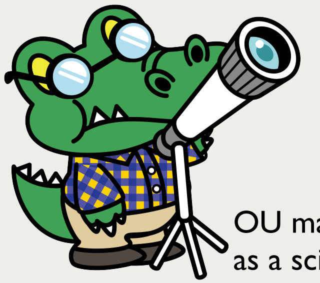
Higgs LFV decays in the model for Dirac neutrino masses and dark matter

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



Kazuki Enomoto (Osaka Univ.)

OU mascot Dr.Wani
as a science member

Collaborators

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Sep. 13th, 2019 Scalars 2019 @ Univ. of Warsaw

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 can be 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 cannot be 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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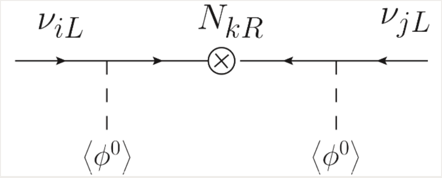
1. Models for neutrino masse and classification of them

What is the origin of tiny neutrino masses ?

Seesaw mechanisms

3 types, Majorana ν masses at tree level

Type-I seesaw

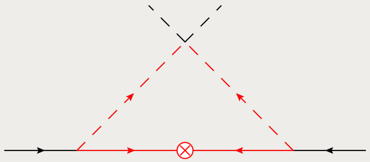


Radiatively generated masses

Majorana or Dirac ν masses at loop level,

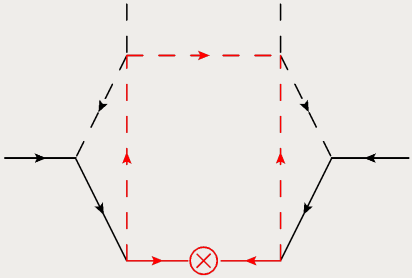
A candidate of dark matter (Additional Z_2 symmetry)

Ma ('03)



Various models

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



Aoki,Kanemura, Seto ('09)

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)

<u>Assumptions</u>

・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

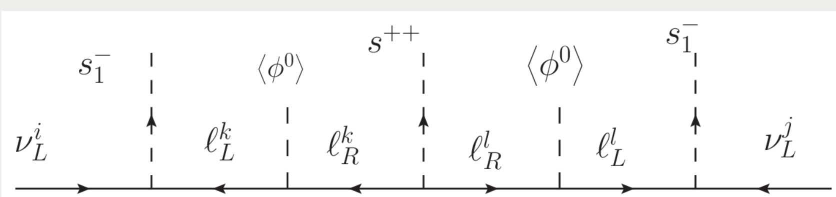
Bilinears	New Scalars: Fields	SU(2)$_\mathrm{L}$	U(1)$_\mathrm{Y}$	Yukawa Interaction
$\overline{L_L^i}\ell_R^j$	ϕ_2	**2**	$+\frac{1}{2}$	$y_i \overline{L_L^i}\phi_2\, \ell_R^j$
$\overline{(\ell_R^i)^c}\ell_R^j$	s^{++}	**1**	$+2$	$(Y_s^S)_{ij}\,\overline{(\ell_R^i)^c}\ell_R^j s^{++}$
$\overline{(L_L^i)^c}L_L^j$	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)$_\mathrm{L}$	**3**	**2**	**1**	**1**	**2**	**1**
U(1)$_\mathrm{Y}$	$+1$	$+1/2$	$+2$	$+1$	$+1/2$	$+1$
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⟩

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

Additional assumptions

- 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
$\mathrm{SU(2)_L}$	**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	✓								✓	✓
D10					✓			✓		
D11		✓			✓				✓	
D12					✓				✓	
D13		✓			✓					✓
D14					✓					✓
D15		✓							✓	✓
D16									✓	✓
D17					✓			✓	✓	
D18								✓		✓

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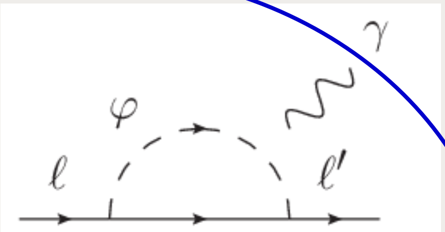
2. Higgs LFV decay in models for neutrino masses

Classification of models by new Yukawa interactions

LFV processes

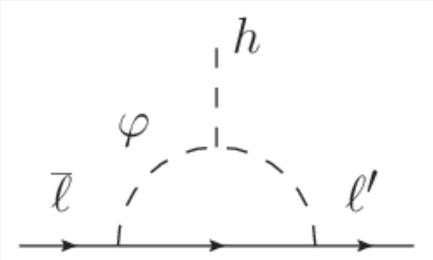
Strongly constrained !

$\ell \to \ell' \gamma$



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}

$h \to \ell\ell'$

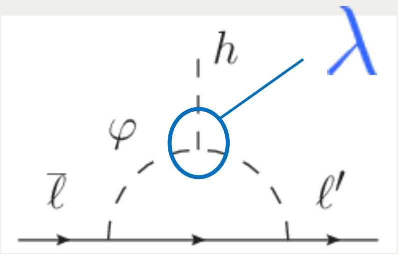


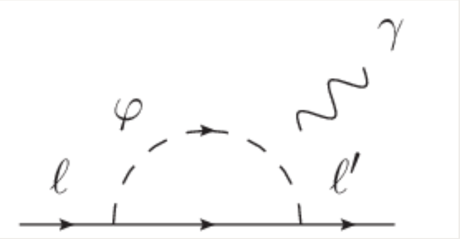
Process	Upper limit
$h \to \mu e$	3.5×10^{-4}
$h \to \tau e$	6.1×10^{-3}
$h \to \mu\tau$	2.5×10^{-3}

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.





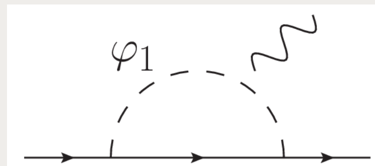
$$(\lambda = O(1))$$

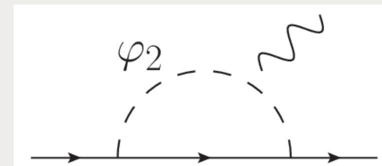
$$\mathrm{Br}(h \to \ell\ell') \sim 10^{-1}\mathrm{Br}(\ell \to \ell'\gamma)$$
$$\lesssim 10^{-9} - 10^{-14}$$

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

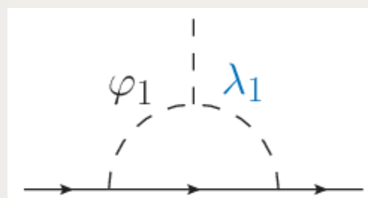
2. Higgs LFV decay in models for neutrino masses

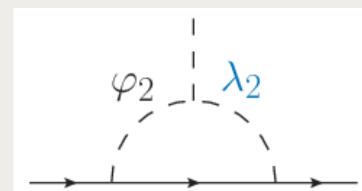
We need that **two or more kind of scalars** interact with left-handed (right-handed) leptons to realize $\mathrm{Br}(h \to \ell\ell') > \mathrm{Br}(\ell \to \ell'\gamma)$

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

$+$ 

$\Bigg|^2$

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

$+$ 

$\Bigg|^2$

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]	**2**	**1**	**1**	**2**	**1**
[illegible]	[illegible]	[illegible]/2	$+2$	$+1$	$+1/2$	$+1$
[illegible]	[illegible]n				Odd	
M1	[illegible]	[illegible]	[illegible]	✓		
M2	[illegible]	[illegible]	[illegible]	[illegible]		
M3		[illegible]	[illegible]	[illegible]	[illegible]	
M4	✓	[illegible]	[illegible]	[illegible]	[illegible]	
M5			[illegible]	[illegible]	[illegible]	✓
M6		✓		[illegible]	[illegible]	[illegible]
M7				[illegible]	[illegible]	[illegible]
M8					[illegible]	[illegible]

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				$\checkmark$		
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 models in D3, 4, 11, 12 groups,

$$(m_\nu)_{\ell i} = m_\ell \left(Y \cdots \right)_{\ell i}$$

$$m_e \ll m_\mu < m_\tau$$

$$\Rightarrow \quad Y_{ea} \gg Y_{\mu a} > Y_{\tau a}$$

$$(\, a = 1, 2, 3 \,)$$

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

	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								✓		✓

2. Higgs LFV decay in models for neutrino masses

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

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	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		✓			✓				✓	

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

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3. Our model

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

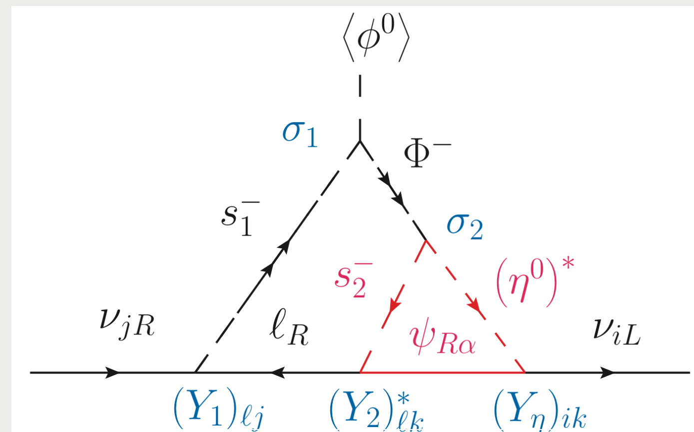
A new model for Dirac neutrino masses which have D17 group's flavor structure.

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



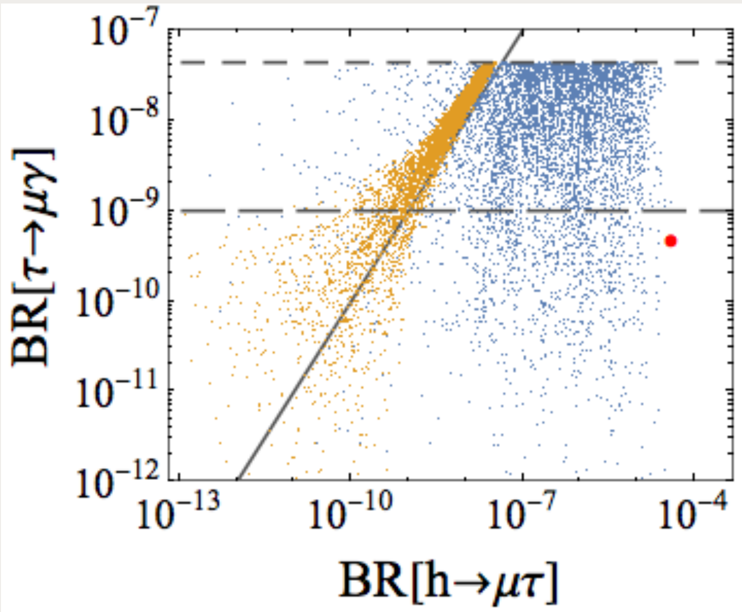
$$\mathcal{L} = (Y_1)_{\ell i} \overline{(\ell_R)^c} \nu_{Ri}\, s_1^+ + (Y_2)_{\ell\alpha} \overline{(\ell_R)^c} \psi_{R\alpha}\, s_2^+ + (Y_\eta)_{\ell\alpha} \overline{L_\ell}\, \eta^c \psi_{R\alpha} + \text{h.c.}$$

$$V \ni \sigma_1 \Phi^\dagger \phi\, s_1^+ + \sigma_2 \Phi^\dagger \eta\, s_2^+ + \text{h.c.}$$

3. Our model

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

LFV Processes $(Y_1)_{\ell i}\overline{(\ell_R)^c}\nu_{Ri}\, s_1^+ + (Y_2)_{\ell\alpha}\overline{(\ell_R)^c}\psi_{R\alpha} s_2^+$



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

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

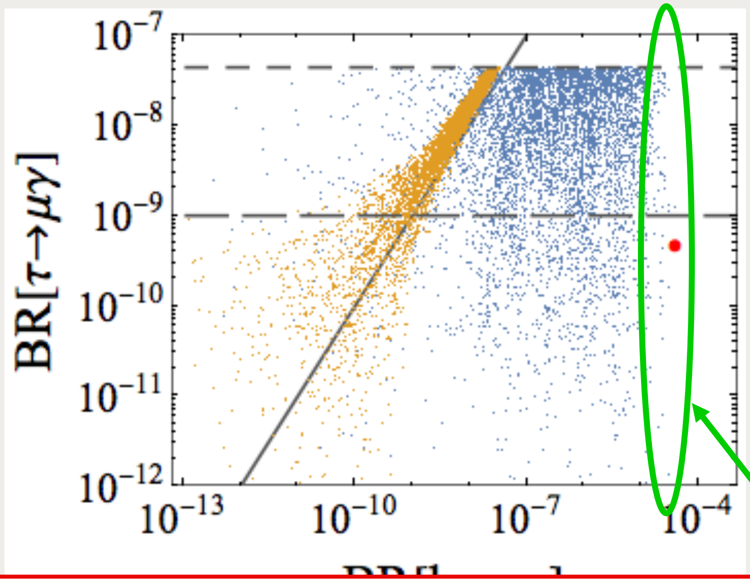
Red point Benchmark scenario

$$Y_a = \begin{pmatrix} 10^{-4} & 10^{-4} & 0.10 \\ x_a & y_a & 10^{-4} \\ z_a & w_a & 10^{-4} \end{pmatrix} \quad -3.0 \leq x_a, y_a, z_a \leq 3.0$$

3. Our model

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

LFV Processes $(Y_1)_{\ell i}\overline{(\ell_R)^c}\nu_{Ri}\, s_1^+ + (Y_2)_{\ell\alpha}\overline{(\ell_R)^c}\psi_{R\alpha} s_2^+$



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

Upper limit 4.4×10^{-8}

Expected limit 1.0×10^{-9}

Belle II @ 50 ab^{-1}

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

ILC250

Expected limit $\mathrm{BR}\,(h\to\mu\tau) = 4.0\times10^{-5}$ $(\mathcal{L} = 1350\ \mathrm{fb}^{-1})$

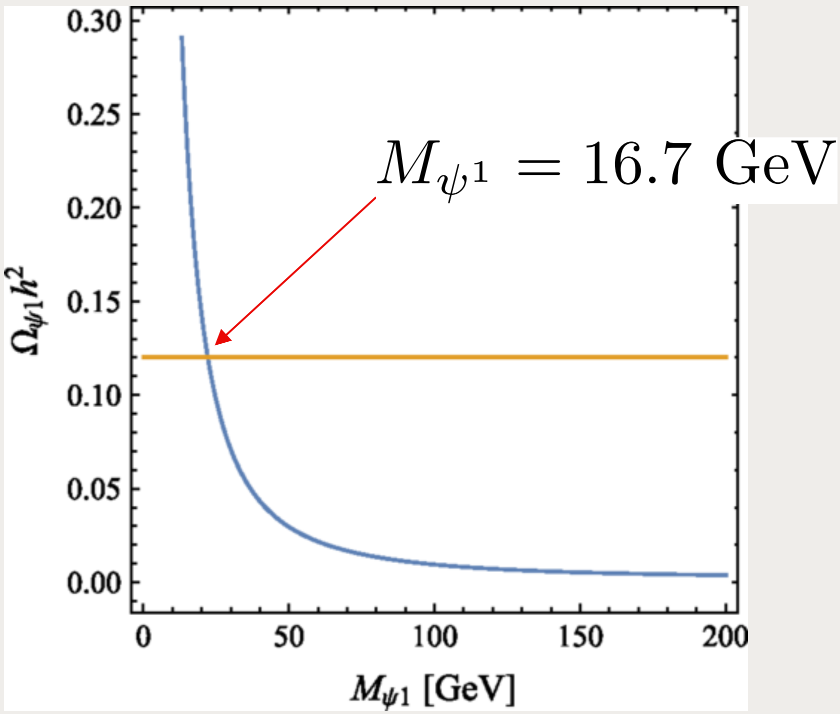
I. Chakraborty, A. Datta, A. Kundu, J.Phys (2016)

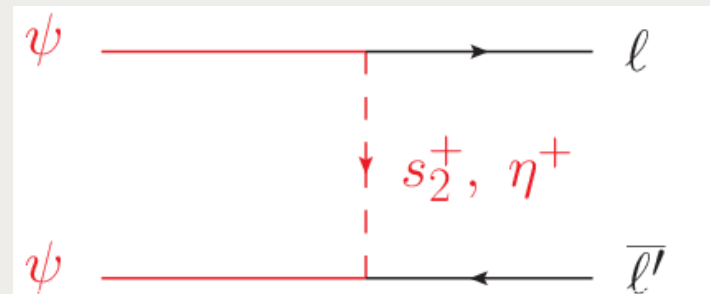
3. Our model

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

Dark matter candidates : η^0, ψ^a $(a = 1,2,3)$

In the benchmark scenario, dark matter particle is the lightest Majorana fermion ψ^1





Relic abundance of ψ^1

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

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4. Summary

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

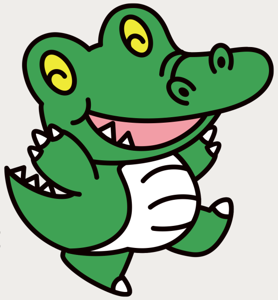
・Our model has a characteristic flavor structure,

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 collider experiment (HL-LHC or ILC).

OU mascot
Dr. Wani



Thank you for listening

Sep. 13th, 2019 Scalars 2019 @ Univ. of Warsaw

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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

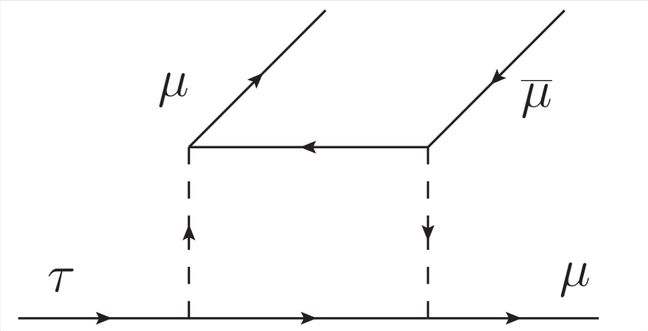
	Scalars			
	Φ	s_R^+	η	s_2^+
$\mathrm{SU(2)_L}$	**2**	**1**	**2**	**1**
$\mathrm{U(1)_Y}$	$+3/2$	$+1$	$+1/2$	$+1$
Z_2	Even	Even	Odd	Odd
Lepton #	-2	-2	-1	-1
Z_2'		$-$	$+$	$+$

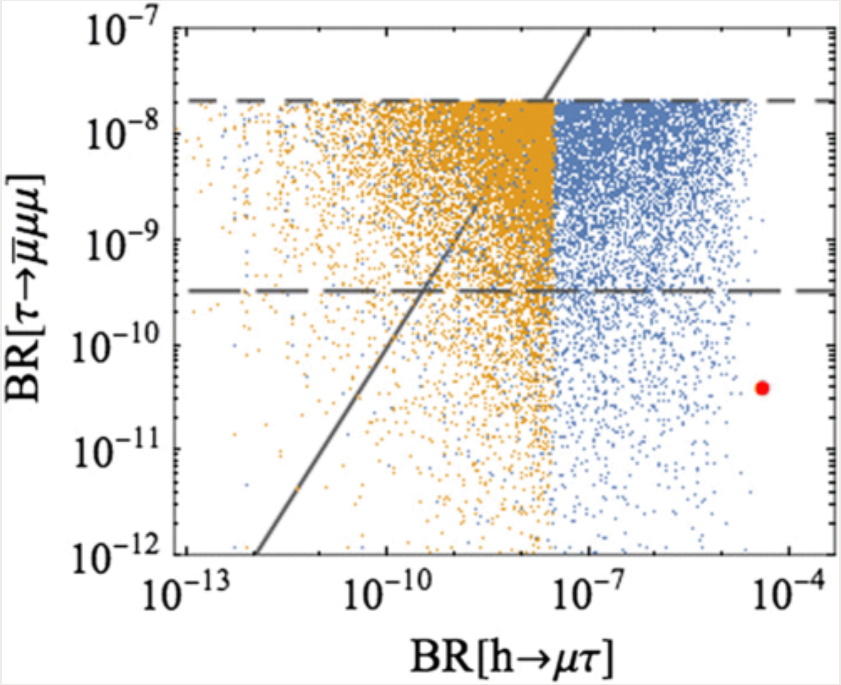
Physical CP-violating parameters

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

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

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





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- - - - - - Upper limit 4.4×10^{-8}

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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 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}