Upgraded experiments with super neutrino beams: Reach versus Exposure

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We introduce exposure as a means to making balanced comparisons of the sensitivities of long-baseline neutrino experiments to a nonzero $\theta_{13}$, to CP violation and to the neutrino mass hierarchy. We illustrate its use by comparing the sensitivities of possible upgrades of superbeam experiments, namely NO$\nu$A*, T2KK and experiments with wide band beams. For the proposed exposures, we find the best nominal CP violation performance for T2KK. For equal exposures, a wide band beam experiment has the best mass hierarchy performance. The physics concept on which NO$\nu$A* is based has the best potential for discovering CP violation only for exposures above a threshold value.

PACS numbers: 14.60.Pq

Introduction. Extensive recent experimental exploration has revealed that neutrinos are massive [1]. This finding necessitates the existence of physics beyond the Standard Model of particle physics. Massive neutrinos may also have far-reaching consequences for cosmology. They may shed light on the origin of the baryon asymmetry in our universe and on why the universe is in an accelerating phase in its expansion. It is therefore imperative that the origin of neutrino masses be determined.

A plethora of neutrino mass models have been proposed and precise knowledge of neutrino parameters is required to test them. Specifically, the value of the mixing angle $\theta_{13}$ and the type of mass hierarchy (i.e., whether $m_1, m_2 < m_3$, called the normal hierarchy or $m_1, m_2 > m_3$, called the inverted hierarchy) will help distinguish between models based on lepton flavor symmetries, models with sequential right-handed neutrino dominance and more ambitious models based on GUT symmetries [2]. A survey of 63 models that are consistent with current oscillation data and have concrete predictions for $\theta_{13}$ found that half of them predict $\sin^2 2\theta_{13} > 0.015$ [3]. GUT models and models with right-handed neutrino dominance naturally yield a normal hierarchy and a relatively large $\theta_{13}$ (although in a few GUT models, an inverted hierarchy can be obtained with fine-tuning). Models based on leptonic symmetries can easily accommodate an inverted hierarchy and small $\theta_{13}$. Thus, experimental establishment of an inverted hierarchy and small $\theta_{13}$ would lend support to models based on leptonic symmetries and reduce the interest in GUT models and models with right-handed neutrino dominance. On the other hand, if $\theta_{13}$ is found to be large, distinguishing between the three different classes of models will be difficult. However, if in addition to a large $\theta_{13}$, the hierarchy is found to be inverted, it will be possible to exclude the subclass of SO(10) GUT models that employ so-called lopsided mass matrices because they predict a normal hierarchy.

Clearly, experiments with good sensitivity to $\theta_{13}$ and the mass hierarchy are indispensable for sifting out a restricted class of neutrino mass models. Precision measurements of deviations of the atmospheric oscillation angle $\theta_{23}$ from $\pi/4$ are also useful in distinguishing between models. The deviation from maximal atmospheric mixing provides an excellent probe of how symmetry breaking occurs in models based on leptonic symmetries. The Dirac CP phase $\delta_{CP}$ in the neutrino mixing matrix may be related to the CP violation required for leptogenesis [4] (which is a direct consequence of the seesaw mechanism) and it may therefore be possible to test both the seesaw and the origin of the baryon asymmetry in our universe by measuring this CP phase.

If neutrinos do not have approximately degenerate masses, the sensitivity of experiments seeking to detect neutrinoless double beta decay (thereby confirming that neutrinos are Majorana particles), is strongly impacted by whether the mass hierarchy is normal or inverted.

Long-baseline neutrino experiments offer the only way to establish a nonzero $\theta_{13}$, to determine the mass hierarchy and to detect neutrino CP violation. There are two strategies being considered for a future experimental program, with combinations of different types of neutrino beams and detector technologies. Off-axis beams have a narrow beam energy, permitting a counting experiment at an oscillation maximum with low background. Wide band beams have a higher flux and allow an experiment that utilizes spectral energy information, but requires sophisticated detectors with good energy resolution and neutral-current rejection to reduce backgrounds.

The Tokai-to-Kamioka (T2K) experiment [5] will use an off-axis beam. The proposed NuMI Off-axis $\nu_e$ Appearance (NO$\nu$A) experiment [6] (and its second phase) and the Tokai-to-Kamioka-and-Korea (T2KK) extension [6] of the T2K experiment also plan to employ off-axis beams. Recently, a wide band beam (WBB) experiment has been advocated [7], the virtues of which have been investigated in Ref. [8]. With the looming possi-
bility of a Deep Underground Science and Engineering Laboratory (DUSEL) \[10\] in the U.S., and its capacity to house very large detectors, it is timely to evaluate the relative merits of the two experimental approaches with upgraded superbeams.

So far, the experimental options and assumptions made in analyses have been so diverse that an objective comparison is not possible. For example, one experiment may seem to have greater sensitivity simply because the exposure assumed is much larger than that of another.

We carry out a technically comprehensive study with a realistic treatment of systematic errors, correlations and degeneracies \[11\]. Our goal is to clarify the physics reach of the different proposals by analyzing them on an equal footing. We present the sensitivities of the experiments to a nonzero $\theta_{13}$, the mass hierarchy and to CP violation as a function of exposure so that merits of the different experimental techniques are evident.

**Experimental setups and analysis techniques.** We use the GLoBES software \[12\] for our simulations. Table I displays parameters of the experiments.

Our simulation of NO\(\nu\)A phase II, which we call NO\(\nu\)A*, is based upon the proposal \[3\] and recent studies on the performance of a Liquid Argon Time Projection Chamber (LArTPC) \[13\]. We assume NO\(\nu\)A* (3 years $\nu$ and 3 years $\bar{\nu}$) with a 100 kt LArTPC, which has a 0.8 signal efficiency and only beam intrinsic $\nu_e$ and $\bar{\nu}_e$ backgrounds. We split the event sample into quasi-elastic (QE) events with 5% energy resolution and the non-QE charged current events with 20% energy resolution. We have carried out a dedicated optimization study in baseline versus off-axis angle plane whose details can be found in Ref. \[14\]. We find that the best location for all measurements is the Ash River site (12 km off-axis at $L = 810$ km) where NO\(\nu\)A phase I is located. None of the alternative sites such as in Ref. \[13\] performs as well as Ash River. This result holds even if NO\(\nu\)A phase I data is taken into account.

For the WBB experiments, we use the simulation from Ref. \[8\] which uses neutrino spectra obtained from 28 GeV protons and a 200 m long decay tunnel, and choose the Fermilab-Homestake baseline $L = 1290$ km for reference. We consider two possible detector technologies: A 300 kt water Cherenkov detector and a 100 kt liquid argon TPC. We assume that five years of neutrino running with a 1 MW beam will be followed by five years of running with a 2 MW beam.

For the NO\(\nu\)A* and WBB setups, we use a systematic uncertainty of 5% on both signal and background, uncorrelated between neutrino and antineutrino channels.

For our T2KK simulation, we employ the values from Ref. \[7\] with a 2.5° off-axis beam. Our simulation is based upon the analysis of the Tokai-to-HyperKamiokande experiment in Ref. \[16\], i.e., we use the spectral information for quasi-elastic (QE) events, and the total event rate for all charged current (CC) events. We include 5% signal and background errors, as well as a 5% background energy calibration error which are correlated between the two detectors in Japan and Korea, but uncorrelated between the neutrino and antineutrino channels.

We adopt $\Delta m^2_{21} = +8 \times 10^{-5}$ eV$^2$, $\Delta m^2_{31} = +2.5 \times 10^{-3}$ eV$^2$, $\sin^2 \theta_{12} = 0.3$, $\sin^2 \theta_{23} = 0.5$ for the oscillation parameters. We assume that the atmospheric oscillation parameters are measured to 10%, the solar parameters are measured to 4%, and the matter density along the baseline is known to 5%. We include all correlations and degeneracies in the analysis. Details of our simulations are presented in Ref. \[14\]. Since we present sensitivities for each of the three performance indicators separately, we use $\chi^2$ distributions for one degree of freedom.

**Results.** In Fig. 1 we show the comparison of superbeam upgrades in the configurations of Table I for the $\sin^2 2\theta_{13}$, CP violation, and normal hierarchy discovery reaches. This comparison illustrates the absolute physics potentials of the planned experiments. Interestingly, the optimal physics performance depends on the performance indicator. The $\sin^2 2\theta_{13} \neq 0$ discovery reaches are very similar for all the experiments. T2KK has the best CP violation potential. The WBB experiments can detect the mass hierarchy down to $\sin^2 2\theta_{13} \approx 10^{-2}$ for all values of $\delta_{\text{CP}}$, which makes them the best upgrade for the mass hierarchy (as a result of their long baseline and high energy and consequently strong matter effects \[17\]). However, this figure does not permit a balanced assessment of which experiment is the best physics concept because of the very different assumptions for the luminosities in each proposed experiment.

In order to make an unbiased comparison of the physics potentials of the experimental setups we consider their sensitivities as functions of exposure which we define to be $\mathcal{L} = \text{detector mass} \times \text{target power} \times \text{running time} \times \text{seconds uptime per year}$. The target power represents the bottleneck in technological difficulty. Note that instead of the running time in years, the exposure uses the actual available time of the accelerator for the neutrino experiment. For NO\(\nu\)A* and the WBB, we use $1.7 \cdot 10^7$ seconds uptime per year, and for T2KK, we use $10^7$ seconds uptime per year (as anticipated in the corresponding documents). Note that this definition does not account for the level of sophistication of different detector technologies, but it will allow for an identification of the break-even point of the detector cost. We show the exposure for the discussed experiments in the last column of Table I. It is evident that NO\(\nu\)A* has the lowest exposure, whereas T2KK has the highest. While we will show a normalized comparison of the experiments based on the exposure, there may be other issues, such as robustness of systematics and a different experiment optimization that may modify the conclusions. We will discuss these issues elsewhere \[14\].

In Fig. 2 we show the discovery reaches for $\sin^2 2\theta_{13}$, CP violation, and normal mass hierarchy versus the exposure for a fraction of $\delta_{\text{CP}}$ of 0.5 (see figure caption).
Table I: Setups considered, numbers of protons on target per year (POT/yr) for the neutrino and antineutrino running modes, running times in which these be achieved, corresponding target power $P_{\text{Target}}$, baselines $L$, detector technology, detector mass $m_{\text{Det}}$, and exposure $L$.

| Setup          | POT $\nu$/yr $t_o$ [yr] | POT $\bar{\nu}$/yr $t_o$ [yr] | $P_{\text{Target}}$ [MW] | $L$ [km] | Detector technology $m_{\text{Det}}$ [kt] | $L$ [Mt MW 10^7 s] |
|----------------|-------------------------|---------------------------------|---------------------------|---------|-------------------------------------------|-------------------|
| NO$\nu$A*      | 10 - 10^{20}            | 3                               | 10 - 10^{20}             | 3       | 1.13                                      | 810               |
| WBB+WC         | 22.5 - 10^{20}          | 5                               | 45 - 10^{20}             | 5       | 1 (\nu), 2 ($\bar{\nu}$)                 | 1290              |
| WBB+LAr        | 22.5 - 10^{20}          | 5                               | 45 - 10^{20}             | 5       | 1 (\nu), 2 ($\bar{\nu}$)                 | 1290              |
| T2KK           | 52 - 10^{20}            | 4                               | 52 - 10^{20}             | 4       | 4                                         | 295+1050          |

FIG. 1: Comparison of superbeam upgrades in the configurations of Table I at the 3$\sigma$ C.L. The plots show the discovery reaches for a nonzero $\sin^2 2\theta_{13}$, CP violation, and the normal hierarchy. The “fraction of $\delta_{CP}$”, quantifies the fraction of all (true) values of $\delta_{CP}$ for which the corresponding quantity can be measured.

The NO$\nu$A* curves for $\sin^2 2\theta_{13}$ and CP violation discoveries are lower than the ones of the other experiments for exposures above 2 Mt MW 10^7 s, whereas the curves for the WBB experiments are lower (for any exposure) than any other curve for the mass hierarchy discovery. If all experiments were operated at the same exposure, these experiments would yield the best results. All the curves scale relatively smoothly as a function of exposure except the CP violation curve for NO$\nu$A*. The bump-like feature is solely due to the interplay of CP effects and the mass hierarchy and is called $\pi$-transit. A further luminosity increase could enhance the NO$\nu$A* potential for CP violation considerably by enabling the resolution of degeneracies at this confidence level; see the light curve in the CPV panel which is made under the assumption that the hierarchy is known to be normal. The other setups are relatively insensitive to small variations in exposure. For CP violation, the WBB-WC and T2KK concepts are more or less equivalent since the curves almost overlap. The WBB-WC and the T2KK curves intersect at some points. These intersections limit the exposure ranges in which one experiment dominates the other. For example, for $\sin^2 2\theta_{13}$, T2KK plans to operate with an exposure for which the WBB-WC concept would perform slightly better, whereas a significantly lower exposure would make T2KK the more sensitive experiment. Finally, one can read off the break-even point between the water Cherenkov and liquid argon-technologies in WBB experiments. For example, for $\sin^2 2\theta_{13}$, the water Cherenkov and liquid argon technologies are separated by about a factor of 4 in exposure, which means that liquid argon is the choice of technology if the cost per kt of liquid argon is smaller than the cost for 4 kt water. Note that the corresponding sensitivities to CP violation and the mass hierarchy are quite similar.

Summary and conclusions. It is crucial that the mixing angle $\theta_{13}$, the nature of the neutrino mass hierarchy and whether CP is violated in the neutrino sector, be determined to complete the parameter set that defines the neutrino mass matrix. This program is of fundamental importance to our understanding of the neutrino sector.
In the not-too-distant future, the planning stage for long-baseline neutrino experiments with super neutrino beams and large detectors will end. We have provided the first analysis of various experimental configurations on an equal-footing by expressing their sensitivities as functions of exposure. By enabling a balanced comparison, our study identifies which physics concept is optimal for each measurement. If a large liquid argon TPC can become a reality, our analysis indicates that with an adequate increase in exposure, an upgraded NOνA* experiment like NOνA* has better sensitivity to a nonzero $\theta_{13}$ and to CP violation than previous estimates suggested. The longer baselines planned for experiments with wide band beams offer better sensitivity to the mass hierarchy.

The power of assessing sensitivities as functions of exposure is manifest in the CPV sensitivity of NOνA*. This method is applicable to all long-baseline neutrino experiments where it may provide crucial insights into optimal experimental configurations. Since exposure is a measure of the integrated luminosity, it can also be used in comparative evaluations of other kinds of experiments.

**Acknowledgments.** We thank M. Bishai, M. Dierckxsens and M. Diwan for useful discussions. This research was supported by the U.S. DoE under Grants No. DE-FG02-95ER40896 and DE-FG02-04ER41308, by the NSF under CAREER Award No. PHY-0544278, by the State of Kansas through KTEC, by the KU GRF Program, and by the Emmy Noether Program of the Deutsche Forschungsgemeinschaft.

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