Discriminating flavor models via neutrino oscillations through dark matter halo

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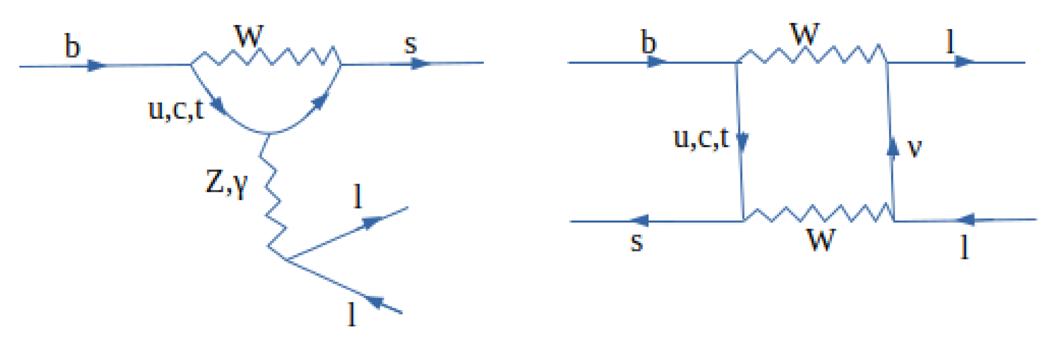
Motivation and Aim

- Recent observations in semi-leptonic B decays reveal potential signs of physics beyond the standard model (SM). 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.
- We study how ν-DM interactions impact cosmic neutrino oscillations through Milky Way's dense dark matter halos, aiding in distinguishing between proposed new physics models with *dark connection*.

$b \to s\ell\ell$ anomalies

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.

$b \to s\mu^+\mu^-$: LFU violating anomalies:

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 0.84 \pm 0.07\,, 3.1\sigma$$

[LHCb 14,19,21]

$$R_{K^*} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)} = 0.68 \pm 0.12\,, 2.4\sigma$$

[LHCb 17]

Can be due to NP in $b \to se^+e^-$ and/or $b \to s\mu^+\mu^-$ sector.

$b \to s\mu^+\mu^-$: Other anomalies

$$\mathcal{B}(B_s \to \phi\,\mu^+\mu^-) \sim 3.5\sigma\,[\text{LHCb13, 15, 21}]$$

$$B \to K^*\mu^+\mu^- \text{angular observable } P_5' \sim 3\sigma$$

[LHCb13,15,20; Belle16; CMS17; ATLAS17]

Can be related to NP only in $b \to s\mu^+\mu^-$.

Neutrino Oscillations

The Hamiltonian describing three-flavor neutrino oscillations is:

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

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

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

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

Dark Matter Halo

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

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

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

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

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

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

We consider 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

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

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.

Majorana Dark Matter Fermion

A model with scalar fields and a Majorana dark matter fermion for $b \to s\mu^+\mu^-$

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 [1]. In this model, interactions between new and SM particles are governed by the Lagrangian:

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

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.

The interaction following the Lagrangian engenders the following effective potential

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

Here, $\lambda_\mu = \sqrt{4\pi}$ and m_{ϕ_μ} is the scalar mediator's mass.

In this model, DM interacts only with ν_μ. For $A_\chi \sim 10^{-2}\,\text{eV}^2$, ν_μ decouples due to near unity survival probability, leaving only $\nu_e - \nu_\tau$ oscillation above this threshold.

For initial pion decay, the produced neutrino flux ratio $(\Phi^s_e : \Phi^s_\mu : \Phi^s_\tau) = (0.33 : 0.66 : 0)$ transforms to $(\Phi^{\oplus'}_e : \Phi^{\oplus'}_\mu : \Phi^{\oplus'}_\tau) = (0.285 : 0.368 : 0.345)$ upon reaching Earth. Here In the vacuum oscillation scenario, the flux ratio is $(\Phi^\oplus_e : \Phi^\oplus_\mu : \Phi^\oplus_\tau) = (0.308 : 0.351 : 0.339)$.

Z' for $(g-2)_\mu$

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

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

Here $D_\mu = \partial_\mu - ig_X Z'_\mu$ represents the covariant derivative with g_X as the new gauge coupling. The dark matter candidate is denoted by χ, 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

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

where the positive and negative sign corresponds to ν_μ and ν_τ, respectively. Here n_χ is the number density of DM.

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.

Conclusion

- 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.

References

[1] D. G. Cerdeño , A. Cheek , P. Martín-Ramiro , J. M. Moreno: *B anomalies and dark matter: a complex connection*, arXiv:1902.01789.

[2] Wei Chao, Yanyan Hu, Siyu Jiang, Mingjie Jin: *Neutrino oscillation in dark matter with $L_\mu - L_\tau$*, arXiv:2009.14703.

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