Emergent two-Higgs doublet models

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work in collaboration with
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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

$$+\,\mathbf{y}_{1d}^{ij}\ \bar{q}_L^i\ \Phi_1\ d_R^j + \mathbf{y}_{2d}^{ij}\ \bar{q}_L^i\ \Phi_2\ d_R^j$$
$$+\ (\text{up sector}) + (\text{lepton sector}) + (\text{h.c.})$$

- two Yukawa matrices in each sector ($\mathbf{y}_{1d}$, $\mathbf{y}_{2d}$)
- **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 $\mathbf{y}_{1d}$ = 0 or $\mathbf{y}_{2d}$ = 0 [Glashow, Weinberg ('77)]

example:

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

then $\mathbf{y}_{1d}$ = 0

$$+\mathbf{y}_{1d}^{ij}\ \bar{q}_L^i\ \Phi_1\ d_R^j + \mathbf{y}_{2d}^{ij}\ \bar{q}_L^i\ \Phi_2\ d_R^j$$

（2） CP invariance in Higgs potential

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

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

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

complex parameters : m_3 , λ_5 , λ_6 , λ_7

absent in Z_2 symmetric model : λ_6 , λ_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 ρ 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)xU(1) → SU(2)xSU(2)xU(1)
- 2HDM is a low energy effective description
- the three assumptions are emerged from gauge symmetry

Model

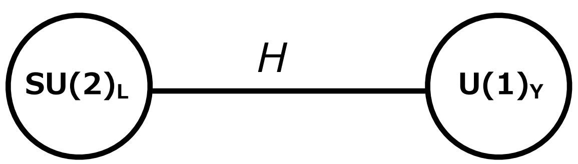
Review: SM Higgs with matrix rep.

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

Higgs potential

$$V(H) = \mu^2 \mathrm{tr}(H^\dagger H) + \lambda \mathrm{tr}(H^\dagger H)^2$$

(moose notation)



gauge sym.

$$H \to [\mathrm{SU}(2)_L] H [\mathrm{U}(1)_Y^\dagger]$$

$$[\mathrm{SU}(2)_L] = e^{iT^a\theta_L^a}$$
$$[\mathrm{U}(1)_Y] = e^{iT^3\theta_Y}$$

global sym. in the potential

$$H \to [\mathrm{SU}(2)_L] H [\mathrm{SU}(2)_R^\dagger]$$

$$[\mathrm{SU}(2)_R] = e^{iT^a\theta_R^a}$$

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

$$H \to [\mathrm{SU}(2)_V] H [\mathrm{SU}(2)_V^\dagger]$$

Model

$SU(2)_0 \times SU(2)_1 \times U(1)_2 \rightarrow U(1)_{QED}$

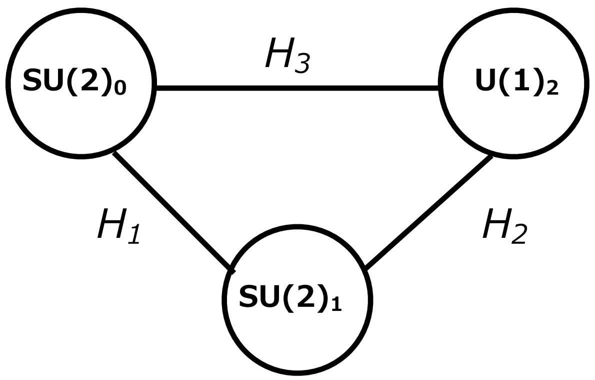
	SU(2)	SU(2)	U(1)
q_L	2	1	1/6
u_R	1	1	2/3
d_R	1	1	-1/3
ℓ_L	2	1	-1/2
e_R	1	1	-1
H_3	2	1	1/2
H_1	2	2	0
H_2	1	2	1/2

gauge sym.

$$H_1 \rightarrow [\mathrm{SU}(2)_0] H_1 [\mathrm{SU}(2)_1^\dagger]$$

$$H_2 \rightarrow [\mathrm{SU}(2)_1] H_2 [\mathrm{U}(1)_2^\dagger]$$

$$H_3 \rightarrow [\mathrm{SU}(2)_0] H_2 [\mathrm{U}(1)_2^\dagger]$$

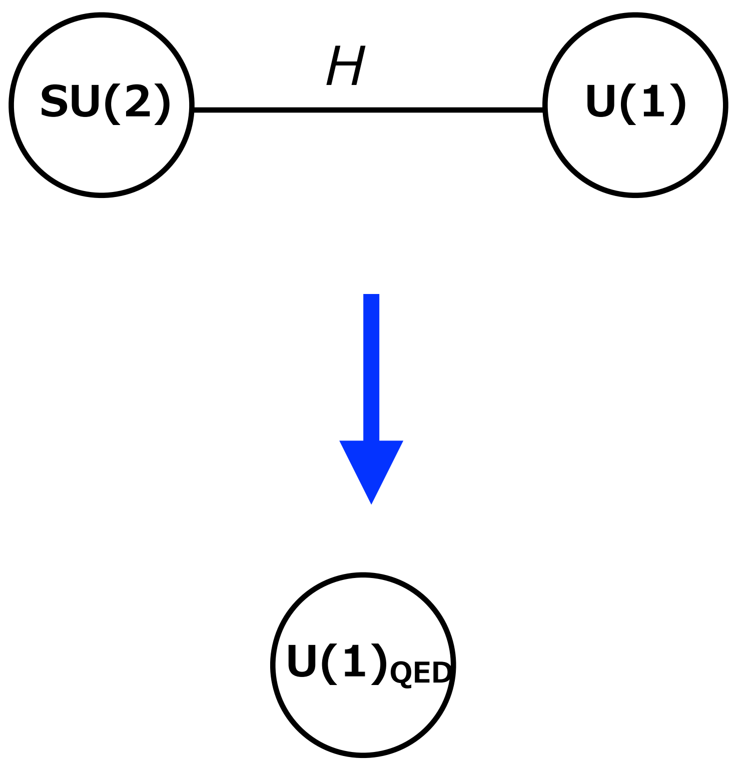


$$H_j = \sigma_j 1_{2\times 2} + i\tau^a \pi_j^a = \begin{pmatrix} \sigma_j + i\pi_j^3 & i\pi_j^+ \\ i\pi_j^- & \sigma_j - i\pi_j^3 \end{pmatrix}$$

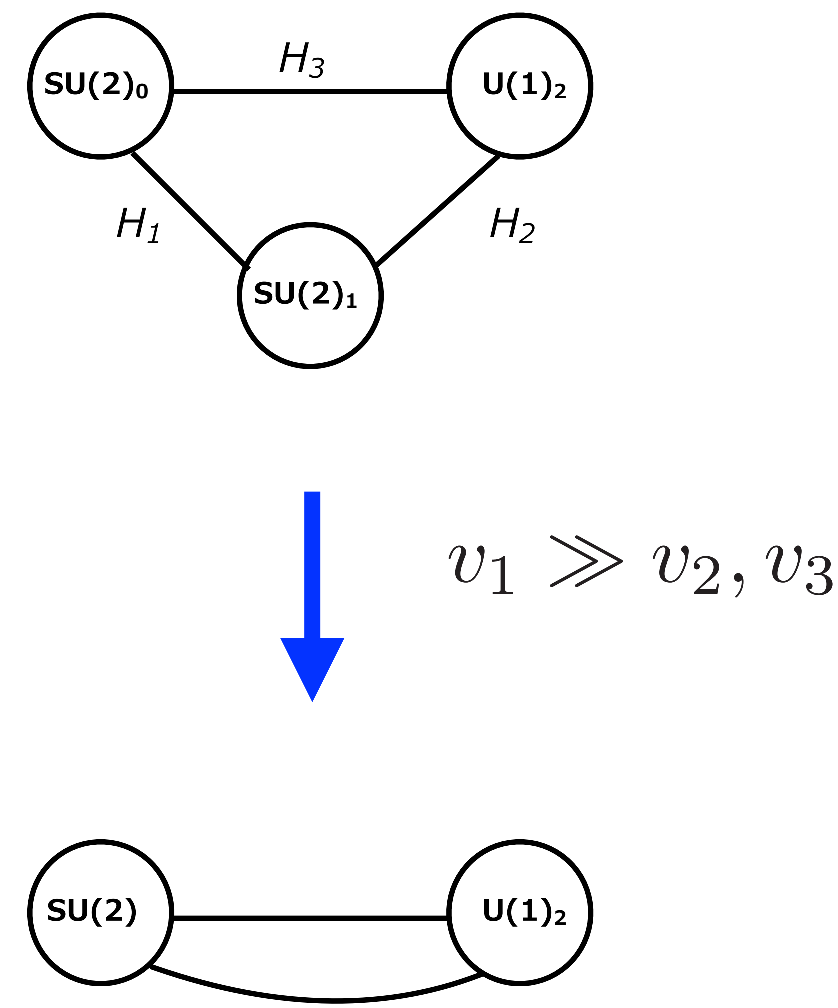
(σ_j and π_j^a are real, not complex.)

intuitive way to understand why 2HDM

SM



our setup



2HDM

Higgs potential

$$
\begin{aligned}
V(H_1, H_2, H_3) =& \mu_1^2 \mathrm{tr}(H_1^\dagger H_1) + \mu_2^2 \mathrm{tr}(H_2^\dagger H_2) + \mu_3^2 \mathrm{tr}(H_3^\dagger H_3) \\
&+ \kappa \mathrm{tr}(H_3^\dagger H_1 H_2) \\
&+ \widetilde{\lambda}_1 \left(\mathrm{tr}\left(H_1^\dagger H_1 \right) \right)^2 + \widetilde{\lambda}_2 \left(\mathrm{tr}\left(H_2 H_2^\dagger \right) \right)^2 + \widetilde{\lambda}_3 \left(\mathrm{tr}\left(H_3 H_3^\dagger \right) \right)^2 \\
&+ \widetilde{\lambda}_{12} \mathrm{tr}\left(H_1^\dagger H_1 \right) \mathrm{tr}\left(H_2^\dagger H_2 \right) + \widetilde{\lambda}_{23} \mathrm{tr}\left(H_2^\dagger H_2 \right) \mathrm{tr}\left(H_3^\dagger H_3 \right) + \widetilde{\lambda}_{31} \mathrm{tr}\left(H_3^\dagger H_3 \right) \mathrm{tr}\left(H_1^\dagger H_1 \right)
\end{aligned}
$$

building block

- $\mathrm{tr}(H_1{}^\dagger H_1)$
- $\mathrm{tr}(H_2{}^\dagger H_2)$
- $\mathrm{tr}(H_3{}^\dagger H_3)$
- $\mathrm{tr}(H_3{}^\dagger H_1 H_2)$

note

- $\mathrm{tr}(H_3{}^\dagger H_1 H_2)$ is real
- κ is real

(1) the potential has **custodial symmetry**

$$
\begin{aligned}
H_1 &\to [\mathrm{SU}(2)_0] H_1 [\mathrm{SU}(2)_1^\dagger] \\
H_2 &\to [\mathrm{SU}(2)_1] H_2 [\mathrm{SU}(2)_2^\dagger] \\
H_3 &\to [\mathrm{SU}(2)_0] H_2 [\mathrm{SU}(2)_2^\dagger]
\end{aligned}
$$

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

(3) **softly broken Z_2 symmetry** in the potential

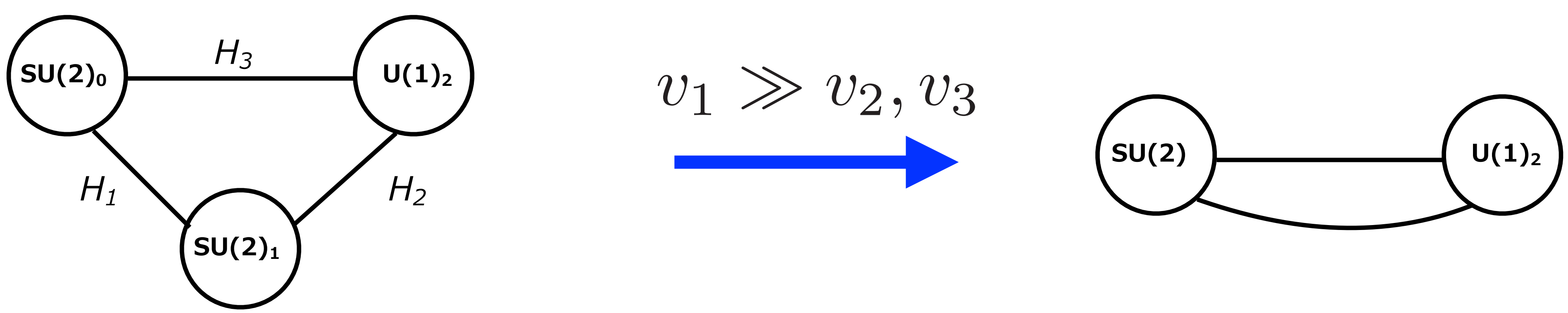
- symmetric ($H_i \to - H_i$)
- broken only by $\mathrm{tr}(H_3{}^\dagger H_1 H_2)$

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)

$$q_L H_2 u_R + q_L H_2 d_R + l_L H_2 e_R$$
$$+ q_L H_1 u_R + q_L H_1 d_R + l_L H_1 e_R$$

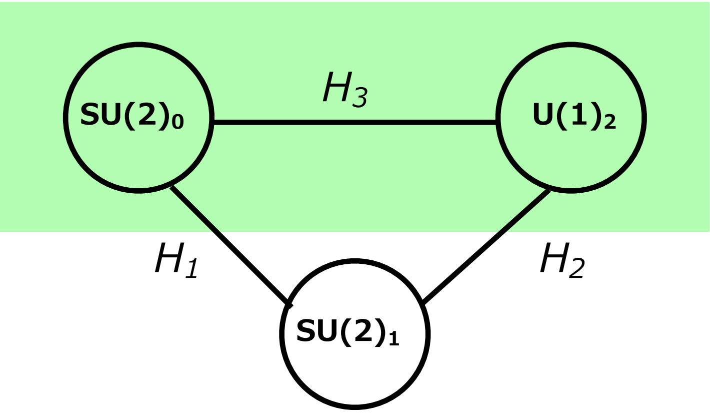
Yukawa interaction

	SU(2)	SU(2)	U(1)
q_L	2	1	1/6
u_R	1	1	2/3
d_R	1	1	-1/3
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

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
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

Yukawa interaction

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

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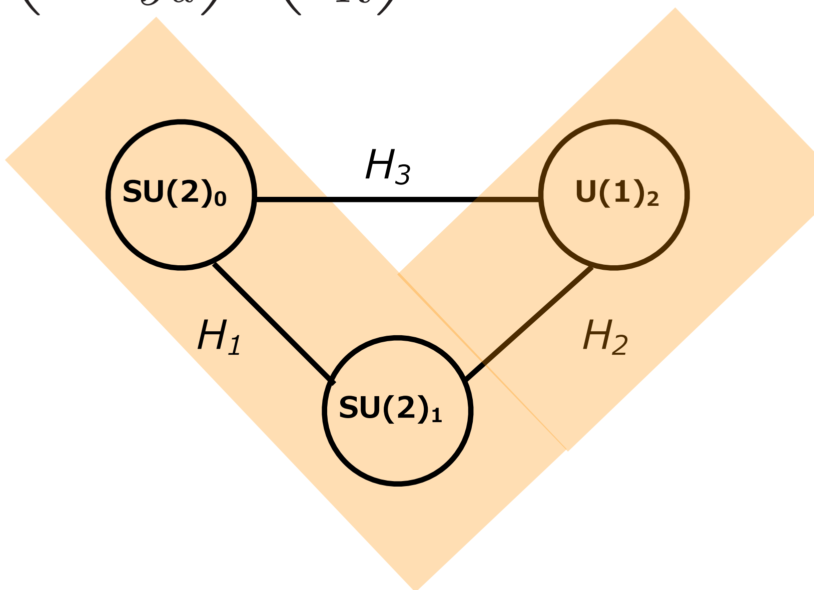

additional Yukawa

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

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

	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
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

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

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

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

$$+ (h.c.)$$

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

$$\mathcal{L}^{Yukawa} \simeq -\bar{q}_L H_3 \begin{pmatrix} y_u & 0 \\ 0 & y_d \end{pmatrix} \begin{pmatrix} u_R \\ d_R \end{pmatrix} - \bar{\ell}_L H_3 \begin{pmatrix} 0 & 0 \\ 0 & y_e \end{pmatrix} \begin{pmatrix} 0 \\ e_R \end{pmatrix}$$
$$- \bar{q}_L H_1 H_2 \left(Y_{Q1} M_Q^{-1} \begin{pmatrix} y_{2u} & 0 \\ 0 & y_{2d} \end{pmatrix} \right) \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$
$$- \bar{\ell}_L H_1 H_2 \left(Y_{L1} M_L^{-1} \begin{pmatrix} 0 & 0 \\ 0 & y_{2e} \end{pmatrix} \right) \begin{pmatrix} 0 \\ e_R \end{pmatrix}$$
$$+ (h.c.)$$

Let us try to assign global U(1) symmetry to forbid unwanted couplings

how to get type-II (cont.)

$$\mathcal{L}^{Yukawa} = -\bar{q}_L H_3 \begin{pmatrix} y_u & 0 \\ 0 & y_d \end{pmatrix} \begin{pmatrix} u_R \\ d_R \end{pmatrix} - \bar{\ell}_L H_3 \begin{pmatrix} 0 & 0 \\ 0 & y_e \end{pmatrix} \begin{pmatrix} 0 \\ e_R \end{pmatrix}$$
$$- \bar{q}_L H_1 Y_{Q1} Q_R - \bar{Q}_R S Y_Q Q_L - \bar{Q}_L H_2 \begin{pmatrix} y_{2u} & 0 \\ 0 & y_{2d} \end{pmatrix} \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$
$$- \bar{\ell}_L H_1 Y_{L1} L_R - \bar{L}_R S Y_L L_L - \bar{L}_L H_2 \begin{pmatrix} 0 & 0 \\ 0 & y_{2e} \end{pmatrix} \begin{pmatrix} 0 \\ e_R \end{pmatrix}$$
$$+ (h.c.)$$

	q_L	Q_L	ℓ_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	$-X_u + X_d$	$-X_d$	$-X_u$	$X_u - X_d$

$$\kappa\, \mathrm{tr}(H_1 H_2 H_3^\dagger)$$

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

	q_L	Q_L	ℓ_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	$-x_u + x_d$	$-x_d$	$-x_u$	$x_u - x_d$

$$\kappa \, \mathrm{tr}(H_1 H_2 H_3^\dagger)$$

Another charge assignment

	q	Q	ℓ	L	Q	L	u	d	e	H	H	H	S
U(1)	0	0	0	0	$\frac{x_u - x_d}{2}$	$\frac{x_u - x_d}{2}$	x_u	x_d	x_d	$-\frac{x_u - x_d}{2}$	$-x_d$	$-x_u$	$\frac{x_u - x_d}{2}$

$$\mathrm{tr}(H_1 H_2 H_3^\dagger) S^*$$