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# $(g-2)_{e,\mu}$  ANOMALIES AND LEPTON FLAVOR VIOLATING DECAYS IN A TWO HIGGS DOUBLET MODEL: INVERTED ORDER SCHEME OF NEUTRINO OSCILLATION DATA

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# MOMENT TỪ DỊ THƯỜNG  $(g-2)_{e,u}$  VÀ CÁC QUÁ TRÌNH RÃ VI PHAM SỐ LEPTON THẾ HỀ TRONG MÔ HÌNH HAI LƯỚNG TUYẾN HIGGS: TRƯỜNG HƠP NEUTRINO PHÂN BẤC NGHICH

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### 1 INTRODUCTION

The Standard Model (SM) of particle physics is to this day an accurate description of the elementary particles and their interactions. Nevertheless, there are still problems that the SM cannot explain, such as the lepton flavor violating (LFV) decays, the origin of the neutrino mass and the lepton flavour violation in the neutrino sector, charged lepton anomalies  $(g-2)_{e,\mu}$ . Besides, neutrino oscillation experiments have shown it has mass and mixing flavours. Therefore, expanding the SM with the Beyond the SM (BSM) theories is indispensable work. A recent work (T. T. Hong et al, 2024) studied all LFV decay satisfying two experimental data of  $(g-2)$  anomalies, namely

*Nguyen Hua Thanh Nha/*Vol 10. No 4\_August 2024| p.17-25<br>
• The latest data of  $a_{\mu} \equiv (g - 2)_{\mu}/2$  was given where  $a_{\epsilon}^{\text{exp}}$  corresponds to in (Aguillard, D. P. *et al.* [Muon g-2], 2023), mental data given in (Fan *Nguyen Hua Thanh Nha/Vol* 10. No 4\_August 2024| p.17-25<br>
The latest data of  $a_{\mu} \equiv (g-2)_{\mu}/2$  was given where  $a_{e}^{\exp}$  corresponds t<br>
in (Aguillard, D. P. *et al.* [Muon g-2], 2023), mental data given in (Fa<br>
which s Nguyen Hua Thanh Nha/Vol 10. No 4\_August 2024| p.17-25<br>
The latest data of  $a_{\mu} \equiv (g-2)_{\mu}/2$  was given<br>
in (Aguillard, D. P. *et al.* [Muon g-2], 2023),<br>
which shows a clear discrepancy from the SM<br>
prediction of  $a_{\mu}$ *Nguyen Hua Thanh Nha/Nol* 10. No 4<sup>1</sup><br>The latest data of  $a_{\mu} \equiv (g-2)_{\mu}/2$  was given<br>in (Aguillard, D. P. *et al.* [Muon g-2], 2023), men<br>which shows a clear discrepancy from the SM<br>prediction of  $a_{\mu}^{\text{SM}} = 11659181$ *Nguyen Hua Thanh Nha/*Vol 10. No 4\_August 202<br> **of**  $a_{\mu} \equiv (g-2)_{\mu}/2$  was given where  $a_e^{\exp}$  co:<br>
D. P. *et al.* [Muon g-2], 2023), mental data g<br>
clear discrepancy from the SM Sukra, B. A. I<br>
s<sup>M</sup> = 116591810(43) × *Nguyen Hua Thanh Nha/*Vol 10. No 4\_August 2024| p.17-25<br>
The latest data of  $a_{\mu} \equiv (g - 2)_{\mu}/2$  was given<br>
in (Aguillard, D. P. *et al.* [Muon g-2], 2023),<br>
which shows a clear discrepancy from the SM<br>
prediction of  $a_{$ Nguyen Hua Thanh Nha/Vol 10. No 4\_August 2024| p.17-25<br>
The latest data of  $a_{\mu} \equiv (g-2)_{\mu}/2$  was given<br>
in (Aguillard, D. P. *et al.* [Muon g-2], 2023), mental data given in (Fan,<br>
which shows a clear discrepancy from t *Nguyen Hua Thanh Nha/Vc*<br>The latest data of  $a_{\mu} \equiv (g-2)_{\mu}/2$  was given<br>in (Aguillard, D. P. *et al.* [Muon g-2], 2023),<br>which shows a clear discrepancy from the SM<br>prediction of  $a_{\mu}^{\text{SM}} = 116591810(43) \times 10^{-11}$ <br>( Nguyen Hua Thanh Nha/Vol 10. No 4\_Augu<br> **u** of  $a_{\mu} \equiv (g - 2)_{\mu}/2$  was given<br>
D. P. *et al.* [Muon g-2], 2023), mental c<br>
clear discrepancy from the SM<br>  $\mu^{\text{SM}} = 116591810(43) \times 10^{-11}$ <br> *t al.*, 2020). The deviation • The latest data of  $a_{\mu} \equiv (g-2)_{\mu}/2$  was given<br>
in (Aguillard, D. P. *et al.* [Muon g-2], 2023), mental data given in (Fa<br>
which shows a clear discrepancy from the SM<br>
(Aoyama, T. *et al.*, 2020). The deviation be-<br>
t in (Aguillard, D. P. *et al.* [Muon g-2], 2023),<br>
which shows a clear discrepancy from the SM<br>
prediction of  $a_{\mu}^{\text{SM}} = 116591810(43) \times 10^{-11}$ <br>
(Aoyama, T. *et al.*, 2020). The deviation be-<br>
tween experiment and SM p

$$
\Delta a_{\mu}^{\rm NP} \equiv a_{\mu}^{\rm exp} - a_{\mu}^{\rm SM} = (2.49 \pm 0.48) \times 10^{-9} (5.1\sigma).
$$
perim (1) *Berna*

$$
\Delta a_e^{\text{NP}} \equiv a_e^{\text{exp}} - a_e^{\text{SM}} = (3.4 \pm 1.6) \times 10^{-13},\tag{2}
$$

where  $a_e^{\text{exp}}$  corresponds to the rece 2024| p.17-25<br>corresponds to the recent experi-<br>a given in (Fan, X., Myers, T. G.,<br>c. D., Gabrielse, G., 2023). 4\_August 2024| p.17-25<br>where  $a_e^{\text{exp}}$  corresponds to the recent experi-<br>mental data given in (Fan, X., Myers, T. G.,<br>Sukra, B. A. D., Gabrielse, G., 2023).<br>The decay rates such as charged LFV

(1) Bernard  $et\ al.$  [BaBar], 2010, Baldini, A. M. = 116591810(43) × 10<sup>-11</sup><br>
., 2020). The deviation be-<br>
and SM prediction used (cLFV), LFV<br>
z-boson (LF<br>
z-boson (LF Sukra, B. A. D., Gabrielse, G. , 2023).<br>
Sukra, B. A. D., Gabrielse, G. , 2023).<br>
• The decay rates such as charged LFV (cLFV), LFV Higgs (LFVh) decays, and LFV Z-boson (LFVZ) decays are constrained ex-4\_August 2024| p.17-25<br>where  $a_e^{\exp}$  corresponds to the recent experimental data given in (Fan, X., Myers, T. G.,<br>Sukra, B. A. D., Gabrielse, G., 2023).<br>The decay rates such as charged LFV<br>(cLFV), LFV Higgs (LFVh) decays 4\_August 2024| p.17-25<br>where  $a_e^{\exp}$  corresponds to the recent experimental data given in (Fan, X., Myers, T. G.,<br>Sukra, B. A. D., Gabrielse, G., 2023).<br>The decay rates such as charged LFV<br>(cLFV), LFV Higgs (LFVh) decays 4\_August 2024| p.17-25<br>where  $a_e^{\text{exp}}$  corresponds to the recent experimental data given in (Fan, X., Myers, T. G.,<br>Sukra, B. A. D., Gabrielse, G., 2023).<br>The decay rates such as charged LFV<br>(cLFV), LFV Higgs (LFVh) deca 4\_August 2024| p.17-25<br>where  $a_e^{\exp}$  corresponds to the recent experi-<br>mental data given in (Fan, X., Myers, T. G.,<br>Sukra, B. A. D., Gabrielse, G., 2023).<br>The decay rates such as charged LFV<br>(cLFV), LFV Higgs (LFVh) deca where  $a_e^{\text{exp}}$  corresponds to the recent experimental data given in (Fan, X., Myers, T. G., Sukra, B. A. D., Gabrielse, G., 2023).<br>The decay rates such as charged LFV (cLFV), LFV Higgs (LFVh) decays, and LFV Z-boson (LF where  $u_e$  corresponds to the recent experimental data given in (Fan, X., Myers, T. G., Sukra, B. A. D., Gabrielse, G., 2023).<br>The decay rates such as charged LFV (cLFV), LFV Higgs (LFVh) decays, and LFV Z-boson (LFVZ) de

	mental and SM for $(g-2)_e$ data is:	• Similarly, the discrepancy between experi-	et al. [MEG], 2016, Abdesselam, A. et al. [Belle], 2021).
		$\Delta a_e^{\text{NP}} \equiv a_e^{\text{exp}} - a_e^{\text{SM}} = (3.4 \pm 1.6) \times 10^{-13},$ (2)	
	Branching ratio (Br)	Most recent	Future sensitivity
	$Br(\tau \to \mu \gamma)$	$< 4.4 \times 10^{-8}$ (Aubert, Bernard <i>et</i> ) al. [BaBar], 2010; Baldini, A. M. et al. [MEG], 2016; Abdesselam, A. et al. [Belle], 2021)	$< 6.9 \times 10^{-9}$ (Baldini, A. M. et al. [MEG II], 2018; Altmannshofer, W. $et \ al.$ [Belle-II], 2020)
$\operatorname{cLFV}$	$\text{Br}(\tau\to e\gamma)$	$< 3.3 \times 10^{-8}$ (Aubert, Bernard <i>et</i> al. [BaBar], 2010; Baldini, A. M. et $al.$ [MEG], 2016; Abdesselam, A. $et$ al. [Belle], 2021)	$< 9.0 \times 10^{-9}$ (Baldini, A. M. <i>et al.</i> [MEG II], 2018; Altmannshofer, W. $et \ al.$ [Belle-II], 2020)
	$\text{Br}(\mu\to e\gamma)$	$< 4.2 \times 10^{-13}$ (Aubert, Bernard <i>et</i> al. [BaBar], 2010; Baldini, A. M. et $al.$ [MEG], 2016; Abdesselam, A. $et$ <i>al.</i> [Belle], 2021)	$< 6 \times 10^{-14}$ (Baldini, A. M. <i>et al.</i> [MEG II], 2018; Altmannshofer, W. $et \ al.$ [Belle-II], 2020)
	$Br(h \to \tau \mu)$	$< 1.5 \times 10^{-3}$ (Sirunyan, A. M. <i>et al.</i> ) [CMS], 2021)	orders of $\mathcal{O}(10^{-4})$ (Qin, Q. <i>et al.</i> ) 2018; Barman, R. K., Dev, P. S. B., Thapa, A., 2023; Aoki, M., Kanemura, S., Takeuchi, M., Za- makhsyari, L., 2023)
LFV <sub>h</sub>	$Br(h \to \tau e)$	[CMS], $2021$ ]	orders of $\mathcal{O}(10^{-4})$ (Qin, Q. et al. 2018)
	$\text{Br}(h\to \mu e)$	$\vert$ < 2.2 × 10 <sup>-3</sup> (Sirunyan, A. M. <i>et al.</i> $< 6.1 \times 10^{-5}$ (Aad, G. <i>et al.</i> [AT- [LAS], 2020) 2018)	orders of $\mathcal{O}(10^{-5})$ (Qin, Q. et al.
	$Br(Z \to \tau^{\pm} \mu^{\mp})$	$< 6.5 \times 10^{-6}$ (Aad, G. <i>et al.</i> [AT- $LAS$ ], $2022$ )	$10^{-6}$ at HL-LHC (Dam, M., 2019) and $10^{-9}$ at FCC-ee (Dam, M., 2019; Abada, A. et al. [FCC], 2019)
LFVZ		$\begin{array}{ l l } \hline \text{Br}(Z\to \tau^\pm e^\mp) &< 5.0\times 10^{-6}(\text{Aad, G. }et~al.~[\text{AT-}\\\text{LAS}],~2022)\\ &\text{Br}(Z\to \mu^\pm e^\mp) &~~2.62\times 10^{-7}(\text{Aad, G. }et~al.~[\text{ATLAS}],\\ &~2023)\hline \end{array}$	$10^{-6}$ at HL-LHC (Dam, M., 2019) and $10^{-9}$ at FCC-ee (Dam, M., 2019; Abada, A. et al. [FCC], 2019)
		2023)	$7 \times 10^{-8}$ at HL-LHC (Aad, G. et al. [ATLAS], 2022) and $10^{-10}$ at FCC- ee (Dam, M., 2019); Abada, A. et al. [FCC], 2019)

*Nguyen Hua Thanh N* Vol 10. No 4\_August 2024| p.17-25<br>Our work is arranged as follows. In section 2, LFVZ, and cLFV decays. All need<br>we will investigate the three LFV decay classes, decay rates  $Br(h \rightarrow e_b e_a)$ ,  $Br(Z$ <br>namely Nguyen Hua Thanh N Vol 10. No 4\_August 2024| p.17-2.<br>
Our work is arranged as follows. In section 2, LFVZ, and cLFV decays. All<br>
we will investigate the three LFV decay classes, decay rates Br( $h \to e_b e_a$ ),<br>
namely  $e_b \to e_a \$ namely  $e_b \to e_a \gamma$ ,  $Z \to e_b^{\pm} e_a^{\mp}$ , and  $h \to e_b^{\pm} e_a^{\mp}$  in  $\text{Br}(e_b \to e_a)$ Nguyen Hua Thanh N Vol 10. No 4\_August 2024| p.17-25<br>Our work is arranged as follows. In section 2, LFVZ, and cLFV decays. All nee<br>we will investigate the three LFV decay classes, decay rates Br( $h \to e_b e_a$ ), Br( $i$ <br>namely *Nguyen Hua Thanh N* Vol 10. No 4\_August 2024| p.17-25<br>Our work is arranged as follows. In section 2, LFVZ, and cLFV decays. All new<br>we will investigate the three LFV decay classes, decay rates Br( $h \rightarrow e_b e_a$ ), Br( $\ldots$ <br>nam *Nguyen Hua Thanh N* Vol 10. No 4\_August 2024| p.17-25<br>Our work is arranged as follows. In section 2, LFVZ, and cLFV decays. All ne<br>we will investigate the three LFV decay classes, decay rates Br( $h \to e_b e_a$ ), Br( $e_b \to e_a \gamma$ Nguyen Hua Thanh N Vol 10. No 4\_August 2024| p.17-25<br>Our work is arranged as follows. In section 2, LFVZ, and cLFV decays. All need<br>we will investigate the three LFV decay classes, decay rates Br( $h \rightarrow e_6e_a$ ), Br( $Z$ <br>namel Nguyen Hua Thanh N Vol 10. No 4\_August 2024| p.17-25<br>Our work is arranged as follows. In section 2, LFVZ, and cLFV decays. All 1<br>we will investigate the three LFV decay classes, decay rates Br( $h \rightarrow e_6e_a$ ), B<br>namely  $e_b \rightarrow e$ Our work is arranged as follows. In section 2, LFVZ, and cLFV decays. All nee<br>we will investigate the three LFV decay classes, decay rates Br( $h \rightarrow e_b e_a$ ), Br( $z_a$ namely  $e_b \rightarrow e_a \gamma$ ,  $Z \rightarrow e_b^+ e_a^+$ , and  $h \rightarrow e_b^+ e_a^+$  in Br( $e$ Our work is arranged as follows. In section 2, LFVZ, and cLFV decays. All ne<br>we will investigate the three LFV decay classes, decay rates  $Br(h \rightarrow e_b e_a)$ ,  $Br(\text{namely } e_b \rightarrow e_a \gamma, Z \rightarrow e_b^+ e_a^+$ , and  $h \rightarrow e_b^+ e_a^+$  in  $Br(e_b \rightarrow e_a \gamma)$  were we will investigate the three LFV decay clumely  $e_b \rightarrow e_a \gamma$ ,  $Z \rightarrow e_b^{\pm} e_a^{\mp}$ , and  $h \rightarrow e_b^{\pm}$ <br>the 2HDM $N_{L,R}$  framework, concentrating c<br>regions of the parameter space accommodatin<br> $1\sigma$  range of the  $(g-2)_{e,\mu}$  experime the 2HDMN<sub>LR</sub> framework, concentrating on the  $al$ , 2024), therefore we do not repeat here<br>regions of the parameter space accommodating the focus on the main ingredients to establis<br>1*σ* range of the  $(g - 2)_{e,\mu}$  experimen where we focus on the dependence of LFV decay<br>
mulated as follows (La<br>
rates on the heaviest active neutrino masses. Fi-<br>
mulated as follows (La<br>
rates on the heaviest active neutrino masses. Fi-<br>
lin, A., Hoferichter 1<br>

# NEUTRINOS

rates on the heaviest active neutrino masses. Find, L. D., Thuc, T. T., Dat, N. T.<br>
nally, we summarize important results in the sec-<br>
tion conclusion.<br>
2018):<br>
2 THE 2HDM WITH INVERSE SEESAW  $Br(e_b \rightarrow e_a \gamma) = \frac{48 \pi^2}{G_F^2 m_b^$ mally, we summarize important results in the sec-<br>
ellin, A., Hoferichter M., Schmidt-<br>
2018):<br>
2 THE 2HDM WITH INVERSE SEESAW  $Br(e_b \rightarrow e_a \gamma) = \frac{48\pi^2}{G_F^2 m_b^2} \left( |c_{(ab)R}|^2 \right)$ <br>
NEUTRINOS<br>
2.1 Particle content and coupling tion conclusion. 2018):<br>
2 THE 2HDM WITH INVERSE SEESAW Br( $e_b \rightarrow e_c$ <br>
NEUTRINOS<br>
2.1 Particle content and couplings where  $G_F =$ <br>
In this work, we will study the model discussed in Br( $\tau \rightarrow e \overline{\nu_e} \nu_{\tau}$ <br>
(T. T. Hong *et* **2.1 Particle content and couplings**  $\text{Br}(e_b \to e_a \gamma) = \frac{48\pi^2}{G_F^2 m_b^2} \left( |c_{(ab)R}| \times \text{Br}(e_b \to e_a \overline{\nu_a}) \right)$ <br> **2.1 Particle content and couplings**  $\text{where } G_F = g^2/(4\sqrt{2}m_W^2)$ ,  $\text{Br}(\mu)$ <br>
In this work, we will study the mode **2 THE 2HDM WITH INVERSE SEESAW**  $Br(e_b \to e_a \gamma) = \frac{48\pi^2}{G_F^2 m_b^2} \left( |c_{(ab)F} \rangle \right)$ <br> **2.1 Particle content and couplings**  $\times Br(e_b \to e_a I)$ <br>
In this work, we will study the model discussed in  $Br(\tau \to e\overline{\nu_e}\nu_{\tau}) \simeq 0.1782$ ,  $Br$ **NEUTRINOS**<br> **C**<sup>2</sup><sub>*C*<sup>0</sup></sub>  $\cdot$ <sup>2</sup> (1°(*ao*)*K*)<br> **2.1 Particle content and couplings**<br> **E** C<sub>*F*</sub> =  $g^2/(4\sqrt{2}m_W^2)$ , Br( $\mu \to e_a\overline{\nu_a}\nu$ <br>
In this work, we will study the model discussed in  $Br(\tau \to e\overline{\nu_e}\nu_{\tau}) \simeq 0.$ **2.1 Particle content and couplings**<br>
where  $G_F = g^2/(4\sqrt{2}m_W^2)$ , Bi<br>
In this work, we will study the model discussed in  $Br(\tau \to e\overline{\nu_e}\nu_{\tau}) \simeq 0.1782$ ,  $Br(\tau$ <br>
(T. T. Hong *et al*, 2024) discussed recently to (Workman, R **2.1 Particle content and couplings**<br>In this work, we will study the model discussed in<br>(T. T. Hong *et al*, 2024) discussed recently to<br>explain experimental data of  $(g - 2)_{e,\mu}$  anomalies,<br>where all LFV processes mention where  $G_F = g^2/(4\sqrt{2m_W})$ , B<br>
where  $G_F = g^2/(4\sqrt{2m_W})$ , B<br>
(T. T. Hong *et al*, 2024) discussed recently to (Workman, R. L. *et al.* [Par<br>
explain experimental data of  $(g-2)_{e,\mu}$  anomalies, 2022), and all relevant analytic<br> In this work, we will study the model discussed in  $Br(\tau \to e\nu_e\nu_\tau) \simeq 0.1782$ ,  $Br(\tau$ <br>
(T. T. Hong *et al*, 2024) discussed recently to (Workman, R. L. *et al.* [Parexplain experimental data of  $(g - 2)_{e,\mu}$  anomalies, 202 explain experimental data of  $(g - z)_{e,\mu}$  anomalies,<br>where all LFV processes mentioned above will be<br>discussed, namely the particle content is of the lep-<br>tons and Higgs sector is listed in Table 2, which is a<br>particular m

s omitted, see reviews in (Mon-<br>  $c_{(ba)R}$  with  $b \neq a$  m:<br>
2022; Branco, G. C. *et al*, 2012). the cLFV rates, espi-<br>
ngian of leptons is (Mondal, T., to  $a_{e_a}$  is from the two<br>  $c_k^+$ , denoted as  $a_{e_a,0}$ <br>  $a_{e_a,0}$ <br>

$$
-\mathcal{L}_Y^{\ell} = \overline{L_L} y_{\ell} H_1 e_R + \overline{L_L} f \tilde{H}_2 N_R + \overline{N_L} y^{\chi} e_R \chi^+ + \overline{N_L} y_N N_R \varphi + \overline{(N_L)^C} \frac{\lambda_L}{\Lambda} N_L \varphi^2 + \text{h.c.}, \qquad a_{e_a,0}(c^{\pm}) = \frac{G_F m_a^2}{\sqrt{2\pi^2}} \times \text{Re}\left\{ \begin{array}{c} (3) \end{array} \right.
$$

where  $\tilde{H}_2 = i\sigma_2 H_2^*$  ,  $y_\ell$ ,  $f$ ,  $Y_N$ ,  $y^\chi$ , and  $\lambda_L$ dal, T., Okada, H., 2022; Branco, G. C. *et al*, 2012). the cLFV rates, especially the m.<br>
The Yukawa Lagrangian of leptons is (Mondal, T., to  $a_{e_a}$  is from the two singly charged only correspond to  $\frac{1}{k_p^+}$ , denote Okada, H., 2022)<br>  $-\mathcal{L}_{Y}^{\ell} = \overline{L_{L}y_{\ell}}H_{1}e_{R} + \overline{L_{L}}f\tilde{H}_{2}N_{R} + \overline{N_{L}}y^{\chi}e_{R}\chi^{+}$ <br>  $+\overline{N_{L}}y_{N}N_{R}\varphi + \overline{(N_{L})^{C}}\frac{\lambda_{L}}{\Lambda}N_{L}\varphi^{2} + \text{h.c.},$   $a_{e_{a},0}(c^{\pm}) = \frac{G_{F}m_{a}^{2}}{\sqrt{2\pi}^{2}} \times \text{Re}\left\{\left[\frac{vt}{\sqrt{2\pi$ analytic fo<br>  $-\mathcal{L}_Y^{\ell} = \overline{L_L} y_{\ell} H_1 e_R + \overline{L_L} f \tilde{H}_2 N_R + \overline{N_L} y^{\chi} e_R \chi^+$ <br>  $+\overline{N_L} y_N N_R \varphi + \overline{(N_L)^C} \frac{\lambda_L}{\Lambda} N_L \varphi^2 + \text{h.c.},$   $a_{e_a,0}(c^{\pm}) =$ <br>
(3)<br>
where  $\tilde{H}_2 = i\sigma_2 H_2^*$ ,  $y_{\ell}$ ,  $f$ ,  $Y_N$ ,  $y^{\chi}$ , and  $\lambda_L$  $-\mathcal{L}_Y = L_L y_\ell n_1 e_R + L_L f n_2 N_R + N_L y^\circ e_R \chi$ <br>  $+ \overline{N_L} y_N N_R \varphi + (\overline{N_L})^C \frac{\lambda_L}{\Lambda} N_L \varphi^2 + \text{h.c.},$   $a_{e_a,0}(c^{\pm}) = \frac{G_F m_a^2}{\sqrt{2\pi^2}} \times \text{Re} \left\{ \left[ \frac{vt}{\Lambda} \right] \times [x_1 + \overline{N_L} y_N N_R \varphi + \overline{N_L} y_N \right\}$ ,  $\chi$  (3)<br>
where  $\tilde{H}_2 = i\sigma_2 H_$ 

Hua Thanh N Vol 10. No 4\_August 2024| p.1<br>lows. In section 2, LFVZ, and cLFV decays<br>LFV decay classes, decay rates Br( $h \rightarrow e_b t$ ), and  $h \rightarrow e_b^{\pm} e_a^{\mp}$  in Br( $e_b \rightarrow e_a \gamma$ ) were deter<br>oncentrating on the al, 2024), therefore  $\frac{1}{b}e_a^{\mp}$  in  $\text{Br}(e_b \to e_a \gamma)$  were determi 0. No 4\_August 2024| p.17-25<br>LFVZ, and cLFV decays. All needed formulas for<br>decay rates  $Br(h \rightarrow e_b e_a)$ ,  $Br(Z \rightarrow e_b e_a)$ , and<br> $Br(e_b \rightarrow e_a \gamma)$  were determined in (T. T. Hong *et* 0. No 4\_August 2024| p.17-25<br>LFVZ, and cLFV decays. All needed formulas for<br>decay rates Br( $h \to e_b e_a$ ), Br( $Z \to e_b e_a$ ), and<br>Br( $e_b \to e_a \gamma$ ) were determined in (T. T. Hong *et*<br>*al*, 2024), therefore we do not repeat here. We 0. No 4\_August 2024| p.17-25<br>LFVZ, and cLFV decays. All needed formulas for<br>decay rates Br( $h \rightarrow e_b e_a$ ), Br( $Z \rightarrow e_b e_a$ ), and<br>Br( $e_b \rightarrow e_a \gamma$ ) were determined in (T. T. Hong *et*<br>*al*, 2024), therefore we do not repeat here. We 0. No 4\_August 2024| p.17-25<br>LFVZ, and cLFV decays. All needed formulas for<br>decay rates  $Br(h \rightarrow e_b e_a)$ ,  $Br(Z \rightarrow e_b e_a)$ , and<br> $Br(e_b \rightarrow e_a \gamma)$  were determined in (T. T. Hong *et*<br>*al*, 2024), therefore we do not repeat here. We just<br> 0. No 4\_August 2024| p.17-25<br>LFVZ, and cLFV decays. All needed formulas for<br>decay rates  $Br(h \rightarrow e_b e_a)$ ,  $Br(Z \rightarrow e_b e_a)$ , and<br> $Br(e_b \rightarrow e_a \gamma)$  were determined in (T. T. Hong *et*<br>*al*, 2024), therefore we do not repeat here. We just<br> 0. No 4\_August 2024| p.17-25<br>LFVZ, and cLFV decays. All needed formulas for<br>decay rates Br( $h \rightarrow e_b e_a$ ), Br( $Z \rightarrow e_b e_a$ ), and<br>Br( $e_b \rightarrow e_a \gamma$ ) were determined in (T. T. Hong *et*<br>*al*, 2024), therefore we do not repeat here. We 0. No 4\_August 2024| p.17-25<br>LFVZ, and cLFV decays. All needed formulas for<br>decay rates  $Br(h \rightarrow e_b e_a)$ ,  $Br(Z \rightarrow e_b e_a)$ , and<br> $Br(e_b \rightarrow e_a \gamma)$  were determined in (T. T. Hong *et*<br>*al*, 2024), therefore we do not repeat here. We just<br> 0. No 4\_August 2024| p.17-25<br>LFVZ, and cLFV decays. All needed formulas for<br>decay rates  $Br(h \rightarrow e_b e_a)$ ,  $Br(Z \rightarrow e_b e_a)$ , and<br> $Br(e_b \rightarrow e_a \gamma)$  were determined in (T. T. Hong *et*<br>*al*, 2024), therefore we do not repeat here. We just<br> LFVZ, and cLFV decays. All needed formulas for<br>decay rates  $Br(h \rightarrow e_b e_a)$ ,  $Br(Z \rightarrow e_b e_a)$ , and<br> $Br(e_b \rightarrow e_a \gamma)$  were determined in (T. T. Hong *et*<br>*al*, 2024), therefore we do not repeat here. We just<br>focus on the main ingredients LFVZ, and cLFV decays. All needed formulas for<br>decay rates  $Br(h \rightarrow e_b e_a)$ ,  $Br(Z \rightarrow e_b e_a)$ , and<br> $Br(e_b \rightarrow e_a \gamma)$  were determined in (T. T. Hong *et*<br>*al*, 2024), therefore we do not repeat here. We just<br>focus on the main ingredients

2018): cus on the main ingredients to establish the IO<br>
neme for numerical investigation.<br>
e branching ratios of the cLFV decays are for-<br>
ulated as follows (Lavoura, L., 2003; Hue, L. T.,<br>
nh, L. D., Thuc, T. T., Dat, N. T. T., mulated as follows (Lavoura, L., 2003; Hue, L. T.,<br>
Ninh, L. D., Thuc, T. T., Dat, N. T. T., 2018; Criv-<br>
ellin, A., Hoferichter M., Schmidt-Wellenburg, P.,<br>
2018):<br>  $Br(e_b \rightarrow e_a \gamma) = \frac{48\pi^2}{G_F^2 m_b^2} \left( |c_{(ab)R}|^2 + |c_{(ba)R}|^2$ 

$$
Br(e_b \to e_a \gamma) = \frac{48\pi^2}{G_F^2 m_b^2} \left( \left| c_{(ab)R} \right|^2 + \left| c_{(ba)R} \right|^2 \right) \times Br(e_b \to e_a \overline{\nu_a} \nu_b), \tag{4}
$$

(1. 1. hong *et al.* 2024) discussed recently to (workinal, R. E. *et al.* [1 article explain experimental data of  $(g - 2)_{e,\mu}$  anomalies, 2022), and all relevant analytic for where all LFV processes mentioned above will d in (Hue, data that is necessary for nur<br>
in this work. The non-zero v<br>  $\begin{aligned} &\text{in (Mon-1)}\quad &\text{in this work. The non-zero v} \\ &\text{in (Mon-2)}\quad &\text{in (Mon-1)}\quad &\text{in (LFV rates, especially the} \\ &\text{in (LFV rates, especially the} \\ &\text{in (C) total, T.},\quad &\text{in (C) circle} \\ &\text{in (C) circle} \\ &\text{in (C) circle} \\ &\text{in (C) circle} \\ &\text$ where  $G_F = g^2/(4\sqrt{2}m_W^2)$ ,  $Br(\mu \to e \overline{\nu_e} \nu_\mu) \simeq 1$ , (Workman, R. L. et al. [Particle Data Group],<br>
2018):<br>  $Br(e_b \rightarrow e_a \gamma) = \frac{48\pi^2}{G_F^2 m_b^2} \left( |c_{(ab)R}|^2 + |c_{(ba)R}|^2 \right)$ <br>  $\times Br(e_b \rightarrow e_a \overline{\nu_a} \nu_b),$  (4)<br>
where  $G_F = g^2/(4\sqrt{2}m_W^2)$ ,  $Br(\mu \rightarrow e \overline{\nu_e} \nu_\mu) \simeq 1$ ,<br>  $Br(\tau \rightarrow e \overline{\nu_e} \nu_\tau) \$ 2018):<br>  $Br(e_b \rightarrow e_a \gamma) = \frac{48\pi^2}{G_F^2 m_b^2} \left( |c_{(ab)R}|^2 + |c_{(ba)R}|^2 \right)$ <br>  $\times Br(e_b \rightarrow e_a \overline{\nu_a} \nu_b),$  (4)<br>
where  $G_F = g^2/(4\sqrt{2}m_W^2)$ ,  $Br(\mu \rightarrow e \overline{\nu_e} \nu_\mu) \simeq 1$ ,<br>  $Br(\tau \rightarrow e \overline{\nu_e} \nu_\tau) \simeq 0.1782$ ,  $Br(\tau \rightarrow \mu \overline{\nu_\mu} \nu_\tau) \simeq 0.1739$ <br> Br( $e_b \rightarrow e_a \gamma$ ) =  $\frac{48\pi^2}{G_F^2 m_b^2} \left( |c_{(ab)R}|^2 + |c_{(ba)R}|^2 \right)$ <br>  $\times \text{Br}(e_b \rightarrow e_a \overline{\nu_a} \nu_b),$  (4)<br> where  $G_F = g^2/(4\sqrt{2}m_W^2)$ ,  $\text{Br}(\mu \rightarrow e \overline{\nu_e} \nu_\mu) \simeq 1$ ,<br>  $\text{Br}(\tau \rightarrow e \overline{\nu_e} \nu_\tau) \simeq 0.1782$ ,  $\text{Br}(\tau \rightarrow \mu \overline{\nu_\mu} \nu_\tau$  $G_F^2 m_b^2$   $(e_{ab})R_1 + e_{ba}R_2$   $($   $e_{ab}R_1)$ <br>  $\times \text{Br}(e_b \rightarrow e_a \overline{\nu_a} \nu_b),$  (4)<br>
where  $G_F = g^2/(4\sqrt{2}m_W^2)$ ,  $\text{Br}(\mu \rightarrow e \overline{\nu_e} \nu_\mu) \simeq 1$ ,<br>  $\text{Br}(\tau \rightarrow e \overline{\nu_e} \nu_\tau) \simeq 0.1782$ ,  $\text{Br}(\tau \rightarrow \mu \overline{\nu_\mu} \nu_\tau) \simeq 0.1739$ <br>
(Workma  $\times$  Br( $e_b \rightarrow e_a \overline{\nu_a} \nu_b$ ), (4)<br>
where  $G_F = g^2/(4\sqrt{2}m_W^2)$ , Br( $\mu \rightarrow e \overline{\nu_e} \nu_\mu$ )  $\simeq 1$ ,<br>
Br( $\tau \rightarrow e \overline{\nu_e} \nu_\tau$ )  $\simeq 0.1782$ , Br( $\tau \rightarrow \mu \overline{\nu_\mu} \nu_\tau$ )  $\simeq 0.1739$ <br>
(Workman, R. L. *et al.* [Particle Data Group],<br>
2 where  $G_F = g^2/(4\sqrt{2}m_W^2)$ ,  $Br(\mu \to e\overline{\nu_e}\nu_\mu) \simeq 1$ ,<br>  $Br(\tau \to e\overline{\nu_e}\nu_\tau) \simeq 0.1782$ ,  $Br(\tau \to \mu\overline{\nu_\mu}\nu_\tau) \simeq 0.1739$ <br>
(Workman, R. L. *et al.* [Particle Data Group],<br>
2022), and all relevant analytic formulas were giv where  $G_F = g^2/(4\sqrt{2}m_W^2)$ ,  $Br(\mu \to e\overline{\nu_e}\nu_\mu) \simeq 1$ ,<br>  $Br(\tau \to e\overline{\nu_e}\nu_\tau) \simeq 0.1782$ ,  $Br(\tau \to \mu\overline{\nu_\mu}\nu_\tau) \simeq 0.1739$ <br>
(Workman, R. L. *et al.* [Particle Data Group],<br>
2022), and all relevant analytic formulas were giv  $Br(\tau \to e\overline{\nu_e}\nu_{\tau}) \simeq 0.1782$ ,  $Br(\tau \to \mu\overline{\nu_{\mu}}\nu_{\tau}) \simeq 0.1739$ <br>(Workman, R. L. *et al.* [Particle Data Group],<br>2022), and all relevant analytic formulas were given<br>in detail in previous research (T. T. Hong *et al*, to  $a_{e_a}$  is from the two singly charged Higgs boson nan, R. L. *et al.* [Particle Data Group],<br>and all relevant analytic formulas were given<br>iil in previous research (T. T. Hong *et al*,<br>We only comment here on important relat-<br>the IO scheme of the neutrino oscillation<br>nat  $c_k^{\pm}$ , denoted as  $a_{e_a,0}(c^{\pm})$  expressed by 22), and all relevant analytic formulas were given<br>detail in previous research (T. T. Hong *et al*,<br>24). We only comment here on important relat-<br>t to the IO scheme of the neutrino oscillation<br>that that is necessary for n in detail in previous research (T. T. Hong *et a*<br>2024). We only comment here on important relat<br>ing to the IO scheme of the neutrino oscillation<br>data that is necessary for numerical investigation<br>in this work. The non-ze

$$
a_{e_a,0}(c^{\pm}) = \frac{G_F m_a^2}{\sqrt{2}\pi^2} \times \text{Re}\left\{ \left[ \frac{vt_{\beta}^{-1} c_{\alpha} s_{\alpha}}{\sqrt{2}m_a} U_{\text{PMNS}} \hat{x}_{\nu}^{1/2} y^{\chi} \right]_{aa} \times [x_1 f_{\Phi}(x_1) - x_2 f_{\Phi}(x_2)] \right\}
$$
\n
$$
(5)
$$
\nwith  $x_k = M_0^2 / m_{c_k}^2$  and\n
$$
\hat{x}_{\nu} \equiv \frac{\hat{m}_{\nu}}{\mu_0} = x_0 \times \text{diag}\left(\frac{m_{n_1}}{m_{n_2}}, 1, \frac{m_{n_3}}{m_{n_2}}\right), x_0 \equiv \frac{m_{n_2}}{\mu_0}.
$$
\n(6)

with  $x_k = M_0^2/m_{c_k}^2$  and

$$
\hat{x}_{\nu} \equiv \frac{\hat{m}_{\nu}}{\mu_0} = x_0 \times \text{diag}\left(\frac{m_{n_1}}{m_{n_2}}, 1, \frac{m_{n_3}}{m_{n_2}}\right), \ x_0 \equiv \frac{m_{n_2}}{\mu_0}.
$$
\n(6)

Symmetry	$L_L$	$e_R$	$N_L$	$N_R$	$H_1$	$H_2$	$\varphi$	$\chi^-$		
$SU(3)_C$	1	1	1	1	1	1	1	1		
$SU(2)_L$	$\bf{2}$	1	1.	1	$\bf{2}$	2	1	1		
$U(1)_Y$	$-\frac{1}{2}$	$-1$	$\Omega$	$\Omega$	$\frac{1}{2}$	$rac{1}{2}$	$\Omega$	$-1$		
$\mathbb{Z}_2$			$^+$	$^+$		$^+$	$^+$			

Nguyen Hua Thanh Nha/Vol 10. No 4\_August 2024| p.17<br>This formula with  $b \neq a$  will result in unaccept-<br>able values of cLFV decay rates excluded by recent<br>experimental constraints. According to this discus-<br> $s_{12}^2 = 0.318$ *Nguyen Hua Thanh Nha/Vol 10.* No 4\_August 2024| p.17-25<br>This formula with  $b \neq a$  will result in unaccept-<br>able values of cLFV decay rates excluded by recent<br>experimental constraints. According to this discus-<br>sion,  $c_{($ Nguyen Hua Thanh Nha/Vol 10. No 4\_August 2024| p.17-2:<br>
This formula with  $b \neq a$  will result in unaccept-<br>
experimental constraints. According to this discus-<br>
experimental constraints. According to this discus-<br>
sion, *Nguyen Hua Thanh Nha/Vol* 10. No 4\_August 2024| p.17-25<br>This formula with  $b \neq a$  will result in unaccept-<br>able values of cLFV decay rates excluded by recent<br>experimental constraints. According to this discus-<br>sion,  $c_{($ *Nguyen Hua Thanh Nha/Nol* 10. No 4\_August 2024| p.17-25<br>
This formula with  $b \neq a$  will result in unaccept-<br>
able values of cLFV decay rates excluded by recent<br>
experimental constraints. According to this discus-<br>
sion, *Nguyen Hua Thanh Nha/Vol 10.* No 4\_Augu<br>
This formula with  $b \neq a$  will result in unaccept-<br>
able values of cLFV decay rates excluded by recent<br>
experimental constraints. According to this discus-<br>
sion,  $c_{(ab)R,0}$  will In particularly,  $y^{\chi}$  is derived in terms of a diagonal<br>
In particularly,  $y^{\chi}$  is derived in terms of a diagonal<br>
In particularly,  $y^{\chi}$  is derived in terms of a diagonal<br>
In the strengthend as follows:<br>
In the st tal constraints. According to this discus-<br>  $\epsilon_{10}$  will be chosen in the diagonal form  $s_{13}^2$ <br>
the Yukawa coupling matrix  $y^{\chi}$  at the  $\Delta m_{21}^2$ <br>
of our numerical investigation  $\Delta m_{32}^2$ <br>  $\omega_{pR,0} \propto \left[ U_{\text{PMNS$ 

$$
c_{(ab)R,0} \propto \left[ U_{\text{PMNS}} \hat{x}_{\nu}^{1/2} y^{\chi} \right]_{ab} \propto \delta_{ab}.
$$
 (7)

matrix  $y^d$  defined as follows:

$$
c_{(ab)R,0} \propto \left[ U_{\text{PMNS}} \hat{x}_{\nu}^{1/2} y^{\chi} \right]_{ab} \propto \delta_{ab}.
$$
 (7) The active mixi  
determined belc  
ticularly,  $y^{\chi}$  is derived in terms of a diagonal  
 $y^d$  defined as follows:  

$$
y^d
$$
  $U_{\text{PMNS}} = \text{diag} \left( \sqrt{\frac{m_{n_1}}{m_{n_2}}}, 1, \frac{m_{n_3}}{m_{n_2}} \right)^{1/2} y^{\chi}$ 
$$
= y^d \equiv \text{diag} \left( y_{11}^d, y_{22}^d, y_{33}^d \right),
$$
 (8)  
 $m_{n_3} < m_{n_1} < m_{n_2}$  with respect to the in-  
order of the neutrino oscillation data will  
there exists, we

In particularly,  $y^{\chi}$  is derived in terms of a diagonal<br>  $\hat{m}_{\nu} = (\hat{m}_{\nu}^2)^{1/2}$ <br>  $\text{matrix } y^d$  defined as follows:<br>  $U_{\text{PMNS}} = \text{diag}\left(\sqrt{m_{n_2}^2 - \Delta m_{21}^2}, m_{n_2}, \Delta m_{21}^2, m_{n_3}\right)$ <br>  $U_{\text{PMNS}} = \text{diag}\left(\sqrt{m_{n_2}^2 - \Delta m_{21}$ In particularly,  $y^{\chi}$  is derived in terms of a diagonal<br>
matrix  $y^d$  defined as follows:<br>  $U_{PMNS} = \text{diag}\left(\sqrt{m_{n_2}^2 - \Delta m_{21}^2}, m_{n_2},\right)$ <br>  $U_{PMNS} =$ <br>  $U_{PMNS} \times \text{diag}\left(\frac{m_{n_1}}{m_{n_2}}, 1, \frac{m_{n_3}}{m_{n_2}}\right)^{1/2} y^{\chi}$ <br>  $= y^d$ In particularly,  $y^{\lambda}$  is derived in terms of a diagonal<br>
matrix  $y^d$  defined as follows:<br>  $U_{PMNS} =$ <br>  $U_{PMNS} \times diag\left(\frac{m_{n_1}}{m_{n_2}}, 1, \frac{m_{n_3}}{m_{n_2}}\right)^{1/2} y^{\lambda}$ <br>  $= y^d \equiv diag\left(y_{11}^d, y_{22}^d, y_{33}^d\right),$ <br>
where  $m_{n_3} < m_{$ matrix  $y^*$  defined as follows:<br>  $U_{PMNS} =$ <br>  $U_{PMNS} \times diag\left(\frac{m_{n_1}}{m_{n_2}}, 1, \frac{m_{n_3}}{m_{n_2}}\right)^{1/2} y^{\chi}$ <br>  $= y^d \equiv diag\left(y_{11}^d, y_{22}^d, y_{33}^d\right),$ <br>
where  $m_{n_3} < m_{n_1} < m_{n_2}$  with respect to the inverted order of the neutr  $\label{eq:UVPMNS} \begin{array}{ll} U_{\rm PMNS} = \\[2mm] U_{\rm PMNS} = \\[2mm] \hline \\[2mm] \h$  $U_{\text{PMNS}} \times \text{diag} \left( \frac{m_{n_1}}{m_{n_2}}, 1, \frac{m_{n_3}}{m_{n_2}} \right)^{\frac{N}{2}} y^{\chi}$   $\left( \begin{array}{cccc} 0.817 & 0.558 \\ -0.389 + 0.091i & 0.521 + 0.06 \\ 0.409 + 0.078i & -0.641 + 0.0 \end{array} \right)$ <br>where  $m_{n_3} < m_{n_1} < m_{n_2}$  with respect to the inwhere  $U_{\$  $\binom{m_{n_2} + m_{n_2}}{m_{n_2}}$  (8)<br>  $= y^d \equiv \text{diag}(y_{11}^d, y_{22}^d, y_{33}^d),$  (8)<br>
where  $m_{n_3} < m_{n_1} < m_{n_2}$  with respect to the in-<br>
verted order of the neutrino oscillation data will<br>
be selected in the numerical examination  $y^a \equiv \text{diag}(y_{11}^a, y_{22}^a, y_{33}^a),$  (8)<br>
where  $m_{n_3} < m_{n_1} < m_{n_2}$  with respect to the in-<br>
verted order of the neutrino oscillation data will<br>
three act<br>
be selected in the numerical examination. We em-<br>
the heav<br>
ph where  $m_{n_3} < m_{n_1} < m_{n_2}$  with respect to the in-<br>verted order of the neutrino oscillation data will<br>be selected in the numerical examination. We em-<br>phasize that Eq.(8) was defined for the IO scheme, is<br>fy two conditi where  $m_{n_3} < m_{n_1} < m_{n_2}$  with respect to the in-<br>where  $U_{\text{PMNS}}$  is<br>verted order of the neutrino oscillation data will<br>be selected in the numerical examination. We em-<br>the heaviest. In<br>phasize that Eq.(8) was defined

The given in (a) 
$$
a_{e_a,0} = \frac{G_F m_a^2 \sqrt{x_0}}{\sqrt{2} \pi^2} \times \text{Re} \left[ \frac{v t_\beta^{-1} c_\alpha s_\alpha}{\sqrt{2} m_a} y^d \right]_{aa}
$$
 is given in (a)  $a_{e_a,0} = \frac{G_F m_a^2 \sqrt{x_0}}{\sqrt{2} \pi^2} \times \text{Re} \left[ \frac{v t_\beta^{-1} c_\alpha s_\alpha}{\sqrt{2} m_a} y^d \right]_{aa}$  is the respective number of formulas with  $m_{n_3}$  must be replaced with  $m_{n_3}$  must be replaced with  $m_{n_3}$  to be a positive. Therefore, the result is  $m_{n_3}$  must be replaced with  $m_{n_3}$  must be replaced with  $m_{n_3}$  must be replaced with  $m_{n_3}$  with  $m_{n_3}$  must be replaced with  $m_{n_3}$  with  $m_{n_3}$  with  $m_{n_3}$  must be replaced with  $m_{n_3}$  with  $m_{n_3}$  with  $m_{n_3}$  with  $m_{n_3}$  must be replaced with  $m_{n_3}$  with  $$ 

$$
x_0 \equiv \frac{m_{n_2}}{\mu_0} \tag{10}
$$

vestigation. The non-unitary of<br>  $x_0 \equiv \frac{m_{n_2}}{\mu_0}$  (10) mixing matrix  $(I_3 - \frac{1}{2}RR^{\dagger}) U_{\text{P}}$ <br>
defining the ratio between the active neutrino mass<br>
and the ISS scale  $\mu_0$ . To be consistent with the right<br>
experim  $x_0 \equiv \frac{m_{n_2}}{\mu_0}$  (10) mix<br>
g the ratio between the active neutrino mass<br>
e ISS scale  $\mu_0$ . To be consistent with the right<br>
mental ranges of  $(g-2)_{e,\mu}$ , it was shown that<br>
st be large enough, namely  $x_0 > \mathcal{O}(10^{-$ 

0. No 4\_August 2024 | p.17-25  
\n(Workman, R. L. *et al.* [Particle Data Group], 2022)  
\n
$$
s_{12}^2 = 0.318_{-0.016}^{+0.016}, s_{23}^2 = 0.578_{-0.010}^{+0.017},
$$
\n
$$
s_{13}^2 = 2.225_{-0.070}^{+0.064} \times 10^{-2}, \delta = 284_{-28}^{+26} \text{ [Deg]},
$$
\n
$$
\Delta m_{21}^2 = 7.5_{-0.20}^{+0.22} \times 10^{-5} \text{ [eV}^2],
$$
\n
$$
\Delta m_{32}^2 = -2.52_{-0.02}^{+0.03} \times 10^{-3} \text{ [eV}^2].
$$
\n(11)  
\nThe active mixing matrix and neutrino masses are determined below  
\n
$$
\hat{m}_{\nu} = (\hat{m}_{\nu}^2)^{1/2}
$$
\n
$$
= \text{diag}\left(\sqrt{m_{n_2}^2 - \Delta m_{21}^2}, m_{n_2}, \sqrt{m_{n_2}^2 + \Delta m_{32}^2}\right),
$$
\n
$$
U_{\text{PMNS}} =
$$
\n
$$
\left(\begin{array}{cc} 0.817 & 0.558 & 0.036 + 0.145i \\ 0.390 + 0.001i & 0.571 + 0.069i & 0.759 \end{array}\right)
$$

The active mixing matrix and neutrino masses are determined below

$$
\Delta m_{21}^2 = 7.5^{+0.22}_{-0.20} \times 10^{-5} [\text{eV}^2],
$$
  
\n
$$
\Delta m_{32}^2 = -2.52^{+0.03}_{-0.02} \times 10^{-3} [\text{eV}^2].
$$
 (11)  
\nThe active mixing matrix and neutrino masses are determined below  
\n
$$
\hat{m}_{\nu} = (\hat{m}_{\nu}^2)^{1/2}
$$
\n
$$
= \text{diag}\left(\sqrt{m_{n_2}^2 - \Delta m_{21}^2}, m_{n_2}, \sqrt{m_{n_2}^2 + \Delta m_{32}^2}\right),
$$
  
\n
$$
U_{\text{PMNS}} =
$$
\n
$$
\begin{pmatrix}\n0.817 & 0.558 & 0.036 + 0.145i \\
-0.389 + 0.091i & 0.521 + 0.062i & 0.752 \\
0.409 + 0.078i & -0.641 + 0.053i & 0.642\n\end{pmatrix}
$$
\n(12)  
\nwhere  $U_{\text{PMNS}}$  is chosen at the best-fit point, while  
\nthree active neutrino masses are functions of  $m_{n_2}$ -  
\nthe heavier. In addition, values of  $m_{n_2}$  must sat-

$$
y^{\chi} \qquad \begin{pmatrix} 0.817 & 0.558 & 0.036 + 0.145i \\ -0.389 + 0.091i & 0.521 + 0.062i & 0.752 \\ 0.409 + 0.078i & -0.641 + 0.053i & 0.642 \end{pmatrix}
$$
(8) (12)

(8)<br>
ect to the in-<br>
where  $U_{\text{PMNS}}$  is chosen at the best<br>
tion data will<br>
tion-We em-<br>
the heaviest. In addition, values of<br>
he IO scheme,<br>
is fy two conditions including the<br>
ne NO scheme<br>
Plank2018 (Aghanim, N. *et a*  $\frac{v t_\beta^{-1} c_\alpha s_\alpha}{\sqrt{\alpha}} y^d$  that  $m_{n_3}$  can small down to the zerocause if we use  $m_{n_3}$  as a variable to investigate, the Eq.(8) will be more difficult to define the inverse for all the same of the same in contribution  $a_{e_{a,0}} = \frac{G_F m_a^2 \sqrt{x_0}}{\sqrt{2\pi^2}} \times \text{Re} \left[ \frac{v t_0^{-1} c_{\alpha s} s_{\alpha}}{\sqrt{2m_a}} y^d \right]_{aa}$ <br>  $\times [x_1 f_{\Phi}(x_1) - x_2 f_{\Phi}(x_2)]$ , (9) cause if (10) very strictly by  $\eta = \frac{1}{2} |RR^{\dagger}| \propto \hat{x}_\nu \propto x_0$  in the  $u_{e_a,0} = \frac{1}{\sqrt{2\pi^2}} \times \text{Re} \left[ \frac{1}{\sqrt{2m_a}} y \right]_{aa}$  the respective maximal one is a <br>  $\times [x_1 f_{\Phi}(x_1) - x_2 f_{\Phi}(x_2)]$ , (9) cause if we use  $m_{n_3}$  as a variable<br>  $E_q$ .(8) will be more difficult to<br>
while formulas with  $\times [x_1 f_{\Phi}(x_1) - x_2 f_{\Phi}(x_2)]$ , (9) cause if we use  $m_{n_3}$  as a variable<br>
Eq.(8) will be more difficult to<br>
matrix with one zero diagonal ei<br>  $m_{n_2}$ , especially the quantity<br>  $x_0 \equiv \frac{m_{n_2}}{\mu_0}$  (10) mixing matrix experimental ranges of (g−2)<sub>e,µ</sub>, it was shown that<br>  $x_0$  must be large enough, namely  $x_0 > \mathcal{O}(10^{-7})$ .<br> **Eq.(8)** will choose  $m_{n_2}$  for convenience<br>
vestigation. The non-unitary of t<br>  $x_0 \equiv \frac{m_{n_2}}{\mu_0}$  (10) mix  $\hat{m}_{\nu} = (\hat{m}_{\nu}^2)^{1/2}$ <br>  $= \text{diag}\left(\sqrt{m_{n_2}^2 - \Delta m_{21}^2}, m_{n_2}, \sqrt{m_{n_2}^2 + \Delta m_{32}^2}\right),$ <br>  $U_{\text{PMNS}} =$ <br>  $\begin{pmatrix} 0.817 & 0.558 & 0.036 + 0.145i \\ -0.389 + 0.091i & 0.521 + 0.062i & 0.752 \\ 0.409 + 0.078i & -0.641 + 0.053i & 0.642 \end{pmatrix}$ = diag  $\left(\sqrt{m_{n_2}^2 - \Delta m_{21}^2}$ ,  $m_{n_2}$ ,  $\sqrt{m_{n_2}^2 + \Delta m_{32}^2}\right)$ ,<br>  $U_{\text{PMNS}}$  =<br>  $\left(-0.389 + 0.091i \t 0.521 + 0.062i \t 0.752 \t 0.409 + 0.078i \t -0.641 + 0.053i \t 0.642 \right)$ <br>
where  $U_{\text{PMNS}}$  is chosen at the best-fit poi  $U_{\text{PMNS}} =$ <br>  $\begin{pmatrix} 0.817 & 0.558 & 0.036 + 0.145i \\ -0.389 + 0.091i & 0.521 + 0.062i & 0.752 \\ 0.409 + 0.078i & -0.641 + 0.053i & 0.642 \end{pmatrix}$ <br>
(12)<br>
where  $U_{\text{PMNS}}$  is chosen at the best-fit point, while<br>
three active neutrino masse  $U_{\text{PMNS}} =$ <br>  $\begin{pmatrix}\n0.817 & 0.558 & 0.036 + 0.145i \\
-0.389 + 0.091i & 0.521 + 0.062i & 0.752 \\
0.409 + 0.078i & -0.641 + 0.053i & 0.642\n\end{pmatrix}$ <br>
(12)<br>
where  $U_{\text{PMNS}}$  is chosen at the best-fit point, while<br>
three active neutrino masse  $\sum_{i=a}^{3} m_{n_a} \leq 0.12$  eV and  $m_{n_2}^2 \geq |\Delta m_{32}^2|$  derived  $\begin{pmatrix} -0.389 + 0.091i & 0.521 + 0.062i & 0.752 \\ 0.409 + 0.078i & -0.641 + 0.053i & 0.642 \end{pmatrix}$ <br>
(12)<br>
here  $U_{PMNS}$  is chosen at the best-fit point, while<br>
rece active neutrino masses are functions of  $m_{n_2}$ -<br>
heaviest. In addi (a.409 + 0.678i - -0.641 + 0.653i - 0.642)<br>
(a.409 + 0.678i - -0.641 + 0.653i - 0.642)<br>
(12)<br>
where  $U_{\text{PMNS}}$  is chosen at the best-fit point, while<br>
three active neutrino masses are functions of  $m_{n_2}$ -<br>
the heaviest. heaviest  $m_{n_2} \in [0.0505, 0.0526]$  eV. The depen-(12)<br>
s chosen at the best-fit point, while<br>
utrino masses are functions of  $m_{n_2}$ -<br>
1 addition, values of  $m_{n_2}$  must sat-<br>
ions including the constraint from<br>
hanim, N. *et al.* [Planck], 2020) that<br>
1.12 eV and  $m_{$ where  $U_{\text{PMNS}}$  is chosen at the best-fit point, while<br>three active neutrino masses are functions of  $m_{n_2}$ -<br>the heaviest. In addition, values of  $m_{n_2}$  must sat-<br>isfy two conditions including the constraint from<br>Pla where  $U_{PMNS}$  is chosen at the best-fit point, while<br>three active neutrino masses are functions of  $m_{n_2}$ -<br>the heaviest. In addition, values of  $m_{n_2}$  must sat-<br>isfy two conditions including the constraint from<br>Plank2 three active neutrino masses are functions of  $m_{n_2}$ -<br>the heaviest. In addition, values of  $m_{n_2}$  must sat-<br>isfy two conditions including the constraint from<br>Plank2018 (Aghanim, N. *et al.* [Planck], 2020) that<br> $\sum_{i=a$ left (right) panel relates to  $m_{n_2}$  ( $m_{n_3}$ ). We can see tions of  $m_{n_2}$ <br>  $n_{n_2}$  must sat-<br>
astraint from<br>
k], 2020) that<br>  $m_{32}^2$  derived<br>
range of the<br>
The depen-<br>
inos on differ-<br>
1, where the<br>
). We can see<br>
value. While<br>
0.015 eV. Best. In addition, values of  $m_{n_2}$  must sat-<br>onditions including the constraint from<br> $(Aghanim, N. et al.$  [Planck], 2020) that<br> $\leq 0.12$  eV and  $m_{n_2}^2 \geq |\Delta m_{32}^2|$  derived<br>12), leading to the allowed range of the<br> $n_{n_2} \in [$ isfy two conditions including the constraint from<br>Plank2018 (Aghanim, N. *et al.* [Planck], 2020) that<br> $\sum_{i=a}^{3} m_{n_a} \leq 0.12$  eV and  $m_{n_2}^2 \geq |\Delta m_{32}^2|$  derived<br>from Eq.(12), leading to the allowed range of the<br>heav Plank2018 (Aghanim, N. *et al.* [Planck], 2020) that  $\sum_{i=a}^{3} m_{n_a} \leq 0.12$  eV and  $m_{n_2}^2 \geq |\Delta m_{32}^2|$  derived from Eq.(12), leading to the allowed range of the heaviest  $m_{n_2} \in [0.0505, 0.0526]$  eV. The dependence n, N. *et al.* [Planck], 2020) that<br>V and  $m_{n_2}^2 \ge |\Delta m_{32}^2|$  derived<br>ag to the allowed range of the<br>.0505, 0.0526] eV. The depen-<br>three active neutrinos on differ-<br>is shown in Fig. 1, where the<br>ates to  $m_{n_2}$  ( $m_{n_$  $\sum_{i=a}^{3} m_{n_a} \leq 0.12$  eV and  $m_{n_2}^2 \geq |\Delta m_{32}^2|$  derived<br>from Eq.(12), leading to the allowed range of the<br>heaviest  $m_{n_2} \in [0.0505, 0.0526]$  eV. The depen-<br>dence of the sum of three active neutrinos on differ-<br>en from Eq.(12), leading to the allowed range of the<br>heaviest  $m_{n_2} \in [0.0505, 0.0526]$  eV. The depen-<br>dence of the sum of three active neutrinos on differ-<br>ent neutrino masses is shown in Fig. 1, where the<br>left (right) pan heaviest  $m_{n_2} \in [0.0505, 0.0526]$  eV. The d<br>dence of the sum of three active neutrinos on<br>ent neutrino masses is shown in Fig. 1, whe<br>left (right) panel relates to  $m_{n_2}$  ( $m_{n_3}$ ). We ca<br>that  $m_{n_3}$  can small down [0.0505, 0.0526] eV. The depen-<br>of three active neutrinos on differ-<br>ses is shown in Fig. 1, where the<br>relates to  $m_{n_2}$  ( $m_{n_3}$ ). We can see<br>all down to the zero value. While<br>ximal one is about 0.015 eV. Be-<br> $n_3$  as dence of the sum of three active neutrinos on differ-<br>ent neutrino masses is shown in Fig. 1, where the<br>left (right) panel relates to  $m_{n_2}$  ( $m_{n_3}$ ). We can see<br>that  $m_{n_3}$  can small down to the zero value. While<br>t ent neutrino masses is shown in Fig. 1, where t<br>left (right) panel relates to  $m_{n_2}$  ( $m_{n_3}$ ). We can s<br>that  $m_{n_3}$  can small down to the zero value. Wh<br>the respective maximal one is about 0.015 eV. I<br>cause if we us  $I_3 - \frac{1}{2}RR^{\dagger}$   $U_{\text{PMNS}}$  is constrained in Fig. 1, where the<br>  $u_{n_2}$  ( $m_{n_3}$ ). We can see<br>
the zero value. While<br>
is about 0.015 eV. Be-<br>
about 0.015 eV. Be-<br>
to define the inverse<br>
al entry. Therefore, we<br>
ence in numerical in-<br>
of the active neutrino<br>  $U_{$ left (right) panel relates to  $m_{n_2}$  ( $m_{n_3}$ ). We can see<br>that  $m_{n_3}$  can small down to the zero value. While<br>the respective maximal one is about 0.015 eV. Be-<br>cause if we use  $m_{n_3}$  as a variable to investigate,  $m_{n_2}$  ( $m_{n_3}$ ). We can see<br>
o the zero value. While<br>
is about 0.015 eV. Be-<br>
iable to investigate, the<br>
lt to define the inverse<br>
nal entry. Therefore, we<br>
nience in numerical in-<br>
y of the active neutrino<br>  $U_{\text{PMNS}}$ that  $m_{n_3}$  can small down to the zero value. While<br>the respective maximal one is about 0.015 eV. Be-<br>cause if we use  $m_{n_3}$  as a variable to investigate, the<br>Eq.(8) will be more difficult to define the inverse<br>matrix the respective maximal one is about 0.015 eV. Be-<br>cause if we use  $m_{n_3}$  as a variable to investigate, the<br>Eq.(8) will be more difficult to define the inverse<br>matrix with one zero diagonal entry. Therefore, we<br>will choo cause if we use  $m_{n_3}$  as a variable to investigate, the<br>Eq.(8) will be more difficult to define the inverse<br>matrix with one zero diagonal entry. Therefore, we<br>will choose  $m_{n_2}$  for convenience in numerical in-<br>vesti matrix with one zero diagonal entry. Therefore, we<br>
rill choose  $m_{n_2}$  for convenience in numerical in-<br>
estigation. The non-unitary of the active neutrino<br>
nixing matrix  $(I_3 - \frac{1}{2}RR^{\dagger}) U_{PMNS}$  is constrained<br>
ery str

$$
m_{n_2}
$$
, especially the quantity  
\n $x_0 \equiv \frac{m_{n_2}}{\mu_0}$  (10) mixing matrix  $(I_3 - \frac{1}{2}RR^{\dagger}) U_{PMNS}$  is constrained  
\n $x_0 \equiv \frac{m_{n_2}}{\mu_0}$  (10) mixing matrix  $(I_3 - \frac{1}{2}RR^{\dagger}) U_{PMNS}$  is constrained  
\n $\text{defining the ratio between the active neutrino mass}$  framework (Mondal, T., Okada, H., 2022).  
\nand the ISS scale  $\mu_0$ . To be consistent with the right  
\n $x_0$  must be large enough, namely  $x_0 > \mathcal{O}(10^{-7})$ .  
\n $y = 0.652$ ,  $G_F = 1.1664 \times 10^{-5}$  GeV,  $s_W^2 = 0.231$ ,  
\n $\alpha_e = 1/137$ ,  $e = \sqrt{4\pi\alpha_e}$ ,  $m_W = 80.377$  GeV,  
\n**THE IO SCHEME**  
\n $\Gamma_h = 4.07 \times 10^{-3}$  GeV,  $\Gamma_Z = 2.4955$  GeV,  
\nIn the IO scheme corresponding to  $m_{n_3} < m_{n_1} < m_e = 5 \times 10^{-4}$  GeV,  $m_\mu = 0.105$  GeV,  
\n $m_{n_2}$ , we choose experimental data as follows  $m_\tau = 1.776$  GeV. (13)



CONSISTED AND THE UP ON THE REVIDENT OF THE SAME OF THE SAME OF THE SAME OF THE SAME OF THE CONTROLL TO CONSULTER THE CRUDE CONSULTER THE CRUDE CONTROLL TO CONSTRUIT (Aghanim, N. *et al.* [Planck], 2020).<br>
To constrain ef Figuer 1. The sum of three neutrino masses as functions of the heaviest (light<br>the left (right) panel. The dashed-red line shows the upper bound from Planl<br>(Aghanim, N. *et al.* [Planck], 2020).<br>To constrain effectively t Figuer 1. The sum of three neutrino masses as functions of<br>the left (right) panel. The dashed-red line shows the upper l<br>(Aghanim, N. *et al.* [Planck], 2020<br>To constrain effectively the most strict allowed work. We list  $Br(\mu \rightarrow e\gamma)$  results in the suppressed  $|y_{12}^d|$  and  $|y_{21}^d|$ , as indicated in previous works (T. T. Hong *et* iguer 1. The sum of three neutrino masses as functions of the heaviest<br>
allelectively panel. The dashed-red line shows the upper bound from<br>
(Aghanim, N. *et al.* [Planck], 2020).<br>
b) constrain effectively the most strict the left (right) panel. The dashed-red<br>
(Aghanim,<br>
To constrain effectively the most strict<br>
ranges of entries of the matrix  $y^d$ , we releas<br>
conditions to determine the crude allowed<br>
Firstly, the most strict experiment For the free parameters of the 2HDMN<sub>L,R</sub> model,<br>the free parameters of the parameters of the matrix  $y^d$ , we release some ters that are more strict<br>conditions to determine the crude allowed ranges. ranges given in Eq.(1 To constrain effectively the most strict allowed work. We list here some allow<br>
ranges of entries of the matrix  $y^d$ , we release some ters that are more strict than<br>
conditions to determine the crude allowed ranges. rang To constrain effectively the most strict<br>ranges of entries of the matrix  $y^d$ , we relea<br>conditions to determine the crude allowed<br>Firstly, the most strict experimental const<br> $Br(\mu \to e\gamma)$  results in the suppressed  $|y_{21}^$ then the crude allowed ranges. Fanges given in<br>
ly, the most strict experimental constraint of<br>  $\rightarrow e\gamma$  results in the suppressed  $|y_{12}^d|$  and<br>
as indicated in previous works (T. T. Hong *et*<br>
In addition, the<br>
leading

\n- 1. Isay, the most short experimental constraint of 
$$
|y_{12}^d|
$$
 and  $|y_{21}^d|$ , as indicated in previous works (T. T. Hong *et al.*, 2024).
\n- 1. For the free parameters of the 2HDMN<sub>L,R</sub> model, the numerical scanning ranges are chosen in general as follows:
\n- $m_{n_2} \in [0.051, 0525] \text{ eV}; M_0, m_{c_{1,2}} \in [1, 10]$  TeV; and  $Br(\hbar \to \mu e) < 1.2 \times m_{n_2} \in [0.051, 0525] \text{ eV}; M_0, m_{c_{1,2}} \in [1, 10]$  TeV; and  $Br(h \to \mu e) < 1.2 \times 2 \times 1$ ,  $|\lambda_4|, |\lambda_5| \in [0, 4\pi]$ ;  $t_\beta \in [5, 30]$ ; the LFVZ decay rate is  $x_0 \in [10^{-5}, 5 \times 10^{-4}]$ ;  $\phi \in [0, \pi]$ ;
\n- $|y_{ab}^d| \leq 3.5 \forall a, b = 1, 2, 3.$
\n- $|y_{ab}^d| \leq 3.5 \forall a, b = 1, 2, 3.$
\n- $|y_{ab}^d| \leq 3.5 \forall a, b = 1, 2, 3.$
\n- $|y_{ab}^d| \leq 3.5 \forall a, b = 1, 2, 3.$
\n- $|y_{ab}^d| \leq 3.5 \forall a, b = 1, 2, 3.$
\n- $|y_{ab}^d| \leq 3.5 \forall a, b = 1, 2, 3.$
\n- $|y_{ab}^d| \leq 3.5 \forall a, b = 1, 2, 3.$
\n- $|y_{ab}^d| \leq 3.5 \forall a, b = 1, 2, 3.$
\n- $|y_{ab}^d| \leq 3.5 \forall a, b = 1,$

able parameters of the 2HDM $N_{L,R}$  model, are predict<br>
are predict<br>
are predict<br>
e numerical scanning ranges are chosen in general<br>  $\text{Br}(\tau \to e \gamma)$ <br>  $\text{Br}(\hbar \to \mu e)$ <br> as follows<br>  $m_{n_2} \in [0.051, 0525]$  eV;  $M_0, m_{c_{1,2}} \in [1, 10]$  TeV;<br>  $m_{n_1} \in [0.051, 0525]$  eV;  $M_0, m_{c_{1,2}} \in [1, 10]$  TeV;<br>  $\text{snr}(h \to \mu e) < 1.2 \times 10^{-9}$ ,  $\text{Br}(h \to \tau e)$ ,  $\text{snr}(h \to \tau e)$ ,  $\text{snr}(h \to \tau e)$ ,  $\text{snr}(h \to \tau e$  $m_{n_2} \in [0.051, 0525]$  eV;  $M_0, m_{c_{1,2}} \in [1, 10]$  TeV; and  $Br(h \rightarrow \tau\mu) < 7.4 \times 10^{-6}$ . On  $\lambda_1, |\lambda_4|, |\lambda_5| \in [0, 4\pi]$ ;  $t_\beta \in [5, 30]$ ; the LFVZ decay rate is large enot  $x_0 \in [10^{-5}, 5 \times 10^{-4}]$ ;  $\phi \in [0, \pi]$ ; expected sen  $m_{n_2} \in [0.051, 0525]$  ev;  $M_0, m_{c_{1,2}} \in [1, 10]$  Tev;<br>  $\lambda_1, |\lambda_4|, |\lambda_5| \in [0, 4\pi]$ ;  $t_\beta \in [5, 30]$ ;<br>  $x_0 \in [10^{-5}, 5 \times 10^{-4}]$ ;  $\phi \in [0, \pi]$ ;<br>  $|y_{ab}^d| \leq 3.5 \forall a, b = 1, 2, 3.$  (14)<br>
In the numerical investigation, we re  $x_0 \in [10^{-5}, 5 \times 10^{-4}]$ ;  $\phi \in [0, \pi]$ ;<br>  $|y_{ab}^d| \leq 3.5 \forall a, b = 1, 2, 3.$  (<br>
In the numerical investigation, we remind<br>
Yukawa and Higgs self couplings must satisfy actional conditions of perturbative limits and Hi<br>
potent

 $|y_{ab}^d| \leq 3.5 \,\forall a, b = 1, 2, 3.$  (14)  $10^{-8}$ .<br>
In the numerical investigation, we remind all The second nume<br>
Yukawa and Higgs self couplings must satisfy addi-<br>
(ab) ≠ (11), (22),<br>
potential constraints indicated prec  $|y_{ab}| \ge 3.5 \text{ v } a, \theta = 1, 2, 3.$  The second numerical results will The second numerical results will experimental investigation, we remind all gions with non-zero  $y_{ab}^d$ :  $0 \le |y_{ab}^d|$  tional conditions of perturbative In the numerical investigation, we remind all<br>
Yukawa and Higgs self couplings must satisfy addi-<br>
Yukawa and Higgs self couplings must satisfy addi-<br>  $(ab) \neq (11), (22), (12), (21), (21).$ <br>
Itional conditions of perturbative limits Yukawa and Higgs self couplings must satisfy addi-<br>
tional conditions of perturbative limits and Higgs<br>
used in (T. T. Hong *et al.* 2024).<br>
Hong *et al.* 2024).<br>
Hong *et al.* 2024).<br>
Firstly, we consider the simplest ca tional conditions of perturbative limits and Higgs<br>potential constraints indicated precisely in (T. T. T. numerical results are discussed<br>shows also the dependence of  $t$  allows also the dependence of  $t$ <br>Firstly, we cons potential constraints indicated precisely in (T. T.<br>
Hong *et al*, 2024).<br>
Firstly, we consider the simplest case that only two<br>
decays on  $m_n$ . It<br>
Firstly, we consider the simplest case that only two<br>
ecays on  $m_n$ . It<br> Hong *et al*, 2024).<br>
Firstly, we consider the simplest case that only two  $e_b \to e_a \gamma$  can reach the present<br>
entries of  $y_{ab}^d$  are non-zeros, which are enough to ac-<br>
experiments given in Table 1. The<br>
commodate two  $(g-$ Firstly, we consider the simplest case that only two<br>e $e_b \rightarrow e_a \gamma$  can reach the presentries of  $y_{ab}^d$  are non-zeros, which are enough to accommodate two<br>confindate two  $(g-2)_{e,\mu}$  data, namely  $y_{11}^d$ ,  $y_{22}^d \neq 0$ .<br> entries of  $y_{ab}^d$  are non-zeros, which are enough to accommodate two  $(g-2)_{e,\mu}$  data, namely  $y_{11}^d$ ,  $y_{22}^d \neq 0$ . This case nearly satisfies the experimental constraints of cLFV decays  $Br(e_b \rightarrow e_a \gamma)$ , namely,  $Br(Z-\text$ changes in the al-<br>
change of LFVh and LFVZ decay rates pamely  $y_{11}^d$ ,  $y_{22}^d \neq 0$ .<br>
case are:<br>
experimental con-<br>  $B_r(Z \to \mu^{\pm}e^{\mp}) \leq 4.12 \times 10^{-8}, B_r(Z \to \mu^{\pm}e^{\mp})$ <br>  $\Rightarrow e_a \gamma$ ), namely,<br>  $B_r(Z \to \tau^{\pm} \mu^{\mp}) \leq 6.49 \times$ commodate two  $(g-2)_{e,\mu}$  data, namely  $y_{11}^d$ ,  $y_{22}^d \neq 0$ .<br>
This case nearly satisfies the experimental con-<br>
straints of cLFV decays Br( $e_b \rightarrow e_a \gamma$ ), namely,<br>
the experimental constraint from Br( $\mu \rightarrow e_{\gamma}$ ) gives<br> This case nearly satisfies the experimental con-<br>straints of cLFV decays  $Br(e_b \to e_a \gamma)$ , namely,<br>the experimental constraint from  $Br(B \to e_b \gamma)$  gives<br>strictly allowed regions of parameter space, especially when it combines wi straints of cLFV decays  $Br(e_b \to e_a \gamma)$ , namely,<br>
the experimental constraint from  $Br(\mu \to e \gamma)$  gives<br>
strictly allowed regions of parameter space, espe-<br>
cially when it combines with two allowed 1 $\sigma$  ranges<br>
of  $(g - 2)_{e,\mu}$ the experimental constraint from Br( $\mu \to e\gamma$ ) gives<br>strictly allowed regions of parameter space, espe-<br>cially when it combines with two allowed 1*o* ranges<br>of  $(g - 2)_{e,\mu}$ . We confirm that all results are con-<br>sistent wi

Figure  $\frac{1}{6. \times 10^{-4}}$  0.001 0.005 0.010<br>
Functions of the heaviest (lightest) mass in<br>
vs the upper bound from Plank 2018 results<br>
[Planck], 2020).<br>
work. We list here some allowed ranges of parame-<br>
ters that are more

$$
t_{\beta} \le 13.6; \ 0.02 \le |y_{11}^d| \le 0.12, \ 0.99 \le |y_{22}^d| \le 2.5. \tag{15}
$$

allowed ranges. ranges given in Eq.(14):<br>
ial constraint of<br>
ressed  $|y_{12}^d|$  and<br>  $t_\beta \le 13.6$ ;  $0.02 \le |y_{11}^d| \le 0.12$ ,<br>
s (T. T. Hong *et*<br>
In addition, the upper bounds<br>
are predicted to be suppresse<br>
with the futu revious works (T. T. Hong *et*<br>
In addition, the up<br>
rs of the 2HDMN<sub>L,R</sub> model,<br>
granges are chosen in general<br>  $\text{Br}(\tau \to e\gamma) < 4 \times$ <br>  $\text{Br}(\tau \to e\gamma) < 4 \times$ <br>  $\text{Br}(\hbar \to \mu e) < 1.2 \times$ <br>  $\forall; M_0, m_{c_{1,2}} \in [1, 10] \text{ TeV};$  and  $\$ For the free parameters of the 2HDM $N_{L,R}$  model,<br>
the numerical scanning ranges are chosen in general<br>
as follows<br>
as follows<br>  $m_{n_2} \in [0.051, 0525]$  eV;  $M_0, m_{c_{1,2}} \in [1, 10]$  TeV;<br>  $M_0, m_{c_{1,2}} \in [1, 10]$  TeV;<br>  $M_0,$ the numerical scanning ranges are chosen in general<br>
as follows<br>  $Br(\tau \to e\gamma) < 4 \times 10^{-14}$ ,  $Br($ <br>  $m_{n_2} \in [0.051, 0525]$  eV;  $M_0, m_{c_{1,2}} \in [1, 10]$  TeV;<br>
and  $Br(h \to \mu e) < 1.2 \times 10^{-9}$ ,  $Br(h \to \tau e) < 7.4 \times 10^{-6}$ .<br>  $\lambda_1, |\lambda_4|,$ functions of the heaviest (lightest) mass in<br>
s the upper bound from Plank 2018 results<br>
[Planck], 2020).<br>
work. We list here some allowed ranges of parame-<br>
ers that are more strict than the general scanning<br>
anges given ome allowed ranges of parame-<br>
rict than the general scanning<br>
14):<br>  $\binom{d}{11} \leq 0.12, \ 0.99 \leq |y_{22}^d| \leq 2.5.$ <br>
(15)<br>
er bounds of LFV decay rates<br>
suppressed when comparing<br>
nsitivities given in Table 1:<br>  $10^{-14}, \text$ of parame-<br>
1 scanning<br>  $\left.\begin{array}{l}\n a_2 \\
 a_2\n \end{array}\right| \leq 2.5.$ <br>
(15)<br>
ecay rates<br>
comparing<br>
Table 1:<br>  $\lt 10^{-12},$ <br>  $3 \times 10^{-7},$ In addition, the upper bound from Plank 2018 results<br>
[Planck], 2020).<br>
Work. We list here some allowed ranges of parame-<br>
ters that are more strict than the general scanning<br>
ranges given in Eq.(14):<br>  $t_{\beta} \leq 13.6; 0.0$ [Planck], 2020).<br>work. We list here some allowed ranges of parame-<br>ters that are more strict than the general scanning<br>ranges given in Eq.(14):<br> $t_{\beta} \le 13.6$ ;  $0.02 \le |y_{11}^d| \le 0.12$ ,  $0.99 \le |y_{22}^d| \le 2.5$ .<br>(15)<br>In ad work. We list here some allowed ranges of parame-<br>ters that are more strict than the general scanning<br>ranges given in Eq.(14):<br> $t_{\beta} \leq 13.6; 0.02 \leq |y_{11}^d| \leq 0.12, 0.99 \leq |y_{22}^d| \leq 2.5.$ <br>(15)<br>In addition, the uppe work. We list here some allowed ranges of parame-<br>ters that are more strict than the general scanning<br>ranges given in Eq.(14):<br> $t_{\beta} \leq 13.6$ ;  $0.02 \leq |y_{11}^d| \leq 0.12$ ,  $0.99 \leq |y_{22}^d| \leq 2.5$ .<br>(15)<br>In addition, the ,  $Br(h \to \mu e) < 1.2 \times 10^{-9}$ ,  $Br(h \to \tau e) < 3 \times 10^{-7}$ ,<br>and  $Br(h \to \tau \mu) < 7.4 \times 10^{-6}$ . On the other hand, than the general scanning<br>  $0.12, 0.99 \le |y_{22}^d| \le 2.5.$ <br>
(15)<br>
bunds of LFV decay rates<br>
pressed when comparing<br>
vities given in Table 1:<br>
4, Br( $\tau \to \mu \gamma$ ) < 10<sup>-12</sup>,<br>
Br( $h \to \tau e$ ) < 3 × 10<sup>-7</sup>,<br>
10<sup>-6</sup>. On the other h ranges given in Eq.(14):<br>  $t_{\beta} \leq 13.6$ ;  $0.02 \leq |y_{11}^d| \leq 0.12$ ,  $0.99 \leq |y_{22}^d| \leq 2.5$ .<br>
(15)<br>
In addition, the upper bounds of LFV decay rates<br>
are predicted to be suppressed when comparing<br>
with the future sen  $\begin{aligned} \text{2.}, \ 0.99 &\leq |y_{22}^d| \leq 2.5. \ \text{(15)}\ \text{s of LFV decay rates} \end{aligned}$ <br>so f LFV decay rates<br>ed when comparing<br>given in Table 1:<br> $\text{2.}(\tau \to \mu\gamma) < 10^{-12}, \ \text{h} \to \tau e) < 3 \times 10^{-7}, \ \text{2.} \text{On the other hand}, \ \text{enough to reach the} \to \mu e) < 1.2 \times 10^{-7}, \end{aligned$  $t_{\beta} \leq 13.6; 0.02 \leq |y_{11}^d| \leq 0.12, 0.99 \leq |y_{22}^d| \leq 2.5.$ <br>
(15)<br>
In addition, the upper bounds of LFV decay rates<br>
are predicted to be suppressed when comparing<br>
with the future sensitivities given in Table 1:<br>  $t_{\beta} \leq 13.6; 0.02 \leq |y_{11}^{\mu}| \leq 0.12, 0.99 \leq |y_{22}^{\mu}| \leq 2.5.$  (15)<br>In addition, the upper bounds of LFV decay rates<br>are predicted to be suppressed when comparing<br>with the future sensitivities given in Table 1:<br> $Br$ In addition, the upper bounds of LFV decay rates<br>are predicted to be suppressed when comparing<br>with the future sensitivities given in Table 1:<br> $Br(\tau \to e\gamma) < 4 \times 10^{-14}$ ,  $Br(\tau \to \mu\gamma) < 10^{-12}$ ,<br> $Br(h \to \mu e) < 1.2 \times 10^{-9}$ ,  $Br(h \to \$ (15)<br>
nds of LFV decay rates<br>
ressed when comparing<br>
ies given in Table 1:<br>  $Br(\tau \to \mu \gamma) < 10^{-12}$ ,<br>  $Br(h \to \tau e) < 3 \times 10^{-7}$ ,<br>  $\gamma^{-6}$ . On the other hand,<br>  $g \to \mu e) < 1.2 \times 10^{-7}$ ,<br>  $Br(Z \to \tau \mu) < 5.3 \times$ <br>
Its will focus on the re  $10^{-8}$ are predicted to be suppressed when comparing<br>with the future sensitivities given in Table 1:<br> $Br(\tau \to e\gamma) < 4 \times 10^{-14}$ ,  $Br(\tau \to \mu\gamma) < 10^{-12}$ ,<br> $Br(h \to \mu e) < 1.2 \times 10^{-9}$ ,  $Br(h \to \tau e) < 3 \times 10^{-7}$ ,<br>and  $Br(h \to \tau \mu) < 7.4 \times 10^{-6}$ . On with the future sensitivities given in Table 1:<br>  $Br(\tau \to e\gamma) < 4 \times 10^{-14}$ ,  $Br(\tau \to \mu\gamma) < 10^{-12}$ ,<br>  $Br(h \to \mu e) < 1.2 \times 10^{-9}$ ,  $Br(h \to \tau e) < 3 \times 10^{-7}$ ,<br>
and  $Br(h \to \tau \mu) < 7.4 \times 10^{-6}$ . On the other hand,<br>
the LFVZ decay rate is la Br( $\tau \to e\gamma$ )  $\lt 4 \times 10^{-14}$ , Br( $\tau \to \mu\gamma$ )  $\lt 10^{-12}$ ,<br>Br( $h \to \mu e$ )  $\lt 1.2 \times 10^{-9}$ , Br( $h \to \tau e$ )  $\lt 3 \times 10^{-7}$ ,<br>and Br( $h \to \tau \mu$ )  $\lt 7.4 \times 10^{-6}$ . On the other hand,<br>the LFVZ decay rate is large enough to reach th  $Br(\tau \to e\gamma) < 4 \times 10^{-3}$ ,  $Br(\tau \to \mu\gamma) < 10^{-3}$ ,<br>  $Br(h \to \mu e) < 1.2 \times 10^{-9}$ ,  $Br(h \to \tau e) < 3 \times 10^{-7}$ ,<br>
and  $Br(h \to \tau \mu) < 7.4 \times 10^{-6}$ . On the other hand,<br>
the LFVZ decay rate is large enough to reach the<br>
expected sensitivities:  $Br$ 

A<sub>1</sub>,  $|A_4|$ ,  $|A_5| \in [0, 4\pi]$ ;  $l_{\beta} \in [0, \pi]$ ; expected sensitivities:  $Br(Z \to \mu$ <br>  $|y_{ab}^d| \leq 3.5 \,\forall a, b = 1, 2, 3.$  (14)  $Br(Z \to \tau e) < 2.1 \times 10^{-9}$ ,  $Br(Z \to \mu$ <br>
In the numerical investigation, we remind all The second numer able 11 and  $\mathbb{R}^n$  are non-zeros, which are enough to ac-<br>
able to ac-<br>
are non-zeros, which are enough to ac-<br>
are two  $(g-2)e_{,\mu}$  data, namely  $y_{11}^{d}$ ,  $y_{22}^{d} \neq 0$ .<br>  $\mathbb{R}^n$  are non-zeros, which are enough remind all The second numerical results<br>
gions with non-zero  $y_{ab}^d$ : 0<br>
atisfy addi-<br>  $(ab) \neq (11), (22), (12), (21)$ . E<br>
and Higgs used in (T. T. Hong *et al*, 2(<br>
y in (T. T. numerical results are discuss<br>
shows also the depe is large enough to reach the<br>  $Br(Z \to \mu e) < 1.2 \times 10^{-7}$ ,<br>  $10^{-9}$ ,  $Br(Z \to \tau \mu) < 5.3 \times$ <br>
results will focus on the re-<br>  $d_a: 0 \le |y_{ab}^d| \le 0.5$  for all<br>
(21). Different from the code<br>  $t$  al, 2024), some interesting<br>
discusse ven in Table 1:<br>  $\rightarrow \mu \gamma$   $\lt 10^{-12}$ ,<br>  $\rightarrow \tau e$   $\lt 3 \times 10^{-7}$ ,<br>
in the other hand,<br>
ough to reach the<br>  $e$   $\gt 1.2 \times 10^{-7}$ ,<br>  $\rightarrow \tau \mu$   $\lt 5.3 \times$ <br>  $\rightarrow$  focus on the re-<br>  $\frac{d}{ab}$   $\leq 0.5$  for all<br>
ent from the code<br>
so Br( $h \to \mu e$ ) < 1.2 × 10<sup>-9</sup>, Br( $h \to \tau e$ ) < 3 × 10<sup>-7</sup>,<br>and Br( $h \to \tau \mu$ ) < 7.4 × 10<sup>-6</sup>. On the other hand,<br>the LFVZ decay rate is large enough to reach the<br>expected sensitivities: Br( $Z \to \mu e$ ) < 1.2 × 10<sup>-7</sup>,<br>Br( $Z \to \tau e$ and Br( $h \to \tau\mu$ ) < 7.4 × 10<sup>-6</sup>. On the other hand,<br>the LFVZ decay rate is large enough to reach the<br>expected sensitivities: Br( $Z \to \mu e$ ) < 1.2 × 10<sup>-7</sup>,<br>Br( $Z \to \tau e$ ) < 2.1 × 10<sup>-9</sup>, Br( $Z \to \tau\mu$ ) < 5.3 ×<br>10<sup>-8</sup>.<br>The sec the LFVZ decay rate is large enough to reach expected sensitivities:  $Br(Z \rightarrow \mu e) < 1.2 \times 10$ <br>Br( $Z \rightarrow \tau e) < 2.1 \times 10^{-9}$ ,  $Br(Z \rightarrow \tau \mu) < 5.3$ <br> $10^{-8}$ .<br>The second numerical results will focus on the gions with non-zero  $y_{ab}^d$ : the LFVZ decay rate is large enough to reach the<br>expected sensitivities:  $Br(Z \rightarrow \mu e) < 1.2 \times 10^{-7}$ ,<br> $Br(Z \rightarrow \tau e) < 2.1 \times 10^{-9}$ ,  $Br(Z \rightarrow \tau \mu) < 5.3 \times 10^{-8}$ .<br>The second numerical results will focus on the re-<br>gions with non-zero expected sensitivities:  $Br(Z \to \mu e) < 1.2 \times 10^{-7}$ ,<br>  $Br(Z \to \tau e) < 2.1 \times 10^{-9}$ ,  $Br(Z \to \tau \mu) < 5.3 \times 10^{-8}$ .<br>
The second numerical results will focus on the regions with non-zero  $y_{ab}^d$ :  $0 \le |y_{ab}^d| \le 0.5$  for all<br>  $(ab) \ne (11), (2$ Br( $Z \rightarrow \tau e$ ) < 2.1 × 10<sup>-9</sup>, Br( $Z \rightarrow \tau \mu$ ) < 5.3 × 10<sup>-8</sup>.<br>The second numerical results will focus on the regions with non-zero  $y_{ab}^{d}$ : 0 ≤  $|y_{ab}^{d}|$  ≤ 0.5 for all (ab) ≠ (11), (22), (12), (21). Different from the co decays on  $m_{n_2}$ . It is shown that all cLFV decays<br>  $e_b \rightarrow e_a \gamma$  can reach the present constraints from<br>
experiments given in Table 1. The maximal values<br>
of LFVh and LFVZ decay rates predicted in this<br>
case are:<br>  $Br(Z \rightarrow \mu$ 

$$
Br(Z \to \mu^{\pm} e^{\mp}) \le 4.12 \times 10^{-8}, Br(Z \to \tau^{\pm} e^{\mp}) \le 2.08 \times 10^{-8},
$$
  
\n
$$
Br(Z \to \tau^{\pm} \mu^{\mp}) \le 6.49 \times 10^{-6}, Br(h \to \mu e) \le 2.6 \times 10^{-11},
$$
  
\n
$$
Br(h \to \tau e) \le 1.8 \times 10^{-3}, Br(h \to \tau \mu) \le 1.5 \times 10^{-3}.
$$
  
\n(16)

 $\langle e_a \gamma \rangle$ , namely,<br>  $Br(Z \to \tau^{\pm} \mu^{\mp}) \leq 6.49 \times 10^{-6}$ ,<br>
ter space, espe-<br>
lowed 1 $\sigma$  ranges<br>
results are con-<br>
This also means that only<br>
in (T. T. Hong is still invisible in the incompase in the al-<br>
stivities listed  $e_b \rightarrow e_a \gamma$  can reach the present constraints from<br>experiments given in Table 1. The maximal values<br>of LFVh and LFVZ decay rates predicted in this<br>case are:<br> $Br(Z \rightarrow \mu^{\pm}e^{\mp}) \leq 4.12 \times 10^{-8}, Br(Z \rightarrow \tau^{\pm}e^{\mp}) \leq 2.08 \times 10^{-8},$ <br> experiments given in Table 1. The maximal values<br>of LFVh and LFVZ decay rates predicted in this<br>case are:<br> $Br(Z \to \mu^{\pm}e^{\mp}) \leq 4.12 \times 10^{-8}, Br(Z \to \tau^{\pm}e^{\mp}) \leq 2.08 \times 10^{-8},$ <br> $Br(Z \to \tau^{\pm}\mu^{\mp}) \leq 6.49 \times 10^{-6}, Br(h \to \mu e) \leq 2.6 \times$ case are:<br>  $Br(Z \to \mu^{\pm}e^{\mp}) \leq 4.12 \times 10^{-8}, Br(Z \to \tau^{\pm}e^{\mp}) \leq 2.08 \times 10^{-8},$ <br>  $Br(Z \to \tau^{\pm}\mu^{\mp}) \leq 6.49 \times 10^{-6}, Br(h \to \mu e) \leq 2.6 \times 10^{-11},$ <br>  $Br(h \to \tau e) \leq 1.8 \times 10^{-3}, Br(h \to \tau\mu) \leq 1.5 \times 10^{-3}.$ <br>
(16)<br>
This also means that only th  $Br(Z \to \mu^{\pm}e^{\mp}) \leq 4.12 \times 10^{-8}, Br(Z \to \tau^{\pm}e^{\mp}) \leq 2.08 \times 10^{-8},$ <br>  $Br(Z \to \tau^{\pm}\mu^{\mp}) \leq 6.49 \times 10^{-6}, Br(h \to \mu e) \leq 2.6 \times 10^{-11},$ <br>  $Br(h \to \tau e) \leq 1.8 \times 10^{-3}, Br(h \to \tau \mu) \leq 1.5 \times 10^{-3}.$ <br>
(16)<br>
This also means that only the LFVh deca  $Br(Z \to \tau^{\pm} \mu^{\mp}) \leq 6.49 \times 10^{-6}$ ,  $Br(h \to \mu e) \leq 2.6 \times 10^{-6}$ <br>  $Br(h \to \tau e) \leq 1.8 \times 10^{-3}$ ,  $Br(h \to \tau \mu) \leq 1.5 \times 10^{-6}$ <br>
This also means that only the LFVh decay  $h \to$ <br>
is still invisible in the incoming experimental s<br>
siti  $\leq 6.49 \times 10^{-6}$ ,  $Br(h \rightarrow \mu e) \leq 2.6 \times 10^{-11}$ ,<br>  $\leq 1.8 \times 10^{-3}$ ,  $Br(h \rightarrow \tau \mu) \leq 1.5 \times 10^{-3}$ .<br>
(16)<br>
ans that only the LFVh decay  $h \rightarrow \mu e$ <br>
e in the incoming experimental sen-<br>
l in Table 1. To end this section, we<br>
our  $Br(h \to \tau e) \le 1.8 \times 10^{-3}$ ,  $Br(h \to \tau \mu) \le 1.5 \times 10^{-3}$ .<br>
This also means that only the LFVh decay  $h \to \mu e$ <br>
is still invisible in the incoming experimental sen-<br>
sitivities listed in Table 1. To end this section, we<br>
conclud do not depend strongly on  $m_{n_2}$ .



only  $y_{11}^d, y_{22}^d \neq 0$ .



 $y_{ab}^d \neq 0$  with two non-zero entries  $(ab) \neq (12), (21)$ .

**Figuer 3.**  $(g-2)_{e,\mu}$  **anomalies and LFV decays as functions of**  $m_{n_2}$  in the general  $y_{ab}^d \neq 0$  with two non-zero entries  $(ab) \neq (12), (21)$ .<br>
4 **CONCLUSIONS** cusom the IO scheme with all the heaviest active neutrin Figuer 3.  $(g - 2)_{e,\mu}$  anomalies and LFV decays as functions of  $m_{n_2}$  in the ger<br>  $y_{ab}^d \neq 0$  with two non-zero entries  $(ab) \neq (12), (21)$ .<br>
4 CONCLUSIONS cus on the IO scheme with all the<br>
line the heaviest active neu Figuer 3.  $(g-2)_{e,\mu}$  anomalies and LFV decays as functions of  $m_{n_2}$  in the ger<br>  $y_{ab}^d \neq 0$  with two non-zero entries  $(ab) \neq (12), (21)$ .<br>
4 CONCLUSIONS cus on the IO scheme with all the heaviest active neutrino masse<br>  $y_{ab}^d \neq 0$  with two non-zero entries  $(ab) \neq (12), (21)$ .<br>
4 **CONCLUSIONS** cus on the IO scheme with all a<br>
the heaviest active neutrino masses<br>
In this work we investigate the allowed parameter that the two schemes IO and

that the two schemes IO and NO predict the same<br>results of LFV decay rates. In additional material control of  $m_{n_2}$  in the general ranges of<br>entries  $(ab) \neq (12), (21)$ .<br>cus on the IO scheme with all allowed ranges of<br>the results of LFV decay rates. In addition, they do not depend strongly on the particle number of  $m_{n_2}$  in the general ranges of entries  $(ab) \neq (12), (21)$ .<br>cus on the IO scheme with all allowed ranges of the heaviest active **ass functions of**  $m_{n_2}$  **in the general ranges of entries**  $(ab) \neq (12), (21)$ .<br>cus on the IO scheme with all allowed ranges of the heaviest active neutrino masses. We have shown that the two schemes IO and NO predict the s as functions of  $m_{n_2}$  in the general ranges of<br>entries  $(ab) \neq (12), (21)$ .<br>cus on the IO scheme with all allowed ranges of<br>the heaviest active neutrino masses. We have shown<br>that the two schemes IO and NO predict the same

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