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PHYSICS OF NUCLEI AND ELEMENTARY PARTICLES

On Neutrino Masses and Source of Dark Energy[1]

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Abstract—We propose a Higgs-extended model in which neutrinos naturally acquire tiny Majorana masses as constrained by the electroweak precision data, while the associated pseudo Nambu–Goldstone boson serves as an attractive candidate for dark enegy.

Keywords: Standard Model, neutrinos and dark energy.

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1. INTRODUCTION

The fact that neutrinos have tiny but nonzero masses, of the order of $\sim 10^{-3}\text{eV}$, has been confirmed by the solar, atmospheric and laboratory neutrino oscillation experiments [1–3]. Such small masses are elegantly generated by the seesaw mechanism where neutrinos acquire naturally small masses [4, 5]. Furthermore, the neutrino masses and dark energy density $\sim (10^{-3}\text{eV})^4$ seem to lie at the same scale. The existence of this small amount of energy is now believed to be the driver of the accelerating expansion of our universe as provided by various cosmological observations [3].

The startling coincidence between neutrino masses and dark energy scales gives rise to the idea of a unifying scenario of neutrinos and dark energy [6]. Indeed lots of ideas in this direction have been proposed and investigated [7, 8] where the wide possible explanation for the neutrino dark energy coincidence has its origin in a scalar field with specific properties or involves the pseudo Nambu–Goldstone boson (pNGB) providing an attractive realization of the dark energy field.

In this letter, we present a neutrino dark energy model consisting of an extended Higgs sector. The model involves in addition to the usual Higgs doublet a scalar triplet whose the interaction with the neutrino sector explains the generation of tiny neutrino masses and the existence of the comparable dark energy density from the scalar sector. In particular, the pNGB associated with the neutrino mass generation provides a consistent candidate for dark energy.

2. MODEL

2.1. Content and Constraints

Neutrinos and dark energy are one of the most powerful signals for new physics beyond the Standard Model (SM) [1–3]. Large investigations of these sectors have led to several models beyond the SM where right-handed neutrinos or new scalars find place [9, 10]. In fact, after the Higgs discovery [11, 12], the hunt for possible Higgs-like bosons has given a new consideration of such scalar extensions of the SM [1, 2]. Here, we extend with one triplet scalar the electroweak sector $SU(2)_L \times U(1)_Y$ of the SM,

$$L_i = (\nu_f, e_f)^T_{f=1,2,3}\left(2,\frac{-1}{2}\right), \quad (1)$$

$$H = (h^0, h^-)^T\left(2,\frac{-1}{2}\right), \quad (2)$$

$$\Delta = (\delta^{++}, \delta^+/\sqrt{2}, \delta^0)^T(3,1), \quad (3)$$

where L_i are the left-handed lepton doublets, H is the Higgs doublet and Δ is the scalar triplet which could be described with the following 2×2 matrix representation,

$$\Delta = \Sigma_i \Delta \boldsymbol{\sigma}_i = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & \delta^+/\sqrt{2} \end{pmatrix}_{Y=1}, \quad (4)$$

where $\boldsymbol{\sigma}_i$ are the three Pauli matrices, δ^0 is the complex neutral component and δ^{++}, δ^+ are the charged ones. This is one of models beyond the SM that allows to address some of the related issues. An implication of this emerges in the full Lagrangian of the model. For that, we will be restricted to the relevant pieces of the Lagrangian.

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[1] The article is published in the original.

We start with the scalar kinetic Lagrangian which reads,

$$\zeta^{H,\Delta}_{\text{kin}} = \left|D_\mu H\right|^2 + Tr\left[\left|D_\mu \Delta\right|\right]^2, \tag{5}$$

from which we can derive the model precision constraints. Indeed, through the contribution of the extra scalar to the electroweak $SU(2)_L \times U(1)_Y$ gauge boson masses which read as,

$$M_Z = \sqrt{\frac{g_1^2 + g_2^2}{2}\left(v_{h^0}^2 + 4v_{\delta^0}^2\right)}, \tag{6}$$

$$M_W = \sqrt{\frac{g_1^2}{2}\left(v_{h^0}^2 + 2v_{\delta^0}^2\right)}, \tag{7}$$

where v_{h^0} and v_{δ^0} are the corresponding vevs of the Higgs and triplet scalars developed by their neutral components, the ρ parameter would be redefined as [2],

$$\rho = \frac{1 + v_{\delta^0}^2/v_{h^0}^2}{1 + 2v_{\delta^0}^2/v_{h^0}^2}. \tag{8}$$

Going beyond the minimal SM, the success of the ρ parameter is an important clue to the symmetry structure of the model. In fact, to be in agreement with the most recent global fits [1, 2], this parameter must be near unity, leading to the vevs requirement,

$$v_{\delta^0} \ll v_{h^0}, \tag{9}$$

at tree level. This requirement, with (8), means that the triplet vev should be much smaller than the electroweak scale $v_{h^0} \sim 10^2$ GeV.

2.2. Smallness of Neutrino Masses

We now turn to the Yukawa sector, for that, we write down the relevant terms for the scalar triplet and lepton Yukawa interactions,

$$\zeta_{L-\Delta} = \frac{1}{2} y_{ij}^L \overline{L_i^c} i\sigma_2 \Delta L_j + \text{h.c.}, \tag{10}$$

where y_{ij}^L are the corresponding dimensionless Yukawa couplings characterizing the strength of the Higgs triplet coupling to the left-handed lepton doublets. With the scalar triplet getting its vev v_{δ^0} by the neutral component (7), the latter can be then redefined as,

$$\delta^0 = \sigma e^{i\alpha/v_{\delta^0}}, \tag{11}$$

with $\langle\sigma\rangle = v_{\delta^0}$. The fields σ, α are the physical neutral boson and the corresponding NGB respectively. The electroweak symmetry breaking takes then place with the vev of the Higgs doublet, which induces small vev to the scalar triplet as (7),

$$\langle\Delta\rangle \equiv \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ v_{\delta^0} & 0 \end{pmatrix}. \tag{12}$$

With this, the Lagrangian (7) reads,

$$\zeta_{\nu-\delta^0} = \frac{1}{2\sqrt{2}} y_{ij}^\nu \sigma \nu_i \nu_j e^{i\alpha_0/v_{\delta^0}} + \text{h.c.} \tag{13}$$

$$= \frac{y_{ij}^\nu}{2\sqrt{2}} \sigma \nu_i \nu_j \left(1 + i\frac{\alpha}{v_{\delta^0}} + \ldots,\right),$$

where the first order term will give rise to the neutrino masses and the remaining ones express the neutrino-NGB interaction $\nu - \alpha$. In fact, this leads after the vev of the Higgs triplet to the 3 × 3 neutrino mass matrix,

$$m_{ij}^\nu = \frac{y_{ij}^\nu}{2\sqrt{2}} v_{\delta^0}, \tag{14}$$

from which we can readily realize the neutrino mass spectrum and mixing. To be consistent with the neutrino oscillation experiments [1, 2], i.e., sub –eV neutrino masses, the scalar triplet vev should be at the order of $v_{\delta^0} \sim 10^{-3}$ eV.

2.3. Origin of Dark Energy

The smallness of the scalar vev keeping the experimental parameter near unity (8), is found to be relevant for the dark energy density in the universe $v_{\text{DE}} \sim (10^{-3}\ \text{eV})^4$. For that, it is natural to consider this small vev as being induced by the Higgs vev suppressed by a underlying high mass scale M as,

$$v_{\delta^0} \simeq \left(\frac{v_{h^0}^2}{M}\right)^n, \tag{15}$$

where the power $n \geq 1$ is for the possible scales of M. Hence, the triplet vev is seesaw-suppressed by the ratio of the electroweak scale v_{h^0} over the high scale M (15). In this approach, for the known dark energy density, the corresponding low scale ($n = 1$) is,

$$M \simeq \frac{v_{h^0}^2}{v_{\delta^0}} \sim 10^{16}\ \text{GeV}, \tag{16}$$

which is nothing but the GUT scale $M \cong M_{\text{GUT}}$. Furthermore, the interaction $\nu - \alpha$ of the neutrinos with the NGB α as,

$$\zeta_{\nu-\alpha} = i\frac{y^\nu}{2\sqrt{2}} \nu\nu\alpha + \ldots, \tag{17}$$

will induce a non-vanishing potential for α, which will acquire a tiny mass[3], and thus becomes the pNGB,

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[2] The ratio of the neutral current to the charged current coupling in the low-energy effective four fermion theory.

which can have direct consequences in cosmology [13, 14]. Such a mass is highly suppressed $m_\sigma :\sim 1/M_{\rm GUT}$ and thus escapes from experimental constraints at low energy scales and can naturally serve as a candidate for the dark energy field.

3. CONCLUSIONS

In this work, we have discussed a model relating the neutrino sector to dark energy by extending only the SM Higgs sector with a scalar triplet. The Majorana tiny neutrino masses are generated by the small vev acquired by the scalar triplet as constrained by the electroweak data. One pNGB with a highly suppressed mass associated with the neutrino mass generation arises in the model, and can play the role of the dark energy field.

The idea of massive neutrino-dark energy deserves more consideration and investigations. This connection could be verified in the present and future experiments, such as the cosmic microwave background and the large scale structure observations, the measurement of the extremely high-energy cosmic neutrinos, and the analysis of the neutrino oscillation data [13–15].

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