Neutrino mass and Hierarchy determination from new physics

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Findings: neutrinos have mass

\[ \Delta m^2_{\text{sol}} \sim (7.0 - 8.0) \times 10^{-5} \text{eV}^2 \]
\[ \Delta m^2_{\text{atm}} \sim (2.26 - 2.65) \times 10^{-3} \text{eV}^2 \]

they mix with each other

\[ \theta_{12} \sim 34^\circ, \quad \theta_{23} \sim 45^\circ \]
\[ \theta_{13} \sim 9^\circ \]

Schwetz et al '2012; Fogli et al '2012

Super Kamiokande, Daya Bay, T2K, SNO expts
# Standard Model

## Table: Gauge Group

<table>
<thead>
<tr>
<th>Left-handed fields:</th>
<th>Isospin Doublet</th>
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<tbody>
<tr>
<td>Right-handed fields:</td>
<td>Isospin Singlet</td>
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No Right-handed Neutrinos: Massless Neutrinos

Explains the strong, the weak and the electromagnetic interactions

a beautiful theory explaining all the fundamental particles known to us and their interactions
Motivation for BSM Physics

★ non-zero Neutrino mass: Theoretical origin ??
★ Dark Matter: Constituting 25% energy density of Universe ?
★ Baryon Asymmetry: Why our present Universe is matter dominated ?
★ Some more unsolved questions in neutrino sector:
  • Whether neutrinos are Dirac or Majorana ??
  • Absolute scale of neutrino mass ?
  • Mass Hierarchy, i.e. whether NH or IH ??
  • CP-Violating Phase

Journey Towards
BEYOND THE STANDARD MODEL PHYSICS
Dirac or Majorana?

- **Dirac Mass:** $M_D \overline{\nu}_L N_R \rightarrow$ Lepton Number is conserved
- **Majorana Mass:** $M_R \overline{N}_R^c N_R \rightarrow$ Lepton Number is Violated

Can be Tested in Neutrinoless Double Beta Decay and Collider experiments
Normal or Inverted?

normal hierarchy (NH)

\[ m^2 \]

\[ \Delta m_{\text{atm}}^2 \]

\[ \Delta m_{\text{sol}}^2 \]

\[ \nu_e \]

\[ \nu_{\mu} \]

\[ \nu_{\tau} \]

\[ \nu_2 \]

\[ \nu_3 \]

inverted hierarchy (IH)

\[ m^2 \]

\[ \Delta m_{\text{sol}}^2 \]

\[ \Delta m_{\text{atm}}^2 \]

\[ \nu_1 \]

\[ \nu_2 \]

\[ \nu_3 \]
Origin of $\nu$ mass: Seesaw Mechanism

★ **Seesaw Mechanism**: Majorana Nature of Neutrinos
★ **Majorana nature of Neutrinos**: Neutrinos are their own antiparticles.
★ **Direct consequence of lepton number violation**: Neutrinoless Double Beta Decay
Canonical Seesaw Mechanisms

★ Type-I Seesaw Mechanism:
- Type-I: SM ($\nu_L$) + RH Neutrinos $N_R$
- Neutrino Mass Matrix $\nu_L, N_R$

$$M = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

- With seesaw approximation, $M_R \gg m_D$ we arrive at

$$m_\nu = -m_D M_R^{-1} m_D^T$$

- The lightness of $m_\nu$ depends upon heavy scale of $M_R$

★ Other known seesaw mechanisms:
- Type-II: SM + Higgs triplet scalar
- Type-III: SM + Fermion triplets

★ Pros: Canonical Seesaw Mechanisms agreeably explain Oscillation data.

★ Cons: They lack direct experimental testability at colliders like LHC.
**Double beta decay can happen in two processes.**

- $(A, Z) \rightarrow (A, Z + 2) + 2e + 2\bar{\nu}$ \hspace{1cm} (2$\nu\beta\beta$)
- $(A, Z) \rightarrow (A, Z + 2) + 2e$ \hspace{1cm} (0$\nu\beta\beta$)

**Neutrino flavour eigenstates** $\nu_\alpha$ **are related to Mass eigenstates** $\nu_i$ **as;** $\nu_\alpha = U_{\alpha i} \nu_i$ **with mass eigenvalues** $m_i$

\[ \mathcal{L}_{CC}^\ell = \frac{g_L}{\sqrt{2}} e_{Li} \gamma^\mu U_{\alpha i} \nu_i W_{\mu L} \]
Extracting LNV Parameters

The Half-life for this $0\nu\beta\beta$ decay process

$$\frac{1}{T_{\frac{1}{2}}^{0\nu}} = G_{01}^{0\nu} \left| M_{\nu}^{0\nu} \right|^2 \left| \eta_{\nu} \right|^2 = G_{01}^{0\nu} \left| \frac{M_{\nu}^{0\nu}}{m_e} \right|^2 \left| m_{\beta\beta} \right|^2, \quad (1)$$
Left-Right Model as New Physics

1. Left-right symmetric models seem appealing:
as they provide a clear description of maximal parity violation and
pave a path naturally for light neutrino masses.


2. Gauge Symmetry

\[ G_{LR} \equiv SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C \]

with electric charge relation

\[ Q = I_{3L} + I_{3R} + \frac{B - L}{2} \]

3. particle Content

\[ q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \equiv [2, 1, \frac{1}{3}, 3], \quad q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \equiv [1, 2, \frac{1}{3}, 3], \]

\[ \ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \equiv [2, 1, -1, 1], \quad \ell_R = \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \equiv [1, 2, -1, 1], \]
Lepton Number Violation in LRSM

1 Symmetry breaking of LRSM

\[
SU(2)_L \times SU(2)_R \times U(1)_{B-L} \xrightarrow{\langle \Delta_R \rangle} SU(2)_L \times U(1)_{Y} \xrightarrow{\langle \phi \rangle} U(1)_{em}
\]

2 Spontaneous symmetry breaking:
With scalar bidoublet \( \Phi(2, 2, 0, 1) \) and triplets \( \Delta_L(3, 1, 2, 1) \), \( \Delta_R(1, 3, 2, 1) \):

3 If the breaking of \( SU(2)_R \times U(1)_{B-L} \) occurs at a scale of few TeV, it leads to interesting collider signatures, neutrinoless double beta decay and lepton flavor violation.
Fermions

\[ q_L(2, 1, 1/3, 3) \quad q_R(1, 2, 1/3, 3) \]
\[ \ell_L(2, 1, -1, 1) \quad \ell_R(1, 2, -1, 1) \]
\[ S(1, 1, 0, 1) \]

Scalars

\[ \Phi(2, 2, 0, 1) \]
\[ \Delta_L(3, 1, 2, 1) \quad \Delta_R(1, 3, 2, 1) \]
\[ H_L(2, 1, -1, 1) \quad H_R(1, 2, -1, 1) \]

Yukawa Interaction Lagrangian:

\[ -\mathcal{L}_{Yuk} = \bar{\ell}_L \left[ Y_3 \Phi + Y_4 \tilde{\Phi} \right] \ell_R + f \left[ (\bar{\ell}_L)^c \ell_L \Delta_L + (\bar{\ell}_R)^c \ell_R \Delta_R \right] + F (\bar{\ell}_R) H_R S_L^c + \text{h.c.} \]

Complete neutral Lepton Mass matrix

in the basis \((\nu_L, S_L, N_R^c)\)

\[
\mathbf{M} = \begin{pmatrix}
\nu_L & S_L & N_R^c \\
\nu_L & M_L & 0 & M_D \\
S_L & 0 & 0 & M \\
N_R^c & M_D^T & M^T & M_R 
\end{pmatrix}.
\]
Mass formula for light left-handed, heavy right-handed and sterile neutrinos:

\[ m_\nu = M_L = U m^d_{\nu} U^T, \]
\[ M_N \equiv M_R = \frac{v_R}{v_L} M_L = \frac{v_R}{v_L} U m^d_{\nu} U^T, \]
\[ M_S = - M M_R^{-1} M^T = - m^2_S \left[ \frac{v_R}{v_L} U m^d_{\nu} U^T \right]^{-1} \]

Complete mixing matrix in the basis \((\nu_L, S_L, N^c_R)\):

\[ V = W \cdot U = \begin{pmatrix}
U_\nu & M_D M^{-1} U_S & M_D M^{-1} U_N \\
(M_D M^{-1})^\dagger U_\nu & U_S & (M_D M^{-1})^\dagger U_N \\
\emptyset & - (M M_R^{-1})^\dagger U_S & U_N
\end{pmatrix} \]
Ingredients for $0\nu\beta\beta$ decay

1. **Charged current interactions:**

\[
\mathcal{L}_{CC}^{\text{mass}} = \frac{g_L}{\sqrt{2}} \left[ \bar{e}_L \gamma_\mu \left\{ V_{ei}^{\nu} \nu + V_{ei}^S S_i + V_{ei}^N N_i \right\} W_{L\mu} \right] + \text{h.c.} \\
+ \frac{g_R}{\sqrt{2}} \left[ \bar{e}_R \gamma_\mu \left\{ V_{ei}^{NS} S_i + V_{ ei}^{NN} N_i \right\} W_{R\mu} \right] + \text{h.c.} \\
\mathcal{L}_{CC}^{q} = \frac{g_L}{\sqrt{2}} \left[ \bar{d} \gamma^\mu P_L u W_{L\mu}^- + \frac{g_R}{\sqrt{2}} \bar{d} \gamma^\mu P_R u W_{R\mu}^- + \text{h.c.} \right]
\]

2. **Gauge Boson Masses and Mixing:** The physical gauge boson states $W_1$ and $W_2$ are related to the mixture of weak eigenstates $W_L$ and $W_R$ as

\[
\mathbb{R}_W \equiv \begin{pmatrix} \cos \xi & \sin \xi \\ -\sin \xi & \cos \xi \end{pmatrix}
\]

where,

\[
|\tan 2\xi| \sim \frac{2v_1 v_2}{u_R^2 + 2v_R^2 - u_L^2 - 2v_L^2}
\]
New Physics contributions to $0\nu\beta\beta$
$0\nu\beta\beta$ with right-handed currents only

★ Type-II seesaw within left-right symmetric model
Shao-Feng, Manfred, Patra; JHEP 1512]
Limiting Absolute scale of neutrino mass

Pritimita Dash, Patra; JHEP 1610 (2016) 147

![Diagram of neutrino mass spectrum and mass hierarchy](image)

P. Pritimita (CosPA-2016)  Neutrino Mass and Mass Hierarchy.
From Lepton Flavour Violation

Dash, Dev, Pritimita, Patra (in preparation)

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Figure: Limiting $m_{\nu}$ for NH (IH) from $\mu \rightarrow e \gamma$, $\mu \rightarrow 3e$, $\mu \rightarrow e$ conversion.

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Neutrino Mass and Mass Hierarchy.
From Dipole moment of electron

Dash, Dev, Pritimita, Patra (in preparation)

\[ d_\alpha = \frac{e \alpha W}{8\pi M^2_{WL}} \text{Im} \left[ \sum_{i=1}^{3} V_{\alpha i}^\nu V_{i\alpha}^{NN} \xi \mathcal{G}_2(x_{Ni}) M_{Ni} \right] \]

\[ d_e = \frac{10^{-27}}{10^{-26}} \text{e cm} \]

\[ m_{1,3} (\text{eV}) \]

\[ \delta_{CP} \]

ACME (90% C.L.)

NH

IH

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Neutrino Mass and Mass Hierarchy..
1. Neutrino Oscillation: Unequivocal evidence of BSM Physics

2. Seesaw Mechanism is a well motivated mechanism for explaining neutrino mass associated with Majorana nature.

3. Observation of neutrinoless double beta decay will prove lepton number violation in nature and Majorana mass of neutrinos

4. TeV scale masses of $W_R^\pm$ and $M_N$ as well as scalar triplets can give dominant non-standard contributions to Lepton Number Violation like $0\nu\beta\beta$ which might be important for experimental searches

5. Bound on Absolute scale of neutrino masses and information on mass hierarchy can be derived from new physics searches at $0\nu\beta\beta$ expts.

6. Normal hierarchy is favorable if we use cosmology and oscillation parameters within Left-Right Type-II Seesaw dominance.
Thank you!