Current status and open questions

Hyper-Kamiokande

DUNE (talk by Antonio Ereditato)

Studies for other long baseline neutrino experiments

Conclusions
CURRENT STATUS

- $\theta_{12} = (33.62^{+0.78}_{-0.76})^\circ$
- $\theta_{23} = (47.2^{+1.9}_{-3.9})^\circ$
- $\theta_{13} = 8.54\pm0.15^\circ$
- $\delta_{CP} = ?$ [only unknown param]
- $|\Delta m^{2}_{32}| = (2.494\pm0.032) \times 10^{-3} \text{eV}^2$
- $\Delta m^{2}_{12} = (7.60\pm0.21) \times 10^{-5} \text{eV}^2$
- Very different from the CKM matrix

OPEN QUESTIONS

- Do neutrino oscillations violate CP symmetry?

  Only in an appearance measurement since $CPT$ requires the disappearance probabilities to be the same
  
  $$P(\nu_{\mu}\rightarrow\nu_{e}) \neq P(\bar{\nu}_{\mu}\rightarrow\bar{\nu}_{e})?$$

- Possibly relevant for understanding origin of matter-dominated Universe (Leptogenesis)
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OPEN QUESTIONS

Is the mass hierarchy “normal” (NH) or “inverted” (IH)?

- Also called “mass ordering”
- Enhancement or suppression depending on hierarchy.
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OPEN QUESTIONS

- What is the “octant” of $\theta_{23}$?
- What is the balance $\nu_\mu$ and $\nu_\tau$?
- Or is the mixing “maximal” (e.g. even split)?
Large $\theta_{13}$ makes the search for CP possible but not ideal.

Degeneracy with the mass hierarchy.

CP violating effects are more pronounced at lower energies.

More intense beam power and larger detectors are needed for the next generation of long baseline experiments to measure CP violation.

Two main experiments are planned:

- Hyper-Kamiokande (Japan): 295 km baseline from J-PARC. Water Cherenkov technology.

- DUNE (US): 1300km baseline w/ Fermilab beam. Liquid Argon technology. Please see today’s talk by Antonio Ereditato

The feasibility of other future projects worldwide is also being investigated.
CURRENT STATUS AND OPEN QUESTIONS

LONG BASELINE EXPERIMENTS IN A NUTSHELL

- Predicted events in the Near Detector.

- Predicted events in the Far Detector.
LONG BASELINE EXPERIMENTS IN A NUTSHELL

Disappearance Channel
- Location of dip: $\Delta m^2_{32}$
- Depth of dip: $\sin^2 2\theta_{23}$

Appearance Channel
- Magnitude of peak linked to $\sin^2 \theta_{13}$, $\delta_{CP}$, and mass hierarchy

$\nu_{\text{beam}}$ near detector
- ~100 m

$\nu_{\text{beam}}$ far detector
- ~100-1000 km
T2K (now) - See talk by Nguyen Thi Hong Van

T2K phase 2 (or T2KII) \(~2021\) - see next slides

Hyper-Kamiokande - future generation long baseline neutrino experiment
T2K PLANS

- $\bar{\nu}$ beam has been operating at 475kW from last Autumn to May. This will equalize the $\nu$ to $\bar{\nu}$ beam ratio.

- Summer 2018 SK has been opened for PMT repair and leak fixing, then Gd (see talk by Yuuchi Nakano)

- T2K originally approved to take $7.8 \times 10^{21}$ POT (~2021).

- T2K-II: proposal to extend T2K running to $20 \times 10^{21}$ POT (~2026).

- Exclude CP conserving values of $\delta_{CP}$ at $3\sigma$ if $\delta_{CP}$ is near current best fit.

- Refurbished near detector to reduce systematic errors.
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- **enhance neutron detection capability**
  - improves low energy antineutrino detection
- Scale up from SK and T2K. Continuous upgrade plan: T2K-II, near detector upgrades, HK far detector
- Requires beam power increase to 1.3MW
- Data taking expected to start in 2026
- Option to put second detector in Korea

The results from Hyper-K are from the HK Design Report ([arXiv:1805.04163](https://arxiv.org/abs/1805.04163) [physics.ins-det])

Feature: Scale up from SK and T2K. Continuous upgrade plan: T2K-II, near detector upgrades, HK far detector.

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Feature: The results from Hyper-K are from the HK Design Report ([arXiv:1805.04163](https://arxiv.org/abs/1805.04163) [physics.ins-det]).
Comparison between the probabilities: $P(\nu_\mu \rightarrow \nu_e)$ vs $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

Up to $\sim \pm 30\%$ variation at $\delta_{CP} = -90^\circ$ in NH (or $90^\circ$ in IH) wrt $\sin\delta_{CP} = 0$
EXPECTED EVENTS IN HYPER-KAMIOKANDE LBN PROJECT

- Comparison: A few % stat. uncertainties on $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signals

- $E\nu$ is reconstructed from $(p, \theta)$ of $e$ or $\mu$

- Realistic estimates of wrong sign & NC BG contamination are based on T2K

<table>
<thead>
<tr>
<th>$\delta_{CP}$</th>
<th>Signal</th>
<th>Wrong sign appearance</th>
<th>$\nu_\mu / \bar{\nu}_\mu$ CC</th>
<th>Beam $\nu_e / \bar{\nu}_e$ contamination</th>
<th>NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$\nu_\mu \rightarrow \nu_e$ CC</td>
<td>15</td>
<td>7</td>
<td>259</td>
<td>134</td>
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<tr>
<td></td>
<td>$\bar{\nu}$ beam</td>
<td>206</td>
<td>4</td>
<td>317</td>
<td>196</td>
</tr>
</tbody>
</table>
Exclusion of $\sin \delta_{CP} = 0$

- $8\sigma$ for $\delta = -90^\circ$ (T2K best fit)
- $80\%$ of coverage of $\delta$ parameter space for CPV discovery $> 3\sigma$

- After 10 years of running, HK will be able to measure $\sim 50\%$ of the $\delta_{CP}$ space to better than $5\sigma$

$\delta_{CP}$ precision measurement

- $22^\circ$ for $\delta = -90^\circ$
- $7^\circ$ for $\delta = 0^\circ$
Exclusion of $\sin \delta_{CP} = 0$

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$\delta_{CP}$ precision measurement

- $22^\circ$ for $\delta = -90^\circ$
- $7^\circ$ for $\delta = 0^\circ$
The resonance appears for $\nu_e$ ($\bar{\nu}_e$) in NH (IH) case.

- Sensitivity enhanced by combining atm & beam $\nu$ data.
- Determination possible by $\sim5$ years. ($\sin^2 \theta_{23}=0.5$) at HK.
Octant determination

\[ |\theta_{23} - 45^\circ| > 2.3^\circ \]
SECOND DETECTOR IN KOREA FOR HYPER-KAMIOKANDE

- Investigating second detector in Korea to enhance mass hierarchy and $\delta_{CP}$ sensitivities
  - 1000 – 1200 km baseline
  - $1.3^\circ$ - $3.0^\circ$ off-axis beam direction

- CP asymmetry between $\nu$ and $\bar{\nu}$ is 3 times larger than the 1st oscillation maximum
  - Less sensitive to systematics errors due to larger CP effect
  - Compensate for factor of 3.7 reduction in statistical significance due to flux reduction for longer baseline
  - Longer baseline (1100 km) leads to larger matter effects
  - MH better determination
- Processes with $\Delta B \neq 0$, including proton decay, are a general prediction of grand unified theories.

- Hyper-Kamiokande will be able to address the proton decays on a wide variety of final states.
- $p \rightarrow e^+ \pi^0$ favoured by non super-symmetric GUTs a nearly model independent reaction

- $p \rightarrow K^+ \bar{\nu}$ feature of SuperSymmetric GUT

![Graphs showing sensitivity for $p \rightarrow \bar{\nu} K^+$ decay with projections from Hyper-K, Super-K, DUNE, HK, and JUNO experiments.](image)
NEUTRINO ASTROPHYSICS/ASTRONOMY

SN BURST

- ~50 – 80 k events/SN @ Galactic Centre (10 kpc)
- Probe of Core-Collapse SN (CCSN) in detail: Explosion mechanism (model identification); Generation of proto-neutron star; Nucleosynthesis in SN
- Physics property of neutrinos
- Multi-messenger measurement: Time & energy profiles with high statistics; 1°pointing for SN @ 10 kpc

SN RELIC NEUTRINOS

- SRN could be observed by HK in 20y with 140±25 events (5.7σ, with 1 tank). We will go beyond the discovery and aim to measurement, e.g. model constrain. 1st discovery by SK-Gd

OTHERS

- 1st discovery by SK-Gd Solar ν (day/night, upturn, Hepv), WIMP ν, surprise?
HYPER-KAMIOKANDE DETECTOR SITE

- Tochibora mine in Kamioka
- ~8km south from Super-K
- Identical baseline (295km) and off-axis angle (2.5°) to Super-K for J-PARC beam
- Overburden ~650m (~1755m.w.e.) cf. SK ~2700m.w.e.
Seismic tomography and reflection imaging were conducted for (400 m)$^3$ wide area.

An excellent site was identified.
HYPER-KAMIOKANDE
PHOTOSENSORS R&D

- Sensitivity: $2 \times SK$
- Time resolution: $\frac{1}{2} \times SK$
- Pressure tolerance: $2 \times SK$

Cover test @ Kamisunagwa, Hokkaido

- ~140 new PMT’s are being installed in Super-K during tank opening.
  - Performance check w/ Cherenkov light for years.
- Continuous effort for improvements. Noise reduction, cover design, light concentrator, etc. under study
International Hyper-K proto-collaboration

- 15 countries, 73 institutes, ~300 members, ~75% from abroad
- International project leaders, steering members, WG conveners

2 host institutes: UTokyo/ICRR and KEK/IPNS (MoU of cooperation for HK)

- UTokyo launched a institute for HK construction: Next Generation Neutrino Science Organization (NNSO)

External review by Advisory Committee


Other recent references:

- Physics potentials with the second Hyper-Kamiokande detector in Korea
  - PTEP 2018 (2018) no.6, 063C01
LONG BASELINE NEUTRINO PROGRAMME IN THE US

- Current LBN experiment NOvA (talk by Brajesh Choudhary)
- Future LBN experiment DUNE (Antonio Ereditato & protoDUNE: Matthew Worcester)

**DUNE:**
- 40 kt LAr-TPC Far Detector (1300 km baseline)
  - Near Detector systems
  - Science collaboration

**LBNF (Long-baseline Neutrino Facility):**
- 1.2 MW wide-band v beam, upgradable to 2.4 MW
- Conventional facilities at Fermilab and SURF
- Cryostats and cryogenic systems at SURF
STUDIES FOR OTHER LONG BASELINE NEUTRINO EXPERIMENTS
CHIPS (CHeerentkov detectors In mine PitS) has two goals: to prove that a detector costing $200-300k/kiloton is viable for measuring accelerator produced neutrinos.

- To contribute to world knowledge of the mixing parameters \( \sin^2\theta_{23}, \sin^2\theta_{13} \) and to \( \delta_{CP}, MH \).

- arXiv:1307.5918

1) **Location**
   - sunk in a flooded mine pit in the path of the NuMI neutrino beam, will make use of the water for cosmic overburden and mechanical support;

2) **Structure design**
   - will allow it to grow in size with time but with no financial penalty beyond the instrumentation costs

3) **PMT choice and layout**
   - 3” PMT's good position and time resolution and beam optimized layout

4) **Electronics**
   - will make use of ubiquitous mobile phone and communications technology and already developed KM3Net Solutions

5) **Simple water purification plant**
   - will use straightforward filtering to maintain water clarity.

- CHIPS 5kton detector are being deployed this Summer.
- Baseline 712km, 7mrad off-axis.
- Data expected for Oct 2018.
The ESS will be a copious source of spallation neutrons.

5 MW average beam power, 125 MW peak power, 2.0 GeV protons, >2.7x10^{23} p.o.t/year.

ESSnuSB Design Study funded by H2020

How to add a neutrino line to SSB:

Linac: double the pulse rate (14 Hz → 28 Hz)

Accumulator (C~400 m) needed to compress to few μs the 2.86 ms proton pulses, affordable by the magnetic horn (350 kA)

Target station (studied in EUROv).

Underground detector (WC à la Hyper-K)
STUDIES FOR OTHER LONG BASELINE EXPERIMENTS

ALTERNATIVE CONFIGURATIONS OF LBN EXPERIMENTS

  - Use ORCA as far detector and create a neutrino beam at Protvino (Omega project, 70 GeV, 450 kW).
  - Baseline: 2590 km. Excellent sensitivity on MH, mild sensitivity on CP

- **Pacific (arXiv:1610:08655)**:
  - Neutrino beam from FNAL similar to NUMI medium energy tune, fired to a 10 Mton KM3NeT-like detector placed at a baseline of 3100 km (Neptune/OOI deep sea observatories).
  - E. ~ 6.2 GeV. It would accumulate 100 more events than Dune for the same number of pot.
CONCLUSIONS

- Open questions in neutrino physics being addressed by current long baseline neutrino experiments, T2K and NOvA
  - CP violation limits
  - Mixing parameters
  - Mass hierarchy
- Hyper-Kamiokande and DUNE will definitely be able to address neutrinos oscillations and CP violation
- Further physics will be addressed as proton decays and astro neutrinos.
- Several studies for new LBN experiments are ongoing: CHIPS, ESSnuSB, P2O, PACIFIC.