Heavy Majorana neutrinos at a linear collider

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The Model

Motivation

Neutrino oscillations imply neutrino masses which aren't included in the standard model.

Add right handed states

$$\mathcal{L} = -\frac{1}{2} \begin{pmatrix} \overline{\nu_L^0} & \overline{(\nu_R^0)^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & m_M \end{pmatrix} \begin{pmatrix} (\nu_L^0)^c \\ \nu_R^0 \end{pmatrix} + h.c.$$

$$\nu_{L,R}^0 = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_{L,R} \qquad (\nu_{L,R}^0)^c = C(\overline{\nu_{L,R}^0})^T$$

- Minimal model including neutrino masses.
- Can't add a left-handed Majorana mass term without further extensions to the standard model (e.g. a Higgs triplet).

Particle Spectrum

This gives six mass eigenstates that are Majorana particles.

$$\begin{pmatrix} \nu \\ N \end{pmatrix} = \begin{pmatrix} \nu_L \\ N_L \end{pmatrix} + \begin{pmatrix} (\nu_L)^c \\ (N_L)^c \end{pmatrix}$$

$$\begin{pmatrix} \nu_L \\ N_L \end{pmatrix} = U^T \begin{pmatrix} \nu_L^0 \\ (\nu_R^0)^c \end{pmatrix}$$

U is a 6×6 unitary matrix that mixes the $SU(2)_L$ eigenstates into states with definite mass.

$$\mathrm{diag}(m_1, ..., m_6) = U^T \begin{pmatrix} 0 & m_D \\ m_D^T & m_M \end{pmatrix} U$$

- Non-diagonal elements allow lepton flavour violation (c.f. flavour changing in quark sector).
- Can also have mixing between the charged leptons, but no Majorana mass terms.

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- Flavour symmetries can allow $m_N \sim 100\,\text{GeV}$ without large suppression of the couplings.

Lagrangian

Expressing the interaction Lagrangian in terms of mass eigenstates:

$$\begin{aligned}
\mathcal{L}_W &= -\frac{g}{\sqrt{2}} W^-_\mu (\overline{l^0_L} \gamma^\mu \nu^0_L) + h.c. \\
&= -\frac{g}{\sqrt{2}} W^-_\mu \left[\bar{l} \gamma^\mu P_L B \begin{pmatrix} \nu \\ N \end{pmatrix} \right] + h.c. \\
B_{ij} &= \sum_{k=1}^{3} V^*_{Lki} U^*_{kj}
\end{aligned}$$

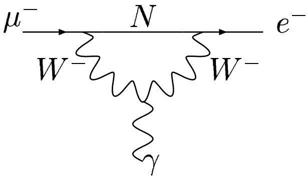
- B is the lepton equivalent of the CKM matrix.
- There can also be flavour changing in neutral current and Higgs field interactions but only for neutrinos.
- Majorana nature of neutrinos allows lepton number (not just lepton flavour) violation.

Low Energy Constraints

Constraints on B from lepton universality and the Z width give

$$\Omega_{ll} \equiv \delta_{ll} - \sum_{i=1}^{3} B_{l\nu_i} B^*_{l\nu_i} = \sum_{i=1}^{3} B_{lN_i} B^*_{lN_i} \lesssim 10^{-2}$$

Further constraints come from FCNC limits.



$$|\Omega_{e\mu}| \lesssim 0.0001 \qquad |\Omega_{e\tau}| \lesssim 0.02 \qquad |\Omega_{\mu\tau}| \lesssim 0.02$$

Production Mechanisms

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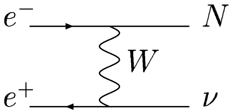
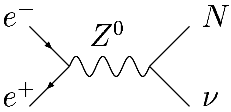
e^+e^- collider





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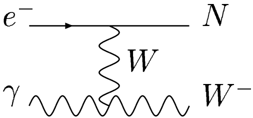

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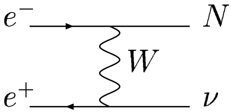

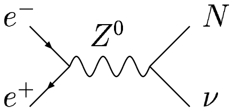

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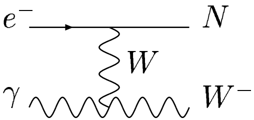

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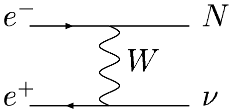

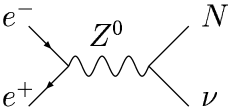

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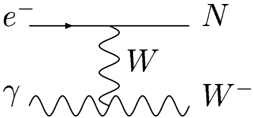
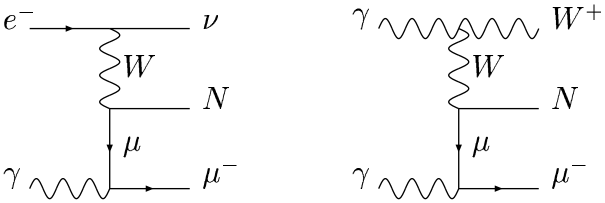


- LNV signal (for $N \to l^+W^-$, W's decaying hadronically).
- B_{eN} could be zero (or at least very small).

More Signals



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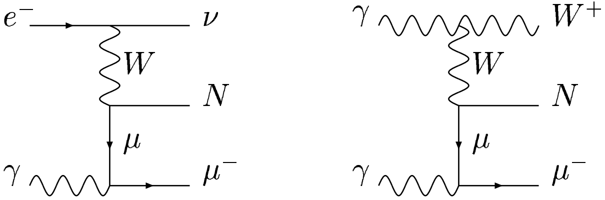

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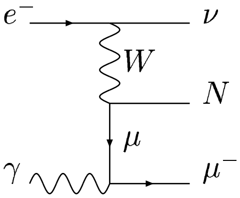

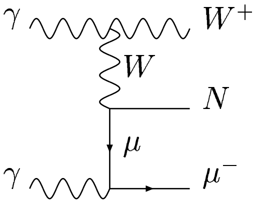

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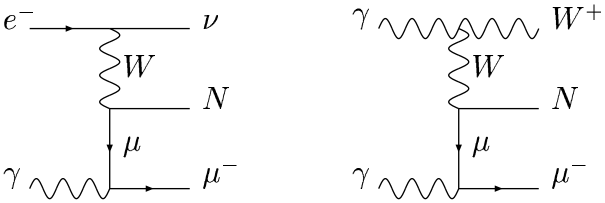


- LNV signal (for $N \to l^- W^+$, W's decaying hadronically).
- Don't rely on heavy neutrinos coupling to electron.
- Far smaller cross-sections.

Example Cross-Sections

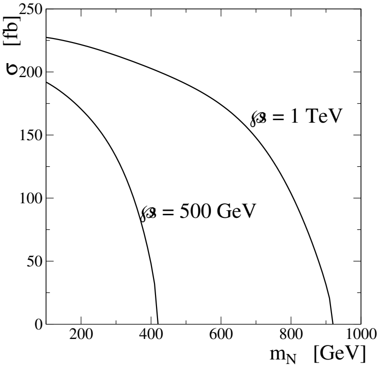


Figure: $e^- \gamma \to W^- N$

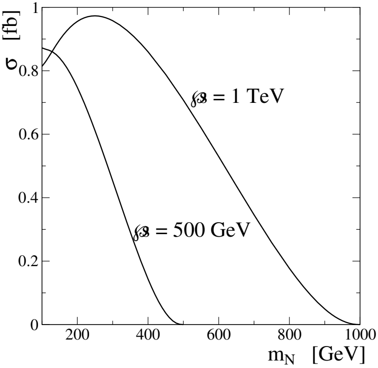
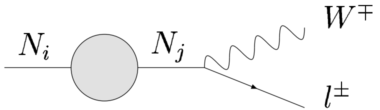


Figure: $e^- \gamma \to N \mu^- \nu$

- "Best case" scenarios.
- Need to multiply by branching ratios.

CP violation

- Neutrinos mix through their self-energy.
- Interference between tree-level graphs and one-loop self-energy transitions induces CP violation.



- Effect can be resonantly enhanced for mass differences of order the neutrino widths.
- Leptogenesis $\rightarrow$ baryogenesis $\rightarrow$ cosmological baryon asymmetry.