Probing Lepton Number Violation on Three Frontiers

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Overview

- Neutrinos
  - Oscillations
  - Absolute Mass

- Neutrinoless Double Beta Decay
  - Light Neutrino Exchange
  - New Physics Mechanisms
  - In Combination with Cosmology

- 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

\[
\nu_i = \sum_{\alpha} U_{i\alpha} \nu_\alpha, \quad \nu_i(t) = e^{-i(E_i t - p_i x)} \nu_i
\]

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

- Solar neutrino oscillations
  Large mixing

- Atmospheric oscillations
  \( \approx \) 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**
  \[ \Sigma = \sum_i m_i < 0.3 - 1 \text{ eV} \]

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

Two possibilities to define mass

Dirac mass, analogous to other fermions (but with tiny coupling to Higgs)

Majorana mass, using only a left-handed neutrino → Lepton Number Violation

Detwiler '12
Dirac vs Majorana

Two possibilities to define mass

**Dirac mass**, analogous to other fermions (but with tiny coupling to Higgs)

**Majorana mass**, using only a left-handed neutrino → Lepton Number Violation

9 out of 10 theorists recommend Majorana neutrinos
Neutrinoless Double Beta Decay

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

- **Uncontroversial detection of** \(0\nu\beta\beta\)
  - 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)

\[
T_{1/2}^{-1} \propto \left| \sum_i U_{ei}^2 m_{\nu_i} \right|
\]

**General Effective Operator**

\[
\frac{\delta m_\nu}{(16 \pi^2)^4} \frac{M^4_w}{M^4} \approx 10^{-23} \text{ eV}
\]

\[
\frac{1}{10^{25}} y \rightarrow M \approx 1 \text{ TeV}
\]

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Probing LNV on Three Frontiers
22/05/2013
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**

\[ m_{\beta \beta} = \left| \sum_i U_{ei}^2 m_{\nu_i} \right| \equiv (m_{\nu})_{ee} \]
Nuclear Matrix Elements

- **Decay Rate**
  \[
  \Gamma = T_{1/2}^{-1} = \frac{m_{\beta\beta}^2}{m_e^2} G^{0\nu} |M^{0\nu}|^2
  \]

- Requires calculation of matrix element of the nuclear transition via intermediate state

- Many-body problem not solvable from first principle

- Factor 2 – 3 uncertainty between different nuclear models
  - Shell Models
  - QRPA
  - IBM

- Important to search for $0\nu\beta\beta$ in several isotopes

Kay (2011)
Rodejohann (2012)
Experimental Situation

Disfavored by $0\nu\beta\beta$


Disfavored by cosmology.

$\langle m_{\beta\beta} \rangle$ [meV] vs $m_{\text{lightest}}$ [meV]

Detwiler (2012)

KamLAND-Zen
(arXiv:1211.3863)

$T_{1/2}$ $^{76}\text{Ge}$ (yr)

$T_{1/2}$ $^{136}\text{Xe}$ (yr)

KamLAND-Zen
90\% C.L.

Combined

90\% C.L.
**Effective 0νββ Observable**

\[
m_{\beta\beta} \equiv (m_\nu)_{ee} = \sum_i U_{ei}^2 m_\nu_i = |m_{\nu_1} V_{e1}|^2 + m_{\nu_2} |V_{e2}|^2 e^{2i\phi_{12}} + m_{\nu_3} |V_{e3}|^2 e^{2i\phi_{23}}
\]

\[
\approx m_1 \sqrt{1 - \sin^2(2\theta_{12}) \sin^2(\phi_{12})}
\]

quasi-deg. neutrinos

**Interplay of mass probes**

Simulation of observables incl. NME and expected exp. uncertainties with

\[m_{\nu_1} = 0.25 \text{ eV}, \phi_{12} = \pi/2\]
Combining $0\nu\beta\beta$ and Cosmology
J. Auger, FFD, O. Lahav, I. Sadeh, D. Waters, Work in Progress

Preliminary
New Physics Contributions to $0\nu\beta\beta$

- **Plethora of New Physics Scenarios**

\[
\Gamma = T_{1/2}^{-1} = e_{NP}^2 G_{NP}^{0\nu} |M_{NP}^{0\nu}|^2
\]

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

...
Disentangling New Physics Scenarios

- **Angular and Energy distribution of emitted electrons**
  (Doi et al. '83; Ali et al. '06; Arnold et al. '10; FFD, Jackson, Nasteva, Söldner-Rembold '10)

\[
\frac{d \Gamma}{d E_1 d E_2 d \cos \theta} = \frac{\Gamma}{2} (1 - k(E_1, E_2) \cos \theta) \quad -1 < k < 1
\]

- Linear in \( \cos \theta \)
- \( k(E_1, E_2) \) depends on 0\(\nu\)\(\beta\beta \) mechanism

- **Comparison of 0\(\nu\)\(\beta\beta \) in multiple isotopes**
  (FFD, Päs PRL 2007)

\[
\frac{T_{1/2}(^AX)}{T_{1/2}(^BY)} = \frac{G(^BY)M(^BY)^2}{G(^AX)M(^AX)^2}
\]

- Depends on 0\(\nu\)\(\beta\beta \) mechanism
- Independent of details of new physics (if one mechanism dominates)
Effective Mass and Seesaw Mechanism

- Effective operator for Majorana neutrino mass

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

- Seesaw Mechanism

Add right-handed neutrinos to the Standard Model particle content, $M \approx 10^{14}$ GeV

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

- Light neutrino mass matrix at low energies

$$m_\nu = m_D^T M^{-1} m_D \quad \text{for} \quad m_D \ll M$$

$$m_\nu \approx 0.1 \text{eV} \left( \frac{m_D}{100 \text{ GeV}} \right)^2 \left( \frac{M}{10^{14} \text{ GeV}} \right)^{-1}$$
Effective Mass and Seesaw Mechanism

**Effective operator for Majorana neutrino mass**

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

**Seesaw Mechanism**

**Sterile Neutrino Mass Scale Unknown**

- \(\approx 10^{14}\) GeV: Naive Seesaw, GUTs
- \(>10^9\) GeV: Thermal Leptogenesis
- \(\approx 10^2\) GeV: Resonant Leptogenesis, Production at LHC
- \(\approx 1\) keV: Dark Matter Candidate
- \(\approx 1\) eV: Oscillation, Cosmology, (Double) Beta Decay
Effective Mass and Seesaw Mechanism

**Effective operator for Majorana neutrino mass**

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

**Seesaw Mechanism**

**Three possible mediators at tree level**

Seesaw II
Effective Mass and Seesaw Mechanism

- Effective operator for Majorana neutrino mass

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

- Seesaw Mechanism

- Three possible mediators at tree level

Seesaw III
Effective Mass and Loops

**Effective operator for Majorana neutrino mass**

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

**Radiative Generation via Loops**

Alternative to Seesaw Mechanism

R-Parity Violating SUSY
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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- **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

- **SUSY Seesaw**
  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
**Minimal Left-Right Symmetrical Model**

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

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

- **Charged current weak interactions**
  \[ J_{W_1}^{\mu -} = \frac{g_L}{\sqrt{2}} \left( \bar{\nu}_i U_{L_i}^{LL} + \bar{N}_i U_{L_i}^{LR} \right) \gamma^\mu \ell_L + \frac{g_R}{\sqrt{2}} \sin \theta_W \left( \bar{\nu}_i U_{L_i}^{RL} + \bar{N}_i U_{L_i}^{RR} \right) \gamma^\mu \ell_R, \]
  \[ J_{W_2}^{\mu -} = -\frac{g_L}{\sqrt{2}} \sin \theta_W \left( \bar{\nu}_i U_{L_i}^{LL} + \bar{N}_i U_{L_i}^{LR} \right) \gamma^\mu \ell_L + \frac{g_R}{\sqrt{2}} \left( \bar{N}_i U_{L_i}^{RR} + \bar{\nu}_i U_{L_i}^{RL} \right) \gamma^\mu \ell_R, \]

- **Neglect any Left-Right mixing**
  \[ J_{W_L}^{\mu -} \approx \frac{g_L}{\sqrt{2}} U_{ei} \bar{\nu}_i \gamma^\mu \ell_L, \]
  \[ J_{W_R}^{\mu -} \approx \frac{g_R}{\sqrt{2}} V_{ei} \bar{N}_i \gamma^\mu \ell_R, \]

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**Pati & Salam '74**
**Mohapatra & Senjanovic '75**
Neutrinoless Double Beta Decay in the LRSM

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

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

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

\[
\frac{M_{W_L}^4}{M_{W_R}^4} \frac{m_p}{M^2_{\Delta R}} \sum_i (U_{ei}^{RR})^2 M_{N_i}
\]
Right-handed Neutrino Production at the LHC
Single Neutrino Production

Monte Carlo Simulation (PROTOS)

Background $t\bar{t}$, $Z$ + jets
(Pythia, Alpgen)

Fast Detector Simulation
(AcerDET)

Selection Criteria

- number of jets $N_j \geq 2$
- number of isolated leptons $N_\ell = 2$
- invariant dilepton mass $m_\ell \ell > 300$ GeV
- total invariant mass $m_{\ell\ell jj} > 1.5$ TeV

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

Opposite Sign + Same Sign Leptons
LHC reach @ 14 TeV, 30 fb$^{-1}$
Consider contributions to $0\nu\beta\beta$ from triplet Higgs

$$\frac{M^4_{W_L}}{M^4_{W_R}} \frac{m_p}{M^2_{\Delta^-}} \sum_i (U^R_{ei})^2 M_{N_i}$$

and heavy neutrinos

$$\frac{M^4_{W_L}}{M^4_{W_R}} \sum_i \frac{(U^R_{ei})^2}{M_{N_i}}$$

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

- Neutrinos much lighter than other fermions
  Strong experimental program to probe absolute mass
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- $0\nu\beta\beta$ 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

![Graph](Lefeuvre_2011)
Conclusion

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

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

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Lefeuvre (2011)