Enhanced violation of Leggett-Garg Inequality in three flavour neutrino oscillations via non-standard interactions

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Introduction

- Neutrino oscillate among themselves and these oscillations have their origin in the non-zero neutrino masses and mixing among the neutrino flavors.
- The standard paradigm of neutrino oscillations involves three flavours of neutrinos which are superpositions of the mass states carrying well-defined masses.
- Effective Hamiltonian for neutrino porpagation

$$\boxed{\mathcal{H} = \mathcal{H}_{\rm vac} + \mathcal{H}_{\rm SI} + \mathcal{H}_{\rm NSI}}$$

where $\mathcal{H}_{\rm vac}$ is the vacuum Hamiltonian and $\mathcal{H}_{\rm SI}, \mathcal{H}_{\rm NSI}$ are the effective Hamiltonians in presence of standard interaction (SI) and NSI respectively.

Leggett-Garg Inequalities

In 1985, Leggett and Garg derived a class of inequalities which have the following assumptions:

Macroscopic realism (MR):

A macroscopic system with two or more macroscopically distinct states available to it will at all times be in one or the other of these states.

Non-Invasive measurability (NIM):

It is possible, in principle, to determine which of the states the system is in, without affecting the states itself or the system's subsequent dynamics.

- Dichotomic observable: $Q = \pm 1$

- Two time correlation functions $C_{ij} = \frac{1}{N}\sum_{q=1}^{N}\langle Q_i^q Q_j^q\rangle$
- Macrorealism restricts the following combination of two time correlation functions:

$$\begin{aligned} K_3 = C_{12} + C_{23} - C_{31} &= \langle Q_1 Q_2\rangle + \langle Q_2 Q_3\rangle - \langle Q_1 Q_3\rangle \\ K_3 &= \langle Q_1 Q_2\rangle + \langle [Q_2 - Q_1]\, Q_3\rangle \\ K_3 &= \begin{cases} 1 + 0 = 1 \\ -1 + (\pm 2) = 1 \quad \text{or} - 3 \end{cases} \end{aligned}$$

This gives the condition

$$-3 \leq K_3 \leq 1$$

- In general we have

$$\begin{aligned} -n \leq K_n \leq (n-2) &\qquad 3 \leq n, \mathrm{odd}; \\ -(n-2) \leq K_n \leq (n-2) &\qquad 4 \leq n, \mathrm{even} \end{aligned}$$

Existing literature on LGI in Neutrino Sector

- D. Gangopadhyay, D. Home, and A. Sinha Roy. Probing the Leggett-Garg Inequality for Oscillating Neutral Kaons and Neutrinos. Phys. Rev., A88(2):022115 2013
- J. A. Formaggio, D. I. Kaiser, M. M. Murskyj, and T. E. Weiss. Violation of the Leggett- Garg Inequality in Neutrino Oscillations. Phys. Rev. Lett., 117(5):050402, 2016.
- Qiang Fu and Xurong Chen. Testing violation of the LeggettGarg-type inequality in neutrino oscillations of the Daya Bay experiment. Eur. Phys. J., C77(11):775, 2017.
- Debashis Gangopadhyay and Animesh Sinha Roy. Three-flavoured neutrino oscillations and the LeggettGarg inequality. Eur. Phys. J., C77(4):260, 2017.
- Javid Naikoo, Ashutosh Kumar Alok, Subhashish Banerjee, S. Uma Sankar, Giacomo Guarnieri, Christiane Schultze, and Beatrix C. Hiesmayr. A quantum information the- oretic quantity sensitive to the neutrino mass-hierarchy. Nucl. Phys. B, 951:114872, 2020.
- Javid Naikoo, Ashutosh Kumar Alok, Subhashish Banerjee, and S. Uma Sankar. Leggett-Garg inequality in the context of three flavour neutrino oscillation. 2019

- Let the initial state of neutrino be prepared in a specific flavor, say muon neutrino $|\nu_\mu\rangle$. Then we have

$$Q = \begin{cases} +1 & \text{for } \nu_\mu \\ -1 & \text{for } \nu_e \text{ or } \nu_\tau \end{cases}$$

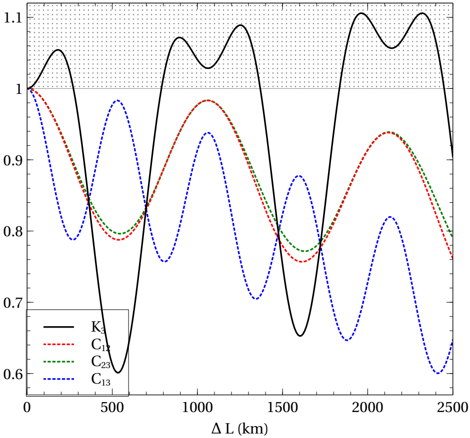
- The correlation function C_{12} can be evaluated by using all the 9 joint probabilities as

$$\begin{aligned} C_{ij} &= P_{\nu_e,\nu_e}(L_i, L_j) - P_{\nu_e,\nu_\mu}(L_i, L_j) - P_{\nu_e,\nu_\tau}(L_i, L_j) \\ &\quad - P_{\nu_\mu,\nu_e}(L_i, L_j) + P_{\nu_\mu,\nu_\mu}(L_i, L_j) + P_{\nu_\mu,\nu_\tau}(L_i, L_j) \\ &\quad - P_{\nu_\tau,\nu_e}(L_i, L_j) + P_{\nu_\tau,\nu_\mu}(L_i, L_j) + P_{\nu_\tau,\nu_\tau}(L_i, L_j) \end{aligned}$$

  where $P_{\nu_\alpha \nu_\beta}(L_i, L_j) = P_{\nu_\mu \to \nu_\alpha}(L_i) P_{\nu_\alpha \to \nu_\beta}(L_j)$

- For maximizing the LGI parameters we take $L_1 = 140.15$km, and $(L_2 - L_1) = (L_3 - L_2) = (L_4 - L_3) = \Delta L$. Energy is taken to be 1 GeV and $\delta = 3\pi/2$. NH is assumed unless otherwise stated.

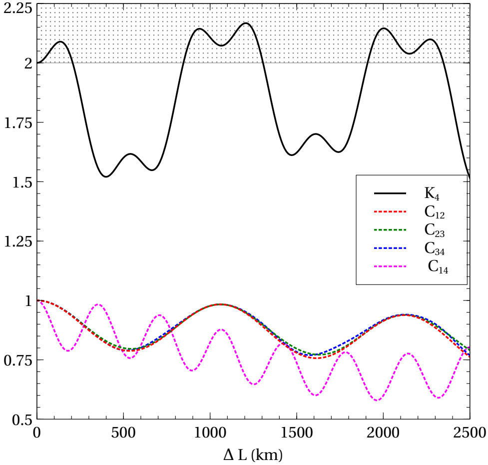
Results



$K_3 = C_{12} + C_{23} - C_{31}$

$-3 \leq K_3 \leq 1$

Figure: SI-K_3



$K_4 = C_{12} + C_{23} + C_{34} - C_{41}$

$-2 \leq K_4 \leq 2$

Figure: SI-K_4

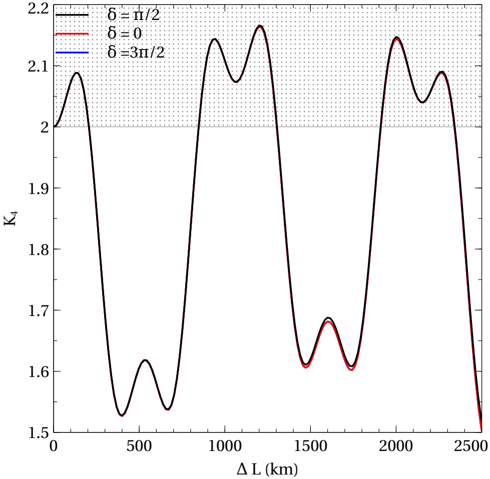


Figure: No dependence on δ

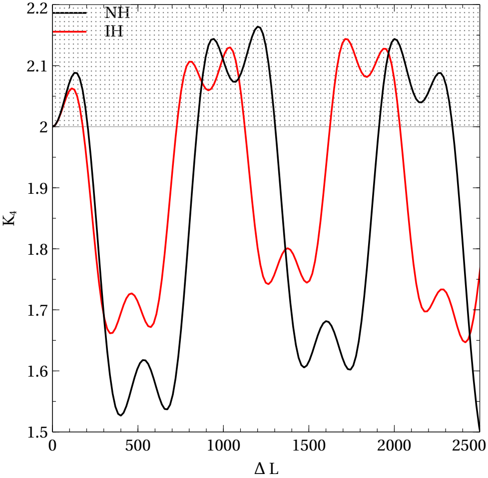


Figure: Mass hierarchy dependence

$$\mathcal{H} = \frac{1}{2E}\mathcal{U}\begin{pmatrix} 0 & & \\ & \delta m^2_{21} & \\ & & \delta m^2_{31} \end{pmatrix}\mathcal{U}^\dagger$$

$$+\frac{A(x)}{2E}\begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}{}^\star & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}{}^\star & \varepsilon_{\mu\tau}{}^\star & \varepsilon_{\tau\tau} \end{pmatrix}$$

where $A(x) = 2E\sqrt{2}G_F n_e(x)$ is the standard charged current potential and $\mathcal{U}$ is the mixing matrix.

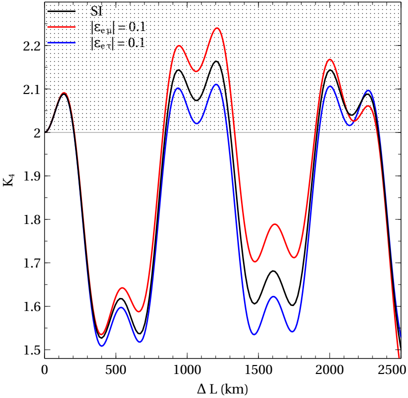


Figure: Non-standard senario

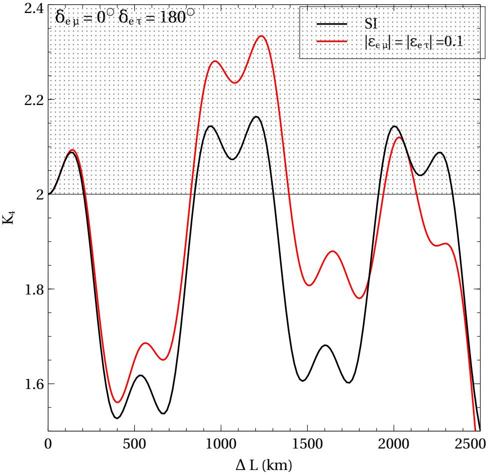
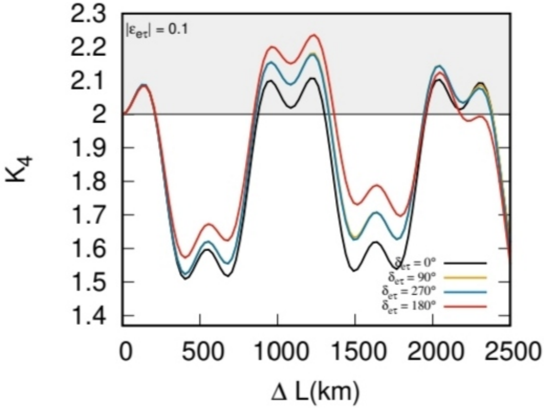


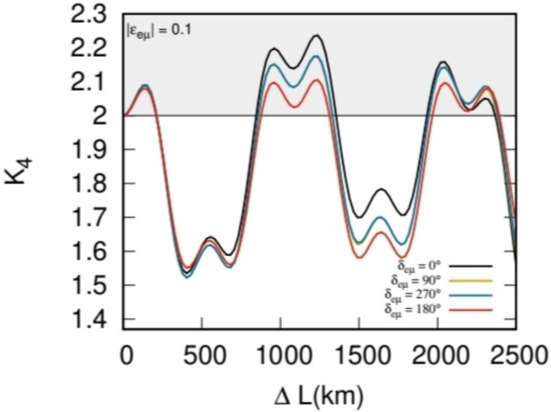
Figure: SI and NSI

Summary

- Exploring Leggett-Garg Inequalities in neutrino sector has been a topic of interest for the past decade.
- Neutrino oscillations, being a quantum mechanical phenomenon, violate LGI.
- LGI parameter does not depend on the CP-violating factor δ.
- It does depend on the mass hierarchy and at large values of ΔL, the curves for the two hierarchies are out of phase with each other.
- In the NSI senario, for $\epsilon_{e\mu} \neq 0$, we achieve an enhancement in the LGI parameter and for $\epsilon_{e\tau} \neq 0$, the LGI parameter is supressed.
- Varying the other NSI parameters, we maximise the value of the LGI parameter for NSI case and note a significant enhancement in the violation of LGI in the NSI senario as compared to the SI senario.
- For more details, please refer to arXiv:2009.12328 [hep-ph]

Thank You


$|\varepsilon_{e\tau}| = 0.1$
K_4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
0
500
1000
1500
2000
2500
ΔL(km)
$\delta_{e\tau} = 0°$
$\delta_{e\tau} = 90°$
$\delta_{e\tau} = 270°$
$\delta_{e\tau} = 180°$



$|\varepsilon_{e\mu}| = 0.1$
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
K_4
0
500
1000
1500
2000
2500
Δ L(km)
$\delta_{e\mu} = 0°$
$\delta_{e\mu} = 90°$
$\delta_{e\mu} = 270°$
$\delta_{e\mu} = 180°$