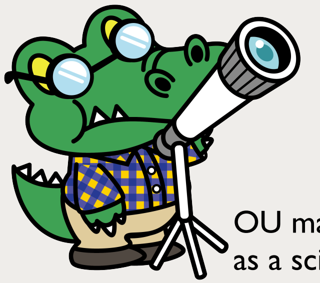
Higgs LFV decays in the model for Dirac neutrino masses and dark matter

Phys. Rev. D100 (2019) no.1, 015044 [arXiv:1904.07039]



OU mascot Dr.Wani as a science member

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Oct. 30th, 2019 LCWS @ Sendai

Summary of this talk

In previous works, it is shown that

if the Lepton Flavor Violating (LFV) decays of the Higgs boson are observed in the near future collider experiments, a wide class of models for neutrino masses are excluded.

S. Kanemura, H. Sugiyama, PLB (2016),
S. Kanemura, K. Sakurai, H. Sugiyama, PLB (2016),
M. Aoki, S. Kanemura, K. Sakurai, H. Sugiyama, PLB (2016)

In our work,

we built a new model which is not excluded in such a case, and show this model can explain tiny neutrino masses and the existence of dark matter under current constraint on LFV processes.

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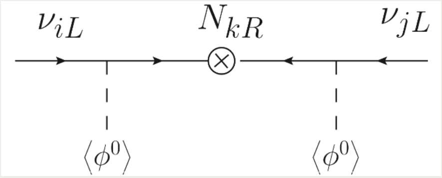
1. Models for neutrino masse and classification of them

What is the origin of tiny neutrino masses ?

Type-I seesaw



Seesaw mechanisms

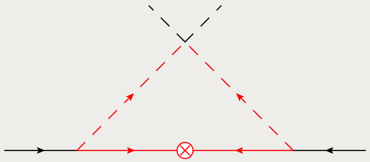
3 types, Majorana ν masses at tree level

Radiatively generated masses

Majorana or Dirac ν masses at loop level,

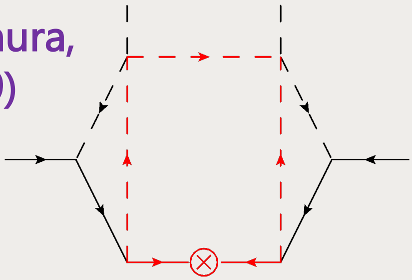
A candidate of dark matter (Additional Z_2 symmetry)

Ma ('03)



Various models

Aoki,Kanemura, Seto ('09)



⇨ Classification of models and phenomenological study in group-by-group

1. Models for neutrino masse and classification of them

〈 Classification of models for Majorana ν by new Yukawa int. 〉

S. Kanemura, H. Sugiyama PLB (2016)

Assumptions

- New scalars : New scalars do not have color or flavor.
- New Symmetry : Exact Z_2 sym. (Dark matter)

  Softly broken Z_2 sym. (Prohibit FCNC @ tree level)
- New Fermion : Gauge-singlet Z_2-odd fermions ψ_R^a $(\mathrm{a} = 1,2,3)$.
- Models include only a minimum kind of scalars for ν masses.

※ Type I, III seesaw mechanisms are not included in this classification.

1. Models for neutrino masse and classification of them

All new Yukawa interactions and new scalars

Z_2-odd fields are in red letters

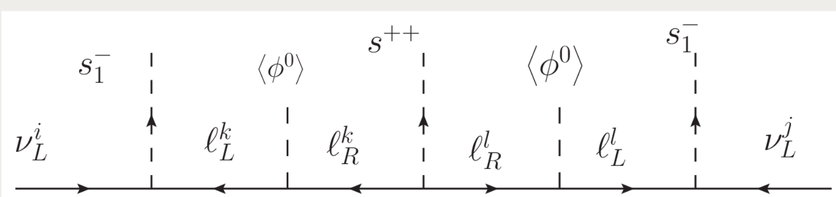
Bilinears	New Scalars: Fields	SU(2)$_L$	U(1)$_Y$	Yukawa Interaction
$\overline{L_L^i}\ell_R^j$	ϕ_2	**2**	$+\frac{1}{2}$	$y_i \overline{L_L^i}\phi_2\, \ell_R^j$
$\overline{(\ell_R^i)^c}\ell_R^j$	s^{++}	**1**	$+2$	$(Y_s^S)_{ij}\,\overline{(\ell_R^i)^c}\ell_R^j s^{++}$
$\overline{(L_L^i)^c}L_L^j$	s_1^+	**1**	$+1$	$(Y_s^A)_{ij}\,\overline{(L_L^i)^c}L_L^j\, s_1^+$
	Δ	**3**	$+1$	$(Y_\Delta^S)_{ij}\,\overline{(L_L^i)^c}\Delta\, L_L^j$
$\overline{(\psi_R^a)^c}\ell_R^i$	s_2^+	**1**	$+1$	$(Y_s)_{ai}\,\overline{(\psi_R^a)^c}\ell_R^i\, s_2^+$
$\overline{L_L^i}\psi_R^a$	η	**2**	$+\frac{1}{2}$	$(Y_\eta)_{ia}\,\overline{L_L^i}\eta^c\psi_R^a$

Select scalars for ν mass diagram

Models for Majorana ν masses

	Δ	ϕ_2	s^{++}	s_L^+	η	s_2^+
SU(2)$_L$	**3**	**2**	**1**	**1**	**2**	**1**
U(1)$_Y$	$+1$	$+1/2$	$+2$	$+1$	$+1/2$	$+1$
Z_2	Even				Odd	
M1			✓	✓		
M2		✓	✓			
M3			✓			
M4	✓					
M5				✓		✓
M6		✓				✓
M7						✓
M8					✓	

e.g.) Mass diagram in M1



1. Models for neutrino masse and classification of them

⟨In the case of Dirac neutrino masses⟩

Additional assumptions

S. Kanemura, K. Sakurai, H. Sugiyama, PLB (2016)

- New fermions :

  $\nu_R^i \ (i = 1,2,3)$

- New symmetries :

  Lepton # conservation

  ✕ $\overline{\nu_R^i}\left(\nu_R^j\right)^c$

  Softly broken Z_2 sym.

  ✕ $\overline{L_L^i}\phi^c\nu_R^j$

	Δ	ϕ_2	ϕ_ν	s^{++}	s_R^+	s_L^+	s^0	η	s_2^+	s_2^0
$SU(2)_L$	**3**	**2**	**2**	**1**	**1**	**1**	**1**	**2**	**1**	**1**
$U(1)_Y$	$+1$	$+1/2$	$+1/2$	$+2$	$+1$	$+1$	0	$+1/2$	$+1$	0
Z_2	Even							Odd		
Lepton #	-2	0	0	-2	-2	-2	-2	-1	-1	-1
Z_2'	Even	Even	Odd	Even	Odd	Even	Even	Even	Even	Odd
D1					✓	✓				
D2	✓				✓					
D3		✓		✓	✓					
D4				✓	✓					
D5		✓			✓		✓			
D6					✓		✓			
D7			✓							
D8						✓			✓	✓
D9	✓								✓	✓
D10					✓			✓		
D11		✓			✓				✓	
D12					✓				✓	
D13		✓			✓					✓
D14					✓					✓
D15		✓							✓	✓
D16									✓	✓
D17					✓			✓	✓	
D18								✓		✓

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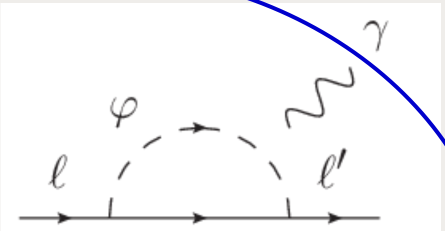
2. Higgs LFV decay in models for neutrino masses

Classification of models by new Yukawa interactions

LFV processes

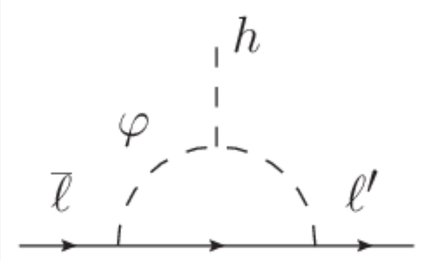
Strongly constrained !

$\ell \to \ell' \gamma$



Process	Upper limit
$\mu \to e\gamma$	4.2×10^{-13}
$\tau \to e\gamma$	3.3×10^{-8}
$\tau \to \mu\gamma$	4.4×10^{-8}

$h \to \ell\ell'$

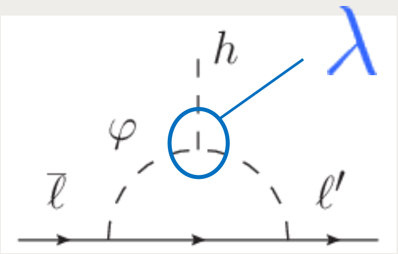


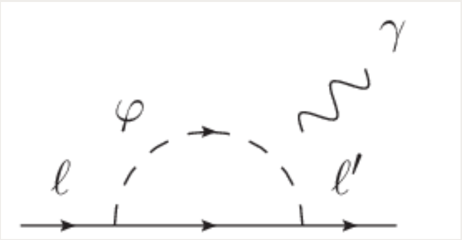
Process	Upper limit
$h \to \mu e$	3.5×10^{-4}
$h \to \tau e$	6.1×10^{-3}
$h \to \mu\tau$	2.5×10^{-3}

2. Higgs LFV decay in models for neutrino masses

Current experimental constraints for LFV decays of the Higgs boson are not so strong, but from theoretical aspects, they have stronger constraints in some models for ν masses.

In the models with a kind of scalars which contribute to LFV processes.





$(\lambda = O(1))$

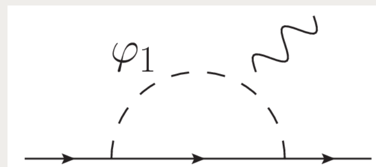
$$\mathrm{Br}(h \to \ell\ell') \sim 10^{-1}\mathrm{Br}(\ell \to \ell'\gamma)$$
$$\lesssim 10^{-9} - 10^{-14}$$

If $h \to \ell\ell'$ are observed in near future collider experiments, such a simple model are excluded.

2. Higgs LFV decay in models for neutrino masses

We need that **two or more kind of scalars** interact with left-handed (right-handed) leptons to realize $\mathrm{Br}(h \to \ell\ell') > \mathrm{Br}(\ell \to \ell'\gamma)$

$\Gamma(\ell \to \ell'\gamma) \propto \Big|$



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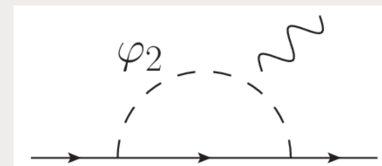
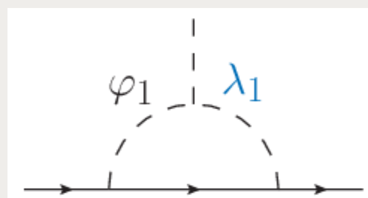


$\Big|^2$

$\Gamma(h \to \ell\ell') \propto \Big|$



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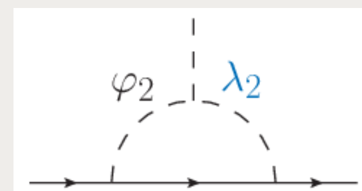

$\Big|^2$

If $\mathrm{sign}(\lambda_1) = -\mathrm{sign}(\lambda_2)$,

$\mathrm{Br}(h \to \ell\ell') > \mathrm{Br}(\ell \to \ell'\gamma)$ in some parameter region

2. Higgs LFV decay in models for neutrino masses

Which groups of models have this flavor structure ?

⟨In the case of Majorana neutrino masses⟩

	Δ	ϕ_2	s^{++}	s_L^+	η	s_2^+
[illegible]	[illegible]	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$
[illegible]	[illegible]	[illegible]/2	$+2$	$+1$	$+1/2$	$+1$
[illegible]	[illegible]n				Odd	
M1				✓		
M2						
M3						
M4	✓					
M5						✓
M6		✓				
M7						
M8						

All groups do not have such a flavor structure

Type-I and -III Seesaw mechanisms

Both mechanisms include only one LFV Yukawa interaction.

2. Higgs LFV decay in models for neutrino masses

Which groups of models have this flavor structure ?

〈In the case of Majorana neutrino masses〉

	Δ	ϕ_2	s^{++}	s_L^+	η	s_2^+
		$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$
		/2	$+2$	$+1$	$+1/2$	$+1$
		n			Odd	
M1				✓		
M2						

All groups do n
a flavor stru

Type-I and -III
Seesaw mechanisms

Both mechanisms include

If LFV decays of the Higgs boson are observed
without the signal of LFV decays of the charged lepton,
M1 ~ M8 (all groups in the classification for Majorana ν masses)
and Type-I and –III seesaw mechanisms are excluded.

2. Higgs LFV decay in models for neutrino masses

Only five groups (D3, 4, 11, 12, 17) have such a flavor structure.

In D3, 4, 11, 12 groups,

It is difficult to make $BR(h \to \ell\ell')$ large enough to detect at near future exp. under constraint from neutrino oscillation data.

	Δ	ϕ_2	ϕ_ν	s^{++}	s_R^+	s_L^+	s^0	η	s_2^+	s_2^0
$\mathrm{SU(2)_L}$	**3**	**2**	**2**	**1**	**1**	**1**	**1**	**2**	**1**	**1**
$\mathrm{U(1)_Y}$	$+1$	$+1/2$	$+1/2$	$+2$	$+1$	$+1$	0	$+1/2$	$+1$	0
Z_2	Even							Odd		
Lepton #	-2	0	0	-2	-2	-2	-2	-1	-1	-1
Z_2'	Even	Even	Odd	Even	Odd	Even	Even	Even	Even	Odd
D1					✓	✓				
D2	✓				✓					
D3		✓		✓	✓					
D4				✓	✓					
D5		✓			✓		✓			
D6					✓		✓			
D7			✓							
D8						✓			✓	✓
D9	✓								✓	✓

In models in D17 group, LFV decays of the Higgs boson **can be large** enough to detect the their signal in the near collider experiments (HL-LHC or ILC).

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3. Our model

K. Enomoto, S. Kanemura, K. Sakurai, H. Sugiyama, PRD(2019)

A new model for Dirac neutrino masses which have D17 group's flavor structure.

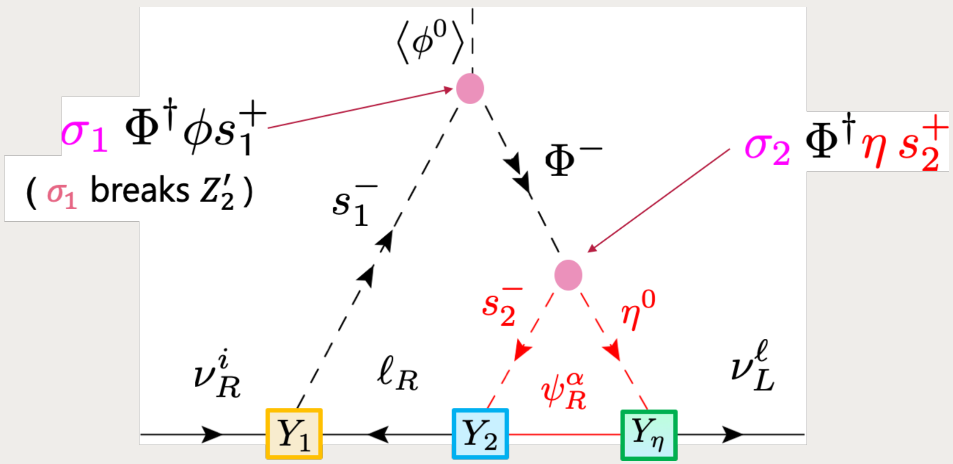
New fields

	Fermions		Scalars			
	ν_{Ri}	$\psi_{R\alpha}$	s_1^+	Φ	s_2^+	η
$\mathrm{SU(2)_L}$	**1**	**1**	**1**	**2**	**1**	**2**
$\mathrm{U(1)_Y}$	0	0	1	3/2	1	1/2
Unbroken $\mathrm{Z_2}$	Even	Odd	Even		Odd	
Z_2'	$-$	$+$	$-$		$+$	$+$
Lepton #	1	0	-2	-2	-1	-1

$i, \alpha = 1 \sim 3$

Neutrino masses

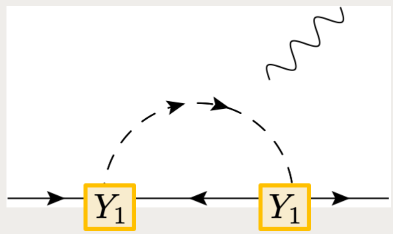
Arrows mean Lepton #

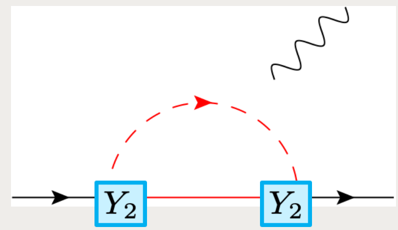


$$\mathcal{L} = \boxed{(Y_1)_{\ell i}}\ \overline{(\ell_R)^c}\nu_R^i\, s_1^+ + \boxed{(Y_2)_{\ell\alpha}}\ \overline{(\ell_R)^c}\psi_R^\alpha\, s_2^+ + \boxed{(Y_\eta)_{\ell\alpha}}\ \overline{L_\ell}\eta^c\psi_R^\alpha$$

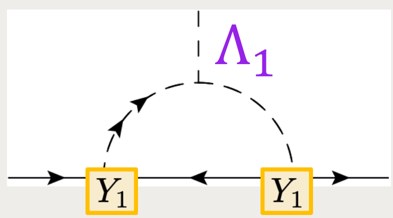
Our model

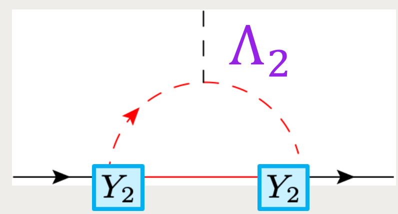
LFV decays in our model ($\mathrm{sign}(\Lambda_1) = -\mathrm{sign}(\Lambda_2)$)

$\Gamma(\ell \to \ell'_R\gamma) \propto \Bigg|$ 

$+$ 

$\Bigg|^2$ Destructive

$\Gamma(h \to \ell\ell'_R) \propto \Bigg|$ 

$+$ 

$\Bigg|^2$ Constructive

$$\mathcal{L} = \boxed{(Y_1)_{\ell i}}\,\overline{(\ell_R)^c}\,\nu_R^i\, s_1^+ + \boxed{(Y_2)_{\ell\alpha}}\,\overline{(\ell_R)^c}\,\psi_R^\alpha\, s_2^+$$

3. Numerical results

$$Y_a = \begin{pmatrix} 10^{-4} & 10^{-4} & 0.1 \\ x_a & y_a & 10^{-4} \\ z_a & \zeta_a & 10^{-4} \end{pmatrix}$$

($a = 1, 2$)

$$-\sqrt{4\pi} < x_a, y_a, z_a, \zeta_a < \sqrt{4\pi}$$

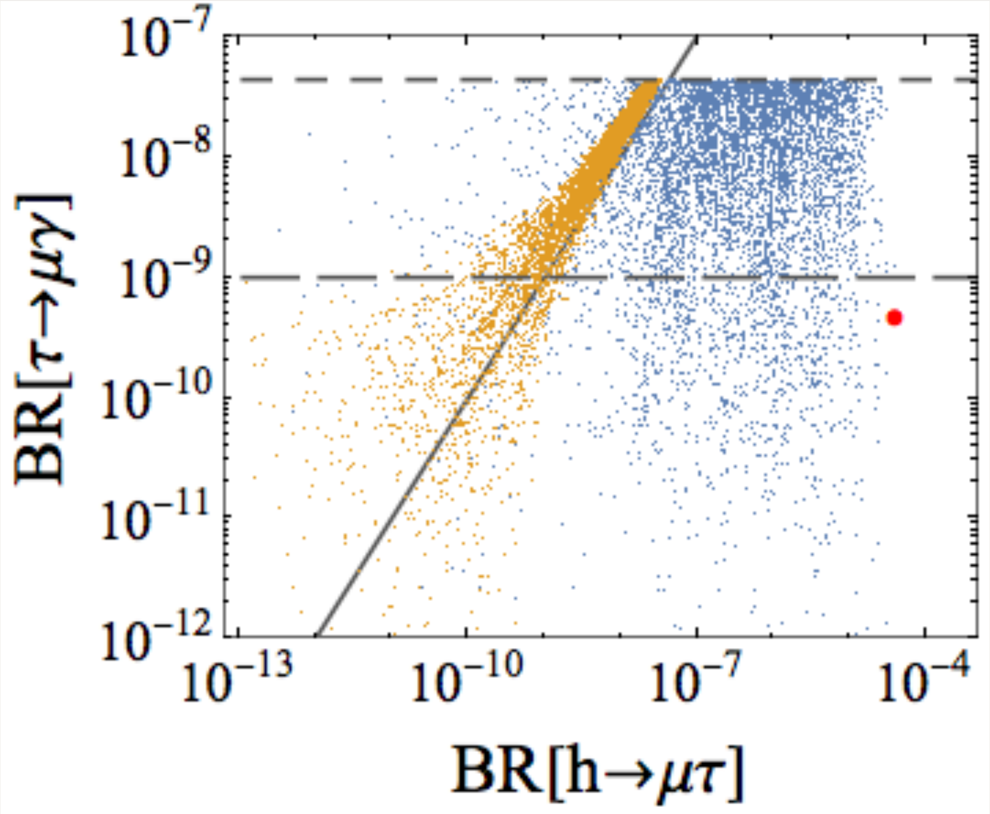
Orange Points

$$\lambda_{hs_1} = \lambda_{hs_2} = 2.0$$

Blue Points

$$\lambda_{hs_1} = -\lambda_{hs_2} = 2.0$$

—— $\mathrm{Br}(\tau \to \mu\gamma) = \mathrm{Br}(h \to \mu\tau)$



Current upper limit

Expected limit

Belle II @ 50 ab^{-1}

3. Numerical results

$$Y_a = \begin{pmatrix} 10^{-4} & 10^{-4} & 0.1 \\ x_a & y_a & 10^{-4} \\ z_a & \zeta_a & 10^{-4} \end{pmatrix}$$

$(a = 1, 2)$

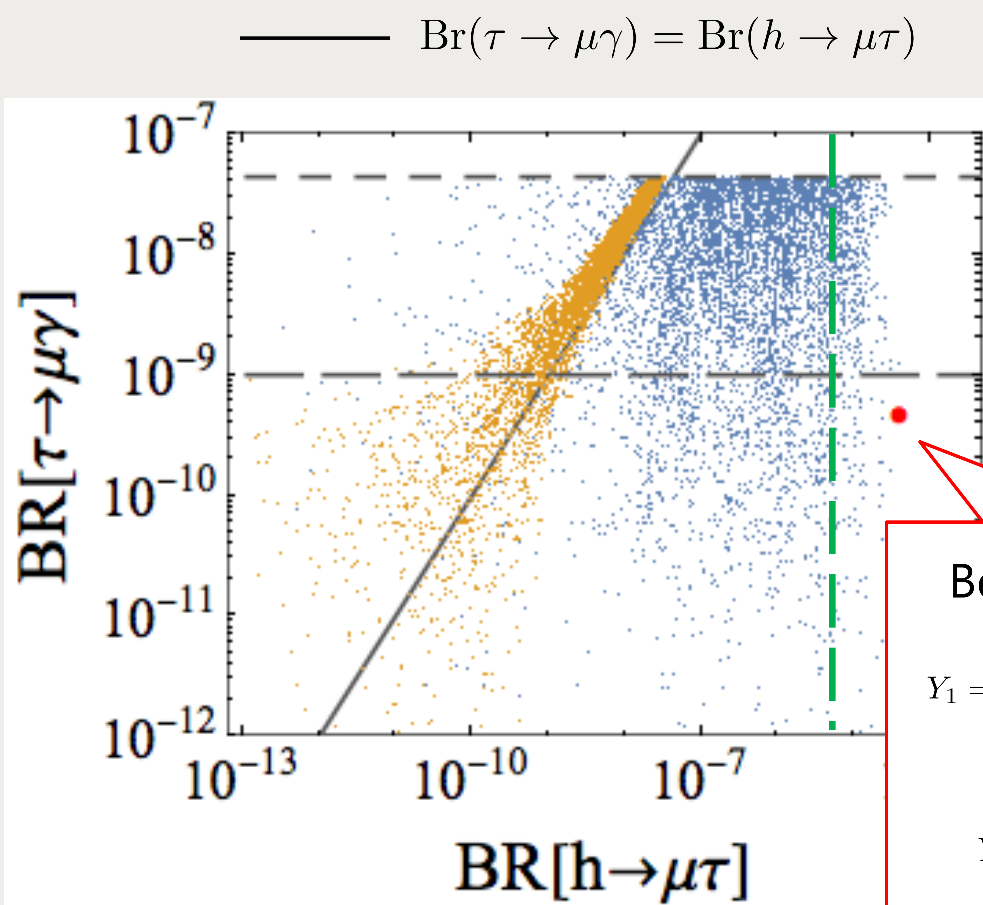
$-\sqrt{4\pi} < x_a, y_a, z_a, \zeta_a < \sqrt{4\pi}$

Orange Points

$$\lambda_{hs_1} = \lambda_{hs_2} = 2.0$$

Blue Points

$$\lambda_{hs_1} = -\lambda_{hs_2} = 2.0$$



Benchmark scenario

$$Y_1 = \begin{pmatrix} 10^{-4} & 10^{-4} & 0.1 \\ 2.74 & 2.14 & 10^{-4} \\ 3.50 & 3.47 & 10^{-4} \end{pmatrix}$$

$$Y_2 = \begin{pmatrix} 10^{-4} & 10^{-4} & 0.1 \\ -3.50 & -3.47 & 10^{-4} \\ 2.26 & 3.50 & 10^{-4} \end{pmatrix}$$

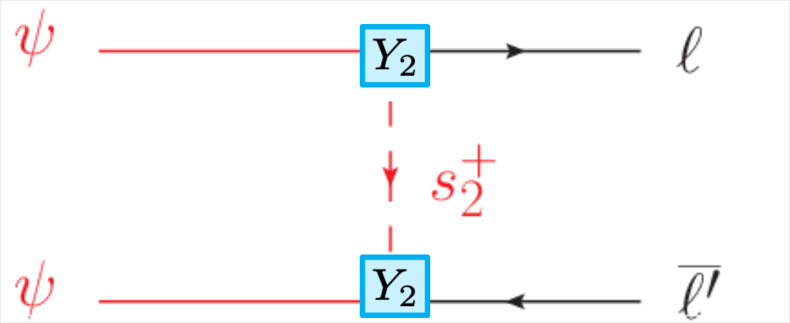
7.0×10^{-6} Expected limit @ ILC250($\mathcal{L} = 8\ \mathrm{ab}^{-1}$)

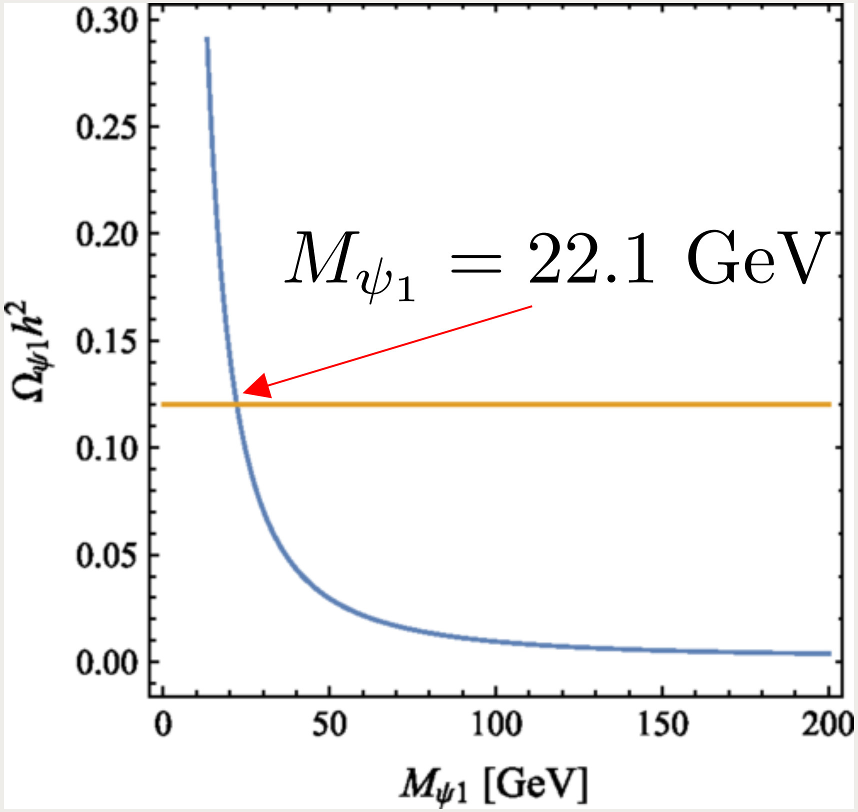
I. Chakraborty, A. Datta, A. Kundu, J.Phys (2016)

3. Numerical results

Dark matter candidates : η^0, ψ_a

DM in the benchmark scenario : ψ_1





$$Y_2 = \begin{pmatrix} 10^{-4} & 10^{-4} & 0.1 \\ -3.50 & -3.47 & 10^{-4} \\ 2.26 & 3.50 & 10^{-4} \end{pmatrix}$$

$$m_{s_2} = 550 \text{ GeV}$$

Relic abundance of ψ_1

$\Omega_{\rm DM} h^2 = 0.1200 \pm 0.0012$

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4. Summary

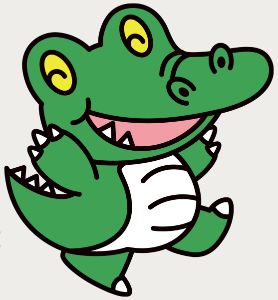
・We built a new model for Dirac neutrino masses and dark matter.

・Our model has a characteristic flavor structure,

and in some parameter region, it predicts the large branching ratio of

LFV decays of the Higgs boson.

It can be tested at near future Higgs precision test (ILC!).



OU mascot
Dr. Wani

Thank you for listening

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Higgs LFV decay in D3, D4, D11, D12 groups

In models in D3, 4, 11, 12 groups,

$$(m_\nu)_{\ell i} = m_\ell (Y \cdots)_{\ell i} \qquad m_e \ll m_\mu < m_\tau$$

It is difficult to explain neutrino oscillation data
if all elements of Y are same order.

$$\Rightarrow Y_{ea} \gg Y_{\mu a} > Y_{\tau a} \qquad (a = 1, 2, 3)$$

Strongly constrained

$$\mathrm{Br}(\mu \to e\gamma) \lesssim 10^{-13}$$

In these models, $BR(h \to \ell\ell') > BR(\ell \to \ell'\gamma)$ can be realized.
However, it is difficult to make large it enough to detect at near future exps.

CP violation terms in Scalar potential

Complex coupling constants in scalar potential

$\sigma_1,\ \sigma_2,\ \sigma_3,\ \xi_1,\ \xi_2,\ \xi_3$

Z_2-Even Φ

$$\sigma_1 \Phi^\dagger \phi s_1^+ + \sigma_2 \Phi^\dagger \eta s_2^+ + \sigma_3 \phi^\dagger \eta^c s_2^+ \boxed{+\xi_1 \eta^\dagger \Phi \eta^\dagger \phi^c + \xi_2 \Phi^\dagger \phi^c \left(s_2^+\right)^2}$$

$$\boxed{+\xi_3 \Phi^\dagger \eta^c s_1^+ s_2^+}$$

Z_2-Odd Φ

Z_2-Odd scalars are in red letters

	Scalars			
	Φ	s_R^+	η	s_2^+
$\mathrm{SU(2)_L}$	**2**	**1**	**2**	**1**
$\mathrm{U(1)_Y}$	$+3/2$	$+1$	$+1/2$	$+1$
Z_2	Even	Even	Odd	Odd
Lepton #	-2	-2	-1	-1
Z_2'		$-$	$+$	$+$

Physical CP-violating parameters

Two of $\sigma_1,\ \sigma_2,\ \sigma_3,\ \xi_1,\ \xi_2$

One of $\sigma_1,\ \sigma_2,\ \sigma_3,\ \xi_3$

Mass eigenstates in our model

Masses of new fermions

ν masses @ tree level are prohibited (generated radiatively)

ψ_R^a $(a = 1,2,3)$ have Majorana masses in the Lagrangian $\frac{1}{2} M_{\psi_a} \overline{\psi_R^a} \, (\psi_R^a)^c$

Masses of new scalars

$$\begin{pmatrix} \pi_1^+ \\ \pi_2^+ \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \Phi^+ \\ s_1^+ \end{pmatrix} \quad \begin{pmatrix} \omega_1^+ \\ \omega_2^+ \end{pmatrix} = \begin{pmatrix} \cos\chi & \sin\chi \\ -\sin\chi & \cos\chi \end{pmatrix} \begin{pmatrix} \eta^+ \\ s_2^+ \end{pmatrix}$$

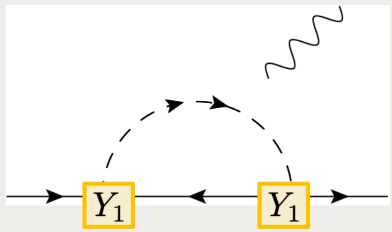
After symmetry breaking, new scalar particles are

$$\pi_1^{\pm}, \pi_2^{\pm}, \ \Phi^{++}, \ \omega_1^{\pm}, \ \omega_2^{\pm}, \ \eta^0$$

To realize BR($h \to \ell\ell'$) > BR($\ell \to \ell'\gamma$)

LFV processes ($\ell \to \ell'\gamma$)

$\Gamma\left(\ell \to \ell'_R\gamma\right) \propto$ $\Big|$



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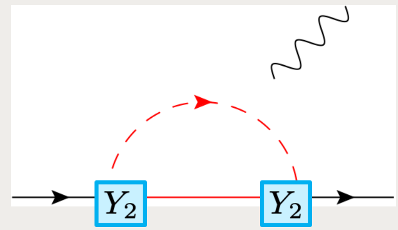

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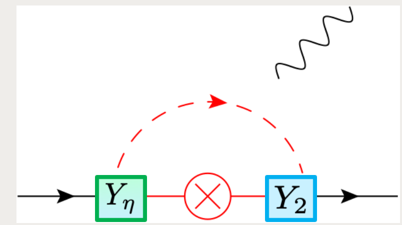
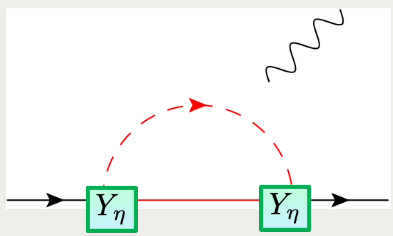


$\Big|^2$

$\Gamma\left(\ell \to \ell'_L\gamma\right) \propto$ $\Big|$



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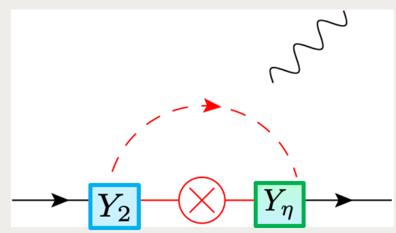


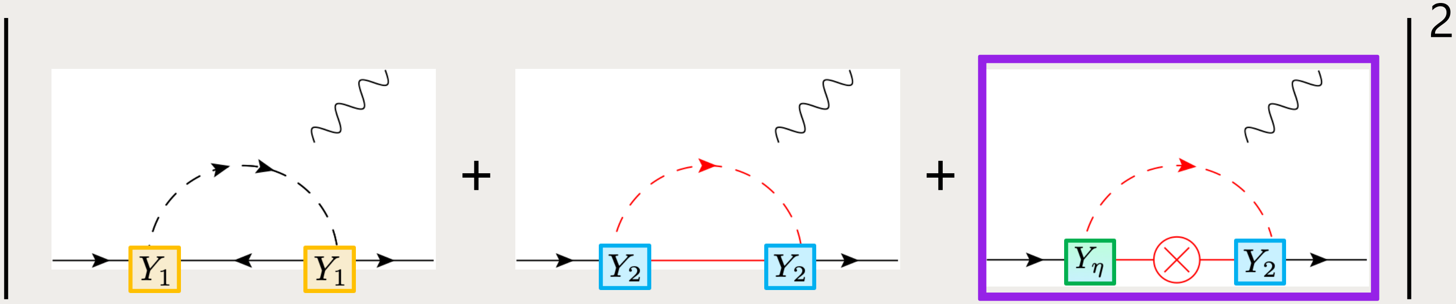
$\Big|^2$

$$\mathcal{L} = \boxed{(Y_1)_{\ell i}}\,\overline{(\ell_R)^c}\,\nu_R^i\, s_1^+ + \boxed{(Y_2)_{\ell\alpha}}\,\overline{(\ell_R)^c}\,\psi_R^\alpha\, s_2^+ + \boxed{(Y_\eta)_{\ell\alpha}}\,\overline{L_\ell}\,\eta^c\psi_R^\alpha$$

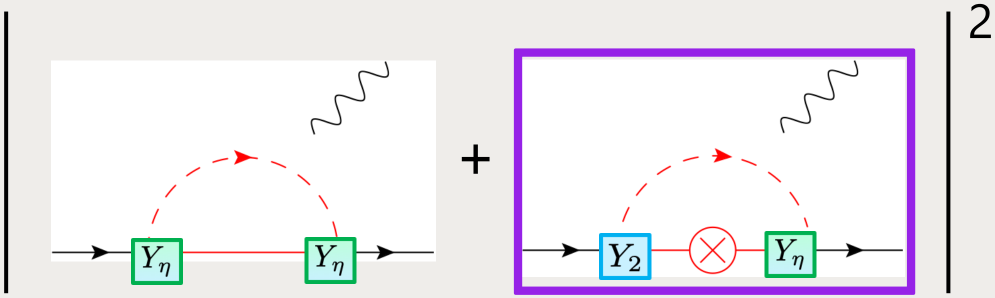
To realize $BR(h \to \ell\ell') > BR(\ell \to \ell'\gamma)$

Assumptions for large $\mathrm{BR}(h \to \ell\ell')$

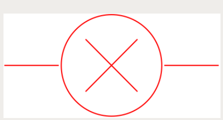
$\Gamma(\ell \to \ell'_R\gamma) \propto$



$\Gamma(\ell \to \ell'_L\gamma) \propto$



Contributions from mixing χ

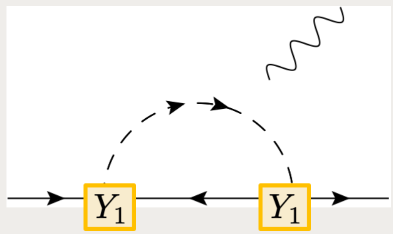


Majorana mass term of ψ_R^α ⇨ Large contributions

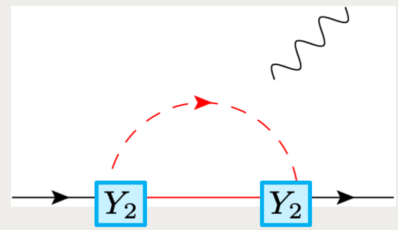
To realize $BR(h \to \ell\ell') > BR(\ell \to \ell'\gamma)$

Assumptions for large BR($h \to \ell\ell'$)

$\Gamma(\ell \to \ell'_R \gamma) \propto \Bigg|$

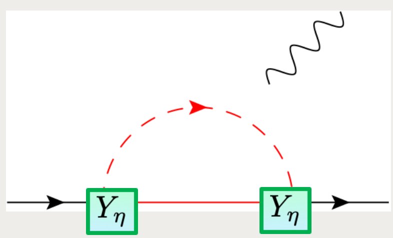


$+$



$\Bigg|^2$

$\Gamma(\ell \to \ell'_L \gamma) \propto \Bigg|$



$\Bigg|^2$

No interference effect

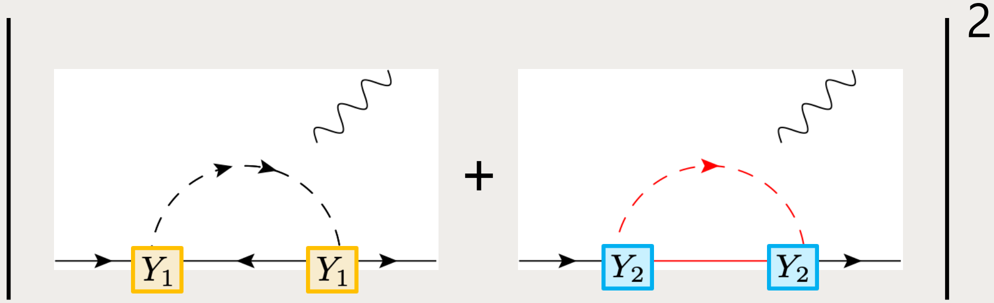
Assumption

$$\chi \simeq 0 \quad (\omega_1^+ \simeq \eta^+, \ \omega_2^+ \simeq s_2^+)$$

To realize $BR(h \to \ell\ell') > BR(\ell \to \ell'\gamma)$

Assumptions for large BR($h \to \ell\ell'$)

$\Gamma\left(\ell \to \ell'_R\gamma\right) \propto$



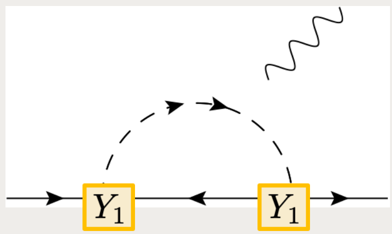
Assumption

$$\chi \simeq 0 \quad (\omega_1^+ \simeq \eta^+,\ \omega_2^+ \simeq s_2^+)\ \&\ Y_\eta \ll 1$$

To realize $BR(h \to \ell\ell') > BR(\ell \to \ell'\gamma)$

Assumptions for large $\mathrm{BR}(h \to \ell\ell')$

$\Gamma(\ell \to \ell'_R\gamma) \propto \Big|$



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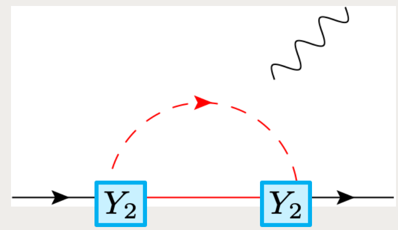
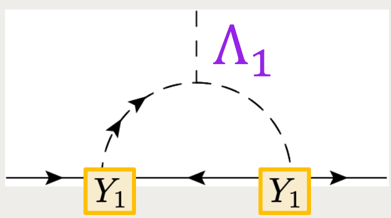


$\Big|^2$ **Destructive**

$\Gamma(h \to \ell\ell'_R) \propto \Big|$



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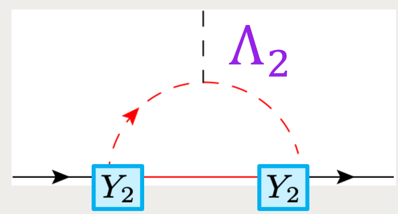


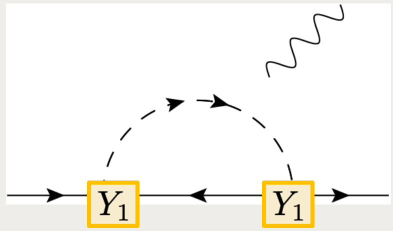
$\Big|^2$ **Constructive**

Assumption

$$\chi \simeq 0 \quad (\omega_1^+ \simeq \eta^+,\ \omega_2^+ \simeq s_2^+) \ \& \ Y_\eta \ll 1 \ \& \ \mathrm{sign}(\Lambda_1) = -\mathrm{sign}(\Lambda_2)$$

Cancelation in $\tau \to 3\mu$

$\Gamma(\tau \to \mu\gamma) \propto \Bigg|$



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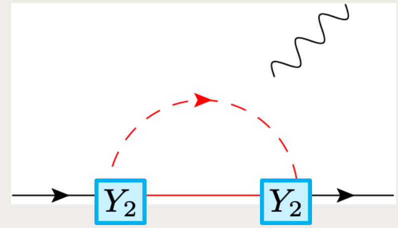


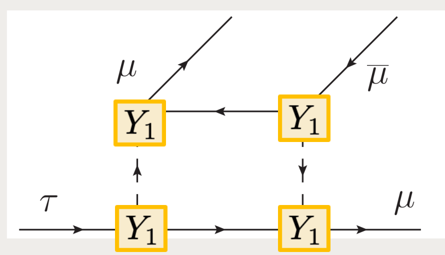
$\Bigg|^2$

For destructive interference,

$$(Y_1 Y_1^\dagger)_{\tau\mu} \times \mathrm{LF} + (Y_2 Y_2^\dagger)_{\tau\mu} \times \mathrm{LF} \simeq 0$$

LF : Loop Function

$\Gamma(\tau \to 3\mu) \propto \Bigg|$



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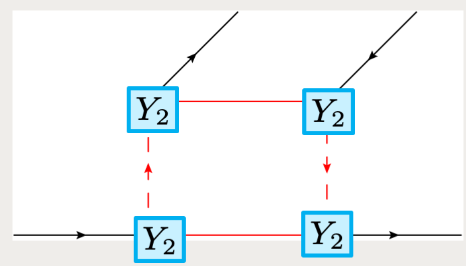
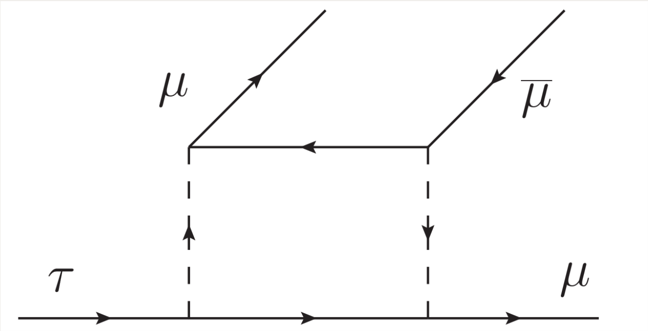


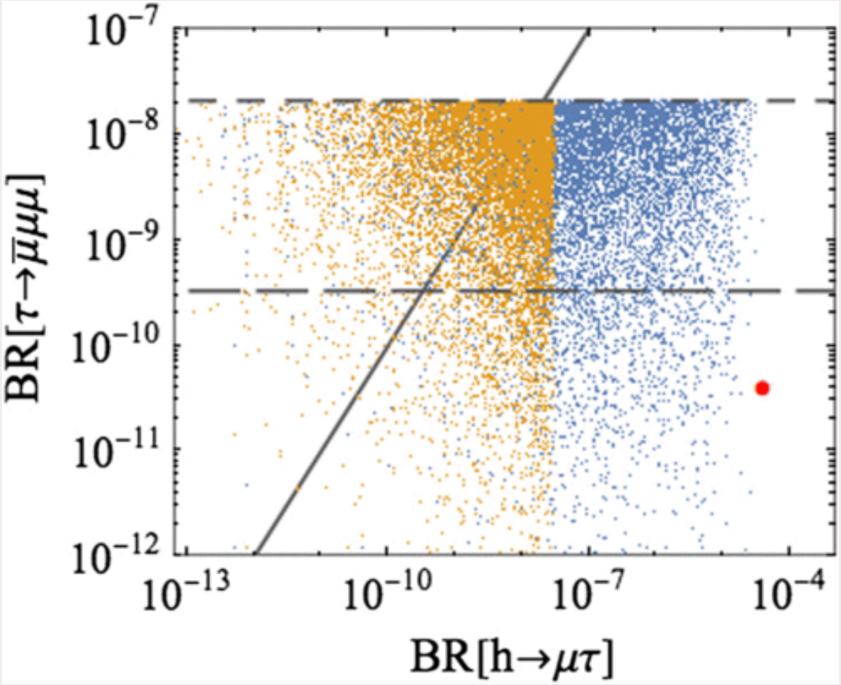
$\Bigg|^2$

For destructive interference,

$$(Y_1 Y_1^\dagger)_{\mu\mu}(Y_1 Y_1^\dagger)_{\tau\mu} \times \mathrm{LF}' + (Y_2 Y_2^\dagger)_{\mu\mu}(Y_2 Y_2^\dagger)_{\tau\mu} \times \mathrm{LF}' \simeq 0$$

$\tau \to \bar{\mu}\mu\mu$ vs $h \to \mu\tau$





$\mathrm{Br}(\tau \to \mu\gamma) = \mathrm{Br}(h \to \mu\tau)$

Upper limit 4.4×10^{-8}

Expected limit 1.0×10^{-9}

Belle II @ 50 ab^{-1}

Orange Points $\lambda_{hs_1} = \lambda_{hs_2} = 2.0$

Blue Points $\lambda_{hs_1} = -\lambda_{hs_2} = 2.0$

Red point Benchmark scenario

LFV decays in the simple model

$$\mathrm{BR}(\ell \to \ell'_X \gamma) \simeq \begin{cases} \dfrac{\alpha \pi^4}{3(16\pi^2)^2 G_F^2} \dfrac{(2-3Q_\varphi)^2 \left|S^2(Y^\dagger Y)_{\ell\ell'}\right|^2}{m_\varphi^4} \mathrm{BR}(\ell \to e\nu_\ell \overline{\nu_e}) & (m_f \ll m_\varphi) \\ \dfrac{\alpha \pi^4}{3(16\pi^2)^2 G_F^2} \dfrac{(1-3Q_\varphi)^2 \left|S^2(Y^\dagger Y)_{\ell\ell'}\right|^2}{m_f^4} \mathrm{BR}(\ell \to e\nu_\ell \overline{\nu_e}) & (m_f \gg m_\varphi) \end{cases},$$

$$\mathrm{BR}(h \to \ell\ell') \simeq \begin{cases} \dfrac{v^2 m_h}{128\pi(16\pi^2)^2 \Gamma_{\mathrm{tot}}} \dfrac{\lambda^2 m_\ell^2 \left|S^2(Y^\dagger Y)_{\ell\ell'}\right|^2}{m_\varphi^4} & (m_f \ll m_\varphi) \\ \dfrac{v^2 m_h}{128\pi(16\pi^2)^2 \Gamma_{\mathrm{tot}}} \dfrac{\lambda^2 m_\ell^2 \left|S^2(Y^\dagger Y)_{\ell\ell'}\right|^2}{m_f^4} \left(3 - \ln \dfrac{m_\psi^2}{m_\varphi^2}\right)^2 & (m_f \gg m_\varphi) \end{cases}$$

$$\mathrm{BR}(h \to \ell\ell') \simeq \frac{\mathrm{BR}(\ell \to \ell'\gamma)}{\mathrm{BR}(\ell \to \ell'\nu_\ell \overline{\nu_{\ell'}})} \times 10^{-2}$$

$$\Rightarrow \quad \begin{aligned} \mathrm{BR}(\mu \to e\gamma) &\simeq \mathrm{BR}(\mu \to e\nu_\mu \overline{\nu_e}) \times 10^{-2} \\ \mathrm{BR}(\tau \to \ell\gamma) &\simeq \mathrm{BR}(\tau \to \ell\nu_\mu \overline{\nu_\ell}) \times 10^{-1} \end{aligned}$$

LFV processes in benchmark scenario

Processes	Numerical results
$\mu \to e\gamma$	2.36×10^{-15}
$\tau \to e\gamma$	8.26×10^{-14}
$\tau \to \mu\gamma$	4.68×10^{-10}

Processes	Numerical results
$h \to \mu e$	1.43×10^{-16}
$h \to \tau e$	1.56×10^{-15}
$h \to \mu\tau$	4.05×10^{-5}

Processes	Numerical results
$\mu \to \bar{e}ee$	1.26×10^{-18}
$\tau \to \bar{e}ee$	4.28×10^{-18}
$\tau \to \overline{\mu}e\mu$	1.97×10^{-11}

Processes	Numerical results
$\mu \to \bar{e}\mu\mu$	1.26×10^{-18}
$\tau \to \bar{e}e\mu$	4.28×10^{-18}
$\tau \to \overline{\mu}ee$	1.97×10^{-11}
$\tau \to \overline{\mu}\mu\mu$	3.98×10^{-11}