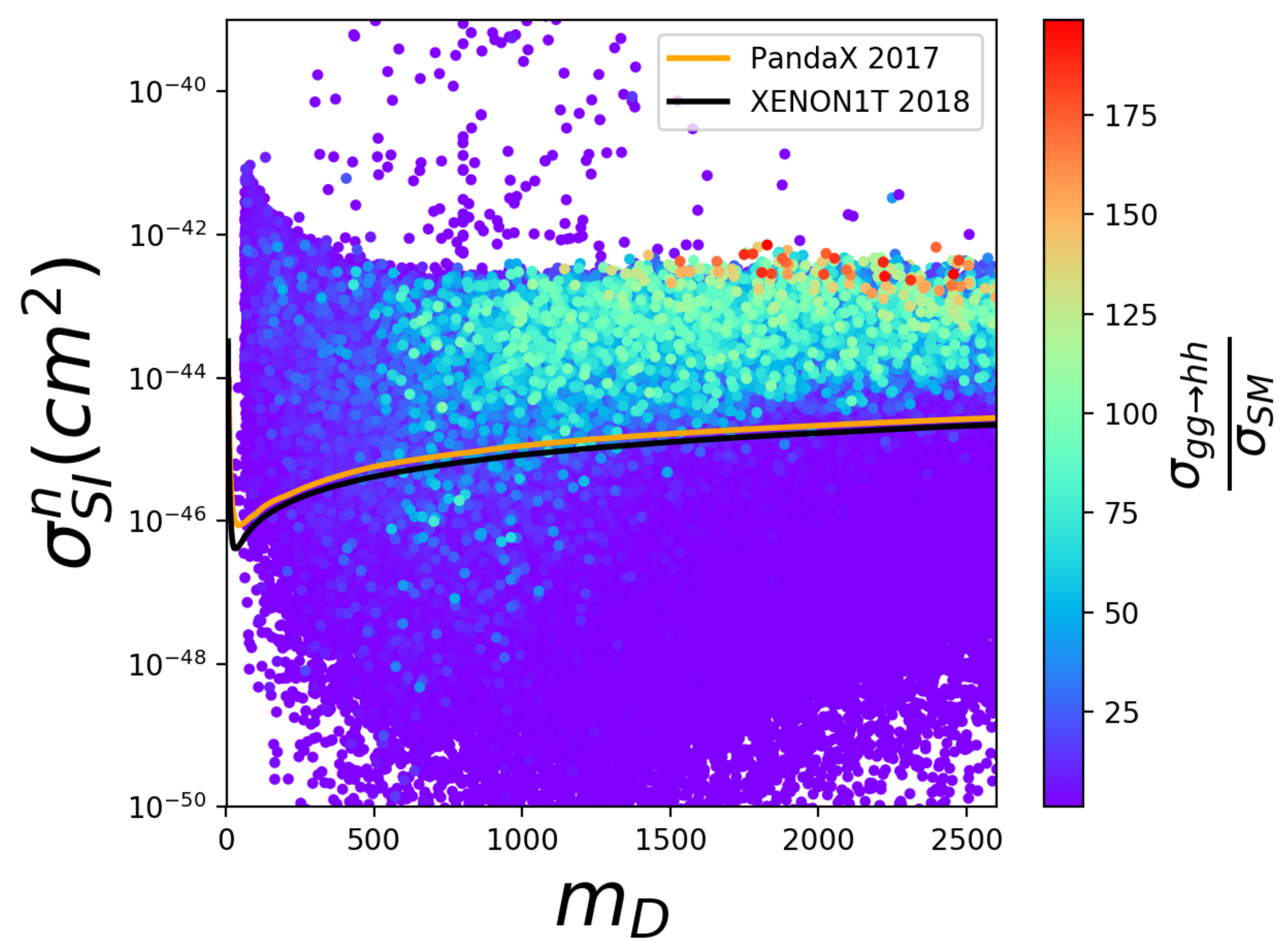
$DD^* \to h_i \to h_1 h_1$

- Direct Detection

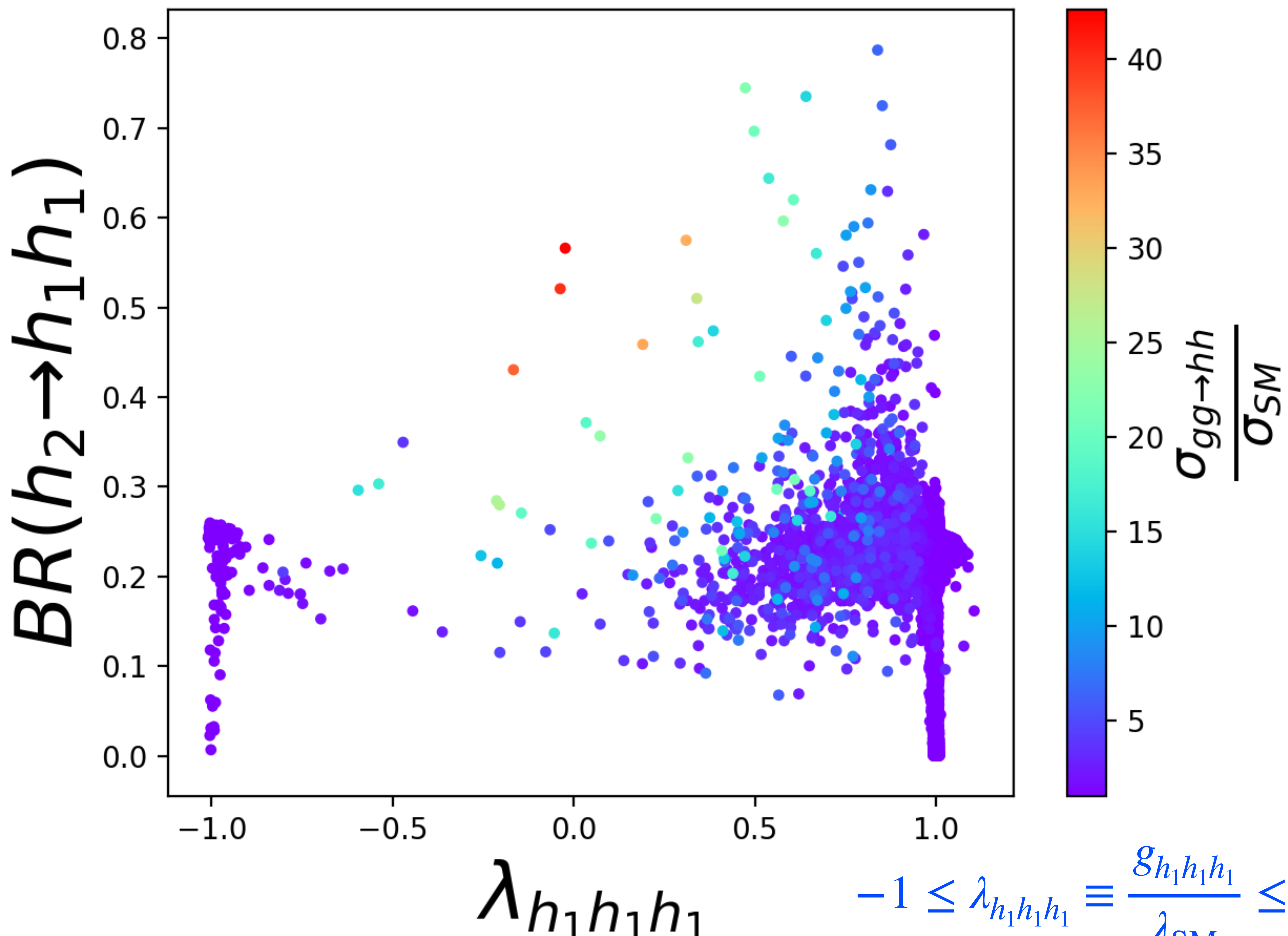
$gg \to \text{top loop} \to h_1$



(a)



(b)



$$-1 \leq \lambda_{h_1h_1h_1} \equiv \frac{g_{h_1h_1h_1}}{\lambda_{\rm SM}} \leq 1.3$$

Only 2% data remains after relic density and direct detection constraints are imposed!

Summary

- We have constructed a model with the 2 Higgs doublets embedded into a 2 dim spinor representation of a new gauge group $SU(2)_H$.
- Spontaneous symmetry breaking of $SU(2)_H$ by a triplet *triggers* the breaking of the SM $SU(2)_L$.
- An inert doublet can be emerged as DM candidate due to local gauge invariance rather than the ad hoc Z_2 discrete symmetry, which is more satisfying!
- Constraints from (PU+VS+HP) on the scalar potential have been carefully studied.
- Double Higgs production at the LHC is computed with constraints from (PU+VS+HP+DM) taken into account. A factor of 10 enhancement can be achieved compared with SM.
- Detailed studies for $\gamma\gamma bb$ and bbbb final states from double Higgs production had been carried out by V. Q. Tran.

Outlook

- DM - relic density, direct/indirect detection, collider (in preparation)
- Confronts electroweak precision data (in preparation)
- Dark Z' & Z'', dark Higgs phenomenology
- Charged Higgs phenomenology
- Can one drop the triplet?
- Can $W'^{\{p,m\}}$ and ν^H be viable DM?
- Long-lived particles (LLPs) in G2HDM?
- Rare Decays (Loop processes)
  - FCNH decay e.g. $h \to \mu\tau$, etc
  - $\mu \to e\gamma$ (MEG), μ-e conversion (Mu2E, COMET), $\mu \to eee$, $(g-2)_\mu$, …
- *etc.*


Thank you for your attention!
Happy New Year