Unified scenario for composite right-handed neutrinos and dark matter[†]

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The Standard Model of particle physics is our most precise theoretical description of Nature and it has been tested to great precision in high energy particle colliders, like LHC. However, we know it represents only a partial description and the most notable missing ingredients are neutrino masses and dark matter, for which there exists a wealth of experimental evidence.

From the theoretical point of view, it is interesting to entertain the possibility that these two physical phenomena are related and emerge from a unified underlying dynamics. In this paper we introduce a new "dark sector" with a confining force, similar to the one of Quantum Chromodynamics (QCD), based on the dark gauge group $SU(3)_D$ and with three dark quarks. This dark sector has small interactions with the Standard Model particles, but more interestingly it contains a large number of composite states (dark mesons, dark baryons etc...) which can be used to successfully construct a low-energy theory with dark matter and right-handed neutrinos.

The construction starts from the dark sector Lagrangian $\mathcal{L}_{\rm DQCD}$ for the $SU(3)_D$ theory, which is well known and identical to the QCD one with three flavors, and proceeds with the addition of three types of higher-dimensional operators, deriving from different high-energy effective scales Λ_X, such that $\mathcal{L} = \mathcal{L}_{\rm DQCD} + \mathcal{L}_{\rm eff}$:

$$\mathcal{L}_{\rm eff} = \frac{\tilde{H}^* \bar{L}_f\, [\psi_i^3]}{\Lambda_f^3} + \frac{[\psi_i^6]}{\Lambda_N^5} + \frac{\bar{\psi}_i \psi_i H^\dagger H}{\Lambda_H} + \text{H.C.}, \quad (1)$$

where $\tilde{H}^* = \epsilon_{ab} H^{a*}$, with H the Standard Model Higgs doublet, and L_f is a lepton doublet of the Standard Model family $f = 1, 2, 3$. In Eq. (1) $i = 1, 2, 3$ and $[\psi_i^n]$ represents any $SU(3)_D$ singlet and Lorentz invariant combinations of n ψ_i quarks that are $\mathbb{Z}_2$ even. The $\mathbb{Z}_2$ symmetry imposed upon the operators in the theory is necessary to have a stable dark matter candidate.

It is important to note that the nature of the operators in Eq. (1) is determined by confinement of the dark gauge group, giving rise to composite states: *e.g.* the operator $[\psi_i^3]$ will transmute into a dark baryonic-like operator below the confinement scale μ_D such that the first term in Eq. (1) describes the interaction between the Higgs, the leptons and a "dark neutron" state, the second term describes oscillations between "dark neutrons," and the third terms describes masses for the dark quarks. The dark neutron oscillations are necessary to create neutrino masses: in our framework, dark neutrons are identified with right-handed neutrinos. Hence, the low-energy description in Eq. (1) will give rise to neutrino masses

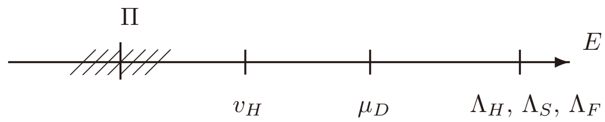

Fig. 1. The figure shows the separation of energy scales.

$$m_\nu \sim \frac{\mu_D^{10} v_H^2}{\Lambda_f^6 \Lambda_N^5}, \quad (2)$$

where $v_H \approx 246$ GeV is the electroweak energy scale. The other scales in Eq. (2) are chosen to reproduce the current known limits for neutrino masses of the order of $m_\nu \lesssim 0.1$ eV: $\mu_D \sim 1$ TeV and $\Lambda_{f,N} \sim 10$ TeV.

The confining nature of the dark sector is also responsible for the presence of a dark matter candidate in the spectrum. Similarly to QCD, the lightest composite particles are dark mesons, states that are made of a pair of dark quark and dark anti-quark. Without loss of generality, we assume that the dark quark masses generated by interactions with the Higgs boson are small and hierarchically distributed $m_1 < m_2 < m_3 \ll \mu_D$. Hence, the octet of lightest mesons comprises the three states

$$P \sim \bar{\psi}_1 \psi_2,\ \kappa \sim \bar{\psi}_1 \psi_3,\ \kappa' \sim \bar{\psi}_2 \psi_3, \quad (3)$$

their antiparticles, and two linear combinations P' and P'' of the flavor-diagonal bilinear $\bar{\psi}_i \psi_i$, analogues of the π^0 and η in QCD.

We will denote these states collectively with the symbol Π, and their masses are compared to the other scales in the theory in Fig. 1. The "dark kaons" κ and κ', containing only one ψ_3, are the only states that are odd under the $\mathbb{Z}_2$ symmetry, because we assume that $\mathbb{Z}_2(\psi_3) = -1 = -\mathbb{Z}_2(\psi_{1,2})$. The dark kaons are the lightest $\mathbb{Z}_2$-odd hadrons and κ will provide a dark matter candidate in this model, since $M_\kappa < M_{\kappa'}$. The mass of κ is related to the confinement scale through a low-energy effective chiral description of the spectrum (similar to QCD) yielding $M_\kappa \sim 10$ GeV. Such a light mass for composite dark matter is very interesting from the experimental point of view, and our scenario can be probed in future experimental setups.

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