Tokai to Hyper-Kamiokande

- Use upgraded J-PARC neutrino beam line (same as T2K) with expected beam power $\geq 750\text{kW}$, $2.5^\circ$ off-axis angle.

- Narrow-band beam at $\sim 600\text{MeV}$ at $2.5^\circ$ off-axis

- Take advantage of Lorentz Boost and 2-body kinematics in $\pi^+ \rightarrow \mu^+ \nu_\mu$

- Pure $\nu_\mu$ beam with $\sim 1\% \nu_e$ contamination
The Hyper-Kamiokande Project

Multi-purpose neutrino experiment.
Wide-variety of scientific goals:

- **Neutrino oscillations:**
  - Neutrino beam from J-PARC
  - Atmospheric neutrinos
  - Solar neutrinos

- **Search for proton decay**

- **Astrophysical neutrinos** (supernova bursts, supernova relic neutrinos, dark matter, solar flare, ...)

- **Neutrino geophysics**
Hyper-K in the World (http://www.hyperk.org)

- Selected one of the 27 ‘top projects’ in the ‘Japanese master plan for large scale research projects’ by the Science Council of Japan.
- Open meetings held twice/year since Aug.2012
- International Board of Representatives formed to discuss contributions, cost-sharing and budget request.
- R&D work ongoing internationally.

As of April 14, 2014

12 countries, 67 institutes, 240 people

<table>
<thead>
<tr>
<th>Europe</th>
<th>106</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>10</td>
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<tr>
<td>Italy</td>
<td>13</td>
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<tr>
<td>Poland</td>
<td>4</td>
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<td>Russia</td>
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<td>Spain</td>
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<td>Switzerland</td>
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<td><strong>UK</strong></td>
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<table>
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<tr>
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<tbody>
<tr>
<td>Japan</td>
<td>64</td>
</tr>
<tr>
<td>Korea</td>
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<table>
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<th>Americas</th>
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</tr>
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<tbody>
<tr>
<td>Brazil</td>
<td>2</td>
</tr>
<tr>
<td>Canada</td>
<td>19</td>
</tr>
<tr>
<td>USA</td>
<td>41</td>
</tr>
</tbody>
</table>
The Hyper-Kamiokande Timeline

- Approved WC prototype for technical studies (2013-2018) ~$1.2M
- Major decisions on experiment design expected before 2018.
The Hyper-Kamiokande Detector
The Hyper-Kamiokande Detector

- **Water Cherenkov**, proven technology & scalability:
  - Excellent PID at sub-GeV region >99%
  - Large mass → statistics always critical for any measurements.

<table>
<thead>
<tr>
<th>Volume Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Volume</td>
<td>0.99 Megaton</td>
</tr>
<tr>
<td>Inner Volume</td>
<td>0.74 Mton</td>
</tr>
<tr>
<td>Fiducial Volume</td>
<td>0.56 Mton (0.056 Mton × 10 compartments)</td>
</tr>
<tr>
<td>Outer Volume</td>
<td>0.2 Megaton</td>
</tr>
</tbody>
</table>

- **Photo-sensors**
  - 99,000 20”Φ PMTs for Inner Detector (ID) (20% photo-coverage)
  - 25,000 8”Φ PMTs for Outer Detector (OD)

- **Tanks**
  - 2 tanks, with egg-shape cross section ≈ 48m (w) × 50m (t) × 250 m (l)
  - 5 optically separated compartments per tank
The Hyper-Kamiokande Detector

- CCQE interaction
- NCπ° interaction
- CCQE interaction
HK is optimized for both appearance and disappearance searches

**νμ Disappearance:** determine $\theta_{23}$ and $\Delta m_{32}^2$

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{32} \sin^2 \left(\frac{\Delta m_{23}^2 L}{4 E_\nu}\right)$$

**νe Appearance:** determine $\theta_{13}$, constrain $\delta_{\text{CP}}$

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4 E_\nu}\right) - \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin \left(\frac{\Delta m_{21}^2 L}{4 E_\nu}\right) + \sin^2 \left(\frac{\Delta m_{31}^2 L}{4 E_\nu}\right) \sin^2 \left(\frac{\Delta m_{21}^2 L}{4 E_\nu}\right) \sin\delta_{\text{CP}} + CPC$$

- $+ \text{matter} + \text{solar terms}$

For maximum power fit both data samples **jointly**
Neutrino Beam for the Experiment

- Same beam configuration as for T2K
  - Same off-axis sub-GeV narrow-band beam.
  - Horn current 320kA
- At least 750kW expected at the starting of the experiment.
- Assumed $7.5\text{MW} \times 10^7 \text{s} \ (1.56 \times 10^{22} \text{POT})$ for the following sensitivity studies
  - 10 years are needed if 750kW per $10^7\text{s/year}$
  - Higher beam power is under study

Expected unoscillated neutrino flux at Hyper-K

Nominal beam sharing between neutrinos and anti-neutrinos in the following sensitivity plots:

- **$\nu$-mode:** $\bar{\nu}$-mode
- 1y : 3y
Expected Events

Large expected number of events. NH, $\sin^2 2\theta_{13} = 0.1$ and $\delta_{CP} = 0$. 

<table>
<thead>
<tr>
<th>Appearance</th>
<th>Signal</th>
<th>Background</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu \rightarrow \nu_e$</td>
<td>$\bar{\nu} \rightarrow \bar{\nu}_e$</td>
<td>$\nu_{\mu}$</td>
<td>$\bar{\nu}_{\mu}$</td>
</tr>
<tr>
<td>$\nu$ mode</td>
<td>3016</td>
<td>28</td>
<td>11</td>
</tr>
<tr>
<td>$\bar{\nu}$ mode</td>
<td>396</td>
<td>2110</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Disappearance</th>
<th>$\nu_{\mu}$</th>
<th>$\bar{\nu}_{\mu}$</th>
<th>$\nu_e$</th>
<th>$\bar{\nu}_e$</th>
<th>NC</th>
<th>$\nu_{\mu} \rightarrow \nu_e$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ mode</td>
<td>17225</td>
<td>1088</td>
<td>11</td>
<td>1</td>
<td>999</td>
<td>49</td>
<td>19372</td>
</tr>
<tr>
<td>$\bar{\nu}$ mode</td>
<td>10066</td>
<td>15597</td>
<td>7</td>
<td>7</td>
<td>1281</td>
<td>6</td>
<td>26964</td>
</tr>
</tbody>
</table>

Letter of Intent to J-PARC, April 2014
Hyper-K Sensitivity to $\delta_{CP}$

Letter of Intent to J-PARC, April 2014

Errors (%) on the expected number of events

<table>
<thead>
<tr>
<th></th>
<th>$\nu$ mode</th>
<th>$\bar{\nu}$ mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>3.0</td>
<td>2.8</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>5.6</td>
<td>4.2</td>
</tr>
<tr>
<td>Flux &amp; ND</td>
<td>3.0</td>
<td>2.8</td>
</tr>
<tr>
<td>ND-independ. xsect</td>
<td>1.2</td>
<td>1.5</td>
</tr>
<tr>
<td>Far Detector</td>
<td>0.7</td>
<td>1.0</td>
</tr>
<tr>
<td>Total</td>
<td>3.3</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Fractional region of $\delta(\%)$ for CPV ($\sin \delta \neq 0$) $> 3,5 \sigma$

$\delta$ coverage for nominal beam power: $\nu$ mode $\nu_\mu$

$\nu_e$ $\nu_\mu$

$\nu_e$ $\nu_\mu$

$\nu_e$ $\nu_\mu$

$\nu_e$ $\nu_\mu$

$\nu_e$ $\nu_\mu$

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$\nu_e$ $\nu_\mu$
**Sensitivity to $\theta_{23}$**

- $\sin^2 \theta_{23}$ and $\Delta m^2_{23}$ free parameters as well as $\sin^2 \theta_{13}$ and $\delta_{\text{CP}}$ in the fit.

- Octant resolution w/ reactor $\theta_{13}$: $\sim 3\sigma$ wrong octant rejection for $\sin^2 \theta_{23} < 0.46$ or $> 0.56$

<table>
<thead>
<tr>
<th>True $\sin^2 \theta_{23}$</th>
<th>1$\sigma$ err $\sin^2 \theta_{23}$</th>
<th>1$\sigma$ err $\Delta m^2_{23}$ (eV$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45</td>
<td>0.006</td>
<td>1.4</td>
</tr>
<tr>
<td>0.50</td>
<td>0.015</td>
<td>1.4</td>
</tr>
<tr>
<td>0.55</td>
<td>0.009</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Octant degeneracy resolved with a constraint from the reactor experiments.

True $\sin^2 \theta_{23} = 0.45$ 

True $\sin^2 \theta_{23} = 0.5$
Use **atmospherics** for **3σ** mass hierarchy determination.

- **3σ** mass hierarchy determination for \( \sin^2 \theta_{23} > 0.42 \) (0.43) for normal (inverted) hierarchy for 10y data taking.
- Also combine with beam data to enhance physics capability.
Proton Decay Sensitivity

- 10 times better sensitivity than Super-K
- Hyper-K surpasses SK limits in ~1 year
- Hyper-K is sensitive in every single mode
  - $p \rightarrow e^+\pi^0: 1.3 \times 10^{35}$ y at 90% CL
  - $p \rightarrow \bar{\nu}K^+: 2.5 \times 10^{34}$ y at 90% CL
  - Many other modes:
    - $p(n \rightarrow e,\mu) + (\pi,\rho,\omega,\eta); 10^{14}-10^{35}$
    - $K^0$ modes
    - $\nu\pi^0, \nu\pi^+$
    - ...

Surpass SK limit in ~1 year
'Other' Physics Topics at Hyper-K

More physics topics can be investigated by Hyper-Kamiokande:

Solar Neutrinos: 200 ν’s / day from Sun → day/night asymmetry of the solar neutrinos flux can be precisely measured at HK.

Astrophysical neutrinos:
- 200k ν’s from Supernova at Galactic center (10kpc) → time variation & energy can be measured with high statistics. Important data to cross check explosion models
- Supernova relic neutrinos → possible $G_d$-doping of Hyper-K

Indirect Searches for Dark Matter: 1) search for excess of neutrinos from the center of the Earth, Sun and galactic centre as compared to atmospheric neutrino background 2) Search for diffuse signal from Milky Way halo.

Search for transient astrophysical phenomena: solar flares, GRBs, etc.

Neutrino geophysics: neutrino radiography w/ atmospheric neutrinos for surveying the internal structure of the Earth.
Two sites are being investigated:

- **Tochibora mine:**
  - ~8km South from Super-K
  - Identical baseline (295km) and off-axis angle (2.5°) to Super-Kamiokande

- **Mozumi mine (same as Super-K):**
  - Deeper than Tochibora
  - Currently finishing design studies
Site(s) and Cavern(s), cont'd

- Rock quality in the two sites is similar.
- Design of the cavity, support structure studies based on geological survey
- Confirmed that the HK cavern can be constructed w/ existing techniques
- Construction schedule for the Tochibora mine: ~2y tunnels, ~3y cavern

Mozumi:
- geological survey performed in 2013
- cavern stability analyses just completed
- Access and approach-tunnels being designed
- ..
- Baseline design expected to finish soon
Tank Design Work

- All major parts of HK tank have been designed: water containment system, photosensors support, layout of water pipes, front-end electronics, cables, calibration holes, plug manholes, etc.

**Electronics & Cable Layout**

- Support structure
- Cable for inner PMT
- Cable for outer PMT
- Network/Power cable
- Hub / Front End Electronics
- Inner photo-sensor (20"")
- Outer photo-sensor (8"")

**Water Containment System**

- Inner top pipe
- Inner bottom pipe
- Outer top pipe
- Outer bottom pipe
- Inlet/Outlet
- Inner barrel pipe
- Outer barrel pipe

**Water Piping Layout**

- Inner top
- Inner barrel
- Inner bottom
- Outer top
- Outer barrel
- Inlet/Outlet

**Photo-sensor Support**

- Mounting Photo-sensor
- Housing

**Separation Wall**
Photodector Development

**PMT**
- Used in Super-K for 18 years
- High reliability

**Under viability test**
- Test in 200 ton tank

**Under development**
- Under evaluation in the air

Venetian blind PMT (50-cm φ Normal QE)

High QE photocathode

Venetian blind PMT (50-cm φ High QE)

PMT improvement

Box and Line PMT (50-cm φ High QE)

New photosensor (HPD)

HPD (New) (20-cm φ Normal QE)

High QE photocathode

Make larger

HPD (50-cm φ High QE)
**Photodector Development**

**PMT**
- Used in Super-K for 18 years
- High reliability

**Under viability test**
- Test in 200 ton tank

**High-QE SK PMT**

**Under development**
- Under evaluation in the air

**New photosensor (HPD)**
- Venetian blind PMT (50-cm φ Normal QE)
- Normal-QE R3600
- High-QE R3600
- Normal-SK PMT
- ZP0007
- ZP0012
- ZP0014
- ZP0015
- ZP0021
- ZP0022
- ZP0024
- ZP0025

**Venetian blind PMT** (50-cm φ High QE)

**PMT improvement**

**Box and Line PMT** (50-cm φ High QE)

**High QE photocathode**

**HPD**
- (New) (20-cm φ Normal QE)
- Make larger
- 50-cm φ High QE
Photosensors Candidates

R&D going to get better performance and lower costs

Established (SK PMT) → Under development (HighQE/CE PMT) → Under development (HighQE hybrid det.)

Quantum Eff. (QE)  
<table>
<thead>
<tr>
<th></th>
<th>22%</th>
<th>30%</th>
<th>30%</th>
</tr>
</thead>
</table>
Collection Eff. (CE)  
|   | 80% | 93% | 95% |
Timing resol (FWHM)  
|   | 5.5 nsec | 2.7 nsec | 1 nsec |

Super-K ID PMTs
- Used for ~20 years
- Guaranteed
- Complex production
- Expensive

Better performance
- Under development
- Same technology
- Lower risk

Far better performance
- Under development
- Simple structure
- Lower cost
- New technology
- Higher risk
Photosensors Tests in Water Tank

- EGADS (for $\text{G}_d$-doped water tests)
- 240 inward-facing PMTs
- EGADS used to test high-QE PMTs
- 227 PMTs (R3600; currently in SK) for reference for photodetector evaluation
- 8'' HPDs, 20'' high-QE PMTs
- Data taking: Sept 2013, May 2014
- Viability tests performed – ongoing process up to 2016.
- Adding (Aug 2014) Box-and-Line PMTs and 2 HPD.
- More tests planned.
- Photosensor choice will be made in 2016, needed to allow time for making mass production

Timeline for photosensors choice

- 20cm normal-QE HPD
- High-QE Super-K PMT
- 50cm high-QE box&line PMT
- 50cm high-QE HPD

- Prototype Performance evaluation production
- Test in the water tank
- Select the Hyper-K photodetector


8'' HPDs
20'' high-QE PMTs
Electronics/DAQ

- Investigating a few approaches for the electronics, eg:
  - QTC (ADC) + TDC (similar to SK4)
  - FADC
- Will evaluate their performance with the WC prototype detector
- Also working on the design of the DAQ

- Digitize all the signal (timing and charge) above ~ 1/4 p.e.
- Define events with software and store the event data.
- Nominal starting point: SK DAQ

Investigating improved system for triggering (redundant, robust)
Calibration

• Review systems used by several experiments (SK, SNO, SNO+, Borexino, KamLAND, Daya Bay) to help in the design of the calibration system for Hyper-K

• Several ongoing R&D activities, some examples:
  - Simple semi-automated calibration system (to be deployed in SK)
  - Computed controlled.
  - Compact and light-shielded.
  - R&D (3D) for HK in 2015-2016
  - Study response & reflection of large photosensors in water (Photosensor Testing Facility at TRIUMF)
  - Optical system with laser, monitor and receiver PMTs in place and tested.
  - Use LED as a light source for optical calibration.
  - Can build an automated system that can illuminate each PMT with known sources
  - Tests of LEDs underway

8” HPD in PTF
Calibration

- Review systems used by several experiments (SK, SNO, SNO+, Borexino, KamLAND, Daya Bay) to help in the design of the calibration system for Hyper-K
- Several ongoing R&D activities, some examples:
  - Simple semi-automated calibration system (to be deployed in SK)
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  - Use LED as a light source for optical calibration.
  - Can build an automated system that can illuminate each PMT with known sources
  - Tests of LEDs underway
New Near Detector Concepts to further enhance the Hyper-K physics potential

“ν-PRISM” (~1 km)
• tall (~50 m) WC detector spanning wide range of off-axis angles
• effectively isolate response in narrow band of energy by comparing interactions at different off-axis angles

“ΤΙΤΟΣ” (~2 km)
• 2 kt Gadolinium-doped WC detector with HPDs and LAPPDs

Several new upgrades planned at a 280m distance, either new detectors or upgrading ND280

See M. Scott talk (WG2 parallel session - Monday)

See M. Rayner poster (Tuesday)
Conclusions

Next generation multi-purpose experiment

➢ Oscillation physics:
  ● able to measure $\delta_{\text{CP}}$ at $3\sigma$ for 76% of its phase space
  ● solve octant degeneracy, mass hierarchy (atmospherics), $\theta_{32}$, $\Delta m^2_{32}$

➢ Astro and other physics:
  ● very sensitive to all the proton decay channels, observe supernovas burst and relic supernova neutrinos, indirect dark matter, transient astrophysical phenomena, etc.

Work ongoing worldwide in all the aspects of the experiment

Data taking around 2025 with current schedule
Stay tuned for many more exciting news from Hyper-Kamiokande!
Additional Slides
Muon Momentum in ND280

**Purity of each sample**

<table>
<thead>
<tr>
<th></th>
<th>CC0π</th>
<th>CC1π</th>
<th>CCother</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC0π</td>
<td>72.6%</td>
<td>6.4%</td>
<td>5.8%</td>
</tr>
<tr>
<td>CC1π</td>
<td>8.6%</td>
<td>49.4%</td>
<td>7.8%</td>
</tr>
<tr>
<td>CCother</td>
<td>11.4%</td>
<td>31%</td>
<td>73.8%</td>
</tr>
<tr>
<td>Bkg(NC+anti-nu)</td>
<td>2.3%</td>
<td>6.8%</td>
<td>8.7%</td>
</tr>
<tr>
<td>Out of FGD1 Fid Vol</td>
<td>5.1%</td>
<td>6.5%</td>
<td>3.9%</td>
</tr>
</tbody>
</table>
T2K Far Detector: Super-Kamiokande

- 50 kton (22.5 kton fiducial) water Cherenkov detector
- Good reconstruction for T2K energy range
- Particle Identification (PID) based on shape of Cherenkov rings

- Inner detector
  - 11,129 20" PMTs
- Outer detector
  - 1885 8" PMTs

Event displays show Monte Carlo

- $\mu^-$ (603 MeV)
  - low scattering - sharply defined ring
- $e^-$ (492 MeV)
  - multiple scattering - fuzzy ring
- $\pi^0$ decay (2$\gamma$)
  - 2 rings reconstructed
Relative uncertainty (%) on the expected number of events 
($\sin^2 2\theta_{13} = 0.1$, $\sin^2 \theta_{23} = 0.5$, $\Delta m^2_{32} = 2.4 \times 10^{-3} \text{eV}^2$, $\delta CP = 0$, $NH$)

<table>
<thead>
<tr>
<th>$\nu_e$</th>
<th>Systematic sources</th>
<th>$\nu_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Flux &amp; Combined Cross-Sections</td>
<td>2.7</td>
</tr>
<tr>
<td>4.7</td>
<td>Independent Cross Sections</td>
<td>5.0</td>
</tr>
<tr>
<td>2.4</td>
<td>$\pi$ Hadronic Interactions (FSI)</td>
<td>3.0</td>
</tr>
<tr>
<td>2.7</td>
<td>SK Detector Efficiencies</td>
<td>4.0</td>
</tr>
<tr>
<td>6.8</td>
<td>TOTAL</td>
<td>7.6</td>
</tr>
</tbody>
</table>
$\nu_\mu \rightarrow \nu_e$ Event Selection

**Event selection:**
- Fully contained in fid. volume
- Only one reconstructed ring
- Ring is electron-like
- Visible energy > 100 MeV
- No Michel Electrons
- Reconstructed energy < 1.25 GeV
- New SK reconstruction (~30% reduction in $\pi^0$ background)
- 28 events in $6.57 \times 10^{20}$ POT

![Graphs showing event distribution and reconstruction algorithm](https://via.placeholder.com/150)
T2K Observation of $\nu_e$ Appearance

- $\nu_e$ appearance in a $\nu_\mu$ beam with 7.3$\sigma$ significance
- Best fit value for $\sin^2 \theta_{13}$ larger than the reactor value
- Due to $\delta_{\text{CP}}$-$\sin^2 \theta_{13}$ correlation, when applying the reactor constraint, region with $\sin^2 \theta_{13}$ small as possible is favoured.

Maximum likelihood fit in $(p_e, \theta_e)$
$\nu_\mu \rightarrow \nu_\mu$ T2K Result

Best-fit oscillation parameter values:

<table>
<thead>
<tr>
<th>Oscillation parameter</th>
<th>NH</th>
<th>IH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$0.514^{+0.055}_{-0.056}$</td>
<td>$0.511 \pm 0.055$</td>
</tr>
<tr>
<td>$\Delta m^2_{32} \times 10^{-3}$ eV$^2$</td>
<td>$2.51 \pm 0.10$</td>
<td>$2.48 \pm 0.10$</td>
</tr>
</tbody>
</table>

Events: 120 (observed), 446.0 ± 22.5 (no oscillation)

Most precise measurement of $\sin^2 \theta_{23}$ and favours Maximal Mixing.
T2K Joint $\nu_\mu + \nu_e$ Analysis

- Likelihood ratio fit to both $\nu_\mu + \nu_e$ event samples
- Plot includes constraint from reactor experiments as given by the PDG2013 ($\sin^2 2\theta_{13} = 0.095 \pm 0.01$)
- Consistent results with a Bayesian analysis

$\sin^2 2\theta_{23}$, $\Delta m^2_{32}$ and $\sin^2 2\theta_{13}$ are marginalized following the 3D $\Delta \chi^2$ surface from Run1+2+3+4

T2K has a slight hint for $\delta_{CP} \sim -\pi/2$

Future: Neutrino & Anti-neutrino running

<table>
<thead>
<tr>
<th>$\delta_{CP}$ excluded regions</th>
<th>Preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best fit</td>
<td>90%CL ($\pi$)</td>
</tr>
<tr>
<td>NH</td>
<td>-0.495</td>
</tr>
<tr>
<td>IH</td>
<td>-0.495</td>
</tr>
</tbody>
</table>
T2K Future Sensitivity to $\delta_{\text{CP}}$

Sensitivity studies to resolve $\sin\delta_{\text{CP}} \neq 0$ with $7.8 \times 10^{21}$ POT. Best sensitivity expected for 50% $\nu$ and 50% anti-$\nu$ beam running. Projected reactor constraint $\sin^2 2\theta_{13} = 0.1 \pm 0.005$.

Using joint oscillation analysis with realistic 2012 systematic errors ($\sim 10\% \nu_e$, $\sim 13\% \nu_\mu$)

Using GloBES, with 50% $\nu$ and anti-$\nu$ running for NOvA too. Solid lines: no syst. error.
J-PARC $\nu$-Beamline

INGRID on-axis

ND280 off-axis
$\theta_{13} - \delta_{\text{CP}}$ allowed region (90%) 

7.5MW×$10^7$sec, $\nu$:anti-$\nu$=1:3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\sin^2 2\theta_{13}$</th>
<th>$\delta_{\text{CP}}$</th>
<th>$\sin^2 2\theta_{23}$</th>
<th>$\Delta m^2_{32}$</th>
<th>Mass hierarchy</th>
<th>$\sin^2 2\theta_{12}$</th>
<th>$\Delta m^2_{12}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>0.10</td>
<td>90, 0, -90</td>
<td>0.50</td>
<td>2.4$\times10^{-3}$</td>
<td>Nominal, Inverted</td>
<td>0.8704</td>
<td>7.6$\times10^{-5}$</td>
</tr>
<tr>
<td>Treatment</td>
<td>Fitted</td>
<td>Fixed</td>
<td>Fitted</td>
<td>Fitted</td>
<td>Known</td>
<td>Fixed</td>
<td>Fixed</td>
</tr>
</tbody>
</table>

Reactor error:
$\delta \sin^2 2\theta_{13} = 0.005$
Significance of $\delta_{CP} = 0$

CPV discovery sensitivity w/ mass hierarchy known: $\Delta \chi^2 = \chi^2_{\text{trial}} - \chi^2(\delta_{CP} = 0, 180)$

Fractional region of $\delta(\%)$ for which the CPV ($\sin \delta \neq 0$) significance is $> 3\sigma$

$1\sigma$ uncertainty of $\delta$ as a function of the beam power: $< 19^\circ (6^\circ)$ for $\delta = 90^\circ (0^\circ)$

CPV > $3\sigma$ ($5\sigma$) for 76%(58%) of $\delta$
• Without assumption of the prior mass hierarchy knowledge, but NH is true.
• True $\delta_{CP} = 0.0$; $\sin^2 2\theta_{13} = 0.10$; Maximal mixing $\sin^2 2\theta_{23} = 1.0$
• Degenerate solution exists at $3\sigma$ in the beam only case.
• The physics capability of the project can be enhanced by combining two complementary measurements.
1kton WC Prototype

Prototype (1kton, \(\sim 10\times10\times10 \text{ m}^3\)) for R&D test approved in Japan as Grant-in-Aid: \(\sim\) USD 1.2M/5 years (2013-18).

It's one of the 27 proposals selected each year from all areas in science.

Main feasibility studies:
- Photosensor and corresponding support structure
- Liners
- Leak water collection detection
- DAQ
- Electronics
- Calibration system
- ....
Overall Cost Estimate

<table>
<thead>
<tr>
<th>Total</th>
<th>800M USD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavern</td>
<td>300M USD</td>
</tr>
<tr>
<td>Tank &amp; structure</td>
<td>200M USD</td>
</tr>
<tr>
<td>Photo-sensors</td>
<td>200M USD</td>
</tr>
<tr>
<td>Near Detector</td>
<td>30M USD</td>
</tr>
</tbody>
</table>

Costs estimated based on the current design and including a new near detector.
Proportional sharing of costs between the interested Countries is expected.