PROCEEDINGS OF SCIENCE

Exploring Long-Range Interactions of $L_\mu - L_\tau$ Symmetry at INO-ICAL

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In a minimal extension of the Standard Model with abelian $U(1)'$, there exists a flavor-dependent long-range leptonic force mediated by an ultralight and neutral gauge boson Z' associated with $L_\mu - L_\tau$ symmetry. We study the impacts of such long-range force in the oscillation of atmospheric neutrinos assuming $Z - Z'$ mixing. We show that the proposed atmospheric neutrino detector ICAL will be able to put tight constraints on such long-range force due to its capabilities of detecting neutrino and antineutrino separately with wide ranges of energies and baselines. The expected upper limit on the parameter of this long-range force at 3σ is 2.82×10^{-51} using 500 kton·year exposure of ICAL.

XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023),
28.08 – 01.09.2023,
University of Vienna, Vienna, Austria

[*] Speaker

PoS(TAUP2023)269

1. Introduction and Theoretical formalism

The magnetized Iron Calorimeter (ICAL) detector under the India-based Neutrino Observatory (INO) aims to determine the neutrino mass ordering by detecting the atmospheric neutrino and antineutrino separately [1]. The ICAL detector also has great potential to explore new physics beyond the Standard Model (SM). In this article, we forecast the sensitivity of ICAL to study flavor-dependent long-range interactions of neutrino that are allowed in an anomaly-free extension of SM by $U(1)'$ with gauged $L_\mu - L_\tau$ symmetry and associated with ultralight Z'. The $Z - Z'$ mixing results in the new interactions between neutrinos and electrons, protons, and neutrons [2] that give rise to addition potentials along with the usual matter potential for neutrinos and antineutrinos [3]. These new potentials induced in long-range interaction of a neutrino with electrons and protons have opposite signs and cancel each other. Therefore, the potential for long-range force with $L_\mu - L_\tau$ symmetry is contributed only by neutrons.

If the mass of Z' is $m_{\mu\tau} \leq 1.32 \times 10^{-18}$ eV (1 AU^{-1} = $(1.5 \times 10^8\ \text{km})^{-1}$), then the neutrons inside the Sun and Earth come in the range of the interaction. Taking into account the total number of the neutrons in the Sun using the spherically symmetric neutron number density inside the Sun [4] and for the Earth, using the PREM profile [5], we obtain total long-range potential $V_{\mu\tau}$ as

$$V_{\mu\tau} = \pm\ 4.4 \times 10^{-14} \times \frac{\alpha_{\mu\tau}}{10^{-50}} \quad \text{eV}\,, \tag{1}$$

where the parameter $\alpha_{\mu\tau}$ is proportional to the coupling strength of the new interactions and $Z - Z'$ mixing angle. We consider only the positive values of $\alpha_{\mu\tau}$ which make the potentials positive for neutrino and negative for antineutrino assuming the long-range force repulsive.

The article is organized in the following way. In Sec. 2, the modifications of atmospheric neutrinos and subsequently the events at ICAL are discussed. Sec. 3 provides the expected limits on LRF. Finally in Sec.4, we summarize and conclude.

2. Impacts on atmospheric neutrino oscillations and events at ICAL

In the presence of the long-range force of $L_\mu - L_\tau$ symmetry, the additional term in the effective Hamiltonian of neutrino flavors in propagation is given by

$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & V_{\mu\tau} & 0 \\ 0 & 0 & \text{-}V_{\mu\tau} \end{bmatrix}. \tag{2}$$

We calculate the oscillation probabilities of neutrinos numerically with 3ν oscillation framework and taking into account the PREM profile [5] of Earth's matter density to take into account the matter effect properly. The left panel of Fig.1 shows the difference in the survival probabilities of ν_μ due to the presence of LRF with $\alpha_{\mu\tau} = 5.5 \times 10^{-51}$ as compared to the SI case ($\alpha_{\mu\tau} = 0$). The values of oscillation parameters we use are $\sin^2\theta_{23} = 0.5$, $|\Delta m^2_{31}| = 2.5 \times 10^{-3}$ eV^2, $\theta_{13} = 8.6°$, $\theta_{12} = 33.8°$, $\Delta m^2_{21} = 7.39 \times 10^{-5}$ eV^2, $\delta_{\rm CP} = 0$, and normal ordering (NO). We observe that in the presence of leptonic flavor-dependent long-range force, the survival probabilities of muon neutrinos are increased and this is true also for antineutrinos.

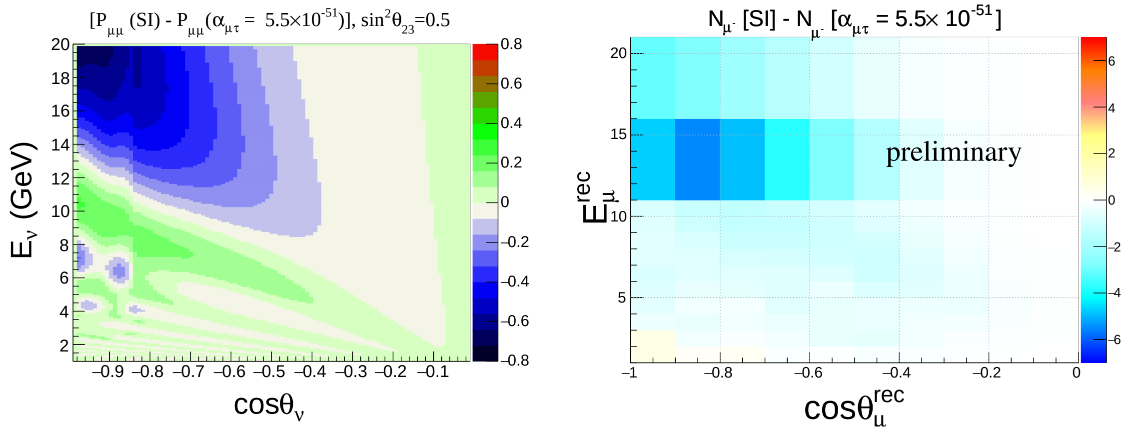

Figure 1: Left panel: the difference in the survival probabilities of ν_μ between SI ($\alpha_{\mu\tau} = 0$) and $\alpha_{\mu\tau} = 5.5 \times 10^{-51}$. Right side: the difference of the μ^- events at ICAL due to the presence of the LRF with SI case as compared to with $\alpha_{\mu\tau} = 5.5 \times 10^{-51}$. Here, we take 500 kton·year exposure ICAL and NO.

To show the impact of the long-range force of $L_\mu - L_\tau$ at the expected events at ICAL, we simulate the neutrino interactions with the NUCANCE event generator and fold with detector properties provided by the collaboration. In right side of Fig.1, one can see that the number of muon events expected in the presence of the LRF is larger than that in the absence of LRF (SI). The interesting region for the exploration of LRF is reconstructed muon energy in the range of 5-20 GeV and $\cos\theta_\mu$ in the range of -1 to -0.4.

3. Expected Limits on LRF

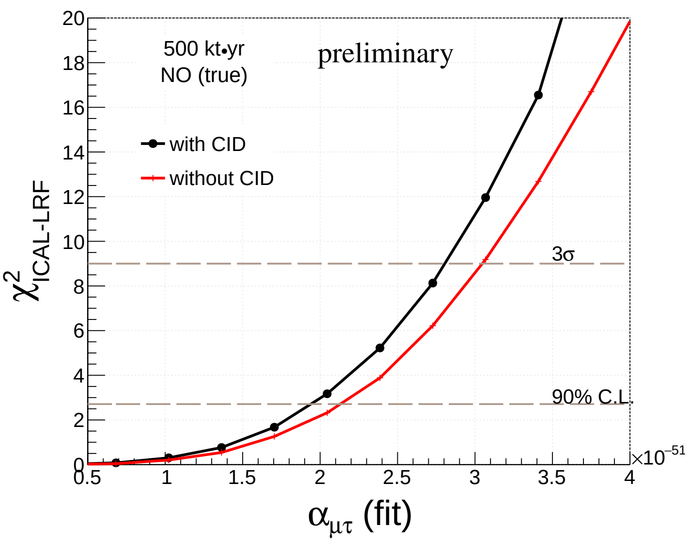

Figure 2: The expected bounds on LRF of $L_\mu - L_\tau$ symmetry from 10-year ICAL data with NO as true MO.

In the statistical analysis of the muon events, we use the reconstructed muon energy (E_μ), reconstructed muon direction ($\cos\theta_\mu$), and reconstructed hadron energy ($E'_{\rm had}$) as observable. We take 10 bins in the range of $E_\mu \in [1, 11]$ GeV and 2 bins in the range of $E_\mu \in [11, 21]$ GeV. In case of E'_{had}, there are 2 bins in the range [0–2] GeV, 1 bin in the range [2–4] GeV, and 1 bin in the range [4 – 25] GeV. For $\cos\theta_\mu$, a total of 10 bins in the range [-1, 0] and 5 bins in the range [0, 1] are taken.

We use the Poissonian χ^2 function for μ^- and μ^+ events separately and finally add these to get the total statistical significance for the difference between 'data' (with SI scenario) and 'theory' (with nonzero $\alpha_{\mu\tau}$). Fig. 2 shows the statistical significance for constraining the LRF as a function of $\alpha_{\mu\tau}$ in fit after marginalization over 3σ uncertainty ranges of oscillation parameters θ_{23}, Δm^2_{32} and two mass orderings. This result is with 500 kton·year exposure of the ICAL detector. We obtained that the ICAL will be able to set an upper limit on LRF of $L_\mu - L_\tau$ symmetry at 2.8×10^{-51} at 3σ C.L. We find that with the charge separation of μ^- and μ^+, the expected constraint is better than that without the charge information. This happens due to dilution of impact of LRF on neutrino and antineutrino channels in the absence of the charge identity of muon in the detector.

4. Summary and Concluding remarks

We study the potential of the ICAL detector at INO to explore the long-range interactions that arise in a minimal extension of the Standard Model with anomaly-free gauged $U(1)'$. Among the allowed symmetries for this new gauge group, we consider the leptonic flavor combination $L_\mu - L_\tau$ which produces new potential for neutrino due to neutrons provided there is mixing between $Z - Z'$. Assuming the ultralight Z', therefore, long-range interaction of neutrino, and taking into account the potential due to neutrons in Sun and Earth, we obtained that the ICAL will be able to put the upper limit on LRF of $L_\mu - L_\tau$ symmetry at 2.8×10^{-51} at 3σ C.L. with 500 kton·year exposure.

Acknowledgement

A.K. acknowledges the financial support by VEGA Grant Agency of the Slovak Republic under Contract No. 1/0418/22 and by Slovak Research and Development Agency (Contract No. APVV-22-0413).

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