Neutrino Mass in TeV-Scale New Physics Models

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This is a short review about relations between new scalars and mechanisms to generate neutrino masses. We investigate leptohilic scalars whose Yukawa interactions are only with leptons. We discuss possibilities that measurements of their leptonic decays provide information on how neutrino masses are generated and on parameters in the neutrino mass matrix (e.g. the lightest neutrino mass).

I. INTRODUCTION

In the standard model of particle physics (SM), neutrinos are regarded as massless particles. However, existence of nonzero masses of neutrinos has been established by a sequence of success of neutrino oscillation measurements [1–6]. If neutrino masses are generated similarly to the other fermion masses via a Yukawa interaction (introducing right-handed neutrinos ν_R) with the $\mathrm{SU}(2)_L$-doublet scalar field Φ_{SM} in the SM, the Yukawa coupling constants must be extremely small ($\sim 10^{-12}$). Since the coupling constant seems too different from the other Yukawa coupling constants to regard it as natural, we might expect that neutrino masses are generated in a different mechanism. The most famous example will be the seesaw mechanism [7] where extremely heavy gauge-singlet fermions are introduced.

In this short review, we consider extensions of the SM with new scalars (in contrast with the seesaw models) along the viewpoint "Higgs as a probe of new physics" of this workshop. Along my viewpoint "neutrino as a guide to new physics", we investigate only leptophilic scalars which couple only with leptons among fermions because such scalars would contribute to mechanism of generating neutrino masses. In order to give predictions, it will not be preferred that two new particles appear in an interaction (Lepton–"New fermion"–"New scalar"). Therefore, let us concentrate on the following types of Yukawa interactions:

$$\text{Lepton–Lepton–"Leptophilic scalar"} \ .$$

The leptophilic scalars here are assumed to be light enough (TeV-scale) to be produced at collider experiments. If the Yukawa interaction relates to the neutrino mass matrix, the flavor structure of decays of the new scalar into leptons would be predicted by using current knowledge on the neutrino oscillation parameters. If the prediction is experimentally confirmed in the future, we would obtain information on the mechanism of the neutrino mass generation and on parameters (e.g. the lightest neutrino mass) which cannot be measured in neutrino oscillation experiments.

We deal with $\mathrm{SU}(2)_L$-singlet, doublet, and triplet scalar fields. Their Yukawa interactions are listed in Table I. For simplicity, mixings between scalars are ignored throughout this article. Leptophilic neutral scalars in doublet and triplet fields are not discussed in this article because their decays via Yukawa interactions are into neutrinos which do not provide information on the flavor structure.

II. BASICS

Neutrinos $\nu_{\ell L}$ ($\ell = e, \mu, \tau$) in the flavor basis are superpositions of mass eigenstates ν_{iL}: $\nu_{\ell L} = \sum_i (U_{\mathrm{MNS}})_{\ell i}\, \nu_{iL}$, where the unitary matrix U_{MNS} is the so-called Maki-Nakagawa-Sakata matrix [8]. When the neutrino mass term is $(m_\nu)_{i\ell} \overline{\nu_{iR}} \nu_{\ell L}$, neutrinos are referred to as the Dirac neutrinos. The mass matrix for Dirac neutrinos is diagonalized with U_{MNS} as $m_\nu U_{\mathrm{MNS}} = \mathrm{diag}(m_1, m_2, m_3)$, where mass eigenvalues m_i are taken to be real and positive. On the other hand, if the neutrino mass term is $(m_\nu)_{\ell\ell'} \overline{(\nu_{\ell L})^c} \nu_{\ell' L}$, we call the neutrinos as the Majorana neutrinos which break the lepton number conservation. The Majorana neutrino mass matrix is diagonalized as $U_{\mathrm{MNS}}^T m_\nu U_{\mathrm{MNS}} = \mathrm{diag}(m_1, m_2 e^{i\alpha_{21}}, m_3 e^{i\alpha_{31}})$, where α_{21} and α_{31} are Majorana phases [9, 10]

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	Yukawa interaction	Decay into leptons	
		Singly charged	Doubly charged
$\mathrm{SU}(2)_L$-singlet	$f_{\ell\ell'}\Big[\overline{L^c_\ell}\, i\sigma_2\, L_{\ell'}\, s^+\Big]$, $\quad f'_{\ell\ell'}\Big[\overline{(\ell_R)^c}\, \ell'_R\, s^{++}\Big]$	$s^+ \to \overline{\ell_L}\,\overline{\nu_{\ell' L}}$	$s^{++} \to \overline{\ell_R}\,\overline{\ell'_R}$
$\mathrm{SU}(2)_L$-doublet	$y_{i\ell}\Big[\overline{\nu_{iR}}\, \Phi_\nu^T i\sigma_2\, L_\ell\Big]$	$\phi_\nu^+ \to \overline{\ell_L}\, \nu_{iR}$	
$\mathrm{SU}(2)_L$-triplet	$h_{\ell\ell'}\Big[\overline{L^c_\ell}\, i\sigma_2\, \Delta\, L_{\ell'}\Big]$	$\Delta^+ \to \overline{\ell_L}\,\overline{\nu_{\ell' L}}$	$\Delta^{++} \to \overline{\ell_L}\,\overline{\ell'_L}$

TABLE I: Yukawa interactions of leptophilic scalar fields and leptonic decays of their singly-charged and doubly-charged components.

which are physical parameters only for Majorana neutrinos. The matrix $U_{\rm MNS}$ can be parameterized as

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

where s_{ij} and c_{ij} stand for $\sin\theta_{ij}$ and $\cos\theta_{ij}$, respectively. Current data of neutrino oscillation measurements [1–6] constrains mixing angles and squared-mass differences ($\Delta m^2_{ij} \equiv m_i^2 - m_j^2$) as

$$\sin^2 2\theta_{23} \simeq 1, \quad \sin^2 2\theta_{13} \simeq 0.089, \quad \sin^2 2\theta_{12} \simeq 0.85, \tag{2}$$
$$\Delta m^2_{21} \simeq 7.5\times 10^{-5}\,\mathrm{eV}^2, \quad |\Delta m^2_{31}| \simeq 2.3\times 10^{-3}\,\mathrm{eV}^2. \tag{3}$$

III. SINGLY CHARGED SCALAR

A. $\mathrm{SU}(2)_L$-singlet I

A singly charged scalar s^+ of an $\mathrm{SU}(2)_L$-singlet with the hypercharge $Y=1$ couples to the lepton doublet $L_\ell = (\nu_{\ell L}, \ell_L)^T$ as

$$f_{\ell\ell'}\Big[\overline{L^c_\ell}\, i\sigma_2\, L_{\ell'}\, s^+\Big] = -2 f_{\ell\ell'}\Big[\overline{(\ell_L)^c}\, \nu_{\ell' L} s^+\Big], \tag{4}$$

where the matrix of Yukawa coupling constants is antisymmetric ($f=-f^T$) and $\sigma_i (i = 1\text{-}3)$ are the Pauli matrices. The scalar s^+ is introduced in e.g. the so-called Zee model [11] where light Majorana neutrino masses are generated at the one-loop level. The simplest version of the Zee model [11, 12] where there is no Flavor-Changing-Neutral-Current (FCNC) was excluded by neutrino oscillation measurements (See e.g. Ref. [13]).

Motivated by the original version of the Zee model where the FCNC exists, we consider a Majorana neutrino mass matrix $(m_\nu)_{\ell\ell'}$ of the following structure in the flavor basis:

$$(m_\nu)_{\ell\ell'} = \Big(X m_\ell^{\rm diag} f + (X m_\ell^{\rm diag} f)^T \Big)_{\ell\ell'}, \tag{5}$$

where X is an arbitrary matrix and $m_\ell^{\rm diag} \equiv \mathrm{diag}(m_e, m_\mu, m_\tau)$. Let us assume that contributions of m_e and m_μ to m_ν are negligible. Then Eq. (5) is simplified as

$$(m_\nu)_{\ell\ell'} \simeq m_\tau \Big(X_{\ell\tau} f_{\tau\ell'} + f_{\ell\tau} X_{\tau\ell'} \Big). \tag{6}$$

Note that m_ν is a rank-2 matrix under this assumption although each term in the right-hand side of Eq. (6) is a rank-1 matrix. Thus, the lightest neutrino becomes massless ($m_1 = 0$ or $m_3 = 0$) while the other two have non-zero masses as required. The m_ν includes four parameters: $f_{e\tau} X_{e\tau}$, $f_{\mu\tau}/f_{e\tau}$, $X_{\mu\tau}/X_{e\tau}$, and $X_{\tau\tau}/X_{e\tau}$. The latter three combinations can be expressed with neutrino mixing parameters by using conditions that $U_{\rm MNS}$ diagonalizes the m_ν (three off-diagonal parts must be zero). Since $f_{e\tau} X_{e\tau}$ is an overall factor for neutrino mass eigenstates, the ratio of nonzero mass eigenstates does not depend on $f_{e\tau}X_{e\tau}$. We see that $m_3 = 0$ (the so-called inverted hierarchy where $m_1/m_2 \simeq 1$) is allowed while $m_1 = 0$ (the so-called normal hierarchy where $m_3/m_2 \gg 1$) cannot be obtained. When we use simple values $\sin^2\theta_{23} = 1/2$ and $\sin^2\theta_{12} = 1/3$ which are almost consistent with neutrino oscillation measurements, $m_1/m_2 \simeq 1$ results in

$$\sin^2 2\theta_{13} \simeq 0.11, \quad \delta \simeq \pi, \quad \alpha_{21} \simeq \pi. \tag{7}$$

The "predicted" value $\sin^2 2\theta_{13} \simeq 0.11$ seems reasonably agree with observations [4, 5]. See Ref. [14] for more detailed analysis of the Zee model.

Partial decay widths $\Gamma_\ell^{(s)}$ for $s^+ \to \overline{\ell_L}\,\overline{\nu_L}$ (where neutrino species are summed) are proportional to $\sum_{\ell'} |f_{\ell\ell'}|^2$. In the discussion above, $f_{\mu\tau}/f_{e\tau}$ is constrained by neutrino mixing parameters. Thus, we obtain the following "prediction" for a combination of branching ratios $\mathrm{BR}_\ell^{(s)} \equiv \mathrm{BR}(s^+ \to \overline{\ell_L}\,\overline{\nu_L})$:

$$\frac{\mathrm{BR}_\tau^{(s)}}{\mathrm{BR}_e^{(s)} - \mathrm{BR}_\mu^{(s)}} \simeq \frac{1+2s_{13}^2}{1-2s_{13}^2} \simeq 1. \tag{8}$$

If this relation is confirmed experimentally, neutrino mass matrix might be of Eq. (6) with parameters in Eq. (7).

B. SU(2)$_L$-singlet II

The singly-charged scalar s^+ is utilized also in the so-called Zee-Babu model [15] where Majorana neutrino masses are generated at the two-loop level. Another example is a model of loop-induced Dirac neutrino masses [16, 17]. Neutrino mass matrix might be given by

$$(m_\nu)_{\ell\ell'} = (f^T X_s f)_{\ell\ell'} \tag{9}$$

for Majorana neutrinos (similarly to the Zee-Babu model) or

$$(m_\nu)_{i\ell}\left[\overline{\nu_{iR}}\,\nu_{\ell L}\right] = (Xf)_{i\ell}\left[\overline{\nu_{iR}}\,\nu_{\ell L}\right] \tag{10}$$

for Dirac neutrinos (similarly to the model in Refs. [16, 17]). The matrix X_s is symmetric while X is arbitrary. Ratios of three elements of $f_{\ell\ell'}$ can be easily obtained as functions of neutrino mixing parameters [18] (See also Refs. [17, 19]). Results are the same for Eqs. (9) and (10). For $\sin^2\theta_{23} = 1/2$ and $\sin^2\theta_{12} = 1/3$, we obtain

$$\mathrm{BR}_e^{(s)} : \mathrm{BR}_\mu^{(s)} : \mathrm{BR}_\tau^{(s)} = \begin{cases} 2:5:5 & (\text{for } m_1 = 0) \\ 2:1:1 & (\text{for } m_3 = 0) \end{cases}. \tag{11}$$

If experiments confirm these ratios, the structure of the neutrino mass matrix in Eq. (9) or (10) might be true.

C. SU(2)$_L$-doublet

Neutrinos might obtain their Dirac masses via a vacuum expectation value (vev) of an additional SU(2)$_L$-doublet scalar field Φ_ν [20, 21]. We refer to the model as the neutrinophilic two-Higgs-doublet model. The Yukawa interaction of neutrinos with Φ_ν is written as

$$-(y_\nu)_{i\ell}\left[\overline{\nu_{iR}}\,\Phi_\nu^T i\sigma_2\, L_\ell\right] = (y_\nu)_{i\ell}\left[\overline{\nu_{iR}}\,\nu_{\ell L}\phi_\nu^0\right] - (y_\nu)_{i\ell}\left[\overline{\nu_{iR}}\,\ell_L\phi_\nu^+\right], \tag{12}$$

where ν_{iR} are right-handed components of mass eigenstates ν_i (so, we do not regard ν_{iR} as new particles here). The mass matrix of the Dirac neutrinos is simply given by $(m_\nu)_{i\ell} = \langle\phi_\nu^0\rangle(y_\nu)_{i\ell}$. The branching ratios $\mathrm{BR}(\phi_\nu^+ \to \overline{\ell_L}\nu_R)$, where neutrino species are summed, are proportional to $(m_\nu^\dagger m_\nu)_{\ell\ell}$. Figure 1 (taken from Ref. [21]) shows behaviors of these branching ratios with respect to the lightest neutrino mass (m_1 for the left panel, and m_3 for the right one) for the case ϕ_ν^+ decays only into leptons. By measuring $e\nu$ mode, it would be possible to extract information on the value of the lightest neutrino mass and on whether $m_1 < m_3$ (left panel in Fig. 1) or not. If experiments show that $\mathrm{BR}(H^+ \to \overline{\tau_L}\nu_R)$ is very different from $\mathrm{BR}(H^+ \to \overline{\mu_L}\nu_R)$, the charged scalar might not contribute to the mechanism of generating neutrino masses in a simple way.

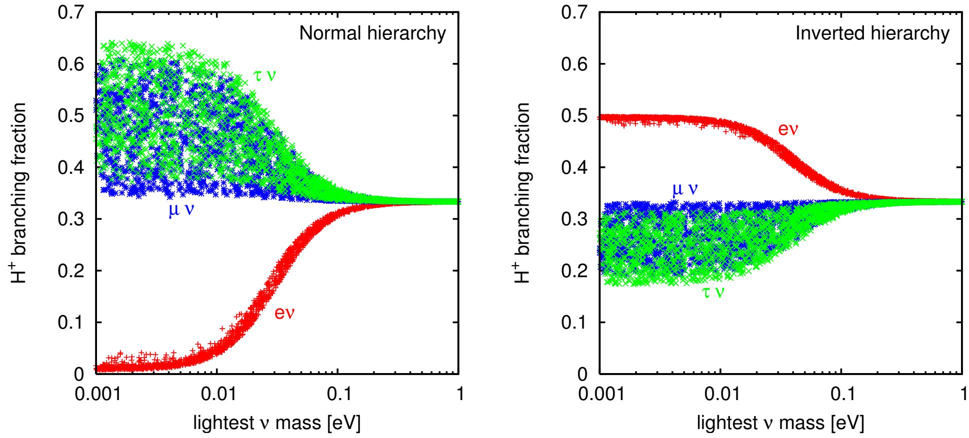

FIG. 1: Behaviors of $\mathrm{BR}(\phi_\nu^+ \to \overline{\ell_L}\nu_R)$ with respect to m_1 (left panel) and m_3 (right panel). This figure is taken from Ref. [21].

D. SU(2)$_L$-triplet

A singly charged scalar exists in an SU(2)$_L$-triplet field Δ with $Y=1$, which can be expressed as

$$\Delta \equiv \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}. \tag{13}$$

The triplet scalar field interacts with the lepton doublet as

$$h_{\ell\ell'}\left[\overline{L_\ell^c}\, i\sigma_2\, \Delta\, L_{\ell'}\right] = -h_{\ell\ell'}\left[\overline{(\ell_L)^c}\,\ell'_L\Delta^{++}\right] - \sqrt{2}\,h_{\ell\ell'}\left[\overline{(\nu_{\ell L})^c}\,\ell'_L\Delta^+\right] + h_{\ell\ell'}\left[\overline{(\nu_{\ell L})^c}\,\nu_{\ell' L}\Delta^0\right], \tag{14}$$

where the Yukawa coupling constants satisfy $h_{\ell\ell'} = h_{\ell'\ell}$. The vev of Δ^0 can generate neutrino masses [10, 22] as

$$(m_\nu)_{\ell\ell'} = 2\langle\Delta^0\rangle h_{\ell\ell'}. \tag{15}$$

Hereafter, we refer to this solo mechanism of generating neutrino masses as the Higgs triplet model. Branching ratios $\mathrm{BR}(\Delta^+ \to \overline{\ell_L}\,\overline{\nu_L})$ in the Higgs triplet model are proportional to $(m_\nu^\dagger m_\nu)_{\ell\ell}$ identically to those in the neutrinophilic two-Higgs-doublet model. Therefore, the discussion in the previous subsection is applicable also for $\Delta^+ \to \overline{\ell_L}\,\overline{\nu_L}$. See e.g. Fig. 16 in Ref. [23] to compare with Fig. 1 in this article. If non-leptonic decays (e.g. $\Delta^+ \to W^-\Delta^{++}$) are not negligible, a ratio of branching ratios of $e\nu$ and $\mu\nu$ modes would be reliable.

IV. DOUBLY CHARGED SCALAR

A. SU(2)$_L$-singlet

An SU(2)$_L$-singlet scalar s^{++} with $Y=2$ has the following Yukawa interaction:

$$f'_{\ell\ell'}\left[\overline{(\ell_R)^c}\,\ell'_R\, s^{++}\right], \tag{16}$$

where the Yukawa coupling constants satisfy $f'_{\ell\ell'} = f'_{\ell'\ell}$. The scalar s^{++} is introduced in e.g. the Zee-Babu model [15] where an SU(2)$_L$-singlet scalar s^+ (see also Sections III A and III B) is also introduced. The Yukawa interaction with s^+ is shown in Eq. (4).

Motivated by the Zee-Babu model, let us take a case in which the structure of neutrino mass matrix $(m_\nu)_{\ell\ell'}$ is given by

$$(m_\nu)_{\ell\ell'} \propto \left[f m_\ell^{\mathrm{diag}} f' m_\ell^{\mathrm{diag}} f^T\right]_{\ell\ell'}, \tag{17}$$

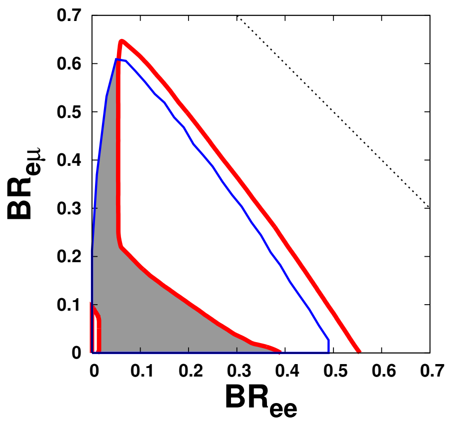

FIG. 2: Two axis are defined as $\mathrm{BR}_{\ell\ell'} \equiv \mathrm{BR}(\Delta^{++} \to \overline{\ell_L}\,\overline{\ell'_L})$. Values of $\mathrm{BR}_{\ell\ell'}$ in the shaded region cannot be achieved in the model when the lightest neutrino mass is zero. This figure is a simplified version of the one in Ref. [25].

where $m_\ell^{\mathrm{diag}} \equiv \mathrm{diag}(m_e, m_\mu, m_\tau)$. Discussion in this subsection is based on Refs. [18, 19] where the Zee-Babu model was studied. The lightest neutrino becomes massless ($m_1 = 0$ or $m_3 = 0$) because of $\mathrm{Det}(m_\nu) \propto \mathrm{Det}(f) = 0$. We simply assume that m_e in Eq. (17) can be ignored so that we can have some "prediction" on the flavor structure of branching ratios $\mathrm{BR}(s^{++} \to \overline{\ell_R}\,\overline{\ell'_R})$ which are proportional to $|f'_{\ell\ell'}|^2$. Then, because of a large mixing angle θ_{23}, we expect $|(m_\nu)_{\mu\mu}| \simeq |(m_\nu)_{\mu\tau}| \simeq |(m_\nu)_{\tau\tau}|$ which results in $|f'_{\mu\mu}| m_\mu^2/m_\tau^2 \simeq |f'_{\mu\tau}| m_\mu/m_\tau \simeq |f'_{\tau\tau}|$. The branching ratios become

$$\mathrm{BR}(s^{++} \to \overline{\mu_R}\,\overline{\mu_R}) : \mathrm{BR}(s^{++} \to \overline{\mu_R}\,\overline{\tau_R}) : \mathrm{BR}(s^{++} \to \overline{\tau_R}\,\overline{\tau_R}) \simeq 1 : 0 : 0. \tag{18}$$

If Eq. (18) turns out to be consistent with measurements, the neutrino mass matrix might be the structure in Eq. (17) where $m_1 = 0$ or $m_3 = 0$ is predicted.

B. $\mathrm{SU}(2)_L$-triplet

A doubly charged scalar exists also in the Higgs triplet model (see also Sec. III D). Let us take a scenario that Δ^{++} dominantly decays into a pair of same-signed leptons: $\Delta^{++} \to \overline{\ell_L}\,\overline{\ell'_L}$. Then branching ratios of leptonic decays are determined by $h_{\ell\ell'}$, and the flavor structure of the branching ratios can provide direct information on the neutrino mass matrix [24, 25]. For example, if branching ratios $\mathrm{BR}(\Delta^{++} \to \overline{e_L}\,\overline{e_L})$ and $\mathrm{BR}(\Delta^{++} \to \overline{e_L}\,\overline{\mu_L})$ are observed in the shaded region in Fig. 2, it would be excluded that the lightest neutrino mass is zero in this model [25]. Note that information on the lightest neutrino mass cannot be obtained by neutrino oscillation measurements.

V. SUMMARY

We discussed relations between the neutrino mass matrix and the flavor structure of decays of leptophilic charged scalars. By assuming how a matrix of Yukawa coupling constants for a leptophilic scalar appears in the neutrino mass matrix, we obtained predictions on the leptonic decays of the scalar.

If the antisymmetric matrix f of Yukawa coupling constants for an $\mathrm{SU}(2)_L$-singlet singly-charged scalar s^+ appears in the neutrino mass matrix as $(m_\nu)_{\ell\ell'} \simeq m_\tau(X_{\ell\tau} f_{\tau\ell'} + f_{\ell\tau} X_{\tau\ell'})$, a combination of branching ratios for $s^+ \to \overline{\ell_L}\,\overline{\nu_L}$ satisfies $\mathrm{BR}_\tau^{(s)}/(\mathrm{BR}_e^{(s)} - \mathrm{BR}_\mu^{(s)}) \simeq 1$. For $\sin^2\theta_{23} = 1/2$ and $\sin^2\theta_{12} = 1/3$, we obtained $\sin^2 2\theta_{13} \simeq 0.11$, $\delta \simeq \pi$, and $\alpha_{21} \simeq \pi$. If the matrix f appears as $m_\nu = f X_s f^T$ or Xf, we predicted $\mathrm{BR}_e^{(s)} : \mathrm{BR}_\mu^{(s)} : \mathrm{BR}_\tau^{(s)} = 2 : 5 : 5$ for $m_1 = 0$ and $2 : 1 : 1$ for $m_3 = 0$. On the other hand, if a leptophilic singly-charged scalar is a member of $\mathrm{SU}(2)_L$-doublet or triplet, a branching ratio for a decay into $\overline{e_L}\,\nu$ (and $\overline{\mu_L}\,\nu$) would provide information on the value of the lightest neutrino mass and on whether $m_1 < m_3$ or not.

The symmetric matrix f' of Yukawa coupling constants for an $\mathrm{SU}(2)_L$-singlet doubly-charged scalar s^{++} might contribute to the neutrino mass matrix as $m_\nu = f m_\ell^{\rm diag} f' m_\ell^{\rm diag} f^T$. When we assume that a contribution of m_e to m_ν is negligible and $|(m_\nu)_{\mu\mu}| \simeq |(m_\nu)_{\mu\tau}| \simeq |(m_\nu)_{\tau\tau}|$, decays of s^{++} into $\overline{\mu_R}\,\overline{\tau_R}$ and $\overline{\tau_R}\,\overline{\tau_R}$ become negligible in comparison with the $\mu\mu$ mode. For the case of Δ^{++} in an $\mathrm{SU}(2)_L$-triplet field, the flavor structure of $\Delta^{++} \to \overline{\ell_L}\,\overline{\ell'_L}$ directly relates to the neutrino mass matrix. We showed that information on the lightest neutrino mass (and Majorana phases etc.) could be obtained by observing the structure of the Δ^{++} decays.

We hope that the mechanism of the neutrino mass generation is uncovered by discovery of such leptophilic scalars at collider experiments. Peaks of their signals may remind us of the Tateyama peaks in Toyama!

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