On the complementarity of Hyper-K and LBNF

The next generation of long-baseline experiments is being designed to measure neutrino oscillations with a precision substantially better than that of the present generation in order to:

- Search for CP-invariance violation (CPiV) in the lepton sector;
- Determine the neutrino mass hierarchy;
- Increase substantially the precision with which the neutrino-mixing parameters are known; and
- Test the three-neutrino-mixing hypothesis (the Standard Neutrino Model, SνM).

Two qualitatively different proposals are being considered for approval:

- Hyper-K [1], a 560 kTonne fiducial mass water Cherenkov detector located 2.5° off-axis at a distance of 295 km from the narrow-band beam produced by an upgraded, ~ 1 MW, proton beam at J-PARC; and
- The Long Baseline Neutrino Facility (LBNF) [2, 3], a 40 kTonne fiducial mass liquid-argon time projection chamber (LAr) illuminated by a new wide-band beam produced by a 1.2 MW proton beam to be built at Fermilab. The specification of the facility, including the baseline of 1 300 km, and the choice of detector technology will take advantage of the design studies already performed for LBNE [4] and LBNO [5–8].

Each project is ambitious and requires an investment significantly larger than any previous single investment in a neutrino experiment. This document outlines the complimentarity between Hyper-K and LBNF.

1 The experiments

The critical features of the Hyper-K proposal that determine the physics performance include:

- *Accelerator-based oscillation measurements:* The relatively short baseline implies small matter effects. This reduces the effect of correlations among the oscillation parameters in, for example, searches for CPiV. The off-axis, narrow-band beam peaks at ~ 600 MeV. The suppressed high-energy tail leads to a reduced neutral-current background in $\overset{\scriptscriptstyle(-)}{\nu}_e$-appearance samples.

- *Non-accelerator-based neutrino measurements:* The large atmospheric-neutrino data set will allow the mass hierarchy to be determined and may be sensitive to new phenomena. In the event of a nearby supernova, a large sample of $\bar{\nu}_e$ events would be recorded.

- *Proton decay:* Hyper-K is unique in its ability to extend the limits on the majority of proton decay modes by an order of magnitude.

- *Accelerator and detector R&D:* Incremental developments to proton source, target and horn are required for the beam power of ~ 1 MW to be delivered. An R&D programme is underway to reduce the cost of photosensors with the required collection efficiency. The T2K near detector programme will provide valuable constraints on neutrino flux and neutrino-interaction rates. The development of a dedicated near detector as part of the Hyper-K programme is essential for the experiment to fulfil its potential.

The critical features of the LBNF proposal that determine the physics performance include:

- *Accelerator-based oscillation measurements:* The long baseline yields a significant matter effect that can be used to determine the mass hierarchy. The excellent energy resolution and background rejection offered by the LAr technique allows the first and second oscillation maxima to be studied. The energy of the LBNF neutrino beam is sufficient for the reaction $\overset{\scriptscriptstyle(-)}{\nu}_\tau N \to \tau^\pm X$ to occur at an appreciable rate and the LAr technique has the potential to isolate samples of $\overset{\scriptscriptstyle(-)}{\nu}_\tau$ of significant size. This will provide an important opportunity to test the SνM.

- *Non-accelerator-based neutrino measurements:* LBNF would accumulate a large "high-resolution" atmospheric neutrino sample. The LAr detector is sensitive to the ν_e (rather than the $\bar{\nu}_e$) component of the supernova flux, which contains information regarding the "neutronization burst" ($p + e^- \rightarrow n + \nu_e$) that is expected to take place in the early stages of the explosion.

- *Proton decay:* The LAr detector, which will be substantially larger than any of those built to date, will offer the opportunity to search for proton-decay modes that are "preferred" by supersymmetric models.

- *Accelerator and detector R&D:* The total fiducial mass of the LAr detector will be implemented using a modular approach. An R&D programme to develop the necessary techniques is underway. The existing LAr-based program that includes ArgoNeuT, MicroBooNE, the LBNE 35 Ton prototype, CAPTAIN and LArIAT and the R&D projects developed at the CERN Neutrino Platform, will provide important information on neutrino-argon interactions, detector response, and reconstruction algorithms. A highly segmented near detector is essential for the facility to fulfil its potential and is under development. The proton-beam power of 1.2 MW will be delivered by the Proton Improvement Plan II upgrade to the Fermilab accelerator complex. This requires a 800 MeV, superconducting H$^-$ linac and a new high-power pion-production target.

2 The qualitative case for both experiments

The accelerator based programmes of both LBNF and Hyper-K have been optimised at the same L/E but the baselines, L, and energies, E, differ by almost a factor of 5. In each experiment, the large atmospheric-neutrino sample will extend substantially the range of L and E that can be studied. The two experiments have similar sensitivities to CPiV and will be able to measure the mixing angles with comparable precision. The longer baseline allows LBNF to determine the mass hierarchy. If the two experiments progress on technically-limited schedules they will compete to discover CPiV. Given the challenging nature of the measurement and the importance of the discovery, independent confirmation by a qualitatively different experiment is likely to be essential.

The differing degree to which the matter effect modifies the oscillation probabilities at Hyper-K and LBNF may be exploited to break parameter degeneracies. The different detector technologies and beam energies imply that neutrino scattering in the two experiments is dominated by different interaction processes and hence different event topologies. In addition, the details of the hadronic processes by which the two nenutrino beams are generated are different. Therefore, the systematics are quite different at Hyper-K and LBNF.

For a given parameter set, the SνM specifies that the oscillation probabilities are functions of L/E. Searches for non-standard phenomena can therefore be made by exploiting the fact that Hyper-K and LBNF have the same L/E but different L and E. To put the SνM to the test requires precise measurements of several observables, including $\overset{\scriptscriptstyle(-)}{\nu}_e$ (and, if possible, $\overset{\scriptscriptstyle(-)}{\nu}_\tau$) appearance from a $\overset{\scriptscriptstyle(-)}{\nu}_\mu$ beam at different values of L and E, comparing neutrino data with antineutrino data and comparing accelerator-based measurements with measurements of $\bar{\nu}_e$ disappearance at reactors.

Hyper-K offers the opportunity to extend the sensitivity to proton decay significantly in several modes, while the LAr detector at LBNF will probe new decay channels that are not accessible to water Cherenkov detectors and will provide nearly background-free searches for other important channels. To understand the mechanisms of supernova explosion requires accurate measurements of the ν_e and $\bar{\nu}_e$ fluxes, along with some neutral current data (which is sensitive to the flux of $\overset{\scriptscriptstyle(-)}{\nu}_{\mu,\tau}$). These measurements can not be made with Hyper-K or LBNF alone.

3 The need to quantify added value

Detailed simulations are required in order to quantify the complimentarity between Hyper-K and LBNF. Some representative questions that need quantitative studies are:

- *Searching for CP-invariance violation:* the degree to which the combined data set enhances the sensitivity of searches for CP-invariance violation;
- *Lifting degeneracies:* the degree to which the combined data set reduces the number of viable regions of multi-parameter space;
- *Improved precision:* the degree to which fits to the combined data set, which assumes the validity of the SνM, will improve the precision of the parameter determination; and
- *Testing the SνM framework:* the degree to which the combined data set enhances the coverage of the non-standard-neutrino-model parameter space.

The benefit that will accrue from the parallel implementation of these complementary experiments should be quantified at an early stage.

References

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A   The ICFA Neutrino Panel

ICFA established the Neutrino Panel with the mandate [9]:

To promote international cooperation in the development of the accelerator-based neutrino-oscillation program and to promote international collaboration in the development a neutrino factory as a future intense source of neutrinos for particle physics experiments.

The membership of the Panel agreed by ICFA at its meeting in February 2013 is shown in table 1. The terms of reference for the panel [10] may be found on the Panel's WWW site [11].

Table 1: Membership of the ICFA Neutrino Panel.

Name	Institution
J. Cao	IHEP/Beijing
A. de Gouvêa	Northwestern University
D. Duchesneau	CNRS/IN2P3
R. Funchal	University of Sao Paulo
S. Geer	Fermi National Laboratory
S.B. Kim	Seoul National University
T. Kobayashi	KEK
K. Long (chair)	Imperial College London and STFC
M. Maltoni	Universidad Automata Madrid
M. Mezzetto	University of Padova
N. Mondal	Tata Institute for Fundamental Resarch
M. Shiozawa	Tokyo University
J. Sobczyk	Wroclaw University
H. A. Tanaka	University of British Columbia and IPP
M. Wascko	Imperial College London
G. Zeller	Fermi National Accelerator Laboratory