New Model for Radiative Neutrino Masses and Higgs LFV Decays

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Osaka Univ.
Dr. Wani

SK, Sugiyama (1015)
SK, Sakurai, Sugiyama (2016)
Aoki, SK, Sakurai, Sugiyama (2017)
Enomoto, SK, Sakurai, Sugiyama (2019)

First Mediterranean Conference on Higgs Physics
at Conseil regional Tanger-Tétouan-AlHoceima, 23-27 September 2019

Evidences of beyond-SM

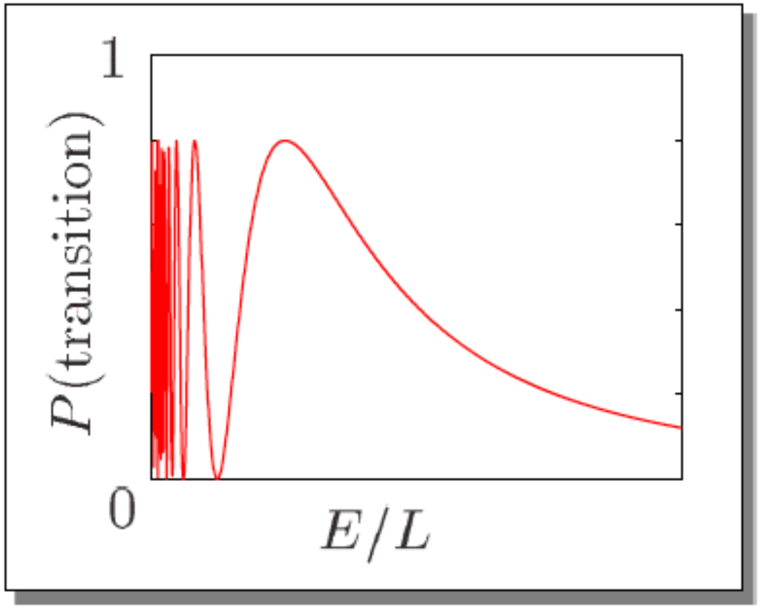
- Dark Matter
- Baryon Asymmetry of Universe
- Neutrino Oscillation
- Cosmic Inflation
- …

Neutrino Oscillation

$$\Delta m^2 \equiv m_2^2 - m_1^2$$

Transition prob.

$$P(\nu_\ell \to \nu_{\ell'}) \simeq \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



Nonzero neutrino masses
cf. Massless in the SM

Lepton flavor violation (LFV)
cf. Conserved in the SM

Two evidences for physics beyond the SM

Tiny Neutrino Masses

If the same mechanism as for quarks or charged leptons,

$$y_\nu \overline{L}\,\epsilon\,\Phi^* \nu_R \longrightarrow m_\nu = \frac{y_\nu}{\sqrt{2}} v$$

$$m_\nu \sim 0.1\,\mathrm{eV} \Longrightarrow y_\nu \sim 10^{-12}$$

Unnaturally small !

Tiny neutrino mass would be generated in a non-trivial way

e.g., $$\left(\frac{1}{16\pi^2}\right)^n \frac{1}{\Lambda} \overline{L}\,\epsilon\Phi^*\Phi^\dagger\epsilon L^c$$

Lepton number violation

Scale-**suppression**

Loop-**suppression**

LFV in Oscillation = Large Mixing

Flavor　　　　　　Mass

$$\nu_\ell = \sum_i (U_{\mathrm{MNS}})_{\ell i}\, \nu_i$$

Mixing : $U_{\mathrm{MNS}} \sim \begin{pmatrix} 0.83 & 0.54 & 0.15 \\ -0.47 & 0.53 & 0.71 \\ 0.31 & -0.66 & 0.69 \end{pmatrix}$ ← **Large** mixings

cf. Quark mixing

$V_{\mathrm{CKM}} \sim \begin{pmatrix} 0.97 & 0.23 & 0 \\ -0.23 & 0.97 & 0 \\ 0 & 0 & 1.0 \end{pmatrix}$ ← Small mixings

Significant sources for LFV associated with neutrinos

This talk

- Classification of neutrino mass models from the view point of LFV sources (new Yukawas)
- If Higgs LFV decays will be discovered in the future, a wide class of simple models for neutrino masses will be excluded
- We discuss a new model which can survive even if Higgs LFV decays are discovered

Classification of neutrino mass models

Models of neutrino mass

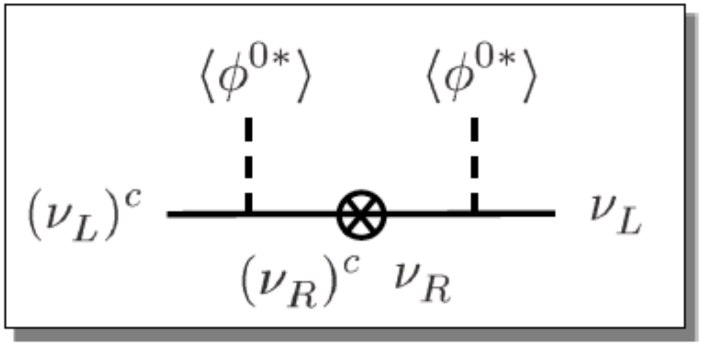
Seesaw Mechanism

$$\mathcal{L} = y_\nu \overline{L} \epsilon \Phi^* \nu_R + \frac{1}{2} M_R \overline{(\nu_R)^c} \nu_R + \cdots$$

(lepton # violation)

$$\Downarrow$$

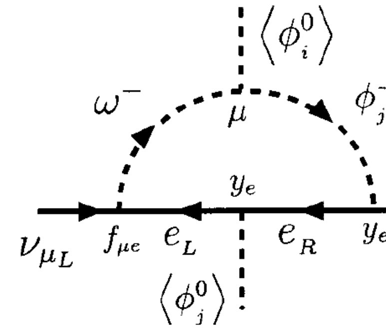
$$\frac{1}{2} m_M \overline{(\nu_L)^c} \nu_L \quad m_M \simeq \frac{y_\nu^2 \langle \phi^{0*} \rangle^2}{M_R}$$



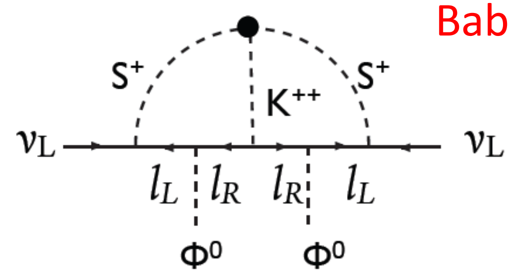
Loop induced masses

Tiny ν-Masses may come from loop effects

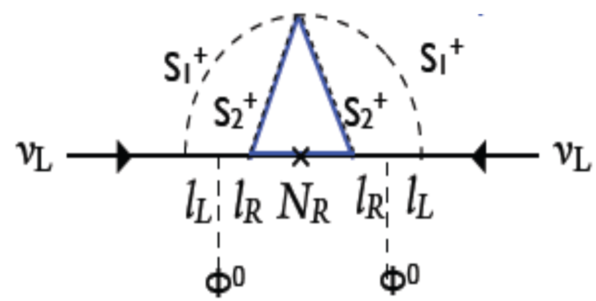
- Zee (1980, 1985)
- Zee, Babu (1988)
- Krauss-Nasri-Trodden (2002)
- Ma (2006),
- .....



Zee

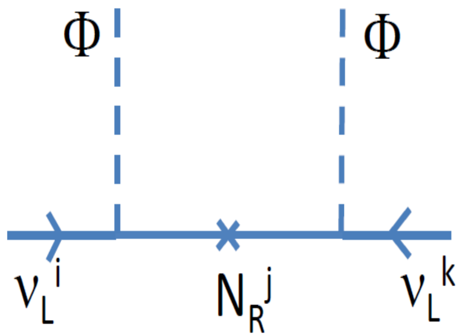


Babu



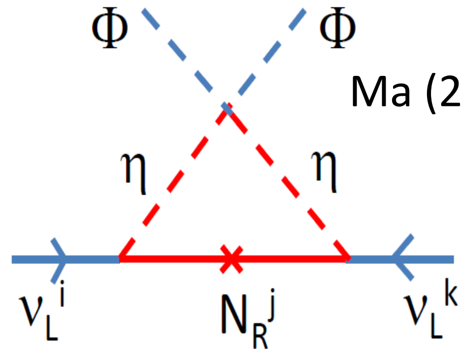
Krauss, Nasri, Trodden

Yanagida; Gell-Mann; Minkowski



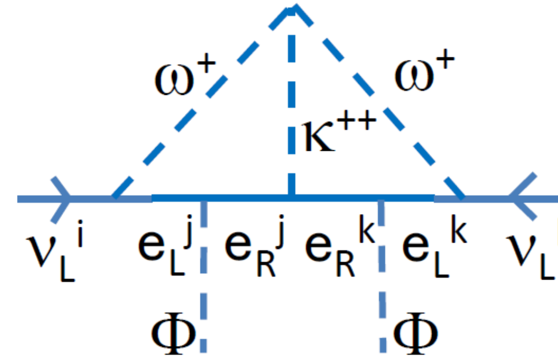
$(m, n)=(0, 0)$

Ma (2006)



(1, 0)

Zee; Babu

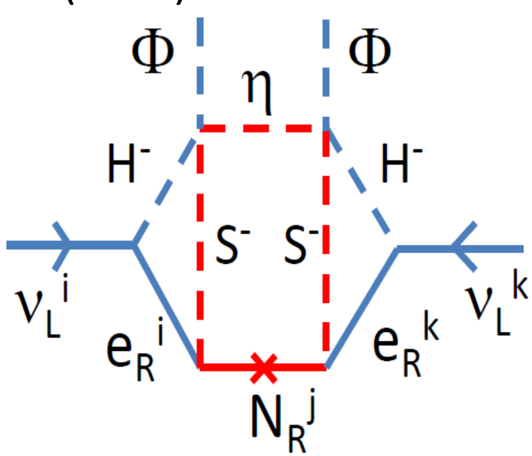


(2, 0)

$$m_\nu \sim c' \left(\frac{1}{16\pi^2}\right)^m \left(\frac{v}{\Lambda}\right)^{2n+1} v$$

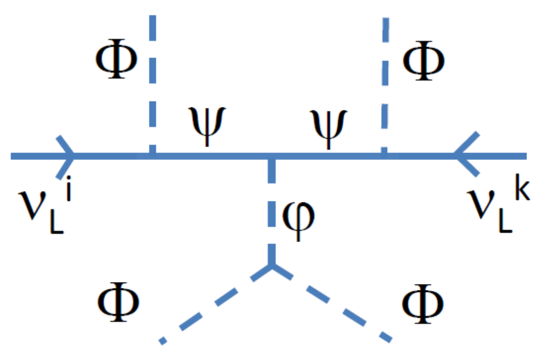
Dim 5+*n* Operator
m-loop induced

Aoki, SK, Seto (2008)



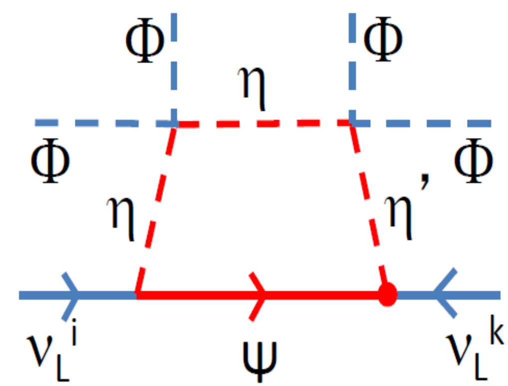
(3, 0)

Bonnet, et al. (2009)



(0, 1)

SK, Ota (2010)

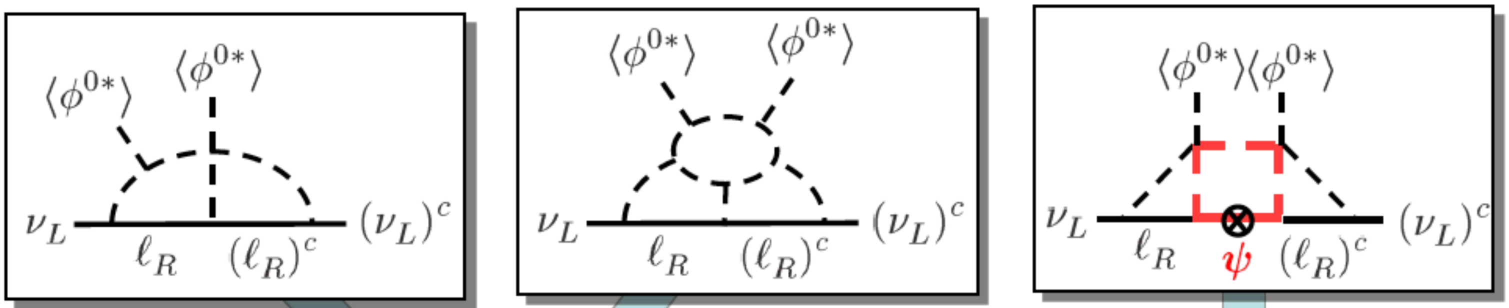


(1, 1)

Z_2-odd fields are in red letters

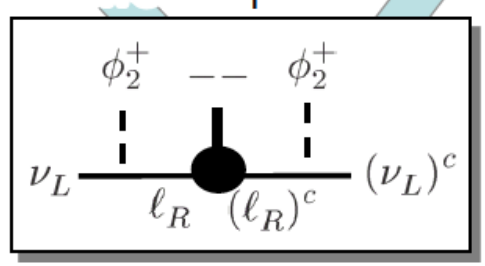
Classification of Models

- Models (full Lagrangian)



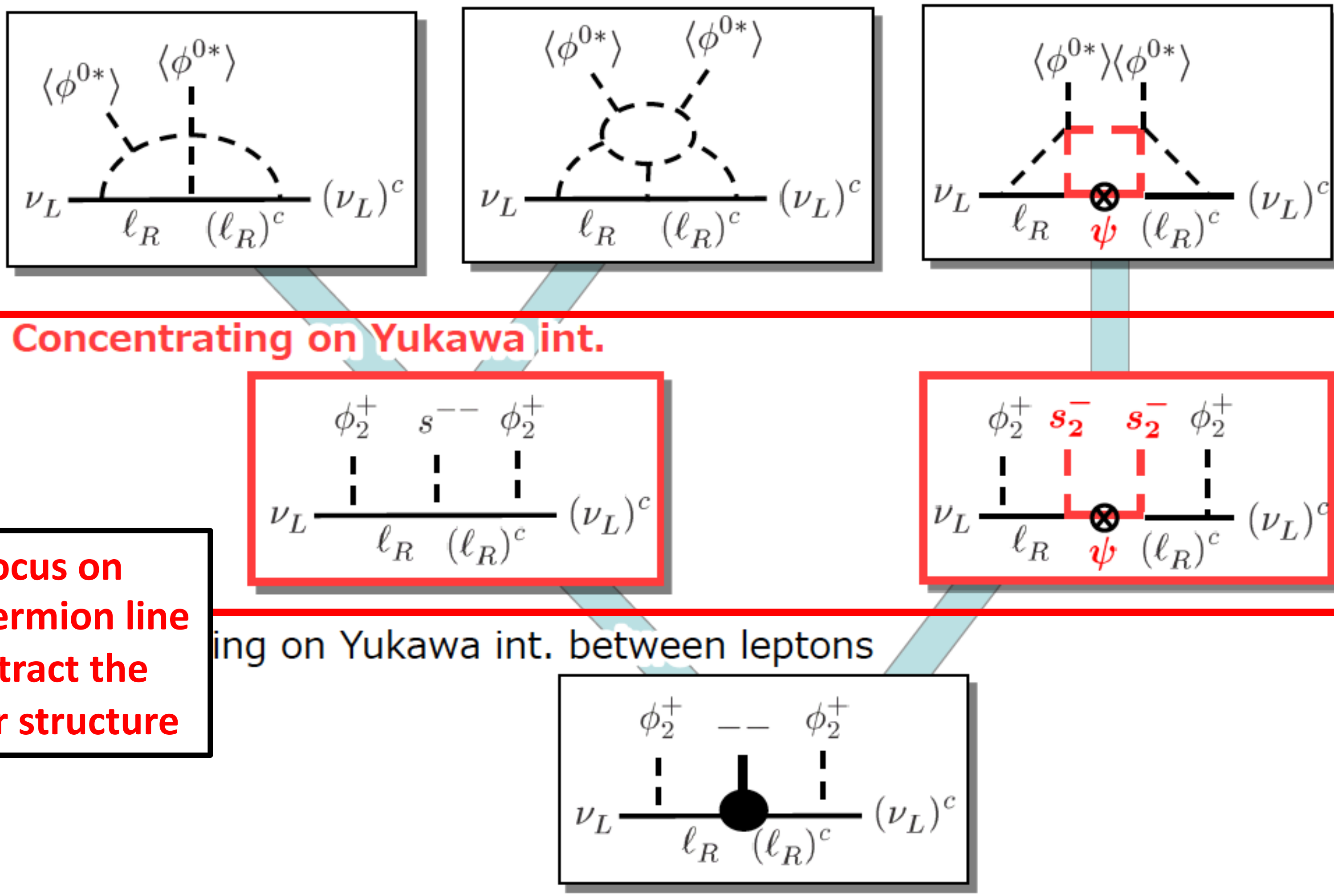
- **Concentrating on Yukawa int.**

- Concentrating on Yukawa int. between leptons



Classification of Models

- Models (full Lagrangian)



- Concentrating on Yukawa int.

...ing on Yukawa int. between leptons

We focus on the fermion line
To extract the flavor structure

Neutrino mass and leptonic Yukawa couplings

Extension of the Higgs sector (scalar sector)

Many models —Classification→ Efficient study

- Setup for our analyses

New scalars with leptonic Yukawa int.

[New scalar] - [Lepton] - [Lepton]

Assumption : **No FCNC at the tree level**

Z_2 -odd singlet fermion ψ_R^0

Z_2 -odd scalars with leptonic Yukawa int.

(unbroken)

} → Dark matter

[Z_2-odd scalar] - [Lepton] - ψ_R^0

ν_R for Dirac neutrinos

(lepton number conservation)

Models for Majorana masses

All new Yukawa interactions and new scalars

Z_2-odd fields are in red letters

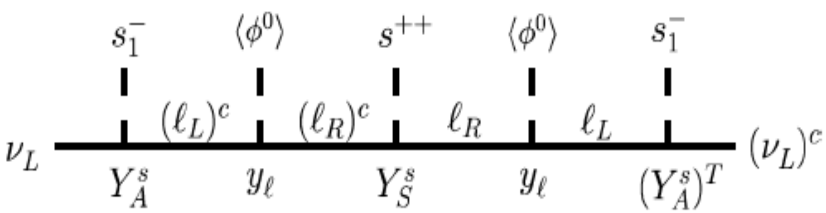
Bilinears	New Scalars: Fields	New Scalars: $\mathrm{SU(2)_L}$	New Scalars: $\mathrm{U(1)_Y}$	Yukawa Interaction
$\overline{L_L^i}\ell_R^j$	ϕ_2	$\mathbf{2}$	$+\frac{1}{2}$	$y_i \overline{L_L^i}\phi_2\,\ell_R^j$
$\overline{(\ell_R^i)^c}\ell_R^j$	s^{++}	$\mathbf{1}$	$+2$	$(Y_s^S)_{ij}\,\overline{(\ell_R^i)^c}\ell_R^j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

Select scalars for ν mass diagram

Models for Majorana ν masses

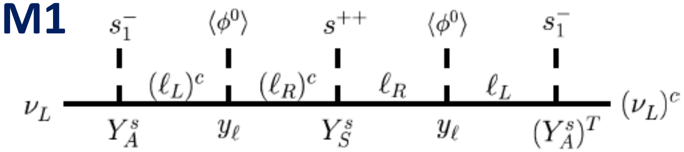
	Δ	ϕ_2	s^{++}	s_L^+	η	s_2^+
$\mathrm{SU(2)_L}$	$\mathbf{3}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$
$\mathrm{U(1)_Y}$	$+1$	$+1/2$	$+2$	$+1$	$+1/2$	$+1$
Z_2	Even				Odd	
M1			✓	✓		
M2		✓	✓			
M3			✓			
M4	✓					
M5				✓		✓
M6		✓				✓
M7						✓
M8					✓	

e.g.) fermion line in M1



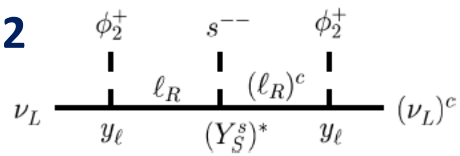
Models of Radiative Neutrino Mass (Majorana Type)

M1



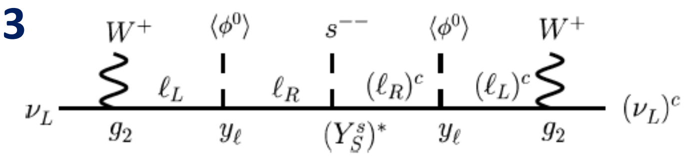
Zee, Babu

M2



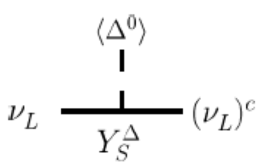
Cheng, Li

M3



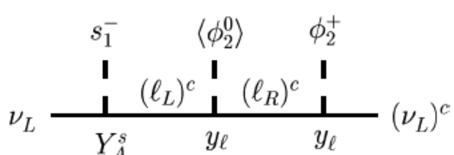
Gustaffson, No, Rivera

M4



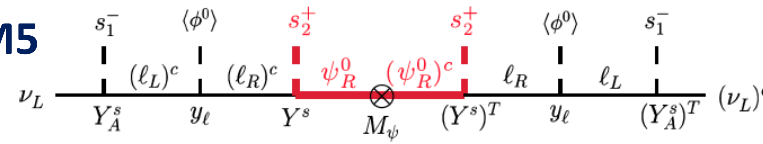
Konetschny, Kummer
Mohapatra, Senjanovic

M9



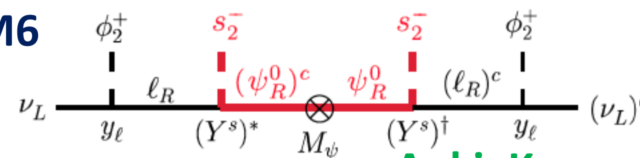
Zee, Wolfenstein

M5



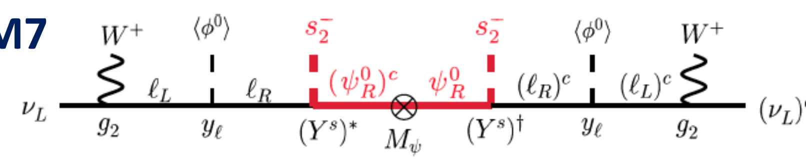
Kraus, Nasri, Troddenn

M6



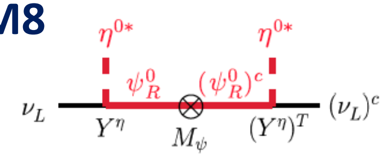
Aoki, Kanemura, Seto

M7



No et al. (dim9)

M8



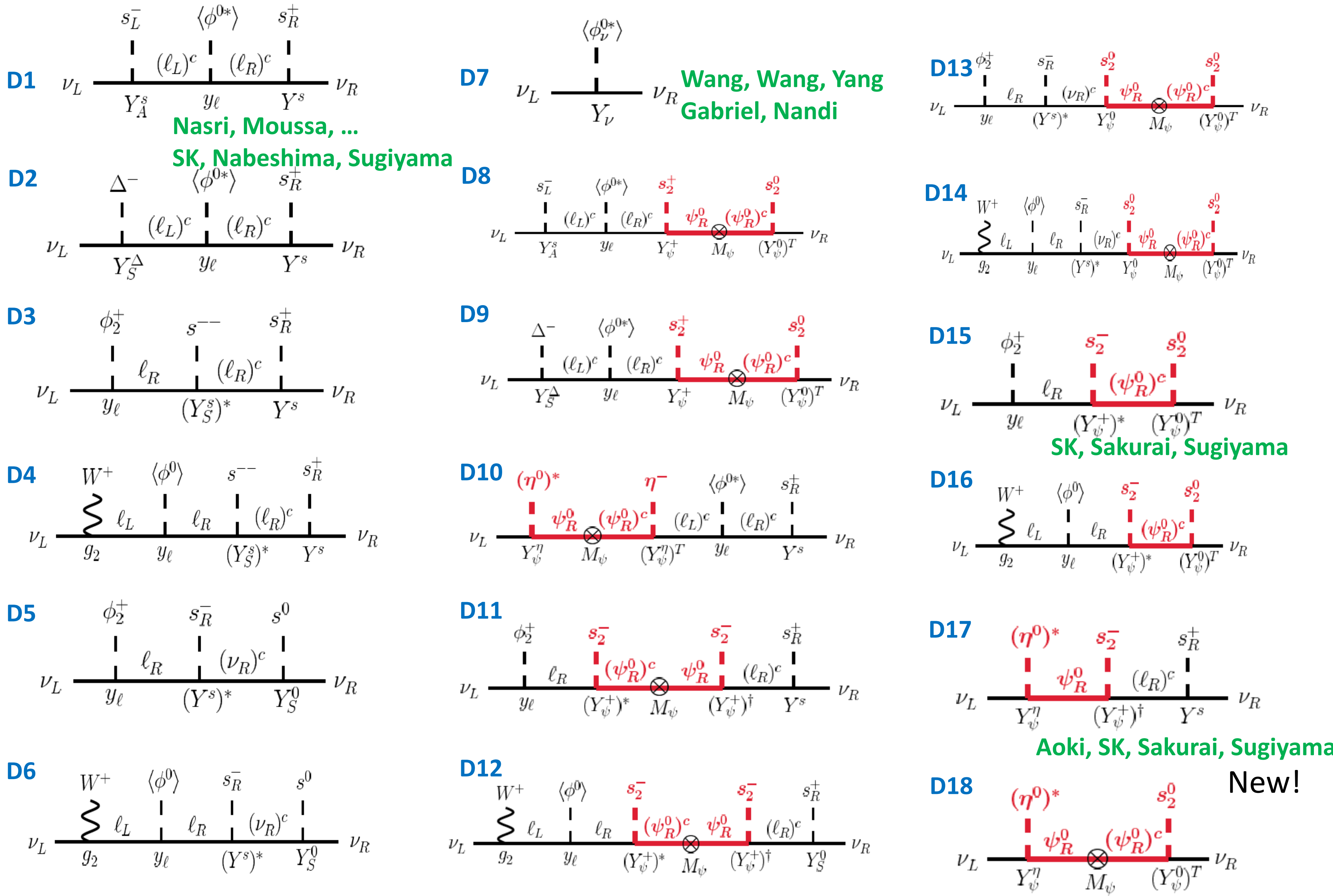
Ma

Models for Majorana masses

	Scalar with leptonic Yukawa int.					
					Z_2-odd	
	s_L^+	s^{++}	Φ_2	Δ	s_2^+	η
$SU(2)_L$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$
$U(1)_Y$	1	2	1/2	1	1	1/2
Unbroken Z_2	+	+	+	+	−	−
M1	✓	✓				
M2		✓	✓			
M3		✓				
M4				✓		
M5	✓				✓	
M6			✓		✓	
M7					✓	
M8						✓

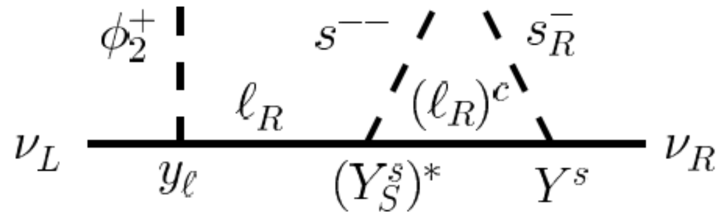
S. K. and H. Sugiyama, 2016

Models of Radiative Neutrino Mass (Dirac Type)



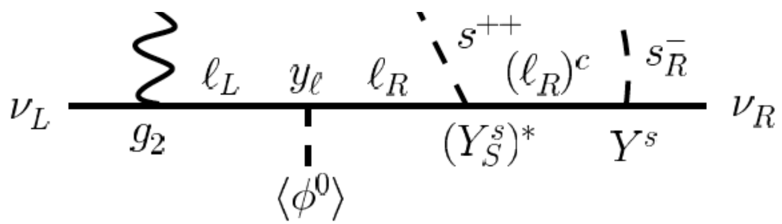
Example to close scalar lines of D3

D3



Example to close scalar lines of D4

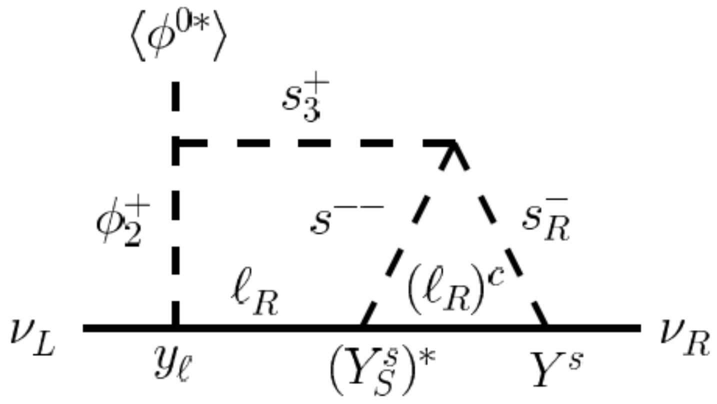
D4



Example to close scalar lines of D3

Dim 4 (2 loop)

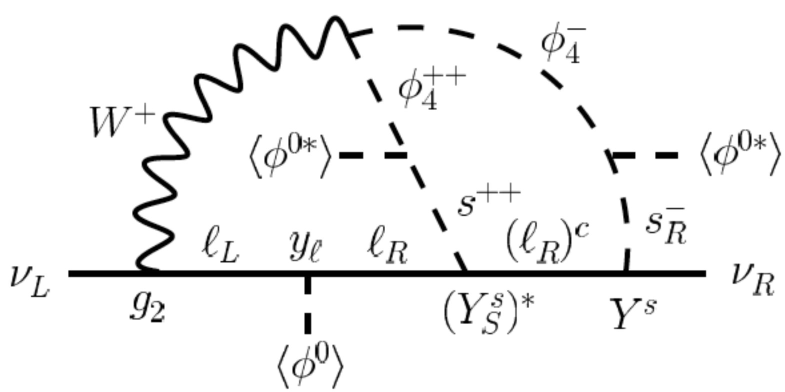
D3



Example to close scalar lines of D4

Dim 6 (2 loop)

D4



Models for Dirac masses

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

<u>Additional assumptions</u>

- 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								✓		✓

S.K., H. Sugiyama and K. Sakurai 2016

Lepton Flavor Violation

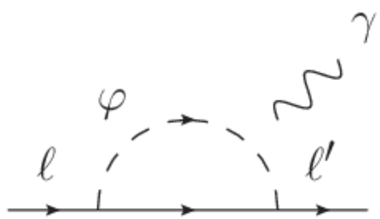
Neutrino oscillation + Models for neutrino masses

⇩

LFV processes

Lepton LFV decays

$\ell \to \ell' \gamma$



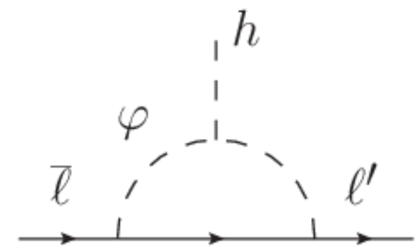
Current constraint

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}

Higgs LHV decays

New observable

$h \to \ell\ell'$



Current constraint

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}

Neutrino oscillation + Models for neutrino masses

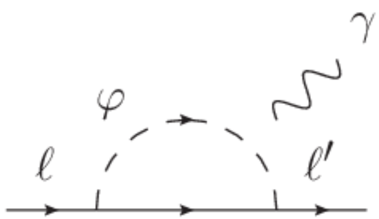
⇩

LFV processes

Lepton LFV decays

$$\ell \to \ell' \gamma$$

Strongly constrained !



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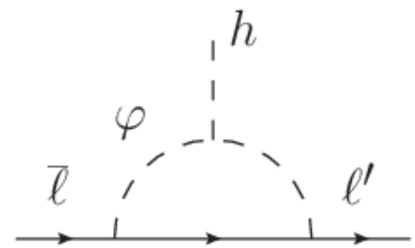
Higgs LHV decays

$$h \to \ell\ell'$$

New observable



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$h \to \mu\tau$	2.5×10^{-3}

Future ILC250 **3.3×10^{-5} (2 ab^{-1})**

LFV decays of the Higgs boson

$$\mathrm{BR}(h \to \ell\ell') \equiv \mathrm{BR}(h \to \bar{\ell}\ell') + \mathrm{BR}(h \to \ell\bar{\ell'})$$

In 2015, there was anomaly for h → μτ

		ATLAS $8\,\mathrm{TeV}, 20.3\,\mathrm{fb}^{-1}$ arXiv:1604.07730	CMS $8\,\mathrm{TeV}, 19.7\,\mathrm{fb}^{-1}$ arXiv:1607.03561; PLB**749**, 337 (2015)
$h \to e\mu$	Limit		$< 3.5 \times 10^{-4}$
	Best fit		
$h \to e\tau$	Limit	$< 1.04 \times 10^{-2}$	$< 6.9 \times 10^{-3}$
	Best fit	$-3.4^{+6.4}_{-6.6} \times 10^{-3}$	
$h \to \mu\tau$	Limit	$< 1.43 \times 10^{-2}$	$< 1.51 \times 10^{-2}$
	Best fit	$5.3^{+5.1}_{-5.1} \times 10^{-3}$	$8.4^{+3.9}_{-3.7} \times 10^{-3}$

2.4σ excess

LFV decays of the Higgs boson

$$\mathrm{BR}(h \to \ell\ell') \equiv \mathrm{BR}(h \to \bar{\ell}\ell') + \mathrm{BR}(h \to \ell\bar{\ell'})$$

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$2.4\,\sigma$ excess

It's already gone!
(No excess now)

Although the previous anomaly has been gone, there can be discovery of $h \to \ell\ell'$ in the future

Esp at ILC

What is the impact on the models for neutrino masses?

Higgs LFV decays occur at loop

Dimension-4 operator

$$\mathcal{L} = \boldsymbol{Y_4}\left[\overline{L}\,\Phi\ell'_R\right]$$

Mass : $\frac{v}{\sqrt{2}}\boldsymbol{Y_4}\left[\overline{\ell_L}\ell'_R\right] \xrightarrow{\text{Diagonalize}} m_\ell\left[\overline{\ell_L}\ell_R\right]$

Int. : $\frac{1}{\sqrt{2}}\boldsymbol{Y_4}\left[\overline{\ell_L}\ell'_R\,h\right] \dashrightarrow \frac{m_\ell}{v}\left[\overline{\ell_L}\ell_R h\right]$ **no LFV**

Higgs LFV decays occur at loop

Dimension-4 operator

$$\mathcal{L} = \mathbf{Y_4}\left[\overline{L}\,\Phi\ell'_R\right]$$

Mass : $\frac{v}{\sqrt{2}}\mathbf{Y_4}\left[\overline{\ell_L}\ell'_R\right] \xrightarrow{\text{Diagonalize}} m_\ell\left[\overline{\ell_L}\ell_R\right]$

Int. : $\frac{1}{\sqrt{2}}\mathbf{Y_4}\left[\overline{\ell_L}\ell'_R\,h\right] \dashrightarrow \frac{m_\ell}{v}\left[\overline{\ell_L}\ell_R h\right]$ **no LFV**

Dimension-6 operator

$$\mathcal{L} = \mathbf{Y_4}\left[\overline{L}\,\Phi\ell'_R\right] + \frac{\mathbf{Y_6}}{\Lambda^2}\left[\overline{L}\,\Phi\ell'_R(\Phi^\dagger\Phi)\right]$$

Mass : $v\left(\frac{1}{\sqrt{2}}\mathbf{Y_4} + \frac{v^2}{2\Lambda^2}\mathbf{Y_6}\right)\left[\overline{\ell_L}\ell'_R\right] \xrightarrow{\text{Diag.}} m_\ell\left[\overline{\ell_L}\ell_R\right]$

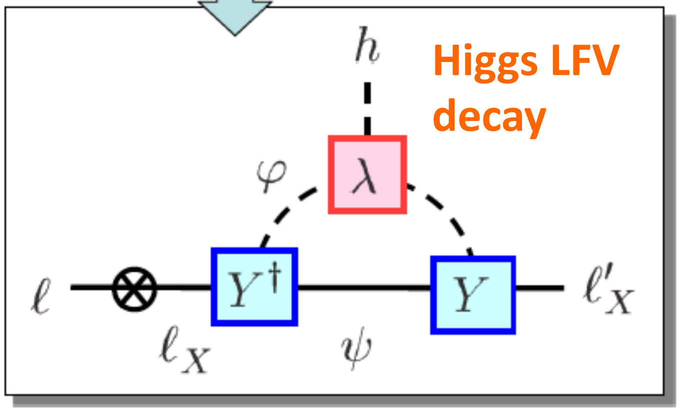
Int. : $\left(\frac{1}{\sqrt{2}}\mathbf{Y_4} + \frac{3v^2}{2\Lambda^2}\mathbf{Y_6}\right)\left[\overline{\ell_L}\ell'_R h\right] \dashrightarrow \left(\frac{m_\ell}{v}\delta_{\ell\ell'} + \boxed{\frac{v^2}{\Lambda^2}\mathbf{Y_6}}\right)\left[\overline{\ell_L}\ell'_R h\right]$ **LFV**

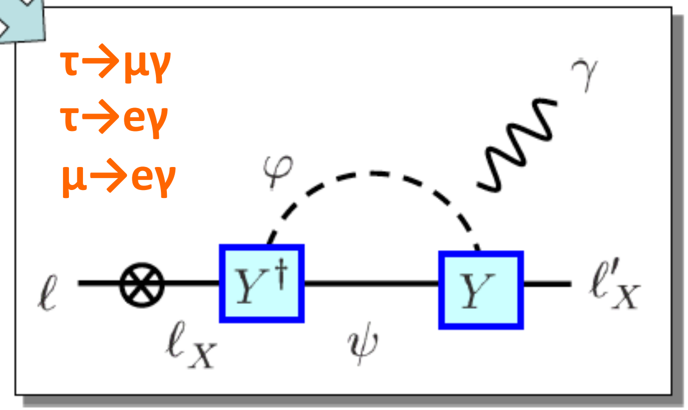
Correlation

Toy model

$$\mathcal{L} = \mathbf{Y}_{a\ell}\left[\overline{\psi_a}\,\ell_X\,\varphi\right] - \boldsymbol{\lambda}\,|\Phi|^2|\varphi|^2 + \cdots$$

$X = L, R$





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

Too small $\mathrm{BR}(h \to \ell\ell')$ to be observed.
If observed, the toy model is excluded.

$\Longleftarrow$

$\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}$
MEG collab., arXiv:1605.05081

$\mathrm{BR}(\tau \to e\gamma) < 3.3 \times 10^{-8}$
$\mathrm{BR}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$
Babar collab., PRL**104**, 021802

If $h \to \ell\ell'$ is observed

Models for Majorana neutrino masses

	Scalar with leptonic Yukawa int.						$\ell \to \ell'\gamma$	
					Z_2-odd			
	s_L^+	s^{++}	Φ_2	Δ	s_2^+	η	ℓ'_L	ℓ'_R
$SU(2)_L$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$		
$U(1)_Y$	1	2	1/2	1	1	1/2		
Unbroken Z_2	+	+	+	+	−	−		
M1	✓	✓					✓	✓
M2		✓	✓					✓
M3		✓						✓
M4				✓			✓	
M5	✓				✓		✓	✓
M6			✓		✓			✓
M7					✓			✓
M8						✓	✓	

Only a LFV Yukawa $\Longrightarrow$ Same as the toy model

If $h \to \ell\ell'$ is observed

Models for Majorana neutrino masses

	Scalar with leptonic Yukawa int.						$\ell \to \ell'\gamma$	
					Z_2-odd			
	s_L^+	s^{++}	Φ_2	Δ	s_2^+	η	ℓ'_L	ℓ'_R
$SU(2)_L$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$		
$U(1)_Y$	1	2	1/2	1	1	1/2		
Unbroken Z_2	+	+	+	+	−	−		
M1	✓	✓					✓	✓
M2		✓	✓					✓
M3		✓						✓
M4				✓			✓	
M5	✓				✓		✓	✓
M6			✓		✓			✓
M7					✓			✓
M8						✓	✓	

Two LFV Yukawa, but no cancellation to suppress $\ell \to \ell'\gamma$

If $h \to \ell\ell'$ is observed

Models for Majorana neutrino masses

	Scalar with leptonic Yukawa int.						$\ell \to \ell'\gamma$	
					Z_2-odd			
	s_L^+	s^{++}	Φ_2	Δ	s_2^+	η	ℓ'_L	ℓ'_R
$SU(2)_L$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$		
$U(1)_Y$	1	2	1/2	1	1	1/2		
Unbroken Z_2	+	+	+	+	−	−		
M1	✓	✓					✓	✓
M2		✓	✓					✓
M3		✓						✓
M4				✓			✓	
M5	✓				✓		✓	✓
M6			✓		✓			✓
M7					✓			✓
M8						✓	✓	

All excluded for Majorana neutrinos !

If $h \to \ell\ell'$ is observed

Models for Dirac neutrino masses (1)

	Scalar with leptonic Yukawa int.										$\ell \to \ell'\gamma$	
								Z_2-odd				
	s^0	s_L^+	s_R^+	s^{++}	Φ_ν	Φ_2	Δ	s_2^0	s_2^+	η	ℓ'_L	ℓ'_R
$\mathrm{SU}(2)_L$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$		
$\mathrm{U}(1)_Y$	0	1	1	2	1/2	1/2	1	0	1	1/2		
LN	−2	−2	−2	−2	0	0	−2	−1	−1	−1		
Z'_2	+	+	−	+	−	+	+	−	+	+		
D1		✓	✓								✓	✓
D2			✓				✓				✓	✓
D3			✓	✓		✓						✓✓
D4			✓	✓								✓✓
D5	✓		✓			✓						✓
D6	✓		✓									✓
D7					✓						✓	

If $h \to \ell\ell'$ is observed

Models for Dirac neutrino masses (1)

	Scalar with leptonic Yukawa int.										$\ell \to \ell'\gamma$	
								Z_2-odd				
	s^0	s_L^+	s_R^+	s^{++}	Φ_ν	Φ_2	Δ	s_2^0	s_2^+	η	ℓ'_L	ℓ'_R
$SU(2)_L$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$		
$U(1)_Y$	0	1	1	2	1/2	1/2	1	0	1	1/2		
LN	−2	−2	−2	−2	0	0	−2	−1	−1	−1		
Z'_2	+	+	−	+	−	+	+	−	+	+		
D1		✓	✓								✓	✓
D2			✓				✓				✓	✓
D3			✓	✓		✓						✓✓
D4			✓	✓								✓✓
D5	✓		✓			✓						✓
D6	✓		✓									✓
D7					✓						✓	

D3 and D4 survive

	Scalar with leptonic Yukawa int.										$\ell \to \ell' \gamma$	
								Z_2-odd				
	s^0	s_L^+	s_R^+	s^{++}	Φ_ν	Φ_2	Δ	s_2^0	s_2^+	η	ℓ'_L	ℓ'_R
$\mathrm{SU}(2)_L$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$		
$\mathrm{U}(1)_Y$	0	1	1	2	1/2	1/2	1	0	1	1/2		
LN	−2	−2	−2	−2	0	0	−2	−1	−1	−1		
Z'_2	+	+	−	+	−	+	+	−	+	+		
D3			✓	✓		✓						✓✓
D4			✓	✓								✓✓

$$\mathrm{BR}(\ell \to \ell'\gamma) \propto \left| \frac{(Y^{s\dagger} Y^s)_{\ell\ell'}}{m^2_{s_R^+}} + \frac{(Y_S^{s\dagger} Y_S^s)_{\ell\ell'}}{m^2_{s^{++}}} \right|^2 \ll \left| \frac{(Y^{s\dagger} Y^s)_{\ell\ell'}}{m^2_{s_R^+}} \right|^2$$

Cancellation is possible

$$\mathrm{BR}(h \to \ell\ell') \propto \left| \lambda_{hs^+} \frac{(Y^{s\dagger} Y^s)_{\ell\ell'}}{m^2_{s_R^+}} + \lambda_{hs^{++}} \frac{(Y_S^{s\dagger} Y_S^s)_{\ell\ell'}}{m^2_{s^{++}}} \right|^2 \sim \left| 2\lambda_{hs^+} \frac{(Y^{s\dagger} Y^s)_{\ell\ell'}}{m^2_{s_R^+}} \right|^2$$

Not cancelled if λ_{hs^+} and $\lambda_{hs^{++}}$ have opposite sign

Models for Dirac neutrino masses (2)

	Scalar with leptonic Yukawa int.										$\ell \to \ell'\gamma$	
								Z_2-odd				
	s^0	s_L^+	s_R^+	s^{++}	Φ_ν	Φ_2	Δ	s_2^0	s_2^+	η	ℓ'_L	ℓ'_R
$SU(2)_L$	**1**	**1**	**1**	**1**	**2**	**2**	**3**	**1**	**1**	**2**		
$U(1)_Y$	0	1	1	2	1/2	1/2	1	0	1	1/2		
LN	−2	−2	−2	−2	0	0	−2	−1	−1	−1		
Z'_2	+	+	−	+	−	+	+	−	+	+		
D8		✓						✓	✓		✓	✓
D9							✓	✓	✓		✓	✓
D10			✓							✓	✓	✓
D11			✓			✓			✓			✓✓
D12			✓						✓			✓✓
D13			✓			✓		✓				✓
D14			✓					✓				✓
D15						✓		✓	✓			✓
D16								✓	✓			✓
D17			✓						✓	✓	✓	✓✓
D18								✓		✓	✓	

Models for Dirac neutrino masses (2)

	Scalar with leptonic Yukawa int.										$\ell \to \ell'\gamma$	
								Z_2-odd				
	s^0	s_L^+	s_R^+	s^{++}	Φ_ν	Φ_2	Δ	s_2^0	s_2^+	η	ℓ'_L	ℓ'_R
$SU(2)_L$	$\mathbf{\underline{1}}$	$\mathbf{\underline{1}}$	$\mathbf{\underline{1}}$	$\mathbf{\underline{1}}$	$\mathbf{\underline{2}}$	$\mathbf{\underline{2}}$	$\mathbf{\underline{3}}$	$\mathbf{\underline{1}}$	$\mathbf{\underline{1}}$	$\mathbf{\underline{2}}$		
$U(1)_Y$	0	1	1	2	1/2	1/2	1	0	1	1/2		
LN	−2	−2	−2	−2	0	0	−2	−1	−1	−1		
Z_2'	+	+	−	+	−	+	+	−	+	+		
D8		✓						✓	✓		✓	✓
D9							✓	✓	✓		✓	✓
D10			✓							✓	✓	✓
D11			✓			✓			✓			✓✓
D12			✓						✓			✓✓
D13			✓			✓		✓				✓
D14			✓					✓				✓
D15						✓		✓	✓			✓
D16								✓	✓			✓
D17			✓						✓	✓	✓	✓✓
D18								✓		✓	✓	

Models for Dirac neutrino masses (1)&(2)

	Scalar with leptonic Yukawa int.										$\ell \to \ell'\gamma$	
								Z_2-odd				
	s^0	s_L^+	s_R^+	s^{++}	Φ_ν	Φ_2	Δ	s_2^0	s_2^+	η	ℓ'_L	ℓ'_R
$SU(2)_L$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$		
$U(1)_Y$	0	1	1	2	1/2	1/2	1	0	1	1/2		
LN	-2	-2	-2	-2	0	0	-2	-1	-1	-1		
Z'_2	$+$	$+$	$-$	$+$	$-$	$+$	$+$	$-$	$+$	$+$		
D3			✓	✓		✓						✓✓
D4			✓	✓								✓✓
D11			✓			✓			✓			✓✓
D12			✓						✓			✓✓
D17			✓						✓	✓	✓	✓✓

These mechanisms for generating masses of Dirac neutrinos can survive after discovery of $h \to \ell\ell'$

Models for Dirac neutrino masses (1)&(2)

	Scalar with leptonic Yukawa int.							Z_2-odd			$\ell \to \ell' \gamma$	
	s^0	s_L^+	s_R^+	s^{++}	Φ_ν	Φ_2	Δ	s_2^0	s_2^+	η	ℓ'_L	ℓ'_R
$\mathrm{SU}(2)_L$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$		
$\mathrm{U}(1)_Y$	0	1	1	2	1/2	1/2	1	0	1	1/2		
LN	-2	-2	-2	-2	0	0	-2	-1	-1	-1		
Z'_2	$+$	$+$	$-$	$+$	$-$	$+$	$+$	$-$	$+$	$+$		
D3			✓	✓		✓						✓✓
D4			✓	✓								✓✓
D11			✓			✓			✓			✓✓
D12			✓						✓			✓✓
D17			✓						✓	✓	✓	✓✓

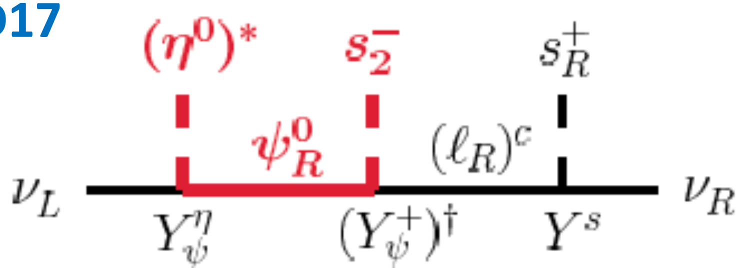
Z_2 odd particles

These mechanisms for generating masses of Dirac neutrinos can survive after discovery of $h \to \ell\ell'$

A new model
for D17 which can survive even if Higgs LFV decays are detected in future experiments

K. Enomoto, SK , K. Sakurai, H. Sugiyama,
Phys. Rev. D100, 015044 (2019)

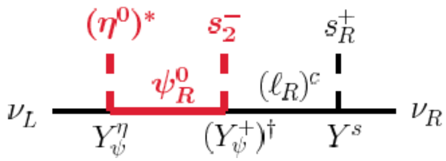
D17



New model for Dirac neutrino masses with the structure of D17

K. Enomoto, SK , K. Sakurai, H. Sugiyama,
Phys. Rew. D100, 015044 (2019)

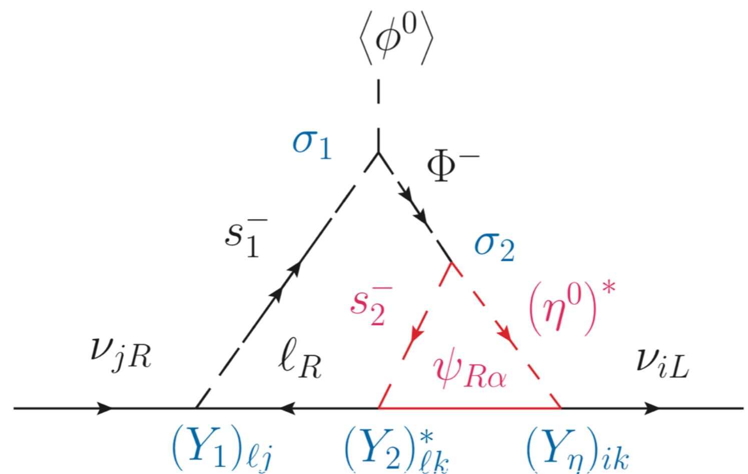
D17



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

$i, \alpha = 1 \sim 3$

<u>Neutrino masses</u>



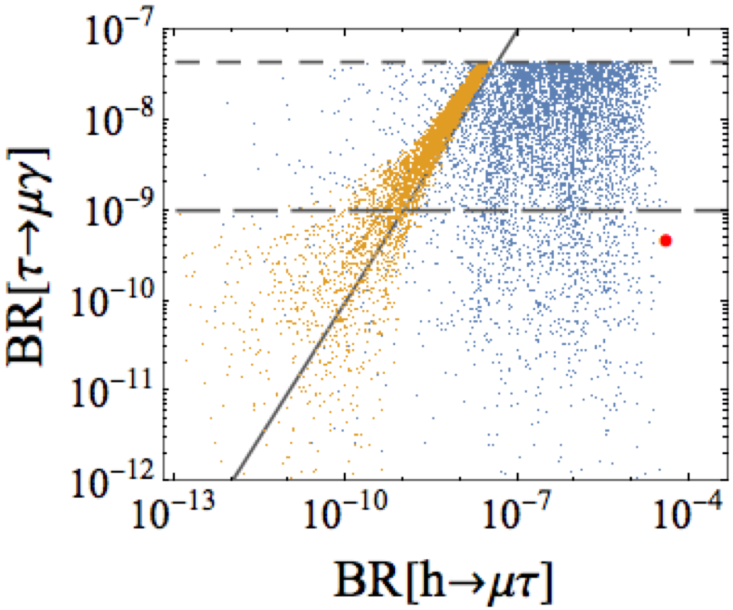
$$\mathcal{L} = (Y_1)_{\ell i} \overline{(\ell_R)^c} \nu_{Ri} s_1^+ + (Y_2)_{\ell \alpha} \overline{(\ell_R)^c} \psi_{R\alpha} s_2^+ + (Y_\eta)_{\ell\alpha} \overline{L_\ell} \eta^c \psi_{R\alpha} + \text{h.c.}$$

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

New model for Dirac neutrino masses with the structure of D17

K. Enomoto, SK , K. Sakurai, H. Sugiyama,
Phys. Rev. D100, 015044 (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 $\lambda_{hs_1} = -\lambda_{hs_2} = 2.0$

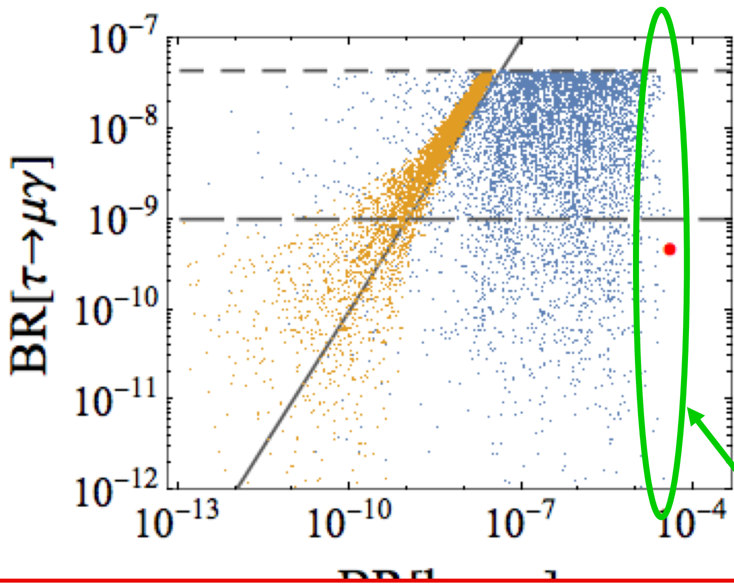
Red point Benchmark scenario

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

New model for Dirac neutrino masses with the structure of D17

K. Enomoto, SK , K. Sakurai, H. Sugiyama, Phys. Rev. D100, 015044 (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

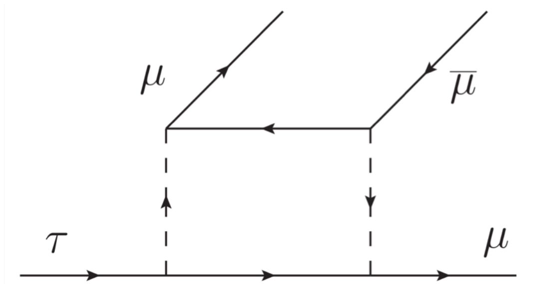
Expected limit $\mathrm{BR}\,(h \to \mu\tau) = 4.0 \times 10^{-5}$ $(\mathcal{L} = 1350\ \mathrm{fb}^{-1})$

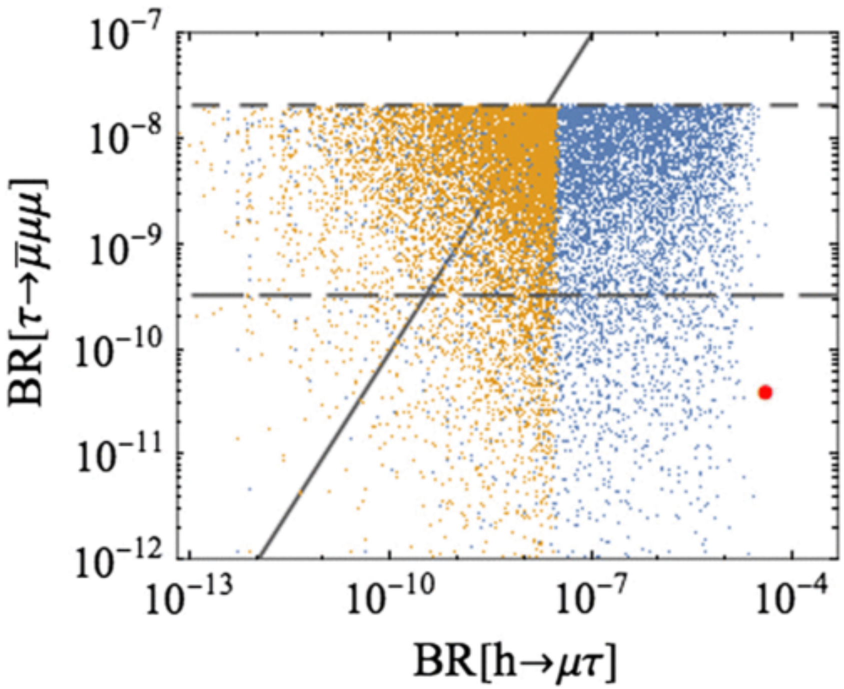
I. Chakraborty, A. Datta, A. Kundu, J.Phys (2016)

New model for Dirac neutrino masses with the structure of D17

K. Enomoto, SK , K. Sakurai, H. Sugiyama, Phys. Rev. D100, 015044 (2019)

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





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

Short-dashed line: Upper limit 4.4×10^{-8}

Long-dashed line: Expected limit 1.0×10^{-9}

Belle II @ 50 ab^{-1}

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

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

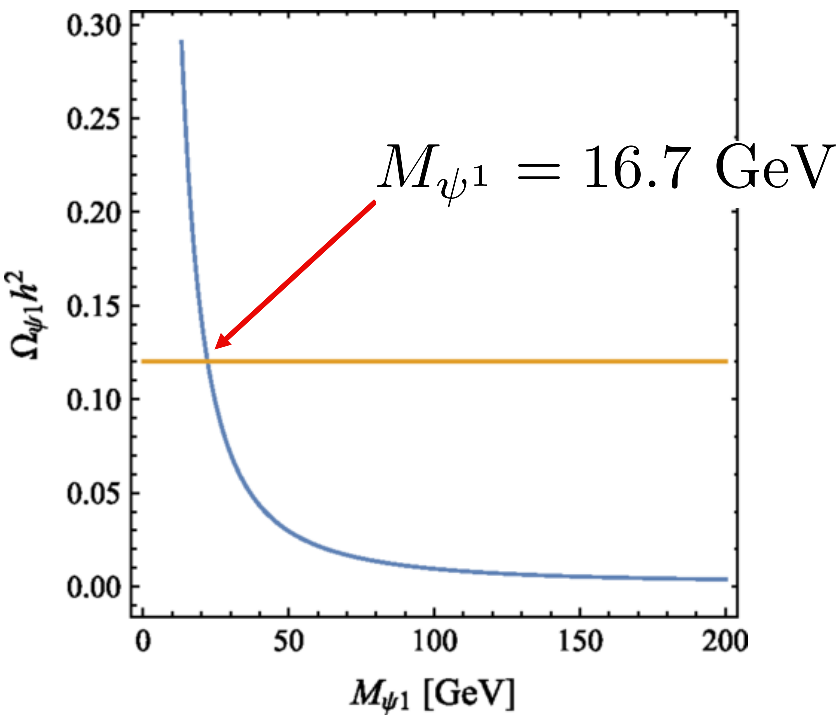
Red point Benchmark scenario

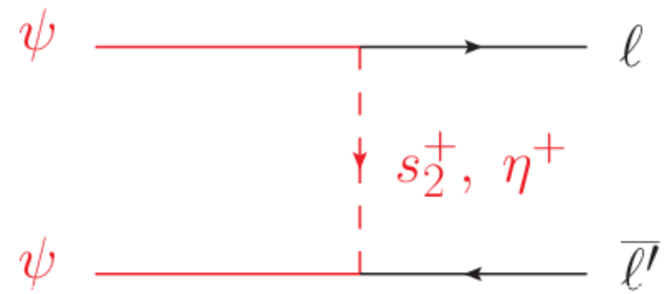
New model for Dirac neutrino masses with the structure of D17

K. Enomoto, SK , K. Sakurai, H. Sugiyama, Phys. Rev. D100, 015044 (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

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

Summary

We discussed how observations of LFV decays of the Higgs boson can narrow down models of neutrino masses

We first classified neutrino mass models by focusing on the combination of new Yukawa coupling matrices with leptons

If Higgs LFV decays $h \to \ell\ell'$ are detected at future colliders, a wide class of models for neutrino masses can be excluded

In particular, simple typical models of Majorana neutrino masses cannot be compatible with the observation of $h \to \ell\ell'$

A model for Dirac neutrino masses can be compatible with a significant rate of the $h \to \ell\ell'$ process

Thank you

Osaka Univ.
Dr. Wani

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}