A 2HDM from 331 Gauge Theories

Kei Yagyu (Osaka U.)

Hiroshi Okada, Nobuchika Okada, Yuta Orikasa, KY

1604.01948 (PRD94, 015002)

Arindam Das, Kazuki Enomoto, Shinya Kanemura, KY

Paper in preparation

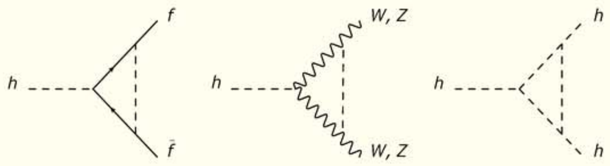
1st MCHP, Tanger, Morocco

26th September, 2019

H-COUP Version 2.0 was released!!

http://www-het.phys.sci.osaka-u.ac.jp/~hcoup/

H-COUP

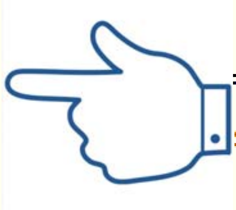


NEW!!

H-COUP version 2.0 (1 Sep. 2019) is a calculation tool composed of a set of Fortran codes to compute the Higgs boson decay rates and the branching ratios with radiative corrections (NNLO for QCD and NLO for EW) in various non-minimal Higgs models, such as the Higgs singlet model, four types of two Higgs doublet models and the inert doublet model. H-COUP ver. 2.0 contains all the functions in H-COUP ver. 1.0.

Authors:
Shinya Kanemura, Mariko Kikuchi, Kentarou Mawatari, Kodai Sakurai and Kei Yagyu

Downloads

- H-COUP version 2.0 : [HCOUP-2.0.zip]  or H-COUP ver. 2.0 will be released soon.]
- H-COUP version 1.0 : [HCOUP-1.0.zip] s here]

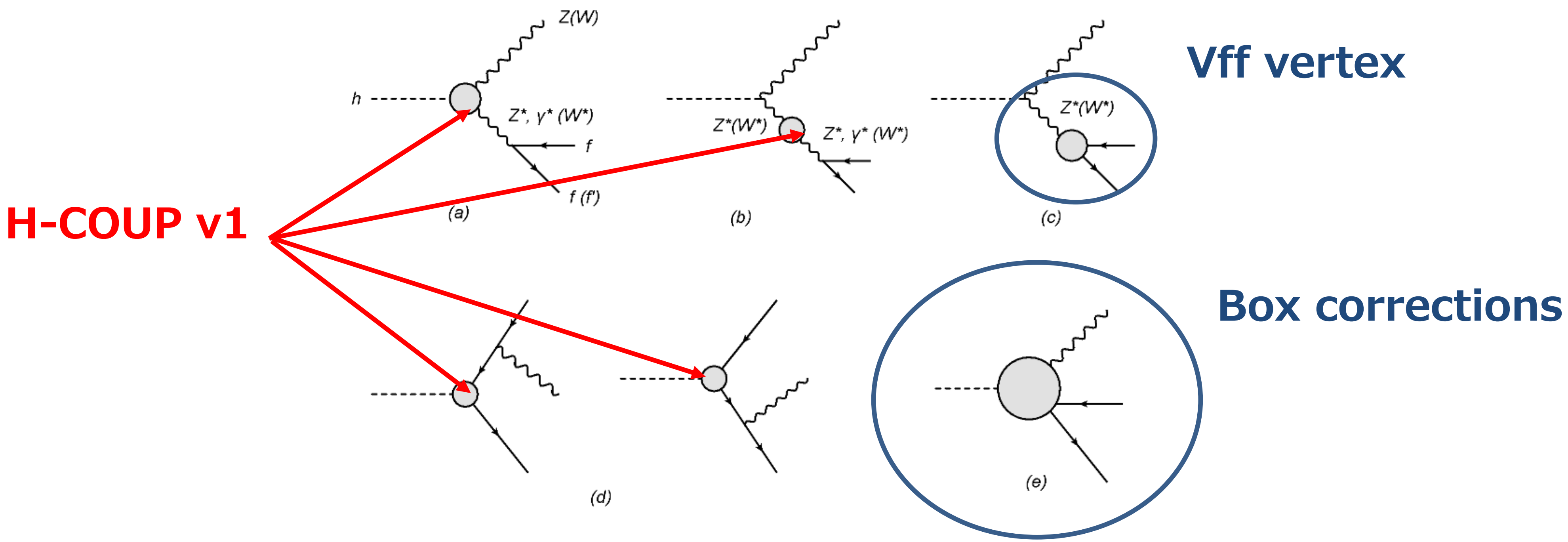
In order to run H-COUP programs, you ne opTools (www.feynarts.de/looptools/).

History

Contact

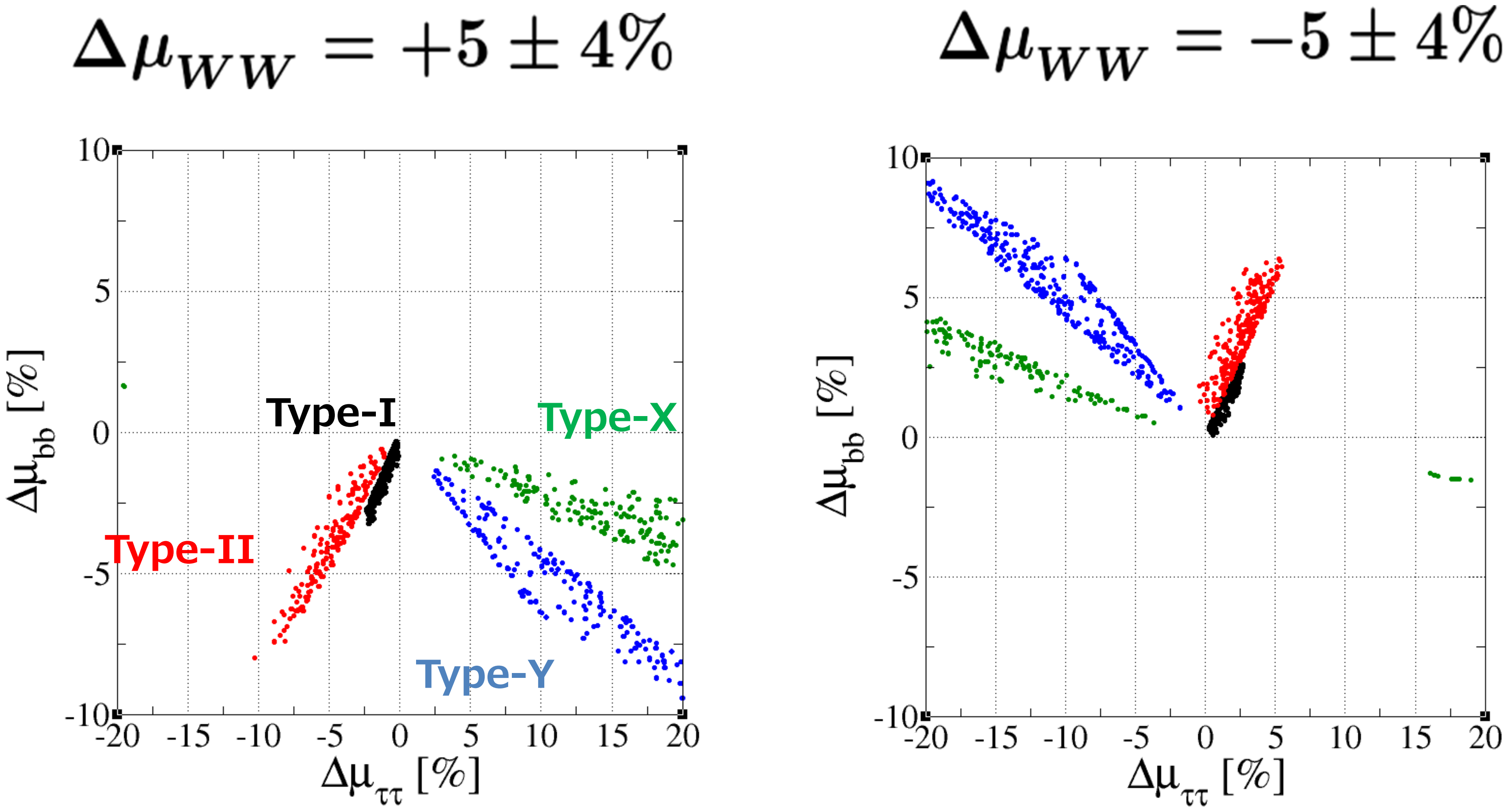
H-COUP Version 2.0

- H-COUP is a tool to calculate **decay rates**, **width** & **BRs** of h(125).
- H-COUP includes **Higgs singlet model**, **2HDMs (4 types)** & **IDM**.
- Calculations are performed with **NLO EW** and **NNLO QCD** corrections.



Application I: Fingerprinting

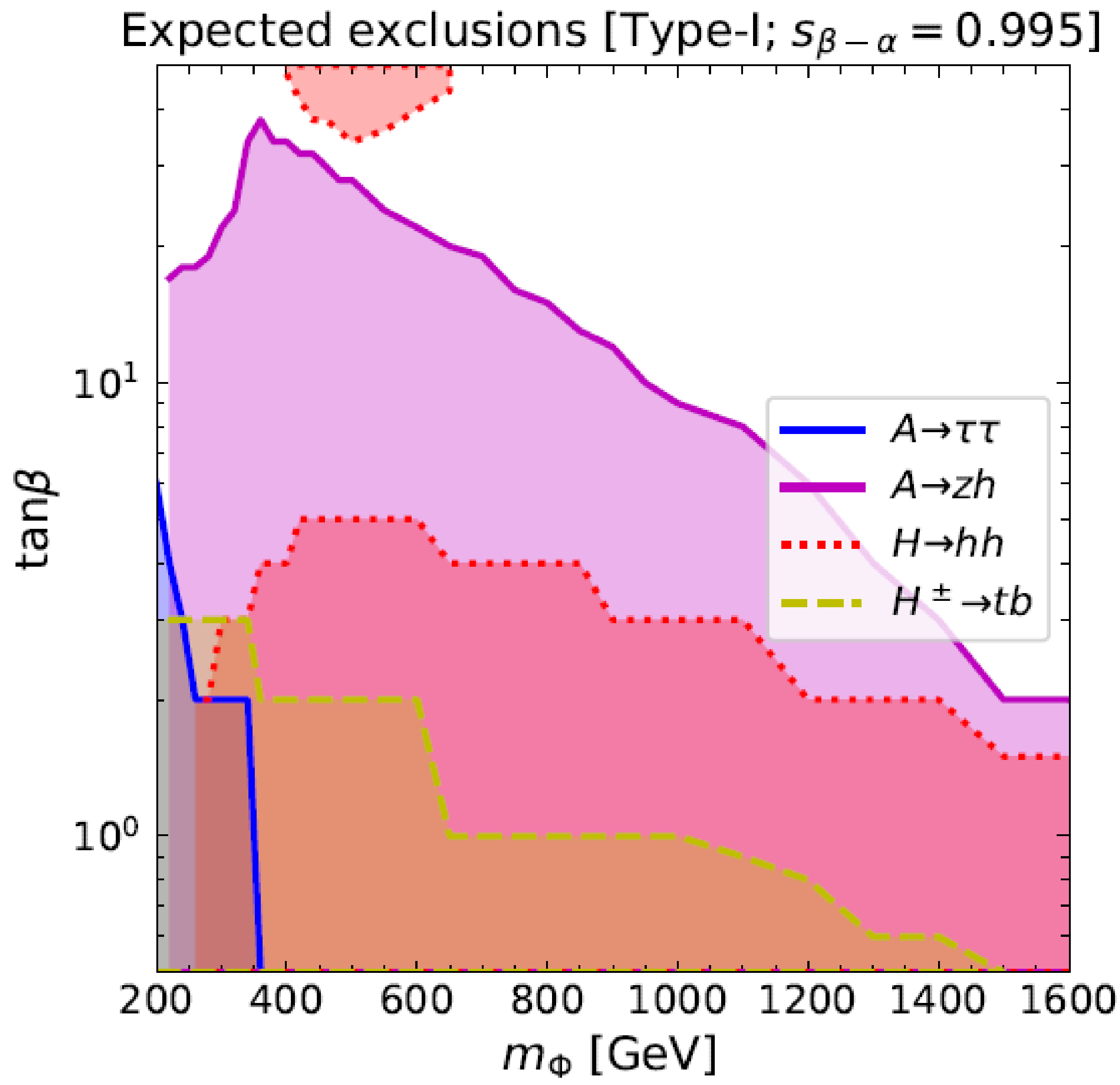
Kanemura, Kikuchi, Mawatari, Sakurai, KY, arXiv:1906.10070



$$\Delta\mu_X \equiv \mathrm{BR}(h \to XX)_{\mathrm{NP}}/\mathrm{BR}(h \to XX)_{\mathrm{SM}} - 1$$

Application II: Synergy

Kanemura, Mawatari, KY, preliminary

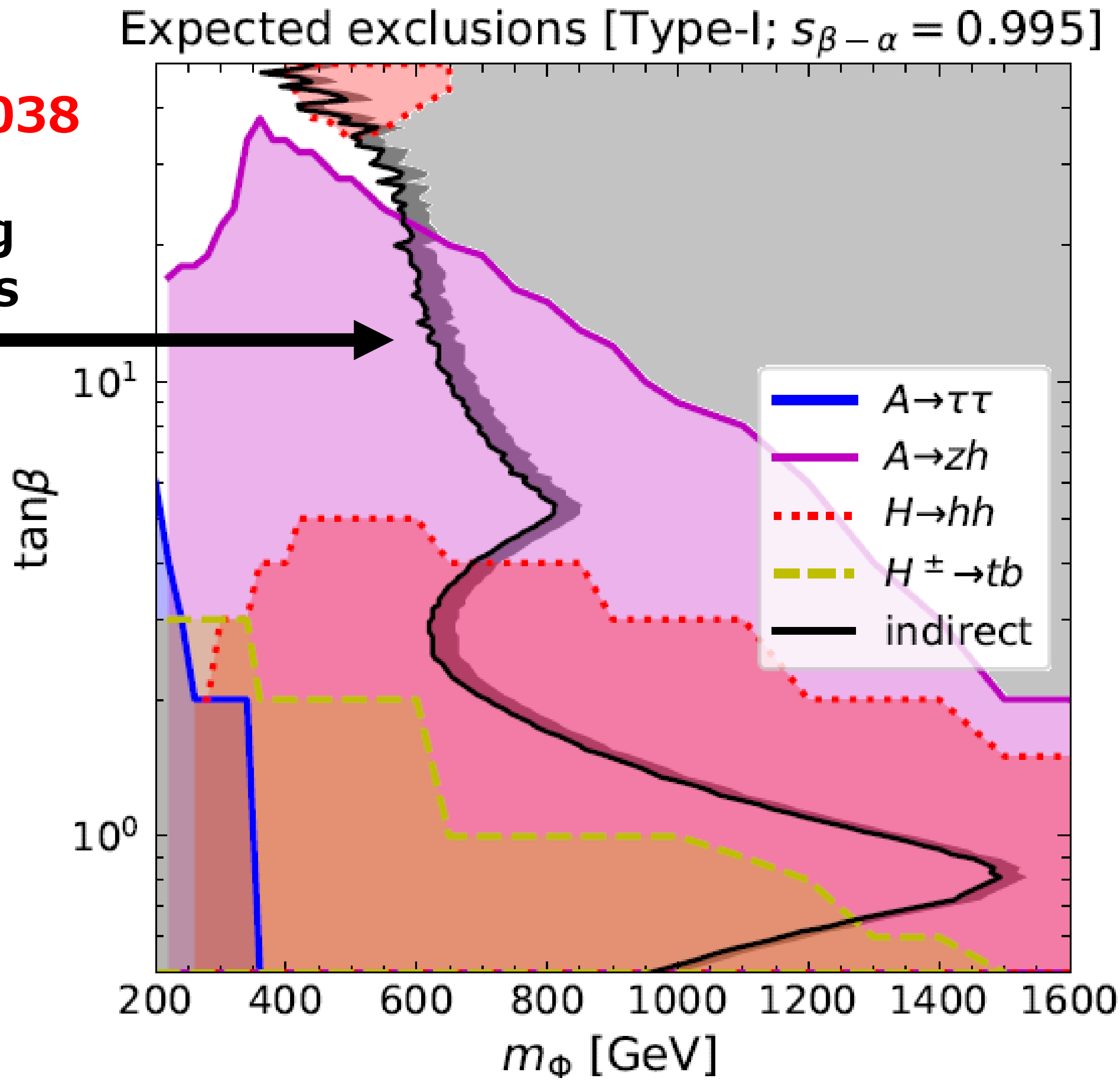


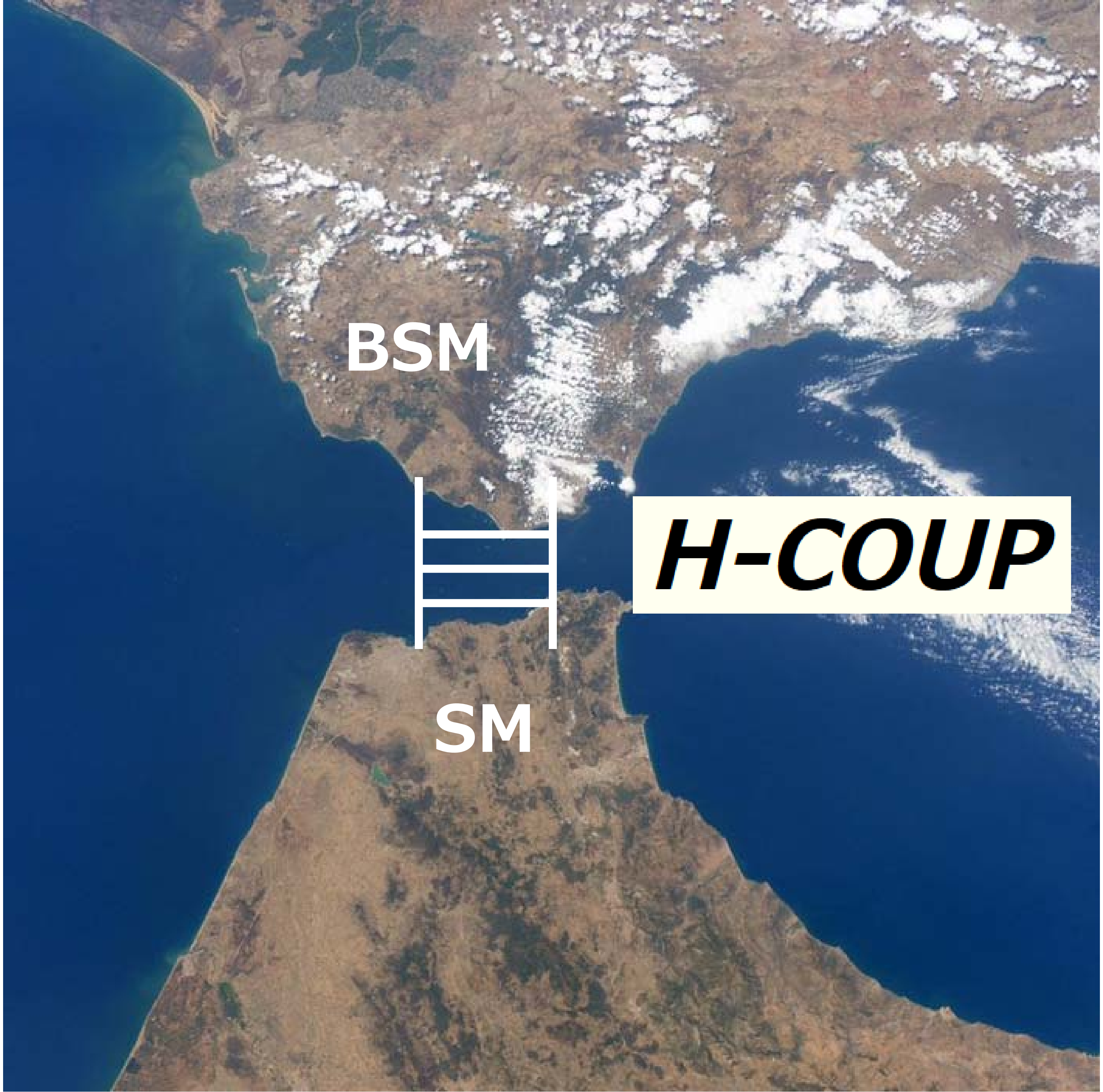
Application II: Synergy

Kanemura, Mawatari, KY, preliminary

$\kappa_V = 0.995 \pm 0.0038$

Higgs coupling measurements




BSM
H-COUP
SM

Contents

0. H-COUP

1. Introduction

2. Model setup

3. Neutrino masses & Higgs phenomenology

4. Summary

Motivation

- Mystery of flavor structure : Why are there 3 gens?

- Mystery of neutrino masses : Why are they so tiny?

331 models can solve them simultaneously!

331 models

M. Singer, J. W. F. Valle and J. Schechter (1980);

J. W. F. Valle and M. Singer (1983) ;

P. H. Frampton (1992)

$$SU(3)_C \times SU(3)_L \times U(1)_X$$

331 models

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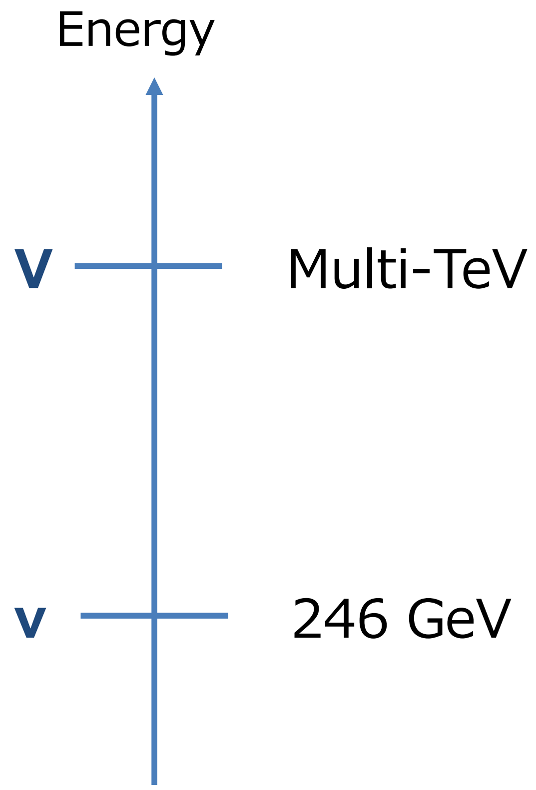
$$SU(3)_C \times SU(3)_L \times U(1)_X$$

$$SU(3)_C \times \quad SU(2)_L \times U(1)_Y$$

$$SU(3)_C \times \qquad U(1)_{\text{em}}$$



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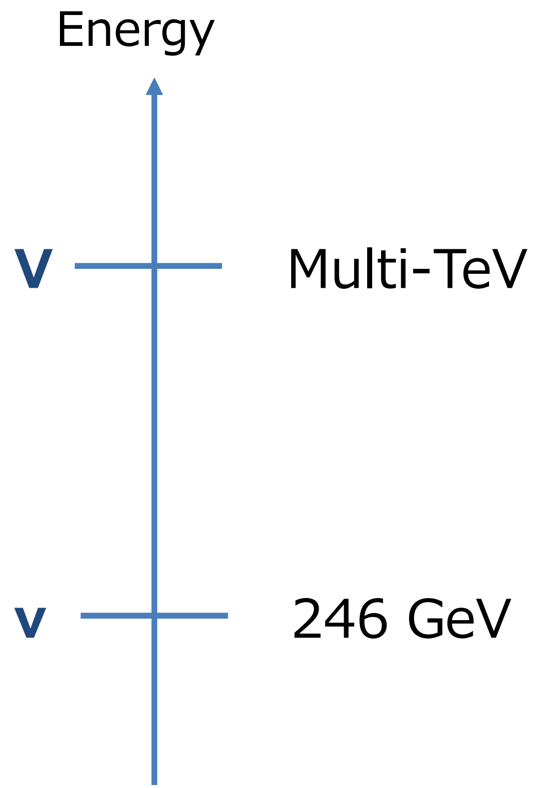
$$SU(3)_C \times \boxed{SU(3)_L} \times U(1)_X$$

Rank 2

$$SU(3)_C \times \quad SU(2)_L \times U(1)_Y$$

$$SU(3)_C \times \qquad U(1)_{\mathrm{em}}$$



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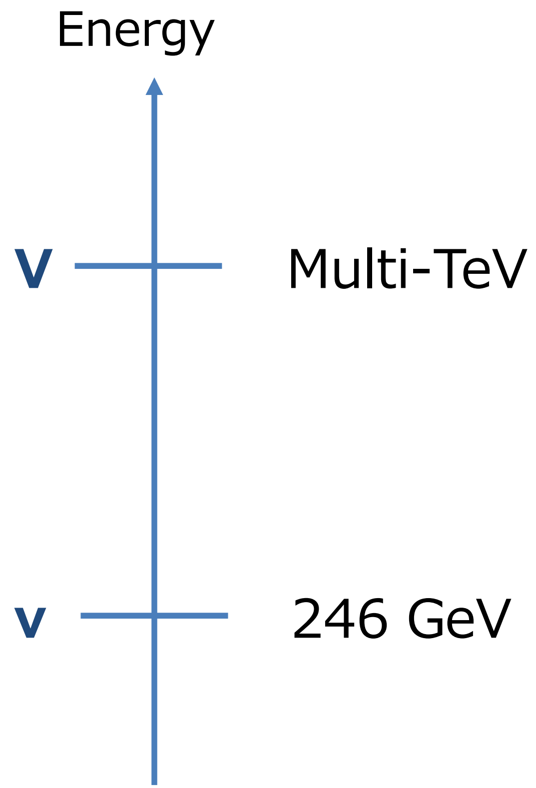

EM charge: Q

$$Q = T_3 + \eta T_8 + X = \begin{pmatrix} +\frac{1}{2} + \frac{\eta}{2\sqrt{3}} + X \\ -\frac{1}{2} + \frac{\eta}{2\sqrt{3}} + X \\ 0 - \frac{\eta}{\sqrt{3}} + X \end{pmatrix}$$

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M. Singer, J. W. F. Valle and J. Schechter (1980);
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$$SU(3)_C \times \boxed{SU(3)_L} \times U(1)_X$$

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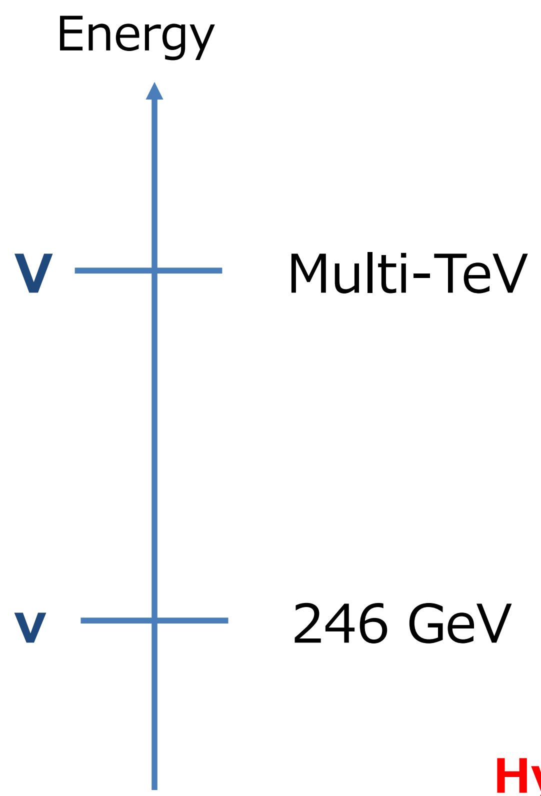


Hypercharge: Y

EM charge: Q

$$Q = T_3 + \eta\, T_8 + X = \begin{pmatrix} +\frac{1}{2} + \frac{\eta}{2\sqrt{3}} + X \\ -\frac{1}{2} + \frac{\eta}{2\sqrt{3}} + X \\ 0 - \frac{\eta}{\sqrt{3}} + X \end{pmatrix}$$

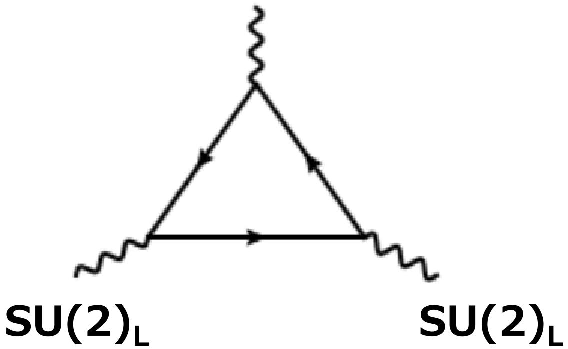
$$\eta \propto \sqrt{3},\ 1/\sqrt{3}\ \text{ or }\ 0$$

In this talk, we take η = -√3

Anomaly cancellation

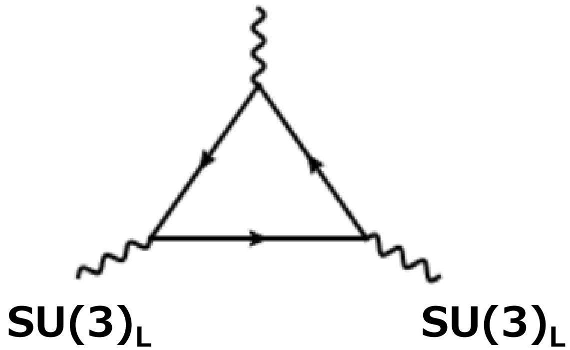
Gauge anomaly: $A_F^{abc} \propto \mathrm{Tr}[\{T_F^a, T_F^b\}T_F^c]$

- SM: Cancelled for each gen.



$$\left\{\frac{\tau^a}{2}, \frac{\tau^b}{2}\right\} = \frac{\delta^{ab}}{2} \qquad \mathrm{Tr}\left(\frac{\tau^a}{2}\right) = 0$$

- 331 models: Cancelled by 3 gens.



3 quarks

$$d^{abc}[3 + N_c(1 - 2)] = 0$$

3 leptons 3 quark

# of generations must be 3 (6, 9, ⋯) because # of color is 3 !

Contents

Our model

Das, Enomoto, Kanemura, KY, in preparation

Fields	L_L^i	e_R^i	E_R^i	$Q_L^{1,2}$	Q_L^3	d_R^i	B_R	u_R^i	$U_R^{1,2}$	Φ_1	Φ_2	Φ_3	Φ_ℓ
$SU(3)_C$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(3)_L$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$
$U(1)_X$	$-2/3$	-1	-1	$1/3$	0	$-1/3$	$-1/3$	$2/3$	$2/3$	$1/3$	$-2/3$	$1/3$	$4/3$

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Das, Enomoto, Kanemura, KY, in preparation

Fields	L_L^i	e_R^i	E_R^i	$Q_L^{1,2}$	Q_L^3	d_R^i	B_R	u_R^i	$U_R^{1,2}$	Φ_1	Φ_2	Φ_3	Φ_ℓ
$SU(3)_C$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(3)_L$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$
$U(1)_X$	$-2/3$	-1	-1	$1/3$	0	$-1/3$	$-1/3$	$2/3$	$2/3$	$1/3$	$-2/3$	$1/3$	$4/3$

Lepton

Quark

Higgs

Our model

Das, Enomoto, Kanemura, KY, in preparation

Fields	L_L^i	e_R^i	E_R^i	$Q_L^{1,2}$	Q_L^3	d_R^i	B_R	u_R^i	$U_R^{1,2}$	Φ_1	Φ_2	Φ_3	Φ_ℓ
$SU(3)_C$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(3)_L$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$
$U(1)_X$	$-2/3$	-1	-1	$1/3$	0	$-1/3$	$-1/3$	$2/3$	$2/3$	$1/3$	$-2/3$	$1/3$	$4/3$

$$L_L^i = \begin{pmatrix} e^i \\ \nu^i \\ E^i \end{pmatrix}_L , \quad Q_L^{1,2} = \begin{pmatrix} u^{1,2} \\ d^{1,2} \\ U^{1,2} \end{pmatrix}_L , \quad Q_L^3 = \begin{pmatrix} b \\ t \\ B \end{pmatrix}_L$$

LH SM fermions

Our model

Das, Enomoto, Kanemura, KY, in preparation

Fields	L_L^i	e_R^i	E_R^i	$Q_L^{1,2}$	Q_L^3	d_R^i	B_R	u_R^i	$U_R^{1,2}$	Φ_1	Φ_2	Φ_3	Φ_ℓ
$SU(3)_C$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(3)_L$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$
$U(1)_X$	$-2/3$	-1	-1	$1/3$	0	$-1/3$	$-1/3$	$2/3$	$2/3$	$1/3$	$-2/3$	$1/3$	$4/3$

$$L_L^i = \begin{pmatrix} e^i \\ \nu^i \\ E^i \end{pmatrix}_L , \quad Q_L^{1,2} = \begin{pmatrix} u^{1,2} \\ d^{1,2} \\ U^{1,2} \end{pmatrix}_L , \quad Q_L^3 = \begin{pmatrix} b \\ t \\ B \end{pmatrix}_L$$

Extra LH fermions

Our model

Das, Enomoto, Kanemura, KY, in preparation

Fields	L_L^i	e_R^i	E_R^i	$Q_L^{1,2}$	Q_L^3	d_R^i	B_R	u_R^i	$U_R^{1,2}$	Φ_1	Φ_2	Φ_3	Φ_ℓ
$SU(3)_C$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(3)_L$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$
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$$L_L^i = \begin{pmatrix} e^i \\ \nu^i \\ E^i \end{pmatrix}_L , \quad Q_L^{1,2} = \begin{pmatrix} u^{1,2} \\ d^{1,2} \\ U^{1,2} \end{pmatrix}_L , \quad Q_L^3 = \begin{pmatrix} b \\ t \\ B \end{pmatrix}_L$$

Extra LH fermions

Extra RH fermions

Our model

Das, Enomoto, Kanemura, KY, in preparation

Fields	L_L^i	e_R^i	E_R^i	$Q_L^{1,2}$	Q_L^3	d_R^i	B_R	u_R^i	$U_R^{1,2}$	Φ_1	Φ_2	Φ_3	Φ_ℓ
$SU(3)_C$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(3)_L$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$
$U(1)_X$	$-2/3$	-1	-1	$1/3$	0	$-1/3$	$-1/3$	$2/3$	$2/3$	$1/3$	$-2/3$	$1/3$	$4/3$

Minimal Higgs sector

Our model

Das, Enomoto, Kanemura, KY, in preparation

Fields	L_L^i	e_R^i	E_R^i	$Q_L^{1,2}$	Q_L^3	d_R^i	B_R	u_R^i	$U_R^{1,2}$	Φ_1	Φ_2	Φ_3	Φ_ℓ
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$SU(3)_L$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$
$U(1)_X$	$-2/3$	-1	-1	$1/3$	0	$-1/3$	$-1/3$	$2/3$	$2/3$	$1/3$	$-2/3$	$1/3$	$4/3$

Minimal Higgs sector

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} v_1 \\ 0 \\ 0 \end{pmatrix}, \quad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \\ 0 \end{pmatrix}, \quad \langle\Phi_3\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \\ V \end{pmatrix}$$

Our model

Das, Enomoto, Kanemura, KY, in preparation

Fields	L_L^i	e_R^i	E_R^i	$Q_L^{1,2}$	Q_L^3	d_R^i	B_R	u_R^i	$U_R^{1,2}$	Φ_1	Φ_2	Φ_3	Φ_ℓ
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V ~ Multi-TeV ~ Mass scale for extra fermions and gauge bosons

$$v \equiv \sqrt{v_1^2 + v_2^2} \simeq \mathbf{246\ GeV}$$

Our model

Das, Enomoto, Kanemura, KY, in preparation

Fields	L_L^i	e_R^i	E_R^i	$Q_L^{1,2}$	Q_L^3	d_R^i	B_R	u_R^i	$U_R^{1,2}$	Φ_1	Φ_2	Φ_3	Φ_ℓ
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$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} v_1 \\ 0 \\ 0 \end{pmatrix}, \quad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \\ 0 \end{pmatrix}, \quad \langle\Phi_3\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \\ V \end{pmatrix}$$

For neutrino masses

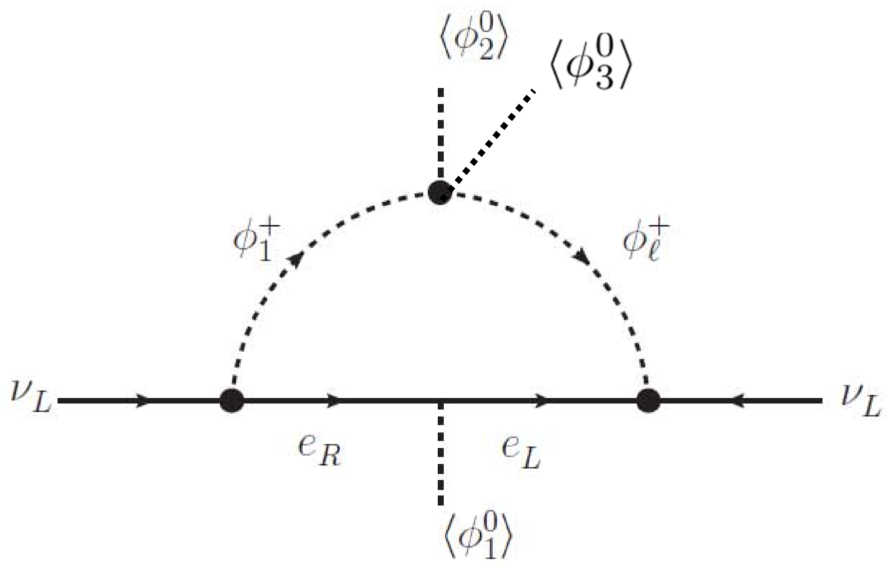
V ~ Multi-TeV ~ Mass scale for extra fermions and gauge bosons

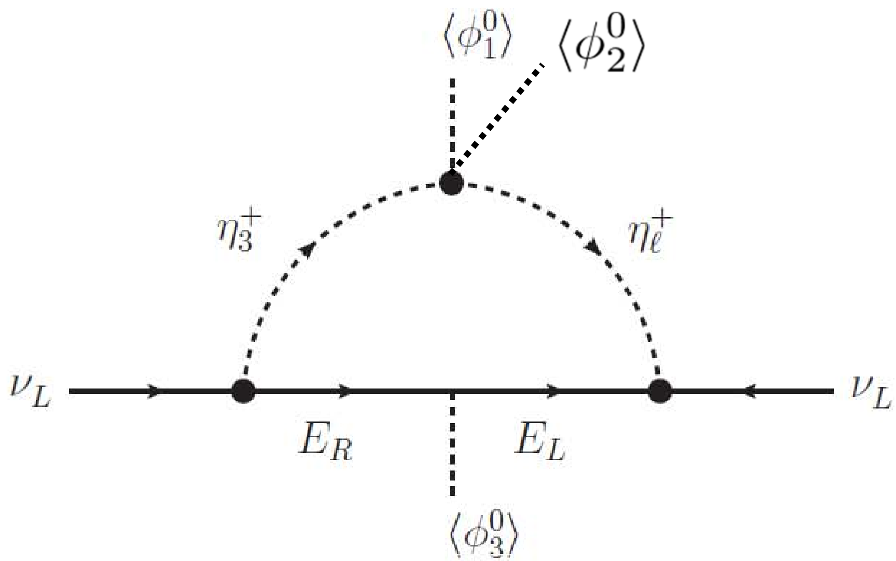
$$v \equiv \sqrt{v_1^2 + v_2^2} \simeq 246\ \text{GeV}$$

Contents

Neutrino masses

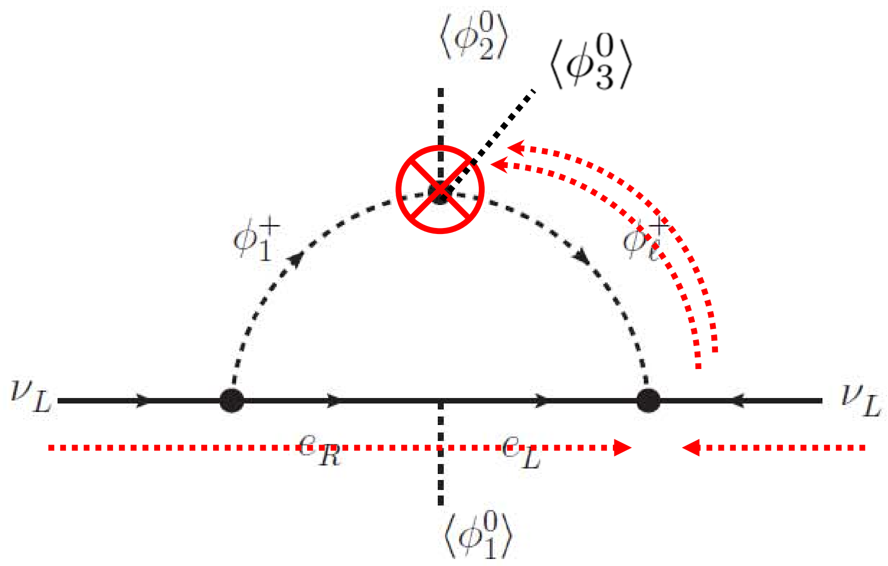
- Majorana neutrino masses (Radiative seesaw mechanism)

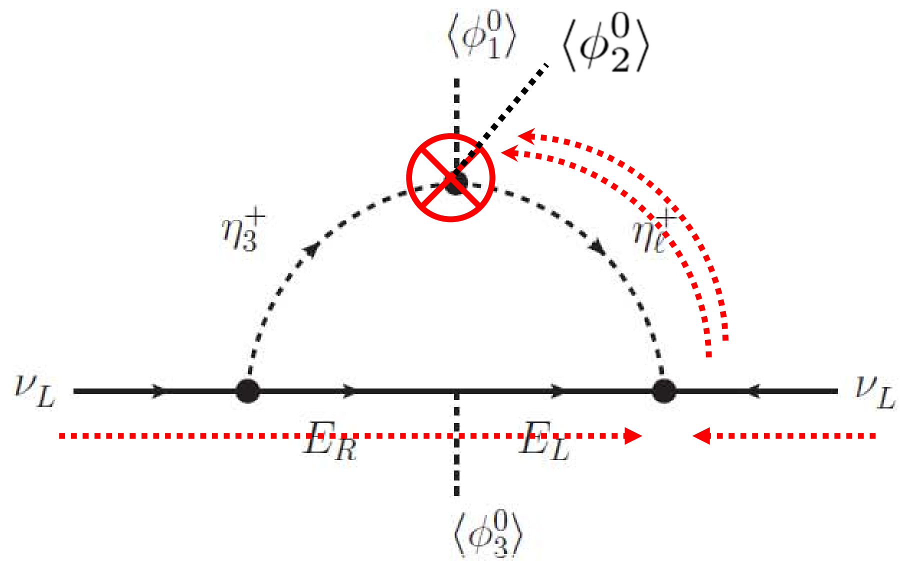




Neutrino masses

- Majorana neutrino masses（Radiative seesaw mechanism）

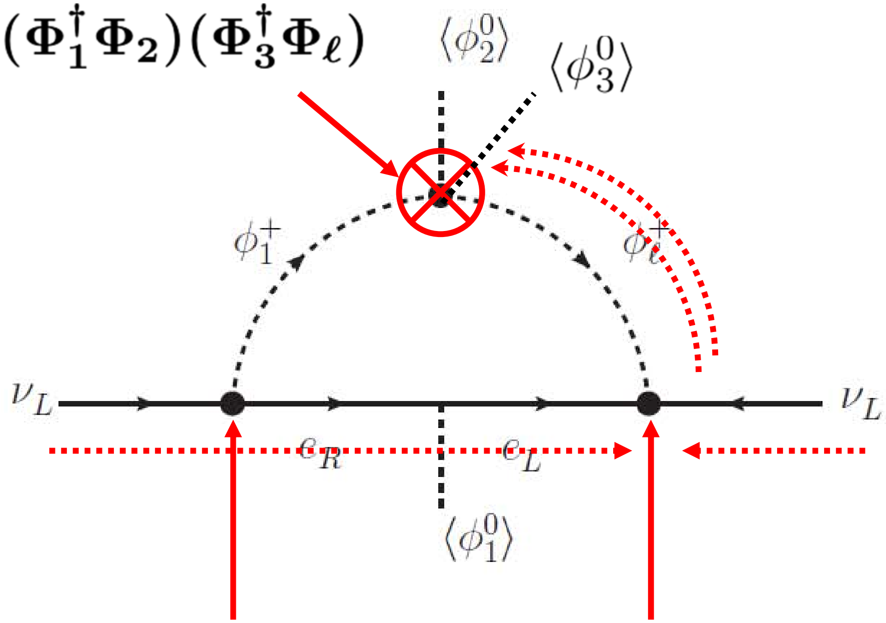


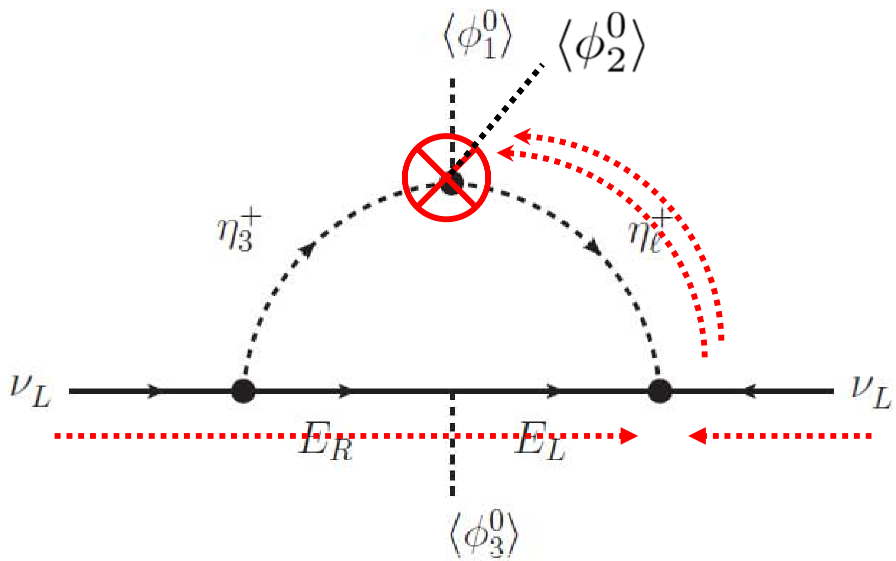


Neutrino masses

- Majorana neutrino masses（Radiative seesaw mechanism）

$$\xi_1(\Phi_1^\dagger\Phi_2)(\Phi_3^\dagger\Phi_\ell)$$



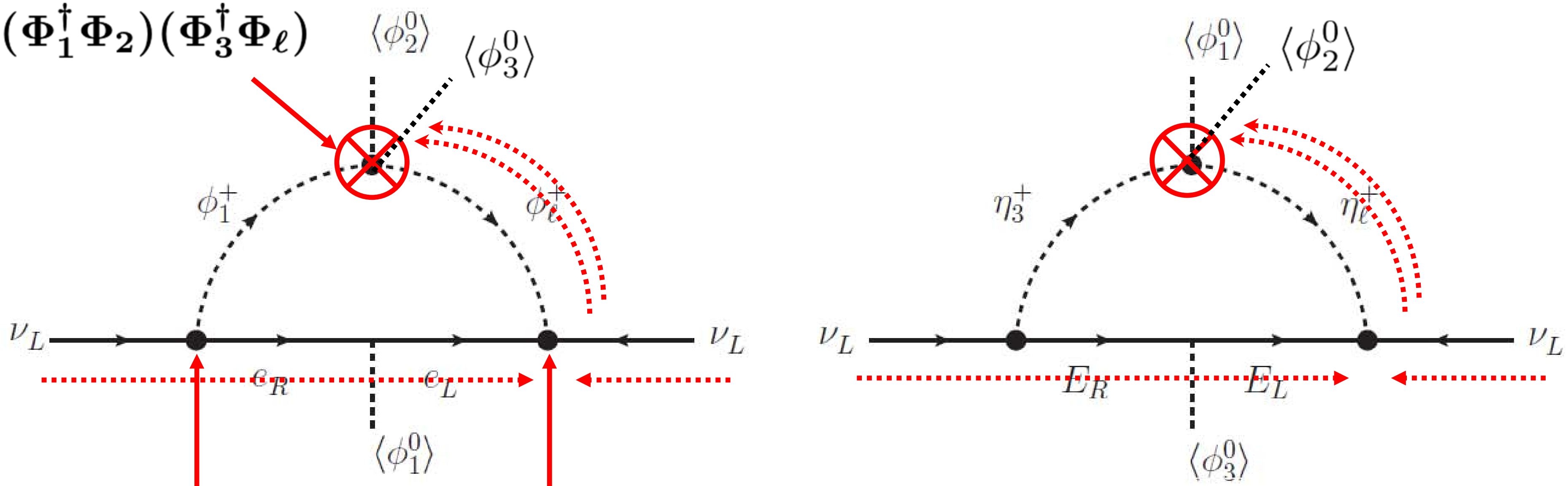


$$\frac{m_e^i}{v_1}\delta^{ij}\bar{L}_L^i\Phi_1 e_R^j \qquad \epsilon_{ABC}f_{ij}(\overline{L_L^{ci}})_A(L_L^j)_B(\Phi_\ell)_C$$

Neutrino masses

- Majorana neutrino masses（Radiative seesaw mechanism）

$$\xi_1(\Phi_1^\dagger\Phi_2)(\Phi_3^\dagger\Phi_\ell)$$



$$\frac{m_e^i}{v_1}\delta^{ij}\bar{L}_L^i\Phi_1 e_R^j \qquad \epsilon_{ABC} f_{ij}(\overline{L_L^{ci}})_A(L_L^j)_B(\Phi_\ell)_C$$

$$M_\nu^e = \frac{C_e}{16\pi^2}\frac{1}{v}f_{ij}m_j^2$$

Same structure as the Zee model

Neutrino Mixing in the Zee Model

$$m_\nu = \begin{pmatrix} 0 & a & b \\ a & 0 & c \\ b & c & 0 \end{pmatrix} \qquad V^T m_\nu V = \mathrm{diag}(m_1, m_2, m_3)$$

$$\Rightarrow \quad m_1 + m_2 + m_3 = 0$$

$$V_{12}^2 = \frac{1}{1 - \frac{m_1}{m_2}} \left[\left(\frac{m_1}{m_2} - \frac{m_3}{m_2} \right) V_{13}^2 - \frac{m_1}{m_2} \right] \qquad \because \ (m_\nu)_{11} = 0 \ \& \ \text{Orthgonality}$$

$$|x| = |m_1/m_2| \lesssim 1$$

$$\Rightarrow \quad V_{12}^2 = \frac{1}{1 - x} \left[(1 + 2x) V_{13}^2 - x \right]$$

- x > 0 [N.H.]
- x < 0 [I.H.]

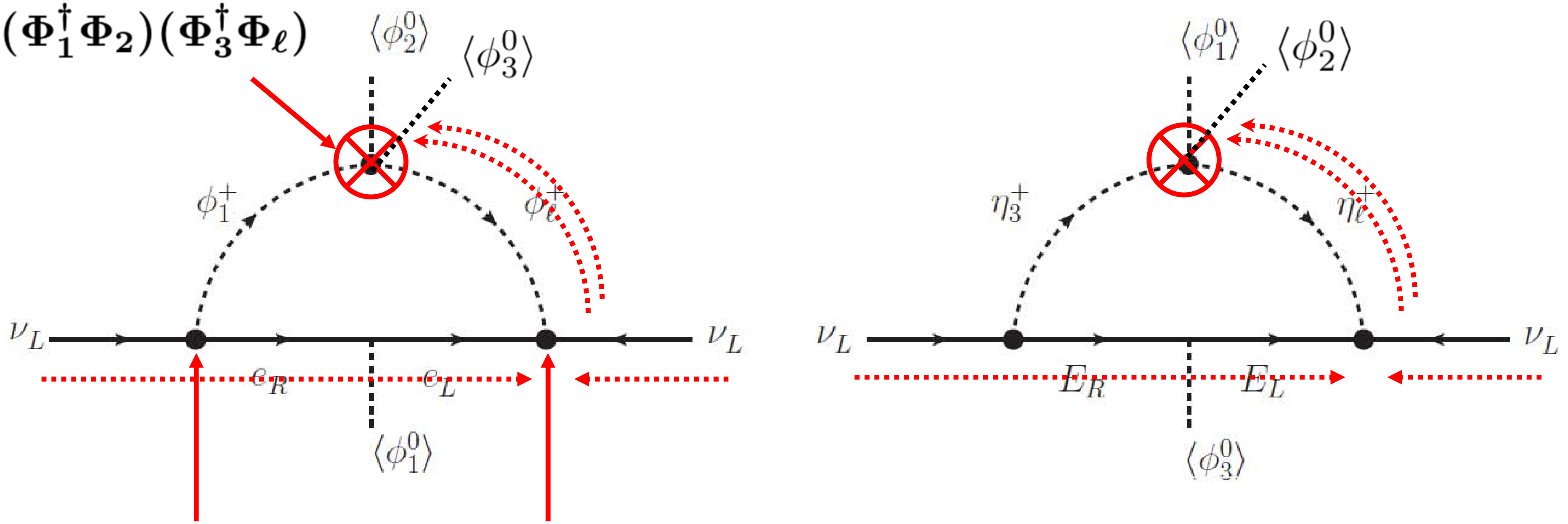
For $V_{13} \ll 1$, only the IH is possible.

$$\Rightarrow \quad \boxed{V_{12}^2 \simeq \frac{1}{2}} \quad \textbf{BUT} \quad \boxed{(V_{12}^{\text{exp}})^2 \sim \frac{1}{3}}$$

Neutrino masses

- Majorana neutrino masses (Radiative seesaw mechanism)

$\xi_1(\Phi_1^\dagger\Phi_2)(\Phi_3^\dagger\Phi_\ell)$



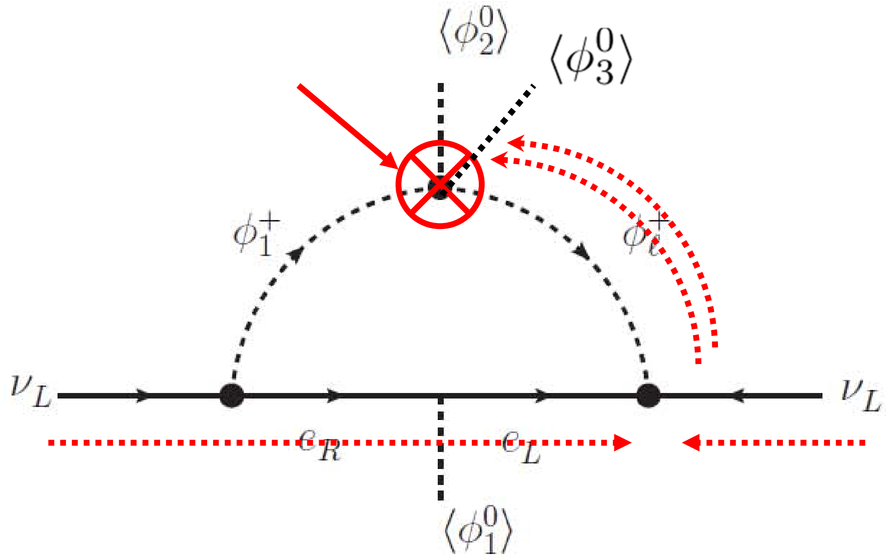
$$\frac{m_e^i}{v_1}\delta^{ij}\bar{L}_L^i\Phi_1 e_R^j \qquad \epsilon_{ABC} f_{ij}(\overline{L_L^{ci}})_A(L_L^j)_B(\Phi_\ell)_C$$

$$M_\nu^e = \frac{C_e}{16\pi^2}\frac{1}{v} f_{ij} m_j^2$$

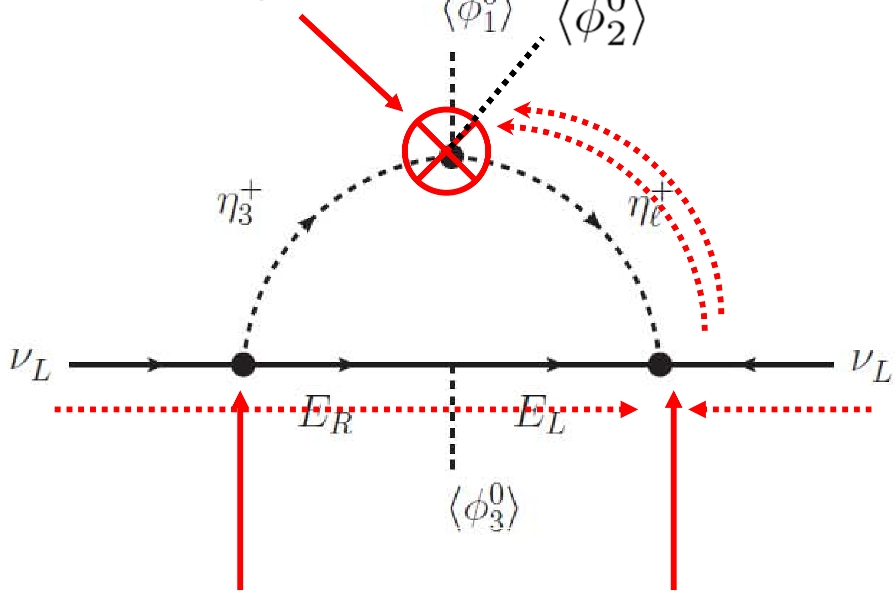
Neutrino mixings cannot be explained!

Neutrino masses

- Majorana neutrino masses （Radiative seesaw mechanism）



$\xi_2(\Phi_2^\dagger\Phi_3)(\Phi_\ell^\dagger\Phi_1)$

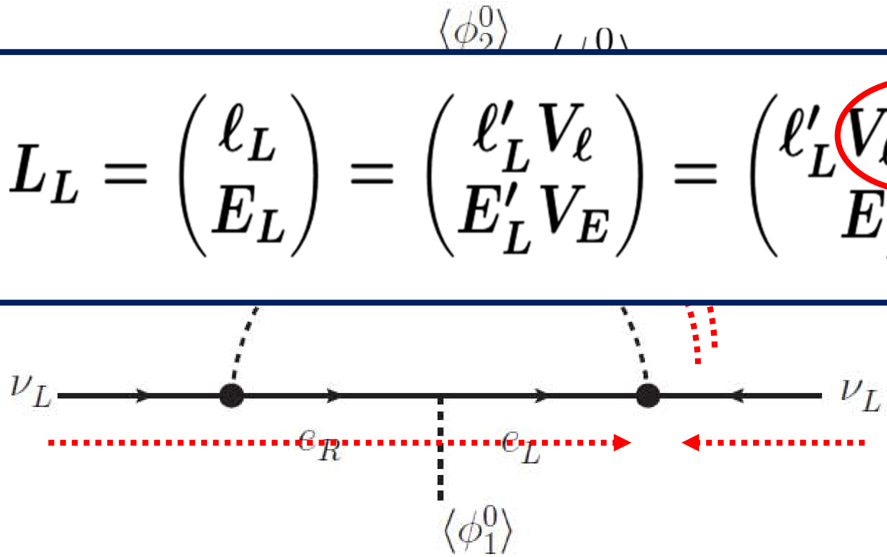


$$\frac{M_E^i}{V}\delta^{ij}\bar{L}_L^i\Phi_3 E_R^j \qquad \epsilon_{ABC} f_{ij}(\overline{L_L^{ci}})_A(L_L^j)_B(\Phi_\ell)_C$$

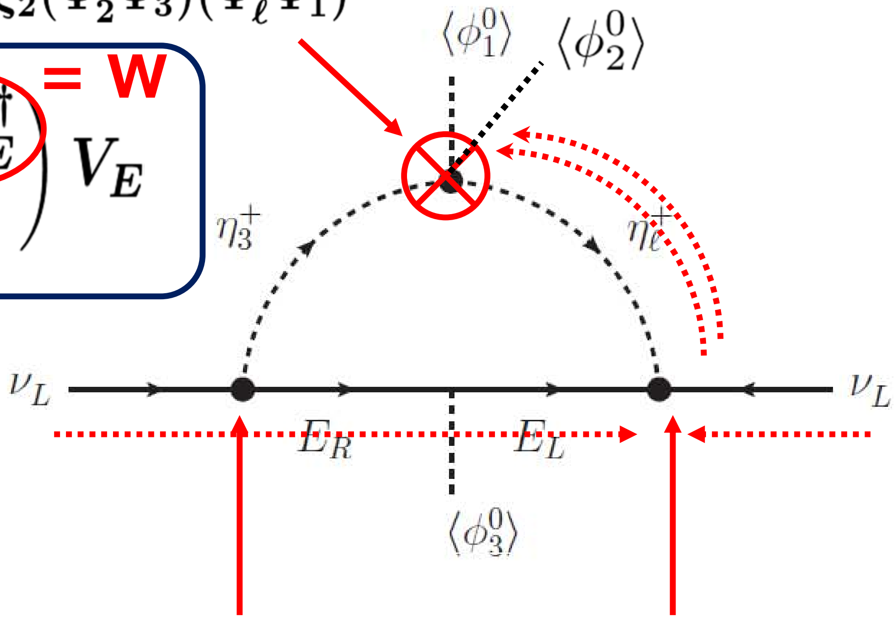
Neutrino masses

- Majorana neutrino masses (Radiative seesaw mechanism)

$$L_L = \begin{pmatrix} \ell_L \\ E_L \end{pmatrix} = \begin{pmatrix} \ell'_L V_\ell \\ E'_L V_E \end{pmatrix} = \begin{pmatrix} \ell'_L \overbrace{V_\ell V_E^\dagger}^{= W} \\ E'_L \end{pmatrix} V_E$$



$$\xi_2(\Phi_2^\dagger\Phi_3)(\Phi_\ell^\dagger\Phi_1)$$

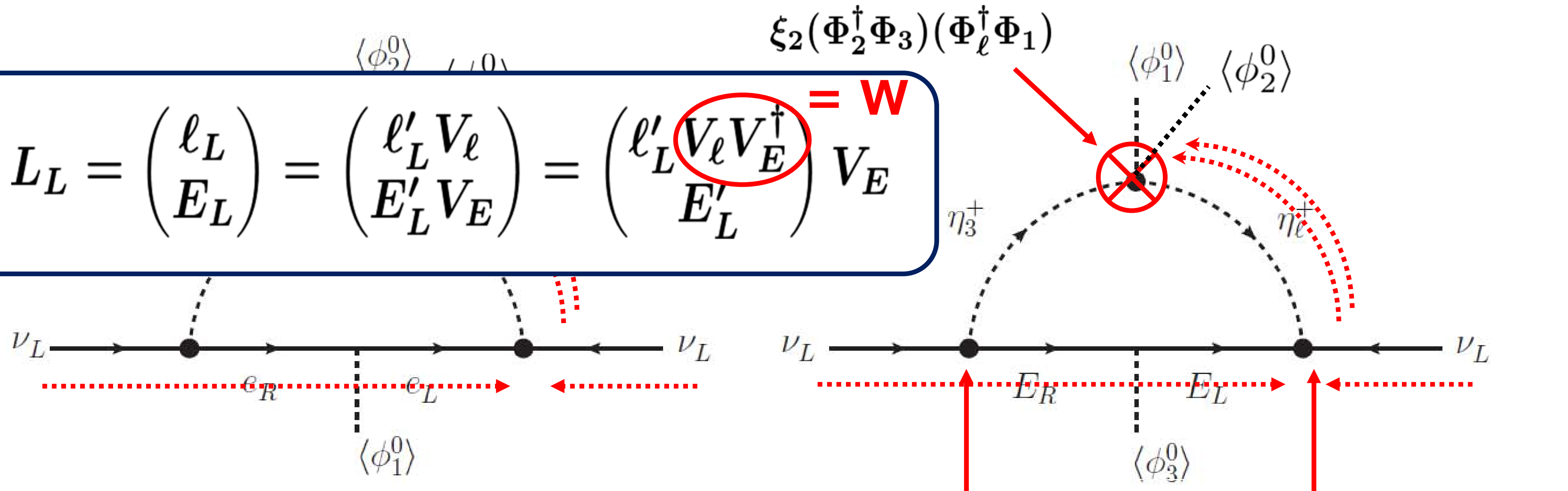


$$\frac{M_E^i}{V}\delta^{ij}\bar{L}_L^i\Phi_3 E_R^j \qquad \epsilon_{ABC} f_{ij}(\overline{L_L^{ci}})_A(L_L^j)_B(\Phi_\ell)_C$$

Neutrino masses

- Majorana neutrino masses（Radiative seesaw mechanism）

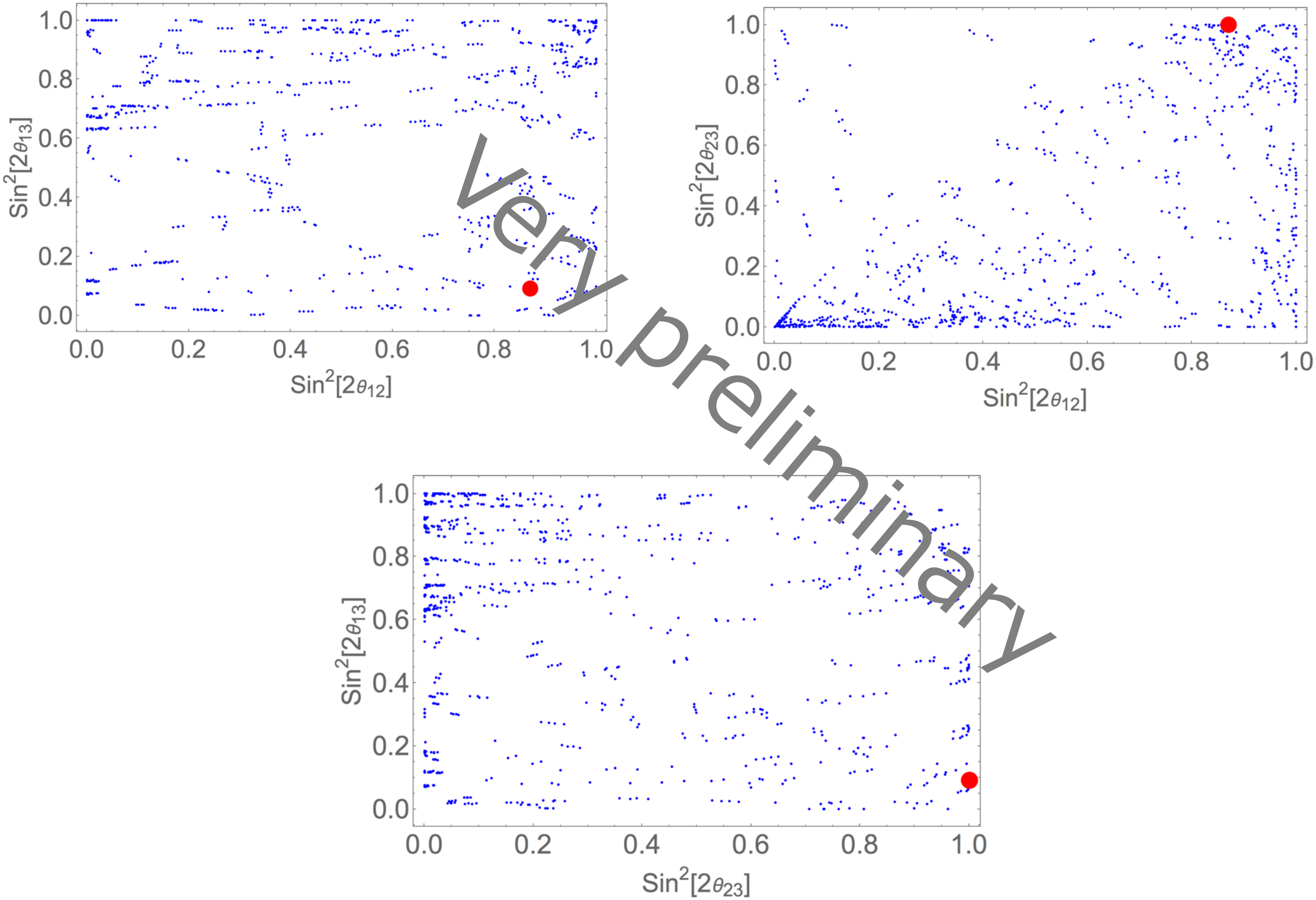
$$L_L = \begin{pmatrix} \ell_L \\ E_L \end{pmatrix} = \begin{pmatrix} \ell'_L V_\ell \\ E'_L V_E \end{pmatrix} = \begin{pmatrix} \ell'_L V_\ell V_E^\dagger \\ E'_L \end{pmatrix} V_E \qquad V_\ell V_E^\dagger = \mathbf{W}$$



$$\frac{M_E^i}{V}\delta^{ij}\bar{L}_L^i\Phi_3 E_R^j \qquad \epsilon_{ABC} f_{ij}(\overline{L_L^{ci}})_A(L_L^j)_B(\Phi_\ell)_C$$

$$M_\nu^E = \frac{C_E}{16\pi^2}\frac{1}{V}(f\mathbf{W})_{ik}M_k^2(\mathbf{W}^\dagger)_{kj}$$

From the mixing matrix W, we can explain ν mixings!!


$\mathrm{Sin}^2[2\theta_{13}]$
$\mathrm{Sin}^2[2\theta_{12}]$
$\mathrm{Sin}^2[2\theta_{23}]$
$\mathrm{Sin}^2[2\theta_{12}]$
$\mathrm{Sin}^2[2\theta_{13}]$
$\mathrm{Sin}^2[2\theta_{23}]$
Very preliminary

Higgs sector at low energy

$$\Phi_1 = \begin{pmatrix} \phi_1^0 \\ \phi_1^+ \\ \eta_1^0 \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^- \\ \phi_2^0 \\ \eta_2^- \end{pmatrix}, \quad \Phi_3 = \begin{pmatrix} \eta_3^0 \\ \eta_3^+ \\ \phi_3^0 \end{pmatrix}, \quad \Phi_\ell = \begin{pmatrix} \eta_\ell^+ \\ \eta_\ell^{++} \\ \phi_\ell^+ \end{pmatrix}$$

Higgs sector at low energy

$$\Phi_1 = \begin{pmatrix} \phi_1^0 \\ \phi_1^+ \\ \boxed{\eta_1^0} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^- \\ \phi_2^0 \\ \boxed{\eta_2^-} \end{pmatrix}, \quad \Phi_3 = \begin{pmatrix} \eta_3^0 \\ \eta_3^+ \\ \phi_3^0 \end{pmatrix}, \quad \Phi_\ell = \begin{pmatrix} \eta_\ell^+ \\ \eta_\ell^{++} \\ \phi_\ell^+ \end{pmatrix}$$

CP-odd

NG bosons (5 degrees of freedom)

Higgs sector at low energy

$$\Phi_1 = \begin{pmatrix} \phi_1^0 \\ \phi_1^+ \\ \boxed{\eta_1^0} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^- \\ \phi_2^0 \\ \boxed{\eta_2^-} \end{pmatrix}, \quad \Phi_3 = \begin{pmatrix} \boxed{\begin{matrix} \eta_3^0 \\ \eta_3^+ \end{matrix}} \\ \phi_3^0 \end{pmatrix}, \quad \Phi_\ell = \begin{pmatrix} \boxed{\begin{matrix} \eta_\ell^+ \\ \eta_\ell^{++} \end{matrix}} \\ \phi_\ell^+ \end{pmatrix}$$

CP-odd

They have an accidental **Z_2-odd** like parity, where

$$\Psi_{\mathrm{SM}} \to +\Psi_{\mathrm{SM}}, \qquad \Psi_{\mathrm{Ext}} \to -\Psi_{\mathrm{Ext}}$$

⇒ The lightest neutral Z_2-odd can be a candidate of **DM**.

Higgs sector at low energy

$$\Phi_1 = \begin{pmatrix} \phi_1^0 \\ \phi_1^+ \\ \boxed{\eta_1^0} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^- \\ \phi_2^0 \\ \boxed{\eta_2^-} \end{pmatrix}, \quad \Phi_3 = \begin{pmatrix} \boxed{\begin{matrix} \eta_3^0 \\ \eta_3^+ \end{matrix}} \\ \phi_3^0 \end{pmatrix}, \quad \Phi_\ell = \begin{pmatrix} \boxed{\begin{matrix} \eta_\ell^+ \\ \eta_\ell^{++} \end{matrix}} \\ \boxed{\phi_\ell^+} \end{pmatrix}$$

CP-even

CP-odd

Decoupled by taking V » v

Higgs sector at low energy

$$\Phi_1 = \begin{pmatrix} \phi_1^0 \\ \phi_1^+ \\ \eta_1^0 \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^- \\ \phi_2^0 \\ \eta_2^- \end{pmatrix}, \quad \Phi_3 = \begin{pmatrix} \eta_3^0 \\ \eta_3^+ \\ \phi_3^0 \end{pmatrix}, \quad \Phi_\ell = \begin{pmatrix} \eta_\ell^+ \\ \eta_\ell^{++} \\ \phi_\ell^+ \end{pmatrix}$$

Remaining Higgs fields at the EW scale

2HDM appears as the EFT.

Higgs basis

- Higgs basis can be defined in the same way as in the 2HDM.

$$\Phi_1 = \left.\begin{pmatrix} \phi_1^0 \\ \phi_1^+ \\ \eta_1^0 \end{pmatrix}\right., \quad \Phi_2 = \begin{pmatrix} \phi_2^- \\ \phi_2^0 \\ \eta_2^- \end{pmatrix}$$

$$\begin{pmatrix} \phi_1^0 \\ \phi_1^+ \end{pmatrix} = \boldsymbol{\phi_1}, \quad \begin{pmatrix} \phi_2^- \\ \phi_2^0 \end{pmatrix} = \boldsymbol{\phi_2}$$

$$\begin{pmatrix} \phi_1 \\ \phi_2^c \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \boxed{\phi} \\ \boxed{\phi'} \end{pmatrix}$$

$$\boldsymbol{\phi = \begin{pmatrix} G^+ \\ \frac{v + h_1' + iG^0}{\sqrt{2}} \end{pmatrix}}$$

$$\boldsymbol{\phi' = \begin{pmatrix} H^+ \\ \frac{h_2' + iA}{\sqrt{2}} \end{pmatrix}}$$

$$\begin{pmatrix} h_1' \\ h_2' \end{pmatrix} = \begin{pmatrix} c_{\beta-\alpha} & s_{\beta-\alpha} \\ -s_{\beta-\alpha} & c_{\beta-\alpha} \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

Effective Yukawa interactions

$$\mathcal{L}_Y^{\text{eff}} = \begin{pmatrix} \bar{\ell}_L^1 & \bar{\ell}_L^2 & \bar{\ell}_L^3 \end{pmatrix} \begin{pmatrix} \mathbf{3} \times \mathbf{3} \end{pmatrix} \phi_1 \begin{pmatrix} e_R \\ \mu_R \\ \tau_R \end{pmatrix}$$

$$+ \begin{pmatrix} \bar{q}_L^1 & \bar{q}_L^2 & \bar{q}_L^3 \end{pmatrix} \begin{pmatrix} \mathbf{3} \times \mathbf{2} & \begin{matrix} \phi_2^c \\ \phi_2^c \end{matrix} \\ \mathbf{3} \times \mathbf{1} & \phi_1 \end{pmatrix} \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix} + \begin{pmatrix} \bar{q}_L^1 & \bar{q}_L^2 & \bar{q}_L^3 \end{pmatrix} \begin{pmatrix} \mathbf{3} \times \mathbf{2} & \begin{matrix} \phi_1^c \\ \phi_1^c \end{matrix} \\ \mathbf{3} \times \mathbf{1} & \phi_2 \end{pmatrix} \begin{pmatrix} u_R \\ c_R \\ t_R \end{pmatrix}$$

Effective Yukawa interactions

$$\mathcal{L}_Y^{\text{eff}} = \begin{pmatrix} \bar{\ell}_L^1 & \bar{\ell}_L^2 & \bar{\ell}_L^3 \end{pmatrix} \begin{pmatrix} \mathbf{3} \times \mathbf{3} \end{pmatrix} \phi_1 \begin{pmatrix} e_R \\ \mu_R \\ \tau_R \end{pmatrix}$$

Flavor dependent structure

$$+ \begin{pmatrix} \bar{q}_L^1 & \bar{q}_L^2 & \bar{q}_L^3 \end{pmatrix} \begin{pmatrix} \mathbf{3} \times \mathbf{2} & \begin{matrix} \phi_2^c \\ \phi_2^c \end{matrix} \\ \mathbf{3} \times \mathbf{1} & \phi_1 \end{pmatrix} \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix} + \begin{pmatrix} \bar{q}_L^1 & \bar{q}_L^2 & \bar{q}_L^3 \end{pmatrix} \begin{pmatrix} \mathbf{3} \times \mathbf{2} & \begin{matrix} \phi_1^c \\ \phi_1^c \end{matrix} \\ \mathbf{3} \times \mathbf{1} & \phi_2 \end{pmatrix} \begin{pmatrix} u_R \\ c_R \\ t_R \end{pmatrix}$$

Effective Yukawa interactions

$$\mathcal{L}_Y^{\text{eff}} = (\bar{\ell}_L^1 \quad \bar{\ell}_L^2 \quad \bar{\ell}_L^3) \begin{pmatrix} \mathbf{3} \times \mathbf{3} \end{pmatrix} \phi_1 \begin{pmatrix} e_R \\ \mu_R \\ \tau_R \end{pmatrix}$$

Flavor dependent structure

$$+ (\bar{q}_L^1 \quad \bar{q}_L^2 \quad \bar{q}_L^3) \begin{pmatrix} \mathbf{3} \times \mathbf{2} & \begin{matrix} \phi_2^c \\ \phi_2^c \end{matrix} \\ \mathbf{3} \times \mathbf{1} & \phi_1 \end{pmatrix} \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix} + (\bar{q}_L^1 \quad \bar{q}_L^2 \quad \bar{q}_L^3) \begin{pmatrix} \mathbf{3} \times \mathbf{2} & \begin{matrix} \phi_1^c \\ \phi_1^c \end{matrix} \\ \mathbf{3} \times \mathbf{1} & \phi_2 \end{pmatrix} \begin{pmatrix} u_R \\ c_R \\ t_R \end{pmatrix}$$

$$= \frac{\sqrt{2}}{v} \left[\bar{\ell}_L M_e^{\text{diag}} \phi e_R + \bar{q}_L M_d^{\text{diag}} \phi d_R + \bar{q}_L M_u^{\text{diag}} \phi^c u_R \right]$$

$$+ \frac{\sqrt{2}}{v} \left(- \tan\beta \bar{\ell}_L M_e^{\text{diag}} \phi' e_R + \bar{q}_L \Gamma_d \phi' d_R + \bar{q}_L \Gamma_u \phi'^c u_R \right)$$

Higgs basis

Effective Yukawa interactions

$$\mathcal{L}_Y^{\rm eff} = \begin{pmatrix} \bar{\ell}_L^1 & \bar{\ell}_L^2 & \bar{\ell}_L^3 \end{pmatrix} \begin{pmatrix} \mathbf{3 \times 3} \end{pmatrix} \phi_1 \begin{pmatrix} e_R \\ \mu_R \\ \tau_R \end{pmatrix}$$

Flavor dependent structure

$$+ \begin{pmatrix} \bar{q}_L^1 & \bar{q}_L^2 & \bar{q}_L^3 \end{pmatrix} \begin{pmatrix} \mathbf{3 \times 2} & \begin{matrix} \phi_2^c \\ \phi_2^c \end{matrix} \\ \mathbf{3 \times 1} & \phi_1 \end{pmatrix} \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix} + \begin{pmatrix} \bar{q}_L^1 & \bar{q}_L^2 & \bar{q}_L^3 \end{pmatrix} \begin{pmatrix} \mathbf{3 \times 2} & \begin{matrix} \phi_1^c \\ \phi_1^c \end{matrix} \\ \mathbf{3 \times 1} & \phi_2 \end{pmatrix} \begin{pmatrix} u_R \\ c_R \\ t_R \end{pmatrix}$$

$$= \frac{\sqrt{2}}{v} \left[\bar{\ell}_L M_e^{\rm diag} \phi e_R + \bar{q}_L M_d^{\rm diag} \phi d_R + \bar{q}_L M_u^{\rm diag} \phi^c u_R \right]$$

$$+ \frac{\sqrt{2}}{v} \left(-\tan\beta \bar{\ell}_L M_e^{\rm diag} \phi' e_R + \boxed{\bar{q}_L \Gamma_d \phi' d_R + \bar{q}_L \Gamma_u \phi'^c u_R} \right)$$

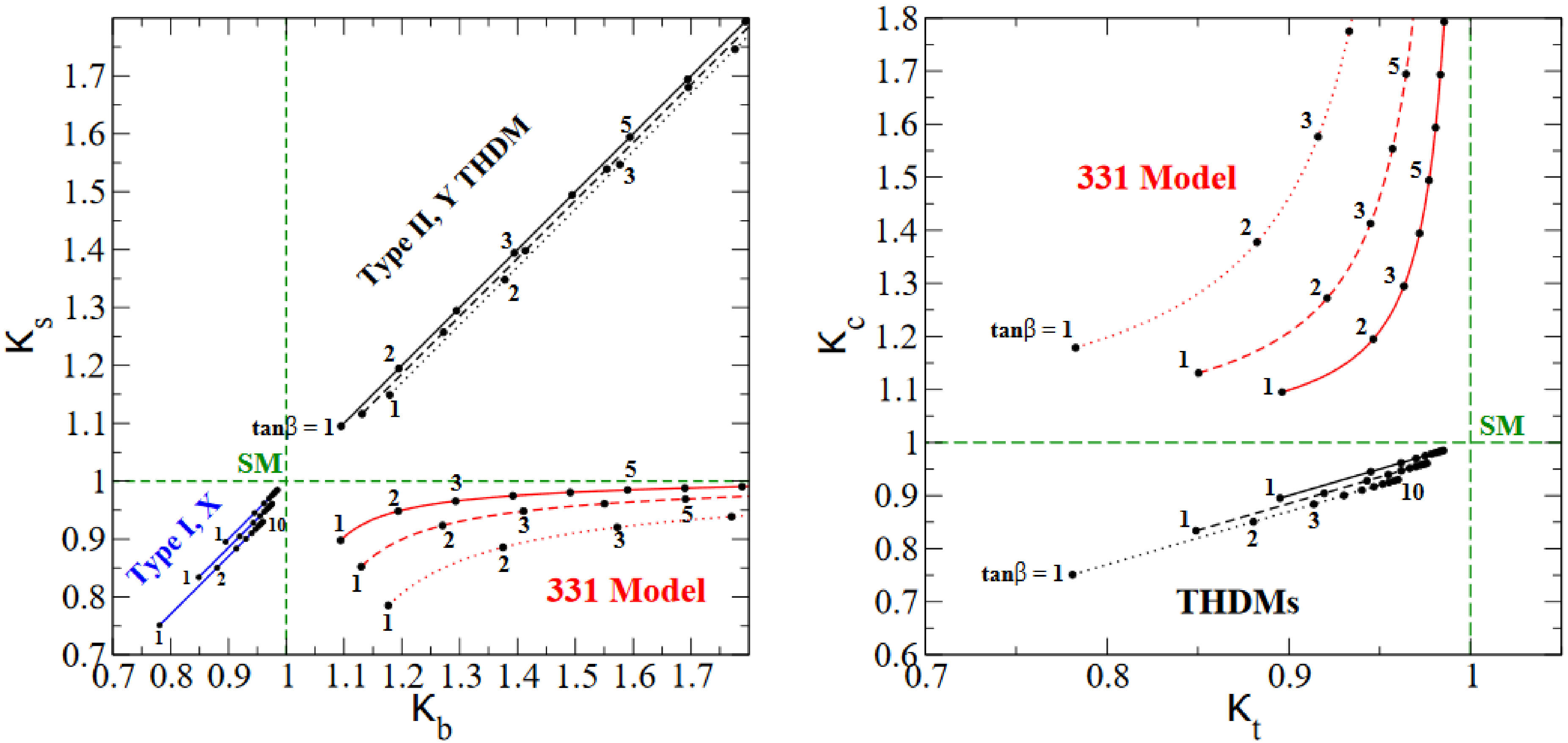
Higgs basis

Flavor off-diagonal elements appear

$$\Gamma_d = (V_L^d)^\dagger \begin{pmatrix} \cot\beta & 0 & 0 \\ 0 & \cot\beta & 0 \\ 0 & 0 & -\tan\beta \end{pmatrix} V_L^d M_d^{\rm diag} \qquad \Gamma_u = (V_L^u)^\dagger \begin{pmatrix} -\tan\beta & 0 & 0 \\ 0 & -\tan\beta & 0 \\ 0 & 0 & \cot\beta \end{pmatrix} V_L^u M_u^{\rm diag}$$

Higgs boson couplings

H. Okada, N. Okada, Y. Orikasa, KY, 1604.01948 (PRD)



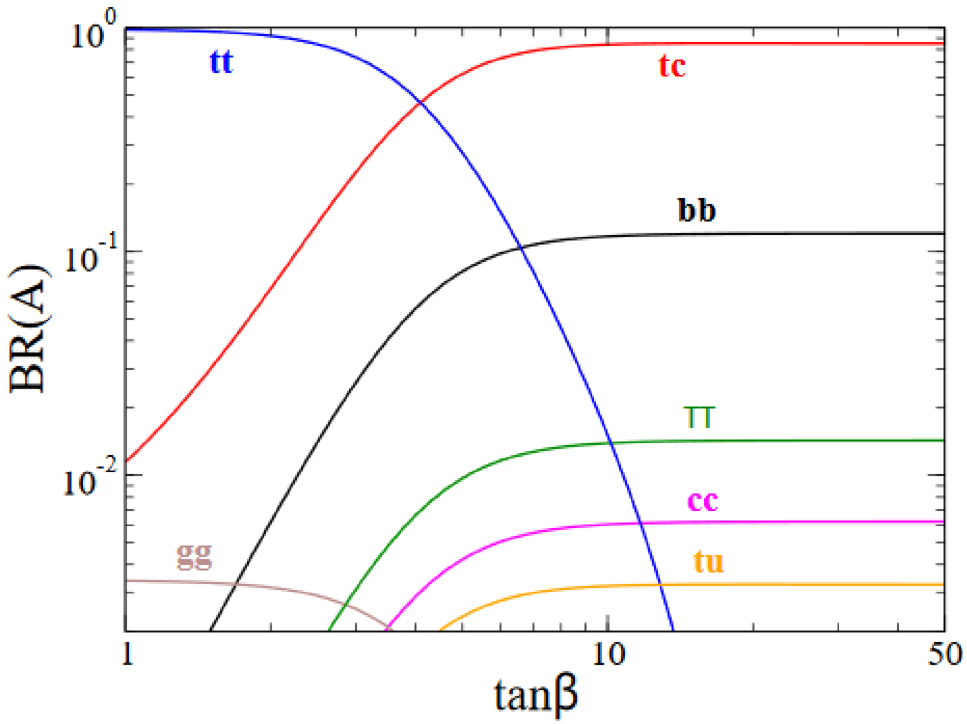
Deviations in quark Yukawa couplings depend on the flavor.

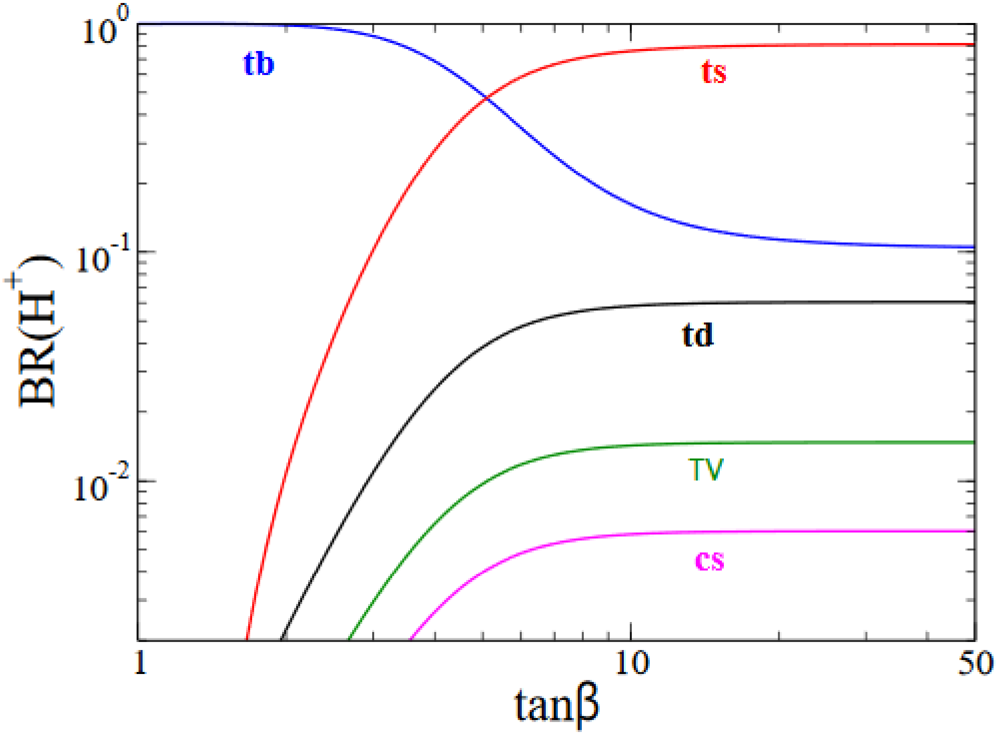
This pattern does not appear in the usual Z_2 symmetric 2HDMs.

Extra Higgs boson decays

H. Okada, N. Okada, Y. Orikasa, KY, 1604.01948 (PRD)

$m_A = m_H = m_{H+} = 600$ GeV, $\sin(\beta\text{-}\alpha) = 1$





Flavor violating decays of **A → tc** and **H⁺ → ts** can be dominant.

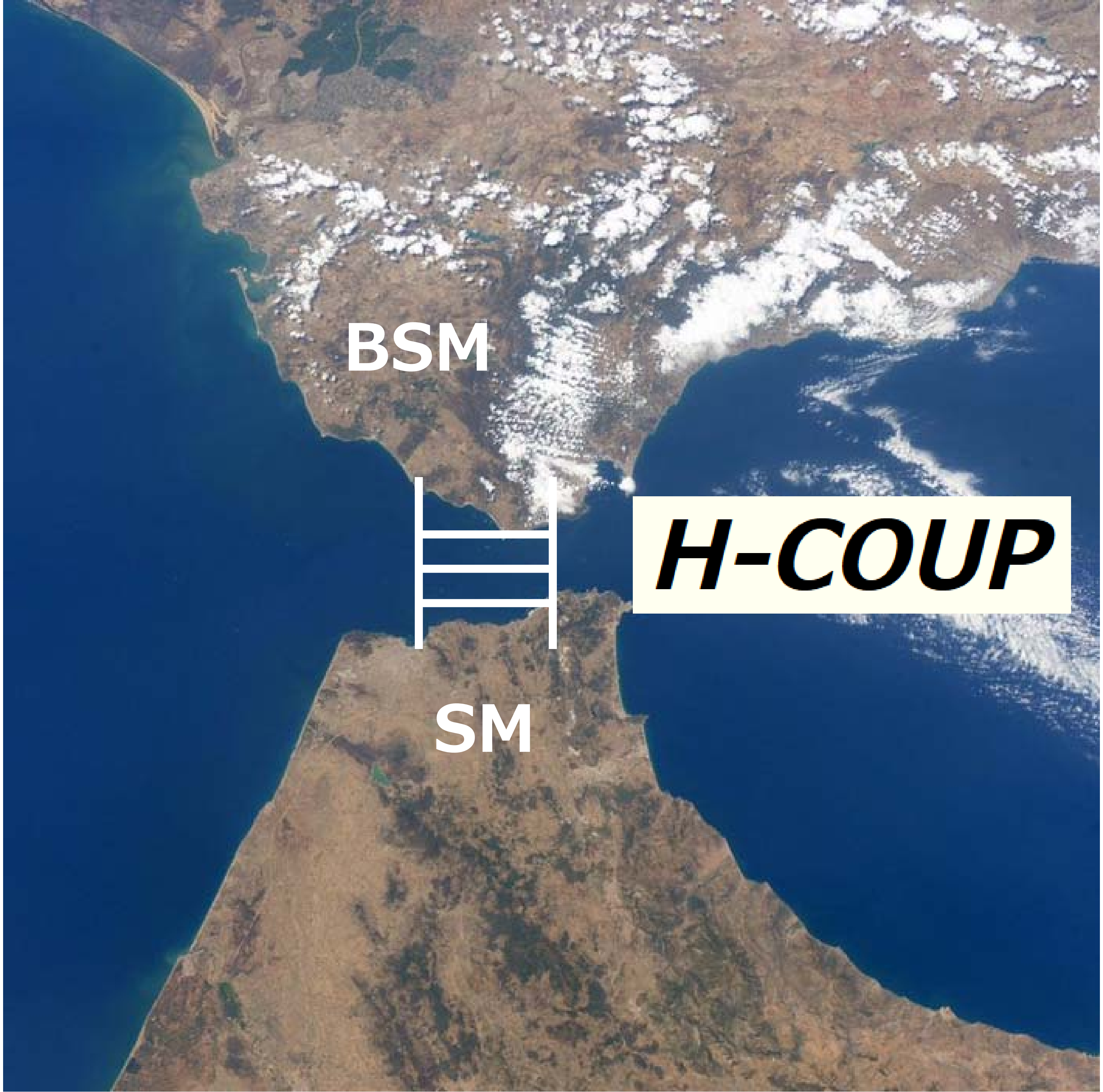
Summary

- Origin of 3 generations can be explained in 331 models.

- Tiny neutrino masses and mixings can be explained by the radiative seesaw mechanism within the 331 model.

- Our 331 model predicts a 2HDM as low energy EFT.

- The quark Yukawa structure is different from usual Z_2 symmetric 2HDMs.


BSM
H-COUP
SM