Neutrino Mass Generation with Multi-Higgs

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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"

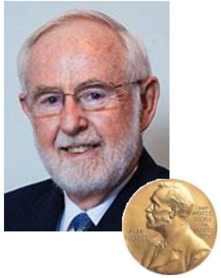
Introduction

Neutrino mass

- 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)

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

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

Unnaturally small

Nontrivial way ?

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

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

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

Many models for m_ν ⟶ Which is the true one ?

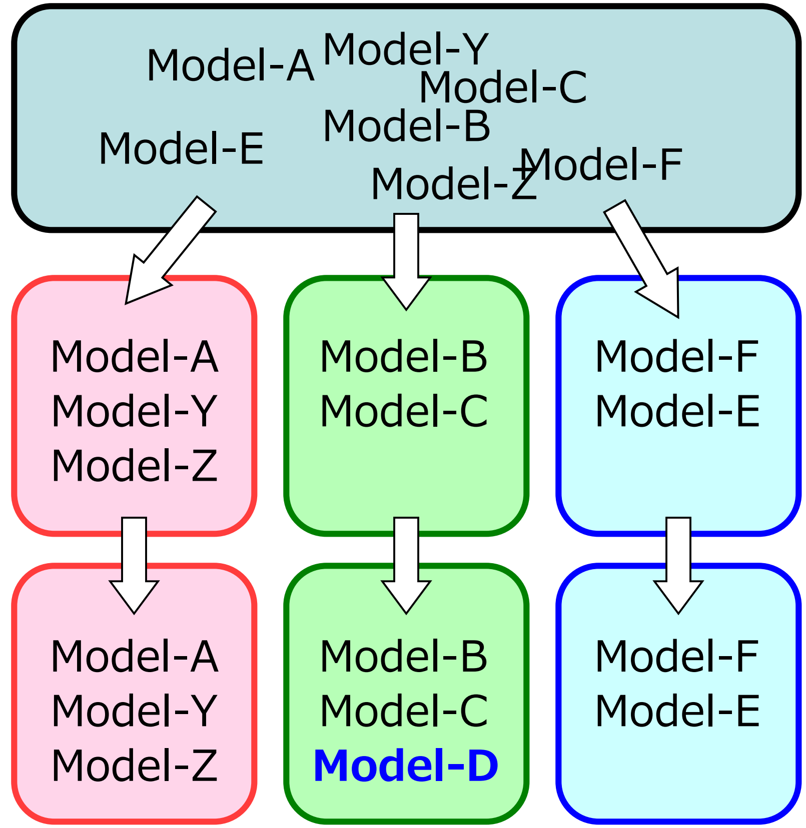
Motivation

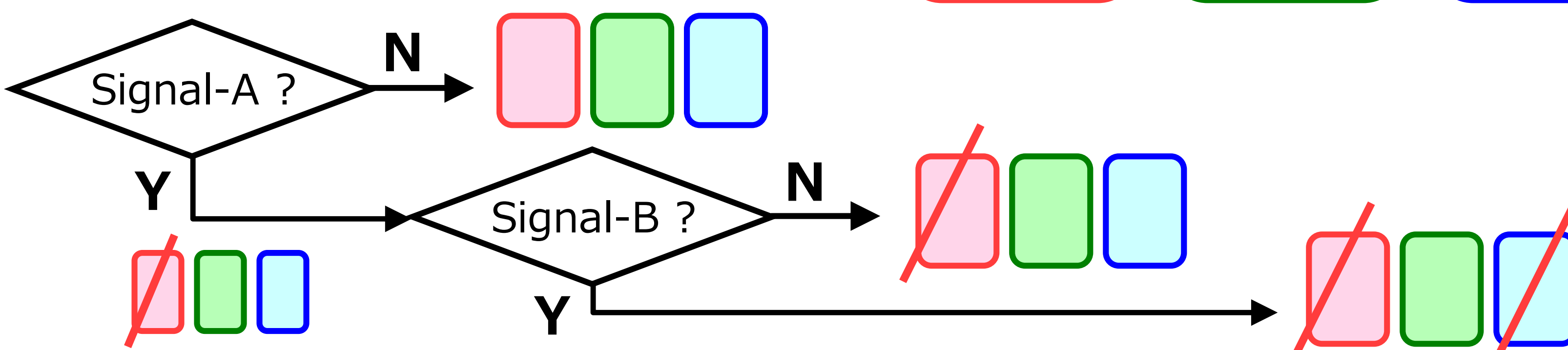
There are (too) many models.

Classification is desired.

Missing models ?

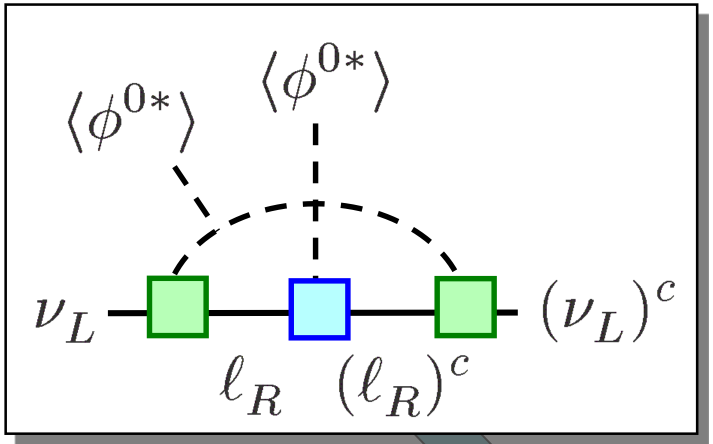
Efficient tests ?

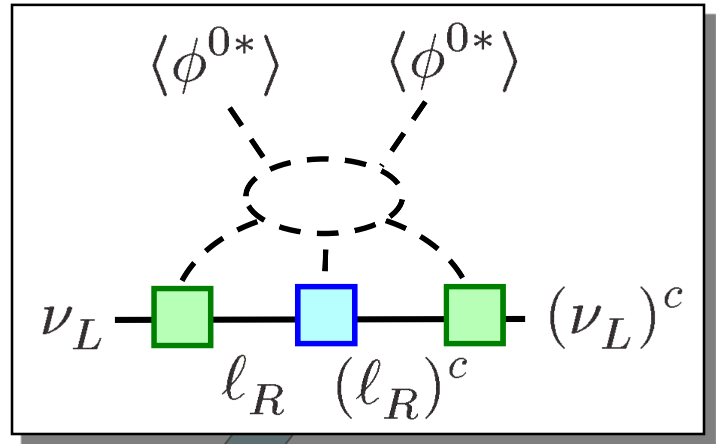




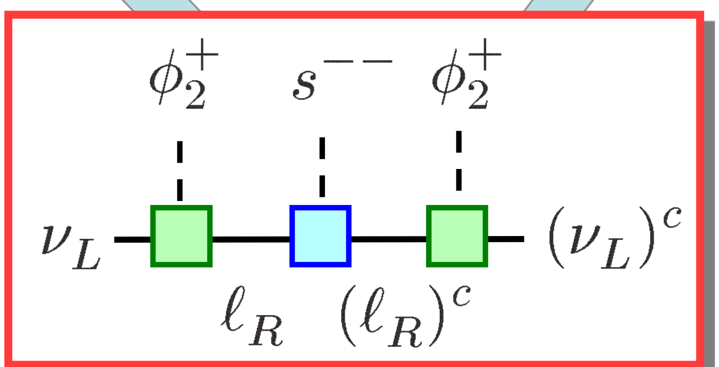
Classification according to Yukawa Int.

- Models (full Lagrangian)



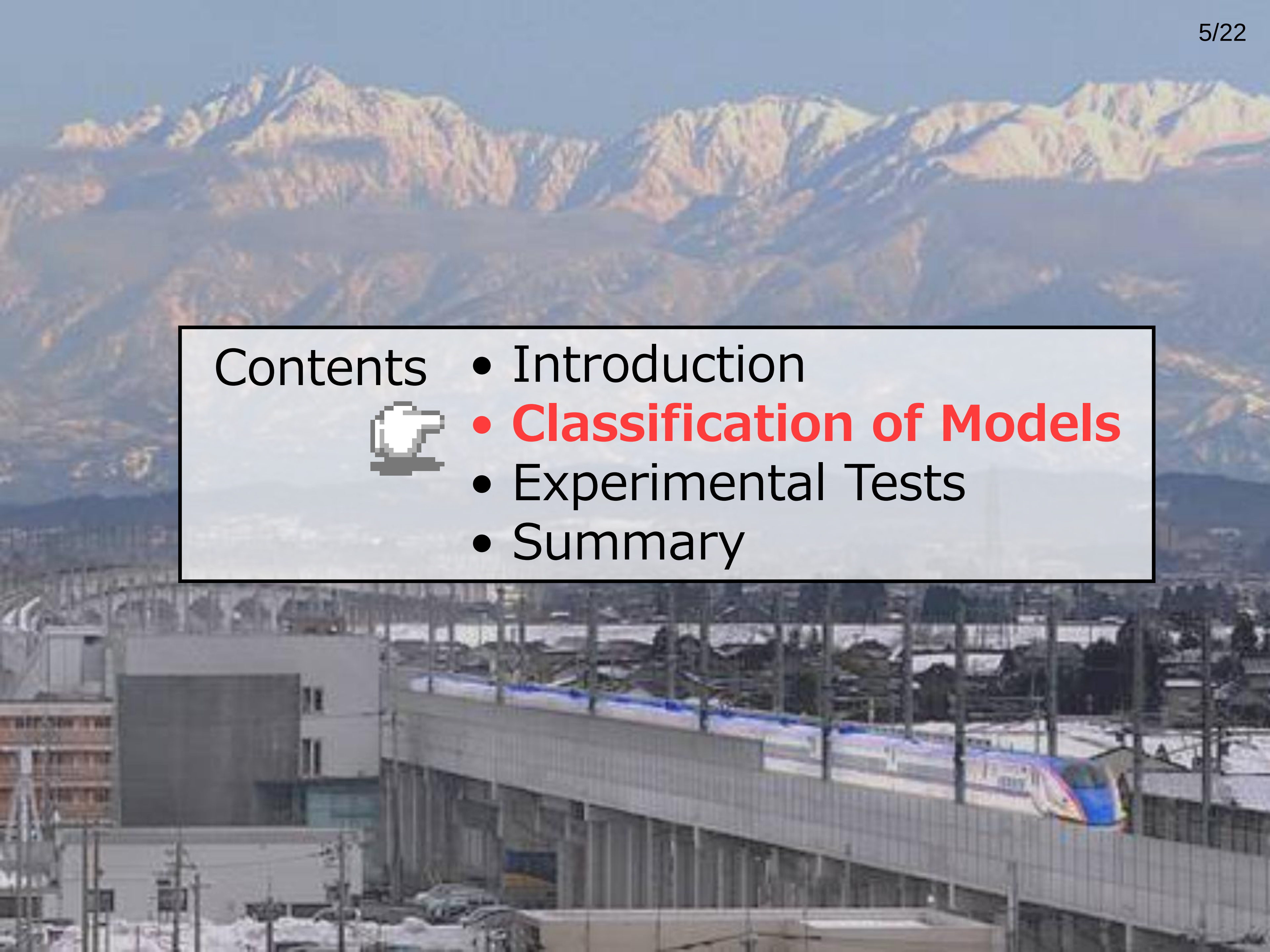


- **"Mechanisms"** : Concentrating on **Yukawa int.** of leptons



Common structure of neutrino mass matrix

(cf. Overall scale depends on detail of models)



Contents

- Introduction
- **Classification of Models**
- Experimental Tests
- Summary

Classification of Models

Set up for "simple" models

Symmetries : SM gauge sym. + Unbroken Z_2 (for dark matter)

Z_2' (Softly broken Z_2) for Dirac neutrino to forbid $y_\nu \overline{L} \epsilon \Phi^* \nu_R$ at the tree level

Another softly broken Z_2 for 2HD cases to forbid FCNC at the tree level

New fermions :
- ν_R : Only for Dirac neutrino, Z_2'-odd
- ψ_R^0 : Gauge-singlet, Z_2 -odd

New scalars : (All possibilities)

Yukawa int. with leptons
- [New scalar] - [Lepton] - [Lepton]
- [Z_2-odd scalar] - ψ_R^0 - [Lepton]

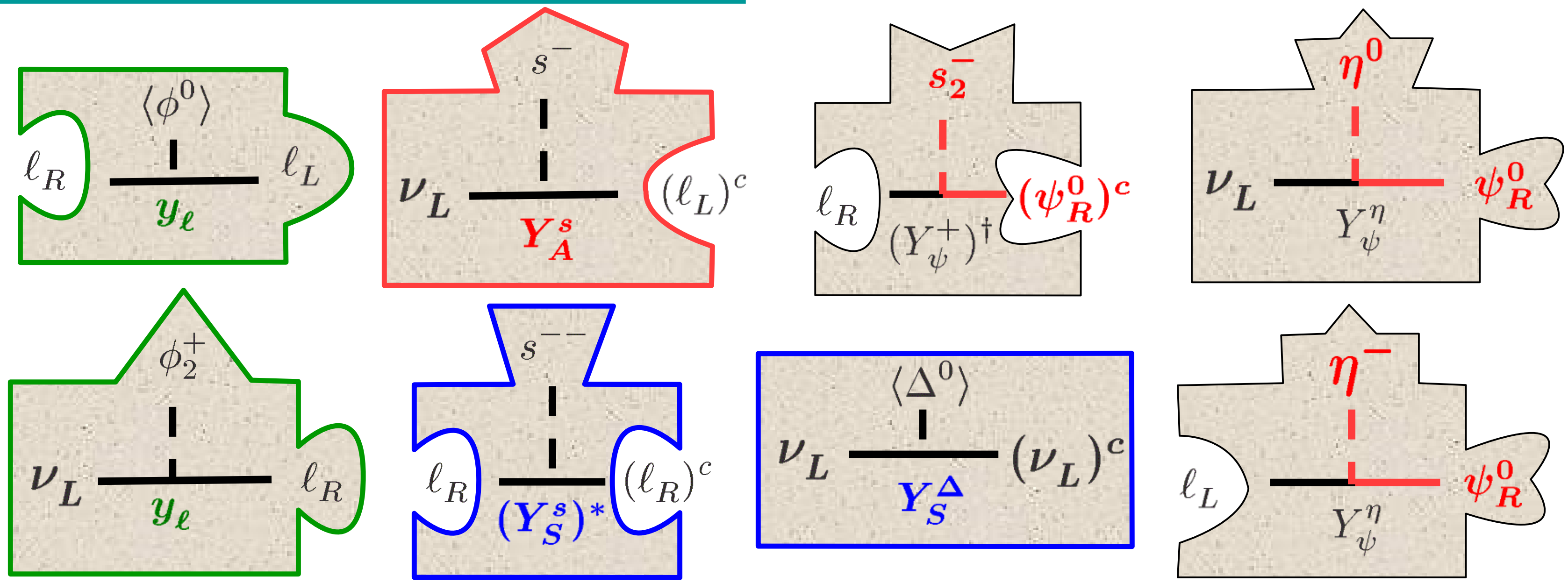
We do not take cases without new scalars (e.g. type-I seesaw)

Scalars with Leptonic Yukawa Int.

Majorana

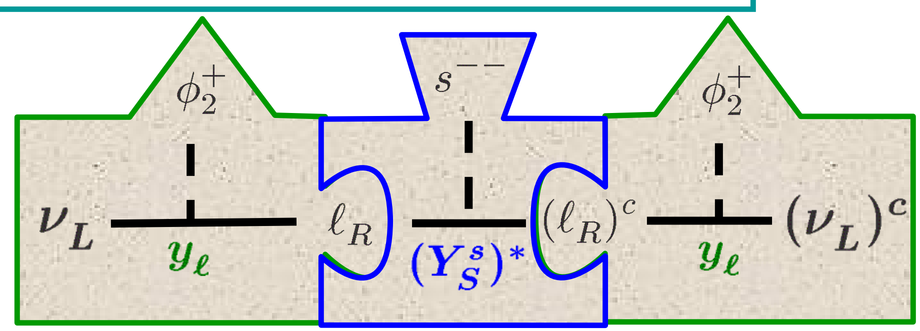
	$SU(2)_L$	$U(1)_Y$	Yukawa int.	Note
s_L^+	$\underline{\mathbf{1}}$	1	$(Y_A^s)_{\ell\ell'}\left[\overline{L_\ell}\,\epsilon L_{\ell'}^c\, s_L^-\right]$	Antisym.
s^{++}	$\underline{\mathbf{1}}$	2	$(Y_S^s)_{\ell\ell'}\left[\overline{(\ell_R)^c}\,\ell'_R\, s^{++}\right]$	Sym.
$\Phi_2 = \begin{pmatrix}\phi_2^+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

Yukawa int. : Puzzle pieces



Neutrino mass : Solutions of the puzzle

For example,



Introduce s^{++}, Φ_2 $\Longrightarrow$ Majorana neutrino mass

$m_L \propto y\,(Y_S^s)^*y$

For **Majorana** ν 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	+	+	+	+	−	−	
	~~✓~~		~~✓~~				Zee-Wolfenstein model
M1	✓	✓					Zee-Babu model
M2		✓	✓				Cheng-Li model
M3		✓					Gustafsson–No–Rivera model
M4				✓			Higgs Triplet model
M5	✓				✓		Crauss-Nasri-Trodden model
M6			✓		✓		Aoki-Kanemura-Seto model
M7					✓		**New**
M8						✓	Ma model

8 Mechanisms

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

Majorana

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

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

Dirac

Lepton number (conserved)

forbid $y_\nu \overline{L}\,\epsilon\,\Phi^* \nu_R$ at tree level (ν_R : $-$)

	$SU(2)_L$	$U(1)_Y$	L#	Z_2'	Yukawa int.	Note
s^0	$\underline{\mathbf{1}}$	0	-2	$+$	$(Y_S^0)_{ij}\left[\overline{(\nu_{iR})^c}\,\nu_{jR}\,s^0\right]$	Sym. ν_R
s_L^+	$\underline{\mathbf{1}}$	1	-2	$+$	$(Y_A^s)_{\ell\ell'}\left[\overline{L_\ell}\,\epsilon L^c_{\ell'}\,s_L^-\right]$	Antisym.
s_R^+	$\underline{\mathbf{1}}$	1	-2	$-$	$(Y^s)_{\ell i}\left[\overline{(\ell_R)^c}\,\nu_{iR}\,s_R^+\right]$	ν_R
s^{++}	$\underline{\mathbf{1}}$	2	-2	$+$	$(Y_S^s)_{\ell\ell'}\left[\overline{(\ell_R)^c}\,\ell'_R\,s^{++}\right]$	Sym.
$\Phi_\nu = \begin{pmatrix}\phi_\nu^+ & \phi_\nu^0\end{pmatrix}^T$	$\underline{\mathbf{2}}$	1/2	0	$-$	$(Y_\nu)_{\ell i}\left[\overline{L_\ell}\,\epsilon\,\Phi_\nu^*\,\nu_{iR}\right]$	ν_R
$\Phi_2 = \begin{pmatrix}\phi_2^+ & \phi_2^0\end{pmatrix}^T$	$\underline{\mathbf{2}}$	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	$+$	$(Y_S^\Delta)_{\ell\ell'}\left[\overline{L_\ell}\,\Delta^\dagger\epsilon\,L^c_{\ell'}\right]$	Sym.
s_2^0 Z_2 odd	$\underline{\mathbf{1}}$	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	$\underline{\mathbf{1}}$	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	$\underline{\mathbf{2}}$	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		✓	✓								Nasri-Moussa model
D2			✓				✓				New
D3			✓	✓		✓					New
D4			✓	✓							New
D5	✓		✓			✓					New
D6	✓		✓								New
D7					✓						ν-philic 2HDM

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

For Dirac ν masses (with DM)

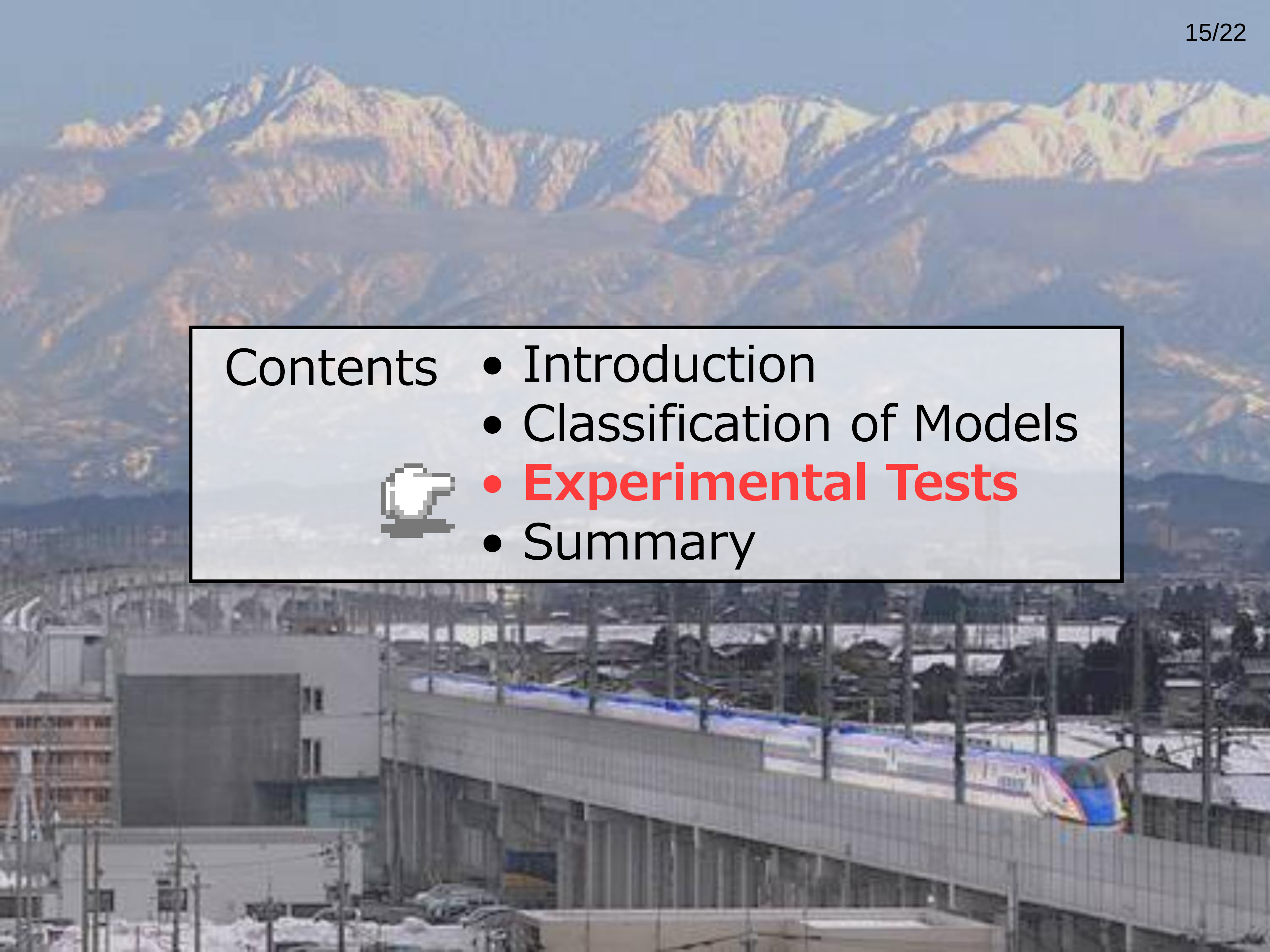
	Scalar with leptonic Yukawa int.									
								Z_2-odd		
	s^0	s_L^+	s_R^+	s^{++}	Φ_ν	Φ_2	Δ	s_2^0	s_2^+	η
$SU(2)_L$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$
$U(1)_Y$	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								✓		✓

New (D8–D17)

Gu-Sarkar model (D18)

18 Mechanisms

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



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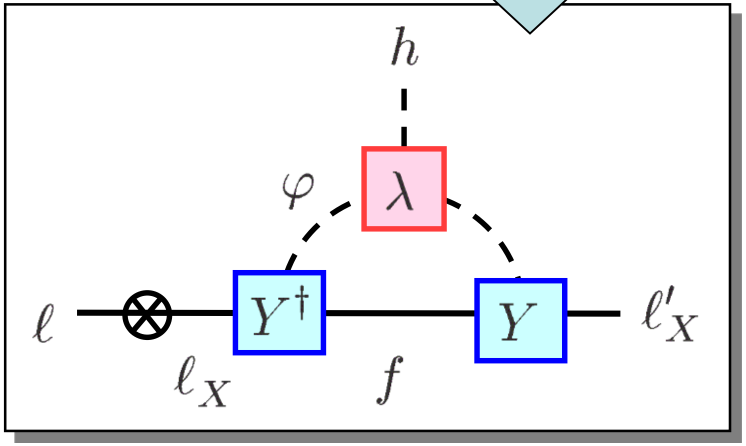
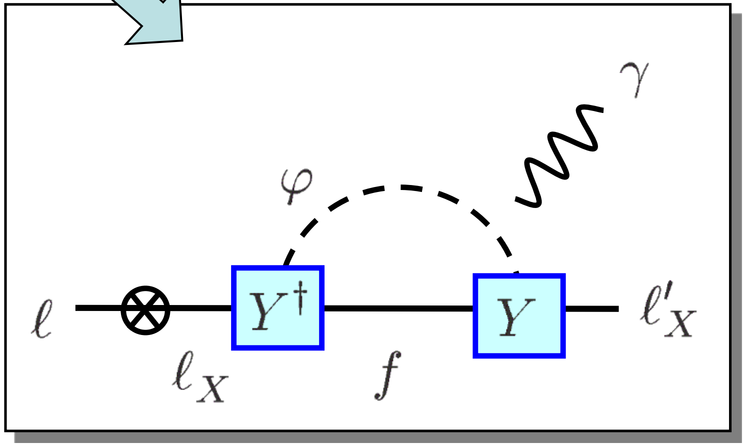
$h \to \ell\ell'$ and $\ell \to \ell'\gamma$

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.				Z_2-odd		$\ell \to \ell'\gamma$	
	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 ! (also type-I seesaw)

"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

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

Cancellation is possible

"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
$SU(2)_L$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$		
$U(1)_Y$	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 $h \to \ell\ell'$

Summary

Simple models to generate **Majorana** ν masses can be classified into **8 Mechanisms**

Simple models to generate **Dirac** ν masses can be classified into **18 Mechanisms**

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

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

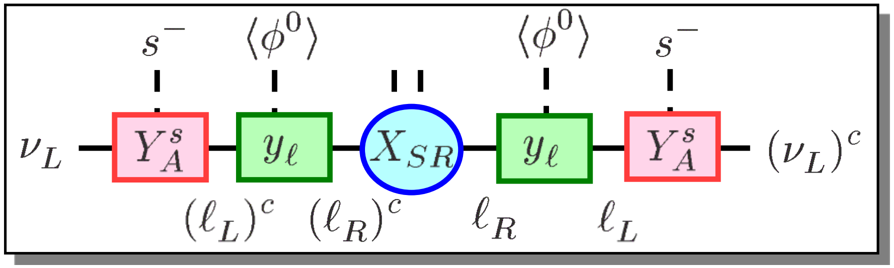
See you again in Osaka

Backup

3 Groups for Majorana ν mass

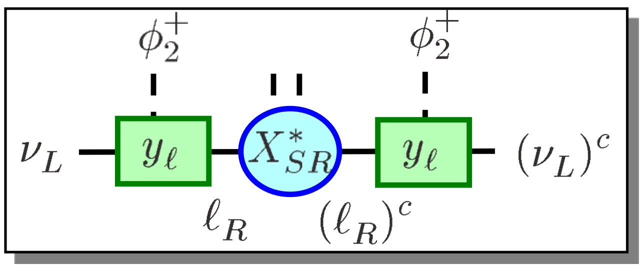
I) $m_L \propto Y_A^s \, y_\ell \, X_{SR} \, y_\ell \, Y_A^{sT}$

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



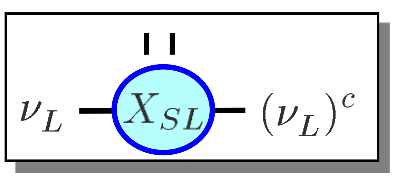
II) $m_L \propto y_\ell \, X_{SR}^* \, y_\ell$

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



III) $m_L \propto X_{SL}$

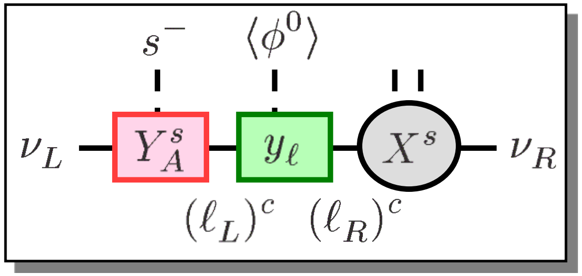
$X_{SL}(X_{SR})$: **Sym.** matrix



7 Groups for Dirac ν mass

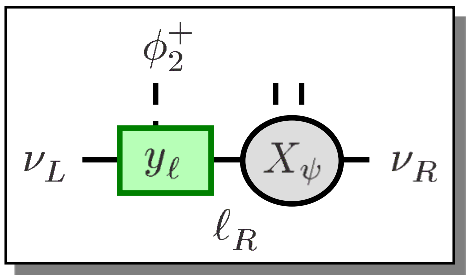
I′) $m_D \propto Y_A^s\, y_\ell\, X^s$

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



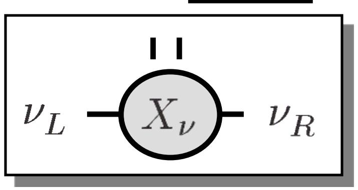
II′) $m_D \propto y_\ell\, X_\psi$

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

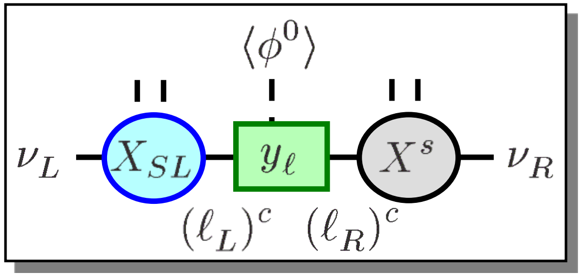


$X_\nu(X^s, X_\psi)$: Arbitrary

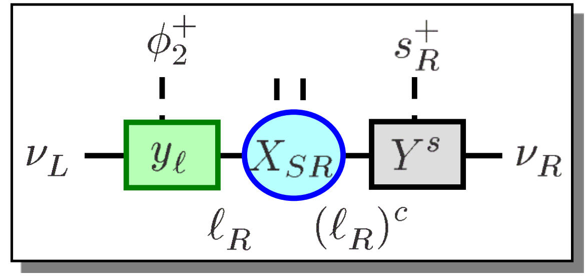
III′) $m_D \propto X_\nu$



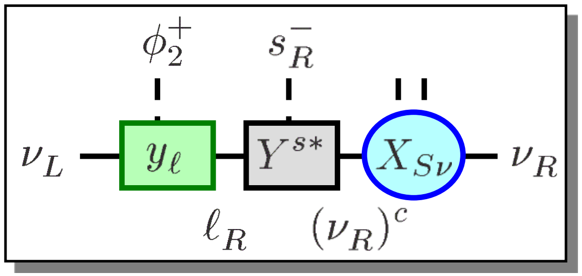
IV) $m_{\rm D} \propto X_{SL}\, y_\ell\, X^s$



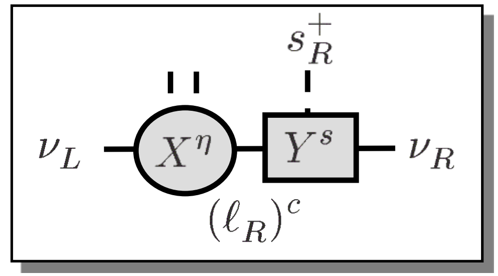
V) $m_{\rm D} \propto y_\ell\, X_{SR}\, Y^s$



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



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



→ **How can we test them ?**

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

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

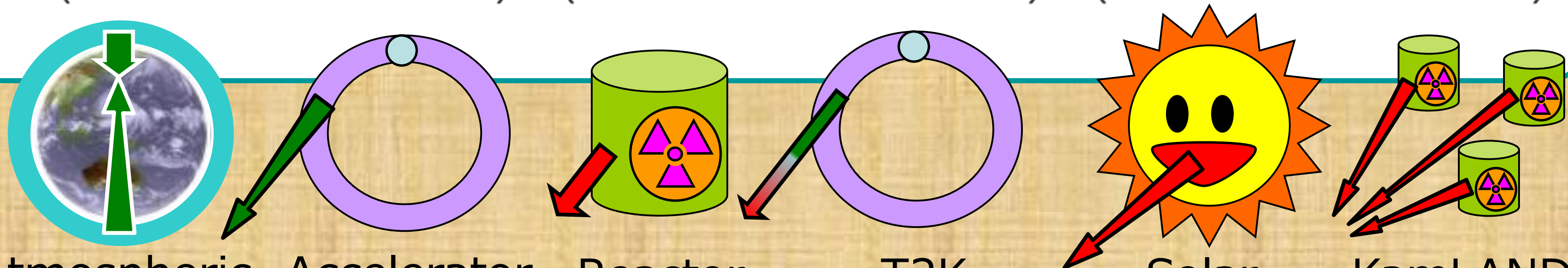
$\ell \to \ell' \nu \bar{\nu}$

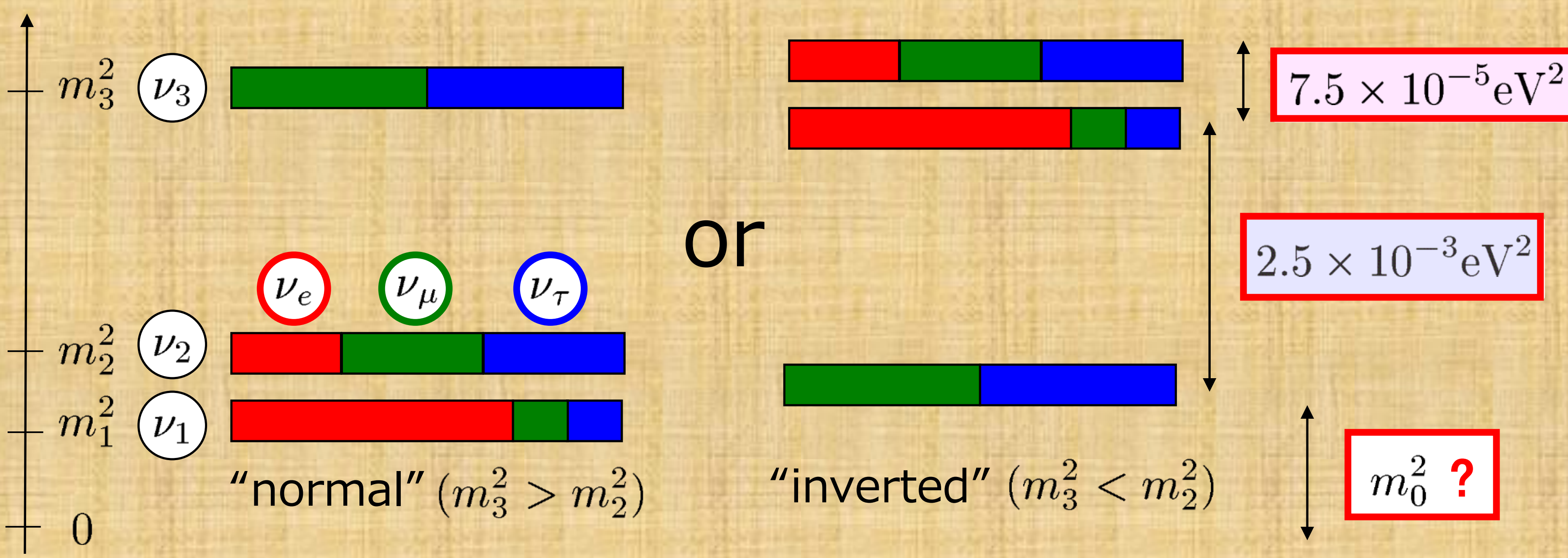
$\ell \to \ell' \gamma$ $\qquad h \to \ell \ell'$

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

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

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

→ $m_1 = 0$ or $m_3 = 0$

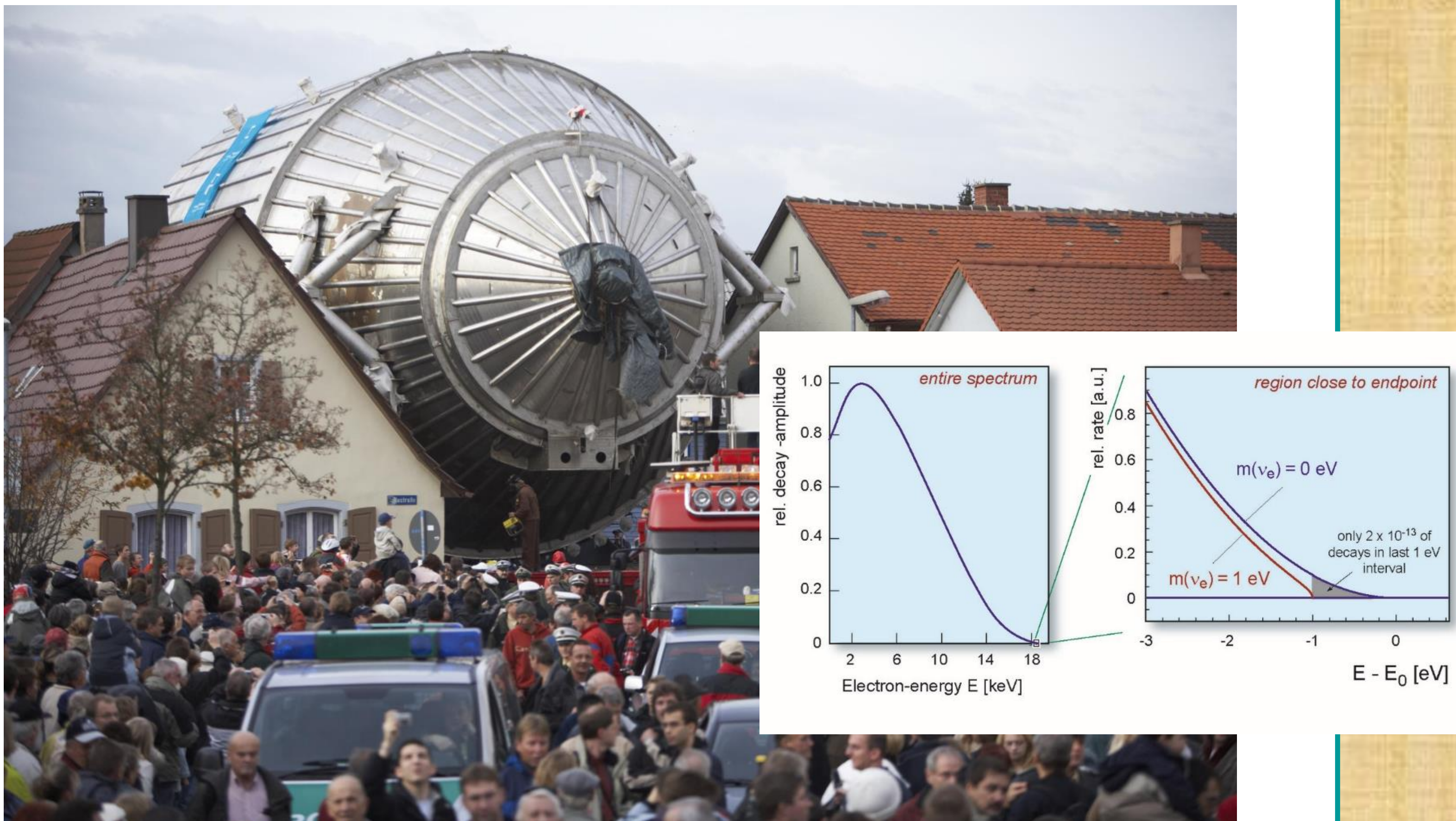
m_i : Neutrino mass eigenvalues
($m_2 \neq 0$ due to solar ν osc.)

→ 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.)

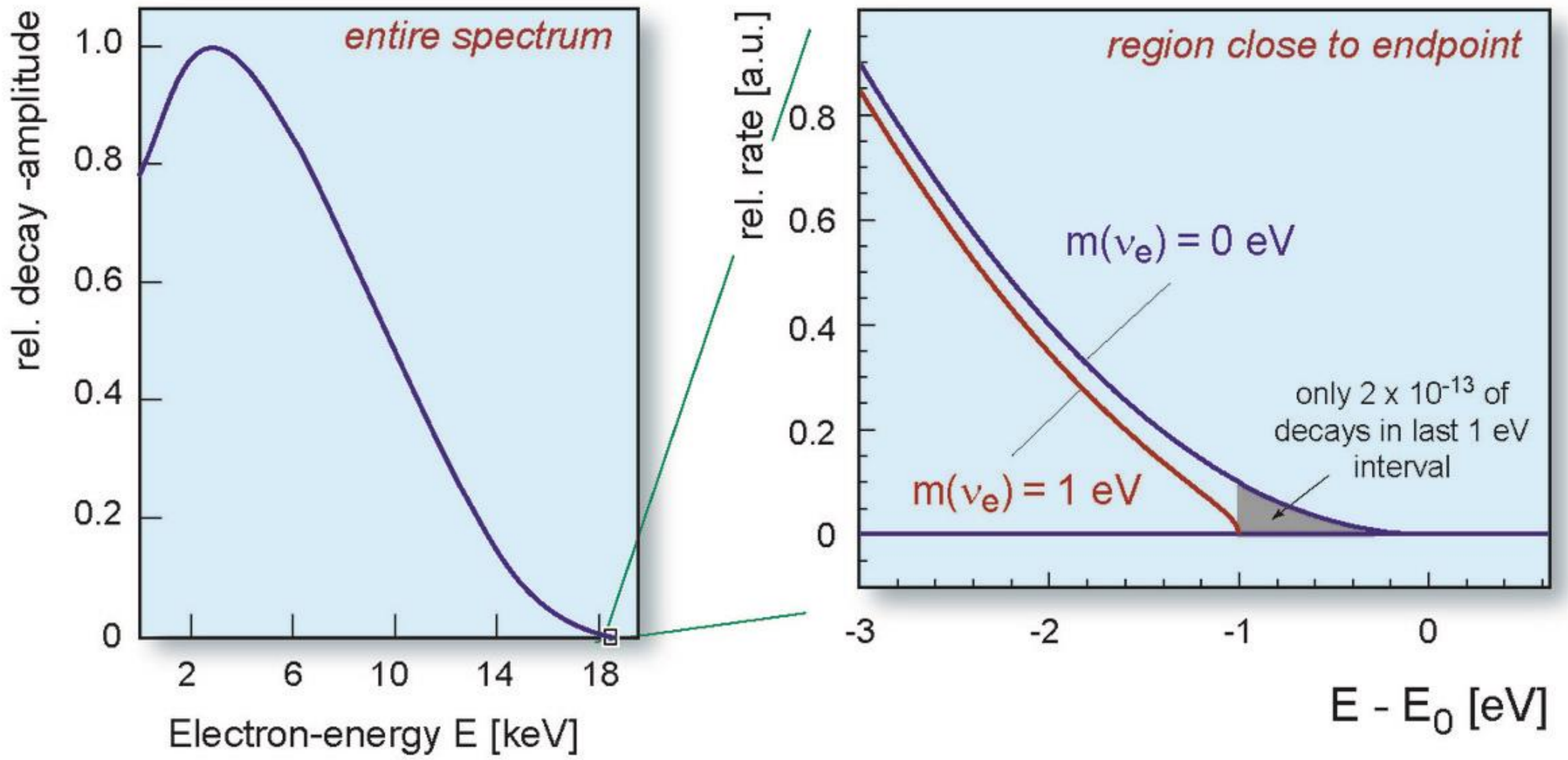
Not for a model but **for all models belong to Group-I and I′**
(e.g. ZB model, KNT model, NM model)



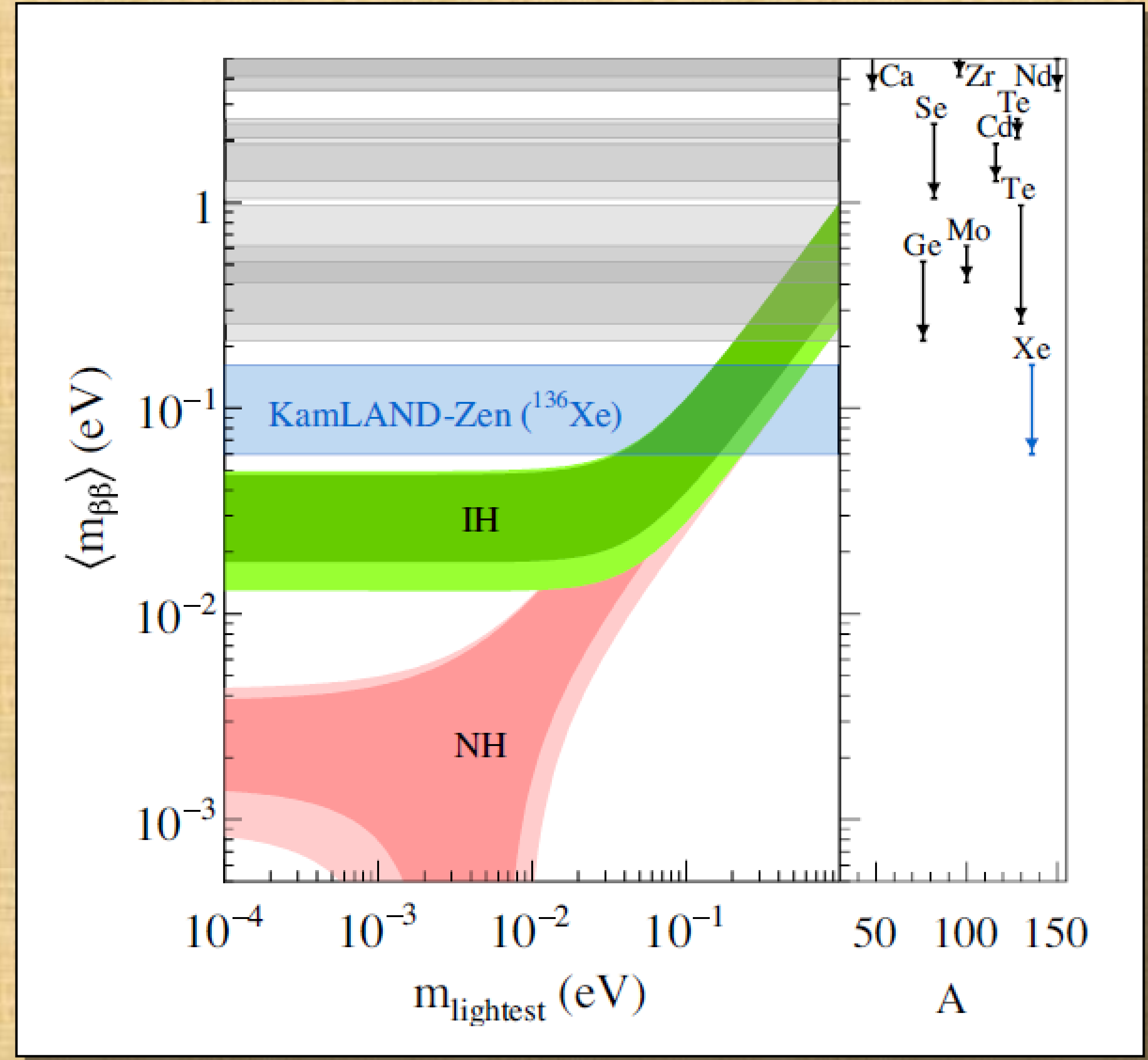
https://www.katrin.kit.edu/213.php

Main spectrometer of KATRIN experiment

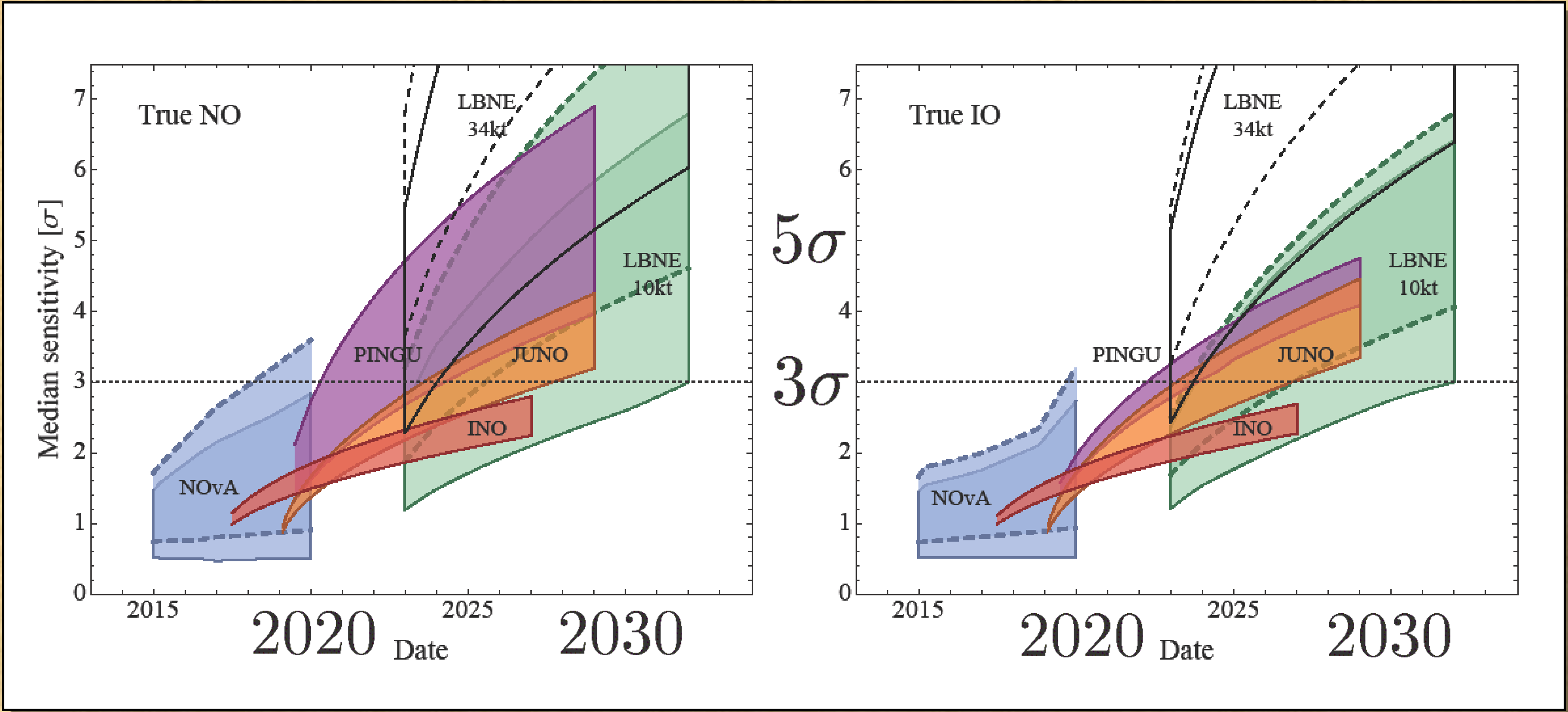
Transport through Leopoldshafen in Germany



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



KamLAND-ZEN collab., PRL**117**, 082503 (2016)



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 EPJC**77**, 70 (2017) $(8\,\mathrm{TeV}, 20.3\,\mathrm{fb}^{-1})$	CMS [1] PLB**763**, 472 (2016) } $(8\,\mathrm{TeV}, 19.7\,\mathrm{fb}^{-1})$ [2] PLB**749**, 337 (2015) } [3] JHEP**1806**, 001 (2018) $(13\,\mathrm{TeV}, 35.9\,\mathrm{fb}^{-1})$
$h \to \mu e$	Limit		$< 0.035 \times 10^{-2}$ [1]
	Best fit		
$h \to \tau e$	Limit	$< 1.04 \times 10^{-2}$	$< 0.61 \times 10^{-2}$ [3]
	Best fit	$-0.34^{+0.64}_{-0.66} \times 10^{-2}$	$0.30^{+0.18}_{-0.18} \times 10^{-2}$ [3]
$h \to \tau\mu$	Limit	$< 1.43 \times 10^{-2}$	$< 1.51 \times 10^{-2}$ [2] $< 0.25 \times 10^{-2}$ [3]
	Best fit	$0.53^{+0.51}_{-0.51} \times 10^{-2}$	$0.84^{+0.39}_{-0.37} \times 10^{-2}$ $(2.4\,\sigma)$ [2] $0.00^{+0.12}_{-0.12} \times 10^{-2}$ [3]

My naïve calc. $(0.8 \pm 1.1) \times 10^{-3}$

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

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

Dim.-6 operator

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

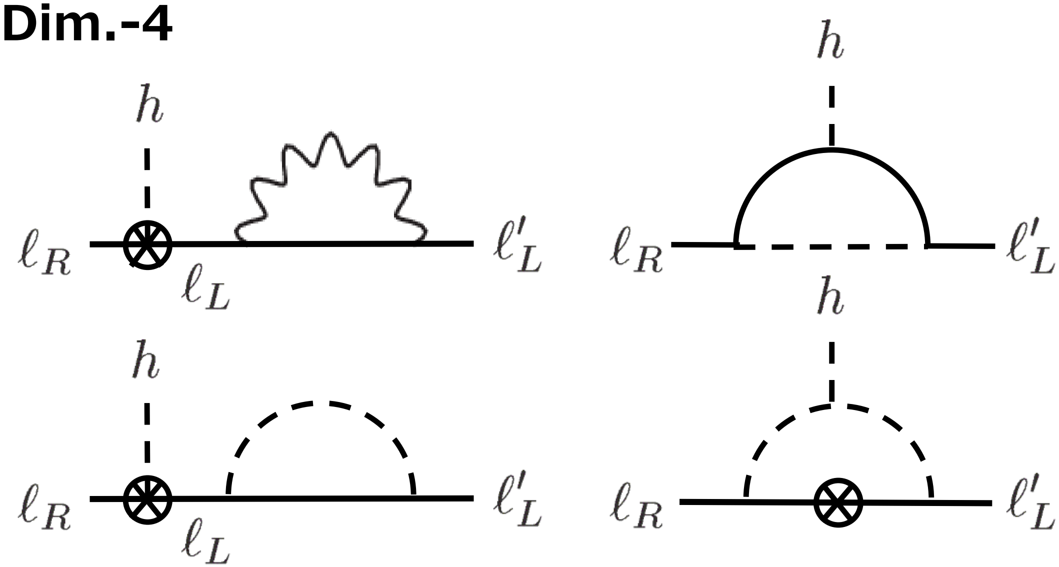
Mass : $v\left(\frac{1}{\sqrt{2}}\mathbf{Y_4} + \frac{v^2}{2\Lambda^2}\mathbf{Y_6}\right)\left[\overline{\ell_L}\ell'_R\right]$ $\xrightarrow{\text{Diag.}}$ $m_\ell\left[\overline{\ell_L}\ell_R\right]$

LFV

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

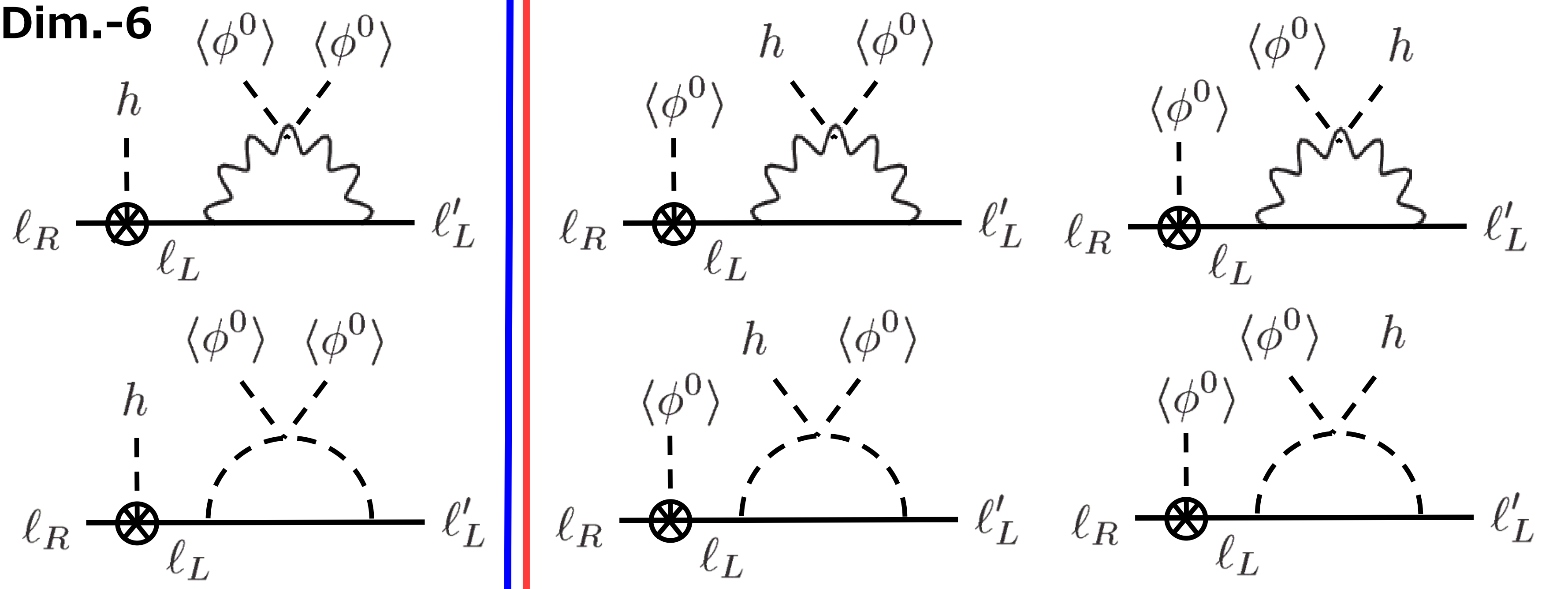
See e.g., R. Harnik, J. Kopp, J. Zupan, JHEP**1303**, 026 (2013)

Dim.-4

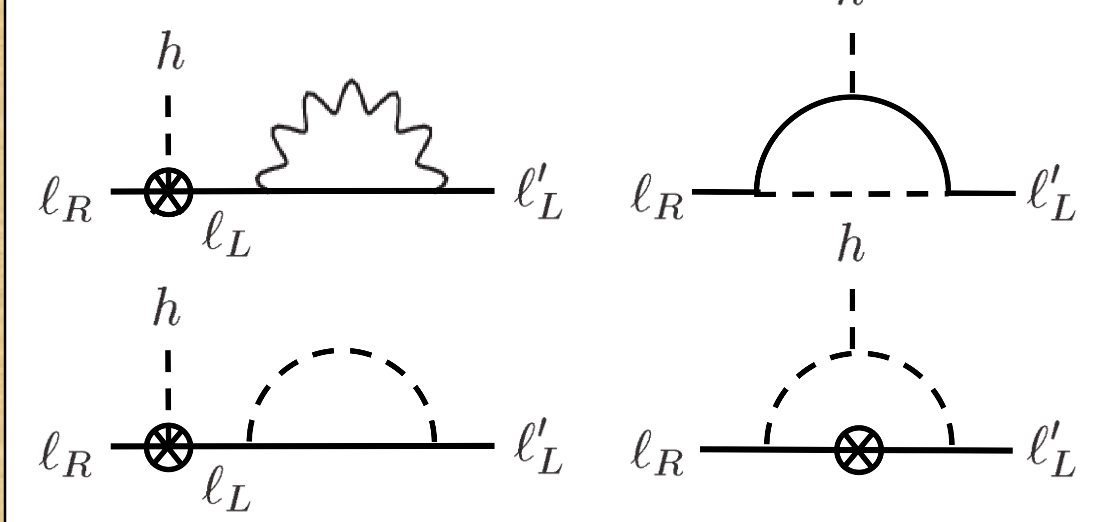


$$\left(\frac{m_\ell}{v}\delta_{\ell\ell'} + \frac{v^2}{\Lambda^2}\mathbf{Y_6}\right)\left[\overline{\ell'_L}\ell_R h\right]$$

Dim.-6



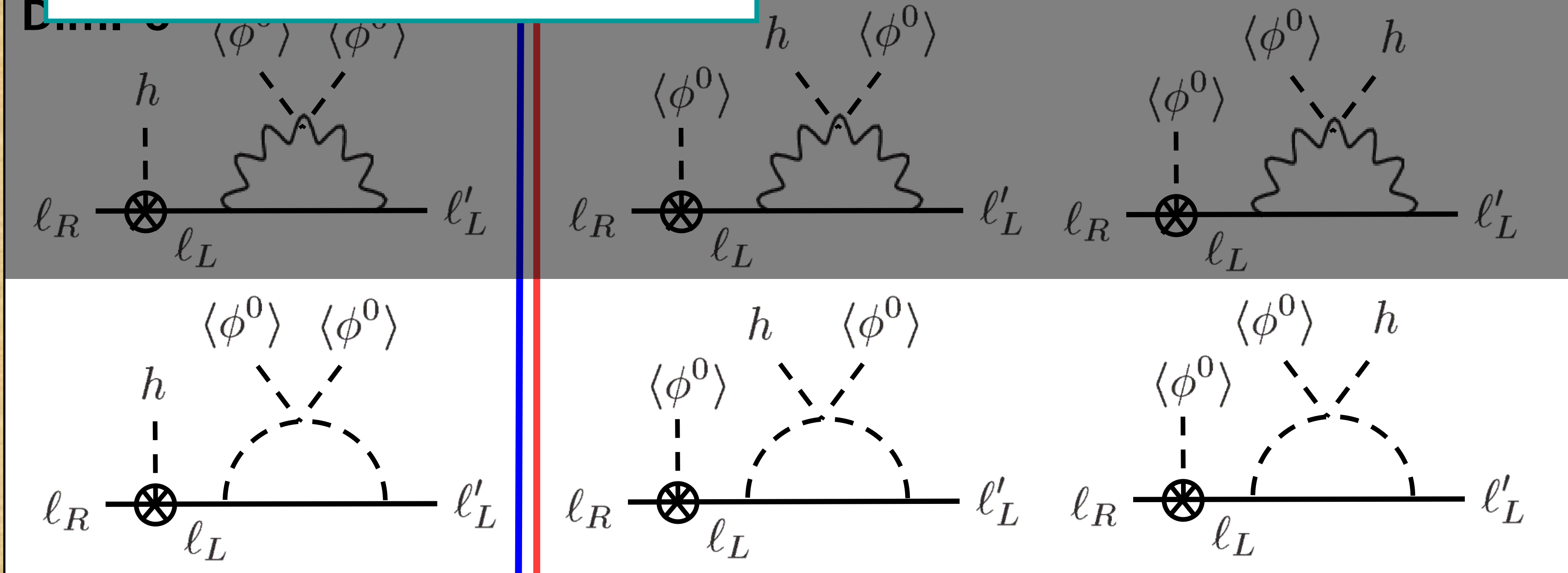
Dim.-4



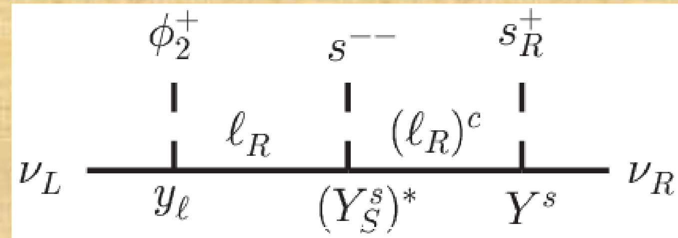
$$\left(\frac{m_\ell}{v}\delta_{\ell\ell'} + \frac{v^2}{\Lambda^2}\mathbf{Y_6}\right)\left[\overline{\ell'_L}\ell_R h\right]$$

Suppressed by GIM mechanism

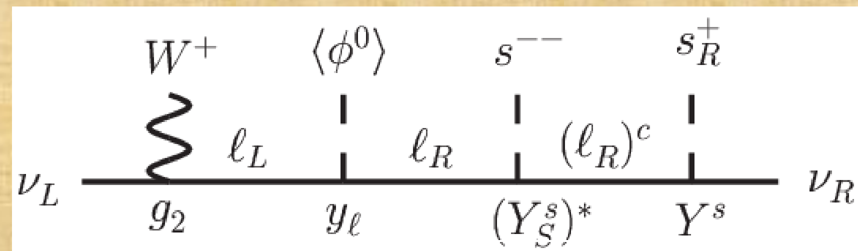
Dim.-6



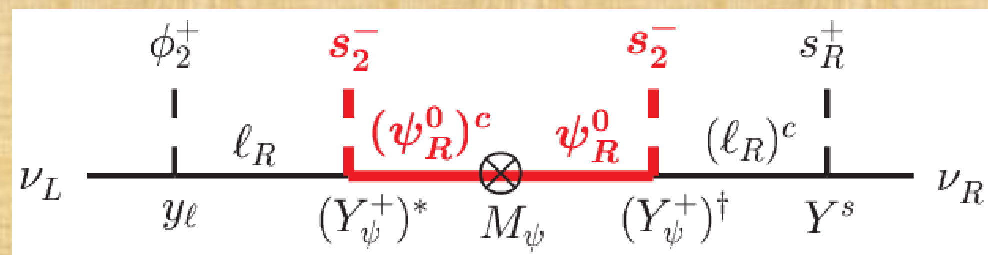
D3



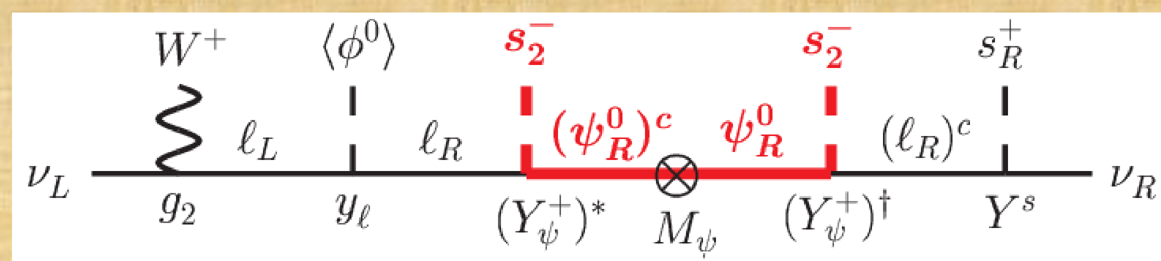
D4



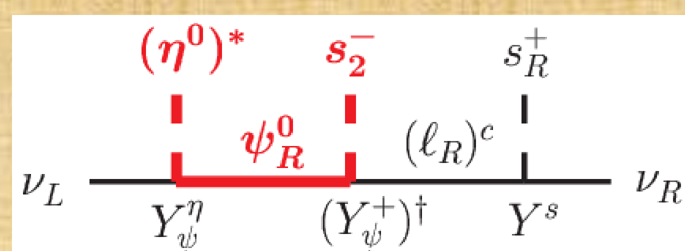
D11

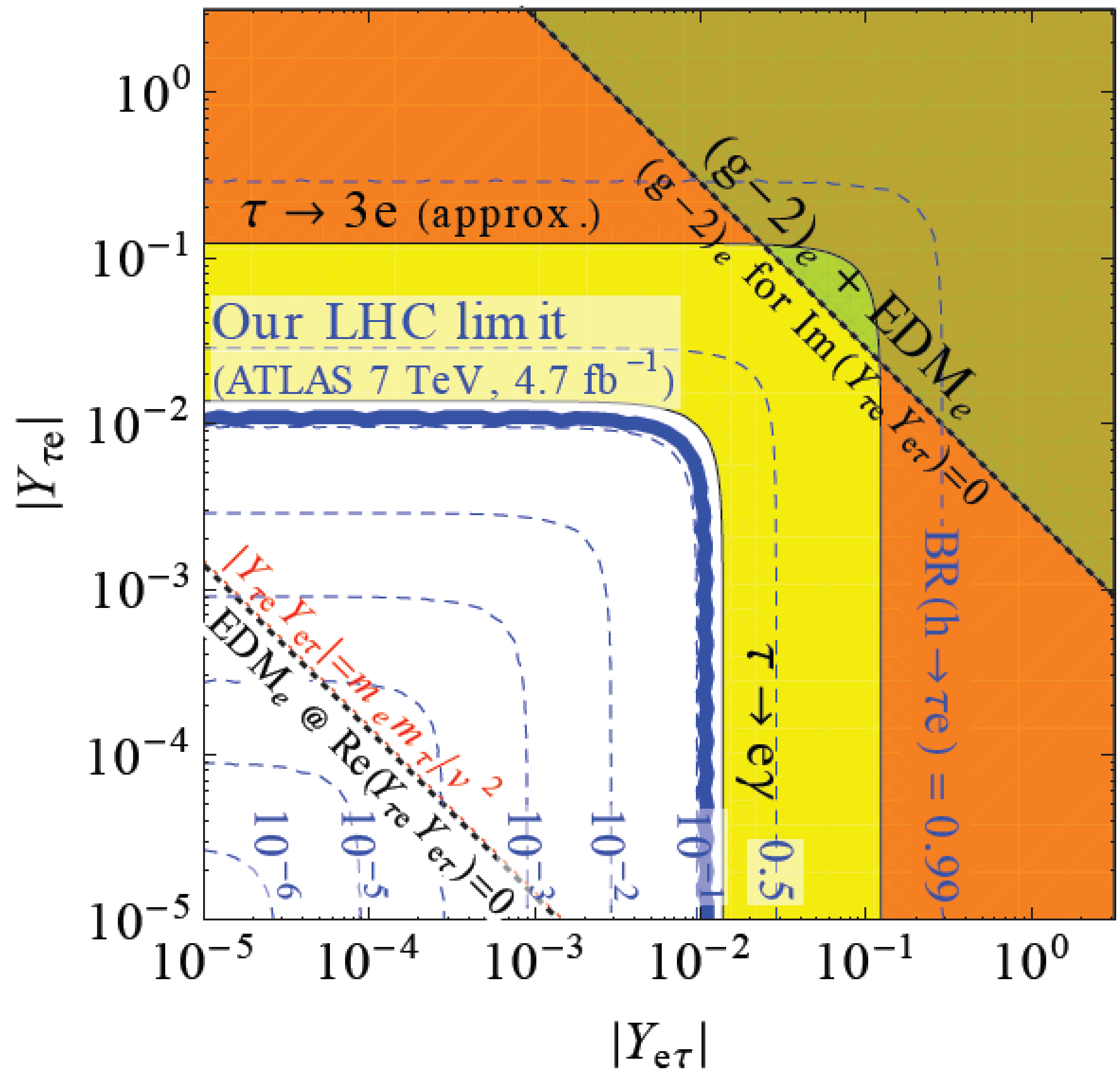


D12

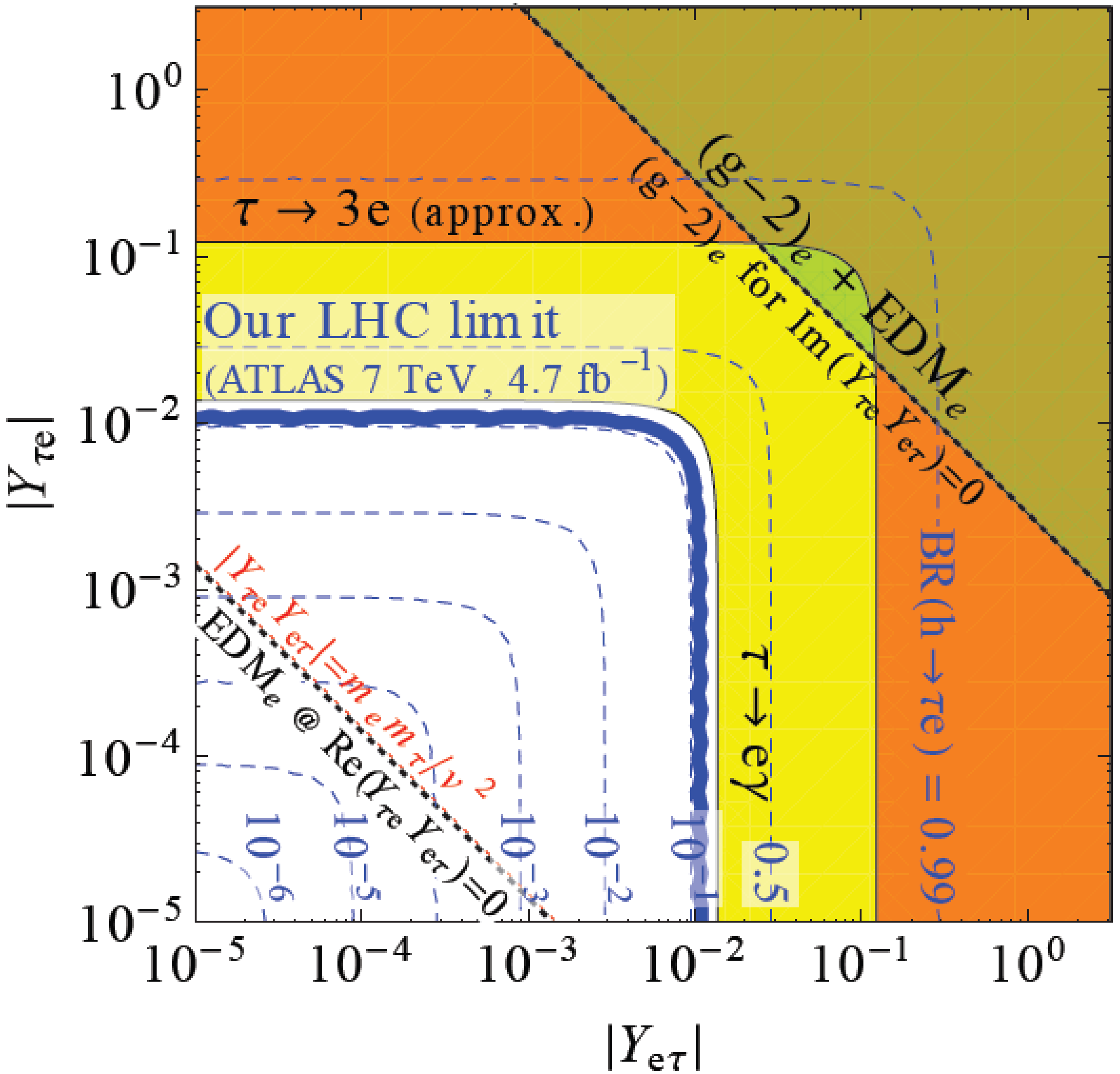


D17

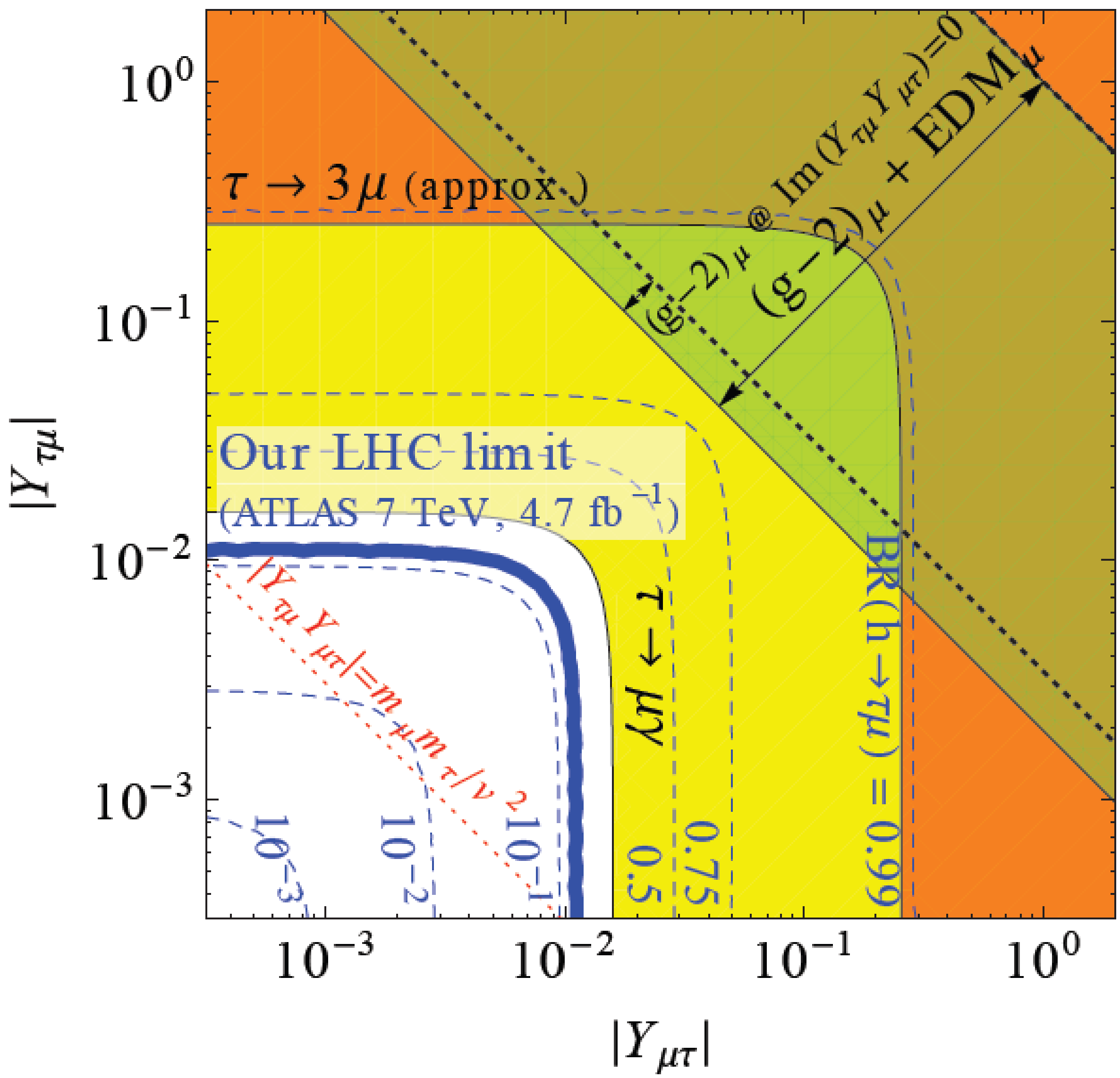




R. Harnik, J. Kopp, J. Zupan, JHEP**1303**, 026 (2013)



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



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

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

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

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

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