NEUTRINO OSCILLATION RESULTS FROM THE T2K EXPERIMENT
THE TOKAI-TO-KAMIOKA EXPERIMENT

• First observation of electron-neutrino appearance in a muon-neutrino beam in 2013

• World-leading precision on $\theta_{23}$, $\Delta m_{32}^2$ and most stringent constraint on leptonic CP violation.

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta_{CP}} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[
(L/E)^{-1}_{T2K} \approx \Delta m_{atm}^2
\]
NEUTRINO OSCILLATIONS AT T2K

\( \nu_\mu \) Disappearance

- Sensitivity to \( |\Delta m^2_{32}| \) and \( \theta_{23} \).
- Is \( \theta_{23} = 45^\circ \)? If not, what octant?
  - Maximal mixing might indicate underlying symmetry.
- Test CPT invariance: \( P(\nu_\mu \to \nu_\mu) \neq P(\bar{\nu}_\mu \to \bar{\nu}_\mu) \)?

\( \nu_e \) Appearance

- Sensitivity to \( \theta_{13}, \delta_{CP}, \theta_{23} \) octant and mass hierarchy through matter effect.
- If \( \delta_{CP} \) not 0 or \( \pi \), CP symmetry is violated in lepton sector.
- \( P(\nu_\mu \to \nu_e) \) enhanced if hierarchy is normal or \( \delta_{CP} \sim -\pi/2 \)
- \( P(\bar{\nu}_\mu \to \bar{\nu}_e) \) enhanced if hierarchy is inverted or \( \delta_{CP} \sim \pi/2 \)
- With the T2K flux, matter effect (\( \propto E \)) is smaller than \( \delta_{CP} \).
  - Complementarity with NOvA, which has similar \( L/E \) but larger \( L \) and \( E \).
Protons are extracted from the J-PARC 30 GeV Main Ring onto a graphite target via the superconducting primary beamline.

$\pi^\pm$ focused by three magnetic horns and allowed to decay into $\mu^\pm$ and $\nu_\mu (\bar{\nu}_\mu)$

- Horn polarity determines charge of the focused $\pi^\pm$ and helicity of neutrinos in the Earth frame.

Muon detectors downstream of beam dump monitor beamline stability.
T2K $\nu_\mu (\bar{\nu}_\mu)$ FLUX

- Very low $\nu_e (\bar{\nu}_e)$ contamination. Less than 1% near oscillation maximum.
  - Irreducible background to $\nu_e (\bar{\nu}_e)$ appearance.
- Wrong sign contamination more significant in antineutrino mode.
FAR DETECTOR $\nu_\mu (\bar{\nu}_\mu)$ FLUX UNCERTAINTIES

- Flux uncertainties dominated by hadron interaction in the target.
  - Constrained by external measurements at NA61/SHINE.
    - See Y. Nagai’s presentation Thursday afternoon.
    - Prior to T2K near detector constraint, absolute flux uncertainties are $\sim 10\%$.
  - Significant cancellation in near-to-far oscillation analysis extrapolation.
INGRID: on axis

- Plastic scintillator and iron neutrino detectors arranged in a grid perpendicular to beam axis.
- Beam stability monitoring with direction and rate measurements.

ND280: 2.5° off-axis

- Detectors in 0.2 T field generated by repurposed UA1/NOMAD magnet.
  - Identify $\mu^-/\mu^+$ from $\nu/\bar{\nu}$ interactions.
- Dedicated $\pi^0$ detector.
- Tracker composed of two plastic scintillator fine-grained detectors (FGDs) and three time projection chambers (TPCs).
- Plastic and water targets.
SUPER-KAMIOKANDE

- 50 kiloton water-Cherenkov detector.
- Optically separated outer detector for tagging entering/escaping particles.
- ~11000 20” photomultiplier tubes (PMTs) facing the inner detector giving a photocathode coverage of 40%.
- ~2000 8” PMTs in the outer detector.
- Measure momentum and direction of particles above Cherenkov threshold.
  - Excellent $\mu^\pm/e^\pm$ separation.
  - No charge selection.
SUPER-KAMIOKANDE SAMPLES

- Hadronic system typically below Cherenkov threshold.
- Signal samples use single-ring events.
- Infer neutrino energy from lepton $p$ and $\theta_{beam}$.

C. Vilela CIPANP 2018
SUPER-KAMIOKANDE SAMPLES

- New sample since summer 2016.
- $\pi^+$ below Cherenkov threshold.
  - Infer from $\mu^+$ decay electron.
- Only neutrino mode $e$-like.
Five samples at Super-K, targeting:
- Charged-current quasi-elastic interactions.
- Charged-current resonant $\pi$ production.

Backgrounds are neutral current $\pi$ production.
- $\pi^0 \rightarrow \gamma\gamma$ misidentified as $e$
- $\pi^+ \rightarrow \mu^+$ misidentified as $\mu$
SUPER-K EVENT RECONSTRUCTION

- New event reconstruction algorithm for Super-K.
- Previously used only for neutral current $\pi^0$ background rejection.
- Maximum-likelihood estimation using all the information in an event, including unhit PMTs.
- Likelihood ratios used to compare event hypotheses.
- Improved particle identification, ring-counting, momentum, vertex and direction resolutions.
- New $\mu / \pi^+$ separation.
- Optimize fiducial volume and neutral current rejection criteria for new event reconstruction.
  - Neutral current rejection criteria chosen for optimal sensitivity to oscillation parameters by running simplified oscillation analysis.
FIDUCIAL VOLUME OPTIMIZATION

• In previous T2K results vertices were required to be $> 2$ m away from the nearest wall.

• For new event selection, fiducial volume defined as a function of:
  • wall: reduces background due to particles entering the detector;
  • towall: ensures adequate number of PMTs sample the ring, improving reconstruction quality.

• Both wall and towall are optimized in a fit to Super-K atmospheric neutrino data, taking into account statistical gains and systematic uncertainties.
FIDUCIAL VOLUME OPTIMIZATION

• Optimize figure of merit that enhances events that change significantly under oscillations:

\[ FOM = \frac{(\partial N/\partial \theta)^2}{N + \sigma_{\text{syst}}^2}, \text{ with } \theta = \delta_{CP}, \theta_{23} \]

• Cut points are optimized for each of the five analysis samples separately.
IMPROVEMENTS FROM NEW SELECTION

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<th>Candidates</th>
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<tbody>
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<td>$\nu$ $\mu$-like, $\leq 1$ decay-e</td>
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<td>79.7%</td>
<td>268.7</td>
<td>68.1%</td>
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<td>$\nu$ e-like, 0 decay-e</td>
<td>69.5</td>
<td>81.2%</td>
<td>56.5</td>
<td>81.4%</td>
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<td>6.9</td>
<td>78.8%</td>
<td>5.6</td>
<td>72.0%</td>
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<tr>
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- $\mu$-like samples: improved **purity** by reducing neutral current background.
**IMPROVEMENTS FROM NEW SELECTION**

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- $\mu$-like samples: improved **purity** by reducing neutral current background.
- $e$-like, 0 decay-e samples: increase **efficiency** by $>20\%$ while keeping previous selection’s purity.
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- $\mu$-like samples: improved **purity** by reducing neutral current background.
- $e$-like, 0 decay-e samples: increase **efficiency** by $>20\%$ while keeping previous selection’s purity.
- $e$-like, 1 decay-e sample: improvement in **purity** from better particle identification and increased **efficiency** from fiducial volume expansion.
DATA TAKING

• Stable accelerator operation with 470 kW beam power.
  • Neutrino-mode data doubled in one year of data taking!

• Up to December 2017 a total of \( 2.65 \times 10^{21} \) protons on target (POT) have been collected.
  • Doubled antineutrino-mode data, in total: 60% in neutrino-mode and 40% in anti-neutrino mode.
  • Keep an eye out for results at Neutrino 2018!

Data included in results presented today:
\[ 2.25 \times 10^{21} \text{ POT } \left( \frac{2}{3} \nu\text{-mode}, \frac{1}{3} \bar{\nu}\text{-mode} \right) \]
OSCILLATION ANALYSIS STRATEGY

NA61/SHINE hadron production measurements

INGRID/Beam monitor DATA

External cross-section measurements

Flux model

Near detector model

Cross-section model

Far detector model

Near Detector Fit

Far Detector Fit

Combined Oscillation Fit

ND280 DATA

Super-K DATA

Oscillation parameters

ND + FD Bayesian analysis

ND → FD Frequentist analysis
NEAR DETECTOR FIT

- Fourteen near detector samples are used to constrain flux and cross-section model.
  - For $\nu$-mode: charged current with: 0 $\pi$; 1$\pi^+$; or other particles.
  - Single-track and multi-track charged current with $\mu^+$ or $\mu^-$ for $\bar{\nu}$-mode.
  - Seven samples for each FGD.
After fit to near detector samples, flux and cross-section uncertainties at far detector reduced from ~15% to ~5%.

Good fit to the data.

p-value: 0.47
FAR DETECTOR DATA

$\nu_\mu$ Disappearance

$\nu_-mode\mu-like$

$\nu_-mode\mu-like$

$\nu_-mode\mu-like$

$\nu_-mode\mu-like$

$\nu_e$ Appearance

$\nu_-mode\mu-like$

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% Errors on predicted event rate at Super-K

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<td>$\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}<em>e)/\sigma(\bar{\nu}</em>\mu)$</td>
<td>0.00</td>
<td>0.00</td>
<td>2.64</td>
<td>1.45</td>
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<td>3.04</td>
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<td>NC1$\gamma$</td>
<td>0.00</td>
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<td>2.42</td>
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<tr>
<td>Total Systematic Error</td>
<td>5.07</td>
<td>4.32</td>
<td>8.81</td>
<td>7.02</td>
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- Largest uncertainties are the Super-K detector modelling and $\pi$ interaction modelling, both for the $e$-like events with one decay electron.
### Systematic Uncertainties

#### % Errors on predicted event rate at Super-K

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- No precise measurement of $\nu_e(\bar{\nu}_e)$ interactions in the near detector.
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<td>0.33</td>
<td>0.98</td>
<td>0.18</td>
</tr>
<tr>
<td>Binding energy</td>
<td>2.42</td>
<td>1.73</td>
<td>7.27</td>
<td>3.70</td>
<td>2.99</td>
<td>3.71</td>
</tr>
<tr>
<td>Total Systematic Error</td>
<td>5.07</td>
<td>4.32</td>
<td>8.81</td>
<td>7.02</td>
<td>18.41</td>
<td>5.87</td>
</tr>
</tbody>
</table>

- No near detector constraint on neutral current modes.
- Uncertainty based on modelling and external data.
## SYSTEMATIC UNCERTAINTIES

<table>
<thead>
<tr>
<th>Error Source</th>
<th>$\nu$-mode</th>
<th>$\bar{\nu}$-mode</th>
<th>$\nu$-mode</th>
<th>$\bar{\nu}$-mode</th>
<th>$\nu$-mode 1 dcy-$e$</th>
<th>$\nu/\bar{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK Detector</td>
<td>2.41</td>
<td>2.02</td>
<td>2.85</td>
<td>2.83</td>
<td>13.26</td>
<td>1.47</td>
</tr>
<tr>
<td>SK final state and secondary interactions</td>
<td>2.21</td>
<td>1.99</td>
<td>3.03</td>
<td>2.34</td>
<td>11.51</td>
<td>1.57</td>
</tr>
<tr>
<td>ND280-constrained flux and cross section</td>
<td>3.25</td>
<td>2.74</td>
<td>3.24</td>
<td>2.90</td>
<td>4.08</td>
<td>2.50</td>
</tr>
<tr>
<td>$\sigma(\nu_e)/\sigma(\nu_\mu), \sigma(\bar{\nu}<em>e)/\sigma(\bar{\nu}</em>\mu)$</td>
<td>0.00</td>
<td>0.00</td>
<td>2.64</td>
<td>1.45</td>
<td>2.63</td>
<td>3.04</td>
</tr>
<tr>
<td>NC1$\gamma$</td>
<td>0.00</td>
<td>0.00</td>
<td>1.08</td>
<td>2.60</td>
<td>0.33</td>
<td>1.50</td>
</tr>
<tr>
<td>NC Other</td>
<td>0.25</td>
<td>0.25</td>
<td>0.15</td>
<td>0.33</td>
<td>0.98</td>
<td>0.18</td>
</tr>
<tr>
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<td>5.87</td>
</tr>
</tbody>
</table>

- Binding energy range based on A. Bodek (arXiv:1801.07975), motivated by electron scattering data.
- Size of effect estimated by running oscillation analyses on simulated data.
• Fit under normal and inverted hierarchy assumptions separately.
• Apply constraint on $\theta_{13}$ from reactor experiments.
• T2K data consistent with maximal mixing.
• Closed contours at 90% CL in $\delta_{CP}$ for fit without external $\theta_{13}$ constraints.

• T2K best fit consistent with PDG 2016.
  • T2K: $\sin^2 \theta_{13} = 0.0279^{+0.0064}_{-0.0048}$ (NH)
  • PDG 2016: $\sin^2 \theta_{13} = 0.0210 \pm 0.0011$
• Best-fit point: -1.83 radian in Normal Hierarchy
• CP conserving values are outside of the 2σ CL intervals.

<table>
<thead>
<tr>
<th></th>
<th>NH</th>
<th>IH</th>
</tr>
</thead>
<tbody>
<tr>
<td>90% CL</td>
<td>[-2.82, -0.85]</td>
<td>∅</td>
</tr>
<tr>
<td>2σ CL</td>
<td>[-2.99, -0.59]</td>
<td>[-1.81, -1.01]</td>
</tr>
</tbody>
</table>
$\theta_{23}$ OCTANT AND MASS HIERARCHY

- Look at posterior probability from Bayesian analysis to infer T2K data preference for $\theta_{23}$ octant and mass hierarchy.
- Equal prior probability given to all hypotheses.

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>$\sin^2\theta_{23} &lt; 0.5$</th>
<th>$\sin^2\theta_{23} &gt; 0.5$</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH ($\Delta m_{32} &gt; 0$)</td>
<td>0.191</td>
<td>0.681</td>
<td>0.872</td>
</tr>
<tr>
<td>IH ($\Delta m_{32} &lt; 0$)</td>
<td>0.024</td>
<td>0.104</td>
<td>0.128</td>
</tr>
<tr>
<td>Sum</td>
<td>0.216</td>
<td>0.784</td>
<td></td>
</tr>
</tbody>
</table>

- Data shows weak preference for *normal* hierarchy and upper octant.
PLANS FOR AN EXTENDED T2K RUN

- 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). arxiv:1609:04111
- Sensitivity to exclude CP conserving values of $\delta_{CP}$ at $3\sigma$ within reach if $\delta_{CP}$ is near current best fit.
- Analysis improvements foreseen to increase sensitivity by 50% compared to 2016 results.
  - 30% already achieved!
- Systematic uncertainties will play significant role in measurement – expect improvement.

![Graph showing sensitivity to exclude CP](image-url)
SUMMARY

• Since summer 2016:
  • Doubled neutrino-mode protons-on-target with steady beam operation at 470 kW.
  • New reconstruction algorithm and event selection improved Super-K samples statistics by > 20%.

• With new data and analysis improvements, CP conserving values of $\delta_{CP}$ are disfavoured at 2$\sigma$.

• Proposal to run T2K until ~2026, accumulating 20x10$^{21}$ POT.
  • Potential to exclude CP conservation in lepton sector at 3$\sigma$ if $\delta_{CP}$ near maximal.

• Expect results with new 2017 antineutrino-mode data soon!
NEUTRAL CURRENT REJECTION

• Optimize selection criterium to reject neutral current $\pi^+$ events in $\nu_\mu (\bar{\nu}_\mu)$ samples.
  • Large uncertainty on cross section degrades precision on disappearance measurements.

• Run simplified oscillation analysis framework, including systematic uncertainties.

• Choose cut point in $\log \left( \frac{L_{\pi^+}}{L_\mu} \right)$ vs $p_\mu$ that maximizes precision on $\sin^2 \theta_{23}$ measurement.
  • Optimal cut point is different for equivalent study with statistical uncertainty only.

• Same procedure for neutral current $\pi^0$ rejection cut optimization for appearance samples.
SIMULATED DATA STUDIES FOR $E_B$

• Generate 2D templates of $\mu$ momentum shifts in $E_\nu$ vs $\theta_\mu$.
  • For each $\nu$ species and for carbon and oxygen targets.
    • Carbon: $25^{+18}_{-9}$ MeV
    • Oxygen: $27^{+18}_{-9}$ MeV
  • Shifts are applied to 1p1h events.

• Produce simulated data sets using $E_B$ templates and run oscillation analysis fit.

• Setting both C and O $E_B$ to the maximum value considered gives:
  • At the near detector: slight decrease in CCQE cross-section parameters; increased 2p2h contribution.
  • At far detector: significant bias in $\Delta m_{32}^2$ estimation; small impact on $\theta_{13}, \delta_{CP}$.

• Setting $E_B$ to maximum for $\nu$ and minimum for $\bar{\nu}$ gives similar results.
\( \delta_{CP} \) SENSITIVITY

- Data constraint on \( \delta_{CP} \) is stronger than the average sensitivity.
- Run toy experiments with normal hierarchy and \( \delta_{CP} = -\pi/2 \).
- Data constraint falls within range for 95.54% of experiments for most \( \delta_{CP} \) points.
- 30% of experiments exclude \( \delta_{CP} = 0 \) at 2\( \sigma \).
- 25% of experiments exclude \( \delta_{CP} = \pi \) at 2\( \sigma \).