keV dark matter in the Minimal left-right symmetric model with TeV scale gauge bosons

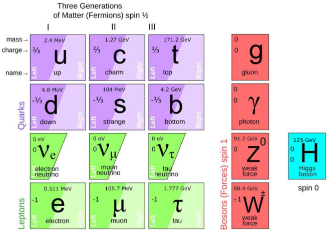
E. Fedotova
in collaboration with M. Dubinin, D. Kazarkin

SINP MSU

The 7th international conference on particle physics and astrophysics
ICPPA 2024
National Research Nuclear University MEPhI

22 – 25 October, 2024
Moscow, Russia

Introduction



M. Shaposhnikov, J. Phys. Conf. Ser. 408 (2013) 012015

SM can not solve
– the problem of neutrino masses
– the DM problem
– the problem of baryon asymmetry in the Universe (BAU)
– ...

Left-right simmetric models based on the group

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

can solve these problems

- the symmetry between right- and left-handed $SU(2)$ groups is restored
- the smallness of m_ν by seesaw mechanism and neutrino oscillations
- BAU
- ...

The most popular is the Minimal Left-Right-Symmetric Model – MLRM

MLRM: fields

- Leptons and quarks

$$L_{iL,R} = \begin{pmatrix} \nu_i' \\ l_i' \end{pmatrix}_{L,R}, \qquad Q_{iL,R} = \begin{pmatrix} u_i' \\ d_i' \end{pmatrix}_{L,R} \tag{1}$$

$$L_L : (1_C, 2_L, 1_R, -1_{B-L}) \qquad Q_L : (3_C, 2_L, 1_R, 1/3_{B-L}) \tag{2}$$

$$L_R : (1_C, 1_L, 2_R, -1_{B-L}) \qquad Q_R : (3_C, 1_L, 2_R, 1/3_{B-L}) \tag{3}$$

- Gauge bosons

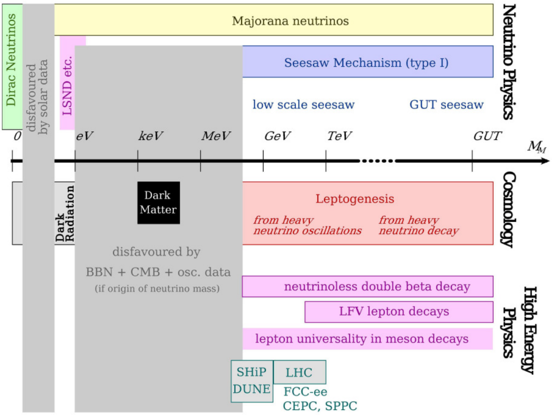
$$W_{L,R} = \begin{pmatrix} W^1 \\ W^2 \\ W^3 \end{pmatrix}_{L,R}, \quad B, \quad G_a, \qquad \begin{matrix} W_L\!: & (1_C; 3_L; 1_R; 0_{B-L}), \\ W_R\!: & (1_C; 1_L; 3_R; 0_{B-L}), \\ B\!: & (1_C; 1_L; 1_R; 0_{B-L}) \end{matrix} \tag{4}$$

- Higgs multiplets

$$\phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}, \quad \Delta_{L,R} = \begin{pmatrix} \frac{\delta^+}{\sqrt{2}} & \delta^{++} \\ \delta^0 & -\frac{\delta^+}{\sqrt{2}} \end{pmatrix}_{L,R}, \qquad \begin{matrix} \phi\!: & (1_C; 2_L; 2_R; 0_{B-L}), \\ \Delta_L\!: & (1_C; 3_L; 1_R; 2_{B-L}), \\ \Delta_R\!: & (1_C; 1_L; 3_R; 2_{B-L}). \end{matrix}$$

$\mathcal{P}$: $\quad SU(2)_L \leftrightarrow SU(2)_R$

$$l_L \leftrightarrow l_R, \qquad q_L \leftrightarrow q_R, \qquad \Delta_L \leftrightarrow \Delta_R, \qquad \phi \leftrightarrow \phi^\dagger$$



1502.00477

MLRM: $M_1 \sim \mathcal{O}(\mathrm{keV})$ and $\Omega_{N_1} = \Omega_{\mathrm{DM}}^{\mathrm{obs}}$ at

- $M_{W_R} \geq 11$ TeV F. Bezrukov, H. Hettmansperger, M. Lindner, Phys. Rev. D81 (2010) 085032
- $M_{W_R} \sim 3\text{-}5$ TeV M. Nemevsek, G. Senjanovic, Y. Zhang, JCAP 1207 (2012) 006

Higgs potential

$$
\begin{aligned}
V(\phi, \Delta_L, \Delta_R) &= -\mu_1^2 \left(Tr[\phi^\dagger \phi] \right) - \mu_2^2 \left(Tr[\tilde{\phi}\phi^\dagger] + \left(Tr[\tilde{\phi}^\dagger \phi] \right) \right) - \mu_3^2 \left(Tr[\Delta_L \Delta_L^\dagger] + Tr[\Delta_R \Delta_R^\dagger] \right) \\
&+ \lambda_1 \left(\left(Tr[\phi\phi^\dagger] \right)^2 \right) + \lambda_2 \left(\left(Tr[\tilde{\phi}\phi^\dagger] \right)^2 + \left(Tr[\tilde{\phi}^\dagger \phi] \right)^2 \right) + \lambda_3 \left(Tr[\tilde{\phi}\phi^\dagger] Tr[\tilde{\phi}^\dagger \phi] \right) \\
&+ \lambda_4 \left(Tr[\phi\phi^\dagger] \left(Tr[\tilde{\phi}\phi^\dagger] + Tr[\tilde{\phi}^\dagger \phi] \right) \right) \\
&+ \rho_1 \left(\left(Tr[\Delta_L \Delta_L^\dagger] \right)^2 + \left(Tr[\Delta_R \Delta_R^\dagger] \right)^2 \right) \\
&+ \rho_2 \left(Tr[\Delta_L \Delta_L] Tr[\Delta_L^\dagger \Delta_L^\dagger] + Tr[\Delta_R \Delta_R] Tr[\Delta_R^\dagger \Delta_R^\dagger] \right) \\
&+ \rho_3 \left(Tr[\Delta_L \Delta_L^\dagger] Tr[\Delta_R \Delta_R^\dagger] \right) \\
&+ \rho_4 \left(Tr[\Delta_L \Delta_L] Tr[\Delta_R^\dagger \Delta_R^\dagger] + Tr[\Delta_L^\dagger \Delta_L^\dagger] Tr[\Delta_R \Delta_R] \right) \\
&+ \alpha_1 \left(Tr[\phi\phi^\dagger] \left(Tr[\Delta_L \Delta_L^\dagger] + Tr[\Delta_R \Delta_R^\dagger] \right) \right) \\
&+ \alpha_2 \left(Tr[\phi\tilde{\phi}^\dagger] Tr[\Delta_R \Delta_R^\dagger] + Tr[\phi^\dagger \tilde{\phi}] Tr[\Delta_L \Delta_L^\dagger] \right) \\
&+ \alpha_2^* \left(Tr[\phi^\dagger \tilde{\phi}] Tr[\Delta_R \Delta_R^\dagger] + Tr[\tilde{\phi}^\dagger \phi] Tr[\Delta_L \Delta_L^\dagger] \right) \\
&+ \alpha_3 \left(Tr[\phi\phi^\dagger \Delta_L \Delta_L^\dagger] + Tr[\phi^\dagger \phi \Delta_R \Delta_R^\dagger] \right) \\
&+ \beta_1 \left(Tr[\phi \Delta_R \phi^\dagger \Delta_L^\dagger] + Tr[\phi^\dagger \Delta_L \phi \Delta_R^\dagger] \right) + \beta_2 \left(Tr[\tilde{\phi} \Delta_R \phi^\dagger \Delta_L^\dagger] + Tr[\tilde{\phi}^\dagger \Delta_L \phi \Delta_R^\dagger] \right) \\
&+ \beta_3 \left(Tr[\phi \Delta_R \tilde{\phi}^\dagger \Delta_L^\dagger] + Tr[\phi^\dagger \Delta_L \tilde{\phi} \Delta_R^\dagger] \right), \qquad (5)
\end{aligned}
$$

GUT and/or SUSY: $\beta_i = 0$ or $\beta_i \simeq 0$

Symmetry breaking

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

1. Parity $\mathcal{P}$ breaks down at $M_{\mathcal{P}} \gg M_{\text{EW}}$
2. The initial LR symmetry is spontaneously broken

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \xrightarrow{\langle \Delta_R \rangle} SU(2)_L \times U(1)_Y, \tag{6}$$

$$\langle \Delta_R \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}. \tag{7}$$

3. The bidoublet and the left handed triplet acquire VEVs as a result of spontaneous symmetry breaking

$$SU(2)_L \times U(1)_Y \xrightarrow{\langle \phi \rangle, \langle \Delta_L \rangle} U(1)_Q, \tag{8}$$

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} k_1 & 0 \\ 0 & k_2 \end{pmatrix}, \qquad \langle \Delta_L \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_L & 0 \end{pmatrix}, \tag{9}$$

where $\sqrt{k_1^2 + k_2^2} = 246$ GeV,

$$v_L = \frac{1}{v_R} \frac{\beta_2 k_1^2 + \beta_1 k_1 k_2 + \beta_3 k_2^2}{(2\rho_1 - \rho_3)} \simeq 0 \qquad \text{VEV seesaw} \tag{10}$$

Flavour basis

$$\mathcal{L} \supset (\overline{\nu_L} \;\; \overline{\nu_R^c}) M_\nu \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}, \qquad \text{where} \qquad M_\nu = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix}, \tag{11}$$

$$M_D = \frac{h_L k_1 + \tilde{h}_L k_2}{\sqrt{2}}, \qquad M_L = \sqrt{2} h_M v_L, \qquad M_R = \sqrt{2} h_M v_R, \tag{12}$$

Mass basis

$$\mathcal{U}^\dagger M_\nu \mathcal{U}^* = \begin{pmatrix} \hat{m} & 0 \\ 0 & \hat{M} \end{pmatrix}, \qquad \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} = P_L \mathcal{U} \begin{pmatrix} \nu \\ N \end{pmatrix} \tag{13}$$

where $\hat{m} = \mathrm{diag}(m_1, m_2, m_3)$, $\hat{M} = \mathrm{diag}(M_1, M_2, M_3)$,

$$\mathcal{U} = W \cdot \begin{pmatrix} U_\nu & 0 \\ 0 & U_N^* \end{pmatrix}, \tag{14}$$

$$\text{where} \qquad W = \exp \begin{pmatrix} 0 & \theta \\ -\theta^\dagger & 0 \end{pmatrix} \simeq \begin{pmatrix} 1 - \frac{1}{2}\theta\theta^\dagger & \theta \\ -\theta^\dagger & 1 - \frac{1}{2}\theta^\dagger\theta \end{pmatrix}, \qquad \theta \ll I \tag{15}$$

$$W^\dagger \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix} W^* = \begin{pmatrix} m_\nu & 0 \\ 0 & M_N \end{pmatrix} \tag{16}$$

$$(12):\qquad \theta \simeq M_D M_R^{-1}, \tag{17}$$

$$(11):\qquad m_\nu = M_L - \theta M_R \theta^T + \mathcal{O}(\theta^2 M_L) \simeq M_L - M_D M_R^{-1} M_D^T, \tag{18}$$

$$(22):\qquad M_N = M_R + \mathcal{O}(\theta^2) \tag{19}$$

$$\nu_L \simeq \left(1 - \frac{1}{2}\theta\theta^\dagger\right) U_\nu \nu_L + \theta U_N^* N_L, \tag{20}$$

$$\nu_R^c \simeq -\theta^\dagger U_\nu \nu_L + \left(1 - \frac{1}{2}\theta\theta^\dagger\right) U_N^* N_L. \tag{21}$$

Mixing matrices

$$U_{\text{PMNS}} \simeq (1+\eta) U_\nu, \qquad \Theta \simeq \theta U_N^* \tag{22}$$

Charged and neutral neutrino currents

$$\mathcal{L}^{\nu}_{CC} = \frac{g}{\sqrt{2}} (U_{\rm PMNS})_{\alpha i}\, \bar{l}_\alpha\, \hat{W}_1 \left(\cos\zeta P_L - \sin\zeta P_R\right) \nu_i + \frac{g}{\sqrt{2}} (U_{\rm PMNS})_{\alpha i}\, \bar{l}_\alpha\, \hat{W}_2 \left(\sin\zeta P_L + \cos\zeta P_R\right) \nu_i + h.c. \quad (23a)$$

$$\mathcal{L}^{\nu}_{NC} = \frac{g}{2c_W} \left(U^\dagger_{\rm PMNS} U_{\rm PMNS}\right)_{ij} \bar{\nu}_i \sum_{X=Z_1,Z_2} \hat{X} \left(a_X^{(L)} P_L - a_X^{(R)} P_R\right) \nu_j \quad (23b)$$

$$\mathcal{L}^{N}_{CC} = -\frac{g}{\sqrt{2}} \Theta_{\alpha J}\, \bar{l}_\alpha\, \hat{W}_1 \left(\cos\zeta P_L - \sin\zeta P_R\right) N_J - \frac{g}{\sqrt{2}} \Theta_{\alpha J}\, \bar{l}_\alpha\, \hat{W}_2 \left(\sin\zeta P_L + \cos\zeta P_R\right) N_J + h.c. \quad (23c)$$

$$\mathcal{L}^{N}_{NC} = \frac{g}{2c_W} (\Theta^\dagger \Theta)_{IJ}\, \bar{N}_I \sum_{X=Z_1,Z_2} \hat{X} \left(a_X^{(L)} P_L - a_X^{(R)} P_R\right) N_J + \quad (23d)$$
$$+ \left(\frac{g}{2c_W} \left(U^\dagger_{\rm PMNS} \Theta\right)_{iJ} \bar{\nu}_i \sum_{X=Z_1,Z_2} \hat{X} \left(a_X^{(L)} P_L - a_X^{(R)} P_R\right) N_J + h.c. \right)$$

$$a^{(R)}_{Z_1} = \frac{c_\phi s_W^2 \sqrt{c_{2W}}}{c_W} - c_\phi s_W^2 - s_\phi \sqrt{c_{2W}} - \frac{s_\phi s_W^2}{c_W}, \quad a^{(R)}_{Z_2} = -s_\phi s_W^2 + \frac{s_\phi s_W^2 \sqrt{c_{2W}}}{c_W} + \frac{c_\phi s_W^2}{c_W} + c_\phi \sqrt{c_{2W}}$$

$$a^{(L)}_{Z_1} = c_\phi c_W^2 - \frac{s_\phi s_W^2}{c_W} + \frac{c_\phi s_W^2 \sqrt{c_{2W}}}{c_W}, \quad a^{(L)}_{Z_2} = s_\phi c_W^2 + \frac{c_\phi s_W^2}{c_W} + \frac{s_\phi s_W^2 \sqrt{c_{2W}}}{c_W}$$

Parametrization of the mixing matrix Θ

This type of parametrization was proposed by J. Casas and A. Ibarra for the SM extended by HNL Casas J., Ibarra A., Nucl.Phys.B 618 (2001) 171.

$$M_N = -M_D^T \left(U_\nu^* \hat{m}^{-1} U_\nu^\dagger - M_L^{-1}\right) M_D, \qquad M_N M_N^{-1} = I \tag{26}$$

$$I = \left[i\sqrt{A} U_\nu^\dagger M_D U_N \sqrt{\hat{M}^{-1}}\right]^T \left[i\sqrt{A} U_\nu^\dagger M_D U_N \sqrt{\hat{M}^{-1}}\right] = \Omega^T \Omega \tag{27}$$

$$M_D = i U_{\mathrm{PMNS}} \sqrt{\tilde{m}} \Omega \sqrt{\hat{M}} U_N^\dagger \tag{28}$$

So,

$$\Theta \simeq \theta U_N^* \simeq i U_{\mathrm{PMNS}} \sqrt{\tilde{m}} \Omega \sqrt{\hat{M}^{-1}}. \tag{29}$$

where

$$\tilde{m} = \hat{m} - U_{\mathrm{PMNS}}^{-1} M_L (U_{\mathrm{PMNS}}^T)^{-1}, \tag{30}$$

where $M_L = \sqrt{2} h_M v_L$. In the approximation $\mathcal{O}(\theta^2) \ll 1$, $\hat{m} \ll \hat{M}$ and assuming $U_N = I$,

$$h_M \simeq \frac{1}{\sqrt{2} v_R} (\theta^\dagger U_\nu \hat{m} U_\nu^T \theta^* + U_N^* \hat{M} U_N^\dagger) \simeq \frac{\hat{M}}{\sqrt{2} v_R}$$

Finally,

$$\tilde{m} = \hat{m} - \frac{v_L}{v_R} U_{\mathrm{PMNS}}^{-1} \hat{M} (U_{\mathrm{PMNS}}^T)^{-1}$$

- If $M_I \ll v_R$ then $\tilde{m} = \hat{m}$

  For example, DM with $m_{W_R} \sim 3$ TeV:
  $M_1 \sim \mathcal{O}(\text{keV})$, $M_2 = m_\pi + m_\mu$, $M_3 = m_\pi + m_e$

$$\tilde{m} \sim \hat{m} - I \cdot v_L \cdot 10^{-6} \qquad \text{and} \qquad \Theta = iU_{\text{PMNS}}\sqrt{\hat{m}}\Omega\sqrt{\hat{M}^{-1}} \tag{31}$$

- If $M_1 \sim \mathcal{O}(\text{keV})$ and $M_{2,3} \sim v_R$ then

$$\tilde{m} = m_{\nu_i} - \mathcal{O}(0.1)v_L \tag{32}$$

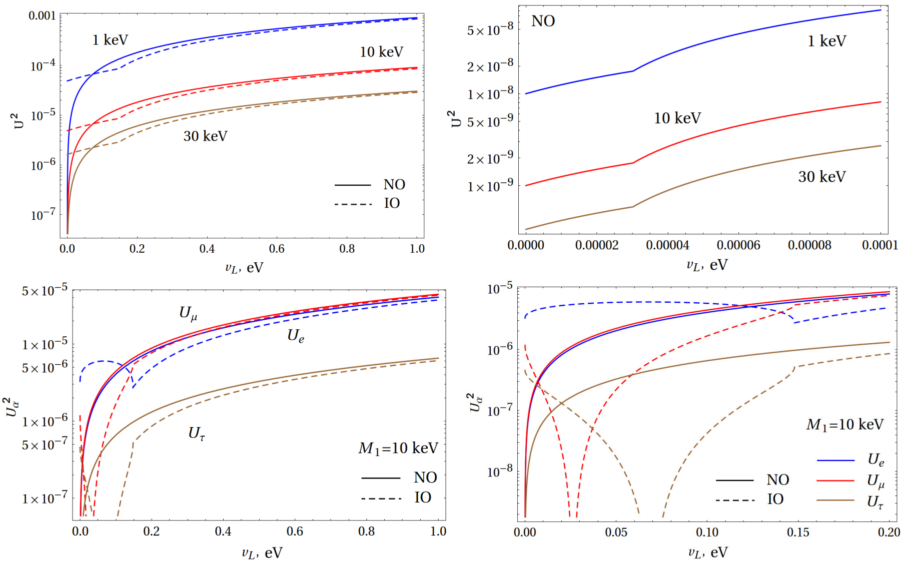
  and nonzero elements of the mixing matrix Θ are

$$\begin{aligned}
\Theta_{e1} &= \frac{i}{\sqrt{M_1}}(U_{e1}\sqrt{\tilde{m}_{11}} + U_{e2}\sqrt{\tilde{m}_{21}} + U_{e3}\sqrt{\tilde{m}_{31}}), \\
\Theta_{\mu 1} &= \frac{i}{\sqrt{M_1}}(U_{\mu 1}\sqrt{\tilde{m}_{11}} + U_{\mu 2}\sqrt{\tilde{m}_{21}} + U_{\mu 3}\sqrt{\tilde{m}_{31}}), \\
\Theta_{\tau 1} &= \frac{i}{\sqrt{M_1}}(U_{\tau 1}\sqrt{\tilde{m}_{11}} + U_{\tau 2}\sqrt{\tilde{m}_{21}} + U_{\tau 3}\sqrt{\tilde{m}_{31}})
\end{aligned} \tag{33}$$

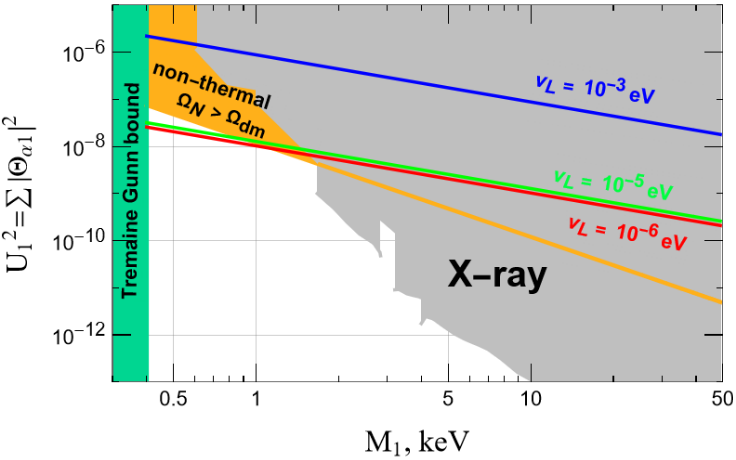
Phenomenologically convenient quantities – mixing parameters:

$$U^2_{\alpha I} = |\Theta_{\alpha I}|^2, \qquad U^2_i = \sum_\alpha U^2_{\alpha I}, \qquad U^2 = \sum_i U^2_i \tag{34}$$

Numerical estimations



$$M_1 = \{1, 10, 30\} \text{ keV}, \; M_{2,3} \sim v_R, \; m_1^{\rm NO} = 10^{-5} \text{ eV}, \; m_1^{\rm IO} = 0.049 \text{ eV}, \; \Omega = I$$



Constraints on the mixing parameter depending on the mass of the dark matter HNL:
– the universal limit from gamma-ray astronomical observations of $\tau_N > 10^{25}$ seconds
– combined constraints from the data of HEAO-1, XMM, [1, 2]
– the Tremaine-Gunn boundary (TG), [3]
– a density of sterile neutrinos greater than the observed value for dark matter

Prospects and conclusions

- We considered the lightest sterile neutrino as DM in the framework of the MLRM
- We found out that the mixing parameter significantly depends on v_L in the regime of $M_1 \sim \mathcal{O}(\text{keV})$ and $M_{2,3} \sim v_R$
- In the framework of numerical analisys, the masses of $M_1 \sim 1 - 2$ keV and left-triplet VEV of $v_L \leq 10^{-5}$ eV are preferable
- We proposed a modified seesaw type II expression for the mixing matrix

$$\Theta = iU_{\text{PMNS}}\sqrt{\tilde{m}}\Omega\sqrt{\hat{M}^{-1}},$$

where

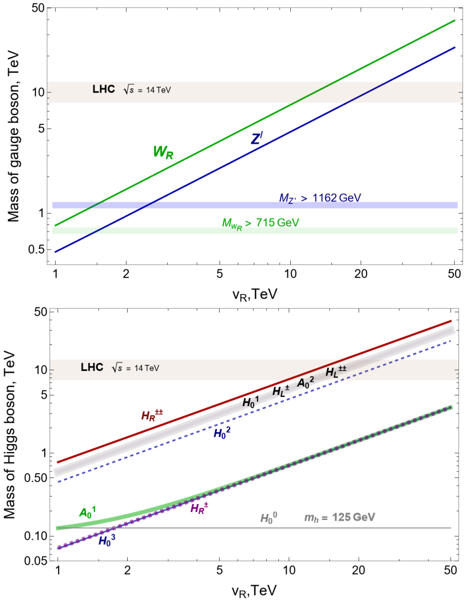
$$\tilde{m} = \hat{m} - \frac{v_L}{v_R}U_{\text{PMNS}}^{-1}\hat{M}(U_{\text{PMNS}}^{T})^{-1}$$

in the approximation $\mathcal{O}(\theta^2) \ll 1$, $\hat{m} \ll \hat{M}$, $U_N = I$

1 T. M. Aliev and M. I. Vysotskii, Sov. Phys. Usp. 24, 1008 (1981)
2 A. Boyarsky, A. Neronov, O. Ruchayskiy, and M. Shaposhnikov, Mon. Not. R. Astron. Soc. 370, 213 (2006)
3 S. Tremaine and J. E. Gunn, Phys. Rev. Lett. 42, 407 (1979)

The research was carried out within the framework of the scientific program of the National Center for Physics and Mathematics, project "Particle Physics and Cosmology"

Thank you for your attention



Mass of gauge boson, TeV
LHC $\sqrt{s}$ = 14 TeV
W_R
Z'
$M_{Z'}$ > 1162 GeV
M_{W_R} > 715 GeV
v$_R$,TeV
Mass of Higgs boson, TeV
LHC $\sqrt{s}$ = 14 TeV
$H_R^{\pm\pm}$
H_0^1
$H_L^{\pm}$
A_0^2
$H_L^{\pm\pm}$
H_0^2
A_0^1
$H_R^{\pm}$
H_0^0
m_h = 125 GeV
H_0^3
v$_R$,TeV