Physics potential of Hyper-Kamiokande for neutrino oscillations
Physics goals for neutrino oscillations

Sensitivity with beam neutrinos and one detector

Atmospheric neutrinos and combination with beam neutrinos

Second tank: staging and Korean detector options

Solar neutrino oscillations
Main physics goals 
(neutrino oscillations)

Mass hierarchy: $m_3 > m_2, m_1$?

PDG 2016 summary table

<table>
<thead>
<tr>
<th>Parameter</th>
<th>best-fit</th>
<th>3σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{21}^2 \ [10^{-5} \text{ eV}^2]$</td>
<td>7.37</td>
<td>6.93 – 7.97</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m_{12}^2</td>
<td>\ [10^{-3} \text{ eV}^2]$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0.297</td>
<td>0.250 – 0.354</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}, \Delta m^2 &gt; 0$</td>
<td>0.437</td>
<td>0.379 – 0.616</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}, \Delta m^2 &lt; 0$</td>
<td>0.569</td>
<td>0.383 – 0.637</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}, \Delta m^2 &gt; 0$</td>
<td>0.0214</td>
<td>0.0185 – 0.0246</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}, \Delta m^2 &lt; 0$</td>
<td>0.0218</td>
<td>0.0186 – 0.0248</td>
</tr>
<tr>
<td>$\delta/\pi$</td>
<td>1.35 (1.32)</td>
<td>(0.92 – 1.99) $(0.83 – 1.99))</td>
</tr>
</tbody>
</table>

Octant of $\theta_{23}$:
$\theta_{23} > \pi/4$?
$\theta_{23} < \pi/4$?

Violation of CP symmetry in neutrino oscillations?

+ improve measurements of oscillation parameters, tests of the 3 neutrino oscillation model
Looking for second order effects

Look for subtle effects by comparing $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

CP violation: $\sin(\delta) \neq 0$?

$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31}$$

$$+ 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos \delta - s_{12} s_{13} s_{23}) \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21}$$

$$- 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin \delta \sin \Delta_{32} \sin \Delta_{31} \sin \Delta_{21}$$

$$+ 4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta) \sin^2 \Delta_{21}$$

$$\sin^2 \Delta_{ij} = \sin^2 (1.27 \Delta m_{ij}^2 L / E)$$

Mass hierarchy: $\Delta m_{32/31}^2 > 0$?

Octant of $\theta_{23}$: $\theta_{23} = \pi/4$ ? $\theta_{23} > \pi/4$ ? $\theta_{23} < \pi/4$ ?

$$P(\nu_\mu \to \nu_\mu) \sim 1 - (\cos^4 \theta_{13} \times \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \times \sin^2 \theta_{23}) \times \sin^2 \frac{\Delta m_{31}^2 \times L}{4E}$$

Need more neutrino events
Hyper-Kamiokande builds on the successful strategies used to study neutrino oscillations in Super-Kamiokande, K2K and T2K with:

- Larger detector for increased statistics
- Improved photo-sensors for better efficiency
- Higher intensity beam and updated/new near detector for accelerator neutrino part

- 60m height x 74m diameter tank
- 190 kton fiducial volume (SK:22.5 kton)
- Construct first tank as soon as possible
- Proposals for a second tank:
  - 6 years later in Japan
  - as soon as possible in Korea
Long baseline oscillations: T2HK

- Candidate site for Hyper-K ~8km south of Super-K
- Baseline (295km) and off-axis angle (2.5°) for J-PARC beam identical to Super-K: very “T2K-like” experimental apparatus

ν production

**ν**

J-PARC beamline

2.5°

νμ

Near detectors

On-axis

280m

Off-axis

Intermediate detector

Spans 1 to 4° off-axis

700m - 2km

Far detector

Hyper-Kamiokande

295 km

Updated ND and new ID to reduce systematics

ND280 upgrade: official T2K project

E61: currently separate collaboration
Long baseline oscillations: T2HK
Sensitivity studies

Setup similar to T2K: sensitivity studies based on framework used to evaluate T2K future sensitivity (PTEP 2015, 043C01 (2015))

- SK MC and reconstruction
- Scaled to one 187kton f.v. tank
- 10 years run with 1.3 MW beam
- Running mode $\nu:\overline{\nu}$ is 1:3
- **Mass hierarchy assumed to be known**

<table>
<thead>
<tr>
<th></th>
<th>Sample</th>
<th>Flux + ND constrained xsec</th>
<th>x-sec ND independant</th>
<th>Far detector</th>
<th>Total</th>
<th>T2K 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$\nu$ mode</strong></td>
<td>e-like</td>
<td>3.0%</td>
<td>0.5%</td>
<td>0.7%</td>
<td><strong>3.2%</strong></td>
<td>6.3%</td>
</tr>
<tr>
<td></td>
<td>$\mu$-like</td>
<td>3.3%</td>
<td>0.9%</td>
<td>1.0%</td>
<td><strong>3.6%</strong></td>
<td>4.4%</td>
</tr>
<tr>
<td><strong>$\overline{\nu}$ mode</strong></td>
<td>e-like</td>
<td>3.2%</td>
<td>1.5%</td>
<td>1.5%</td>
<td><strong>3.9%</strong></td>
<td>6.4%</td>
</tr>
<tr>
<td></td>
<td>$\mu$-like</td>
<td>3.3%</td>
<td>0.9%</td>
<td>1.1%</td>
<td><strong>3.6%</strong></td>
<td>3.8%</td>
</tr>
</tbody>
</table>

Systematic uncertainties estimated based on T2K experience + expected improvement:
- Updated near detector and Intermediate detector
- Larger atmospheric control sample for far detector

<table>
<thead>
<tr>
<th></th>
<th>Nominal values:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sin^2(2\theta_{13})=0.1$</td>
</tr>
<tr>
<td></td>
<td>$\sin^2(\theta_{23})=0.5$</td>
</tr>
<tr>
<td></td>
<td>$\Delta m_{32}^2=2.4\times10^{-3}$ $\text{ev}^2/c^4$</td>
</tr>
<tr>
<td></td>
<td>$\sin^2(2\theta_{12})=0.8704$</td>
</tr>
<tr>
<td></td>
<td>$\Delta m_{21}^2=7.6\times10^{-5}$ $\text{ev}^2/c^4$</td>
</tr>
</tbody>
</table>
Long baseline oscillations: T2HK
Expected number of events: appearance

- Expect >1000 signal events in each running mode
- Differences between the different values of $\delta$ in terms of number of events and spectrum

<table>
<thead>
<tr>
<th></th>
<th>Signal</th>
<th>Background</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_{\mu} \rightarrow \nu_e$</td>
<td>1643</td>
<td>400</td>
<td>2058</td>
</tr>
<tr>
<td>$\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e$</td>
<td>15</td>
<td>517</td>
<td>1906</td>
</tr>
</tbody>
</table>

![Graphs showing event distribution vs. reconstructed energy for v-mode and v-mode](image)

![Graphs showing difference in event distribution vs. reconstructed energy for v-mode and v-mode](image)
After 10 years of running:
➢ Exclude CP conservation at 5σ (3σ) for 57% (76%) of possible true values of δ
➢ Measure δ with 7° (true δ=0) to 23° (true δ=90°) precision

(Mass hierarchy assumed to be known)
Long baseline oscillations: T2HK

Expected number of events: disappearance

- Expect more than 10000 events in each running mode
- Clear oscillation pattern in the spectra
- Larger “wrong-sign” background in $\bar{\nu}$-mode

<table>
<thead>
<tr>
<th></th>
<th>$\nu_\mu$ CCQE</th>
<th>$\nu_\mu$ CC non QE</th>
<th>$\bar{\nu}_\mu$ CCQE</th>
<th>$\bar{\nu}_\mu$ CC non QE</th>
<th>Bkg</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$-mode</td>
<td>6043</td>
<td>2981</td>
<td>348</td>
<td>194</td>
<td>515</td>
<td>10080</td>
</tr>
<tr>
<td>$\bar{\nu}$-mode</td>
<td>2699</td>
<td>2354</td>
<td>6099</td>
<td>1961</td>
<td>614</td>
<td>13726</td>
</tr>
</tbody>
</table>

Disappearance $\nu$ mode

Disappearance $\bar{\nu}$ mode

![Graphs showing expected number of events](image-url)
Long baseline oscillations: T2HK
Sensitivity to atmospheric parameters

After 10 years:
- Measure $\Delta m^2_{32}$ with $1.4 \times 10^{-5}$ ev$^2$/c$^4$ precision
- Measure $\sin^2(\theta_{23})$ with precision 0.006 to 0.017
- Some ability to determine octant of $\theta_{23}$

Normal hierarchy, “reactor constraint” $\sin^2(2\theta_{13}) = 0.1 \pm 0.005$
Atmospheric neutrinos

T2HK baseline is only 295km → limited sensitivity to mass hierarchy
Hyper-K can study oscillation of atmospheric $\nu$’s like Super-K

Sensitivity studies based on SK analysis
  ➢ Scaled SK MC
  ➢ 10 years running with one 186 kt fv detector
  ➢ No improvement of Super-K systematics assumed
  ➢ True mass hierarchy not assumed to be known

$P(\nu_\mu \rightarrow \nu_e)$

$E_\nu$ [GeV]
Atmospheric neutrinos

Using only atmospheric neutrinos:
➢ Can hope to determine mass hierarchy at 3σ in the NH case
➢ Some sensitivity to $\theta_{23}$ octant, but lower than beam neutrinos
➢ Sensitivities depend on true $\theta_{23}$ value

Mass hierarchy determination

Octant determination

Error bands: uncertainty due to unknown $\delta$ value
Atmospheric + beam neutrinos
Mass hierarchy

Atmospheric neutrinos
➢ Sensitive to mass hierarchy through matter induced resonance
➢ Size of the effect depends of $\theta_{23}$
➢ Limited precision for $\theta_{23}$ and $|\Delta m_{32}^2|$ measurements

Beam neutrinos
➢ Very limited sensitivity to MH
➢ Good precision for $\theta_{23}$ and $|\Delta m_{32}^2|$ measurements

Combining the two:
✔ >3σ ability to reject wrong MH
✔ 5σ for larger values of $\sin^2(\theta_{23})$

<table>
<thead>
<tr>
<th>$\sin^2(\theta_{23})$</th>
<th>Atmospheric only</th>
<th>Atmospheric +beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>2.2 $\sigma$</td>
<td>3.8 $\sigma$</td>
</tr>
<tr>
<td>0.6</td>
<td>4.9 $\sigma$</td>
<td>6.2 $\sigma$</td>
</tr>
</tbody>
</table>
Atmospheric + beam neutrinos
Sensitivity to CP violation

- Sensitivity to CP violation mainly coming from beam neutrinos
- Atmospheric neutrinos allow to break possible degeneracies between MH and $\delta$ when MH is unknown

\[ \text{True } \delta=0 \]

\[ \text{True } \delta=90^\circ \]
Second detector
Staging approach

- Build first detector as soon as possible
- Second, identical detector coming later
- Assume here 2\textsuperscript{nd} detector comes online 6 years later

Mass hierarchy determination (beam + atmospheric)

\begin{align*}
\sin^2(\theta_{23}) &= 0.4 \\
\sin^2(\theta_{23}) &= 0.5 \\
\sin^2(\theta_{23}) &= 0.6
\end{align*}

Sensitivity to CP violation (beam only)

<table>
<thead>
<tr>
<th></th>
<th>Exclude CP conservation</th>
<th>Precision of $\delta$ measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$&gt; 3\sigma$</td>
<td>$&gt; 5\sigma$</td>
</tr>
<tr>
<td>$\delta=0$</td>
<td>$\delta=90^\circ$</td>
<td></td>
</tr>
<tr>
<td>1 tank</td>
<td>76%</td>
<td>57%</td>
</tr>
<tr>
<td>23°</td>
<td></td>
<td>7°</td>
</tr>
<tr>
<td>Staging</td>
<td>78%</td>
<td>62%</td>
</tr>
<tr>
<td>21°</td>
<td></td>
<td>7°</td>
</tr>
</tbody>
</table>
Exploring the idea of putting second detector in Korea

- 2 identical detectors with different baseline
- Longer baseline to Korea: study mass hierarchy with beam neutrinos
- Different L/E regions

Candidate sites at different OAA and L

<table>
<thead>
<tr>
<th>Site</th>
<th>Off-axis angle</th>
<th>Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mt. Bisul</td>
<td>1.3°</td>
<td>1088 km</td>
</tr>
<tr>
<td>Mt. Bohyun</td>
<td>2.2°</td>
<td>1040 km</td>
</tr>
</tbody>
</table>
Second detector in Korea
Expected number of events

<table>
<thead>
<tr>
<th>L=1100km</th>
<th>OAA=1.5°</th>
<th>δ=0</th>
<th>Signal</th>
<th>Background</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>ν-mode</td>
<td>νµ → νe</td>
<td>140.6</td>
<td>81.8</td>
<td>224.8</td>
<td></td>
</tr>
<tr>
<td>ν-bar mode</td>
<td>ν̅µ → ν̅e</td>
<td>2.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ν̅-mode</td>
<td>ν̅µ → ν̅e</td>
<td>159.1</td>
<td>95.5</td>
<td>278.5</td>
<td></td>
</tr>
</tbody>
</table>

OAA=2.5°, L=295 km, T2HK (Japan)

OAA=1.5°, L=1100 km, ~ Mt. Bisul (Korea)

sin^2(2θ_{13})=0.085, sin^2(θ_{23})=0.5, Δm^2_{32}=2.5×10^{-3} \text{ ev}^2/\text{c}^4, \text{ normal hierarchy}
Second detector in Korea
Mass hierarchy determination

- Longer baseline to Korea: sensitivity to mass hierarchy with beam neutrinos
- Can determine mass hierarchy at 5σ after 10 years
- Combining with atmospheric neutrinos increases sensitivity

Error bands: uncertainty due to unknown δ value
JD: Japanese Detector, KD: Korean detector, JDx2 does not assume staging
True normal mass hierarchy
Second detector in Korea
Sensitivity to CP violation

With only beam neutrinos:
- Solve degeneracy between $\delta$ and MH if MH is unknown
- Increased precision on $\delta$ measurement around $\pm \pi/2$

Ability to exclude CP conservation
Precision of $\delta$ measurement

True hierarchy: NH
Different analysis than beam only for one Japanese detector showed in previous slides
Octant of $\theta_{23}$

With 10 years of beam and atmospheric data:
- Can determine octant at $5\sigma$ if $\sin^2(\theta_{23}) < 0.46$ or $\sin^2(\theta_{23}) > 0.56$ with one detector
- Increased sensitivity with a second detector

Error bands: uncertainty due to unknown $\delta$ value
JD: Japanese Detector, KD: Korean detector, JDx2 does not assume staging
Future improvements

So far, sensitivities evaluated with tools from current experiments (T2K, SK) → a number of developments planned

**Updates form recent T2K analyses**
- New reconstruction algorithm and analysis at far detector
- Extended fiducial volume
- Additional appearance sample(s)
- Additional shape information for appearance samples

**Systematic uncertainties**
- Move to more detailed systematic model
- Reduction with updated near and intermediate detectors
- Improvement on far detector calibration
- Flux uncertainties using external data

**Updates from SK analysis**
- Use of neutron tagging
- Extension of fiducial volume
- Constraint on tau appearance background for electron samples

**Simulation**
- Move from scaled SK MC (SKDetsim) to real HK (WCSim) MC
- Effect of improved photosensors
Due to matter effects, expected rate of solar neutrinos is higher during night time.

Observing this asymmetry can allow to resolve tension between solar neutrino and KamLAND measurements of $\Delta m^2_{21}$.

- Reject no asymmetry (0.3% syst)
- Distinguish solar/KamLAND $\Delta m^2_{21}$:
  - with 0.3% systematics
  - with 0.1% systematics
Solar neutrino oscillations
Spectrum upturn

- Transition from matter-dominated energy region to vacuum-dominated one for $\nu_e$ survival probability creates an upturn in the spectrum
- Precise measurements of the spectrum allows to confirm MSW-LMA model and distinguish between standard oscillations and new physics
- Key parameter is the energy threshold (reduce radon background)

Upturn observation sensitivity

- 4.5 MeV energy threshold
- 3.5 MeV energy threshold

Super-K
Summary

- Hyper-Kamiokande will allow to study the three main open questions in neutrino oscillations: CP violation, mass hierarchy and octant of $\theta_{23}$.

- With one detector and 10 years of beam and atmospheric neutrino data:
  - Exclude CP conservation at $5\sigma$ ($3\sigma$) for 57% (76%) of possible true values of $\delta$
  - Measure $\delta$ with 7° (true $\delta=0$) to 23° (true $\delta=90°$) precision
  - Can determine mass hierarchy with $>3\sigma$ significance
  - Can determine octant at $5\sigma$ if $\sin^2(\theta_{23})<0.46$ or $\sin^2(\theta_{23})>0.56$

- Increased sensitivity with a second detector
  - In particular second detector in Korea would give access to mass hierarchy with beam neutrinos, and study oscillations at the second maximum
Additional slides
Neutrino oscillations

Flavor eigenstates (interaction)

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\times
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Mass eigenstates (propagation)

Mixing (or Pontecorvo-Maki-Nagawa-Sakata) matrix
link between the two sets of eigenstates

\[P(\nu_\alpha \to \nu_\beta) \text{ oscillates as a function of distance } L \text{ traveled by the neutrino with periodicity } \Delta m^2_{ij} L/E\]

\[(\Delta m^2_{ij} = m_i^2 - m_j^2)\]
Neutrino oscillations
Parameters

\[ U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix} \begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix} \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix} \]

(c_{ij} = \cos(\theta_{ij}), s_{ij} = \sin(\theta_{ij}))

P(\nu_\alpha \rightarrow \nu_\beta) depends on 6 parameters:

→ 3 mixing angles: \( \theta_{12}, \theta_{23}, \theta_{13} \)
→ 2 mass splittings: \( \Delta m^2_{ij} \)
→ 1 (complex) phase: The CP phase \( \delta \)

Amplitude
Periodicity
Difference in oscillations \( \nu/\bar{\nu} \)
(matter / anti-matter)
Man-made neutrino beam produced by an accelerator

Several advantages:
- Better knowledge and control of neutrino flux
- Can select neutrino energy range
- Can use near detectors to reduce uncertainties
- Know direction of neutrinos reaching far detector
- Can produce either neutrino or anti-neutrino beam
  (compare oscillations of neutrinos and anti-neutrinos)
New 50cmφ PMT for Hyper-K

Photo-detection efficiency (1p.e.)

- Twice better photo-detection efficiency than SK PMTs
- Timing resolution (TTS): 1.1 ns
  - cf. SK PMT: 2.1 ns
- Higher pressure tolerance: >80 m
Long baseline oscillations: T2HK
Systematic uncertainties used
Long baseline oscillations: T2HK
Systematic uncertainties used

Correlation between the systematic uncertainties in the different Erec bins: