# Constraints on the parameters of the neutrino extension of the Standard Model

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The Standard Model of particle physics (SM) has been extensively tested in accelerator experiments up to an energy of approximately 15 TeV and is consistent up to a very high energy scale, potentially up to the Planck scale. However, the SM fails to account for certain phenomena such as the neutrinos' mass, dark matter, and the imbalance of baryons in the universe. Therefore, the SM is an incomplete theory and necessitates an expansion.

The Standard Model can be extended in the neutrino sector in the simplest renormalizable way that is consistent with neutrino experiments (minimal neutrino modification of the Standard Model $\nu$MSM, proposed in 2005 [1] -[2]). This extension involves three right-handed (sterile) singlet neutrinos, denoted as $N_I$ ($I = 1, 2, 3$) with the most general gauge-invariant interactions described by the Lagrangian:

$$\delta\mathcal{L} = i\bar{N}_I\partial_\mu\gamma^\mu N_I - F_{\alpha I}\bar{L}_\alpha N_I\Phi - \frac{M_I}{2}\bar{N}_I^c N_I + h.c. \tag{1}$$

Here, $\alpha$ represents different flavors of leptons ( $e, \mu, \tau$), while $\Phi$ and $L_\alpha$ are the Higgs and lepton doublets, respectively. In this formulation, we have chosen a basis in which the mass matrices for right-handed neutrinos are real and diagonal ($M_I$), and $F_{\alpha I}$ are elements of the Yukawa matrix $F$. The lightest sterile neutrino in the $\nu$MSM is the particle of dark matter with a mass of order 10 keV. Two other sterile neutrinos are heavy particles with almost equal masses. They provide a generation of baryon asymmetry in the Universe.

Observable in the experiments on colliders parameters of the Lagrangian (1) are constructed as follows [3]:

$$S_{\alpha\beta} \equiv (FM^{-1*}M^{-1}F^\dagger)_{\alpha\beta} = \sum_I S^I_{\alpha\beta} = \sum_I F_{\alpha I}F^\dagger_{I\beta}M_I^{-2}, \tag{2}$$

$$R_{\alpha\beta} = \sum_I R^I_{\alpha\beta} = \sum_I S^I_{\alpha\beta}\ln\frac{M_I}{M_W} = \sum_I F_{\alpha I}F^\dagger_{I\beta}M_I^{-2}\ln\frac{M_I}{M_W}. \tag{3}$$

The elements of the Yukawa matrix can be expressed via observable parameters of neutrino oscillation using the Casas-Ibarra parametrization [4]. The lightest sterile neutrino in the $\nu$MSM is the long-lived particle of dark matter and can not be observed in collider experiments. So, in the following, we consider the simple case of adding to the SM only two heavy sterile neutrinos.

Using Casas-Ibarra parametrization, a simple relationship between the experimentally observed quantities (elements of the matrices $S_{\alpha\beta}$ and $R_{\alpha\beta}$) has been obtained, which is valid for non-zero masses of active neutrinos and different values of masses of heavy sterile neutrinos.

$$S_{\alpha\beta}\Big(M_1 \ln\frac{M_2}{M_W} + M_2 \ln\frac{M_1}{M_W}\Big) = R_{\alpha\beta}(M_1+M_2), \quad S_{\alpha\alpha}S_{\beta\beta} = |S_{\alpha\beta}|^2 \quad R_{\alpha\alpha}R_{\beta\beta} = |R_{\alpha\beta}|^2. \tag{4}$$

Using constraints (4) we have been able to improve experimental constraints on the elements of the $S_{\alpha\beta}$ and $R_{\alpha\beta}$ matrices. Using numerical data from Particle Data Group constraints on $U^2_{tot}$ depending on the mass of a heavy neutrino with right chirality have been obtained. $U^2_{tot}$ is a widely used parameter of the neutrino modification of SM

$$U^2_{tot} = \sum_{\alpha,I} |\Theta_{\alpha I}|^2 = \frac{v^2}{M^2}\mathrm{tr}(FF^\dagger), \tag{5}$$

where $\Theta_{\alpha I}$ is the mixing angle between left-handed and right-handed neutrinos $\nu_\alpha$ and $N_I$ respectively; $M_1 \approx M_2 \approx M$ is the mass of the right-handed neutrinos; $v$ is the vacuum expectation value. Obtained constraints on $U^2_{tot}$ accords with results of [5].

In [1] the generation of baryon asymmetry in the early Universe in the $\nu MSM$ (the case of tree sterile neutrinos) was theoretically investigated. It was demonstrated that the baryon asymmetry can be expressed in terms of the lepton asymmetry of active neutrinos. Using results of [1] we have been able to express constraints on the generation of baryon asymmetry in the early universe in terms of observable parameters $S_{\alpha\beta}$ and $R_{\alpha\beta}$. For example, in the case of normal neutrino hierarchy, the baryon asymmetry of the Universe can be expressed as

$$\Delta B \leq \frac{7\pi^{\frac{3}{2}}\sin^3\phi}{7584\cdot 3^{\frac{1}{3}}\Gamma(\frac{5}{6})} \frac{M_0^{\frac{7}{3}} M^5(m_3 + 2m_2 + 2\sqrt{m_3 m_2})}{T_W v^2 (\Delta M^2_{21})^{\frac{2}{3}}} \sum_{\alpha,\beta\neq\alpha} |S_{\alpha\alpha}||S_{\alpha\beta}|, \tag{6}$$

where $M_0 \simeq 7\cdot 10^{17}$ GeV, $T_W \approx 100$ GeV, $\sin\phi \simeq 0.02$; $m_2$, $m_3$ are masses of the active neutrinos, and we used $M_2 \approx M_1 \approx M$.

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