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Complementarity between long-baseline and atmospheric neutrino experiments: Implications for the European neutrino programme

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Recent measurements have shown that the value of θ_{13} in nature is moderately large. This allows the possibility of measuring the neutrino mass hierarchy, octant of θ_{23} and CP-violating phase δ_{CP} at the next generation of neutrino oscillation experiments. We discuss the synergy between atmospheric and long-baseline experiments. We find that there is a marked improvement in the sensitivity of long-baseline experiments for unfavourable values of parameters, when data from atmospheric experiments are also taken into account. We present our results in the context of planned upcoming oscillation experiments.

In this work our aim is to obtain the minimum exposure required for the proposed Long Baseline Neutrino Oscillation (LBNO) experiment to determine the above unknowns. We emphasize on the advantage of exploiting the synergies offered by the existing and upcoming long-baseline and atmospheric neutrino experiments in economising the LBNO configuration. In particular, we do a combined analysis for LBNO, T2K, NOνA and INO. We consider three prospective LBNO setups – CERN-Pyhäsalmi (2290 km), CERN-Slanic (1500 km) and CERN-Fréjus (130 km) and evaluate the adequate exposure required in each case. Our analysis shows that the exposure required from LBNO can be reduced considerably due to the synergies arising from the inclusion of the other experiments.

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1. Introduction

The reactor neutrino experiments have collectively given us a 10σ signal for a non-zero value of θ_{13} $[1-3]$. This discovery sets the stage for the determination of the remaining unknown neutrino oscillation parameters, namely – the ordering of neutrino mass eigenstates or mass hierarchy, the octant of the atmospheric mixing angle θ_{23} and the leptonic CP phase δ_{CP}. We expect the first indications on these quantities to come from the current and upcoming long-baseline (LBL) experiments T2K and NOνA. The India-based Neutrino Observatory (INO) with a magnetized iron calorimeter (ICAL) which is an upcoming atmospheric neutrino experiment will also have some sensitivity to these parameters.

There exist synergies between LBL experiments and INO because of the different baselines, energies, matter effects and source and detector characteristics involved in the various experiments. Thus the oscillation probabilities at each of them have a different dependence on the parameters. This complementary nature of data means that combining information from these experiments increases the sensitivity. However from the results obtained in previous studies one concludes that even after combining results from T2K, NOνA and INO, a conclusive 5σ evidence for the unknown parameters would require new experiments.

The LAGUNA-LBNO project in Europe is one of the proposals for a future oscillation experiment. The source of neutrinos for this experiment is likely to be at CERN. Various potential sites for the detector are being considered in Europe. Studies have shown that some of these potential experiments can have very good capability for measuring the unknown parameters [4, 5]. The precise configuration of the LBNO experiment is currently under discussion. It is desirable to quantify the information that can be gleaned from the current generation of LBL+atmospheric experiments in the planning of LBNO. To this end, we determine the configuration for LBNO with ‘adequate’ exposure which can determine the unknown oscillation parameters in combination with the current and upcoming experiments NOνA, T2K and INO. The ‘adequate’ configuration is defined as one with the minimal exposure which would give a 5σ discovery potential for hierarchy and octant and 3σ discovery potential for δ_{CP}. This configuration can be viewed as the first step in a staged approach that has been advocated by previous studies [5].

2. Simulation details

In this work, all long-baseline experiments were simulated using the GLoBES package. NOνA, with 7.3×10^{20} protons on target (pot) per year is assumed to run for 3 years each in neutrino and antineutrino mode. We have used the new efficiencies and resolutions for NOνA which are optimized for the current value of θ_{13} [6]. For T2K, we have adjusted the runtime so as to get a total of $\sim 8 \times 10^{21}$ pot. We have assumed that T2K will run entirely with neutrinos. The ICAL detector at the INO site in southern India is a 50 kt magnetized iron calorimeter. We have considered a 10 year run for this atmospheric neutrino experiment, giving it a total exposure of 500 kt yr. The detector specifications are as given in Ref. [7]. For LBNO, out of the various possible options, we consider the following three:(a) CERN-Pyhäsalmi (2290 km, LArTPC detector, specifications as in Ref. [5]), (b) CERN-Slanic (1540 km, LArTPC detector, specifications as in Ref. [5]) and (c) CERN-Fréjus (130 km, Water Čerenkov detector, specifications as in Ref. [11]).

We have fixed the 'true' values of the parameters: $\sin^2\theta_{12} = 0.304$, $|\Delta_{31}| = 2.4 \times 10^{-3}$ eV^2, $\Delta_{21} = 7.65 \times 10^{-5}$ eV^2 and $\sin^2 2\theta_{13} = 0.1$. Three representative true values of θ_{23} have been considered – 39°, 45° and 51° (except in the case of octant determination where a wider range and more intermediate values have been included). The true value of δ_{CP} is varied in its entire allowed range. All our results are shown for both cases – normal hierarchy (NH) and inverted hierarchy (IH). The 'test' values of the parameters are allowed to vary in the following ranges – $\theta_{23} \in [35^\circ, 55^\circ]$, $\sin^2 2\theta_{13} \in [0.085, 0.115]$, $\delta_{CP} \in [0, 2\pi)$. The test hierarchy is allowed to run over both possibilities. We have imposed a prior on the value of $\sin^2 2\theta_{13}$ with an error $\sigma(\sin^2 2\theta_{13}) = 0.005$, which is the expected precision on this parameter from the reactor neutrino experiments.

In the following sections, we analyze the ability of the experiments NOνA, T2K, ICAL@INO and LBNO to collectively determine the neutrino mass hierarchy, octant of θ_{23} and discover CP violation. We demand that this combination of experiments determine the mass hierarchy and octant of θ_{23} with a statistical significance corresponding to $\chi^2 = 25$, and that CP violation be discovered with $\chi^2 = 9$. The aim of this exercise is to find the least exposure required from LBNO in order to fulfil the above demands. Therefore, we have evaluated the sensitivity to hierarchy/octant/CP violation for various different exposures of LBNO, combined with NOνA, T2K and INO. From this, we estimate the adequate amount of exposure required by LBNO. We express the exposure in units of pot-kt. This is a product of three experimental quantities:

$$\text{exposure (pot-kt)} = \text{beam intensity (pot/yr)} \times \text{runtime (yr)} \times \text{detector mass (kt)}\ . \tag{2.1}$$

Thus, a given value of exposure can be achieved experimentally by adjusting the intensity, runtime and detector mass. The advantage of using this measure is that while the physics goals are expressed in terms of simply one number (the exposure), the experimental implementation of this exposure can be attained by various combinations of beam, detector and runtime settings. In the terminology used in this paper, the exposures given correspond to each mode (neutrino and antineutrino). Thus, a runtime of n years implies n years each in neutrino and antineutrino mode totalling to $2n$ years.

3. Determining the mass hierarchy

It is known that combining information from NOνA and T2K improves the hierarchy sensitivity in the unfavourable range of δ_{CP} [8]. On the other hand, the hierarchy sensitivity of an atmospheric neutrino experiment like ICAL is almost independent of δ_{CP}. Thus combining ICAL results with those of T2K and NOνA is expected to increase sensitivity to mass hierarchy independently of the value of δ_{CP} [9, 10]. We find that NOνA+T2K+ICAL can collectively give $\chi^2 \approx 9$ sensitivity to the hierarchy. Therefore, we need to determine the minimum exposure for LBNO, such that the combination NOνA+T2K+ICAL+LBNO crosses the $\chi^2 = 25$ threshold for all values of δ_{CP}. For this, we have evaluated the combined sensitivity of NOνA+T2K+ICAL+LBNO for various values of LBNO exposure.

In Fig. 1, we have shown the sensitivity for the experiments as a function of the LBNO exposure. We considered three true values of θ_{23} – $39^\circ, 45^\circ, 51^\circ$ and chose the least favourable of these in generating the figures. Thus, our results represent the most conservative case. The results are shown for two baselines – 2290 km and 1540 km, and for both hierarchies. For the baseline of 130 km, it is not possible to cross $\chi^2 = 25$ even with extremely high exposure. Therefore we have not

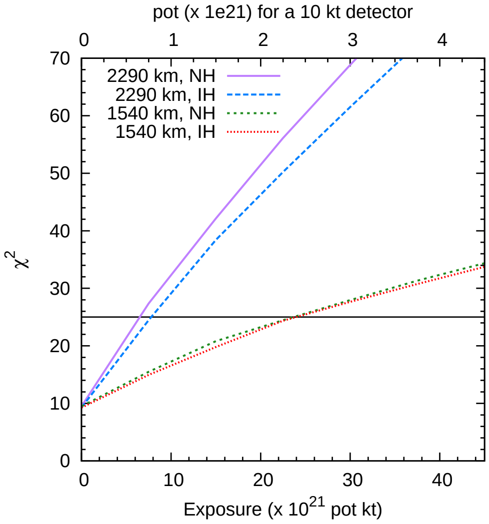

Figure 1: Hierarchy sensitivity χ^2 vs LBNO exposure, for both baselines and hierarchies under consideration. The additional axis along the upper edge of the graph shows the required total pot assuming a detector mass of 10 kt.

shown the corresponding plot for this baseline. We see that for 2290(1540) km, it is sufficient for LBNO to have an exposure of around $8 \times 10^{21}(24 \times 10^{21})$ pot-kt in order to get $\chi^2 = 25$ sensitivity for all values of δ_{CP}. Along the upper edge of the graph, we have provided an additional axis, which denotes the total pot required if we assume that the detector has a mass of 10 kt. For 2290(1540) km, we need a total of $0.8 \times 10^{21}(2.4 \times 10^{21})$ pot.

4. Determining the octant of θ_{23}

As in the case of hierarchy, adding information from various experiments enhances the octant sensitivity. However, it is the precise knowledge of the value of θ_{13} that plays a crucial role in determining the octant correctly. We have determined the sensitivity of NOνA+T2K+ICAL+LBNO for various values of LBNO exposure. We generated the results for various true values of δ_{CP}, and the results shown are for the most conservative case.

In Fig. 2, we have shown how the octant sensitivity of these experiments increases with LBNO exposure. For this, we have chosen the true value of θ_{23} to be 39°. It is seen from the left panel that irrespective of the hierarchy, it is sufficient to have an exposure of around $57 \times 10^{21}(65 \times 10^{21})$ pot-kt to reach $\chi^2 = 25$ with a baseline of 2290(1540) km. The upper axis shows the total pot required, with a 10 kt detector. For instance, for 1540 km, we see that 6.5×10^{21} pot is sufficient if we have a 10 kt detector. The right panel shows this for the 130 km baseline. As expected, because of smaller matter effects, the exposure required to determine the octant is much higher than for the other two baselines. We need an exposure of around 2700×10^{21} pot-kt in this case. However, for a large mass detector like MEMPHYS that is being planned for the Fréjus site [11], this exposure is not difficult to attain. The upper axis of the graph shows the required pot if we consider a 440 kt detector, as proposed for MEMPHYS. We see that for such a large mass detector, only around

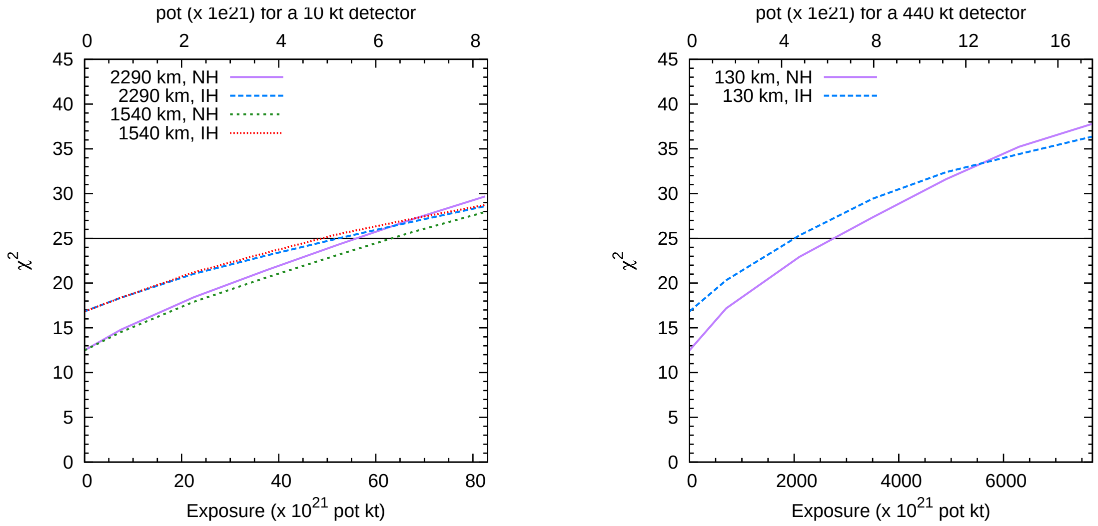

Figure 2: Octant sensitivity χ^2 vs LBNO exposure, for the 2290 km and 1540 km baselines (left panel) and the 130 km baseline (right panel) and both hierarchies, with $\theta_{23} = 39°$. The additional axis along the upper edge of the graph shows the required total pot assuming a detector mass of 10 (440) kt.

6×10^{21} pot is adequate to exclude the octant for $\theta_{23} = 39°$. Thus the adequate beam intensity in pot is comparable to the other two set-ups.

5. Discovering CP Violation

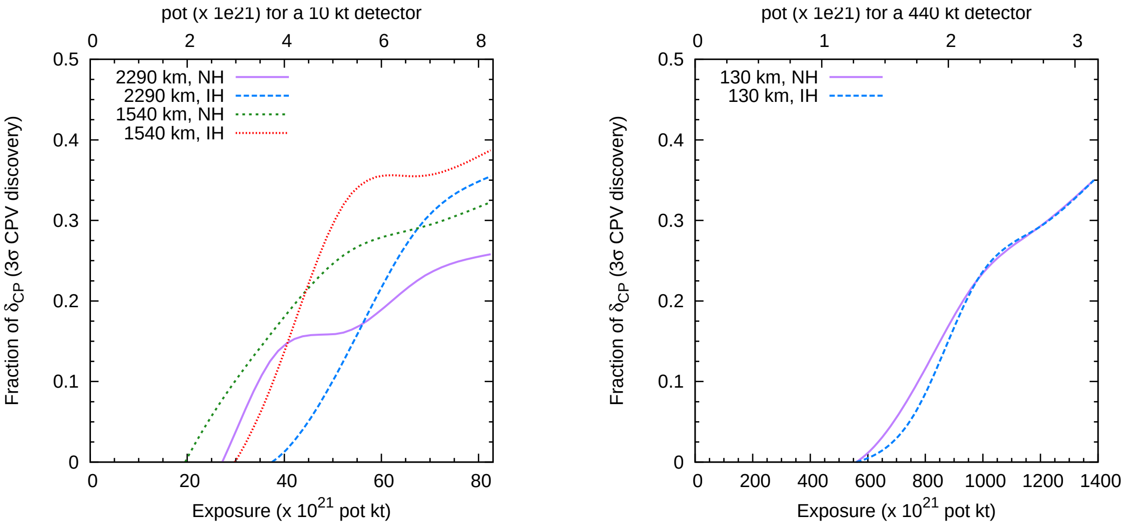

Figure 3: Fraction of the full δ_{CP} range for which it is possible to discover CP violation (exclude $\delta_{CP} = 0, \pi$) at 3σ vs LBNO exposure, for the 2290 km and 1540 km baselines (left panel) and the 130 km baseline (right panel) and both hierarchies. The additional axis along the upper edge of the graph shows the required total pot assuming a detector mass of 10 (440) kt.

Here, we discuss the discovery of CP violation, i.e. the ability of an experiment to exclude the cases $\delta_{CP} = 0$ or π. Like in the case of hierarchy exclusion, we have minimized over three different true values of θ_{23}, thus choosing the most conservative case possible. The hierarchy-δ_{CP} degeneracy of NOνA and T2K can be lifted by including information from ICAL, which excludes the wrong hierarchy solution [12]. Thus, in spite of not having intrinsic δ_{CP} sensitivity, adding atmospheric neutrino data can improve the CP sensitivity of LBL experiments.

Adding LBNO data with increasing exposure can enhance the CP discovery potential of T2K+NOνA+ICAL, and even help to achieve $\chi^2 = 9$ for some range of δ_{CP}. In Fig. 3, we have plotted the fraction of δ_{CP} for which CP violation can be discovered with $\chi^2 = 9$, as a function of the LBNO exposure. As an example, if we aim to discover CP violation for at least 20% of δ_{CP} values, then we require around $62 \times 10^{21} (45 \times 10^{21})$ pot-kt exposure from LBNO with a baseline of 2290(1540) km, as seen in the left panel. The upper axis shows that these values correspond to $6.2 \times 10^{21} (4.5 \times 10^{21})$ pot, if we consider a 10 kt detector. The right panel of this figure shows the results for the 130 km option. Once again, we see that an exposure much higher than the longer baselines is required. In this case, CP discovery for 20% δ_{CP} values requires an exposure of around 950×10^{21} pot-kt. But this is not difficult to achieve with a large MEMPHYS-like detector. In fact, the total pot required by a 440 kt detector at 130 km is only around 2.2×10^{21} pot, which is less than that required by a 10 kt detector at the other sites.

6. Conclusion

	adequate exposure (pot-kt) for		
	2290 km	1540 km	130 km
Hierarchy exclusion ($\chi^2 = 25$)	$8(10) \times 10^{21}$	$24(40) \times 10^{21}$	–
Octant exclusion at 39° ($\chi^2 = 25$)	$57(91) \times 10^{21}$	$65(106) \times 10^{21}$	$2700(4700) \times 10^{21}$
CP violation discovery ($\chi^2 = 9$) for 20% fraction of δ_{CP}	$62(62) \times 10^{21}$	$45(45) \times 10^{21}$	$950(1400) \times 10^{21}$

Table 1: Summary of results: 'adequate' exposure in pot-kt for three LBNO configurations to achieve the physics goals. The numbers given in parentheses indicate the required exposure if atmospheric data from ICAL is not included.

In this paper we have quantified the 'adequate' configuration for LBNO that can exclude the wrong hierarchy ($\chi^2 = 25$), exclude the wrong octant ($\chi^2 = 25$) and discover CP violation ($\chi^2 = 9$) in conjunction with NOνA, T2K and ICAL. We have determined the adequate exposure in pot-kt for the least favourable true hierarchy, θ_{23} and δ_{CP}. We consider three prospective LBNO configurations: CERN-Pyhäsalmi (2290 km) baseline with a LArTPC, CERN-Slanic (1500 km) with a LArTPC and CERN-Fréjus (130 km) with a Water Čerenkov detector. The 'adequate' exposure needed is summarized in Table 1. Inclusion of atmospheric data from ICAL can play a significant role in reducing the exposure required for hierarchy and octant determination for the 2290 and 1540 km set-ups and for octant and δ_{CP} discovery for the 130 km set up. This is also seen in the table, where the numbers given in parentheses denote the exposure required if ICAL data is not included.

In general, we find that the baseline of 2290 km is best suited to determine the mass hierarchy (due to its 'bimagic' properties), while 1540 km is better for discovering CP violation. However, with a large mass detector, 130 km is the best candidate for CP violation physics. The 'adequate' exposures listed in this work can be attained by various combinations of beam power, runtime and detector mass. These minimal values can be used to set up the first phase of LBNO, if an incremental/staged approach is being followed. We emphasize that the synergies between the existing and upcoming LBL and atmospheric experiments can play an important role and should be taken into consideration in planning economised future facilities.

More detailed discussions and results can be found in Ref. [13] on which this article is based.

References

[1] D. Forero, M. Tortola, and J. Valle, *Global status of neutrino oscillation parameters after Neutrino-2012*, *Phys.Rev.* **D 86** (2012) 073012 [`arXiv:1205.4018`].

[2] G. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo, et al., *Global analysis of neutrino masses, mixings and phases: entering the era of leptonic CP violation searches*, *Phys.Rev.* **D 86** (2012) 013012 [`arXiv:1205.5254`].

[3] M. Gonzalez-Garcia, M. Maltoni, J. Salvado, T. Schwetz, *Global fit to three neutrino mixing: critical look at present precision*, *JHEP* **1212** (2012) 123 [`arXiv:1209.3023`].

[4] P. Coloma, T. Li, S. Pascoli, *A comparative study of long-baseline superbeams within LAGUNA for large θ_{13}*, `arXiv:1206.4038`.

[5] S. K. Agarwalla, T. Li, A. Rubbia, *An Incremental approach to unravel the neutrino mass hierarchy and CP violation with a long-baseline Superbeam for large θ_{13}*, *JHEP* **1205** (2012) 154 [`arXiv:1109.6526`].

[6] S. K. Agarwalla, S. Prakash, S. K. Raut, S. U. Sankar, *Potential of optimized NOνA for large theta(13) and combined performance with a LArTPC and T2K*, *JHEP* **1212** (2012) 075 [`arXiv:1208.3644`].

[7] A. Chatterjee, P. Ghoshal, S. Goswami, S. K. Raut, *Octant sensitivity for large theta(13) in atmospheric and long-baseline neutrino experiments*, *JHEP* **1306** (2013) 010 [`arXiv:1302.1370`].

[8] S. Prakash, S. K. Raut, S. U. Sankar, *Getting the Best Out of T2K and NOνA*, *Phys.Rev.* **D 86** (2012) 033012 [`arXiv:1201.6485`].

[9] M. Blennow, T. Schwetz, *Identifying the Neutrino mass Ordering with INO and NOνA*, *JHEP* **1208** (2012) 058 [`arXiv:1203.3388`].

[10] A. Ghosh, T. Thakore, S. Choubey, *Determining the Neutrino Mass Hierarchy with INO, T2K, NOνA and Reactor Experiments*, *JHEP* **1304** (2013) 009 [`arXiv:1212.1305`].

[11] J.-E. Campagne, M. Maltoni, M. Mezzetto, T. Schwetz, *Physics potential of the CERN-MEMPHYS neutrino oscillation project*, *JHEP* **04** (2007) 003 [`hep-ph/0603172`].

[12] M. Ghosh, P. Ghoshal, S. Goswami, S. K. Raut, *Role of atmospheric neutrinos in discovering CP violation*, `arXiv:1306.2500`.

[13] M. Ghosh, P. Ghoshal, S. Goswami, S. K. Raut, *Synergies between neutrino oscillation experiments: An 'adequate' exposure for LBNO*, `arXiv:1308.5979`.