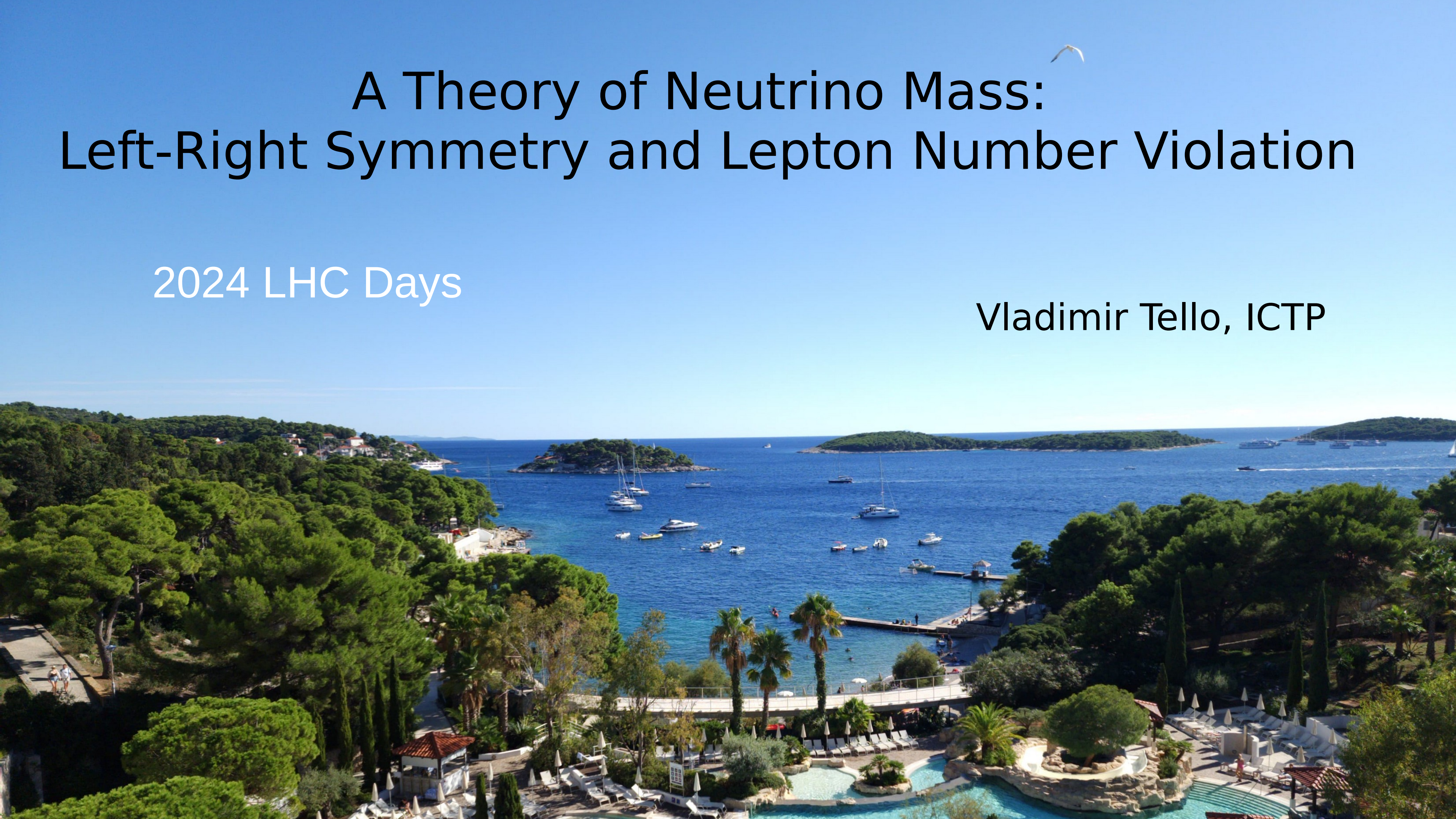


A Theory of Neutrino Mass:
Left-Right Symmetry and Lepton Number Violation

2024 LHC Days

Vladimir Tello, ICTP

Parity violation in SM

- Principle of the conservation of parity (Wigner ‘27)
- Parity Not a Symmetry of Weak Interactions. Maximally broken. Lee-Yang ‘56, Wu ‘56
- V-A theory, Marshak-Sudarshan ‘57, Feynman-Gell-Mann ‘57

This is not a flaw in the SM but a feature — nature just works this way at low energies

What if nature isn't maximally asymmetric?

Could there be a hidden symmetry at higher energies?

Neutrino Mass Problem

- Neutrinos are extremely light compared to other fermions
- Experimental evidence confirms neutrino oscillations ⇒ Neutrinos have mass
- SM predicts massless neutrinos. Needs beyond SM explanations

Parity Restoration: A path to Neutrino Mass

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \leftrightarrow \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

Left-Right Symmetry

Automatically implies massive neutrinos

$$m_\nu \, \overline{\nu_L} \nu_R$$

Pati, Salam ‘74
Mohapatra, Pati ‘74
Mohapatra, Senjanović ‘75
Senjanović ‘79

Parity Restoration: A path to Neutrino Mass

- LR symmetry solves parity violation and predicted neutrino mass decades before experimental confirmation.
- Offers a natural explanation for neutrino masses.
- Lepton Number Violation: A Window into New Interactions?
- The search for lepton number violation (neutrinoless double beta decay, LHC signatures) could reveal the dynamics of the Left-Right model.

Left-Right Model

Mohapatra, Senjanović '79,81

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

Gauge Bosons: W_L, W_R, Z, Z', γ

Symmetric Representations for quarks and leptons

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

$$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad \ell_R = \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

Left-Right Symmetry $P \longrightarrow \; q_L \leftrightarrow q_R, \; \ell_L \leftrightarrow \ell_R, \; W_L \rightarrow W_R$

Is not just aesthetic but also leads to
a solution for the neutrino mass problem through the seesaw mechanism

Left-Right Model

Symmetric representations for scalar fields: bidoublet, triplets

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & -\phi_2^{0*} \end{pmatrix} \qquad \Delta_L = \begin{pmatrix} \frac{\Delta_L^+}{\sqrt{2}} & \Delta_L^{++} \\ \Delta_L^0 & -\frac{\Delta_L^+}{\sqrt{2}} \end{pmatrix}, \quad \Delta_R = \begin{pmatrix} \frac{\Delta_R^+}{\sqrt{2}} & \Delta_R^{++} \\ \Delta_R^0 & -\frac{\Delta_R^+}{\sqrt{2}} \end{pmatrix}$$

Pattern of symmetry breaking

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \xrightarrow[\langle \Delta_R \rangle]{} SU(2)_L \times U(1)_Y \xrightarrow[\langle \Phi \rangle]{} U(1)_{EM}$$

$$\frac{M_{W_L}}{M_{W_R}} \propto \frac{\langle \Phi \rangle}{\langle \Delta_R \rangle} \ll 1$$

Left-Right Symmetry

- Right-handed quark mixing matrix
- Dirac Matrix of neutrinos
- Lepton Flavor Violation: LHC, neutrinoless double beta decay
- Lepton Number Violation

Right-Handed Quark Mixing Matrix

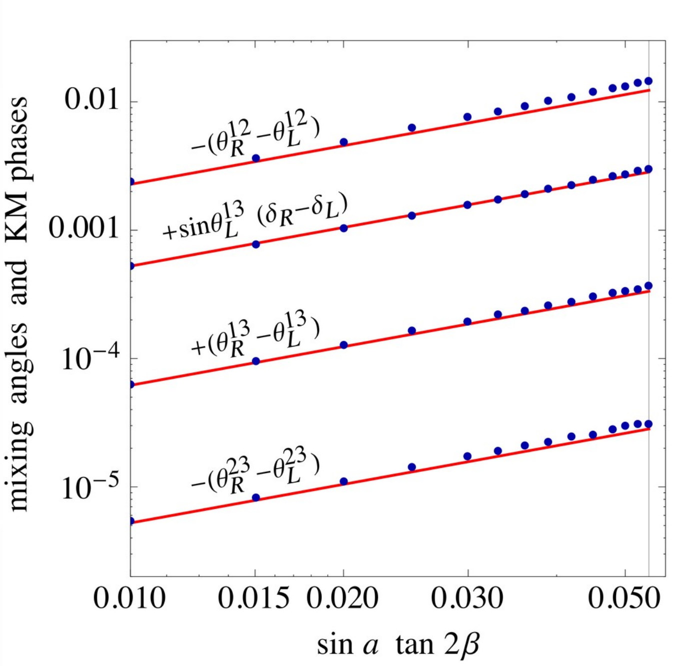
Senjanović, VT ‘15

$$(V_R)_{ij} = (V_L)_{ij} - i\epsilon \frac{(V_L)_{ik}(V_L^\dagger m_u V_L)_{kj}}{m_{d_k} + m_{d_j}}$$

$$\theta_R^{12} - \theta_L^{12} \simeq -\epsilon \frac{m_t}{m_s} s_{23} s_{13} s_\delta,$$

$$\theta_R^{23} - \theta_L^{23} \simeq -\epsilon \frac{m_t}{m_b}\frac{m_s}{m_b} s_{12} s_{13} s_\delta$$

$$\theta_R^{13} - \theta_L^{13} \simeq -\epsilon \frac{m_t}{m_b}\frac{m_s}{m_b} s_{12} s_{23} s_\delta,$$



- Right-handed Quark mixing matrix closely matches left-handed CKM.
- Small deviations due to parity breaking.

Conclusion: the LR symmetry relates the left and right quark mixing matrices

Neutrino Masses in LRSM

Minkoswski '77
Mohapatra, Senjanović '79
Yanagida '79
Glashow '79
Gell-man et al. '79

Dirac-like interaction $Y_\Phi \, \overline{\ell_L} \Phi \ell_R + \text{h.c.}$

Majorana-like interaction $Y_L \, \ell_L^T \epsilon \Delta_L \ell_L + Y_R \, \ell_R^T \epsilon \Delta_R \ell_R + \text{h.c.}$

$$M_\nu = -M_D^T \frac{1}{M_N} M_D$$

$$M_D \propto \langle \Phi \rangle = v = \text{scale of } W_L$$
$$M_N \propto \langle \Delta_R \rangle = v_R = \text{scale of } W_R$$

Seesaw relation: As mN increases, mν decreases.

- Natural explanation for tiny neutrino masses due to large mN.
- Small neutrino mass = near maximal P violation

$$m_\nu \propto \frac{M_{W_L}^2}{M_{W_R}}$$

Determination of MD

Nemevšek, Senjanović, VT '13

The Dirac mass matrix is determined by its inherent symmetry properties

$$M_D = \text{symmetric matrix}$$

$$M_D = i M_N \sqrt{\frac{1}{M_N} M_\nu}$$

$$M_\nu = V_L^* m_\nu V_L^\dagger$$

Probed by low energy experiments, oscillations, NDBD

$$M_N = V_R m_N V_R^T$$

Can be determined at high energy colliders, next slides

Dirac neutrino couplings are predicted and in turn a plethora of particle decays

Fermion masses and mixings

Standard Model V_L^{CKM}, m_q, m_ℓ

Left-Right Model additional masses and mixings:

$$V_R(q), \{V_L^{PMNS}, m_\nu\}, \{V_R(\ell), m_N\}, M_D$$

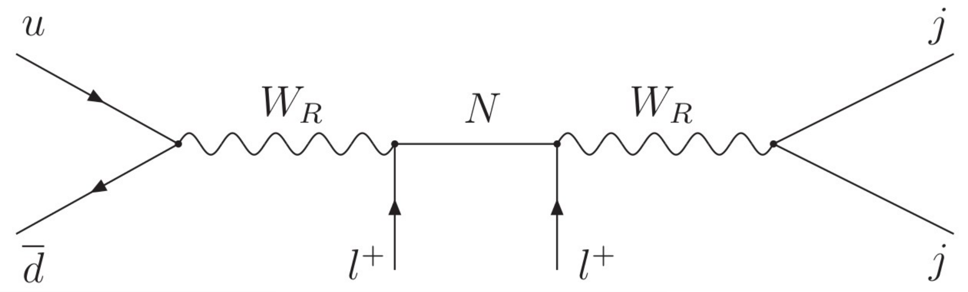
Left-Right model predictions

$$V_R = f_1(V_L^{CKM}, m_q), \ \ M_D = f_2(V_L^{PMNS}, m_\nu, V_R(l), m_N)$$

LHC Signatures

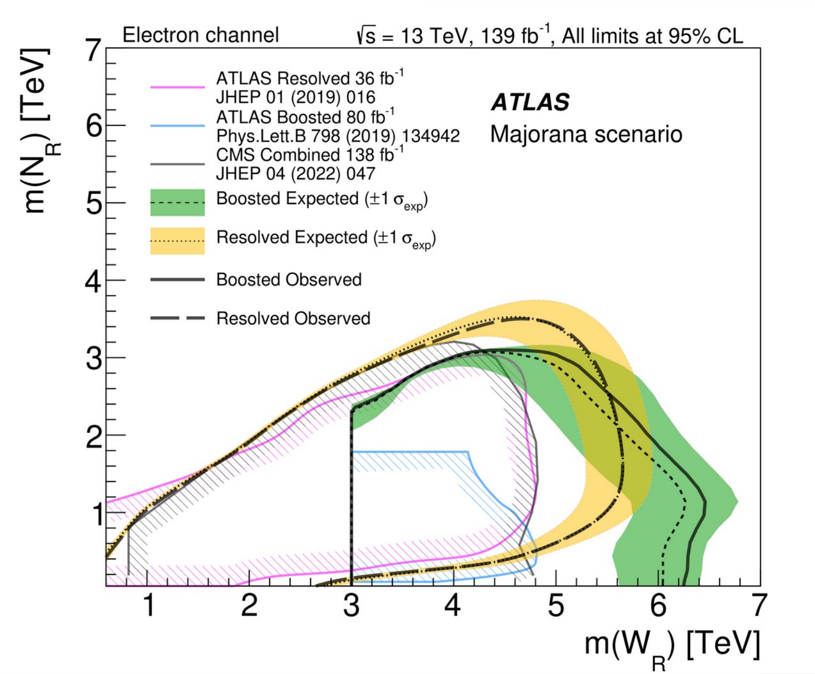
- Potential for discovery of right-handed charged gauge boson WR.
- Production of heavy right-handed neutrinos at LHC.
- Same-sign lepton pairs as a signal of lepton number violation.

Production of RH neutrino: Keung-Senjanovic process



Keung,Senjanovic ‘83

- Production and decay of heavy Majorana neutrinos at hadron colliders
- Same-sign charged leptons (ℓ+ℓ+) without missing energy, indicating lepton number violation.
- Key process for probing the Majorana nature of neutrinos
- Allows for the determination of the RH neutrino masses and mixings (in turns allows for the determination of the Dirac Yukawa couplings)



Direct Searches 4TeV

‘24 ATLAS

$$W_R \to tb$$

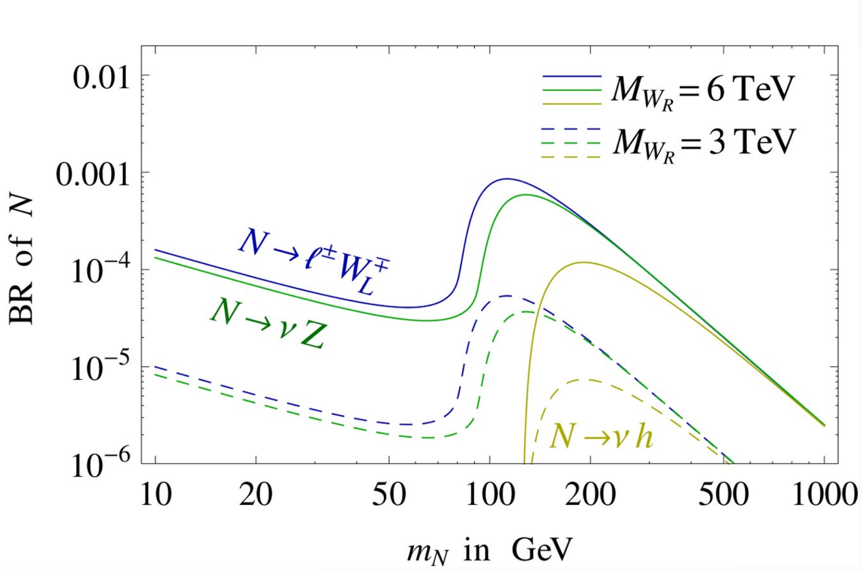
Decay of the RH neutrinos

Nemevšek, Senjanović, VT '13

$$N \to \ell^\pm W_L^\mp,\ \nu Z,\ \nu h$$

Example for $V_R = V_L^*$

$$M_D = V_L^* \sqrt{m_\nu m_N} V_L^\dagger$$



Probes Dirac Couplings and allows for probing the origin of neutrino mass

(self contained seesaw)

Probing the origin of neutrino mass

The SM decays allows probing the charged lepton masses

$$\Gamma(h \to \bar{f}f) \propto \frac{m_f^2}{M_W^2}\, m_h$$

The LR decays model allows probing the neutrino masses

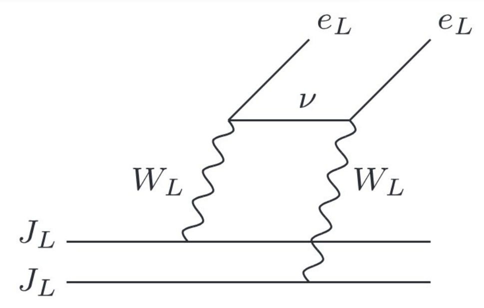
$$\Gamma(N \to W\ell) \propto \frac{m_N^2}{M_W^2}\, m_\nu\, .$$

This is thus a predictive theory of neutrino mass

Neutrinoless Double Beta Decay

- A key test for Majorana nature of neutrinos
- Experimental efforts and bounds GERDA, EXO-200, Cuore, KamLAND-Zen

ν .

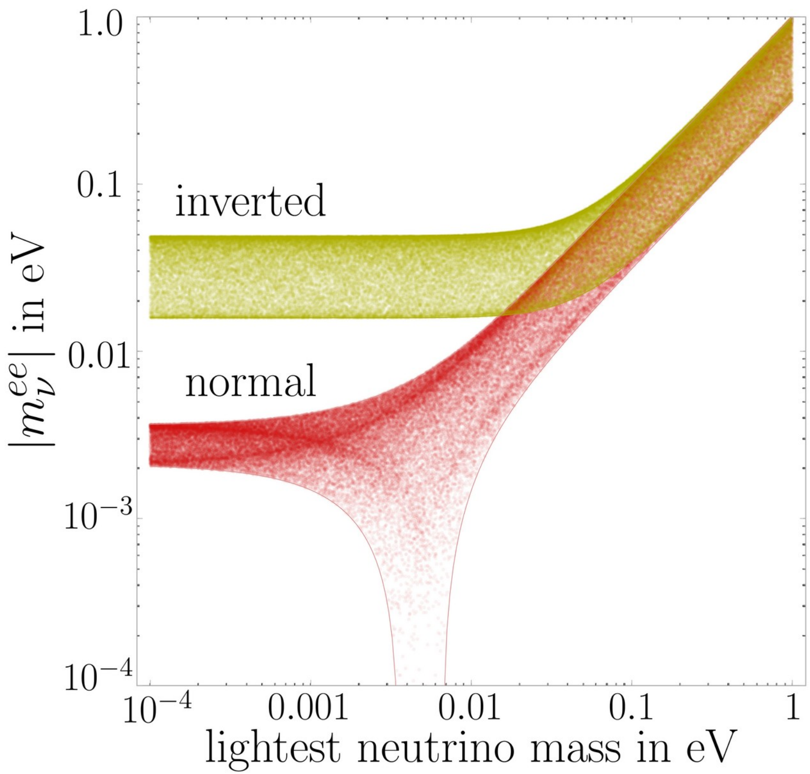


$$\propto \; G_F^2 \, \frac{(M_\nu)^{ee}}{p^2}$$

$$T_{1/2} > 1.8 \times 10^{26} \text{yr}$$

$$|(M_\nu)_{ee}| \leq 0.18 \text{ eV}$$

GERDA



mν < 0.45 eV KATRIN

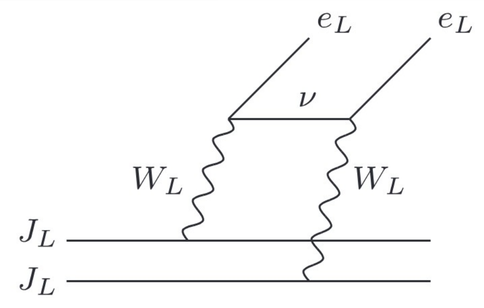
mν < (0.07-0.2) eV Cosmology

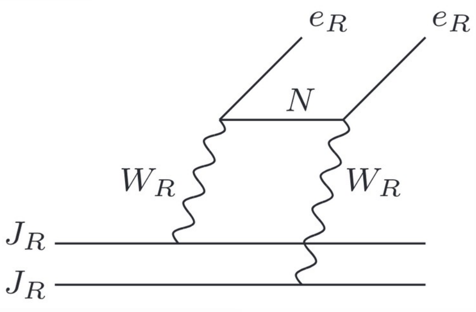
$$< 180 \, \text{meV} \, (^{76}\text{Ge})(\text{GERDA}), < 350 \text{meV} (^{130}\text{Te})(\text{CUORE}), < 165 \text{meV} (^{136}\text{Xe})(\text{KamLAND-Zen})$$

Neutrinoless Double Beta Decay

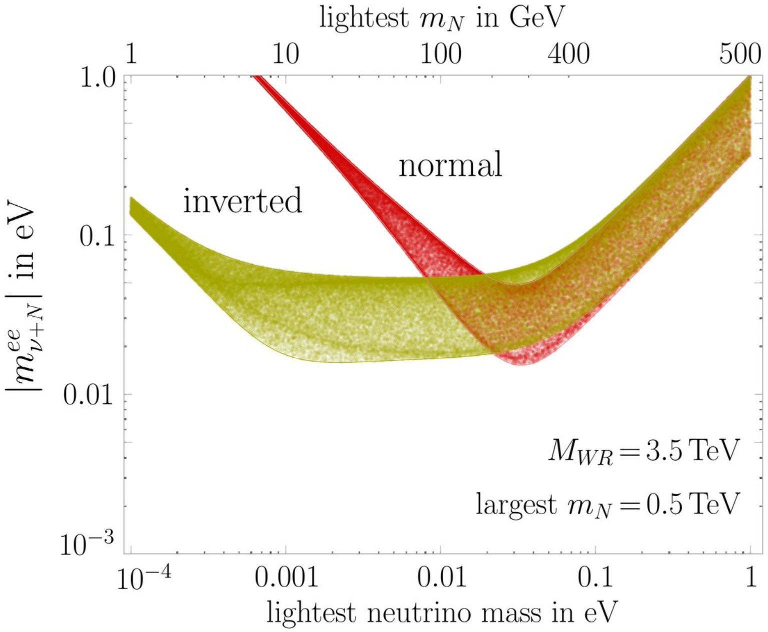
Mohapatra, Senjanović,‘79,‘81
VT et all ‘11

- LR symmetry enhances the process via right-handed currents.
- Contributions from both light and heavy neutrinos.





$$|T_{1/2}|^{-1} \propto \left|\frac{M_\nu^{ee}}{p^2}\right|^2 + \left|\frac{M_{W_L}^4}{M_{W_R}^4}\frac{1}{M_N^{ee}}\right|^2$$



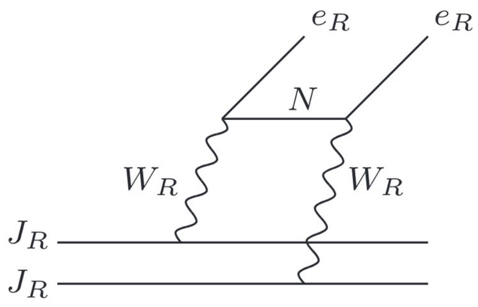
Example

$$V_R = V_L^*$$

$$m_N \propto m_\nu$$

Signal from Neutrinoless Double Beta Decay?

Nemevšek, Nesti, Senjanović, VT ‘11



If outgoing right-handed electrons is the LR model.

$$\frac{M_{W_L}^4}{M_{W_R}^4}\frac{p^2}{m_N} \sim 100\,\mathrm{meV} \longrightarrow M_{W_R} \lesssim 20\,\mathrm{TeV}$$

$$(m_N \simeq 1 \text{ GeV})$$

Would suggest a WR within the reach of the LHC or future colliders

Probe of new physics scale

Lepton Flavor Violation

$$\Delta_L^{++} \to \ell_i^+ \ell_j^+ , \;\; \Delta_R^{++} \to \ell_i^+ \ell_j^+$$

Triplet-Fermion Interactions $Y_L\, \ell_L^T \epsilon \ell_L\, \Delta_L + Y_R\, \ell_R^T \epsilon \ell_R\, \Delta_R$

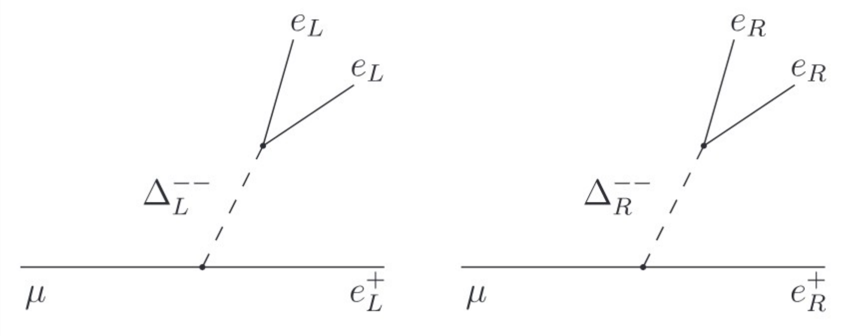
RH neutrino mass $M_N = v_R Y_R$

Left and Right triplet interactions governed by the RH neutrino mass matrix

$$Y_L = Y_R \propto \frac{M_N}{M_{W_R}}$$

Lepton Flavor Violation

Cirigliano, Kurylov, Ramsey-Musolf, Vogel ‘04
VT, PHD thesis ‘12



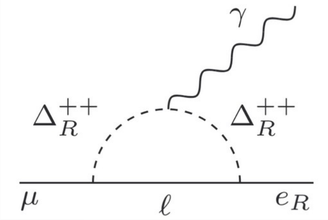
$$B(\mu \to e e \bar{e}) = \frac{1}{2} \frac{M_{W_L}^4}{M_{W_R}^4} \frac{\left|(M_N)_{e\mu}(M_N)_{ee}\right|^2}{m_{\Delta^{++}}^4}$$

$B(\mu \to 3e) < 10^{-12}$ SINDRUM

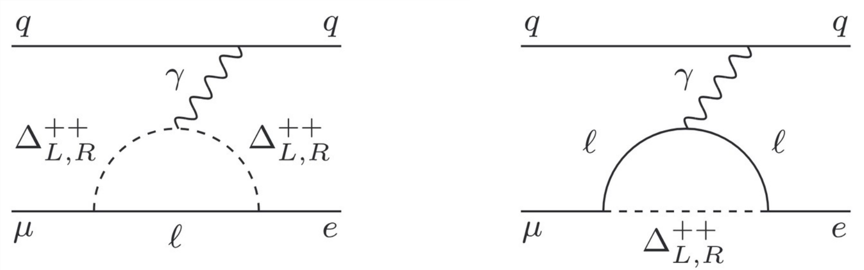
- For light WR, can be under control with light or degenerate N
- Does not probe the WR scale: light doubly charged scalars can be doing the job

Lepton Flavor Violation

Cirigliano, Kurylov, Ramsey-Musolf, Vogel ‘04
VT, PHD thesis ‘12



$$B(\mu \to e\,\gamma) < 4.2 \times 10^{-13}$$ MEG



$$B(\mu\, Au \to e\, Au) < 7 \times 10^{-13}$$

SINDRUM II

same flavour structure $$B(\mu X \to eX) \simeq B(\mu \to e\gamma)$$

Message

- Neutrinoless double beta decay (right-handed electrons) signals new physics beyond the Standard Model at the LHC or future colliders
- Lepton number violation at colliders, through the Keung-Senjanović process, can probe the Majorana nature of neutrinos.
- The Left-Right model can be considered a theory of neutrino mass, just as the Standard Model is considered a theory of charged lepton masses
- The discovery of right-handed gauge bosons at colliders would be a significant test of Left-Right symmetry, offering direct evidence for parity restoration at higher energies

Thank you