The $\mu \to e\gamma$ decay in an EW-scale non-sterile right-handed neutrino model

Dinh Nguyen Dinh

Institute of Physics, Hanoi, Vietnam

Online workshop: Darkness on the table, 2021

Introduction

- Neutrino oscillation discovery is evidence of massive and missing neutrinos; also lepton flavor violation (LFV). However, it has not been determined in the charged lepton sector.
- In minimal extended models, LFV process branching ratios in charged lepton sector is extremely tiny; $\mathrm{Br}(\mu \to e\gamma) \sim 10^{-55}$.
- Current and future expected sensitivities by MEG:

$$\begin{aligned} \mathrm{BR}(\mu^+ \to e^+\gamma) &< 4.2 \times 10^{-13}, \\ \mathrm{BR}(\mu^+ \to e^+\gamma) &< 6.0 \times 10^{-14}. \end{aligned}$$

$\Longrightarrow$ Not possible to determine in practice!

MEG: *Eur. Phys. J., Vol. C76, No. 8, P.434, 2016*; *Arxiv:2107.10767*

Introduction

- There are more experimental confirmations prove that SM requires to be modified beside massive neutrino problem, such as dark matter, matter anti-matter asymmetry, ...
- In those extensions, the LFV branching ratios might be much higher and reach the experimental sensitivities.
- In this report, we discuss $\mu \to e\gamma$ decay in a EW-scale ν_R model
  - Derive the branching ratio
  - Set constraints on relevant parameters, predict observable possibilities by current and future experiments.

Outline

1. Briefly introduce the model
2. Calculate the form factors and derive decay branching ratio
3. Discussions and set constraints on involving couplings, for the cases of one-loop diagrams involving
   - W boson
   - singly charged scalars
   - Heavy neutral scalars
   - Light neutral scalar
4. Conclusion

Model overview

- The model is constructed based on a symmetric group $SU(2) \times U(1)_Y \times U(1)_{SM} \times U(1)_{MF}$, where $SU(2) \times U(1)_Y$ is gauge group, and $U(1)_{SM} \times U(1)_{MF}$ is a global symmetry.
- The particle contents are

SM particles	Mirror partners
$\ell_L = (\nu_L,\ e_L)^T,\ e_R$	$\ell_R^M = (\nu_R,\ e_R^M)^T,\ e_L^M$
$q_L = (u_L, d_L)^T,\ u_R,\ d_R$	$q_R^M = (u_R^M,\ d_R^M)^T,\ u_L^M,\ d_L^M.$

- The Higgs sector consists of:
  - Two Higgs doublets: $\Phi_2 = (\phi_2^+, \phi_2^0)$, $\Phi_{2M} = (\phi_{2M}^+, \phi_{2M}^0)$,
  - A $Y = 0$ real triplet $\xi = \left(\xi^+, \xi^0, \xi^-\right)$, and a $Y = 2$ complex triplet $\tilde{\chi}$

$$\tilde{\chi} = \frac{1}{\sqrt{2}}\vec{\tau}.\vec{\chi} = \begin{pmatrix} \frac{1}{\sqrt{2}}\chi^+ & \chi^{++} \\ \chi^0 & -\frac{1}{\sqrt{2}}\chi^+ \end{pmatrix},$$

  - A Higgs singlet ϕ_S.

Model overview

- Global symmetry
  - Global symmetry $U(1)_{SM} \times U(1)_{MF}$ is imposed to prevent some unexpected couplings.
  - Transformations of matter and Higgs fields are defined as following:
    i) $U(1)_{SM}$: $\Psi = \left\{\Phi_2,\ q_L^{SM},\ \ell_L^{SM}\right\}$ transforms as $\Psi \to e^{i\alpha_{SM}}\Psi$,
    ii) $U(1)_{MF}$: $\Psi = \left\{\Phi_{2M},\ q_R^{M},\ \ell_R^{M}\right\}$ transforms as $\Psi \to e^{i\alpha_{MF}}\Psi$,
    iii) $\phi_S \to e^{-i(\alpha_{MF}-\alpha_{SM})}\phi_S$, $\tilde{\chi} \to e^{-2i\alpha_{MF}}\tilde{\chi}$,
  - The unmentioned fields are singlets.
- The Yukawa couplings are:

$$\mathcal{L}_Y^{\ell} = g_\ell \bar{\ell}_L \Phi_2 e_R + g_\ell^M \bar{\ell}_R^M \Phi_{2M} e_L^M + g_{\ell s}\bar{\ell}_L \phi_s \ell_R^M + h.c.$$

$$\mathcal{L}_Y^{q} = g_u \bar{q}_L \tilde{\Phi}_2 u_R + g_d \bar{q}_L \Phi_2 d_R + g_u^M \bar{q}_R^M \tilde{\Phi}_{2M} u_L^M + g_d^M \bar{q}_R^M \Phi_{2M} d_L^M + g_{qs}\bar{q}_L \phi_S q_R^M + h.c.$$

$$\mathcal{L}_{\nu_R} = g_M l_R^{M,T}\, \sigma_2\, \tilde{\chi}\, l_R^M\ ,$$

where σ_2 is the second Pauli matrix, $\tilde{\Phi}_2 = i\sigma_2\Phi_2^*$ and $\tilde{\Phi}_{2M} = i\sigma_2\Phi_{2M}^*$.

Symmetry breaking

- Higgs fiels develop their VEVs as: $\langle\Phi_2\rangle = (0, v_2/\sqrt{2})^T$, $\langle\Phi_{2M}\rangle = (0, v_{2M}/\sqrt{2})^T$, $\langle\chi^0\rangle = v_M$, and $\langle\phi_S\rangle = v_S$,
- Charged lepton masses:
  - The mass matrix

$$M_\ell = \begin{pmatrix} m_\ell & m_\ell^D \\ (m_\ell^D)^\dagger & m_{\ell M} \end{pmatrix},$$

where $m_\nu^D = m_\ell^D = g_{\ell s} v_S$, $m_\ell = g_\ell v_2/\sqrt{2}$, and $m_{\ell M} = g_\ell^M v_{2M}/\sqrt{2}$.

  - For $m_\ell^D \ll m_{\ell M}$, $m_\ell^D \ll m_\ell$

$$M_\ell = \begin{pmatrix} m_\ell & m_\ell^D \\ (m_\ell^D)^\dagger & m_{\ell M} \end{pmatrix} = \begin{pmatrix} I & R_\ell \\ -R_\ell^\dagger & I \end{pmatrix}^\dagger \begin{pmatrix} \tilde{m}_\ell & 0 \\ 0 & \tilde{m}_{\ell M} \end{pmatrix} \begin{pmatrix} I & R_\ell \\ -R_\ell^\dagger & I \end{pmatrix},$$

where $R_\ell \approx \frac{m_\ell^D}{m_{\ell M}} \ll 1$, $\tilde{m}_\ell \approx m_\ell$, $\tilde{m}_{\ell M} \approx m_{\ell M}$.

  - If we express $\tilde{m}_\ell = U_{\ell L} m_\ell^d U_{\ell R}^\dagger$, $\tilde{m}_{\ell M} = U_{\ell L}^M m_{\ell M}^d U_{\ell R}^{M\,\dagger}$, then

$$\begin{pmatrix} \ell_{L(R)} \\ \ell^M_{L(R)} \end{pmatrix} = \begin{pmatrix} U_{\ell L(R)} & -R_\ell U^M_{\ell L(R)} \\ R_\ell^\dagger U_{\ell L(R)} & U^M_{\ell L(R)} \end{pmatrix} \begin{pmatrix} \ell'_{L(R)} \\ \ell^{M\prime}_{L(R)} \end{pmatrix}.$$

Symmetry breaking

- Neutrino masses:
  - The mass matrix

$$M_\nu = \begin{pmatrix} 0 & m_\nu^D \\ (m_\nu^D)^T & M_R \end{pmatrix}. \qquad (1)$$

where $m_\nu^D = m_\ell^D = g_{\ell s} v_S$, $M_R = g_M v_M$.

  - For $m_\nu^D \ll M_R$, we can approximately blocked diagonalized

$$M_\nu = \begin{pmatrix} 0 & m_\nu^D \\ (m_\nu^D)^T & M_R \end{pmatrix} = \begin{pmatrix} I & R_\nu \\ -R_\nu^\dagger & I \end{pmatrix}^T \begin{pmatrix} \tilde{m}_\nu & 0 \\ 0 & \tilde{m}_{\nu R} \end{pmatrix} \begin{pmatrix} I & R_\nu \\ -R_\nu^\dagger & I \end{pmatrix},$$

where $R_\nu \approx \frac{m_\nu^D}{M_R}$, and

$$\tilde{m}_\nu \approx -\frac{(m_\nu^D)^2}{M_R} = -\frac{(g_{\ell s} v_S)^2}{g_M v_M}, \quad \tilde{m}_{\nu R} \approx M_R. \qquad (2)$$

  - Suppose that $\tilde{m}_\nu = U_\nu^* m_\nu^d U_\nu^\dagger$, $\tilde{m}_{\nu R} = U_\nu^{M*} m_{\nu M}^d U_\nu^{M\dagger}$, then

$$\begin{pmatrix} \nu_L \\ (\nu_R)^c \end{pmatrix} = \begin{pmatrix} U_\nu & -R_\nu U_\nu^M \\ R_\nu^\dagger U_\nu & U_\nu^M \end{pmatrix} \begin{pmatrix} \chi_\nu \\ \chi_M \end{pmatrix}.$$

Symmetry breaking in Higgs sector

- If there is only one Higgs triplet, the quantity $\rho = M_w/(M_z \cos\theta_w) = 1$ might be spoiled out, thus Higgs triplets ξ, $\tilde{\chi}$ are introduced.
- It is proved in M.S. Chanowitz et. al., Phys. Lett. B 165 (1985) 105 that if the two triplets combined to form $(3,3)$ representation under global $SU(2)_L \times SU(2)_R$ of the Higgs potential; After gaining VEV, the symmetry is broken downto a custodial $SU(2)$, then $\rho = 1$.
- In this model, two triplets and doublets form $(3,3)$ and $(2,2)$ representations as:

$$\chi = \begin{pmatrix} \chi^0 & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^{0*} \end{pmatrix},$$

$$\Phi_2 = \begin{pmatrix} \phi_2^{0,*} & \phi_2^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}, \quad \Phi_{2M} = \begin{pmatrix} \phi_{2M}^{0,*} & \phi_{2M}^+ \\ \phi_{2M}^- & \phi_{2M}^0 \end{pmatrix}.$$

- $\langle \Phi_2^0 \rangle = (v_2/\sqrt{2})$, $\langle \Phi_{2M}^0 \rangle = (v_{2M}/\sqrt{2})$ and $\langle \chi^0 \rangle = v_M$,

$$v_2^2 + v_{2M}^2 + 8\, v_M^2 = v^2 = (246\ \text{GeV})^2, \ s_2 = \frac{v_2}{v}; \ \ s_{2M} = \frac{v_{2M}}{v}; \ \ s_M = \frac{2\sqrt{2}\ v_M}{v}.$$

Symmetry breaking in Higgs sector

- Generated physical scalars as representations of the global custodial symmetry as:

$$\begin{aligned} \text{five-plet (quintet)} &\rightarrow H_5^{\pm\pm},\ H_5^{\pm},\ H_5^0; \\ \text{triplet} &\rightarrow H_3^{\pm},\ H_3^0; \\ \text{triplet} &\rightarrow H_{3M}^{\pm},\ H_{3M}^0; \\ \text{three singlets} &\rightarrow H_1^0,\ H_{1M}^0,\ H_1^{0\prime}. \end{aligned}$$

- Three singlets $H_1^0,\ H_{1M}^0,\ H_1^{0\prime}$ are not mass eigenstates; $H_1^0 = \sum_i^3 \alpha_i \tilde{H}_i$, $H_{1M}^0 = \sum_i^3 \alpha_i^M \tilde{H}_i$, where $\sum_i^3 |\alpha_i|^2 = 1$ and $\sum_i^3 |\alpha_i^M|^2 = 1$.
- The light singlet ϕ_s^0.

LFV vertexes

Vertices	Couplings
$(\bar{e}'_L \gamma^\mu \chi_L) W^-_\mu$	$-i \frac{g}{\sqrt{2}} U^L_{W_\mu} = -i \frac{g}{\sqrt{2}} U_{PMNS}$
$(\bar{e}'_L \gamma^\mu \chi^M_L) W^-_\mu$	$i \frac{g}{\sqrt{2}} U^{ML}_{W_\mu} = i \frac{g}{\sqrt{2}} \tilde{R}_\nu \left(U^M_{PMNS}\right)^*$
$(\bar{e}'_R \gamma^\mu \chi^c_L) W^-_\mu$	$-i \frac{g}{\sqrt{2}} U^R_{W_\mu} = -i \frac{g}{\sqrt{2}} \tilde{R}^T_\nu (U_{PMNS})^*$
$\bar{e}'_R \chi_L H^-_3$	$-i \frac{g}{2} Y^L_{H^-_3} = -i \frac{g\, s_M}{2 M_W c_M} m^d_\ell U_{PMNS}$
$\bar{e}'_R \chi^M_L H^-_3$	$i \frac{g}{2} Y^{ML}_{H^-_3} = i \frac{g\, s_M}{2 M_W c_M} m^d_\ell \tilde{R}_\nu \left(U^M_{PMNS}\right)^*$
$\bar{e}'_L \chi^{Mc}_L H^-_3$	$-i \frac{g}{2} Y^{MR}_{H^-_3} = -i \frac{g\, s_M}{2 M_W c_M} \tilde{R}_\ell m^d_{\ell M} U^M_{PMNS}$
$\bar{e}'_R \chi_L H^-_{3M}$	$-i \frac{g}{2} Y^L_{H^-_{3M}} = -i \frac{g\, s_{2M}}{2 M_W s_2 c_M} m^d_\ell U_{PMNS}$
$\bar{e}'_R \chi^M_L H^-_{3M}$	$i \frac{g}{2} Y^{ML}_{H^-_{3M}} = i \frac{g\, s_{2M}}{2 M_W s_2 c_M} m^d_\ell \tilde{R}_\nu \left(U^M_{PMNS}\right)^*$
$\bar{e}'_L \chi^{Mc}_L H^-_{3M}$	$-i \frac{g}{2} Y^{MR}_{H^-_{3M}} = -i \frac{g\, s_M}{2 M_W s_{2M} c_M} \tilde{R}_\ell m^d_{\ell M} U^M_{PMNS}$
$\bar{e}'_R e^{M\prime}_L \phi^0_s$	$-i \frac{g}{2} Y^{ML}_{\phi^0_s} = -i U^\dagger_{\ell R} g_{\ell s} U^M_{\ell L}$
$\bar{e}'_L e^{M\prime}_R \phi^0_s$	$-i \frac{g}{2} Y^{MR}_{\phi^0_s} = -i\, U^\dagger_{\ell L} g_{\ell s} U^M_{\ell R}$

Tabelle: Vertices that contribute to the decay rates $\ell \to \ell' \gamma$.

LFV vertexes

-
$$
\begin{aligned}
(\bar{e}'_R e^{M\prime}_L \tilde{H}^0_i) \quad & -i\frac{g}{2}Y^{ML}_{\tilde{H}^0_i} = -i\frac{g}{2M_W}\left[\frac{\alpha_i}{s_2}m^d_\ell \tilde{R}_\ell + \frac{\alpha^M_i}{s_{2M}}\tilde{R}_\ell m^d_{\ell M}\right],\\
(\bar{e}'_L e^{M\prime}_R \tilde{H}^0_i) \quad & -i\frac{g}{2}Y^{MR}_{\tilde{H}^0_i} = -i\frac{g}{2M_W}\left[\frac{\alpha_i}{s_2}m^d_\ell \tilde{R}_\ell + \frac{\alpha^M_i}{s_{2M}}\tilde{R}_\ell m^d_{\ell M}\right],\\
(\bar{e}'_R e^{M\prime}_L H^0_3) \quad & -i\frac{g}{2}Y^{ML}_{H^0_3} = -i\frac{g}{2M_W}\left[\frac{s_M}{c_M}m^d_\ell \tilde{R}_\ell + \frac{s_M}{c_M}\tilde{R}_\ell m^d_{\ell M}\right],\\
(\bar{e}'_L e^{M\prime}_R H^0_3) \quad & -i\frac{g}{2}Y^{MR}_{H^0_3} = -i\frac{g}{2M_W}\left[-\frac{s_M}{c_M}m^d_\ell \tilde{R}_\ell - \frac{s_M}{c_M}\tilde{R}_\ell m^d_{\ell M}\right],\\
(\bar{e}'_R e^{M\prime}_L H^0_{3M}) \quad & -i\frac{g}{2}Y^{ML}_{H^0_{3M}} = -i\frac{g}{2M_W}\left[-\frac{s_{2M}}{s_2}m^d_\ell \tilde{R}_\ell - \frac{s_2}{s_{2M}}\tilde{R}_\ell m^d_{\ell M}\right],\\
(\bar{e}'_L e^{M\prime}_R H^0_{3M}) \quad & -i\frac{g}{2}Y^{MR}_{H^0_{3M}} = -i\frac{g}{2M_W}\left[\frac{s_{2M}}{s_2}m^d_\ell \tilde{R}_\ell + \frac{s_2}{s_{2M}}\tilde{R}_\ell m^d_{\ell M}\right].
\end{aligned}
$$

Here the notations $U_{PMNS} = U^\dagger_\ell U_\nu$, which is the famous neutrino mixing PMNS matrix, $U^M_{PMNS} = U^{M\dagger}_\ell U^M_\nu$ and $\tilde{R}_{\ell(\nu)} = U^\dagger_\ell R_{\ell(\nu)} U^M_\ell$ have been used. For simplicity, we have also neglected the complex phases in U_ℓ and U^M_ℓ.

Formfactors & Br$(\mu \to e + \gamma)$

- The effective Lagrangian has form:

$$\mathcal{L}_{eff} = -4\frac{eG_F}{\sqrt{2}} m_\mu \left(A_R \bar{e}\sigma_{\mu\nu}P_R\mu + A_L \bar{e}\sigma_{\mu\nu}P_L\mu\right) F^{\mu\nu} + H.c.$$

$$\begin{aligned} A_R = \; & -\sum_{H^Q,k} \frac{M_W^2}{64\pi^2 M_H^2}\left[\left(Y_H^L\right)_{\mu k}\left(Y_H^L\right)^*_{ek} G_H^Q(\lambda_k) + \frac{m_k}{m_\mu}\left(Y_H^R\right)_{\mu k}\left(Y_H^L\right)^*_{ek} \times R_H^Q(\lambda_k)\right] \\ & + \frac{1}{32\pi^2}\sum_k \left[\left(U^L_{W_\mu}\right)_{\mu k}\left(U^L_{W_\mu}\right)^*_{ek} G_\gamma(\lambda_k) - \left(U^R_{W_\mu}\right)_{\mu k}\left(U^L_{W_\mu}\right)^*_{ek}\frac{m_k}{m_\mu} R_\gamma(\lambda_k)\right], \end{aligned}$$

$$\begin{aligned} A_L = \; & -\sum_{H^Q,k} \frac{M_W^2}{64\pi^2 M_H^2}\left[\left(Y_H^R\right)_{\mu k}\left(Y_H^R\right)^*_{ek} G_H^Q(\lambda_k) + \frac{m_k}{m_\mu}\left(Y_H^L\right)_{\mu k}\left(Y_H^R\right)^*_{ek} R_H^Q(\lambda_k)\right] \\ & + \frac{1}{32\pi^2}\sum_k \left[\left(U^R_{W_\mu}\right)_{\mu k}\left(U^R_{W_\mu}\right)^*_{ek} G_\gamma(\lambda_k) - \left(U^L_{W_\mu}\right)_{\mu k}\left(U^R_{W_\mu}\right)^*_{ek}\frac{m_k}{m_\mu} R_\gamma(\lambda_k)\right], \end{aligned}$$

where $H^Q = \phi_S^0, \tilde{H}_i^0\ (i = 1,2,3), H_3^0, H_{3M}^0, H_3^+, H_{3M}^+$, and m_k are the masses of associated fermions that along with either H^Q or W_μ to form loops, and $\lambda_k = m_k^2/M^2_{W_\mu(H^Q)}$.

Formfactors & $\mathrm{Br}(\mu \to e + \gamma)$

- The branching ratio of $\mu \to e + \gamma$ decay is easily obtained as

$$\mathrm{Br}(\mu \to e + \gamma) = 384\pi^2 (4\pi\alpha_{em}) \left(|A_R|^2 + |A_L|^2\right),$$

where $\alpha_{em} = 1/137$ is the fine-structure constant.

- Functions $G_H^Q(x)$, $R_H^Q(x)$, $G_\gamma(x)$, and $R_\gamma(x)$ are defined as:

$$G_H^Q(x) = -\frac{(3Q-1)x^2 + 5x - 3Q + 2}{12(x-1)^3} + \frac{1}{2}\frac{x(Qx - Q + 1)}{2(x-1)^4}\log(x), \quad (3)$$

$$R_H^Q(x) = \frac{(2Q-1)x^2 - 4(Q-1)x + 2Q - 3}{2(x-1)^3} - \frac{Qx - (Q-1)}{(x-1)^3}\log(x), \quad (4)$$

$$G_\gamma(x) = \frac{20x^2 - 7x + 2}{4(x-1)^3} - \frac{3}{2}\frac{x^3}{(x-1)^4}\log(x), \quad (5)$$

$$R_\gamma(x) = -\frac{x^2 + x - 8}{2(x-1)^2} + \frac{3x(x-2)}{(x-1)^3}\log(x). \quad (6)$$

$\nu - w$ 1-loop diagrams

- Contribution of the light neutrinos to the process are extremely small

$$\sum_{k=1}^{3} \left(U^L_{W_\mu}\right)_{\mu k} \left(U^L_{W_\mu}\right)^*_{ek} G_\gamma(\lambda_k) \approx \sum_{k=1}^{3} \left(U^L_{W_\mu}\right)_{\mu k} \left(U^L_{W_\mu}\right)^*_{ek} G_\gamma(0) = \left(U^{L\dagger}_{W_\mu} U^L_{W_\mu}\right)_{e\mu} G_\gamma(0) \approx 0.$$

$$\sum_{k=1}^{3} \left(U^L_{W_\mu}\right)_{\mu k} \left(U^R_{W_\mu}\right)^*_{ek} \frac{m_k}{m_\mu} \sim 10^{-9}$$

$\nu - w$ 1-loop diagrams

- Contribution of the light neutrinos to the process are extremely small

$$\sum_{k=1}^{3}\left(U^L_{W_\mu}\right)_{\mu k}\left(U^L_{W_\mu}\right)^*_{ek} G_\gamma(\lambda_k) \approx \sum_{k=1}^{3}\left(U^L_{W_\mu}\right)_{\mu k}\left(U^L_{W_\mu}\right)^*_{ek} G_\gamma(0) = \left(U^{L\dagger}_{W_\mu} U^L_{W_\mu}\right)_{e\mu} G_\gamma(0) \approx 0.$$

$$\sum_{k=1}^{3}\left(U^L_{W_\mu}\right)_{\mu k}\left(U^R_{W_\mu}\right)^*_{ek} \frac{m_k}{m_\mu} \sim 10^{-9}$$

$\nu - w$ loop contribution

$$\left(U^L_{W_\mu}\right)_{\mu k}\left(U^L_{W_\mu}\right)^*_{ek} G_\gamma(\lambda_k) - \left(U^L_{W_\mu}\right)_{\mu k}\left(U^R_{W_\mu}\right)^*_{ek} \frac{m_k}{m_\mu} R_\gamma(\lambda_k)$$

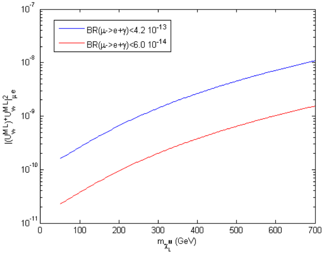
$\nu - w$ 1-loop diagrams

- Contribution of the light neutrinos to the process are extremely small

$$\sum_{k=1}^{3}\left(U^L_{W_\mu}\right)_{\mu k}\left(U^L_{W_\mu}\right)^*_{ek} G_\gamma(\lambda_k) \approx \sum_{k=1}^{3}\left(U^L_{W_\mu}\right)_{\mu k}\left(U^L_{W_\mu}\right)^*_{ek} G_\gamma(0) = \left(U^{L\dagger}_{W_\mu} U^L_{W_\mu}\right)_{e\mu} G_\gamma(0) \approx 0.$$

$$\sum_{k=1}^{3}\left(U^L_{W_\mu}\right)_{\mu k}\left(U^R_{W_\mu}\right)^*_{ek} \frac{m_k}{m_\mu} \sim 10^{-9}$$

- Heavy neutrinos



+ $\left|U^{ML\dagger}_W U^{ML}_W\right|_{e\mu} \sim |R_\nu|^2 < 10^{-5}\ (3\times 10^{-6})$
+ $\tilde{m}_\nu = \frac{(m^D_\nu)^2}{M_R} \sim 10^{-10}$ GeV $\Rightarrow R_\nu = \frac{m^D_\nu}{M_R} \sim 10^{-5}\sqrt{\frac{1\text{GeV}}{M_R}}$ thus $|R_\nu|^2 \sim 10^{-12}$ for $M_R \sim 100$ GeV

$\nu - H^-$ loop diagrams

- The interfered terms give dominated contributions

$$\frac{m_k}{m_\mu} \sim \frac{100\ \text{GeV}}{100\ \text{MeV}} \sim 10^3.$$

$\nu - H^-$ loop diagrams

- The interfered terms give dominated contributions

$$\frac{m_k}{m_\mu} \sim \frac{100 \text{ GeV}}{100 \text{ MeV}} \sim 10^3.$$

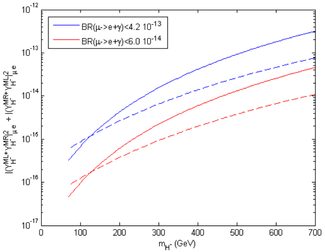
$\nu - H^-$ loop contribution

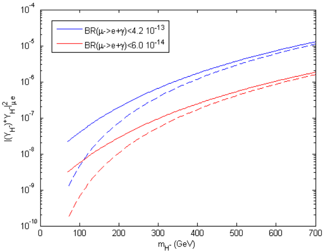
$$\left(Y_H^L\right)_{\mu k} \left(Y_H^L\right)^*_{ek} G_H^Q(\lambda_k) + \frac{m_k}{m_\mu} \left(Y_H^R\right)_{\mu k} \left(Y_H^L\right)^*_{ek} \times R_H^Q(\lambda_k)$$

$\nu - H^-$ loop diagrams

- The interfered terms give dominated contributions

$$\frac{m_k}{m_\mu} \sim \frac{100 \text{ GeV}}{100 \text{ MeV}} \sim 10^3.$$



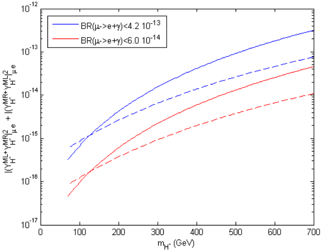


$\nu - H^-$ loop diagrams

- The interfered terms give dominated contributions
- From the figure, we have:

$$|(Y^{ML}_{H^-})^\dagger Y^{MR}_{H^-}|^2_{\mu e} + |(Y^{MR}_{H^-})^\dagger Y^{ML}_{H^-}|^2_{\mu e} \lesssim 3.0 \times 10^{-16} (6.0 \times 10^{-16}) \text{ for } m_{\chi^M_L} = 80\ (200)\ \text{GeV},$$

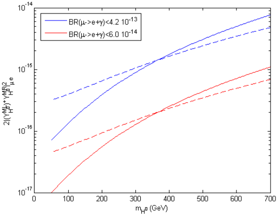
$$|(Y^{ML}_{H^-})^\dagger Y^{MR}_{H^-}|^2_{\mu e} + |(Y^{MR}_{H^-})^\dagger Y^{ML}_{H^-}|^2_{\mu e} \lesssim 4.0 \times 10^{-17} (8.0 \times 10^{-17}) \text{ for } m_{\chi^M_L} = 80\ (200)\ \text{GeV}.$$

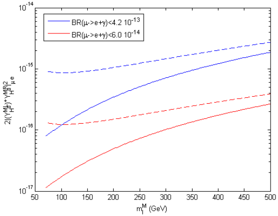


$$H_3^-: \left|Y^{L\dagger}_{H_3^-} Y^R_{H^-_{3M}}\right|^2_{21} + \left|Y^{R\dagger}_{H^-_{3M}} Y^L_{H_3^-}\right|^2_{21} \sim 2.2 \times 10^{-29} \left(\frac{s_M^2}{c_M^2}\right)^2$$

$$H^-_{3M}: \left|Y^{L\dagger}_{H^-_{3M}} Y^R_{H^-_{3M}}\right|^2_{21} + \left|Y^{R\dagger}_{H^-_{3M}} Y^L_{H^-_{3M}}\right|^2_{21} \sim 2.2 \times 10^{-29} \left(\frac{s_M}{s_2 c_M^2}\right)^2$$

$\ell^M - H^0$ loop diagrams





- Constraints obtained from the left panel

$$2|(Y^{ML}_{H^0})^\dagger Y^{MR}_{H^0}|^2_{\mu e} \lesssim 7.0 \times 10^{-17}(3.0 \times 10^{-16}) \text{ for } m^M_\ell = 80\ (200)\text{ GeV (green lines)}$$

$$2|(Y^{ML}_{H^0})^\dagger Y^{MR}_{H^0}|^2_{\mu e} \lesssim 1.0 \times 10^{-17}(4.5 \times 10^{-17}) \text{ for } m^M_\ell = 80\ (200)\text{ GeV (red lines)}$$

- Theoretical estimations

$$2\left|Y^{L\dagger}_{H^0} Y^{R}_{H^0}\right|^2_{21} = 2\alpha^4 \times \frac{\left|\tilde{R}_\ell (m^d_{\ell M})^2 \tilde{R}_\ell\right|^2_{21}}{M^4_W} \sim 4.4 \times 10^{-23}\alpha^4,$$

where α stands for $\frac{\alpha_i}{s_2}$, $\frac{s_M}{c_M}$ or $\frac{s_2}{s_{2M}}$, corresponding to $\tilde{H}^0_i$, $(i = 1, 2, 3)$, H^0_3 or H^0_{3M}, respectively.

$\ell^M - H^0$ loop diagrams

- Constraints obtained from the left panel

$$2|(Y^{ML}_{H^0})^\dagger Y^{MR}_{H^0}|^2_{\mu e} \lesssim 7.0 \times 10^{-17} (3.0 \times 10^{-16}) \text{ for } m^M_\ell = 80\ (200) \text{ GeV (green lines)}$$

$$2|(Y^{ML}_{H^0})^\dagger Y^{MR}_{H^0}|^2_{\mu e} \lesssim 1.0 \times 10^{-17} (4.5 \times 10^{-17}) \text{ for } m^M_\ell = 80\ (200) \text{ GeV (red lines)}$$

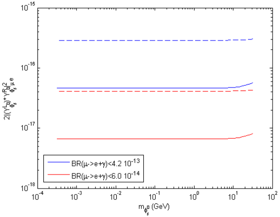
- Theoretical estimations

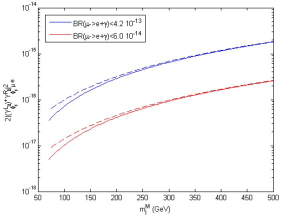
$$2\left|Y^{L\dagger}_{H^0} Y^R_{H^0}\right|^2_{21} = 2\alpha^4 \times \frac{\left|\tilde{R}_\ell (m^d_{\ell M})^2 \tilde{R}_\ell\right|^2_{21}}{M^4_W} \sim 4.4 \times 10^{-23} \alpha^4,$$

where α stands for $\frac{\alpha_i}{s_2}$, $\frac{s_M}{c_M}$ or $\frac{s_2}{s_{2M}}$, corresponding to $\tilde{H}^0_i$, $(i = 1, 2, 3)$, H^0_3 or H^0_{3M}, respectively.

In the H^0_3 case, for $c_M = 0.01$, the factor $2\left|Y^{L\dagger}_{H^0} Y^R_{H^0}\right|^2_{21} \sim 4.4 \times 10^{-15}$, which is about two order higher than the expected sensitive limit of the future experiment. In fact, our calculation show that the factor might be lager than 10^{-17} for $c_M \lesssim 0.03$.

$\ell^M - \phi_s^0$ loop diagrams





- One obtains from the left panel

$$2|(Y^L_{\phi^0_s})^\dagger Y^R_{\phi^0_s}|^2_{\mu e} \lesssim 4.7 \times 10^{-17} (3.0 \times 10^{-16}) \text{ for } m^M_\ell = 80\ (200)\ \text{GeV},$$

$$2|(Y^L_{\phi^0_s})^\dagger Y^R_{\phi^0_s}|^2_{\mu e} \lesssim 6.5 \times 10^{-18} (4.2 \times 10^{-17}) \text{ for } m^M_\ell = 80\ (200)\ \text{GeV}.$$

- Theoretical estimations

$$\left.\begin{array}{l} |g_{\ell s}| \lesssim 2.3 \times 10^{-5} (3.6 \times 10^{-5}) \text{ for } m^M_\ell = 80\ (200)\ \text{GeV} \\ |g_{\ell s}| \lesssim 1.4 \times 10^{-5} (2.3 \times 10^{-5}) \text{ for } m^M_\ell = 80\ (200)\ \text{GeV} \end{array}\right\} \Longrightarrow v_s \text{ at GeV order or higher.}$$

Conclusion

- We have introduce the model, calculate the form-factor and derive the $\mu \to e\gamma$ decay branching ratio.
- Contribution of the $\nu - W_\mu$ loop diagrams is less important and does not give any meaning constraint on the model's parameters.
- The branching ratio might reach the future experimental sensitivities due to the main contributions from heavy Higgs scalar loop diagrams, in which the neutral scalar channels are the most important.
- The couplings $g_{\ell s}$ is constrained to be in order of 10^{-5}, which implies that v_s magnitude is in range of few GeVs to several ten GeVs.

Thanks you!