Heavy Right Handed Neutrinos: phenomenology and future searches

Jilberto Zamora-Saá
Dzhelepov Laboratory of Nuclear Problems
Joint Institute for Nuclear Research
Dubna, Russia.

January 30, 2017

Contents:

Introduction

- Evidence of neutrino oscillations $\Rightarrow$ Neutrino are massive

  m_1, m_2, m_3: $\Delta m_{12}^2 \sim 10^{-5} eV^2$, $\Delta m_{23}^2 \sim 10^{-3} eV^2$.

- Bounds from Astrophysics/Cosmology:

$$\sum_{i=1}^{3} m_i < 1eV$$

...but in the Standard Model (SM), neutrinos are massless!!!

$\Rightarrow$ We enter physics Beyond the SM!!! $\Rightarrow$ New questions arise:

- Why neutrino masses are so small?
- Are massive neutrinos Majorana or Dirac fermions?

Where does Neutrinos mass come from?

Introduction

- Consider Dirac masses (due to Yukawa couplings):

$$\overbrace{L_y = y_e \left(\bar{\nu}_L \quad \bar{e}_L\right) \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix}}^{\text{charged leptons}} e_R \rightarrow \underbrace{y_e \frac{v}{\sqrt{2}}}_{m_e} \bar{e}_L e_R \quad ; \quad v = 246 GeV.$$

- To include a Dirac neutrino mass, we need an extra field: ν_R:

$$L_y = y_e \left(\bar{\nu}_L \quad \bar{e}_L\right) \begin{pmatrix} \Phi^0 \\ -\Phi^- \end{pmatrix} \nu_R \rightarrow \underbrace{y_\nu \frac{v}{\sqrt{2}}}_{m_\nu} \bar{e}_L e_R.$$

In general for fermions, we have:

Fermion	Mass (MeV)	Yukawa y_α
top quark	$171 \cdot 10^3$	1
u quark	2	10^{-5}
electron	0.5	10^{-6}
neutrino	$\sim 10^{-7}$	10^{-12}

$\Rightarrow$New physics scale

$$\mathcal{L} = \mathcal{L}_{SM} + k_{d=5} \frac{\mathcal{O}_{d=5}}{M} + k_{d=6} \frac{\mathcal{O}_{d=6}}{M^2} + \ldots$$

$$\frac{\lambda}{M} \underbrace{(LLHH)}_{\mathcal{O}_{d=5}} \rightarrow \frac{\lambda v^2}{M} \bar{\nu}\nu$$

Introduction

The Majorana mass term is also allowed $\Rightarrow L_Y = y_\nu \bar{L}\Phi^c \nu_R + \frac{1}{2} M \bar{\nu^c}_R \nu_R$

There are many possible scenarios for seesaw

- Type I:

$$L_{mass} = \frac{1}{2} \begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^c \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

  - Masses: $m_{light} \sim \frac{m_D^2}{M}$; $m_{heavy} \sim M$
  - Mixing: $\nu_e \sim \nu_{light} + \sin\theta N_H$; $\sin\theta \sim \frac{m_D}{M}$

- Low Scale seesaw ("inverse seesaw") $\rightarrow$ Additional neutrino S:

$$L_{mass} = \frac{1}{2} \begin{pmatrix} \bar{\nu}_L^c & \bar{\nu}_R & \bar{S} \end{pmatrix} \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_\chi \\ 0 & M_\chi^T & \mu \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \\ S^c \end{pmatrix}$$

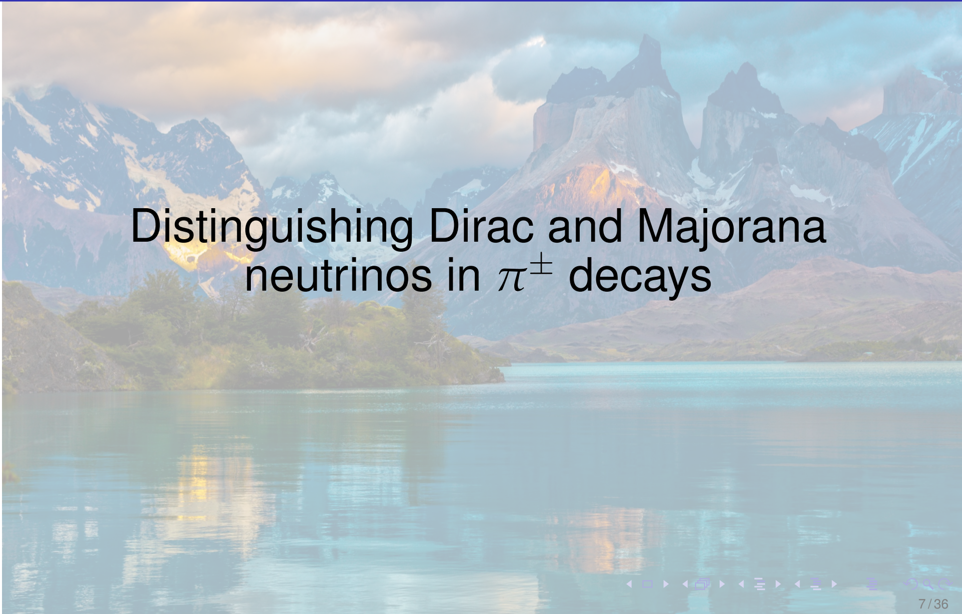
  - Masses: $m_{light} \sim \mu \frac{m_D^2}{M^2}$; $m_{heavy} \sim M$ (M not required to be huge).
  - $\Rightarrow \theta \sim \frac{m_D}{M}$ not so small (maybe observable).

Introduction

The range of right handed neutrino masses:

- $\mathbf{M_N} \gtrsim \mathbf{10^9}$ **GeV**: This range is motivated by Yukawa couplings $y_\nu \sim 1$. In addition, this range allow to generate the observed baryon density in the universe in CP-violating decays of ν_R neutrinos.
- $\mathbf{M_N} \sim$ **TeV**:The origin of BAU may be explained by leptogenesis from CP-violating decays if two ν_R masses are degenerate. Neutrino masses are explained by the seesaw mechanism. From an experimental viewpoint this mass range is favourable because it is accessible by high energy experiments, such as LHC.
- $\mathbf{M_N} \sim$ **GeV**: If M has at least two eigenvalues $\sim$GeV and another eigenvalue in the keV range, then the FV, BAU and DM can be described, and no other physics between the electroweak and Planck scales is required.
- $\mathbf{M_N} \sim$ **keV**: ν_R with keV masses are promising candidates for the DM.
- $\mathbf{M_N} \sim$ **eV**: ν_R with eV masses can provide an explanation for the anomalies , which are observed in some neutrino experiments and cosmological data.
- $\mathbf{M_N} = \mathbf{0}$: In this case neutrinos are Dirac particles. Then neutrino masses are generated by the Higgs mechanism in precisely the same way as other fermion masses, and their smallness can only be assigned to very tiny Yukawa couplings.

Pion Decays:



Distinguishing Dirac and Majorana neutrinos in $\pi^{\pm}$ decays

Pion Decays:

Let's assume the existence of at least one heavy "sterile" neutrino in the ∼GeV mass range and define the neutrino flavor state as:

$$\nu_\ell = \sum_{j=1}^{3} B_{\ell j}\nu_j + B_{\ell N_1}N_1 + B_{\ell N_2}N_2 + \ldots + B_{\ell N_n}N_n$$

Here $B_{\ell j} = |B_{\ell j}|e^{i\theta_{\ell j}}$ are the elements of the $(3+n)\times(3+n)$ PMNS matrix.

The CC interaction becomes:

$$\mathcal{L}_{\ell WN} = \frac{g}{2\sqrt{2}}\left[\bar{\ell}\gamma_\mu(1-\gamma_5)\underbrace{\left(\sum_{j=1}^{3} B_{\ell j}\nu_j + B_{\ell N_1}N_1 + B_{\ell N_2}N_2 + \ldots\right)}_{\nu_\ell} W_- + \mathrm{h.c.}\right]$$

Pion Decays:

Let's assume the existence of at least one heavy "sterile" neutrino in the ∼GeV mass range and define the neutrino flavor state as:

$$\nu_\ell = \sum_{j=1}^{3} B_{\ell j}\nu_j + B_{\ell N_1}N_1 + B_{\ell N_2}N_2 + \ldots + B_{\ell N_n}N_n$$

Here $B_{\ell j}$ and $B_{\ell N_n}$ are the elements of the PMNS matrix which is $(3+n)\times(3+n)$.
The CC interaction becomes:

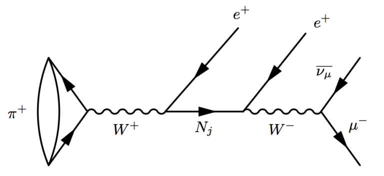
$$\mathcal{L}_{\ell WN} = \frac{g}{2\sqrt{2}}\left[\bar{\ell}\gamma_\mu(1-\gamma_5)\underbrace{\left(\sum_{j=1}^{3} B_{\ell j}\nu_j + B_{\ell N_1}N_1 + B_{\ell N_2}N_2 + \ldots\right)}_{\nu_\ell} W_- + \text{h.c.}\right]$$

How does it work?

Pion Decays:

How does it work?

$$\mathcal{L}_{\ell W N} = \frac{g}{2\sqrt{2}}\left[\overline{\ell}\gamma_\mu(1-\gamma_5)\underbrace{\left(\sum_{j=1}^{3} B_{\ell j}\nu_j + B_{\ell N_1} N_1 + B_{\ell N_2} N_2 + \dots\right)}_{\nu_\ell} W_- + \text{h.c.}\right]$$

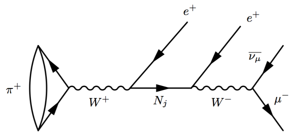


The produced (on-shell) massive neutrino N could survive during its flight through the detector, and would decay later outside it. Such decays are thus not detected and should be eliminated from the width and the branching ratio of the considered process.

$$P_N = 1 - \exp\left[-\frac{L}{\tau_N \gamma_N \beta_N}\right] \approx \frac{\Gamma_N L}{\gamma_N} \qquad \text{if } P_N \ll 1 \text{ and } \beta \approx 1$$

Pion Decays:

How does it work?:



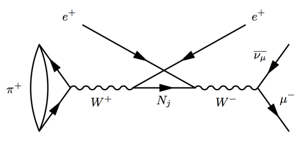
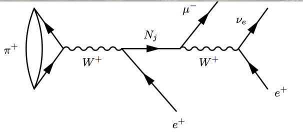


Figure: Left Side: Direct Channel of (LNV) Decay. Right Side: Crossed Channel of (LNV) Decay. (J. Zamora-Saa, et al. J.Phys. G41 (2014) 075004).



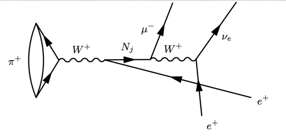


Figure: Left Side: Direct Channel of (LNC) Decay. Right Side: Crossed Channel of (LNC) Decay. (J. Zamora-Saa, et al. J.Phys. G41 (2014) 075004).

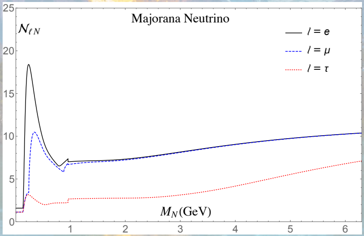
Pion Decays:

Heavy neutrino Decay width:

$$\Gamma_N = \widetilde{\mathcal{K}}\overline{\Gamma}_N(M_N) \quad ; \quad \overline{\Gamma}_N(M_N) \equiv \frac{G_F^2 M_N^5}{96\pi^3},$$

the factor $\widetilde{\mathcal{K}}$ contains the dependence on the heavy-light mixing factors

$$\widetilde{\mathcal{K}}(M_N) \equiv \widetilde{\mathcal{K}} = \mathcal{N}_{eN}\,|B_{eN}|^2 + \mathcal{N}_{\mu N}\,|B_{\mu N}|^2 + \mathcal{N}_{\tau N}\,|B_{\tau N}|^2$$



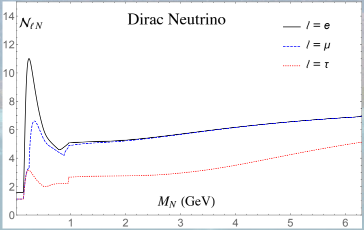


Figure: The effective mixing coefficients $\mathcal{N}_{\ell N}$ ($\ell = e, \mu, \tau$), as a function of the mass M_N of the neutrino N. (J. Zamora-Saa, et al. Phys.Rev. D89 (2014) no.9, 093012)

Pion Decays:

Pion decay width:

$$\Gamma^{(X)}(\pi^\pm \to e^\pm e^\pm \mu^\mp \nu) = |k^{(X)}|^2 [\widetilde{\Gamma}_\pi^{(X)}(DD^*) + \widetilde{\Gamma}_\pi^{(X)}(CC^*) + \widetilde{\Gamma}_{\pi,\pm}^{(X)}(DC^*) + \widetilde{\Gamma}_{\pi,\pm}^{(X)}(CD^*)]$$

here X stand for LNV and LNC processes and consequently $k^{(\mathrm{LNV})} = B_{eN}^2$, $k^{(\mathrm{LNC})} = B_{eN} B_{\mu N}^*$; the $\widetilde{\Gamma}_\pi^{(X)}(YZ^*)$ are the normalized decay widths

$$\widetilde{\Gamma}_{\pi,\pm}^{(X)}(YZ^*) = K_\pi^2 \frac{1}{2!} \frac{1}{2M_\pi} \frac{1}{(2\pi)^8} \int d_4 \; P^{(X)}(Y) P^{(X)}(Z)^* \; T_{\pi,\pm}^{(X)}(YZ^*)$$

$$d_4 = \left(\prod_{j=1}^{2} \frac{d^3 \vec{p}_j}{2E_e(\vec{p}_j)} \right) \frac{d^3 \vec{p}_\mu}{2E_\mu(\vec{p}_\mu)} \frac{d^3 \vec{p}_\nu}{2|\vec{p}_\nu|} \delta^{(4)} \left(p_\pi - p_1 - p_2 - p_\mu - p_\nu \right)$$

The propagators are

$$P^{(\mathrm{LNC})}(D) = \frac{1}{[(p_\pi - p_1)^2 - M_N^2 + i\Gamma_N M_N]}, \qquad P^{(\mathrm{LNV})}(D) = M_N P^{(\mathrm{LNC})}(D)$$

$$P^{(\mathrm{LNC})}(C) = \frac{1}{[(p_\pi - p_2)^2 - M_N^2 + i\Gamma_N M_N]}, \qquad P^{(\mathrm{LNV})}(C) = M_N P^{(\mathrm{LNC})}(C)$$

The pion decay rates may be nonnegligible only if the intermediate neutrino N is on-shell $(M_\mu + M_e) < M_N < (M_\pi - M_e)$.

Pion Decays:

Pion branching ratio :

$$\mathrm{Br}^{(\mathrm{Dir.})}_{\mathrm{eff}}(\pi^{\pm} \to e^{\pm}e^{\pm}\mu^{\mp}\nu) = |B_{eN}|^2|B_{\mu N}|^2 \left(\frac{L}{1\mathrm{m}}\right) \overbrace{\overline{\mathrm{Br}}_{\pi,\mathrm{eff}}}^{\lesssim 10^{-6}}$$

$$\mathrm{Br}^{(\mathrm{Maj.})}_{\mathrm{eff}}(\pi^{\pm} \to e^{\pm}e^{\pm}\mu^{\mp}\nu) = |B_{eN}|^2(|B_{eN}|^2 + |B_{\mu N}|^2) \left(\frac{L}{1\mathrm{m}}\right) \overbrace{\overline{\mathrm{Br}}_{\pi,\mathrm{eff}}}^{\lesssim 10^{-6}}$$

where

$$\overline{\mathrm{Br}}_{\pi,\mathrm{eff}} = P_N \frac{\Gamma(\pi^{\pm} \to e^{\pm}e^{\pm}\mu^{\mp}\nu)}{\Gamma(\pi^{\pm} \to \mathrm{all})} = P_N \overline{\mathrm{Br}}_{\pi}$$

and

$$\overline{\mathrm{Br}}_{\pi} = \frac{1}{16\pi} \frac{K_{\pi}^2 M_{\pi}^3}{G_F^2 \Gamma(\pi^+ \to \mathrm{all})} \frac{1}{x_{\pi}^3} \lambda^{1/2}(x_{\pi}, 1, x_e) \left[x_{\pi} - 1 + x_e(x_{\pi} + 2 - x_e)\right] \mathcal{F}(x_{\mu}, x_e)$$

Pion Decays:

The presently known experimental bounds on the mixing parameters $|B_{\ell N}|^2$ ($\ell = e, \mu$) in our relevant mass range, are: $|B_{eN}|^2 \lesssim 10^{-8}$; $|B_{\mu N}|^2 \lesssim 10^{-6}$. The future pion factories, such as the Project X at Fermilab, will be designed to produce charged pions with lab energies E_π of a few GeV, and $\sim 10^{29}$ charged pions could be expected per year.

- If the larger among the mixing elements ($|B_{\ell N}|^2$, $\ell = e, \mu$) is $|B_{\mu N}|^2$ ($\lesssim 10^{-6}$), the LNC processes dominate, and the effective branching ratios have the common upper bounds:

$$\mathrm{Br}_{\mathrm{eff}}^{(\mathrm{Dir.,Maj.})} \lesssim |B_{eN}|^2 |B_{\mu N}|^2 10^{-6} \lesssim |B_{eN}|^2 10^{-12} \qquad (3)$$

  If in this case $|B_{eN}|^2$ is close to its present upper bound, $|B_{eN}|^2 \sim 10^{-8}$, we obtain $\mathrm{Br}_{\mathrm{eff}}^{(\mathrm{Dir.,Maj.})} \lesssim 10^{-20}$. This implies that up to 10^9 events $\pi^\pm \to e^\pm e^\pm \mu^\mp \nu$ could be detected per year in such a scenario.

Pion Decays:

The presently known experimental bounds on the mixing parameters $|B_{\ell N}|^2$ ($\ell = e, \mu$) in our relevant mass range, are: $|B_{eN}|^2 \lesssim 10^{-8}$; $|B_{\mu N}|^2 \lesssim 10^{-6}$. The future pion factories, such as the Project X at Fermilab, will be designed to produce charged pions with lab energies E_π of a few GeV, and $\sim 10^{29}$ charged pions could be expected per year.

- If the larger among the mixing elements $(B_{\ell N}|^2, \ell = e, \mu)$ is $|B_{eN}|^2$ ($\lesssim 10^{-8}$), the LNV processes dominate, and the effective branching ratios have the following upper bounds:

$$\mathrm{Br}_{\mathrm{eff}}^{(\mathrm{Dir.})} \lesssim |B_{\mu N}|^2 10^{-14} \qquad \text{(4a)}$$

$$\mathrm{Br}_{\mathrm{eff}}^{(\mathrm{Maj.})} \lesssim 10^{-22} \qquad \text{(4b)}$$

In such a case we have $|B_{\mu N}|^2 < |B_{eN}|^2 \lesssim 10^{-8}$, and up to 10^7 events could be detected per year.

Pion Decays:

Pion differential branching ratio $\left(\frac{d\overline{\text{Br}}_\pi}{dE_\mu} = \frac{1}{\Gamma_{\pi\to\text{all}}}\frac{d\overline{\Gamma}_\pi}{dE_\mu}\right)$:

The combined canonical branching ratio

$$\frac{d\overline{\text{Br}}_\pi(\alpha)}{dE_\mu} \equiv \alpha\frac{d\overline{\text{Br}}_\pi^{(\text{LNV})}}{dE_\mu} + (1-\alpha)\frac{d\overline{\text{Br}}_\pi^{(\text{LNC})}}{dE_\mu}$$

here α is an admixture parameter

$$\alpha_M = \frac{|k^{(\text{LNV})}|^2}{(|k^{(\text{LNV})}|^2 + |k^{(\text{LNC})}|^2)} = \frac{|B_{eN}|^2}{(|B_{eN}|^2 + |B_{\mu N}|^2)}$$

The differential branching ratio for Dirac and Majorana neutrinos are:

$$\frac{d\text{Br}^{(\text{Dir.})}(\pi^\pm \to e^\pm e^\pm \mu^\mp \nu)}{dE_\mu} = \frac{|k^{(\text{LNC})}|^2}{\widetilde{\mathcal{K}}^{(\text{Dir.})}}\frac{d\overline{\text{Br}}_\pi(\alpha=0)}{dE_\mu}$$

$$\frac{d\text{Br}^{(\text{Maj.})}(\pi^\pm \to e^\pm e^\pm \mu^\mp \nu)}{dE_\mu} = \frac{(|k^{(\text{LNV})}|^2 + |k^{(\text{LNC})}|^2)}{\widetilde{\mathcal{K}}^{(\text{Maj.})}}\frac{d\overline{\text{Br}}_\pi(\alpha=\alpha_M)}{dE_\mu}$$

Pion Decays:

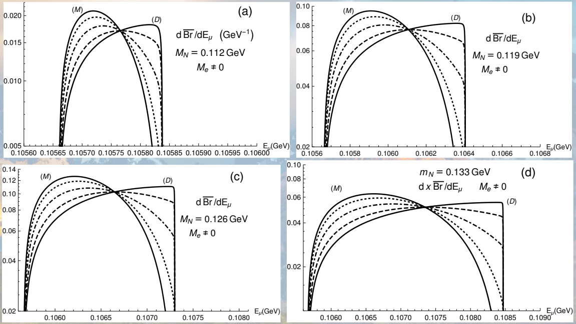


Figure: The canonical differential branching ratio $d\overline{\mathrm{Br}}_{\pi}(\alpha_M)/dE_{\mu}$ as a function of the muon energy in the neutrino N rest frame, E_{μ}. In each graph there are five curves, corresponding to different values of the admixture parameter α_M: $\alpha_M = 1.0$ is the solid (M) curve; 0.8 (dotted); 0.5 (dot-dashed); 0.2 (dashed). The case mediated by a Dirac neutrino ($\alpha_M = 0$) is the solid line labelled (D). (Work in progress with: A. Gago & M. Delgado de la Flor, Minerνa.)

τ decays:

CP violation in τ decays:

τ Decays:

CP violation in τ decays: Let's consider: $\nu_\ell = \sum_{j=1}^{3} B_{\ell j}\nu_j + B_{\ell N_1} N_1 + B_{\ell N_2} N_2$

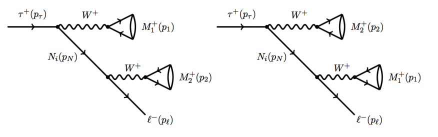


Figure: Feynmann diagrams for the process $\tau^+ \to M_1^+ M_2^+ \ell^-$. Left side: Direct channel D. Right side: Crossed channel C. (J. Zamora-Saa. arXiv:1612.07656)

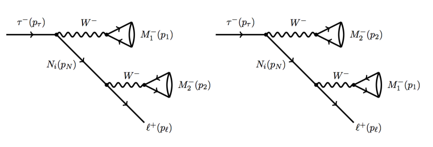


Figure: Feynmann diagrams for the process $\tau^- \to M_1^- M_2^- \ell^+$. Left side: Direct channel D. Right side: Crossed channel C. (J. Zamora-Saa. arXiv:1612.07656)

τ Decays: Decay width

The decay with of the process is

$$\Gamma(\tau^{\pm}) = \frac{1}{2!}(2-\delta_{M_1 M_2}) \sum_{i=1}^{2}\sum_{j=1}^{2} k_i^{(\pm)} k_j^{(\pm)*} \times \left[\widetilde{\Gamma}_{\tau}(DD^*)_{ij} + \widetilde{\Gamma}_{\tau}(CC^*)_{ij} + \widetilde{\Gamma}_{\tau\pm}(DC^*)_{ij} + \widetilde{\Gamma}_{\tau\pm}(CD^*)_{ij}\right],$$

where $\left(k_j^{(+)} = B_{\ell N_j} B^*_{\tau N_j}\right)$ and $\left(k_j^{(-)} = (k_j^{(+)})^*\right)$ and the canonical decay widths is given as

$$\widetilde{\Gamma}_{\tau\pm}(XY^*)_{ij} \equiv K_\tau^2 \frac{1}{2M_\tau}\int d_3\, P_i(X) P_j(Y)^* \not{L}_{\pm}^{X} \not{L}_{\pm}^{Y\dagger},$$

here

$$d_3 \equiv \frac{d^3\vec{p}_1}{2E_1(\vec{p}_1)} \frac{d^3\vec{p}_2}{2E_2(\vec{p}_2)} \frac{d^3\vec{p}_\ell}{2E_\ell(\vec{p}_\ell)} \delta^{(4)}\left(p_\tau - p_1 - p_2 - p_\ell\right)$$

τ Decays: Decay width

The decay with of the process is:

$$\Gamma(\tau^{\pm}) = \frac{1}{2!}\sum_{i=1}^{2}\sum_{j=1}^{2} k_i^{(\pm)} k_j^{(\pm)*} \times [\widetilde{\Gamma}_\tau(DD^*)_{ij} + \widetilde{\Gamma}_\tau(CC^*)_{ij}]$$
$$= |B_{\ell N_1}|^2 |B_{\tau N_1}|^2 \widetilde{\Gamma}_\tau(DD^*)_{11} + |B_{\ell N_2}|^2 |B_{\tau N_2}|^2 \widetilde{\Gamma}_\tau(DD^*)_{22}$$
$$+ 2|B_{\ell N_1}||B_{\ell N_2}||B_{\tau N_1}||B_{\tau N_2}|\widetilde{\Gamma}_\tau(DD^*)_{11}\cos(\theta_{12})\delta_{12}\ ,$$

here $\delta_{12} \equiv \frac{\Re\left[\widetilde{\Gamma}_\tau(DD^*)_{12}\right]}{\widetilde{\Gamma}_\tau(DD^*)_{11}}$ measures the effect of $N_1 - N_2$ overlap

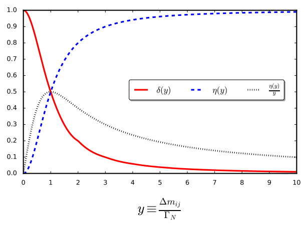


Figure: Red line overlap function δ_{12}. Blue line $\eta(y)$ function. Black line $\eta(y)/y$ function. (J. Zamora-Saa. arXiv:1612.07656)

τ Decays: CP violation in τ decays

$$\mathrm{Br}^{\mathrm{eff}}(\tau^{\pm}) = P_{N_j}\mathrm{Br}(\tau^{\pm}) = P_{N_j}\frac{\Gamma(\tau^{\pm})}{\Gamma(\tau^{\pm} \to \mathrm{all})}.$$

Where does CP violation come from:

- Complex phases in the transition amplitudes.
  - The CP-odd phases are those that come from the Lagrangian of the theory, in other words from the heavy-light mixing elements; these phases change sign between a process and its conjugate.
  - On the other hand, the CP-even phases appear as absorptive parts in the propagators and do not change sign for the conjugate process

The observable effects only arise due to interference of at least two amplitudes.

τ Decays: CP violation in τ decays

- $$A_{CP}\, Br^{\text{eff}}(\tau^+) = \frac{\Gamma(\tau^+) - \Gamma(\tau^-)}{\Gamma(\tau^+) + \Gamma(\tau^-)}\, Br^{\text{eff}}(\tau^+) \approx P_{N_j}\, \frac{\Gamma(\tau^+) - \Gamma(\tau^-)}{2\Gamma(\tau^+ \to all)}$$

- $$\Gamma(\tau^+) - \Gamma(\tau^-) \approx 4|B_{\ell N_1}||B_{\ell N_2}||B_{\tau N_1}||B_{\tau N_2}|\ \sin\theta_{12}\ \Im\left[\widetilde{\Gamma}_\tau(DD^*)_{12}\right]$$

- $$\Im\left[\widetilde{\Gamma}_\tau(DD^*)_{12}\right] = \frac{1}{2M_\tau}\int d_3\ \Im\left[P_1(D)P_2(D)^*\right]|\overline{\mathcal{T}}_+^D|^2\ .$$

$$\Im\left[P_1(D)P_2(D)^*\right] = \frac{\left(p_N^2 - M_{N_1}^2\right)\Gamma_{N_2}M_{N_2} - \Gamma_{N_1}M_{N_1}\left(p_N^2 - M_{N_2}^2\right)}{\left[\left(p_N^2 - M_{N_1}^2\right)^2 + \Gamma_{N_1}^2 M_{N_1}^2\right]\left[\left(p_N^2 - M_{N_2}^2\right)^2 + \Gamma_{N_2}^2 M_{N_2}^2\right]}$$

$$\approx \overbrace{\frac{\pi}{M_{N_2}^2 - M_{N_1}^2}}^{\text{Resonant CP Violation}}\ \left[\delta(p_N^2 - M_{N_2}^2) + \delta(p_N^2 - M_{N_1}^2)\right]\ ;$$

τ Decays: CP violation in τ decays

The validity of RCPV strongly depends on the assumption $\Gamma_{N_j} \ll M_{N_2} - M_{N_1}$. However, it is useful introduce the parameter $\eta(y)$ where $y \equiv \frac{\Delta M_N}{\Gamma_N}$, which parametrizes any deviation of RCPV when $\Gamma_{N_j} \not\ll |\Delta M_N|$:

$$\eta(y) = \frac{\Im\left[\widetilde{\Gamma}_\tau(DD^*)_{12}\right]_{\text{NWA}}}{\Im\left[\widetilde{\Gamma}_\tau(DD^*)_{12}\right]_{\text{NUM}}} \, ,$$

$$A_{CP}\, Br^{\text{eff}}(\tau^+) \approx \frac{\eta(y)}{y}\, \frac{L}{\gamma_N}\, |B_{\ell N}|^2 |B_{\tau N}|^2 \sin\theta_{12}\, \frac{3\pi K_M^2}{2G_F^2 M_\tau^8 M_N} \times \lambda^{1/2}\left(1, \frac{M_\ell^2}{M_N^2}, \frac{M_M^2}{M_N^2}\right) \times Z(M_\tau, M_N, M_M, M_\ell)\, .$$

τ Decays: Effective Branching ratio

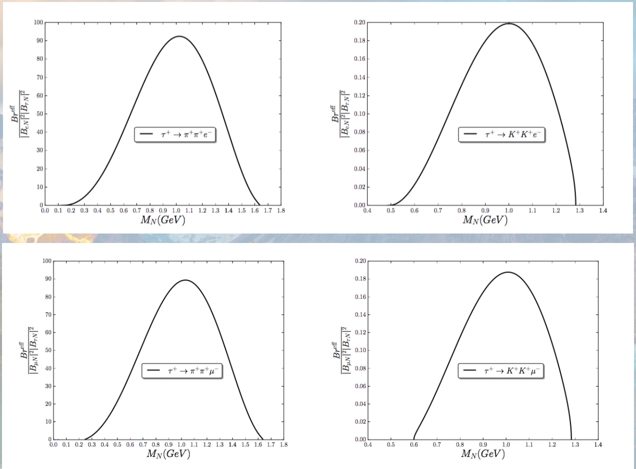


Figure: Effective branching ratios per unit of $|B_{\ell N}|^2|B_{\tau N}|^2$. Here we use the following input parameters: $\cos\theta_{12} = 1/\sqrt{2}$, overlap factor $\delta_{12} = 0.5$, detector length $L = 1$ mts, neutrino speed $\beta = 1$ and Lorentz factor $\gamma_N = 2$. (J. Zamora-Saa. arXiv:1612.07656)

τ Decays:

CP violation in τ decays: The CTF in Novosibirsk, Russia is expected to collect 10^{10} pairs of $\tau^{\pm}$ leptons after few years of operation, therefore under the latter considerations we can estimate the mixing region that can be explored in such experiment.

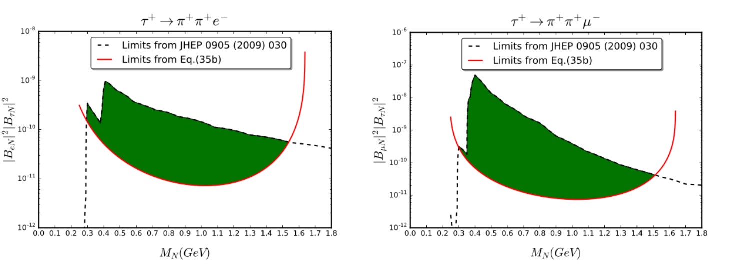
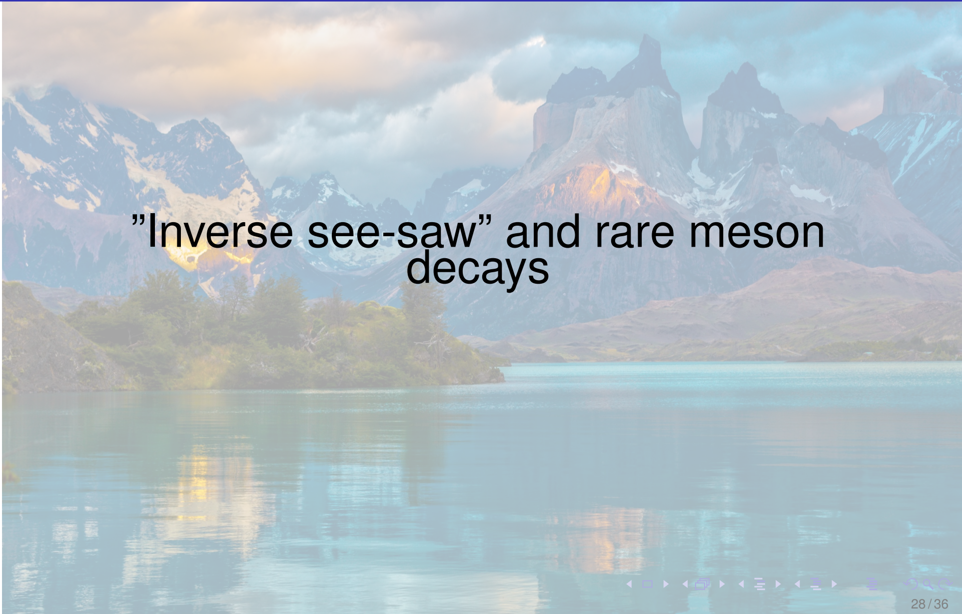


Figure: The green region shows the limits over the mixings parameter which could be reached in the future $\tau^{\pm}$ factory. Right side: Limits for $|B_{eN}|^2|B_{\tau N}|^2$. Left side: Limits for $|B_{\mu N}|^2|B_{\tau N}|^2$. Here we use the following input parameters: $\eta(y)/y = 0.5$, $N_\tau = 10^{10}$, $\cos\theta_{12} = 1/\sqrt{2}$, $L = 1$ mts, $\beta = 1$ and $\gamma_N = 2$. (J. Zamora-Saa. arXiv:1612.07656)

RMD 3PQDν:



”Inverse see-saw” and rare meson decays

RMD 3PQDν:

Let's consider a general "inverse see-saw":

$$L_{\text{mass}} = \frac{1}{2} \begin{pmatrix} \bar{\nu}_L^c & \bar{\nu}_R & \bar{S} \end{pmatrix} \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_\chi \\ 0 & M_\chi^T & \mu \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \\ S^c \end{pmatrix}$$

- Masses: $m_{light} \sim \mu \frac{m_D^2}{M^2} \quad (\mu \ll m_D \ll M_\chi)$.
- $m_{heavy} \sim M \quad (M \sim GeV, TeV)$.
- $|B_{\ell N}| \sim \frac{m_D}{M}$ not so small (maybe observable).
- In order to reproduce the RCPV conditions, "there are arguments"!!!, one of them based on naturalness, which produces a heavy neutrino mass spectrum with three pairs of quasi-degenerate neutrinos.

Let's consider the semi-hadronic meson decay:

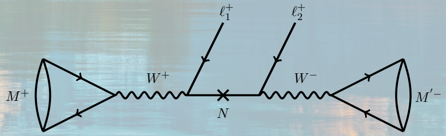


Figure: The s-channel of the lepton number violating decay $M^+ \to \ell_1^+ \ell_2^+ M'^-$.

RMD 3PQDν:

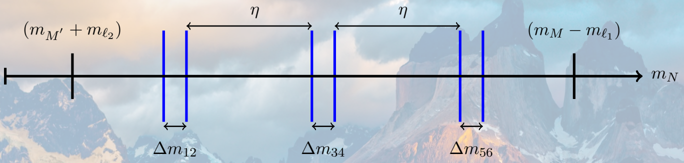


Figure: Schematic representation of the pairs distribution in on-shell mass range.

$$\Gamma_{\text{RMD}} = \frac{1}{2!}(2-\delta_{\ell_1\ell_2})\frac{1}{2M_M(2\pi)^6}\int d_3|M_M|^2 = 2(2-\delta_{\ell_1\ell_2})\left[\sum_{i=1}^{6}|B_{\ell_1 N_i}|^2|B_{\ell_2 N_i}|^2\widetilde{\Gamma}_M^{(ii)}\right.$$

$$+\sum_{j,k>j} 2|B_{\ell_1 N_j}||B_{\ell_1 N_k}||B_{\ell_2 N_j}||B_{\ell_2 N_k}|\widetilde{\Gamma}_M^{(jj)}\cos\theta_{jk}\delta_{jk} + 2|B_{\ell_1 N_1}||B_{\ell_1 N_2}||B_{\ell_2 N_1}||B_{\ell_2 N_2}|\widetilde{\Gamma}_M^{(11)}\cos\theta_{12}\delta_{12}$$

$$\left.+2|B_{\ell_1 N_3}||B_{\ell_1 N_4}||B_{\ell_2 N_3}||B_{\ell_2 N_4}|\widetilde{\Gamma}_M^{(33)}\cos\theta_{34}\delta_{34} + 2|B_{\ell_1 N_5}||B_{\ell_1 N_6}||B_{\ell_2 N_5}||B_{\ell_2 N_6}|\widetilde{\Gamma}_M^{(55)}\cos\theta_{56}\delta_{56}\right],$$

$$\widetilde{\Gamma}_M^{(jj)} = \frac{K_M^2 m_M^5}{128\pi^2}\frac{m_{N_j}}{\Gamma_{N_j}}\lambda^{1/2}(1,x_j,x_{\ell_1})\times\lambda^{1/2}\left(1,\frac{x'}{x_j},\frac{x_{\ell_2}}{x_j}\right)\times Q(x_j;x_{\ell_1},x_{\ell_2},x').$$

RMD 3PQDν:

$$\mathrm{Br}^{\mathrm{eff}}(M) = P_{N_j}\mathrm{Br}(M) = P_{N_j}\frac{\Gamma_{\mathrm{RMD}}}{\Gamma(M^{\pm} \to \mathrm{all})}.$$

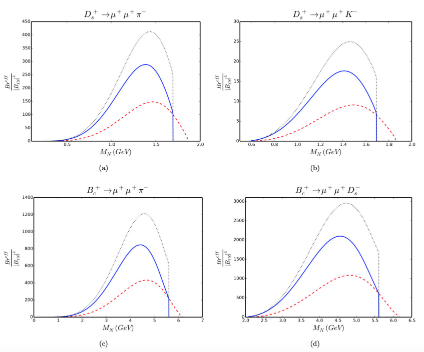


Figure: Effective Branching ratio divided by $|B_{\ell N}|^4$, as function of sterile neutrino mass, for $L = 1\overline{m}$, $\gamma_N = 2$ and $\eta = 0.1 m_N$. We regard the cases with CP violation ($\delta_{ij} = 0.5$) and $\cos\theta_{jk} = \frac{1}{\sqrt{2}}$. (G. Moreno, J. Zamora-Saa. Phys.Rev. D94 (2016) no.9, 093005).

THANK YOU

π decays

$$\frac{d\widetilde{\Gamma}^{(\mathrm{LNV})}(\pi^\pm \to e^\pm e^\pm \mu^\mp \nu)}{dE_\mu}$$
$$= \frac{K_\pi^2}{2(2\pi)^4}\frac{1}{\Gamma_N M_\pi^3}\lambda^{1/2}(M_\pi^2, M_N^2, M_e^2) \times \left[M_\pi^2 M_N^2 - M_N^4 + M_e^2(M_\pi^2 + 2M_N^2 - M_e^2)\right]$$
$$\times E_\mu\sqrt{E_\mu^2 - M_\mu^2}\,\frac{(M_N^2 - 2M_N E_\mu + M_\mu^2 - M_e^2)^2}{(M_N^2 - 2M_N E_\mu + M_\mu^2)} \quad \left(M_\mu \le E_\mu \le \frac{(M_N^2 + M_\mu^2 - M_e^2)}{2M_e}\right).$$

$$\frac{d\overline{\mathrm{Br}}_\pi^{(\mathrm{LNC})}}{dE_\mu} \equiv 2\frac{\widetilde{\mathcal{K}}}{\Gamma_\pi}\frac{d\widetilde{\Gamma}^{(\mathrm{LNC})}(\pi^\pm \to e^\pm e^\pm \mu^\mp \nu)}{dE_\mu}$$
$$= \frac{1}{M_N^6 M_\mu^2 (M_\pi^2 - M_\mu^2)^2(1+\delta g_\pi)}\lambda^{1/2}(M_\pi^2, M_N^2, M_e^2)\frac{1}{\left[M_\mu^2 + M_N(-2E_\mu + M_N)\right]^3}$$
$$\times\Big\{8\sqrt{(E_\mu^2 - M_\mu^2)}M_N\left[(2E_\mu - M_N)M_N - M_\mu^2 + M_e^2\right]^2$$
$$\times\left[M_\pi^2 M_N^2 - M_N^4 + M_e^2(M_\pi^2 + 2M_N^2) - M_e^4\right]$$
$$\times\Big[8E_\mu^3 M_N^2 - 2M_\mu^2 M_N(M_\mu^2 + M_N^2 + 2M_e^2) - 2E_\mu^2 M_N\left(5(M_\mu^2 + M_N^2) + M_e^2\right)$$
$$+E_\mu\left(3M_\mu^4 + 10M_\mu^2 M_N^2 + 3M_N^4 + 3M_e^2(M_\mu^2 + M_N^2)\right)\Big]\Big\} \qquad (M_\mu \le E_\mu \le (E_\mu)_{\max})$$

Acceptance Factor P_N

The number of decays per unit time

$$-\frac{dN}{dt} = \lambda N$$

where $\lambda = \Gamma_N$ is the decay constant

$$N(t) = N_0 e^{-\lambda t} = N_0 e^{\frac{-t}{\tau}}$$

where $N(t)$ is the number of particle "surviving" after time t. If $\left(\frac{-t}{\tau} \ll 1\right) \Rightarrow$

$$e^{\frac{-t}{\tau}} \approx 1 - \left(\frac{-t}{\tau_{LAB}}\right) = 1 - \left(\frac{L\Gamma_N}{\beta_N\, \gamma_N}\right)$$

here $t \approx L/\beta_N$; $\tau_{LAB} = \gamma_N \tau_N$, and the non survivible probability is:

$$P_N = 1 - e^{\frac{-t}{\tau}} \approx \left(\frac{L\Gamma_N}{\beta_N\, \gamma_N}\right)$$

τ Decays

The narrow with approximation

$$\frac{\Gamma_{N_j} M_{N_j}}{(x - M_{N_j}^2)^2 + \Gamma_{N_j}^2 M_{N_j}^2} = \pi\delta(x - M_{N_j}^2)$$

The product of propagators $P_1(X)P_2(X)^*$ (where $X = D, C$) can be expressed as the sum of the real and imaginary parts

$$P_1(X)P_2(X)^* = \underbrace{M_{N_1} M_{N_2} \frac{(P_N^2(X) - M_{N_1}^2)(P_N^2(X) - M_{N_2}^2) + \Gamma_{N_1}\Gamma_{N_2} M_{N_1} M_{N_2}}{\left((P_N^2(X) - M_{N_1}^2)^2 + \Gamma_{N_1}^2 M_{N_1}^2\right)\left((P_N^2(X) - M_{N_2}^2)^2 + \Gamma_{N_2}^2 M_{N_2}^2\right)}}_{\text{Rear part}}$$

$$- i\, \underbrace{M_{N_1} M_{N_2} \frac{(P_N^2(X) - M_{N_2}^2) M_{N_1}\Gamma_{N_1} - (P_N^2(X) - M_{N_1}^2) M_{N_2}\Gamma_{N_2}}{\left((P_N^2(X) - M_{N_1}^2)^2 + \Gamma_{N_1}^2 M_{N_1}^2\right)\left((P_N^2(X) - M_{N_2}^2)^2 + \Gamma_{N_2}^2 M_{N_2}^2\right)}}_{\text{Imaginary part}}$$

3PQDν

$$
\begin{aligned}
L_{\text{mass}} &= m_D \overline{\nu_L} \nu_R + M \overline{\nu_R^c} S + [\mu \text{ term}] + Hc \\
&= m_\ell \overline{\nu_\ell^c} \nu_\ell + m_1 \overline{N_1^c} N_1 + m_2 \overline{N_2^c} N_2 \\
&= m_\ell \overline{\nu_\ell^c} \nu_\ell + m_1 (\overline{N_1^c} N_1 + \overline{N_2^c} N_2) + \Delta \overline{N_2^c} N_2
\end{aligned}
$$