

Discovery of Light Sterile Neutrino ($M_N < M_W$) at the LHC

arXiv:1509.00000

C. S. Kim
(Yonsei University)

Outline

- **1. Introduction**
- **2. Probing Majorana Neutrinos at the LHC – short review**
- **3. Discovery of Light Sterile Neutrino at LHC**
- **4. Summary and Conclusions**

1. Introduction

- Neutrinos are massless in the SM
 - No right-handed ν 's \rightarrow Dirac mass term is not allowed.
 - Conserves the SU(2)_L gauge symmetry, and only contains the Higgs doublet (the SM accidentally possesses ($B - L$) symmetry); \rightarrow Majorana mass term is forbidden.

- Why are physicists interested in neutrino mass ?
 - ➔ Window to high energy physics beyond the SM!

- How exactly do we extend it?
 - ➔ Without knowing if neutrinos are Dirac or Majorana, any attempts to extend the Standard Model are not successful.

- Effective Observability of Difference between Dirac and Majorana Nu is proportional to

$$\Delta(D - M) \propto m / E$$

Possible range of (Sterile) Nu mass

(a) From neutrino oscillation and WMAP:

- $|\Delta m_{12}^2| \approx 10^{-5} eV^2$ $\Delta m_{13}^2 \approx 10^{-3} eV^2$ from neutrino oscillation
- $\Sigma m_i < 1eV$ from WMAP and Astrophysics
- $m_1 \approx O(10^{-5})eV$ from nuMSM (a model)
-

(b) From dark matter searches:

- $m_{N_1} \approx O(10)keV$ from nuMSM, warm DM, ...
- $m_N \approx O(1-10)GeV$ from DAMA, CDMS, XENON, ...
- $m_N \approx O(100-1000)GeV$ from SUSY, EDM, ...

(C) From BAU and Inflation $m_N \leq 20GeV$

(D) From usual see-saw $m_N \approx O(10^{12})GeV$

(E) We can assume any value of m_N , which will be determined by experiments.

Possible bound of (Sterile) N mixing $\nu_\ell = \sum_{j=1}^3 B_{\ell\nu_j} \nu_j + B_{\ell N} N$

→ $B_{\ell\nu_j}$ = PMNS Mixing $B_{\ell N}$ = Sterile N Mixing

- Present bounds for heavy N [Nardi et al, PLB327,319]

$$\sum_N |U_{Ne}|^2 \equiv (s_L^{\nu_e})^2 \leq 0.005, \quad (s_L^{\nu_\mu})^2 \leq 0.002, \quad (s_L^{\nu_\tau})^2 \leq 0.010$$

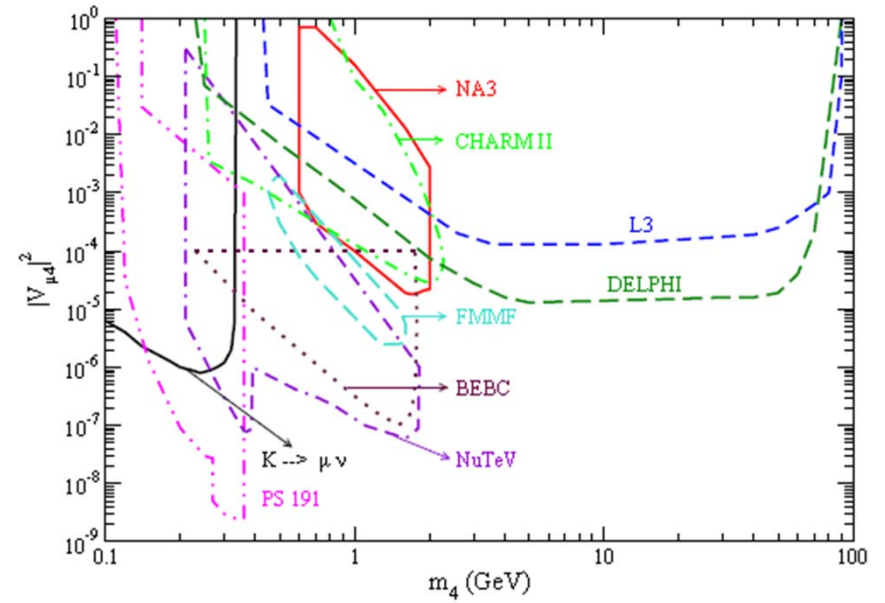
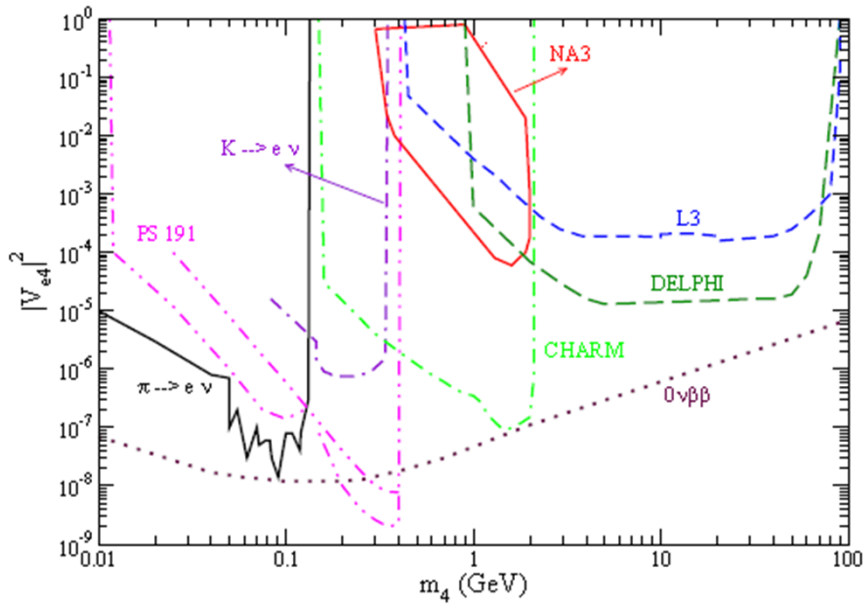
- M. Aoki *et al.* [PIENU Collaboration], Phys. Rev. D 84, 052002 (2011)

current bound on the mixing element $|B_{eN}|^2 \lesssim 10^{-8}$

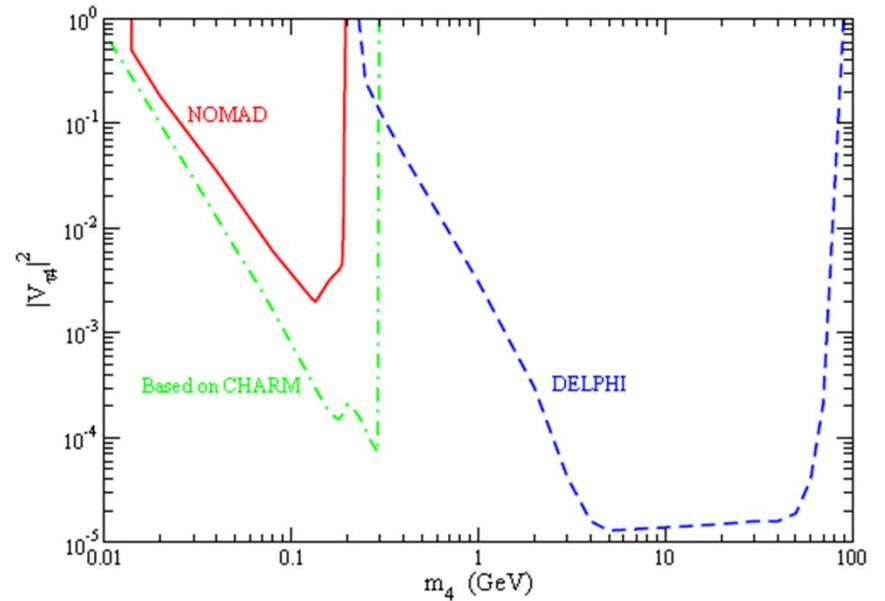
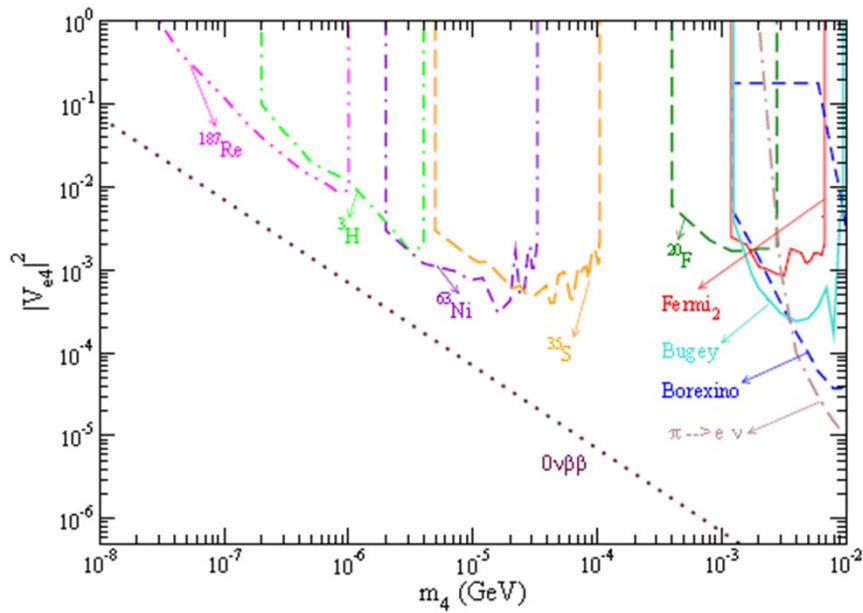
- In nuMSM, see-saw with (light RH sterile) N gives:

$$m_{\beta\beta} = \left| \sum_i m_i U_{ei}^2 + M_1 \Theta_{e1}^2 \right|, \quad |M_1 \Theta_{e1}^2| = \frac{|M_{1e}^{D2}|}{M_1}, \quad \Theta_{eN} = M^D / M_N$$

- We can assume any value of $B_{\ell N}$, which will be determined by experiments.



A. Atre et al, JHEP05(2009)030



2. Probing Majorana neutrinos

- Lepton number violation by 2 units $\Delta L = 2$ plays a crucial role to probe the **Majorana** nature of ν 's,

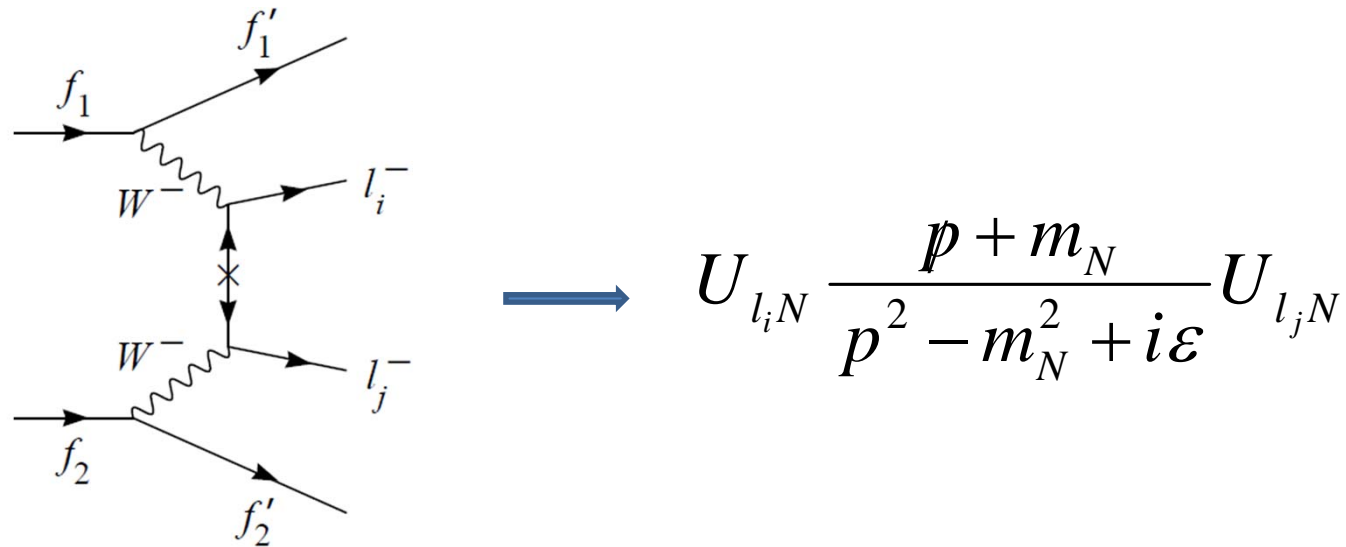
Probing Majorana Neutrinos at LHC

- In accelerator-based experiments, neutrinos in the final state are undetectable by the detectors, leading to the “missing energy”.

So it is desirable to look for charged leptons in the final state.

- It is **hard to avoid** the TeV-scale physics to contribute to **flavor-changing effects** in general whatever it is,
 - SUSY, extra dimensions, TeV seesaw, technicolor, Higgsless, little Higgs

Basic process we consider



- transition rates are proportional to

$$\left\{ \begin{array}{ll} \langle m \rangle_{l_1 l_2}^2 = \left| \sum_{i=1}^3 U_{l_1 i} U_{l_2 i} m_i \right|^2 & \text{for light } \nu \\ \left| \sum_{i=4}^{3+n} \frac{U_{l_1 i} U_{l_2 i}}{m_i} \right|^2 & \text{for heavy } \nu \\ \frac{\Gamma(N \rightarrow i) \Gamma(N \rightarrow f)}{m_N \Gamma_N} & \text{for resonant } N \text{ production} \end{array} \right.$$

Testability at the LHC

- Two necessary conditions to test at the LHC:
 - Masses of heavy Majorana V 's must be less than TeV
 - Light-heavy neutrino mixing (i.e., M_D/M_R) must be large enough.

$$\Delta(D - M) \propto m / E \Rightarrow m \approx O(100\text{GeV} - 1\text{TeV})$$

- LHC signatures of heavy Majorana v 's are essentially decoupled from masses and mixing parameters of light Majorana v 's.
- Non-unitarity of the light neutrino flavor mixing matrix might lead to observable effects.

- Nontrivial limits on heavy Majorana neutrinos can be derived at the **LHC**, if the SM backgrounds are small for a specific final state.

$\Delta L = 2$ like-sign dilepton events

$$pp \rightarrow W^\pm W^\pm \rightarrow \mu^\pm \mu^\pm jj \text{ and } pp \rightarrow W^\pm \rightarrow \mu^\pm N \rightarrow \mu^\pm \mu^\pm jj$$

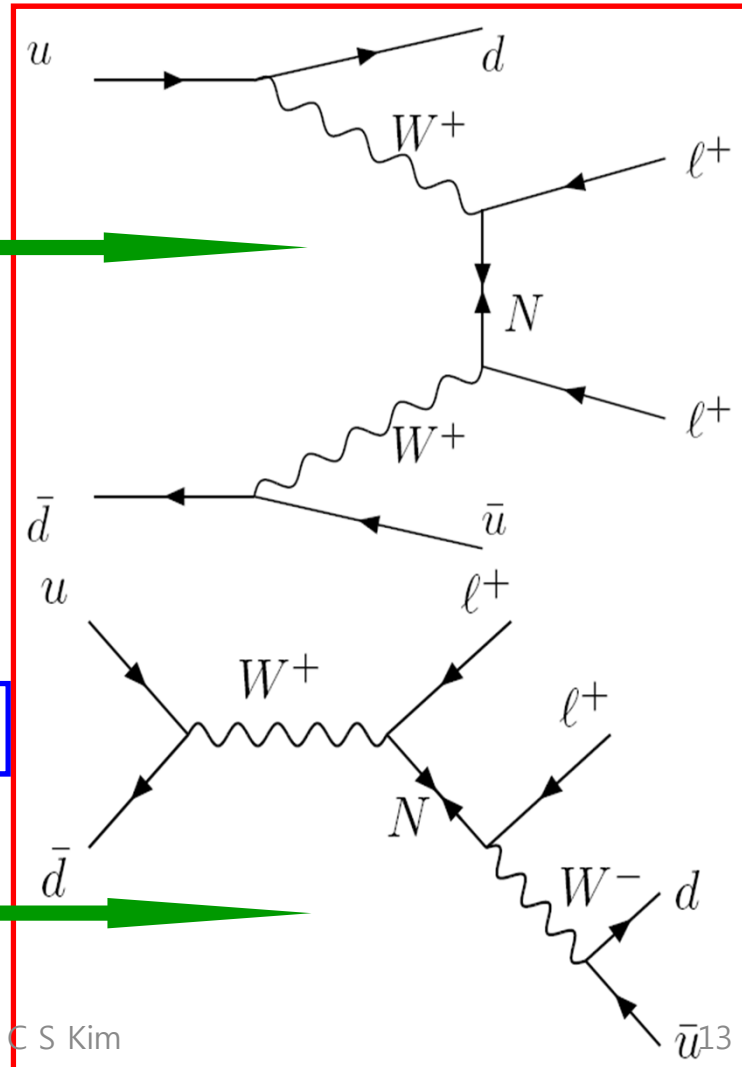
Collider Signature

Lepton number violation: like-sign dilepton events at hadron colliders, such as Tevatron (~ 2 TeV) and LHC (~ 14 TeV).

collider analogue to $0\nu\beta\beta$ decay

dominant channel

N can be produced on resonance



Some Results

- Cross sections are generally smaller for larger masses of heavy Majorana neutrinos. [Han, Zhang (hep-ph/0904064)]
- Signal & background cross sections (in fb) as a function of the heavy Majorana neutrino mass (in GeV) :
[Del Aguila *et al* (hep-ph/0906198)]

*Background could be much larger by soft-piling up !!

Tevatron

LHC

m_N	$\mu^\pm \mu^\pm jj$	$W^\pm W^\pm W^\mp$	$\mu^\pm \mu^\pm jj$	$W^\pm W^\pm W^\mp$
	signal	background	signal	background
100	0.40	0.0001	2.0	0.0012
200	0.071	0.0004	0.48	0.0044
300	0.014	0.0001	0.16	0.0023
400	0.0032	0.00005	0.068	0.0012
500	0.0008	0.00001	0.034	0.0007

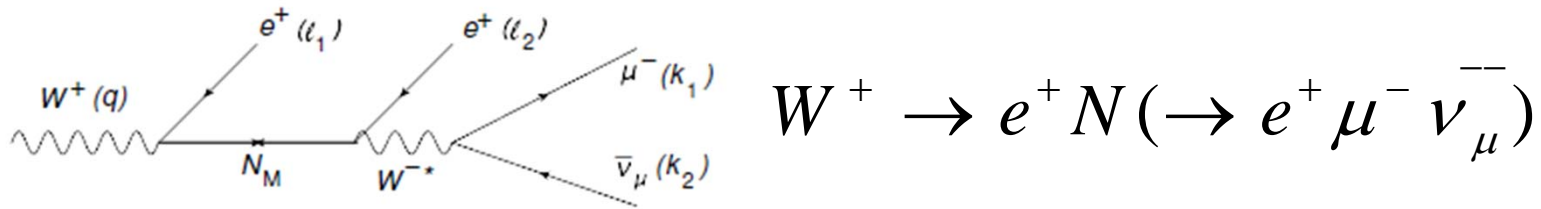
3. Discovery of light sterile N

- In previous works for LHC, $m_N \geq m_W$ covered.
 - Is a way to cover $m_N \leq m_W$?
 - Cosmology & astrophysics motivate strongly $m_N \approx 0.1 \leftrightarrow 50$ GeV.
 - How about on-shell W leptonic decays? $W^+ \rightarrow l^+ l^+ \mu^- \bar{\nu}_\mu$

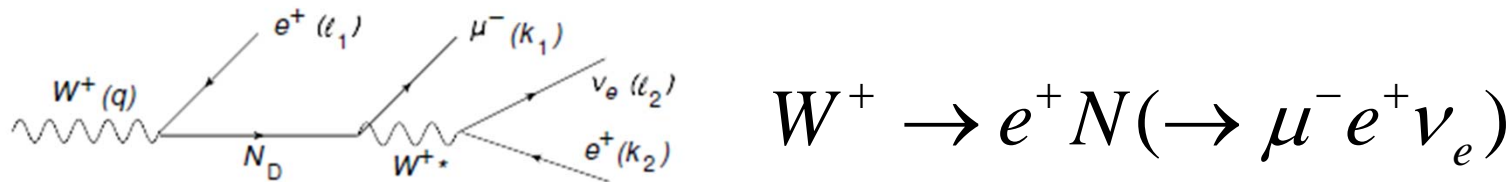
- Possible problems
 - Large radiative decays, $W^+ \rightarrow \mu^+ \nu_\mu + \gamma^* (\rightarrow e^+ e^-)$
→ we choose μ^- from W^+ decay (no radiative bg)
 - Final neutrino flavor not observed
→ $W^+ \rightarrow e^+ e^+ \mu^- \bar{\nu}_\mu$ or $W^+ \rightarrow e^+ e^+ \mu^- \nu_e$
→ LNV (Majorana N) or LNC-LFV (Maj./Dirac N)

$$W^+ \rightarrow e^+ e^+ \mu^- \bar{\nu}_\mu \quad \text{VS} \quad W^+ \rightarrow e^+ e^+ \mu^- \nu_e$$

- two competing processes (for $m_\mu \leq m_N \leq m_W$):



→ LNV (only Majorana neutrino N)



→ LNC but LFV (Majorana or Dirac neutrino N)

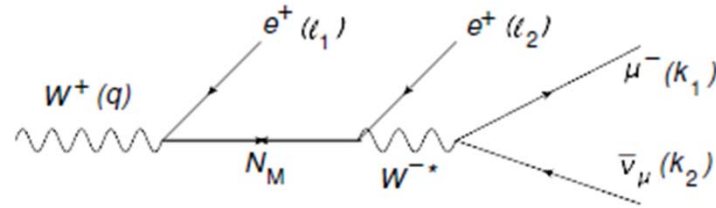
** We cannot identify the final neutrino flavor,

$\bar{\nu}_\mu$ or ν_e

Comments:

1. Same processes $W^+ \rightarrow e^+ e^+ \mu^- \bar{\nu}_\mu$, $W^+ \rightarrow \mu^+ \mu^+ e^- \bar{\nu}_e$,
and their C.C. (as long as no + - for the same flavor)
2. Comparison of $W^+ \rightarrow l^+ l^+ l^- \nu$ vs. $W^+ \rightarrow l^+ l^+ jj$
 - need well isolated energetic 2 jets (same for $pp \rightarrow l^+ l^+ jj$)
(otherwise large background from WW, instead of WWW)
 - $\rightarrow m(N) > \sim m(W)$ for $W \rightarrow lljj$
 $\rightarrow m(N) \ll m(W)$ for $W \rightarrow ll\nu$
3. [arXiv:1504.02470](#) considered only $W^+ \rightarrow e^+ e^+ \mu^- \bar{\nu}_\mu$,
not $W^+ \rightarrow e^+ e^+ \mu^- \nu_e$ (flavor of final nu unidentifiable)
4. Reconstruction of on-shell W at LHC (hadronic colliders)
 $W^+ \rightarrow l^+ l^+ l^- \nu$ or $W^+ \rightarrow l^+ \nu$ for $m(\nu) \sim 0$
reconstructable event-by-event by using $p(l)$ and m_T .

LNV, Pure Majorana, Process: $W^+ \rightarrow e^+ e^+ \mu^- \bar{\nu}_\mu$



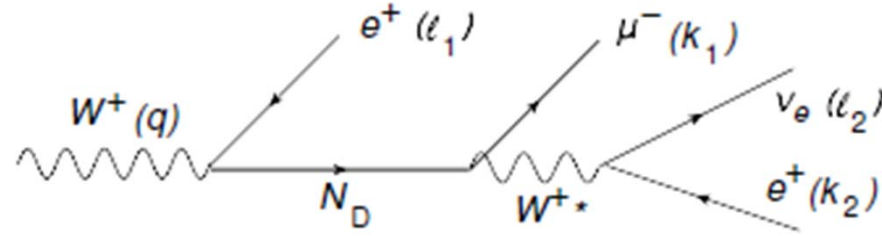
$$|\overline{\mathcal{M}}|^2 = 256 \frac{\sqrt{2}}{3} G_F^3 M_W^2 |U_{Ne}|^4 \frac{1}{(k_N^2 - m_N^2)^2 + m_N^2 \Gamma_N^2} m_N^2 (k_2 \cdot \ell_2) \left\{ (k_1 \cdot \ell_1) + \frac{2}{M_W^2} (q \cdot k_1)(q \cdot \ell_1) \right\}$$

$$\Gamma(W^+ \rightarrow e^+ e^+ \mu^- \bar{\nu}_\mu) = \frac{G_F^3 M_W^3}{12\sqrt{2} \pi^4} \frac{|U_{Ne}|^4 m_N}{\Gamma_N} \left(1 - \frac{m_N^2}{M_W^2}\right)^2 \left(1 + \frac{m_N^2}{2M_W^2}\right) \int_0^{m_N/2} dE_{k_1} (m_N E_{k_1}^2 - 2E_{k_1}^3)$$

$$Br(W^+ \rightarrow e^+ e^+ \mu^- \bar{\nu}_\mu) = \frac{1}{12 \times 96\pi} \left(\frac{G_F M_W^3}{\sqrt{2} \Gamma_W}\right) \left(|U_{Ne}|^4 \frac{G_F^2 m_N^5}{\pi^3 \Gamma_N}\right) \left(1 - \frac{m_N^2}{M_W^2}\right)^2 \left(1 + \frac{m_N^2}{2M_W^2}\right)$$

$$\approx 4.8 \times 10^{-3} \frac{|U_{Ne}|^4}{\sum_{\ell=e,\mu,\tau} |U_{N\ell}|^2} \left(1 - \frac{m_N^2}{M_W^2}\right)^2 \left(1 + \frac{m_N^2}{2M_W^2}\right).$$

LNC but LFV, Pure Dirac, Process: $W^+ \rightarrow e^+ e^+ \mu^- \nu_e$



$$|\overline{\mathcal{M}}|^2 = 256 \frac{\sqrt{2}}{3} G_F^3 M_W^2 |U_{Ne} U_{N\mu}|^2 \times \frac{1}{(k_N^2 - m_N^2)^2 + m_N^2 \Gamma_N^2} \\ \times (k_1 \cdot \ell_2) \left\{ 2(k \cdot k_2) \left[(k \cdot \ell_1) + \frac{2}{M_W^2} (q \cdot k)(q \cdot \ell_1) \right] - m_N^2 \left[(k_2 \cdot \ell_1) + \frac{2}{M_W^2} (q \cdot k_2)(q \cdot \ell_1) \right] \right\}$$

$$\Gamma(W^+ \rightarrow e^+ e^+ \mu^- \nu_e) = \frac{G_F^3 M_W^3}{12\sqrt{2}\pi^4} |U_{Ne} U_{N\mu}|^2 \frac{m_N}{\Gamma_N} \left(1 - \frac{m_N^2}{M_W^2}\right)^2 \left(1 + \frac{m_N^2}{2M_W^2}\right) \int_0^{m_N/2} dE_{k_1} \left(\frac{m_N}{2} E_{k_1}^2 - \frac{2}{3} E_{k_1}^3\right)$$

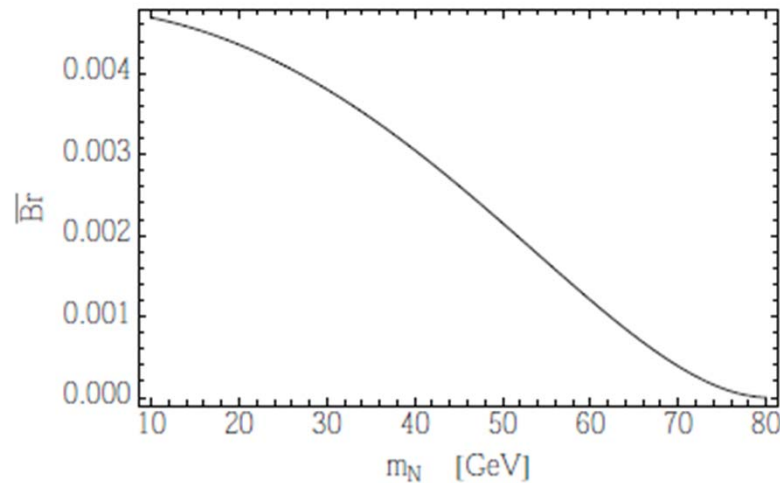
$$Br(W^+ \rightarrow e^+ e^+ \mu^- \nu_e) = \frac{1}{12 \times 96\pi} \left(\frac{G_F}{\sqrt{2}} \frac{M_W^3}{\Gamma_W}\right) \left(|U_{Ne} U_{N\mu}|^2 \frac{G_F^2 m_N^5}{\pi^3 \Gamma_N}\right) \left(1 - \frac{m_N^2}{M_W^2}\right)^2 \left(1 + \frac{m_N^2}{2M_W^2}\right)$$

$$\approx 4.8 \times 10^{-3} \frac{|U_{Ne}|^2 |U_{N\mu}|^2}{\sum_{\ell=e,\mu,\tau} |U_{N\ell}|^2} \left(1 - \frac{m_N^2}{M_W^2}\right)^2 \left(1 + \frac{m_N^2}{2M_W^2}\right).$$

Numerical studies and discussions

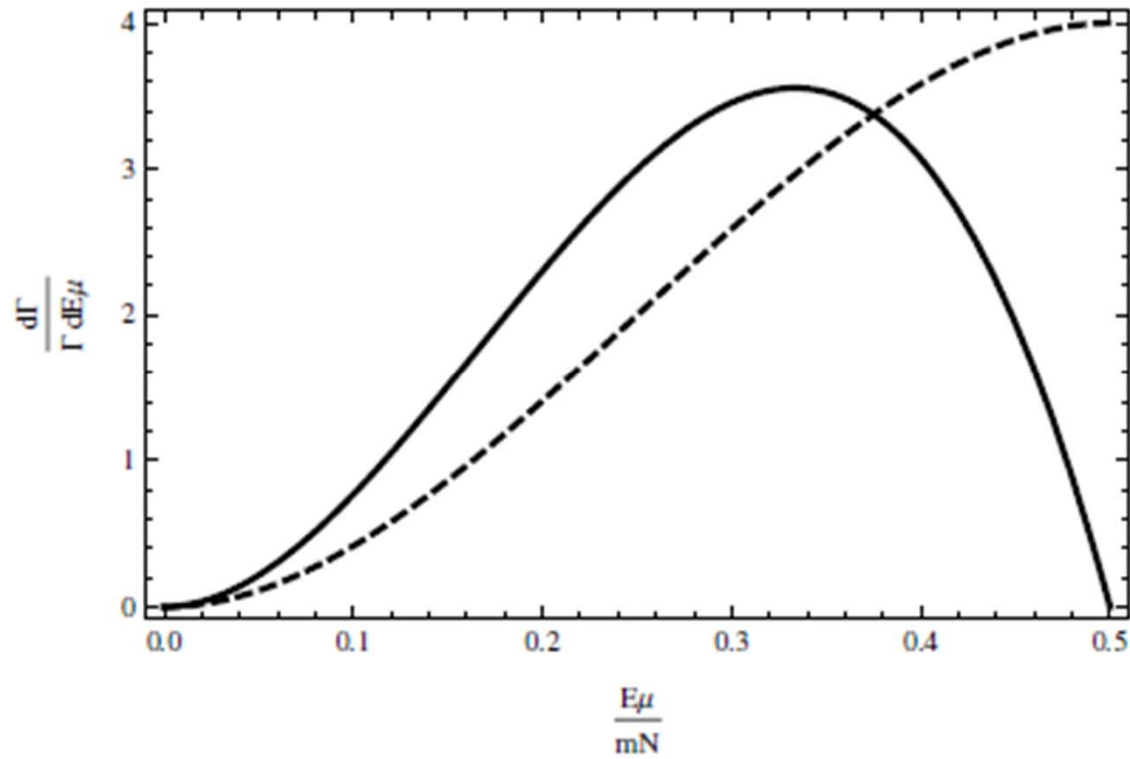
(A) **branching ratios:**

reduced BR for $W^+ \rightarrow e^+ e^+ \mu^- \nu$



$Br = \overline{Br} \times |U_{Ne}|^4 / (\sum_{\ell} |U_{N\ell}|^2)$ and $Br = \overline{Br} \times |U_{Ne} U_{N\mu}|^2 / (\sum_{\ell} |U_{N\ell}|^2)$, respectively.

(B) **Spectrum analysis** to separate Majorana from Dirac neutrino:



Normalized muon energy spectrum, $(1/\Gamma)d\Gamma/dE_\mu$

$$\left(\frac{1}{\Gamma_{LNV} + \Gamma_{LNC}} \right) \frac{d\Gamma}{d\varepsilon_\mu} = \frac{1}{|U_{Ne}|^2 + |U_{N\mu}|^2} \left\{ |U_{Ne}|^2 (\varepsilon_\mu^2 - 2\varepsilon_\mu^3) + |U_{N\mu}|^2 \left(\frac{1}{2}\varepsilon_\mu^2 - \frac{2}{3}\varepsilon_\mu^3 \right) \right\}$$

where $\varepsilon_\mu = E_\mu/m_N$ is the normalised muon energy in the N rest frame.

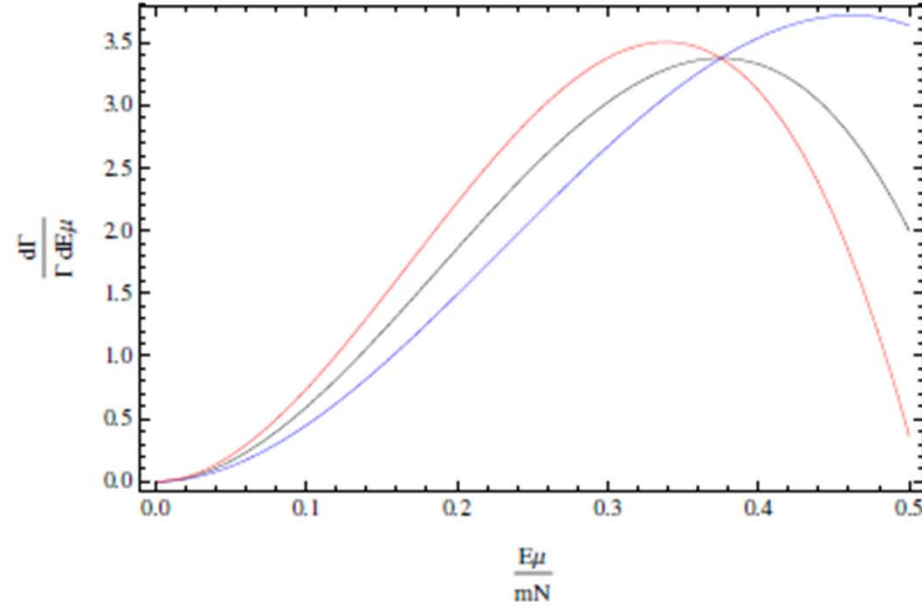


Figure 5. Normalized muon energy spectrum for the signal + background $d\Gamma/dE_\mu(W^+ \rightarrow e^+e^+\mu^-\bar{\nu}_\mu) + d\Gamma/dE_\mu(W^+ \rightarrow e^+e^+\mu^-\nu_e)$, normalised by the sum of the two rates. The two rates are proportional to $|U_{Ne}|^2$ and $|U_{N\mu}|^2$, respectively. The curves correspond to $|U_{Ne}|^2/|U_{N\mu}|^2 = 10^{-1}, 1, \text{ and } 10$ (blue, black and red lines, respectively).

4. Summary and Conclusions

- Knowing that **neutrinos are Dirac or Majorana** is THE MOST important to go beyond the SM.
- We have discussed **a new way to probe Majorana neutrinos** with much less uncertainty for **mass ranges** of $m_\mu \leq m_N \leq m_W$, from the rare **leptonic** decay of **on-shell** $W^+ \rightarrow e^+ e^+ \mu^- \nu$
- We investigated **$\text{Br}(W^+ \rightarrow e^+ e^+ \mu^- \nu)$** as well as **the energy spectrum** of the decays to separate the Majorana neutrino from Dirac one.