Spectral Signatures of Multi-Mediator Astrophysical Neutrino Self-Interactions at Ultra-High Energies

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Abstract

We investigate the impact of multiple mediators on the scattering of astrophysical neutrinos at ultra-high energies, $\mathcal{O}(100$ TeV) and beyond, with relic neutrinos from the Cosmic Neutrino Background (CνB). We demonstrate that such interactions can lead to distinctive features in the observed neutrino energy spectrum at detectors such as IceCube. In particular, we analyze the superposition of scattering amplitudes arising from mediators with closely spaced but non-degenerate masses, highlighting the resulting modifications to the spectral shape.

Furthermore, we emphasize the importance of including off-resonant t- and u-channel contributions in addition to the commonly studied resonant s-channel processes. As a concrete realization, we consider a $L_\mu - L_\tau$ gauge symmetry embedded in an extra-dimensional framework, which naturally gives rise to a tower of Kaluza–Klein (KK) vector bosons mediating neutrino self-interactions.

We show that in such scenarios, the resulting flux spectrum exhibits characteristic deviations from Standard Model expectations, particularly at the highest energies, providing a potential observational signature of multi-mediator dynamics in the neutrino sector.

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