Testing neutrino mass generation mechanisms from the lepton flavor violating decay of the Higgs boson

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Introduction

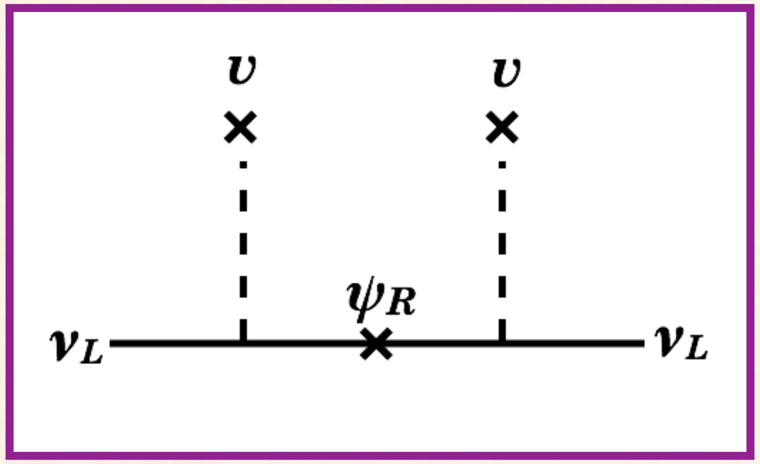
- Neutrino mass scale is much smaller than the *q* and *ℓ* masses.

$m_\nu \sim 0.1$ eV $\ll$ m_q, m_ℓ

- The origin of the neutrino mass might be different from that of *q* and *ℓ*.

Seesaw Mechanism

Type-I

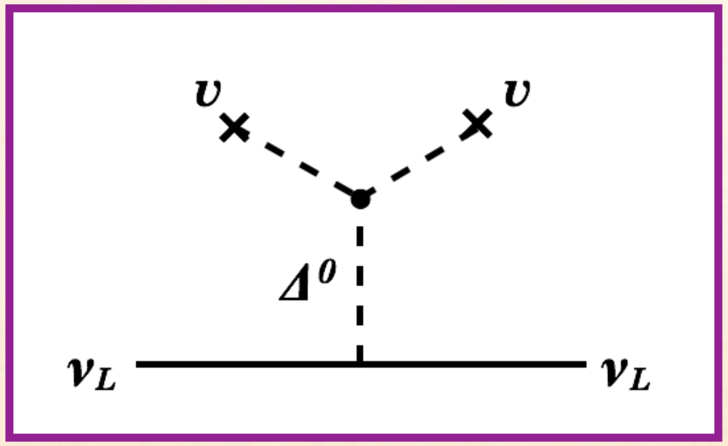


ψ_R : Right-handed neutrino

$$m_\nu \simeq \frac{v^2 y^2}{2M}$$

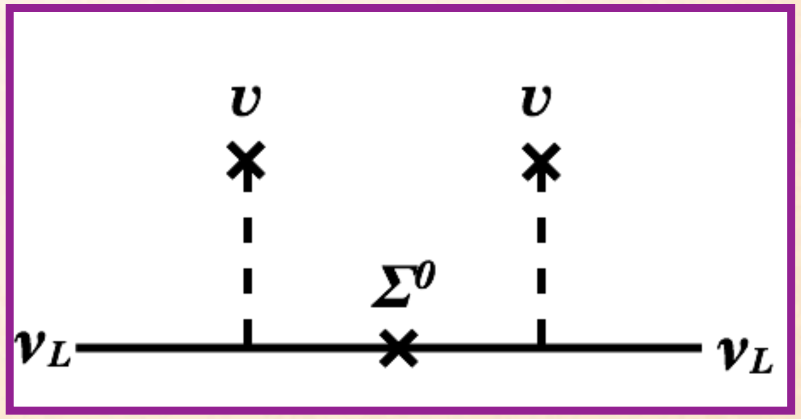
- y ~O(1), M~10^{14} GeV — Far from experimental reach
- $y \sim y_e$, M~100 GeV

Type-II



Δ: SU(2) triplet scalar

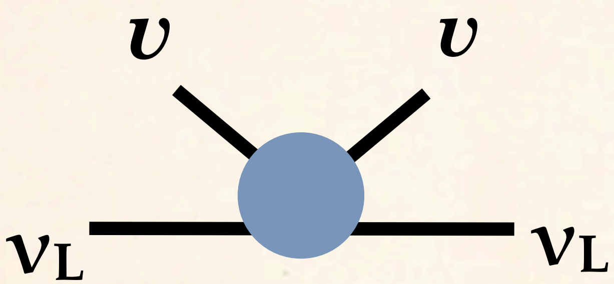
Type-III



Σ : SU(2) triplet fermion

Introduction

Radiative Seesaw Mechanism



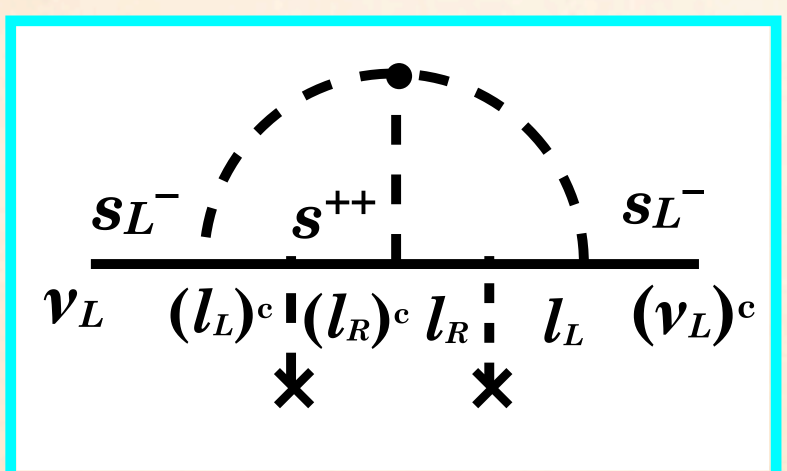
N-loop: $m_\nu^{ij} = \left(\frac{1}{16\pi^2}\right)^N \frac{f_{ij}}{\Lambda} \langle \phi^0 \rangle^2$

- Neutrino masses are generated via the radiative effect.
- Due to the loop suppression factor, the neutrino masses would be explained in a natural way by the TeV-scale dynamics with the unsuppressed couplings.

e.g.) 2-loop model

Zee-Babu model

Zee (1986); Babu (1988)

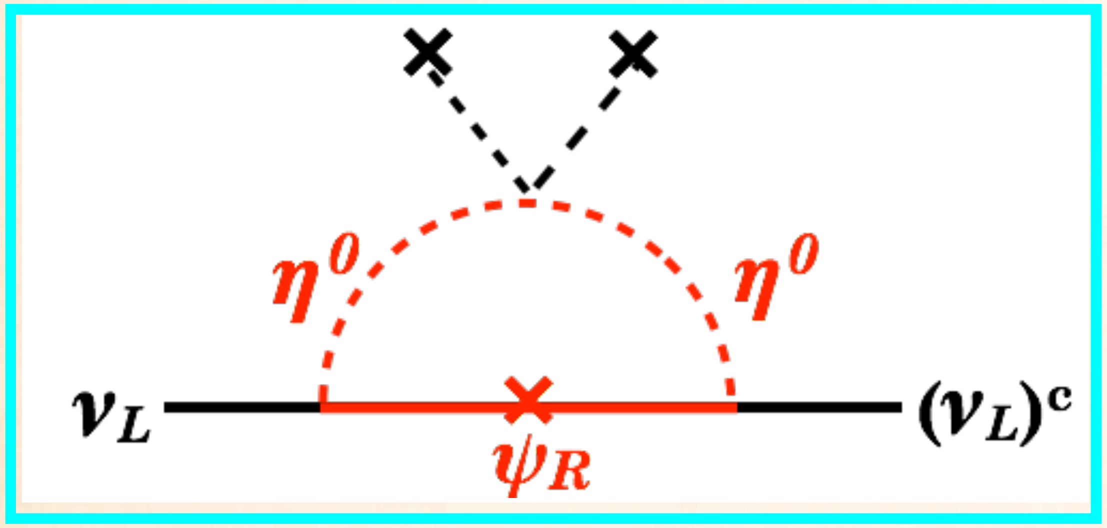


- New particles: s_L^- , s^{++}
- f ~O(1), M~10^3 GeV

Introduction

Model with dark matter particle

e.g.) Ma model Ma (2006)



- Z_2 symmetry is introduced.
- New particles: Z_2 odd ψ_R , η

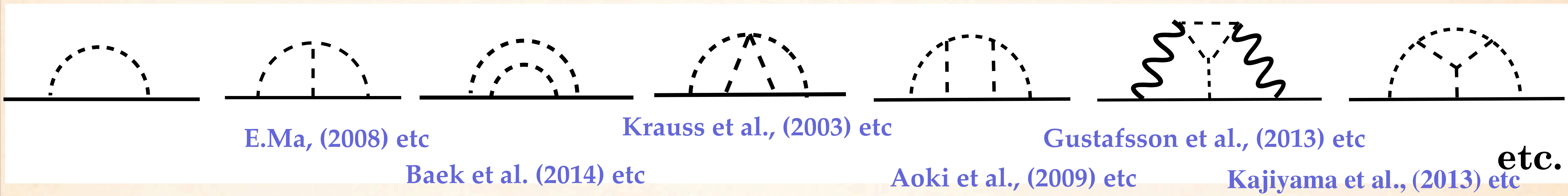
η: Inert doublet scalar

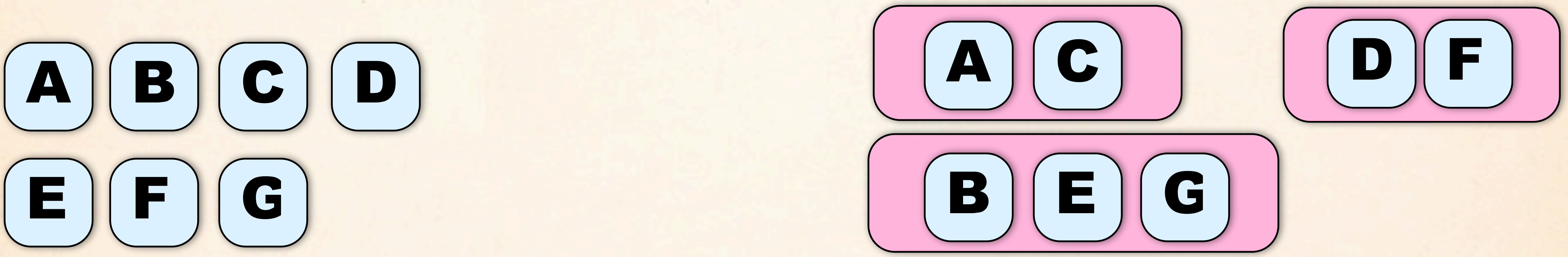
$$\eta = \begin{pmatrix} \eta^+ \\ (\eta_R^0 + i\eta_I^0)/\sqrt{2} \end{pmatrix}, \qquad \langle \eta \rangle = 0$$

- The Z_2 symmetry forbids the Dirac ν mass term and guarantees the stability of DM.
- DM candidates : ψ_R , η^0_R , η^0_I
- The framework would explain the neutrino mass and the DM.

Introduction

Many variety of radiative seesaw models





- Classification of models into several groups **by some common features** enables us to test neutrino mass generation mechanisms.

Our work

- The models are classified by focusing on **the combinations of new Yukawa coupling.**
- The mechanisms are tested by LFV phenomena.

charged LFV, LFV decays of the Higgs boson

Introduction

- LFV decays of the Higgs boson $h \to ll'$

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

$\mathrm{BR}(h \to \mu\tau)$

			Best Fit	
CMS	8TeV	< 1.51 %	$0.84^{+0.39}_{-0.37}$ %	2.4σ excess
	13TeV	< 1.20 %	$-0.76^{+0.81}_{-0.84}$ %	No excess observed
ATLAS	8TeV	< 1.43 %	$0.53^{+0.51}_{-0.51}$ %	

Future colliders → O(0.01) %

Han and Marfatia (2001), Kanemura et.al. (2004)

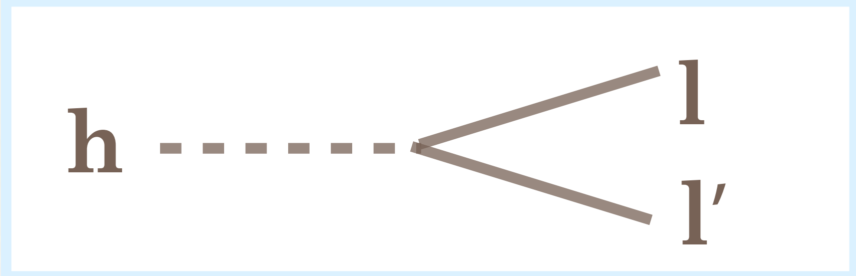
$\mathrm{BR}(h \to e\mu)$ CMS 8TeV $< 3.5\times10^{-2}$ %

$\mathrm{BR}(h \to e\tau)$ CMS 8TeV $< 6.9\times10^{-1}$ %

- We discuss impact of future discoveries of $h \to ll'$ **on the mechanisms to generate neutrino masses.**

Introduction

$h \to ll'$

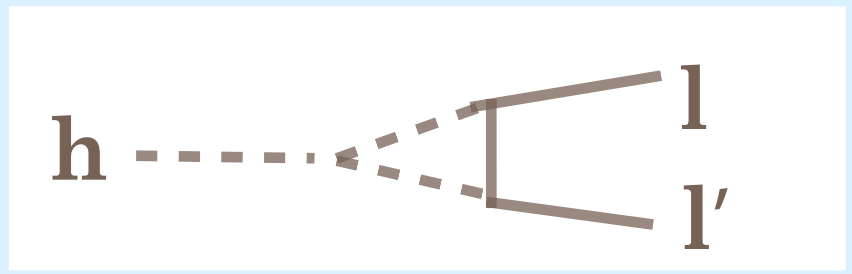


- Tree-level LFV

e.g) Type III two Higgs doublet model $\mathcal{L}_Y = y^1_{ij}\bar{\psi}_i\psi_j\Phi_1 - y^2_{ij}\bar{\psi}_i\psi_j\Phi_2$

We consider the FCNC interactions at the tree level are absent.

(by imposing the softly-broken Z_2 symmetry)



- Loop-level LFV

Model with new Yukawa interaction between new scalar and lepton.

Dimension- 4 and -6 operators

$$\mathcal{L} = Y[\overline{L}\Phi\ell'_R] + \frac{Y_6}{\Lambda^2}[\overline{L}\Phi\ell'_R(\Phi^\dagger\Phi)]$$

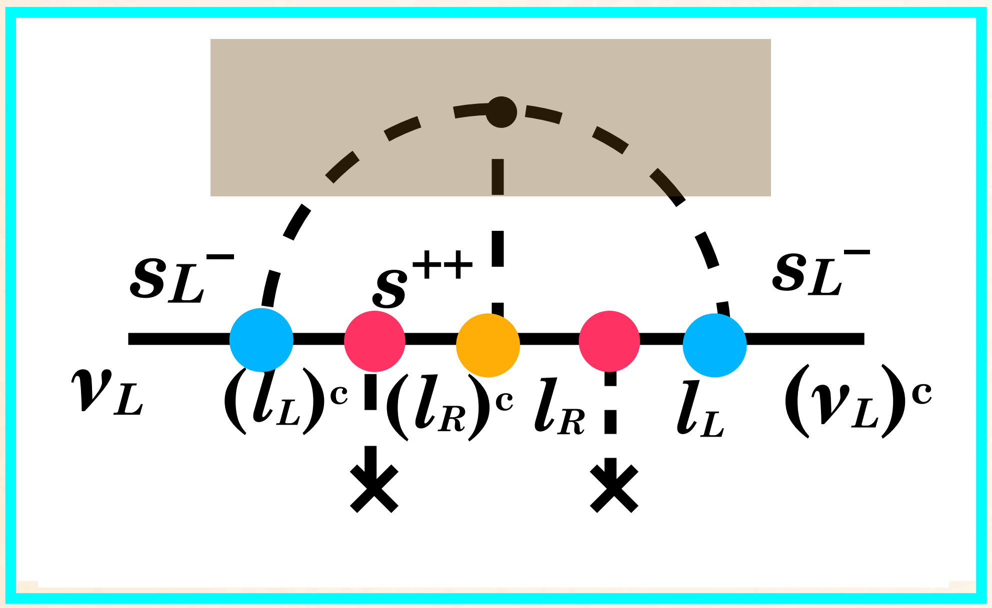
$$\to \left(\frac{v}{\sqrt{2}}Y + \frac{v^3}{2\Lambda^2}Y_6\right)[\ell_L\ell'_R] + \left(\frac{1}{\sqrt{2}}Y + 3\frac{v^2}{2\Lambda^2}Y_6\right)[\ell_L\ell'_R h]$$

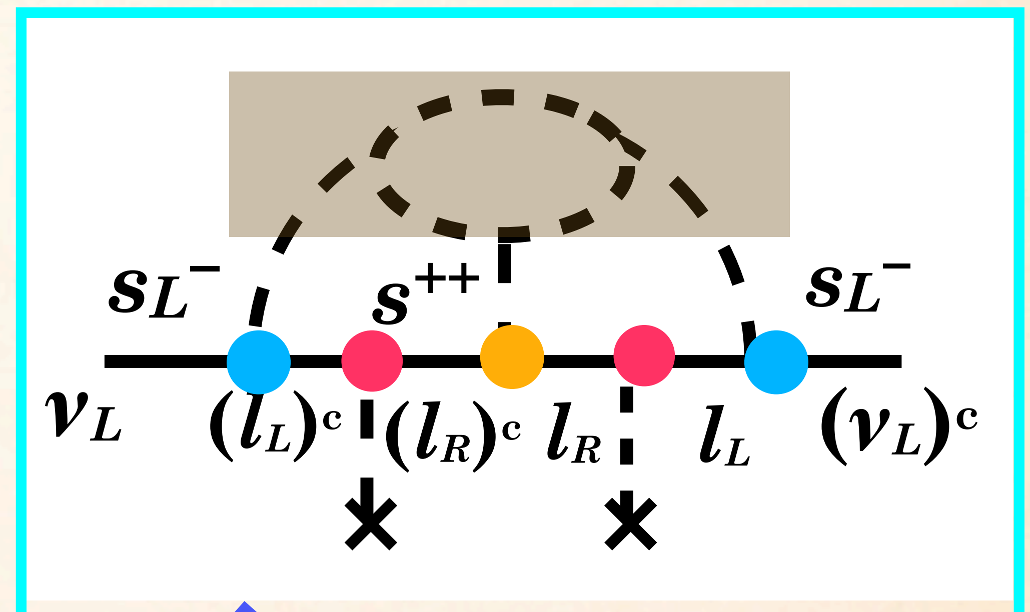
Misalignment

1. Introduction
2. Classification of models
3. $h \to ll'$
4. Summary

Classification of Models

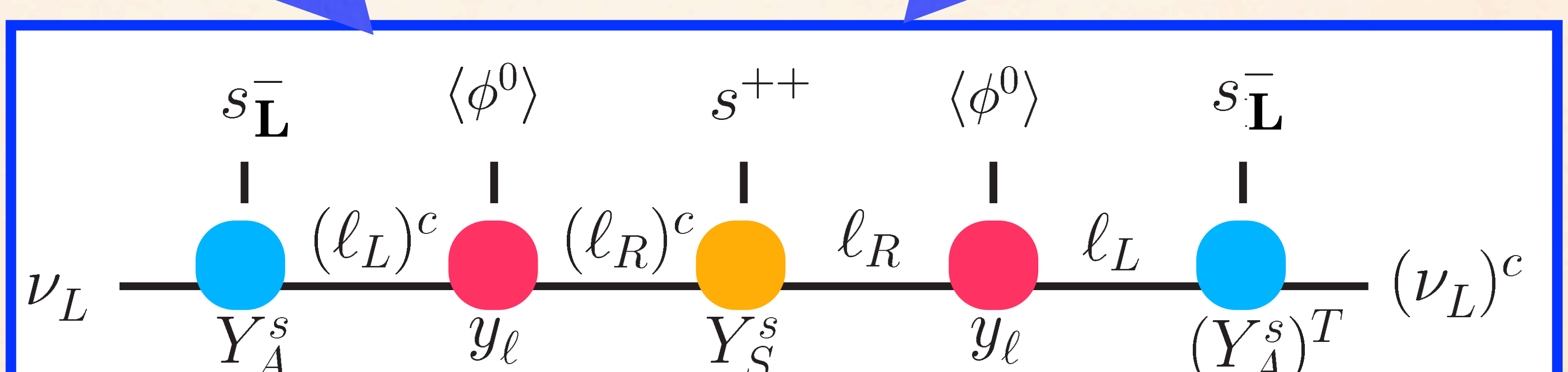
- We classify the models by focusing only on the combinations of Yukawa coupling matrices.





"Mechanism"

M1

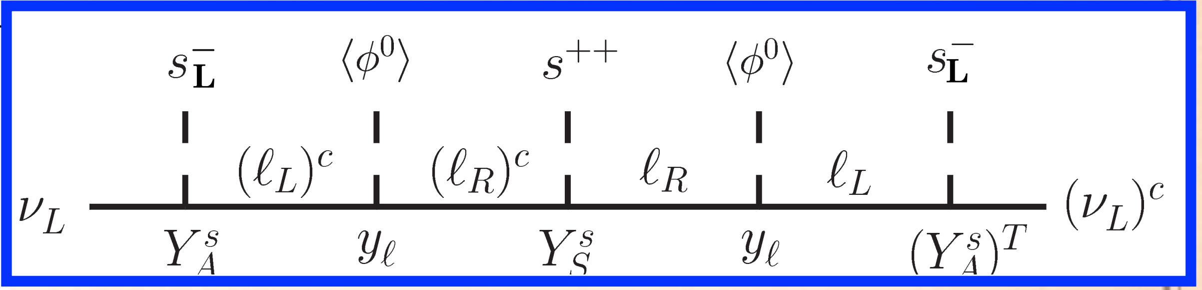


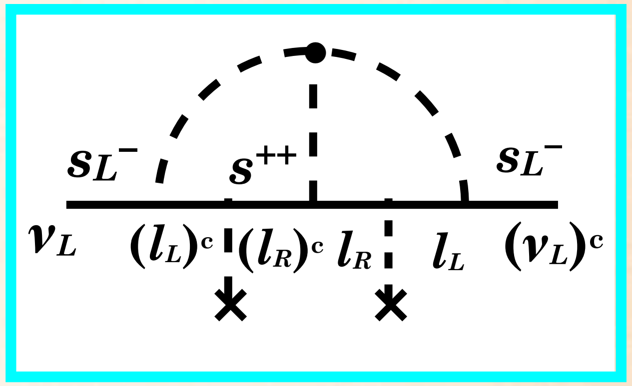
Majorana Neutrino

Kanemura, Sugiyama (2016)

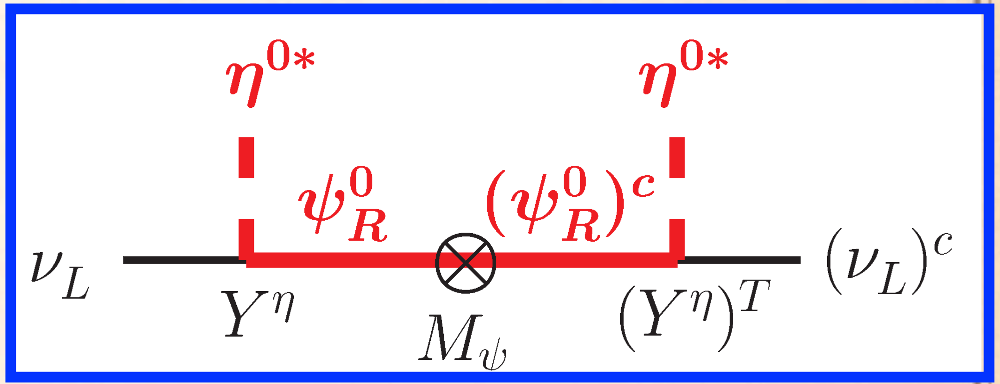
	Scalar with leptonic Yukawa int.					
					Z_2-odd	
	s_L^+	s^{++}	Φ_2	Δ	s_2^+	η
$SU(2)_L$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$
$U(1)_Y$	1	2	1/2	1	1	1/2
Unbroken Z_2	+	+	+	+	−	−
M1	✓	✓				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

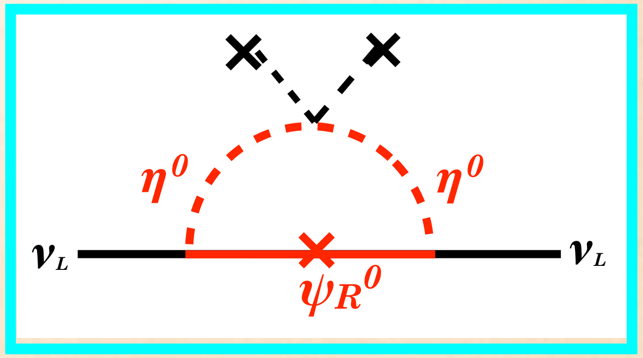
M1





M8



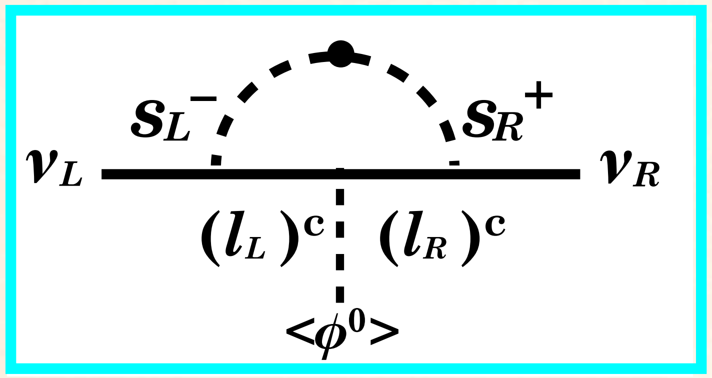


Classification of Models

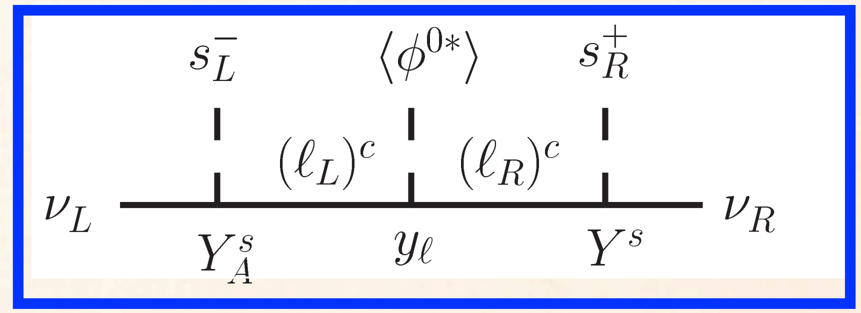
Dirac Neutrino

- Dirac masses can be generated at the the loop level.

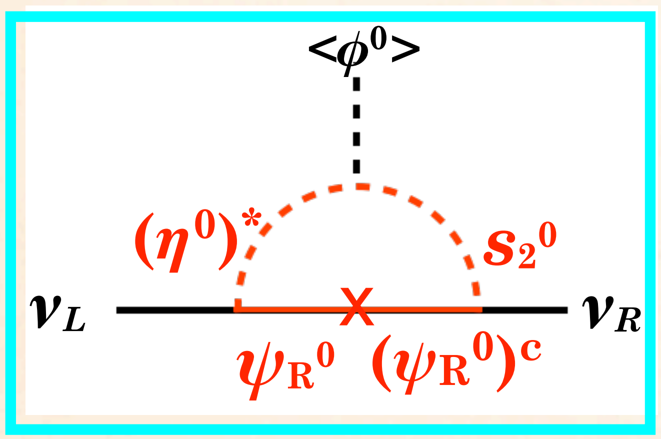
Nasri, Moussa (2002)



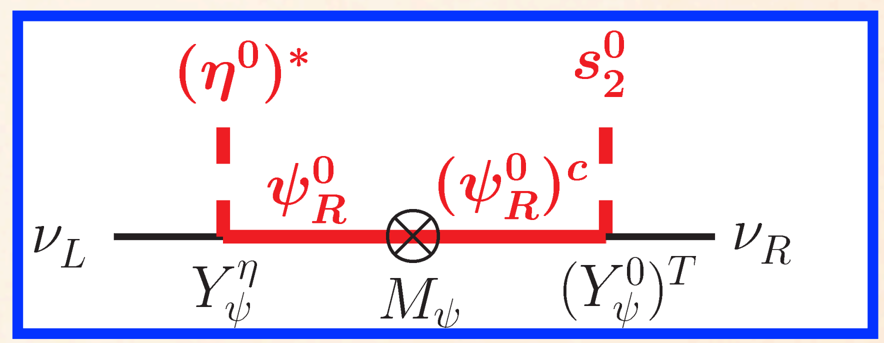
D1



Gu, Sarkar (2008)



D18



- In order to forbid the $L\Phi\nu_R$, the softly-broken Z_2 symmetry (Z_2') is introduced.

ν_R : Z_2' odd

Dirac Neutrino

Kanemura, Sakurai, Sugiyama (2016)

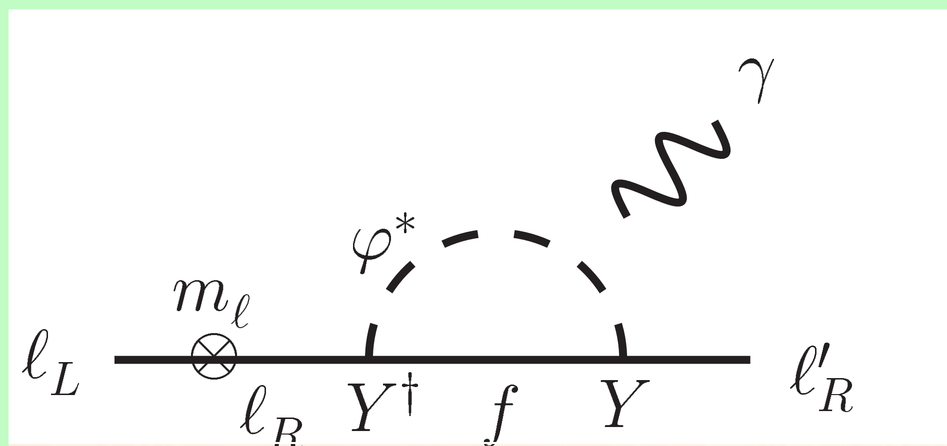
Scalar with leptonic Yukawa int.

	s^0	s_L^+	s_R^+	s^{++}	Φ_ν	Φ_2	Δ
$\mathrm{SU}(2)_L$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$
$\mathrm{U}(1)_Y$	0	1	1	2	1/2	1/2	1
Lepton number	−2	−2	−2	−2	0	0	−2
Z_2'	+	+	−	+	−	+	+
D1		✓	✓				
D2			✓				✓
D3			✓	✓		✓	
D4			✓	✓			
D5	✓		✓			✓	
D6	✓		✓				
D7					✓		

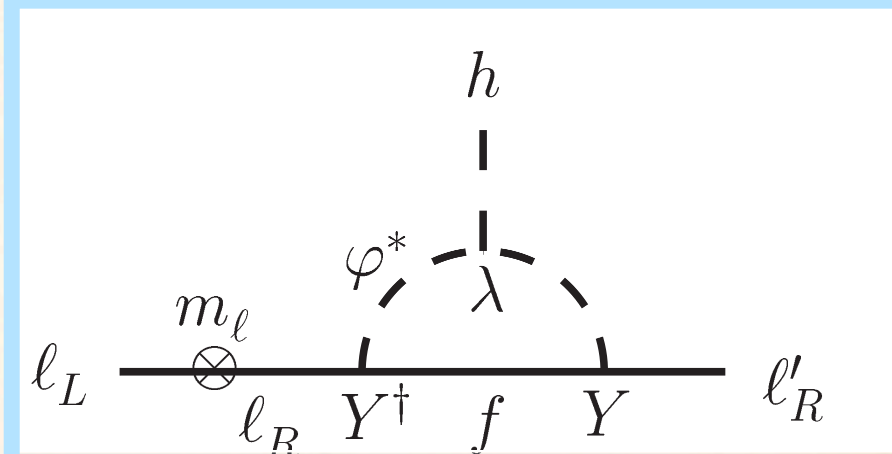
								Z_2-odd		
	s^0	s_L^+	s_R^+	s^{++}	Φ_ν	Φ_2	Δ	s_2^0	s_2^+	η
$\mathrm{SU}(2)_L$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$
$\mathrm{U}(1)_Y$	0	1	1	2	1/2	1/2	1	0	1	1/2
Lepton number	−2	−2	−2	−2	0	0	−2	−1	−1	−1
Z_2'	+	+	−	+	−	+	+	−	+	+
D8		✓						✓	✓	
D9							✓	✓	✓	
D10			✓							✓
D11			✓			✓			✓	
D12			✓						✓	
D13			✓			✓		✓		
D14			✓					✓		
D15						✓		✓	✓	
D16								✓	✓	
D17			✓						✓	✓
D18								✓		✓

$h \to ll'$

$l \to l'\gamma$



$h \to ll'$



$$\mathrm{BR}(\ell \to \ell'_X\gamma) \sim 0.1 \frac{\lambda^2}{(2-3Q_\varphi)^2} \mathrm{BR}(h \to \ell\ell')$$

- **Under the constraint from the cLFV, the BR of *h* LFV decay is too small to be observed if it is radiatively produced.**

$$\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}, \quad \mathrm{BR}(\tau \to l'\gamma) < 10^{-8}$$

- **If *h* LFV decay is observed, we might take FCNC at the tree level or take some extension to suppress $l \to l'\gamma$ by cancellation.**

$h \to ll'$

- Each of the Mechanisms has new Yukawa interactions, which can produce both $l \to l'\gamma$ and $h \to ll'$.

- 14 Mechanisms will be excluded if $h \to ll'$ is observed.

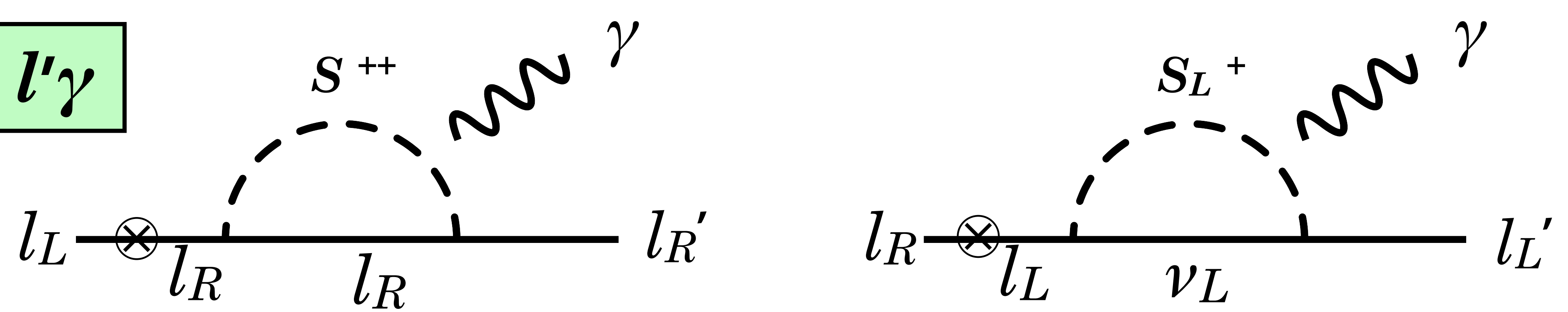
- All other Mechanisms have two kinds of new Yukawa interactions.
- In the Mechanisms-M1, M5, D1, D2, D8, D9 and D10, their effects to $l \to l'\gamma$ cannot be cancelled with each other.

M1

$(Y_S^s)_{\ell\ell'} \left[\overline{(\ell_R)^c}\, \ell'_R\, s^{++}\right]$

$(Y_A^s)_{\ell\ell'} \left[\overline{L_\ell}\, \epsilon\, L^*_{\ell'}\, s_L^-\right]$

$l \to l'\gamma$



Different chiralities of charged leptons

$h \to ll'$

- **Some Mechanisms for Dirac neutrino masses can be compatible with the observation of $h \to ll'$.**

	s^0	s_L^+	s_R^+	s^{++}	Φ_ν	Φ_2	Δ	$\ell \to \ell'\gamma$: ℓ'_L	$\ell \to \ell'\gamma$: ℓ'_R
$SU(2)_L$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$		
$U(1)_Y$	0	1	1	2	1/2	1/2	1		
Lepton number	−2	−2	−2	−2	0	0	−2		
Z'_2	+	+	−	+	−	+	+		
D1		✓	✓					✓	✓
D2			✓				✓	✓	✓
D3			✓	✓		✓			✓✓
D4			✓	✓					✓✓
D5	✓		✓			✓			✓
D6	✓		✓						✓
D7					✓			✓	

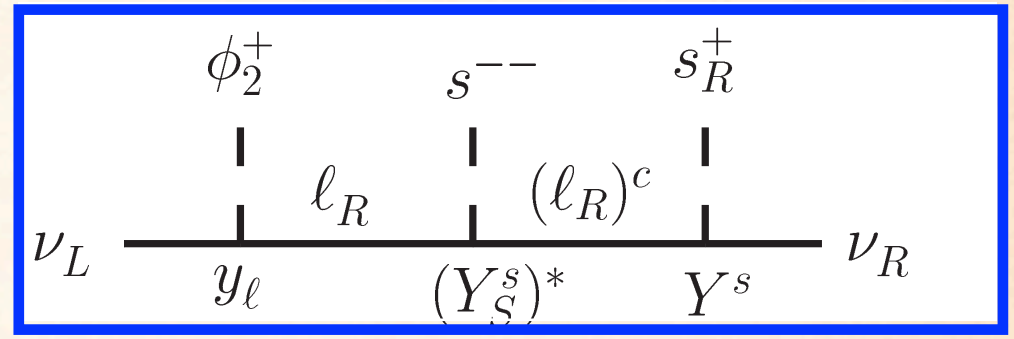
	s^0	s_L^+	s_R^+	s^{++}	Φ_ν	Φ_2	Δ	Z_2-odd: s_2^0	Z_2-odd: s_2^+	Z_2-odd: η	$\ell \to \ell'\gamma$: ℓ'_L	$\ell \to \ell'\gamma$: ℓ'_R
$SU(2)_L$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$		
$U(1)_Y$	0	1	1	2	1/2	1/2	1	0	1	1/2		
Lepton number	−2	−2	−2	−2	0	0	−2	−1	−1	−1		
Z'_2	+	+	−	+	−	+	+	−	+	+		
D8		✓						✓	✓		✓	✓
D9							✓	✓	✓		✓	✓
D10			✓							✓	✓	✓
D11			✓			✓			✓			✓✓
D12			✓						✓			✓✓
D13			✓			✓		✓				✓
D14			✓					✓				✓
D15						✓		✓	✓			✓
D16								✓	✓			✓
D17			✓						✓	✓	✓	✓✓
D18								✓		✓	✓	

$h \to ll'$

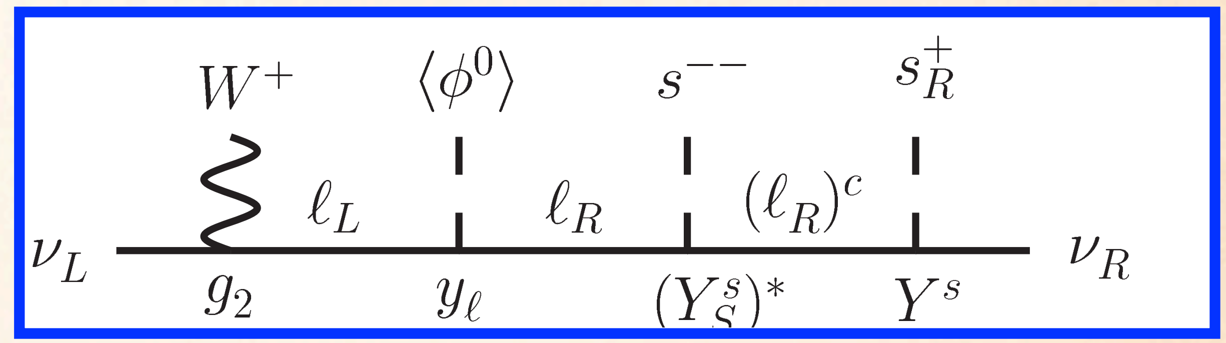
- **Some Mechanisms for Dirac neutrino masses can be compatible with the observation of $h \to ll'$.**

	s^0	s_L^+	s_R^+	s^{++}	Φ_ν	Φ_2	Δ	$\ell \to \ell'\gamma$	
								ℓ'_L	ℓ'_R
$SU(2)_L$	**1**	**1**	**1**	**1**	**2**	**2**	**3**		
$U(1)_Y$	0	1	1	2	1/2	1/2	1		
Lepton number	−2	−2	−2	−2	0	0	−2		
Z'_2	+	+	−	+	−	+	+		
D1		✓	✓					✓	✓
D2			✓				✓	✓	✓
D3			✓	✓		✓			✓✓
D4			✓	✓					✓✓
D5	✓		✓			✓			✓
D6	✓		✓						✓
D7					✓			✓	

D3



D4



- **The singlet scalars s_R^+ and s^{++} interact with ℓ_R.**

s_R^+

$$(Y^s)_{\ell i}\left[\overline{(\ell_R)^c}\,\nu_{iR}\,s_R^+\right]$$

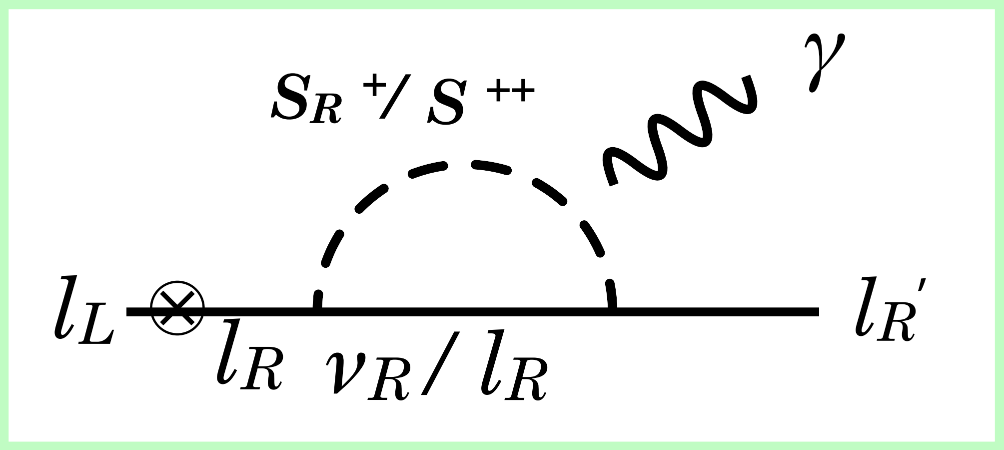
s^{++}

$$(Y_S^s)_{\ell\ell'}\left[\overline{(\ell_R)^c}\,\ell'_R\,s^{++}\right]$$

$h \to ll'$

D3, D4

$l \to l'\gamma$



- **Contributions of these scalars to $\ell \to \ell_R\, \gamma$ can be destructive.**

$$\mathrm{BR}(\ell \to \ell'\gamma) \propto \left| \frac{(Y^{s\dagger}Y^{s})_{\ell\ell'}}{m^2_{s_R^+}} + 16\frac{(Y_S^{s\dagger}Y_S^{s})_{\ell\ell'}}{m^2_{s^{++}}} \right|^2 \ll \left| \frac{(Y^{s\dagger}Y^{s})_{\ell\ell'}}{m^2_{s_R^+}} \right|^2,$$

- **The 10^{-3} tuning of two amplitudes is required for the cancellation to satisfy BR($l \to l'\gamma$) < 10^{-8} , since BR($h \to \mu\tau$) ~ 10^{-3} naively corresponds to BR($\tau \to \mu\gamma$) ~ 10^{-2}.**

$h \to ll'$

- The contributions of s_R^+ and s^{++} to $h \to ll'$ can be constructive.

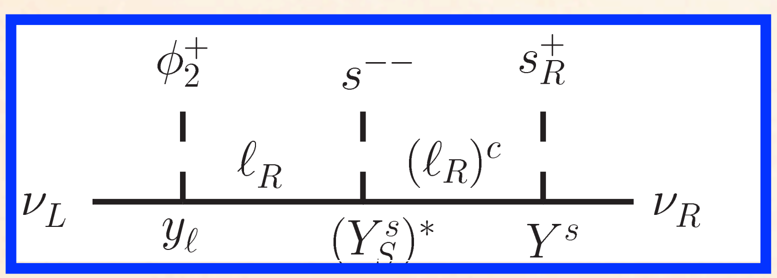
$h \to ll'$

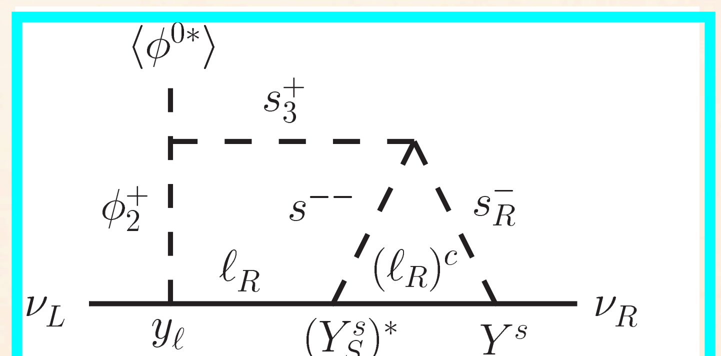
$$\mathrm{BR}(h \to \ell\ell') \propto \left| \lambda_{hs^+} \frac{(Y^{s\dagger} Y^s)_{\ell\ell'}}{m_{s_R^+}^2} + 4\lambda_{hs^{++}} \frac{(Y_S^{s\dagger} Y_S^s)_{\ell\ell'}}{m_{s^{++}}^2} \right|^2 \sim \left| \lambda_{hs^+} \frac{(Y^{s\dagger} Y^s)_{\ell\ell'}}{m_{s_R^+}^2} \right|^2 ,$$

- The λ_{hS+} and λ_{hS++} should have the opposite sign.
- The scalar interactions $\lambda_{hs^+} v h |s_R^+|^2, \ \lambda_{hs^{++}} v h |s^{++}|^2$ are not used for the neutrino mass generation. They are free from constraints from neutrino oscillation experiments.

(e.g.) Kanemura, Sakurai, Sugiyama (2016)

D3



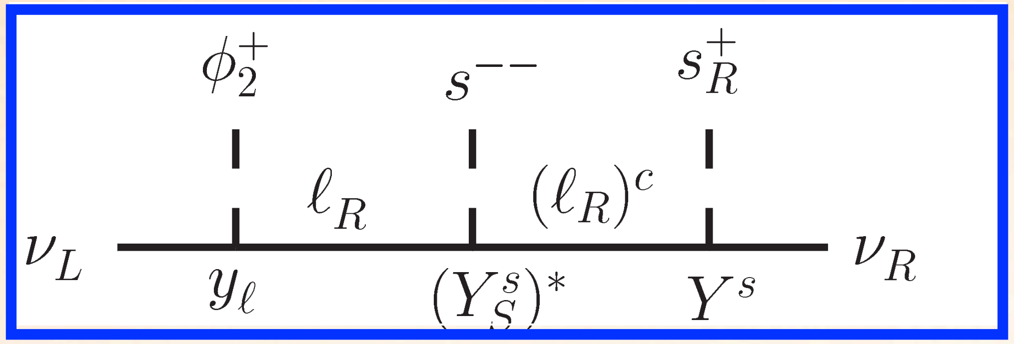


Scalar	$SU(2)_L$	$U(1)_Y$	L#
s_3^+	$\underline{1}$	1	0

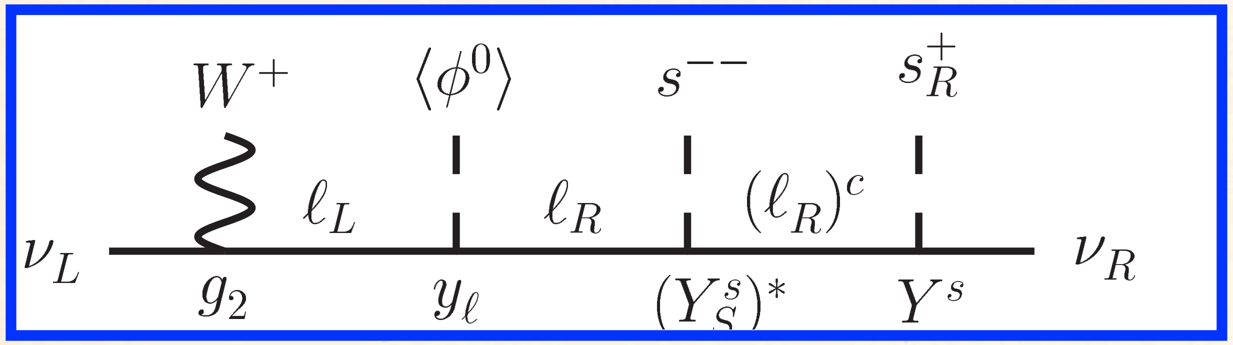
- The Mechanisms-D3, D4, D11, D12, and D17 of the Dirac neutrino mass would be preferred when $h \to ll'$ is observed.

Neutrino mass matrix

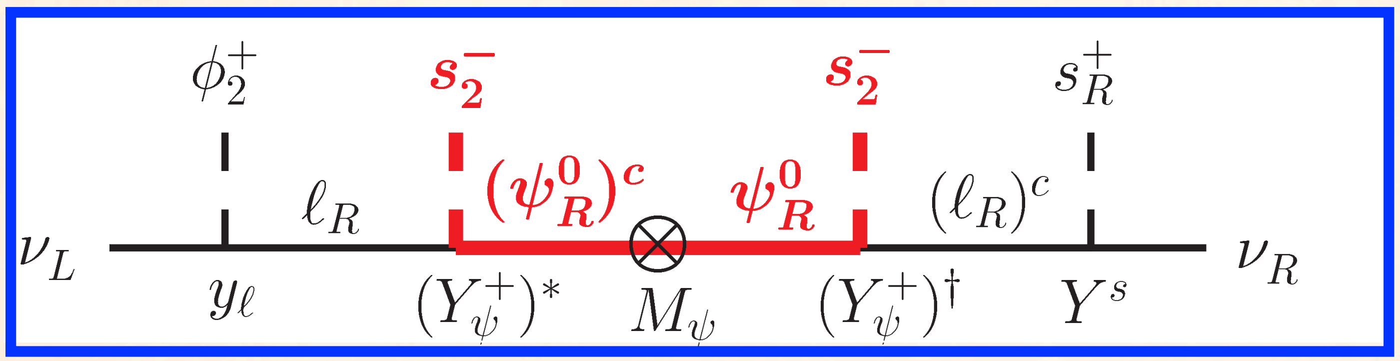
D3



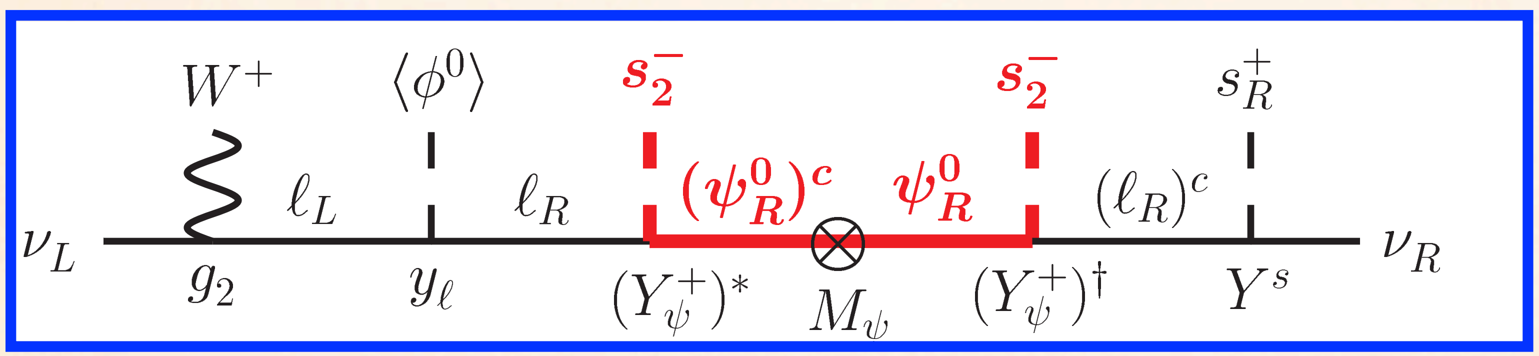
D4



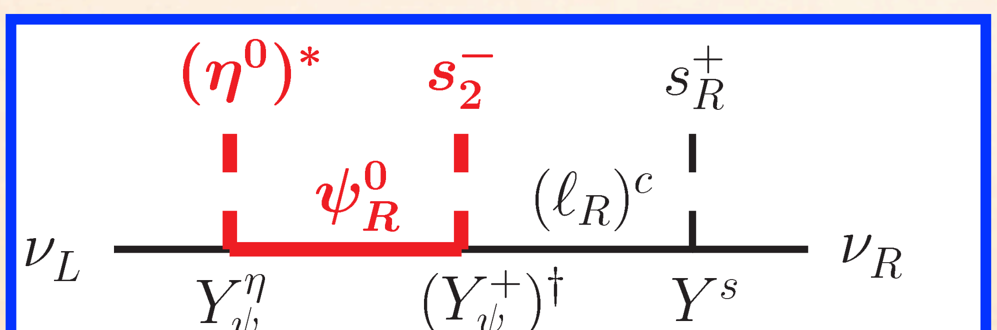
D11



D12



D17



$$m_{\rm D} \propto y_\ell \underline{X_{SR}^*} Y^s$$

symmetric matrix

$$X_{SR} = \begin{cases} Y_S^s & \text{D3, D4} \\ (Y_\psi^+)^* M_\psi (Y_\psi^+)^\dagger & \text{D11, D12} \end{cases}$$

$$m_{\rm D} \propto Y_\psi^\eta (Y_\psi^+)^\dagger Y^s$$

Summary

- We have studied the LFV decay of the Higgs boson in a wide set of models for neutrino masses.

- The simple models of Majorana neutrinos are excluded if $h \to ll'$ is discovered.

- The five Mechanisms for Dirac neutrinos can give a significant amount of $h \to ll'$ with the suppressed $l \to l'\gamma$ process.
    - Two kinds of scalar particles couple to l_R.
    - Their contributions to $l \to l'\gamma$ can be cancelled with each other.

D3, D4	S_R^+ , S^{++}
D11, D12, D17	S_R^+ , S_2^+ (Z2 odd)

- Future discovery of the nonzero BR($h \to ll'$) shall be a strong probe of models for neutrino masses.