Neutrino Mass Models in the LHC Era

R. N. Mohapatra

NOW, 2010
Outline of Talk

0. Seesaw mechanism

1. Seesaw Scale: Theory insights, LHC, other searches

2. Large mixings and unification with quarks

3. A new possibility for neutrino masses

(only three active neutrinos will be considered-MINOS and MiniBooNe not discussed; see E. Akhmedov’s talk)
Neutrino Mass

→ New physics

- Standard model: no $\nu_R \rightarrow m_\nu = 0$

- Two possibilities for $m_\nu$

(i) $\text{SM} + \nu_R \rightarrow L_Y = h_\nu \bar{L}H \nu_R + h.c. \rightarrow m_\nu = h_\nu \nu_{wk}$

Observations $\rightarrow h_\nu \cong 10^{-12}$: any justification?

(ii) Mass from high scale physics: $\frac{LHLH}{M}$
What is the new physics?

**Seesaw paradigm:** New fermions $N_R$ or Higgs

<table>
<thead>
<tr>
<th>Type I</th>
<th>Type II</th>
<th>Type III</th>
<th>Inverse</th>
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$m_{\nu} \equiv -\frac{h^2 v_{wk}^2}{M_R}$

$m_{\nu} = -2Y_{\Delta} v^2 \frac{\mu_{\Delta}}{M^2_{\Delta}}$

$m_{\nu} = -\frac{v^2}{2} Y^T \frac{1}{M_{\Sigma}} Y_{\Sigma}$

$m_{\nu} \equiv -m_D^T M^{-1} \mu M^{-1} m_D$

- Majorana
- Triplet Higgs
- Triplet Fermion
- Dirac
Seesaw scale?

- Seesaw assumption by itself cannot tell – need to know Dirac mass

- Plausible guesses motivate different scales
Is seesaw physics accessible at LHC?

- **Type I case**, if \( m_D \approx m_e \) scale \( \sim \) TeV

- **Inverse seesaw** \( \Rightarrow \) scale at TeV even with \( m_D \approx m_t \)

- if there is a 4\(^{th}\) gen., \( M \) necessarily TeV.
  
  Scale being TeV- no guarantee of LHC visibility:

  **key parameter:** \( \varepsilon \equiv \frac{m_D}{M_N} \)  \( < 10^{-7} \) (type I); \( > 10^{-3} \) (Inverse)
LHC signal for simplest TeV seesaw

- **Type I and Inverse:**
- Basic manifestations of seesaw: $\nu - N$ mixing

Collider production for $M_N < \text{TeV}$

- Negligible for type I seesaw but observable for inverse seesaw $M_N \sim \text{TeV}$
- **Situation different** with other seesaws and seesaw with gauge forces!!
Type II and III at LHC

- New particles are SM non-singlets:

- **Type II:** \( \Delta = \begin{pmatrix} \delta^+ / \sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+ / \sqrt{2} \end{pmatrix} \), couples only to leptons

\[
\nu\bar{\nu} \rightarrow \delta^{++} \delta^{--}; u\bar{d} \rightarrow \delta^{++} \delta^{-}
\]

directly probes neutrino mass matrix.

4-lepton signal \( \ell^+ \ell^+ \ell^- \ell^- \) (Han, Perez, Huang, Li, Wang;...)

- **Type III:** \( \Sigma = \begin{pmatrix} \Sigma^0 / \sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0 / \sqrt{2} \end{pmatrix} \).

\[
q\bar{q} \rightarrow Z^* / \gamma^* \rightarrow \Sigma^+ \Sigma^- \\
q\bar{q}' \rightarrow W^* \rightarrow \Sigma^+ \Sigma^0
\]

(Bajc, Senjanovic, Nemevsek)
Accessing seesaw scale in low energy expts

Possible new operators from new physics:

Type I: \[ \delta \mathcal{L}_{d=6} = c_{\alpha\beta}^{d=6} \left( \ell_L \tilde{\phi} \right) i \slashed{\partial} \left( \tilde{\phi}^\dagger \ell_L \beta \right) \]

\[ \mathcal{E}^2 \]

\[ \rightarrow \text{Leads to non-unitarity of PMNS: SBL tests possible for } \mathcal{E} > 10^{-2} \]

Current bounds:

\[ |\eta| < \begin{pmatrix}
2.0 \times 10^{-3} & 3.5 \times 10^{-5} & 8.0 \times 10^{-3} \\
3.5 \times 10^{-5} & 8.0 \times 10^{-4} & 5.1 \times 10^{-3} \\
8.0 \times 10^{-3} & 5.1 \times 10^{-3} & 2.7 \times 10^{-3}
\end{pmatrix} \]

Type II: \[ \delta \mathcal{L}_{4F} = \frac{1}{M_\Delta^2} \left( \ell_L Y_\Delta \tilde{\tau} \ell_L \right) \left( \ell_L \tilde{\tau} Y_\Delta^\dagger \ell_L \right) \]

Type III: \[ \delta \mathcal{L}_{d=6} = c_{\alpha\beta}^{d=6} \left( \ell_L \tilde{\tau} \phi \right) i \slashed{\partial} \left( \tilde{\phi}^\dagger \tilde{\tau} \ell_L \beta \right) \]

\[ \sim \mathcal{E}^2 \]

Abada, Biggio, Gavela, Bonnet, Hambye; Antusch, Fernandez, Malinsky, Meloni, Ohlsson, Winter, Zhang,...
Seesaw and new gauge forces:

- Seesaw strongly suggests gauge forces
- **Type I**: why seesaw scale so far below Planck scale:
- **Inverse seesaw case**:

  \[
  \begin{pmatrix}
  0 & h_{\nu_{wk}} & 0 \\
  h_{\nu_{wk}} & 0 & M \\
  0 & M & \mu
  \end{pmatrix}
  \]

  why not

  \[
  \begin{pmatrix}
  0 & h_{\nu_{wk}} & h'_{\nu_{wk}} \\
  h_{\nu_{wk}} & M' & M \\
  h'_{\nu_{wk}} & M & \mu
  \end{pmatrix}
  \]

- **Local B-L** symmetry --a plausible answer!
- Collider profile of seesaw undergoes drastic change!!
What Gauge Symmetry?

- **Standard model: gauge sym.** $SU(2)_L \times U(1)_Y$
- **Fermions:**
  \[
  m_v = 0
  \]

- **$N_R \rightarrow$ Gauge group:**
  \[
  SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}
  \]
  \[
  \begin{array}{c}
  W^+_L \\
  W^+_R \\
  Z, Z', \gamma
  \end{array}
  \]
- **New**
Bounds on LR Scale

- Most stringent bounds come from CP viol. Observables $\varepsilon, \varepsilon', d_n^e$; depends on how CP is introduced:
  $$M_{W_R} \geq 2.5\text{TeV} \text{ to } 4\text{TeV}$$
  Zhang et al; Maiezza et al.

- New contributions to nu-less double beta decay (Type I) (RNM, 86; Hirsch, Klapdor, Panella 96)

$$m_{W_R} \geq 1.1 \left( \frac{\langle m_N(V) \rangle}{1\text{TeV}} \right)^{-1/4} [\text{TeV}]$$

From Ge76:
- Collider limits (D0,CDF) > 750 GeV
TeV WR signal from $\beta\beta_{0\nu}$

- **Nu contribution:**
  - Inverse hierarchy
  - Normal hierarchy
    (Ferruglio, Strumia, Vissani; Petcov, Passcoli, Bilenky)

**Punch line:**
- Suppose long baseline $\rightarrow \Delta m^2_{31} > 0$
- and nonzero signal for $\beta\beta_{0\nu}$

$\rightarrow$ could be a signal of TeV WR and type I
Theory insights into seesaw scale

- **Upper limits: Supersymmetry**
  Supersymmetry restricts potential for SUSY LR type I seesaw

\[ M_{W_R} < \frac{M_{\text{susy}}}{f} \]

- **Sneutrino or KK Nu\_R dark matter**

\[ M_{W_R} < \text{few TeV} \]
Is Grand unification idea any help?

- Gauge couplings unify with TeV scale SUSY-MSSM

  → Suggests grand unified Th.

- Connects quark and lepton physics-
- SU(5) does not help- Seesaw scale free parameter: (proton decay ?)
SO(10) just right:

- \{16\} - spinor for all matter
  - includes RH neutrino

Q-l unification predicts

\[ m_D \approx m_t \]

Type I case: seesaw scale

\[ M_R \approx 10^{14} \text{GeV} \]

Very appealing picture: predictive with extra global family symmetries;

TeV scale for type I does not unify:

(Parida, Raichoudhuri, Majee, Sarkar; Kopp, Lindner, Niro, Underwood)
Inverse seesaw in SO(10) - LHC accessible

New result! **Inverse seesaw** does unify –TeV WR Z’

\[ M_{W_R} < M_{Z'} \]

\[ M_{W_R} > M_{Z'} \]

\[ SO(10) \xrightarrow{M_G} 3_c 2_L 2_R 1_{B-L} \xrightarrow{M_R} 3_c 2_L 1_Y (MSSM) \xrightarrow{M_{SUSY}} 3_c 2_L 1_Y (SM) \xrightarrow{M_Z} 3_c 1_Q \]

\[ M_U \cong 10^{16} \text{ GeV}; M_{BL,R} \cong \text{TeV} \]

(Dev, RNM, 09; PRD; arXiv 1003:6102)
Leptogenesis and TeV WR

- **Formula for baryon asym**

\[ \eta_B \simeq 10^{-2} \sum_{i,\alpha} \epsilon_{i\alpha} \kappa_{i\alpha} \]

- **Resonant lepto:** \( \varepsilon \sim \frac{h_D^2 \delta}{\Delta M / M} \); \( \kappa \sim \frac{D}{D + S} \exp[-W_{L=2}^{ID\ldots}] \)

- **Type I case:** \( h_D^2 \sim 10^{-12} \); \( \frac{\Delta M}{M} \sim 10^{-12} \); S can be \( \gg \) D

- **Washout depends on WR mass:** MWR > 17 TeV (Frere, Hambye, Vertogenen)

- **Inverse seesaw** \( h_D^2 \sim 10^{-2} \rightarrow D \gg S \); \( W_{L=2} \sim \frac{\mu}{M} \sim 10^{-7} \rightarrow \kappa \sim 1 \)

- **Not so sensitive dependence on WR.** MWR > 1.5 TeV (Blanchet, Dev, RNM, to appear)
Type I vs Inverse left-right seesaw at LHC

- **WR and Z’:**
  
  \[
  u\bar{d} \rightarrow W_R \rightarrow l^+ N \quad \text{and} \quad u\bar{u} \rightarrow Z' \rightarrow NN
  \]

  (Keung, Senjanovic; Han, Perez, Huang, Li, Wang; Del Aguila, Aguilar-Saavedra; de Blas, Azuelos, ...)

- **N-decay:**
  
  (a) \( \nu N \) xing \( \epsilon \) l/or (b) exchange \( W_R \)

- **type I:**
  
  \( \epsilon \ll 10^{-3}, M_{W_R} < 4 \text{TeV} \) negligible; \( N \rightarrow l^\pm jj \)

- **Signal**
  
  \( pp \rightarrow l^\pm l^\pm jj + X \)

- **Inv. Seesaw**
  
  \( \epsilon > 10^{-3} \)

  \( N \rightarrow l^- jj, l^- l^+ \nu \)

  \( pp \rightarrow lll\nu + X \)

  \( \text{LHC reach} < 4 \text{ TeV} \)

- **Determination of chirality:** tb decay mode (Gopalakrishna, Han, Lewis, Si, Zhou)
2. Understanding Large mixings

**Issue 1.** Large lepton mixings: why?

**Leptons:**

\[ U_{PMNS} \approx \begin{pmatrix} \frac{\sqrt{6}}{3} & \frac{\sqrt{3}}{3} & 0 \\ -\frac{\sqrt{6}}{3} & \frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \\ \frac{\sqrt{6}}{6} & -\frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \end{pmatrix} + \delta U \]

**Issue 2.** How to have a unified understanding of quark and lepton mixings

\[ U_{CKM} = \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \]
Lepton mixings

(i) **Family symmetries**:

\[ S_{2(\mu-\tau)} \subseteq S_3, S_4, A_4, \Delta(3n^2), \ldots \]

- **Generically leads to TBM + small corrections**
  
  *(Talks by Morisi and Hagedorn)*

(ii) **Dynamical e.g. RH neutrino dominance** *(King)*

  *generically predicts large \( \theta_{13} \);*

  \( \rightarrow \) no explanation of TBM;
A strategy for flavor unification

\[ M_u = M_0 + \delta_u \]
\[ M_d = rM_0 + \delta_d \]
\[ M_l = rM_0 + \delta_l \]

\[ m_\nu = f v_L \]

\[ \delta_{u,d,l} \ll M_0 \]

→ Anarchic \( M_0, f \) → quark mixings small while lepton mixings large +

\[ m_b \equiv m_\tau \]

Natural in SO(10)+ type II seesaw

\[ \text{Rank 1 } M_0 \] → explains mass hierarchies
An $S_4 \times SO(10)$-example

- Symmetries make theory predictive: e.g. $S_4$

- Solar mass

\[ \frac{m_{\text{solar}}}{m_{\text{atm}}} \cong \lambda \cong \theta_c \]

- Bottom-tau:

\[ m_b \approx m_\tau \quad \text{and} \quad m_\mu = -3m_s \]

- Leading order PMNS- Tri-bi-maximal

  Corrections: Testable

\[ \theta_{13} = \frac{\theta_c}{3\sqrt{2}} \cong 0.05 \]

- Prediction for atmospheric angle: $\theta_{23} \cong 35^0 - 40^0$

- Current fit: $\theta_{23} = 42.8^{+4.7}_{-2.9}^{+10.7}_{-7.3}$

(Gonzalez-Garcia, Maltoni, Salvador, 2010)

Dutta, Mimura, RNM arXiv:0911.2242, JHEP
Generic GUT predictions

- **Normal hierarchy** \( m_1 < m_{\text{solar}} < m_{\text{atm}} \)

- **\( \theta_{13} \)** predictions for GUT vs non-GUT

(Compilation by Albright, Rodejohann)
3. Schizophrenic neutrinos

- Common assumption: Neutrinos are either Dirac or Majorana

- “Neutrino---neu-ter---(not either)”; E. Lisi, Neutrino 2010 summary talk

- Could it be that neutrinos are neither fully Dirac or fully Majorana but little bit of both i.e. Schizophrenic?
How could that be?

- Experiments $\rightarrow U_{PMNS}$, which relates mass to flavor eigenstates
  $$v_{flavor} = U_{PMNS} v_{mass}$$

- May be some some **mass eigenstates** are Dirac – others Majorana; **each flavor will then be both Dirac and Majorana** mixings and masses are unaffected.

- Specific example: $$v_2 = \frac{1}{\sqrt{3}}(v_e + v_\mu + v_\tau)$$ Dirac - others Majorana

- Why this combo? $$S_3$$ sym permuting: $$(L_e, L_\mu, L_\tau)$$

- \{1\}: $$\frac{1}{\sqrt{3}}(L_e + L_\mu + L_\tau)$$ Dirac; \{2\}: $$\left[ \frac{1}{\sqrt{2}}(L_\mu - L_\tau), \frac{1}{\sqrt{6}}(2L_e - L_\mu - L_\tau) \right]$$ Maj

(Allahverdi, Dutta, RNM, arXiv:1008.1232)
Implications for Nu-less double beta decay-IH

- $M_{\beta\beta}^{\text{min}} = 17 \text{ meV (usual IH)}$ vs $34 \text{ meV (Schizo-nu IH)}$ – schizo-nu easier to rule out if LBL $\rightarrow$ IH
Why? Inflation $\rightarrow$ Schizophrenia

- Susy B-L theory for seesaw $\rightarrow$ 3 RH neutrinos

- To fit neutrino observations, we only need two RH nu’s- so what is the third one (N3) doing?
- Could its superpartner be the inflaton?

- Inflation requires $\sim$flat potential
- In the B-L theory $(\tilde{N} + \tilde{L} + H_u)$ is one provided $h_D$ is tiny.

(Allahverdi, Kusenko, Mazumdar; Allahverdi, Dutta, Mazumdar)
Implications for neutrinos

→ How small is $h_D$?

→ COBE $\frac{\delta \rho}{\rho} \sim 10^{-5} \Rightarrow h_D \sim 10^{-12}$ for only one RH neutrino; just right for a Dirac nu:

→ That RH neutrino cannot mix with others to maintain flatness.

→ Immediately suggests this scenario for nu masses
Conclusion:

- **Seesaw:** Compelling big picture idea for neutrino masses;

(i) LHC can discover TeV scale seesaw; even in SO(10) models; **Must it discover? NO**

(ii) Most appealing neutrino models are based on type II+ SO(10) GUT seesaw; **No LHC signal; Can also unify flavor with extra sym.**

(iii) An inflation inspired schizophrenic neutrino scenario.
Other advantages of a Low seesaw scale

- **Leptogenesis**: High scale leptogenesis + hierarchical NR (as in type I or II SO(10)) →

  \[ M_N \geq 10^9 \text{GeV} \quad \text{versus} \quad T_R < 10^6 - 10^9 \text{GeV} \]

  - adequate leptogenesis
  - gravitino reheat constraint

  → Low scale resonant leptogen as alternative:

- **Suppression of proton decay**: High scale seesaw SO(10) with 16-Higgs has proton decay problem from operator;

  \[
  \frac{(16_m)^3 16_H}{M_{Pl}}
  \]

  → suppressed for TeV B-L breaking.
SO(10) with type II seesaw → realization of flavor ansatz

SO(10) → fermion mass formulae:

\[
\begin{align*}
Y_u &= h + r_2 f + r_3 h' \\
Y_d &= r_1 (h + f + h') \\
Y_e &= r_1 (h - 3f + c_e h')
\end{align*}
\]

\[m_v \cong f v_\Delta\]

(Babu, Mohapatra’92)

Bajc, Senjanovic, Vissani’03

For \(f, h' \ll h\), → yields ansatz part A at \(M_u\);

Rank (part B) from flavor symmetry:

Rank solves the proton decay problem also
LHC accessible non-seesaw models

- Seesaw scenarios based on operator: \( \frac{LHLH}{M} \)

- Higher the dimension of operator, lower the scale:
  e.g. \( LLHH(H^\dagger H)/M^3 \) (Babu, Nandi and Tavartkiladze)

→ TeV scale theory; predicts a field \( \Phi^{+++} \) \( M < \text{TeV} \)
  observable via decays: \( \Phi^{+++} \rightarrow W^+W^+W^+ , W^+\ell^+\ell^+ \)
Inverse Seesaw: details

- Rate plots: