TeV Seesaw Mechanisms and $(\beta\beta)_{0\nu}$-Decay

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NEUTRINO MASSES AND MIXING

Experiments with *solar*, *atmospheric*, *reactor* and *accelerator* neutrinos

$\Downarrow$

Flavour Neutrino Oscillations

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- at least two mass eigenstates ν_j with masses $m_j \neq 0$
- existence of neutrino mixing:

$$\nu_{\ell\mathrm{L}}(x) = \sum_j (U_{\mathrm{PMNS}})_{\ell j}\, \nu_{j\mathrm{L}}(x), \quad \ell = e, \mu, \tau$$

NEUTRINO MASSES AND MIXING

- The left-handed fields $\nu_{\ell L}(x)$ enter into the charged current and neutral current weak interactions
- Data on the invisible Z decay width $\Longrightarrow$ 3 flavour active neutrinos $\nu_{\ell L}$, $\ell = e, \mu, \tau$
- The number of mass eigenstate ν_j can be larger than 3 (*sterile neutrinos ?*), *but* at least 3 of the ν_j should be "light":

$$m_{1,2,3} < 1 \text{ eV and } m_1 \neq m_2 \neq m_3$$

- ^{3}H $\beta-$decay experiments and astrophysical observations

$$\Downarrow$$

$$m_j \lesssim 0.5\,\mathrm{eV} \qquad m_j/m_{\ell,q} \lesssim 10^{-6}$$

- Two important questions:
    1. *a new fundamental "heavy" mass scale Λ in particle physics ?*
    2. *are neutrinos Majorana or Dirac particles ?*

SEE-SAW MECHANISMS

A Majorana mass term for $\nu_{\ell L}(x)$ can arise after EWSB from the (unique) d=5 operator:

$$\frac{c_{\ell\ell'}}{\Lambda}\left(\overline{L^c_\ell}\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger L_{\ell'}\right) + \mathrm{H.c.}$$

$$L_\ell(x) \;=\; (\nu_{\ell L}(x), \ell_L(x))\;, \qquad \tilde{\phi}(x) \;=\; i\tau_2\phi(x)$$

$$\Downarrow$$

Three possible extensions of the SM. Tree-level exchange of new "heavy" particles:

1. Type I See-Saw scenario: *SM-singlet fermions*
2. Type II See-Saw scenario: *$SU(2)$-triplet scalars*
3. Type III See-Saw scenario: *$SU(2)$-triplet fermions*

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$$\Downarrow$$

see-saw mechanism is underconstrained

The Majorana nature of the active light neutrinos ν_j can be revealed in experiments searching for $(\beta\beta)_{0\nu}$-decays of even-even nuclei

The see-saw scenarios can be directly tested if the mass scale of the exchanged particles is accessible at colliders

SEE-SAW MECHANISMS

- In type I and type III see-saw scenarios the neutral heavy fermion fields involved in the generation of light neutrino masses are *Majorana particles*
- The Majorana nature of the heavy fermions of TeV scale see-saw mechanisms can be established in principle in experiments with high energy accelerators, *e.g.* LHC
- Strong constraints on the $|\Delta L| = 2$ processes associated with the production and decay cross sections of the Majorana heavy fields are imposed by the *light neutrino mass scale* and the experimental upper limit on the $(\beta\beta)_{0\nu}$*-decay rate*

A.Ibarra, E.M., S.T.Petcov, JHEP 1009:108, 2010

TYPE I SEE-SAW SCENARIO

- See-Saw scenarios with *two mass scales* (M_D, M_R):

$$\mathcal{L}_\nu \;=\; -\,\overline{\nu_{\ell L}}\,(M_D)_{\ell a}\,\nu_{aR} - \frac{1}{2}\,\overline{\nu^C_{aL}}\,(M_N)_{ab}\,\nu_{bR} \;+\; \text{H.c.}$$

- A Majorana mass term for LH flavour fields $\nu_{\ell L}(x)$ is generated by the interplay between the Dirac (M_D) and Majorana (M_N) mass terms of RH neutrino singlets $\nu_{aR}(x)$, $a = 1, \ldots, k$.

- Neutrino mass eigenstates (χ_i, N_j), $i = 1, 2, 3,\quad j = 1, \ldots, k$:

$$\Omega^T \begin{pmatrix} \mathbf{O}_{3\times 3} & M_D \\ M_D^T & M_N \end{pmatrix} \Omega \;=\; \begin{pmatrix} U^*\hat{m}U^\dagger & \mathbf{O}_{3\times k} \\ \mathbf{O}_{k\times 3} & V^*\hat{M}V^\dagger \end{pmatrix}$$

$$\hat{m} \;=\; \text{diag}(m_1, m_2, m_3) \qquad \hat{M} \;=\; \text{diag}(M_1, M_2, \ldots, M_k)$$

TYPE I SEE-SAW SCENARIO

Hierarchy between the mass scales of M_D and M_N:

$$\Omega = \exp\begin{pmatrix} \mathbf{O}_{3\times 3} & R \\ -R^\dagger & \mathbf{O}_{k\times k} \end{pmatrix} = \begin{pmatrix} \mathbf{1} - \frac{1}{2}RR^\dagger & R \\ -R^\dagger & \mathbf{1} - \frac{1}{2}R^\dagger R \end{pmatrix} + \mathcal{O}(R^3)$$

$$m_\nu \cong -(RV)^* \hat{M} (RV)^\dagger \cong -M_D M_N^{-1} M_D^T$$

$$V^* \hat{M} V^\dagger \simeq M_N(1 + \mathcal{O}(R^2))$$

- *Standard type I see-saw scenario*:
  $M_D \approx 100$ GeV and $m_j \approx 0.05$ eV $\Longrightarrow$ $M_j \approx 10^{14}$ GeV
- *Alternative see-saw scenarios*:
  $M_j = 100 \div 1000$ GeV $\Longrightarrow$ approx. conserved lepton charge,
  Branco, Grimus, Lavoura, 1989
  inverse see-saw models or "large" fine tuning of neutrino Yukawa couplings

Possibility of testing the see-saw mechanism at colliders

TEV SCALE TYPE I SEE-SAW SCENARIO

- The mixing of the heavy (RH) Majorana neutrinos with the LH flavour neutrinos is constrained by low energy data (*neutrino oscillations, lepton universality tests, ..., and $(\beta\beta)_{0\nu}$-decay*)
- CC and NC weak interactions of *light* Majorana neutrinos χ_j:

$$
\begin{aligned}
\mathcal{L}_{CC}^{\nu} &= -\frac{g}{\sqrt{2}}\,\bar{\ell}\,\gamma_\alpha\,((1+\eta)U)_{\ell j}\,\chi_{jL}\,W^\alpha + \text{H.c.}\,,\\
\mathcal{L}_{NC}^{\nu} &= -\frac{g}{2c_w}\,\overline{\chi_{iL}}\,\gamma_\alpha\,\left(U^\dagger(1+\eta+\eta^\dagger)U\right)_{ij}\,\chi_{jL}\,Z^\alpha
\end{aligned}
$$

- CC and NC interactions of *heavy* Majorana fields N_k:

$$
\begin{aligned}
\mathcal{L}_{CC}^{N} &= -\frac{g}{2\sqrt{2}}\,\bar{\ell}\,\gamma_\alpha\,(RV)_{\ell k}(1-\gamma_5)\,N_k\,W^\alpha + \text{H.c.}\,,\\
\mathcal{L}_{NC}^{N} &= -\frac{g}{4c_w}\,\overline{\nu_{\ell L}}\,\gamma_\alpha\,(RV)_{\ell k}(1-\gamma_5)\,N_k\,Z^\alpha + \text{H.c.}
\end{aligned}
$$

TEV SCALE TYPE I SEE-SAW SCENARIO

- Deviation from unitarity of neutrino mixing matrix $U_{\mathrm{PMNS}} = (\mathbf{1} + \eta)U$:

$$\eta \;=\; -\frac{1}{2}RR^{\dagger}$$

$|\eta_{ij}| \lesssim \mathcal{O}(10^{-3})$ Antusch, Baumann, Fernandez-Martinez, 2009

Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, 2006

- The mixing of the heavy Majorana fields N_j is constrained by the light neutrino mass scale:

$$\boxed{\sum_k |(RV)^{*}_{\ell' k}\, M_k\, (RV)^{\dagger}_{k\ell}| \lesssim 1 \text{ eV}\,,\;\; l', l = e, \mu, \tau}$$

del Aguila, Aguilar-Saavedra, Pittau, 2006; Kersten, Smirnov, 2007; Xing, 2009

- Barring accidental cancellations:

$$|(RV)_{\ell k}| \;\lesssim 3 \times 10^{-6} \left(\frac{100 \text{ GeV}}{M_R}\right)^{1/2}\,,\;\;\; \ell = e, \mu, \tau,\;\; j = 1, 2, ..., k$$

NEUTRINOLESS DOUBLE BETA DECAY

$$(A,Z) \implies (A,Z+2) + e^- + e^-$$

$$^{48}\mathrm{Ca},\ ^{76}\mathrm{Ge},\ ^{82}\mathrm{Se},\ ^{124}\mathrm{St},\ ^{130}\mathrm{Te},\ ^{136}\mathrm{Xe}$$

- The decay rate of the nucleus is: $\Gamma_{0\nu\beta\beta} \propto |(m_\nu)_{\rm eff}|^2$:

$$|(m_\nu)_{\rm eff}| \cong \left|\sum_i (U_{\rm PMNS})^2_{ei}\, m_i - \sum_k F(A,M_k)\,(RV)^2_{ek}\, M_k\right|$$

- From the see-saw mass relation:

$$|(m_\nu)_{\rm eff}| \cong \left|\sum_k (RV)^2_{ek}\, M_k\,(1+F(A,M_k))\right|$$

- The function $F(A,M_k)$ exhibits a rather weak dependance on A:

Haxton, Stephenson, 1984; Blennow, Fernandez-Martinez, Lopez-Pavon, Menendez, 2010

$$F(A,M_k) \cong \left(\frac{M_a}{M_k}\right)^2 f(A)$$

$$M_a \cong 0.9\,{\rm GeV}\,, \qquad M_k \gtrsim 100\,{\rm GeV}\,, \qquad f(A) \approx 10^{-2} \div 10^{-1}$$

CASE OF A BROKEN SYMMETRY

$$M_D = \begin{pmatrix} 0 & m^D_{e2} & m^D_{e3} \\ 0 & m^D_{\mu 2} & m^D_{\mu 3} \\ 0 & m^D_{\tau 2} & m^D_{\tau 3} \end{pmatrix}, \qquad M_N = \begin{pmatrix} M_{11} & 0 & 0 \\ 0 & 0 & M_{23} \\ 0 & M_{23} & 0 \end{pmatrix}$$

- $m^D_{\ell 1} = 0 \Longrightarrow$ the heavy Majorana field $N_1 = (\nu_{1R} + \nu^C_{1L})$ is decoupled
- $m_\nu = 0$, *e.g.*, in the limit $m^D_{\ell 2} = 0 \Longrightarrow$ conserved lepton charge: $L' = L_e + L_\mu + L_\tau + L_3 - L_2$, with $L_a(\nu_{bR}) = -\delta_{ab}$, for $a = 2, 3$

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General Conserved Lepton Charge:

$$L' = \sum_{k=e,\mu,\tau,\ldots} (-1)^{n_k} L_k, \quad n_k = 0, 1, \quad L_k \neq 0$$

$$\text{massive Dirac neutrinos}: \quad \min(n_+(L'), n_-(L'))$$

$$\text{massless neutrinos}: \quad |n_+(L') - n_-(L')|$$

Leung, Petcov, 1983; Weyler, Wolfenstein, 1983

CASE OF A BROKEN SYMMETRY

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- the mass eigenstates N_2 and N_3 have $M_2 = M_3 = |M_{23}|$ and $C\overline{N_k}^T = \rho_k N_k$, $k = 2, 3$, where $\rho_2 = -1$ and $\rho_3 = +1 \Longrightarrow$ *Dirac field* $N_D = (N_2 + N_3)/\sqrt{2}$:

$$\nu_{2R} = N_{DR} = \frac{1}{\sqrt{2}}\left(N_{2R} + N_{3R}\right)\,, \quad \nu_{3R} = N^C_{DR} = \frac{1}{\sqrt{2}}\left(-\,N_{2R} + N_{3R}\right)$$

$$\nu^C_{2L} = N^C_{DL} = \frac{1}{\sqrt{2}}\left(-\,N_{2L} + N_{3L}\right)\,, \quad \nu^C_{3L} = N_{DL} = \frac{1}{\sqrt{2}}\left(N_{2L} + N_{3L}\right)$$

CASE OF A BROKEN SYMMETRY

- *for* $m^D_{\ell 2,3\neq 0}$ L' *is not conserved:*
  $(m_\nu)_{\ell\ell'} \cong -(m^D_{\ell 2} m^D_{\ell' 3} + m^D_{\ell' 2} m^D_{\ell 3})/M_{23} \lesssim 1\,\mathrm{eV}$

$$\Downarrow$$

$$|m^D_{\ell 2} m^D_{\ell' 3}| \lesssim 10^{-7}\mathrm{GeV}^2 \left(\frac{M_{23}}{100\,\mathrm{GeV}}\right), \quad \ell,\ell' = e,\mu,\tau$$

$$(R)^*_{\ell 2} \;=\; m^D_{\ell 3}/(M_{23}), \qquad (R)^*_{\ell 3} \;=\; m^D_{\ell 2}/(M_{23})$$

- $|m^D_{\ell 2}| \approx |m^D_{\ell 3}| \lesssim 3\times 10^{-4}\,\mathrm{GeV}$
  $N_{2,3}$ cannot be produced in particle accelerators

- $m^D_{\ell 2} \approx 5\times 10^{-9}\,\mathrm{GeV}, \qquad m^D_{\ell 3} \approx 1\,\mathrm{GeV}$
  N_2 and N_3 couple to the charged leptons as a *pseudo-Dirac field*:
  $N_{PD} = (N_2 + N_3)/\sqrt{2}$, $M_3 - M_2 \;=\; m_3 - m_2 \lesssim 1$ eV

it is impossible to reveal the Majorana nature of the RH neutrino fields

INVERSE SEE SAW SCENARIOS

$$\mathcal{L}_\mu = -\overline{\nu_{\ell L}}(m_D)_{\ell a}\nu_{aR} - \overline{S_{\beta L}}(M_R)_{\beta a}\nu_{aR} - \frac{1}{2}\overline{S}_{\beta L}(\mu)_{\beta\beta'}S^C_{\beta' R} + \mathrm{H.c.}$$

- $m_\nu = U^*\hat{m}U^\dagger \cong m_D M_R^{-1}\mu\left(M_R^{-1}\right)^T m_D^T$

$$\eta = -\frac{1}{2}m_D^*\left(M_R^{-1}\right)^*\mu^*\left(M_R^{-1}\right)^\dagger\left(M_R^{-1}\right)\mu\left(M_R^{-1}\right)^T m_D^T - \frac{1}{2}m_D^*\left(M_R^{-1}\right)^\dagger\left(M_R^{-1}\right)m_D^T$$

- $\eta \approx 10^{-4}$ and $M_R \approx 100$ GeV $\Longrightarrow \mu \approx m_\nu/\eta \approx 10$ keV
- for $\eta \approx 10^{-4} \Longrightarrow N_{PD} = (N_1 + N_2)/\sqrt{2}$, $|M_1 - M_2| \approx \mu$:

$$\mathcal{L}_{CC}^{N_{PD}} = -\frac{g}{2\sqrt{2}}\left(\epsilon_\ell\,\overline{\ell}\gamma_\alpha(1-\gamma_5)N_{PD} + \epsilon'_\ell\overline{N_{PD}}\gamma_\alpha(1+\gamma_5)\ell^C\right)W^\alpha + \mathrm{H.c.}$$

$$\epsilon_\ell = \frac{m^D_{\ell 1}}{M_R}, \quad \epsilon'_\ell = \frac{\mu}{M_R}\frac{m^D_{\ell 1}}{M_R} \approx 10^{-9}\left(\frac{M_R}{100\,\mathrm{GeV}}\right)^2$$

NO SYMMETRY BUT $m_\nu = 0$ AT LEADING ORDER

$$M_D = \begin{pmatrix} 0 & 0 & m^D_{e3} \\ 0 & 0 & m^D_{\mu 3} \\ 0 & 0 & m^D_{\tau 3} \end{pmatrix}, \qquad M_N = \begin{pmatrix} M_{11} & 0 & 0 \\ 0 & 0 & M_{23} \\ 0 & M_{23} & M_{33} \end{pmatrix}$$

- L' is not conserved but $m_\nu = 0$ at leading order
  $m_\nu \neq 0$ *at one or two loop order*

  Pilaftsis, 1992

- $|\Delta L| = 2$ Majorana effects vanish in the limit $M_{33} = 0$
  we recover pesudo-Dirac neutrino for $M_{33} \ll M_{23}$

- *no constraints* from light neutrino mass scale
  large couplings of $N_{2,3}$ *to* $W^\pm$ *and* Z^0

NO SYMMETRY BUT $m_\nu = 0$ AT LEADING ORDER

$$RV = \frac{1}{M_{23}} \begin{pmatrix} 0 & m^D_{e3}\cos\theta & m^D_{e3}\sin\theta \\ 0 & m^D_{\mu 3}\cos\theta & m^D_{\mu 3}\sin\theta \\ 0 & m^D_{\tau 3}\cos\theta & m^D_{\tau 3}\sin\theta \end{pmatrix}$$

$\cos^2\theta = M_3/(M_3 + M_2)$, $\sin^2\theta = M_2/(M_3 + M_2)$, $M_3 - M_2 = M_{33}$

1. $(m_\nu)_{\ell\ell'} = 0$ at tree-level:

$$|(m_\nu)_{\text{eff}}| \cong \left| \frac{(m^D_{e3})^2}{M^2_{23}} \left(M_3\, F(A, M_3) \sin^2\theta - M_2\, F(A, M_2) \cos^2\theta \right) \right|$$

$$\cong \left| \frac{(m^D_{e3})^2}{M^2_{23}} f(A)\, M^2_a \frac{M_3 - M_2}{M_2\, M_3} \right| \cong \left| f(A) \frac{(m^D_{e3})^2}{M^2_{23}} \frac{M^2_a}{M^2_{23}} M_{33} \right|$$

2a. for $(m^D_{e3}/M_{23})^2 \approx 8 \times 10^{-3}$ and $M_{23} \approx 100$ GeV:
$M_{33} \lesssim 2 \times 10^{-3} M_{23} \cong 0.2$ GeV $\ll M_{23}$

2b. for $(m^D_{e3}/M_{23})^2 \approx 10^{-6}$ and $M_{23} \approx 100$ GeV: $M_{33} \lesssim M_{23}$

NO SYMMETRY BUT $m_\nu = 0$ AT LEADING ORDER

- same sign di-muon production in $p - p$ collisions: one μ^- produced with *real or virtual* $N_{2,3}$ in decay of a virtual W^-, while the second μ^- from the decay $N_{2,3}^{(*)} \to W^+ + \mu^-$
- $A(p + p \to \mu^- + \mu^- + 2\text{jets} + X)$:

$$\propto \quad \frac{(m^D_{\mu 3})^2}{M_{23}^2} \left[\frac{\sin^2\theta M_3}{p^2 - M_3^2 + i\Gamma_3 M_3} - \frac{\cos^2\theta M_2}{p^2 - M_2^2 + i\Gamma_2 M_2} \right]$$

$$\cong \quad \frac{(m^D_{\mu 3})^2}{M_{23}^2} \frac{M_2 M_3}{M_3 + M_2} \frac{M_3^2 - M_2^2 - i(\Gamma_3 M_3 - \Gamma_2 M_2)}{(p^2 - M_3^2 + i\Gamma_3 M_3)(p^2 - M_2^2 + i\Gamma_2 M_2)}$$

- $\Gamma_{2,3} M_{2,3} \propto G_F M^3_{2(3)}$

$$\boxed{A(p + p \to \mu^- + \mu^- + 2\text{jets} + X) \propto (M_3 - M_2) = M_{33}}$$

$M_{33} \ll M_{23} \Longrightarrow$ *same sign di-muon production is highly suppressed*

EXTREME FINE-TUNING CASE

- two generation scenario:

  Casas, Ibarra, 2001

$$\begin{aligned} M_D &= iU^*_{\mathrm{PMNS}}\sqrt{\hat{m}}O\sqrt{\hat{M}}V^\dagger = M_{D+} + M_{D-} \\ RV &= -iU_{PMNS}\sqrt{\hat{m}}O^*\sqrt{\hat{M}^{-1}} \end{aligned}$$

$$O = \begin{pmatrix} \cos\hat{\theta} & \sin\hat{\theta} \\ -\sin\hat{\theta} & \cos\hat{\theta} \end{pmatrix} = \frac{e^{i\hat{\theta}}}{2}\begin{pmatrix} 1 & -i \\ i & 1 \end{pmatrix} + \frac{e^{-i\hat{\theta}}}{2}\begin{pmatrix} 1 & i \\ -i & 1 \end{pmatrix}$$

$\hat{\theta} = \omega - i\xi$, $\xi > 0$

- M_{D-} cannot be neglected: correct neutrino parameters $\Longrightarrow$ *large amount of fine tuning:*

$$\frac{(M_{D-})_{ij}}{(M_{D+})_{ij}} \sim e^{-2\xi} \sim \frac{m_i M_j}{(M_D)^2_{ij}}$$

$M_D \sim \mathcal{O}(1\,\mathrm{GeV})$ and $M_2 \sim \mathcal{O}(100\,\mathrm{GeV}) \Longrightarrow$ tuning of one part in 10^9 in order to have $m_i \sim \mathcal{O}(10^{-2})$ eV

EXTREME FINE-TUNING CASE

- for $M_D \sim \mathcal{O}(1\,\mathrm{GeV})$ and $M_2 \sim \mathcal{O}(100\,\mathrm{GeV})$, from $(\beta\beta)_{0\nu}$-decay:

$$
\begin{aligned}
|(m_\nu)_{\rm eff}| &\cong \left| \sum_k F(A, M_k)\,(RV)^2_{ek}\, M_k \right| \\
&\cong \left| \sum_k (U_{\rm PMNS}\sqrt{\hat{m}}O^*)^2_{ek} \frac{M_a^2}{M_k^2} f(A) \right| \\
&\cong \left| \frac{1}{4}\frac{M_D^2}{M_2^2}\frac{M_a^2}{M_2^2} f(A)(M_2 - M_1) \right| \cong 10^{-10}(M_2 - M_1)
\end{aligned}
$$

- *non observation of $(\beta\beta)_{0\nu}$-decay, implies a degeneracy of at least one percent*

$$\Downarrow$$

suppression of the cross section for same sign di-muon production in $p-p$ collisions

AVOIDING THE CONSTRAINTS ?

- light neutrino masses and upper limit on the $(\beta\beta)_{0\nu}$-decay rate imply that the Majorana nature of RH singlets in TeV scale type I or inverse see-saw scenarios cannot be tested at colliders
- such constraints can be avoided if additional TeV scale physics is present:

1. Huitu, Khalil, Okada, Rai, 2008; Basso, Belyaev, Moretti, Shepherd-Themistocleous, 2009
   extra $U(1)$ gauge symmetry broken at TeV scale, under which SM particles and RH neutrinos are charged: *i*) production cross section of N_j can be enhanced; *ii*) N_j relative long-lived particles, implying displaced vertex in detectors; *iii*) production and decays of Majorana N_j can lead to observable same sign muon events
2. Franceschini, Hambye, Strumia, 2008
   TeV scale type III see-saw mechanism: fermion $SU(2)-$triplet $\Sigma^{\pm}$, Σ^0, with *i*) Σ^+ and Σ^0 produced at colliders via gauge interactions; *ii*) $\Sigma^+ \to \mu^+ + Z^0$ and $\Sigma^0 \to \mu^+ + W^-$; *iii*) for $m_{\Sigma^{\pm,0}} \lesssim 1$ TeV, $\mu^+ + \mu^+ + 4$ jets events observable at LHC

SUMMARY

- $|(m_\nu)_{\ell\ell'}| \lesssim 1$ eV and non-observation of $(\beta\beta)_{0\nu}$-decay implies extremely suppressed CC and NC interactions of N_j with SM charged leptons and neutrinos, unless N_j form a pseudo-Dirac pair (symmetry) or their mass splitting is “small”

- In the low scale type I see-saw or multiple see-saw scenarios with RH fermion singlets, the Majorana nature of RH neutrinos is hardly detected in collider experiments, *e.g.* in LHC

- the observation of $|\Delta L| = 2$ processes at colliders may be possible if *i*) there exist *additional TeV scale interaction* terms between the RH neutrinos and SM particles (extra $U(1)$ gauge symmetry broken at TeV scale, TeV scale type III see-saw mechanism, ...) *or ii*) for neutrino masses generated by a mechanism other than the see-saw (*e.g.* radiatively at one or two loops)