Abstract

The Standard Model (SM) of particle physics stands as our most successful framework for understanding the fundamental constituents of the universe. Within this model, neutrinos emerge as fascinating, elusive particles that were initially believed to be massless. However, the phenomenon of neutrino oscillations revealed that they actually have tiny, nonzero masses. This discovery showed that our current understanding of particle physics was incomplete and pointed to new physics beyond the SM. To delve deeper into neutrino oscillations, we need to consider potential new physics beyond the SM. One such aspect is non-standard interactions (NSI), among other new physics effects. Neutrinos, treated as a three-mode system and mapped to a three-qubit system, offer a unique avenue for exploring quantum correlations. Neutrino oscillations exhibit nonclassical traits in Bell's inequality, and they serve as an excellent candidate for testing theories of local hidden variables grounded in the principles of locality and realism.

In entangled systems like neutrinos, Bell's inequality violation has been used to measure nonlocal correlations. However, recent studies suggest that a measure called Nonlocal Advantage of Quantum Coherence (NAQC) is a stronger measure of nonlocality than Bell's inequality parameter in neutrino systems. We investigated this in two-flavor neutrino oscillations across various experiments (DUNE, MINOS, T2K, KamLAND, JUNO, and Daya Bay), considering the impact of NSI. Our findings reveal that while NAQC is a stronger measure of nonlocality, it is relatively less sensitive to NSI effects than Bell's inequality. Entanglement is another interesting feature to analyze in the neutrino oscillation system. In this work, we investigated the effect of NSI on entanglement measurements such as entanglement of formation, concurrence, and negativity for a three-flavor neutrino oscillation framework in six accelerator and reactor studies. Although it has recently been demonstrated that negativity is a weaker measure than the other two entanglement measures, we discover that negativity is more susceptible to NSI. The effect of NSI also depends on the baseline of an experiment; that's why DUNE shows more sensitivity. The recent anomaly observed in NOνA and T2K experiments in standard three-flavor neutrino oscillation could potentially signal physics extending beyond the SM. For the NSI parameters that can accommodate this anomaly, i.e., $\epsilon_{e\mu}$ or $\epsilon_{e\tau}$, we explore the violation of Leggett-Garg type inequalities (LGtI) within the context of three-flavor neutrino oscillations. LGtI violation is significantly enhanced in normal ordering (NO) for the $\epsilon_{e\tau}$ scenario, whereas it is suppressed for the $\epsilon_{e\mu}$ scenario for T2K, NOνA, and DUNE experiment set-up for the three-flavor neutrino oscillation framework. Scalar NSI introduces a coupling between neutrinos and scalar fields, resulting in corrections to the neutrino mass term. There is a growing interest in examining the effects of scalar NSI on experiments that explore neutrino oscillations. We analyze the effect of scalar NSI on various quantum correlation measures in the DUNE experiment.