Heavy neutrino signals in models with extended lepton sector

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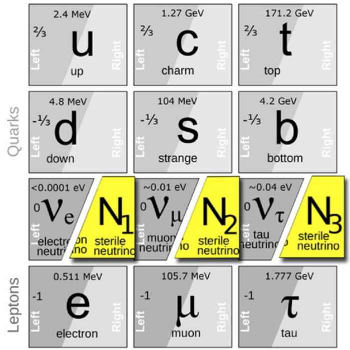
Introduction



- See-saw mechanism

We extend SM by adding $i = 1, 2, ..., k$ heavy neutral leptons N_i, $l = (e, \mu, \tau)$:

$$\mathcal{L}_\nu = -\bar{\nu}_{lL}(m_D)_{li}N_{iR} - \frac{1}{2}\overline{N}^c_{iR}(m_N)_{ij}N_{jR} + h.c.$$

where m_D - mass matrix for light neutrinos and m_N - for heavy neutrinos. The matrix equation for the physical masses of the observed neutrinos:

$$m_\nu = -m_D m_N^{-1} m_D^T$$

Model with Dirac lepton sector

The transition from flavor states to mass states is described by the Pontecorvo-Maki-Nakagawa-Sakata matrix:

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{rotation matrices with ordinary phases}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}}_{\text{Majorana phases}}$$

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}, i, j = 1, 2, 3$. Then $\nu_{lL} = \sum_{i=1}^{3} (U_{\text{PMNS}})_{li}\nu_{iL}$. Weak charged current for neutrinos:

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}}\bar{l}_n\gamma_\alpha\nu_{nL}W^\alpha + h.c. = -\frac{g}{\sqrt{2}}\bar{l}_n\gamma_\alpha(U_{\text{PMNS}})_{ni}\nu_{iL}W^\alpha + h.c.$$

Here l_n - SM leptons e, μ, τ. Writing the terms by analogy with the quark sector, we get:

$$\mathcal{L}_1 = -Y^l_{mn}\bar{L}'_m H l_n + h.c. \quad \mathcal{L}_2 = -Y^\nu_{ij}U_{li}\bar{L}'_i\tilde{H}\nu_j + h.c.$$

L'_m - "rotated" lepton doublet with mixing, the masses of physical neutrinos are obtained from eigenvalues of Yukawa matrix y_ν: $m_{\nu i} = \frac{y_\nu}{\sqrt{2}}v$, where v - Higgs vacuum, $j = 1, 2, 3$.
The result of CompHEP for the total decay width of the Z^0-boson $\Gamma^Z_{tot} = 2,502$ GeV. Electroweak radiation corrections are small. Experimental value $\Gamma^Z_{tot} = 2.4952 \pm 0.0023$ GeV.

Model with a Majorana lepton sector

The complete mass matrix M_ν for neutrinos is obtained and diagonalized by the see-saw mechanism. The mechanism requires a hierarchy of $m_D \ll m_N$ and $\det m_N \neq 0$, so an inverse matrix exists.

$$m_\nu = -m_D m_N^{-1} m_D^T, \quad M_N = m_N$$

- Simplified model with a single heavy neutrino

Let's consider a light neutrino ν_L with real mass m_D and heavy neutral lepton - Majorana neutrino N_R with real mass m_N. Lagrangian:

$$\mathcal{L}_\nu = -m_D \bar{\nu_L} N_R - \frac{m_N}{2} \bar{N_R^c} N_R + h.c. =$$

$$= -\frac{1}{2} \begin{pmatrix} \bar{\nu_L} & \bar{N_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & m_N \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix} + h.c.$$

Transition to massive states ν_L' and N_R' from SU(2) states ν_L и N_R have the form:

$$\begin{pmatrix} \nu_L \\ N_R \end{pmatrix} = \begin{pmatrix} s_\alpha & c_\alpha \\ -c_\alpha & s_\alpha \end{pmatrix} \begin{pmatrix} \nu_L' \\ N_R' \end{pmatrix}$$

Where $\sin\alpha = s_\alpha$ and $\cos\alpha = c_\alpha$. After substituting in the Lagrangian, we get the following expressions for angles:

$$s_\alpha^2 = \frac{1}{2}(1 \pm \sqrt{1-a}), \quad c_\alpha^2 = \frac{1}{2}(1 \mp \sqrt{1-a})$$

Model with a Majorana lepton sector

Using the obtained form of angles, we can obtain relations for the masses of physical states m_{ne} and m_{Ne}:

$$m_N = m_{ne} + m_{Ne}, \quad m_D = \sqrt{-m_{ne} m_{Ne}}$$

By finding eigenvalues and eigenvectors, we can get the vectors of mass states:

$$\nu' = \begin{pmatrix} 1 - \frac{m_D^2}{2m_N^2} \\ -\frac{m_D}{m_N} \end{pmatrix}, \quad N' = \begin{pmatrix} \frac{m_D}{m_N} \\ 1 - \frac{m_D^2}{2m_N^2} \end{pmatrix}$$

The mixing parameter and the flavor state have the form:

$$U = -\frac{m_D}{m_N} = \frac{\sqrt{-m_{ne} m_{Ne}}}{m_{ne} + m_{Ne}}, \quad \nu = \nu'(1 - \frac{U^2}{2}) + UN'$$

We consider the process $e^+e^- \to Z^0$ with decays $Z^0 \to N_e \nu_e$, $N_e \to W^+ e^-$ and $W^+ \to jets$. Diagrams for $e^+e^- \to \nu_e e^- u\bar{d}$ are shown on fig. 1. Contours and surfaces for cross sections are shown on fig. 2 and 3.

Model with a Majorana lepton sector

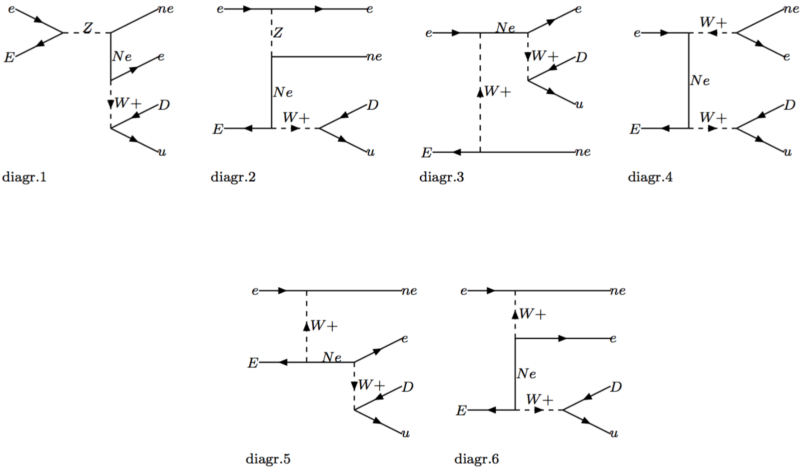


Figure 1 : Feynman diagrams for the process $e^+e^- \to \nu_e e^- u\bar{d}$

Model with a Majorana lepton sector

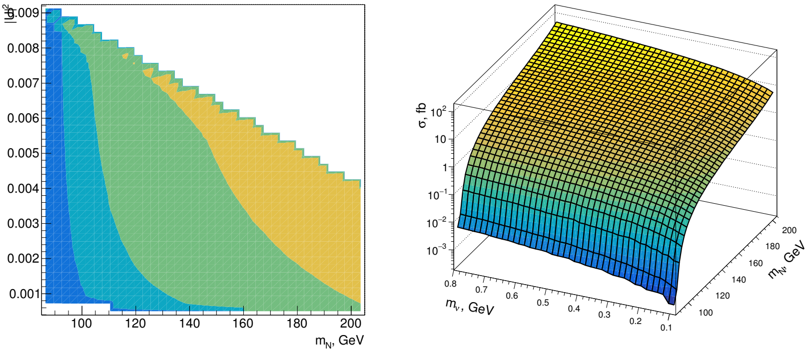
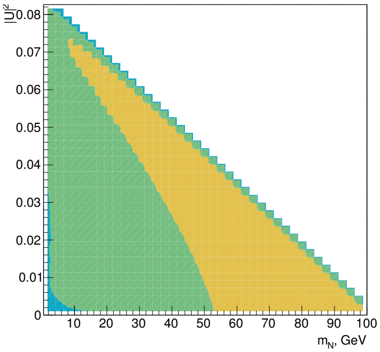


Figure 2 : Contour and surface: mixing parameter $|U|^2$ as a function m_N for mass of light neutrino from 0.08 to 0.8 GeV and mass of heavy from 85 to 205 GeV. Levels on contours are divided by characteristic luminosities for the number of events $N = 10$ from 0.1 to 1000 fb^{-1}.

Model with a Majorana lepton sector



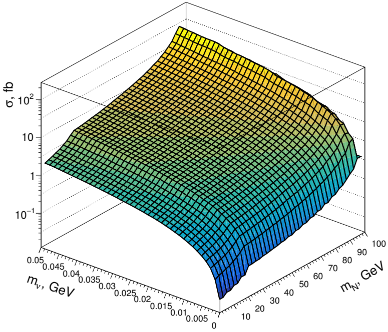


Figure 3 : Contour and surface: mixing parameter $|U|^2$ as a function m_N for mass of light neutrino from 5×10^{-7} to 0.05 GeV and mass of heavy from 0.5 to 100 GeV. Levels on contours are made by characteristic luminosities for the number of events $N = 10$ from 0.1 to 1000 fb^{-1}.

Model with a Majorana lepton sector

- Complete model with three heavy neutrinos

Generaly we can add k heavy right neutrino fields N_{iR}, $i = 1, ..., k$.

$$\mathcal{L}_\nu = -\bar{\nu}_{lL}(m_D)_{li}N_{iR} - \frac{1}{2}\overline{N}^c_{iR}(m_N)_{ij}N_{jR} + h.c.$$

The complete mass matrix is diagonalized in the block form:

$$W^T \begin{pmatrix} 0 & m_D \\ m_D^T & m_N \end{pmatrix} W = \begin{pmatrix} U^* m U^\dagger & 0 \\ 0^T & V^* M V^\dagger \end{pmatrix}$$

Where W is $(3+k) \times (3+k)$ unitary matrix, $m = diag(m_1, m_2, m_3)$ - diagonal mass matrix for light, $M = diag(M_1, M_2, ..., M_k)$ - for heavy massive states. The diagonalizing matrix can be expressed as the exponent of the anti-hermitian matrix:

$$W = exp \begin{pmatrix} 0 & R \\ -R^\dagger & 0 \end{pmatrix} = \begin{pmatrix} 1 - \frac{1}{2}RR^\dagger & R \\ -R^\dagger & 1 - \frac{1}{2}R^\dagger R \end{pmatrix} + O(R^3)$$

R is $3 \times k$ complex matrix, second equation were obtained under the condition that R is "small".

Model with a Majorana lepton sector

Charged and neutral currents for heavy Majorana fields N_j:

$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}}\bar{l}\gamma_\alpha (RV)_{lk}(1-\gamma_5)N_k W^\alpha + h.c.$$

$$\mathcal{L}_{NC} = -\frac{g}{2c_w}\bar{\nu}_{lL}\gamma_\alpha (RV)_{lk}N_{kL} Z^\alpha + h.c.$$

The mixing are characterized by matrix RV. Using the equation for diagonalization of the block mass matrix and the explicit form for W, we can obtain that $R^* \simeq m_D m_N^{-1}$ and express the mass of light and heavy neutrinos by m_N and R:

$$m_\nu = U^* \hat{m} U^\dagger = -R^* m_N R^\dagger; \quad V^* \hat{M} V^\dagger \simeq m_N + R^T R^* m_N + m_N R^\dagger R$$

Using unitary transformations by the W matrix, one can first make "block" diagonalization, and then diagonalization of non-zero mass "blocks" using the U and V matrices. Using the existing upper limits on the squares of neutrino masses and mixing angles obtained from oscillation experiments, it is possible to obtain possible ranges of m_ν values. We took a rough estimation $|(m_\nu)_{l'l}| \lesssim 1$ eV, $l', l = e, \mu, \tau$. Then we can express:

$$\sum_k |(RV)^*_{l'k} M_k (RV)^\dagger_{kl}| \lesssim 1\text{eV}, \quad l', l = e, \mu, \tau \tag{1}$$

Model with a Majorana lepton sector

The main difficulty is to "adjust" all matrices in our model so that diagonalization actually occurs and they satisfy the expression (1). A general way to set the m_D matrix is to parameterize it as follows:

$$m_D = iU^*_{\mathsf{PMNS}}\sqrt{\hat{m}}\Omega\sqrt{\hat{M}}V^\dagger$$

where Ω - an arbitrary complex orthogonal matrix. Hence, choosing a convenient form of the Ω matrix, you can always construct a Dirac matrix for neutrinos with the necessary orders of eigenvalues, from which the physical parameters follow.

For example, we can consider the simplest case of an orthogonal complex matrix $\Omega = iI$ and take $m_N = \hat{M}$ - the case of a diagonal matrix for heavy neutrinos, i.e. $V = I$.

For simplicity we write Pontecorvo-Maki-Nakagawa-Sakata matrix as:

$$U_{\mathsf{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{m1} & U_{m2} & U_{m3} \\ U_{t1} & U_{t2} & U_{t3} \end{pmatrix}$$

Then, substituting all matrices in the parametrization, we get the form of the matrix R:

$$RV = R = -\begin{pmatrix} U_{e1}\sqrt{\frac{m_1}{M_1}} & U_{e2}\sqrt{\frac{m_2}{M_2}} & U_{e3}\sqrt{\frac{m_3}{M_3}} \\ U_{m1}\sqrt{\frac{m_1}{M_1}} & U_{m2}\sqrt{\frac{m_2}{M_2}} & U_{m3}\sqrt{\frac{m_3}{M_3}} \\ U_{t1}\sqrt{\frac{m_1}{M_1}} & U_{t2}\sqrt{\frac{m_2}{M_2}} & U_{t3}\sqrt{\frac{m_3}{M_3}} \end{pmatrix}$$

One can test this model using the LanHEP package and plot contours and surfaces for this test model in CompHEP. The structure of mixing is non-trivial, since the non-zero widths of all three heavy leptons are taken into account at the same time. For the lightest lepton, the contour and surface are shown in 4. We took values $M_1 = 10$ Kev, $M_2 = 400$ MeV, $M_3 = 420$ MeV for example calculation.

Since N_1 is considered to play the role of dark matter, its contribution to the see-saw matrix must be insignificant in order to play no role in the baryogenesis of the Universe.

Model with a Majorana lepton sector

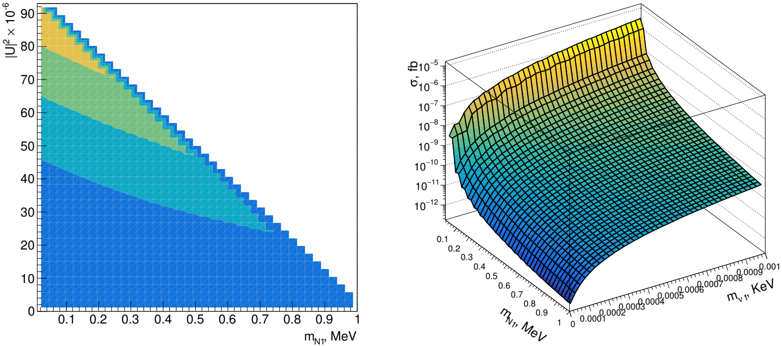


Figure 4 : Contour and surface: mixing parameter $|U|^2$ as a function m_{N_1} for mass of light neutrino from 10^{-9} to 10^{-3} KeV and mass of heavy from 0.01 to 1 MeV.

As it can be seen from fig. 4, width of N_1 relatively small and there is almost no dependence on mixing.

Model with a Majorana lepton sector

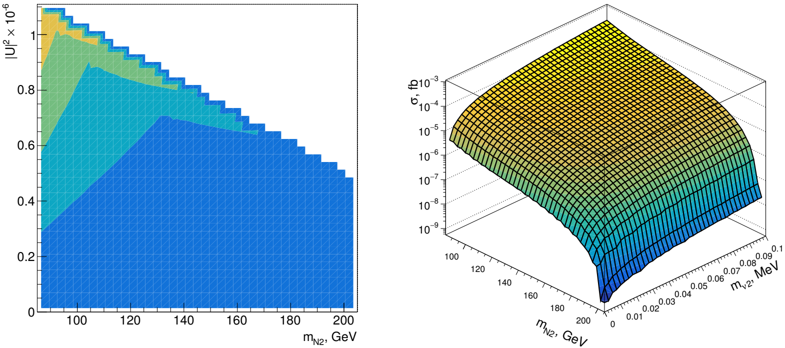


Figure 5 : Contour and surface: mixing parameter $|U|^2$ as a function m_{N_2} for mass of light neutrino from 10^{-7} to 0.1 MeV and mass of heavy from 85 to 205 GeV.

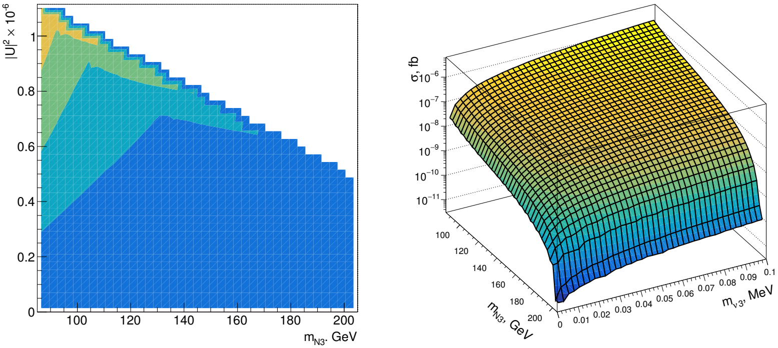


Figure 6 : Contour and surface: mixing parameter $|U|^2$ as a function m_{N_3} for mass of light neutrino from 10^{-7} to 0.1 MeV and mass of heavy from 85 to 205 GeV.

Conclusions

- The model using only the Dirac type of neutrino mass is hard to compare the precision experimental data of the LEP2 Collider.
- Two models were considered for Majorana neutrinos: a simplified model with one light neutrino and a heavy lepton, and a complete model with three generations. Block diagonalization of the total neutrino mass matrix was performed.
  The results were presented as calculations of cross sections, cross section contours and surfaces for simple and complete models for the $e^+e^- \to \nu_e e^- u\bar{d}$ process. The levels on the contours were divided according to the characteristic luminosities for the number of events $N = 10$ from 0.1 to 1000 fb^{-1}. Based on the characteristic luminosities, it is possible to determine which experiments can use such parameters to detect heavy leptons.
- For the complete model, contours were calculated for the specific case of parametrization of the Dirac mass matrix.

Conclusions

Thank you for your attention!