Extended Higgs sectors and CLFV

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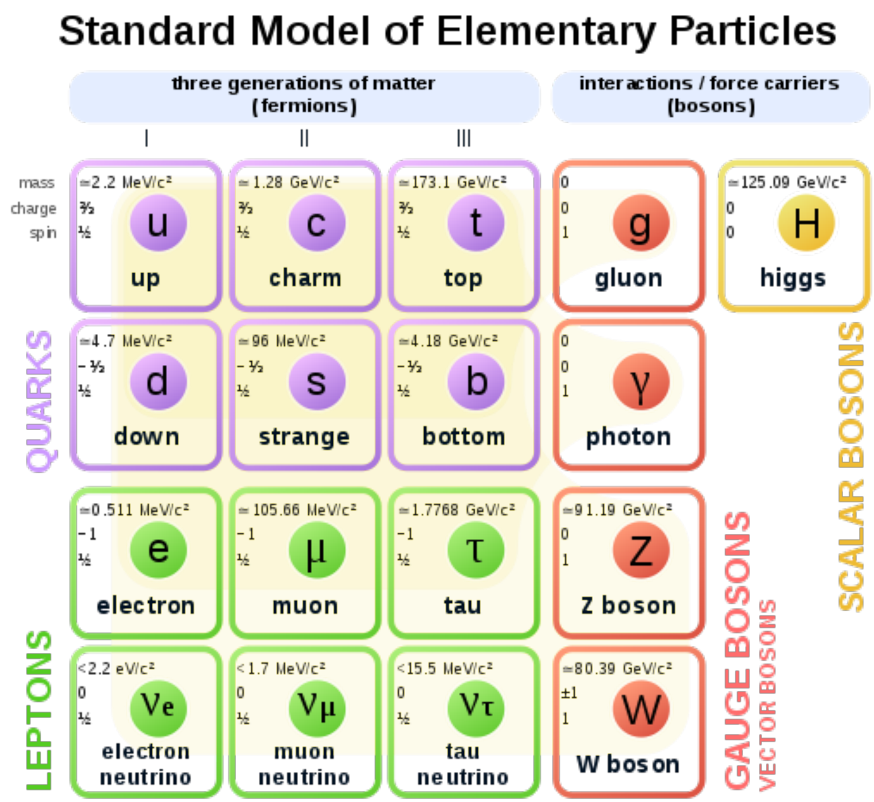
2019-06-18 CLFV2019 @ Fukuoka

1. Introduction

The standard model (SM) of particle physics is successful



The only scalar boson in the SM

H: $SU(2)_L$ doublet
$U(1)_Y$ charge 1/2

The SM is based on gauge symmetry $SU(3)_c \times SU(2)_L \times U(1)_Y$

However there should be beyond the SM (BSM) physics

No reason we have only one scalar field around EW scale

Some issues suggesting BSM physics

Non-zero neutrino mass

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

Anomalous muon magnetic moment (muon g-2)

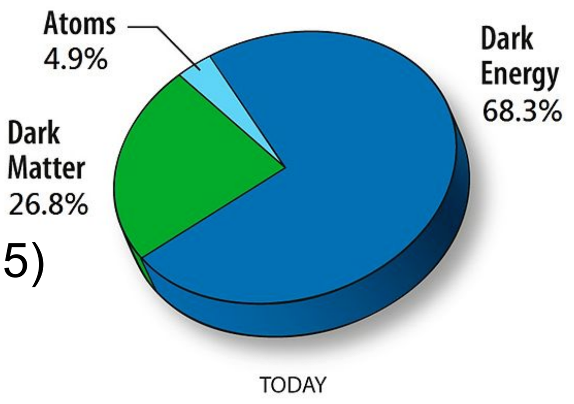
- **Deviation from SM prediction**

$$\Delta a_\mu = a_\mu^{\exp} - a_\mu^{SM} = (28.8 \pm 8.0) \times 10^{-10}$$

Existence of dark matter in our Universe

- **Observed relic density**

$$\Omega_{DM} h^2 = 0.1188 \pm 0.0010$$ Planck (2015)



Some issues suggesting BSM physics

□ Non-zero neutrino mass

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

□ Anomalous muon magnetic moment (muon g-2)

- ❖ **Deviation from SM prediction**

$$\Delta a_\mu = a_\mu^{\exp} - a_\mu^{SM} = (28.8 \pm 8.0) \times 10^{-10}$$

It can be explained by extended Higgs sector

⇨ Connection to CLFV processes

□ Existence of dark ma

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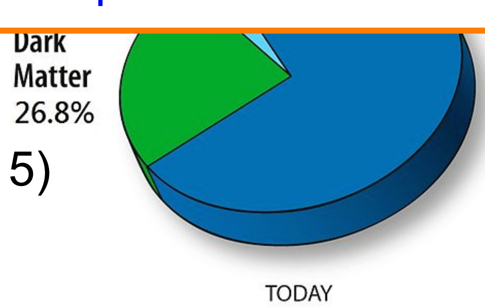
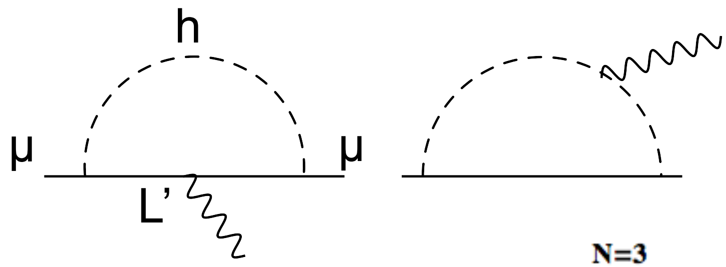


Muon g-2 and extended Higgs sector

◆ New charged scalar + extra vector-like lepton

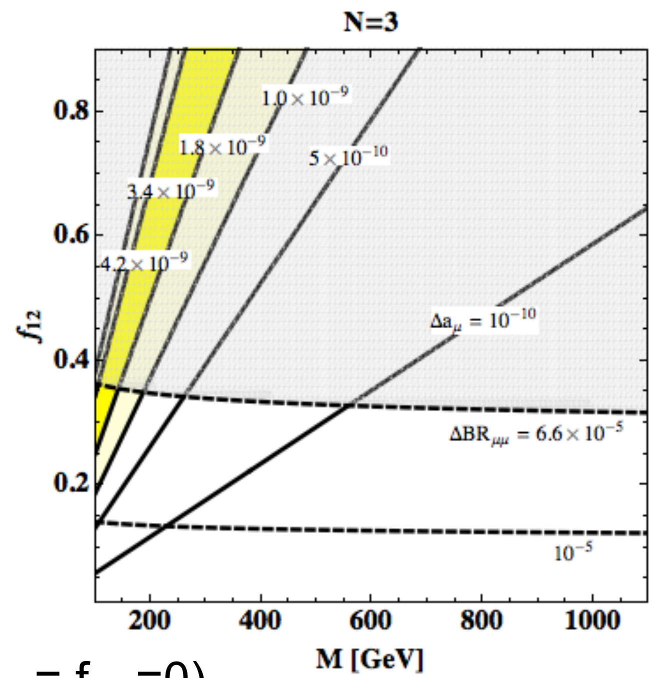
h^{+n} (n: electric charge) $L' = (\psi^{-n}, \psi^{-n-1})$ (Hypercharge N = 2n+1)

$$-L_Y = f_{ia}\bar{L}_{L_i} L'_{R_a} h^n + h.c.$$



Sizable contribution to muon g-2 is possible

- ✓ L’ mass around few×100 GeV
- ✓ Constraint from ΔBR(Z→μ+μ-)
- ✓ To avoid LFV tuning of f_{ia} is required

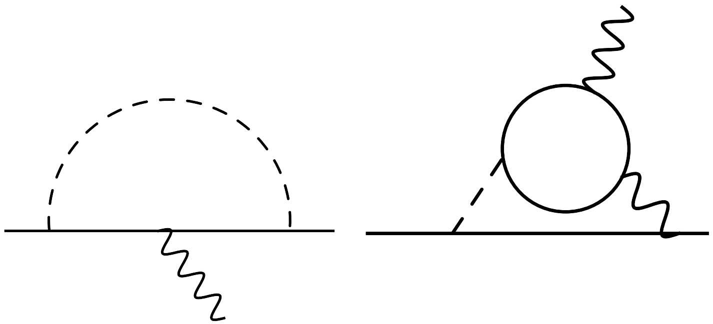


(T.N., H.Okada arXiv:1903.05958)

($f_{13} = f_{11} = 0$)

Muon g-2 and extended Higgs sector

◆ 2 Higgs doublet model (2HDM)



- ✓ New scalar boson contributions
- ✓ One- and two-loop contributions
- ✓ By Yukawa couplings :

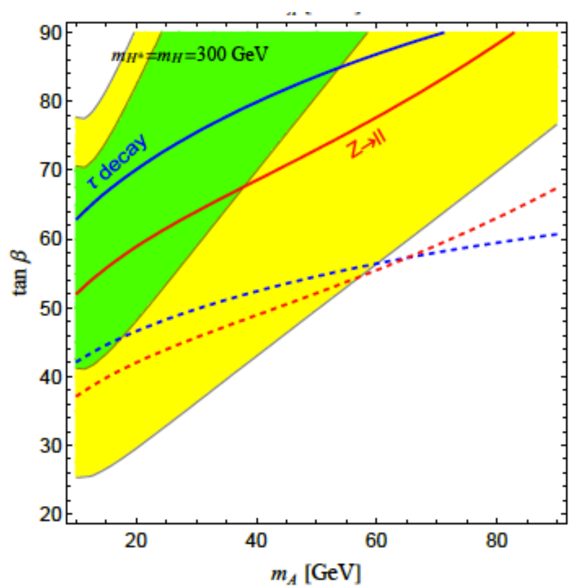
$$-L_Y = \bar{Q}_L Y_u^1 u_R \Phi_1^c + \bar{Q}_L Y_u^2 u_R \Phi_2^c + \bar{Q}_L Y_d^1 d_R \Phi_1 + \bar{Q}_L Y_d^2 d_R \Phi_2 + \bar{L}_L Y_\ell^1 \ell_R \Phi_1 + \bar{L}_L Y_\ell^2 \ell_R \Phi_2$$

Ex) type-X 2HDM

Z_2 symmetry to suppress FCNC:

$$\Phi_2 \to -\Phi_2, \quad u_R \to -u_R, \quad d_R \to -d_R$$

$$-L_Y = \bar{Q}_L Y_u^2 u_R \Phi_2^c + \bar{Q}_L Y_d^2 d_R \Phi_2 + \bar{L}_L Y_\ell^1 \ell_R \Phi_1$$



(E.J.Chun, J.S.Kim, JHEP 1607 (2016))

❖ CLFV processes are induced without Z_2

➡ **It will be discussed in this talk**

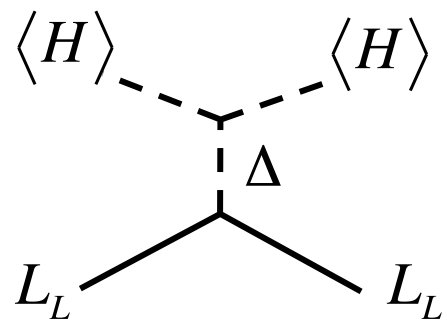
Neutrino mass and extended Higgs sector

◆ SM + Higgs triplet Δ

W.Konetschny, W.Kummer (1977) T. P. Chen, L. F. Li (1980)

J. Schechter, J. W. F. Valle (1980)

$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ (v_\Delta + \delta^0 + i\eta^0)/\sqrt{2} & -\delta^+/\sqrt{2} \end{pmatrix}$$



✓ Neutrino mass by VEV of triplet ⇨ $y_\Delta \overline{L^c} \Delta L \to \dfrac{y_\Delta v_\Delta}{\sqrt{2}} \overline{\nu}^c \nu$

✓ CLFVs are induced by the Yukawa interaction

Doubly charged scalar from Higgs triplet

➡ Specific signatures at the collider experiments

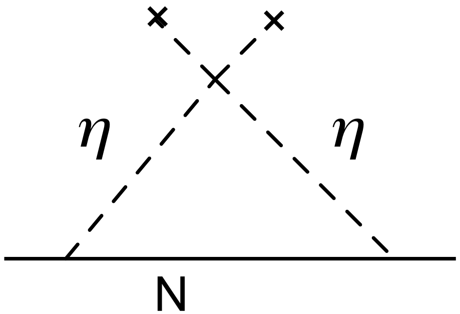
$$pp \to \delta^{++}\delta^{--} (\delta^{\pm\pm} \to \ell^\pm \ell^\pm, W^\pm W^\pm)$$

Neutrino mass and extended Higgs sector

◆ SM + second Higgs doublet (+ some extra fields)

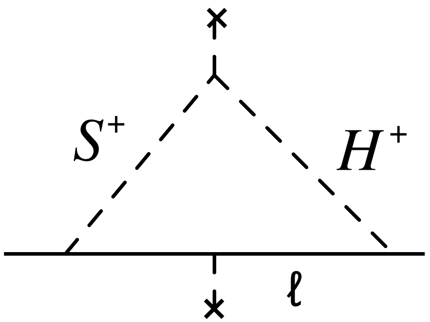
EX)

× : VEV



Scotogenic model (inert doublet η)

Ma (2006)



Zee-model (charged scalar S^+)

Zee (1980)

Radiative neutrino mass case is interesting

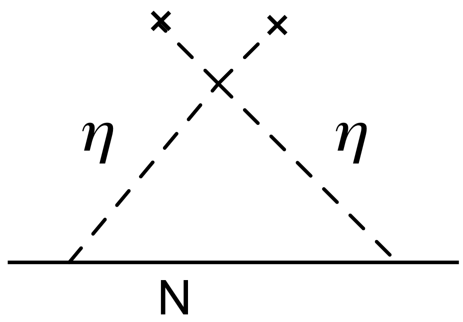
⇨ New particles could be around TeV scale

1. Introduction

Neutrino mass and extended Higgs sector

◆ SM + second Higgs doublet (+ some extra fields)

EX)



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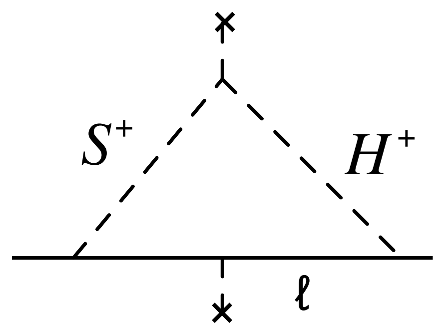


Zee-model (charged scalar S^+)

Zee (1980)

Radiative neutrino mass case is interesting

➡ New particles could be around TeV scale

Zee-model: only Higgs sector is extended

➢ In this talk we discuss Zee-model with flavor dependent global U(1)

In this talk we will discuss

(1) General 2HDM explaining muon g-2 and CLFV

R. Benbrik, C. Chen, T.N. PRD 93 (2016)

(2) Zee-model with flavor symmetry
neutrino mass generation and related CLFV

T.N., K. Yagyu, arXiv:1905.11568

1. Introduction
2. Muon g-2 and CLFV in 2HDM
3. Zee-model with flavor symmetry
4. Summary and discussion

General two Higgs doublet model

⇨ **SM fermion contents + two Higgs doublet $\Phi_{1,2}$**

$$\Phi_i = \begin{pmatrix} \phi_i^+ & \frac{1}{\sqrt{2}}\left(v_i + \phi_i + i\eta_i\right) \end{pmatrix}$$

☐ Yukawa interactions

$$-L_Y = \bar{Q}_L Y_u^1 u_R \Phi_1^c + \bar{Q}_L Y_u^2 u_R \Phi_2^c + \bar{Q}_L Y_d^1 d_R \Phi_1 + \bar{Q}_L Y_d^2 d_R \Phi_2 + \bar{L}_L Y_\ell^1 \ell_R \Phi_1 + \bar{L}_L Y_\ell^2 \ell_R \Phi_2$$

☐ Scalar potential

$$\begin{aligned} V(\Phi_1,\Phi_2) \;=\; & m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 \\ & + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ & + \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \left(\lambda_6\Phi_1^\dagger\Phi_1 + \lambda_7\Phi_2^\dagger\Phi_2\right)\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}\right] . \end{aligned}$$

Physical mass eigenstates for scalars

$$\begin{aligned} h &= -s_\alpha \phi_1 + c_\alpha \phi_2 \,, \\ H &= c_\alpha \phi_1 + s_\alpha \phi_2 \,, \\ H^\pm(A) &= -s_\beta \phi_1^\pm(\eta_1) + c_\beta \phi_2^\pm(\eta_2) \end{aligned}$$

$$\left(\begin{array}{l} c_\alpha(s_\alpha) = \cos\alpha(\sin\alpha) \\ c_\beta = \cos\beta = v_1/v, \quad s_\beta = \sin\beta = v_2/v \end{array} \right)$$

SM fermion masses

$$M_f = \frac{v}{\sqrt{2}}\left(Y_f^1 \cos\beta + Y_f^2 \sin\beta\right) \quad \Rightarrow \quad m_f = U_L^f M_f \left(U_R^f\right)^\dagger$$

$$f_{L,R} \to \left(U_{L,R}^f\right)^\dagger f_{L,R}$$

Leptonic Yukawa couplings in mass basis

$$\begin{aligned} (\mathrm{y}_h^\ell)_{ij} &= -\frac{s_\alpha}{c_\beta}\frac{m_i}{v}\delta_{ij} + \frac{c_{\beta\alpha}}{c_\beta}X_{ij}^\ell \,, \\ (\mathrm{y}_H^\ell)_{ij} &= \frac{c_\alpha}{c_\beta}\frac{m_i}{v}\delta_{ij} - \frac{s_{\beta\alpha}}{c_\beta}X_{ij}^\ell \,, \\ (\mathrm{y}_A^\ell)_{ij} &= -\tan\beta\frac{m_i}{v}\delta_{ij} + \frac{X_{ij}^\ell}{c_\beta} \,, \end{aligned}$$

$$\left(\begin{array}{l} X^u = U_L^u \dfrac{Y_u^1}{\sqrt{2}}\left(U_R^u\right)^\dagger \\ X^d = U_L^d \dfrac{Y_d^2}{\sqrt{2}}\left(U_R^d\right)^\dagger \\ X^\ell = U_L^\ell \dfrac{Y_\ell^2}{\sqrt{2}}\left(U_R^\ell\right)^\dagger \end{array} \right)$$

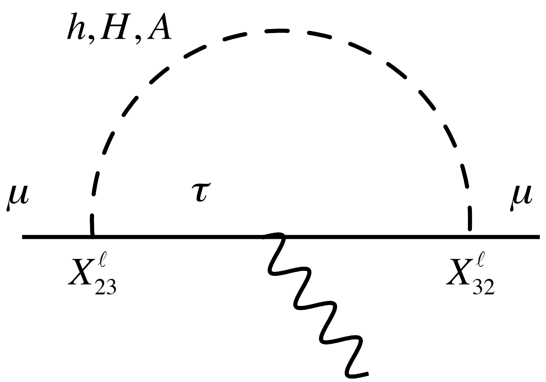
Flavor changing Yukawa interactions (neural scalar)

$$-L_Y \supset \overline{\ell}_L \left[-\frac{s_\alpha}{v c_\beta} m_\ell + \frac{c_{\beta\alpha}}{c_\beta} X^\ell \right] \ell_R h + \overline{\ell}_L \left[\frac{c_\alpha}{v c_\beta} m_\ell - \frac{s_{\beta\alpha}}{c_\beta} X^\ell \right] \ell_R H$$

$$+ \overline{\ell}_L \left[-\frac{t_\beta}{v} m_\ell + \frac{1}{c_\beta} X^\ell \right] \ell_R A + h.c.$$

- ✓ CLFV processes are induced by these interactions
- ✓ Muon g-2 can be enhanced by LFV coupling

Flavor changing couplings and muon g-2



- ✓ Enhancement by tau lepton mass
- ✓ Positive contribution from H loop

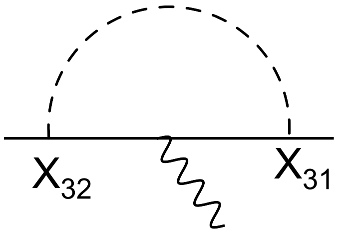
$$\Delta a_\mu \approx \frac{m_\mu m_\tau X^{\ell}_{23} X^{\ell}_{32}}{8\pi^2 c^2_\beta} Z_\phi$$

$$Z_\phi = \frac{c^2_{\beta\alpha}\left(\ln\left(\frac{m_h^2}{m_\tau^2}\right)-\frac{3}{2}\right)}{m_h^2} + \frac{s^2_{\beta\alpha}\left(\ln\left(\frac{m_H^2}{m_\tau^2}\right)-\frac{3}{2}\right)}{m_H^2} - \frac{\ln\left(\frac{m_A^2}{m_\tau^2}\right)-\frac{3}{2}}{m_A^2}$$

- ➢ Sizable muon g-2 at one-loop level can be obtained
- ➢ The flavor changing couplings contribute to LFV process

CLFV decays via Yukawa couplings

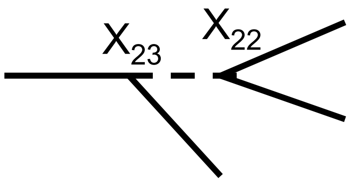
□ μ→eγ process



$$\frac{BR(\mu \to e\gamma)}{BR(\mu \to e\bar{\nu}_e\nu_\mu)} = \frac{3\alpha_e}{4\pi G_F^2}\left(|C_L|^2 + |C_R|^2\right)$$

$$\left(\begin{aligned} C_{L(R)} &= C^{\phi}_{L(R)} + C^{H^\pm}_{L(R)}\,, \\ C^{\phi}_{L} &= \frac{X^{\ell}_{32}X^{\ell}_{13}}{2c_\beta^2}\frac{m_\tau}{m_\mu}Z_\phi\,, \\ C^{H^\pm}_{L} &= -\frac{1}{12m^2_{H^\pm}}\left(\frac{2X^{\ell}_{23}X^{\ell}_{13}}{c_\beta^2}\right), \end{aligned}\right)$$

□ τ→3μ process

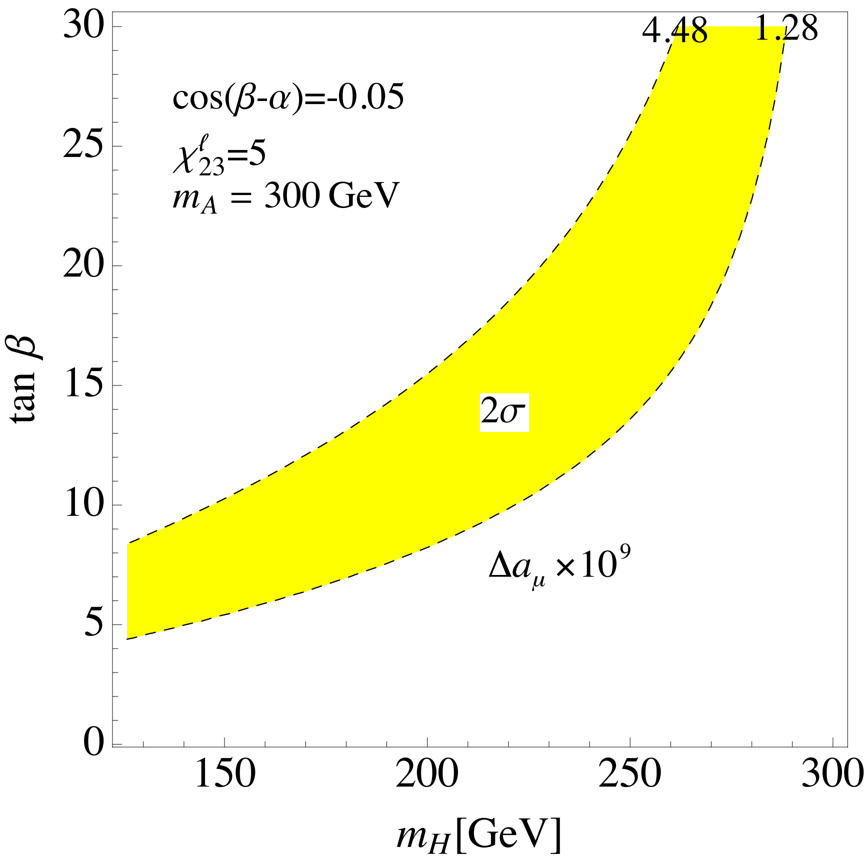


$$BR(\tau \to 3\mu) = \frac{\tau_\tau m_\tau^5}{3\cdot 2^9\pi^3}\frac{|X^{\ell}_{23}|^2}{c_\beta^2}\left[\left|\frac{c_{\beta\alpha}y^{\ell}_{h22}}{m_h^2} - \frac{s_{\beta\alpha}y^{\ell}_{H22}}{m_H^2}\right|^2 + \left|\frac{y^{\ell}_{A22}}{m_A^2}\right|^2\right]$$

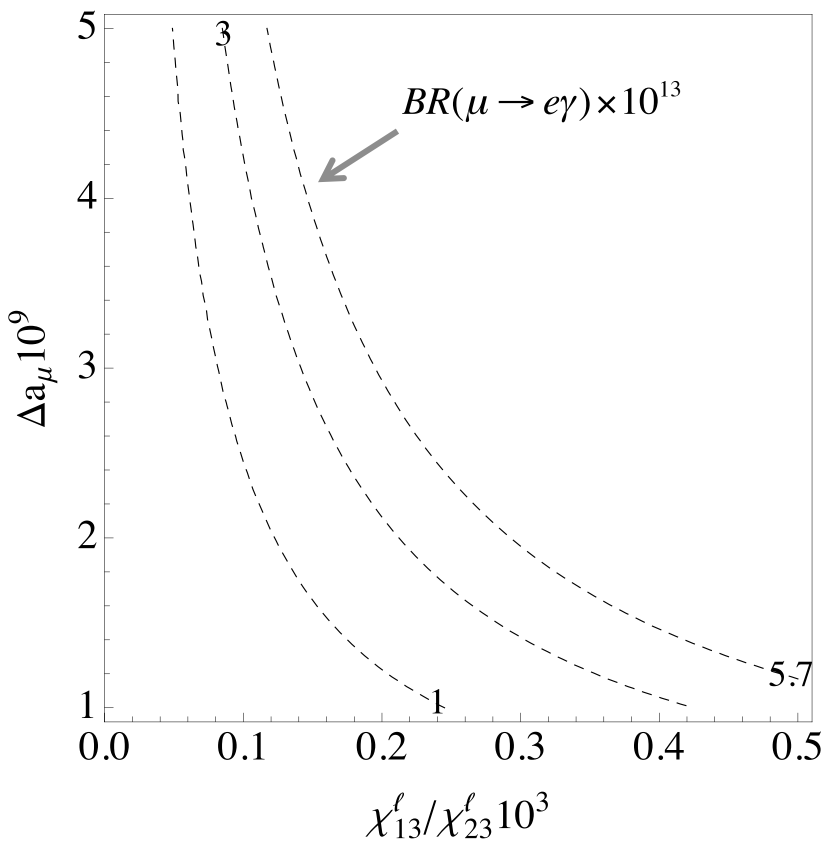
Here we apply ansatz: $X^{\ell}_{ij} = \dfrac{\sqrt{m_i m_j}}{v}\chi^{\ell}_{ij}$

2. Muon g-2 and CLFV in 2HDM

Muon g-2



Muon g-2 and BR(μ→eγ)



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

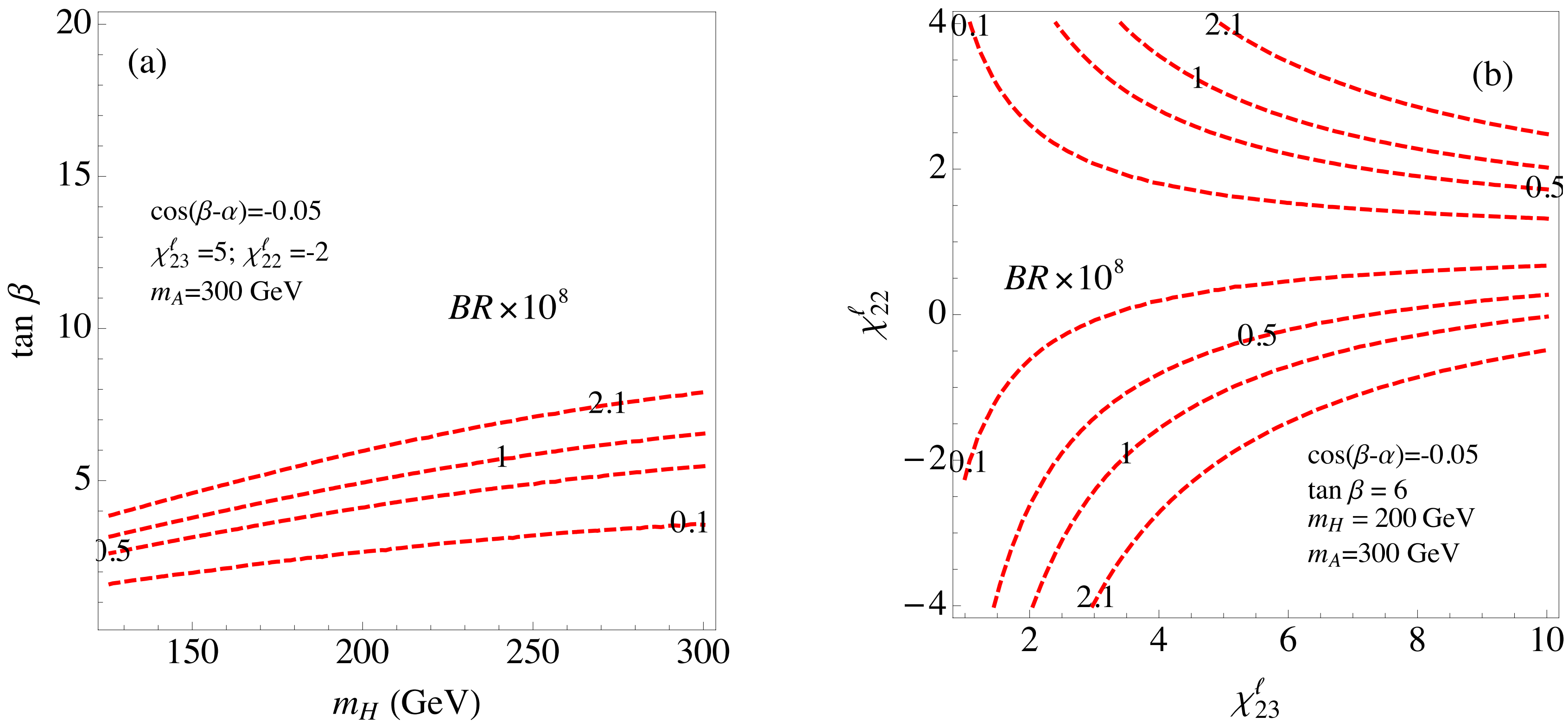
MEG (2016)

✓ Muon g-2 can be explained for $m_H < m_A$

✓ Coupling χ_{13} is strongly constrained by μ→eγ

2. Muon g-2 and CLFV in 2HDM

BR(τ→3μ)



- ✓ Sizable BR for τ→3μ
- ✓ More parameter region can be tested in future

$$\mathrm{BR}(\tau \to \mu\mu\mu) < 2.1 \times 10^{-8}$$

Belle (2010)

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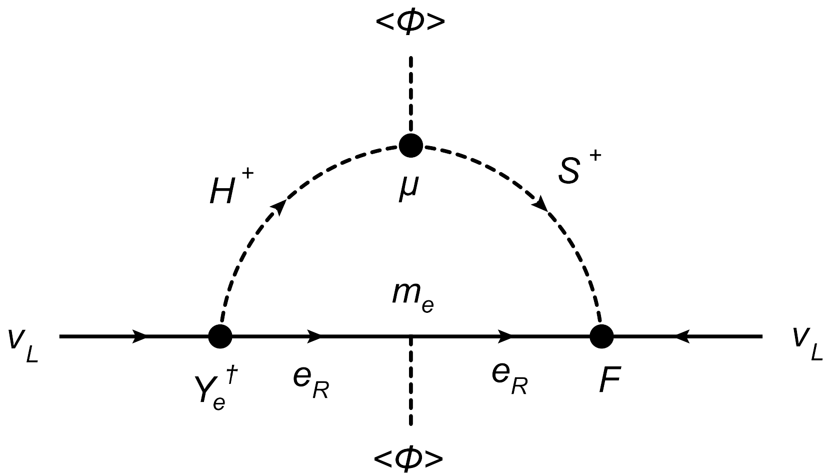
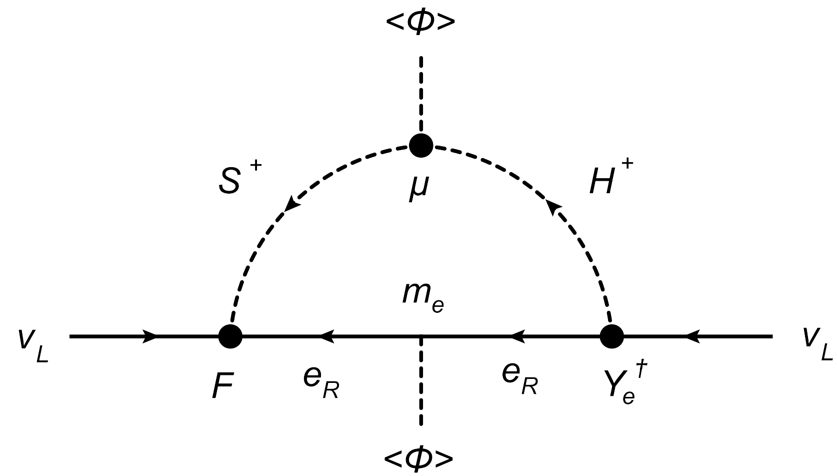
Original Zee-model for neutrino mass





One-loop mass generation

Realized by SM + second Higgs doublet + charged scalar

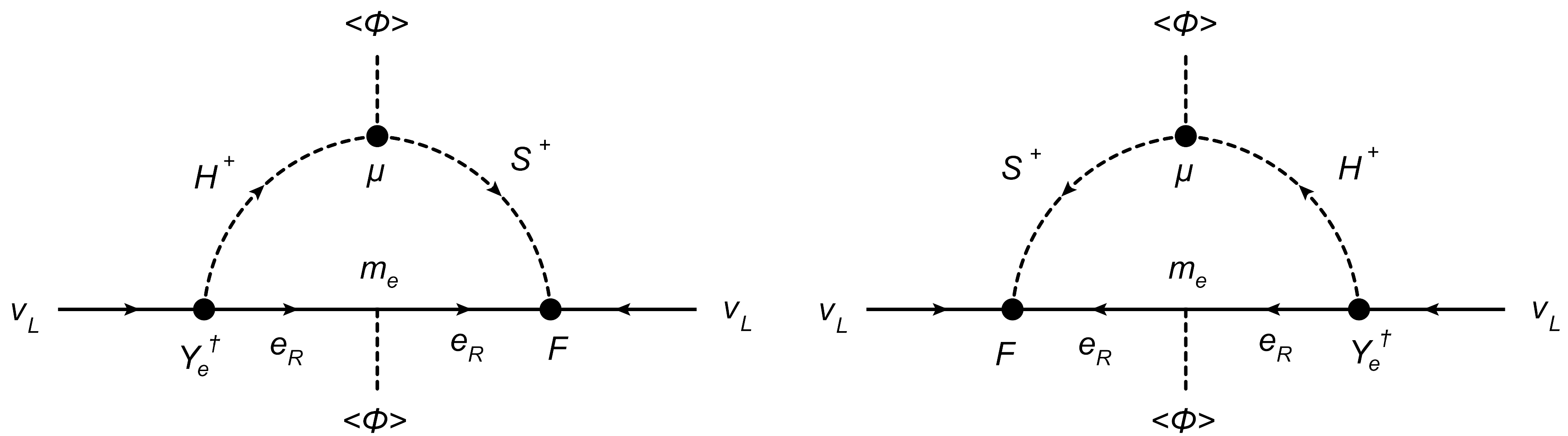
Softly-broken Z_2 symmetry is assigned to forbid FCNC: $\Phi_2 \to -\Phi_2$

	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: $\Phi_2 \to -\Phi_2$

⇨ 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

- 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)

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Charged lepton mass and relevant couplings

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

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

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

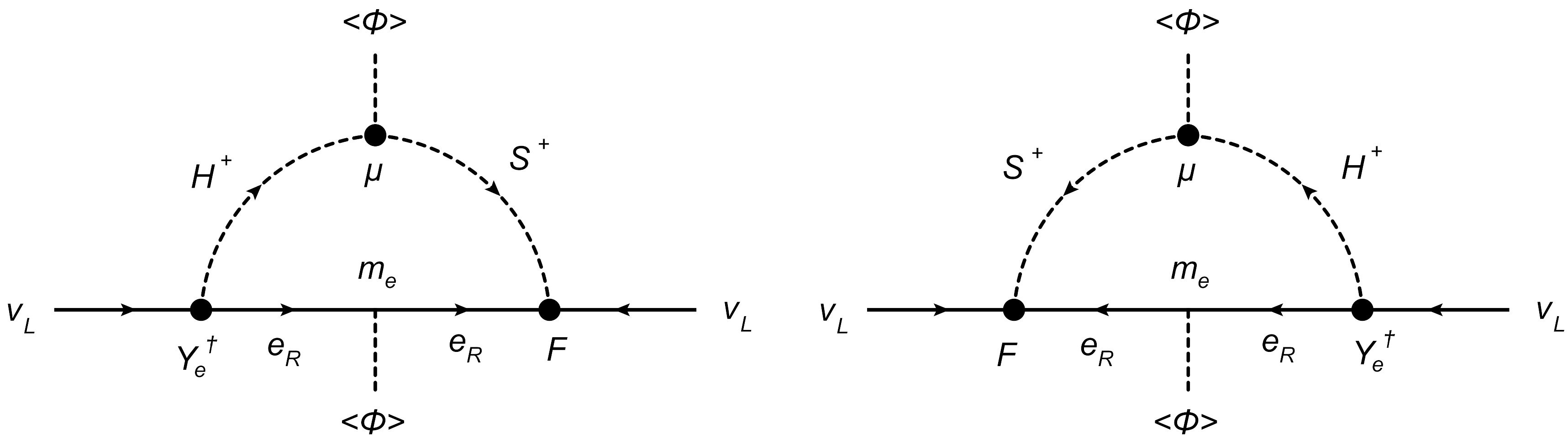
Couplings in charged lepton mass basis

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

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

$$F = \tilde{F} U_R$$

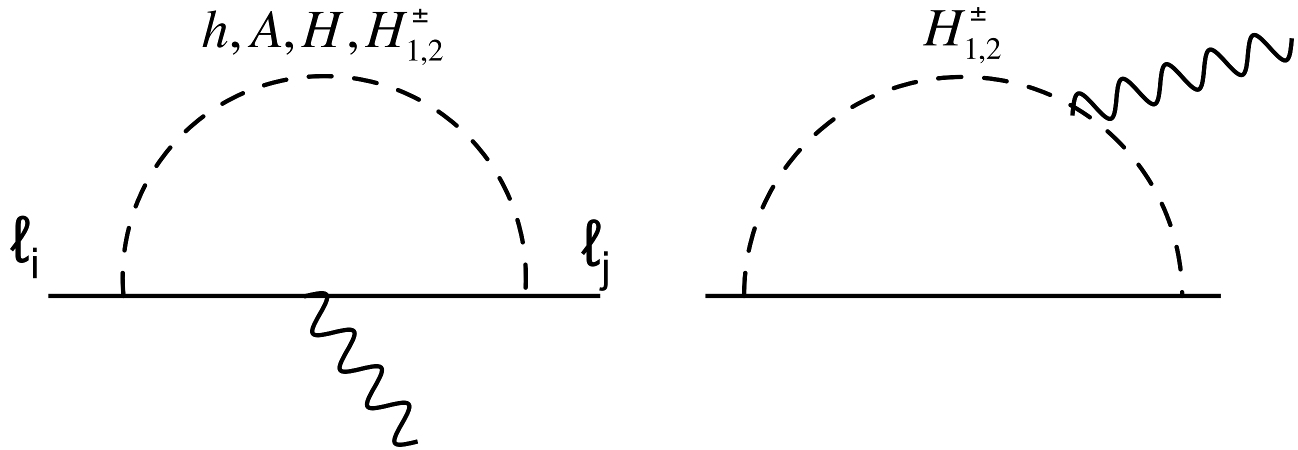
Neutrino mass generation at one loop level



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

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

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



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

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

Numerical analysis

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

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

$\Downarrow$

Calculate BRs for CLFV processes by allowed parameters

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

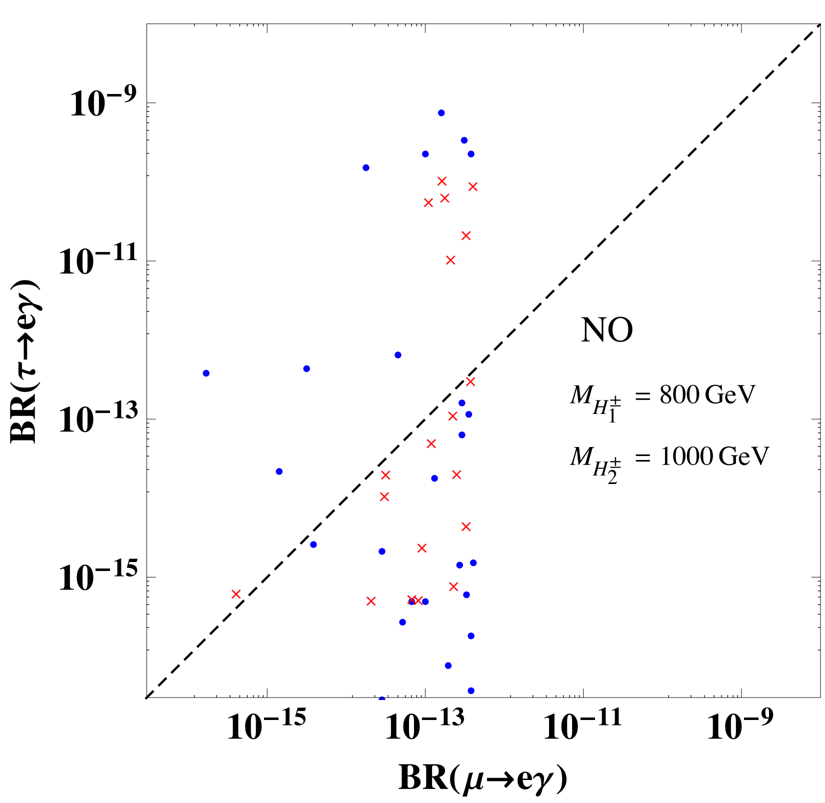
$$\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13},\ \mathrm{BR}(\tau \to e\gamma) < 3.3 \times 10^{-8},\ \mathrm{BR}(\tau \to \mu\gamma) < 4.4 \times 10^{-8},$$

- Prediction for LFV decay of heavy Higgs H

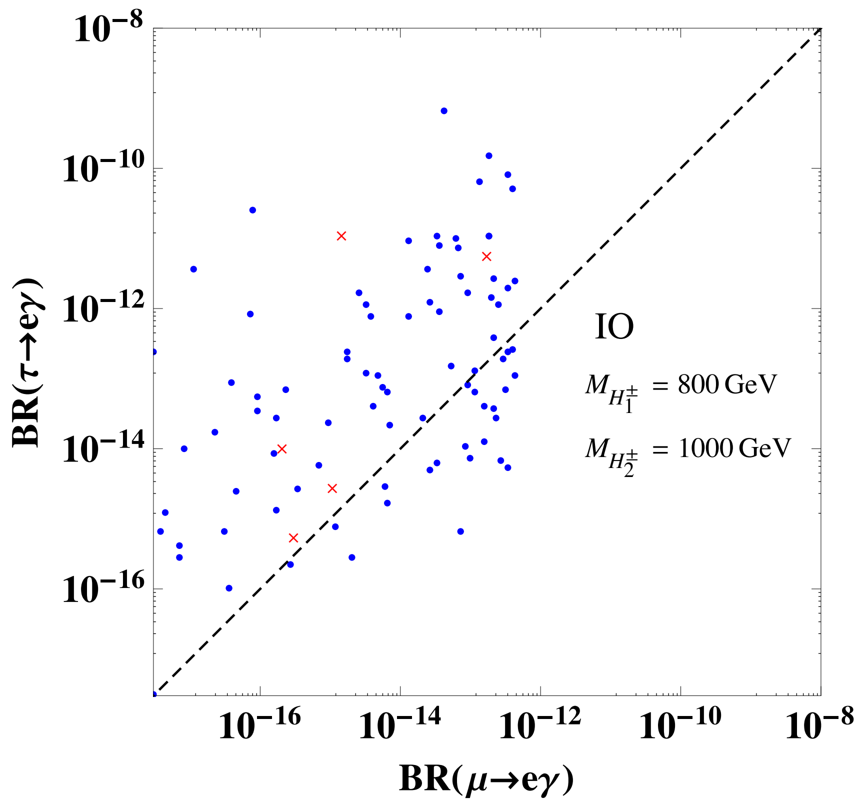
3. Zee-model with flavor symmetry

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

Normal ordering



Inverted ordering

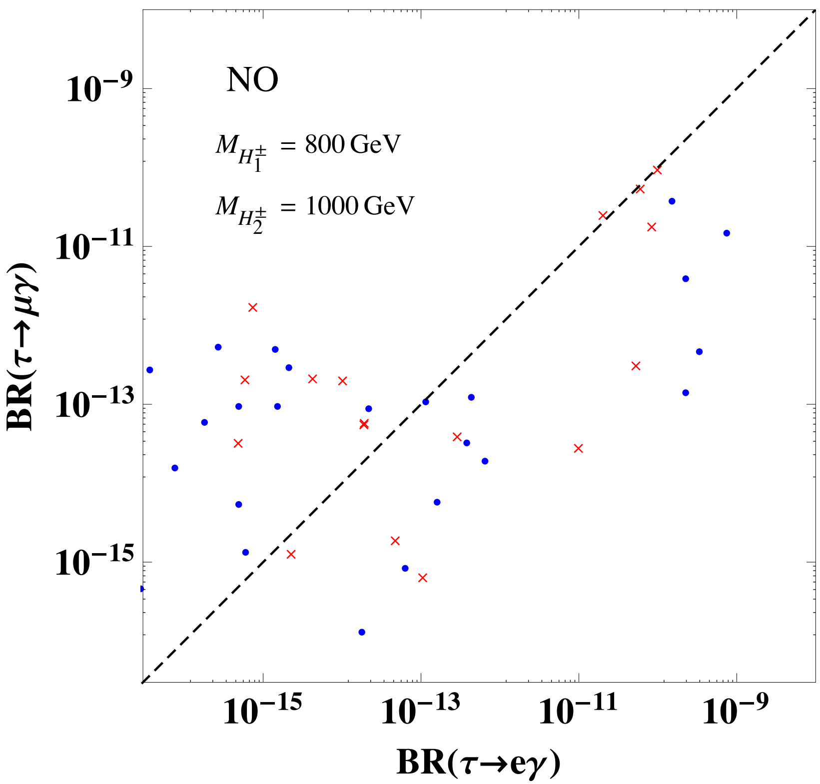


Blue dot : 1 < tanβ < 10,   Red cross : 10 < tanβ < 30

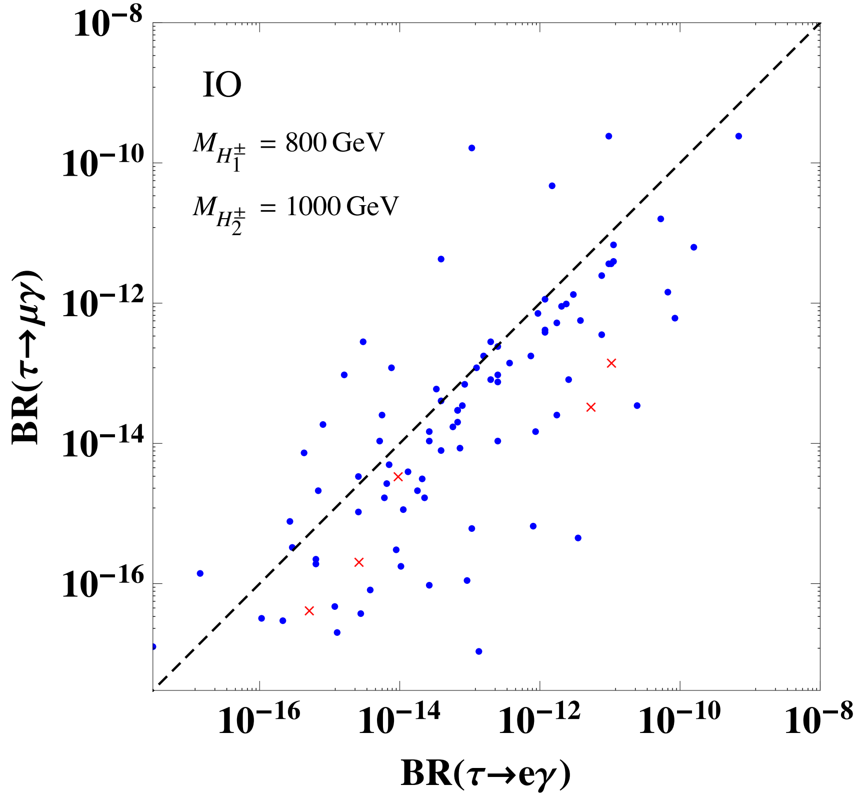
✓ Normal ordering case tends to give larger BR(μ→eγ)

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

Normal ordering

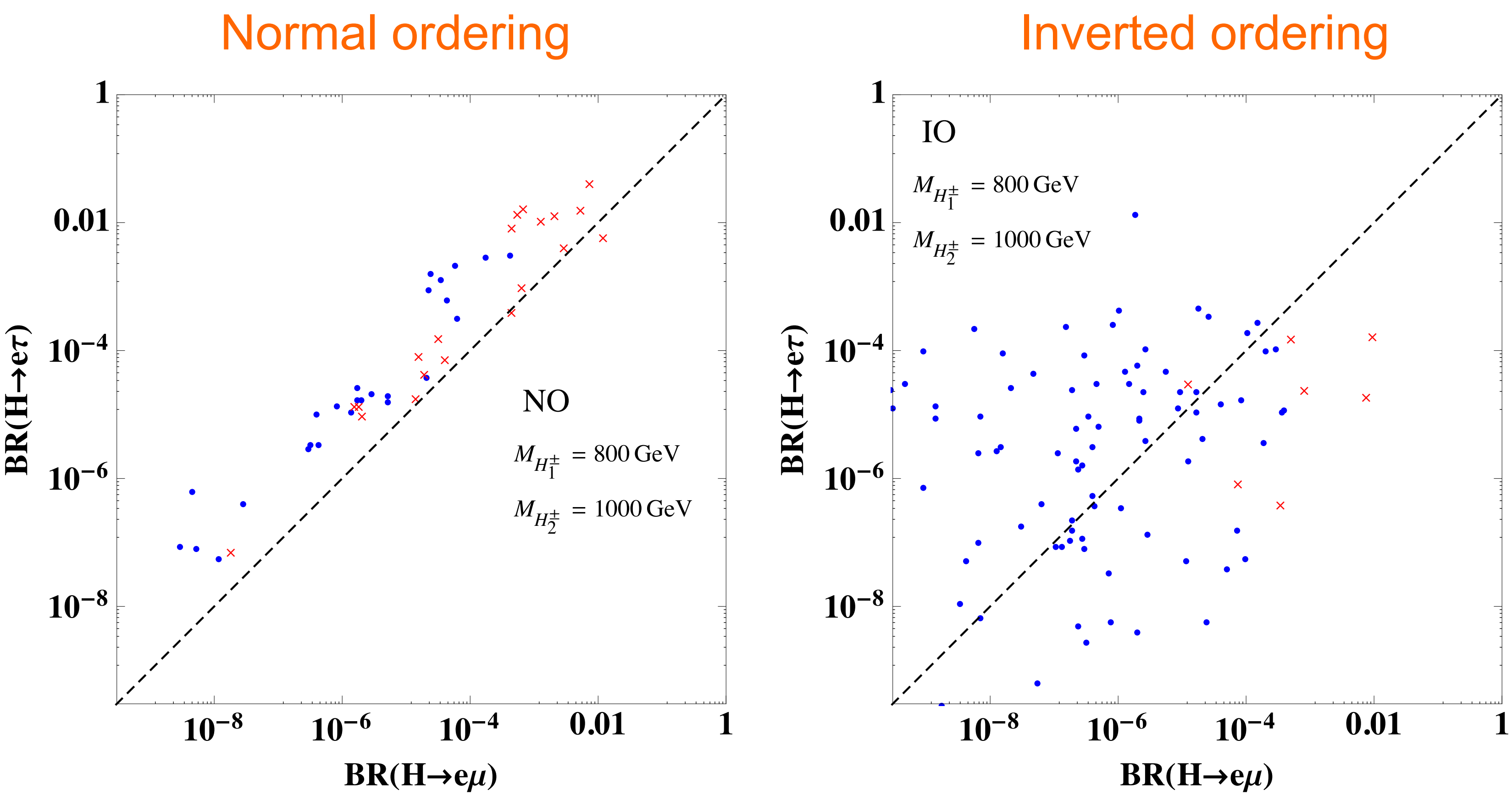


Inverted ordering



✓ BRs are more correlated for inverted ordering case

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



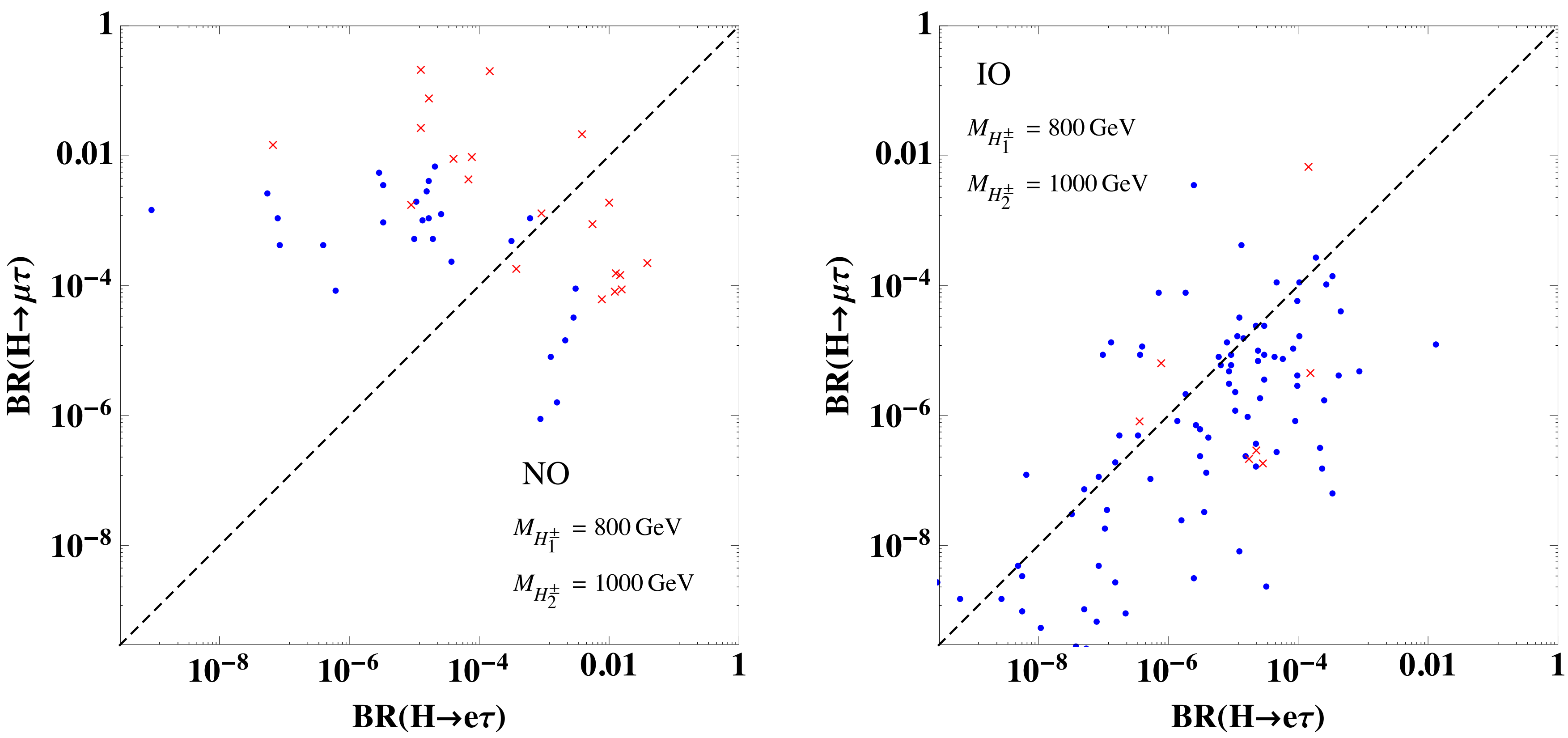
✓ Correlation in normal ordering case

✓ Inverted ordering case is less correlated

◆ 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

- Extended Higgs sector is attractive BSM candidate
- New Yukawa couplings with extra scalar give CLFV
  - In particular CLFV would be related to muon g-2 and/or neutrino mass
- We discussed models with CLFV
  - Muon g-2 explained by 2HDM and related CLFV
  - Zee-model with flavor symmetry
    connecting neutrino mass and CLFV

Thanks for listening !

All Yukawa interactions in general 2HDM

$$
\begin{aligned}
-\mathcal{L}_Y^h &= \bar{u}_L \left[\frac{c_\alpha}{v s_\beta}\mathbf{m_u} - \frac{c_{\beta\alpha}}{s_\beta}\mathbf{X}^u\right] u_R h + \bar{d}_L \left[-\frac{s_\alpha}{v c_\beta}\mathbf{m_d} + \frac{c_{\beta\alpha}}{c_\beta}\mathbf{X}^d\right] d_R h \\
&+ \bar{\ell}_L \left[-\frac{s_\alpha}{v c_\beta}\mathbf{m}_\ell + \frac{c_{\beta\alpha}}{c_\beta}\mathbf{X}^\ell\right] \ell_R h + h.c.\,,
\end{aligned}
$$

$$
\begin{aligned}
-\mathcal{L}_Y^{H,A} &= \bar{u}_L \left[\frac{s_\alpha}{v s_\beta}\mathbf{m_u} + \frac{s_{\beta\alpha}}{s_\beta}\mathbf{X}^u\right] u_R H + \bar{d}_L \left[\frac{c_\alpha}{v c_\beta}\mathbf{m_d} - \frac{s_{\beta\alpha}}{c_\beta}\mathbf{X}^d\right] d_R H \\
&+ \bar{\ell}_L \left[\frac{c_\alpha}{v c_\beta}\mathbf{m}_\ell - \frac{s_{\beta\alpha}}{c_\beta}\mathbf{X}^\ell\right] \ell_R H + i\bar{u}_L \left[-\frac{\cot\beta}{v}\mathbf{m_u} + \frac{\mathbf{X}^u}{s_\beta}\right] u_R A \\
&+ i\bar{d}_L \left[-\frac{\tan\beta}{v}\mathbf{m_d} + \frac{\mathbf{X}^d}{c_\beta}\right] d_R A + i\bar{\ell}_L \left[-\frac{\tan\beta}{v}\mathbf{m}_\ell + \frac{\mathbf{X}^\ell}{c_\beta}\right] \ell_R A + h.c.
\end{aligned}
$$

$$
\begin{aligned}
-\mathcal{L}_Y^{H^\pm} &= \sqrt{2}\bar{d}_L V_{CKM}^\dagger \left[-\frac{\cot\beta}{v}\mathbf{m_u} + \frac{\mathbf{X}^u}{s_\beta}\right] u_R H^- \\
&+ \sqrt{2}\bar{u}_L V_{\text{CKM}} \left[-\frac{\tan\beta}{v}\mathbf{m_d} + \frac{\mathbf{X}^d}{c_\beta}\right] d_R H^+ \\
&+ \sqrt{2}\bar{\nu}_L V_{\text{PMNS}} \left[-\frac{\tan\beta}{v}\mathbf{m}_\ell + \frac{\mathbf{X}^\ell}{c_\beta}\right] \ell_R H^+ + h.c.\,,
\end{aligned}
$$

CLFV amplitudes in Zee-model

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

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

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

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

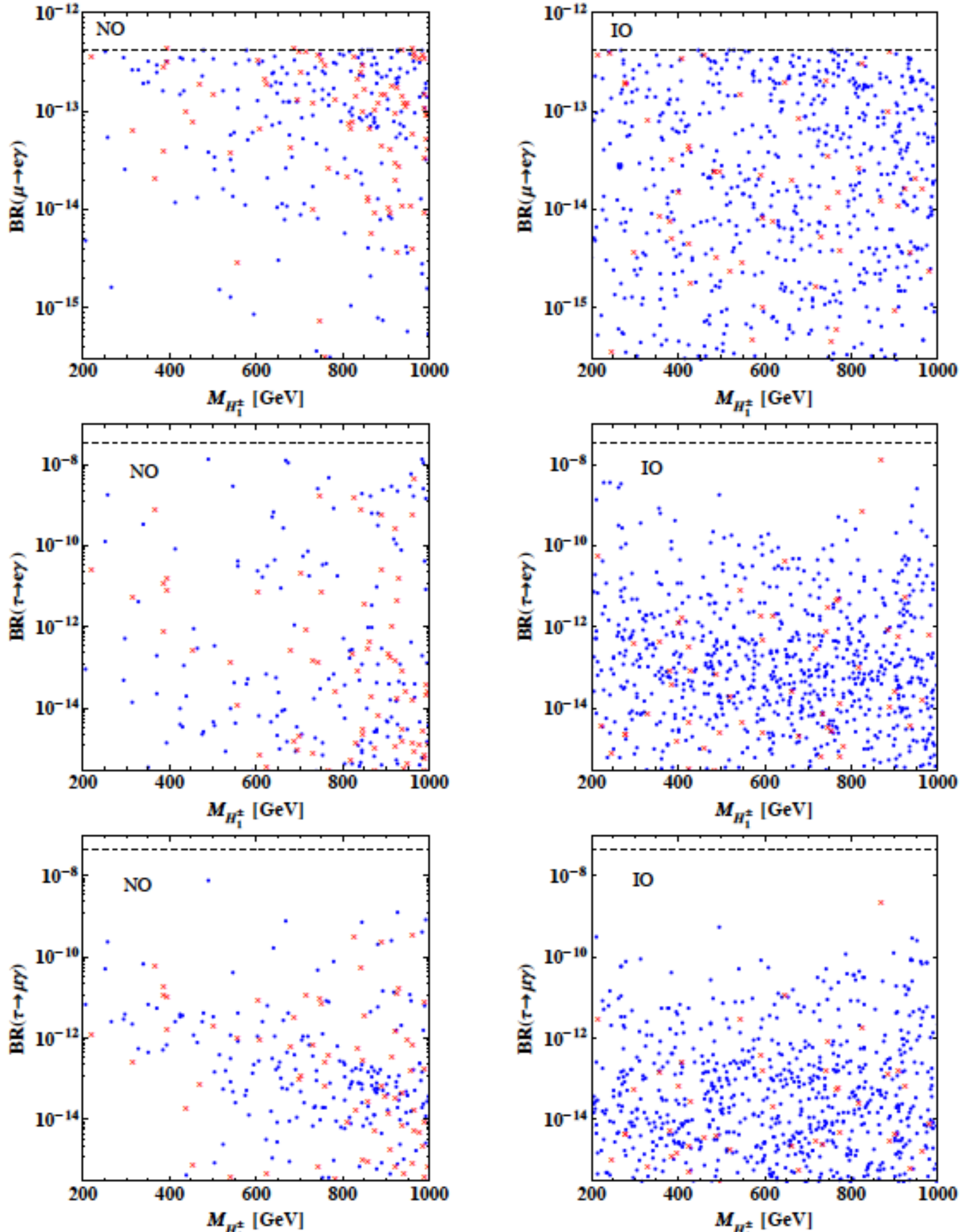
$$(a_R^\varphi)_{ij} = \frac{1}{8\pi^2}\sum_{k=1}^{3}\int [dX]\frac{xym_{\ell_i}f_\varphi^{jk}f_\varphi^{ki} + xzm_{\ell_j}g_\varphi^{jk}g_\varphi^{ki} + (1-x)m_{\ell_k}f_\varphi^{jk}g_\varphi^{ki}}{-x(1-x)m_{\ell_i}^2 - xz(m_{\ell_j}^2 - m_{\ell_i}^2) + (z+y)m_{\ell_k}^2 + xm_\varphi^2},$$

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

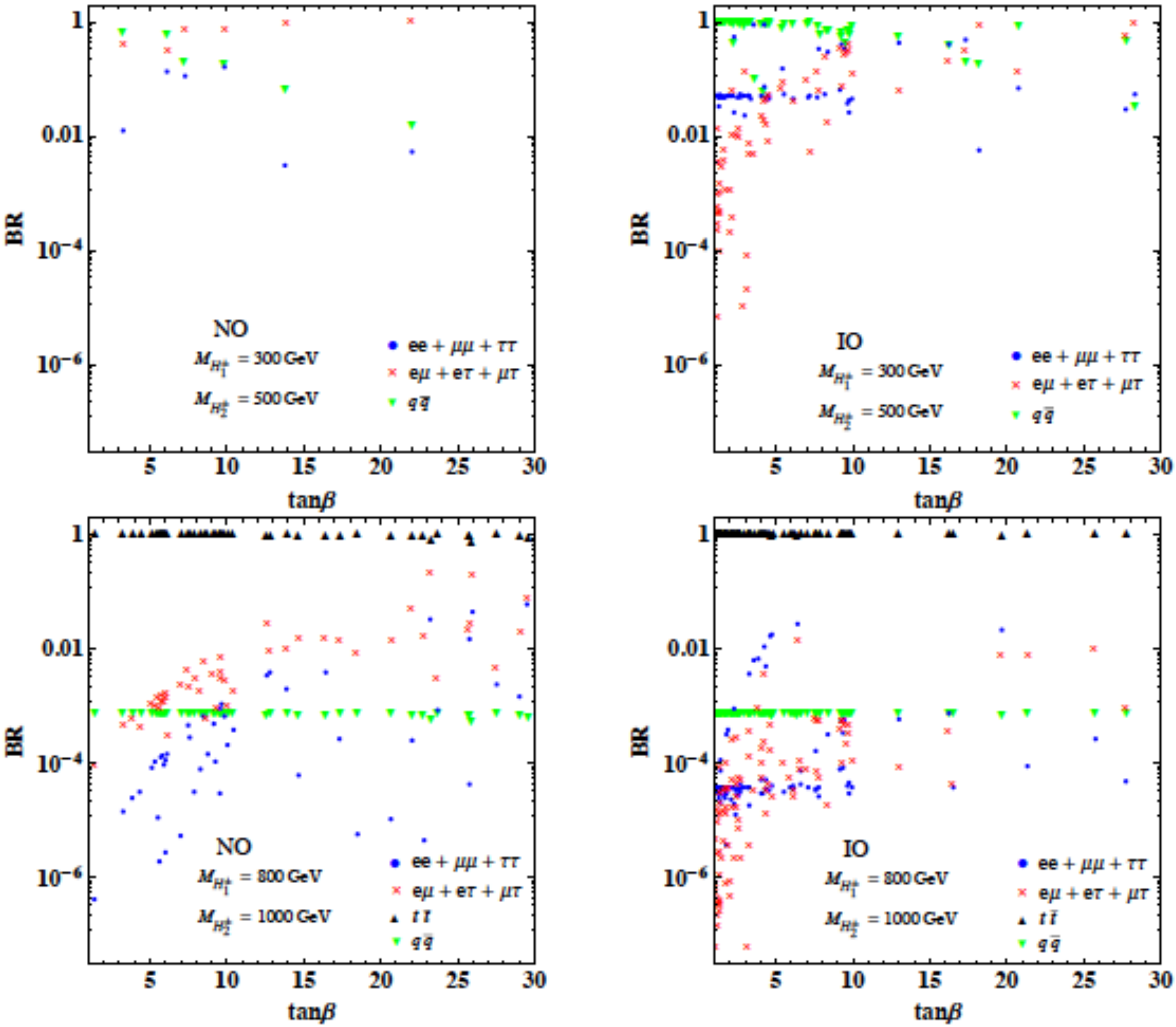
$$f_h^{ij} = \frac{\sqrt{2}m_{\ell_i}}{v}s_{\beta-\alpha}\delta_{ij} + \frac{1}{\sqrt{2}}(Y_\ell^0)^*_{ji}c_{\beta-\alpha}, \quad g_h^{ij} = \frac{\sqrt{2}m_{\ell_i}}{v}s_{\beta-\alpha}\delta_{ij} + \frac{1}{\sqrt{2}}(Y_\ell^0)_{ij}c_{\beta-\alpha}$$

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

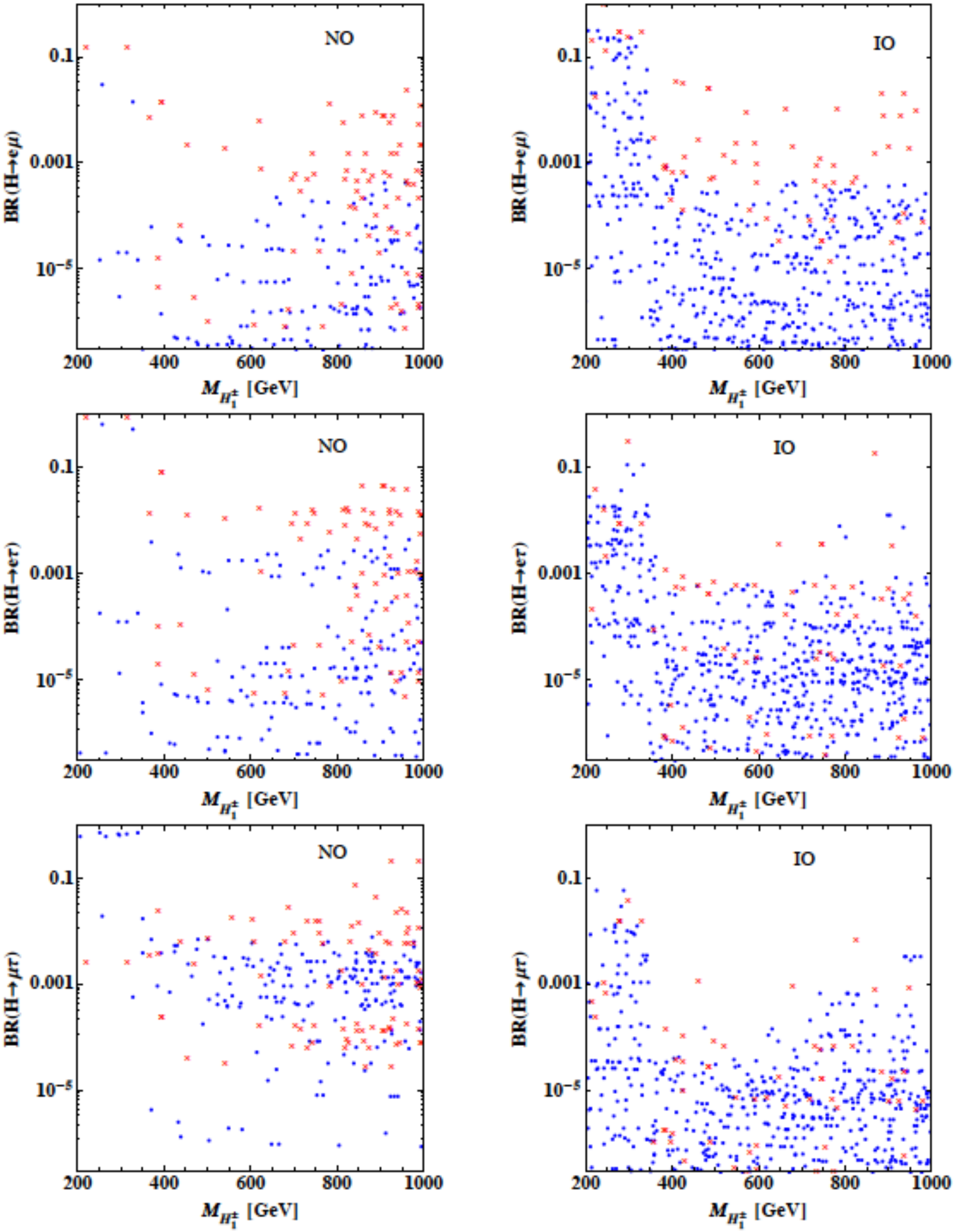
$$f_A^{ij} = -\frac{i}{\sqrt{2}}(Y_\ell^0)^*_{ji}c_{\beta-\alpha}, \quad g_A^{ij} = \frac{i}{\sqrt{2}}(Y_\ell^0)_{ij}c_{\beta-\alpha}.$$



NO
IO
BR($\mu \to e\gamma$)
BR($\tau \to e\gamma$)
BR($\tau \to \mu\gamma$)
$M_{H_1^\pm}$ [GeV]



NO
$M_{H_1^\pm} = 300$ GeV
$M_{H_2^\pm} = 500$ GeV
IO
$M_{H_1^\pm} = 300$ GeV
$M_{H_2^\pm} = 500$ GeV
NO
$M_{H_1^\pm} = 800$ GeV
$M_{H_2^\pm} = 1000$ GeV
IO
$M_{H_1^\pm} = 800$ GeV
$M_{H_2^\pm} = 1000$ GeV
$ee + \mu\mu + \tau\tau$
$e\mu + e\tau + \mu\tau$
$t\bar{t}$
$q\bar{q}$
BR
$\tan\beta$


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