T2K: Tokai (JPARC) to Kamioka (SuperKamiokande)

Long baseline (295 km) neutrino oscillation experiment with off-axis technique:

Far Detector:

huge water cherenkov detector (50 kTon) with optimal $\mu/e$ identification to distinguish $\nu_e, \nu_\mu$

Near Detectors:

On-axis:

iron/CH scintillator monitoring of beam angle and position

Off-axis:

full tracking and particle reconstruction in near detectors (magnetized TPC!)

$\nu_\mu$ clear ring

$\nu_e$ fuzzy ring

1% mis-id
T2K beam

- Production of **muon neutrino beam:**

- Flux prediction tuned from pion and kaon production measurements at **NA61 experiment** at CERN

- **Off-axis** → narrow flux at the maximum of the neutrino oscillation

- **Neutrino and antineutrino mode** changing the horn current (→ focusing hadrons of opposite charge)
T2K oscillation analysis

- $\nu$-mode: $7.48 \times 10^{20}$ POT
- $\bar{\nu}$-mode: $7.47 \times 10^{20}$ POT

Large disappearance signal and clear oscillation shape (beyond counting experiment)

Clear signal in antineutrino as well!

7.5 sigma observation of $\nu_e$ appearance

Growing statistics of $\bar{\nu}_e$ appearance: (~20% of final design statistics)
First 90% limits on $\delta_{CP}$!!

Full joint fit of all data ($\nu_\mu \rightarrow \nu_\mu/e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu/e$) with all proper statistical and systematic uncertainty included and exploiting also shape information:

\begin{align*}
\text{Feldman-Cousins confidence interval:} \\
\delta_{CP} &= [-3.13, -0.39] \; \text{NH} \\
&\quad \quad [-2.09, -0.74] \; \text{IH} \; \text{(NH slightly favoured)}
\end{align*}

Not Gaussian behaviour $\rightarrow$ need to through toys to evaluate correct confidence interval

Feldman-Cousins confidence interval:

\begin{align*}
\delta_{CP} &= [-3.13, -0.39] \; \text{NH} \\
&\quad \quad [-2.09, -0.74] \; \text{IH} \; \text{(NH slightly favoured)}
\end{align*}
Growing statistics

- Big improvement in $\delta_{CP}$ limits from data in antineutrino mode

2015 $\nu$ only: $T2K$  $\text{T2K+ }\theta_{13}$ from reactors

2016 $\nu+\bar{\nu}$: $T2K$  $\text{T2K+}\theta_{13}$ from reactors

- Statistics growing faster and faster: improvements in beam power

new results in summer 2017: $\nu$ POT doubled since last summer
The other oscillation parameters ($\theta_{23}$, $|\Delta m^2_{32}|$):
mostly from $\nu_{\mu}$ and $\bar{\nu}_{\mu}$ disappearance

- $\sin^2\theta_{23}$ enhance/suppress both $\nu_{\mu}$ and $\bar{\nu}_{\mu}$ disappearance
- $|\Delta m^2_{32}|$ regulate the position of the oscillation maximum as a function of the energy

T2K data show maximal disappearance $\rightarrow$ prefer maximal mixing: $\theta_{23} = \pi/4$ ($\sin^2\theta_{23} = 0.5$)

NOVA data excludes maximal mixing at 2.5$\sigma$
Prospects for future

NOVA – T2K combination with final dataset (~2021):

sensitivity CPV \((\text{True NH})\)

\[
\Delta \chi^2 \text{ vs. True } \delta_{CP}^{(\circ)}
\]

sensitivity MH \((\text{True NH})\)

\[
\Delta \chi^2 \text{ vs. True } \delta_{CP}^{(\circ)}
\]
Mass Hierarchy

- NOVA can reach $3\sigma$ on MH for favorable $\delta_{\text{CP}}$ values
- Various other projects on-going aiming to $3\sigma$ on MH: JUNO, ORCA, PINGU
- Matter effects is a relatively small effect at T2K: ~10% versus the dominant effect of $\delta_{\text{CP}}$ (30%) → small sensitivity to MH
CP sensitivity at T2K

- At T2K very clean $\delta_{\text{CP}}$ measurement:
  - small $\delta_{\text{CP}}$-MH degeneracy
  - very large far detector (SuperKamiokande → Hyperkamiokande) with narrow beam → mostly a counting experiment $\nu_e$ vs $\nu_e$

at the end of T2K ($7.8 \times 10^{21}$ POT in 2021) we will still be limited by statistics and not by systematics

- 5σ $\delta_{\text{CP}}$ measurement at DUNE/HK after 2030 → a lot of room for interesting results before that and need to keep physics output and analysis know-how before DUNE/HK start taking data

<table>
<thead>
<tr>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2K</td>
<td></td>
<td>T2K-2!!</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HK/DUNE building and commissioning</td>
<td></td>
<td>HK/DUNE physics</td>
</tr>
</tbody>
</table>
Request for new run of T2K beyond design statistics ($7.8 \times 10^{21}$ POT by) → $20 \times 10^{21}$ POT by 2026:

JPARC Main Ring upgrade approved: beam power up to 1.3MW in view of HyperKamiokande

today: 32 $\nu_e$ event, 4 $\bar{\nu}_e$ events
T2K-2: 400 $\nu_e$ events, 100 $\bar{\nu}_e$ events

→ good chances to observe CP violation at $>3\sigma$ by 2026 for a sizeable fraction of $\delta_{CP}$ values
Systematics and near detector

- In T2K-2 the **systematics starts to be a limiting factor for sensitivity**
  
  Even more important for definitive $\delta_{CP}$ measurement at next generation of long baseline experiments: HyperKamiokande, DUNE

- **Crucial role of near detector:** example from $\nu_e$ appearance at T2K

<table>
<thead>
<tr>
<th>Systematics $\delta N_e/N_e$</th>
<th>w/o ND280 constraint</th>
<th>w/ ND280 constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux</td>
<td>8.94%</td>
<td>3.64%</td>
</tr>
<tr>
<td>Cross Section</td>
<td>7.17%</td>
<td>4.13%</td>
</tr>
<tr>
<td>Flux + Cross Section</td>
<td>11.5%</td>
<td>2.88%</td>
</tr>
<tr>
<td>Final State/Secondary interaction Super-K</td>
<td>2.50%</td>
<td>2.50%</td>
</tr>
<tr>
<td>Super-K detector</td>
<td>2.39%</td>
<td>2.39%</td>
</tr>
<tr>
<td>Total</td>
<td>11.9%</td>
<td>5.41%</td>
</tr>
</tbody>
</table>
Neutrino-nucleus interaction

- Xsec measured with limited precision on free nucleons in old bubble chamber experiments. In modern experiment ν interacts with target detectors of carbon, water or argon → large nuclear effects not well known.

Cross section of main T2K signal:

Charged Current Quasi-Elastic

higher order corrections in nuclear target

Model developed by Martini et al. (CEA, SPhN)

- CCQE
- CCQE + multi-nucleon interactions

\[0.70 < \text{true } \cos \theta_\mu < 0.80\]

\[0.700 \leq \text{True-µ } \cos \theta_\mu < 0.800\]

ν interactions on carbon

ν interactions on water
T2K-II will require a 2% precision on the expected number of events at SK (~5% today) to match the 400 $\nu_e$ appearance events

→ We are currently studying an upgrade of the near detector ND280 to improve the constraints on the systematics

→ better understanding of neutrino-nucleus interactions crucial also for next-generation of experiments (DUNE/HK)
Physics drivers

- Keep the very good $e/\mu$ separation
- Improving the angular acceptance over the full polar angle and
- Lower threshold for low momentum particles (muons, protons, pions)
Possible configuration

- Add new target+TPCs with 'horizontal' geometry
- Add Time Of Flight detectors to identify track direction
- Surrounded by same ECAL and magnet as ND280
New TPCs

- New horizontal TPCs to enlarge high angle acceptance

- Development of resistive bulk Micromegas for the TPC read-out (CEA) → improve spatial resolution and/or decrease the number of channels

- Front and back-end TPC electronics (CEA and LPNHE)
R&D for TPC

- **Resistive foil** with sputtered Diamond-like carbon as used for ILC TPC R&D and ATLAS New Small Wheels

![Resistivity vs N₂ content](chart)

- Light **field cage** to minimize the background due to interactions on passive material (similar to Aleph/ILC field cage)

![Field cage diagram]
Possible design for new target

**WAGASCI (LLR):** new grid-like geometry allowing for low threshold or to be filled with water for same target as far detector

First prototype already installed at T2K on-axis and taking data

sand-muons rate

\[ \chi^2 / \text{ndf} = 23.97 / 29 \]

Total POT: 1.050e+20
Further R&D

- More sophisticated target under study: **fully 3D scintillator**

- Different **ToF technologies**, eg:
  - scintillator+fibers
  - light reader on the plastic (joint R&D with SHIP)

Timing resolution ~100ps
ND280 upgrade: status

- **3 workshops with large participation** (2 at CERN and 1 in Japan)
  Linked with work on High Pressure TPC to measure neutrino cross-section and as possible DUNE near detector

- **Expression of Interest well received by CERN** (SPSC-EOI-015)
  signed by ~190 physicists from Bulgaria, Canada, France, Italy, Japan, Germany, Poland, Spain, Sweden, Switzerland, UK, USA, CERN

  → full proposal in Fall

- **Important role of French T2K groups (CEA, LLR, LPNHE)**
  New collaborators welcome!!!
Summary

- First 90% CL exclusion of CP conservation: hint for maximal $\nu$-$\bar{\nu}$ asymmetry
  
  T2K $\delta_{CP}$ measurement will be until the end (2021) limited by statistics

- Request for **T2K-2**: 2.5 larger statistics by 2026
  
  $\rightarrow$ 3$\sigma$ evidence for CP violation possible
  
  - JPARC Main Ring upgrade
  - Upgrade of the near detector to minimize the systematics

- Precise measurements of $\nu$-nucleus xsec (and better theoretical nuclear modeling) thanks to T2K-2 will be also crucial for the success of DUNE and HyperKamiokande
BACKUP slides
NOVA $\delta_{CP}$

NOVA has taken $6.05 \times 10^{20}$ POT in $\nu$ mode (no $\bar{\nu}$ data yet):

\[ \nu_{\mu} \rightarrow \nu_e \text{ events} \]

NOVA in agreement with T2K: favours maximal CPV and slightly favour NH

First combination of all data (T2K, NOVA, SK, ...)

CP conservation excluded at 2$\sigma$

Lisi et al.
NEUTRINO 2016
Expected events as a function of $\delta_{CP}$ and MH:

- $\nu_e$ events
- $\bar{\nu}_e$ events

- $\delta_{CP} = -\pi/2$ (maximal CPV)
- $\delta_{CP} = 0$ (CP conserved)
- $\delta_{CP} = \pm\pi$ (CP conserved)

Normal Hierarchy (NH)

Inverted Hierarchy (IH)
$\delta_{CP}$ and MH mainly from $\nu_\mu \rightarrow \nu_e / \bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Expected events as a function of $\delta_{CP}$ and MH:

- $\nu_e$ events
  - Normal Hierarchy (NH)
  - Inverted Hierarchy (IH)

Results favour maximal CP violation (and slightly favour NH)
Non standard scenarios

- **CPT violation** in T2K by comparing disappearance $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_\mu$

- **Sterile neutrinos**: combination of MINOS, DayaBay and Bugey

- Limits on non-standard neutrino interactions from MINOS+

$4|U_{\mu 4}|^2|U_{e 4}|^2 = \sin^2 \theta_{24} \sin^2 (2\theta_{14}) \equiv \sin^2 (2\theta_{\mu e})$

→ important to constrain to avoid degeneracies and biases with future precise $\delta_{CP}$ measurement!

S.Bolognesi – Apero Sept 2016 – slide 16
NOVA – T2K comparison: nue appearance

- Observe 33 events passing $\nu_e$ selection
- On 8.2 background
NOVA – T2K comparison: $\nu_\mu$ disappearance

T2K: agreement between $\nu$ and $\bar{\nu}$ data

No clear suspect → T2K-NOVA difference is maybe just a statistical fluctuation?

<table>
<thead>
<tr>
<th></th>
<th>NOVA $\nu$</th>
<th>T2K $\nu$</th>
<th>T2K $\bar{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected w/o oscillations</td>
<td>$473 \pm 30$</td>
<td>$522 \pm 26$</td>
<td>$185 \pm 10$</td>
</tr>
<tr>
<td>Best fit</td>
<td>82</td>
<td>136</td>
<td>64</td>
</tr>
<tr>
<td>Observed</td>
<td>78</td>
<td>135</td>
<td>66</td>
</tr>
</tbody>
</table>
# T2K systematics uncertainties (joint oscillation analysis)

Fractional error on the number of expected events at SK with and without ND280

<table>
<thead>
<tr>
<th></th>
<th>$\nu_\mu$ sample 1R$_\mu$ FHC</th>
<th>$\nu_e$ sample 1R$_e$ FHC</th>
<th>$\bar{\nu}<em>\mu$ sample 1R$</em>\mu$ RHC</th>
<th>$\bar{\nu}_e$ sample 1R$_e$ RHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ flux w/o ND280</td>
<td>7.6%</td>
<td>8.9%</td>
<td>7.1%</td>
<td>8.0%</td>
</tr>
<tr>
<td>$\nu$ flux with ND280</td>
<td>3.6%</td>
<td>3.6%</td>
<td>3.8%</td>
<td>3.8%</td>
</tr>
<tr>
<td>$\nu$ cross-section w/o ND280</td>
<td>7.7%</td>
<td>7.2%</td>
<td>9.3%</td>
<td>10.1%</td>
</tr>
<tr>
<td>$\nu$ cross-section with ND280</td>
<td>4.1%</td>
<td>5.1%</td>
<td>4.2%</td>
<td>5.5%</td>
</tr>
<tr>
<td>$\nu$ flux+cross-section</td>
<td>2.9%</td>
<td>4.2%</td>
<td>3.4%</td>
<td>4.6%</td>
</tr>
<tr>
<td>Final or secondary hadron int.</td>
<td>1.5%</td>
<td>2.5%</td>
<td>2.1%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Super-K detector</td>
<td>3.9%</td>
<td>2.4%</td>
<td>3.3%</td>
<td>3.1%</td>
</tr>
<tr>
<td>Total w/o ND280</td>
<td>12.0%</td>
<td>11.9%</td>
<td>12.5%</td>
<td>13.7%</td>
</tr>
<tr>
<td>Total with ND280</td>
<td>5.0%</td>
<td>5.4%</td>
<td>5.2%</td>
<td>6.2%</td>
</tr>
</tbody>
</table>
## T2K systematics uncertainties (joint oscillation analysis)

<table>
<thead>
<tr>
<th>Source</th>
<th>$\nu_\mu$ sample 1$R_\mu$ FHC</th>
<th>$\nu_e$ sample 1$R_e$ FHC</th>
<th>$\bar{\nu}<em>\mu$ sample 1$R</em>\mu$ RHC</th>
<th>$\bar{\nu}_e$ sample 1$R_e$ RHC</th>
<th>1$R_e$ FHC/RHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ flux+cross-section constrained by ND280</td>
<td>2.8%</td>
<td>2.9%</td>
<td>3.3%</td>
<td>3.2%</td>
<td>2.2%</td>
</tr>
<tr>
<td>$\nu_e/\nu_\mu$ and $\bar{\nu}<em>e/\bar{\nu}</em>\mu$ cross-sections</td>
<td>0.0%</td>
<td>2.7%</td>
<td>0.0%</td>
<td>1.5%</td>
<td>3.1%</td>
</tr>
<tr>
<td>NC $\gamma$</td>
<td>0.0%</td>
<td>1.4%</td>
<td>0.0%</td>
<td>3.0%</td>
<td>1.5%</td>
</tr>
<tr>
<td>NC other</td>
<td>0.8%</td>
<td>0.2%</td>
<td>0.8%</td>
<td>0.3%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Final or secondary hadron int.</td>
<td>1.5%</td>
<td>2.5%</td>
<td>2.1%</td>
<td>2.5%</td>
<td>3.6%</td>
</tr>
<tr>
<td>Super-K detector</td>
<td>3.9%</td>
<td>2.4%</td>
<td>3.3%</td>
<td>3.1%</td>
<td>1.6%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5.0%</strong></td>
<td><strong>5.4%</strong></td>
<td><strong>5.2%</strong></td>
<td><strong>6.2%</strong></td>
<td><strong>5.8%</strong></td>
</tr>
</tbody>
</table>

*Fractional error on the number of expected events at SK*
How does it work?

**SUPERKAMIOKANDE**

- **Signal:** (anti)$\nu_\mu \rightarrow$ (anti)$\nu_e$ oscillation

- **Backgrounds:**
  - Outer volume with outward facing PMT to veto external background
  - **PMT timing** to select beam bunches and reconstruct vertex position in fiducial volume
  - Lepton momentum and angle $\rightarrow$ neutrino energy
  - Select events with no outgoing pions (1 ring)
    (Quasi-Elastic interactions) $\nu n \rightarrow l^- p$ (outgoing nucleon undetected)
  - $\nu$ interactions from beam:
    - intrinsic $\nu_e$ component in the beam
    - pions: $\pi^\pm$ not detected and $\pi^0 \rightarrow \gamma \gamma \rightarrow$ e-like ring + $\gamma$ undetected
    - $\bar{\nu}$ oscillations: intrinsic $\bar{\nu}$ component in the beam

No magnetic field $\rightarrow$ no charge measurement ($\nu/\bar{\nu}$)

**R&D: Gd doping** to tag neutrons to distinguish: $\nu n \rightarrow l^- p$ from $\nu p \rightarrow l^+ n$

**HYPERKAMIOKANDE:** Working to improve PMTs and on Gd doping.
Electronics and calibration system very similar to SuperK
From SuperK to HyperK

<table>
<thead>
<tr>
<th></th>
<th>Total volume</th>
<th>Fiducial volume</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tanks</strong></td>
<td>50 kTon</td>
<td>990 kTon</td>
</tr>
<tr>
<td>1 cylindrical</td>
<td>22.5 kTon</td>
<td>560 kTon</td>
</tr>
<tr>
<td>41.4m (h) x 39.3m (d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 egg-shape tanks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>48m (w) x 50m (h) x 250m (l)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| PMTs                  | 11.129       | 50.000          |
| inner detector        |              |                 |
| outer detector        | 1885         | 25.000          |

| Photocoverage         | 40%          | 20%             |
|                       |              |                 |

| Sensor efficiency     | 18% (22x80%) | 29% (30x95%)   |
| (Collection x Quantum eff.) |        |                 |

Tanks and PMT design under discussion:

- minimize risk due to pressure on PMTs (avoid cascade implosion as in SK 2001 incident)
- minimize cost (volume vs #PMTs)
- need PMT R&D (next slide)
R&D on PMTs

- **Response to single photoelectron:**
  
  - **Charge resolution**
  - **Time resolution**

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

- Optimization should include **pressure resistance**
  
  - Possible to put protective cover
  
  - Need precise control of glass quality

- Integrated system of inner and outer PMTs under study (solve problems of pressure and in-water electronics)

- **3' PMTs for inner detector**
- **Large PMT for outer detector veto**
Gadolinium doping

- $\bar{\nu}_p \rightarrow l^+ n \rightarrow n$ get captured in Gd with emission of few $\gamma \sim 8\text{MeV}$
  - for beam neutrino physics: $\nu$ vs $\bar{\nu}$ separation,
    but also useful to enhance sensitivity to SuperNova $\nu$ and proton decay
- R&D studies (eg, WATCHMAN) as reactor monitoring
- **EGADS**: 200 ton scale model of SuperK fully operative in Kamioka mine

Neutron capture time tested with $\text{Am}/\text{Be}$ source: data-MC perfect agreement

All the trick is about keeping water pure and transparent without losing Gd (dedicated filtration system)

- SuperKamiokande will run with loaded Gd in next years!
Liquid Argon technology

Ionizing particle in LAr $\rightarrow$ 2 measurements:
- **charge from ionization** $\rightarrow$ tracking and calorimetry
- **scintillation light** $\rightarrow$ trigger and $t_0$ (drift time $\rightarrow$ third coordinate for non-beam events)

DUNE: staged approach with 4 modules of $\sim$10kTon fiducial mass each

- $\mu$ track momentum from range (or from multiple scattering if not contained)
- PID from $dE/dx$
- Very good electron/$\gamma$ ID and $\pi^0$ reconstruction
- Calorimetric energy from total collected charge (+ light)

4 x (60m x 12m x 12m)
Many other challenges

- **scintillation light:** single phase: first test of *wavelength shifting bars to SiPM* integrated with a TPC
  - double phase: *standard PMTs* (with coating),
- **high voltage on large surfaces:** cathode-anode $\Delta V \sim$ few hundreds V (double phase)
  - $\sim$180 V (single phase)
- **large number of channels**
  - electronics in gas accessible only in double phase design
  - calibration and uniformity
    - (eg: flattening of cathode and of charge readout plane, $E$ field between different modules of charge readout ...)
- **software for automatic reconstruction**
  - huge amount of info (efficient zero suppression)
- **LAr TPC as calorimeter**
  - fully omogeneous with very low threshold
  - very good resolution and detailed tracking
  - inside shower $\rightarrow$ potential to improve shower models!

**ICARUS:**
- Low energy electrons:
  - $\sigma(E)/E = 11%/\sqrt{E\text{ (MeV)}} + 2$
- Electromagnetic showers:
  - $\sigma(E)/E = 3%/\sqrt{E\text{ (GeV)}}$
- Hadron shower (pure LAr):
  - $\sigma(E)/E \approx 30%/\sqrt{E\text{ (GeV)}}$
Water Cherenkov vs Liquid Argon

- Hyperkamiokande much more sensitive to CP violation while DUNE much more sensitive to Mass Herarchy (see backup). But sensitivities depend on assumed beam power, detector mass and on baseline.

- Comparison of technologies:

  **WATER CHERENKOV**
  - well known and solid technology
  - very large mass (~MTon)
  - info only about particles above Cherenkov threshold
    → model dependent assumptions to reconstruct $E_\nu$
    → no need of precise $E_\nu$ shape: mainly a counting experiment

  **LIQUID ARGON**
  - successfull R&D → first very large scale realization
  - size limited by drift length (~40KTon)
  - full reconstruction of tracks and showers down to very low threshold, very good particle ID
    → precise $E_\nu$ shape accessible and needed for good sensitivity
    → need to reach very good control on detector calibration/uniformity and on neutrino interaction modelling
Sensitivities

HK 3 years (1MTon): CPV measured at 3s (5s) for 75% (60%) of dCP values

DUNE 10 years (40 kTon): CPV measured at 3s (5s) for >50% (~25%) of dCP values

DUNE 10 years: definitive determination of MH

HK 10 years: wrong MH excluded at 3s

CP violation sensitivity

Mass hierarchy sensitivity
Moving to larger energies ...
Moving to larger energies ...
Moving to larger energies ...

Need to control well all different xsec, each process has very different detector acceptance.