G2HDM
— Recent Progress —

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Introduction

- Dark matter (DM) & neutrino oscillations imply BSM.
- 2 Higgs doublet model (2HDM) are very popular to address new physics. For example,
  - In MSSM, 2 Higgs doublets are needed due to holomorphic nature of the superpotential $\partial W/\partial \bar{Z}_i = 0$.
  - 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.
- With various kinds of scalar triplets included, one can address neutrino mass: Scotogenic triplet (Ma), GM triplet (Arhrib *et al*, Chiang *et al*, Hung *et al*, Kanemura *et al*, …), …

Extended Higgs Sector with global discrete symmetry imposed by hand!

Some Highlights of G2HDM

- Extended gauge group $SU(2)_L \otimes U(1)_Y \otimes SU(2)_H \otimes U(1)_X$
- Motivated by $U(1)_H$ (Ko, Omura and Yu, 2014). We embed the two Higgs doublets into a fundamental representation of a new gauge group $SU(2)_H$.
- Extended fermion sector. Free of perturbative gauge and gravitational anomalies and non-perturbative global SU(2) anomaly. Renormalizable.
- Extended Higgs sector. Symmetry breaking for SM is triggered or induced by $SU(2)_H$ breaking from a triplet VEV.
- Accidental Z_2 symmetry emerges naturally in which all SM particles are even.
- One of the Higgs doublet (H_2), being Z_2 odd, can be inert and may play some role of dark matter, whose stability is protected by the accidental Z_2 symmetry.
- Compare with Left-Right symmetric models (Mohapatra & Senjanovic, 1980,1981), the complex vector fields $W'^{(p,m)}$ in G2HDM are electrically neutral and Z_2 odd. Alternative DM candidate!
- No tree level FCNC in the Yukawa couplings (for SM sector) as well as the extended neutral gauge boson couplings!
- *etc*

Outline

- Motivation
- G2HDM
  - Particle Content
  - Higgs Potential & Symmetry Breaking
  - Mass Spectra
- Phenomenology

  (1) Scalar and Gauge Sector Constraints (SGSC)
  - Perturbative Unitarity
  - Vacuum Stability
  - Higgs Phenomenology (LHC)
  - EWPT (LEP I + II), LHC Z' Drell-Yan, …

  (2) Double Higgs Production at the LHC

  (3) Complex Scalar Dark Matter
- Summary

Based on works

1. Chuan-Ren Chen, Yu-Xiang Lin, Chrisna Setyo Nugroho, Raymundo Ramos, Sming Tsai, TCY, arXiv:1910.13138
2. Cheng-Tse Huang, Raymundo Ramos, Van Que Tran, Sming Tsai, TCY, arXiv:1905.02396, JHEP 1909 (2019) 048
3. Chuan-Ren Chen, Yu-Xiang Lin, Van Que Tran, TCY, arXiv:1810.04837, PRD99 (2019) no.7, 075027
4. Adelssalem Arhrib, Wei-Chih Huang, Raymundo Ramos, Y. L. Sming Tsai, TCY, arXiv:1806.05632, PRD98 (2018) no.9, 095006
5. Wei-Chih Huang, Hiroyuki Ishida, Chih-Ting Lu, Y. L. Sming Tsai, TCY, arXiv:1708.02355, EPJC78 (2018) no.8, 613
6. Wei-Chih Huang, Y. L. Sming Tsai, TCY, arXiv:1512.07268, NPB909 (2016) 122-134
7. Wei-Chih Huang, Y. L. Sming Tsai, TCY, arXiv:1512.00229, JHEP04 (2016) 019

G2HDM

	Fields	Spin	$SU(3)_C$	$SU(2)_L$	$SU(2)_H$	$U(1)_Y$	$U(1)_X$
Scalars	$H = (H_1 \;\; H_2)^{\mathrm{T}}$	0	1	2	2	$\frac{1}{2}$	1
	$\Delta_H = \begin{pmatrix} \Delta_3/2 & \Delta_p/\sqrt{2} \\ \Delta_m/\sqrt{2} & -\Delta_3/2 \end{pmatrix}$	0	1	1	3	0	0
	$\Phi_H = (\Phi_1 \;\; \Phi_2)^{\mathrm{T}}$	0	1	1	2	0	1
Fermions	$Q_L = (u_L \;\; d_L)^{\mathrm{T}}$	$\frac{1}{2}$	3	2	1	$\frac{1}{6}$	0
	$U_R = \left(u_R \;\; u_R^H\right)^{\mathrm{T}}$	$\frac{1}{2}$	3	1	2	$\frac{2}{3}$	1
	$D_R = \left(d_R^H \;\; d_R\right)^{\mathrm{T}}$	$\frac{1}{2}$	3	1	2	$-\frac{1}{3}$	-1
	u_L^H	$\frac{1}{2}$	3	1	1	$\frac{2}{3}$	0
	d_L^H	$\frac{1}{2}$	3	1	1	$-\frac{1}{3}$	0
	$L_L = (\nu_L \;\; e_L)^{\mathrm{T}}$	$\frac{1}{2}$	1	2	1	$-\frac{1}{2}$	0
	$N_R = \left(\nu_R \;\; \nu_R^H\right)^{\mathrm{T}}$	$\frac{1}{2}$	1	1	2	0	1
	$E_R = \left(e_R^H \;\; e_R\right)^{\mathrm{T}}$	$\frac{1}{2}$	1	1	2	-1	-1
	ν_L^H	$\frac{1}{2}$	1	1	1	0	0
	e_L^H	$\frac{1}{2}$	1	1	1	-1	0
Vectors	$g_\mu^a (a = 1, \cdots, 8)$	1	8	1	1	0	0
	$W_\mu^i (i = 1, 2, 3)$	1	1	3	1	0	0
	$W_\mu'^i (i = 1, 2, 3)$	1	1	1	3	0	0
	B_μ	1	1	1	1	0	0
	X_μ	1	1	1	1	0	0

TABLE I. Particle 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 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.
- f_L^H singlets are added for cancellation of perturbative gauge and gravitational anomalies.

Higgs Potential (1/3)

- Scalar potential in general 2HDM

$$V = +\mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 + \left(\mu_{12}^2 H_1^\dagger H_2 + \mathrm{h.c.}\right)$$
$$+\lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^\dagger H_2|^2$$
$$+\frac{\lambda_5}{2}\left[\left(H_1^\dagger H_2\right)^2 + \mathrm{h.c.}\right] + \left[\lambda_6 |H_1|^2 + \lambda_7 |H_2|^2\right]\left(H_1^\dagger H_2 + \mathrm{h.c.}\right)$$

- Many variants, *e.g.* IHDM.

Z_2 symmetry : $H_1 \to H_1$, $H_2 \to -H_2$

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

(Eliminates λ_6, λ_7 terms!)

$$H_2^0 = \frac{1}{\sqrt{2}}(S + iP),\ m_{S,P}^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 \pm \lambda_5)v^2$$

Higgs Potential (2/3)

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

- Scalar potential in G2HDM

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

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

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

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

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

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

Higgs Potential (3/3)

$$V_{\text{mix}}(H, \Delta_H, \Phi_H)$$

$$= \boxed{+M_{H\Delta}(H^\dagger \Delta_H H) - M_{\Phi\Delta}(\Phi_H^\dagger \Delta_H \Phi_H)}$$

$$\boxed{\begin{aligned} &+ \lambda_{H\Phi}(H^\dagger H)(\Phi_H^\dagger \Phi_H) + \lambda'_{H\Phi}(H^\dagger \Phi_H)(\Phi_H^\dagger H) \\ &+ \lambda_{H\Delta}(H^\dagger H)\mathrm{Tr}(\Delta_H^2) + \lambda_{\Phi\Delta}(\Phi_H^\dagger \Phi_H)\mathrm{Tr}(\Delta_H^2). \end{aligned}}$$

- Six new parameters from V_{mix}! $M_{H\Phi}$ and $M_{\Phi\Delta}$ has mass dimension 1.
- All couplings are real, thus no CP violation in the scalar potential.
- 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! In general, they mix!

Hidden Parity (h-parity)

- Accidental Z_2 symmetry can be extended to Yukawa as well as gauge interactions!

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

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

- Hidden Parity (h-parity):

Fields	h-parity
$h,\ G^{\pm,0},\ \phi_2,\ G_H^0,\ \delta_3,\ f,\ W_{1,2,3}^{\mu},\ B_\mu,\ X^\mu,\ W_3^{\mu\prime},\ G^{\mu a}$	1
$G_H^{p,m},\ H_2^0,\ H_2^{0*},\ H^{\pm},\ \Delta_{p,m},\ f^H,\ W_{1,2}^{\mu\prime}$	-1

TABLE II. Classification of all the fields in G2HDM under h-parity.

Chuan-Ren Chen, Yu-Xiang Lin, Chrisna Setyo Nugroho, Raymundo Ramos, Sming Tsai, TCY, arXiv:1910.13138.

Scalar Mass Spectrum (1/4)

- Expand the scalar fields around the vacua

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

$$\Phi_{\text{Physical}} \equiv \{h, H^\pm, H_2^0, H_2^{0*}, \phi_2, \delta_3, \Delta_{p,m}\} \qquad \Phi_{\text{Goldstone}} \equiv \{G^0, G^\pm, G_H^0, G_H^{p,m}\}$$

- 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 (Z). The two unbroken generators are

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

- The dark photon (Z) could be the fuzzy dark matter, which may solves the core-cusp problem (Hui, Ostriker, Tremaine, Witten (2017); Zhang, Tsai, Kuo, Cheung, Chu (2018)).

- It's possible to add two Stueckelberg masses M_Y and M_X!

Scalar Mass Spectrum (2/4)

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

basis $S = \{h, \phi_2, \delta_3\}$ $\Rightarrow$ $h_i = O^H_{1i} h + O^H_{2i}\phi_2 + O^H_{3i}\delta_3$

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

$$h_1 = O^H_{11} h + O^H_{12}\phi_2 + O^H_{13}\delta_3$$

- However, the Higgs mixing is constrained to be quite small, suppressed by v/v_Φ as $v \sim 246$ GeV and $v_\Phi \geq 20$ TeV due to LEP Z-Z′ mixing constraint and LHC Run II data for high invariant mass dilepton resonance (1708.02355,1905.02396)!

Scalar Mass Spectrum (3/4)

$G = \{G_H^p, H_2^{0*}, \Delta_p\}$ **basis** **Sharing same params as $\mathscr{M}_0^2$**

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

- The above mass matrix has zero determinant!
- The zero eigenvalue state is the Goldstone boson $\tilde{G}^{p,m}$
$$\tilde{G}^{p,m} \sim v_\Phi G_H^{p,m} - vH_2^{0*,0} + 2v_\Delta \Delta_{p,m}$$
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.

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

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

Complex Fields (No definite CP)

Scalar Mass Spectrum (4/4)

- 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:

$m^2_{H^\pm} = \mu^2_2 + \frac{1}{2}\lambda_3 v^2$ (IHDM)

In G2HDM, all 3 VEVs enter!

Theoretical and Phenomenological Constraints (Scalar Sector)

- Vacuum Stability (VS)
  - Scalar potential should be bounded from below (copositivity)
- Perturbative Unitarity (PU)
  - All 2 to 2 Scattering amplitudes in the scalar sector
- Higgs Physics (HP)
  - Diphoton signal strength of the 125 GeV Higgs

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

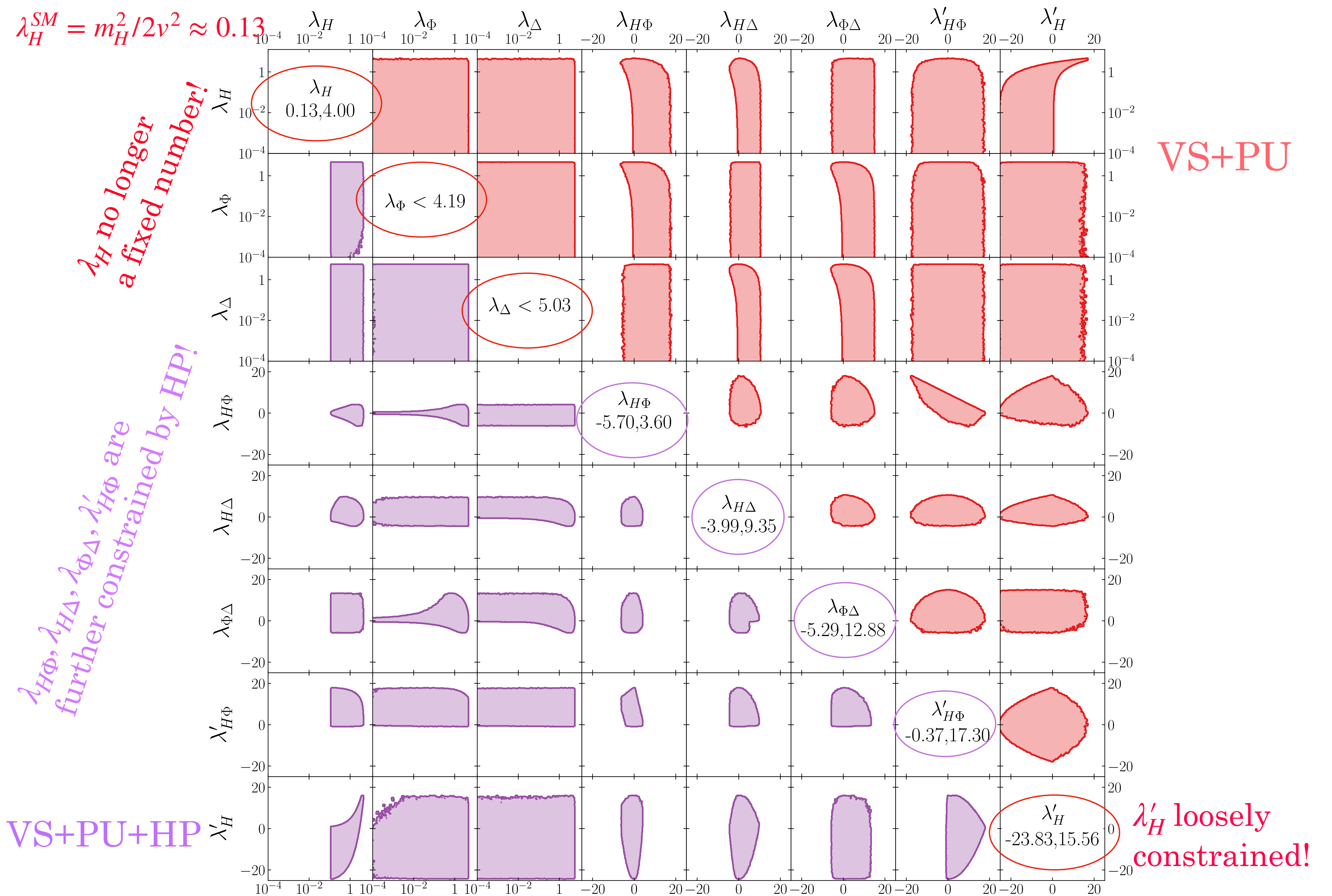


FIG. 9. A summary of the parameter space allowed by the theoretical and phenomenological constraints. The red regions show the results from the theoretical constraints (VS + PU) of Sec. III. The magenta regions are constrained by Higgs physics as well as the theoretical constraints (HP + VS + PU), as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

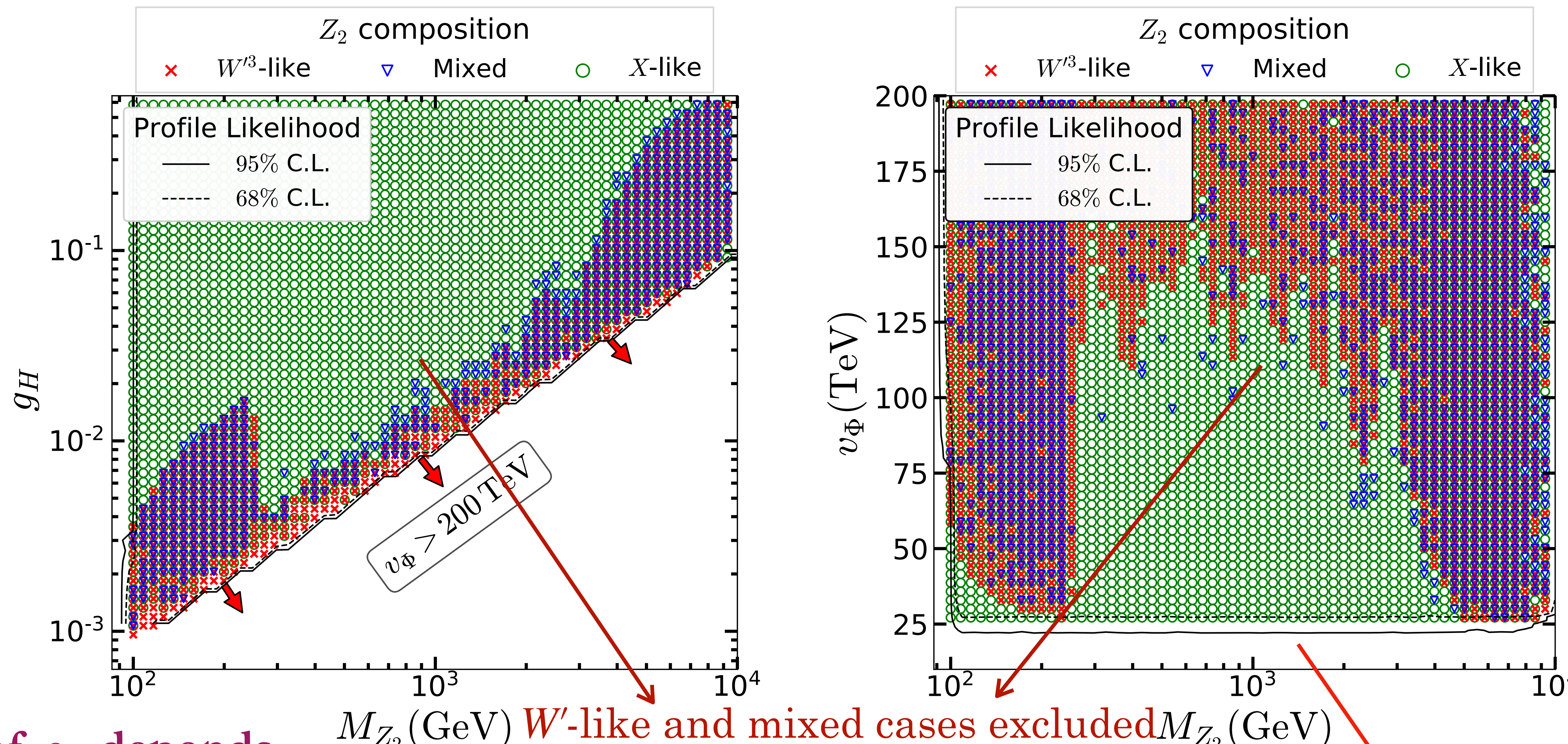
Constraints on the Gauge Sector

1. LEP Z-pole observables
2. LEP-II constraints on contact interactions
3. Constraints from Drell-Yan data from Z at LHC
4. Constraints from high-mass resonance from Z' LHC Run II data

Cheng-Tse Huang, Raymundo Ramos, Van Que Tran, Y. L. Sming Tsai, TCY, JHEP 1909 (2019) 048, arXiv:1905.02396

Heavy M_X Scenario $\boxed{Z_i = \mathcal{O}_{1i} Z^{SM} + \mathcal{O}_{2i} W'^3 + \mathcal{O}_{3i} X}$

$Z_1 \sim 91.1876$ GeV $Z_2 \sim Z'$, $Z_3 \sim Z''$, $m_{2,3} \geq m_1$



W'-like and mixed cases excluded by ATLAS high mass resonance from Z' Run II data

Limits of g_H depends on Z_2 composition and its mass $m_{Z_2} \sim g_H v_\Phi/2$

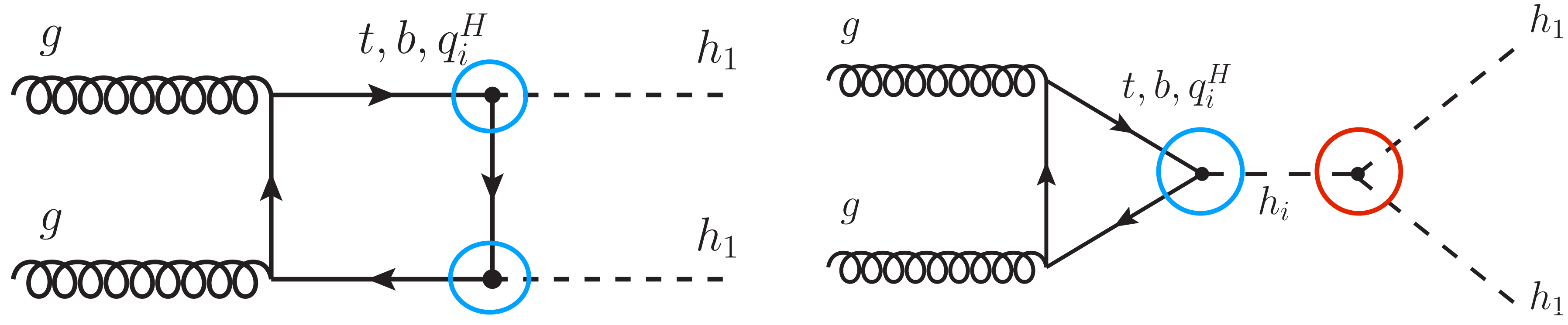
(a) (b)

Lower limit for $v_\Phi > 20$ TeV (EWPT)

FIG. 3. Scatter plots in (a) (M_{Z_2}, g_H) plane and (b) (M_{Z_2}, v_Φ) plane for the heavy M_X scenario. The color code is the same as Fig. 2. The 1σ and 2σ contours of the profile likelihood are also shown.

Double Higgs Production in G2HDM

Ref: Chuan-Ren Chen, Sean Yu-Xiang Lin, Van Que Tran, TCY, arXiv:1810.04837, PRD99 (2019) no.7, 075027



(a) (b)

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

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

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

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

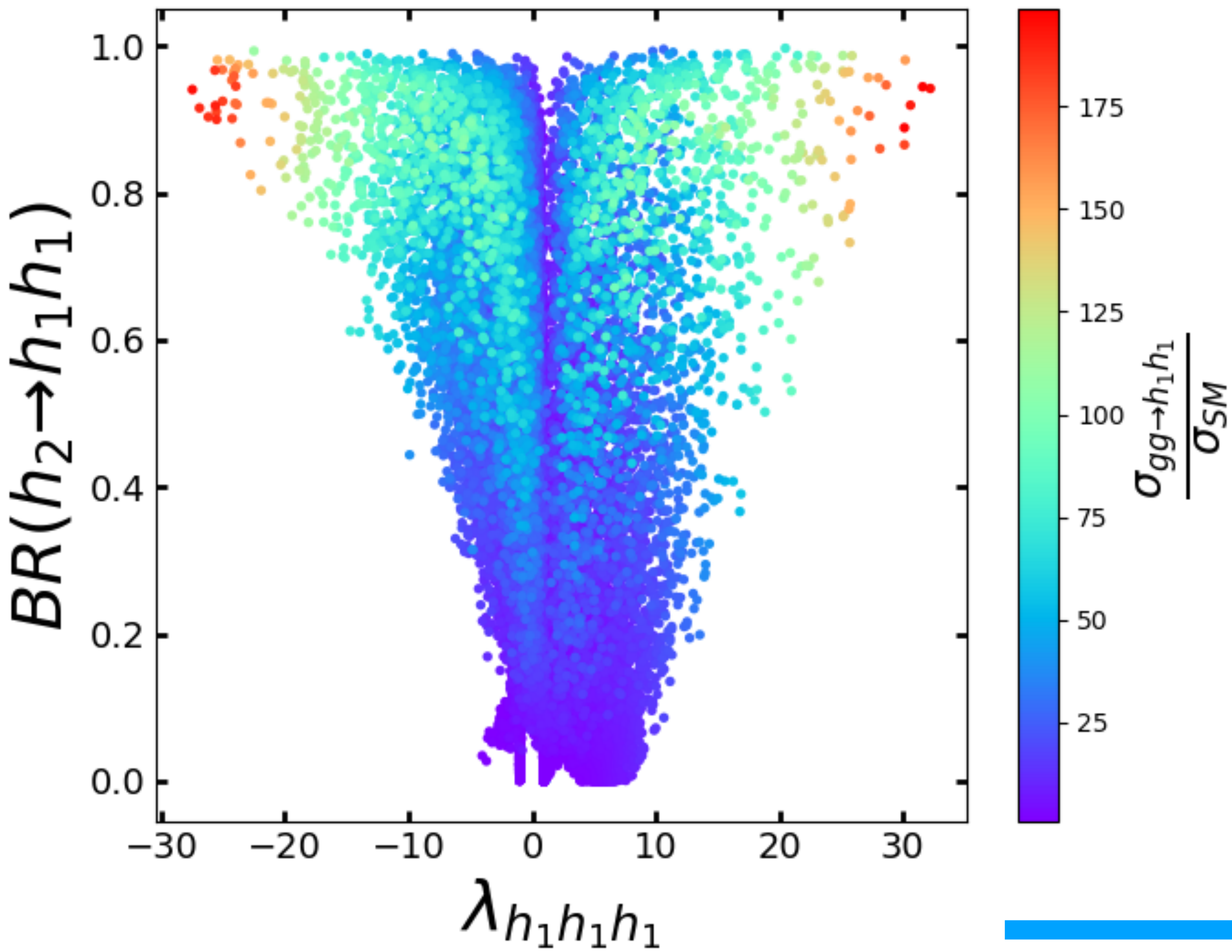
$$2m_{h_1} \lesssim m_{h_2} \ll m_{h_3}$$

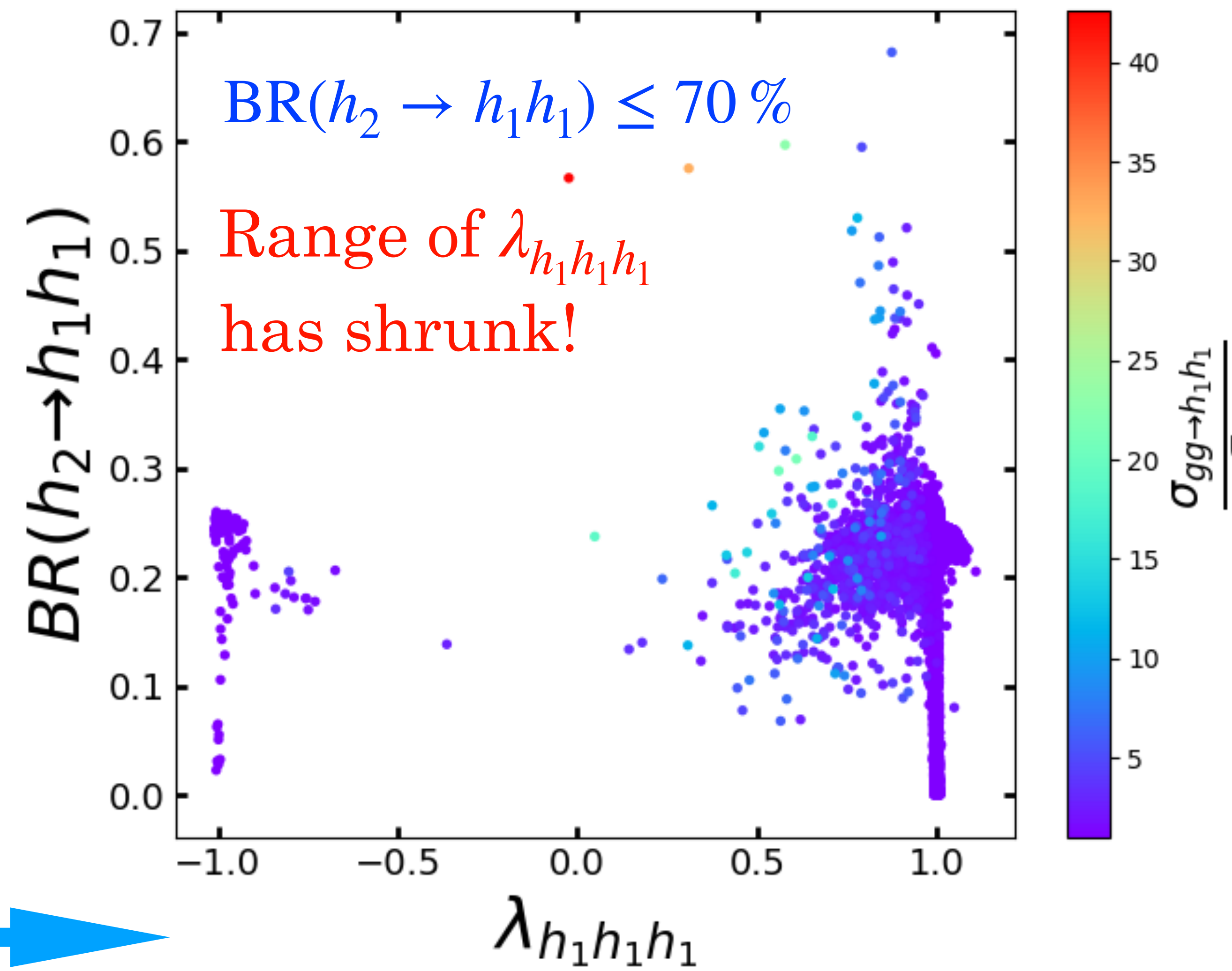
$$h_2 \to h_1 h_1$$

Before and after imposing DM constrains

$$h_2 \to h_1 h_1$$

$$h_1 \nrightarrow DD$$





$$-29 \leq \lambda_{h_1 h_1 h_1} \equiv \frac{g_{h_1 h_1 h_1}}{\lambda_{\rm SM}} \leq 32 \qquad\qquad -1 \leq \lambda_{h_1 h_1 h_1} \equiv \frac{g_{h_1 h_1 h_1}}{\lambda_{\rm SM}} \leq 1.3$$

Negative values provide **constructive** interferences!

In SM, box and triangle top quark loops are destructively interfered!

Summary: Compared with previous results without DM constraints, only 2% data remains after relic density (within 3 sigma PLANCKS) and direct detection constraints (below upper limits of PandaX-II and XENON1T) are imposed!

Dark Matter in G2HDM

- Parity odd neutral particles as DM

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

Spin 0 1/2 1

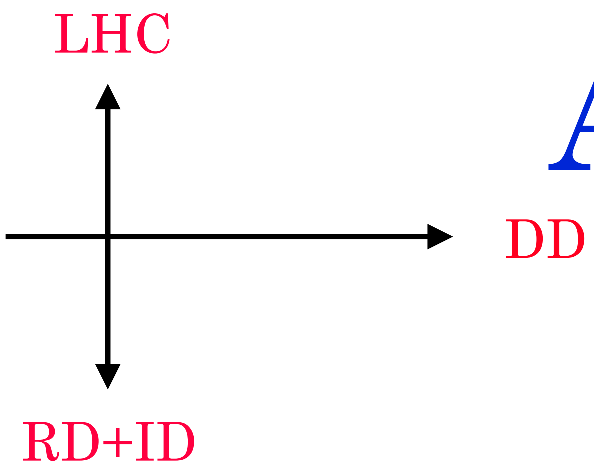
- Dark photon (Z) with mass 10^{-22} eV as fuzzy DM (h-parity even!)
- Triplet Δ_H can give rise to dark 't Hooft-Polyakov monopole as topological stable DM,
Baek, Ko and Park, JCAP 1410 (2014) 067

Complex Scalar DM Composition

$$D = O^D_{12} G^p_H + O^D_{22} H^{0*}_2 + O^D_{32} \Delta_p$$

- Inert doublet-like $f_{H_2^*} = (O^D_{22})^2 > 2/3$
- SU(2)$_H$ triplet-like $f_{\Delta_p} = (O^D_{32})^2 > 2/3$
- Goldstone boson like $f_{G^p} = (O^D_{12})^2 > 2/3$

$$f_{G^p} + f_{H_2} + f_{\Delta_p} = 1$$



A Tale of Two Portals

$$(D^* \overleftrightarrow{\partial_\mu} D)(\bar{q}\gamma^\mu q) \xrightarrow{NR} 1$$

Vertex not presence in IHDM

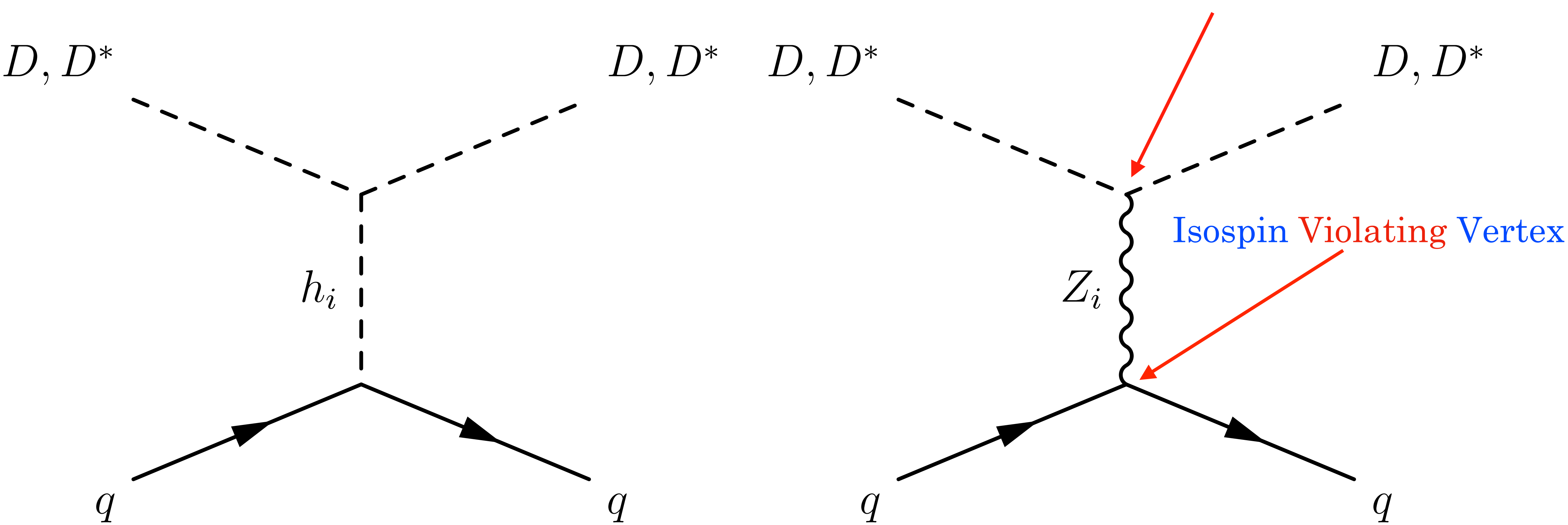
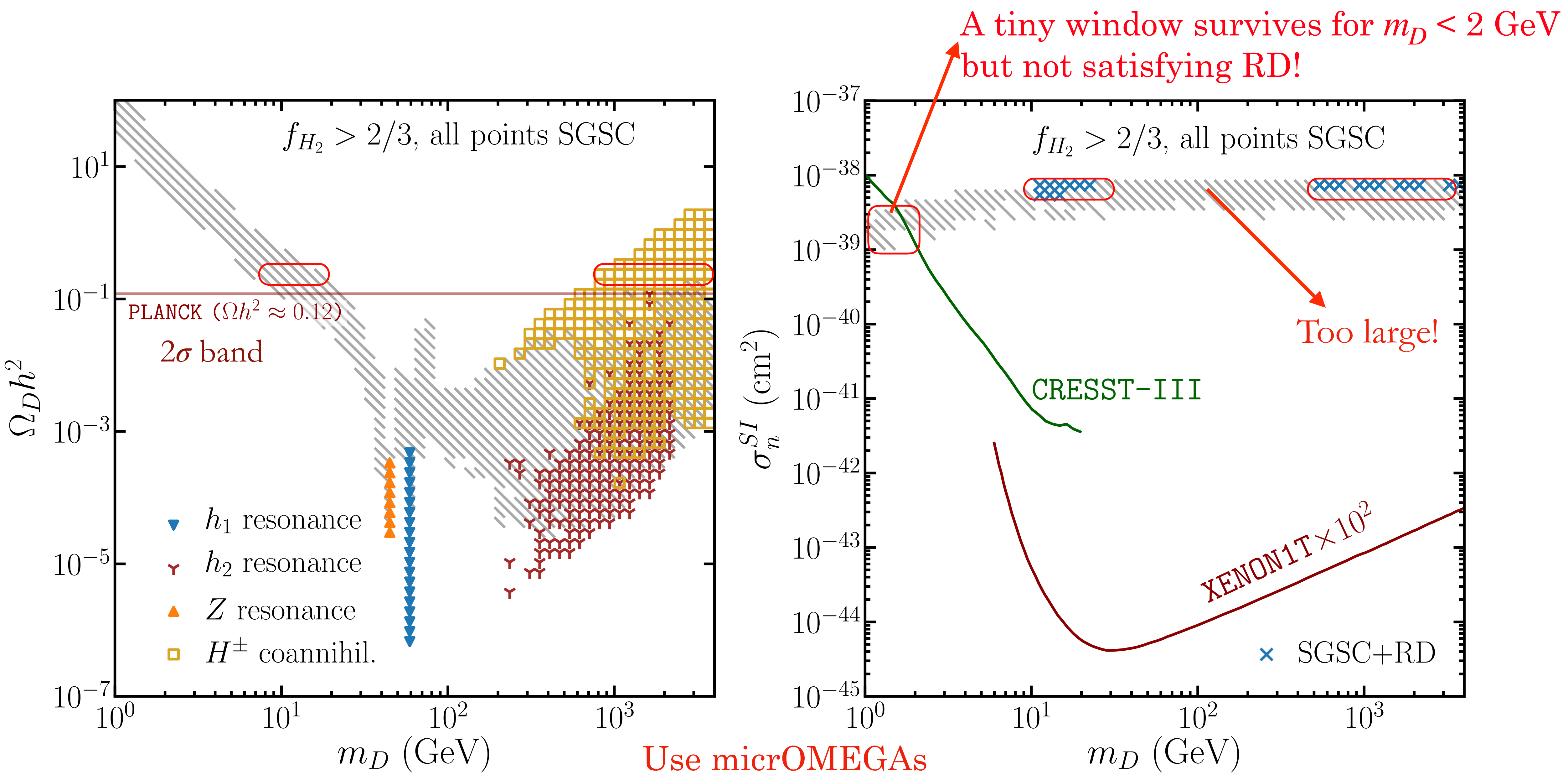


FIG. 2. The dominant Feynman diagrams with the $\mathcal{Z}_2$-even Higgs bosons (left) and neutral gauge bosons (right) exchange for direct detection of DM.

- Higgs Portal + Vector Portal

Inert Doublet-like DM in G2HDM

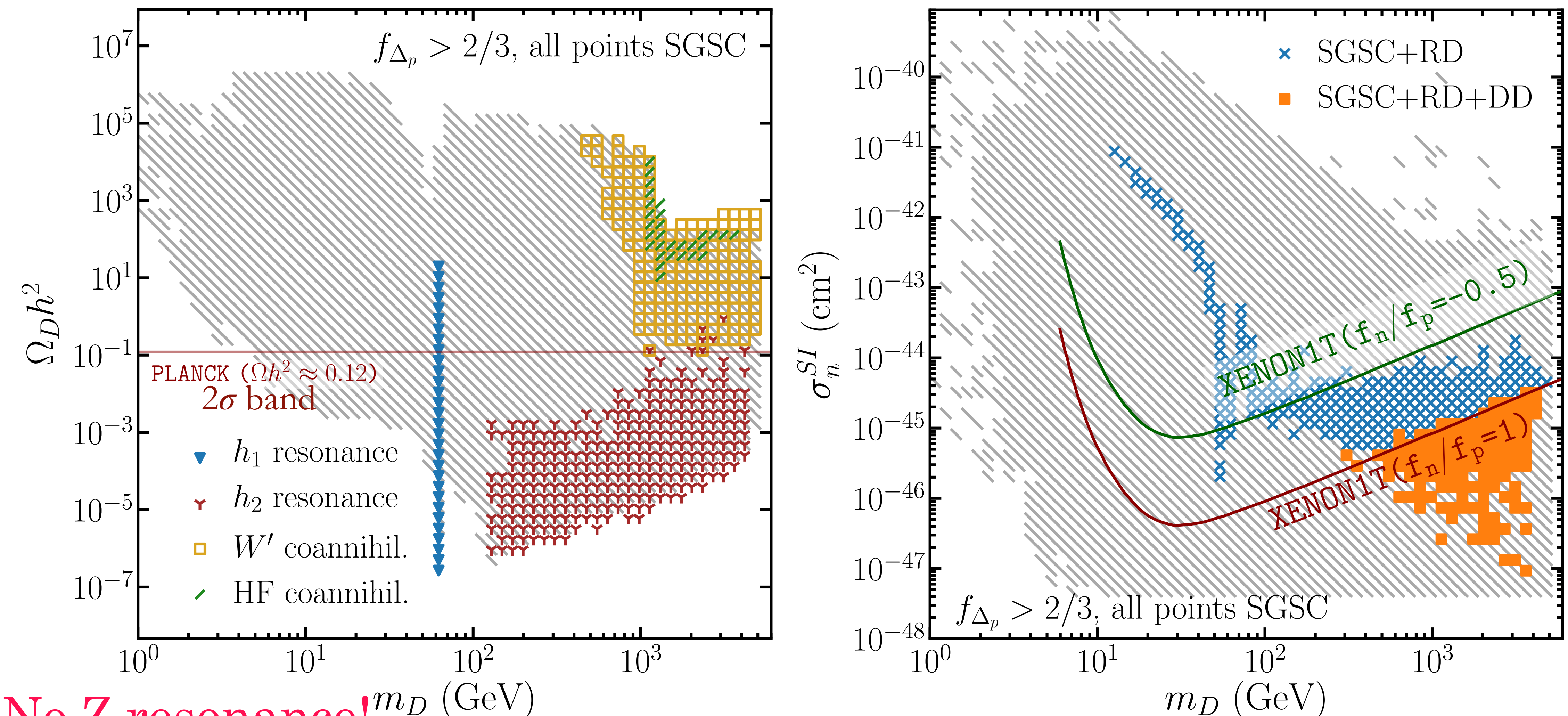


Vector + Higgs portals in action!

FIG. 3. Doublet-like **SGSC** allowed regions projected on (m_D, $\Omega_D h^2$) (left) and (m_D, σ_n^{SI}) (right) planes. The gray area in the left has no coannihilation or resonance. The gray area in the right is excluded by PLANCK data at 2σ.

SGSC=Scalar + Gauge Sectors Constraints

Triplet-like DM in G2HDM (1/2)



No Z resonance!

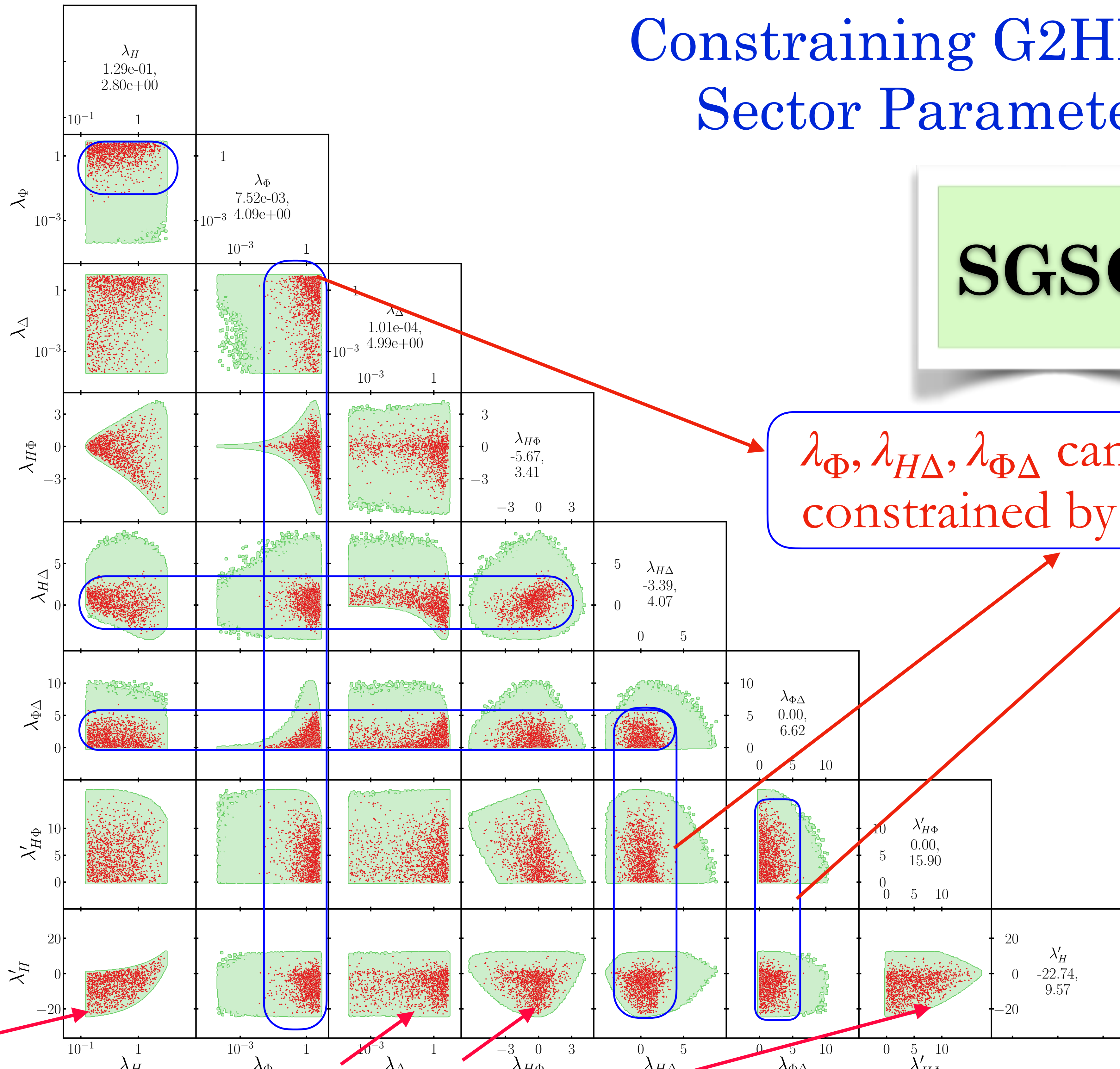
Only Higgs portal in action!

Use micrOMEGAs

FIG. 4. Triplet-like **SGSC** allowed regions projected on (m_D, $\Omega_D h^2$) (left) and (m_D, σ_n^{SI}) (right) planes. The gray area in the left has no coannihilation or resonance. The gray area on the right is excluded by PLANCK data at 2σ. Some orange squares are above the XENON1T limit due to ISV cancellation at nucleus level.

Constraining G2HDM Scalar Sector Parameter Space

SGSC



$\lambda_\Phi, \lambda_{H\Delta}, \lambda_{\Phi\Delta}$ can be further constrained by RD+DD!

$\lambda_H\,, \lambda_\Delta\,, \lambda'_H\,, \lambda_{H\Phi}\,, \lambda'_{H\phi}$ not constrained by RD+DD.

Fig. 6.11 A summary plot for the scalar parameter space allowed by the **SGSC** constraints (green region) and **SGSC+RD+DD** constraints (red scatter points). The numbers written in the first block of each column are the 1D allowed range of the parameter denoted in x-axis after **SGSC+RD+DD** cut.

Summary on Complex Scalar DM in G2HDM

- In G2HDM, a DM candidate exists due to local gauge invariance rather than the ad hoc Z_2 discrete symmetry, which is more satisfying! Z_2 discrete symmetry (h-parity) *emerges* accidentally!
- In general, DM in G2HDM has 3 compositions: We studied inert doublet like, triplet-like and Goldstone boson like.
- Features from both Higgs-portal and vector-portal DM models are in action!
- Inert doublet like DM in G2HDM is excluded by current data.
- Triplet-like DM is most favorable, survived the challenges by experimental data from SGSC, DD, RD and ID. Future CTA experiment can further constrain the model parameter space.
- Goldstone boson like DM is not entirely excluded, but its parameter span must be very fine-tuned to ISV with particular value of $f_p/f_n = -1.86$.!

Thank You
for Your Attention!

Backup Slides

Yukawa Couplings (1/2)

- 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

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

- 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)

Yukawa Couplings (2/2)

- The main reason to introduce the $SU(2)_H$ scalar doublet $\mathbf{\Phi}_H = (\mathbf{\Phi}_1\ \mathbf{\Phi}_2)^T$ is to give masses to the new heavy fermions f^H.

$$\mathcal{L}_{\text{Yuk}} \supset -y'_d \overline{d^H_L} \left(d^H_R \Phi_2 - d_R \Phi_1 \right) - y'_u \overline{u^H_L} \left(u_R \Phi_1^* + u^H_R \Phi_2^* \right)$$
$$- y'_e \overline{e^H_L} \left(e^H_R \Phi_2 - e_R \Phi_1 \right) - y'_\nu \overline{\nu^H_L} \left(\nu_R \Phi_1^* + \nu^H_R \Phi_2^* \right) + \text{H.c.}.$$

- SM neutrinos get Dirac masses, since we introduce ν_R. However all new fermions f^H remain massless!
- 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,

$$\overline{u^H_L} U_R \epsilon \Phi_H \sim \overline{u^H_L} (u_R \Phi_2 - u^H_R \Phi_1), \cdots$$

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

$$\overline{\nu^{Hc}_L} \nu^H_L$$

Neutral Gauge Bosons Z1,Z2,Z3 (1/2)

Stueckelberg Mass:

Ruegg & Ruiz-Altaba, '04

SM with nonzero M_Y! The theory is well defined! But photon can a mass, neutrino couples to photon, charged particles have axial couplings with photon, …

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

StSM SM $\times\, U(1)_X$ with both M_X and M_Y nonzero!

$$|\epsilon| = |M_Y/M_X| \leq \overset{0.036}{\cancel{0.061}}\sqrt{1-(M_Z/M_X)^2}$$

(Z-mass shift)

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

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

Two M_X, M_Y are Stueckelberg masses are introduced with one Stueckelberg field. Always lead to one massless state, identified as photon.

Note: $m_\gamma^{\exp} \leq 8.4 \times 10^{-19}\mathrm{eV} \cdot \mathrm{c}^{-2}$ from modelling the magnetic fields of the solar system in magnetohydrodynamics. Use FRB 121102 to limit m_γ, Ellis *et al*. (2017).

Neutral Gauge Bosons Z1,Z2,Z3 (2/2)

Set $M_Y = 0 \implies Q = T_{3L} + Y!$

$$\mathcal{O}^{4\times4}_{M_Y=0} = \begin{pmatrix} \overset{\text{SM}}{\boxed{\begin{matrix} c_W & -s_W \\ s_W & c_W \end{matrix}}} & \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} \\ \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} & \begin{matrix} 1 & 0 \\ 0 & 1 \end{matrix} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & & & \\ 0 & & \mathcal{O} & \\ 0 & & & \end{pmatrix},$$

$$\longrightarrow \quad (\overset{\text{SM}}{\boxed{\gamma, Z^{\text{SM}},}} W'^3, X) \qquad \boxed{s_W = \frac{g'}{\sqrt{g^2 + g'^2}}}$$

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

$$(\mathcal{O}^{4\times4})^T \mathcal{M}^2_{\text{gauge}} \mathcal{O}^{4\times4} = \text{diag}(0, M^2_{Z_1}, M^2_{Z_2}, M^2_{Z_3}), \qquad \{g_H, g_X, v_\Phi, M_X\}$$

$$\boxed{(Z_1, Z_2, Z_3)^T = \mathcal{O}^T \cdot (Z^{SM}, W'^3, X)^T.} \qquad \boxed{Z_i = \mathcal{O}_{1i} Z^{SM} + \mathcal{O}_{2i} W'^3 + \mathcal{O}_{3i} X}$$

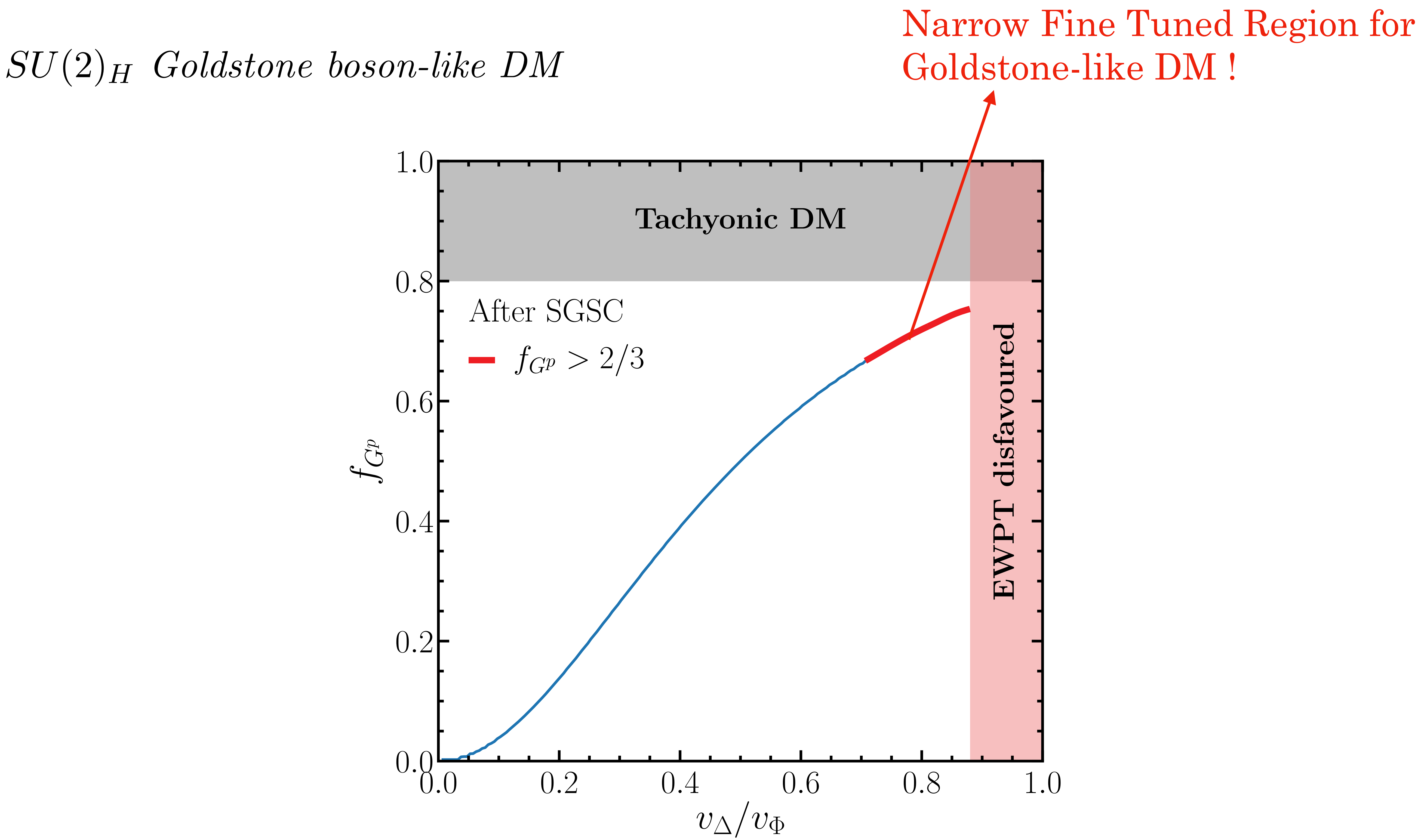
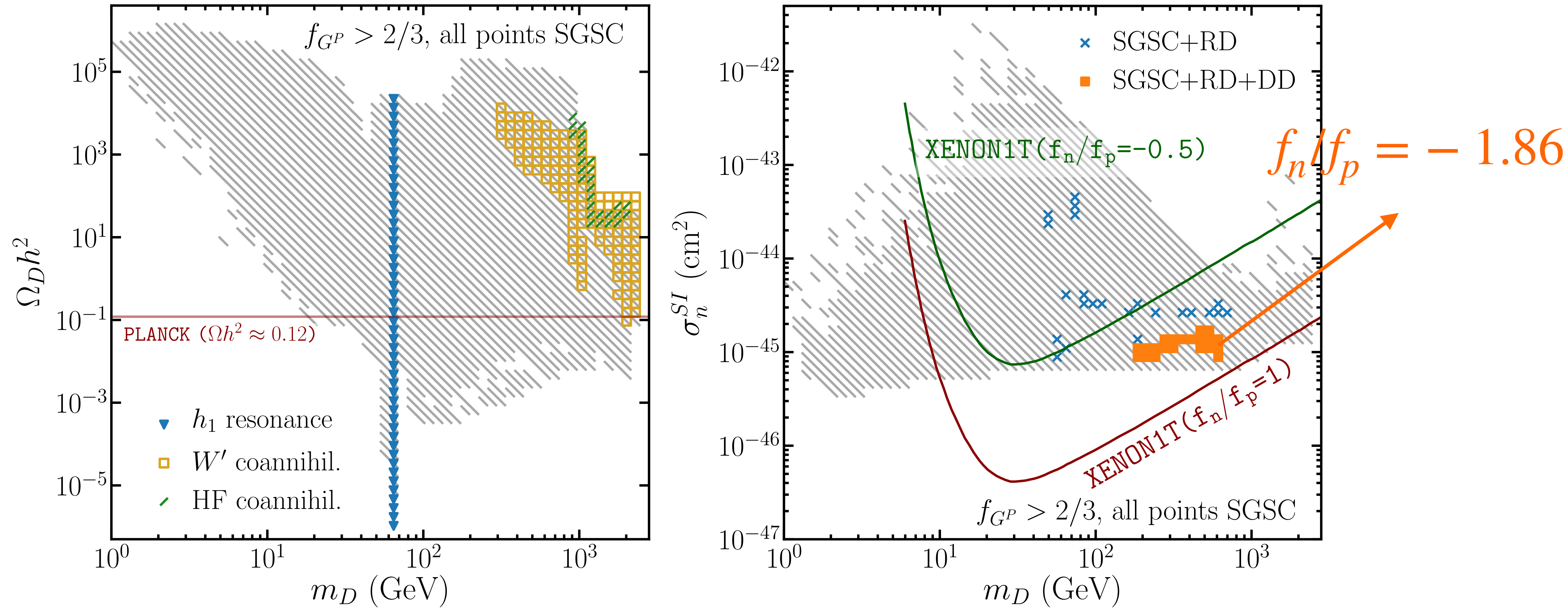


FIG. 1. Correlation between the ratio v_Δ/v_Φ and the composition mixing parameter f_{G^p} for all the DM types after applying constraints from the scalar and gauge sectors.

Goldstone boson like DM in G2HDM (1/2)

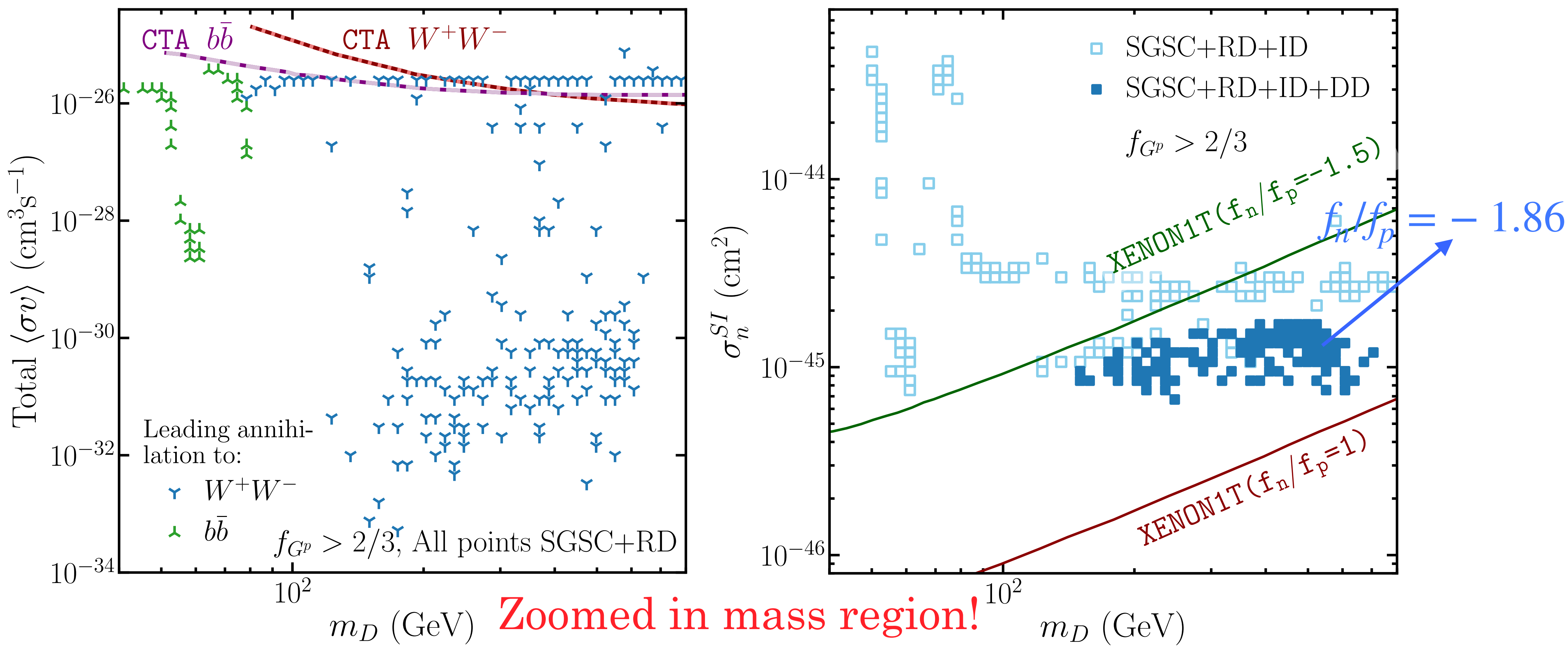


Only Higgs portal in action!

FIG. 7. Goldstone-like DM **SGSC** allowed regions projected on $(m_D, \Omega_D h^2)$ (left) and (m_D, σ_n^{SI}) (right) planes. The gray area in the left has no coannihilation or resonance. The gray area on the right is excluded by PLANCK data at 2σ. The orange squares above the XENON1T limit present ISV cancellation at nucleus level. The lower red solid line is XENON1T limit considering isospin conservation, while the upper green solid line is the same limit but for ISV with $f_n/f_p = -0.5$.

Goldstone boson like DM in G2HDM (2/2)

ID constraint before and after DD constraint!



Zoomed in mass region!

Requires ISV cancellation with special value of $f_n/f_p = -1.86$ to pass XENON1T constraint!

FIG. 8. The present time total annihilation cross section by dominant annihilation channels (left) and DM-neutron elastic scattering cross-section (right) for $f_{G^p} > 2/3$ in the Goldstone-like DM case versus the DM mass m_D. Two-dimensional 2σ criteria of the ID constraints is $\Delta\chi^2 = 5.99$ based on Fermi dSphs gamma-ray flux data. Future CTA measurements may help constrain regions with DM masses above $\mathcal{O}(10^2)$ GeV as shown in the left panel. In the right panel, the lower red solid line is the published XENON1T

Constraining G2HDM Remaining Parameter Space

SGSC

Only g_H, v_Φ can be further constrained by RR+DD!

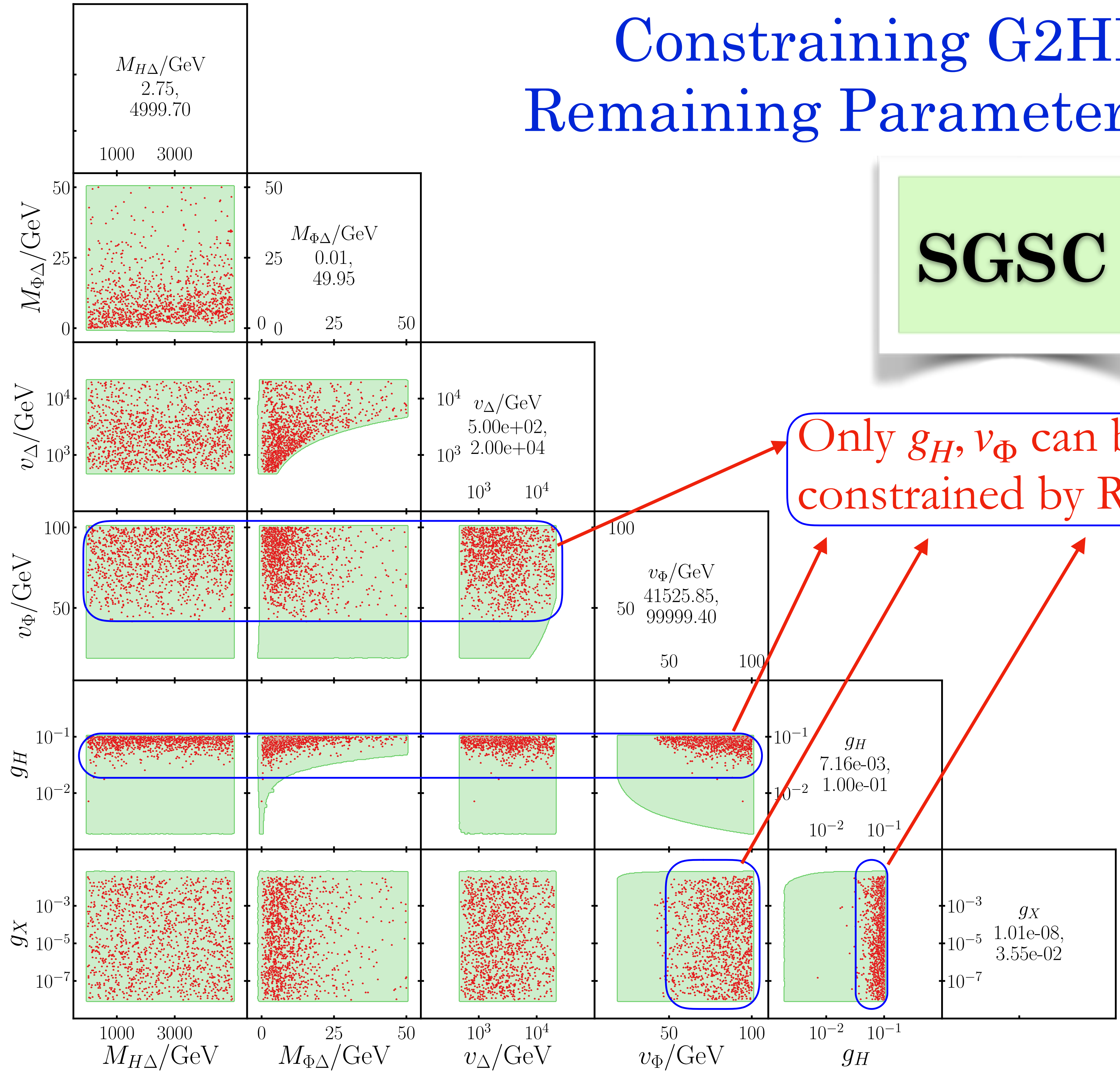


Fig. 6.12 A summary plot table of the parameter space of two VEVs, M_{ij} term, and new gauge couplings. The color scheme is same as Fig. 6.11.

Outlook

- Dark Z′ & Z′′, dark Higgs phenomenology
- Charged Higgs phenomenology
- Can one drop the triplet?
- Can $W^{\prime(p,m)}$ 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), $\mu \to eee$, $(g\text{-}2)_\mu$, …
- Can one address hierarchy problem in G2HDM?
- Lepton number violation via $\overline{\nu_L^{Hc}}\nu_L^H$? Leptogenesis to Baryogenesis?