Emergent two-Higgs doublet models

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Two-Higgs doublet model

Simple extension from the SM
  • SM + doublet scalar

Rich phenomenology
  • B physics
  • muon g-2
  • effect to $h(125)$ couplings
  • ...

Many free parameters
  • assumptions are made to reduce the number of free parameters

Three popular assumptions:
  (1) softly broken $Z_2$ symmetry
  (2) CP invariance in Higgs potential
  (3) custodial symmetry in Higgs potential
(1) softly broken $Z_2$ symmetry

(ex) Yukawa terms in the down quark sector

$$ + y_{1d}^{ij} \bar{q}^i_L \Phi_1 d_R^j + y_{2d}^{ij} \bar{q}^i_L \Phi_2 d_R^j $$

+ (up sector) + (lepton sector) + (h.c.)

- two Yukawa matrices in each sector ($y_{1d}$, $y_{2d}$)
- $18$ free parameters are added to each sector (compared to the SM)
- flavor changing Higgs coupling exist (e.g. h-d-s)

$Z_2$ symmetry makes $y_{1d} = 0$ or $y_{2d} = 0$ [Glashow, Weinberg ('77)]

example:

if $\Phi_1 \rightarrow +\Phi_1$, $\Phi_2 \rightarrow -\Phi_2$, $q_L \rightarrow +q_L$, $d_R \rightarrow -d_R$

then $y_{1d} = 0$

$$ + y_{1d}^{ij} \bar{q}^i_L \Phi_1 d_R^j + y_{2d}^{ij} \bar{q}^i_L \Phi_2 d_R^j $$
(2) CP invariance in Higgs potential

\[ m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - \left( m_3^2 \Phi_1^\dagger \Phi_2 + (h.c.) \right) \]

\[ + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 \cdot + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \]

\[ + \left( \frac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + (h.c.) \right) \]

complex parameters: \( m_3, \lambda_5, \lambda_6, \lambda_7 \)

absent in \( Z_2 \) symmetric model: \( \lambda_6, \lambda_7 \)

\( (m_3 \) breaks \( Z_2 \) symmetry softly) 

**CP is violated** in general

**However**, in many cases, **CP invariance is assumed for simplicity**
(3) Custodial symmetry

strong constraint from $\rho$ parameter
- BSM sector should respect SU(2)$_C$ custodial symmetry

If custodial SU(2)$_C$ symmetry is exact in 2HDM, then CP-odd and charged Higgs forms triplet, $(A^0, H^+, H^-)$.

SU(2)$_C$ is violated by **the mass difference**

$$m_A^2 - m_{H^\pm}^2 = \frac{\lambda_4 - \lambda_5}{2} v^2$$  
(CP symmetry in the Higgs potential is assumed)

$\lambda_4 = \lambda_5$ are assumed to enhance SU(2)$_C$
Origin of the three assumptions?

Three assumptions:

1. softly broken $Z_2$ symmetry
2. CP invariance in Higgs potential
3. custodial symmetry in Higgs potential

They are reasonable assumptions, but are there origin of them?

Our work

- extend electroweak symmetry: $SU(2)\times U(1) \rightarrow SU(2)\times SU(2)\times U(1)$
- 2HDM is a low energy effective description
- the three assumptions are emerged from gauge symmetry
Model
Review: SM Higgs with matrix rep.

\[ H = 1_{2 \times 2} \sigma + i T^a \pi^a = \begin{pmatrix} \sigma + i \pi^3 & i \sqrt{2} \pi^+ \\ i \sqrt{2} \pi^- & \sigma - i \pi^3 \end{pmatrix} \]

Higgs potential

\[ V(H) = \mu^2 \text{tr}(H^\dagger H) + \lambda \text{tr}(H^\dagger H)^2 \]

(moose notation)

\[ \text{SU}(2)_L \xrightarrow{H} \text{U}(1)_Y \]

gauge sym.

\[ H \rightarrow [\text{SU}(2)_L] H [\text{U}(1)_Y] \]

\[ [\text{SU}(2)_L] = e^{i T^a a_L} \]

\[ [\text{U}(1)_Y] = e^{i T^3 a_Y} \]

global sym. in the potential

\[ H \rightarrow [\text{SU}(2)_L] H [\text{SU}(2)_R] \]

\[ [\text{SU}(2)_L] = e^{i T^a a_L} \]

\[ [\text{SU}(2)_R] = e^{i T^a a_R} \]

custodial sym. (\( \theta_L = \theta_R \equiv \theta_V \))

\[ H \rightarrow [\text{SU}(2)_V] H [\text{SU}(2)_V]^\dagger \]
Model

SU(2)_0 x SU(2)_1 x U(1)_2 → U(1)_{QED}

|     | SU(2) | SU(2) | U(1) |
|-----|-------|-------|------|
| q_L | 2     | 1     | 1/6  |
| u_R | 1     | 1     | 2/3  |
| d_R | 1     | 1     | -1/3 |
| ℓ_L | 2     | 1     | -1/2 |
| e_R | 1     | 1     | -1   |
| H_3 | 2     | 1     | 1/2  |
| H_1 | 2     | 2     | 0    |
| H_2 | 1     | 2     | 1/2  |

gauge sym.

H_1 → [SU(2)_0] H_1 [SU(2)_1]^\dagger
H_2 → [SU(2)_1] H_2 [U(1)_2]^\dagger
H_3 → [SU(2)_0] H_2 [U(1)_2]^\dagger

H_j = σ_j 1_{2×2} + iπ^a_j π^a_j = \begin{pmatrix} σ_j + iπ^3_j & iπ^+_j \\ iπ^-_j & σ_j - iπ^3_j \end{pmatrix}

(σ_j and π^a_j are real, not complex.)
intuitive way to understand why 2HDM

SM

\[ \text{SU}(2) \xrightarrow{H} \text{U}(1) \]

\[ \text{U}(1)_{\text{QED}} \]

our setup

\[ \begin{array}{c}
\text{SU}(2)_0 \xrightarrow{H_3} \text{U}(1)_2 \\
\text{SU}(2)_1 \xrightarrow{H_2} \\
\text{SU}(2) \xrightarrow{v_1} v_2, v_3
\end{array} \]

2HDM

\[ \text{SU}(2) \xrightarrow{H} \text{U}(1) \]
Higgs potential

\[ V(H_1, H_2, H_3) = \mu_1^2 \text{tr}(H_1^\dagger H_1) + \mu_2^2 \text{tr}(H_2^\dagger H_2) + \mu_3^2 \text{tr}(H_3^\dagger H_3) \\ + \kappa \text{tr}(H_3^\dagger H_1 H_2) \\ + \tilde{\lambda}_1 \left( \text{tr}(H_1^\dagger H_1) \right)^2 + \tilde{\lambda}_2 \left( \text{tr}(H_2^\dagger H_2) \right)^2 + \tilde{\lambda}_3 \left( \text{tr}(H_3^\dagger H_3) \right)^2 \\ + \tilde{\lambda}_{12} \text{tr}(H_1^\dagger H_1) \text{tr}(H_2^\dagger H_2) + \tilde{\lambda}_{23} \text{tr}(H_2^\dagger H_2) \text{tr}(H_3^\dagger H_3) + \tilde{\lambda}_{31} \text{tr}(H_3^\dagger H_3) \text{tr}(H_1^\dagger H_1) \]

**building block**
- \( \text{tr}(H_1^\dagger H_1) \)
- \( \text{tr}(H_2^\dagger H_2) \)
- \( \text{tr}(H_3^\dagger H_3) \)
- \( \text{tr}(H_3^\dagger H_1 H_2) \)

**note**
- \( \text{tr}(H_3^\dagger H_1 H_2) \) is real
- \( \kappa \) is real

(1) the potential has **custodial symmetry**
- \( H_1 \rightarrow [\text{SU}(2)_0] H_1 [\text{SU}(2)_1^\dagger] \)
- \( H_2 \rightarrow [\text{SU}(2)_1] H_2 [\text{SU}(2)_2^\dagger] \)
- \( H_3 \rightarrow [\text{SU}(2)_0] H_2 [\text{SU}(2)_2^\dagger] \)

(2) **no CP violation** in the potential

(3) **softly broken \( Z_2 \) symmetry** in the potential
- symmetric (\( H_i \rightarrow - H_i \))
- broken only by \( \text{tr}(H_3^\dagger H_1 H_2) \)
Summary
Summary

- **Three popular assumptions in 2HDM**
  - softly broken $Z_2$ symmetry
  - CP invariance in Higgs potential
  - custodial symmetry in Higgs potential

- **Extension of the electroweak gauge symmetry**
  - three assumptions are emerged from gauge symmetry
Backup
Yukawa in 2HDM

4 types of models under the $Z_2$ symmetry

- **type-I:** $q_L H_2 u_R + q_L H_2 d_R + l_L H_2 e_R$
- **type-II:** $q_L H_2 u_R + q_L H_1 d_R + l_L H_1 e_R$
- **type-X (lepton-specific):** $q_L H_2 u_R + q_L H_2 d_R + l_L H_1 e_R$
- **type-Y (flipped):** $q_L H_2 u_R + q_L H_1 d_R + l_L H_2 e_R$

**If not $Z_2$ symmetry** (type-III)

$q_L H_2 u_R + q_L H_2 d_R + l_L H_2 e_R$

$+ q_L H_1 u_R + q_L H_1 d_R + l_L H_1 e_R$
Yukawa interaction

|   | SU(2) | SU(2) | U(1) |
|---|-------|-------|------|
| $q_L$ | 2     | 1     | 1/6  |
| $u_R$ | 1     | 1     | 2/3  |
| $d_R$ | 1     | 1     | -1/3 |
| $\ell_L$ | 2   | 1     | -1/2 |
| $e_R$ | 1     | 1     | -1   |
| $H_3$ | 2     | 1     | 1/2  |
| $H_1$ | 2     | 2     | 0    |
| $H_2$ | 1     | 2     | 1/2  |

Yukawa interaction

$\bar{q}_L H_3 \begin{pmatrix} y_u & 0 \\ 0 & y_d \end{pmatrix} \begin{pmatrix} u_R \\ d_R \end{pmatrix} + \bar{\ell}_L H_3 \begin{pmatrix} 0 & 0 \\ 0 & y_d \end{pmatrix} \begin{pmatrix} 0 \\ e_R \end{pmatrix} + (h.c.)$

- This emerges type-I 2HDM.
- Need another Yukawa in. for other types of 2HDM
Yukawa interaction

| SU(2) | SU(2) | U(1) |
|-------|-------|------|
| $q_L$ | 2     | 1    | 1/6  |
| $u_R$ | 1     | 1    | 2/3  |
| $d_R$ | 1     | 1    | -1/3 |
| $\ell_L$ | 2 | 1   | -1/2 |
| $e_R$ | 1     | 1    | -1   |
| $H_3$ | 2     | 1    | 1/2  |
| $H_1$ | 2     | 2    | 0    |
| $H_2$ | 1     | 2    | 1/2  |

Yukawa interaction

$$
\bar{q}_L H_3 \begin{pmatrix} y_u & 0 \\ 0 & y_d \end{pmatrix} \begin{pmatrix} u_R \\ d_R \end{pmatrix} + \bar{\ell}_L H_3 \begin{pmatrix} 0 & 0 \\ 0 & y_d \end{pmatrix} \begin{pmatrix} 0 \\ e_R \end{pmatrix} + (h.c.)
$$

- This emerges type-I 2HDM.
- Need another Yukawa in. for other types of 2HDM

additional Yukawa

$$
\frac{1}{\Lambda} \bar{q}_L H_1 H_2 \begin{pmatrix} y_u' & 0 \\ 0 & y_d' \end{pmatrix} \begin{pmatrix} u_R \\ d_R \end{pmatrix} + \frac{1}{\Lambda} \bar{\ell}_L H_1 H_2 \begin{pmatrix} 0 & 0 \\ 0 & y_e' \end{pmatrix} \begin{pmatrix} 0 \\ e_R \end{pmatrix} + (h.c.)
$$

How to get these dim.5 op?
- introduce vector-like fermions
- see-saw
- details are discussed in the paper [TA, Omura ’16]
add vector-like fermions

add vector-like fermions

|      | SU(2) | SU(2) | U(1) |
|------|-------|-------|------|
| $q_L$ | 2     | 1     | 1/6  |
| $u_R$ | 1     | 1     | 2/3  |
| $d_R$ | 1     | 1     | -1/3 |
| $\ell_L$ | 2   | 1     | -1/2 |
| $e_R$ | 1     | 1     | -1   |
| $H_3$ | 2     | 1     | 1/2  |
| $H_1$ | 2     | 2     | 0    |
| $H_2$ | 1     | 2     | 1/2  |
| $Q_L$ | 1     | 2     | 1/6  |
| $Q_R$ | 1     | 2     | 1/6  |
| $L_L$ | 1     | 2     | -1/2 |
| $L_R$ | 1     | 2     | -1/2 |

Yukawa interaction

$$\mathcal{L}_{Yukawa} = -\bar{q}_L H_3 \begin{pmatrix} y_u & 0 \\ 0 & y_d \end{pmatrix} \begin{pmatrix} u_R \\ d_R \end{pmatrix} - \bar{\ell}_L H_3 \begin{pmatrix} 0 & 0 \\ 0 & y_e \end{pmatrix} \begin{pmatrix} 0 \\ e_R \end{pmatrix}$$

$$- \bar{q}_L H_1 Y_{Q1} Q_R - \bar{Q}_R M_Q Q_L - \bar{Q}_L H_2 \begin{pmatrix} y_{2u} & 0 \\ 0 & y_{2d} \end{pmatrix} \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

$$- \bar{\ell}_L H_1 Y_{L1} L_R - \bar{L}_R M_L L_L - \bar{L}_L H_2 \begin{pmatrix} 0 & 0 \\ 0 & y_{2e} \end{pmatrix} \begin{pmatrix} 0 \\ e_R \end{pmatrix}$$

$$+ (h.c.)$$

additional Yukawa

seesaw by $M_Q$ and $M_L$ are large

$$\mathcal{L}_{Yukawa} \simeq -\bar{q}_L H_3 \begin{pmatrix} y_u & 0 \\ 0 & y_d \end{pmatrix} \begin{pmatrix} u_R \\ d_R \end{pmatrix} - \bar{\ell}_L H_3 \begin{pmatrix} 0 & 0 \\ 0 & y_e \end{pmatrix} \begin{pmatrix} 0 \\ e_R \end{pmatrix}$$

$$- \bar{q}_L H_1 H_2 \begin{pmatrix} y_{2u} & 0 \\ 0 & y_{2d} \end{pmatrix} \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

$$- \bar{\ell}_L H_1 H_2 \begin{pmatrix} 0 & 0 \\ 0 & y_{2e} \end{pmatrix} \begin{pmatrix} 0 \\ e_R \end{pmatrix}$$

$$+ (h.c.)$$

type-III
How to type-II, -X, and -Y 2HDM

example: type-II

- (up-type quark) vs (down-type quarks, leptons)
- $y_d = 0, \ y_e = 0, \ y_{2u} = 0$ are required

$$\mathcal{L}^{Yukawa} \sim -\bar{q}_L H_3 \begin{pmatrix} y_u & 0 \\ 0 & y_d \end{pmatrix} \begin{pmatrix} u_R \\ d_R \end{pmatrix} - \bar{\ell}_L H_3 \begin{pmatrix} 0 & 0 \\ 0 & y_e \end{pmatrix} \begin{pmatrix} 0 \\ e_R \end{pmatrix}$$

$$- \bar{q}_L H_1 H_2 \left( Y_{Q1} M_Q^{-1} \begin{pmatrix} y_{2u} & 0 \\ 0 & y_{2d} \end{pmatrix} \right) \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

$$- \bar{\ell}_L H_1 H_2 \left( Y_{L1} M_L^{-1} \begin{pmatrix} 0 & 0 \\ 0 & y_{2e} \end{pmatrix} \right) \begin{pmatrix} 0 \\ e_R \end{pmatrix}$$

+ (h.c.)

Let us try to assign global $U(1)$ symmetry to forbid unwanted couplings
how to get type-II (cont.)

\[ \mathcal{L}^{Yukawa} = -\bar{q}_L H_3 \begin{pmatrix} y_u & 0 \\ 0 & y_d \end{pmatrix} \begin{pmatrix} u_R \\ d_R \end{pmatrix} - \bar{\ell}_L H_3 \begin{pmatrix} 0 & 0 \\ 0 & y_e \end{pmatrix} \begin{pmatrix} e_R \end{pmatrix} \\
- \bar{q}_L H_1 Y_Q Q_R - \bar{Q}_R SY Q_L - \bar{Q}_L H_2 \begin{pmatrix} y_{2u} & 0 \\ 0 & y_{2d} \end{pmatrix} \begin{pmatrix} u_R \\ d_R \end{pmatrix} \\
- \bar{\ell}_L H_1 Y_L L_R - \bar{L}_R SY L_L - \bar{L}_R H_2 \begin{pmatrix} 0 & 0 \\ 0 & y_{2e} \end{pmatrix} \begin{pmatrix} e_R \end{pmatrix} + (h.c.) \]

|   | q_L | Q_L | \ell_L | L_L | Q_R | L_R | u_R | d_R | e_R | H_1 | H_2 | H_3 | S |
|---|-----|-----|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|---|
| U(1) | 0   | 0   | 0      | 0   | x_u - x_d | x_u - x_d | x_u | x_d | x_d | -x_u + x_d | -x_d | -x_u | x_u - x_d |

\[ \kappa \text{ tr}(H_1 H_2 H_3^\dagger) \]

**global U(1) symmetry can forbid unwanted couplings**

(For other types, see our paper [TA, Omura '16])
Another U(1) charge assignment

what we found

|   | qL | QL | lL | LL | QR | LR | uR | dR | eR | H1 | H2 | H3 | S |
|---|----|----|----|----|----|----|----|----|----|----|----|----|---|
| U(1) | 0  | 0  | 0  | 0  | 0  | xu - xd | xu - xd | Xu | xd | -xu + xd | -xd | -xu | xu - xd |

\[ \kappa \text{tr}(H_1 H_2 H_3^+) \]

Another charge assignment

|   | q | Q | l | L | Q | L | u | d | e | H | H | H | S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| U(1) | 0 | 0 | 0 | 0 | 0 | xu - xd | xu - xd | Xu | xd | -xu + xd | -xd | -xu | xu - xd |

\[ \text{tr}(H_1 H_2 H_3^+) S^* \]