Testable Seesaw Variants

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Based on My Recent Works:

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Plan of the Talk

Low scale Seesaw Variants and SM extensions

- Neutrino Mass
- Lepton Number Violation and Neutrinoless Double beta decay
- Lepton Flavor Violation and non-uniaiarity effects
- Collider Study

Low scale Seesaw Variants and Left-Right Theories

Low scale Seesaw Variants and GUT Connection

Conclusion
Elusive Neutrinos
And Neutrino Oscillation

Neutrinos: Lightest neutral leptons, take part in weak interaction

Neutrino was postulated to conserve energy-momentum

\[ n \rightarrow p + e^- + \bar{\nu}_e \]

They travel almost at the speed of light;

Origin of non-zero neutrino masses confirmed by Atmospheric, Solar and Reactor Neutrino Oscillation Experiments
Origin of $\nu$-mass?  

Seesaw Mechanism

Natural theoretical way to understand why 3 $\nu$-masses are small

Type-I: SM + 3 right-handed Majorana $\nu$’s

(Minkowski 77; Mohapatra, Senjanovic 79)

Type-II: SM + 1 Higgs triplet

Lazarides, Shafi, Wetterich ; Schechter, Valle (1980)

Type-III: SM + 3 triplet fermions (R. Foot et al 89)

Other Testable Seesaw Variants:

Inverse, Linear Seesaw

Malinsky, Romao, Valle (2005)

Extended Inverse/Linear (SP, Parida, Awasthi 2013..)

\[ M_\nu \approx -v^2 Y_\nu \frac{1}{M_R} Y_T^T \]

\[ M_\nu \approx \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta} \]

\[ M_\nu \approx -v^2 Y_T \frac{1}{M_T} Y_T^T \]
Why TeV Seesaws?

★ In Canonical Seesaw Mechanism with Singlet Fermion

★ The Light Neutrino mass formula

\[ m^I_\nu \simeq -m_D M_R^{-1} m_D = y_\nu v^2 / M_R \]

★ In order to be compatible with the neutrino oscillation data, i.e., \( |m_\nu| \simeq \sqrt{\Delta m^2_{\text{atm}}} = 0.0495 \text{ eV} \), one requires \( M_N \simeq 10^{14-15} \text{ GeV} \) taking the Yukawa couplings in their natural values i.e, \( \mathcal{O}(1) \).

★ Type-II Seesaw mechanism with Higgs scalar triplet

★ The Type II seesaw formula for light Neutrino mass \( m^{II}_\nu \simeq f v_L \), where \( v_L = \mu \Delta v^2 / M^2_\Delta \) is the VEV of triplet scalar.

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★ An obvious setting would be \( f \simeq \mathcal{O}(1) \) and \( \mu \sim M_\Delta \simeq 10^{14-15} \text{ GeV} \) in order to explain sub-eV scale of light neutrino masses

★ Although these seesaw mechanisms look promising while explaining neutrino oscillation data, they lack the direct experimental testability in the ongoing experiments like Large Hadron Collider (LHC) or any future experiment like International Linear Collider.

★ This motivates to think of TeV Scale Seesaw and other Low scale Seesaw Variants which can be probed at LHC
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Low scale Seesaw Variants and SM Extensions

Small $\nu$-masses can be generated from slight deviation from this complete “structural cancellation”, by deforming $M_D$ or $M_R$. (Within Type-I)

Kersten, Smirnov 07) + Bhupal and others.....

★ $\text{SM}(\nu) + \text{Additional singlet fermions (N,S)}$

\[
\begin{align*}
\text{Inverse Seesaw} & : & \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix} \\
\text{Linear Seesaw} & : & \begin{pmatrix} 0 & m_D & m_L \\ m_D^T & 0 & M \\ m_L & M^T & 0 \end{pmatrix}
\end{align*}
\]

★ Extended Inverse Seesaw

\[
\begin{align*}
\text{Extended Inverse Seesaw} & : & \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & M_R & M \\ 0 & M^T & \mu \end{pmatrix} \\
\text{Extended Linear Seesaw} & : & \begin{pmatrix} 0 & m_D & m_L \\ m_D^T & M_R & M \\ m_L & M^T & 0 \end{pmatrix}
\end{align*}
\]
Testability of Seesaw Variants

In Generic Inverse/Linear Seesaw Mechanism
[Mohapatra '86: Mohapatra. Valle '86]

Malinsky, Romao, Valle (2005)

\[ m_\nu \sim \left( \frac{m_D}{M} \right)^2 \mu; \text{ inverse or, } m_\nu \sim \left( \frac{m_D}{M} \right) m_L; \text{ Linear,} \]

While Heavy neutrinos form a pseudo-Dirac pair. Thus LNV effects from heavy neutrinos are suppressed.

In Extended Inverse/Linear Seesaw Mechanism

TeV scale \( M_N \) even with large \( M_D \sim m_t \) for \( \mu \sim \text{keV} \).

Smallness of \( \mu \) is natural in 't Hooft sense.

\[ m_{\text{int}} \sim \frac{M^2}{M_R}, \]
\[ m_{\text{heavy}} \sim M_R \]

LNV \( 0\nu\beta\beta \) parameter is given as

\[ \eta_\nu = \frac{1}{m_e} \left( \sum_{i=1}^{3} U_{ei}^2 m_i \right) \approx \frac{m_{ee}}{m_e}, \]
\[ \eta_N = -m_p \left( \sum_{i} U_{ei}^2 \frac{1}{m_i} + \sum_{i} U_{ei}^2 \frac{1}{m_i} \right) = -\frac{m_p}{m_e}. \]
Neutrinoless Double beta decay

Double beta decay can happen in two processes

\[(A,Z) \rightarrow (A,Z+2)+2e+2\nu-(2\nu\beta\beta)\]

\[(A,Z) \rightarrow (A,Z+2)+2e (0\nu\beta\beta)\]

While \((2\nu\beta\beta)\) is already observed,

Expts. Like GERDA, EXO, KAMLAND are designed to observe \((0\nu\beta\beta)\)

The \((0\nu\beta\beta)\) is sought for in special isotopes with even-even nuclei in which single beta decay is energetically forbidden.

Lepton Number Violation within Conformal Inv. Inverse Seesaw

Pascal, Manfred, SP, J. Smirnov

ArXiv:1505.07453 [hep-ph]
Lepton number violation:
Same like-sign dilepton events at hadron colliders, such as Tevatron (~2 TeV) and LHC (~14 TeV).

collider analogue to $0\nu\beta\beta$ decay

$N$ can be produced on resonance

dominant channel

See Martin Hirsch’s Talk for Citation credits therein.
Left-Right Theory and Sizable Effects

Mohapatra, Pati 74) Senjanovic 75)

Senjanovic, Keung, 1983; Tello et al.; Nemevsek et al.

(LNV at colliders: Deppisch)
Constraints from Lepton Flavor Violation

Rodejohann JHEP 1309
Adding diagrams

$d_R \rightarrow u_R$ \hspace{1cm} $d_L \rightarrow u_L$

$W_R \rightarrow e_R^-$ \hspace{1cm} $W \rightarrow e_L^-$

$N_{R,i} \rightarrow e_R^-$ \hspace{1cm} $U_{ei} \rightarrow q$

$m_{\text{lightest}} (\text{eV})$

$T_{1/2} (\text{yr})$

$IH$ \hspace{1cm} $NH$

$M_{W_R} = 3 \text{ TeV}$ \hspace{1cm} $M_{N_i} = 1 \text{ TeV}$
Neutrino Oscillation gives the phenomena of Lepton Flavor Violation. The contributions from light neutrinos are suppressed.

\[ \mu \rightarrow e + \gamma, \mu \rightarrow eee, \tau \rightarrow \mu ee, \mu \rightarrow e \]

Indicates new physics contributions currently running MEG experiment:

\[ \text{Br.}(\mu \rightarrow e + \gamma) < 5.7 \times 10^{-13} \]

MEG Collaboration

F. Deppisch, Gonzalo, SP, Sarkar, Sahu

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. Provides Large light-heavy neutrino mixing relevant for LHC, LFV and 0nbb process

. We have embedded the idea in SO(10) Model and Study gauge coupling unification and Collider Study.

Low Scale Seesaw Mechanism and their LNV, BNV, LFV and Collider Complementarity within GUT Models.

Parida, Awasthi, SP JHEP 1308 (2013) 122
Signal of WR gauge boson at LHC


LHC: recent data from CMS on dilepton + 2jets signal can be explained with 2.4 TeV right-handed charged gauge boson WR which arise in a D-parity violating leftright symmetric model.

TeV scale WR would imply B − L violation at the TeV scale (the first evidence for baryon or lepton number violation)
Stringent Dilepton Bounds on Left-Right Models using LHC data

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In canonical left-right symmetric models the lower mass bounds on the charged gauge bosons are in the ballpark of $3 - 4$ TeV, resulting into much stronger limits on the neutral gauge boson $Z_R$, making its production unreachable at the LHC. However, if one evokes different patterns of left-right symmetry breaking the $Z_R$ might be lighter than the $W_R^\pm$ motivating an independent $Z_R$ collider study. In this work, we use the 8 TeV ATLAS 20.3 fb$^{-1}$ luminosity data to derive robust bounds on the $Z_R$ mass using dilepton data. We find strong lower
SUMMARY

- Testable Seesaw Variants are important in the context of LNV, LFV and Collider complementarity study and operative at few TeV scale

- Low scale extended Inverse/Linear Seesaw is well connected to Neutrino Mass, Matter-antimatter asymmetry, keV Dark Matter, LNV, LFV effects and feasible at LHC

Possible extensions of the SM is expected to be detected at LHC, which includes Left-Right Models and Can give Sizable effects

- Whatever new physics we observe at LHC Run-II, will lead us to a new era in particle physics !!