Neutrino Mass Models and Lepton Flavor Violating Decays of the Higgs boson

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- Introduction
- Classification of Models
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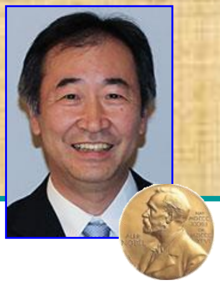
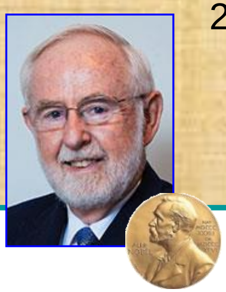
Based on “S. Kanemura, HS, PLB753, 161”
“S. Kanemura, K. Sakurai, HS, PLB758, 465”
“M. Aoki, S. Kanemura, K. Sakurai, HS, PLB763,352”

Introduction



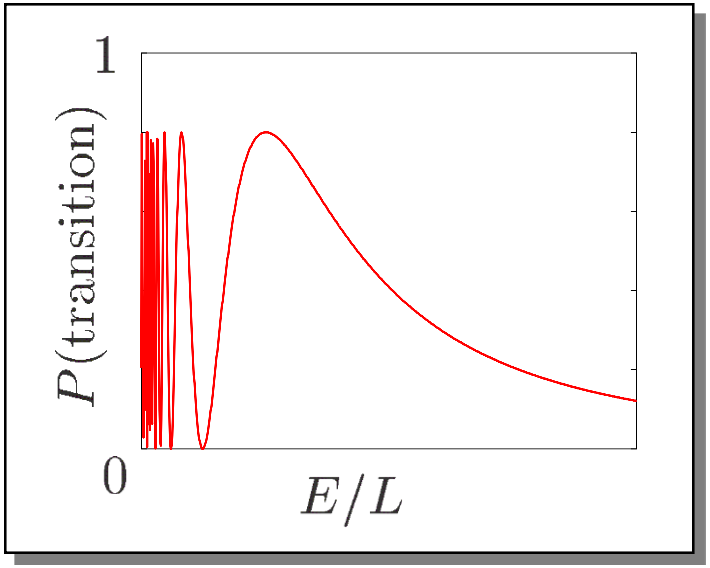


Neutrino oscillation

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

Transition prob.

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



Non-zero neutrino mass

cf. Massless in SM

↓

Very tiny mass

Lepton Flavor Violation (LFV)

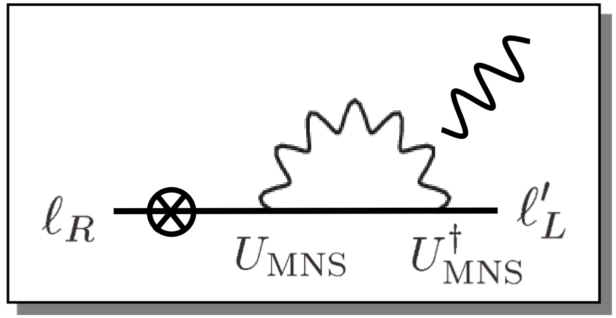
cf. Conserved in SM

↓

Large mixings exist

($\theta_{23} \simeq 45^\circ$, $\theta_{12} \simeq 33^\circ$)

} **Two** new physics beyond the standard model (SM)



ν oscillation results

Large mixings in U_{MNS}

↓

Potentially large LFV

Suppressed by $\frac{m_\nu^4}{m_W^4}$

LFV (other than ν osc.)

e.g., $\ell \to \overline{\ell_1}\ell_2\ell_3$

$\ell \to \ell'\gamma$

$h \to \ell\ell'$

New observable

Models for tiny neutrino masses

New Yukawa matrices as origin of LFV
(potentially large)

↓

New scalar fields with leptonic Yukawa interactions

Not necessarily suppressed

LFV (other than ν osc.)

e.g., $\ell \to \overline{\ell_1}\ell_2\ell_3$

$\ell \to \ell'\gamma$

$h \to \ell\ell'$

New observable

Discrimination of models

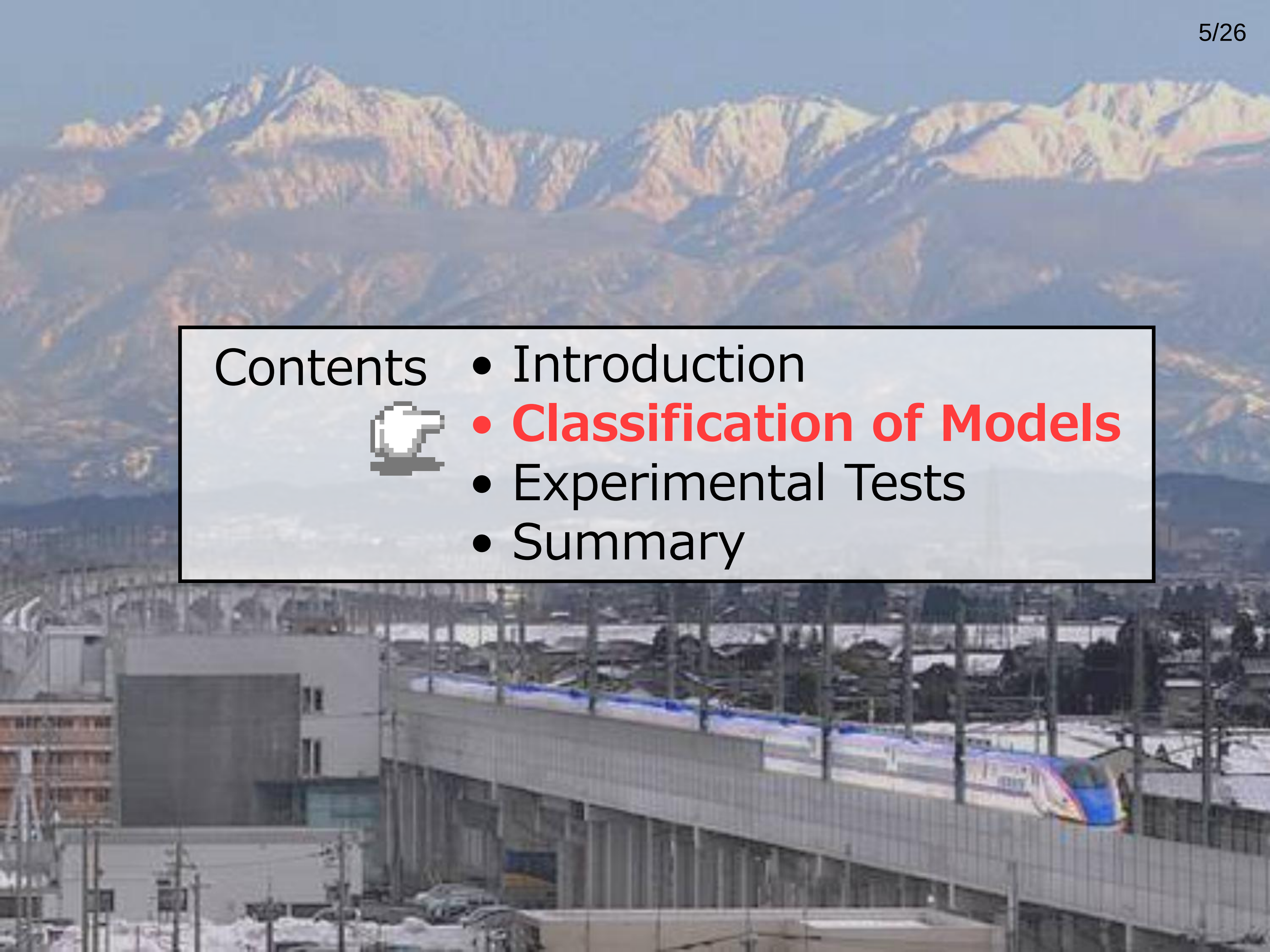
Models for tiny neutrino masses

New Yukawa matrices as origin of LFV (potentially large)

↓

New scalar fields with leptonic Yukawa interactions

Not necessarily suppressed



Contents

Neutrino Mass in New Physics Models

- The standard model (SM) ⟶ Massless
- Neutrino oscillation ⟶ **Non-zero masses**

$\Downarrow$

<u>Two possible neutrino masses</u>

Dirac mass : $m_D \overline{\nu_L} \nu_R$ (introduce ν_R)

$$y_\nu \overline{L} \epsilon \Phi^* \nu_R \implies m_D = \frac{y_\nu}{\sqrt{2}} v$$

$$(m_D \sim 0.1\,\mathrm{eV} \implies y_\nu \sim 10^{-12})$$

Unnaturally small

Nontrivial way ?

Majorana mass : $m_L \overline{\nu_L} (\nu_L)^c$ (Lepton # violation)

$$Q_{\rm EM} : \; 0 + 0 = 0$$

Specific to neutrinos ⟶ **How to generate ?**

Many possibilities ⟶ Which is the true one ?

Classification of Models of Neutrino Mass

There are (too) many models.

↓

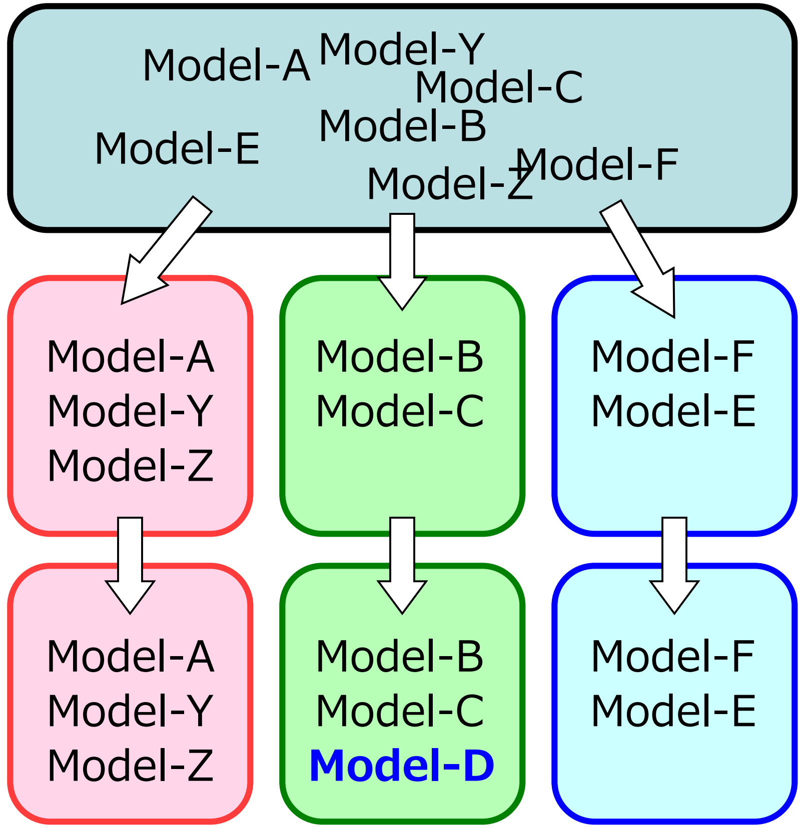
Classification is desired.

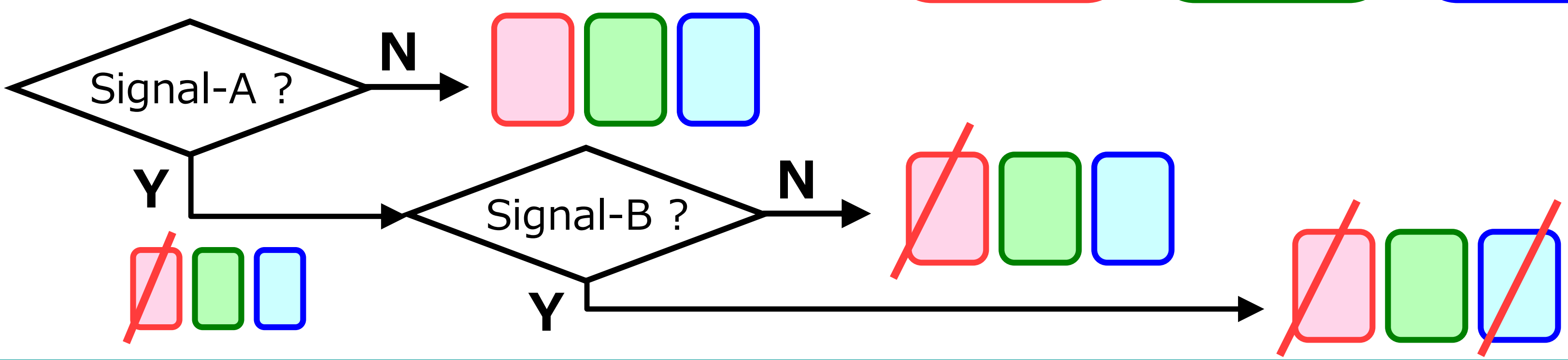
↓

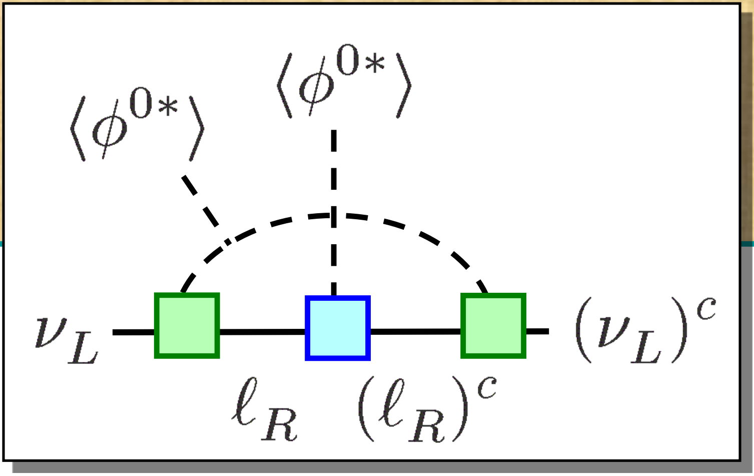
Missing models ?

↓

Efficient tests ?







How to classify ?

Properties of neutrino mass matrix

Overall scale ← { New particle masses
Topology of diagram (tree, one-loop, ...)
Sizes of coupling constants (Yukawa, potential)

Matrix structure ← { Products of Yukawa matrices
Structures of Yukawa (sym., antisym., diag.)

Only Yukawa. Not detail of models

$\Downarrow$

Classification by concentrating on Yukawa int. with leptons

Setup

New scalars : Required to be introduced

cf. No new scalars $\Rightarrow$ Seesaw

$\Rightarrow$ Difficult to be tested

No lepton flavor

cf. Sleptons for SUSY

Flavor symmetry

No color

cf. Scalar leptoquarks

No flavor changing neutral current at tree level

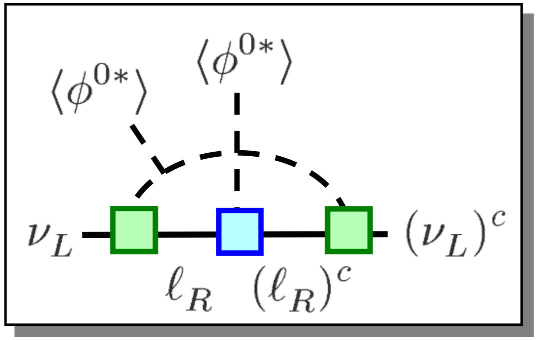
New fermions : ν_R only for Dirac neutrinos (no $m_R \overline{(\nu_R)^c} \nu_R$)

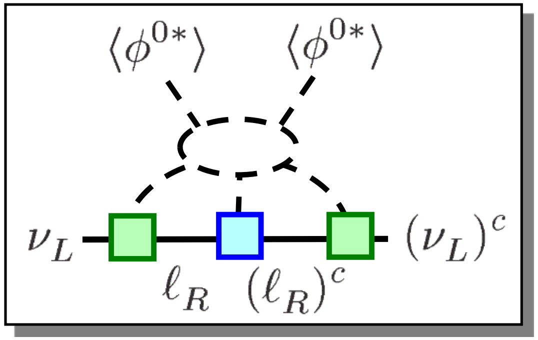
ψ_R^0
- Gauge-singlet
- Z_2 **odd**
- Majorana fermion $m_\psi \overline{(\psi_R^0)^c} \psi_R^0$

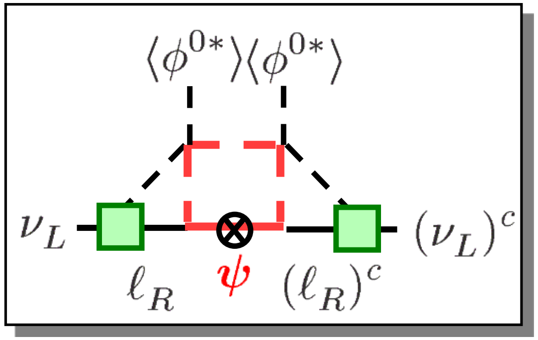
Classification according to interactions of leptons

- Models (full Lagrangian)

Red lines : Z_2 - odd



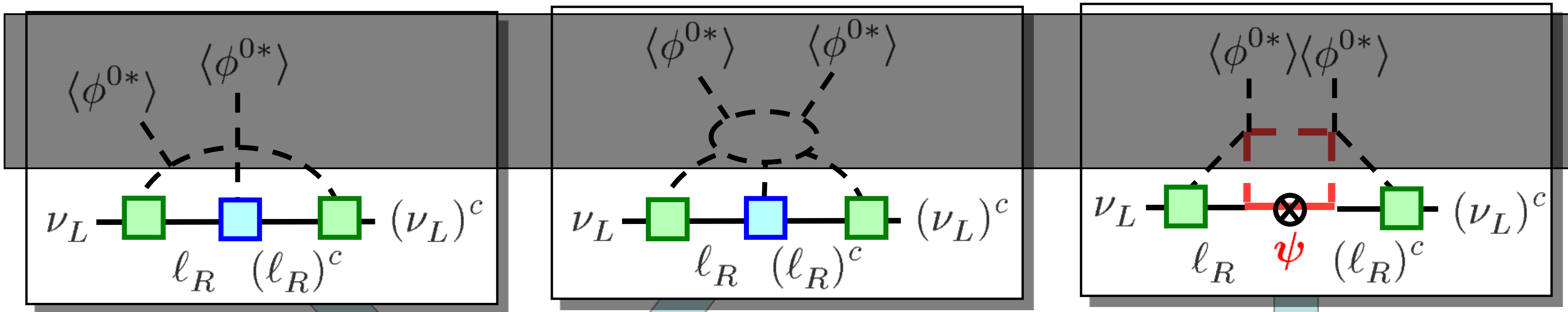




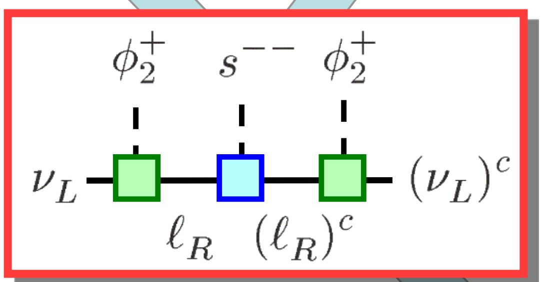
Classification according to interactions of leptons

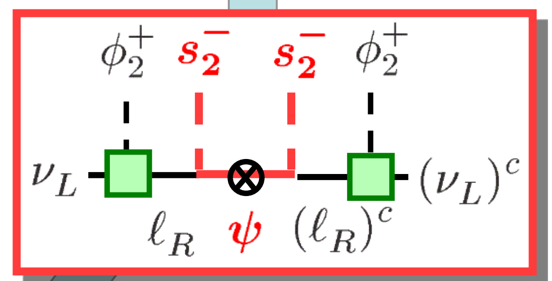
- Models (full Lagrangian)

Red lines : Z_2 - odd

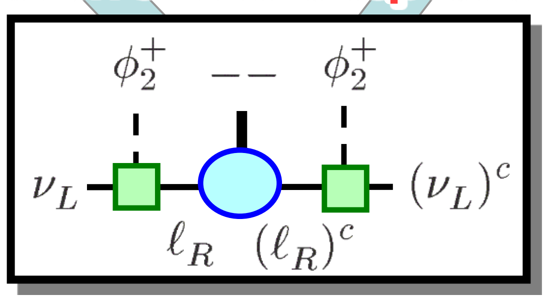


- Concentrating on **Yukawa int.**





- Concentrating on interactions **between two leptons** (effective)



Scalars with Leptonic Yukawa Int.

Majorana

	$SU(2)_L$	$U(1)_Y$	L#	Z_2'	**Yukawa int.**	Note
						Sym.
s_L^+	$\underline{\mathbf{1}}$	1	-2	$+$	$(Y_A^s)_{\ell\ell'}\left[\overline{L_\ell}\,\epsilon L_{\ell'}^c\, s_L^-\right]$	**Antisym.**
s^{++}	$\underline{\mathbf{1}}$	2	-2	$+$	$(Y_S^s)_{\ell\ell'}\left[\overline{(\ell_R)^c}\,\ell'_R\, s^{++}\right]$	**Sym.**
$\Phi_2 = \begin{pmatrix}\phi_2^+ & \phi_2^0\end{pmatrix}^T$	$\underline{\mathbf{2}}$	$1/2$	0	$+$	$y_\ell\left[\overline{L_\ell}\,\Phi_2\,\ell_R\right]$	**Diag.**
$\Delta = \begin{pmatrix}\Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2}\end{pmatrix}$	$\underline{\mathbf{3}}$	1	-2	$+$	$(Y_S^\Delta)_{\ell\ell'}\left[\overline{L_\ell}\,\Delta^\dagger\epsilon\, L_{\ell'}^c\right]$	**Sym.**
s_2^+ **Z_2 odd**	$\underline{\mathbf{1}}$	1	-1	$+$	$(Y_\psi^+)_{\ell i}\left[\overline{(\ell_R)^c}\,\psi_{iR}^0\, s_2^+\right]$	ψ_R^0
$\eta = \begin{pmatrix}\eta^+ & \eta^0\end{pmatrix}^T$ **Z_2 odd**	$\underline{\mathbf{2}}$	$1/2$	-1	$+$	$(Y_\psi^\eta)_{\ell i}\left[\overline{L_\ell}\,\epsilon\,\eta^*\,\psi_{iR}^0\right]$	ψ_R^0

For Majorana ν masses ($m_L \overline{\nu_L} (\nu_L)^c$)

	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						✓

8 combinations

S. Kanemura, HS, PLB**753**, 161 (2016)

Dirac

Lepton number (conserved)

forbid $y_\nu \overline{L}\,\epsilon\,\Phi^* \nu_R$ at tree level
$+\;+\;-$

	$SU(2)_L$	$U(1)_Y$	L#	Z'_2	**Yukawa int.**	Note
s^0	**1**	0	-2	$+$	$(Y_S^0)_{ij}\left[\overline{(\nu_{iR})^c}\,\nu_{jR}\,s^0\right]$	**Sym.**
s_L^+	**1**	1	-2	$+$	$(Y_A^s)_{\ell\ell'}\left[\overline{L_\ell}\,\epsilon L^c_{\ell'}\,s_L^-\right]$	**Antisym.**
s_R^+	**1**	1	-2	$-$	$(Y^s)_{\ell i}\left[\overline{(\ell_R)^c}\,\nu_{iR}\,s_R^+\right]$	ν_R
s^{++}	**1**	2	-2	$+$	$(Y_S^s)_{\ell\ell'}\left[\overline{(\ell_R)^c}\,\ell'_R\,s^{++}\right]$	**Sym.**
$\Phi_\nu = \begin{pmatrix}\phi_\nu^+ & \phi_\nu^0\end{pmatrix}^T$	**2**	$1/2$	0	$-$	$(Y_\nu)_{\ell i}\left[\overline{L_\ell}\,\epsilon\,\Phi_\nu^*\,\nu_{iR}\right]$	ν_R
$\Phi_2 = \begin{pmatrix}\phi_2^+ & \phi_2^0\end{pmatrix}^T$	**2**	$1/2$	0	$+$	$y_\ell\left[\overline{L_\ell}\,\Phi_2\,\ell_R\right]$	**Diag.**
$\Delta = \begin{pmatrix}\Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2}\end{pmatrix}$	**3**	1	-2	$+$	$(Y_S^\Delta)_{\ell\ell'}\left[\overline{L_\ell}\,\Delta^\dagger\epsilon\,L^c_{\ell'}\right]$	**Sym.**
s_2^0 Z_2 **odd**	**1**	0	-1	$-$	$(Y_\psi^0)_{ij}\left[\overline{(\nu_{iR})^c}\,\psi^0_{jR}\,s_2^0\right]$	ν_R ψ^0_R
s_2^+ Z_2 **odd**	**1**	1	-1	$+$	$(Y_\psi^+)_{\ell i}\left[\overline{(\ell_R)^c}\,\psi^0_{iR}\,s_2^+\right]$	ψ^0_R
$\eta = \begin{pmatrix}\eta^+ & \eta^0\end{pmatrix}^T$ Z_2 **odd**	**2**	$1/2$	-1	$+$	$(Y_\psi^\eta)_{\ell i}\left[\overline{L_\ell}\,\epsilon\,\eta^*\,\psi^0_{iR}\right]$	ψ^0_R

For Dirac ν masses (without DM)

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

S. Kanemura, K. Sakurai, HS, PLB**758**, 465 (2016)

For Dirac ν masses (with DM)

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

18 combinations

S. Kanemura, K. Sakurai, HS, PLB**758**, 465 (2016)

Combinations of Yukawa int. (or scalar fields)

For Majorana mass : **8 combinations**

For Dirac mass : **18 combinations**

→ How can we **test them ?**

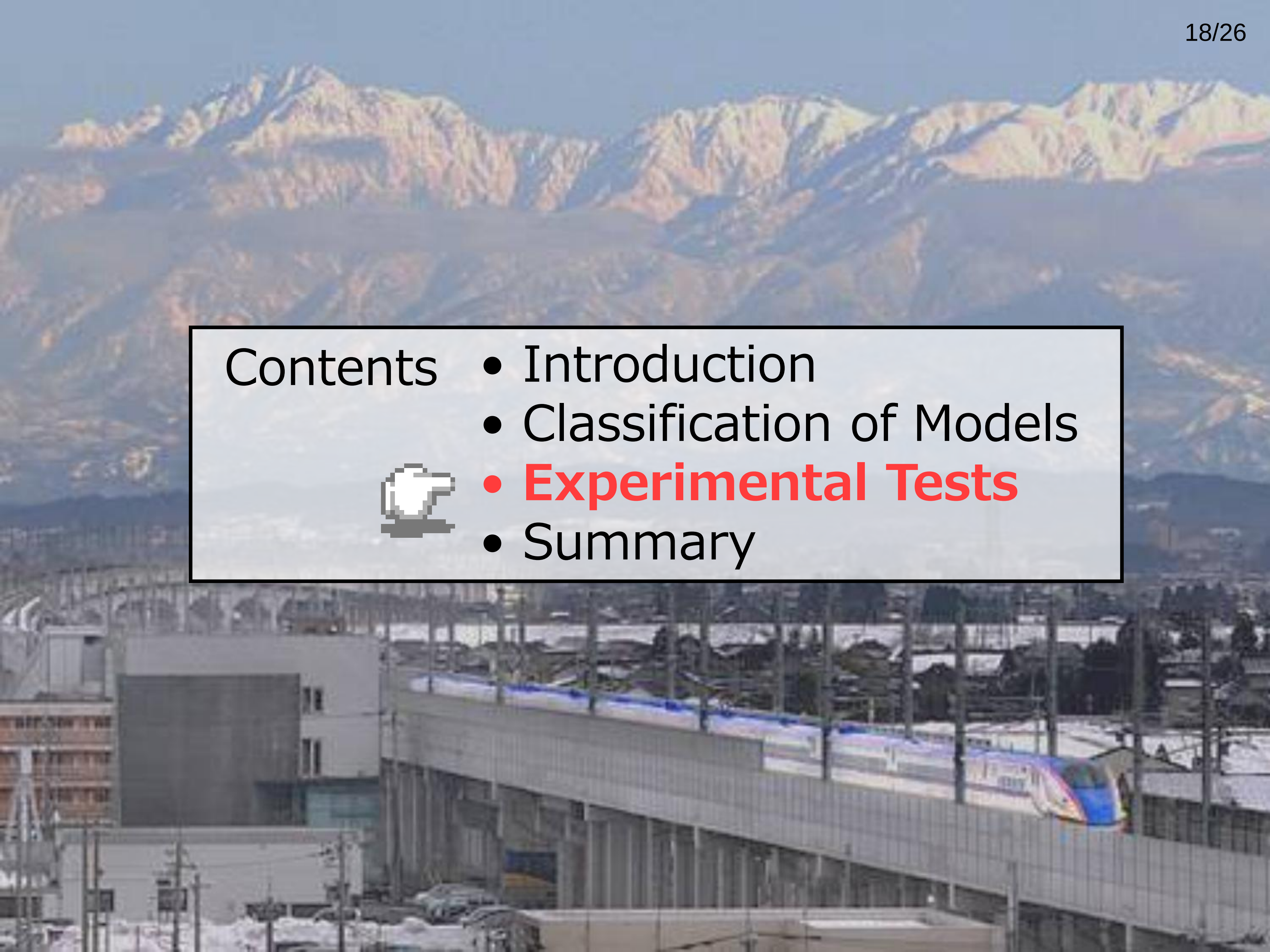
→ Concentrating on Yukawa $\Rightarrow$ **Flavor experimens**

$\ell \to \bar{\ell}_1 \ell_2 \ell_3$

$\ell \to \ell' \nu \bar{\nu}$

$\ell \to \ell' \gamma$

$h \to \ell \ell'$



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LFV Decay of the Higgs Boson

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

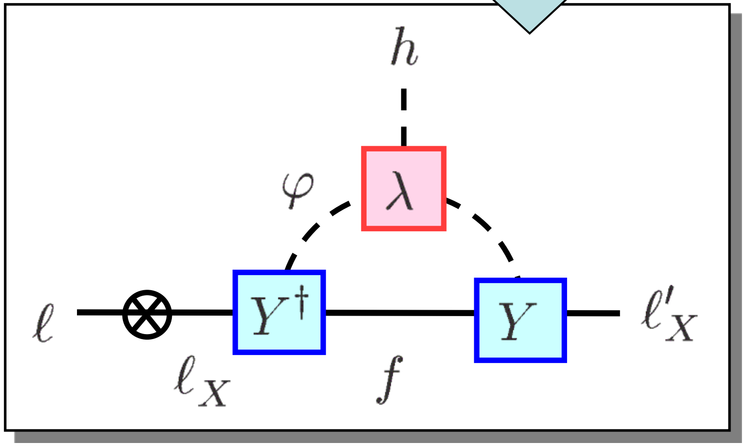
		ATLAS arXiv:1604.07730 $(8\,\mathrm{TeV}, 20.3\,\mathrm{fb}^{-1})$	CMS [1] PLB**763**, 472 (2016) [2] PLB**749**, 337 (2015) $(8\,\mathrm{TeV}, 19.7\,\mathrm{fb}^{-1})$ (for [1], [2]) [3] CMS PAS HIG-16-005 $(13\,\mathrm{TeV}, 2.3\,\mathrm{fb}^{-1})$
$h \to \mu e$	Limit		$< 3.5 \times 10^{-4}$ [1]
	Best fit		
$h \to \tau e$	Limit	$< 1.04 \times 10^{-2}$	$< 6.9 \times 10^{-3}$ [1]
	Best fit	$-3.4^{+6.4}_{-6.6} \times 10^{-3}$	
$h \to \tau\mu$	Limit	$< 1.43 \times 10^{-2}$	$< 1.51 \times 10^{-2}$ [2] $< 1.20 \times 10^{-2}$ [3]
	Best fit	$5.3^{+5.1}_{-5.1} \times 10^{-3}$	$8.4^{+3.9}_{-3.7} \times 10^{-3}$ $(2.4\,\sigma)$ [2] $-7.6^{+8.1}_{-8.4} \times 10^{-3}$ [3]

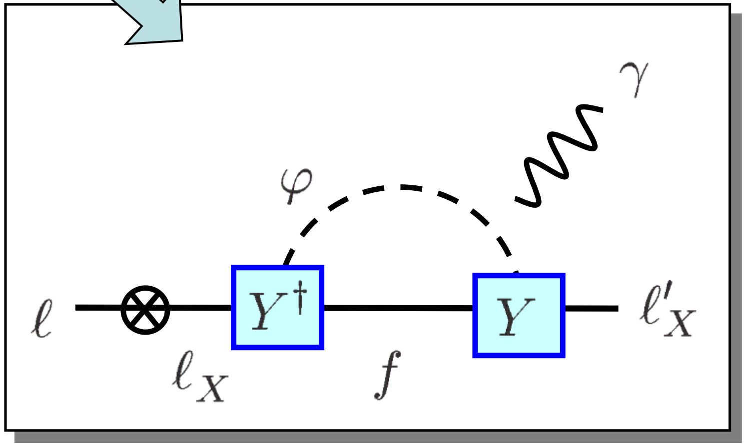
My naïve calc. (combining the two CMS best fits for $h \to \tau\mu$): $(5.6 \pm 3.5) \times 10^{-3}$ $(1.6\,\sigma)$

$h \to \ell\ell'$ and $\ell \to \ell'\gamma$

Toy model : $\mathcal{L} = \boldsymbol{Y_{a\ell}} \left[\overline{f_a}\, \ell_X\, \varphi \right] - \boldsymbol{\lambda} |\Phi|^2 |\varphi|^2 + \cdots$

$X = L, R$





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

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., EPJC**76**, no.8, 434

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

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

M. Aoki, S. Kanemura, K. Sakurai, HS,
PLB**763**, 352 (2016)

"Mechanisms" for Majorana ν mass

	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						✓	✓	

$h \to \ell\ell'$ signal $\Rightarrow$ $\mathrm{BR}(\ell \to \ell'\gamma)$ is too large $\Rightarrow$ **Excluded**

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

M. Aoki, S. Kanemura, K. Sakurai, HS,
PLB**763**, 352 (2016)

"Mechanisms" for Majorana ν mass

	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 !

"Mechanisms" for Dirac ν mass (without DM)

	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		
L#	−2	−2	−2	−2	0	0	−2	−1	−1	−1		
Z'_2	+	+	−	+	−	+	+	−	+	+		
D1		✓	✓								✓	✓
D2			✓				✓				✓	✓
D3			✓	✓		✓						✓✓
D4			✓	✓								✓✓
D5	✓		✓			✓						✓
D6	✓		✓									✓
D7					✓						✓	

D3 and D4 survive

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

Cancellation is possible

"Mechanisms" for Dirac ν mass (with DM)

	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	+	+	−	+	−	+	+	−	+	+		
D8		✓						✓	✓		✓	✓
D9							✓	✓	✓		✓	✓
D10			✓							✓	✓	✓
D11			✓			✓			✓			✓✓
D12			✓						✓			✓✓
D13			✓			✓		✓				✓
D14			✓					✓				✓
D15									✓			✓
D16								✓	✓			✓
D17			✓						✓	✓	✓	✓✓
D18								✓		✓	✓	

D11, D12, and D17 survive

"Mechanisms" for Dirac ν mass

	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			✓	✓								✓✓
D11			✓			✓			✓			✓✓
D12			✓						✓			✓✓
D17			✓						✓	✓	✓	✓✓

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

Summary

Simple models to generate **Majorana** ν masses can be classified into **8 combinations** of Yukawa int. (New scalars)

Simple models to generate **Dirac** ν masses can be classified into **18 combinations** of Yukawa int. (New scalars)

$h \to \ell\ell'$ ⟶

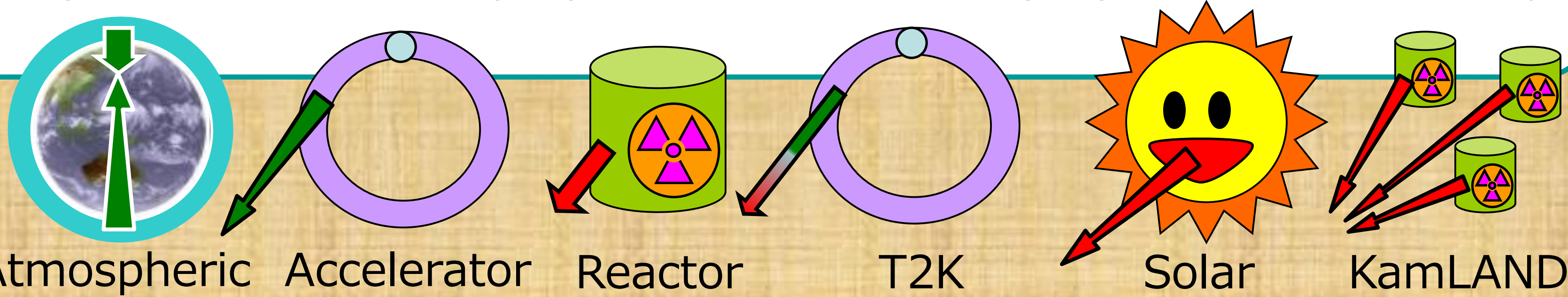
- Simple models for **Majorana** ν masses are **excluded**
- Some simple models for **Dirac** ν masses can **survive**

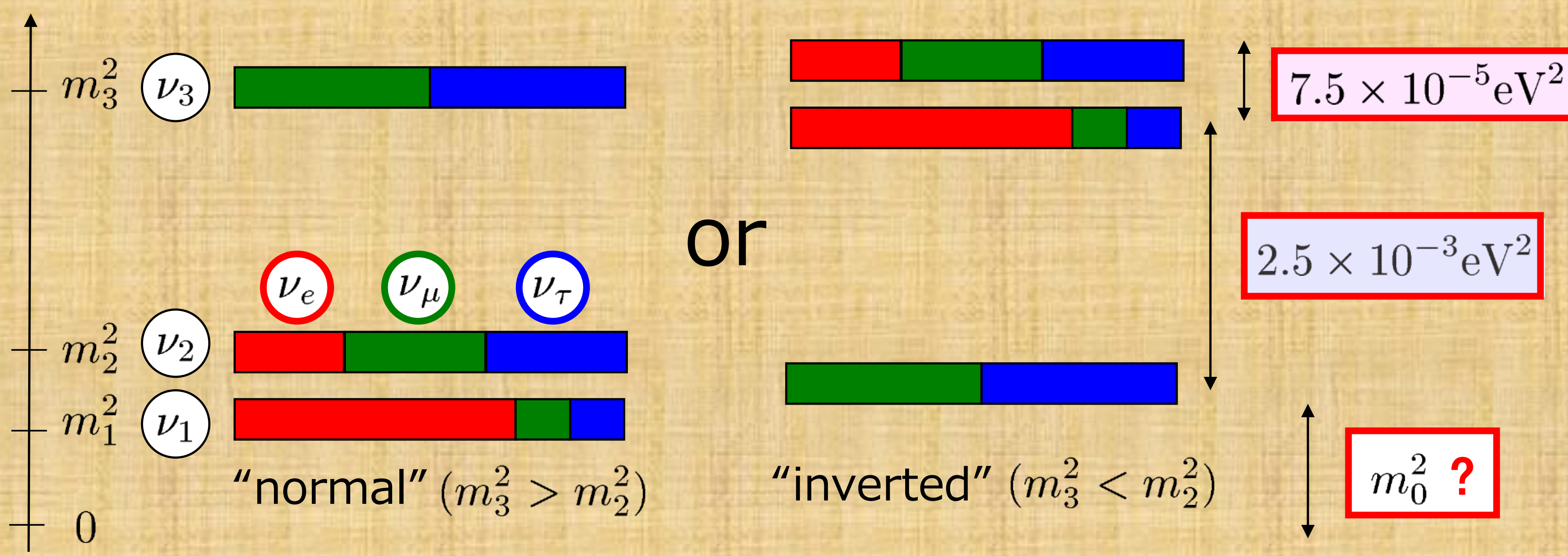
Backup

Current knowledge

$\theta_{23} \simeq 45^\circ$ $\theta_{13} \simeq 9^\circ$ δ **?** $\theta_{12} \simeq 33^\circ$

$$U_{\rm MNS} \simeq \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0.71 & 0.71 \\ 0 & -0.71 & 0.71 \end{pmatrix} \begin{pmatrix} 0.99 & 0 & 0.15 \\ 0 & 1 & 0 \\ 0.15 & 0 & 0.99 \end{pmatrix} \begin{pmatrix} 0.83 & 0.55 & 0 \\ -0.55 & 0.83 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$





Oscillation Data

$$m_\nu = U^*_{\rm MNS}\,{\rm diag}(m_1 e^{i\alpha_{12}},\, m_2,\, m_3 e^{i\alpha_{32}})\,U^\dagger_{\rm MNS}$$

$$U_{\rm MNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij} \qquad s_{ij} \equiv \sin\theta_{ij}$$

T2K :

$$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}, \qquad \Delta m^2_{32} = (2.51 \pm 0.10) \times 10^{-3}\,{\rm eV}^2$$

$$\sin^2\theta_{23} = 0.511^{+0.055}_{-0.055}, \qquad \Delta m^2_{23} = (2.48 \pm 0.10) \times 10^{-3}\,{\rm eV}^2$$

K. Abe *et al*., PRL**112**, 181801 (2014)

Daya Bay :

$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

R.P. An *et al*., PRL**112**, 061801 (2014)

$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

R.P. An *et al*., PRL**115**, 111802 (2015)

SNO :

$$\tan^2\theta_{12} = 0.427^{+0.027}_{-0.024}, \qquad \Delta m^2_{21} = 7.46^{+0.20}_{-0.19} \times 10^{-5}\,{\rm eV}^2$$

B. Aharmim *et al*., PRC**88**, 025501 (2013)

Absolute Mass Scale

I) $m_\nu \propto Y_A\, y_\ell\, X_{SR}\, y_\ell\, Y_A^T$

I′) $m_D \propto Y_A^s\, y_\ell\, X^s$

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

$\mathrm{Det}(m_\nu) \propto \mathrm{Det}(Y_A) = 0$

→ $m_1 = 0$ or $m_3 = 0$

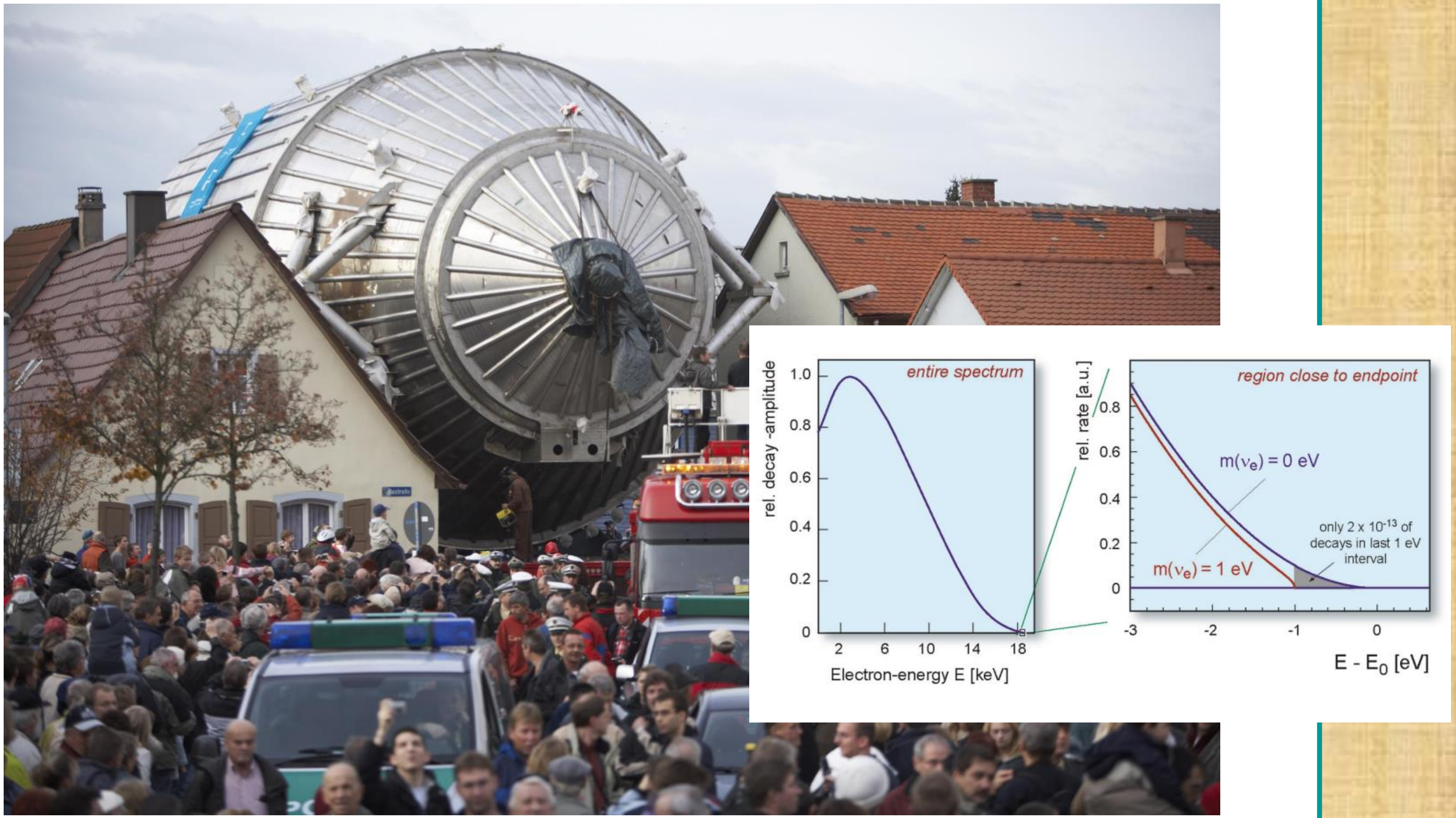
m_i : Neutrino mass eigenvalues
($m_2 \neq 0$ due to solar ν osc.)

→ If $\min(m_i) \neq 0$ experimentally $\Rightarrow$ **Excluded**

Direct (^3H β-decay): $m_\nu \simeq 0.35\,\mathrm{eV}$ ($5\,\sigma$ sensitivity)

Indirect (Cosmology): $\Sigma m_i = \mathcal{O}(0.01)\,\mathrm{eV}$ ($95\,\%$ CL sens.)

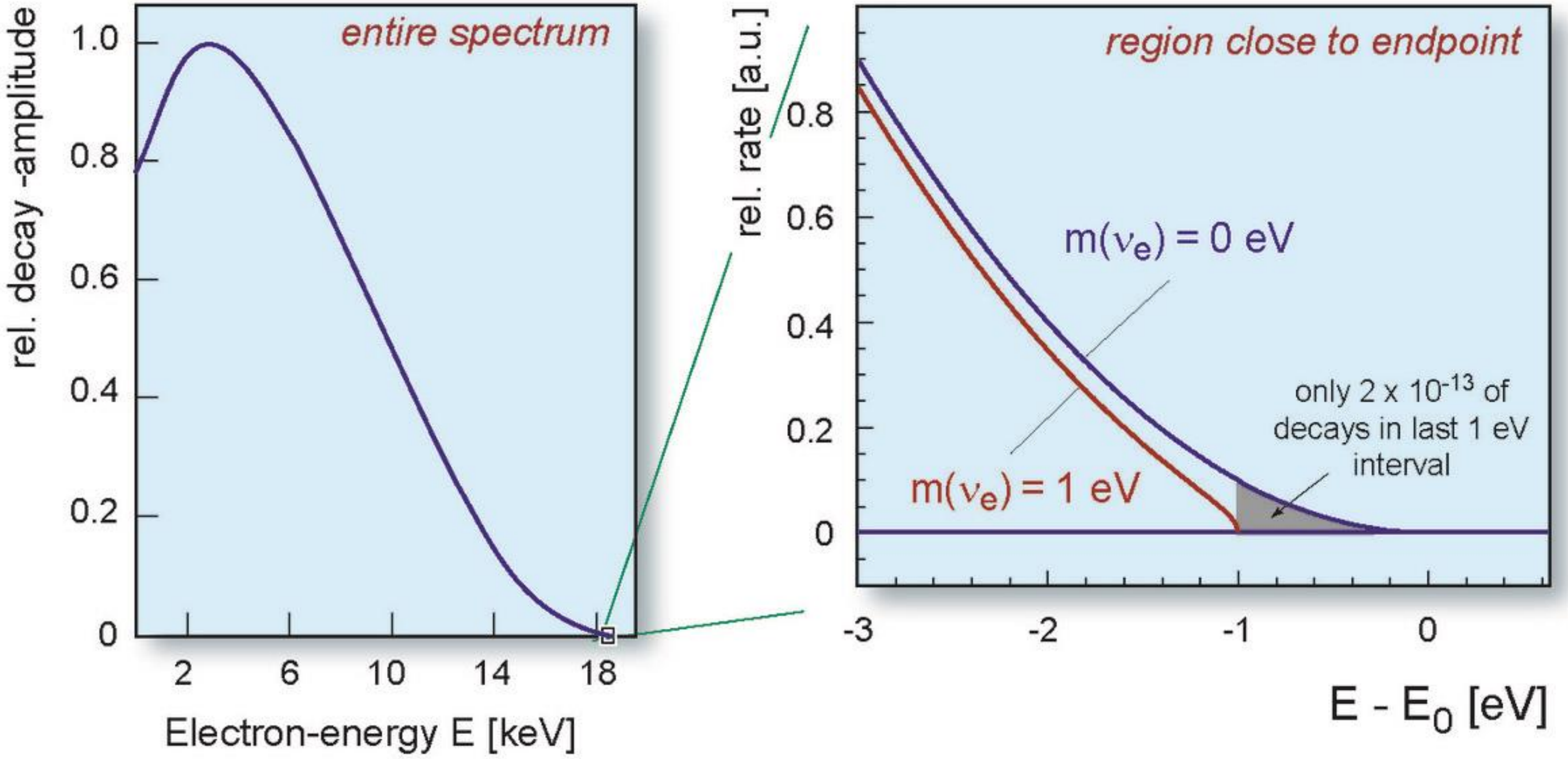
Not for a model but **for all models belong to Group-I and I′**
(e.g. ZB model, KNT model, NM model)



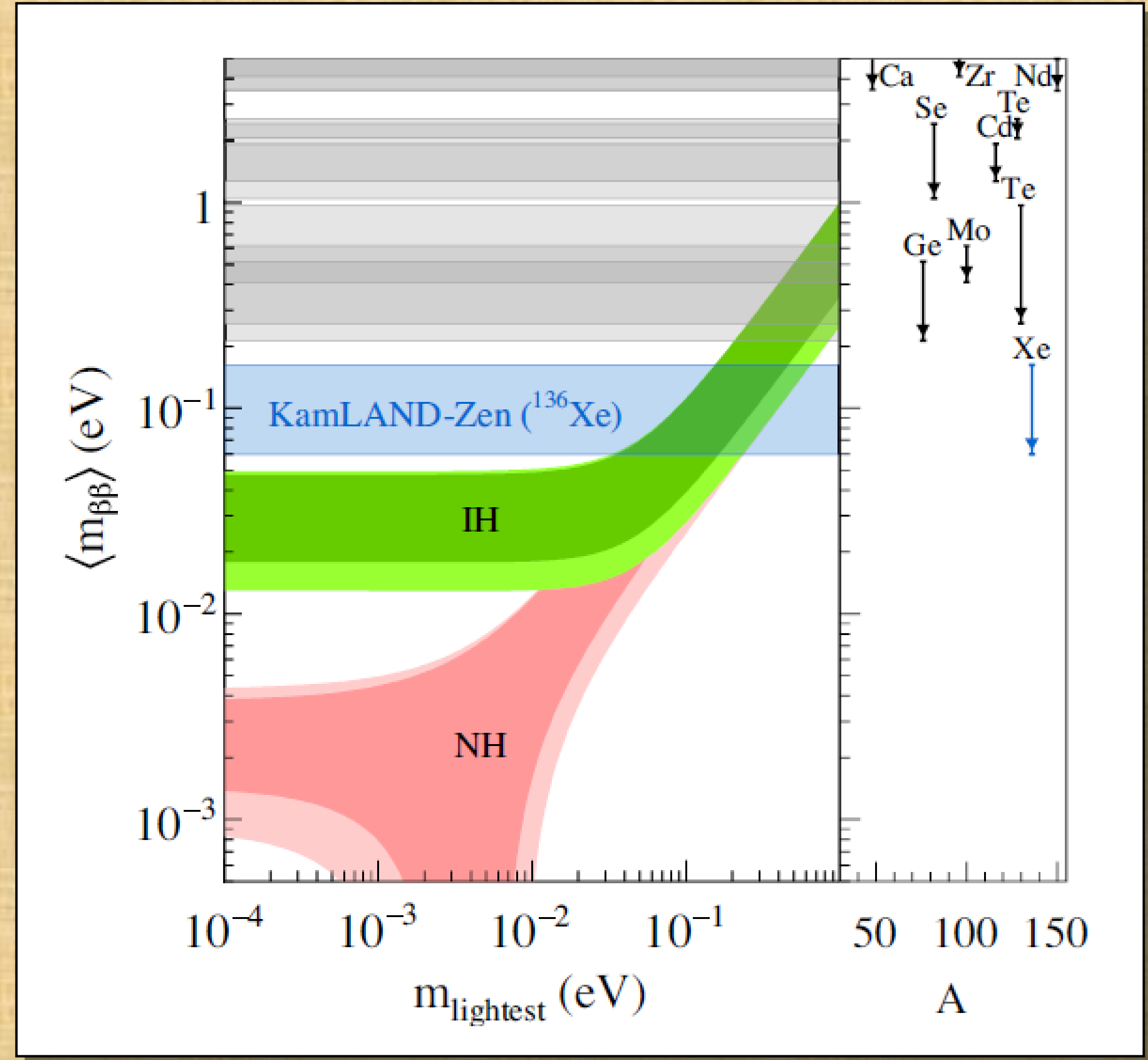
https://www.katrin.kit.edu/213.php

Main spectrometer of KATRIN experiment

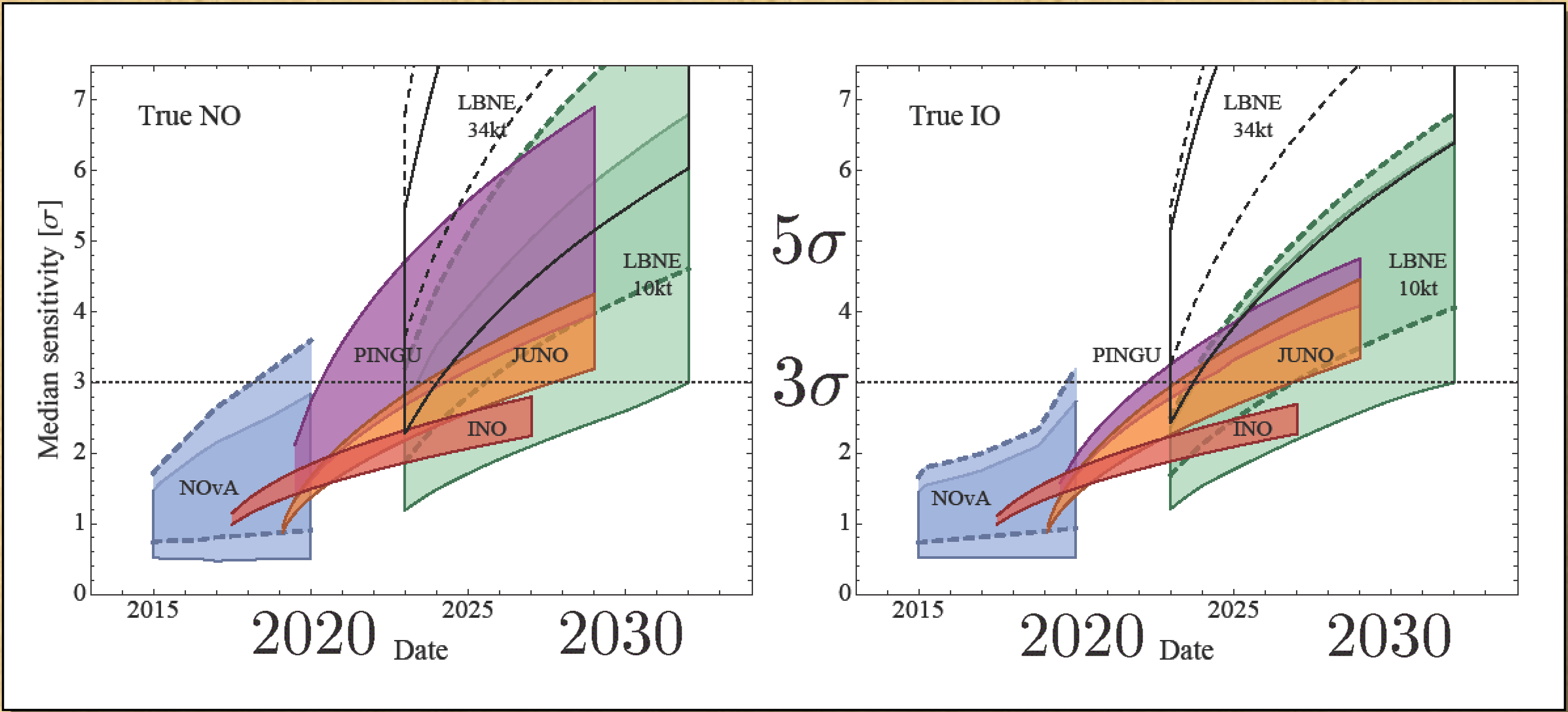
Transport through Leopoldshafen in Germany



http://www.katrin.kit.edu/79.php



KamLAND-ZEN collab., arXiv:1605.02889



M. Blennow *et al.*, JHEP**1403**, 028 (2014)

LFV Decay of the Higgs Boson

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

		ATLAS arXiv:1604.07730 $(8\,\mathrm{TeV}, 20.3\,\mathrm{fb}^{-1})$	CMS [1] arXiv:1607.03561 [2] PLB**749**, 337 (2015) (both $(8\,\mathrm{TeV}, 19.7\,\mathrm{fb}^{-1})$) [3] CMS PAS HIG-16-005 $(13\,\mathrm{TeV}, 2.3\,\mathrm{fb}^{-1})$
$h \to \mu e$	Limit		$< 3.5 \times 10^{-4}$ [1]
	Best fit		
$h \to \tau e$	Limit	$< 1.04 \times 10^{-2}$	$< 6.9 \times 10^{-3}$ [1]
	Best fit	$-3.4^{+6.4}_{-6.6} \times 10^{-3}$	
$h \to \tau\mu$	Limit	$< 1.43 \times 10^{-2}$	$< 1.51 \times 10^{-2}$ [2] $< 1.20 \times 10^{-2}$ [3]
	Best fit	$5.3^{+5.1}_{-5.1} \times 10^{-3}$	$8.4^{+3.9}_{-3.7} \times 10^{-3}$ $(2.4\,\sigma)$ [2] $-7.6^{+8.1}_{-8.4} \times 10^{-3}$ [3]

My naïve calc. (combining the CMS best fits): $(5.6 \pm 3.5) \times 10^{-3}$ $(1.6\,\sigma)$

$h \to \ell\ell'$ at the loop level

Dim.-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**

Dim.-6 operator

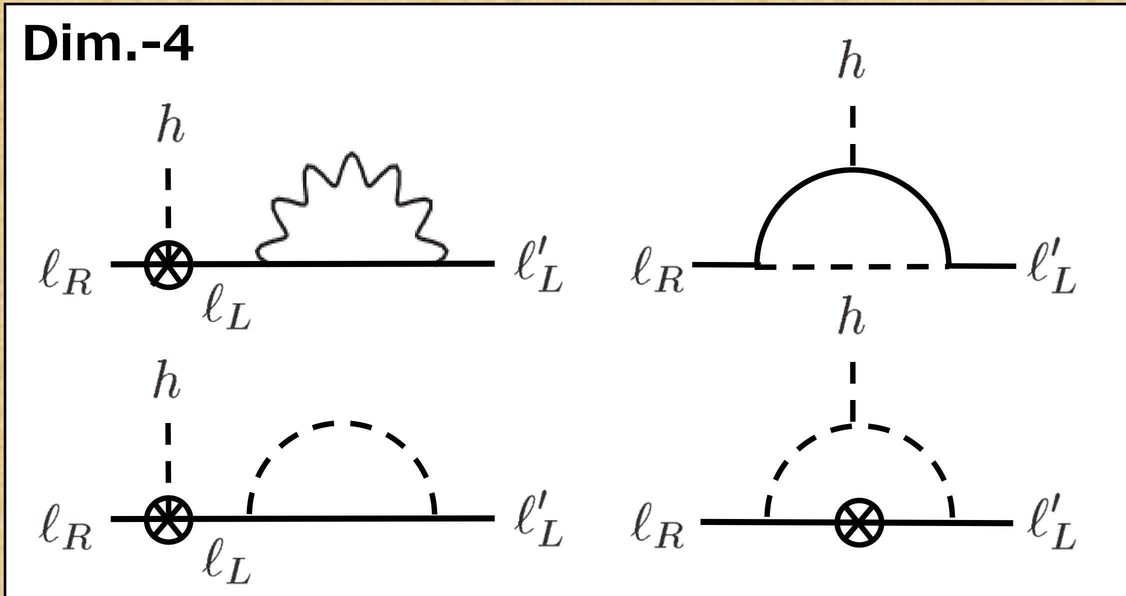
$$\mathcal{L} = \boldsymbol{Y_4}\left[\overline{L}\,\Phi\ell'_R\right] + \frac{\boldsymbol{Y_6}}{\Lambda^2}\left[\overline{L}\,\Phi\ell'_R(\Phi^\dagger\Phi)\right]$$

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

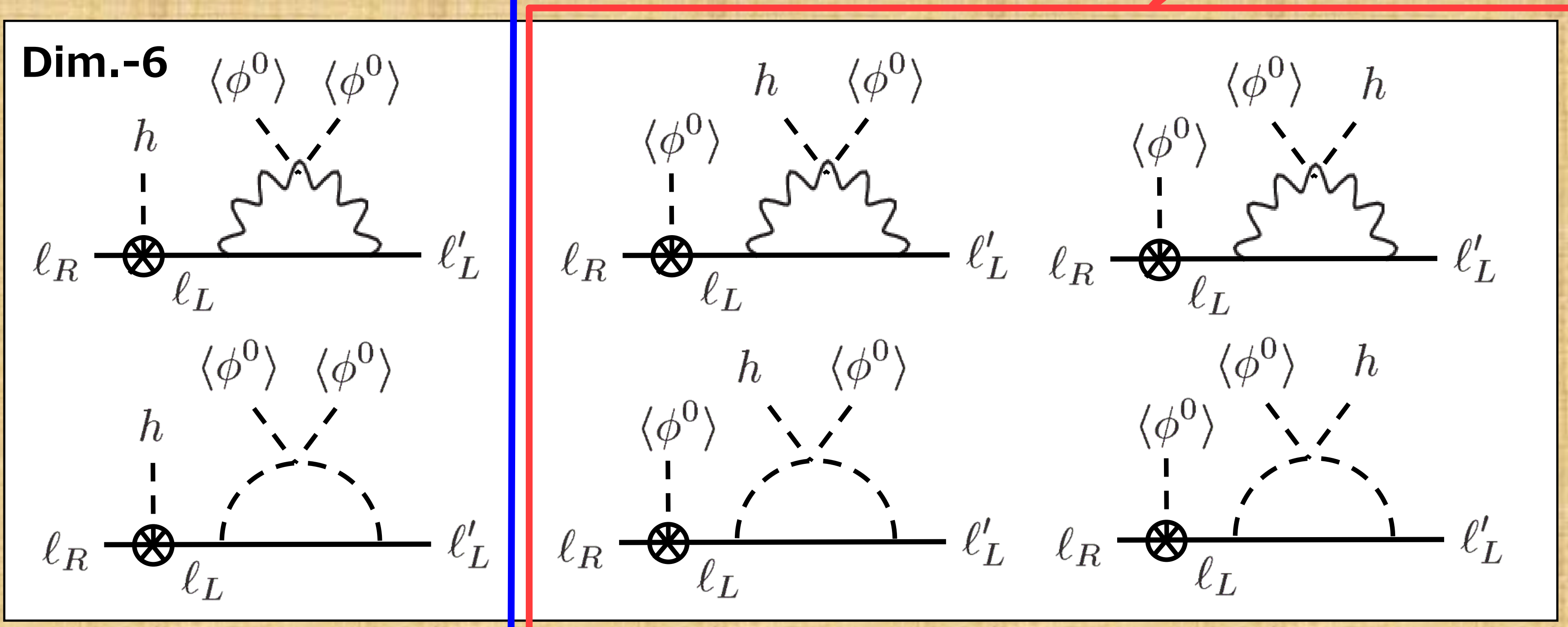
Int. : $\left(\frac{1}{\sqrt{2}}\boldsymbol{Y_4} + \frac{\mathbf{3}v^2}{2\Lambda^2}\boldsymbol{Y_6}\right)\left[\overline{\ell_L}\ell'_R h\right] \dashrightarrow \left(\frac{m_\ell}{v}\delta_{\ell\ell'} + \boxed{\frac{v^2}{\Lambda^2}\boldsymbol{Y_6}}\right)\left[\overline{\ell_L}\ell'_R h\right]$

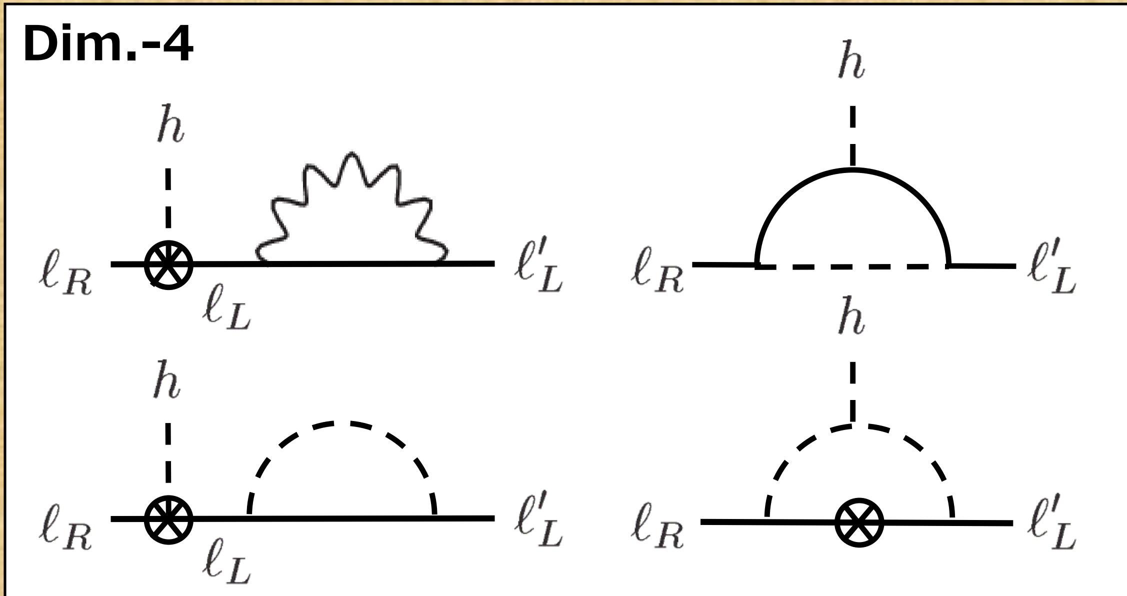
LFV

See e.g., R. Harnik, J. Kopp, J. Zupan, JHEP**1303**, 026 (2013)



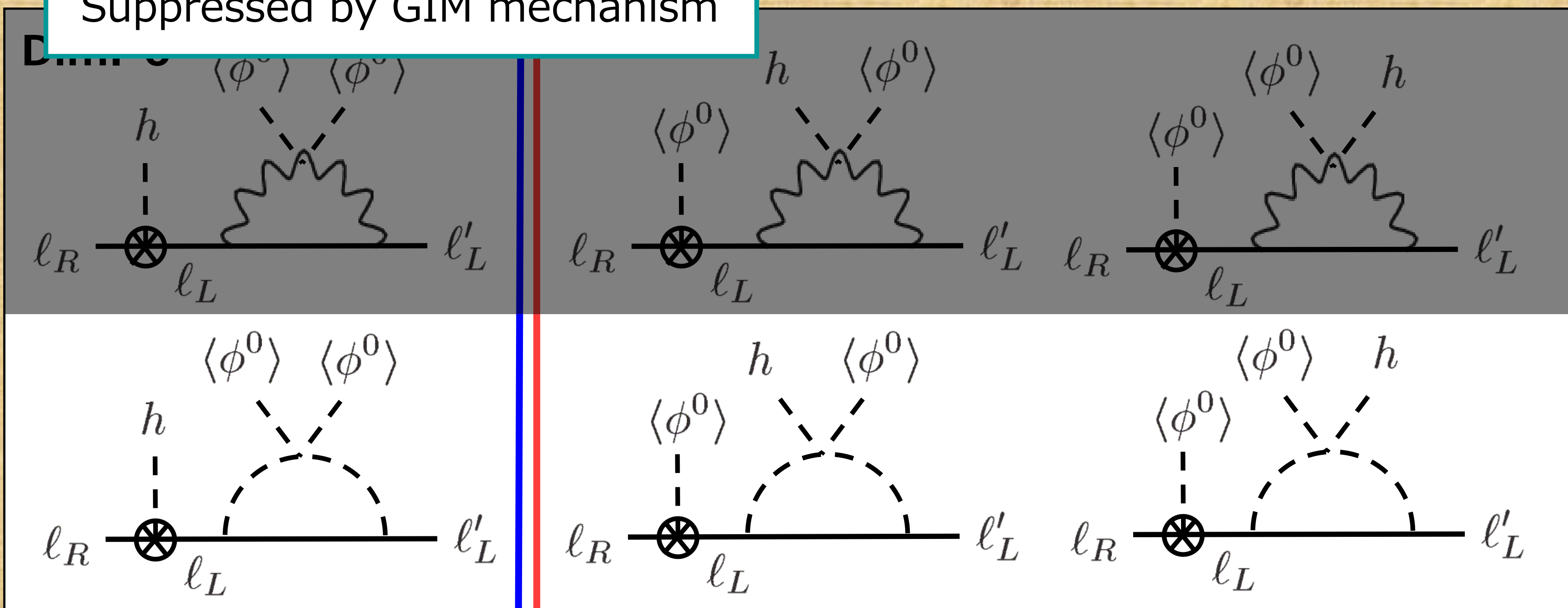
$$\left(\frac{m_\ell}{v}\delta_{\ell\ell'} + \frac{v^2}{\Lambda^2}\mathbf{Y_6}\right)\left[\overline{\ell'_L}\ell_R h\right]$$



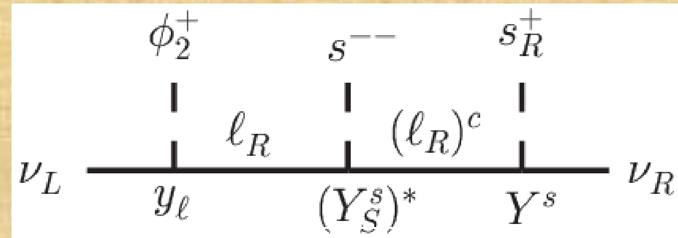


$$\left(\frac{m_\ell}{v}\delta_{\ell\ell'} + \frac{v^2}{\Lambda^2}\mathbf{Y_6}\right)\left[\overline{\ell'_L}\ell_R h\right]$$

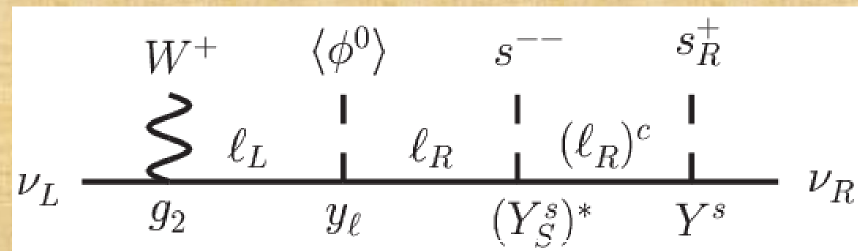
Suppressed by GIM mechanism



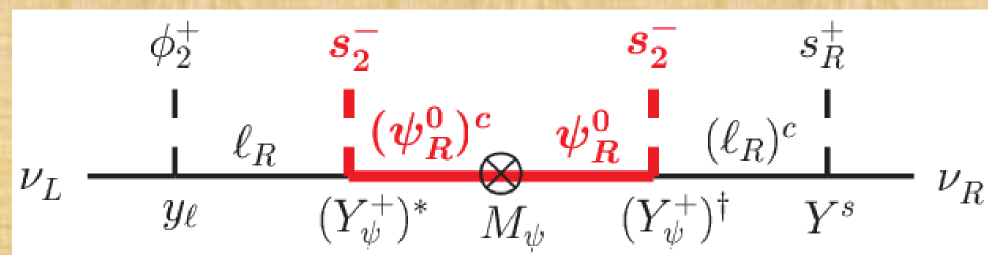
D3



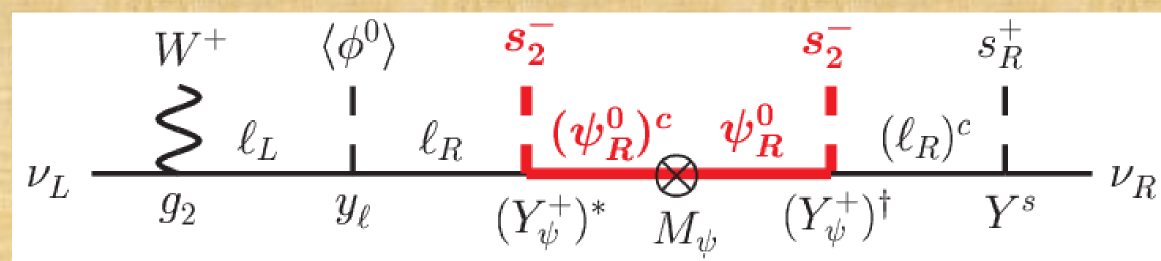
D4



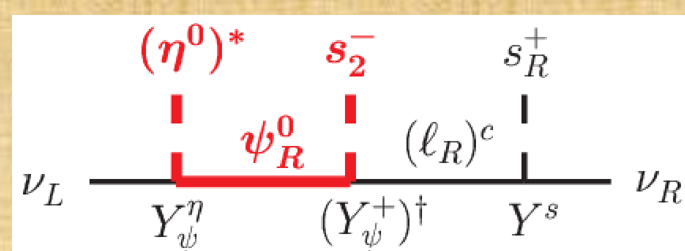
D11

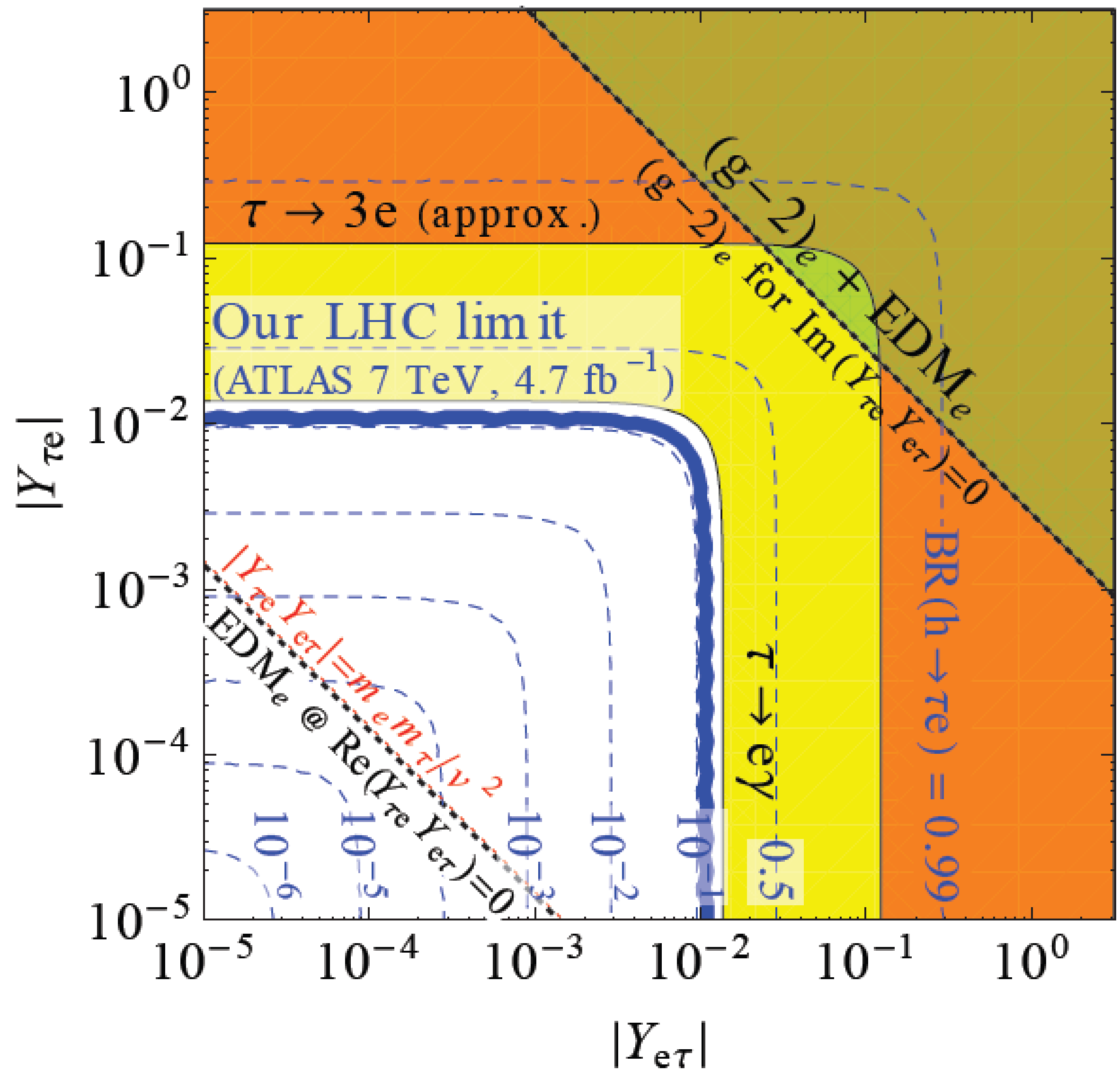


D12

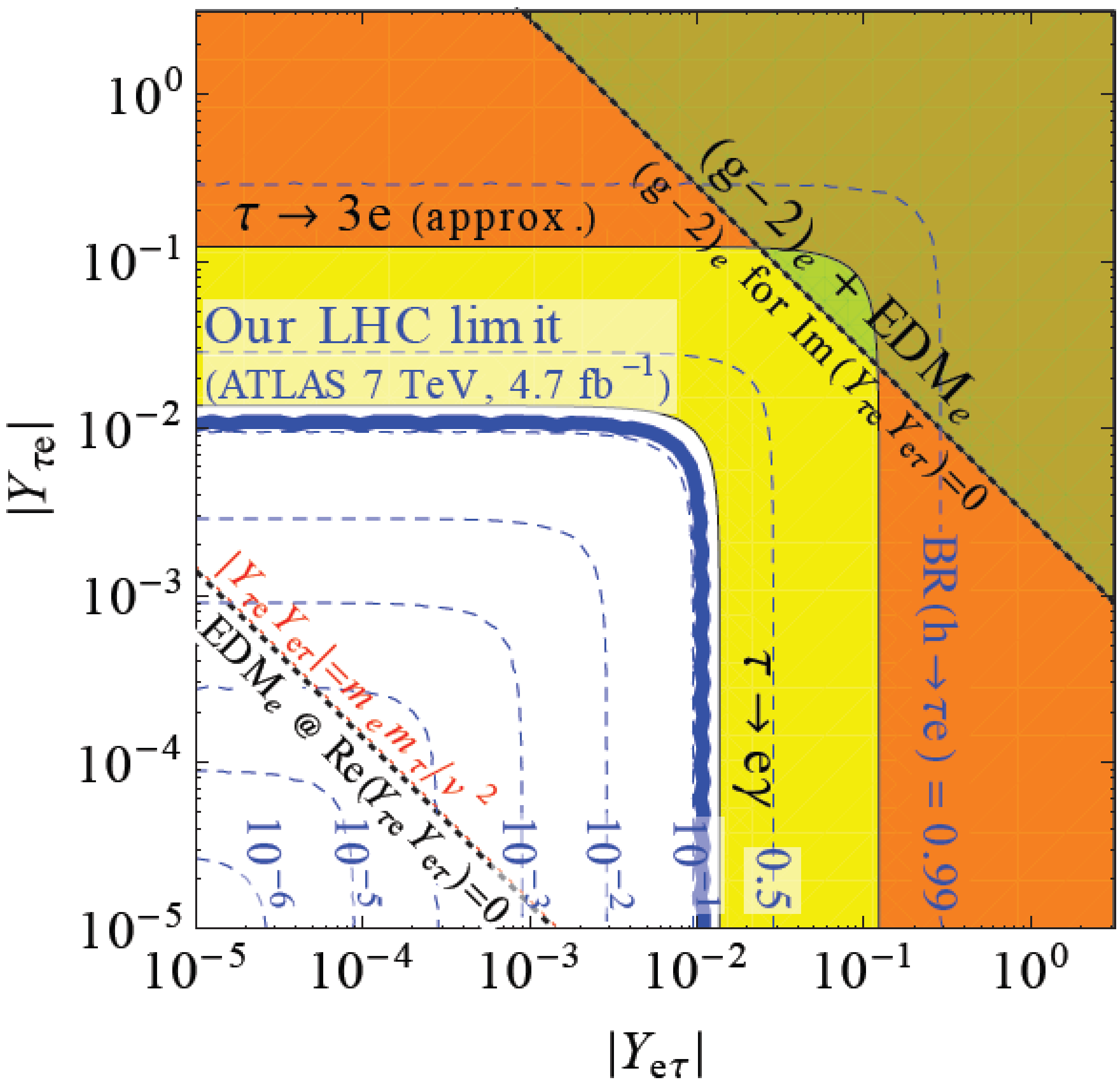


D17

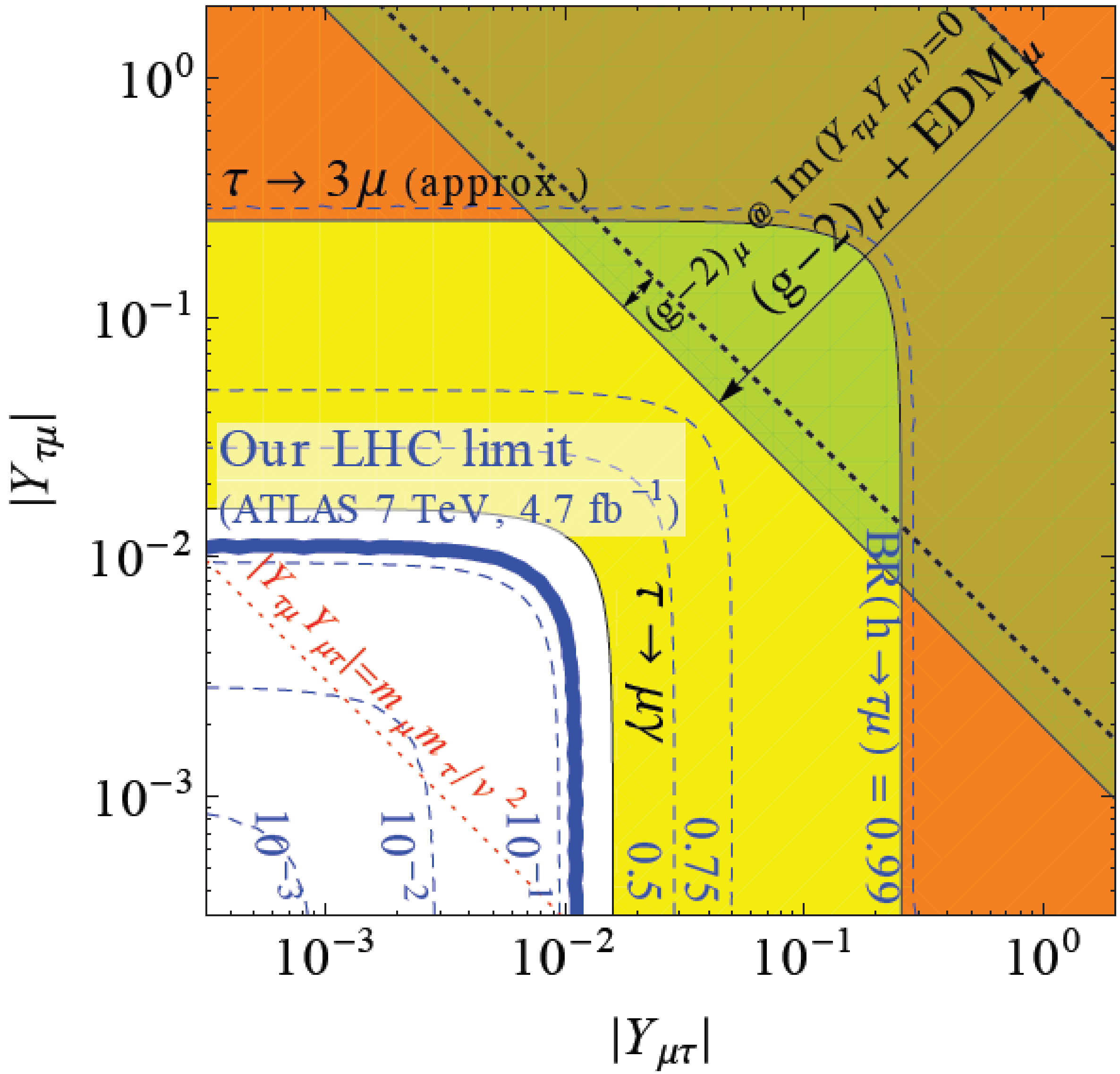




R. Harnik, J. Kopp, J. Zupan, JHEP**1303**, 026 (2013)



R. Harnik, J. Kopp, J. Zupan, JHEP**1303**, 026 (2013)



R. Harnik, J. Kopp, J. Zupan, JHEP**1303**, 026 (2013)

$$\Phi_{\rm LQ} = (\phi_{\rm LQ}^{2/3},\ \phi_{\rm LQ}^{-1/3})^T \qquad Y = 1/6$$

$$\begin{cases} \overline{Q}\Phi_{\rm LQ}\nu_R \longrightarrow \overline{u_L}\nu_R\,\phi_{\rm LQ}^{2/3} \\ \overline{d_R}\Phi_{\rm LQ}^T\epsilon L \longrightarrow \overline{d_R}\ell_L\,\phi_{\rm LQ}^{2/3} \end{cases}$$

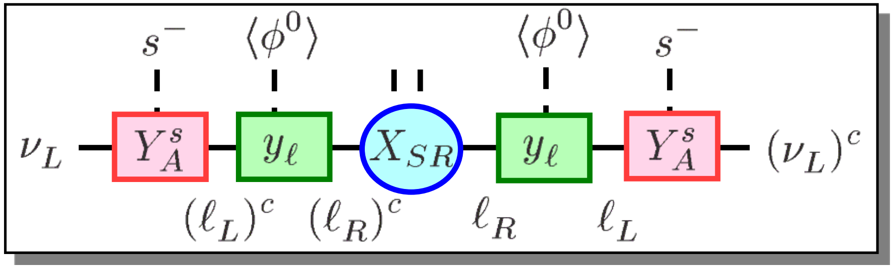
$$\Phi'_{\rm LQ} = (\phi_{\rm LQ}^{\prime\,5/3},\ \phi_{\rm LQ}^{\prime\,2/3})^T \qquad Y = 7/6$$

$$\begin{cases} \overline{Q}\Phi'_{\rm LQ}\ell_R \longrightarrow \overline{d_L}\ell_R\,\phi_{\rm LQ}^{\prime\,2/3} \\ \overline{u_R}\Phi_{\rm LQ}^{\prime T}\epsilon L \longrightarrow \overline{u_R}\nu_L\,\phi_{\rm LQ}^{2/3} \end{cases}$$

3 Groups for Majorana ν mass

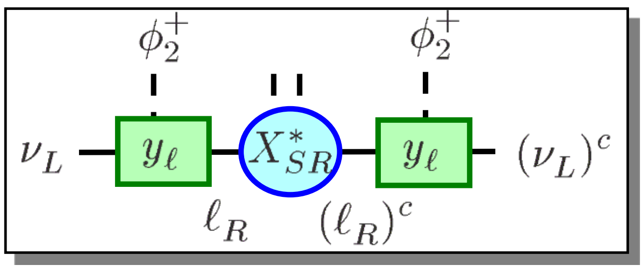
I) $m_L \propto Y_A^s\, y_\ell\, X_{SR}\, y_\ell\, Y_A^{sT}$

Y_A : **Antisym.** Yukawa for s^-



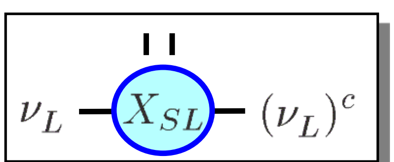
II) $m_L \propto y_\ell\, X_{SR}^*\, y_\ell$

y_ℓ : **Diagonal** Yukawa ($\propto m_\ell$) for Φ



III) $m_L \propto X_{SL}$

$X_{SL}(X_{SR})$: **Sym.** matrix



For Dirac ν masses (without DM)

	Scalar with leptonic Yukawa int.										
								Z_2-odd			
	s^0	s_L^+	s_R^+	s^{++}	Φ_ν	Φ_2	Δ	s_2^0	s_2^+	η	
$SU(2)_L$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	
$U(1)_Y$	0	1	1	2	1/2	1/2	1	0	1	1/2	
L#	−2	−2	−2	−2	0	0	−2	−1	−1	−1	
Z_2'	+	+	−	+	−	+	+	−	+	+	
D1		✓	✓								→ I′
D2			✓				✓				→ IV
D3			✓	✓		✓					} → V
D4			✓	✓							} → V
D5	✓		✓			✓					} → VI
D6	✓		✓								} → VI
D7					✓						→ III′

S. Kanemura, K. Sakurai, HS, PLB**758**, 465 (2016)

For Dirac ν masses (with DM)

	Scalar with leptonic Yukawa int.										
								Z_2-odd			
	s^0	s_L^+	s_R^+	s^{++}	Φ_ν	Φ_2	Δ	s_2^0	s_2^+	η	7 Groups
$SU(2)_L$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	
$U(1)_Y$	0	1	1	2	1/2	1/2	1	0	1	1/2	
L#	−2	−2	−2	−2	0	0	−2	−1	−1	−1	
Z_2'	+	+	−	+	−	+	+	−	+	+	
D8		✓						✓	✓		→ I′
D9							✓	✓	✓		IV
D10			✓							✓	IV
D11			✓			✓			✓		V
D12			✓						✓		V
D13			✓			✓		✓			VI
D14			✓					✓			VI
D15						✓		✓	✓		II′
D16								✓	✓		II′
D17			✓						✓	✓	→ VII
D18								✓		✓	→ III′

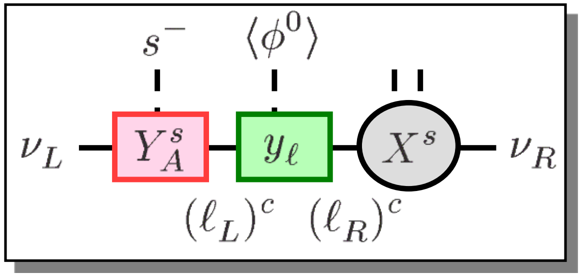
18 Mechanisms

S. Kanemura, K. Sakurai, HS, PLB**758**, 465 (2016)

7 Groups for Dirac ν mass

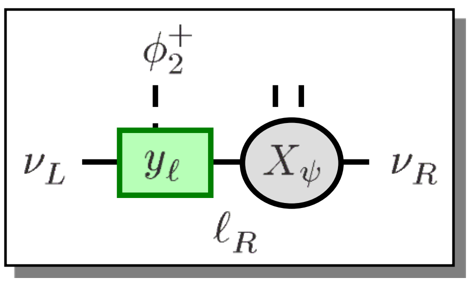
I′) $m_{\mathrm{D}} \propto Y_A^s \, y_\ell \, X^s$

Y_A : **Antisym.** Yukawa for s^-



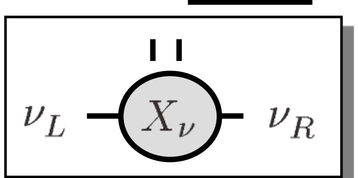
II′) $m_{\mathrm{D}} \propto y_\ell \, X_\psi$

y_ℓ : **Diagonal** Yukawa ($\propto m_\ell$) for Φ

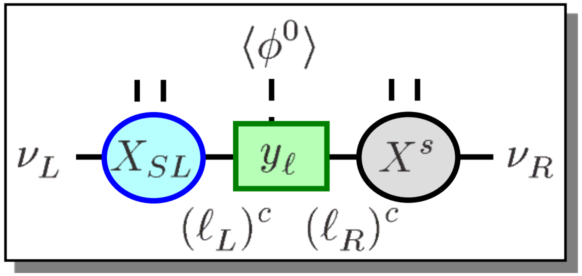


$X_\nu(X^s, X_\psi)$: Arbitrary

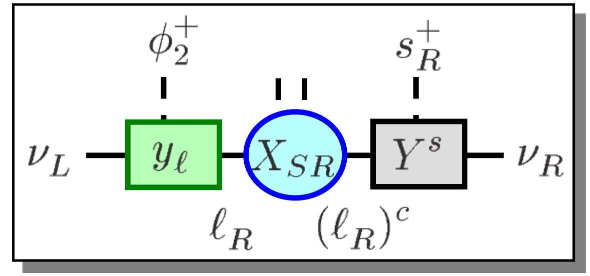
III′) $m_{\mathrm{D}} \propto X_\nu$



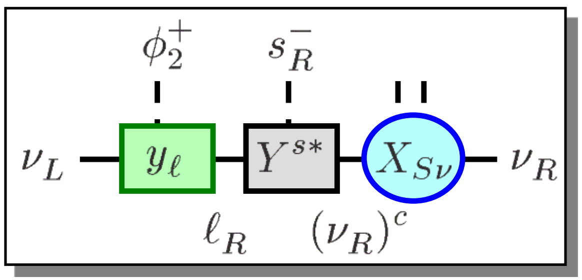
IV) $m_{\rm D} \propto X_{SL}\, y_\ell\, X^s$



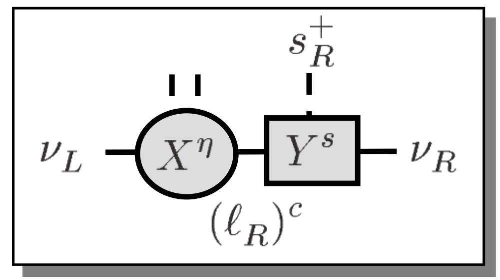
V) $m_{\rm D} \propto y_\ell\, X_{SR}\, Y^s$



VI) $m_{\rm D} \propto y_\ell\, (Y^s)^*\, X_{S\nu}$



VII) $m_{\rm D} \propto X^\eta\, Y^s$



→ **How can we discriminate them ?**
(mainly **I**, **II**, **III**, **I′**, **II′**, **III′**)

→ Concentrating on Yukawa $\Rightarrow$ **Flavor experimens**

$\ell \to \overline{\ell}_1 \ell_2 \ell_3$

$\ell \to \ell' \nu \overline{\nu}$

$\ell \to \ell' \gamma \qquad h \to \ell \ell'$

$\tau \to \overline{\ell}_1 \ell_2 \ell_3$ for Majorana case

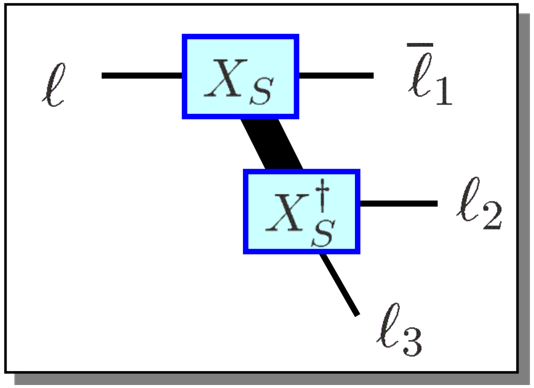
S. Kanemura, HS, PLB**753**, 161

I) $Y_A^s y_\ell X_{SR} y_\ell Y_A^{sT}$ **II)** $y_\ell X_{SR}^* y_\ell$ **III)** X_{SL}

X_{SR} : $(\ell_R)^c$ - ℓ_R - [scalars]

X_{SL} : ℓ_L - $(\ell_L)^c$ - [scalars]

X_S causes $\ell \to \overline{\ell}_1 \ell_2 \ell_3$



Stringent constraint $\mathrm{BR}(\mu \to \overline{e}ee) < 10^{-12}$

⟶ Naively, no signal of $\tau \to \overline{\ell}_1 \ell_2 \ell_3$

(Expected sensitivity : $\mathrm{BR} \sim 10^{-9}$)

Belle-II collab., arXiv:1011.0352

Signal of $\tau \to \overline{\ell}_1 \ell_2 \ell_3$ $\Rightarrow$ $(X_S)_{ee} = 0$ or $(X_S)_{e\mu} = 0$

II) **III)** $\Rightarrow$ $(m_L)_{ee} = 0$ or $(m_L)_{e\mu} = 0$

$\Rightarrow$ Prediction for flavor structure of $\tau \to \overline{\ell}_1 \ell_2 \ell_3$

I) has no prediction

	I)	II) $y_\ell X^*_{SR} y_\ell$			III) X_{SL}		
		$(m_\nu)_{ee}=0$	$(m_\nu)_{e\mu}=0$		$(m_\nu)_{ee}=0$	$(m_\nu)_{e\mu}=0$	
		N	N	I	N	N	I
$\tau \to \bar{e}ee$	✓	/	**✓**	**✓**	/	✓	✓
$\bar{e}e\mu$	✓	**✓**	/	/		/	/
$\bar{e}\mu\mu$	✓	✓			✓	✓	✓
$\bar{\mu}ee$	✓	/	✓	✓	/	✓	✓
$\bar{\mu}e\mu$	✓	✓	/	/	✓	/	/
$\bar{\mu}\mu\mu$	✓				✓	✓	✓

N : $m_1 < m_3$ (Normal)
I : $m_1 > m_3$ (Inverted)

can be determined by ν osc.

✓ : Largest
✓ : can be observed

	I)	II) $y_\ell X^*_{SR} y_\ell$			III) X_{SL}		
		$(m_L)_{ee}$ …	…	…	$(m_L)_{ee} = 0$	$(m_L)_{e\mu} = 0$	
		N			N	N	I
$\tau \to \bar{e}ee$	✓		**✓**	**✓**		✓	✓
$\bar{e}e\mu$	✓	**✓**					
$\bar{e}\mu\mu$	✓	✓			✓	✓	✓
$\bar{\mu}ee$	✓		✓	✓		✓	✓
$\bar{\mu}e\mu$	✓	✓			✓		
$\bar{\mu}\mu\mu$	✓				✓	✓	✓

$X^*_{SR} \propto y_\ell^{-1} m_L y_\ell^{-1}$

Electron-philic

N : $m_1 < m_3$ (Normal)
I : $m_1 > m_3$ (Inverted)

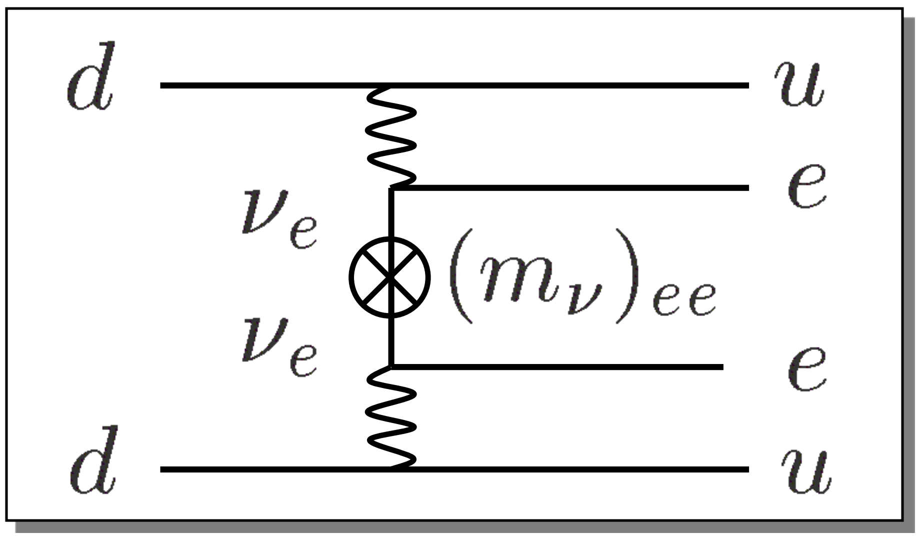
can be determined by ν osc.

✓ : Largest
✓ : can be observed

No $0\nu\beta\beta$ (e.g. ${}^{136}_{56}\mathrm{Xe} \to {}^{136}_{58}\mathrm{Ba} + 2e^-$)

	I)	II) $y_\ell X^*_{SR} y_\ell$			III) X_{SL}		
		$(m_L)_{ee}=0$	$(m_L)_{e\mu}=0$		$(m_L)_{ee}=0$	$(m_L)_{e\mu}=0$	
		N	N	I	N	N	I
$\tau \to \bar{e}ee$	✓	/	✓	✓	/	✓	✓
$\bar{e}e\mu$							/
$\bar{e}\mu\mu$							✓
$\bar{\mu}ee$							✓
$\bar{\mu}e\mu$							/
$\bar{\mu}\mu\mu$							✓

$0\nu\beta\beta$ (Half-life $\propto (m_\nu)_{ee}^{-2}$)



{ ... served

can be determined by ν osc.

	I)	II) $y_\ell X^*_{SR} y_\ell$			III) X_{SL}		
		$(m_L)_{ee}=0$	$(m_L)_{e\mu}=0$		$(m_L)_{ee}=0$	$(m_L)_{e\mu}=0$	
		N	N	I	N	N	I
$\tau \to \bar{e}ee$	✓		**✓**	**✓**		✓	✓
$\bar{e}e\mu$	✓	**✓**					
$\bar{e}\mu\mu$	✓	✓			✓	✓	✓
$\bar{\mu}ee$	✓		✓	✓		✓	✓
$\bar{\mu}e\mu$	✓	✓			✓		
$\bar{\mu}\mu\mu$	✓				✓	✓	✓

N : $m_1 < m_3$ (Normal)
I : $m_1 > m_3$ (Inverted)

can be determined by ν osc.

✓ : Largest
✓ : can be observed

	I)	II) $y_\ell X^*_{SR} y_\ell$			III) X_{SL}		
		$(m_L)_{ee}=0$	$(m_L)_{e\mu}=0$		$(m_L)_{ee}=0$	$(m_L)_{e\mu}=0$	
		N	N	I	N	N	I
$\tau \to \bar{e}ee$	✓		**✓**	**✓**		✓	✓
$\bar{e}e\mu$	✓	**✓**					
If observed		✓			✓	✓	✓
$\bar{\mu}ee$	✓		✓	✓		✓	✓
$\bar{\mu}e\mu$	✓	✓			✓		
$\bar{\mu}\mu\mu$	✓				✓	✓	✓

N : $m_1 < m_3$ (Normal)
I : $m_1 > m_3$ (Inverted)

can be determined by ν osc.

✓ : Largest
✓ : can be observed

No $0\nu\beta\beta$ (e.g. ${}^{136}_{56}\mathrm{Xe} \to {}^{136}_{58}\mathrm{Ba} + 2e^-$)

If $0\nu\beta\beta$ is observed

If observed

	I)	II) $y_\ell X^*_{SR} y_\ell$			III) X_{SL}		
		$(m_L)_{ee} = 0$	$(m_L)_{e\mu} = 0$		$(m_L)_{ee} = 0$	$(m_L)_{e\mu} = 0$	
			N	I	N	N	I
$\tau \to \bar{e}ee$	✓		**✓**	**✓**		✓	✓
$\bar{e}e\mu$	✓	**✓**					
		✓			✓	✓	✓
$\bar{\mu}ee$	✓		✓	✓		✓	✓
$\bar{\mu}e\mu$	✓	✓			✓		
$\bar{\mu}\mu\mu$	✓				✓	✓	✓

N : $m_1 < m_3$ (Normal)
I : $m_1 > m_3$ (Inverted)

can be determined by ν osc.

✓ : Largest
✓ : can be observed

$\tau \to \ell\nu\overline{\nu}$ for Dirac case

S. Kanemura, K. Sakurai, HS, PLB758, 465

II′) $m_D \propto y_\ell X_\psi$

III′) $m_D \propto X_\nu$

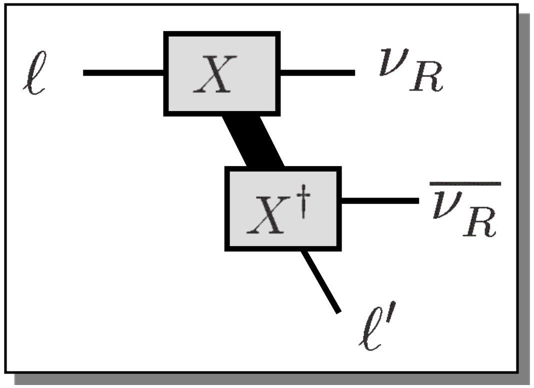
X_ψ : ℓ_R - ν_R - [scalars]

X_ν : ℓ_L - ν_R - [scalars]

$\ell \to \ell' \nu_R \overline{\nu_R}$ via X

$$\begin{cases} \mu \to e\nu\overline{\nu} \longrightarrow G_F^2 \\ \tau \to \ell'\nu\overline{\nu} \longrightarrow G_{\tau\ell'}^2 \end{cases}$$

⇕ Deviation



II′) $m_D \propto y_\ell X_\psi$	**III′)** $m_D \propto X_\nu$
$G_{\tau\mu}^2 \simeq G_{\tau e}^2 \lesssim G_F^2$	$\begin{cases} G_{\tau\mu}^2 \gtrsim G_{\tau e}^2 \simeq G_F^2 & (m_1 < m_3) \\ G_{\tau\mu}^2 \lesssim G_{\tau e}^2 \simeq G_F^2 & (m_1 > m_3) \end{cases}$

$G_{\tau e}^2 / G_F^2 = 1.0029 \pm 0.0046$ PDG

$G_{\tau\mu}^2 / G_{\tau e}^2 = 1.0036 \pm 0.0020$ Babar collab., PRL105, 051602 (2010)