CP and Lepton Number Violation from Heavy Neutrinos at the LHC

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*Based on work by S. Bray, J. S. Lee and A. Pilaftsis. Paper in preparation.

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- It is not yet known if neutrinos are Dirac or Majorana particles, so consider both possibilities.

A model with Majorana neutrinos

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

$$\nu_L^0 = (\nu_{eL}, \nu_{\mu L}, \nu_{\tau L})^T$$

- 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).
- Expect $m_M \gg m_D$
- Three light, plus n_R heavy, Majorana neutrinos.

A model with Dirac neutrinos

$$\mathcal{L} = -\frac{1}{2} \begin{pmatrix} \bar{\nu}_L^0 & (\bar{\nu}_R^0)^c & \bar{S}_L^0 \end{pmatrix} \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M^T \\ 0 & M & 0 \end{pmatrix} \begin{pmatrix} (\nu_L^0)^c \\ \nu_R^0 \\ (S_L^0)^c \end{pmatrix} + \text{h.c.}$$

[D. Wyler and L. Wolfenstein, *Nucl. Phys.* **B218**, 205 (1983); R. N. Mohapatra and J. W. F. Valle, *Phys. Rev.* **D34**, 1642 (1986)]

- S_L^0 are singlets, i.e. they don't couple to the weak gauge bosons.
- $B - L$ imposed as a global symmetry.
- After diagonalisation of the mass matrix, this contains three massless neutrinos and n_R heavy Dirac neutrinos.
- Can add Majorana masses for light neutrinos, but this has no effect on collider observables.

Neutrino interactions

Weak states are a mix of mass eigenstates

$$\nu^0_{Ll} = \sum_{i=1}^{3+n_R} B_{li} \begin{pmatrix} \nu_L \\ N_L \end{pmatrix}_i$$

Expressing the Lagrangian in terms of the latter

$$\mathcal{L}_W = \sum_{i=1}^{3+n_R} -\frac{g}{\sqrt{2}} W^-_\mu \left[\bar{l} \gamma^\mu P_L B_{li} \begin{pmatrix} \nu \\ N \end{pmatrix}_i \right] + h.c.$$

- B is a $3 \times (3 + n_R)$ unitary matrix - the lepton equivalent of the CKM matrix.
- Both light and heavy neutrinos also couple to Z and H, with FCNC's possible for neutrinos (but not the charged leptons) at tree level.

Experimental constraints on couplings

B is unitary, so can define

$$\Omega_{ll'} \equiv \delta_{ll'} - \sum_{i=1}^{3} B_{l\nu_i} B^*_{l'\nu_i} = \sum_{i=1}^{n_R} B_{lN_i} B^*_{l'N_i}$$

From non-observation at LEP, for $m_N < M_Z$, $|\Omega_{ll'}| \lesssim 10^{-4} - 10^{-5}$.
Constraints on B from lepton universality and the Z width give

$$\Omega_{ll} \lesssim 10^{-2}$$

Further constraints come from FCNC limits

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

and the non-observation of neutrinoless double beta decay

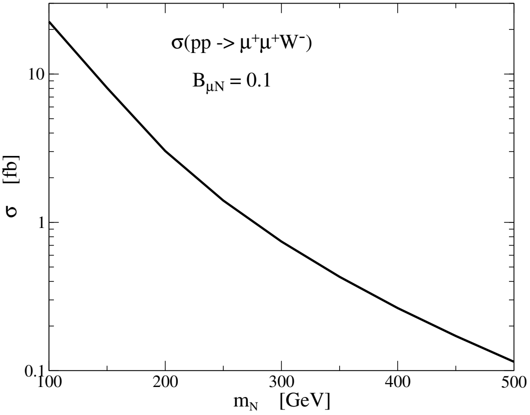
$$\left| \sum_i \frac{B^2_{eN_i}}{m_{N_i}} \right| \lesssim 5 \times 10^{-8}\,\mathrm{GeV}^{-1}$$

Production processes at the LHC

- Cross section falls rapidly with heavy neutrino mass.
- Clearest signals from $N \rightarrow l^{\pm} W^{\mp}$, with the W boson subsequently decaying hadronically.
- For Dirac neutrinos, look for Lepton Flavour Violation (LFV).
- For Majorana neutrinos, Lepton Number Violation (LNV) is also possible.
- Dominant SM background comes from $W^{\pm} W^{\pm} W^{\mp}$, two of which decay into charged leptons and undetected light neutrinos.

[T. Han and B. Zhang hep-ph/0604064; F. del Aguila, J. A. Aguilar-Saavedra, R. Pittau hep-ph/0606198]

The "best case scenario"

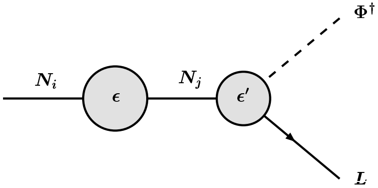


$p_T > 15$ GeV and $|\eta| > 2.5$ for both leptons and W boson.

CP violation

Requires at least two heavy neutrinos.
Due to the interference of the tree-level graph with the absorptive part of the one-loop corrections.
Using the terminology from the $K^0\bar{K}^0$ system, this can be distinguished into two mechanisms:

- ϵ-type: That due to interference with the self-energy correction.
- ϵ'-type: That due to interference with the vertex correction.



Resonant CP violation

If two or more heavy neutrinos are nearly degenerate in mass, then the ϵ-type mechanism can be resonantly enhanced. The formalism used to describe this is based on a resummation approach for the propagator.

[A. Pilaftsis, *Nucl. Phys.* **B504**, 61 (1997); A. Pilaftsis, *Phys. Rev.* **D56**, 5431 (1997)]

$$\hat{S}(\not{p}) = \left[\begin{array}{cc} \not{p} - m_{N_1} + \mathrm{iIm}\hat{\Sigma}_{11}(\not{p}) & \mathrm{iIm}\hat{\Sigma}_{12}(\not{p}) \\ \mathrm{iIm}\hat{\Sigma}_{21}(\not{p}) & \not{p} - m_{N_2} + \mathrm{iIm}\hat{\Sigma}_{22}(\not{p}) \end{array} \right]^{-1}$$

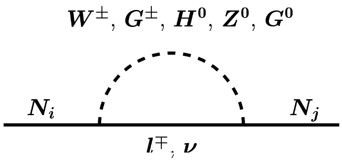
where

$$\mathrm{Im}\,\hat{\Sigma}_{ij}(\not{p}) = A_{ij}(p^2)\not{p}P_L + A_{ij}^*(p^2)\not{p}P_R.$$

The neutrino widths are given by

$$\Gamma_{N_i} = 2 m_{N_i} A_{ii}(m_{N_i}^2).$$

The heavy neutrino self-energy



$$A_{ij}(p^2) = \frac{g^2 C_{ij}}{128\pi p^4 M_W^2}\Big[4M_W^2(p^2 - M_W^2)^2 + 2M_Z^2(p^2 - M_Z^2)^2 +$$

$$m_{N_i} m_{N_j}\left(2(p^2 - M_W^2)^2 + (p^2 - M_Z^2)^2 + (p^2 - M_H^2)^2\right)\Big]$$

$$C_{ij} = \sum_l B_{li}^* B_{lj}$$

Theoretical constraints for Majorana neutrinos

For Majorana neutrinos, ignoring the light neutrino masses, their couplings have to satisfy the constraint

$$\sum_i m_{N_i} B_{li} B_{l'i} = 0.$$

For three heavy neutrinos, this translates to leaving four of the couplings as free paramenters (for example B_{l1} and B_{e2}). The others are then given by

$$B_{e3} = \pm i \sqrt{\frac{m_{N_1} B_{e1}^2 + m_{N_2} B_{e2}^2}{m_{N_3}}}, \qquad B_{li} = \frac{B_{l1} B_{ei}}{B_{e1}}$$

Unfortunately, this rules out scenarios with observable levels of CP violation.

CP-violating signals

- Due to the enhanced contribution from valence quarks, W^+ bosons will be created more frequently than W^-'s.
- True CP-violating observables can be formed either by taking into account the theoretically calculable difference expected due to the different PDF's, or by considering ratios of cross-sections such that this factor drops out.

For example,

$$\begin{aligned}
A_{CP}(LNV) &= \frac{\sigma(pp \to e^+e^+W^-) - K\sigma(pp \to e^-e^-W^+)}{\sigma(pp \to e^+e^+W^-) + K\sigma(pp \to e^-e^-W^+)} \\
A_{CP}(LFV) &= \frac{\sigma(pp \to e^+\mu^-W^+) - K\sigma(pp \to e^-\mu^+W^-)}{\sigma(pp \to e^+\mu^-W^+) + K\sigma(pp \to e^-\mu^+W^-)} \\
A_{CP}(LFNV) &= \frac{\sigma(pp \to e^+\mu^+W^-) - K\sigma(pp \to e^-\mu^-W^+)}{\sigma(pp \to e^+\mu^+W^-) + K\sigma(pp \to e^-\mu^-W^+)}
\end{aligned}$$

CP-violating signals

Alternatively,

$$R_{CP}(LNV) = \frac{R^+_{LNV} - R^-_{LNV}}{R^+_{LNV} + R^-_{LNV}}\,, \qquad R_{CP}(LFV) = \frac{R^+_{LFV} - R^-_{LFV}}{R^+_{LFV} + R^-_{LFV}}$$

with

$$R^+_{LNV} = \frac{\sigma(pp \to e^+e^+W^-)}{\sigma(pp \to e^+\mu^+W^-)}\,, \qquad R^-_{LNV} = \frac{\sigma(pp \to e^-e^-W^+)}{\sigma(pp \to e^-\mu^-W^+)}\,,$$

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- The R_{CP} type of observable has the advantage of not relying on the function K, which has to be calculated theoretically.
- They can also give larger signals as the CP violation from different channels can combine constructively. However, this makes it harder to distinguish which couplings are responsible.

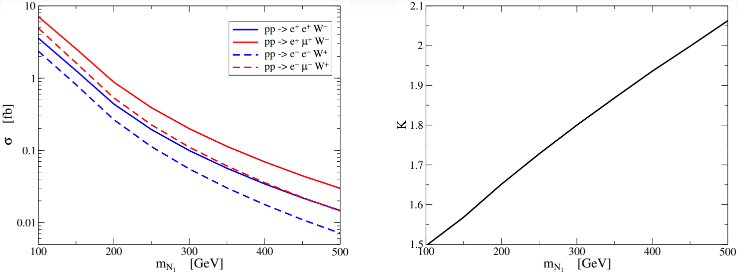


Figure: $B_{lN} = 0.05$, No CP-violation. $K = \frac{\sigma(pp \to (W^+)^* \to X)|_{\not{C}P=0}}{\sigma(pp \to (W^-)^* \to \bar{X})|_{\not{C}P=0}}$

- Cross sections independent of mass splitting for $\Delta m_N \ll m_N$.
- K is universal whichever signal process is considered. It is also independent of the magnitudes of the neutrinos couplings, being just a function of the PDF's for producing (off-shell) W^+ vs W^-.

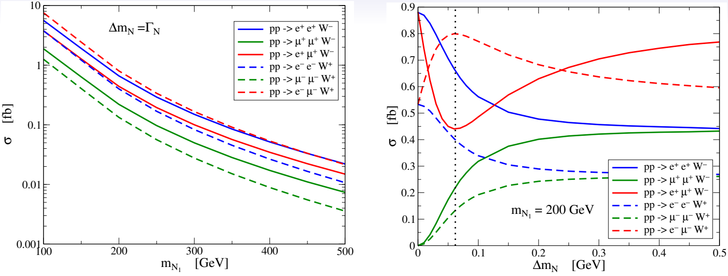
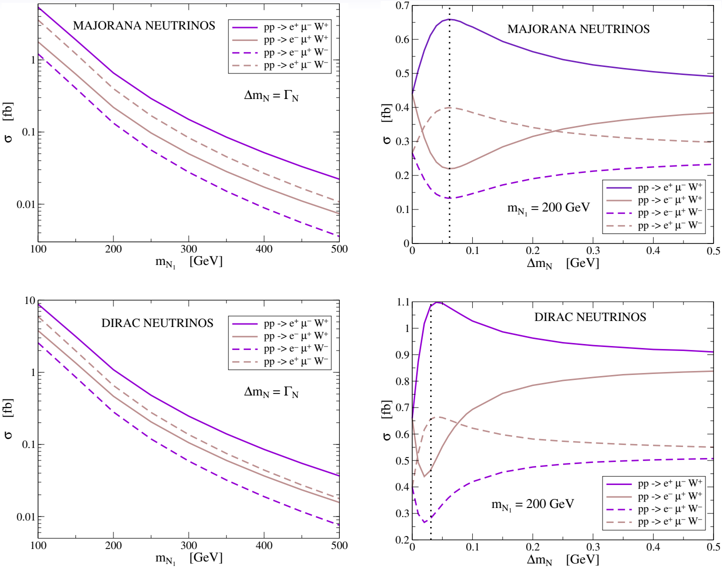


Figure: $B_{\mu 2} = 0.05i$ and $B_{\tau 2} = -0.05$. All other couplings equal 0.05.

- Large CP-asymmetries for both Dirac and Majorana neutrinos.
- Requires at least four heavy neutrinos in the Majorana case to avoid constraints.
- Also requires couplings from other neutrinos (or other BSM particles) to satisfy limit from $\mu \to e\gamma$.



MAJORANA NEUTRINOS
pp -> e+ μ− W+
pp -> e− μ+ W+
pp -> e− μ+ W−
pp -> e+ μ− W−
ΔmN = ΓN
σ [fb]
mN1 [GeV]
MAJORANA NEUTRINOS
mN1 = 200 GeV
ΔmN [GeV]
DIRAC NEUTRINOS
ΔmN = ΓN
DIRAC NEUTRINOS
mN1 = 200 GeV

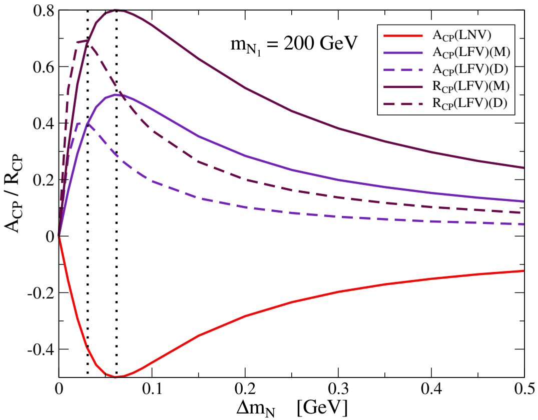
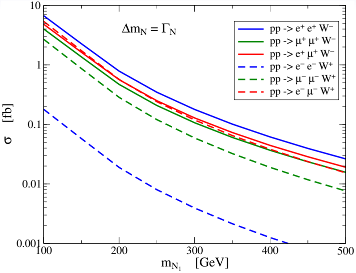
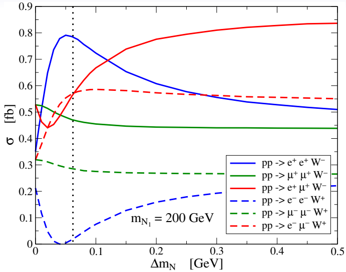


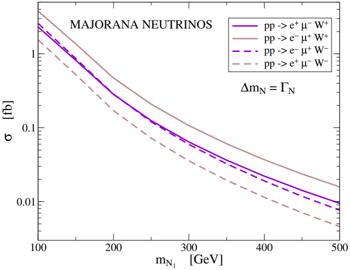
Figure: $B_{\mu 2} = 0.05i$ and $B_{\tau 2} = -0.05$. All other couplings equal 0.05. Large CP-asymmetries for both Dirac and Majorana neutrinos.



ΔmN = ΓN
pp -> e+ e+ W−
pp -> μ+ μ+ W−
pp -> e+ μ+ W−
pp -> e− e− W+
pp -> μ− μ− W+
pp -> e− μ− W+
σ [fb]
mN1 [GeV]



pp -> e+ e+ W−
pp -> μ+ μ+ W−
pp -> e+ μ+ W−
pp -> e− e− W+
pp -> μ− μ− W+
pp -> e− μ− W+
mN1 = 200 GeV
σ [fb]
ΔmN [GeV]



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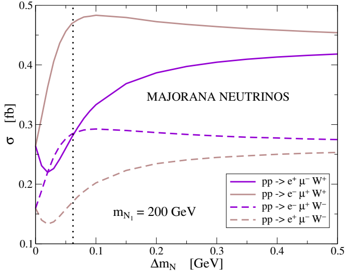
pp -> e+ μ− W+
pp -> e− μ+ W+
pp -> e− μ+ W−
pp -> e+ μ− W−
ΔmN = ΓN
σ [fb]
mN1 [GeV]



MAJORANA NEUTRINOS
pp -> e+ μ− W+
pp -> e− μ+ W+
pp -> e− μ+ W−
pp -> e+ μ− W−
mN1 = 200 GeV
σ [fb]
ΔmN [GeV]

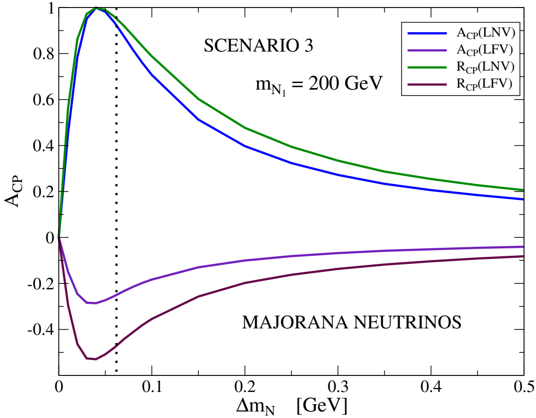


Figure: $B_{e2} = 0.05i$, all other couplings equal 0.05. Only CP violation for Majorana neutrinos.

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- If two heavy neutrinos are separated by a mass splitting of order their widths, then resonant CP violation can occure which can be maximal.
- For Majorana neutrinos, this requires at least four heavy neutrinos in the theory.