Neutrino Oscillations at the T2K and Hyper-Kamiokande Experiments

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Neutrino Oscillation Experiments

Over hundreds of km baselines, study change of neutrino flavor through oscillations

Mass states propagate with relative phases

Produce neutrinos as weak states

Interact as weak eigenstates
Far detectors are general purpose experiments:
- Atmospheric neutrinos
- Supernova neutrinos
- Solar neutrinos
- Nucleon decay searches
- Dark matter searches
- ....
Neutrino Oscillation Parameters

PMNS mixing matrix in standard 3-neutrino mixing framework:

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

Accessible through neutrino oscillations

\[s_{12} = \sin \theta_{12}, \text{ etc.}\]

Three mixing angles \(\theta_{12}, \theta_{13}, \theta_{23}\)

Majorana phases if neutrinos are Majorana particles

\[\delta, \alpha_{21} \text{ and } \alpha_{31} \text{ may introduce new sources of CP violation}\]

The flavor content of states oscillate as they traverse matter or vacuum:

\[
P_{\alpha \to \beta} = \delta_{\alpha \beta} - 4 \sum_{i > j} \Re \left( U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \right) \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4E} \right) \\
+ 2 \sum_{i > j} \Im \left( U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \right) \sin \left( \frac{\Delta m_{ij}^2 L}{2E} \right)
\]

Dependence on mass squared differences of mass states, distance and energy
Neutrino Sources and Measurements

**Solar**
\[ \theta_{12} = 33.65^\circ \pm 0.80^\circ \]
\[ \Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2 \]

**Reactor**
\[ \theta_{13} = 8.49^\circ \pm 0.14^\circ \]
\[ \Delta m^2_{32} = (2.45 \pm 0.05) \times 10^{-3} \text{ eV}^2 \]
\[ \text{or} \]
\[ \Delta m^2_{32} = (-2.52 \pm 0.05) \times 10^{-3} \text{ eV}^2 \]

**Accelerator**
\[ \theta_{23} = 47.1^\circ \pm 1.6^\circ \]
\[ \delta_{cp} = ?? \]

**Atmospheric**

**New source of CP violation?**
Mass Hierarchy (Ordering)

- Sensitive to mass ordering through oscillation effect when neutrinos propagate through matter
- Important interplay with neutrinoless double beta decay experiments

Preferred at ~3σ significance in global fits

arXiv:1910.04688
Long Baseline Neutrinos at T2K

Super-Kamiokande (ICRR, Univ. Tokyo)

ND280 Near Detector

J-PARC Main Ring (KEK-JAERA, Tokai)

~500 members, 69 Institutes, 12 countries
T2K Overview

- J-PARC accelerator complex and neutrino beamline
- 30 GeV Main Ring
- 400 MeV LINAC

J-Parc

ν production

ν → ν

2.5°

On-axis: INGRID

Off-axis: ND280

280m

Near detectors

Super-Kamiokande

295 km

Far detector

- Characterise ν beam
- Constrain systematic uncertainties

Study ν oscillations

Off-axis beam

ν → ν

P(θ, δ) = 0

CP-δ

NH, δ = 0

IH, δ = π/2

P(θ, δ) = 1.0

CP-δ

NH, δ = 0

IH, δ = π/2

Δm^2 = 2.4 × 10^{-3} eV^2

ν_e, ν_x (A.U.)

sin^2 2θ_{13} = 0.1

sin^2 2θ_{13} = 1.0

2.4 × 10^{-3} eV^2

θ_{13} = 0.1

θ_{13} = 2.3

sin^2 2θ_{13} = 0

sin^2 2θ_{13} = π/2

sin^2 2θ_{13} = π/2
Neutrino Oscillations at T2K

- **Muon (anti)neutrino survival** depends on $\sin^2(2\theta_{23})$ and $\Delta m^2_{32}$
- **Electron (anti)neutrino appearance**
  - $\sin^2(\theta_{23})$, $\sin^2(2\theta_{13})$ and $\Delta m^2_{32}$ in leading term
  - Sub-leading dependence on $\delta_{cp}$
    - CP conservation at $\delta_{cp}=0,\pi$
    - Maximal CP violation at $\delta_{cp}=-\pi/2,\pi/2$
  - Matter effect $\rightarrow$ dependence on the mass hierarchy
    - Normal Hierarchy (NH): enhanced rate for neutrinos, decreased for antineutrinos
Neutrino Detection at Super-K

Electron neutrino appearance signal:

\[ \nu_e \rightarrow e^- \]

Detected electron produces a shower: “fuzzy” ring

Muon neutrino survival signal:

\[ \nu_\mu \rightarrow \mu^- \]

Detected muon produces a sharp ring

Likelihood-based reconstruction development led by TRIUMF
Using Near Detector Data

Neutrino-nucleus Interaction Model

ND280 Data

Neutrino Flux Model

Fit to ND280 data constrains neutrino flux parameters and interaction model parameters
Analysis shown today: $3.1 \times 10^{21}$ POT, 50%/50% neutrino/antineutrino
Data collected through 2018

Future analysis: 33% increase in neutrino mode statistics
Accelerator has achieved 515 kW stable operation in 2019
Fitted ND280 Data - Neutrino Mode

Before Fit

After Fit

Model-data agreement significantly improved by fit of model to data
What We Observe

Predictions for $\delta_{\text{CP}} = -\pi/2$

<table>
<thead>
<tr>
<th></th>
<th>$1\text{e0de }\nu\text{-mode}$</th>
<th>$1\text{e0de }\bar{\nu}\text{-mode}$</th>
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<tbody>
<tr>
<td>$\nu_\mu \rightarrow \nu_e$</td>
<td>59.0</td>
<td>3.0</td>
<td>5.4</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$</td>
<td>0.4</td>
<td>7.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Background</td>
<td>13.8</td>
<td>6.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Total predicted</td>
<td>73.2</td>
<td>16.9</td>
<td>6.9</td>
</tr>
<tr>
<td>Systematic uncertainty</td>
<td>8.8%</td>
<td>7.1%</td>
<td>18.4%</td>
</tr>
<tr>
<td>Data</td>
<td>75</td>
<td>15</td>
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- Results largely consistent with $\delta_{\text{CP}} = -\pi/2$ hypothesis
- Observe 15 events in the single decay electron sample when 7 predicted
- Probability of fluctuation this large or larger in any of 5 samples is 7%
What We Observe

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- Observe 15 events in the single decay electron sample when 7 predicted
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T2K Results $\delta_{cp}$

- Include constraint on $\theta_{13}$ from reactor experiments

$\sin^2(\theta_{23})$

$\sin^2(\theta_{13})$

1$\sigma$ interval

$3\sigma$ range for $\delta_{cp}$

NH: $[-3.41, -0.03]$

IH: $[-2.54, -0.32]$

- CP conserving value $\delta_{cp} = -\pi$ is still included in $3\sigma$ interval

- Both CP conserving values ($\delta_{cp} = 0, -\pi$) are disfavored at $2\sigma$

- Normal mass hierarchy preferred with posterior probability of 0.89
• T2K measures $\sin^2\theta_{23}=0.53\pm0.03-0.04$

• Remains consistent with 45° at the 1 sigma level
T2K Results - Atmospheric Parameters

T2K measures $\sin^2 \theta_{23} = 0.53 \pm 0.03$. Remains consistent with 45º at the 1 sigma level.

$\sin^2 \theta_{23}$:

<table>
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<tr>
<td>0.3</td>
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$2\sigma$ limits for $m_{32}^2$ (eV$^2$):

- Normal - 68CL
- Inverted - 68CL
- Normal - 90CL
- Inverted - 90CL

Best fit: T2K Run 1-9 Preliminary

• Hyper-K Canada group formed in 2018
  • Supported by NSERC project grant
  • Currently 11 faculty from 8 institutes - looking to grow
  • Hyper-K is now an IPP project
Hyper-K Canada

Hyper-K Canada Collaboration

• Hyper-K Canada group formed in 2018
  • Supported by NSERC project grant
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Hyper-Kamiokande

- Fiducial mass is **8x larger than Super-Kamiokande**
- Neutrino beam from J-PARC will be **2.5 times more intense** (1.3 MW proton beam)
- New **photon detectors and near detectors**
- **20x the rate** of long baseline neutrinos than the T2K experiment
- Not just accelerator-based neutrino experiment:
  - Proton decay searches
  - Supernova neutrino detection
  - Atmospheric neutrino detection
  - Solar neutrino detection
  - Dark matter search
  - ...

Hyper-K approved in January 2020
Construction phase has started!
Start of operation planned in 2027

Access tunnel construction to start in FY2021
Access tunnel entrance

Construction of the entrance yard is proceeding!
Proton Decay

Discovery Potential

- Hyper-K excels in the \( p \rightarrow e^+\pi^0 \) channel, very high efficiency
- Largest fiducial mass

- Hyper-K is competitive \( p \rightarrow \nu K^+ \) channel, very high efficiency
- DUNE has potential for better efficiency since kaon is visible
- Inverse beta decay and neutrino-electron scattering channels
- 54k-90k events for 10 kpc distant supernova
- ~10 neutrino events for supernova in Andromeda
- Neutrino-electron scattering introduces pointing capability
- 1.0-1.3 degree accuracy for 10 kpc distant supernova
Recall that T2K and NOvA are observing 10’s of candidate events.

Hyper-K will observe $\sim2000$ electron neutrino and electron antineutrino candidates each.

- 3% statistical error on the CP violation measurement is achieved.
- Controlling systematic errors is critical: T2K’s current errors are $\sim6\%$. 

arXiv:1805.04163
Oscillation Measurements

Known Mass Hierarchy

- CP violation discovery for:
  - 76% of values at 3σ
  - 57% of values at 5σ

- With atmospheric neutrino data, achieve >4σ rejection of the wrong mass hierarchy
Systematic Error Reduction with IWCD

- Intermediate detector for Hyper-K
- Located about 1 km from neutrino source
- 600 ton water Cherenkov detector
- Position can be moved to different off-axis angles
- Loading with Gd to enhance neutron detection
- Using new high resolution multi-PMT modules inspired by KM3NeT
- Project led by Canadian institutes

Approved Hyper-K project includes IWCD
Stage-1 approval at J-PARC as E61

Multi-PMT (mPMT) Photosensor

- 19 3-inch diameter PMTs integrated in module with high voltage and readout electronics
- 3-inch PMTs developed with Hamamatsu to achieve 1.7 ns FWHM timing resolution
- Improved spatial and timing resolution compared to 20-inch PMTs is necessary for detector of IWCD size
- Considered as a photodetector for Hyper-K detector as well
Machine Learning

• Improve reconstruction of indiscernible event topologies:
  • e/γ separation possible with improved granularity of mPMT in IWCD
  • Multi-ring: directionality of high-energy atmospheric ν, nucleon decay
  • Neutron tagging
  • First application of ResNet (type of CNN) looks promising
• Investigating several architectures:
  • Graph CNN, PointNet, GAN, UNET
Photogrammetry Calibration

- Fiducial volume of IWCD must be known with a bias of <1 cm
- The position of all mPMTs and calibration sources must be precisely measured
- Positions can change after water filling, so need in-situ measurement

**Photogrammetry:**

- Fixed cameras and remote operated submersible take pictures of the tank interior
- Software able to build an accurate 3-D model of the detector
Water Cherenkov Test Experiment

• Aim for unprecedented precision to reconstruct high energy events in a water Cherenkov detector of IWCD size

• Need platform to test the hardware and validate the calibration, modeling and reconstruction techniques

• Operate detector with 4 m diameter in test beam line with incident particle fluxes of known type and moment

Location: CERN East Area
Proposal: CERN-SPSC-2020-005
Planned operation in 2022
EMPHATIC Experiment

- Table top hadron production experiment - improve neutrino flux simulation
- Unique application of technologies to hadron production measurements
  - Silicon strip tracking layers
  - Halbach array permanent magnet
  - Aerogel ring imaging Cherenkov detector for PID
- Operating in Fermilab MTEST beam line
  - 2018 - Pilot Run
  - 2020 - First Physics run with 100 mrad acceptance
  - 2021 - Second physics run with 400 mrad acceptance
Conclusions

• T2K is providing world leading measurements of neutrino oscillations parameters

• Next phase: move to precisions measurements at Hyper-Kamiokande
  • Program includes neutrino oscillations, proton decay, supernova neutrinos, dark matter and more
  • Construction has started and planned start of operation in 2027

• Many Canadian efforts for Hyper-K focussed on control of systematic errors for precision measurements
  • Still room for new collaborators. Come join us!
Thank You
Mass Ordering Preference

- One of our analyses uses Markov Chain Monte Carlo to fit oscillation parameters
- Perform Bayesian statistical inference
  - Posterior probabilities and credible intervals
- Start with equal prior probability of normal and inverted hierarchy
- Normal hierarchy is preferred with posterior probability of 0.89
### T2K Systematic Errors

<table>
<thead>
<tr>
<th>Systematic Error Source</th>
<th>Uncertainty on $\nu_e/\bar{\nu}_e$ Candidates (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super-K Detector Model</td>
<td>1.47</td>
</tr>
<tr>
<td>Pion Reinteractions</td>
<td>1.58</td>
</tr>
<tr>
<td>Near Detector Constrained Parameters</td>
<td>2.31</td>
</tr>
<tr>
<td><strong>Nuclear Binding Energy</strong></td>
<td><strong>3.74</strong></td>
</tr>
<tr>
<td>$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$</td>
<td>3.03</td>
</tr>
<tr>
<td>NC1$\gamma$ Production</td>
<td>1.49</td>
</tr>
<tr>
<td>Other NC Interactions</td>
<td>0.18</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5.87</strong></td>
</tr>
</tbody>
</table>

- Uncertainty on the relative rate of electron neutrino and electron antineutrino interactions
  - This is a purely theoretical estimate, no measurement
- Uncertainty on how nuclear effects impact inference of the neutrino energy