New Physics for Neutrinoless Double Beta Decay

Pei-Hong Gu
Shanghai Jiao Tong University

CEPC-SppC Study Group workshop, Beihang U., 03.09.2016

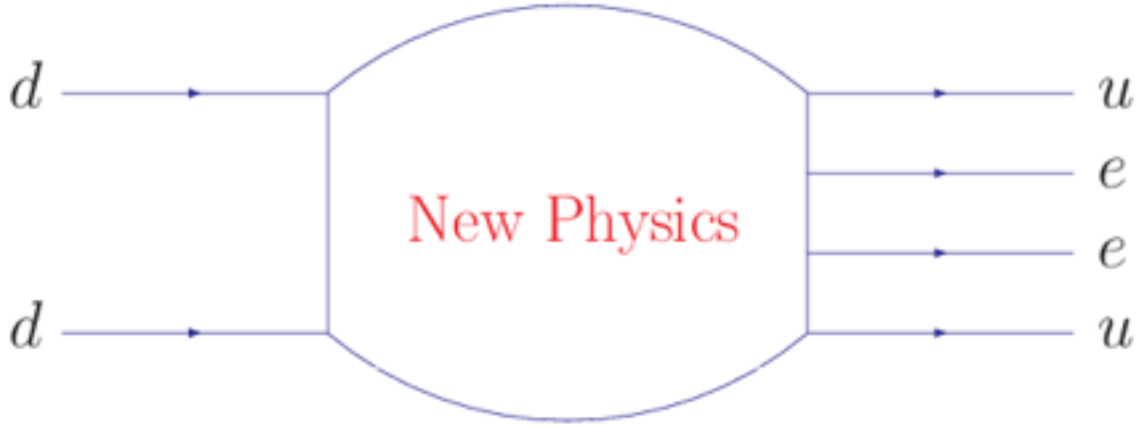
Outline

1. General Picture of Neutrinoless Double Beta Decay
2. Standard Neutrinoless Double Beta Decay
3. Non-standard Neutrinoless Double Beta Decay
4. Neutrinoless Double Beta Decay in the Extended Two Higgs Doublet Models
5. Neutrinoless Double Beta Decay in the Linear Seesaw Models
6. Summary

General Picture of Neutrinoless Double Beta Decay

$$(Z, A) \rightarrow (Z+2, A) + 2e^{-}$$

W.H. Furry,1939

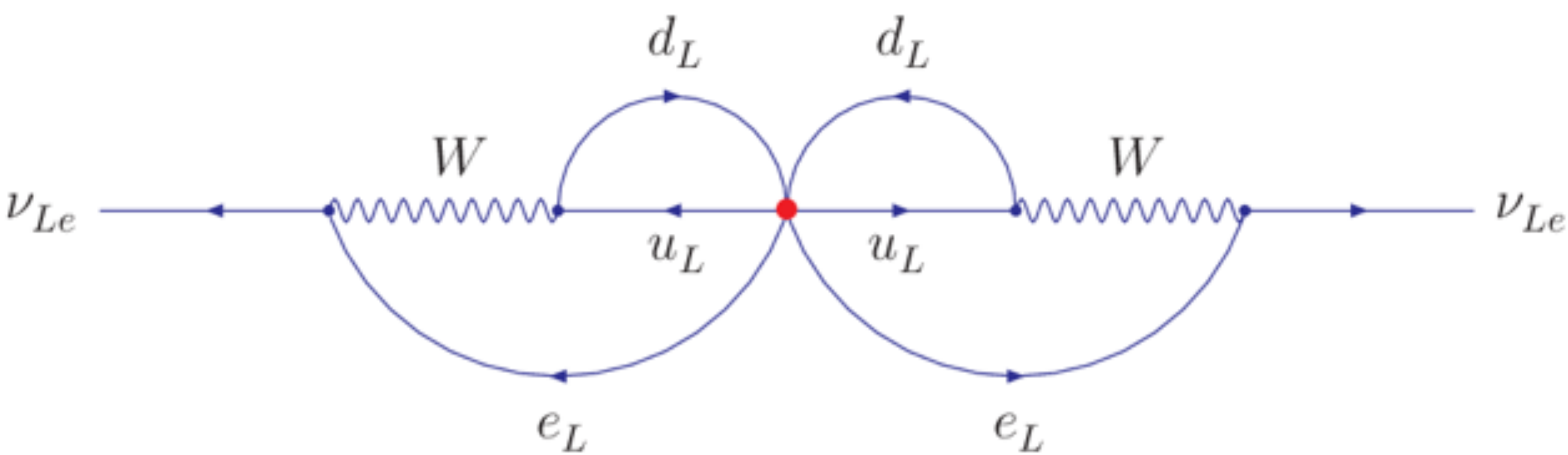


$$\Delta L = 2$$

$I. \quad \Delta L = 2 \quad \Rightarrow \quad$ Majorana Neutrino Masses $\quad \Rightarrow \quad$ Neutrinoless Double Beta Decay

$II. \quad \Delta L = 2 \quad \Rightarrow \quad$ Neutrinoless Double Beta Decay $\quad \Rightarrow \quad$ Majorana Neutrino Masses

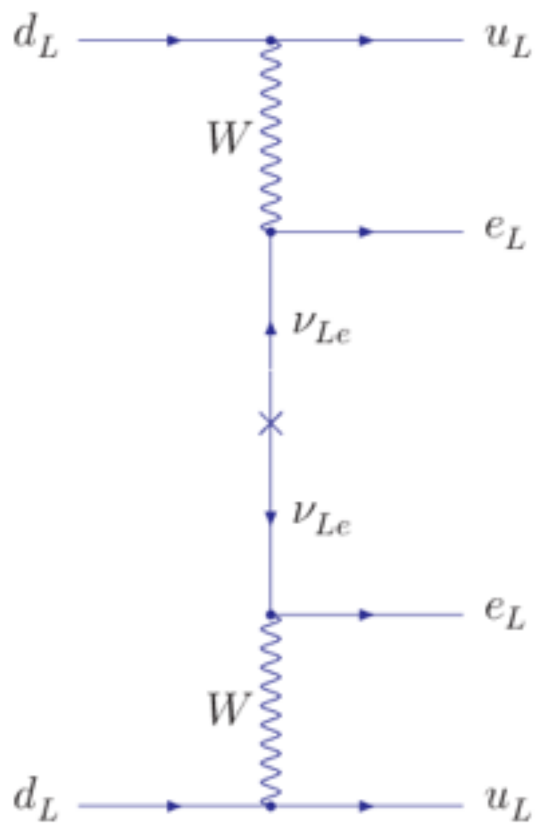
$$III. \quad \Delta L = 2 \quad \Rightarrow \quad \begin{cases} \text{Majorana Neutrino Masses} \\ \text{Neutrinoless Double Beta Decay} \end{cases}$$



Neutrinoless Double Beta Decay $\Longleftrightarrow$ Majorana Neutrinos

J. Schechter and J.W.F. Valle,1982

Standard Neutrinoless Double Beta Decay



$$\mathcal{L} \supset 16\, G_F^2 \bar{u}_L \gamma^\mu d_L \bar{e}_L \gamma_\mu \frac{(m_\nu)_{ee}}{q^2} \gamma_\nu e_L^c \bar{u}_L \gamma^\nu d_L$$

$$\frac{1}{T_{1/2}^{0\nu}} = G_{01}^{0\nu}|M_{LL}^{0\nu}|^2 \frac{|(m_\nu)_{ee}|^2}{m_e^2}$$

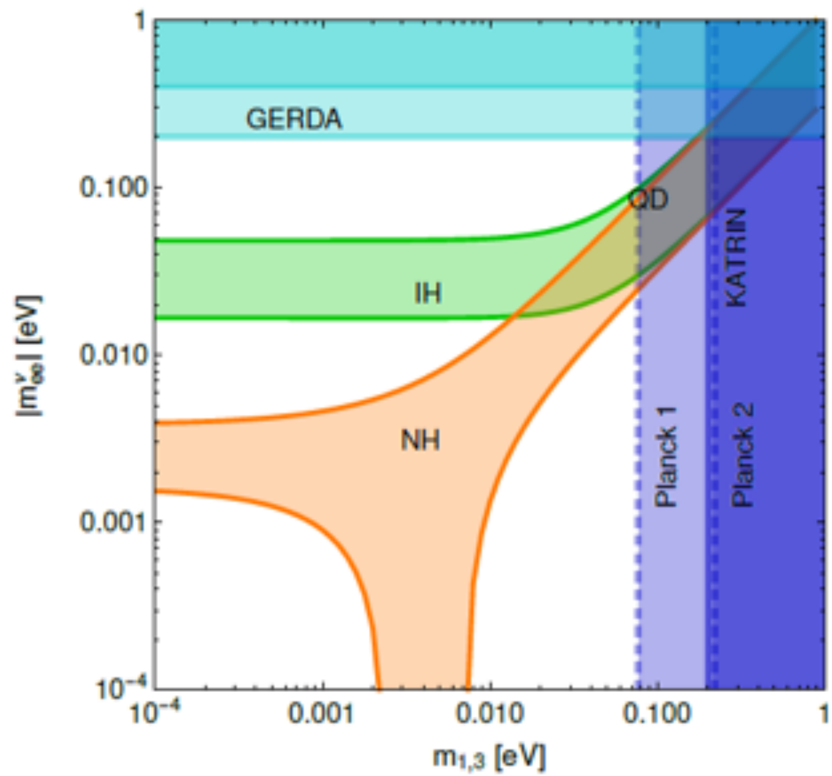
$$^{136}\mathrm{Xe}: G_{01}^{0\nu} = 3.56 \times 10^{-14}\,\mathrm{yr}^{-1},\ M_{LL} = 1.57 - 3.85$$

$$^{76}\mathrm{Ge}: G_{01}^{0\nu} = 5.77 \times 10^{-15}\,\mathrm{yr}^{-1},\ M_{LL} = 2.58 - 6.64$$

G. Pantis, F. Simkovic, J.D. Vergados, and A. Faessler, 1996; J. Kotila and F. Iachello, 2012.

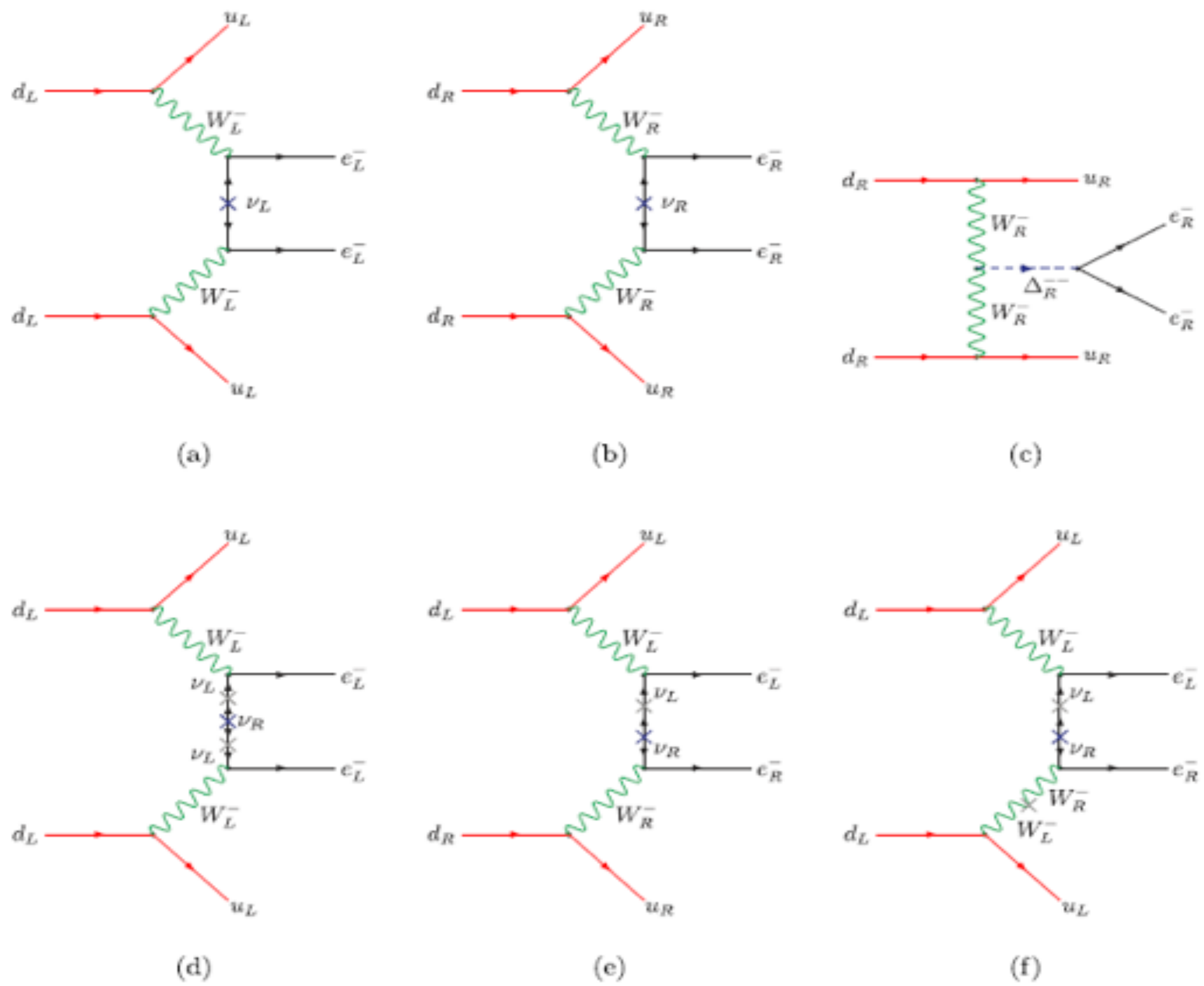
$$\mathrm{KamLAND\text{-}Zen}: T_{1/2}^{0\nu}(^{136}\mathrm{Xe}) > 3.4 \times 10^{25}\,\mathrm{yr}$$ PRL 110, 062502 (2013)

$$\mathrm{GERDA}: T_{1/2}^{0\nu}(^{76}\mathrm{Ge}) > 3.0 \times 10^{25}\,\mathrm{yr}$$ PRL 111, 122503 (2013)

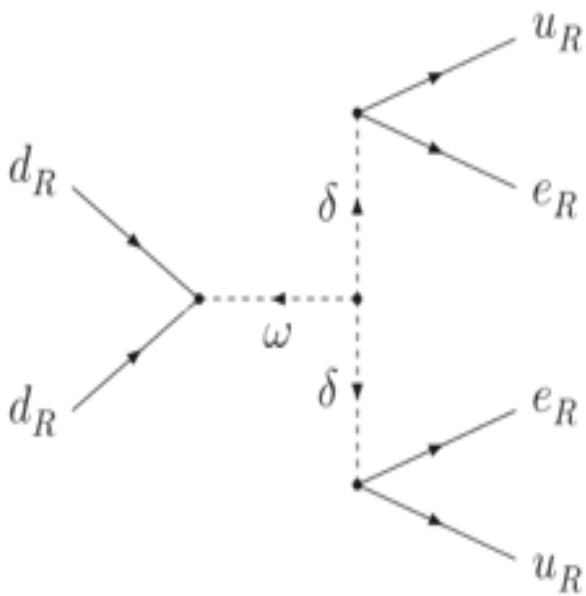


S.F. Ge, M. Lindner, and S. Patra, 2015

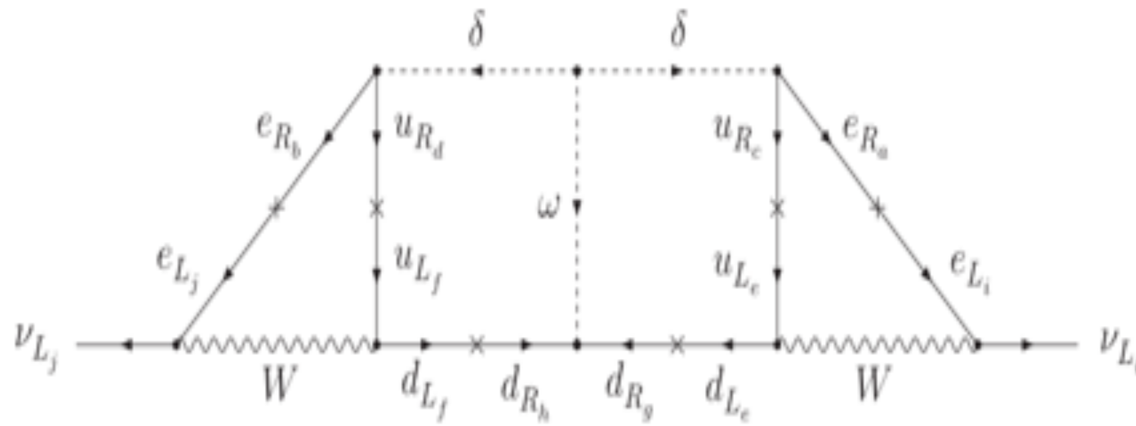
Non-standard Neutrinoless Double Beta Decay

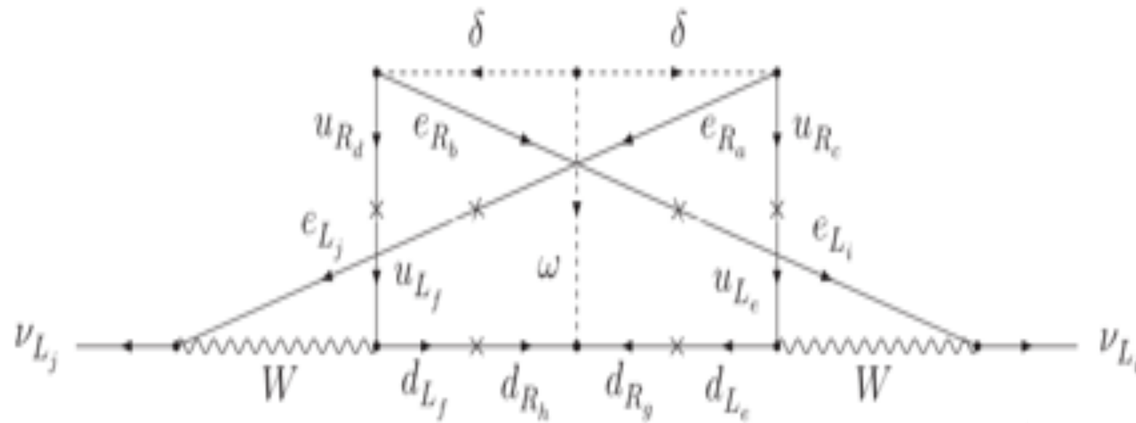


R.N. Mohapatra, G. Senjanovic, 1980; C.H. Lee, P.S. Bhupal Dev, R.N. Mohapatra, 2013; ...



$$\delta m_{\nu_{ij}} \lesssim \frac{g^4}{2^{15}\pi^8}\frac{\mu m_\tau^2 m_t^2 m_b^2}{m_\omega^2 m_\delta^4}$$





PHG, 2011

For a summary of renormalizable models for non-standard neutrinoless double beta decay, see F. Bonnet, M. Hirsch, T. Ota, W. Winter, JHEP 1303, 055 (2013).

- Usually the models for non-standard neutrinoless double beta decay contain quite a few unknown parameters. In consequence, theses non-standard neutrinoless double beta decay is irrelevant to the neutrino mass generation.

- In the following I will demonstrate the non-standard neutrinoless double beta decay in some extended two Higgs doublet models and the so-called linear seesaw model. In these models, the neutrinoless double beta decay can arrive at a testable level if the Majorana mass of electron neutrino is extremely small even zero. These models contain new particles near the TeV scale and hence they may be interested to the CEPC/SppC.

Neutrinoless Double Beta Decay in the Extended Two Higgs Doublet Models

$$\phi_1(1,2,+\tfrac{1}{2}) = \begin{bmatrix} \phi_1^+ \\ \phi_1^0 \end{bmatrix}, \quad \phi_2(1,2,+\tfrac{1}{2}) = \begin{bmatrix} \phi_2^+ \\ \phi_2^0 \end{bmatrix}$$

$$q_L(3,2,+\tfrac{1}{6}) = \begin{bmatrix} u_L \\ d_L \end{bmatrix}, \quad d_R(3,1,-\tfrac{1}{3}), \quad u_R(3,1,+\tfrac{2}{3}),$$

$$l_L(1,2,-\tfrac{1}{2}) = \begin{bmatrix} \nu_L \\ e_L \end{bmatrix}, \quad e_R(1,1,-1)$$

$$\delta^{\pm}(1,1,\pm 1), \quad \xi^{\pm\pm}(1,1,\pm 2)$$

Zhen Liu, PHG, 2016

$$\chi = \begin{bmatrix} \chi^+ \\ \chi^0 \end{bmatrix} = \phi_1 \cos\beta - \phi_2 \sin\beta \,,$$

$$\varphi = \begin{bmatrix} \varphi^+ \\ \varphi^0 \end{bmatrix} = \phi_1 \sin\beta + \phi_2 \cos\beta \,.$$

$$\tan\beta = \frac{\langle\phi_1\rangle}{\langle\phi_2\rangle} = \frac{v_1}{v_2} \quad \text{with} \quad \langle\phi_{1(2)}\rangle = \begin{bmatrix} 0 \\ \frac{1}{\sqrt{2}} v_{1(2)} \end{bmatrix}$$

$$\langle\chi\rangle = 0 \,,$$

$$\langle\varphi\rangle = \begin{bmatrix} 0 \\ \frac{1}{\sqrt{2}} v \end{bmatrix} \quad \text{with} \quad v = \sqrt{v_1^2 + v_2^2} \simeq 246\,\mathrm{GeV}$$

$$\begin{aligned} V = {} & \mu_\varphi^2 |\varphi|^2 + \mu_\chi^2 |\chi|^2 + \kappa_1 |\varphi|^4 + \kappa_2 |\chi|^4 + \kappa_3 |\varphi|^2 |\chi|^2 \\ & + \kappa_4 \varphi^\dagger \chi \chi^\dagger \varphi + \kappa_5 [(\varphi^\dagger \chi)^2 + \mathrm{H.c.}] + (\mu_\delta^2 + \kappa_{\varphi\delta} |\varphi|^2 \\ & + \kappa_{\chi\delta} |\chi|^2 + \kappa_{\varphi\chi\delta} \varphi^\dagger \chi + \mathrm{H.c.}) |\delta|^2 + \kappa_\delta |\delta|^4 + (\mu_\xi^2 \\ & + \kappa_{\varphi\xi} |\varphi|^2 + \kappa_{\chi\xi} |\chi|^2 + \kappa_{\varphi\chi\xi} \varphi^\dagger \chi + \mathrm{H.c.}) |\xi|^2 \\ & + \kappa_\xi |\xi|^4 + \kappa_{\delta\xi} |\delta|^2 |\xi|^2 + \frac{1}{2} \omega (\xi^{++} \delta^- \delta^- + \mathrm{H.c.}) \\ & + \sigma (\delta^- \varphi^T i\tau_2 \chi + \mathrm{H.c.}) \,. \end{aligned}$$

$$\mathcal{L}_Y = -y'_u\bar{q}_L\tilde{\phi}_1 u_R - y'_d\bar{q}_L\phi_1 d_R - y'_e\bar{l}_L\phi_1 e_R - \frac{1}{2}f\xi^{--}\bar{e}_R e^c_R + \text{H.c.} \quad \text{with} \quad f = f^T$$

$$\mathcal{L}_Y = -y'_u\bar{q}_L\tilde{\phi}_1 u_R - y'_d\bar{q}_L\phi_1 d_R - y'_e\bar{l}_L\phi_2 e_R - \frac{1}{2}f\xi^{--}\bar{e}_R e^c_R + \text{H.c.} \quad \text{with} \quad f = f^T$$

$$\mathcal{L}_Y = -y'_u\bar{q}_L\tilde{\phi}_1 u_R - y'_d\bar{q}_L\phi_2 d_R - y'_e\bar{l}_L\phi_1 e_R - \frac{1}{2}f\xi^{--}\bar{e}_R e^c_R + \text{H.c.} \quad \text{with} \quad f = f^T$$

$$\mathcal{L}_Y = -y'_u\bar{q}_L\tilde{\phi}_1 u_R - y'_d\bar{q}_L\phi_2 d_R - y'_e\bar{l}_L\phi_2 e_R - \frac{1}{2}f\xi^{--}\bar{e}_R e^c_R + \text{H.c.} \quad \text{with} \quad f = f^T$$

- *Case-1*:

$$\mathcal{L}_Y = -y_u\bar{q}_L\tilde{\varphi}u_R - y_d\bar{q}_L\varphi d_R - y_e\bar{l}_L\varphi e_R - (y_u\cot\beta)\bar{q}_L\tilde{\chi}u_R - (y_d\cot\beta)\bar{q}_L\chi d_R - (y_e\cot\beta)\bar{l}_L\chi e_R - \frac{1}{2}f\xi^{--}\bar{e}_R e^c_R + \text{H.c.}$$

- *Case-2*:

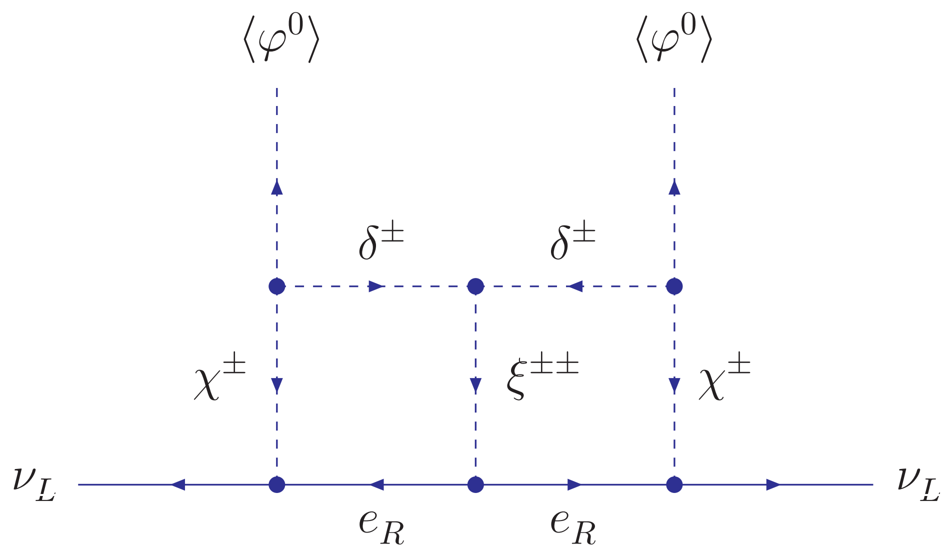
$$\mathcal{L}_Y = -y_u\bar{q}_L\tilde{\varphi}u_R - y_d\bar{q}_L\varphi d_R - y_e\bar{l}_L\varphi e_R - (y_u\cot\beta)\bar{q}_L\tilde{\chi}u_R - (y_d\cot\beta)\bar{q}_L\chi d_R + (y_e\tan\beta)\bar{l}_L\chi e_R - \frac{1}{2}f\xi^{--}\bar{e}_R e^c_R + \text{H.c.}$$

- *Case-3*:

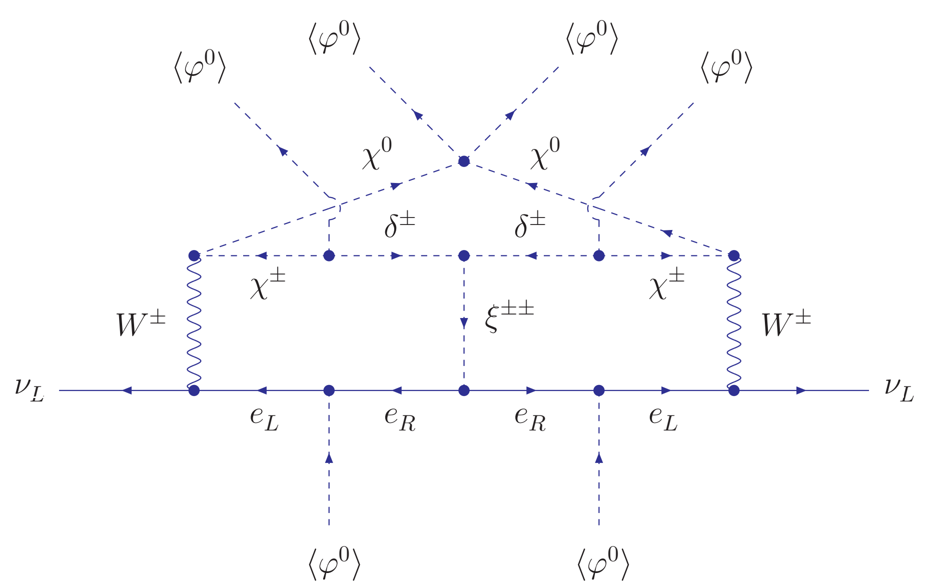
$$\mathcal{L}_Y = -y_u\bar{q}_L\tilde{\varphi}u_R - y_d\bar{q}_L\varphi d_R - y_e\bar{l}_L\varphi e_R - (y_u\cot\beta)\bar{q}_L\tilde{\chi}u_R + (y_d\tan\beta)\bar{q}_L\chi d_R - (y_e\cot\beta)\bar{l}_L\chi e_R - \frac{1}{2}f\xi^{--}\bar{e}_R e^c_R + \text{H.c.}$$

- *Case-4*:

$$\mathcal{L}_Y = -y_u\bar{q}_L\tilde{\varphi}u_R - y_d\bar{q}_L\varphi d_R - y_e\bar{l}_L\varphi e_R - (y_u\cot\beta)\bar{q}_L\tilde{\chi}u_R + (y_d\tan\beta)\bar{q}_L\chi d_R + (y_e\tan\beta)\bar{l}_L\chi e_R - \frac{1}{2}f\xi^{--}\bar{e}_R e^c_R + \text{H.c.}$$



$\langle\varphi^0\rangle$
$\langle\varphi^0\rangle$
$\delta^\pm$
$\delta^\pm$
$\chi^\pm$
$\xi^{\pm\pm}$
$\chi^\pm$
ν_L
ν_L
e_R
e_R



$\langle\varphi^0\rangle$
$\langle\varphi^0\rangle$
$\langle\varphi^0\rangle$
$\langle\varphi^0\rangle$
χ^0
χ^0
$\delta^\pm$
$\delta^\pm$
$\chi^\pm$
$\chi^\pm$
$W^\pm$
$\xi^{\pm\pm}$
$W^\pm$
ν_L
ν_L
e_L
e_R
e_R
e_L
$\langle\varphi^0\rangle$
$\langle\varphi^0\rangle$

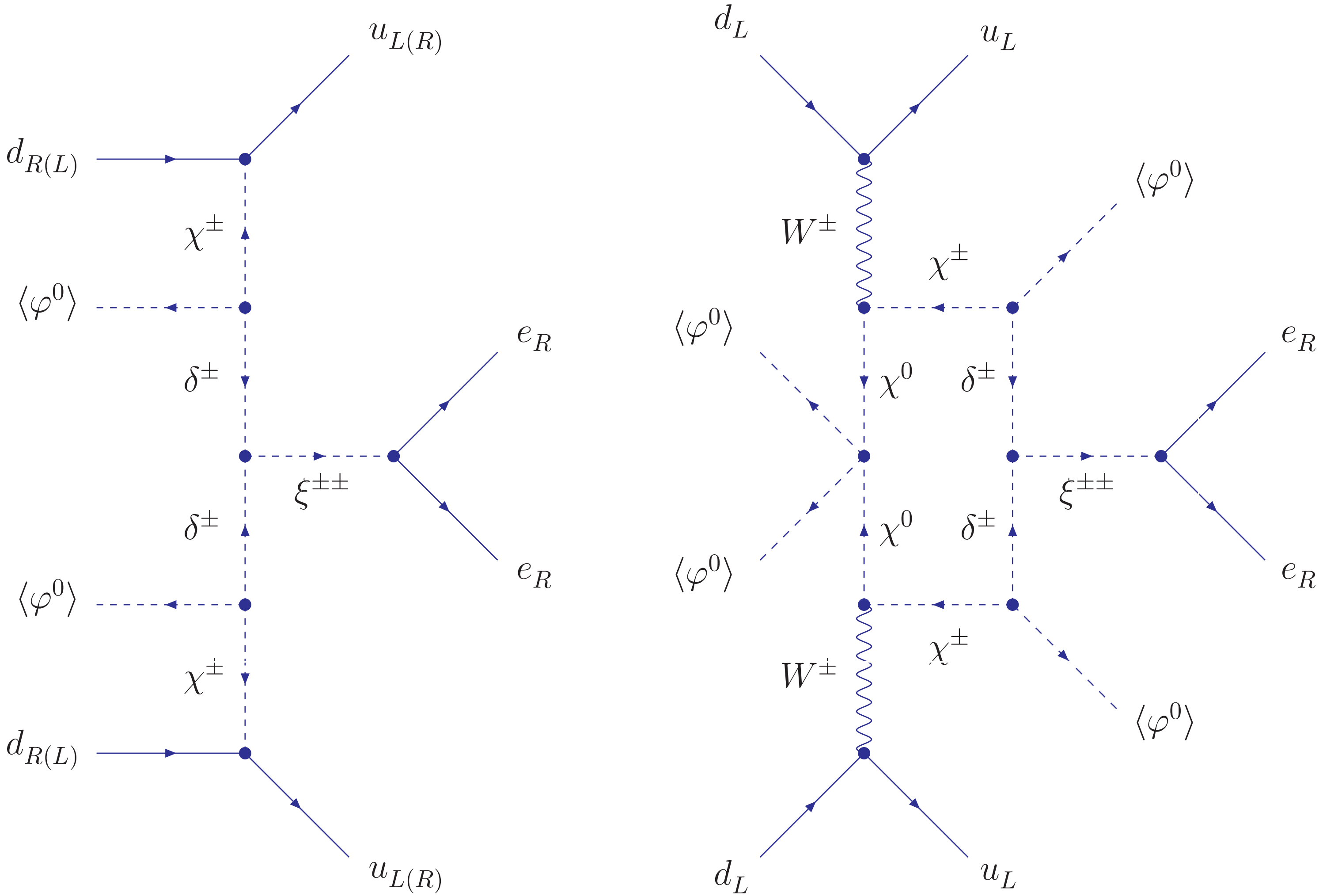
$$m_\nu^{\text{2-loop}} = \frac{cI_2\sin^2 2\theta}{2(16\pi^2)^2}\hat{y}_e f \hat{y}_e \omega = \frac{cI_2\sin^2 2\theta}{2^8\pi^4}\frac{\hat{m}_e f \hat{m}_e}{v^2}\omega$$

$$\text{with} \quad c = \begin{cases} \cot^2\beta & \text{in } \textit{Case-1,3}, \\ \tan^2\beta & \text{in } \textit{Case-2,4}. \end{cases}$$

$$\hat{\chi}^\pm = \chi^\pm\cos\theta - \delta^\pm\sin\theta$$
$$\hat{\delta}^\pm = \chi^\pm\sin\theta + \delta^\pm\cos\theta$$

$$\begin{aligned} f &= \frac{2^8\pi^4 v^2}{cI_2\sin^2 2\theta}\frac{1}{\hat{m}_e}m_\nu\frac{1}{\hat{m}_e}\frac{1}{\omega} \\ &= 2.8\times\left(\frac{1}{c}\right)\left(\frac{1}{I_2}\right)\left(\frac{1}{\sin^2 2\theta}\right) \\ &\quad \times\left(\frac{m_e}{\hat{m}_e}\right)\left(\frac{m_\nu}{0.1\,\text{eV}}\right)\left(\frac{m_\mu}{\hat{m}_e}\right)\left(\frac{1\,\text{TeV}}{\omega}\right) \end{aligned}$$

$$|f| < \sqrt{4\pi} \quad \text{for} \quad c \lesssim \begin{cases} 10 & \text{in } \textit{Case-1}, \\ 1.2\times 10^5 & \text{in } \textit{Case-2}, \\ 10 & \text{in } \textit{Case-3}, \\ 2.2\times 10^4 & \text{in } \textit{Case-4}. \end{cases}$$



$u_{L(R)}$
$d_{R(L)}$
$\chi^{\pm}$
$\langle\varphi^0\rangle$
$\delta^{\pm}$
e_R
$\xi^{\pm\pm}$
$\delta^{\pm}$
e_R
$\langle\varphi^0\rangle$
$\chi^{\pm}$
$d_{R(L)}$
$u_{L(R)}$
d_L
u_L
$\langle\varphi^0\rangle$
$W^{\pm}$
$\chi^{\pm}$
$\langle\varphi^0\rangle$
χ^0
$\delta^{\pm}$
e_R
$\xi^{\pm\pm}$
χ^0
$\delta^{\pm}$
$\langle\varphi^0\rangle$
e_R
$\chi^{\pm}$
$W^{\pm}$
$\langle\varphi^0\rangle$
d_L
u_L

$$T_{1/2}^{0\nu}(^{136}\mathrm{Xe}) = 4.80 \times 10^{26}\,\mathrm{yr} \times \left(\frac{10^{-7}\,\mathrm{eV}}{|m_{ee}|}\right)^2 \left(\frac{m_\xi}{1\,\mathrm{TeV}}\right)^4$$
$$\times \left(\frac{c}{1}\right)^2 \left(\frac{I_2}{1}\right)^2 \left(\frac{1}{I_1}\right)^2 ,$$
$$T_{1/2}^{0\nu}(^{76}\mathrm{Ge}) = 1.67 \times 10^{26}\,\mathrm{yr} \times \left(\frac{10^{-6}\,\mathrm{eV}}{|m_{ee}|}\right)^2 \left(\frac{m_\xi}{1\,\mathrm{TeV}}\right)^4$$
$$\times \left(\frac{c}{1}\right)^2 \left(\frac{I_2}{1}\right)^2 \left(\frac{1}{I_1}\right)^2 .$$

$$
\begin{aligned}
\Gamma_{\mu\to 3e} &= \frac{|f_{\mu e}f_{ee}|^2}{3\times 2^8\pi^3}\frac{m_\mu^5}{m_{\xi^{\pm\pm}}^4} \\
&= \frac{2^8\pi^5}{3\,c^2 I_2^2 \sin^4 2\theta}\frac{v^4 m_\mu^4 |m_{ee}||m_{e\mu}|}{m_e^3\omega^2 m_{\xi^{\pm\pm}}^4}
\end{aligned}
$$

$$
\Gamma_{\mu\to e\gamma} = \frac{\alpha m_\mu^5}{9\times 2^{10}\,\pi^3}\frac{4|f_{\mu e}f_{ee}|^2 + 4|f_{\mu e}f_{\mu\mu}|^2 + 16|f_{\mu\tau}f_{e\tau}|^2}{m_{\xi^{\pm\pm}}^4}
$$

$$
\Delta a_\mu = -\frac{m_\mu^2}{24\pi^2}\frac{4|f_{\mu e}|^2}{m_{\xi^{\pm\pm}}^2}
$$

Testability at Colliders

1. The non-SM scalars are near the TeV scale. Their existence may be tested at the running and/or future colliders.

2. The Yukawa couplings of the doubly charged scalar to the right-handed leptons fully determine the structure of the neutrino mass matrix. This neutrino mass generation may be tested at the colliders.

3. Even if the electron neutrino has an extremely small Majorana mass, the neutrinoless double beta decay can arrive at a testable level.

Neutrinoless Double Beta Decay in the Linear Seesaw Models

- The linear seesaw has an interesting feature that the left-handed neutrinos have a Majorana mass matrix proportional to the Dirac mass term between the left- and right-handed neutrinos.

- The linear seesaw can be realized in some left-right symmetric models.

A Simple Linear Seesaw Model

$$\chi_L(1,2,1,-1), \quad \chi_R(1,1,2,-1), \quad \Phi(1,2,2,0)$$

$$\chi_{L,R} = \begin{bmatrix} \chi^0_{L,R} \\ \chi^-_{L,R} \end{bmatrix}, \quad \Phi = \begin{bmatrix} \phi^0_1 & \phi^+_2 \\ \phi^-_1 & \phi^0_2 \end{bmatrix} \equiv [\phi_1 \quad \tilde{\phi}_2].$$

$$q_L(3,2,1,+\tfrac{1}{3}) = \begin{bmatrix} u_L \\ d_L \end{bmatrix}, \quad q_R(3,1,2,+\tfrac{1}{3}) = \begin{bmatrix} u_R \\ d_R \end{bmatrix},$$

$$l_L(1,2,1,-1) = \begin{bmatrix} \nu_L \\ e_L \end{bmatrix}, \quad l_R(1,1,2,-1) = \begin{bmatrix} \nu_R \\ e_R \end{bmatrix}.$$

$$\xi_R(1,1,1,0).$$

$$\mathcal{L} \supset -y_q \bar{q}_L \Phi q_R - \tilde{y}_q \bar{q}_L \tilde{\Phi} q_R - y_l \bar{l}_L \Phi l_R - \tilde{y}_l \bar{l}_L \tilde{\Phi} l_R - f_L \bar{l}_L \chi_L \xi_R - f_R \bar{l}^c_R \chi^*_R \xi_R + \text{H.c.}\,.$$

$$\mathcal{L} \not\supset -\frac{1}{2} m_\xi \bar{\xi}^c_R \xi_R + \text{H.c.} \quad \text{with} \quad m_\xi = m_\xi^T\,.$$

$$q_L \overset{CP}{\longleftrightarrow} q^c_R,\ l_L \overset{CP}{\longleftrightarrow} l^c_R,\ \xi_R \overset{CP}{\longleftrightarrow} \xi_R,\ \chi_L \overset{CP}{\longleftrightarrow} \chi^*_R,\ \Phi \overset{CP}{\longleftrightarrow} \Phi^T$$

$$y_q = y_q^T\,,\ \tilde{y}_q = \tilde{y}_q^T\,,\ y_l = y_l^T\,,\ \tilde{y}_l = \tilde{y}_l^T\,,\ f_L = f_R = f.$$

$$\mathcal{L} \supset -m_u \bar{u}_L u_R - m_d \bar{d}_L d_R - m_e \bar{e}_L e_R - m_D \bar{\nu}_L \nu_R + \text{H.c.}$$

$$m_{u(D)} \ = \ y_{q(l)} \langle \phi_1 \rangle + \tilde{y}_{q(l)} \langle \phi_2 \rangle \,, \quad m_{d(e)} = y_{q(l)} \langle \tilde{\phi}_2 \rangle + \tilde{y}_{q(l)} \langle \tilde{\phi}_1 \rangle \,.$$

$$\mathcal{L} \supset -\frac{1}{2} [\, \bar{\nu}_L \ \ \bar{\nu}_R^c \ \ \bar{\xi}_R^c \,] \begin{bmatrix} 0 & m_D & f \langle \chi_L \rangle \\ m_D^T & 0 & f \langle \chi_R \rangle \\ f^T \langle \chi_L \rangle & f^T \langle \chi_R \rangle & 0 \end{bmatrix} \begin{bmatrix} \nu_L^c \\ \nu_R \\ \xi_R \end{bmatrix} + \text{H.c.} \ \text{ with } \ m_D = m_D^T \,.$$

$$\mathcal{L} \supset -\frac{1}{2} m_\nu \bar{\nu}_L \nu_L^c + \text{H.c.} \ \text{ with } \ m_\nu = -2 m_D \frac{\langle \chi_L \rangle}{\langle \chi_R \rangle} \,.$$

S.M. Barr, 2003

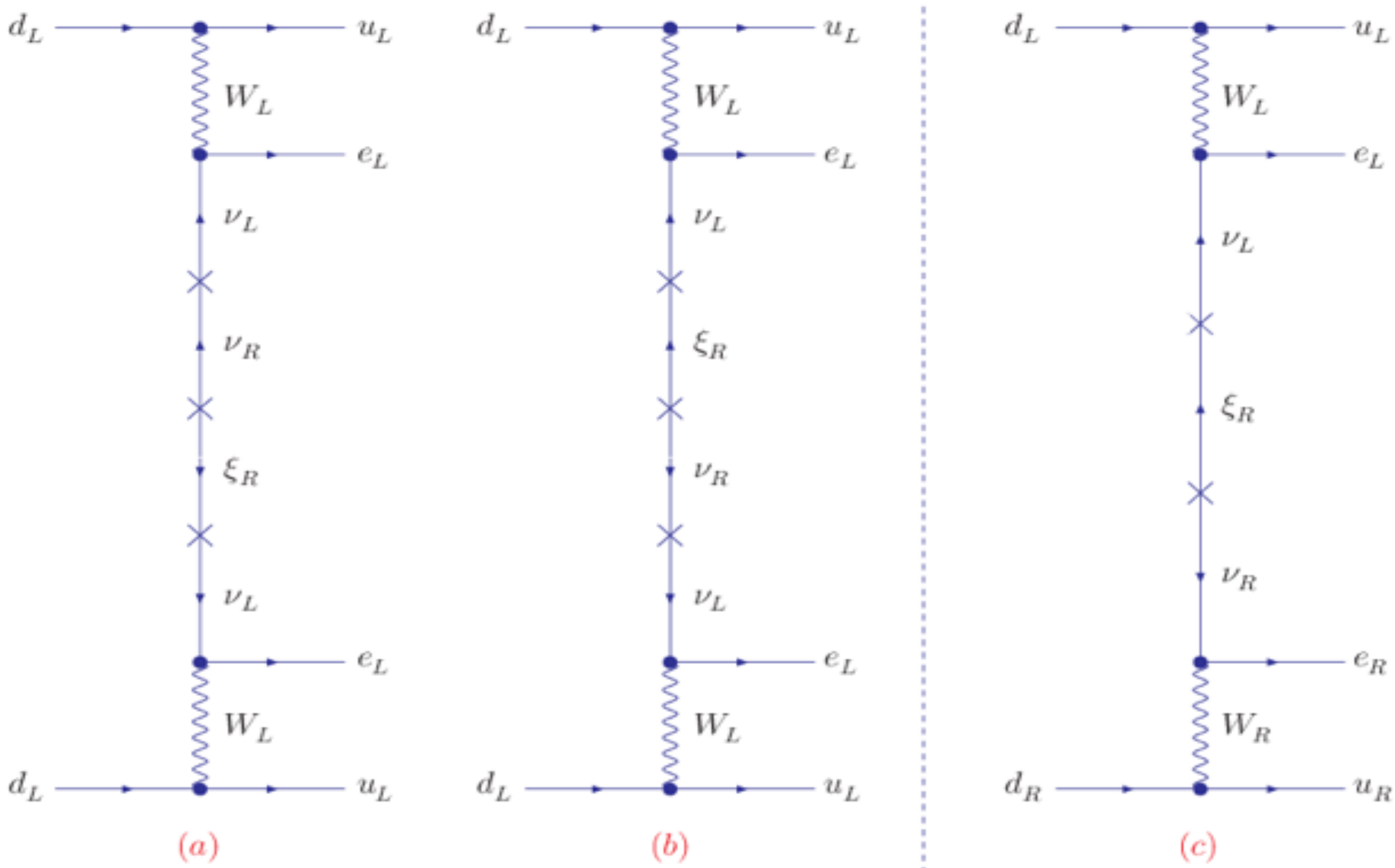
$$\nu_R = U_R \hat{\nu}_R \,, \quad \xi_R = U_\xi \hat{\xi}_R \,, \quad \hat{f} = U_R^T f U_\xi$$

$$\begin{bmatrix} 0 & m_D U_R & \hat{f}\langle\chi_L\rangle U_R^\dagger \\ U_R^T m_D & 0 & \hat{f}\langle\chi_R\rangle \\ U_R^* \hat{f}\langle\chi_L\rangle & \hat{f}\langle\chi_R\rangle & 0 \end{bmatrix}$$

$$\mathcal{L} \supset \frac{g}{\sqrt{2}}(\bar{u}_L\gamma^\mu d_L W_{L\mu}^+ + \bar{e}_L\gamma^\mu \nu_L W_{L\mu}^- + \bar{u}_R\gamma^\mu d_R W_{R\mu}^+ + \bar{e}_R\gamma^\mu U_R \hat{\nu}_R W_{R\mu}^-) \,.$$

$$M_{W_L}^2 = \frac{1}{2}g^2\langle\varphi\rangle^2 \,, \quad M_{W_R}^2 = \frac{1}{2}g^2\langle\chi_R\rangle^2$$

$$\varphi \equiv \frac{\langle\phi_1\rangle\phi_1 + \langle\phi_2\rangle\phi_2 + \langle\chi_L\rangle\chi_L}{\sqrt{\langle\phi_1\rangle^2 + \langle\phi_2\rangle^2 + \langle\chi_L\rangle^2}} \text{ with } \langle\varphi\rangle = 174\,\text{GeV} \,.$$



$$\mathcal{L} \supset 16\, G_F^2 \bar{u}_L \gamma^\mu d_L \bar{e}_L \gamma_\mu \frac{(m_\nu)_{ee}}{q^2} \gamma_\nu e_L^c \bar{u}_L \gamma^\nu d_L + 8 \frac{\langle \chi_L \rangle}{\langle \chi_R \rangle} \frac{M_{W_L}^2}{M_{W_R}^2} G_F^2 \bar{u}_L \gamma^\mu d_L \bar{e}_L \gamma_\mu \frac{\not{q}}{q^2} \gamma_\nu e_R^c \bar{u}_R \gamma^\nu d_R$$

$$\frac{1}{T_{1/2}^{0\nu}}=G_{01}^{0\nu}\left[|M_{LL}^{0\nu}|^2\frac{|(m_\nu)_{ee}|^2}{m_e^2}+|M_{LR}^{0\nu}|^2\frac{1}{4}\frac{\langle\chi_L\rangle^2}{\langle\chi_R\rangle^2}\frac{M_{W_L}^4}{M_{W_R}^4}\right]$$

$$|y_{q(l)}|, |\tilde{y}_{q(l)}| < \sqrt{4\pi} \implies \langle\chi_L\rangle \simeq \langle\varphi\rangle$$

$$\langle\chi_L\rangle/\langle\chi_R\rangle = \langle\chi_L\rangle/\langle\varphi\rangle \cdot M_{W_L}/M_{W_R} \simeq M_{W_L}/M_{W_R}$$

$$^{136}\mathrm{Xe}: \; G_{01}^{0\nu} = 3.56 \times 10^{-14}\,\mathrm{yr}^{-1}, \; M_{LL} = 1.57 - 3.85\,, \; M_{LR} = 1.92 - 2.49$$

$$^{76}\mathrm{Ge}: \; G_{01}^{0\nu} = 5.77 \times 10^{-15}\,\mathrm{yr}^{-1}, \; M_{LL} = 2.58 - 6.64\,, \; M_{LR} = 1.75 - 3.76$$

G. Pantis, F. Simkovic, J.D. Vergados, and A. Faessler, 1996; J. Kotila and F. Iachello, 2012.

$$\mathrm{KamLAND\text{-}Zen}: T_{1/2}^{0\nu}(^{136}\mathrm{Xe}) > 3.4 \times 10^{25}\,\mathrm{yr} \longrightarrow 4.0 \times 10^{26}\,\mathrm{yr}$$

$$\mathrm{GERDA}: \; T_{1/2}^{0\nu}(^{76}\mathrm{Ge}) > 3.0 \times 10^{25}\,\mathrm{yr} \longrightarrow 2.0 \times 10^{26}\,\mathrm{yr}$$

$$^{76}\mathrm{Ge}: M_{W_R} = 5.8 - 7.4\,\mathrm{Tev} \rightarrow \; 7.9 - 10.2\,\mathrm{TeV}$$

$$^{136}\mathrm{Xe}: M_{W_R} = 8.2 - 8.9\,\mathrm{Tev} \rightarrow 12.4 - 13.5\,\mathrm{TeV}$$

A Realistic Linear Seesaw Model

$$U_{L,R}(3,1,1,+4/3),\ D_{L,R}(3,1,1,-2/3),\ E_{L,R}(1,1,1,-2).$$

$$\sigma(1,1,1,0),\ \chi_{L1,2}(1,2,1,-1),\ \chi_{R1,2}(1,1,2,-1),\ \Phi(1,2,2,0) \equiv [\phi_1\ \tilde{\phi}_2].$$

The $U(1)_{PQ}$ charges.

$(q_L, l_L, U_L, D_L, E_L) \stackrel{CP}{\longleftrightarrow} (q_R^c, l_R^c, U_R^c, D_R^c, E_R^c)$	$(\chi_{L1}, \chi_{L2}^*, \Phi, \sigma) \stackrel{CP}{\longleftrightarrow} (\chi_{R1}^*, \chi_{R2}, \Phi^T, \sigma)$	$\xi_R \stackrel{CP}{\longleftrightarrow} \xi_R$
+1	+2	+3

$$\sigma = \frac{1}{\sqrt{2}}(f_{PQ} + h_{PQ})\exp(ia/f_{PQ}) \qquad f_{PQ} = \sqrt{2}\langle\sigma\rangle$$

$$\chi_R \equiv \frac{\sum_a \langle\chi_{Ra}\rangle\chi_{Ra}}{\sqrt{\sum_a \langle\chi_{Ra}\rangle^2}}, \quad \varphi \equiv \frac{\sum_a (\langle\phi_a\rangle\phi_a + \langle\chi_{La}\rangle\chi_{La})}{\sqrt{\sum_a (\langle\phi_a\rangle^2 + \langle\chi_{La}\rangle^2)}}$$

$$\langle\phi_{1,2}\rangle \ll \langle\varphi\rangle \ll \langle\chi_R\rangle$$

$$\mathcal{L} \supset -[\bar{e}_L \;\; \bar{E}_L]\begin{bmatrix} y_l\langle\tilde{\phi}_2\rangle & y_E\langle\tilde{\chi}_{L2}\rangle \\ y_E^T\langle\tilde{\chi}_{R2}^\dagger\rangle & f_E\langle\sigma\rangle \end{bmatrix}\begin{bmatrix} e_R \\ E_R \end{bmatrix} - [\bar{u}_L \;\; \bar{U}_L]\begin{bmatrix} y_q\langle\phi_1\rangle & y_U\langle\chi_{L1}\rangle \\ y_U^T\langle\chi_{R1}^\dagger\rangle & f_U\langle\sigma\rangle \end{bmatrix}\begin{bmatrix} u_R \\ U_R \end{bmatrix} - [\bar{d}_L \;\; \bar{D}_L]\begin{bmatrix} y_q\langle\tilde{\phi}_2\rangle & y_D\langle\tilde{\chi}_{L2}\rangle \\ y_D^T\langle\tilde{\chi}_{R2}^\dagger\rangle & f_D\langle\sigma\rangle \end{bmatrix}\begin{bmatrix} d_R \\ D_R \end{bmatrix}$$

$$-\frac{1}{2}[\bar{\nu}_L \;\; \bar{\nu}_R^c \;\; \bar{\xi}_R^c]\begin{bmatrix} 0 & y_l\langle\phi_1\rangle & f\langle\chi_{L2}\rangle \\ y_l^T\langle\phi_1\rangle & 0 & f\langle\chi_{R2}\rangle \\ f^T\langle\chi_{L2}\rangle & f^T\langle\chi_{R2}\rangle & 0 \end{bmatrix}\begin{bmatrix} \nu_L^c \\ \nu_R \\ \xi_R \end{bmatrix} + \text{H.c.}.$$

$$\mathcal{L} \supset -m_u \bar{u}_L u_R - m_d \bar{d}_L d_R - m_e \bar{e}_L e_R - M_U \bar{U}_L U_R$$
$$-M_D \bar{D}_L D_R - M_E \bar{E}_L E_R + \text{H.c.} \quad \text{with}$$

$$M_U = f_U \langle \sigma \rangle \,, \quad m_u = y_q \langle \phi_1 \rangle - y_U \frac{\langle \chi_{L1} \rangle \langle \chi_{R1}^\dagger \rangle}{M_U} y_U^T \,;$$

$$M_D = f_D \langle \sigma \rangle \,, \quad m_d = y_q \langle \tilde{\phi}_2 \rangle - y_D \frac{\langle \tilde{\chi}_{L2} \rangle \langle \tilde{\chi}_{R2}^\dagger \rangle}{M_D} y_D^T \,;$$

$$M_E = f_E \langle \sigma \rangle \,, \quad m_e = y_l \langle \tilde{\phi}_2 \rangle - y_E \frac{\langle \tilde{\chi}_{L2} \rangle \langle \tilde{\chi}_{R2}^\dagger \rangle}{M_E} y_E^T \,,$$

$$\mathcal{L} \supset -M_N \bar{\nu}_R^c \xi_R - \frac{1}{2} m_\nu \bar{\nu}_L \nu_L^c \quad \text{with}$$

$$M_N = f \langle \chi_{R2} \rangle \,, \quad m_\nu = -2 y_l \langle \phi_1 \rangle \frac{\langle \chi_{L2} \rangle}{\langle \chi_{R2} \rangle}$$

$$\mathcal{L} \supset 16 G_F^2 \bar{u}_L \gamma^\mu d_L \bar{e}_L \gamma_\mu \frac{(m_\nu)_{ee}}{q^2} \gamma_\nu e_L^c \bar{u}_L \gamma^\nu d_L + 8 \frac{\langle \chi_{L2} \rangle}{\langle \chi_{R2} \rangle} \frac{M_{W_L}^2}{M_{W_R}^2} G_F^2 \bar{u}_L \gamma^\mu d_L \bar{e}_L \gamma_\mu \frac{\not{q}}{q^2} \gamma_\nu e_R^c \bar{u}_R \gamma^\nu d_R$$

$$^{136}\mathrm{Xe}: \; G_{01}^{0\nu} = 3.56 \times 10^{-14}\,\mathrm{yr}^{-1}, \; M_{LL} = 1.57 - 3.85\,, \; M_{LR} = 1.92 - 2.49$$

$$^{76}\mathrm{Ge}: \; G_{01}^{0\nu} = 5.77 \times 10^{-15}\,\mathrm{yr}^{-1}, \; M_{LL} = 2.58 - 6.64\,, \; M_{LR} = 1.75 - 3.76$$

G. Pantis, F. Simkovic, J.D. Vergados, and A. Faessler, 1996; J. Kotila and F. Iachello, 2012.

$$\text{KamLAND-Zen}: T_{1/2}^{0\nu}(^{136}\mathrm{Xe}) > 3.4 \times 10^{25}\,\mathrm{yr} \rightarrow 4.0 \times 10^{26}\,\mathrm{yr}$$

$$\text{GERDA}: \; T_{1/2}^{0\nu}(^{76}\mathrm{Ge}) > 3.0 \times 10^{25}\,\mathrm{yr} \rightarrow 2.0 \times 10^{26}\,\mathrm{yr}$$

$$\langle \chi_{R2} \rangle \gg \langle \chi_{L2} \rangle \quad \rightarrow \quad \langle \chi_{R2} \rangle = 10\,\langle \chi_{L2} \rangle$$

$$^{76}\mathrm{Ge}: M_{W_R} = 24.7 - 36.2\,\mathrm{TeV}$$

$$^{136}\mathrm{Xe}: M_{W_R} = 48.5 - 55.3\,\mathrm{TeV}$$

$$\mathcal{L} \supset \frac{\partial_\mu a}{f_{PQ}} \left(\bar{u}\gamma^\mu\gamma_5 u + \bar{d}\gamma^\mu\gamma_5 d + \bar{U}\gamma^\mu\gamma_5 U + \bar{D}\gamma^\mu\gamma_5 D\right)$$

The global symmetry U(1)_PQ is the Peccei-Quinn symmetry, while the Goldstone boson *a* is an axion!

R.D. Peccei and H.R. Quinn, Phys. Rev. Lett. 38, 1440 (1977); S. Weinberg, Phys. Rev. Lett. 40, 223 (1978); F. Wilczek, Phys. Rev. Lett. 40, 279 (1978).
A.R. Zhitnitsky, Sov. J. Nucl. Phys. 31, 260 (1980); M. Dine, W. Fischler, M. Srednicki, Phys. Lett. B 104, 199 (1981).
J.E. Kim, Phys. Rev. Lett. 43, 103 (1979); M.A. Shifman, A.I. Vainshtein, V.I. Zakharov, Nucl. Phys. B 166, 493 (1980).

Testability at Colliders

1.The new gauge bosons are near the TeV scale. Their existence may be tested at the running and/or future colliders.

2.The Higgs bidoublet has a seesaw-suppressed vacuum expectation value, so its Yukawa couplings to the quarks can only give a negligible contribution to the quark masses and hence their values can be set flexibly.

3.The Yukawa couplings of this Higgs bidoublet to the leptons are completely determined by the neutrino mass matrix.

4.The Higgs bidoublet is allowed near the TeV scale, so that it may be tested at the running and/or planning colliders.

5.The decays of the Higgs bidoublet into the charged leptons can open a window to measure the neutrino mass matrix.

Summary

- Any neutrinoless double beta decay processes require the new physics with the lepton number violation of two units.

- The lepton number violation for the neutrinoless double beta decay may lead to a negligible contribution to the Majorana neutrino masses. A pseudo Dirac neutrino can be consistent with an observable neutrinoless double beta decay.

- Some extended two Higgs doublet models can simultaneously provide a testable neutrino mass generation and an enhanced neutrinoless double beta decay.

- In a class of left-right symmetric models for the linear seesaw, a neutrinoless double beta decay can be irrelevant to the neutrino mass matrix. This neutrinoless double beta decay can reach the experimental sensitivities if the right-handed charged gauge boson is below the 100 TeV scale.

- These new physics for the testable neutrinoless double beta decay may be tested at the running and planning colliders.

谢谢！