PROCEEDINGS OF SCIENCE

Constraining the Scalar Non-Standard Interactions in Neutrino Oscillation Experiment

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Neutrinos are unique tools to probe new physics scenarios such as non-standard interactions (NSIs) of neutrinos with matter. The coupling of neutrinos to a scalar field gives rise to a new interaction known as Scalar NSI. Unlike the vector NSI case, which contributes to the usual matter potential, the scalar NSI appears as a correction to the neutrino mass term. In this work, we perform a phenomenological study of neutrino oscillation along with the scalar NSI and its impact on the determination of neutrino mass ordering (NMO) at the JUNO experiment. We find that in the presence of scalar NSI the survival probabilities $P_{\rm ee}$ and $\bar{P}_{\rm ee}$ depend upon the $\delta_{\rm CP}$ and octant of θ_{23}, which is not the case, had the scalar NSI been absent in the Hamiltonian. We explore the role of diagonal scalar NSI parameters namely η_{ee}, $\eta_{\mu\mu}$, and $\eta_{\tau\tau}$ and it is noted that η_{ee} significantly affects the mass ordering determination of JUNO. The constraints on such diagonal scalar NSI elements have also been obtained in this work.

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1. Introduction

Over the past two decades, the experimental data have firmly established the phenomenon of neutrino oscillation [1, 2] where one flavour of neutrino changes into another flavour after traveling a sufficient distance from the source to the detector. Nevertheless, secondary effects such as non-standard interactions, quantum decoherence, neutrino decay, etc. offer unique opportunities to look for new physics scenarios beyond the standard model in neutrino oscillation experiments. In this era of precision in neutrino physics experiments, it is imperative to delve into the repercussions of these sub-leading phenomena.

In this proceeding, we explore the potential of an upcoming reactor neutrino experiment, specifically JUNO, to constrain the parameters of diagonal scalar Non-Standard Interactions (sNSI). Additionally, we will elucidate the impact of these sNSI on the measurement of neutrino mass ordering (NMO) at JUNO. This proceeding is structured as follows. In the next section, we will provide a comprehensive overview of the sNSI formalism, accompanied by a concise description of the simulation techniques employed in our analysis. Subsequently, we will present our findings. To conclude, we will summarize and provide concluding remarks.

2. Formalism

According to the Standard Model, the weak interaction of neutrinos with the ambient matter can be of two types; charged current (CC) interactions and neutral current (NC) interactions mediated by $W^{\pm}$ boson and Z boson, respectively [3]. The effect of such standard interactions is to introduce an extra matter potential term in the neutrino Hamiltonian. In addition to this, neutrinos may also couple to the matter fermions via scalar fields. Such non-standard interactions offer a promising avenue for exploring new physics in neutrino oscillation. The effective Lagrangian corresponding to the scalar NSI can be written as [4, 5]

$$\mathcal{L}^{\text{eff}}_{\text{sNSI}} = \frac{y_f Y_{\alpha\beta}}{m^2_{\Phi}} [\bar{\nu}_\alpha \nu_\beta][\bar{f} f], \tag{1}$$

where y_f and $Y_{\alpha\beta}$ are the Yukawa couplings of scalar field Φ with matter fermions $f \in \{e, u, d\}$, and neutrinos with Φ, respectively. In the above Lagrangian $\alpha, \beta = e, \mu, \tau$ refers to the flavour indices for neutrino and m_Φ denotes the mass of scalar mediator Φ. The Yukawa type structure of scalar NSI (Eq. 1) indicates that it is no longer a vector current and hence will not contribute as matter potential term in neutrino Hamiltonian. In fact, the scalar NSI will modify the neutrino mass matrix and appear as a correction to the neutrino mass term. Therefore, the corresponding Hamiltonian including scalar NSI takes the form

$$\mathcal{H}^{\text{eff}}_{\text{sNSI}} \approx \frac{1}{2E}\left[(\mathcal{M} + \delta M)(\mathcal{M} + \delta M)^\dagger + 2EV_{CC}\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}\right], \tag{2}$$

where $\delta M \equiv \sum_f \frac{N_f y_f Y_{\alpha\beta}}{m_\phi^2}$ is the contribution due the scalar NSI and N_f is number density of matter fermions. In the above expression, $\mathcal{M} = U \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} U^\dagger$ is the neutrino mass matrix in flavour basis and $V_{CC} = \pm\sqrt{2} G_F N_e$ is the matter potential term due to the CC standard interactions of neutrinos with matter where G_F is the Fermi coupling constant and U is standard PMNS mixing matrix [6]. For the phenomenological study of scalar NSI, the matrix δM is parameterised as [7]

$$\delta M \equiv \sqrt{|\Delta m_{31}^2|} \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta_{e\mu}^\star & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta_{e\tau}^\star & \eta_{\mu\tau}^\star & \eta_{\tau\tau} \end{pmatrix}, \tag{3}$$

where $\eta_{\alpha\beta}$ represents the strength of scalar NSI. One of the striking features of this model is that the neutrino oscillation probability depends upon the absolute neutrino masses, unlike the standard case where only mass-squared differences are relevant. It should be noted here, that in the present work, we only consider diagonal NSI elements of the above NSI matrix taking one at a time.

3. Simulation Details

The Jiangmen Underground Neutrino Observatory (JUNO) [8] is a forthcoming reactor-based neutrino experiment in China. The main purpose of the JUNO is to resolve the neutrino mass ordering issue by measuring the electron antineutrino disappearance probability, $P_{\bar{\nu}_e \to \bar{\nu}_e}$. In this work, we consider a liquid scintillator detector of 20 kton fiducial mass situated at an average baseline of approximately 53 km from the reactors. For this small baseline, we neglect the matter effect in the present analysis. In order to understand the role of scalar NSI at the JUNO experiment, we have used the GLoBES software package [9] where new physics effects have been included using Eqs. 2 and 3 and all the experimental details such as energy resolution, backgrounds, systematic errors, antineutrino fluxes and, cross-sections are adopted from Ref. [8] and have been incorporated in GLoBES. A combined signal and background events of around 140, 000 have been considered for the present work. The value of the standard neutrino oscillation parameters have been taken from Ref. [10].

4. Results

In this section, we present the main outcomes of our work. Since the signals at JUNO are the inverse beta-decay (IBD) events, $\bar{\nu}_e + p \longrightarrow e^+ + n$, in Fig. 1, we have presented the IBD events as a function of neutrino energy. The left panel is for normal mass ordering (NO) while the right panel is for inverted mass ordering (IO). In each panel, the solid red curve corresponds to the case when scalar NSI is absent ($\eta_{\alpha\beta} = 0$, SI) in the three flavour oscillation picture. The effects of positive values of diagonal NSI elements ($\eta_{ee}, \eta_{\mu\mu}, \eta_{\tau\tau}$) are shown by dashed curves (for negative NSI elements and other details, please see [11]). From this Figure, we understand that scalar NSI significantly affects the event spectrum of JUNO and its impact is more revealing in the case of IO (since even a smaller value of sNSI element for instance $\eta_{\alpha\alpha} = 0.002$, induces a large change in the event rates). Moreover, the spectra are less degenerate in the case of inverted mass ordering as compared to the normal one. These points suggest obtaining better constraints on the scalar NSI parameters when the neutrino mass ordering is inverted. A positive value of $\eta_{ee} = 0.012$ suppresses

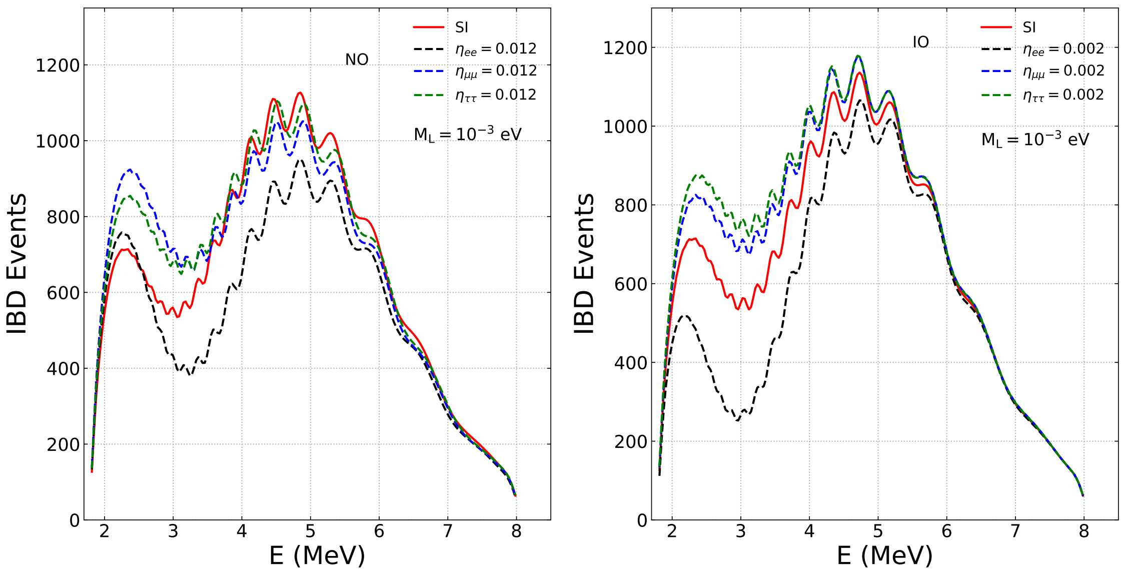

Figure 1: Event rates at JUNO as a function of neutrino energy in the presence of scalar NSI. The left (right) panel is for NO (IO). The lightest neutrino mass M_L is taken to be 10^{-3} eV.

the antineutrino event rate by almost 10-15 % in the energy range ~ 2.5 MeV to 6.0 MeV. The effect of positive values of $\eta_{\mu\mu}$ and $\eta_{\tau\tau}$, on the other hand, is to enhance the event rates for the lower neutrino energy range of ~ 2.5 MeV to 3.5 MeV.

4.1 Constraints on Scalar NSI from JUNO Experiment

In Fig. 2, we present the bounds on diagonal scalar NSI parameters in the m_{lightest} - $|\eta_{\alpha\alpha}|$ plane. In each case, the solid (dashed) curves correspond to the positive (negative) values of sNSI elements. In order to obtain Fig. 2, a "true data" is generated assuming the standard case when all $\eta_{\alpha\alpha} = 0$ which is then compared with the test data, where we include sNSI by varying m_{lightest} and $\eta_{\alpha\alpha}$ in the range as shown in the plots. We have marginalised over θ_{12}, Δm^2_{21} and Δm^2_{31} in the allowed $\pm 3\sigma$ range. Note that in this case, we consider the same mass ordering of neutrinos in both true and test data. For every $(m_{\text{lightest}}, |\eta_{\alpha\alpha}|)$, we compute a least-$\chi^2$ by fitting it with "true data". It can be observed from the plots that constraints for both positive and negative values of sNSI parameters are more or less the same. As expected from the previous discussions, the results for IO are better than NO in each case by almost an order of magnitude.

4.2 Neutrino mass ordering of JUNO in the presence of scalar NSI

In Fig. 3, we show the neutrino mass ordering sensitivity of JUNO in the presence of scalar non-standard interaction. The method to obtain this Figure is the same as described in the previous sub-section. The only difference is that here we consider the neutrino mass ordering to be the opposite of what has been assumed to generate the "true data". The results are displayed in the

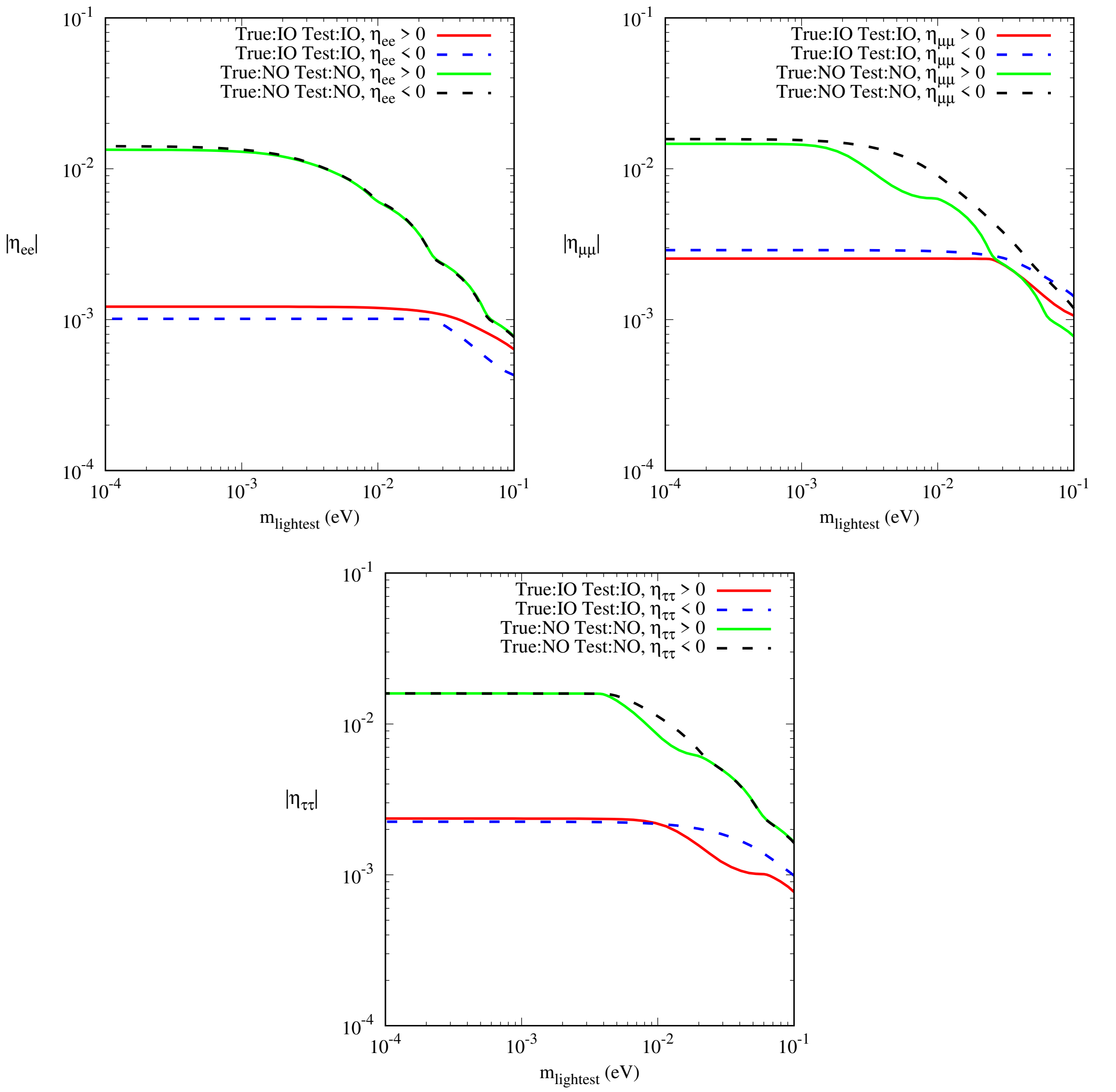

Figure 2: Constraints on scalar NSI with JUNO. Top left (right) panel is for $|\eta_{ee}|$ ($|\eta_{\mu\mu}|$). Bottom panel is for $|\eta_{\tau\tau}|$.

m_{lightest} - $|\eta_{\alpha\alpha}|$ parameter space. We find that depending upon the values of m_{lightest} and $|\eta_{\alpha\alpha}|$, the wrong mass hierarchy of neutrinos is allowed at 3σ.

5. Concluding Remarks

With the tremendous progress in the field of neutrino physics and being in the precision era for neutrino oscillation, it becomes very important to investigate the various subleading interactions of neutrinos and their impact on the goal of the current and future neutrino detectors. In this proceeding, we have explored the possibility of constraining the scalar non-standard interaction of neutrinos in the context of JUNO experiment. We have neglected the Earth matter effects which is a good assumption for JUNO baselines (≈ 53 km) and antineutrino energies ($\approx 1-8$ MeV). We have shown that the electron antineutrino event rates of JUNO get significantly modified if scalar NSI is

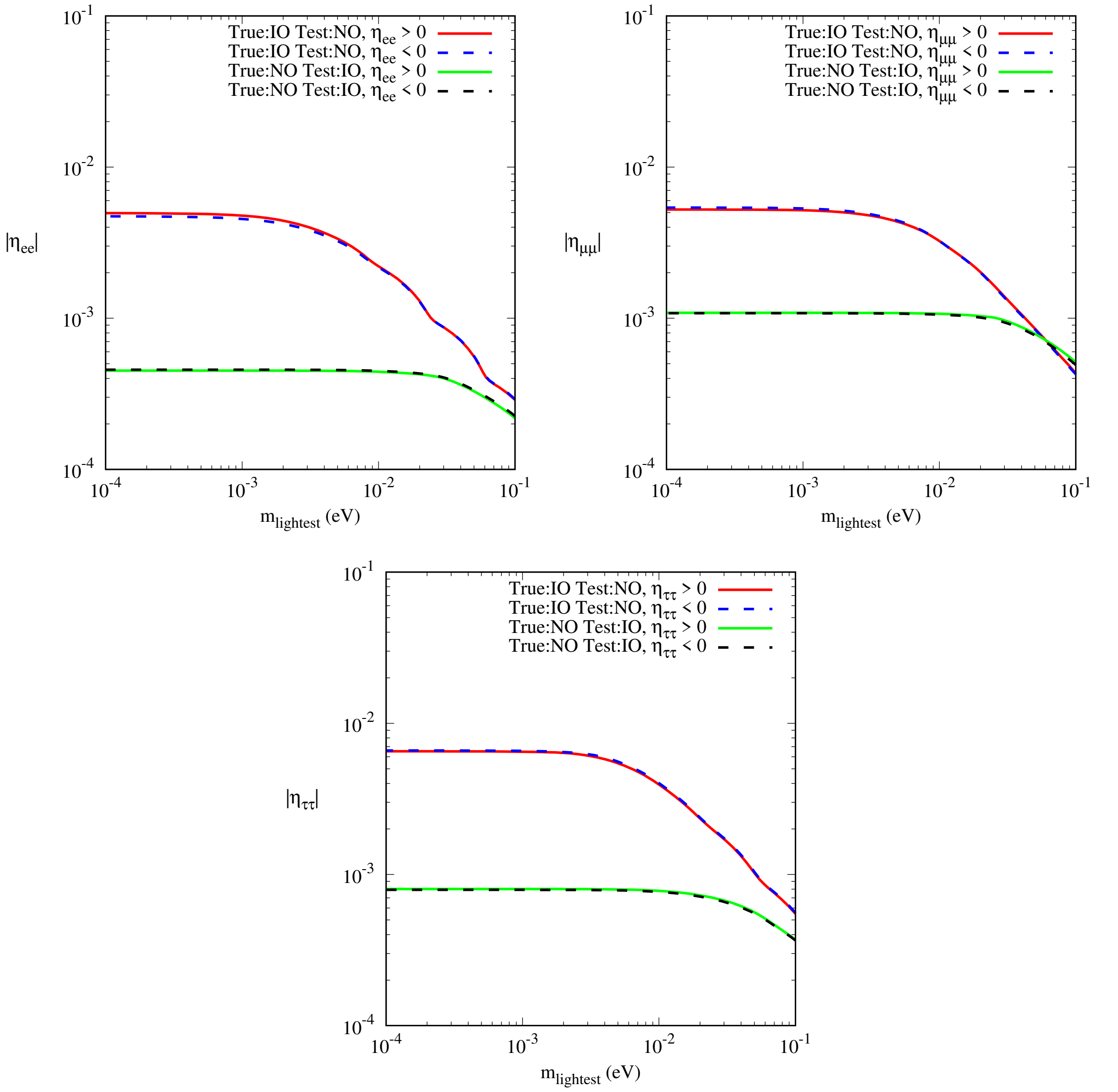

Figure 3: Exclusion capability of the wrong mass ordering with JUNO in the presence of scalar NSI. Top left (right) panel is for $|\eta_{ee}|$ ($|\eta_{\mu\mu}|$). Bottom panel is for $|\eta_{\tau\tau}|$.

included in the Hamiltonian. In our analysis, we find that JUNO can put very stringent constraints on the diagonal scalar NSI parameters. Moreover, the exclusion reach is an-order-of-magnitude better if inverted mass ordering is considered. Regarding the neutrino mass ordering sensitivity of JUNO, we observe that for a given true value of NMO, the wrong mass ordering is allowed at 3σ for certain allowed values of sNSI parameters in the $\eta_{\alpha\alpha}$-$\mathrm{m_{lightest}}$ parameter space.

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