Lepton number violation: from neutrinoless double beta decay to the LHC

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1. Present status of neutrino physics and the discovery of $\theta_{13}$

2. Lepton number violation

3. Neutrinoless double beta decay

4. LNV in rare decays and the LHC

5. Linking LNV signatures with neutrino masses

6. Conclusions
Present status of (standard) neutrino physics

\[ \Delta m_s^2 \ll \Delta m_A^2 \] implies at least 3 massive neutrinos.

\[
\begin{align*}
m_1 &= m_{\text{min}} \\
m_2 &= \sqrt{m_{\text{min}}^2 + \Delta m_{\text{sol}}^2} \\
m_3 &= \sqrt{m_{\text{min}}^2 + \Delta m_A^2}
\end{align*}
\]

Measuring the masses requires: \( m_{\text{min}} \) and the ordering.
Mixing is described by the Pontecorvo-Maki-Nakagawa-Sakata matrix,

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} \sum_{k\alpha} (U_{\alpha k}^* \bar{\nu}_k L \gamma^\rho l_\alpha L W_\rho + \text{h.c.})$$

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}_{\text{Solar, reactor } \theta_\odot \sim 30^\circ}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}_{\text{Atm, Acc. } \theta_A \sim 45^\circ}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & e^{-i\delta} & 1 \end{pmatrix}_{\text{CPV phase}}$$

$$= \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}_{\text{Reactor, Acc. } \theta < 12^\circ}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{-i\alpha_{31}/2+i\delta} \end{pmatrix}_{\text{CPV Majorana phases}}$$

If $U \neq U^*$, there is leptonic CP-violation

$$P(\nu_l \rightarrow \nu_{l'}) \neq P(\bar{\nu}_l \rightarrow \bar{\nu}_{l'})$$

CP-conservation requires $U$ is real $\Rightarrow \delta = 0, \pi$
Up to 2011, oscillation experiments had measured with good precision 2 mass squared-differences and 2 mixing angle. The third one was constrained to be small but only hints of a nonzero value could be found.

- **MINOS** looked for appearance by distinguishing NC from e-like events. The 2011 results provided a 1.7 sigma hint of nonzero $\theta_{13}$. 

**MINOS Coll, 1108.0015**
T2K first data in May 2011. It observed 6 events with a background of 1.5:

$$\sin^2 2\theta_{13} |_{BF} = 0.11$$

T2K event in 2011, PRL 107 (2011)
Since April 2011: stable data taking.

First Results from DChooz (9/11/11)

$$\sin^2 2\theta_{13} = 0.085 \pm 0.051$$

Started data taking in April.

Daya Bay: reactor neutrino experiment in China, Courtesy of Roy Kaltschmidt

Expected Sensitivity
0.36% systematic error (relative)
5 years, \( \sin^2(2\theta_{13}) < 0.01 \) (90% C.L.)

Two near detector data taking
In 2012, previous hints (DoubleCHOOZ, T2K, MINOS) for a nonzero third mixing angle were confirmed by Daya Bay and RENO: important discovery.

**Daya Bay, PRL 108 (2012)**

**Observed:** 9901 neutrinos at far site,
**Prediction:** 10530 neutrinos if no oscillation

\[ R = 0.940 \pm 0.011 \text{(stat)} \pm 0.004 \text{(syst)} \]

\[ \sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005 \]

**RENO, PRL 108 (2012)**

Y. Wang, March 2012
All oscillation parameters are measured with good precision, except for the mass hierarchy and the delta phase.
Phenomenology questions for the future

- What is the nature of neutrinos (Majorana vs Dirac)?
- What are the values of the masses?
- Is there CP-violation? What are the values of mixing angles (tribimaximal mixing?)?
- Is the standard picture correct?

A wide experimental programme is under way or at the proposal stage. Other relevant searches are: solar (Borexino), atmospheric (megaton-scale detector, INO), supernova neutrinos, SBL exp for sterile neutrino searches.
Neutrinos can be **Majorana** or **Dirac** particles. In the SM only neutrinos can be Majorana because they are **neutral**.

**Majorana** particles are indistinguishable from antiparticles.

**Dirac** neutrinos are labelled by the **lepton number**.

The **nature** of neutrinos is linked to the conservation of the **Lepton number (L)**. This information is crucial in understanding the **Physics BSM: with or without L-conservation?**
Lepton number is a symmetry of the SM.

• Its conservation is crucial information to understand the **Physics BSM: with or without L-conservation?**

• Lepton number violation is a necessary condition for **Leptogenesis**.

**Can we test lepton number violation?**

• At low energy, **neutrinoless double beta decay**

• LNV tau and meson decays

• LNV at colliders
Neutrinoless double beta decay, \((A, Z) \rightarrow (A, Z+2) + 2\ e\), will test the nature of neutrinos. It violates \(L\) by 2 units.

The half-life time depends on neutrino properties:

\[
\left[ T_{0\nu}^{1/2}(0^+ \rightarrow 0^+) \right]^{-1} \propto |M_F - g_A^2 M_{GT}|^2 |<m>|^2
\]

\[
|m| \equiv |m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{i\alpha_{21}} + m_3|U_{e3}|^2 e^{i\alpha_{31}}|
\]

Mixing angles (mostly known)\n\nCPV phases (unknown)
Predictions for betabeta decay

The predictions for $|<m>|$ depend on the neutrino mass spectrum

- **NH** $(m_1 \ll m_2 \ll m_3)$: $|<m>| \sim 2.5\text{--}3.9 \text{ meV}$
  \[ |<m>| \simeq \sqrt{\Delta m^2_{\odot}} \cos^2 \theta_{13} \sin^2 \theta_{13} + \sqrt{\Delta m^2_{\text{atm}}} \sin^2 \theta_{13} e^{i \alpha_{32}} \]

- **IH** $(m_3 \ll m_1 \sim m_2)$: $10 \text{ meV} < |<m>| < 50 \text{ meV}$
  \[ \sqrt{\Delta m^2_{\text{atm}}} \cos 2\theta_{\odot} \leq |<m>| \simeq \sqrt{\left(1 - \sin^2 2\theta_{\odot} \sin^2 \frac{\alpha_{21}}{2}\right) \Delta m^2_{\text{atm}}} \leq \sqrt{\Delta m^2_{\text{atm}}} \]

- **QD** $(m_1 \sim m_2 \sim m_3)$: $44 \text{ meV} < |<m>| < m_1$
  \[ |<m>| \simeq m_{\nu_e} \left| \left( \cos^2 \theta_{\odot} + \sin^2 \theta_{\odot} e^{i \alpha_{21}} \right) \cos^2 \theta_{13} + \sin^2 \theta_{13} e^{i \alpha_{31}} \right| \]
\[ |\langle m \rangle| \sim |m_1 \cos^2 \theta_{12} + m_2 \sin^2 \theta_{12} e^{i\alpha_{21}} + m_3 \sin^2 \theta_{13} e^{i\alpha_{31}}| \]

Wide experimental program for the future: a positive signal would indicate that L is violated!

SP from Nakamura, Petcov review in PDG
Dependence on the oscillation parameters

- \( \sin^2 2\theta_{13} = 0.039 \)

\( \cos 2\theta_{12} \) controls this term:
\[ |\langle m \rangle|_{\text{min}} = \sqrt{\Delta m^2_{31}} \cos 2\theta_{12} \]

- \( \theta_{13} \) determines the cancellation in the NH spectrum and consequently the minimal value of \( |\langle m \rangle| \).
Determining neutrino masses with neutrinoless double beta decay

If $|<m>| > 0.2$ eV, then the neutrino spectrum is QD. The measurement of $m_1$ is entangled with the value of the Majorana phase.
• If no signal down to $|<m>| \sim 10$ meV, then only normal ordering is allowed.
• If LBL experiments find inverted ordering, this would imply that neutrinos are Dirac particles (without fine-tuned cancellations).
Other mechanisms

Neutrinoless double beta decay can also be mediated by other LNV mechanisms.

- Light sterile neutrinos
- Heavy sterile neutrinos
- R-parity violating SUSY
- Extra dimensional models
- Left-Right models
In most cases they are subdominant as the NME for heavy particles suppress their contribution w.r.t. the long range processes.

\[ m_i^2 \ll p^2 \]

\[ M_i^2 \gg p^2 \]

The NME behaviour changes at \( p \sim 100 \, \text{MeV} \), the scale of the process.
Experimental searches of betabeta decay

Neutrinoless double beta decay, \((A, Z) \rightarrow (A, Z+2) + 2 e\), proceeds in nuclei in which single beta decay is kinematically forbidden but double beta decay \((A, Z) \rightarrow (A, Z+2) + 2 e + 2 \nu\) is allowed.

B. Schwingenheuer, Annalen der Physik, 2012

Depending on treatment of background, from 4.2 to 1.3 sigma
Thanks to Schoenert, EPS-HEP11

B. Schwingenheuer, Annalen der Physik, 2012

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**Table 3 Selection of $0\nu\beta\beta$ experiments.**

<table>
<thead>
<tr>
<th>experiment</th>
<th>isotope</th>
<th>mass [kg]</th>
<th>method</th>
<th>start / end</th>
</tr>
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<tbody>
<tr>
<td>past experiments</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heidelberg-Moscow</td>
<td>$^{76}\text{Ge}$</td>
<td>11</td>
<td>ionization</td>
<td>-2003</td>
</tr>
<tr>
<td>Cuoricino</td>
<td>$^{130}\text{Te}$</td>
<td>11</td>
<td>bolometer</td>
<td>-2008</td>
</tr>
<tr>
<td>NEMO-3</td>
<td>$^{100}\text{Mo}$, $^{82}\text{Se}$</td>
<td>7.1</td>
<td>track. + calorim.</td>
<td>-2011</td>
</tr>
<tr>
<td>current experiments</td>
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<td></td>
</tr>
<tr>
<td>EXO-200</td>
<td>$^{136}\text{Xe}$</td>
<td>175</td>
<td>liquid TPC</td>
<td>2011-</td>
</tr>
<tr>
<td>KamLAND-Zen</td>
<td>$^{136}\text{Xe}$</td>
<td>330</td>
<td>liquid scintil.</td>
<td>2011-</td>
</tr>
<tr>
<td>GERDA-I/GERDA-II</td>
<td>$^{76}\text{Ge}$</td>
<td>15/35</td>
<td>ionization</td>
<td>2011-/2013-</td>
</tr>
<tr>
<td>CANDLES</td>
<td>$^{48}\text{Ca}$</td>
<td>0.35</td>
<td>scint. crystal</td>
<td>2011-</td>
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<td>funded experiments</td>
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<tr>
<td>NEXT</td>
<td>$^{136}\text{Xe}$</td>
<td>100</td>
<td>gas TPC</td>
<td>2015</td>
</tr>
<tr>
<td>CUORE0/CUORE</td>
<td>$^{130}\text{Te}$</td>
<td>10/200</td>
<td>bolometer</td>
<td>2012-2015-</td>
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<tr>
<td>Majorana Demo.</td>
<td>$^{76}\text{Ge}$</td>
<td>30</td>
<td>ionization</td>
<td>2013</td>
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<tr>
<td>SuperNEMO demo/total</td>
<td>$^{82}\text{Se}$</td>
<td>7/100</td>
<td>track. + calorim.</td>
<td>2014-??</td>
</tr>
<tr>
<td>SNO+</td>
<td>$^{150}\text{Nd}$</td>
<td>44</td>
<td>liquid scint.</td>
<td>2013</td>
</tr>
</tbody>
</table>
GERDA. On Jul 6, 5 Ge diodes deployed at LNGS.

KamLAND-Zen: strong backgrounds.

$T^{0\nu}_{1/2} > 6.2 \times 10^{24}$ years (KL-Zen 112 days)

The new generation of experiments is already taking data or nearly ready (e.g., EXO, KamLAND-ZEN, CUORE, GERDA,...) and more powerful ones are planned for the future (e.g., NExT, SNO+, SuperNEMO, COBRA,...)!!
Majorana masses break LN by two units.

- In the SM plus Majorana neutrinos, LNV effects will be controlled by light neutrino masses.

- LNV effects arise in presence of sterile neutrinos (the simplest extension of the SM) which mix with the active ones and have a Majorana mass (LNV!).

\[
\begin{align*}
|\nu_1\rangle &= \cos \theta |\nu_e\rangle - \sin \theta |\nu_s\rangle \\
|N_2\rangle &= \sin \theta |\nu_e\rangle + \cos \theta |\nu_s\rangle
\end{align*}
\]

More in general, one has

\[
\nu_{aL} = \sum_{m=1}^{3} U_{am} \nu_{mL} + \sum_{m'=4}^{n} V_{am'} N_{m'L}^c
\]
Current constraints on the mixing angles.
Rare tau and meson decays

Tau and Meson decays get resonantly enhanced for $M \sim \text{GeV}$.
LNV at colliders

LNV shows up as a same-sign dilepton signal with no missing energy.

- **LNV effects** due to active neutrinos will depend on m1, m2, m3. Completely **negligible in colliders**.

- But can be relevant if sterile neutrinos are present. They are **produced** and then they can **decay into SM particles**, due to mixing.
Even for very small mixing, the decay length is very small.

As the mass increases, more channels become kinematically available.

If the decay length ~ few m, one could search for displaced vertices.

Atre et al., 0901.3589
In colliders, the dominant mechanism due to mixing is

\[ \sigma(pp \rightarrow \ell\ell W) \approx \sigma(pp \rightarrow \ell N) Br(N \rightarrow \ell W) \sim |V_{\ell 4}|^2 \sigma_0 \]

where N goes on resonance and the cross section for the process can be approximated as.

Searches will be controlled by \textbf{production} which depends on the mixing.
Sensitivity reachable at Tevatron

\[ S_{\mu,\mu} \]

\[ m_4 \text{ (GeV)} \]

Atre et al., 0901.3589
Luminosity: 100 fb$^{-1}$. Atre et al., 0901.3589
Luminosity: ATLAS 34 pb⁻¹  
CMS 35 pb⁻¹  

Searches have resulted in no positive signal so far. LHCb has searched for di-muon decays of B, improving bounds by 30-40, PRL 108 and PRD.
LNV and neutrino masses

Majorana masses violate lepton number and conversely lepton number violation leads to Majorana masses.

See-saw Type I

Fermion singlet

Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

See-saw Type II

Scalar triplet

Magg, Wetterich, Lazarides, Shafi, Mohapatra, Senjanovic, Schecter, Valle

See-saw Type III

Fermion triplet

Ma, Roy, Senjanovic, Hambye

Lepton number violation!
The see saw mechanism: type I, LNV at the LHC and neutrino masses

- Introduce a right handed neutrino $N$ (sterile neutrino)
- Couple it to the Higgs and left handed neutrinos

For smaller coupling, $M$ can be at the electroweak scale.

The Lagrangian is

$$\mathcal{L} = -Y_{\nu} \bar{N} L \cdot H - \frac{1}{2} \bar{N} c M_R N$$

First studies in colliders by Almeida et al.; Ali, Borisov, Zamorin.
In general we expect mixing to be very small:

- Without cancellations, there is a contribution to neutrino masses:

\[ m_\nu \approx \frac{m_D^2}{M} \approx \sin^2 \theta M \]

- **Production is extremely suppressed**

In see-saw type I, all LNV effects are suppressed at colliders. Other production mechanisms need to be considered.

Kersten, Smirnov; Ibarra, Molinaro, Petcov
Sufficient N production can be achieved if Ns have additional interactions. With 3 N, B-L can be gauged and N can be produced via Z'. Other models include: triplet see-saw, loop models, see-saw type II...

Fileviez-Perez, Han, Li, 0907.4186

Li, He, 0907.4193
The see saw mechanism: type I, neutrinoless double beta decay and neutrino masses

LNV will generate neutrino masses, induce neutrinoless double beta decay and, if the TeV scale, could have signatures at the LHC.

The effects due to neutrino masses typically dominate due to the NME, see models discussed before.

This is not the case if neutrino masses are suppressed. In inverse see-saw and extended see-saw models, two sterile neutrinos are introduced.

\[ \mathcal{L} = Y \bar{L} \cdot H N_1 + Y_2 \bar{L} \cdot H N_2^c + \Lambda \bar{N}_1 N_2 + \mu' N_1^T C N_1 + \mu N_2^T C N_2 \]
Depending on the assignment one can have different lepton numbers:

\[
\begin{pmatrix}
0 & Y_\nu & Y_{2\nu} \\
Y_\nu & \mu' & \Lambda \\
Y_{2\nu} & \Lambda & \mu
\end{pmatrix}
\]

\(N_1=1, N_2=1:\)

\[
\begin{pmatrix}
0 & Y_\nu & Y_{2\nu} \\
Y_\nu & \mu' & \Lambda \\
Y_{2\nu} & \Lambda & \mu
\end{pmatrix}
\]

\(N_1=0, N_2=-1:\)

\[
\begin{pmatrix}
0 & Y_\nu & Y_{2\nu} \\
Y_\nu & \mu' & \Lambda \\
Y_{2\nu} & \Lambda & \mu
\end{pmatrix}
\]

\(N_1=1, N_2=0:\)

\[
\begin{pmatrix}
0 & Y_\nu & Y_{2\nu} \\
Y_\nu & \mu' & \Lambda \\
Y_{2\nu} & \Lambda & \mu
\end{pmatrix}
\]

\(N_1=0, N_2=0:\)

\[
\begin{pmatrix}
0 & Y_\nu & Y_{2\nu} \\
Y_\nu & \mu' & \Lambda \\
Y_{2\nu} & \Lambda & \mu
\end{pmatrix}
\]
This implies that neutrino masses require

- \( Y v, \mu' \) (= standard see-saw plus light sterile neutrino)
- \( Y v, \Lambda, \mu, \) and/or \( Y_2 v \) and/or \( \mu' \)

\[
m_{\text{tree}} \approx -m_D^T M^{-1} m_D \approx \frac{v^2}{2(\Lambda^2 - \mu' \mu)} \left( \mu Y_1^T Y_1 + \mu' Y_2^T Y_2 - \Lambda (Y_2^T Y_1 + Y_1^T Y_2) \right)
\]

Small neutrino masses associated to small breaking of L.

Two limits:

- **Inverse see-saw:** \( \Lambda \gg \mu, Y_2 v, \mu' \)

Two quasi-Dirac neutrinos with large mixing

\[
m_4 \approx -m_5 \approx \bar{M}_1 \approx -\bar{M}_2 \approx \Lambda, \quad U_{e4} \approx U_{e5} \approx \frac{Y_{1e} v}{2\Lambda},
\]

\[
\Delta \tilde{M} \equiv |\tilde{M}_2| - |\tilde{M}_1| \approx \mu',
\]

- **Extended see-saw:** \( \mu' \gg \Lambda, \mu \)

\[
m_4 \approx \bar{M}_1 \approx -\Lambda^2/\mu', \quad U_{e4} \approx \frac{Y_{1e} v}{\sqrt{2}\Lambda}
\]

\[
m_5 \approx \bar{M}_2 \approx \mu', \quad U_{e5} \approx \frac{Y_{1e} v}{\sqrt{2}\mu'}
\]
If LNV terms are small (to explain neutrino masses), the effects in neutrinoless double beta decay and LHC will be also suppressed. However, there is the case of an accidental cancellation in neutrino masses but large LNV

$$\mu = 0 \quad \text{and} \quad Y_2 = 0$$

Large mixing implies large effects in neutrinoless double beta decay due to new physics:

$$A_{extra} \propto \frac{v^2 \mu' Y_{1e}^2}{2 \Lambda^4}$$

$$\mu'$$ can be very large inducing neutrinoless double beta decay without contradicting the bounds from neutrino masses.

Mitra, Senjanovic, Vissani; Ibarra, Molinaro, Petcov
Neutrino masses are generated at one loop.

\[ \delta m_{LL} = \frac{1}{(4\pi v)^2} m_D^T M \left\{ \frac{3 \ln (M^2/M_Z^2)}{M^2/M_Z^2 - 1} + \frac{\ln (M^2/M_H^2)}{M^2/M_H^2 - 1} \right\} m_D \]

Two limits:

- Inverse see-saw

\[ \delta m_{LL} \approx \frac{1}{(4\pi)^2} \frac{Y_1^T Y_1}{2} \frac{M_H^2 + 3M_Z^2}{\Lambda^2} \mu' \]

- Extended see-saw

\[ \delta m_{LL} \approx \frac{1}{(4\pi)^2} \frac{Y_1^T Y_1}{2} \left[ \frac{3M_Z^2}{\mu'} \ln \left( \frac{\Lambda^4}{M_Z^4} \right) + \frac{M_H^2}{\mu'} \ln \left( \frac{\Lambda^4}{M_H^4} \right) \right] \]
The loop suppression is not very strong and light neutrino masses usually dominate neutrinoless double beta decay.
These effects depend on $Y$.

Allowed regions for heavy neutrino masses.

**Inverse see-saw:** small region around 5GeV.

**Extended see-saw:** one of the sterile neutrinos is very light, $M_1 < 100$ MeV.

Lopez-Pavon, Pascoli, Wong
Is it possible to check the allowed regions? And in particular a possible cancellation between heavy and light contribution?

\[ \Gamma^{\nu N}_{Ge} = G_{Ge} | \eta_\nu M_{\nu, Ge} + \eta_N M_{N, Ge} |^2 \sim 0, \quad \Rightarrow \quad \eta_N = -\eta_\nu \times \frac{M_{\nu, Ge}}{M_{N, Ge}} \]

The NME are different for different nuclei

\[ |m_{\beta\beta}|_i = |\langle m_\nu \rangle \times (1 - \frac{M_{\nu, Ge} \cdot M_{N,i}}{M_{N,Ge} \cdot M_{\nu,i}})| \]

Choosing the right nuclei, the cancellation will not be significant and neutrinoless double beta decay could be observed.

Pascoli, Wong, in prep
Lepton Number Violation determines the nature of neutrino and tells us about the symmetries of the physics BSM and the feasibility of Leptogenesis.

It is testable in neutrinoless double beta decay, rare tau and meson decays. In colliders it shows up as same dilepton channels.

As it linked to neutrino masses, effects at the LHC are suppressed unless production is enhanced.

Similarly, NP is typically subdominant in neutrinoless double beta decay in see-saw models, even when neutrino masses are kept zero at tree-level.