Gauging The Popular Two Higgs Doublet Model

TC Yuan
(IoP, Academia Sinica)

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Collaborators: Wei-Chih Huang and Yue-Lin Sming Tsai

Based on

- Wei-Chih Huang, Y. L. Sming Tsai, TCY, arxiv:1512.00229, JHEP04(2016)019.
- Adelssalem Arhrib, Wei-Chih Huang, Y. L. Sming Tsai, TCY, work in progress.

Motivation

- Dark matter (DM) & neutrino masses $\longrightarrow$ 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 $SU(2)_H$.

Some Highlights of G2HDM

- New gauge group $SU(2)_H \otimes U(1)_X$
- 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 the role of dark matter, whose stability is protected by gauge invariance
- Unlike Left-Right symmetric models, the complex vector fields $W'^{(p,m)}$ are electrically neutral
- etc

Outline

- Motivation
- Model Setup
  - Particle Content
  - Higgs Potential & Symmetry Breaking
  - Yukawa Couplings
  - Anomaly Cancellation
  - Theoretical Constraints
- Phenomenology
  - Mass Spectra
  - Z-Z'-Z'' Mixing
  - Higgs Physics
- Summary & Outlook

Particle 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
$U_R = (u_R \;\; u_R^H)^T$	3	1	2	2/3	1
$D_R = (d_R^H \;\; d_R)^T$	3	1	2	$-1/3$	-1
$L_L = (\nu_L \;\; e_L)^T$	1	2	1	$-1/2$	0
$N_R = (\nu_R \;\; \nu_R^H)^T$	1	1	2	0	1
$E_R = (e_R^H \;\; e_R)^T$	1	1	2	-1	-1
χ_u	3	1	1	2/3	0
χ_d	3	1	1	$-1/3$	0
χ_ν	1	1	1	0	0
χ_e	1	1	1	-1	0
$H = (H_1 \;\; H_2)^T$	1	2	2	1/2	1
$\Delta_H = \begin{pmatrix} \Delta_3/2 & \Delta_p/\sqrt{2} \\ \Delta_m/\sqrt{2} & -\Delta_3/2 \end{pmatrix}$	1	1	3	0	0
$\Phi_H = (\Phi_1 \;\; \Phi_2)^T$	1	1	2	0	1

TABLE I. Matter field contents and their quantum number assignments.

- H_1 and H_2 are embedded into a $SU(2)_H$ doublet
- $SU(2)_L$ doublet fermions are singlets under $SU(2)_H$ while $SU(2)_L$ singlet fermions pair up with heavy fermions as $SU(2)_H$ doublets
- VEVs of $\mathbf{\Phi}_H$ and $\mathbf{\Delta}_H$ give a mass to $SU(2)_H$ gauge bosons
- VEV of $\mathbf{\Phi}_H$ gives a Dirac mass to heavy fermions

VEV of Δ_H give mass to charged Higgs

Higgs Potential

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

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

(IHDM)

$$\begin{aligned} V(H) &= \mu_H^2 H^\dagger H + \lambda_H \left(H^\dagger H\right)^2 \ , \\ &= \mu_H^2 \left(H_1^\dagger H_1 + H_2^\dagger H_2\right) + \lambda_H \left(H_1^\dagger H_1 + H_2^\dagger H_2\right)^2 \ , \end{aligned}$$

Higgs Potential

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

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

(IHDM)

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

$$\begin{aligned} V(H) &= \mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 \ , \\ &= \mu_H^2 \left(H_1^\dagger H_1 + H_2^\dagger H_2\right) + \lambda_H \left(H_1^\dagger H_1 + H_2^\dagger H_2\right)^2 \ , \\ V(\Phi_H) &= \mu_\Phi^2 \Phi_H^\dagger \Phi_H + \lambda_\Phi \left(\Phi_H^\dagger \Phi_H\right)^2 \ , \\ &= \mu_\Phi^2 \left(\Phi_1^* \Phi_1 + \Phi_2^* \Phi_2\right) + \lambda_\Phi \left(\Phi_1^* \Phi_1 + \Phi_2^* \Phi_2\right)^2 \ , \\ V(\Delta_H) &= -\mu_\Delta^2 \operatorname{Tr}\left(\Delta_H^\dagger \Delta_H\right) + \lambda_\Delta \left(\operatorname{Tr}\left(\Delta_H^\dagger \Delta_H\right)\right)^2 \ , \\ &= -\mu_\Delta^2 \left(\frac{1}{2}\Delta_3^2 + \Delta_p \Delta_m\right) + \lambda_\Delta \left(\frac{1}{2}\Delta_3^2 + \Delta_p \Delta_m\right)^2 \ , \end{aligned}$$

$$\Delta_H = \begin{pmatrix} \Delta_3/2 & \Delta_p/\sqrt{2} \\ \Delta_m/\sqrt{2} & -\Delta_3/2 \end{pmatrix}$$

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

Higgs Potential

$$
\begin{aligned}
V_{\rm mix}\left(H,\Delta_H,\Phi_H\right) = & + M_{H\Delta}\left(H^\dagger\Delta_H H\right) - M_{\Phi\Delta}\left(\Phi_H^\dagger\Delta_H\Phi_H\right) \\
& + \lambda_{H\Delta}\left(H^\dagger H\right)\mathrm{Tr}\left(\Delta_H^\dagger\Delta_H\right) + \lambda_{H\Phi}\left(H^\dagger H\right)\left(\Phi_H^\dagger\Phi_H\right) \\
& + \lambda_{\Phi\Delta}\left(\Phi_H^\dagger\Phi_H\right)\mathrm{Tr}\left(\Delta_H^\dagger\Delta_H\right) \; , \\
= & + M_{H\Delta}\left(\frac{1}{\sqrt{2}}H_1^\dagger H_2\Delta_p + \frac{1}{2}H_1^\dagger H_1\Delta_3 + \frac{1}{\sqrt{2}}H_2^\dagger H_1\Delta_m - \frac{1}{2}H_2^\dagger H_2\Delta_3\right) \\
& - M_{\Phi\Delta}\left(\frac{1}{\sqrt{2}}\Phi_1^*\Phi_2\Delta_p + \frac{1}{2}\Phi_1^*\Phi_1\Delta_3 + \frac{1}{\sqrt{2}}\Phi_2^*\Phi_1\Delta_m - \frac{1}{2}\Phi_2^*\Phi_2\Delta_3\right) \\
& + \lambda_{H\Delta}\left(H_1^\dagger H_1 + H_2^\dagger H_2\right)\left(\frac{1}{2}\Delta_3^2 + \Delta_p\Delta_m\right) \\
& + \lambda_{H\Phi}\left(H_1^\dagger H_1 + H_2^\dagger H_2\right)\left(\Phi_1^*\Phi_1 + \Phi_2^*\Phi_2\right) \\
& + \lambda_{\Phi\Delta}\left(\Phi_1^*\Phi_1 + \Phi_2^*\Phi_2\right)\left(\frac{1}{2}\Delta_3^2 + \Delta_p\Delta_m\right) \; ,
\end{aligned}
$$

Note that term like $\Phi_H^T\epsilon\Delta_H\Phi_H$ is $SU(2)_H$ invariant but forbidden by $U(1)_X$!

Symmetry Breaking

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

- If $\langle \boldsymbol{\Delta}_3 \rangle = -v_\Delta \neq 0$, the quadratic terms for H_1 and H_2 read:

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

- If $\langle \boldsymbol{\Delta}_3 \rangle = -v_\Delta \neq 0$, the quadratic terms for $\boldsymbol{\Phi}_1$ and $\boldsymbol{\Phi}_2$ read:

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

➢ Therefore, $SU(2)_H$ spontaneous symmetry breaking can trigger $SU(2)_L$ symmetry breaking even if μ_H^2 is positive

Symmetry Breaking

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

Minimization:

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

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

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

Cubic Equation for v_Δ

$$\boxed{v_\Delta^3 + a_2 v_\Delta^2 + a_1 v_\Delta + a_0 = 0}$$

where $a_2 = C_2/C_3$, $a_1 = C_1/C_3$ and $a_0 = C_0/C_3$ with

$$\begin{aligned}
C_0 &= 2\left(\lambda_{H\Phi} M_{\Phi\Delta} - 2\lambda_\Phi M_{H\Delta}\right)\mu_H^2 + 2\left(\lambda_{H\Phi} M_{H\Delta} - 2\lambda_H M_{\Phi\Delta}\right)\mu_\Phi^2 \ , \\
C_1 &= 2\left[2\left(2\lambda_{H\Delta}\lambda_\Phi - \lambda_{H\Phi}\lambda_{\Phi\Delta}\right)\mu_H^2 + 2\left(2\lambda_H\lambda_{\Phi\Delta} - \lambda_{H\Delta}\lambda_{H\Phi}\right)\mu_\Phi^2\right. \\
&\qquad \left. +2\left(4\lambda_H\lambda_\Phi - \lambda_{H\Phi}^2\right)\mu_\Delta^2 + \lambda_H M_{\Phi\Delta}^2 - \lambda_{H\Phi} M_{H\Delta} M_{\Phi\Delta} + \lambda_\Phi M_{H\Delta}^2\right] \ , \\
C_2 &= 3\left[\left(\lambda_{H\Delta}\lambda_{H\Phi} - 2\lambda_H\lambda_{\Phi\Delta}\right) M_{\Phi\Delta} + \left(\lambda_{H\Phi}\lambda_{\Phi\Delta} - 2\lambda_{H\Delta}\lambda_\Phi\right) M_{H\Delta}\right] \ , \\
C_3 &= 4\left[\lambda_H\left(\lambda_{\Phi\Delta}^2 - 4\lambda_\Delta\lambda_\Phi\right) - \lambda_{H\Delta}\lambda_{H\Phi}\lambda_{\Phi\Delta} + \lambda_{H\Delta}^2\lambda_\Phi + \lambda_\Delta\lambda_{H\Phi}^2\right] \ .
\end{aligned}$$

Solution:

Girolamo Cardano (1501-1576)

$$\begin{aligned}
v_{\Delta\,1} &= -\frac{1}{3}a_2 + (S+T) \ , \\
v_{\Delta\,2} &= -\frac{1}{3}a_2 - \frac{1}{2}(S+T) + \frac{1}{2}i\sqrt{3}\,(S-T) \ , \\
v_{\Delta\,3} &= -\frac{1}{3}a_2 - \frac{1}{2}(S+T) - \frac{1}{2}i\sqrt{3}\,(S-T) \ ,
\end{aligned}$$

$$\begin{aligned}
S &\equiv \sqrt[3]{R+\sqrt{D}} \ , & Q &\equiv \frac{3a_1 - a_2^2}{9} \ , \\
T &\equiv \sqrt[3]{R-\sqrt{D}} \ , & R &\equiv \frac{9a_1a_2 - 27a_0 - 2a_2^3}{54} \ . \\
D &\equiv Q^3 + R^2 \ ,
\end{aligned}$$

Yukawa Couplings

- We choose to pair SM $SU(2)_L$ singlet fermions with heavy fermions to form $SU(2)_H$ doublets as

$$\mathcal{L}_{\text{Yuk}} \supset y_d \bar{Q}_L \left(D_R \cdot H\right) + y_u \bar{Q}_L \left(U_R \cdot \tilde{H}\right) + \text{H.c.},$$
$$= y_d \bar{Q}_L \left(d_R^H H_2 - \underbrace{\boxed{d_R H_1}}_{\text{SM}}\right) - y_u \bar{Q}_L \left(\underbrace{\boxed{u_R \tilde{H}_1}}_{\text{SM}} + u_R^H \tilde{H}_2\right) + \text{H.c.},$$

$$\boxed{\begin{array}{l} U_R^T = (u_R \ u_R^H)_{2/3} \\ D_R^T = (d_R^H \ d_R)_{-1/3} \end{array}}$$

- To give a mass to heavy fermions, we add "left-handed" partners with the help of the $SU(2)_H$ scalar doublet $\mathbf{\Phi}_H$:

$$\mathcal{L}_{\text{Yuk}} \supset y'_d \overline{\chi}_d \left(D_R \cdot \Phi_H\right) + y'_u \overline{\chi}_u \left(U_R \cdot \tilde{\Phi}_H\right) + \text{H.c.},$$
$$= y'_d \overline{\chi}_d \left(d_R^H \Phi_2 - d_R \Phi_1\right) - y'_u \overline{\chi}_u \left(u_R \tilde{\Phi}_1 + u_R^H \tilde{\Phi}_2\right) + \text{H.c.},$$

$$\boxed{\begin{array}{c} \Phi_H = (\Phi_1 \ \Phi_2)^T \\ \chi_u, \chi_d \end{array}}$$

Absence of FCNC interaction!
(Natural flavor conservation: Weinberg & Glashow, '77; Paschos, '77
Minimal flavor violation: G. D'Ambrosio, G. F. Giudice, G. Isidori, A. Strumia '02)

If the second doublet H_2 is inert, it could be DM candidate if it is lighter than all heavy fermions and scalars.

Yukawa Couplings

- Similarly, for the lepton sector we have:

$$
\begin{aligned}
\mathcal{L}_{\text{Yuk}} \supset\ & y_e \bar{L}_L \left(E_R \cdot H\right) + y_\nu \bar{L}_L \left(N_R \cdot \tilde{H}\right) + y'_e \overline{\chi}_e \left(E_R \cdot \Phi_H\right) + y'_\nu \overline{\chi}_\nu \left(N_R \cdot \tilde{\Phi}_H\right) + \text{H.c.}, \\
=\ & y_e \bar{L}_L \left(e_R^H H_2 - \boxed{\underset{\text{SM}}{e_R H_1)}}\right. - y_\nu \bar{L}_L \left(\nu_R \tilde{H}_1 + \nu_R^H \tilde{H}_2\right) \\
+\ & y'_e \overline{\chi}_e \left(e_R^H \Phi_2 - e_R \Phi_1\right) - y'_\nu \overline{\chi}_\nu \left(\nu_R \tilde{\Phi}_1 + \nu_R^H \tilde{\Phi}_2\right) + \text{H.c.},
\end{aligned}
$$

where we introduce the right-handed neutrino and its $SU(2)_H$ partner, $N_R = \left(\nu_R \ \ \nu_R^H\right)^T$

- The SM neutrinos have only Dirac masses unless the Majorana mass is introduced such as:

$\overline{N_R^c} \Delta_N N_R$ $\Rightarrow$ where $U(1)_X$ is broken because N_R carries $U(1)_X$ charge

H_1 does not couple to heavy fermions. So the SM Higgs signal strengths are not affected by the new fermions.

Anomaly Cancellation

- The anomaly cancellation for the SM gauge groups $SU(3)_C \times SU(2)_L \times U(1)_Y$ is guaranteed since addition heavy particles of the same hypercharge form Dirac pairs. Therefore, contributions of the left-handed currents from χ_u, χ_d, χ_ν and χ_e cancel those of right-handed ones from u_R^H, d_R^H, ν_R^H and e_R^H respectively.

- For $[SU(2)_H]^2 U(1)_Y$ from the doublets U_R, D_R, N_R and E_R with the following result, one has

$$
\begin{aligned}
2\mathrm{Tr}[T^a\{T^b, Y\}] =& 2\delta^{ab}\left(\sum_l Y_l - \sum_r Y_r\right) = -2\delta^{ab}\sum_r Y_r \\
=& -2\delta^{ab}\left(3\cdot 2\cdot Y(U_R) + 3\cdot 2\cdot Y(D_R) + 2\cdot Y(N_R) + 2\cdot Y(E_R)\right)
\end{aligned}
$$

Anomaly Cancellation

- In terms of $U(1)_X$, one has to check $[SU(3)_C]^2U(1)_X$, $[SU(2)_H]^2U(1)_X$, $[U(1)_X]^3$, $[U(1)_Y]^2U(1)_X$ and $[U(1)_X]^2U(1)_Y$. The first three terms are zero due to cancellation between U_R and D_R and between E_R and N_R with opposite $U(1)_X$ charges. For $[U(1)_Y]^2U(1)_X$ and $[U(1)_X]^2U(1)_Y$, one has respectively

$$2 \cdot \left(3 \cdot \left(Y(U_R)^2 X(U_R) + Y(D_R)^2 X(D_R)\right) + Y(E_R)^2 X(E_R)\right)$$
$$2 \cdot \left(3 \cdot \left(X(U_R)^2 Y(U_R) + X(D_R)^2 Y(D_R)\right) + X(E_R)^2 Y(E_R)\right).$$

- One can also check the perturbative gravitational anomaly associated with the hypercharge and $U(1)_X$-charge current couples to two gravitons is proportional to the following sum of the hypercharge

$$3 \cdot (2 \cdot Y(Q_L) + Y(\chi_u) + Y(\chi_d) - 2 \cdot Y(U_R) - 2 \cdot Y(D_R))$$
$$+2 \cdot Y(L_L) + Y(\chi_\nu) + Y(\chi_e) - 2 \cdot Y(N_R) - 2 \cdot Y(E_R),$$

[Alvarez-Gaume and Witten, '84]

and $U(1)_X$-charge

$$X(U_R) + X(D_R) + X(E_R) + X(N_R).$$

Also, there are a total of 12 $SU(2)_L$ doublets and a total of 24 $SU(2)_H$ doublets. Free of Witten SU(2) global anomaly too!

[Witten, '82]

Particle 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
$U_R = (u_R \;\; u_R^H)^T$	3	1	2	2/3	1
$D_R = (d_R^H \;\; d_R)^T$	3	1	2	$-1/3$	-1
$L_L = (\nu_L \;\; e_L)^T$	1	2	1	$-1/2$	0
$N_R = (\nu_R \;\; \nu_R^H)^T$	1	1	2	0	1
$E_R = (e_R^H \;\; e_R)^T$	1	1	2	-1	-1
χ_u	3	1	1	2/3	0
χ_d	3	1	1	$-1/3$	0
χ_ν	1	1	1	0	0
χ_e	1	1	1	-1	0
$H = (H_1 \;\; H_2)^T$	1	2	2	1/2	1
$\Delta_H = \begin{pmatrix} \Delta_3/2 & \Delta_p/\sqrt{2} \\ \Delta_m/\sqrt{2} & -\Delta_3/2 \end{pmatrix}$	1	1	3	0	0
$\Phi_H = (\Phi_1 \;\; \Phi_2)^T$	1	1	2	0	1

TABLE I. Matter field contents and their quantum number assignments.

Optional $\Delta_N(1,1,3,0,-2)$ to provide Majorana neutrino masses.

- H_1 and H_2 are embedded into a $SU(2)_H$ doublet
- $SU(2)_L$ doublet fermions are singlets under $SU(2)_H$ while $SU(2)_L$ singlet fermions pair up with heavy fermions as $SU(2)_H$ doublets
- VEVs of $\mathbf{\Phi}_H$ and $\mathbf{\Delta}_H$ give a mass to $SU(2)_H$ gauge bosons
- VEV of $\mathbf{\Phi}_H$ gives a Dirac mass to heavy fermions

VEV of Δ_H give mass to charged Higgs

Theoretical Constraints

- Vacuum Stability
  - Scalar potential should be bounded from below
- Perturbative Unitarity
  - Scattering amplitudes in the scalar sector

Potential (Quartic terms)

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

$$
\begin{aligned}
\mathcal{X}^2 &= h^2 + (G^0)^2 + 2G^+G^- + S^2 + P^2 + 2H^+H^- \\
\mathcal{Y}^2 &= \phi_2^2 + (G_H^0)^2 + 2G_H^p G_H^m \\
\mathcal{Z}^2 &= \delta_3^2 + 2\Delta_p\Delta_m
\end{aligned}
$$

$$
V_4 = \frac{1}{4}\left(\lambda_H \mathcal{X}^4 + \lambda_\Phi \mathcal{Y}^4 + \lambda_\Delta \mathcal{Z}^4 + \lambda_{H\Delta}\mathcal{X}^2\mathcal{Z}^2 + \lambda_{H\Phi}\mathcal{X}^2\mathcal{Y}^2 + \lambda_{\Phi\Delta}\mathcal{Y}^2\mathcal{Z}^2\right)
$$

Scalar Bosons Scattering Amplitudes

$$\mathcal{M}_1 = \begin{pmatrix} 6\lambda_H & \lambda_H & \lambda_H & \lambda_H & \lambda_H & \lambda_H & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Delta} & \lambda_{H\Delta} \\ \lambda_H & 6\lambda_H & \lambda_H & \lambda_H & \lambda_H & \lambda_H & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Delta} & \lambda_{H\Delta} \\ \lambda_H & \lambda_H & 6\lambda_H & \lambda_H & \lambda_H & \lambda_H & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Delta} & \lambda_{H\Delta} \\ \lambda_H & \lambda_H & \lambda_H & 6\lambda_H & \lambda_H & \lambda_H & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Delta} & \lambda_{H\Delta} \\ \lambda_H & \lambda_H & \lambda_H & \lambda_H & 6\lambda_H & \lambda_H & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Delta} & \lambda_{H\Delta} \\ \lambda_H & \lambda_H & \lambda_H & \lambda_H & \lambda_H & 6\lambda_H & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Delta} & \lambda_{H\Delta} \\ \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Phi} & 6\lambda_\Phi & \lambda_\Phi & \lambda_\Phi & \lambda_{\Phi\Delta} & \lambda_{\Phi\Delta} \\ \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_\Phi & 6\lambda_\Phi & \lambda_\Phi & \lambda_{\Phi\Delta} & \lambda_{\Phi\Delta} \\ \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_{H\Phi} & \lambda_\Phi & \lambda_\Phi & 6\lambda_\Phi & \lambda_{\Phi\Delta} & \lambda_{\Phi\Delta} \\ \lambda_{H\Delta} & \lambda_{H\Delta} & \lambda_{H\Delta} & \lambda_{H\Delta} & \lambda_{H\Delta} & \lambda_{H\Delta} & \lambda_{\Phi\Delta} & \lambda_{\Phi\Delta} & \lambda_{\Phi\Delta} & 6\lambda_\Delta & \lambda_\Delta \\ \lambda_{H\Delta} & \lambda_{H\Delta} & \lambda_{H\Delta} & \lambda_{H\Delta} & \lambda_{H\Delta} & \lambda_{H\Delta} & \lambda_{\Phi\Delta} & \lambda_{\Phi\Delta} & \lambda_{\Phi\Delta} & \lambda_\Delta & 6\lambda_\Delta \end{pmatrix}$$

The first row corresponds to the processes

$$hh \longleftrightarrow hh, G^0G^0, G^+G^-, SS, PP, H^+H^-, \phi_2\phi_2, G_H^0G_H^0, G_H^pG_H^m, \delta_3\delta_3, \Delta_p\Delta_m\,.$$

The second row is for

$$G^0G^0 \longleftrightarrow hh, G^0G^0, G^+G^-, SS, PP, H^+H^-, \phi_2\phi_2, G_H^0G_H^0, G_H^pG_H^m, \delta_3\delta_3, \Delta_p\Delta_m\,.$$

And so on. Here we decompose $H_2^{0*} = (S - iP)/\sqrt{2}$ and consider S and P separately. This was usually done in IHDM. Unitarity constraints require all eigenvalues of $\mathcal{M}_1$ to satisfy

$$|\lambda_i| \leq 8\pi\ ,\ \forall i = 1, \cdots, 11$$

$$\mathcal{M}_2 = \begin{pmatrix} \lambda_{H\Phi}\mathcal{I}_{18\times 18} & 0 & 0 \\ 0 & \lambda_{\Phi\Delta}\mathcal{I}_{6\times 6} & 0 \\ 0 & 0 & \lambda_{H\Delta}\mathcal{I}_{12\times 12} \end{pmatrix}$$

where $\mathcal{I}_{n\times n}$ is the $n \times n$ unit matrix. The first block corresponds to

$$\begin{aligned} h\phi_2 \longleftrightarrow h\phi_2, hG_H^0 \longleftrightarrow hG_H^0, hG_H^p \longleftrightarrow hG_H^p, \\ G^0\phi_2 \longleftrightarrow G^0\phi_2, G^0G_H^0 \longleftrightarrow G^0G_H^0, G^0G_H^p \longleftrightarrow G^0G_H^p, \\ \cdots \text{ and so on.} \end{aligned}$$

The second block corresponds to

$$\begin{aligned} \phi_2\delta_3 \longleftrightarrow \phi_2\delta_3, \phi_2\Delta_p \longleftrightarrow \phi_2\Delta_p, \\ G_H^0\delta_3 \longleftrightarrow G_H^0\delta_3, G_H^0\Delta_p \longleftrightarrow G_H^0\Delta_p, \\ G_H^p\delta_3 \longleftrightarrow G_H^p\delta_3, G_H^p\Delta_p \longleftrightarrow G_H^p\Delta_p. \end{aligned}$$

The third block corresponds to

$$\begin{aligned} h\delta_3 \longleftrightarrow h\delta_3, h\Delta_p \longleftrightarrow h\Delta_p, \\ G^0\delta_3 \longleftrightarrow G^0\delta_3, G^0\Delta_p \longleftrightarrow G^0\Delta_p, \\ G^+\delta_3 \longleftrightarrow G^+\delta_3, G^+\Delta_p \longleftrightarrow G^+\Delta_p, \\ \cdots \text{ and so on.} \end{aligned}$$

Eigenvalues of $\mathcal{M}_2$ are $\lambda_{H\Phi}$, $\lambda_{\Phi\Delta}$ and $\lambda_{H\Delta}$. Unitarity requires

$$\begin{aligned} |\lambda_{H\Phi}| &\leq 8\pi \ , \\ |\lambda_{\Phi\Delta}| &\leq 8\pi \ , \\ |\lambda_{H\Delta}| &\leq 8\pi \ . \end{aligned}$$

- $\lambda_H\,,\ \lambda_\Phi\,,\ \lambda_\Delta$ must be positive definite:

$$\lambda_H\,,\ \lambda_\Phi\,,\ \lambda_\Delta\ > 0\,. \tag{73}$$

- $\lambda_{H\Phi}\,,\ \lambda_{\Phi\Delta}\,,\ \lambda_{H\Delta}$ can be positive or negative. Their ranges are determined by unitarity constraint

$$|\lambda_{H\Phi}|\,,\ |\lambda_{\Phi\Delta}|\,,\ |\lambda_{H\Delta}|\ < 8\pi\,. \tag{74}$$

(1) $\lambda_{H\Phi}\,,\ \lambda_{\Phi\Delta}\,,\ \lambda_{H\Delta} > 0$

$$\lambda_{H\Phi}\,,\ \lambda_{\Phi\Delta}\,,\ \lambda_{H\Delta}\ < 8\pi\,. \tag{75}$$

(2) $\lambda_{H\Phi}\,,\ \lambda_{\Phi\Delta}\ > 0\,;\ \lambda_{H\Delta} < 0$

$$4\lambda_H\lambda_\Delta - \lambda_{H\Delta}^2 > 0 \tag{76}$$

Similar conditions for two other permutation cases.

(3) $\lambda_{H\Phi} > 0\,;\ \lambda_{\Phi\Delta}\,,\ \lambda_{H\Delta}\ < 0$

$$\begin{aligned} 4\lambda_\Phi\lambda_\Delta - \lambda_{\Phi\Delta}^2 &> 0 \\ 4\lambda_H\lambda_\Delta - \lambda_{H\Delta}^2 &> 0 \\ 2\lambda_\Delta\lambda_{H\Phi} - \lambda_{H\Delta}\lambda_{\Phi\Delta} &> -\sqrt{(4\lambda_H\lambda_\Delta - \lambda_{H\Delta}^2)\,(4\lambda_\Phi\lambda_\Delta - \lambda_{\Phi\Delta}^2)} \end{aligned} \tag{77}$$

Similar conditions for two other permutation cases.

(4) $\lambda_{H\Phi}\,,\ \lambda_{\Phi\Delta}\,,\ \lambda_{H\Delta} < 0$

$$\begin{aligned} 4\lambda_H\lambda_\Phi - \lambda_{H\Phi}^2 &> 0 \\ 4\lambda_\Phi\lambda_\Delta - \lambda_{\Phi\Delta}^2 &> 0 \\ 4\lambda_H\lambda_\Delta - \lambda_{H\Delta}^2 &> 0 \\ 2\lambda_\Phi\lambda_{H\Delta} - \lambda_{H\Phi}\lambda_{\Phi\Delta} &> -\sqrt{(4\lambda_H\lambda_\Phi - \lambda_{H\Phi}^2)\,(4\lambda_\Phi\lambda_\Delta - \lambda_{\Phi\Delta}^2)} \\ 2\lambda_H\lambda_{\Phi\Delta} - \lambda_{H\Phi}\lambda_{H\Delta} &> -\sqrt{(4\lambda_H\lambda_\Phi - \lambda_{H\Phi}^2)\,(4\lambda_H\lambda_\Delta - \lambda_{H\Delta}^2)} \\ 2\lambda_\Delta\lambda_{H\Phi} - \lambda_{\Phi\Delta}\lambda_{H\Delta} &> -\sqrt{(4\lambda_\Phi\lambda_\Delta - \lambda_{\Phi\Delta}^2)\,(4\lambda_H\lambda_\Delta - \lambda_{H\Delta}^2)} \end{aligned} \tag{78}$$

- All eigenvalues λ_i of $\mathcal{M}_1$ in (66) must be constrained by $|\lambda_i| < 8\pi$.

Phenomenology

Scalar mass spectrum

- First, we Taylor expand scalar fields around the vacua

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

$$H_2 = (H_2^+ \; H_2^0)^T$$

$\Psi_G \equiv \{G^+, G^0, G_H^p, G_H^0\}$ are Goldstone bosons

$\Psi \equiv \{h, H_2, \Phi_1, \phi_2, \delta_3, \Delta_p\}$ are the physical fields

Mass Matrix is 10 x 10

➢ We have 6 Goldstone bosons, absorbed by 3 SM gauge bosons and 3 $SU(2)_H$ ones, yielding the massless photon and dark photon

More later!

- We have the mixing between $\{h, \delta_3, \phi_2\}$ and $\{G_H^p, \Delta_p, H_2^{0*}\}$ due to:

$$V_{\rm mix}(h,\delta_3,\phi_2) \supset + M_{H\Delta}\left(\frac{1}{2}H_1^\dagger H_1 \Delta_3\right) + \lambda_{H\Delta}\left(H_1^\dagger H_1\right)\left(\frac{1}{2}\Delta_3^2\right) + \lambda_{H\Phi}\left(H_1^\dagger H_1\right)\left(\Phi_2^*\Phi_2\right) + \lambda_{\Phi\Delta}\left(\Phi_2^*\Phi_2\right)\left(\frac{1}{2}\Delta_3^2\right) - M_{\Phi\Delta}\left(\frac{1}{2}\Phi_2^*\Phi_2\Delta_3\right)$$

$$V_{\rm mix}(G_H^p,\Delta_p,H_2^{0*}) \supset + M_{H\Delta}\left(\frac{1}{\sqrt{2}}H_1^\dagger H_2\Delta_p + \frac{1}{\sqrt{2}}H_2^\dagger H_1\Delta_m\right) - M_{\Phi\Delta}\left(\frac{1}{\sqrt{2}}\Phi_1^*\Phi_2\Delta_p + \frac{1}{\sqrt{2}}\Phi_2^*\Phi_1\Delta_m\right)$$

Scalar Mass Spectrum

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

$$S = \{h, \delta_3, \phi_2\}$$

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

- The determinant of the second mass matrix is zero since one of the mass eigenstates and its complex conjugate correspond to the Goldstone bosons, eaten by $SU(2)_H$ W'

- For H_2^0 to be the DM candidate, one has to make sure it is lighter than its charged component $H_2^{\pm}$ of mass $M_{H\Delta}v_{\Delta}$

$$\mathcal{M}_0'^2 = \begin{pmatrix} M_{\Phi\Delta}v_\Delta & -\frac{1}{2}M_{\Phi\Delta}v_\Phi & 0 \\ -\frac{1}{2}M_{\Phi\Delta}v_\Phi & \frac{1}{4v_\Delta}\left(M_{H\Delta}v^2 + M_{\Phi\Delta}v_\Phi^2\right) & \frac{1}{2}M_{H\Delta}v \\ 0 & \frac{1}{2}M_{H\Delta}v & M_{H\Delta}v_\Delta \end{pmatrix}$$

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

Scalar mass spectrum

- The charged components of H_2 do not mix with other neutral scalars:

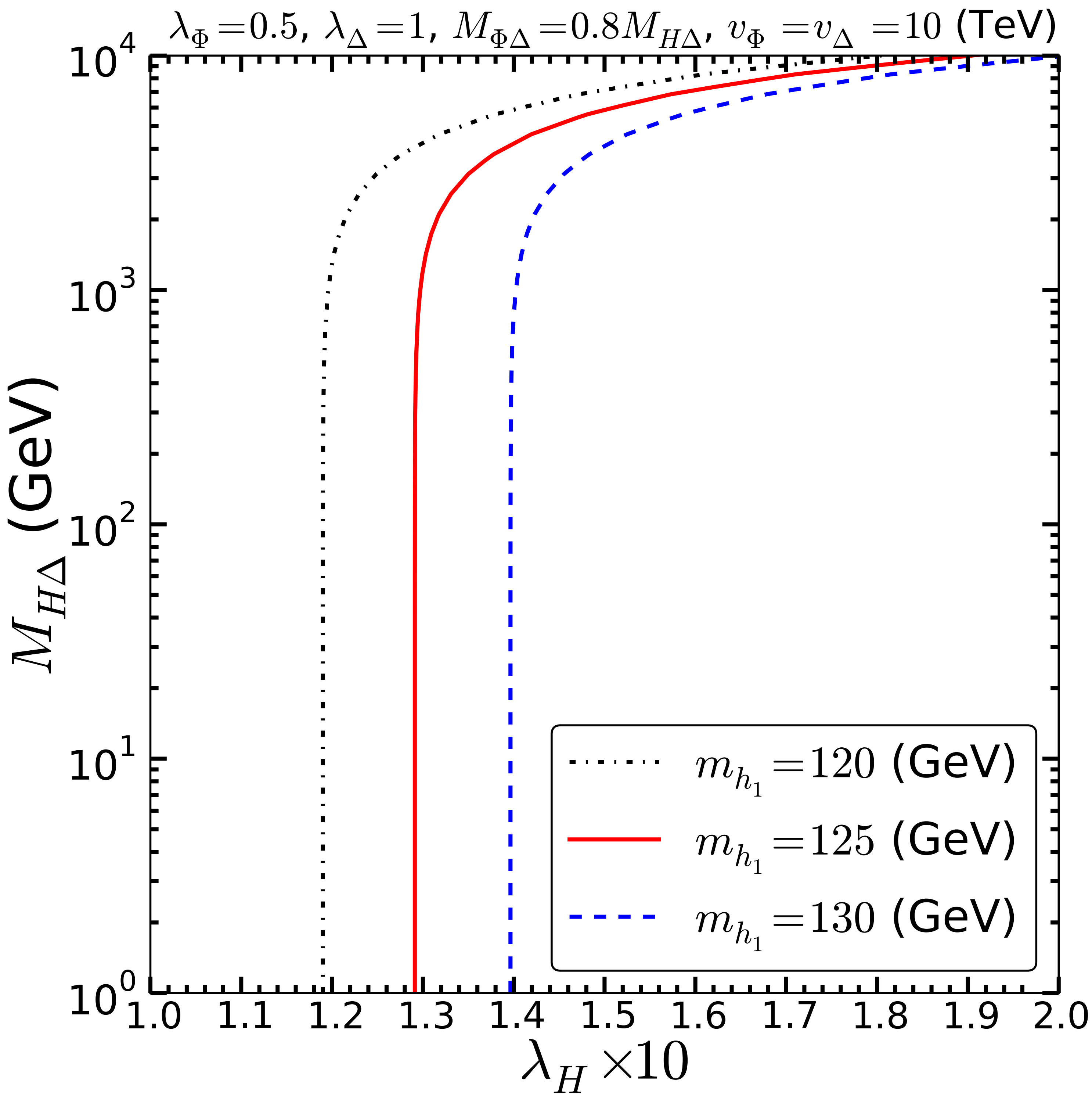
$$m^2_{H_2^\pm} = M_{H\Delta} v_\Delta$$

Different from IHDM!!

- The rest is the Goldstone bosons:

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

Reproducing the SM 125 GeV Higgs



Gauge boson mass spectrum

- We have 6 Goldstone bosons: 2 absorbed by SM W, 2 eaten by $SU(2)_H$ W' and the rest two by Z and Z'.

- The SM W bosons acquire a mass by eating the charged components of H_1 as in the SM since H_2 does not get a VEV and the other scalars ($\boldsymbol{\Phi}_H$ and $\boldsymbol{\Delta}_H$) are neutral

$$M_{W^\pm} = \frac{1}{2} g v$$

- $SU(2)_H$ W' bosons receive a mass from all VEVs, $\langle \boldsymbol{\Delta}_3 \rangle$, $\langle \boldsymbol{\Phi}_2 \rangle$ and $\langle H_1 \rangle$:

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

Gauge boson mass spectrum

- $<\boldsymbol{\Delta}_3>$ gives a mass to $SU(2)_H$ W' bosons but not W'^3 while one linear combination of W'^3 and X obtains a mass from $<\boldsymbol{\Phi}_2>$

- $<H_1>$ also gives a mass to W'^3 and X because of its quantum numbers. Hence, W'^3 and X mix with the SM W_3 and Y.

$$\mathcal{M}_1^2 = \begin{pmatrix} \frac{g'^2 v^2}{4} & -\frac{g' g\, v^2}{4} & \frac{g' g_H v^2}{4} & \frac{g' g_X v^2}{2} \\ -\frac{g' g\, v^2}{4} & \frac{g^2 v^2}{4} & -\frac{g g_H v^2}{4} & -\frac{g g_X v^2}{2} \\ \frac{g' g_H v^2}{4} & -\frac{g g_H v^2}{4} & \frac{g_H^2 \left(v^2 + v_\Phi^2\right)}{4} & \frac{g_H g_X \left(v^2 - v_\Phi^2\right)}{2} \\ \frac{g' g_X v^2}{2} & -\frac{g g_X v^2}{2} & \frac{g_H g_X \left(v^2 - v_\Phi^2\right)}{2} & g_X^2 \left(v^2 + v_\Phi^2\right) \end{pmatrix}$$

No v_Δ dependent!

Gauge boson mass spectrum

- The mass matrix contains 2 massive particles, identified as SM Z and additional Z' and also two massless photon γ and dark photon γ'
- γ' also couples to SM fermions and are thermally produced in the early universe. It would be excluded, for instance, by CMB observables
- There exist at least two solutions: Stueckelberg mass terms (Kors and Nath '04 '05) or simply setting g_X zero.
- In the following, we present results for the second solution.

Gauge boson mass spectrum

- The 3-by-3 mass matrix can be diagonalized by only 2 mixing angles:

$$\begin{pmatrix} m_\gamma^2 & 0 & 0 \\ 0 & m_Z^2 & 0 \\ 0 & 0 & m_{Z'}^2 \end{pmatrix} = R_{23}\left(\theta_{ZZ'}\right)^T R_{12}\left(\theta_w\right)^T \begin{pmatrix} \frac{g'^2 v^2}{4} & -\frac{g' g\, v^2}{4} & \frac{g' g_H v^2}{4} \\ -\frac{g' g\, v^2}{4} & \frac{g^2 v^2}{4} & -\frac{g g_H v^2}{4} \\ \frac{g' g_H v^2}{4} & -\frac{g g_H v^2}{4} & \frac{g_H^2\left(v^2+v_\Phi^2\right)}{4} \end{pmatrix} R_{12}\left(\theta_w\right) R_{23}\left(\theta_{ZZ'}\right)$$

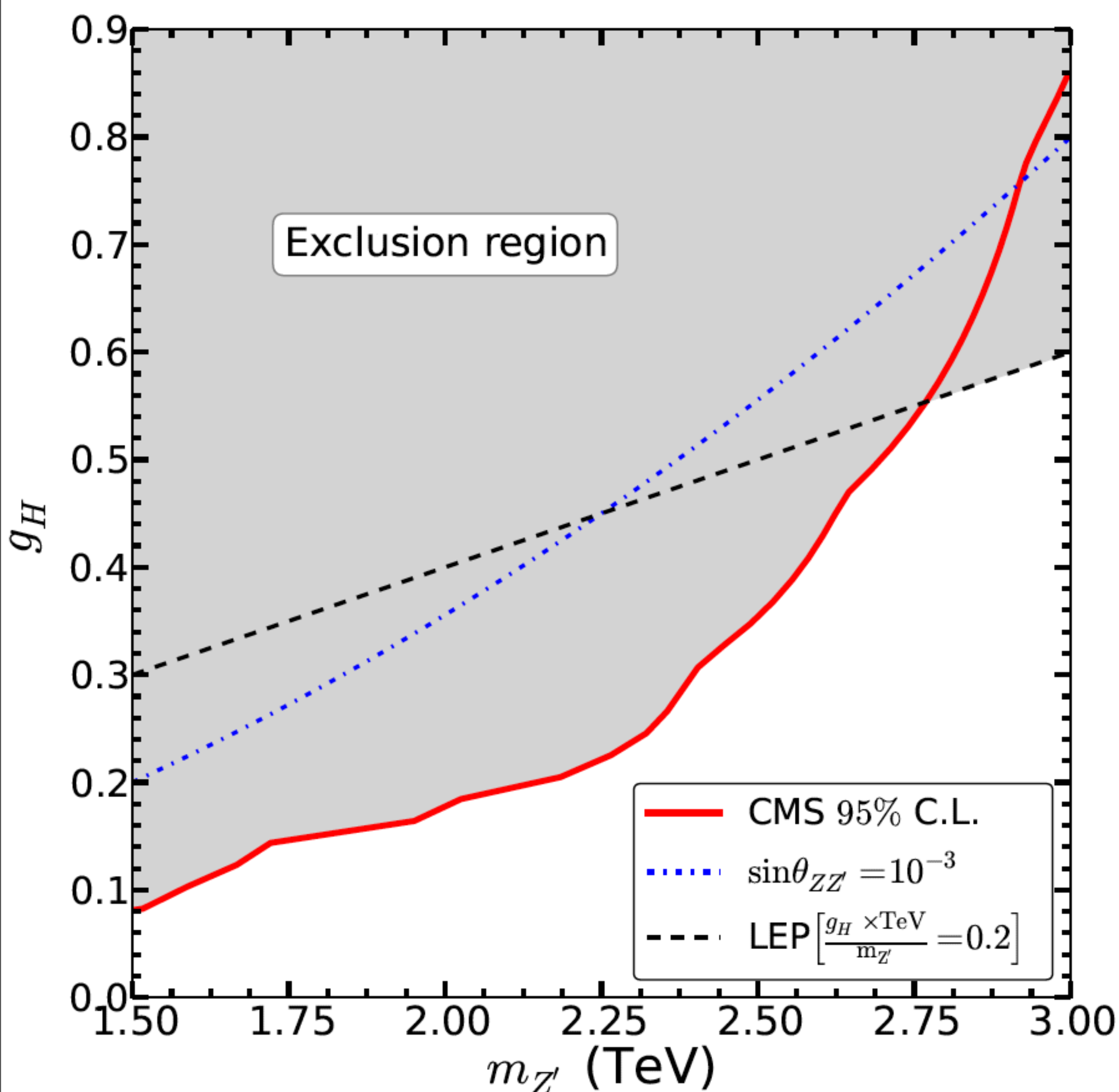
$$m_Z \simeq \sqrt{g^2+g'^2}\frac{v}{2}$$

$$m_{Z'} \simeq g_H \frac{v_\Phi}{2}$$

$$\sin\theta_w = \frac{g'}{\sqrt{g^2+g'^2}}$$, Q= Y + I_3 is a good quantum number

$$\sin\theta_{ZZ'} \approx \frac{\sqrt{g^2+g'^2}\, v^2}{g_H\, v_\Phi^2} \quad (\text{in the limit of } v_\Phi \gg v)\ ,$$

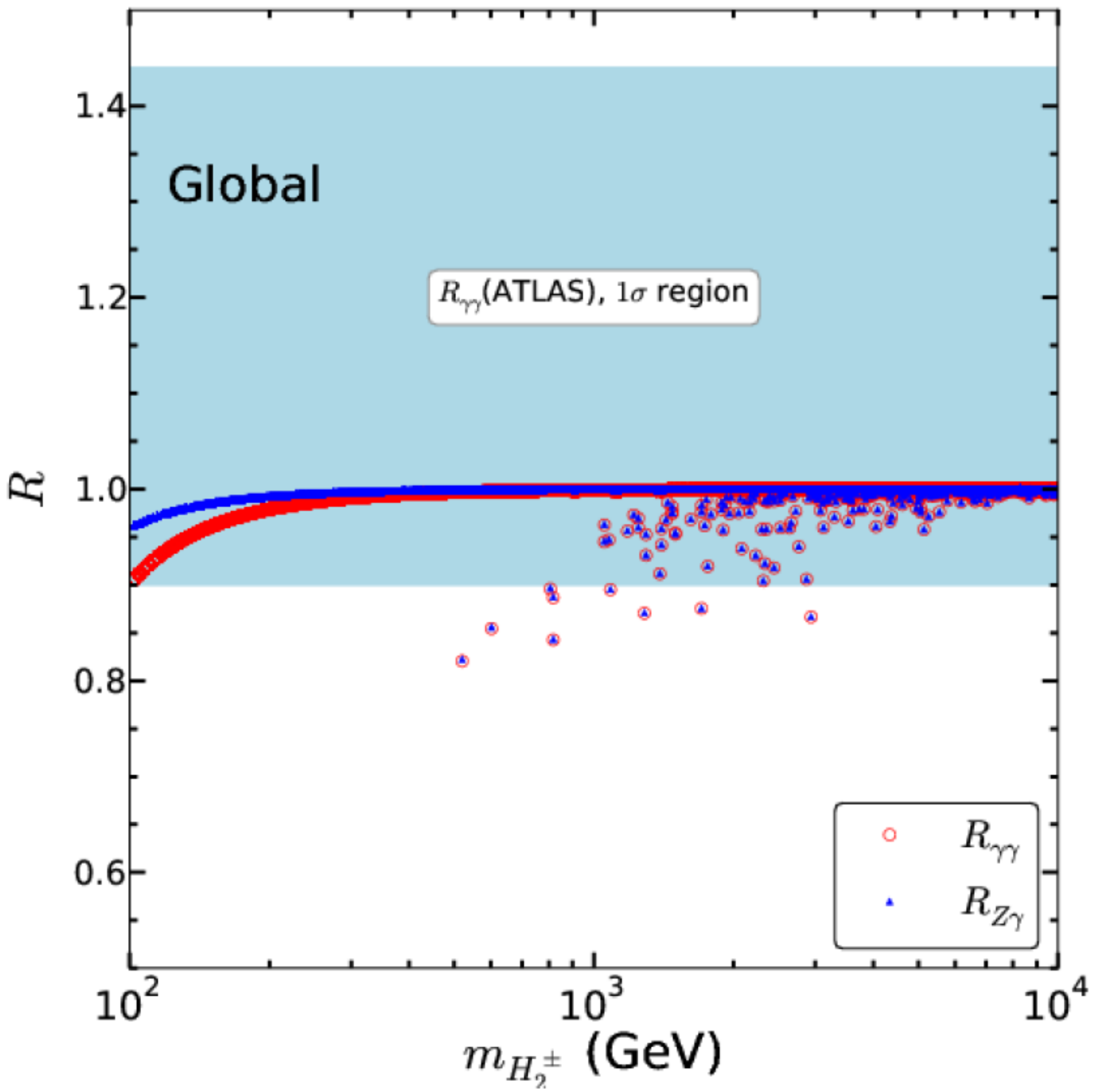
Experimental constraints on Z'



- The red line comes from direct Z' resonance searches (1412.6302)
- The black dashed line comes from LEP constraints on the cross-section of $e^+e^- \to e^+e^-$ (hep-ex/0312023) $\Rightarrow v_\Phi > 10$ TeV
- The blue dotted line comes from EWPT data and collider constraints on the Z-Z' mixing(0906.2435, 1406.6776)

$$m_{Z'} \simeq g_H \frac{v_\Phi}{2}$$

$h \to H_2^\pm$ loop $\to \gamma\gamma$ or $Z\gamma$



Predictions of $h \to \gamma\gamma$ and $h \to Z\gamma$ in this model. Due to the fact $\lambda_H(\approx m_h^2/2v^2)$ is positive, $R_{\gamma\gamma}$ is always less than the SM prediction while $R_{Z\gamma}$ ranges from 0.9 to 1, given the ATLAS and CMS measurements on $R_{\gamma\gamma}$:

CMS: 1.13 ± 0.24 and ATLAS: 1.17 ± 0.27 (1408.7084 and CMS-PAS-HIG-14-009 (2014)).

$$
\begin{aligned}
V(H) &= \mu_H^2 H^\dagger H + \lambda_H \left(H^\dagger H\right)^2 \,, \\
&= \mu_H^2 \left(H_1^\dagger H_1 + H_2^\dagger H_2\right) + \lambda_H \left(H_1^\dagger H_1 + H_2^\dagger H_2\right)^2 \,,
\end{aligned}
$$

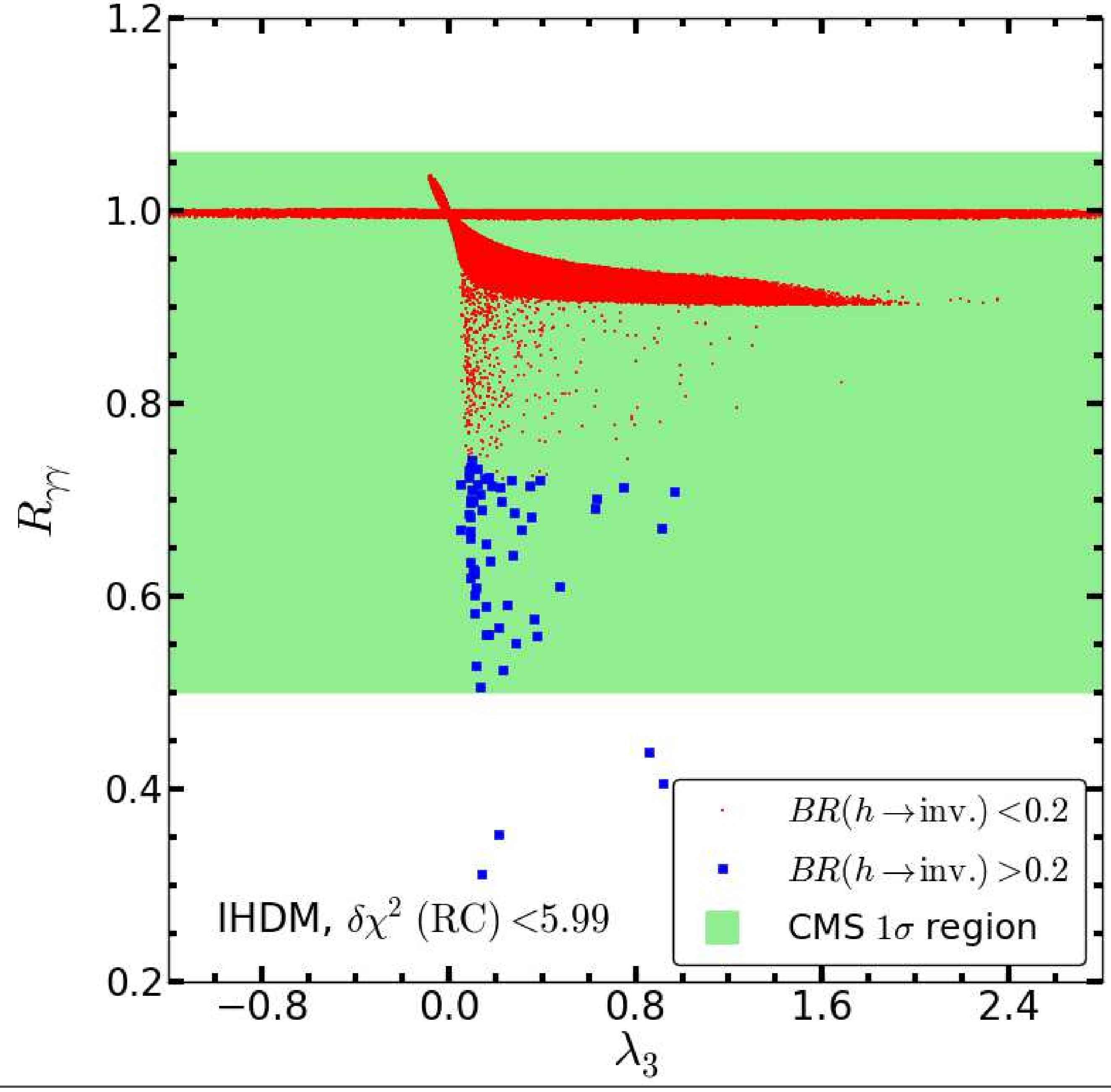
IHDM

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}, \qquad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(S + iA) \end{pmatrix}$$

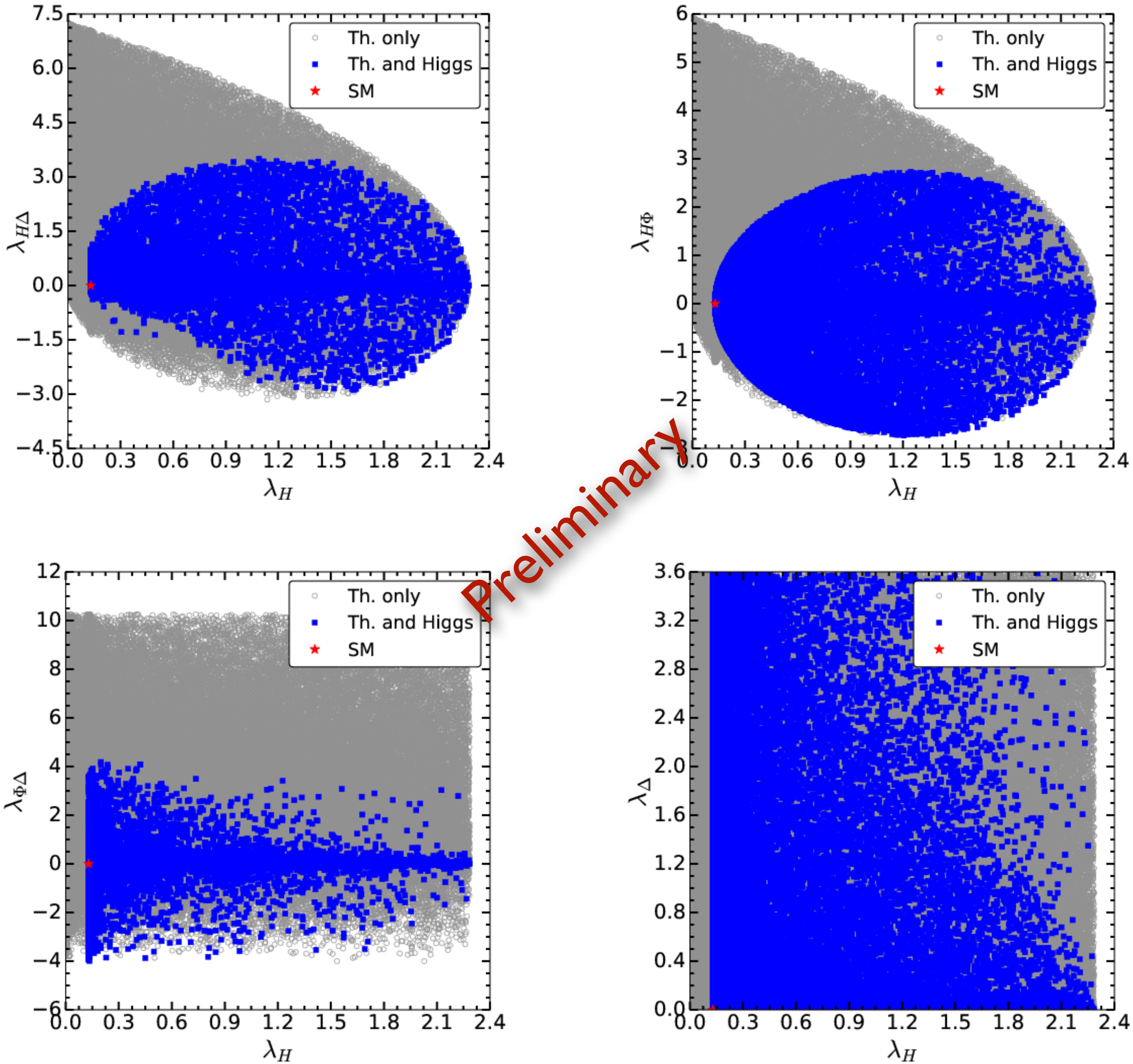
$$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left\{(H_1^\dagger H_2)^2 + \text{h.c.}\right\}.$$

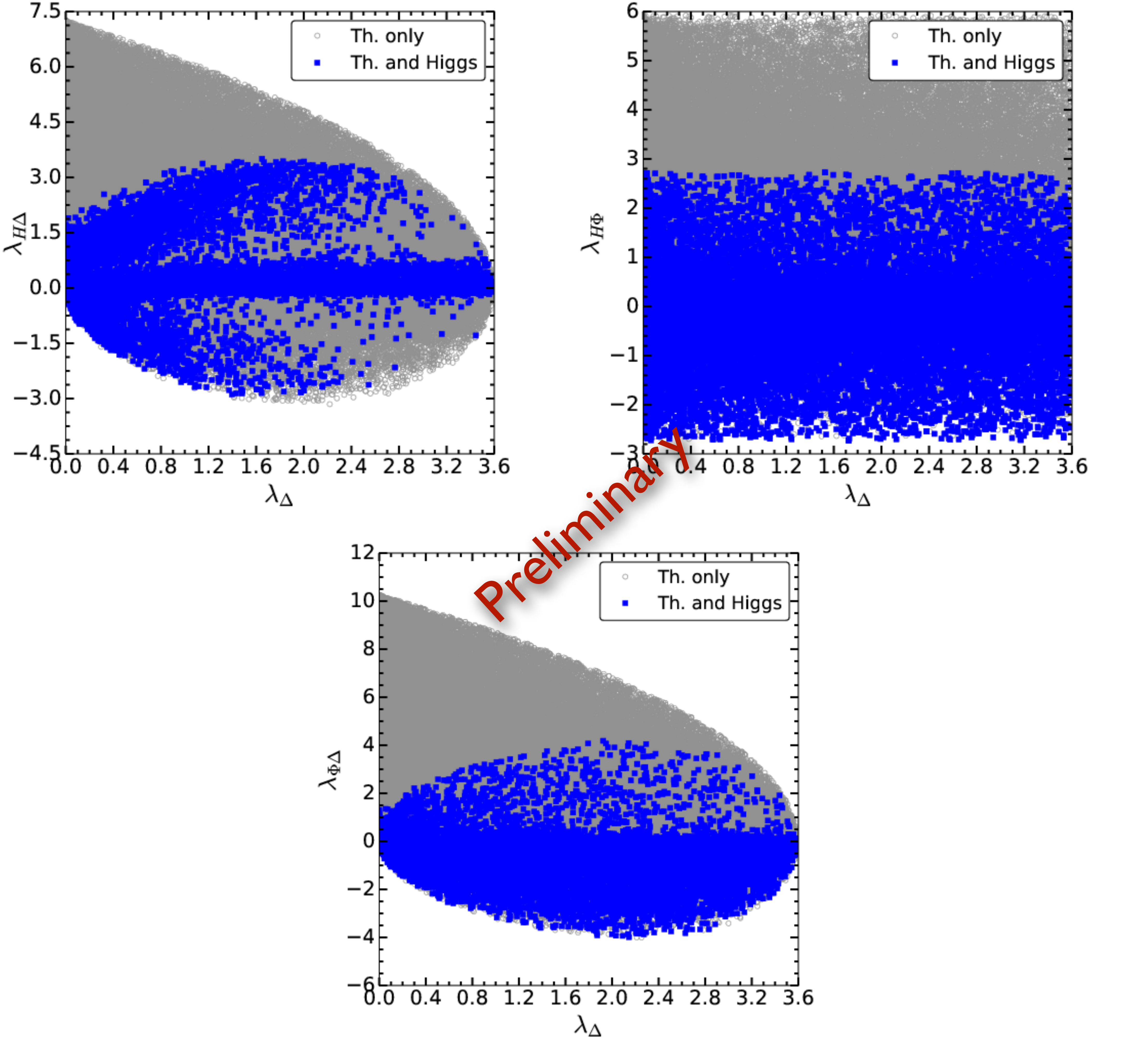
$$m_h^2 = -2\mu_1^2 = 2\lambda_1 v^2$$
$$m_S^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v^2 = \mu_2^2 + \lambda_L v^2$$
$$m_A^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)v^2 = \mu_2^2 + \lambda_A v^2$$
$$m_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2$$

$$\lambda_{L,A} = \frac{1}{2}(\lambda_3 + \lambda_4 \pm \lambda_5).$$

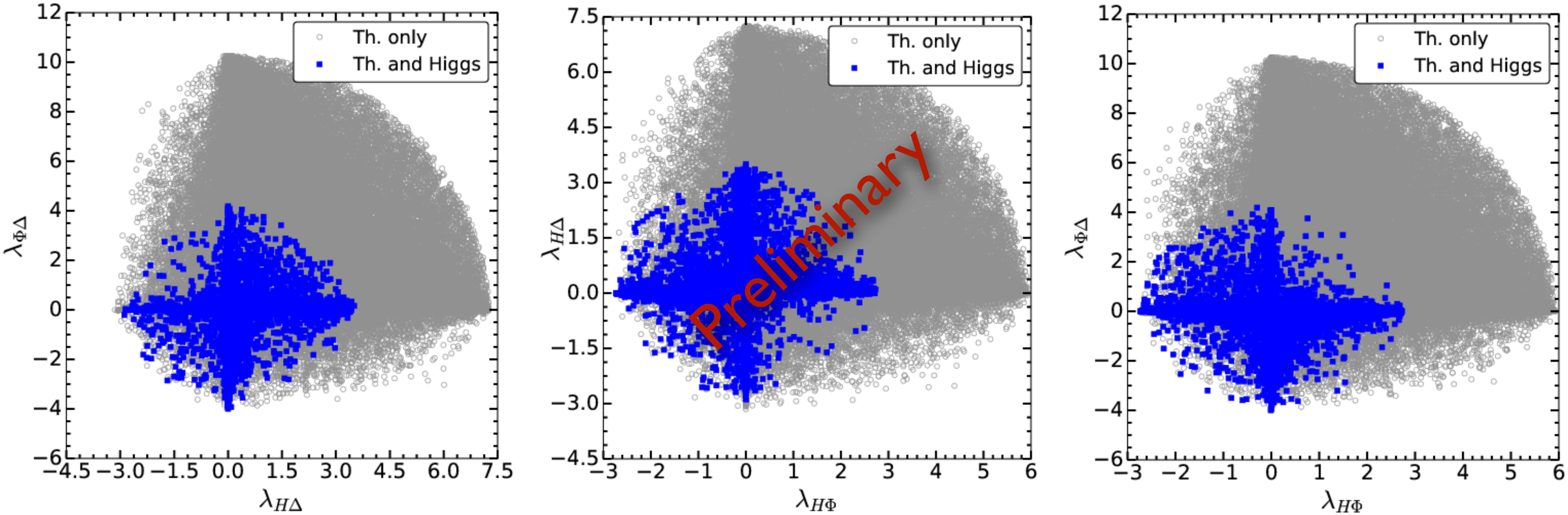


Arhrib, Tsai, Yuan, TCY, JCAP 06, (2014), 030

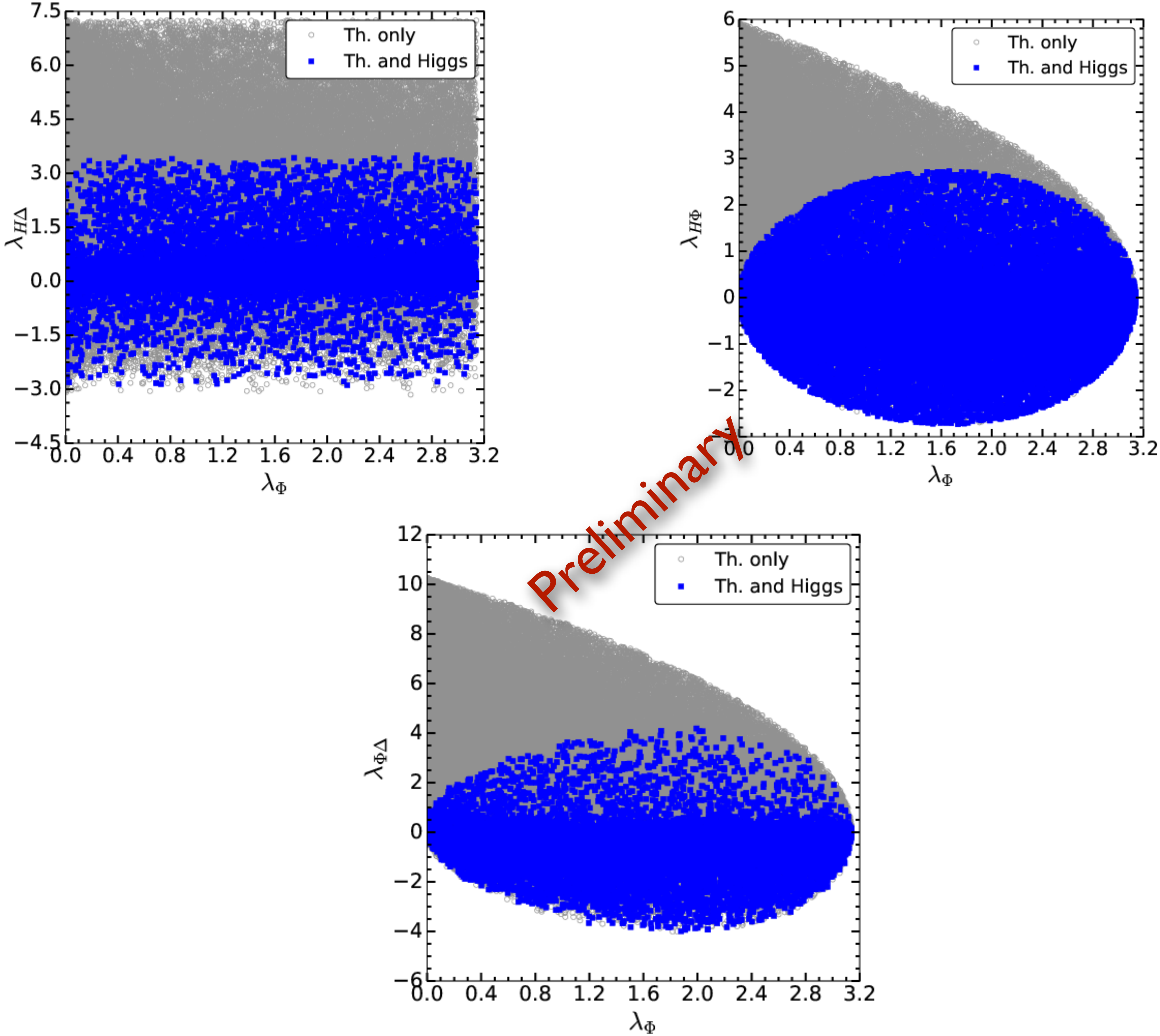

Th. only
Th. and Higgs
SM
$\lambda_{H\Delta}$
λ_H
$\lambda_{H\Phi}$
$\lambda_{\Phi\Delta}$
λ_Δ
Preliminary



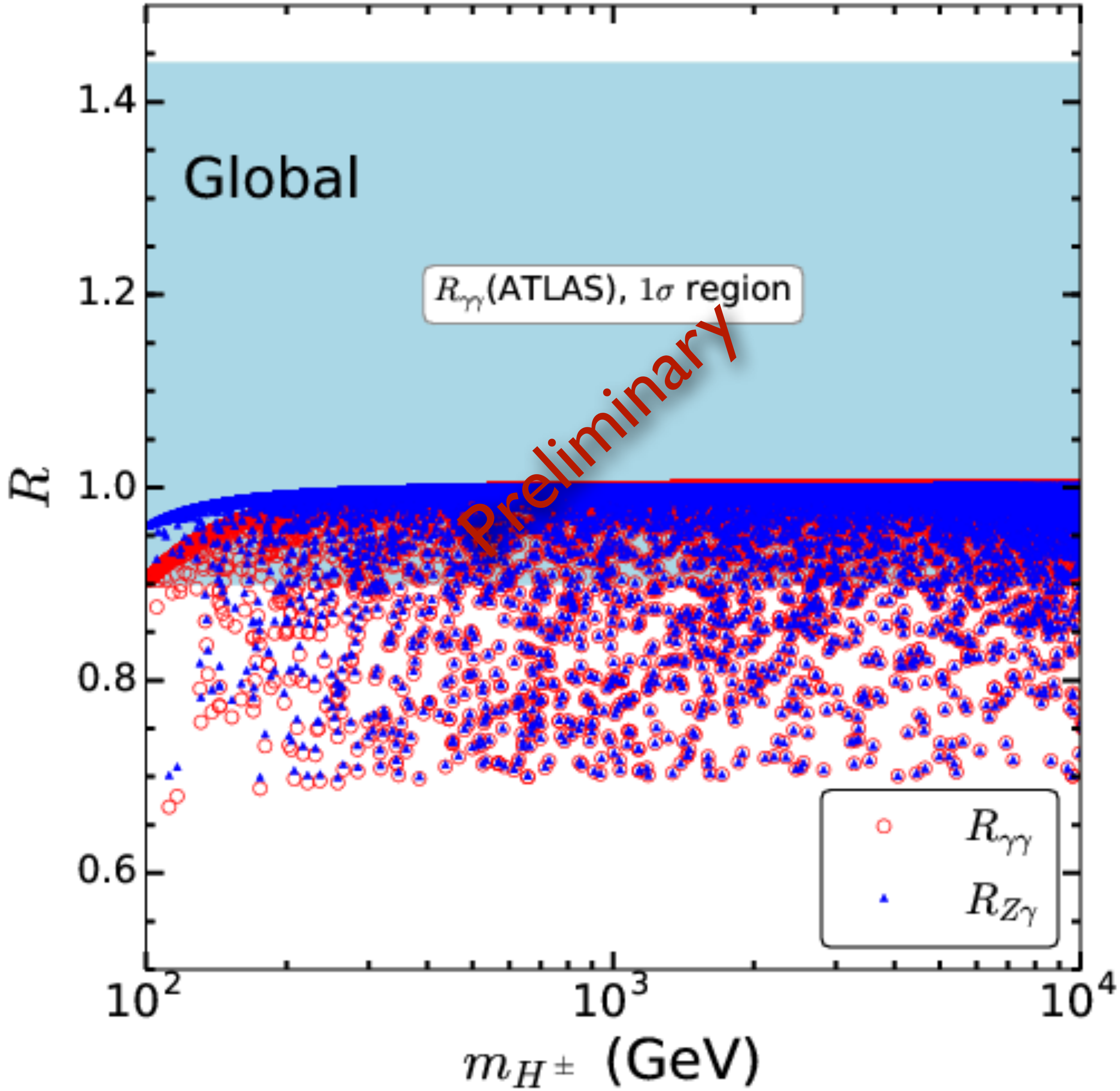
Th. only
Th. and Higgs
$\lambda_{H\Delta}$
λ_{Δ}
$\lambda_{H\Phi}$
$\lambda_{\Phi\Delta}$
Preliminary



Th. only
Th. and Higgs
Preliminary
$\lambda_{\Phi\Delta}$
$\lambda_{H\Delta}$
$\lambda_{H\Phi}$


Th. only
Th. and Higgs
$\lambda_{H\Delta}$
λ_Φ
$\lambda_{H\Phi}$
$\lambda_{\Phi\Delta}$
Preliminary

Signal Strengths $R_{\gamma\gamma}$ and $R_{\gamma Z}$ versus Charged Higgs Mass



Conclusions and Outlook

- 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.
- $W^{\{p,m\}}$ gauge bosons are complex fields but electrically neutral.
- Z-Z' mixing is constrained to be small by LEP data, direct Z' search at LHC, etc implies the VEV $v_\Phi \geq 10$ TeV and a heavy Z'. This also implies the mixings between SM Higgs and other heavy scalars are small.
- Signal strengths for $h\gamma\gamma$ and $hZ\gamma$ are consistent with LHC data provided that the charged Higgs is heavier than 100 GeV. They are always <1, in contrast with IHDM which can > or < 1!

Conclusions and Outlook

- EWPT (S, T, U) - new contributions from extra scalars and gauge bosons. (Note: They vanish in the exact $SU(2)_H$ limit!)
- LHC phenomenology of heavy fermions, gauge particles Z', Z'', $W^{\{p,m\}}$ and scalars
- Rare Decays (Loop processes)
  - FCNH decay e.g. $h \to \mu\tau$, etc
  - $\mu \to e\gamma$ (MEG), μ-e conversion (Mu2E, COMET), etc
- DM (relic density, direct/indirect detection, collider)

Thank you for your attention!