Searching for neutrino oscillation parameters in long baseline experiments

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Developing neutrino astronomy requires a good understanding of the neutrino oscillations mechanism. The European strategy for neutrino oscillation physics sets a high priority on future long baseline neutrino experiments with the aim to measure the intrinsic parameters that govern the neutrino oscillations. In this talk we take a look at the next generation of long baseline experiments and discuss their prospects in future research.

1 Introduction

The dream of using neutrino telescopes as messengers of the universe in the future is built on the idea that the neutrino oscillation mechanism is eventually resolved in the neutrino oscillation experiments. The prospects of these experiments include both determining the parameters of the standard three-neutrino paradigm and probing non-standard interactions (NSI) that may follow from potential Beyond Standard Model theories.

Neutrino oscillation experiments are typically categorized into solar, reactor, atmospheric and accelerator-based experiments. In this work we focus on long baseline neutrino experiments where an intense muon neutrino beam is directed to traverse long distances underground.

In the Standard Model of particle physics (SM) neutrino sector the relationship between the three neutrino mass states (ν_1, ν_2, ν_3) and the three flavour states $(\nu_e, \nu_\mu, \nu_\tau)$ is usually expressed as a 3×3 matrix known as the PMNS matrix after Bruno Pontecorvo, Ziro Maki, Masami Nakagawa and Shoichi Sakata. The mixing of neutrino states is the source to the phenomenon that is known as neutrino oscillations. The PMNS matrix can be written in terms of the three mixing angles and one phase in the form:

$$\begin{aligned} U \;=\; & \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \\ & \times diag\left(e^{i\alpha_1/2}, e^{i\alpha_2/2}, 1\right) \end{aligned} \tag{1}$$

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$ for $i, j = 1, 2, 3$, $\theta_{ij} = [0, \pi/2]$ are the intrinsic mixing angles, $\delta_{CP} = [0, 2\pi]$ is the Dirac CP violation phase and α_1, α_2 are two Majorana CP violation phases.

The transition probability between two neutrino flavour states $\nu_l \to \nu_{l'}$ is calculated as:

$$P_{ll'} = \sum_{j,k} U^*_{lj} U_{l'j} U_{lk} U^*_{l'k} e^{-iL\Delta m^2_{jk}/2E}, \tag{2}$$

where L is the baseline length of the experiment and E is the energy of the neutrino produced. Here neutrino mass squared differences $\Delta m^2_{jk} = m^2_j - m^2_k$ for $j, k = 1, 2, 3$ are calculated from the neutrino masses m_1, m_2 and m_3.

The expression in Equation (2) can be further simplified into

$$P_{ll'} = \delta_{ll'} - \sum_{j,k;j>k} \left[4 \sin^2 \Delta_{kj} \operatorname{Re} W^{jk}_{ll'} - 2 \sin 2\Delta_{kj} \operatorname{Im} W^{jk}_{ll'} \right], \tag{3}$$

where $W^{jk}_{ll'} = U^*_{lj} U_{l'j} U_{lk} U^*_{l'k}$ and $\Delta_{kj} = \Delta m^2_{kj} L/4E$. It is seen from expression (3) that the oscillation probabilities can be tuned to desirable values by choosing L/E conveniently.

In this paper, we analyze the potential of the planned long baseline neutrino oscillation experiment LBNO at two tasks. On the one hand we study its performance for resolving the intrinsic θ_{23} octant degeneracy and on the other hand we study its ability to probe the matter NSI effects. That is, we derive numerically the values of θ_{23} for which the octant degeneracy can be resolved and also calculate the new upper bounds that LBNO could give to $|\varepsilon^m_{\alpha\beta}|$ where $\alpha, \beta = e, \mu, \tau$.

2 Oscillation parameters: A general outlook

The present values of the oscillation parameters are given in Table 1. The values of the reactor and solar mixing angles (θ_{13} and θ_{12} respectively) have been determined in previous neutrino experiments with good precision, but the value of the atmospheric mixing angle θ_{23} has yet to be determined accurately. The other unknown quantities are the sign of Δm^2_{31} and the amount of CP violation $\delta_{\rm CP}$ in the leptonic sector.

Parameter	Value
θ_{12}	31.8°... 37.8°
θ_{13}	7.7°... 9.9°
θ_{23}	38.8°... 53.3°
Δm^2_{21}	$(7.11 \ldots 8.18) \cdot 10^{-5}\text{eV}^2$
$\lvert\Delta m^2_{31}\rvert$	$(2.20 \ldots 2.65) \cdot 10^{-3}\text{eV}^2$
δ_{CP}	$0 \ldots 360°$

Table 1: Standard neutrino oscillation parameters [1]. For the unknown δ_{CP} we have denoted the values considered in numerical calculations, and the extra phases $\alpha_{1,2}$ only come into play in double-beta decay experiments.

3 Simulation of long baseline neutrino experiments

In LBNO the aim is to send neutrino and antineutrino beams, produced at the CERN SPS accelerator, towards the Pyhäsalmi mine, located in central Finland at the distance 2288 km from CERN, where they will be measured using a two-phase Liquid Argon Time Projection Chamber (LArTPC) combined with a magnetized muon detector (MIND). In this experiment, the size of the LArTPC detector is planned to have 20 kton fiducial mass. In this phase a 0.75 MW conventional neutrino beam from the CERN SPS will be used. In this work we also study LBNO with other baseline lengths.

The analysis is done by using the GLoBES simulation software [2, 3]. GLoBES calculates the oscillation probabilities and the corresponding neutrino rates for any given set of oscillation parameter values. The standard set of the software simulates the neutrino propagation from source to detector and computes the standard matter interactions (SI) for the distance that neutrinos travel. A software extension then allows us to perform the same calculation but may also include all matter-induced NSI effects in the propagation. The software computes χ^2 distributions to compare different sets of oscillation parameter values, both with SI and NSI.

We will determine for both mass hierarchies the 1σ, 2σ and 3σ sensitivity limit of the angle θ_{23} that LBNO can achieve with 5+5 –years neutrino and antineutrino run, allowing the CP phase to vary in the range 180° to +180°. We will also determine the new 90% confidence level upper bounds that LBNO could set to the absolute values of $\varepsilon^m_{\alpha\beta}$ parameters that describe the strength of non-standard interactions between neutrinos and the matter.

4 Determination of the θ_{23} octant

In long baseline experiments one is interested mainly in the oscillation channels $\nu_\mu \to \nu_\mu$ (disappearance channel) and $\nu_\mu \to \nu_e$ (appearance channel). In leading order, whereby omitting terms proportional to the small quantities $\Delta m^2_{21}/\Delta m^2_{31}$ and $\sin\theta_{13}$, the θ_{23} dependence of the oscillation probability $P_{\mu\mu}$ is of the form $\sin^2 2\theta_{23} \sin^2 \Delta$ where $\Delta = \Delta m^2_{31} L/4E$. Since

$$P_{\mu\mu}(90^\circ - \theta_{23}) = P_{\mu\mu}(90^\circ), \tag{4}$$

the measurements of the channel $\nu_\mu \to \nu_\mu$ are not suitable for resolving the octant degeneracy. There are non-leading terms that are sensitive to the octant but they are typically too much suppressed to be useful.

In a future long baseline neutrino experiment this problem with θ_{23} octants is resolved by studying the electron appearance from $\nu_\mu \to \nu_e$ oscillations. The leading term of $P_{\mu e}$ has a dependence on θ_{23} that is not octant degenerate, and hence the $\nu_\mu \to \nu_e$ oscillations bring in the primary component to the determination of θ_{23} octant.

Using the GLoBES software, we simulated the hypothetical experiment that was described in the LBNO design study (see [4] for more details).

The results are presented in Figure 1. In both panels the white regions in the plots are the areas for which the values of θ_{23}, $\delta_{\rm CP}$ can be established with a confidence level greater than 3σ. So for all θ_{23}, $\delta_{\rm CP}$ data points in these areas, one can eliminate with a confidence level larger than 3 the possibility for these parameters to lie in the other octant. Conversely the coloured regions illustrate the cases where no such distinction is possible with the indicated confidence level.

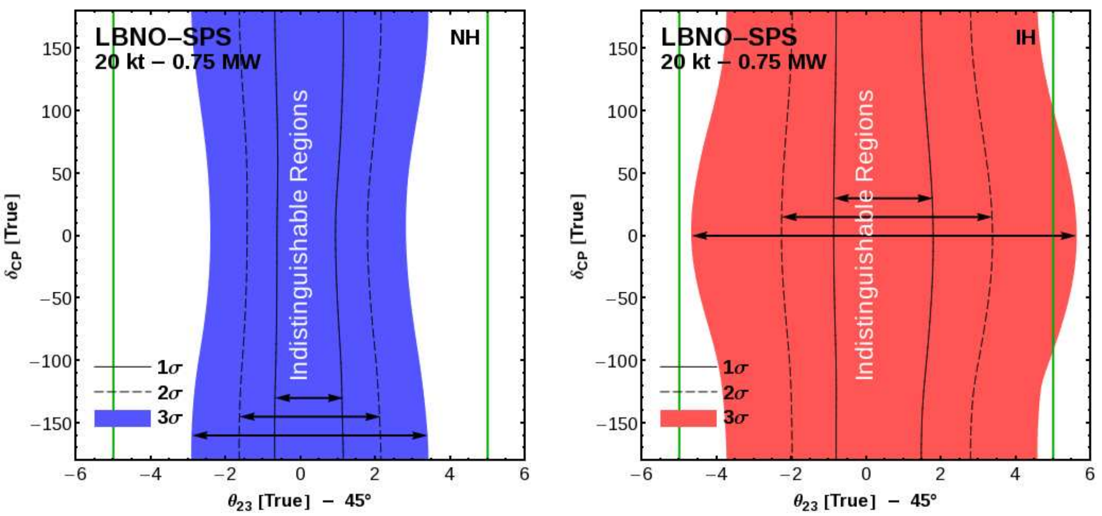

Figure 1: Determination ability of the θ_{23} octant in LBNO [4] in normal hierarchy mode.

In Figure 1 we have also marked the MINOS favoured θ_{23} values 40° and 50° by green lines. It is seen that for this particular setup the right θ_{23} octant can be asserted in NH with at least 3σ confidence level. As for IH this limit is reached for the lower octant, but for the higher octant it fails to be reached for δ_{CP} values between -100° and +100°.

5 Constraining non-standard interaction parameters

In the low-energy regime, NSI can be parametrized in terms of effective charged current like (CC) and neutral current like (NC) Lagrangians, given respectively by

$$\begin{aligned}\mathcal{L}_{NSI}^{CC} &= -2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{ff',C}(\overline{\nu}_\alpha\gamma^\mu P_L\ell_\beta)(\overline{f}\gamma^\mu P_C f'),\\ \mathcal{L}_{NSI}^{NC} &= -2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{f,C}(\overline{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\overline{f}\gamma^\mu P_C f).\end{aligned} \tag{5}$$

Here f and f' label charged leptons or quarks (ℓ_i, u_i, d_i, $i = 1, 2, 3$), $G_F = 1.166 \times 10^{-5}\mathrm{GeV}^{-2}$ is the Fermi coupling constant, α, β refer to neutrino flavour (e, μ, τ), and $C = L, R$ refers to the chirality structure of the charged lepton interaction, P_L and P_R being the chiral projection operators. The NSI parameters $\varepsilon_{\alpha\beta}^{ff',C}$ and $\varepsilon_{\alpha\beta}^{f,C}$ are dimensionless numbers. It is assumed here that the effective non-standard interactions have V–A Lorentz structure, and for the charged fermions we allow both left-handed ($P_C = P_L$) and right-handed ($P_C = P_R$) couplings. The charged current Lagrangian $\mathcal{L}_{NSI}^{CC}$ is relevant for the NSI effects in the source and detector, since both in the creation and detection processes involve charged fermions. The neutral current Lagrangian $\mathcal{L}_{NSI}^{NC}$ in turn is relevant for the NSI matter effects. The effective low-energy Lagrangians (5) are assumed to follow from some unspecified beyond-the-standard-model theory after integrating out heavy degrees of freedom.

Concerning the propagation in matter, NSI could contribute to the coherent forward scattering of neutrinos in the Earths crust. The effective Hamiltonian describing the time evolution of a neutrino state would take the form

$$H = \frac{1}{2E_\nu}\left[U\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + V\right] \tag{6}$$

where E_ν is the energy neutrino, U is the ordinary mixing matrix and V is the effective matter potential which includes both the SM and NSI matter effects:

$$V = A\begin{pmatrix} 1+\varepsilon^m_{ee} & \varepsilon^m_{e\mu} & \varepsilon^m_{e\tau} \\ \varepsilon^{m*}_{e\mu} & \varepsilon^m_{\mu\mu} & \varepsilon^m_{\mu\tau} \\ \varepsilon^{m*}_{e\tau} & \varepsilon^{m*}_{\mu\tau} & \varepsilon^m_{\tau\tau}\end{pmatrix}. \tag{7}$$

We study numerically how the future neutrino oscillation experiments would constrain various NSI parameters. We will concentrate here on the future long baseline neutrino experiments, using the LBNO setup with a high-intensity beam, a baseline of 2300 km and 20 kt double-phase liquid argon detector as our benchmark. For each $\delta_{\rm CP}$ value, we have calculated the 90% confidence level contour baseline range 100–5000 km and $\log_{10}|\varepsilon^m_{\alpha\beta}|$ range from 3.0 to 0.5. In every case, a 90% confidence level contour is found and the results merged in a contour band. The bands in $(L, \varepsilon^m_{\alpha\beta})$–plane are plotted in Figure 2.

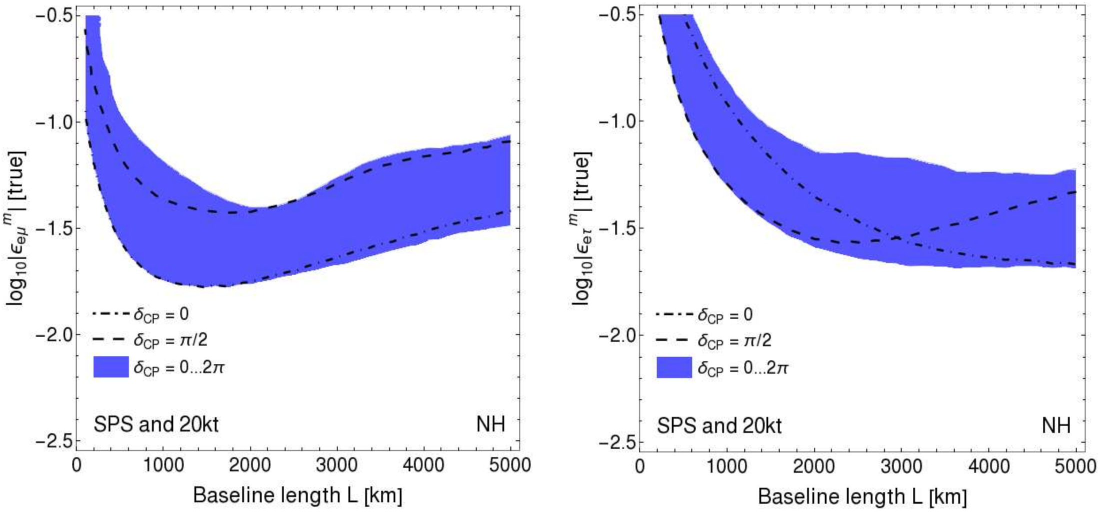

Figure 2: Constraining capability of LBNO for the absolute values of the non-standard interaction parameters $\varepsilon^m_{e\mu}$ and $\varepsilon^m_{e\tau}$. See Reference [5] for more details.

6 Summary

In this work we have presented the measurement potential of a potential future long baseline neutrino experiment in the determination of the θ_{23} octant and constraining the $|\varepsilon^m_{e\mu}|$ and $|\varepsilon^m_{e\tau}|$ parameter spaces for non-standard neutrino interactions that arise from the neutrino propagation in matter. In both cases we have demonstrated the interference both of these tasks suffer from the δ_{CP} parameter whose value is still unknown. We used the recent LBNO design study as our benchmark model and performed the numerical study with the GLoBES software.

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