# A testable model: Gauged Two Higgs Doublet Model

Yue-Lin Sming Tsai

(NCTS, HsinChu)

The 1st CEPC analysis and physics workshop

This work is in collaboration with

Wei-Chih Huang and Tzu-Chiang Yuan

References: 1512.00229 (JHEP), 1512.07268 (NPB)

# Outline

Motivations

Model configuration

Phenomenology

- Mass spectra of scalar and gauge bosons
- Stability and perturbative constraints
- Dark Matter and charged Higgs at CEPC/ILC

Conclusions

# Motivation (I): three unknown questions, killing three birds with one stone

1. After the Standard Model (SM) Higgs discovery, does there exist other scalar particles?
   (A discrete Z2 symmetry might be needed to avoid FCNC!)

2. What is dark matter (DM)?
   (A discrete Z2 symmetry might be needed to protect DM stability!)

3. Where does the tiny neutrino mass come from?
   (A discrete Z2 symmetry might be needed to kill tree-level contribution!)

# Motivation (II):
# 2HDM and left-right alignment

1. A wonder of the standard model (SM) is why the left and right representation is not symmetric?

2. 2HDM is a good model because its simple extension of SM scalar sector, yet with rich phenomenology, freely to adopt various Yukawa types: Type 1,2,X,Y, and Inert Higgs. An unexplained Z2 discrete symmetry is needed to do so.

3. A new continuous gauge symmetry SU(2)H to align 2HDM as new doublet is used to replace the artificial discrete Z2 symmetry. (Now left and right representation is a complete symmetric, horizontal symmetry.)

# Model configuration

# Alignment and the replacement of Z2 symmetry

| 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 |
| $\chi_u$ | 3 | 1 | 1 | 2/3 | 0 |
| $\chi_d$ | 3 | 1 | 1 | −1/3 | 0 |
| $\chi_\nu$ | 1 | 1 | 1 | 0 | 0 |
| $\chi_e$ | 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 in G2HDM.

- Extra gauge groups: SU(2)H * U(1)X
- SU(2)L symmetry breaking can be induced by SU(2)H symmetry breaking.
- One of Higgs doublets H_2 can be inert and its stability are protected by the SU(2)H gauge symmetry and Lorentz invariance.
- Unlike Left-Right (LR) symmetric models, the complex gauge fields are electrically neutral.
- Neutrinos would be Dirac fermions unless additional lepton number violation terms are involved. Dirac neutrino is minimum setting.

# Particle contents

| 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 | $-1$ | $-1$ |
| $\chi_u$ | 3 | 1 | 1 | 2/3 | 0 |
| $\chi_d$ | 3 | 1 | 1 | $-1/3$ | 0 |
| $\chi_\nu$ | 1 | 1 | 1 | 0 | 0 |
| $\chi_e$ | 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 |

- $H_1$ 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 $\Phi_H$ and $\Delta_H$ give a mass to $SU(2)_H$ gauge bosons
- VEV of $\Phi_H$ gives a Dirac mass to heavy fermions

**Anomaly cancelation**: We have to introduce x_u , x_d, and x_e to cancel those of right-handed ones from uH_R, dH_R, and eH_R respectively.
X_nu is for keeping neutrino mass term.

# Particle contents

| 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 |
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| $D_R = (d_R^H \;\; d_R)^T$ | 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 | $-1$ | $-1$ |
| $\chi_u$ | 3 | 1 | 1 | 2/3 | 0 |
| $\chi_d$ | 3 | 1 | 1 | $-1/3$ | 0 |
| $\chi_\nu$ | 1 | 1 | 1 | 0 | 0 |
| $\chi_e$ | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| $H = (H_1 \;\; H_2)^T$ | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| $\Delta_H = \begin{pmatrix} \Delta_3/2 & \Delta_p/\sqrt{2} \\ \Delta_m/\sqrt{2} & -\Delta_3/2 \end{pmatrix}$ | 1 | 1 | 3 | 0 | 0 |
| $\Phi_H = (\Phi_1 \;\; \Phi_2)^T$ | 1 | 1 | 2 | 0 | 1 |

DM candidates

- $H_1$ 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 $\Phi_H$ and $\Delta_H$ give a mass to $SU(2)_H$ gauge bosons
- VEV of $\Phi_H$ gives a Dirac mass to heavy fermions

Triplet Higgs induced to keep the splitting of H1 and H2.

# Comparison with LR symmetric models

$$U_L \begin{pmatrix} h_1^0 & h_2^+ \\ h_1^- & h_2^0 \end{pmatrix} U_R^\dagger$$

$$U_R \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

LR Symmetry

$W_R^\pm$ and $Z_R$

$$U_L \begin{pmatrix} h_1^0 & h_2^0 \\ h_1^- & h_2^- \end{pmatrix} U_R^\dagger \qquad U_R \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

$$U_R \begin{pmatrix} u_R \\ u_R^H \end{pmatrix} \qquad U_R \begin{pmatrix} d_R^H \\ d_R \end{pmatrix}$$

SU(2)H Symmetry

$W'^{\{p,m\}}$ and $Z'$

**Unlike Left-Right (LR) symmetric models, the complex gauge fields are electrically neutral.**

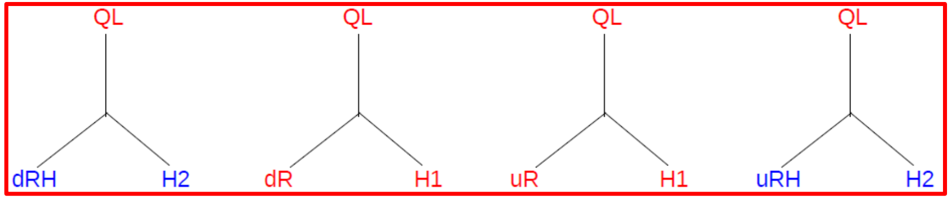
# The Yukawas

$$\mathcal{L}_{\rm Yuk} \supset y_d \bar{Q}_L \left(D_R \cdot H\right) + y_u \bar{Q}_L \left(U_R \cdot \tilde{\tilde{H}}\right) + {\rm H.c.},$$

$$= y_d \bar{Q}_L \left(d_R^H H_2 - d_R H_1\right) - y_u \bar{Q}_L \left(u_R \tilde{H}_1 + u_R^H \tilde{H}_2\right) + {\rm H.c.},$$

$$U_R^T = (u_R \;\; u_R^H)_{2/3}$$
$$D_R^T = (d_R^H \;\; d_R)_{-1/3}$$

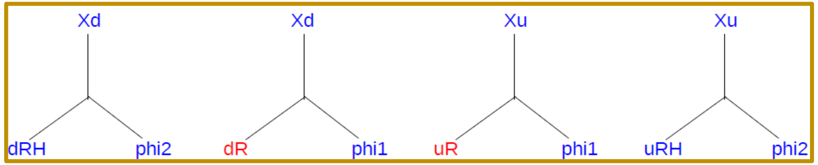
where $\tilde{\tilde{H}} \equiv (\tilde{H}_2 \;\; -\tilde{H}_1)^T$ with $\tilde{H}_{1,2} = i\tau_2 H_{1,2}^*$. After the EW symmetry breaking $\langle H_1 \rangle \neq 0$




After the EW symmetry breaking the vev of H1 is not zero, u and d obtain their masses but uHR and dHR remain massless since H2 does not get a vev.

$$\mathcal{L}_{\rm Yuk} \supset -y_d' \overline{\chi}_d \left(D_R \cdot \Phi_H\right) + y_u' \overline{\chi}_u \left(U_R \cdot \tilde{\Phi}_H\right) + {\rm H.c.},$$

$$= -y_d' \overline{\chi}_d \left(d_R^H \Phi_2 - d_R \Phi_1\right) - y_u' \overline{\chi}_u \left(u_R \Phi_1^* + u_R^H \Phi_2^*\right) + {\rm H.c.},$$




- Yukawas couplings for leptons

$$\mathcal{L}_{\rm Yuk} \supset y_e \bar{L}_L \left(E_R \cdot H\right) + y_\nu \bar{L}_L \left(N_R \cdot \tilde{H}\right) - y_e' \overline{\chi}_e \left(E_R \cdot \Phi_H\right) + y_\nu' \overline{\chi}_\nu \left(N_R \cdot \tilde{\Phi}_H\right) + {\rm H.c.},$$

$$= y_e \bar{L}_L \left(e_R^H H_2 - e_R H_1\right) - y_\nu \bar{L}_L \left(\nu_R \tilde{H}_1 + \nu_R^H \tilde{H}_2\right)$$

$$- y_e' \overline{\chi}_e \left(e_R^H \Phi_2 - e_R \Phi_1\right) - y_\nu' \overline{\chi}_\nu \left(\nu_R \Phi_1^* + \nu_R^H \Phi_2^*\right) + {\rm H.c.},$$

$$\Phi_H = (\Phi_1 \;\; \Phi_2)^T$$

# Scalar Potential

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

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

Simple

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

Things get ugly quickly!

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

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

U(1)X is optional but useful.

# Scalar Potential

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

And more uglier!

Coefficients of the quadratic terms of $H_1$ and $H_2$:

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

$H_1$ can develop a VEV while $H_2$ not, provided that the second term is large enough! $H_2$ can be inert!

U(1)x symmetry helps to simplify the potential, e.g. term like $\Phi_H^T\Delta_H\Phi_H$ would be allowed by just $SU(2)_H$.

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

# Phenomenology

# Symmetry Breaking

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

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

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

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

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

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

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

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

# Scalar Mass Spectrum

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

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

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

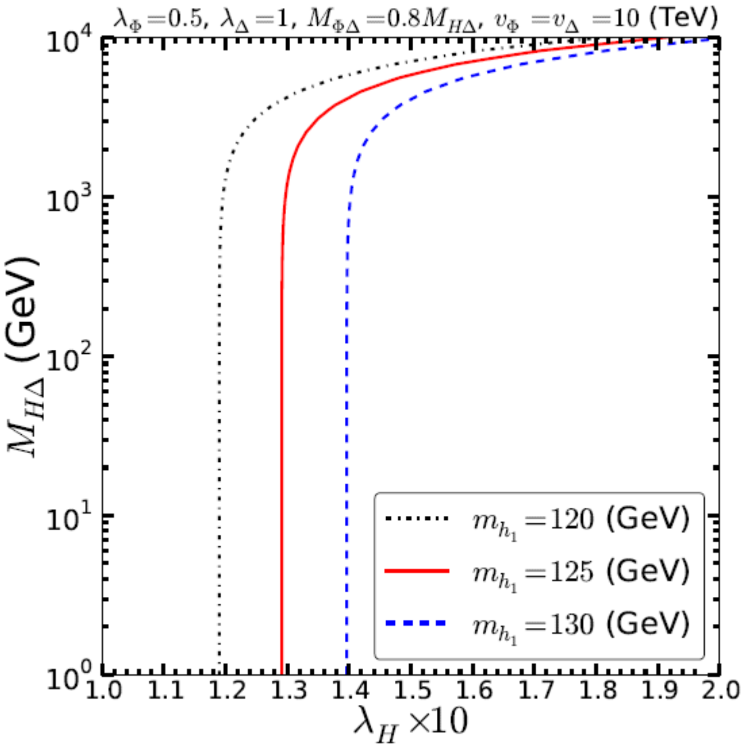
$$\mathcal{M}_0'^2 = \begin{pmatrix} M_{\Phi\Delta} v_\Delta & -\frac{1}{2} M_{\Phi\Delta} v_\Phi & 0 \\ -\frac{1}{2} M_{\Phi\Delta} v_\Phi & \frac{1}{4v_\Delta}\left(M_{H\Delta} v^2 + M_{\Phi\Delta} v_\Phi^2\right) & \frac{1}{2} M_{H\Delta} v \\ 0 & \frac{1}{2} M_{H\Delta} v & M_{H\Delta} v_\Delta \end{pmatrix}$$

Has one zero eigenvalue and the other two nontrivial eigenvalues are

$$M_{\tilde{\Delta},D}^2 = \frac{1}{8v_\Delta}\Big\{M_{H\Delta} v^2 + 4\left(M_{H\Delta} + M_{\Phi\Delta}\right) v_\Delta^2 + M_{\Phi\Delta} v_\Phi^2$$
$$\pm \left[\left(M_{H\Delta}\left(v^2 + 4v_\Delta^2\right) + M_{\Phi\Delta}\left(v_\Phi^2 + 4v_\Delta^2\right)\right)^2 - 16 M_{H\Delta} M_{\Phi\Delta} v_\Delta^2 \left(v^2 + 4v_\Delta^2 + v_\Phi^2\right)\right]^{\frac{1}{2}}\Big\}$$

$D$ is dark matter candidate. Other possibilities are $\nu^H, \chi_\nu, W'$.

$$m_{G^\pm}^2 = m_{G^0}^2 = m_{G_H^0}^2 = 0\,, \qquad m_{H_2^\pm}^2 = M_{H\Delta} v_\Delta$$




One can find a very non-SM like Higgs in the parameter space.

# Stability and perturbative constraints

- Vacuum Stability

– Scalar potential should be bounded from below

- Perturbative Unitarity

– Scattering amplitudes in the scalar sector

Stability and perturbative constraints make the lambda(s) with confined ranges.

- $\lambda_H$, $\lambda_\Phi$, $\lambda_\Delta$ 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) $\lambda_{H\Phi} > 0;\ \lambda_{\Phi\Delta}\,,\ \lambda_{H\Delta}\ < 0$

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

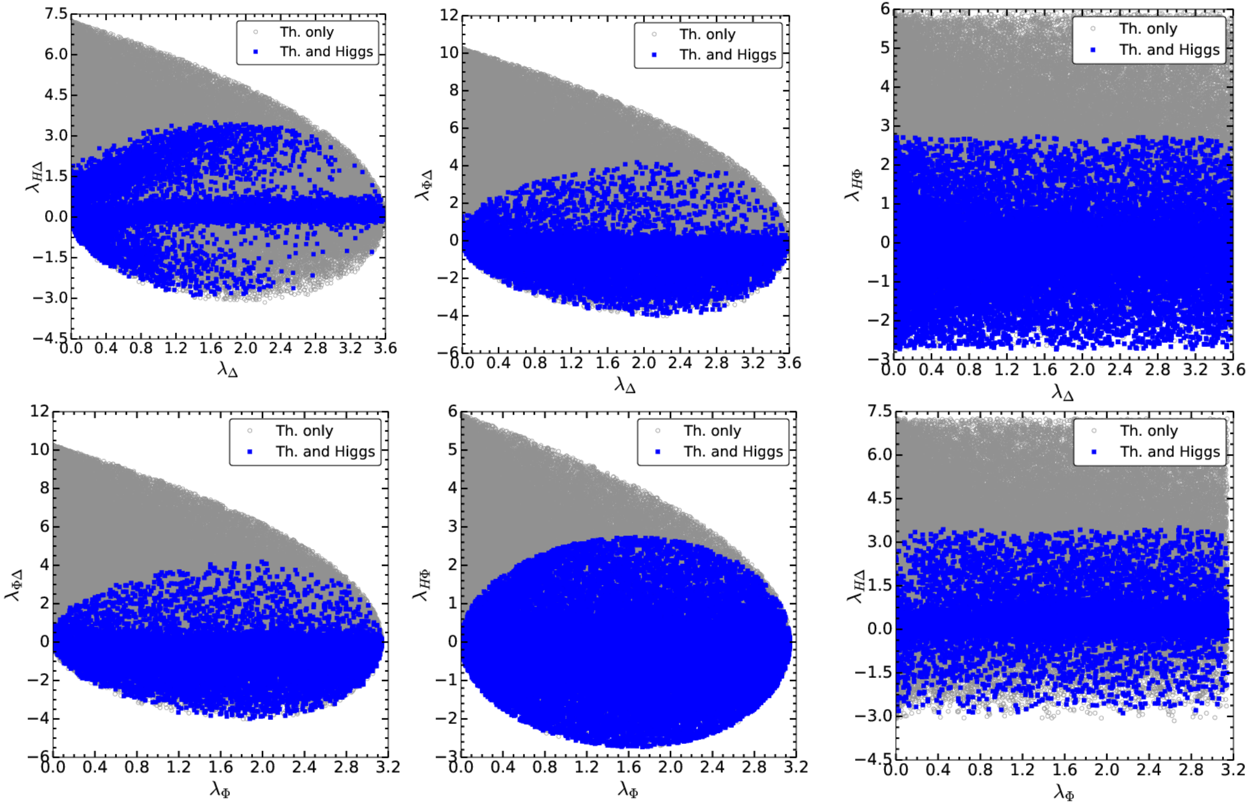
Similar conditions for two other permutation cases.

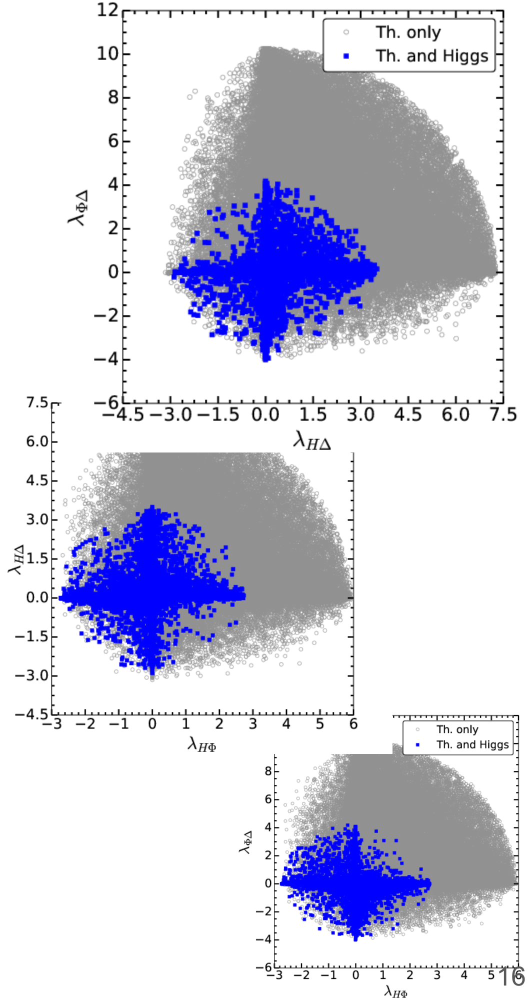
(4) $\lambda_{H\Phi}\,,\ \lambda_{\Phi\Delta}\,,\ \lambda_{H\Delta} < 0$

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

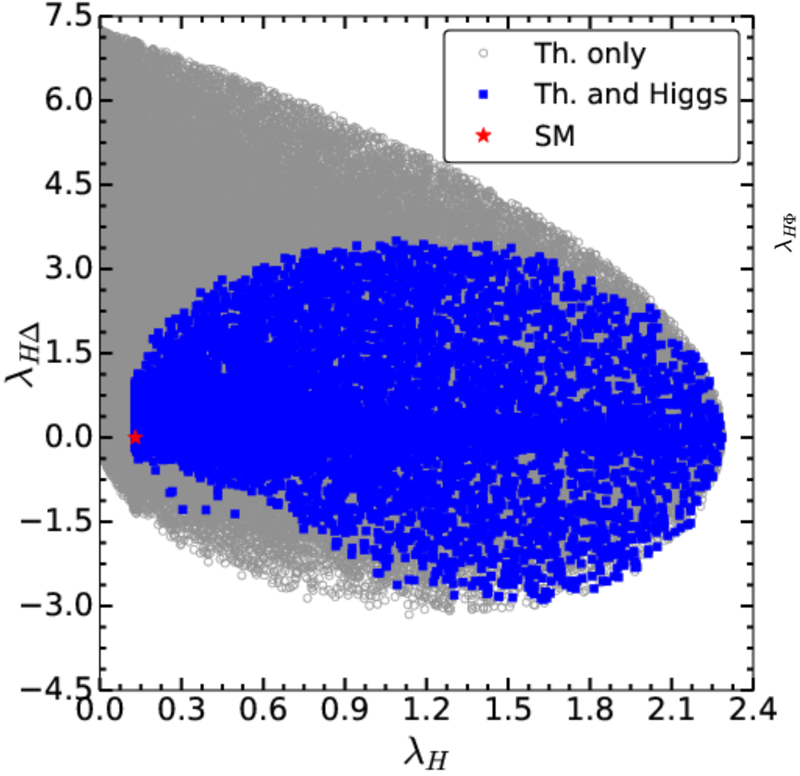
- All eigenvalues $\lambda_i$ of $\mathcal{M}_1$ in (66) must be constrained by $|\lambda_i| < 8\pi$.

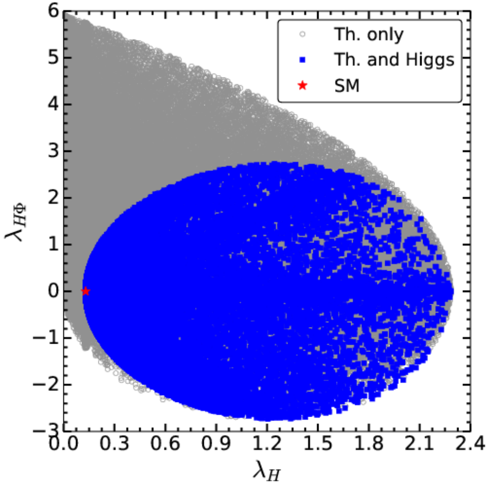
# Stability and perturbative constraints

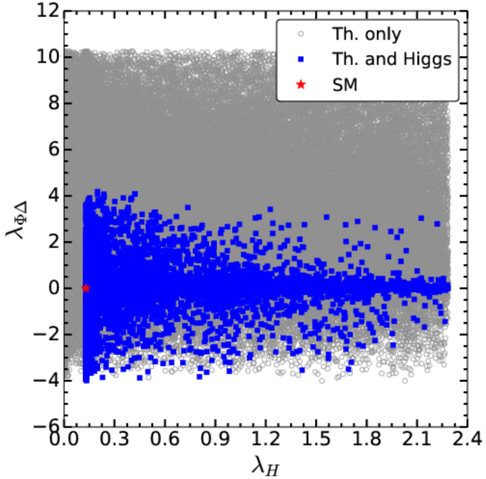


# Stability and perturbative constraints




0<laH<2.285
0<laPhi<pi
0<laD<3.6

-2.65<laHP<5.95
-3.55<laPD<10.3
-3.0<laHD<7.26

Theory constraints favor the small lambdas but further reduced by Higgs data.

# Current Mass Limits (pre CEPC/ILC)

| 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 | $-1$ | $-1$ |
| $\chi_u$ | 3 | 1 | 1 | 2/3 | 0 |
| $\chi_d$ | 3 | 1 | 1 | $-1/3$ | 0 |
| $\chi_\nu$ | 1 | 1 | 1 | 0 | 0 |
| $\chi_e$ | 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 |

| Triplet Higgs | W' and Z' | New charged fermions | New neutral fermions | Phi_2 |
|---|---|---|---|---|
| ~10 TeV | ~ TeV | > 100 GeV LEP limits | ~DM | ~TeV |

| Charged Higgs | Inert Higgs |
|---|---|
| > 100 GeV ~inert Higgs | ~DM |

This is large gH scenario.
For very small gH scenario,
triplet Higgs mass can be ~100 GeV scale,
story is totally different!

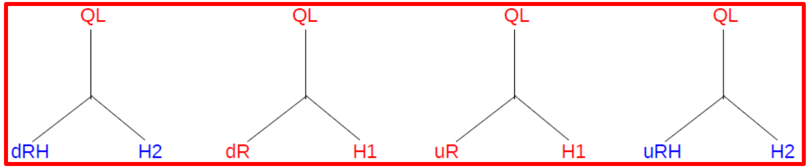
The precise mass limit depends on

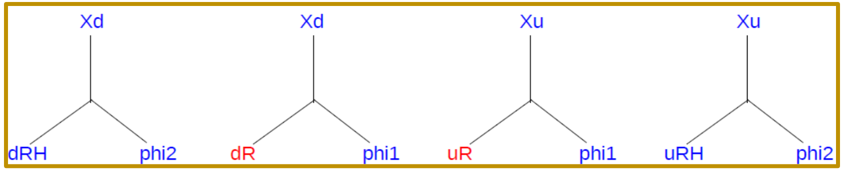
A. Dark Matter candidates

B. mass splitting between charged and neutral particles

# Dark Matter and charged Higgs @ CEPC/ILC

| Production | decay | Final state |
|---|---|---|
| Charged Higgs<br>e+e- > Z > H+ H- | H+ > W+ H2 | l+, neutrino, missing energy |
| e+e- > Z' > e+e- | None | e+e- |
| Vector boson Fusion<br>SM Higgs | h> two photons,<br>FCNC decay $h \to \mu\ \tau$ | (two photons, muon tau)<br>+ (missing energy or two electrons) |
| Mono X<br>e+e- > X H2 H2 | None | X(=photon, W, Z), missing energy |
| Heavy charged fermion production | many, see below | jets, leptons, missing energy |



# Inert Higgs Dark Matter

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

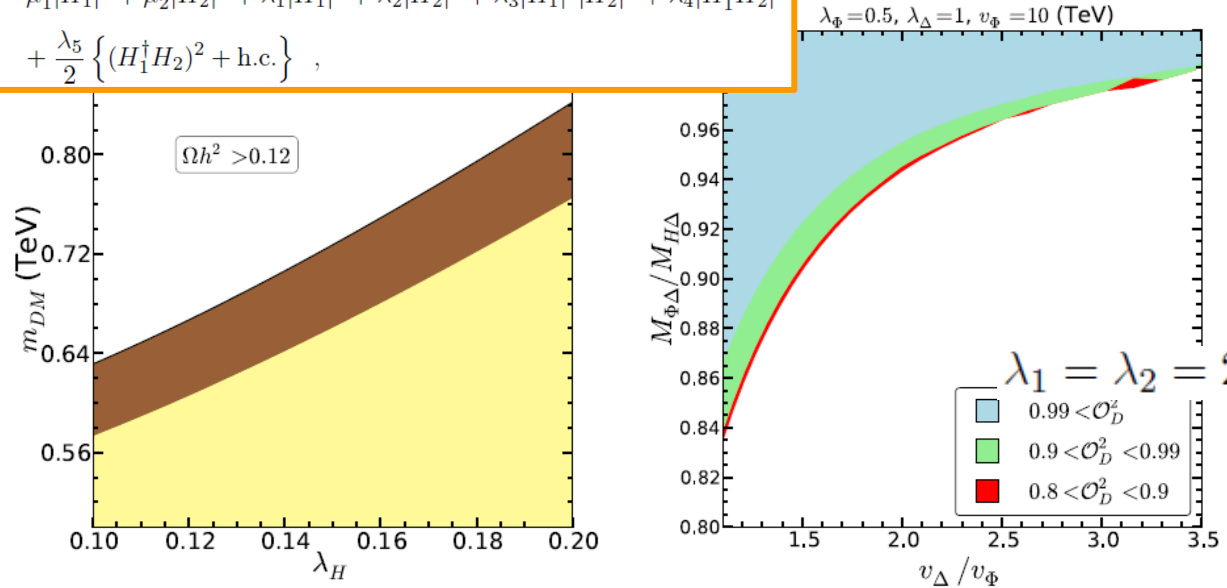



**Figure 5.** Left: the contour of relic density on $(\lambda_H,\ m_{DM})$ plane. The upper brown region is with the relic density between 0.1 and 0.12 but the lower yellow region is the relic density less than 0.1. Right: accepted DM mass region projected on $(v_\Delta/v_\Phi,\ M_{\Phi\Delta}/M_{H\Delta})$ plane. The red, green and light blue regions present the DM inert Higgs fraction $0.8 < \mathcal{O}_D^2 < 0.9$, $0.9 < \mathcal{O}_D^2 < 0.99$ and $0.99 < \mathcal{O}_D^2$, respectively. See the text for detail of the analysis.

- Focus on the case of H2^0 DM.
- The limit of inert Higgs doublet model:

$$\lambda_1 = \lambda_2 = 2\lambda_3 = \lambda_H \text{ with } \lambda_4 = \lambda_5 = 0$$

- H2-Hc coannilation is always the main channel in the early universe.

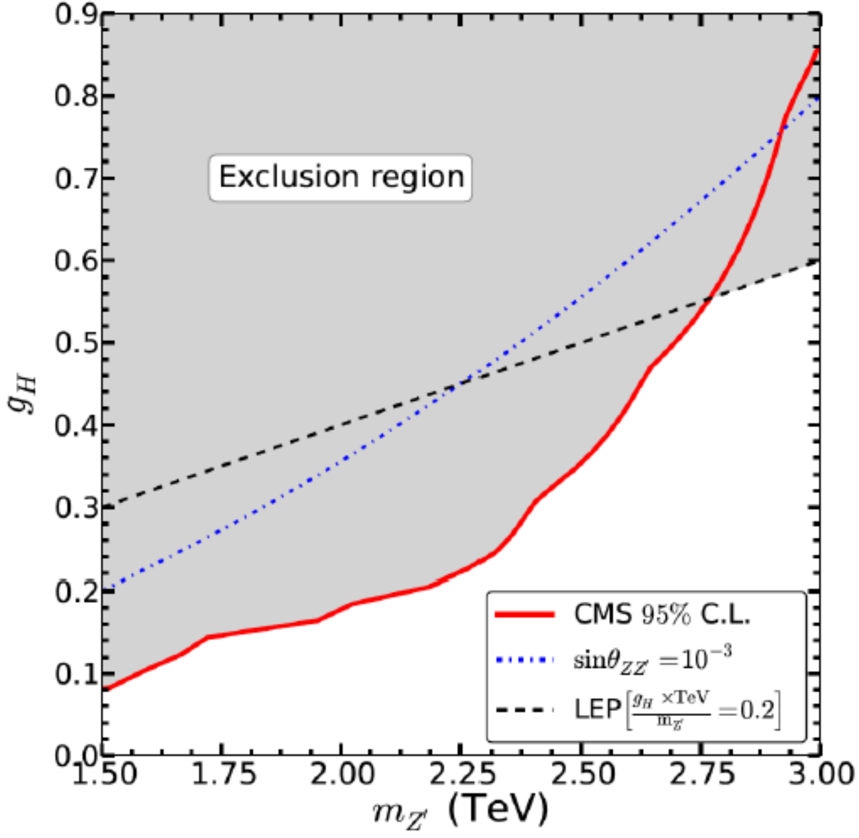
# Summary and outlook

- A novel horizontal symmetry to embed two Higgs doublets, H1 and H2 into a doublet under a non-abelian gauge symmetry SU(2)H and the SU(2)H doublet is charged under an additional abelian group U(1)X.

- To ensure the model is anomaly-free and SM Yukawa couplings preserve the additional SU(2)H×U(1)X symmetry, we choose to place the SM right-handed fermions and new heavy right-handed fermions into SU(2)H doublets while SM SU(2)L fermion doublets are singlets under SU(2)H .

- Additional gauge bosons are all electrically neutral unlike Left-Right symmetric models.
- Model satisfies unitarity, perturbative, and stability constraints.
- Many of interesting and rich phenomenology.
- CEPC Signatures of the Heavy Higgs boson and Fermions.

# 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)

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