Future Long Baseline Neutrino Oscillation Experiments

Ed Blucher
University of Chicago
Outline

• Motivations for future long baseline experiments
• Searching for CP violation
• Future experiments: DUNE and HyperK*
• Summary

*Both experiments will have broad physics programs including SN bursts, nucleon decay, etc., but I will focus only on neutrino oscillations.
The universe appears to made up of matter (not equal amounts of matter and antimatter).
Current universe with \( \sim \) no antimatter corresponds to a tiny quark-antiquark asymmetry at early times:

\[
\frac{n_q - n_{\bar{q}}}{n_q} \sim 10^{-9}
\]

Searching for clues to how this asymmetry developed is a major motivation for many experiments in particle physics.

CP violation in neutrino sector could be responsible for the matter-antimatter asymmetry (leptogenesis)

\[
\Gamma(N \rightarrow \ell^+ + H^-) > \Gamma(N \rightarrow \ell^- + H^+)
\]

The antilepton excess is converted to a baryon excess through nonperturbative S.M. B+L violating, but B-L conserving processes.
How to investigate leptogenesis

Ideally, you would produce heavy neutrinos (N) and measure their leptonic decays. Probably much too massive to be possible.

Alternative: build a "circumstantial case"

1) Other ideas don’t seem to work.
2) Search for CP violation in neutrino sector
3) Search for neutrinoless double beta decay, to demonstrate that neutrinos are their own antiparticles
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2) Search for CP violation in neutrino sector ← DUNE, HyperK
3) Search for neutrinoless double beta decay, to demonstrate that neutrinos are their own antiparticles

Connection of CPV in neutrino oscillations to CPV in heavy neutrinos is model dependent, but there are models in which $\delta_{\text{CP}}$ can play a dominant role in leptogenesis (Moffat, Pascoli, Petcov, and Turner, arXiv:1809.08251)
Standard Three Neutrino Paradigm

Unitary PNMS matrix described by 3 Euler angles ($\theta_{12},\theta_{13},\theta_{23}$) and 1 complex phase ($\delta$). $\delta \neq \{0, \pi\} \rightarrow$ CP Violation

$$U_{\text{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$s_{ij} = \sin \theta_{ij} ; c_{ij} = \cos \theta_{ij}$$

$\Delta m^2_{\text{atm}} \sim 2.5 \times 10^{-3}$ eV$^2$

$\Delta m^2_{\text{sol}} \sim 7.5 \times 10^{-5}$ eV$^2$
Key Questions in Neutrino Physics

- Do neutrinos violate CP symmetry?

\[ P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = -16s_{12}c_{12}s_{13}c_{13}c_{23}\sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E}L\right) \sin\left(\frac{\Delta m_{13}^2}{4E}L\right) \sin\left(\frac{\Delta m_{23}^2}{4E}L\right) \]

- What is the mass ordering?
- Why are the quark and neutrino mixing matrices so different?

- Are there additional neutrino states?
- Are neutrinos their own antiparticles?
- What is the neutrino mass?
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How to search for CP violation

• Compare oscillation oscillation rates for $\nu_s$ and $\bar{\nu}_s$

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c^2_{13} s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m^2_{12}}{4E} L\right) \sin\left(\frac{\Delta m^2_{13}}{4E} L\right) \sin\left(\frac{\Delta m^2_{23}}{4E} L\right)$$

(in vacuum)

• As in quark sector, CP violating effects

$$\propto J \equiv c_{12} c_{23} c_{13}^2 s_{12} s_{23} s_{13} \sin\delta$$

and require no degenerate masses

• We know mixing angles and mass differences, so we can measure $P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ and determine $\delta$, but there is a complication...
Matter Effects

• In real experiments, even in the absence of CPV,

\[ P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \neq 0 \]

Neutrinos travel through material that is not CP symmetric, i.e., matter not antimatter

• In vacuum, the mass eigenstates \( \nu_1, \nu_2, \nu_3 \) correspond to the eigenstates of the Hamiltonian:
  - they propagate independently (with appropriate phases)

• In matter, there is an effective potential due to the forward weak scattering processes. **Effect depends on Mass Ordering**

\[ V = \pm \sqrt{2} G_F n_e \]

Different sign for \( \nu_e \) vs \( \bar{\nu}_e \)

(M. Thomson)
Possible Experimental Strategies

EITHER:
• Keep L small (~200 km): so that matter effects are insignificant
  ▪ First oscillation maximum:
    \[
    \frac{\Delta m_{31}^2 L}{4E} \sim \frac{\pi}{2} \Rightarrow E_\nu < 1 \text{ GeV}
    \]
  ▪ Want high flux at oscillation maximum
    ➡️ Off-axis beam: narrow range of neutrino energies
OR:
• Make L large (>1000 km): measure the matter effects (i.e., MH)
  ▪ First oscillation maximum:
    \[
    \frac{\Delta m_{31}^2 L}{4E} \sim \frac{\pi}{2} \Rightarrow E_\nu > 2 \text{ GeV}
    \]
  ▪ Unfold CPV from matter effects through E dependence
    ➡️ On-axis beam: wide range of neutrino energies
Possible Experimental Strategies

EITHER:
- Keep $L$ small ($\sim 200$ km): so that matter effects are insignificant
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HyperK and DUNE

HyperK: Off-axis narrow-band beam peaked at \( \sim 0.6 \) GeV, \( L = 295 \) km

DUNE: On-axis, broad-band beam covering 1\(^{\text{st}}\) and most of 2\(^{\text{nd}}\) oscillation, \( L = 1300 \) km
HyperK and DUNE

HyperK: Water Cherenkov

DUNE: Liquid Argon TPC

$\nu_\mu$ CC ($E_\nu = 3.1$ GeV)
DUNE and HyperK:

Near Detectors

- Measure the neutrino beam rate and spectrum to predict un-oscillated event rates in the far detector
- Minimize differences between near and far detectors
  - Ideally, measure neutrino interactions on same nuclei
  - If possible, use “functionally identical” detectors to take advantage of some cancellation of detector systematics
Near Detectors

DUNE

HyperK

1 kt H₂O

L=1-2km

L=280m

L=575m
Both NDs incorporate off-axis running

HyperK
DUNE-Prism

Beamsimulation

▶ Beam simulation run using 1.5 × 10^8 POT.
▶ Uses PTiBKBx2/1M;BM22`2/a2TikyRd_2pB2r;9H#M7 macro.

▶ 120:20, 1.2 Jq proton beam

▶ 1.1 × 10^21 POT per year

On axis predictions are in line with official beam group plots.

![Graph showing neutrino flux for On Axis and 30 m off axis configurations with distances 6m, 12m, 18m, 24m, 30m, 36m from on axis.](image)
HyperK

260 kt H$_2$O
200 kt fid. mass
8× SuperK
Gd loading opt.
HyperK

260 kt H₂O
200 kt fid. mass
8× SuperK
Gd loading opt.

J-PARC 1.3MW beam power

Being upgraded for T2K

2.5 deg off-axis beam
## HyperK Parameters

<table>
<thead>
<tr>
<th></th>
<th>KAM</th>
<th>SK</th>
<th>HK-1TankHD</th>
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<tr>
<td><strong>Depth</strong></td>
<td>1,000 m</td>
<td>1,000 m</td>
<td>650 m</td>
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<td><strong>Dimensions of water tank</strong></td>
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<tr>
<td>diameter</td>
<td>15.6 m (\phi)</td>
<td>39 m (\phi)</td>
<td>74 m (\phi)</td>
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<tr>
<td>height</td>
<td>16 m</td>
<td>42 m</td>
<td>60 m</td>
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<tr>
<td><strong>Total volume</strong></td>
<td>4.5 kton</td>
<td>50 kton</td>
<td>258 kton</td>
</tr>
<tr>
<td><strong>Fiducial volume</strong></td>
<td>0.68 kton</td>
<td>22.5 kton</td>
<td>187 kton</td>
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<tr>
<td><strong>Outer detector thickness</strong></td>
<td>(\sim 1.5 \text{ m})</td>
<td>(\sim 2 \text{ m})</td>
<td>(1 \sim 2 \text{ m})</td>
</tr>
<tr>
<td><strong>Number of PMTs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>inner detector (ID)</td>
<td>948 (50 cm (\phi))</td>
<td>11,129 (50 cm (\phi))</td>
<td>40,000 (50 cm (\phi))</td>
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<tr>
<td>outer detector (OD)</td>
<td>123 (50 cm (\phi))</td>
<td>1,885 (20 cm (\phi))</td>
<td>6,700 (20 cm (\phi))</td>
</tr>
<tr>
<td><strong>Photo-sensitive coverage</strong></td>
<td>20%</td>
<td>40%</td>
<td>40%</td>
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<tr>
<td><strong>Single-photon detection efficiency of ID PMT</strong></td>
<td>unknown</td>
<td>12%</td>
<td>24%</td>
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<tr>
<td><strong>Single-photon timing resolution of ID PMT</strong></td>
<td>(\sim 4 \text{ nsec})</td>
<td>2-3 nsec</td>
<td>1 nsec</td>
</tr>
</tbody>
</table>

![HQE 50 cm R12860 PMT](image)
HyperK (10 years: $10^8$ s at 1.3 MW)

Note: Assumes 3× more running time in antineutrino mode.
Variation with $\delta_{CP}$

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HyperK CP Sensitivities

Can observe CP violation at 3σ (5σ) over 76% (57%) of $\delta_{CP}$ range.
Allowed regions shown for true values of $\delta_{CP} = -90, 0, 90, 180^\circ$
HyperK: Second detector in Korea

- 1-2 degrees off-axis at a baseline of ~1100 km
- Aim to build this detector after Kamioka detector is running

Longer baseline: mass hierarchy sensitivity + some benefits to CP sensitivity

arXiv:1611.06118
HyperK Status

In 2018, Japanese seed funding and University of Tokyo commitment to 2020 start. Decision from Japanese government about construction start by the end of 2019
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Breaking news from Japan, where MEXT (the Japanese funding agency for science) has announced that they will as the Ministry of Finance for funds to begin serious construction of Hyper Kamiokande next year! This is a very significant step for the project, as it amounts to approval of the project and budget by MEXT. Now we need to convince the MoF as well!
Deep Underground Neutrino Experiment

1106 collaborators from 184 institutions in 31 countries

1st DUNE Collab. Meeting, April 2015
LBNF/DUNE Overview

- Muon neutrinos/antineutrinos from high-power proton beam
  - 1.2 MW from day one; upgradeable to 2.4 MW
- Massive underground Liquid Argon Time Projection Chambers
  - 4 x 17 kton fiducial mass of > 40 kton
- Near detector to characterize the beam (100s of millions of neutrino interactions)
LBNF/DUNE Overview
DUNE Far Site
Ross Campus of 4850 ft level of Sanford Underground Research Facility

Davis Campus:
• LUX
• Majorana demo.
• ...
• LZ

Ross Campus:
• CASPAR
• ...
• DUNE

Green = new construction
DUNE Far Site
Ross Campus of 4850 ft level of Sanford Underground Research Facility

Davis Campus:
- LUX
- Majorana demo.
- ...
- LZ

Site of Ray Davis solar neutrino experiment
DUNE Far Detector

Long-Baseline Neutrino Facility
South Dakota Site

Ross Shaft
1.5 km to surface

4850 Level of Sanford Underground Research Facility

145 m

Neutrinos from Fermi National Accelerator Laboratory in Illinois

Facility and cryogenic support systems

One of four detector modules of the Deep Underground Neutrino Experiment

Each module > 10 kt fiducial
LBNF/DUNE Groundbreaking, 21 July 2017
Pre-excavation Work Under Way

- Ross Shaft Renovation
- Refuge Chamber Capacity Increase
- Building Ore Pass Wall
- Brakes & Clutches Replacement
LAr TPCs: Basic Idea

- **Build a large tank of liquid argon (-186 °C / -303 °F)**
  - Apply a very strong electron field
  - Drift ionization electrons towards planes of wires
  - Detect charge and reconstruct particle tracks

![Diagram of LAr TPC](image)
**LAr TPCs: Basic Idea**

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DUNE Far Detector Technologies

DUNE is planning to employ (and is prototyping) two LAr readout technologies:

- Ionization charges drift horizontally and are read out with wires
- No signal amplification in liquid
- 3.5 m maximum drift

- Ionization charges drift vertically and are read out on PCB anode
- Amplification of signal in gas phase by LEM
- 12 m maximum drift

500 V/cm
DUNE Single-phase TPC Design
DUNE Single-phase TPC Design

Size of ProtoDUNE-SP

14 m

12 m

APA

DUNE APA
ProtoDUNEES

DUNE has constructed 1 kton-scale prototypes of LAr TPCs with single and dual phase readout
ProtoDUNE

DP

SP
ProtoDUNE-SP data

Excellent performance: HV, liquid argon purity, and signal-to-noise

2 GeV electron shower
ProtoDUNE data
DUNE Neutrino Oscillation Strategy

Initial neutrino energy spectra (left) will be modified by neutrino oscillation probabilities (right).

- $\nu_e$ appearance probability depends on $\theta_{13}$, $\theta_{23}$, $\delta_{\text{CP}}$, and matter effects. All four can be measured in a single experiment.
- Wide-band beam and long baseline break the degeneracy between CP violation and matter effects.
DUNE Sensitivity Evaluation

- DUNE TDR submitted to LBNC for review in July 2019, including full update of physics sensitivities.
  - Full far detector (FD) MC simulation, automated event reconstruction, and event selection
  - Convolutional neural network for event classification: $\nu_e$ CC, $\nu_\mu$ CC, NC
  - Energy reconstruction:
    - Muons by range (or multiple Coulomb scattering)
    - Electrons and hadronic showers by calorimetry

  \textbf{Avg. resolutions}  
  $\nu_e$ CC: 13%  
  $\nu_\mu$ CC: 18%

- G4 simulation of LAr ND events with parametrized reconstruction included in the fit
- Simultaneous ND+FD fitting framework
- Equal $\nu / \bar{\nu}$ running; 56% beam uptime assumed based on NUMI experience.

\[ \nu_e \text{ CC (} E_\nu = 3.1 \text{ GeV)} \]

\[ \text{Appearance Efficiency (FHC)} \]
Appearance and disappearance spectra

\[ \nu_e, \bar{\nu}_e \]

\[ \nu_\mu, \bar{\nu}_\mu \]
Variation with mass ordering and $\delta_{CP}$

Mass ordering variation

$\nu_e$ $\bar{\nu}_e$

$\delta_{CP}$ variation

$\nu_e$ $\bar{\nu}_e$
After 7 years (staged):
• CP Violation: $5\sigma$ if $\delta_{CP}$ near $\pm\pi/2$
• Mass hierarchy determination: $>5\sigma$ for all parameter values
DUNE Sensitivity vs. time

CP Violation Sensitivity

Mass Hierarchy Sensitivity

Important sensitivity milestones throughout beam physics program
DUNE Measurement of $\delta_{CP}$

$\delta_{CP}$ resolution

- DUNE Sensitivity
- All Systematics
- Normal Ordering

$\sin^2\theta_{13} = 0.088 \pm 0.003$

$\sin^2\theta_{23} = 0.580$ unconstrained

Graph showing the resolution of $\delta_{CP}$ with different systematics and orders over different years.
DUNE and HyperK have similar sensitivity to CP violation.
CP Sensitivity vs Time

DUNE Sensitivity (Staged)
- All Systematics
- Normal Ordering
- $\sin^2\theta_{13} = 0.088 \pm 0.003$
- $\sin^2\theta_{23} = 0.580$ unconstrained

HyperK
- $\delta_{CP} = -\pi/2$
- $5\sigma$
- $3\sigma$
- T2K
- HK
- $\delta_{CP} = -90^\circ$

Years

σ = $\sqrt{\chi^2}$
Summary

• DUNE and HyperK promise substantial progress on many key issues in neutrino physics + SN bursts, nucleon decay, etc.

• The discovery of CP violation in the neutrino sector would be a major piece of evidence in understanding the matter-antimatter asymmetry in the universe.

• DUNE and HyperK will be able to detect CP violation at 3σ (5σ) over about 75% (60%) of the possible values of the true CP phase.

• **DUNE status:** Far site construction underway. Detector prototypes built and operated successfully. Far detector installation planned to start in 2024. TDR submitted to Long Baseline Neutrino Committee in July 2019

• **HyperK status:** “Japanese seed funding and U. Tokyo commitment to 2020 start.” Construction decision at end of 2019.
backup
Resolving the $\theta_{23}$ octant

DUNE

HyperK
DUNE Staging assumptions

• 1.2 MW with 20 kt FD at start
• 1.2 MW with 30 kt FD after 1 year
• 1.2 MW with 40 kt FD after 3 years
• 2.4 MW with 40 kt after 6 years