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The νMSM and muon to electron conversion experiments

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Abstract We review briefly the different constraints on the three right-handed neutrinos of the νMSM, an extension of the Standard Model that can explain baryon asymmetry, dark matter and neutrino masses. We include in the discussion the proposed experiments on muon to electron conversion Mu2e (Carey et al., Mu2e Collaboration, 2012), COMET and PRISM (Hungerford, COMET Collaboration, AIP Conf Proc 1182:694, 2009; Cui et al., COMET Collaboration, 2012). We find that the expected sensitivity of these experiments is weaker by about two orders of magnitude than the constraints coming from successful baryogenesis.

Keywords Leptogenesis · Dark matter · Sterile neutrinos · νMSM

1 Introduction

There is a strong interplay between particle physics and cosmology. Indeed, the early Universe was very hot and dense and interactions between elementary particles were essential. They determined the structure of the Universe we see today. Therefore, observations of our Universe can motivate the elaboration of new particle physics models and/or to constrain them. Among these observations, the most important are the asymmetry between matter and anti-matter and the dark matter, which are not explained by the Standard Model (SM). The literature on these topics is very rich and we will not describe it in any detail in this paper. Instead, we will focus the discussion

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on one possible model, the νMSM, which is an extension of the SM by three right-handed neutrinos (other equivalent names for them are Majorana leptons or sterile neutrinos). In this model, leptonic flavors are not conserved. At the same time, the proposals for new experiments looking at the muon to electron conservation have been made. We will compare the expected sensitivities of these experiments to the requirement that the νMSM sterile neutrinos explain the baryon asymmetry of our Universe.

The paper is organised as follow. We briefly review the main features of the νMSM in Section 2 and the principal constraints on its right-handed neutrinos in Section 3. Finally, in Section 4, we compare the expected sensitivities of the Mu2e, COMET and PRISM experiments and the parameter space of the νMSM.

2 The νMSM

The νMSM is a simple extension of the Standard Model by three right-handed neutrinos with masses below the electroweak scale. It can account for baryogenesis, dark matter production and neutrino masses (for a review see [4]). One right-handed neutrino has a keV scale mass and plays the role of the dark matter particle. The two others have quasi-degenerate $O(1)$ GeV masses. They generate active neutrinos masses and are responsible for creating the baryon asymmetry.

A detailed quantitative study of the cosmological applications of the model was recently performed in [5] (the main results have been summarized in [6]).

The νMSM Lagrangian reads

$$\mathcal{L}_{\nu\text{MSM}} = \mathcal{L}_{SM} + i\bar{N}\gamma_\mu\partial^\mu N - \bar{L}_L F N\tilde{\Phi} - \bar{N}F^\dagger L_L\tilde{\Phi}^\dagger \\ -\frac{1}{2}\left(\bar{N^c} M_M N + \bar{N} M_M^\dagger N^c\right). \quad (1)$$

We suppressed flavor and isospin indices. $\mathcal{L}_{SM}$ is the Lagrangian of the Standard Model. F is a matrix of Yukawa couplings and M_M a Majorana mass term for the right handed neutrinos N. $L_L = (\nu_L, e_L)^T$ are the left handed lepton doublets in the SM and Φ is the Higgs doublet. We chose a basis where the charged lepton Yukawa couplings and M_M are diagonal and we also chose N_1 to be the dark matter candidate and $N_{2,3}$ to be the seesaw partners.

The Lagrangian (1) coincides with the seesaw Lagrangian, but the scale of Majorana masses M_M is chosen to be below the Fermi scale, contrary to $M \sim 10^{10}$ GeV in the traditional see-saw mechanism.

3 Constraints on sterile neutrinos

In this section, we present the different constraints on the sterile neutrinos of the νMSM [4, 5], see Figs. 1 and 2.

For the dark matter candidate N_1, the first requirement concerns its stability. The sterile neutrino N_1 must have a lifetime larger than the age of our Universe. Secondly, its production mechanism must be efficient enough to explain the dark matter abundance Ω_{DM} that we observe today. In the region above the upper black

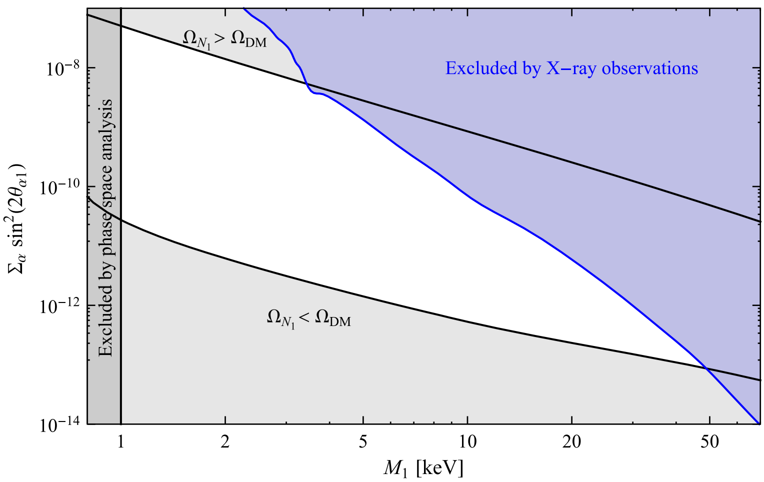

Fig. 1 Constraints on the dark matter mixing angle $\theta_{\alpha 1} = \frac{v}{M} F_{\alpha 1}$ (where v is the Higgs vacuum expectation value) coming from X-ray observations, from Lyman-α forest and from the dark matter abundance. This figure is taken from [5]

line of Fig. 1, the abundance of the Majorana fermion Ω_{N_1} is bigger than Ω_{DM}. Below the lower black line, Ω_{N_1} is smaller than Ω_{DM}.

Direct observations of N_1 are not possible because its mixings with the other neutrinos are too weak. But it may affect structure formation. If N_1 is too light, it may have considerable free streaming length and erase fluctuations on small scales. This can be checked by the study of Lyman-α forest spectra of distant quasars and structure of dwarf galaxies. This constraint is related to the vertical line in Fig. 1. Moreover, N_1 two-body decay, $N_1 \to \gamma\ \nu$, produces a narrow line which can be detected by X-ray telescopes. This line has not been seen yet, excluding the region above the blue line in Fig. 1.

As for the seesaw partners $N_{2,3}$, we require that they must explain active neutrino masses. Therefore, their mixing angle to active neutrinos U^2 cannot be too small. The mixing U^2 is defined by:

$$U^2 = \frac{v^2}{M^2} tr\left[F^\dagger F\right], \qquad (2)$$

where v is the Higgs vacuum expectation value. This excludes the region below the seesaw line in Fig. 2. We also require that they create the right amount of baryon asymmetry, which is possible for the region between the two BAU blue lines in Fig. 2. Finally, $N_{2,3}$ should decay sufficiently before Big Bang Nucleosynthesis (BBN), in order not to spoil its predictions. This excludes the region below the BBN dashed line in the figure mentioned above.

There are two types of direct searches for $N_{2,3}$: the beam dump experiments where the sterile neutrinos are created in decay of mesons from a proton beam and peak searches which look at the decay of charged mesons into charged leptons and neutrinos. The most relevant experiments for the νMSM are CERN PS191 [7, 8], CHARM [9] and NuTeV [10]. They are shown by green lines on Fig. 2. Only the CERN PS191 experiment has entered into cosmologically interesting part of the parameter space of the νMSM.

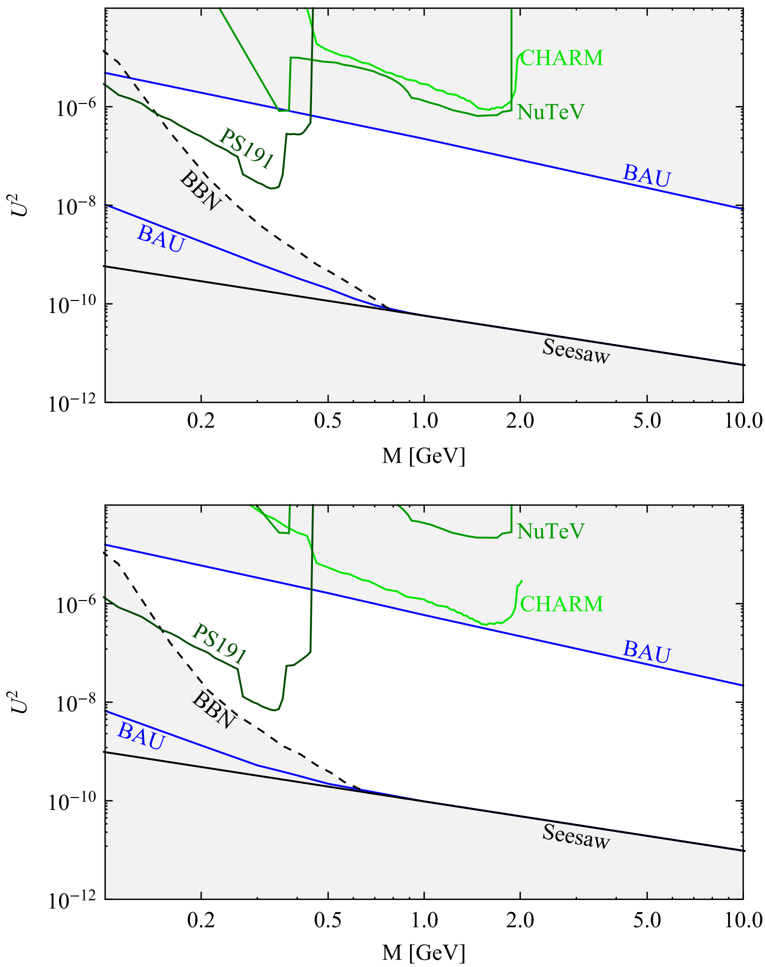

Fig. 2 Constraints on U^2 and the average seesaw partners mass M coming from the baryon asymmetry of the universe (*blue solid lines*), from the seesaw formula (*black long dotted line*) and from the big bang nucleosynthesis (*black short dotted line*). Experimental searched regions are in *green solid lines*. *Upper panel*—normal hierarchy, *lower panel*—inverted hierarchy. This figure is taken from [5]

All types of neutrino experiments can provide constraints on the νMSM parameters. Interestingly, the model makes the prediction of the scale of active neutrino masses [11] and of the Majorana mass which governs the neutrino double β decay [12].

4 Future searches

Several experiments which should be carried out to detect sterile neutrinos of the νMSM are described in [4, 5, 13]. In this section, we discuss some future experiments that can potentially provide indirect evidence for their existence.

In the Standard Model, leptonic flavors are not conserved. If the sterile neutrinos are very heavy, as in the seesaw mechanism, the lepton number non-conservation

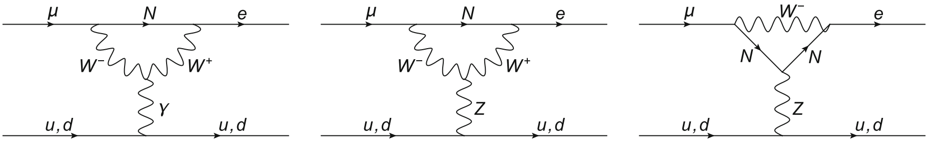

Fig. 3 Some penguin diagrams that contribute to the muon to electron conversion in presence of right-handed neutrinos. On these diagrams, N represents generically the neutral leptons mass eigenstates

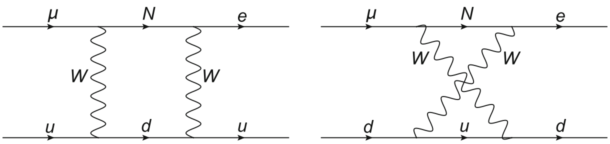

Fig. 4 Some box diagrams that contribute to the muon to electron conversion in presence of right-handed neutrinos

processes are very suppressed and cannot be observed experimentally [14]. However, leptonic flavor changing processes are enhanced in the presence of relatively light right-handed neutrinos [15]. In the lowest order, they correspond to one loop diagrams, mediated by gauge bosons, that are of the penguin shape (see Fig. 3) or of the box shape (see Fig. 4).

There is a number of proposals for new experiments for muon to electron conversion at single event sensitivity around 10^{-16} and below. The COMET experiment [2, 3] and its extension PRISM will be based at the Japanese Hadron Accelerator (J-PARC). The Mu2e experiments [1] will be based at the Fermi National Accelerator. These experiments will constraint the mixing angle between electronic and muonic flavors $|U_{e\mu}| = \frac{v^2}{M^2}|[F^\dagger F]_{e\mu}|$ and their sensitivities are compared in [15].

It is important to understand whether any indirect evidence of existence of Majorana leptons of the νMSM, explaining baryon asymmetry, dark matter and neutrino masses, can be derived from these experiments. To answer this question we determined the range of values of the mixing $|U_{e\mu}|$ which leads to the successful baryogenesis with the use of results of [5].

In [5], the baryon asymmetry was computed in the following way. First, the active neutrino masses and mixings were fixed at their experimental values. Then, the asymmetry was computed as a function of the sterile neutrino average mass M and the sterile mixing angle and extremized with respect to all other parameters (CP-violating phases and right-handed neutrino mass difference). The values of the mixing $|U_{e\mu}|$ corresponding to the set of parameters leading to the baryon asymmetry exceeding the observed value correspond to the white region between the BAU lines in Fig. 5. This observed value can be reached by some combination of phases and other parameters of the νMSM. Outside this region, the baryon asymmetry is always smaller than the observed one. The BAU lines on this figure have uncertainty, related to the extremization procedure of the CP-violating phases used in [5]. We expect that this procedure cannot change the upper limit by a factor bigger than three.

Figure 5 shows that the requirement of successful baryogenesis is much stronger—3(2) orders of magnitude for normal (inverted) hierarchy—than the predicted sensi-

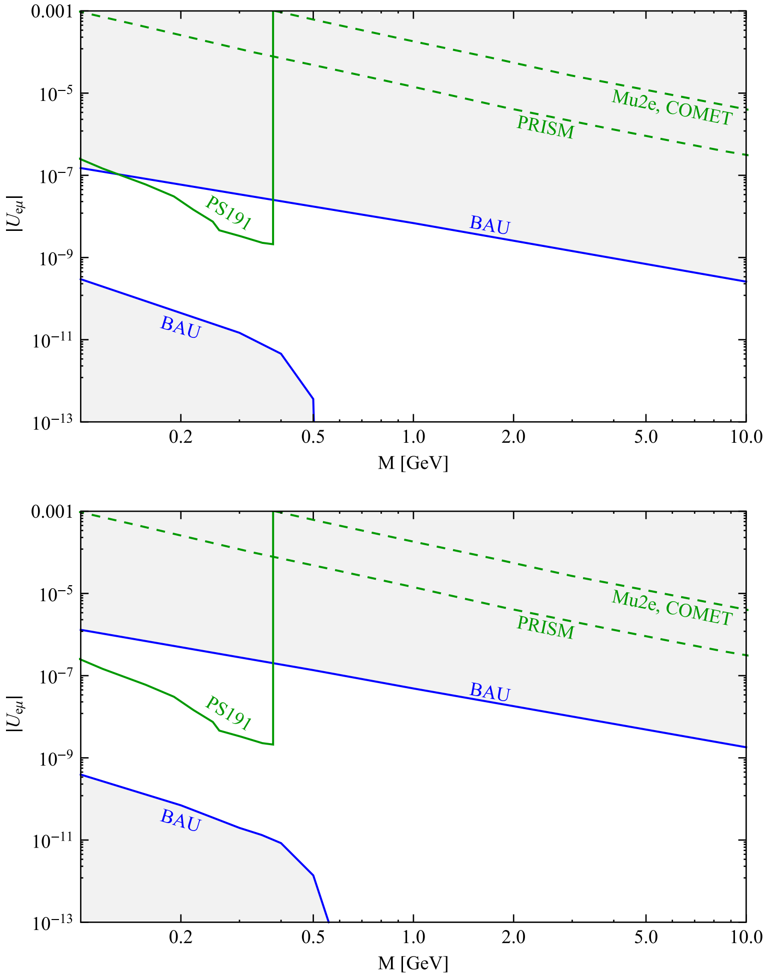

Fig. 5 Constraints on $|U_{e\mu}|$ and the average seesaw partner mass M coming from the baryon asymmetry of the universe (*blue solid lines*), from the CERN PS191 experiment (*green solid line*) and from the Mu2e, COMET and PRISM experiments (*green dotted line*). *Upper panel*—normal hierarchy, *lower panel*—inverted hierarchy

tivity of the PRISM experiment. Therefore, it is unlikely that these experiments will find an evidence of the existence of the νMSM sterile neutrinos.

The above statement is only true if we require that the νMSM is responsible for baryogenesis and dark matter simultaneously. In principle, one can consider the νMSM as a theory of baryogenesis only (no dark matter candidate is required). In this case the constraints on the model parameters become weaker [16]. In this version of the model, the implications of successful baryogenesis on the model parameters have not been fully explored yet and we cannot exclude that the precision experiments can enter into cosmologically interesting region.

Suppose now (perhaps unrealistically) that the sensitivity of leptonic flavor violation searches can be increased by many orders of magnitude. Can the model be excluded by the experiments? The answer to this question depends on the CP-violating phases. For some specific combinations of their values, the requirement of successful baryogenesis in the νMSM does not imply a lower bound on $|U_{e\mu}|$, as in Fig. 5. So, if this relation is realised in Nature, the model cannot be excluded by non-observation of μ to e transitions. At the same time, the unknown phases can be fixed by the future long base line neutrino experiments and by neutrinoless double β decay searches. If they do not match the specific combinations mentioned above, the lower bound on $|U_{e\mu}|$ generically appears.

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