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Discriminating flavor models via neutrino oscillations through dark matter halo

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In recent times several signatures of beyond standard model (SM) physics have appeared in a number of observables related to the semi-leptonic decays of B mesons. Further, the magnetic moment of muon also shows deviation from SM at the level of 4σ. A number of proposed new physics models can accommodate these anomalies. A class of these models also contain dark matter (DM) candidates. We intend to distinguish between a $L_\mu - L_\tau$ DM which is considered to reconcile the $(g-2)_\mu$ anomaly and a heavier muonphilic DM candidate which can also account for the B-anomalies. We find that one type of the DM compels the neutrinos to change the flavor ratios whereas for the other type of DM, the neutrinos mimic the flavor ratio of the vacuum. The DM-neutrino interaction, thus, has the potential to discriminate between flavor models with a dark connection.

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1. Introduction

The $b \to s\ell\ell$ ($l = e, \mu$) transition occurs at the loop level within the SM. It induces several decay modes: $B \to (K, K^*)\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$, $B_s \to \mu^+\mu^-$, etc. Recent observations in a number of observables in these decay mode reveal potential signs of physics beyond the standard model (SM). This includes lepton flavor universality violating as well as conserving observables. Furthermore, the muon's magnetic moment deviates from SM predictions by around 4σ. A number of proposed new physics models can accommodate these anomalies. A class of these models also contain dark matter (DM) candidates [1]. We study how neutrino (ν)-DM interactions which can impact cosmic neutrino oscillations through Milky Way's dense dark matter halos can be utilized in distinguishing between some of these proposed new physics models with *dark connection* [2].

2. Neutrino oscillations through DM halo

The Hamiltonian describing three-flavor neutrino oscillations is:

$$\mathcal{H}_0 = \frac{1}{2E}\left[V\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}V^\dagger\right], \tag{1}$$

where V is the PMNS matrix, $\Delta m^2_{ji} = m_j^2 - m_i^2$ and E is the neutrino energy. The presence of matter gives rise to the following matrix

$$\mathcal{H}_M = \frac{1}{2E}\begin{pmatrix}A_{CC} & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}, \tag{2}$$

where $A_{CC} = 2\,E\,V_{CC}$. V_{CC} is the potential of charge current interaction involving electrons.

Neutrinos encountering the DM Halo acquire an extra potential, altering the total Hamiltonian as

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_M + \mathcal{H}_\chi\,. \tag{3}$$

The form of $\mathcal{H}_\chi$ depends upon the nature of the DM. For DM charged under $L_\mu - L_\tau$, $\mathcal{H}_\chi$ given as

$$\mathcal{H}_\chi = \frac{1}{2E}\begin{pmatrix}0 & 0 & 0\\ 0 & A_\chi & 0\\ 0 & 0 & -A_\chi\end{pmatrix}. \tag{4}$$

Here $A_\chi = 2\,E\,V_\chi$ and V_χ is the dark matter potential. If DM interacts only with ν_μ, then

$$\mathcal{H}_\chi = \frac{1}{2E}\begin{pmatrix}0 & 0 & 0\\ 0 & A_\chi & 0\\ 0 & 0 & 0\end{pmatrix}. \tag{5}$$

We consider the propagation of neutrino flux through a DM halo where the DM potential dominates over the ordinary matter potential i.e. $A_{CC} << A_\chi$. Thus the Hamiltonian reduces to

$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_\chi$. This Hamiltonian, in general, can be written as

$$\mathcal{H} = \frac{1}{2E}\left[\tilde{V}\begin{pmatrix}\tilde{m}_1^2 & 0 & 0\\ 0 & \tilde{m}_2^2 & 0\\ 0 & 0 & \tilde{m}_3^2\end{pmatrix}\tilde{V}^\dagger\right], \tag{6}$$

where $\tilde{V}$ is the PMNS matrix and $\tilde{m}_i$'s are the eigenvalues of the Hamiltonian in the presence of DM. This $\tilde{V}$ and $\tilde{m}_i$'s play the role of V and m_i's, respectively in the DM environment.

3. Results

We analyze a model involving a Majorana DM particle, χ, and two scalar fields, ϕ_q and ϕ_l, with ϕ_q possessing color charge [3]. This is a modified version of model considered in [4], where the fermionic dark matter field was accompanied by both a scalar and a colored fermion. In this model, interactions between new and SM particles are governed by the Lagrangian:

$$\mathcal{L} = \lambda_{Q_i}\bar{Q}_i\phi_q P_R\chi + \lambda_{L_i}\bar{L}_i\phi_l P_R\chi + \text{h.c.}\,. \tag{7}$$

Here Q_i and L_i stand for SM left-handed quark and lepton doublets, while λ_{Q_i} and λ_{L_i} are new physics couplings. Here, the coupling of the new particles with only muons is considered. These new particles contribute to $b \to s\mu^+\mu^-$ process at one loop level. Due to $SU(2)$ symmetry, muon neutrinos can also interact with the DM.The interaction following the Lagrangian (7) engenders the following effective potential

$$V_\chi = \left(\frac{\lambda_\mu}{4m_{\phi_\mu}}\right)^2 n_\chi\,, \tag{8}$$

where $\lambda_\mu = \sqrt{4\pi}$ and m_{ϕ_μ} is the scalar mediator's mass. Here n_χ is the number density of DM.

We examine a situation in which an origin point for ultra-high-energy cosmic neutrino flux, spanning from 100 TeV to 1 PeV, is positioned near the core of the Milky Way. This configuration is assumed for its potential to have the greatest impact, given that the galactic center harbors the densest concentration of DM. Should the cosmic neutrino flux pass through the Milky Way's spiral arms, where DM density is notably lower than at the core, any discernible fluctuations in flavor composition would be too subtle to observe.

We find that for $A_\chi \sim 10^{-2}\,\text{eV}^2$, the survival probability of ν_μ approaches unity, i.e., the probability of oscillation from ν_μ to other neutrino flavors and vice versa, becomes zero. Thus ν_μ decouples from the other two neutrino flavors leaving only $\nu_e - \nu_\tau$ oscillation above this threshold. For initial pion decay, the produced neutrino flux ratio $(\Phi_e^s : \Phi_\mu^s : \Phi_\tau^s) = (0.33 : 0.66 : 0)$ transforms to $(\Phi_e^{\oplus\prime} : \Phi_\mu^{\oplus\prime} : \Phi_\tau^{\oplus\prime}) = (0.285 : 0.368 : 0.345)$ upon reaching Earth. Here we assumed cosmic neutrino flux of energy $E = 1$ PeV passing through a muonphilic DM sub-halo of radius 10^{-3} pc with $A_\chi = 0.1\,\text{eV}^2$. Such a large value of A_χ can be possible in the RAR-type of DM density distribution [5]. For vacuum oscillations, the flux ratio is $(\Phi_e^\oplus : \Phi_\mu^\oplus : \Phi_\tau^\oplus) = (0.308 : 0.351 : 0.339)$. This difference is, in principle, within the reach of the future experimental precision [6].

In [7], a $U(1)_{L_\mu - L_\tau}$ model was considered to explain the observed muon $(g-2)$ anomaly. This model also included a vector-like fermion which is a DM particle. The model's extended

Lagrangian beyond the SM Lagrangian is expressed as

$$\mathcal{L} \;=\; \overline{\chi} i \not{D} \chi + (D_\mu \Phi)^\dagger (D^\mu \Phi) - m_\chi \overline{\chi}\chi + \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2 \,. \tag{9}$$

Here $D_\mu = \partial_\mu - i g_X Z'_\mu$ represents the covariant derivative with g_X as the new gauge coupling. The dark matter candidate is denoted by χ which is a vector-like fermion, while Φ stands for the complex scalar singlet. In this model, the SM particles, including μ- and τ-neutrinos, can interact with the DM particle χ through the mediator Z'. Thus μ- and τ-neutrinos can interact with the DM.

The effective potential generated due to the DM interaction with ν_μ and ν_τ is given by

$$V_\chi = \pm \left(\frac{g_X}{m_{Z'}} \right)^2 n_\chi \,, \tag{10}$$

where the positive and negative sign corresponds to ν_μ and ν_τ, respectively. For the $L_\mu - L_\tau$ DM, all the three neutrino flavors are decoupled and hence the flux ratio on earth will resemble the case of vacuum oscillations.

4. Conclusions

In a model featuring a Majorana DM candidate, along with two new scalar fields contributing to $b \to s$ decays at the one-loop level, we observe that the neutrino oscillation pattern changes when passing through the DM halo, leading to a distinct flavor ratio on Earth compared to oscillations in free space. On the other hand, a Z' model driven by $L_\mu - L_\tau$ symmetry relinquishes a flavor ratio similar to that of vacuum oscillations. Therefore interaction of ultra high energy cosmic muon neutrinos with a dense halo of dark matter has the potential to be a good discriminant of new physics models which accommodate current anomalies in $b \to s\mu^+\mu^-$ sector and/or muon $(g-2)$ and having a liaison with the dark sector.

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