Radiative neutrino mass generation and Lepton flavor violation

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Based on T.N. and K. Yagyu, JHEP 1910 (2019) 105

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Neutrino mass is one of the mystery in particle physics

Non-zero neutrino mass

- **We need a mechanism to generate neutrino mass**
- **Also smallness of the mass should be explained**

Neutrino mixing

- **Mixing is described by PMNS mixing matrix**
- **What is origin of flavor structure?**

$$U_{\mathrm{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \mathrm{diag}(1, e^{i\alpha_{21}/2}, e^{i\alpha_{31}/2})$$

Neutrino mass is one of the mystery in particle physics

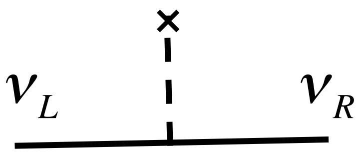
Observables from neutrino oscillation experiments

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK-atm	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.62 \to 36.27$
	$\sin^2\theta_{23}$	$0.582^{+0.015}_{-0.019}$	$0.428 \to 0.624$	$0.582^{+0.015}_{-0.018}$	$0.433 \to 0.623$
	$\theta_{23}/^\circ$	$49.7^{+0.9}_{-1.1}$	$40.9 \to 52.2$	$49.7^{+0.9}_{-1.0}$	$41.2 \to 52.1$
	$\sin^2\theta_{13}$	$0.02240^{+0.00065}_{-0.00066}$	$0.02044 \to 0.02437$	$0.02263^{+0.00065}_{-0.00066}$	$0.02067 \to 0.02461$
	$\theta_{13}/^\circ$	$8.61^{+0.12}_{-0.13}$	$8.22 \to 8.98$	$8.65^{+0.12}_{-0.13}$	$8.27 \to 9.03$
	$\delta_{CP}/^\circ$	217^{+40}_{-28}	$135 \to 366$	280^{+25}_{-28}	$196 \to 351$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.525^{+0.033}_{-0.031}$	$+2.431 \to +2.622$	$-2.512^{+0.034}_{-0.031}$	$-2.606 \to -2.413$

arxiV:1811.05487

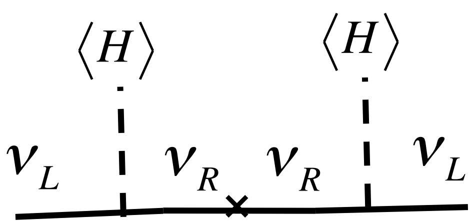
Neutrino mass generation ?

Dirac type:



Seesaw mechanisms

Type-I



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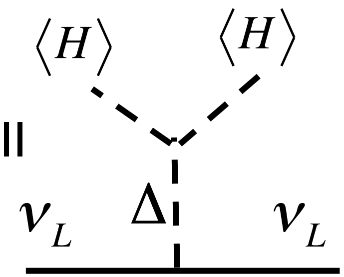
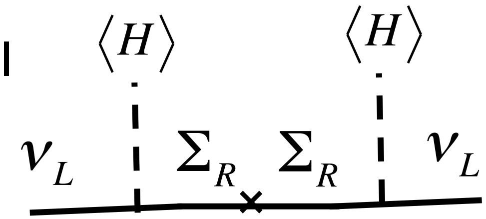


Type-III



Neutrino mass is generate at tree level

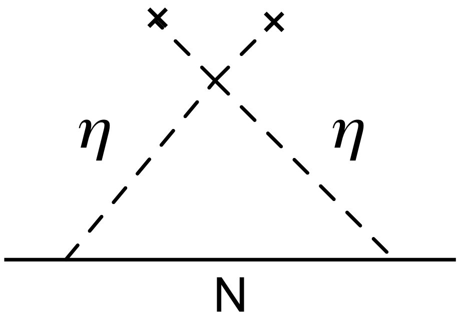
⇨ Heavy masses and/or small couplings are required

Alternative mechanism ➡ Mass generation @ loop level

1. Introduction

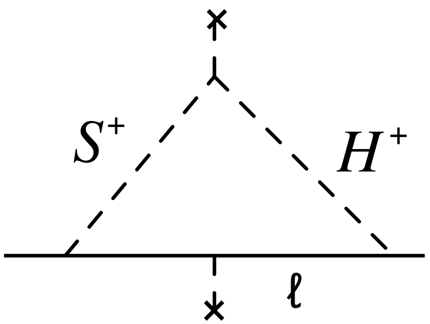
Neutrino mass generation via loop diagram

Examples of one-loop generation model



Scotogenic model (η: inert doublet)

Ma (2006)



× :Higgs VEV

Zee-model (S^+ :charged scalar)

Zee (1980)

☐ Zee model

- ➢ It is based on two Higgs doublet model (THDM) + singlet charged scalar
- ➢ No right-handed neutrino

☐ Scotogenic model

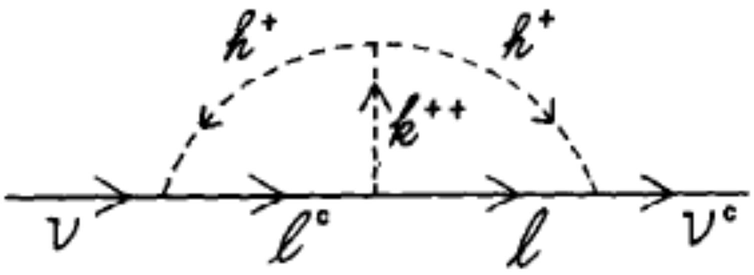
- ➢ Tree level neutrino mass is forbidden by Z_2 symmetry in scotogenic model
- ➢ The lightest Z_2 odd neutral particle can be DM

Neutrino mass generation via loop diagram

Example of two-loop generation model

□Zee-Babu model

Babu (1986)



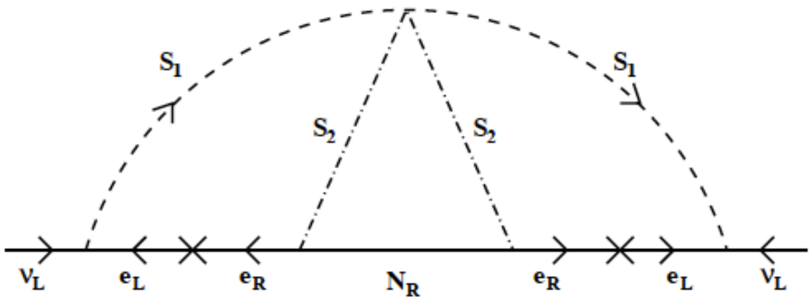
$$L \supset f_{ij}\overline{L}_i^c L_j h^+ + g_{ij}\overline{e}_R^i e_R^j k^{++} + h.c.$$

- Singly and doubly charged scalars are introduced
- No right-handed neutrino
- Majorana neutrino mass is induced

Neutrino mass generation via loop diagram

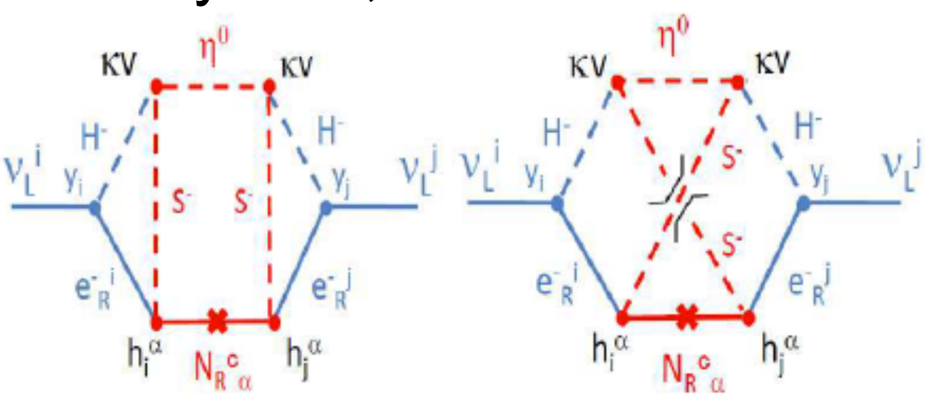
Example of three-loop generation model

□Model by Krauss, Nasri and Trodden (2002)



With Z_2 symmetry

□Model by Aoki, Kanemura and Seto (2008)



$Z_2 \times Z_2$ symmetry

Higher loop generation ⇨ More symmetry and new particles

Neutrino mass generation via loop diagram

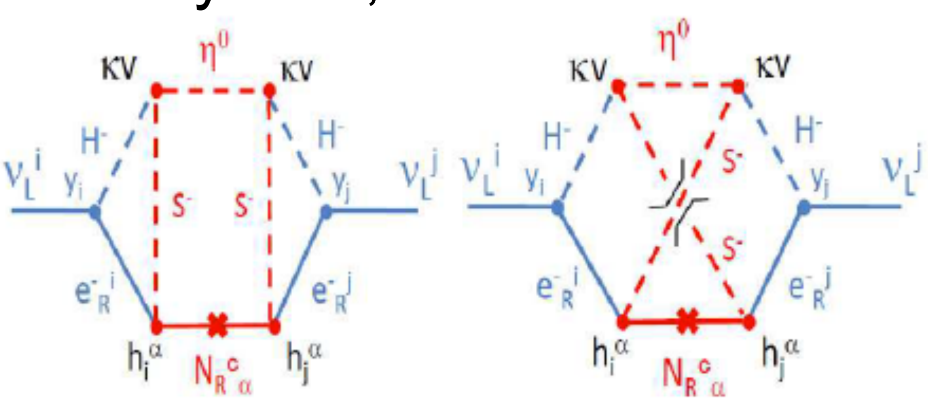
Example of three-loop generation model

- Model by Krauss, Nasri and Trodden (2002)

Four loop generation is also possible

T.N. and Hiroshi Okada PLB755 (2016)
T.N. and Hiroshi Okada PLB770 (2017)

- Model by Aoki, Kanemura and Seto (2008)



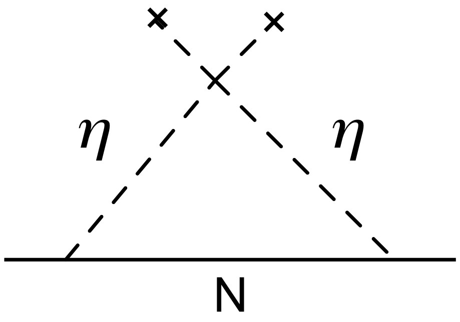
$Z_2 \times Z_2$ symmetry

Higher loop generation ⇨ More symmetry and new particles

Radiative neutrino mass and LFV

In general we have LFV in radiative neutrino mass models

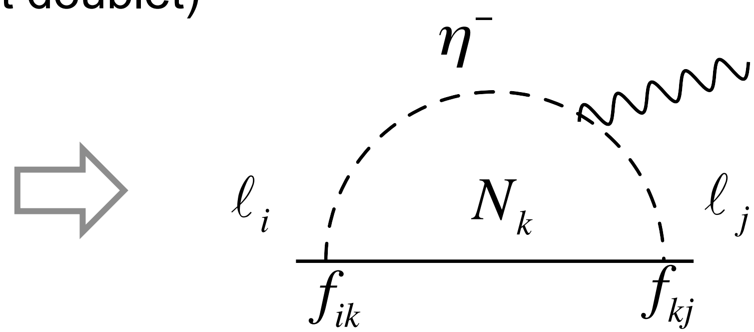
EX)



$$L \supset f_{ij} \bar{L}_i \eta N + h.c.$$

Flavor dependent coupling

Scotogenic model (η: inert doublet)



LFV decay is induced from Yukawa coupling

Experimental constraints should be taken into account

Ex) $\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ MEG (2016)

One interesting approach in controlling flavor

⇨ Applying flavor symmetry

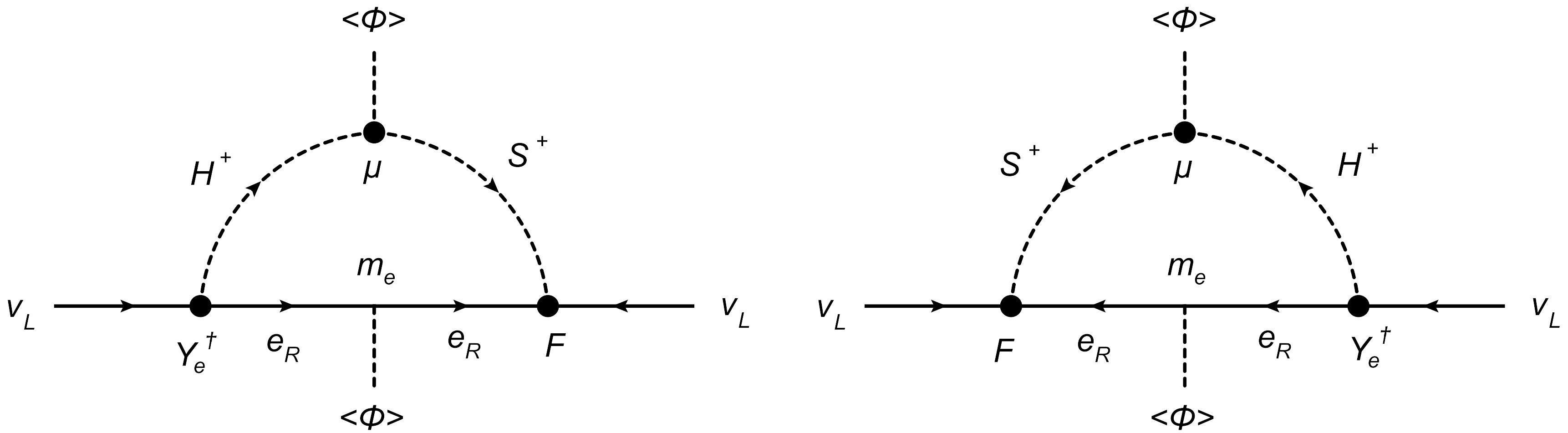
Radiative neutrino mass model + flavor symmetry

In this talk we discuss…

Zee model with global U(1) flavor symmetry

T.N. and K. Yagyu, JHEP 1910 (2019) 105

Original Zee-model for neutrino mass



One-loop mass generation

Realized by SM + second Higgs doublet + charged scalar

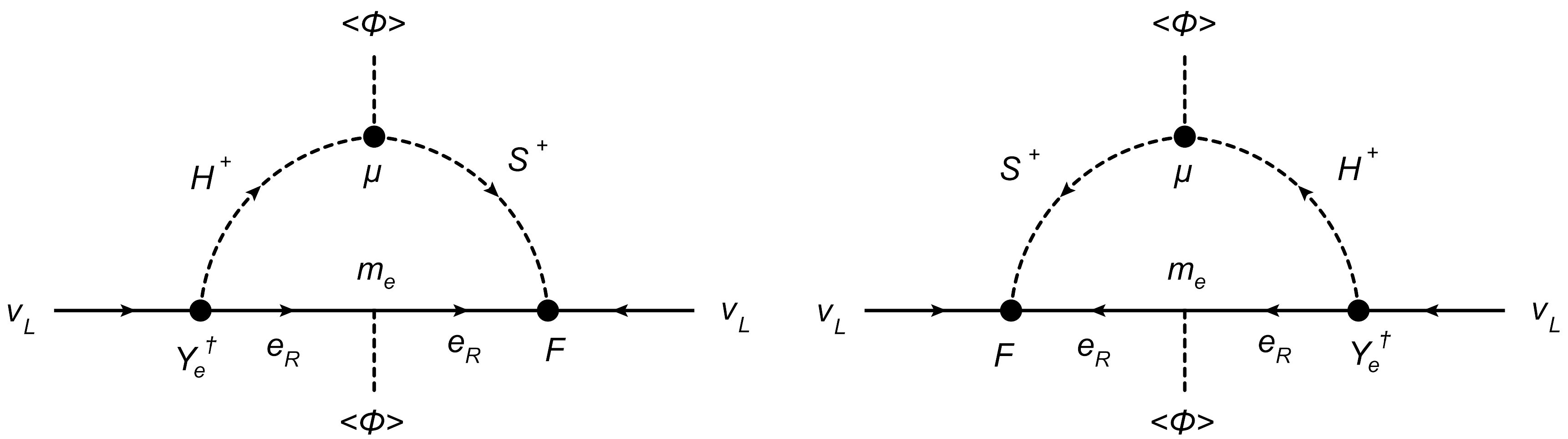
Softly-broken Z_2 symmetry is assigned to forbid FCNC: $\Phi_2 \to -\Phi_2$

	Q_L^i	u_R^i	d_R^i	L_L^i	ℓ_R^i	Φ_1	Φ_2	S^+
$SU(3)_c$	**3**	**3**	**3**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**2**	**2**	**1**
$U(1)_Y$	1/6	2/3	−1/3	−1/2	−1	1/2	1/2	1

$$L \supset F_{ij} \overline{L}_L^{ic} L_L^j S^+ + \frac{\sqrt{2} m_\ell}{v} \cot\beta \overline{\nu}_L e_R H^+$$
$$+ \mu \left[\Phi_1^T (i\sigma_2) \Phi_2 (S^+)^* + h.c. \right]$$

Zee (1980)

Original Zee-model for neutrino mass



One-loop mass generation
Realized by SM + second Higgs doublet + charged scalar

Softly broken Z_2 symmetry is assigned to forbid FCNC: $\Phi_2 \rightarrow -\Phi_2$

⇨ Current neutrino oscillation data can not be fitted

- ✓ We relax Z_2 symmetry to get more general structure of couplings
- ✓ To avoid FCNC in quark sector, we introduce global U(1) symmetry

Zee-model with global U(1) symmetry

T.N. and K. Yagyu, JHEP 1910 (2019) 105

- We assign global U(1) charge for leptons and scalars

	Q_L^i	u_R^i	d_R^i	L_L^i	ℓ_R^i	Φ_1	Φ_2	S^+
$SU(3)_c$	**3**	**3**	**3**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**2**	**2**	**1**
$U(1)_Y$	1/6	2/3	−1/3	−1/2	−1	1/2	1/2	1
$U(1)'$	0	0	0	q_L^i	q_R^i	q	0	q_S

Particle contents are the same as the original Zee-model

Lepton flavor dependent

◆ Yukawa interactions

$$-L_Y = \left(\tilde{Y}_u\right)_{ij} \bar{Q}_L^i \Phi_2^c u_R^j + \left(\tilde{Y}_d\right)_{ij} \bar{Q}_L^i \Phi_2 d_R^j + \left(\tilde{Y}_\ell^1\right)_{ij} \bar{L}_L^i \Phi_1 \ell_R^j + \left(\tilde{Y}_\ell^2\right)_{ij} \bar{L}_L^i \Phi_2 \ell_R^j + \tilde{F}_{ij} \bar{L}_L^{ci} (i\sigma_2) L_L^j S^+ + h.c.$$

◆ Relevant term for neutrino mass generation in Higgs potential

$$V \supset \mu\left[\Phi_1^T (i\sigma_2) \Phi_2 (S^+)^* + h.c.\right]$$

Structure of Yukawa coupling with global U(1)

- **Class I :** $q_R = (0,0,-q), \quad q_L = q_S = 0$

$$\Rightarrow \quad \tilde{Y}_\ell^1 = \begin{pmatrix} 0 & 0 & \times \\ 0 & 0 & \times \\ 0 & 0 & \times \end{pmatrix}, \quad \tilde{Y}_\ell^2 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ \times & \times & 0 \end{pmatrix}, \quad \tilde{F} = \begin{pmatrix} 0 & \times & \times \\ & 0 & \times \\ & & 0 \end{pmatrix},$$

- **Class II :** $q_R = 0, \quad q_L = (0,0,q), \quad q_S = -q$

$$\Rightarrow \quad \tilde{Y}_\ell^1 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}, \quad \tilde{Y}_\ell^2 = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix} \quad \tilde{F} = \begin{pmatrix} 0 & 0 & \times \\ & 0 & \times \\ & & 0 \end{pmatrix}$$

- **Class III :** $q_R = (0,0,q), \quad q_L = (0,0,-2q), \quad q_S = q$

$$\Rightarrow \quad \tilde{Y}_\ell^1 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}, \quad \tilde{Y}_\ell^2 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \tilde{F} = \begin{pmatrix} 0 & 0 & \times \\ & 0 & \times \\ & & 0 \end{pmatrix}$$

Structure of Yukawa coupling with global U(1)

- **Class I :** $q_R = (0,0,-q), \quad q_L = q_S = 0$

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$$\Rightarrow \quad \tilde{Y}_\ell^1 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}, \quad \tilde{Y}_\ell^2 = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix} \quad \tilde{F} = \begin{pmatrix} 0 & 0 & \times \\ & 0 & \times \\ & & 0 \end{pmatrix}$$

- **Class III :** $q_R = (0,0,q), \quad q_L = (0,0,-2q), \quad q_S = q$

$$\Rightarrow \quad \tilde{Y}_\ell^1 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}, \quad \tilde{Y}_\ell^2 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \tilde{F} = \begin{pmatrix} 0 & 0 & \times \\ & 0 & \times \\ & & 0 \end{pmatrix}$$

Charged lepton mass and relevant couplings

Charged lepton mass:

$$M_\ell = \frac{v}{\sqrt{2}}\left(c_\beta \tilde{Y}_\ell^1 + s_\beta \tilde{Y}_\ell^2\right)$$

$$\ell_{L,R} \to U_{L,R}\ell_{L,R}$$

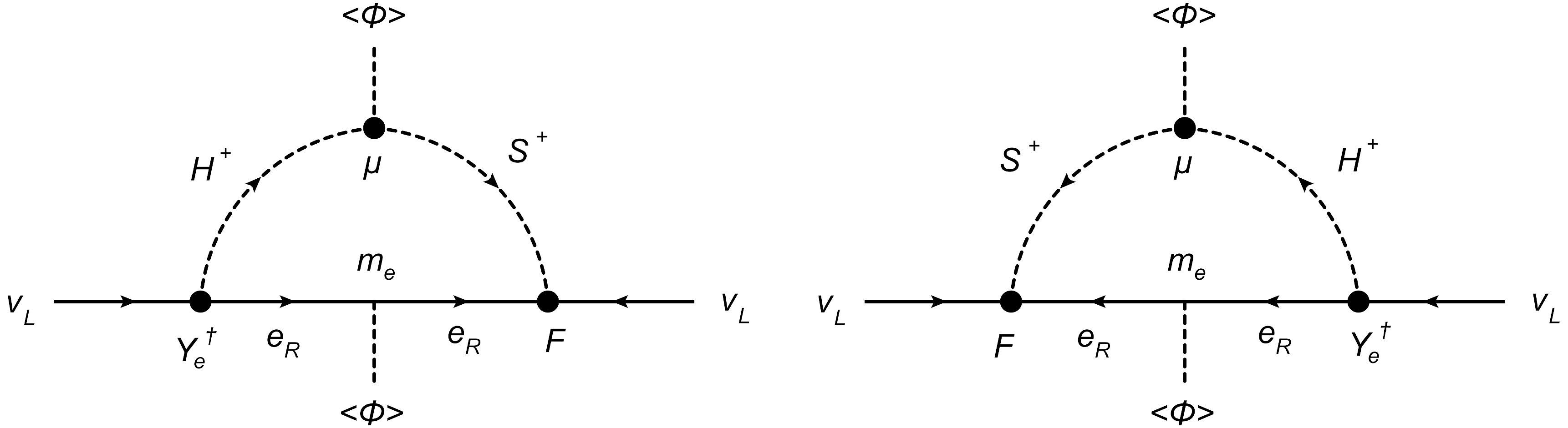
$$\Longrightarrow \quad U_L^\dagger M_\ell U_R = \left(m_e, m_\mu, m_\tau\right)$$

Couplings in charged lepton mass basis

$$-L_Y \supset \begin{pmatrix} \bar{\nu}_L & \bar{\ell}_L \end{pmatrix}\left[\frac{\sqrt{2}}{v}\begin{pmatrix} M_\ell U_R G^+ \\ m_\ell \Phi^0 \end{pmatrix} + \begin{pmatrix} Y_\ell H^+ \\ Y_\ell^0 \Phi'^0 \end{pmatrix}\right]\ell_R - 2F\bar{\nu}^c \ell_R S^+ + h.c.$$

$$\left(\begin{array}{l} Y_\ell^0 = U_L^\dagger \tilde{Y}_\ell U_R, \quad Y_e = \tilde{Y}_\ell U_R, \quad \left(\tilde{Y}_\ell = -s_\beta \tilde{Y}_\ell^1 + c_\beta \tilde{Y}_\ell^2\right) \\ F = \tilde{F} U_R \end{array}\right)$$

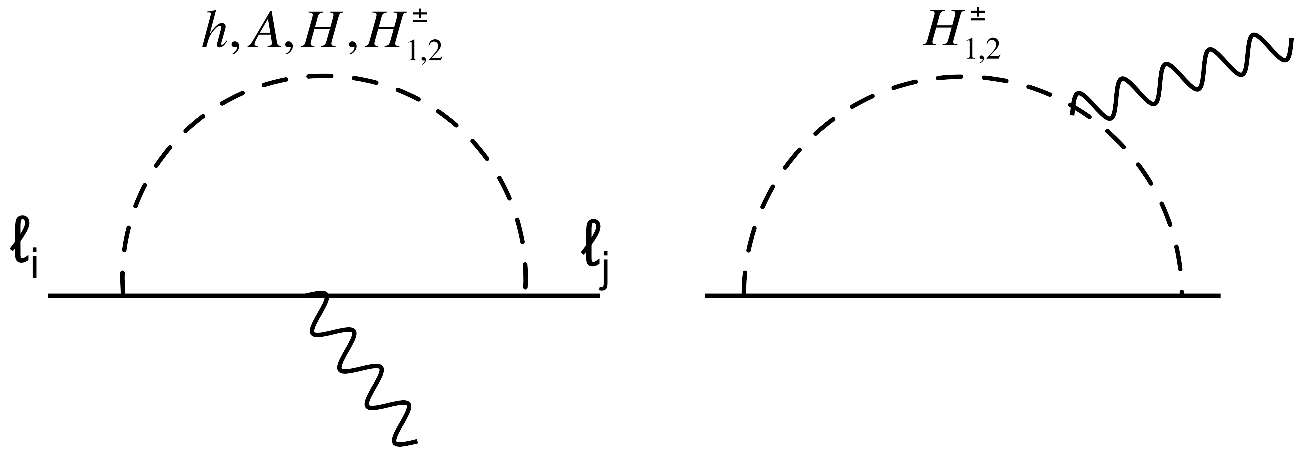
Neutrino mass generation at one loop level



$$M_\nu^{ij} = \frac{1}{16\pi^2} \frac{\sqrt{2} v \mu}{m_{H_2^\pm}^2 - m_{H_1^\pm}^2} \ln\left(\frac{m_{H_2^\pm}^2}{m_{H_1^\pm}^2}\right)\left(F m_\ell Y_\ell^\dagger\right) + \left(i \leftrightarrow j\right)$$

✓ Two charged scalar mass eigenstate : $H_1^\pm, H_2^\pm$

□ LFV decay of charged lepton $\ell_i \to \ell_j \gamma$



$$\frac{BR(\ell_i \to \ell_j \gamma)}{BR(\ell_i \to \ell_j \nu_i \bar{\nu}_j)} \approx \frac{48\pi^3 \alpha_{em}}{G_F^2 m_{\ell_i}^2} \left(\left| \sum_{\phi} (a_R^{\phi})_{ij} \right|^2 + \left| \sum_{\phi} (a_L^{\phi})_{ij} \right|^2 \right) \qquad \phi = h, H, A, H_1^{\pm}$$

[$a^{\phi}_{L,R}$: Amplitude estimated from diagrams and given by Yukawa couplings]

1. Introduction
2. Zee-model with flavor symmetry
3. Prediction for LFV
4. Summary and discussion

Numerical analysis

Searching for Yukawa couplings with mixing $U_{L,R}$ satisfying:

$$\{F_{ij}, (Y_\ell)_{ij}\}$$

- Charged lepton mass
- Neutrino mass matrix which can fit neutrino oscillation data

Calculate BRs for CLFV processes by allowed parameters

- Imposing constraint on $\ell_i \to \ell_j \gamma$:

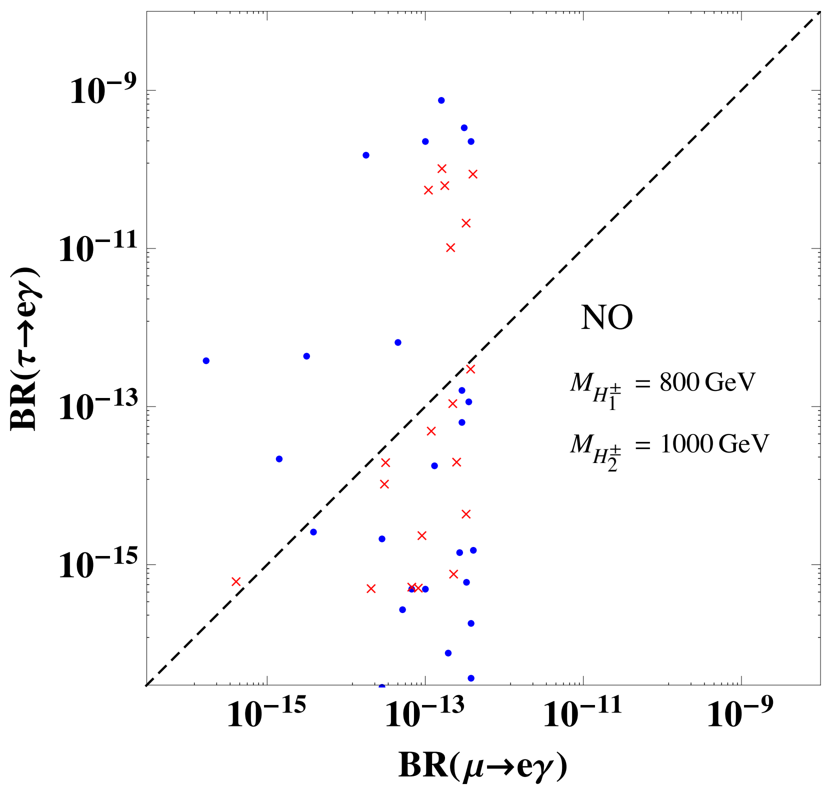
$$\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}, \ \mathrm{BR}(\tau \to e\gamma) < 3.3 \times 10^{-8}, \ \mathrm{BR}(\tau \to \mu\gamma) < 4.4 \times 10^{-8},$$

MEG(2016) Belle(2008) Babar(2010)

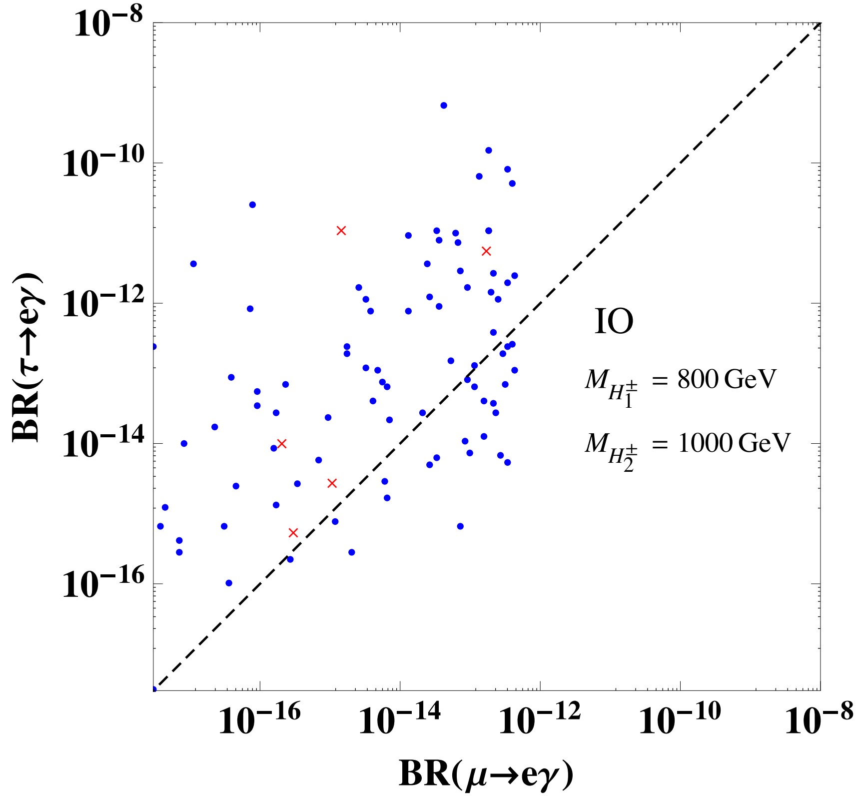
- Prediction for LFV decay of heavy Higgs H

◆ Correlation between BR of μ→eγ and τ→eγ

Normal ordering



Inverted ordering



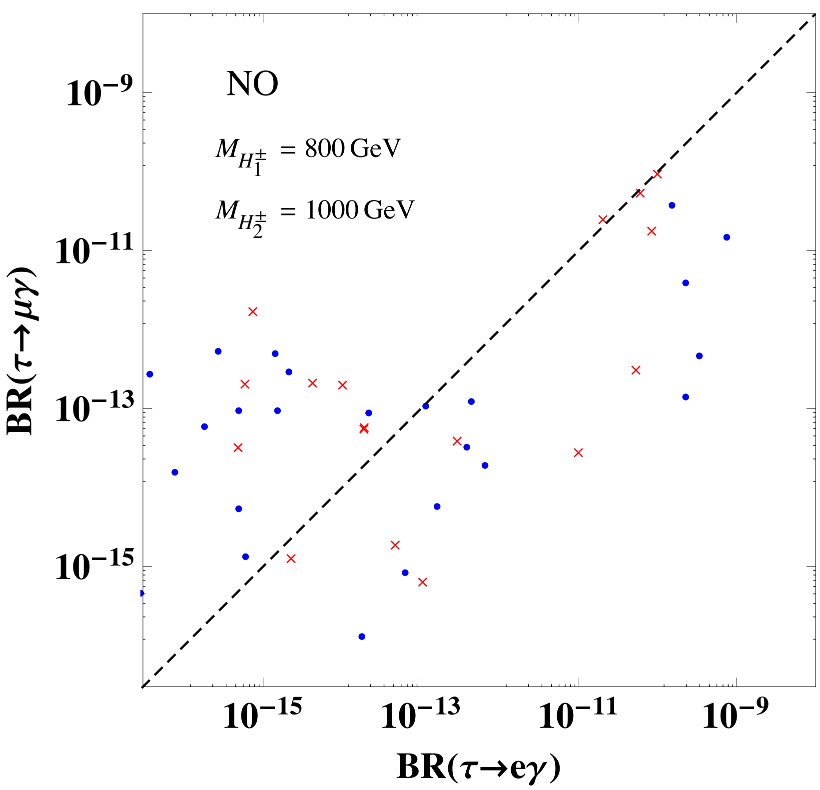
Blue dot : 1 < tanβ < 10, Red cross : 10 < tanβ < 30

✓ Normal ordering case tends to give larger BR(μ→eγ)

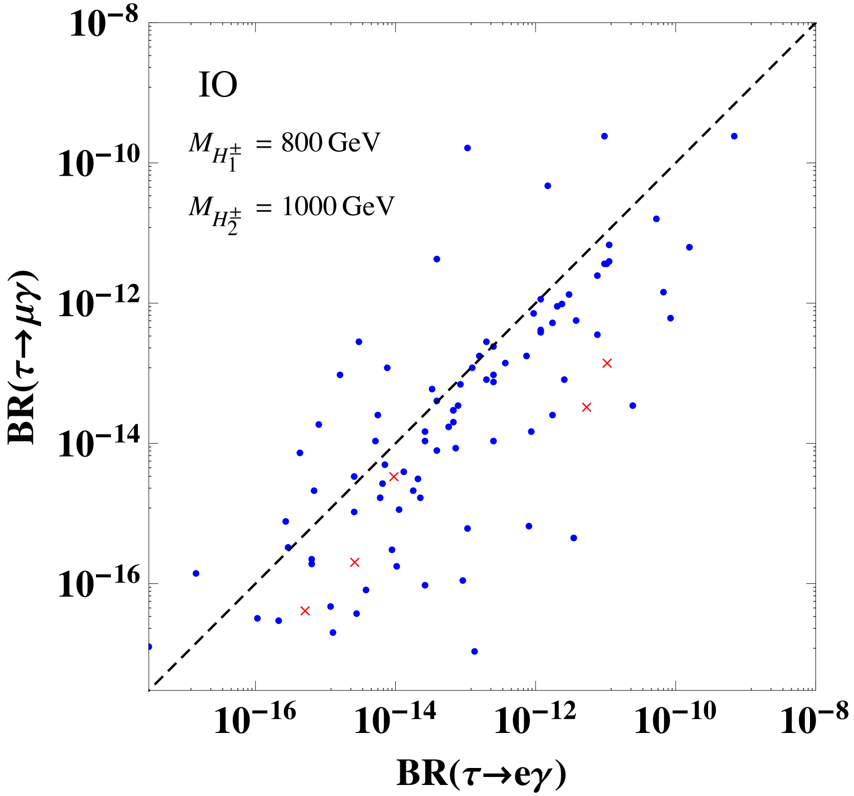
3. Prediction for LFV

◆ Correlation between BR of τ→eγ and τ→μγ

Normal ordering

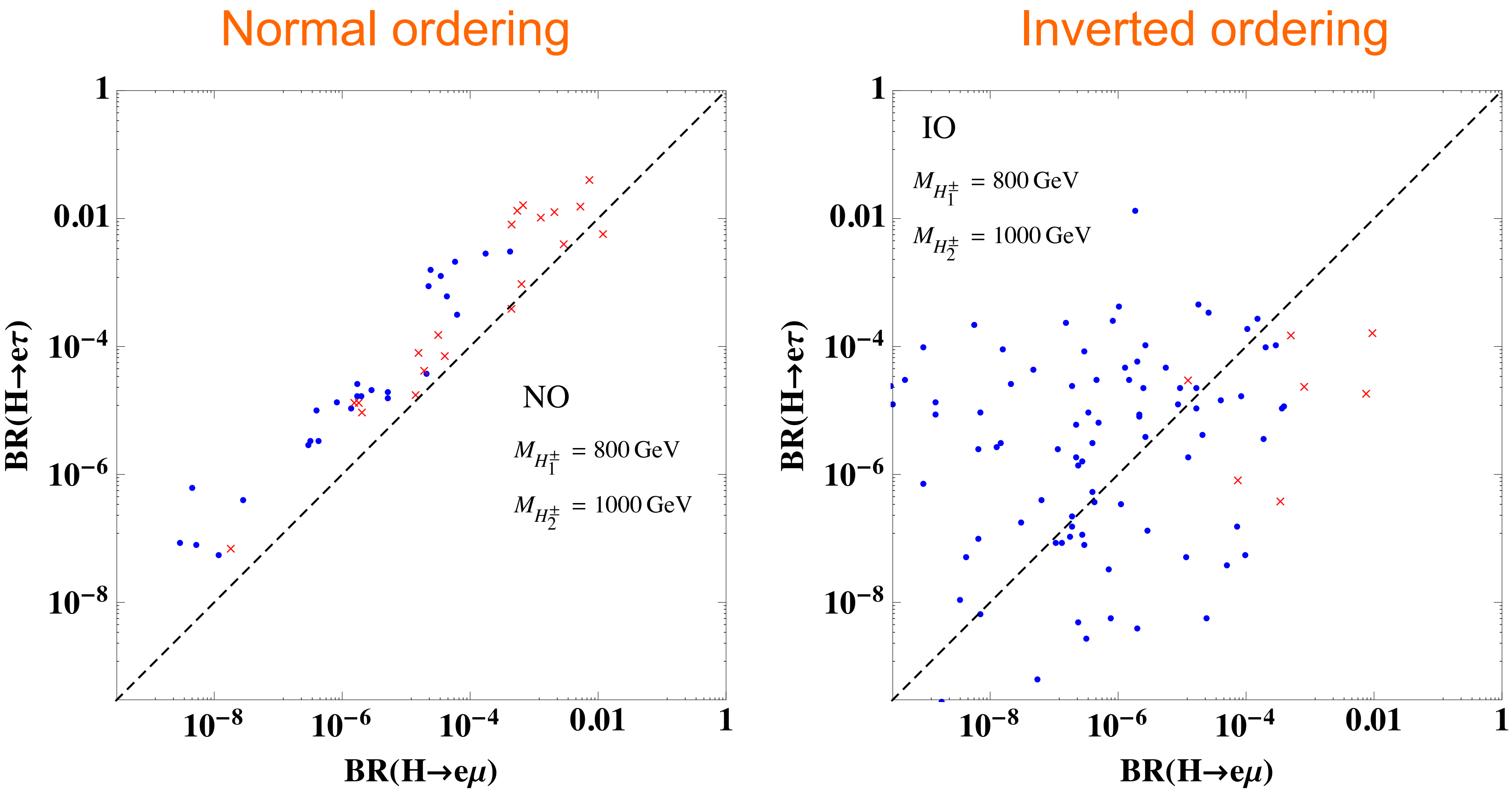


Inverted ordering



✓ BRs are more correlated for inverted ordering case

◆ Correlation between BR of H→eμ and H→eτ

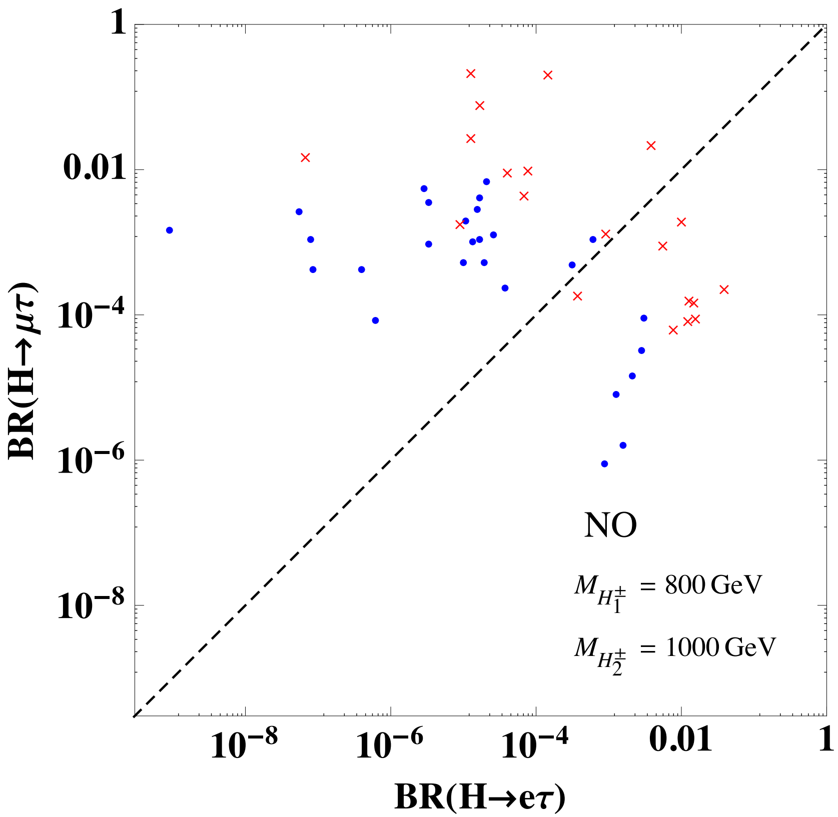


- ✓ Correlation in normal ordering case
- ✓ Inverted ordering case is less correlated

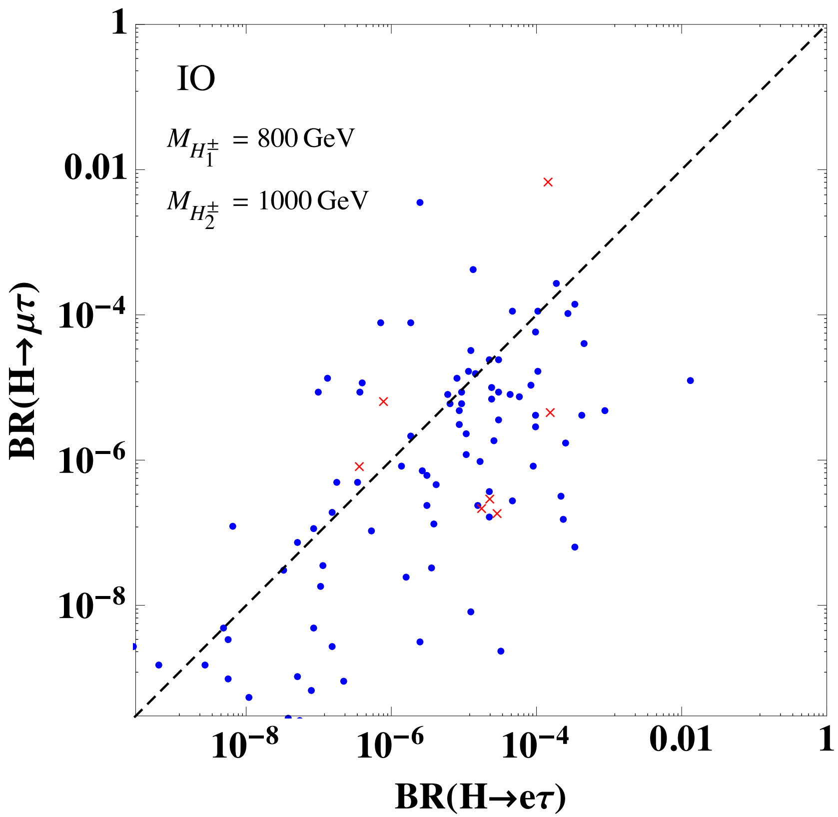
3. Prediction for LFV

◆ Correlation between BR of H→eτ and H→μτ

Normal ordering



Inverted ordering



- ✓ BRs are more correlated for inverted ordering case
- ✓ These LFV H decay could be searched for at the LHC

Summary and discussion

- Radiative neutrino mass generation is reviewed
- Zee-model with flavor symmetry
  - It connects neutrino mass generation and LFV pattern
  - LFV decay of Higgs boson is predicted
  - We also show LFV branching ratio of heavy Higgs

Thanks for listening !

CLFV amplitudes in Zee-model

$$(a_R^{H_1^\pm})_{ij} = \frac{1}{16\pi^2}\sum_{k=1}^{3}\left[(Y_\ell)^*_{kj}(Y_\ell)_{ki}c_\chi^2 F_1(m_{\ell_i}, m_{\ell_j}, m_{H_1^\pm}) - F^*_{kj}F_{ki}s_\chi^2 F_2(m_{\ell_i}, m_{\ell_j}, m_{H_2^\pm})\right], \quad \text{(C1)}$$

$$(a_L^{H_1^\pm})_{ij} = \frac{1}{16\pi^2}\sum_{k=1}^{3}\left[(Y_\ell)^*_{kj}(Y_\ell)_{ki}c_\chi^2 F_2(m_{\ell_i}, m_{\ell_j}, m_{H_1^\pm}) - F^*_{kj}F_{ki}s_\chi^2 F_1(m_{\ell_i}, m_{\ell_j}, m_{H_2^\pm})\right], \quad \text{(C2)}$$

$$(a_R^{H_2^\pm})_{ij} = (a_R^{H_1^\pm})_{ij}\Big|_{c_\chi^2 \leftrightarrow s_\chi^2}, \quad (a_L^{H_2^\pm})_{ij} = (a_L^{H_1^\pm})_{ij}\Big|_{c_\chi^2 \leftrightarrow s_\chi^2}. \quad \text{(C3)}$$

$$F_{1[2]}(m_1, m_2, m_3) = \int [dX]\frac{xzm_2[xym_1]}{(x^2-x)m_1^2 + xz(m_1^2 - m_2^2) + (y+z)m_3^2},$$

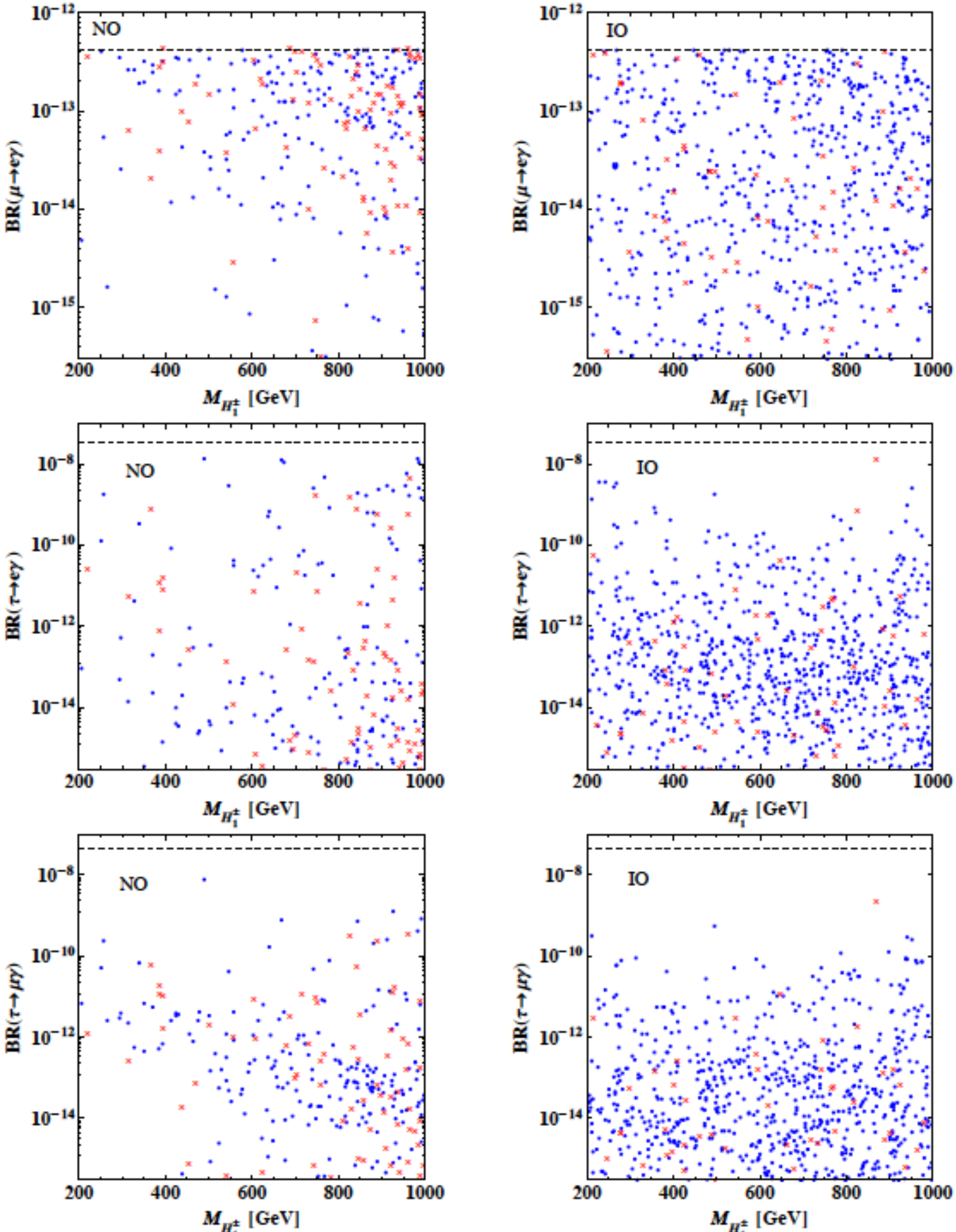
$$(a_R^\varphi)_{ij} = \frac{1}{8\pi^2}\sum_{k=1}^{3}\int [dX]\frac{xym_{\ell_i}f_\varphi^{jk}f_\varphi^{ki} + xzm_{\ell_j}g_\varphi^{jk}g_\varphi^{ki} + (1-x)m_{\ell_k}f_\varphi^{jk}g_\varphi^{ki}}{-x(1-x)m_{\ell_i}^2 - xz(m_{\ell_j}^2 - m_{\ell_i}^2) + (z+y)m_{\ell_k}^2 + xm_\varphi^2},$$

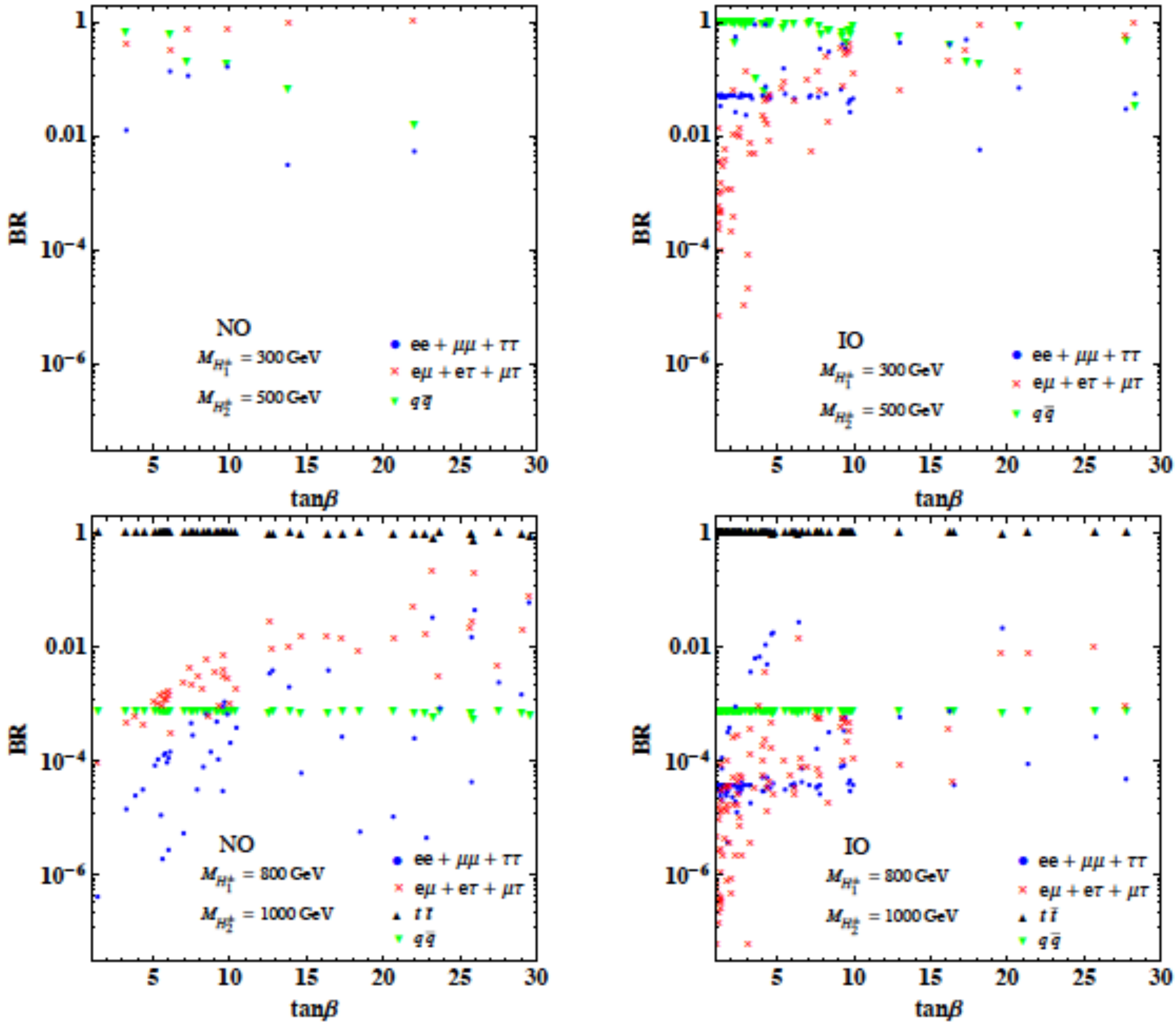
$$(a_L^\varphi)_{ij} = \frac{1}{8\pi^2}\sum_{k=1}^{3}\int [dX]\frac{xzm_{\ell_i}f_\varphi^{jk}f_\varphi^{ki} + xym_{\ell_j}g_\varphi^{jk}g_\varphi^{ki} + (1-x)m_{\ell_k}g_\varphi^{jk}f_\varphi^{ki}}{-x(1-x)m_{\ell_i}^2 - xz(m_{\ell_j}^2 - m_{\ell_i}^2) + (z+y)m_{\ell_k}^2 + xm_\varphi^2},$$

$$f_h^{ij} = \frac{\sqrt{2}m_{\ell_i}}{v}s_{\beta-\alpha}\delta_{ij} + \frac{1}{\sqrt{2}}(Y_\ell^0)^*_{ji}c_{\beta-\alpha}, \quad g_h^{ij} = \frac{\sqrt{2}m_{\ell_i}}{v}s_{\beta-\alpha}\delta_{ij} + \frac{1}{\sqrt{2}}(Y_\ell^0)_{ij}c_{\beta-\alpha}$$

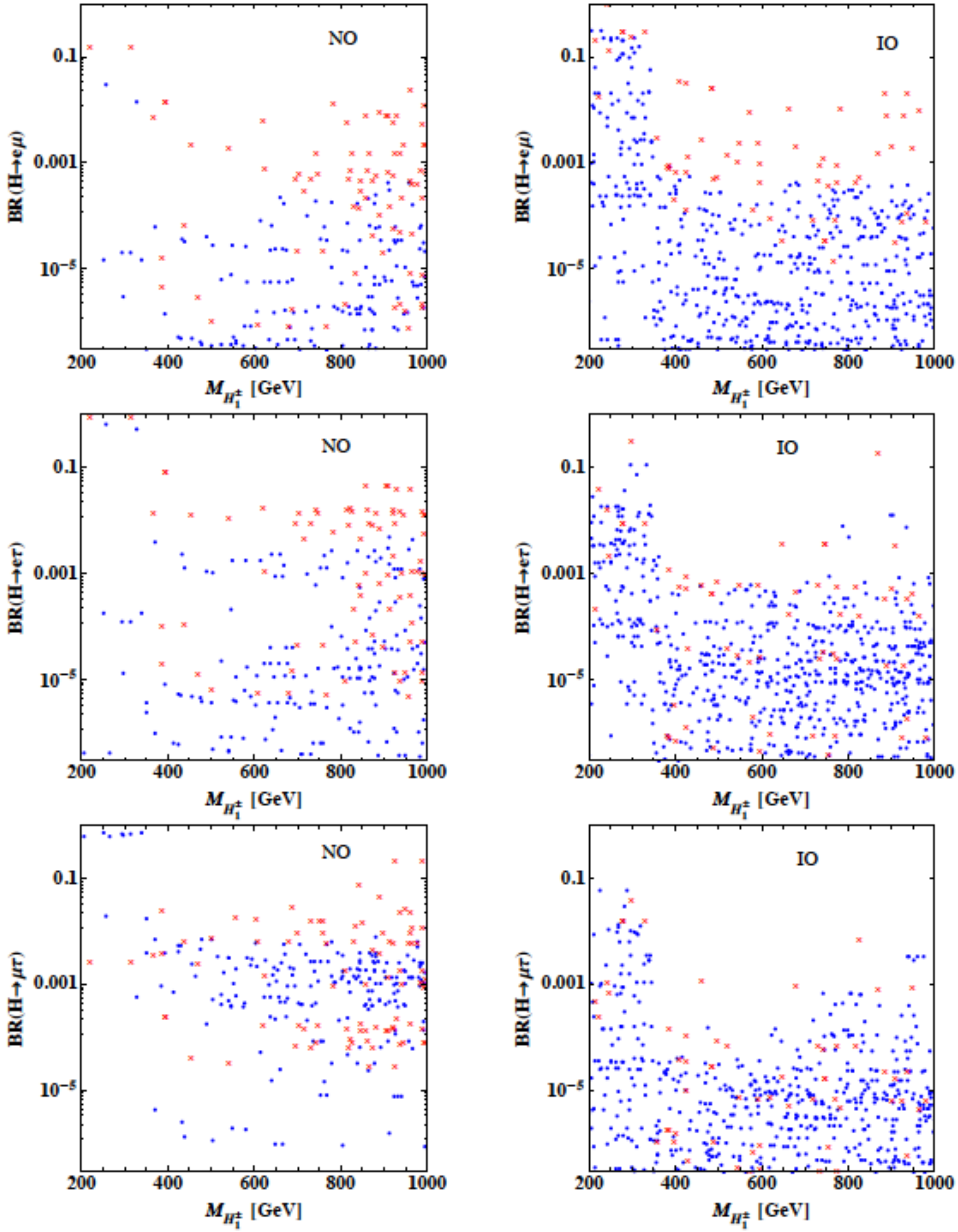
$$f_H^{ij} = \frac{\sqrt{2}m_{\ell_i}}{v}c_{\beta-\alpha}\delta_{ij} - \frac{1}{\sqrt{2}}(Y_\ell^0)^*_{ji}s_{\beta-\alpha}, \quad g_H^{ij} = \frac{\sqrt{2}m_{\ell_i}}{v}c_{\beta-\alpha}\delta_{ij} - \frac{1}{\sqrt{2}}(Y_\ell^0)_{ij}s_{\beta-\alpha}$$

$$f_A^{ij} = -\frac{i}{\sqrt{2}}(Y_\ell^0)^*_{ji}c_{\beta-\alpha}, \quad g_A^{ij} = \frac{i}{\sqrt{2}}(Y_\ell^0)_{ij}c_{\beta-\alpha}.$$


NO
IO
BR(μ→eγ)
BR(τ→eγ)
BR(τ→μγ)
$M_{H_1^\pm}$ [GeV]
200
400
600
800
1000
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-8}
10^{-10}



NO
$M_{H_1^\pm}$ = 300 GeV
$M_{H_2^\pm}$ = 500 GeV
ee + μμ + ττ
eμ + eτ + μτ
$q\bar{q}$
IO
$M_{H_1^\pm}$ = 300 GeV
$M_{H_2^\pm}$ = 500 GeV
ee + μμ + ττ
eμ + eτ + μτ
$q\bar{q}$
NO
$M_{H_1^\pm}$ = 800 GeV
$M_{H_2^\pm}$ = 1000 GeV
ee + μμ + ττ
eμ + eτ + μτ
$t\bar{t}$
$q\bar{q}$
IO
$M_{H_1^\pm}$ = 800 GeV
$M_{H_2^\pm}$ = 1000 GeV
ee + μμ + ττ
eμ + eτ + μτ
$t\bar{t}$
$q\bar{q}$
BR
tanβ
1
0.01
10^{-4}
10^{-6}
5
10
15
20
25
30


NO
IO
BR(H→eμ)
BR(H→eτ)
BR(H→μτ)
0.1
0.001
10^{-5}
200
400
600
800
1000
$M_{H_1^\pm}$ [GeV]