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Investigating two heavy neutral leptons neutrino seesaw mechanism at SHiP

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Summary. — One of the main purposes of the SHiP experiment is to shed light on neutrino mass generation mechanisms like the so-called seesaw one. We consider a minimal type-I seesaw neutrino mass mechanism model with two heavy neutral leptons (right-handed or sterile neutrinos) with arbitrary masses. The extremely high active-sterile mixing angle requires a correlation between the phases of the Dirac neutrino couplings. Actual experimental limits on the half-life of neutrinoless double beta decay $0\nu\beta\beta$-rate on the active-sterile mixing angle are not significative for SHiP.

1. – Introduction

The SHiP (Search for Hidden Particles) experiment [1] is a new experiment with the intent of searching for the particles predicted by a large number of models of hidden sectors, capable therefore of explaining dark matter, neutrino oscillations and baryon asymmetry. Among these, an especially important candidate is a Heavy Neutral Lepton (HNL), meant as a right-handed neutrino which is able, through various possible mechanisms, to produce mass for the Standard Model neutrinos. In this work we focus on the HNLs as a means to realize the seesaw mechanism, focusing on the minimal choice of having only two right-handed neutrinos. This report is based on the work presented in [2].

2. – The seesaw mechanism

While it is experimentally known that at least two of the three neutrinos of the Standard Model possess a mass, the Standard Model as it stands is not able to account for it. The main difference between neutrinos and the other leptons in this respect is the extreme smallness of the masses of the former with respect to the latter. A possible mechanism which is able to explain the neutrino masses and the smallness of their values is the so-called seesaw mechanism type I [3,4], which requires the introduction of a number of right-handed partners to the Standard Model neutrinos equal to the number of neutrinos which are required to get the mass. The minimal choice is therefore two HNL.

The two HNL are coupled to the Standard Neutrinos by Dirac mass terms; further, they have Majorana mass terms which are much larger than the Standard Model masses. The structure of the mass matrix is therefore

$$M_\nu = \begin{bmatrix} 0_{3\times3} & m_{D(3\times2)} \\ m^T_{D(2\times3)} & M_{2\times2} \end{bmatrix}. \tag{1}$$

This is a symmetric, in general complex, matrix, which can be brought to a diagonal form by a unitary 5-by-5 matrix U:

$$M_{diag} = U^T M_\nu U. \tag{2}$$

The matrix U can be written in the form

$$\begin{pmatrix} & \text{PMNS} & & U_{e4} & U_{e5} \\ & & & U_{\mu4} & U_{\mu5} \\ & & & U_{\tau4} & U_{\tau5} \\ U_{4e} & U_{4\mu} & U_{4\tau} & & \\ U_{5e} & U_{5\mu} & U_{5\tau} & & \end{pmatrix}, \tag{3}$$

where by PMNS we mean the 3-by-3 Pontecorvo-Maki-Nakagawa-Sakata matrix. It can then be proven that, if the elements of the matrix m_D are much smaller than the elements of the matrix M, three of the eigenvalues of the matrix M_ν can be found by diagonalizing the matrix $m_D M^{-1} m_D^T$: one of these turns out to vanish identically, while the other two will naturally be very small by virtue of the small ratio of the elements of m_D to the elements of M.

3. – The SHiP experiment

The SHiP experiment is a new experiment to be installed in a beam dump facility at the SPS. It will perform a search for hidden particles weakly interacting. The main idea of the experiment lies in a 400 GeV proton beam impinging on a hadronic beam, producing outgoing particles which are then detected by a spectrometer placed at the end of a decay vessel of 50 m length. The whole experiment is performed with a minimum background, due to the muon background shield present before the vessel. The sensitivity to the HNL arises because of their possible production from the weak decay of the D_s resonance. The decay produces an intermediate neutrino of definite flavor, which then oscillates to the outgoing mass eigenstate of a right-handed neutrino, identified by an index i running from 1 to 2. The amplitude for production is then proportional to the matrix element $U_{\alpha i}$, where α is the active neutrino index. This right-handed neutrino can then be detected by its weak decay into the spectrometer at the exit of the decay vessel. The rate of detected events will then be proportional to the quantity

$$U^2 = \sum_{i,\alpha} |U_{\alpha i}|^2. \tag{4}$$

The possibility of detection is of course connected with the decay time of the right-handed neutrino, which must be such that the HNL decays inside the vessel: this is the main restriction on the sensitivity of the experiment. The SHiP experiment is sensitive to HNL masses of order 1 to 10 GeV. Our theoretical work was mainly concerned with the analysis of the mixing angle U^2.

4. – Predictions for the mixing angle

The seesaw model has to obey a number of physical constraints in order to be accepted as an explanation of neutrino masses. First, it must be such that the elements of m_D are much smaller than the right-handed masses, the elements of M. We will later show a mathematical form for this constraint. Further, it must be such as to reproduce the Standard Model neutrino mass matrix. It is possible to show that this result is achieved by choosing m_D according to the so called Casas and Ibarra parameterization [5],

$$m_D = U_{\text{PMNS}}\sqrt{m_\nu}R\sqrt{M}, \tag{5}$$

where R is an orthogonal 3-by-2 matrix. Such a matrix can be put in the form

$$R = \begin{bmatrix} 0 & 0 \\ \cos\theta & \sin\theta \\ -\kappa\sin\theta & \kappa\cos\theta \end{bmatrix}, \tag{6}$$

where θ is generally a complex number. In this way we see that, for a fixed choice of the neutrino masses, there is a further free parameter identified in the form of a complex angle.

Now if there were just one left-handed and one right-handed neutrino one would expect the light neutrino mass to be

$$m_\nu \sim \frac{m_D^2}{M} \tag{7}$$

and the mixing angle to be

$$U^2 \sim \left(\frac{m_D}{M}\right)^2 \sim \frac{m_\nu}{M}. \tag{8}$$

For a benchmark choice of $m_\nu \sim 0.1\,\text{eV}$ and $M \sim 1\,\text{GeV}$, one would obtain $U^2 \sim 10^{-10}$.

This simple estimate, which would be too small to be detectable at SHiP, must be corrected in the many-flavor case by the matrix R, the order of magnitude of whose elements is $e^{\theta''}$, θ'' being the imaginary part of the complex rotation angle. This means that, in this case,

$$U^2 \sim \frac{m_\nu}{M} e^{2\theta''}. \tag{9}$$

This correction factor may be so large as to cause U^2 to become of order 10^{-2}.

From the previous discussion we draw the conclusion that the smallest possible value for U^2 is obtained in the case $\theta'' = 0$; this means that there is a natural lower bound on the mixing angle,

$$U^2_{min} = \frac{m_{\nu 2}}{M_1} + \frac{m_{\nu 3}}{M_2}, \tag{10}$$

which is of the order of the simple estimate previously made. Of course θ'' cannot be made too large, in order not to violate the condition that the elements of m_D must be much smaller than those of M. The magnitude of the allowed values for θ'' depends of course on the precision with which we need to reproduce the experimental results, and therefore it depends upon the precision of the measurements of the neutrino oscillation parameters. It can be shown that

$$e^{\theta''_{max}} \simeq 2\zeta\sqrt{\frac{M_1}{m_{\nu 3}}}, \tag{11}$$

where ζ is a dimensionless parameter which quantifies the precision of the reproduction of the oscillation parameters. It turns out that in order to reproduce the data within the experimental uncertainties, this parameter should be $\zeta \simeq 0.2$. We can therefore find the upper bound on the mixing angle:

$$U^2_{max} \simeq \zeta^2 \frac{M_1}{m_{\nu 3}}(m_{\nu 2} + m_{\nu 3}) \left(\frac{1}{M_1} + \frac{1}{M_2}\right). \tag{12}$$

To confirm the validity of these bounds, a Monte Carlo generation has been performed. All the parameters have been varied in the allowed range, and for each generation the comparison with the experimental results has been verified. The numerical analysis has allowed a separate analysis for the three mixing angles $U^2_\alpha = \sum_i |U_{\alpha i}|^2$, which are not amenable to an analytic treatment.

Two further limits can be imposed on the mixing angles, which will be seen to be even more constraining than the ones derived above. A first bound comes from the consistency with the Big Bang Nucleosynthesis (BBN), which requires the right-handed neutrino lifetime not to be too large. The decay process happens via the weak coupling of the flavor neutrino eigenstates, and the order of magnitude is expected to be, by dimensional arguments,

$$\frac{1}{\tau} \sim G_F^2 U^2 M^5. \tag{13}$$

This decay rate should be larger than approximately 10 s^{-1} [6].

Another constraint comes from the non-observation of the neutrinoless double beta decay. The lifetime for this process is theoretically expected to be [7]

$$T^{-1} = \mathcal{A}\left|\frac{m_p}{\langle p^2\rangle}\sum_{\alpha=1}^{3} U^2_{e\alpha} m_{\nu\alpha} + m_p \sum_{N=1}^{2} \frac{U^2_{e(N+3)} M_N}{\langle p^2\rangle + M_N^2}\right|. \tag{14}$$

Here $\mathcal{A}$ and $\langle p^2\rangle$ are parameters specific of the analyzed nucleus, and depend upon the adopted nuclear model. For this work we have used the most stringent bounds coming from the analyses on the germanium nucleus [8], $T^{Ge} = 8.0 \times 10^2 5\,\mathrm{s}$, and the xenon nucleus [9], $T^{Xe} = 10.7 \times 10^2 5\,\mathrm{s}$.

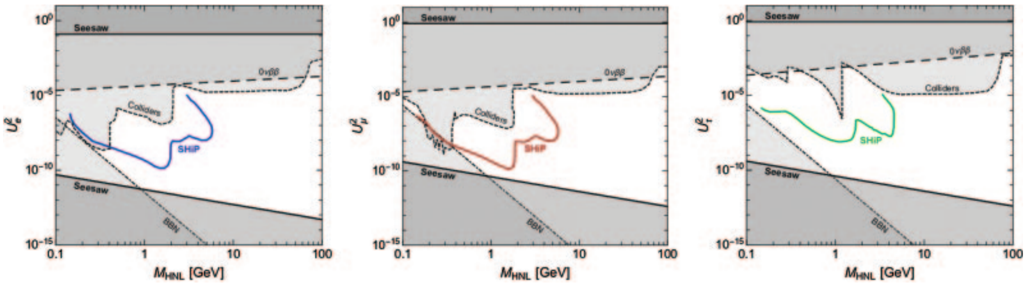

Fig. 1. – Constraints on the mixing angles as a function of the mass of the lightest right-handed neutrinos. SHiP sensitivity to different flavor parameters has been taken from [10] (colored lines). The two seesaw lines are the upper and lower limits predicted from the sole requirement of the seesaw condition. The current experimental limits (gray bands) are: the constraints by colliders data (short-dashed lines); the lower limits coming from BBN (dot-dashed lines); the upper limits coming from the non-observation of neutrinoless double beta decay lifetime (long-dashed lines).

5. – Results

The results for the constraints on the mixing angles are best represented as a function of the right-handed neutrino masses; we do so in fig. 1.

We notice that the constraints coming from double beta decay are not particularly competitive with the limits already coming from the collider experiments.

A point of special interest is the fact, already mentioned, that in order to have large mixing angles a large value of θ'' is required. This is particularly interesting in that it is possible to verify that in the limits of large θ'' the neutrino mass matrix asymptotes to a limiting form in which the elements satisfy certain relations, which might be symptoms of an underlying symmetry. We show an example of this in fig. 2, where the phases of certain elements of the neutrino mass matrix are shown to lie on an hyperbole for those values of the mixing angle larger than 10^{-7}.

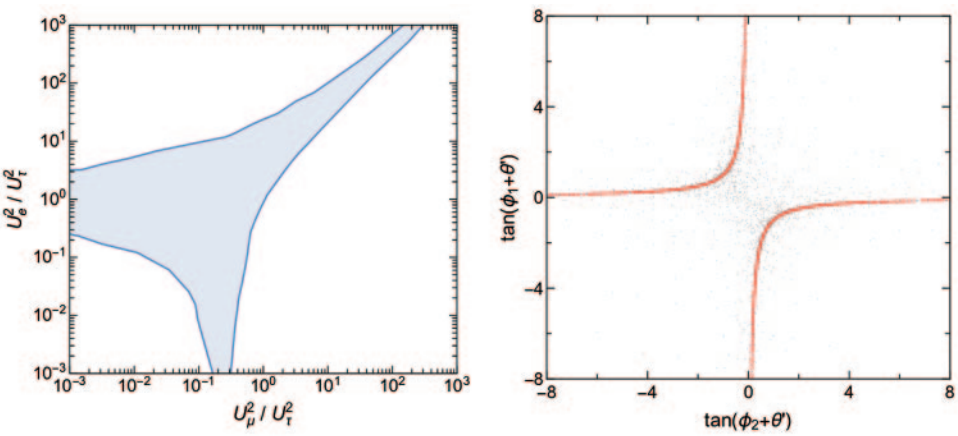

Fig. 2. – Left: mixing angles ratios obtained in the numerical analysis. Right: relation between the phases ϕ_1 of the matrix element M_{D11} and ϕ_2 of the matrix element M_{D12}. The gray points have $U^2 < 10^{-7}$, while the red points have $U^2 \geq 10^{-7}$.

Further, the ratios between the mixing angles in the three different flavors cannot take any arbitrary value, but are constrained in a region of the parameter space, which is shown in fig. 2.

6. – Conclusions

Our work was aimed at obtaining an analysis of the SHiP experiment potential in investigating a minimal seesaw model with just two sterile neutrinos. This analysis was completed with a study of the bounds coming both from cosmology and particle physics experiments, and it was extended to a discussion of the flavor mixing angle ratios. A further interesting point was the presence of a limiting structure approached by the neutrino mass matrix in order to obtain large values of the mixing angles.

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