Near Detectors for the Hyper-K Experiment

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Hyper-Kamiokande Experiment

- Water Cherenkov detector with **187 kton fiducial mass** (8x larger than Super-Kamiokande)
- Broad physics program including neutrino oscillations with accelerator neutrinos
- **1.3 MW beam** from J-PARC (2.5x higher than current T2K beam power)
- New near/intermediate detectors to control systematic uncertainties
Strong non-accelerator component of physics program:

- **Atmospheric neutrinos**
- **Nucleon decay**
- **Supernova relic neutrinos**
- **Solar neutrinos**
- **Supernova burst**
Current long baseline experiments observe 10s of neutrino and antineutrino candidates.

Hyper-K will observe ~2000 electron neutrino and electron antineutrino candidates each.

- 3% statistical error on the CP violation measurement will be achieved.
- Controlling systematic errors is critical: T2K’s current errors are ~6%.

\[ N = \Phi_{\text{flux}} \cdot \sigma_{\text{xsec}} \cdot \epsilon_{\text{eff}} \]

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Neutrino Beam Modeling Systematic Errors
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- Particle production modeling constrained by hadron production measurements
Neutrino Beam Modeling Systematic Errors

Diagram showing the interaction of protons, pions, muons, and neutrinos. The graph illustrates the distribution of outgoing neutrinos, $\Phi_{\nu^\mu}$, as a function of energy $E_\nu$ in GeV for different orientation angles OA 0.0°, OA 2.0°, and OA 2.5°.
Neutrino Beam Modeling Systematic Errors
Beam direction uncertainty = uncertainty in peak energy in off-axis beam
Neutrino Beam Modeling Systematic Errors
Wrong-sign (defocussed) component of the beam is important background when searching for CP violation.
Neutrino Interaction Modeling Systematic Errors

- Primary scattering process on a single bound nucleon
- Nucleon below threshold in water Cherenkov detector
- Energy inferred from charged lepton kinematics
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- Nuclear effects such as scattering involving multiple nucleons increase cross section and change energy inference
- Dominant source of systematic uncertainty
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- Lepton mass is also important
  - Muon neutrinos at near detectors, but electron neutrinos at far detector
  - $>3\%$ theoretical error on $[\sigma(\nu_\mu)/\sigma(\nu_e)] / [\sigma(\bar{\nu}_\mu)/\sigma(\bar{\nu}_e)]$

On-axis detector: measure beam direction, monitor event rate

Off-axis magnetized tracker: charge separation (measurement of wrong-sign background), study of recoil system

- Expect upgrades of detector inherited from T2K will be necessary

Off-axis spanning water Cherenkov detector: intrinsic backgrounds, electron (anti)neutrino cross-sections, neutrino energy vs. observables, H₂O target, neutron multiplicity measurement
INGRID Detector

- 14 modules in cross configuration on beam direction
- Iron and scintillator layers with 7 tons of target mass per module
- Monitor neutrino event rate to ensure stable beam operation
- Measure the beam direction with <0.25 mrad accuracy
  - Uncertainty on predicted peak energy of neutrino spectrum <2 MeV

On-axis Detector (INGRID)

NIMA, V694, (2012), 211-223
Upgraded ND280 Detector

- T2K is in the process of upgrading the magnetized ND280 detector
- Planned installation in 2021 and operation from 2022
- New Super-FGD and horizontal TPCs replace the P0D

TOF detector give better relative timing to improve direction measurement of particles

- A well understood detector from day one of Hyper-K operation
- Additional upgrades for Hyper-K for performance and longevity
- Upgrades informed by T2K measurement program
Upgraded ND280 Physics

- New TOF detectors allow to better distinguish direction of high angle muons
  - Necessary for wrong-sign measurement
- High-angle TPCs give full angular coverage for track reconstruction
- Super-FGD target improves reconstruction of the hadronic recoil system
  - Good timing and spatial resolution to detect neutron scatters and reconstruct energy by TOF
- Improved capability to probe nuclear effects and do calorimetric energy reconstruction
Intermediate Water Cherenkov Detector

- 1 kton scale water Cherenkov detector located ~750 m from the neutrino production point
- Position of detector can be moved vertically to make measurements at different off-axis angle to probe relationship of neutrino energy and final state lepton kinematics
- Can be loaded with Gd to measure neutron multiplicities in neutrino interactions
- Use multi-PMT photosensors with excellent spatial (80 mm) and timing (1.6 ns FWHM) resolution
Off-axis Angle Analysis Method

Spectra at each off-axis bin

Observed muon kinematic distributions

Subtract off low energy and high energy sidebands of flux → produce very narrow beam to measure energy response.

Measure non-quasi-elastic component with 5% uncertainty
Electron (anti)Neutrino Cross Section

✦ Use intrinsic electron (anti)neutrino flux from muon and kaon decays (<1% of beam)

✦ Water Cherenkov is ideal for the electron (anti)neutrino cross section measurement

✦ Large active volume allows for veto of background from externally produced high energy gammas

✦ Measurements at larger off-axis angle have high flux fraction

✦ Simulation studies show 3.5-7% precision

✦ Reduction of systematic errors under investigation
Water Cherenkov Test Experiment

- 1% level calibration is critical for IWCD
- Plan test experiment in tertiary beam to evaluate detector response and calibration procedure
  - Operation with $p, e, \pi^\pm, \mu^\pm$, momentum range from 140 MeV/c-1200 MeV/c
- Planning operation at CERN after long shutdown (proposal submission in January 2020)
  - Collaborators welcome
The rich Hyper-K physics program will include precision oscillation measurements and the most statistically powerful search for CP violation.

Controlling systematic uncertainties on modeling of neutrino flux and interactions is critical.

Hyper-K plans a suite of near/intermediate detectors:

- INGRID - beam direction measurement and beam monitoring
- Upgraded ND280 - charge selection for wrong-sign measurement and study of hadronic recoil system
- IWCD - Water target with measurements at varying off-axis angles and measurements of electron (anti)neutrino cross sections
Thank You
<table>
<thead>
<tr>
<th>Systematic Source</th>
<th>Required Precision</th>
<th>For Which Measurement</th>
<th>Detector</th>
<th>Achievable Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(\nu_e)/\sigma(\nu_\mu)$</td>
<td>3-5%</td>
<td>CP Violation,</td>
<td>IWCD</td>
<td>3.5-5%</td>
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<tr>
<td></td>
<td></td>
<td>$\delta_{cp}$ precision at $\sin(\delta_{cp}) \sim 0$,</td>
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<tr>
<td></td>
<td></td>
<td>$\theta_{23}$ precision at $\sin(\theta_{23}) \sim 0.5$</td>
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<td></td>
</tr>
<tr>
<td>$-\sigma(\nu_e)/\sigma(\nu_\mu)$</td>
<td>3-5%</td>
<td>CP Violation,</td>
<td>IWCD</td>
<td>4-7%</td>
</tr>
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<td>$\theta_{23}$ precision at $\sin(\theta_{23}) \sim 0.5$</td>
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<tr>
<td>Wrong-sign background normalization</td>
<td>9%</td>
<td>CP Violation,</td>
<td>ND280</td>
<td>TBD (expect &lt;9%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\delta_{cp}$ precision at $\sin(\delta_{cp}) \sim 0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intrinsic $\nu_{e},\nu_{e}$ and NC</td>
<td>3-4%</td>
<td>CP Violation,</td>
<td>IWCD</td>
<td>2.3% (neutrino)</td>
</tr>
<tr>
<td>backgrounds</td>
<td></td>
<td>$\delta_{cp}$ precision at $\sin(\delta_{cp}) \sim 0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normalization of non-QE with $E_\nu$&gt;0.7</td>
<td>5%</td>
<td>$\theta_{23}$ precision at $\sin(\theta_{23}) \neq 0.5$</td>
<td>IWCD</td>
<td>5% (neutrino)</td>
</tr>
<tr>
<td>GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normalization of non-QE with all energies</td>
<td>5%</td>
<td>$\delta_{cp}$ precision at $\sin(\delta_{cp}) \sim 0$</td>
<td>IWCD, ND280*</td>
<td>5% (IWCD neutrino)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\Delta m^2_{32}$ precision</td>
<td></td>
<td>&lt;4% (N280 neutrino)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt;7% (ND280 antineutrino)</td>
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</tbody>
</table>

*Complementary approaches in IWCD and ND280. IWCD relies on flux model in linear combination method, but minimizes cross section model dependence. ND280 fits transverse variables to constrain cross section model.
# Summary of Requirements and Performance

<table>
<thead>
<tr>
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<tr>
<td>Beam Direction</td>
<td>0.6 mrad (4 MeV shift)</td>
<td>$\delta_{cp}$ precision at $\sin(\delta_{cp}) \sim 0$ $\Delta m^2_{32}$ precision</td>
<td>INGRID</td>
<td>&lt;0.3 mrad (&lt;2 MeV)</td>
</tr>
<tr>
<td>Removal (binding) energy</td>
<td>4 MeV*</td>
<td>$\delta_{cp}$ precision at $\sin(\delta_{cp}) \sim 0$ $\Delta m^2_{32}$ precision</td>
<td>IWCD, ND280</td>
<td>2.6 MeV (IWCD on O) $\sim$ 1 MeV (ND280 on C)</td>
</tr>
<tr>
<td>High angle measurement (cos$\theta$$&lt;0.2$)</td>
<td>4%</td>
<td>CP Violation, $\delta_{cp}$ precision at $\sin(\delta_{cp}) \sim 0$</td>
<td>IWCD, ND280</td>
<td>&lt;4% statistical precision in both detectors</td>
</tr>
<tr>
<td>Beam rate monitoring</td>
<td>~1% per day</td>
<td>General monitoring of beam quality</td>
<td>INGRID</td>
<td>&lt;0.5% per day for neutrinos and antineutrinos</td>
</tr>
<tr>
<td>Neutron Multiplicity</td>
<td>TBD</td>
<td>Atmospheric neutrino Nucleon decay</td>
<td>IWCD, ND280</td>
<td>&lt;5% IWCD $&lt;4%$ ND280</td>
</tr>
<tr>
<td>$\mu\pi^0$ cross section &amp; neutron multiplicity</td>
<td>TBD</td>
<td>$e\tau^0$ proton decay</td>
<td>IWCD</td>
<td>TBD</td>
</tr>
</tbody>
</table>

*Energy scale in detectors must be calibrated to 0.5% to achieve this level*