Lepton Flavour and Number Violation in Models with Left-Right Symmetry

Frank Deppisch
f.deppisch@ucl.ac.uk

University College London

HEP Seminar, UCL
London, May 18, 2012
Overview

- Neutrinos
- Neutrino Mass Generation
  - Seesaw Mechanism
  - SUSY Seesaw
  - Left-Right Symmetry
- Lepton Flavour Violation
- Lepton Number Violation
- Signals at the LHC
- Conclusions
Neutrino Oscillations

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

\[ \nu_i = \sum_\alpha U_{i\alpha} \nu_\alpha, \quad \nu_i(t) = e^{-i(E_\nu t - p_x)} \nu_i \]

\[ \Rightarrow P_{\alpha \rightarrow \beta} = \sin^2 (2 \theta) \sin^2 \left( 1.27 \frac{\Delta m^2}{E_{\text{GeV}}^2} \frac{L}{\text{km}} \right) \]

- Solar neutrino oscillations
  Large mixing

- Atmospheric oscillations
  \( \approx \) Maximal mixing

- Reactor and accelerator neutrinos
  Antineutrino disappearance at Daya Bay (& Reno)

\[ \sin^2 (2 \theta_{13}) = 0.092 \pm 0.021 \]
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
  \[ \Sigma = \sum_i m_i < 0.4 \text{ -- } 1 \text{ eV} \]

- Neutrinoless Double Beta Decay
  \[ m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_{\nu_i} \right| < 0.2 \text{ -- } 2.0 \text{ eV} \]
  Future Experiments:
  \( m_{\beta\beta} \approx 0.01 \text{ eV} \)
Seesaw Mechanism

- Add right-handed neutrinos to (MS)SM particle content, $M_R \approx 10^{14}$ GeV

\[
W = W_{\text{MSSM}} - \frac{1}{2} \hat{\nu}_R^c M_R \hat{\nu}_R^c + \hat{\nu}_R^c Y \hat{L} \cdot \hat{H}_u
\]

- Integrate out heavy right-handed neutrinos

\[
\left( \begin{array}{c} \nu_L \\ \nu_R^c \\ m_D \\ m_D \\ M_R \end{array} \right) \left( \begin{array}{cc} 0 & m_D \\ m_D & M_R \end{array} \right) \left( \begin{array}{c} \nu_L \\ \nu_R^c \end{array} \right)^T
\quad \text{with} \quad m_D = Y \sqrt{\langle H_u^0 \rangle} \ll M_R
\]

- Effective light neutrino mass matrix at low energies

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

<table>
<thead>
<tr>
<th></th>
<th>Seesaw I</th>
<th>Seesaw II</th>
<th>Inverse Seesaw</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$(\nu_i, e_i^c, \nu_i^c)$</td>
<td>$(\nu_i, e_i^c, \nu_i^c)$</td>
<td>$(\nu_i, e_i^c, \nu_i^c, S_i)$</td>
</tr>
<tr>
<td></td>
<td>$(0 \ m_D^T )$</td>
<td>$(m_{LL} \ m_D^T )$</td>
<td>$(0 \ m_D^T \ 0)$</td>
</tr>
<tr>
<td></td>
<td>$(m_D \ M_R)$</td>
<td>$(m_D \ M_R)$</td>
<td>$(m_D \ 0 \ M_R^T)$</td>
</tr>
<tr>
<td></td>
<td>$m_D \ll M_R \Rightarrow$</td>
<td>$m_D \ll M_R \Rightarrow$</td>
<td>$\mu, m_D \ll M_R \Rightarrow$</td>
</tr>
<tr>
<td></td>
<td>$m_\nu = m_D^T M_R^{-1} m_D$</td>
<td>$m_\nu = m_{LL} - m_D^T M_R^{-1} m_D$</td>
<td>$m_\nu = m_D^T M_R^{T^{-1}} \mu M_R^{-1} m_D$</td>
</tr>
</tbody>
</table>

#### Diagrams

- **Seesaw I**
  - $\nu_L \rightarrow T \rightarrow \nu_R$
  - $e_L \rightarrow T \rightarrow \nu_R$

- **Seesaw II**
  - $\nu_L \rightarrow T \rightarrow \nu_R$
  - $e_L \rightarrow T \rightarrow \nu_R$

- **Inverse Seesaw**
  - $\nu_R \rightarrow T \rightarrow \nu_L$
  - $e_R \rightarrow T \rightarrow \nu_L$
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

Possible Solutions

- **SUSY Seesaw**
  Testable LFV effects on sleptons
- **Bended Seesaw mechanisms**
  LNV at low scale allows low mass right-handed neutrinos
- **Left-Right symmetry models**
  Right-handed neutrinos couple with gauge strength to charged leptons
Minimal Left-Right Symmetrical Model

Based on

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

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

Generating r.h. Neutrino + WR + ZR masses

\[ M_{N_i} \approx M_{W_R} \approx M_{Z_R} \approx <\Delta_R> \]

Charged current weak interactions

\[ J^\mu W = \frac{g_L}{\sqrt{2}} (\bar{\nu} U_{LL} + \bar{N}_c U_{LR}) \gamma^\mu e_L + \frac{g_R}{\sqrt{2}} \sin \zeta_W (\bar{\nu} U_{RL} + \bar{N}_U U_{RR}) \gamma^\mu e_R, \]

\[ J^\mu W' = -\frac{g_L}{\sqrt{2}} \sin \zeta_W (\bar{\nu} U_{LL} + \bar{N}_U U_{LR}) \gamma^\mu e_L + \frac{g_R}{\sqrt{2}} (\bar{N}_U U_{RR} + \bar{N}_U U_{RL}) \gamma^\mu e_R, \]

Pati & Salam '74  
Mohapatra & Senjanovic '75

Frank Deppisch  
LFV and LNV in LRSM  
18/05/2012
Charged Lepton Flavour Violation

- Lepton flavour practically conserved in the Standard Model

\[ Br(\mu \to e \gamma) = \frac{3 \alpha}{32 \pi} \left| \sum_i U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{m_W^2} \right|^2 \approx 10^{-56} \]

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

- **Current bounds**
  - \( \text{Br}(\mu \rightarrow e \gamma) < 2.4 \cdot 10^{-12} \) (MEG)
  - \( \text{Br}(\tau \rightarrow \mu \gamma) < 4.4 \cdot 10^{-8} \) (BaBar)
  - \( \text{Br}(\tau \rightarrow e \gamma) < 3.3 \cdot 10^{-8} \) (BaBar)
  - \( R(\mu N \rightarrow e N) < 7 \cdot 10^{-13} \) (Sindrum)
  - \( \mu \rightarrow 3e, \tau \rightarrow 3\mu \) (LHC?), etc.

- **Correlation between processes of same flavour transition**

![Graph showing correlation between processes](graph.png)
Rare LFV Processes in the LRSM

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

$$\text{BR}(\mu \rightarrow eee) \approx 300 \times R(\mu \rightarrow e)$$
Neutrinoless Double Beta Decay

- **Process:** \((A, Z) \rightarrow (A, Z+2) + 2e^-\)

- **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**
    \[
    \frac{\overline{u} u e e d}{M^5}
    \]

Heidelberg-Moscow
\[T_{1/2}^{\text{Ge}} \approx 1.9 \cdot 10^{25} \text{ y}\]
\[\langle m_{\nu} \rangle \approx (0.3 - 0.6) \text{ eV}\]
Neutrinoless Double Beta Decay in the LRSM

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

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

\[ \sin^2 \zeta \sum_i U_{ei}^{LL} U_{ei}^{LR} \]

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

\[ \frac{M_{W_L}^4}{M_{W_R}^4} M_{\Delta_R}^{-2} \sum_i (U_{ei}^{RR})^2 M_{N_i} \]
Dilepton signals at the LHC in the LRSM

(a) $W_R^\pm$ production

(b) $Z_R$ production
### Single Right-handed Neutrino Production

#### Opposite Sign + Same Sign Leptons

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

<table>
<thead>
<tr>
<th>Number of Jets</th>
<th>$N_j \geq 2$</th>
</tr>
</thead>
<tbody>
<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>$m_{\ell\ell jj} &gt; 1.5$ TeV</td>
</tr>
</tbody>
</table>

#### ATLAS Exclusion

<table>
<thead>
<tr>
<th>OS, SF</th>
<th>OS, OF</th>
<th>SS, OF</th>
<th>SS, SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^-$ $\mu^+\mu^-$</td>
<td>$e^+\mu^- e^-\mu^+$</td>
<td>$e^+\mu^+ e^-\mu^-$</td>
<td>$e^+e^+ e^-e^- \mu^+\mu^+ \mu^-\mu^-$</td>
</tr>
<tr>
<td>$t + \bar{t}$</td>
<td>190</td>
<td>170</td>
<td>$\lesssim 10$</td>
</tr>
<tr>
<td>$Z + j$</td>
<td>181</td>
<td>187</td>
<td>0</td>
</tr>
<tr>
<td>Signal</td>
<td>289</td>
<td>192</td>
<td>228</td>
</tr>
<tr>
<td>Eff. [%]</td>
<td>51</td>
<td>33</td>
<td>42</td>
</tr>
</tbody>
</table>

ATLAS exclusion @ 2.1 fb$^{-1}$
Lepton Flavour Violation

- Single r.h. Neutrino Exchange
- Maximal mixing of r.h. neutrino to e and \( \mu \) only

LHC reach @ 14 TeV, 30 fb\(^{-1}\)
Sensitivity to lepton mixing couplings

LHC reach @ 14 TeV, 30 fb⁻¹

\[ M_{W_s} = 2.5 \text{ TeV}, \quad M_N = 0.5 \text{ TeV} \]
Two Neutrino Exchange

- Two neutrinos exchanged with maximal mixing and 1% mass splitting
- Correlation with low energy LFV processes

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

- Two neutrinos exchanged with maximal mixing and 1% mass splitting
- Correlation with low energy LFV processes

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

- Two neutrinos exchanged with maximal mixing and 1% mass splitting
- Correlation with low energy LFV processes

LHC reach @ 14 TeV, 30 fb⁻¹
Two Neutrino Exchange

- Two neutrinos exchanged with maximal mixing and 1% mass splitting
- Correlation with low energy LFV processes
- Low energy LFV processes GIM suppressed as
  \[ \frac{\Delta m_N^2}{m_W^2} \]
- On-shell production suppressed as
  \[ \frac{\Delta m_N^2}{m_N \Gamma_N} \]
Lepton Number Violation

- Correlation with neutrinoless double beta decay
- Contributions from triplet Higgs and heavy neutrinos

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

- Neutrinos much lighter than other fermions
  Strong experimental program to probe absolute mass
  Mechanism of mass generation?
  What about charged lepton flavour violation?

- High Energy Seesaw Mechanism not testable
  Consider alternatives with lower masses and stronger couplings?

- Seesaw Mechanism in Left-Right Symmetry Models
  Strong interplay with low energy LFV and LNV processes

- LHC still has chance to probe individual flavour couplings
Including couplings to taus

<table>
<thead>
<tr>
<th>( \ell ) ( \ell' )</th>
<th>e</th>
<th>( \mu )</th>
<th>( \tau )</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>0.555</td>
<td>0.501</td>
<td>0.175</td>
</tr>
<tr>
<td>( \mu )</td>
<td>0.524</td>
<td>0.480</td>
<td>0.172</td>
</tr>
<tr>
<td>( \tau )</td>
<td>0.203</td>
<td>0.192</td>
<td>0.058</td>
</tr>
</tbody>
</table>

- \( M_W = 1.5 \text{ TeV} \)
- \( m_N = 0.8 \text{ TeV} \)
- LHC 5 fb\(^{-1}\)
- LHC 2.1 fb\(^{-1}\)