Probing Lepton Number Violation in Double Beta Decay and at the LHC

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Overview

- Neutrinos
  - Oscillations
  - Absolute Mass

- Neutrinoless Double Beta Decay
  - Light Neutrino Exchange
  - New Physics Mechanisms

- Neutrino Mass Models
  - Effective Mass and Seesaw
  - Minimal Left-Right Symmetry

- LFV and LNV at the LHC

- Conclusion
Neutrino Oscillations

- Neutrino interaction states different from mass eigenstates
  Neutrino flavour can change through propagation

\[ \nu_i = \sum_\alpha U_{i\alpha} \nu_\alpha, \quad \nu_i(t) = e^{-i(E,t-p,x)} \nu_i \]
\[ \Rightarrow P_{\alpha \rightarrow \beta} = \sin^2(2 \theta) \sin^2 \left( 1.27 \frac{\Delta m^2}{eV^2} \frac{L}{km} \frac{E}{GeV} \right) \]

- Solar neutrino oscillations
  Large mixing

- Atmospheric oscillations
  \( \delta \) Maximal mixing

- Reactor and accelerator neutrinos

\[ \sin^2(2 \theta_{13}) = 0.092 \pm 0.021 \]

- Experimental unknowns and anomalies
  CP violation? Sign of \( \Delta m_{23} \)? Sterile Neutrinos?
Absolute Neutrino Mass

- **Energy endpoint in Beta decay**

  \[ m_{\beta}^2 = \sum_i |U_{ei}|^2 m_i^2 < (2.2 \text{eV})^2 \]

  Katrin: \( m_{\beta} \approx 0.2 \text{ eV} \)

- **Impact on Large Scale Structure**

  \[ \Sigma = \sum_i m_i < 0.4 - 1 \text{ eV} \]

- **Neutrinoless Double Beta Decay**

  \[ m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_{\nu_i} \right| < 0.2 - 2.0 \text{ eV} \]

  Future Experiments:
  \( m_{\beta\beta} \approx 0.01 \text{ eV} \)
Neutrinoless Double Beta Decay

**Process:** \((A, Z)^{23}_{11} \rightarrow (A, Z+2) + 2e^-\)

**Uncontroversial detection of 0νββ of utmost importance**
- Prove lepton number to be broken
- Prove neutrinos to be Majorana particles (Schechter, Valle '82)

**Which mechanism triggers the decay?**

- **Light Neutrino Exchange** (LH Current, Mass Mechanism)
  \[
  T_{1/2}^{-1} \propto \sum_i U_{ei}^2 m_{\nu_i}
  \]

- **General Effective Operator**
  \[
  \delta m_{\nu} \approx \frac{1}{(16\pi^2)^4} \frac{\text{MeV}^5}{M_W^4} \approx 10^{-23} \text{ eV}
  \]

\[
\begin{align*}
T_{1/2}^{-1} &\approx 10^{25} \text{ y} \\
M &\approx 1 \text{ TeV}
\end{align*}
\]
Light Neutrino Exchange

- **Standard Mass Mechanism**
- **Decay Rate**
  \[ \Gamma = T_{1/2}^{-1} = \frac{m_{\beta\beta}^2}{m_e^2} G^{0\nu} |M^{0\nu}|^2 \]
- **Effective Mass**
  \[ m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_{\nu_i} \right| \equiv (m_{\nu})_{ee} \]

Heidelberg-Moscow
\[ T_{1/2}^{76\text{Ge}} \approx 1.9 \times 10^{25} \text{y} \]
\[ \Delta m_{\nu} \approx 0.3 - 0.6 \text{eV} \]

Lindner, Merle, Rodejohann (2005)
Experimental Situation

\[ \langle m_{\beta\beta} \rangle \text{[meV]} \]

\[ m_{\text{lightest}} \text{[meV]} \]

Detwiler (2012)

KamLAND-Zen (arXiv:1211.3863)


Disfavored by $0\nu\beta\beta$

Normal

Inverted

Disfavored by cosmology:
New Physics Contributions to $0\nu\beta\beta$

**Plethora of New Physics Scenarios**

New Physics

\[ \Gamma = T_{1/2}^{-1} = e_{NP}^2 G^{0\nu}_NP \left| M^{0\nu}_{NP} \right|^2 \]

\[ T_{1/2} = \frac{1}{e_{NP}^2 G^{0\nu}_NP \left| M^{0\nu}_{NP} \right|^2} \]

- Left-Right Symmetry
- Extra Dimensions
- Majorons
- R-Parity Violating
- SUSY
- Leptoquarks

...
Effective Mass and Seesaw Mechanism

- **Effective operator for Majorana neutrino mass**

\[
L = \frac{1}{2} \frac{h_{ij}}{\Lambda_{\text{LNV}}} (\bar{L}^c_i \cdot \tilde{H}) (\tilde{H}^T \cdot L_j) \rightarrow \frac{1}{2} (m_\nu)_{ij} \bar{\nu}_i^c \nu_j
\]

Unique dim-5 Operator

- **Seesaw Mechanism**

Add right-handed neutrinos to the Standard Model particle content, \( M \approx \frac{5}{8} \times 10^{14} \text{ GeV} \)

\[
L = L_{\text{SM}} - \frac{1}{2} \bar{\nu}_R^c M \nu_R + \bar{\nu}_R Y_\nu L \cdot H_u
\]

- **Light neutrino mass matrix at low energies**

\[
m_\nu = m_D^T M^{-1} m_D \quad \text{for} \quad m_D \ll M_R \quad m_\nu \approx 0.1\text{eV} \left( \frac{m_D}{100 \text{ GeV}} \right)^2 \left( \frac{M}{10^{14} \text{ GeV}} \right)^{-1}
\]
Problems of Seesaw Mechanism

- Introduces high energy scale
- **Right-handed neutrinos are singlets**
  Couple only via small mixture with active neutrinos
- **Mechanism not testable with low energy observables**
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Possible Solutions

- **SUSY Seesaw**
  
  Testable LFV effects from sleptons
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Possible Solutions

- SUSY Seesaw
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- “Bent” Seesaw mechanisms
  LNV at low scale allows low mass of right-handed neutrinos
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Possible Solutions

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  Testable LFV effects from sleptons
- “Bent” Seesaw mechanisms
  LNV at low scale allows low mass of right-handed neutrinos
- Left-Right symmetric models
  Right-handed neutrinos couple with gauge strength to charged leptons
Based on

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

Pati & Salam '74
Mohapatra & Senjanovic '75

Higgs Sector:
Bidoublet (EW Breaking) + Left-handed Triplet + Right-handed Triplet (Breaking Lepton Number + Parity + SU(2)_R)

Generate \( N_i + W_R + Z_R \) masses

\[ M_{N_i} \approx M_{W_R} \approx M_{Z_R} \approx <\Delta_R> \approx 0.5 - 5 \text{ TeV} \]

General Seesaw II Mechanism

\[ M_\nu = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix}, \]

Neglect any Left-Right mixing

Charged current weak interactions

\[
\begin{align*}
J_{W_1}^{\mu} & = \frac{g_L}{\sqrt{2}} \left( \bar{\ell}_i U_{Li}^{LL} + \bar{N}_i U_{Li}^{LR} \right) \gamma^\mu \ell_L + \frac{g_R}{\sqrt{2}} \sin \zeta_W \left( \bar{\ell}_i U_{Li}^{RL} + \bar{N}_i U_{Li}^{RR} \right) \gamma^\mu \ell_R, \\
J_{W_2}^{\mu} & = -\frac{g_L}{\sqrt{2}} \sin \zeta_W \left( \bar{\ell}_i U_{Li}^{LL} + \bar{N}_i U_{Li}^{LR} \right) \gamma^\mu \ell_L + \frac{g_R}{\sqrt{2}} \left( \bar{N}_i U_{Li}^{RR} + \bar{\ell}_i U_{Li}^{RL} \right) \gamma^\mu \ell_R,
\end{align*}
\]

\[
\begin{align*}
J_{W_L}^{\mu} & \approx \frac{g_L}{\sqrt{2}} U_{ei} \bar{\nu}_i \gamma^\mu \ell_L, \\
J_{W_R}^{\mu} & \approx \frac{g_R}{\sqrt{2}} V_{ei} \bar{N}_i \gamma^\mu \ell_R,
\end{align*}
\]
Neutrinoless Double Beta Decay in the LRSM

\[ \sum_i (U_{ei}^{LL})^2 \frac{m_{\nu_i}}{m_e} = \langle m_{\nu} \rangle / m_e \]

\[ \left( \frac{M_{W_L}}{M_{W_R}} \right)^2 \sum_i U_{ei}^{LL} U_{ei}^{LR} \]

\[ \frac{M_{W_L}^4}{M_{W_R}^4} \frac{m_p}{M_{\Delta_R}^2} \sum_i (U_{ei}^{RR})^2 M_{N_i} \]

\[ \frac{M_{W_L}^4}{M_{W_R}^4} \sum_i \left( \frac{U_{ei}^{RR}}{M_{N_i}} \right)^2 \]

\[ \sin^2 \zeta \sum_i U_{ei}^{LL} U_{ei}^{LR} \]
Charged Lepton Flavour Violation

- Lepton flavour practically conserved in the Standard Model

\[
Br(\mu \to e \gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U^*_{\mu i} U_{e i} \frac{\Delta m^2_{1i}}{m_W^2} \right|^2 \approx 10^{-54}
\]

LFV is clear sign for BSM physics

- Flavour violation in quark and neutrino sector
  Strong case to look for charged LFV

- LFV can shed light on
  - Grand Unification models
  - Flavour symmetries
  - Origin of flavour
Rare LFV Processes

Mediated by right-handed neutrinos and doubly charged Higgs bosons

\[
\text{BR}(\mu \rightarrow e\gamma) \approx 2 \times 10^{-9} \sin^2(2\phi) \left( \frac{\Delta m_{12}^2}{m_{W_R}^2} \right)^2 \left( \frac{2 \text{ TeV}}{m_{W_R}} \right)^4 ,
\]

\(\mu\)-\(e\) conversion in nuclei enhanced via box diagrams

\[
R(\mu \rightarrow e) \approx \text{Br}(\mu \rightarrow e\gamma)
\]

\(\mu\rightarrow eee\) strongly enhanced due to tree level contribution

\[
\text{Br}(\mu \rightarrow eee) \approx 10^2 \times R(\mu \rightarrow e)
\]

BSM Flavour Problem
Small mixing and / or mass differences required
Right-handed Neutrino Production at the LHC

- Diagram showing the production of right-handed neutrinos at the LHC.
- Diagram illustrating the interaction of quarks and leptons with right-handed gauge bosons.
- Left-handed quark currents interacting with right-handed gauge bosons.
- Triangle diagrams depicting the production of a right-handed neutrino $N_i$.
- Quark-$W_R$ and lepton-$W_R$ interactions.

21/01/2013
Frank Deppisch
Probing LNV in DBD and at the LHC
Single Neutrino Production
Sensitivity Reach

- Monte Carlo Simulation (PROTOS)
- Background ttbar, Z + jets (Pythia, Alpgen)
- Fast Detector Simulation (AcerDET)
- Selection Criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of jets</td>
<td>$N_j \geq 2$</td>
</tr>
<tr>
<td>number of isolated leptons</td>
<td>$N_\ell = 2$</td>
</tr>
<tr>
<td>invariant dilepton mass</td>
<td>$m_{\ell\ell} &gt; 300$ GeV</td>
</tr>
<tr>
<td>total invariant mass</td>
<td>$m_{\ell\ell\ell\ell} &gt; 1.5$ TeV</td>
</tr>
</tbody>
</table>

ATLAS exclusion @ 2.1 fb$^{-1}$

Opposite Sign + Same Sign Leptons
LHC reach @ 14 TeV, 30 fb$^{-1}$
Single Neutrino Production
Sensitivity Reach

- **Reconstruction of** $W_R$ and $N$

  $$m_{W_R} = 2 \text{ TeV}$$

  $m_{W_R}$ vs $m_{ijl}$ [TeV]

  $$m_N = 0.5 \text{ TeV}$$

  $m_N$ vs $m_{ijl_2}$ [TeV]

  ATLAS exclusion @ 2.1 fb$^{-1}$

  Opposite Sign + Same Sign Leptons
  LHC reach @ 14 TeV, 30 fb$^{-1}$
Single Neutrino Production
General e-\(\mu\) Mixing

\[
\begin{pmatrix}
  l_{jL} & e_R & \mu_R & \tau_R \\
  U_{PMNS} & 0 & 0 & 0 \\
  0 & V_{Ne} & V_{N\mu} & 0 \\
  0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 \\
\end{pmatrix}
\]

\[ V_{Ne}^2 + V_{N\mu}^2 \leq 1 \]

\[ V_{Ne}^2 + V_{N\mu}^2 = 1 \]

\[ (V_{Ne}^2)_{min} = 0.5 \]

\[ m_W = 2.5 \text{ TeV}, m_N = 0.5 \text{ TeV} \]

LHC reach @ 14 TeV, 30 fb\(^{-1}\)
Two Neutrino Oscillations

Maximal Lepton Flavour Violation

- Two neutrinos exchanged with maximal mixing and 1% mass splitting

\[
U_{\text{PMNS}} = \begin{pmatrix}
0 & 0 & 0 \\
0 & \cos \phi & \sin \phi & 0 \\
0 & -\sin \phi & \cos \phi & 0 \\
0 & 0 & 0 & 0
\end{pmatrix}
\]

\[\phi = \pi / 4\]

- Correlation with low energy LFV processes

LHC reach @ 14 TeV, 30 fb\(^{-1}\)
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l_{jL} & e_R & \mu_R & \tau_R \\
0 & 0 & 0 & 0 \\
0 & \cos \phi & \sin \phi & 0 & N_1 \\
0 & -\sin \phi & \cos \phi & 0 & N_2 \\
0 & 0 & 0 & 0 & N_3
\end{pmatrix} \nu_i
\]

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Two Neutrino Oscillations
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- Correlation with low energy LFV processes

LHC reach @ 14 TeV, 30 fb\(^{-1}\)
Two Neutrino Oscillations
Mixing Angle and Mass Difference

- Two neutrinos exchanged with mixing angle $\phi$ and mass diff. $\Delta m_N$

$$l_{jL} = \begin{pmatrix} e_R & \mu_R & \tau_R \\ 0 & 0 & 0 \\ 0 & \cos \phi & \sin \phi \\ 0 & -\sin \phi & \cos \phi \\ 0 & 0 & 0 \end{pmatrix} U_{PMNS} \begin{pmatrix} \nu_i \\ N_1 \\ N_2 \\ N_3 \end{pmatrix}$$

suppressed as

$$\Delta m_N^2 / (m_N \Gamma_N)$$

- Correlation with low energy LFV processes

suppressed as

$$\Delta m_N^2 / m_{W_R}^2$$

- LHC reach @ 14 TeV, 30 fb$^{-1}$

$$m_{W_R} = 2.5 \text{ TeV}, m_N = 0.5 \text{ TeV}$$
Single Neutrino Production
Unitary $e-\mu-\tau$ Mixing

- Including coupling to taus

\[
U_{PMNS} = \begin{pmatrix}
l_j & e_R & \mu_R & \tau_R \\
0 & V_{Ne} & V_{N\mu} & V_{N\tau} \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\end{pmatrix}
\]

- Tau reconstruction efficiency reduced by

\[
Br(\tau \rightarrow e(\mu) \bar{\nu} \bar{\nu}) \approx 1/3
\]

- Highly boosted secondary leptons
- No cut on missing $p_T$
Consider contributions to $0\nu\beta\beta$ from triplet Higgs

$$\frac{M_{W_L}^4}{M_{W_R}^4} \frac{m_p}{M_{\Delta_r}^2} \sum_i (U_{ei}^{RR})^2 M_{N_i}$$

and heavy neutrinos

$$\frac{M_{W_L}^4}{M_{W_R}^4} \sum_i \frac{(U_{ei}^{RR})^2}{M_{N_i}}$$

LHC reach @ 14 TeV, 30 fb$^{-1}$
Conclusion

- Neutrinos much lighter than other fermions
  Strong experimental program to probe absolute mass
Conclusion

- **Neutrinos much lighter than other fermions**
  Strong experimental program to probe absolute mass

- **Neutrinos are the only neutral fermions**
  Dirac or Majorana? Lepton Number Violation?
Neutrinos much lighter than other fermions
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Neutrinos are the only neutral fermions
Dirac or Majorana? Lepton Number Violation?

$0\nu\beta\beta$ is crucial probe for BSM physics

- *Hope for the best*
  New LNV physics at the EW scale

- *Prepared for the worst*
  Only 5-dim operator from LNV at the GUT scale
Conclusion

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  Strong experimental program to probe absolute mass

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  - *Hope for the best*
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    Only 5-dim operator from LNV at the GUT scale

- Rich phenomenology in models of neutrino mass generation
  - Charged lepton flavour violation
  - LFV and LNV processes at the LHC
  - Connection to Leptogenesis?