Effects of Heavy Fermions on Complex Scalar DM Relic Density and Direct Detection in G2HDM[2]

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[2] Follow up from C.R. Chen, Y.X. Lin, C.S. Nugroho, R. Ramos, Y.L. Sming Tsai, T.C. Yuan (1910.13138)

Outline

Gauged Two Higgs Doublet Model

G2HDM: embedding two Higgs doublet into a doublet of a non-Abelian gauge group $SU(2)_H$

- New gauge group $SU(2)_H \times U(1)_X$ simplifies the scalar potential.
- EWSB is induced via SSB of the $SU(2)_H$ triplet.
- All new gauge fields are neutral including W' as opposed to the LRSM.
- No tree level FCNC thanks to the gauge symmetry.
- Anomaly free with additional new heavy fermions.
- Contains the Inert Higgs $\rightarrow$ potential DM candidate protected by $SU(2)_H$ gauge symmetry.
- Accidental Z_2 symmetry.

G2HDM Matter Content

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

G2HDM Matter Content

Matter Fields	$SU(3)_C$	$SU(2)_L$	$SU(2)_H$	$U(1)_Y$	$U(1)_X$
$H = (H_1 \quad H_2)^T$	1	2	2	1/2	1
$\Delta_H = \begin{pmatrix} \frac{\Delta_3}{2} & \frac{\Delta_p}{\sqrt{2}} \\ \frac{\Delta_m}{\sqrt{2}} & -\frac{\Delta_3}{2} \end{pmatrix}$	1	1	3	0	0
$\Phi_H = (\Phi_1 \quad \Phi_2)^T$	1	1	2	0	1

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+h}{\sqrt{2}} + i\frac{G^0}{\sqrt{2}} \end{pmatrix}, \qquad H_2 = \begin{pmatrix} H^+ \\ H_2^0 \end{pmatrix},$$

$$\Phi_H = \begin{pmatrix} G_H^p \\ \frac{v_\Phi+\phi_2}{\sqrt{2}} + i\frac{G_H^0}{\sqrt{2}} \end{pmatrix}, \quad \Delta_H = \begin{pmatrix} \frac{-v_\Delta+\delta_3}{2} & \frac{1}{\sqrt{2}}\Delta_p \\ \frac{1}{\sqrt{2}}\Delta_m & \frac{v_\Delta-\delta_3}{2} \end{pmatrix}.$$

Z_2 Classification

- The G2HDM particles can be further categorized based on their Z_2 charge as follow

Z_2 Even	$h_1,\ h_2,\ h_3$	$W^{\pm},\ Z,\ Z',\ Z''$	$f_{L,R}^{SM}$
Z_2 Odd	$D,\ \tilde{\Delta},\ H^{\pm}$	$W'^{(p,m)}$	$f_{L,R}^{H}$

Table: 1. The Z_2 assignments in G2HDM model.

Heavy Fermion (HF) f^H

- The heavy fermion gets its mass from Yukawa term

$$m_{f^H} = \frac{y_{f^H} v_\Phi}{\sqrt{2}} \, .$$

- In the old set up we set

$$m_{f^H} = max[1.5\,\mathrm{TeV}, 1.20\,\mathrm{m_D}] \, .$$

- We relieve the old set up by setting

$$m_{f^H} = max[150\,\mathrm{GeV}, 1.05\,\mathrm{m_D}] \, .$$

- Lower bound around Top quark mass.
- 5 % mass difference to account for coannihilation.

Complex Scalar DM Candidate

- Let's remind ourselves for two Higgs doublets H

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+h}{\sqrt{2}} + i\frac{G^0}{\sqrt{2}} \end{pmatrix}, \; H_2 = \begin{pmatrix} H^+ \\ H_2^0 \end{pmatrix}$$

- For additional $SU(2)_H$ scalars with scale hierarchy $v_\Phi \geq v_\Delta > v$

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

- The Z_2 odd mixing matrix $\mathcal{M}_D^2$ in the basis of $\{G_H^p, H_2^{0*}, \Delta_p\}$ is given by

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

Complex Scalar DM Candidate

- $\mathcal{M}_D^2$ is diagonalized by an orthogonal matrix O^D such that the physical fields and unphysical ones are related via

$$\{G_H^p, H_2^{0*}, \Delta_p\}^T = O^D \cdot \{\widetilde{G}^p, D, \widetilde{\Delta}\}^T$$

- The complex scalar DM D can be written in terms of its components as

$$D = O_{12}^D G_H^p + O_{22}^D H_2^{0*} + O_{32}^D \Delta_p.$$

- We have three different types of complex scalar DM:
  - Inert doublet-like DM: $(O_{22}^D)^2 \equiv f_{H_2^*} > 2/3$
  - $SU(2)_H$ triplet-like DM: $(O_{32}^D)^2 \equiv f_{\Delta_p} > 2/3$
  - Goldstone boson-like DM: $(O_{12}^D)^2 \equiv f_{G_H^p} > 2/3$

$SU(2)_H$ Triplet-like DM Δ_p

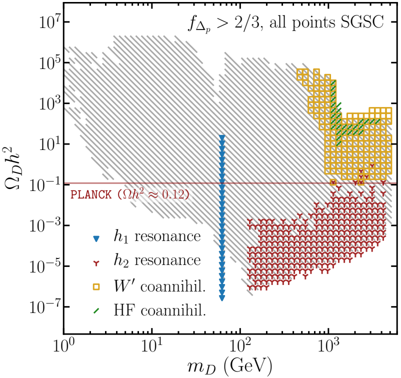


Figure: 1a. $\Omega_D h^2$ of Δ_p DM (C.R.Chen et al. 1910.13138).

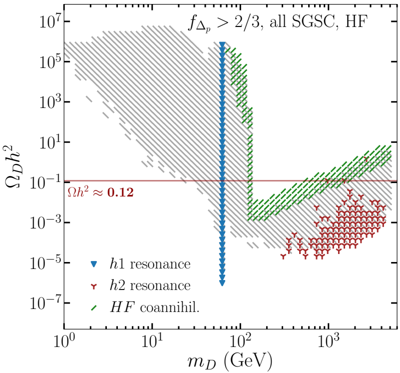


Figure: 1b. $\Omega_D h^2$ of Δ_p DM with HF.

$SU(2)_H$ Goldstone boson-like DM G^p

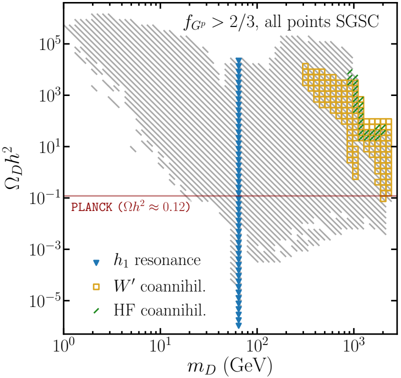


Figure: 2a. $\Omega_D h^2$ of G^p DM (C.R.Chen et al. 1910.13138).

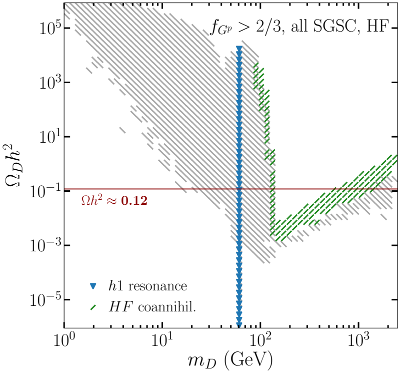
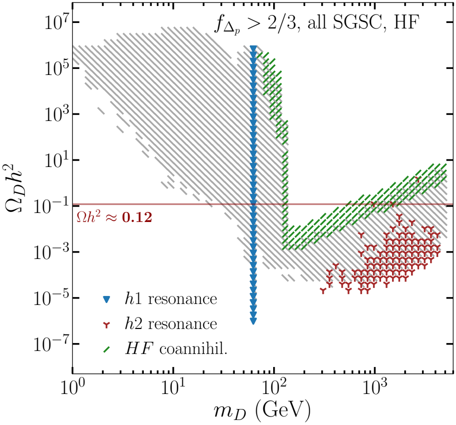


Figure: 2b. $\Omega_D h^2$ of G^p DM with HF.

$SU(2)_H$ Triplet-like DM Δ_p



- For $m_D > 150$ GeV, the dominant DM-DM annihilation: $DD^* \to W_L^+ W_L^-, h_1 h_1, Z_L Z_L$ (55%).
- Dominant coannihilation: $\bar{q}^H q^H \to \bar{q}q, gg$ (40%).

QCD Sommerfeld Correction and BSF

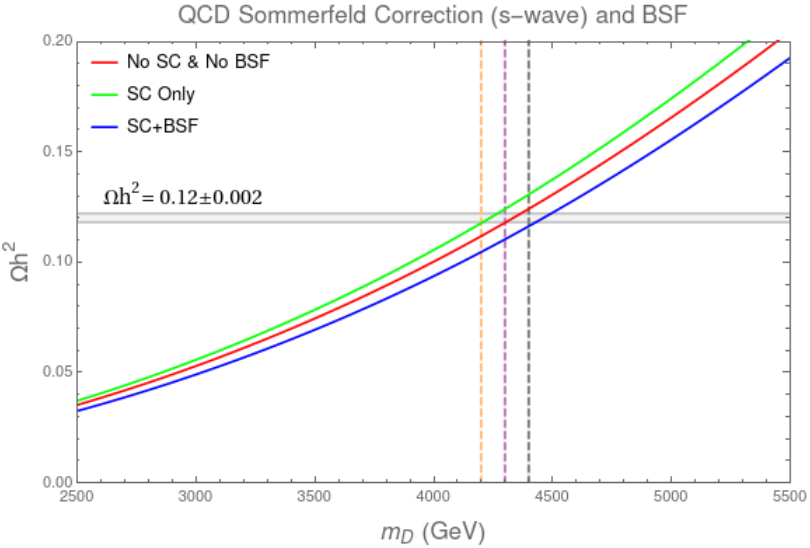


Figure: 3. DM Relic density including QCD Sommerfeld Correction and BSF.

EM Correction to QCD BSF

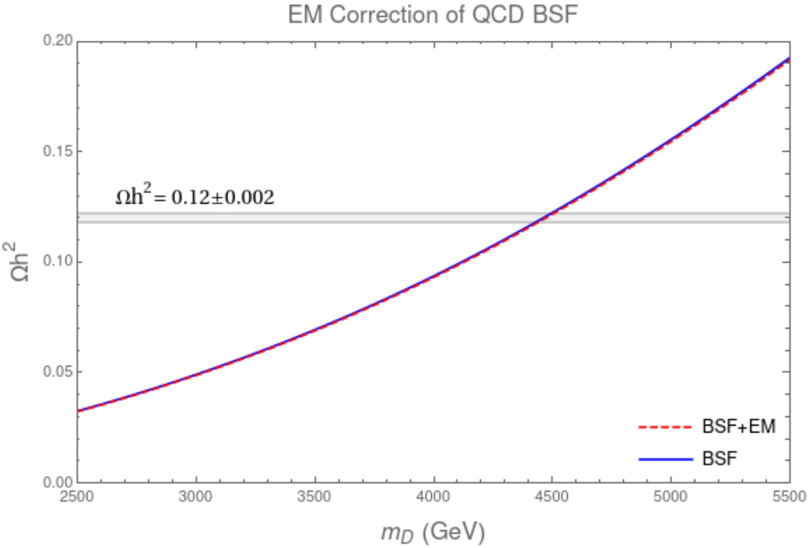


Figure: 4 DM Relic density including QCD BSF with EM correction.

$SU(2)_H$ Triplet-like DM Δ_p

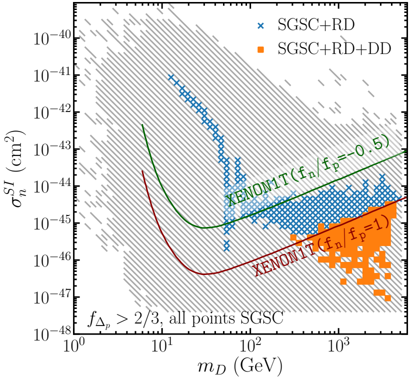


Figure: 5a. σ_n^{SI} of Δ_p DM (C.R.Chen et al. 1910.13138).

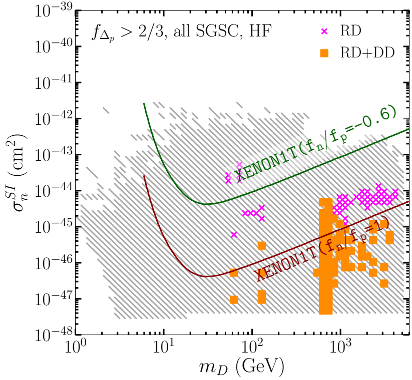


Figure: 5b. σ_n^{SI} of Δ_p DM with HF.

$SU(2)_H$ Goldstone boson-like DM G^p

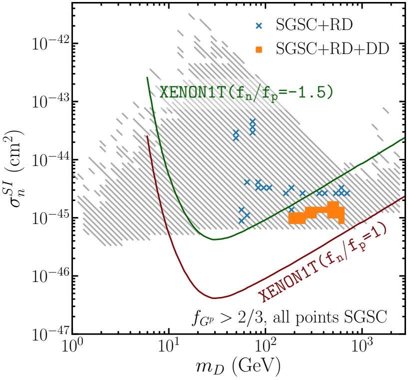


Figure: 6a. σ_n^{SI} of G^p DM (C.R.Chen et al. 1910.13138).

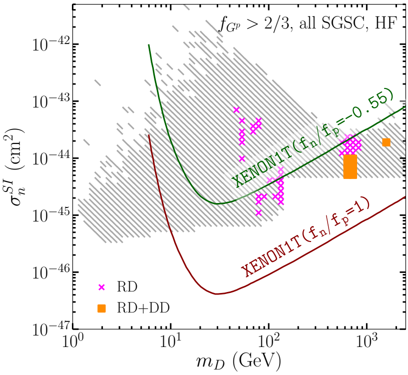
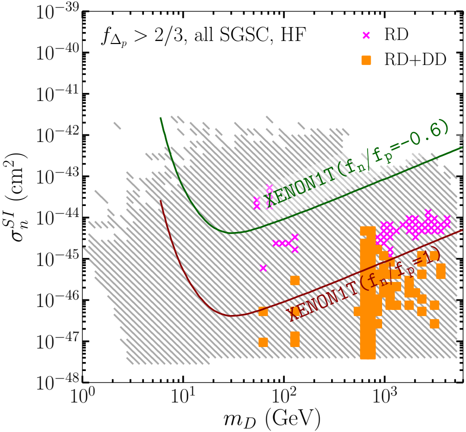


Figure: 6b. σ_n^{SI} of G^p DM with HF.

$SU(2)_H$ Triplet-like DM Δ_p



- Δ_p interacts with nucleon via h_i, Z_i, and f^H exchange.
- There is destructive interference between h_i and f^H diagram.
- The f^H and Z_i add upp constructively.

Surviving Parameter

Parameter Ranges No HF	Parameter Ranges with HF
$6.35\times10^{-3} < \lambda_\Phi < 4.09$	$1.83\times10^{-3} < \lambda_\Phi < 4.17$
$-3.39 < \lambda_{H\Delta} < 4.07$	$-3.35 < \lambda_{H\Delta} < 3.55$
$-0.07 < \lambda_{\Phi\Delta} < 6.62$	$-0.40 < \lambda_{\Phi\Delta} < 6.48$
$-5.67 < \lambda_{H\Phi} < 3.41$	$-5.53 < \lambda_{H\Phi} < 3.03$
$-0.01 < \lambda'_{H\Phi} < 15.90$	$0.00 < \lambda'_{H\Phi} < 15.27$
$1.29\times10^{-1} < \lambda_H < 2.80$	$1.30\times10^{-1} < \lambda_H < 2.71$
$-22.74 < \lambda'_H < 9.57$	$-22.24 < \lambda'_H < 9.92$
$1.01\times10^{-4} < \lambda_\Delta < 4.99$	$1.01\times10^{-4} < \lambda_\Delta < 5.02$
$7.16\times10^{-3} < g_H < 0.10$	$2.97\times10^{-3} < g_H < 0.10$
$1.01\times10^{-8} < g_X < 3.55\times10^{-2}$	$1.01\times10^{-8} < g_X < 2.86\times10^{-2}$

Table: 2 The surviving parameter space after DM constraints.

Surviving Parameter

Parameter Ranges No HF (GeV)	Parameter Ranges with HF (GeV)
$2.75 < M_{H\Delta} < 4.99 \times 10^3$	$1.75\times 10^3 < M_{H\Delta} < 3.91 \times 10^3$
$0.01 < M_{\Phi\Delta} < 49.9$	$0.01 < M_{\Phi\Delta} < 46.9$
$5.00 \times 10^2 < v_\Delta < 2.00 \times 10^4$	$5.09\times 10^2 < v_\Delta < 2.00 \times 10^4$
$4.15 \times 10^4 < v_\Phi < 1.00 \times 10^5$	$4.38 \times 10^4 < v_\Phi < 9.99 \times 10^4$

Table: 3 The surviving dimensionful parameter space after DM constraints.

Summary

- G2HDM is a new framework with a rich but simple scalar sector.
- The Gauge group exhibits accidental Z_2 symmetry that protects DM stability.
- The new heavy fermions effectively reduce the DM relic abundance.
- The new heavy fermions reduce the DM nucleon interaction.
- The inclusion of heavy fermions constraint the allowed parameter space significantly.

Back Up Slides

ISV and XENON1T Limit

- Due to the isospin violating (ISV) nature of the DM-nucleon interaction one needs to take careful consideration when imposing the experimental result on the theoretical calculation.
- The ISV originated from the following coupling

$$g^{V}_{\bar{q}qZ_k} = \frac{i}{2}\left[\frac{g}{c_W}\left(T_3 - 2Q_q s_W^2\right)\mathcal{O}^G_{1k} + g_H T_3' \mathcal{O}^G_{2k} + g_X X \mathcal{O}^G_{3k}\right] . \quad (1)$$

- To accommodate ISV, we compute the DM nucleon cross section in nucleus level

$$\sigma_{D\mathcal{N}} = \frac{4\mu_{\mathcal{A}}^2}{\pi}[f_p Z + (A-Z) f_n]^2 . \quad (2)$$

- The XENON1T limit is rescaled to the nucleus level

$$\sigma^{X1T}_{D\mathcal{N}} = \sigma_p^{SI}(X1T) \times \frac{\mu_{\mathcal{A}}^2}{\mu_p^2} \times \left[\mathcal{Z} + \frac{f_n}{f_p}(\mathcal{A} - \mathcal{Z})\right]^2 . \quad (3)$$

- Remark: $\sigma_{D\mathcal{N}} = 0$ when $f_n/f_p = -Z/(A-Z) \approx -0.7 \rightarrow$ maximal cancellation.

Direct Search Feynman Diagrams

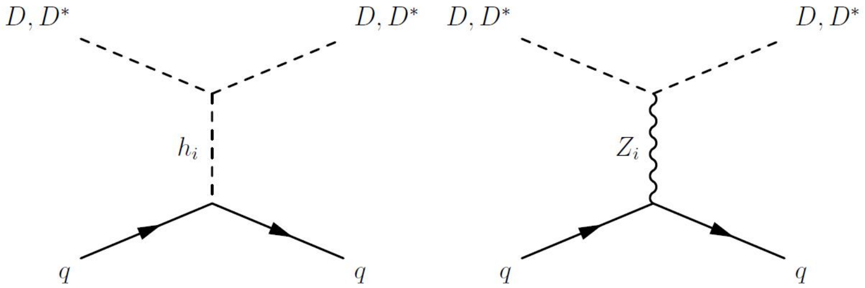


Figure: 7. Feynman diagram relevant to the DM direct detection.

Direct Search Feynman Diagrams

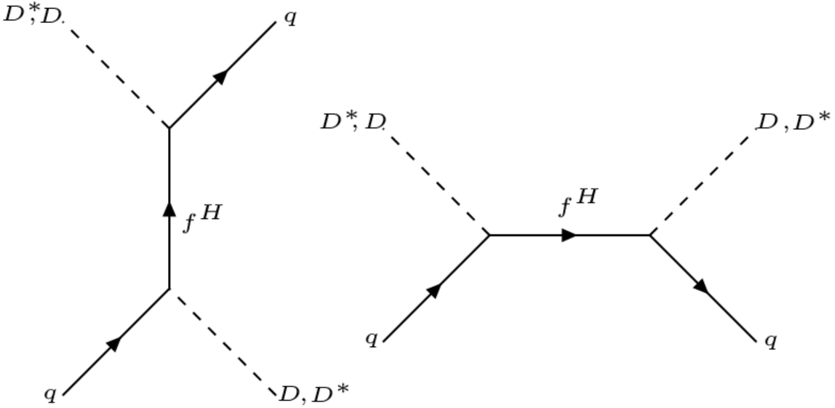


Figure: 8. Feynman diagram relevant to the DM direct detection.

Scan Range

Parameter	Doublet-like	Triplet-like	Goldstone-like
λ_H	$[0.12, 2.75]$	$[0.12, 2.75]$	$[0.12, 2.75]$
λ_Φ	$[10^{-4}, 4.25]$	$[10^{-4}, 4.25]$	$[10^{-4}, 4.25]$
λ_Δ	$[10^{-4}, 5.2]$	$[10^{-4}, 5.2]$	$[10^{-4}, 5.2]$
$\lambda_{H\Phi}$	$[-6.2, 4.3]$	$[-6.2, 4.3]$	$[-6.2, 4.3]$
$\lambda_{H\Delta}$	$[-4.0, 10.5]$	$[-4.0, 10.5]$	$[-4.0, 10.5]$
$\lambda_{\Phi\Delta}$	$[-5.5, 15.0]$	$[-5.5, 15.0]$	$[-5.5, 15.0]$
$\lambda'_{H\Phi}$	$[-1.0, 18.0]$	$[-1.0, 18.0]$	$[-1.0, 18.0]$
λ'_H	$[-8\sqrt{2}\pi, 8\sqrt{2}\pi]$	$[-8\sqrt{2}\pi, 8\sqrt{2}\pi]$	$[-8\sqrt{2}\pi, 8\sqrt{2}\pi]$
$M_{H\Delta}/\text{GeV}$	$[0.0, 15000]$	$[0.0, 5000.0]$	$[0.0, 5000.0]$
$M_{\Phi\Delta}/\text{GeV}$	$[0.0, 5.0]$	$[-50.0, 50.0]$	$[0.0, 700]$
v_Δ/TeV	$[0.5, 2.0]$	$[0.5, 20.0]$	$[14.0, 20.0]$
v_Φ/TeV	$[20, 100]$	$[20, 100]$	$[20, 28.0]$
g_H	[see text, 0.1]	[see text, 0.1]	[see text, 0.1]
g_X	$[10^{-8}, 1.0]$	$[10^{-8}, 1.0]$	$[10^{-8}, 1.0]$

Table: Parameter ranges used in the scans of G2HDM.