Long lived heavy neutrino search at the underground experiments

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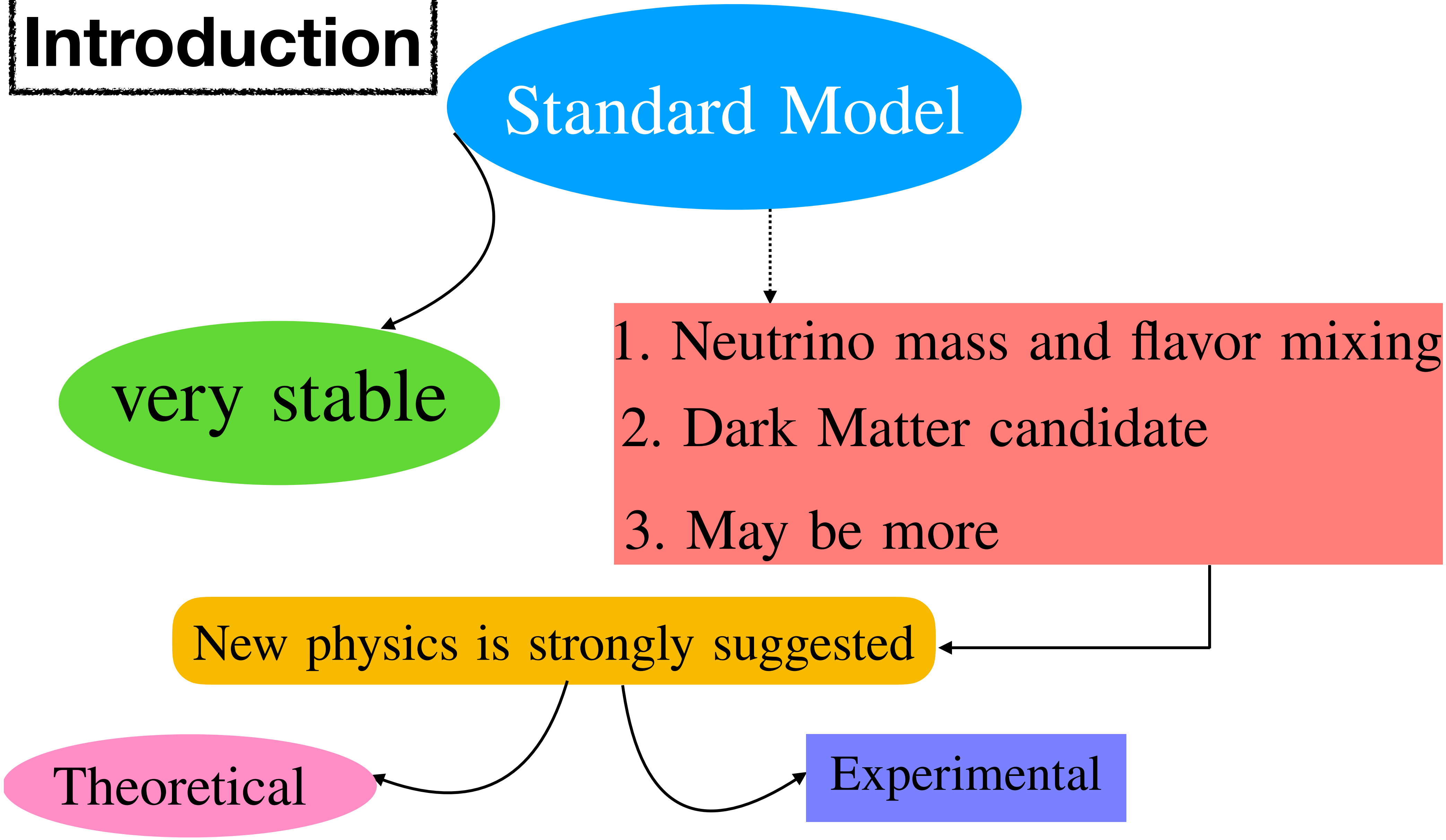
Introduction



We definitely need new physics to provide missing pieces

Particle content of the model

	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$			$U(1)_X$
q_L^i	**3**	**2**	$+1/6$	x_q	$=$	$\frac{1}{6}x_H + \frac{1}{3}x_\Phi$
u_R^i	**3**	**1**	$+2/3$	x_u	$=$	$\frac{2}{3}x_H + \frac{1}{3}x_\Phi$
d_R^i	**3**	**1**	$-1/3$	x_d	$=$	$-\frac{1}{3}x_H + \frac{1}{3}x_\Phi$
ℓ_L^i	**1**	**2**	$-1/2$	x_ℓ	$=$	$-\frac{1}{2}x_H - x_\Phi$
e_R^i	**1**	**1**	-1	x_e	$=$	$-x_H - x_\Phi$
H	**1**	**2**	$+1/2$	x'_H	$=$	$\frac{1}{2}x_H$
N_R^i	**1**	**1**	0	x_ν	$=$	$-x_\Phi$
Φ	**1**	**1**	0	x'_Φ	$=$	$2x_\Phi$

$$m_{Z'} = 2\, g_X v_\Phi$$

x_H, x_Φ will appear the coupling with Z'

3 generations of SM singlet right handed neutrinos (anomaly free)

Charges before the anomaly cancellations

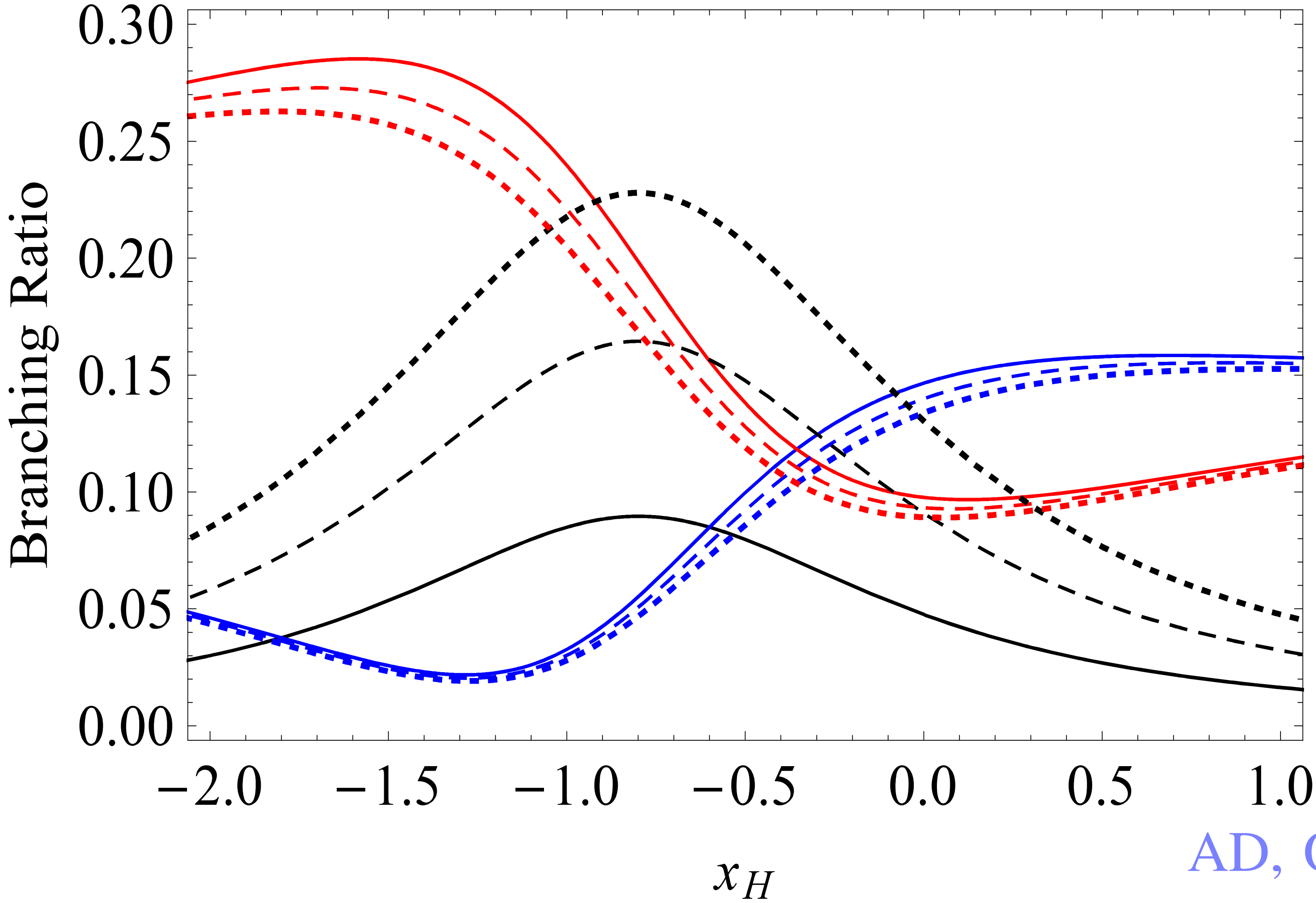
Charges after Imposing the anomaly cancellations

$U(1)_X$ **breaking**

$$\mathcal{L}_Y \supset -\sum_{i,j=1}^{3} Y_D^{ij}\overline{\ell_L^i} H N_R^j - \frac{1}{2}\sum_{i=k}^{3} Y_N^k \Phi \overline{N_R^{k\,c}} N_R^k + \text{h.c.},$$

$$\boxed{m_D^{ij} = \frac{Y_D^{ij}}{\sqrt{2}} v_h} \qquad \boxed{m_{N^i} = \frac{Y_N^i}{\sqrt{2}} v_\Phi} \qquad m_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix} \qquad m_\nu \simeq -M_D M_N^{-1} M_D^T$$

The branching ratios of Z' boson as a function of x_H with a fixed $M_{Z'} = 3.0$ TeV



Solid : $M_{N_1} = \frac{M_{Z'}}{4}$, $M_{N_{2,3}} > \frac{M_{Z'}}{2}$

Dashed : $M_{N_{1,2}} = \frac{M_{Z'}}{4}$, $M_{N_3} > \frac{M_{Z'}}{2}$

Dotted : $M_{N_{1,2,3}} = \frac{M_{Z'}}{4}$

AD, Okada, Raut, 1710.03377

Top → bottom : Solid (Red, Black, Blue)

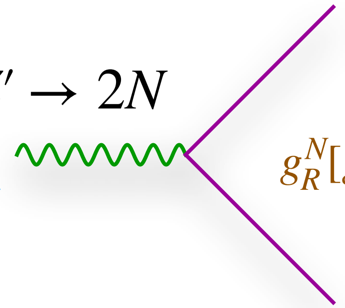
Up and down quarks

Heavy neutrinos

Charged leptons

Right handed neutrino pair production

$Z' \to 2N$

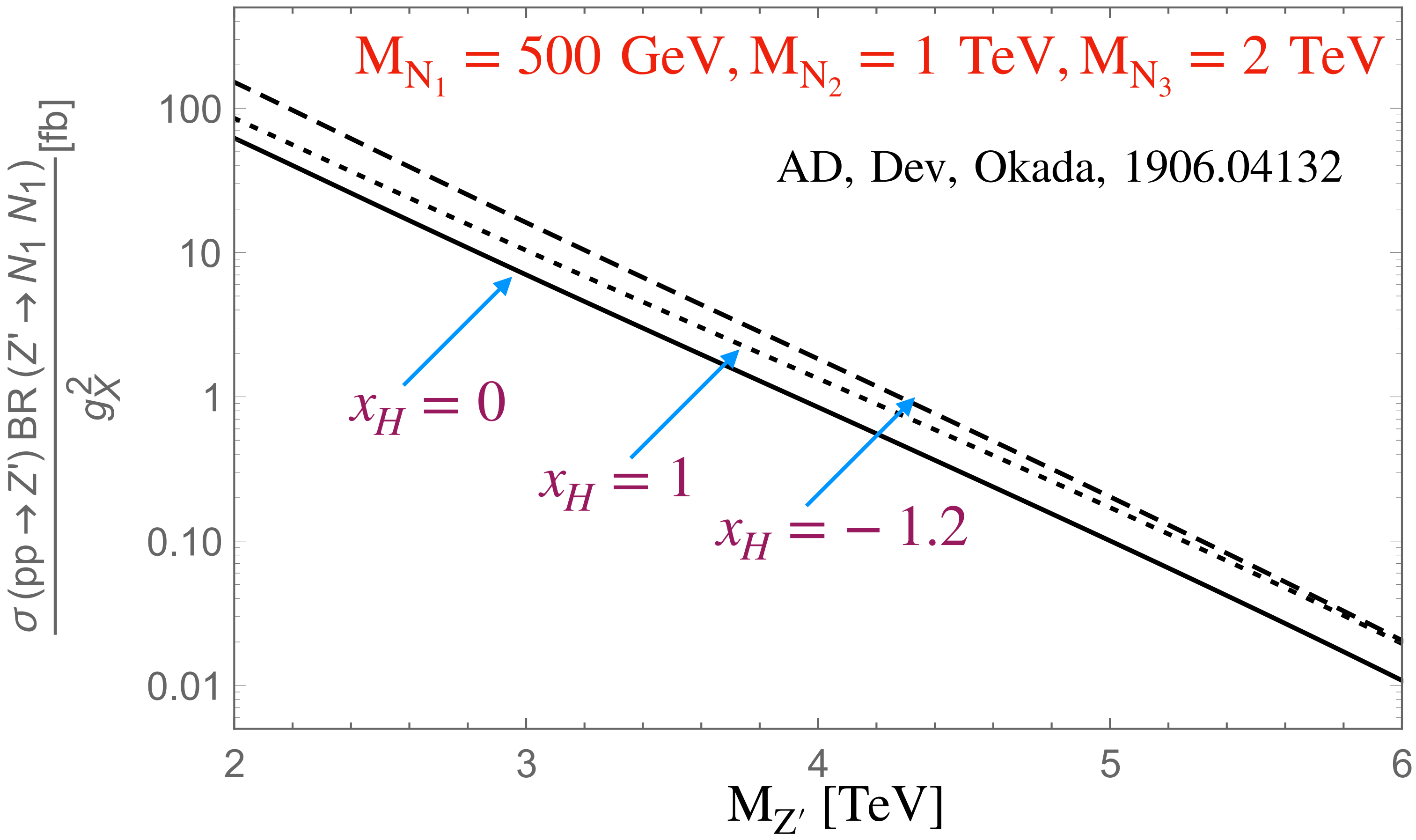


$$g_R^N[g_x, x_H] = \left(0\ x_H + (-1)\right) g_x$$

$M_{Z'} > 2M_N$ (at least)

$$M_N = \frac{Y_N^i}{\sqrt{2}} v_\Phi$$

$$\boxed{\Gamma[Z' \to 2N_i] = \frac{M_{Z'}}{24\pi} g_R^N[g_x, x_H]^2 \left(1 - 4\frac{M_{N_i}^2}{M_{Z'}^2}\right)^{\frac{3}{2}}}$$



Neutrino oscillation data

$$\Delta m_{12}^2 = m_2^2 - m_1^2 = 7.6 \times 10^{-5}\ \mathrm{eV}^2 \qquad \Delta m_{23}^2 = |m_3^2 - m_2^2| = 2.4 \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2 2\theta_{12} = 0.87 \qquad \sin^2 2\theta_{23} = 1.0 \qquad \sin^2 2\theta_{13} = 0.092$$

$$U_{\mathrm{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\rho_1} & 0 \\ 0 & 0 & e^{i\rho_2} \end{pmatrix} \qquad \delta = \frac{3\pi}{2}$$

NoνA, T2K

Partial decay width of RHN

$$\Gamma(N_i \to \ell_\alpha W)^{\mathrm{NH/IH}} = \frac{|\mathcal{R}_{\alpha i}^{\mathrm{NH/IH}}|^2}{16\pi} \frac{(m_{N_i}^2 - m_W^2)^2 (m_{N_i}^2 + 2m_W^2)}{m_{N_i}^3 v^2},$$

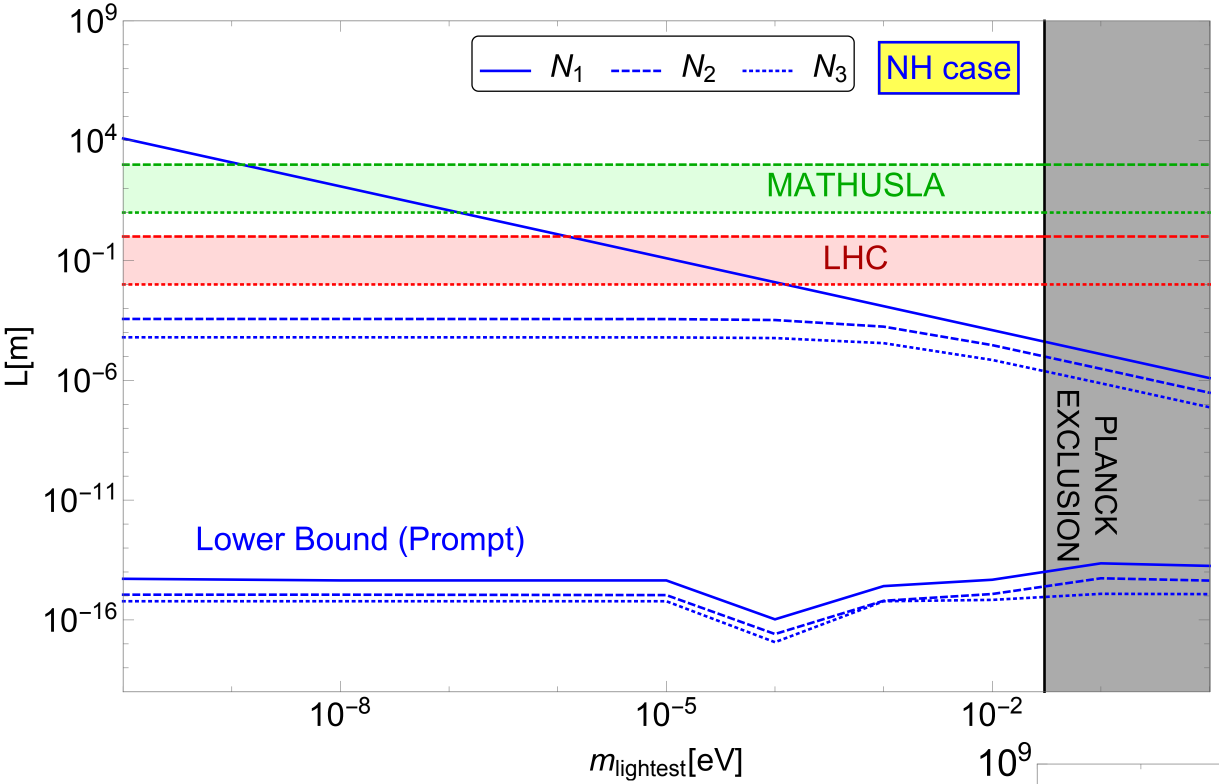
$$\Gamma(N_i \to \nu^\alpha Z)^{\mathrm{NH/IH}} = \frac{|\mathcal{R}_{\alpha i}^{\mathrm{NH/IH}}|^2}{32\pi} \frac{(m_{N_i}^2 - m_Z^2)^2 (m_{N_i}^2 + 2m_Z^2)}{m_{N_i}^3 v^2}, \qquad \Gamma(N_i \to \nu^\alpha h)^{\mathrm{NH/IH}} = \frac{|\mathcal{R}_{\alpha i}^{\mathrm{NH/IH}}|^2}{32\pi} \frac{(m_{N_i}^2 - m_h^2)^2}{m_{N_i} v^2}$$

$$\boxed{\Gamma_{N_i}^{\mathrm{NH/IH}} = \sum_{\alpha=e,\mu,\tau} \left[\Gamma(N_i \to \ell_\alpha W)^{\mathrm{NH/IH}} + \Gamma(N_i \to \nu_\alpha Z)^{\mathrm{NH/IH}} + \Gamma(N_i \to \nu_\alpha h)^{\mathrm{NH/IH}}\right]}$$

Decay length of RHN

$$L_i^{\mathrm{NH/IH}} = \frac{1.97 \times 10^{-13}}{\Gamma_{N_i}^{\mathrm{NH/IH}}[\mathrm{GeV}]}\ [\mathrm{mm}].$$

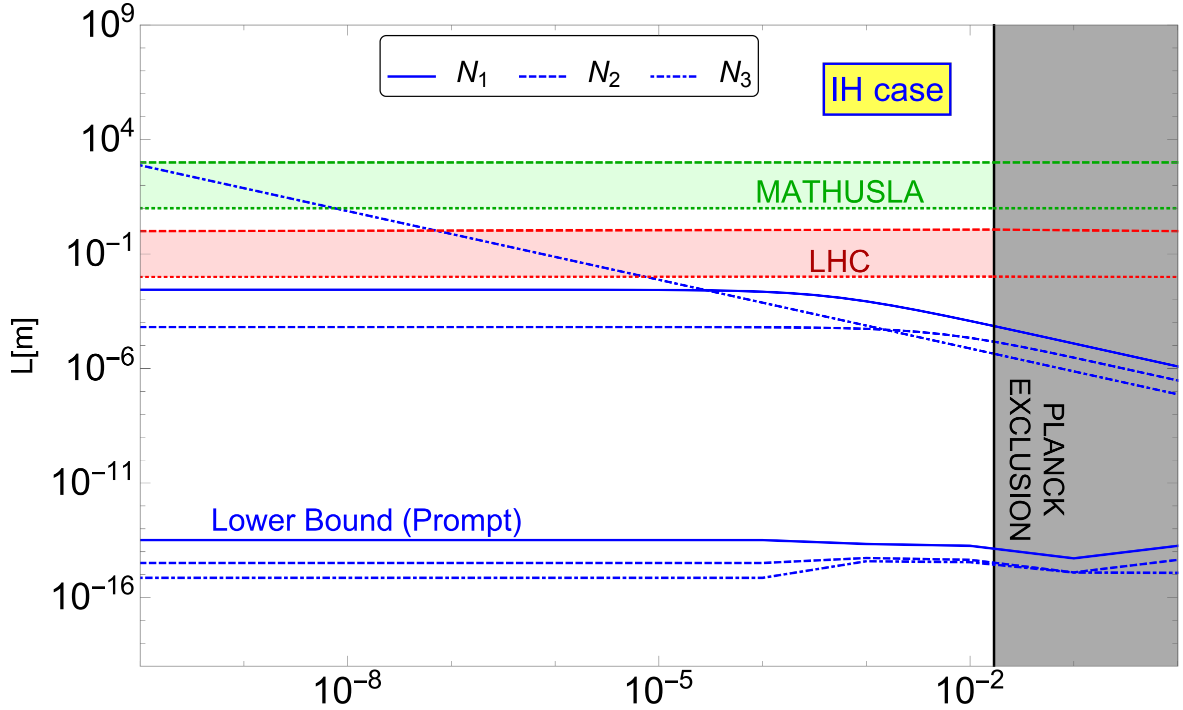
Decay length of RHNs neutrinos as a function of lightest active neutrino mass



$M_{N_1} = 500$ GeV $M_{N_2} = 1$ TeV

$M_{N_3} = 2$ TeV

1906.04132



Type – III seesaw

Das, Mandal; will appear soon

$$\mathcal{L} = \mathcal{L}_{\rm SM} + {\rm Tr}(\overline{\Psi} i\gamma^\mu D_\mu \Psi) - \frac{1}{2} M {\rm Tr}(\overline{\Psi}\Psi^c + \overline{\Psi^c}\Psi) - \sqrt{2}(\overline{\ell_L} Y_D^\dagger \Psi H + H^\dagger \overline{\Psi} Y_D \ell_L)$$

$$\Psi = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix} \text{ and } \Psi^c = \begin{pmatrix} \Sigma^{0c}/\sqrt{2} & \Sigma^{-c} \\ \Sigma^{+c} & -\Sigma^{0c}/\sqrt{2} \end{pmatrix}$$

$$-\mathcal{L}_{\rm mass} = \begin{pmatrix} \overline{e}_L & \overline{\Sigma}_L \end{pmatrix} \begin{pmatrix} m_\ell & Y_D^\dagger v \\ 0 & M \end{pmatrix} \begin{pmatrix} e_R \\ \Sigma_R \end{pmatrix} + \frac{1}{2} \begin{pmatrix} \overline{\nu_L^c} & \overline{\Sigma_R^0} \end{pmatrix} \begin{pmatrix} 0 & Y_D^T \frac{v}{\sqrt{2}} \\ Y_D \frac{v}{\sqrt{2}} & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \Sigma_R^{0c} \end{pmatrix} + h.c.$$

$$\boxed{m_\nu \simeq -\frac{v^2}{2} Y_D^T M^{-1} Y_D = M_D M^{-1} M_D^T}$$

$$\Gamma(\Sigma^\pm \to \nu W) = \frac{g^2 |V_{\ell\Sigma}|^2}{32\pi}\left(\frac{M^3}{M_W^2}\right)\left(1 - \frac{M_W^2}{M^2}\right)^2\left(1 + 2\frac{M_W^2}{M^2}\right)$$

$$\Gamma(\Sigma^\pm \to \ell Z) = \frac{g^2 |V_{\ell\Sigma}|^2}{64\pi \cos^2\theta_W}\left(\frac{M^3}{M_Z^2}\right)\left(1 - \frac{M_Z^2}{M^2}\right)^2\left(1 + 2\frac{M_Z^2}{M^2}\right)$$

$$\Gamma(\Sigma^\pm \to \ell h) = \frac{g^2 |V_{\ell\Sigma}|^2}{64\pi}\left(\frac{M^3}{M_W^2}\right)\left(1 - \frac{M_h^2}{M^2}\right)^2,$$

$$\Gamma(\Sigma^\pm \to \Sigma^0 \pi^\pm) = \frac{2G_F^2 V_{ud}^2 \Delta M^3 f_\pi^2}{\pi}\sqrt{1 - \frac{m_\pi^2}{\Delta M^2}}$$

$$\Gamma(\Sigma^\pm \to \Sigma^0 e \nu_e) = \frac{2G_F^2 \Delta M^5}{15\pi}$$

$$\Gamma(\Sigma^\pm \to \Sigma^0 \mu \nu_\mu) = 0.12\Gamma(\Sigma^\pm \to \Sigma^0 e \nu_e)$$

$$\Gamma(\Sigma^0 \to \ell^+ W) = \Gamma(\Sigma^0 \to \ell^- W) = \frac{g^2 |V_{\ell\Sigma}|^2}{64\pi}\left(\frac{M^3}{M_W^2}\right)\left(1 - \frac{M_W^2}{M^2}\right)^2\left(1 + 2\frac{M_W^2}{M^2}\right)$$

$$\Gamma(\Sigma^0 \to \nu Z) = \Gamma(\Sigma^0 \to \overline{\nu} Z) = \frac{g^2 |V_{\ell\Sigma}|^2}{128\pi \cos^2\theta_W}\left(\frac{M^3}{M_Z^2}\right)\left(1 - \frac{M_Z^2}{M^2}\right)^2\left(1 + 2\frac{M_Z^2}{M^2}\right)$$

$$\Gamma(\Sigma^0 \to \nu h) = \Gamma(\Sigma^0 \to \overline{\nu} h) = \frac{g^2 |V_{\ell\Sigma}|^2}{128\pi}\left(\frac{M^3}{M_W^2}\right)\left(1 - \frac{M_h^2}{M^2}\right)^2,$$

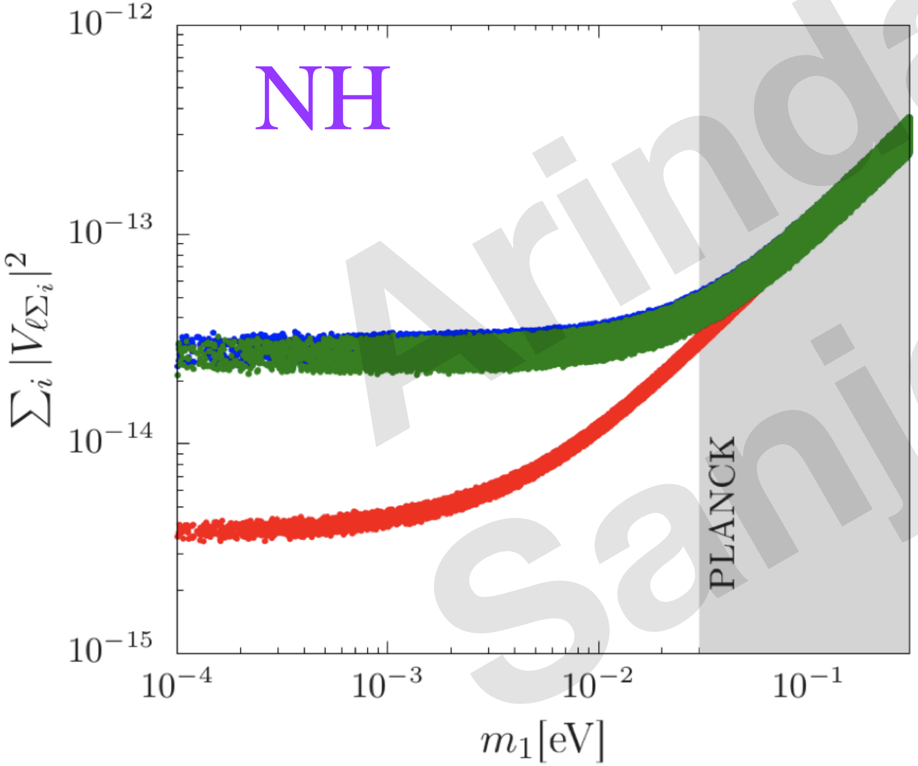
Limits on the mixing

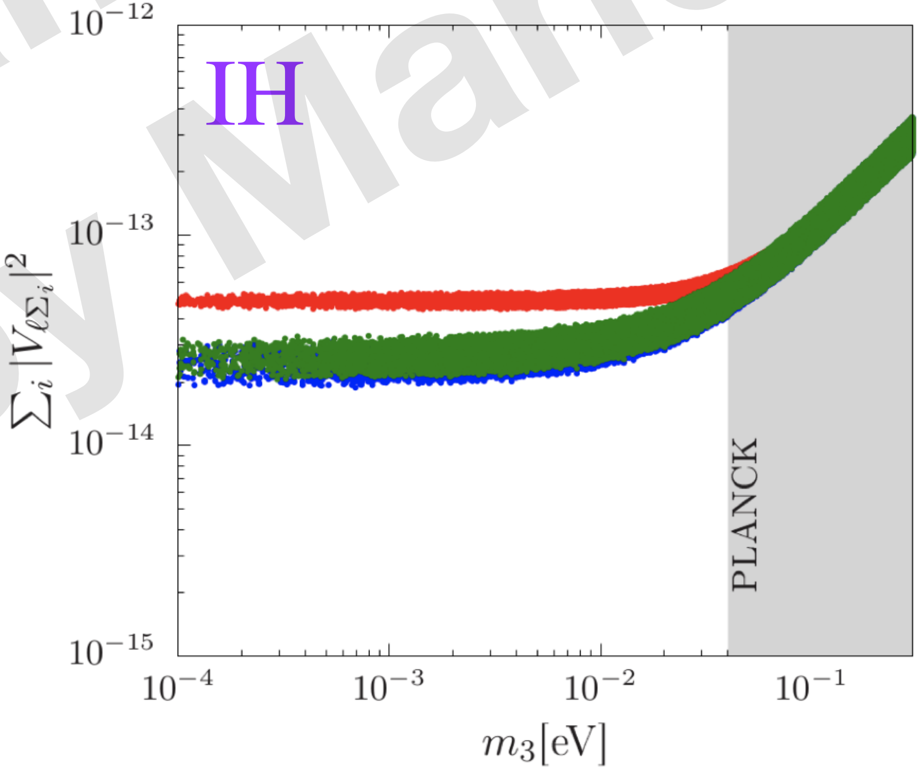
Das, Mandal; will appear soon

$$M_D^{\mathrm{NH/IH}} = V^*_{\mathrm{PMNS}} \sqrt{D_{\mathrm{NH/IH}}} \sqrt{M}.$$

$$\Sigma_i |V_{\ell\Sigma_i}|^2 = |V_{\ell\Sigma_1}|^2 + |V_{\ell\Sigma_2}|^2 + |V_{\ell\Sigma_3}|^2$$

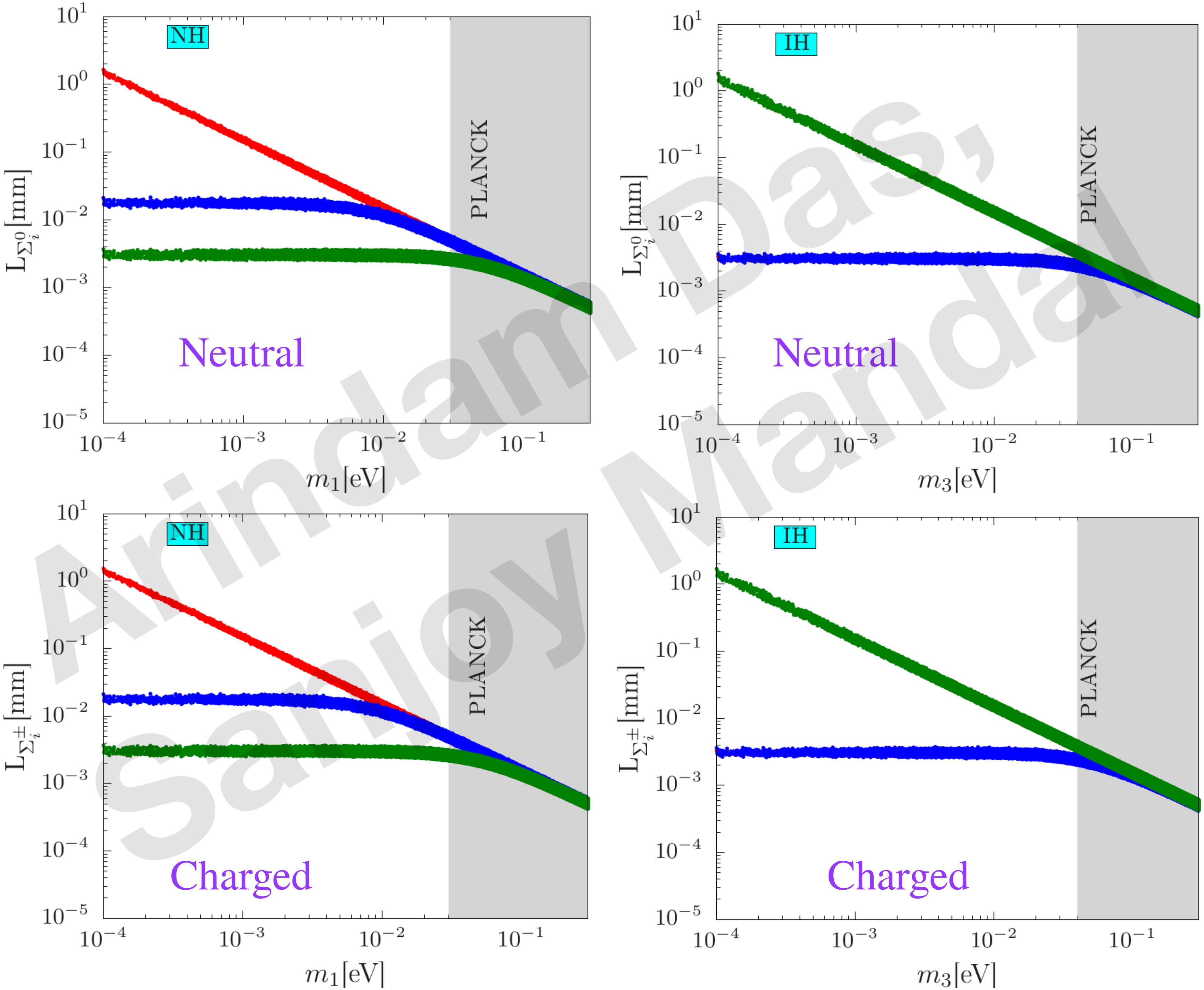
$M = 1$ TeV.





Proper Decay Length

Das, Mandal; will appear soon



Conclusions

We study the models with the heavy fermions under the simple extensions of the SM where the neutrino mass is generated by the seesaw mechanism to reproduce the neutrino oscillation data.

We find that such heavy fermions can be tested at the underground experiments such as Large Hadron Collider and International Linear Collider. The interesting fact is such scenarios can be tested by the displaced vertex searches. We have calculated the total proper decay lengths of the and found that could be probed at the high energy collider experiments.

Thank You