Recent Results and Prospects

T2K Collaboration (2018)

~500 members, 67 Institutes, 12 countries

Japan
ICRR Kamioka
ICRR RCON
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Educ.
Okayama U.
Osaka City U.
Tokyo Institute Tech.
Tokyo Metropolitan U.
U. Tokyo
Tokyo U of Science
Yokohama National U.

Poland
HII-PAN, Cracow
NCBJ, Warsaw
U. Silesia,
Kadowice
U. Warsaw
Warsaw U. T.
Wroclaw U.

Switzerland
ETH Zurich
U. Bern
U. Geneva

United Kingdom
Imperial C.
London
Lancaster U.
Oxford U.
Queen Mary U. L.
Royal Holloway
U. L.
STFC/Daresbury
STFC/RAL
U. Glasgow
U. Liverpool
U. Sheffield
U. Warwick

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana State U.
Michigan S.U.
SLAC
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

Vietnam
IFIRSE
IOP, VAST

Alain Blondel

Koichiro Nishikawa (1949-2018)
Idea of T2K was born 1999-2001 hep-ex/0106019 combining:

-- existing SuperKamiokande detector (50kton W.Č., 22.5 kton fiducial) excellent mu/e separation esp. in the sub-GeV region.

-- JAERI-KEK Japanese Proton Accelerator Research Complex (JPARC) at TOKAI including a high power, 0.75MW/30GeV Proton Synchrotron neutrino beam from pion decay $\pi^+ \rightarrow \mu^+ \nu_\mu$

-- baseline 295 km $\rightarrow$ neutrino energy for first maximum is ~650 MeV achievable by pion-decay beam at 2.5 degrees off-axis
-- designed for $\nu_\mu \rightarrow \nu_e$ appearance search (discovered in 2011-13); now main aim is CPV

-- Off axis beam $\rightarrow$ narrow spectrum peak energy given by off axis angle

-- Hadron production spectrum measured at CERN (SHINE/NA61)
  -- thin target (used, 10% on flux)
  -- replica target (will be used, 5%)

Alain Blondel  T2K latest results and prospects
Knowledge of off-axis angle provides beam energy scale with % level precision.
The Off-Axis Near Detector monitors event rates (vs flavour, kinematics, topology)

- *not* functionally identical to FD
- but covers full muon momentum
- and extracts details of interactions
- mostly forward muons

Fine grain detector of light material
-- one FGD has 50% water layers
-- Scintillators with MPPC readout
  (60’000 channels!)
-- TPC tracker in 0.2T magnetic field

UA1/NOMAD magnet donated by CERN
A few ND280 neutrino interaction candidates

- quasi-elastic candidate
- single pion candidate
- DIS candidate
Recent T2K publications

1) Search for heavy neutrinos with the T2K near detector ND280 arXiv:1902.07598 [hep-ex].

2) Search for light sterile neutrinos with the T2K far detector Super-Kamiokande at a baseline of 295 km arXiv:1902.06529 [hep-ex].


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Super Kamiokande Neutrino Detection

- Use Cherenkov light to reconstruct the particle energy, direction, etc.
- Can distinguish between muons (produced by $\nu_\mu$) and electrons (produced by $\nu_e$) at T2K beam energies for CC interactions:

  **Muon Neutrino Detected**
  
  ![Muon Neutrino Detected]

  **Electron Neutrino Detected**
  
  ![Electron Neutrino Detected]
neutrino oscillations in T2K: beam energy peaks at oscillation max.
sin $\delta$ term is CP violating

$\cos \delta$ term is not.

sensitivity to $\delta$ (precision on $\delta$ measurement) is driven by $\sin \delta$ term if $\delta$ is close to 0 or $\pi$ $\rightarrow$ rate asymmetry $\nu_e$ vs $\bar{\nu}_e$

$\cos \delta$ term if $\delta$ is close to $\pm \pi/2$ $\rightarrow$ E shift, common to $\nu_e$ and $\bar{\nu}_e$

different systematics!
Beam delivery has been steadily improving to 500kW beam power. Run started in 2009, interrupted by Giant Earthquake (2011) and rad incident (2013). Recent run mostly in anti-neutrino (50% more statistics wrt neutrino 2018 results)
Collider-style plot

T2K Yearly POT

- Last year (2017-2018) was our best year for datataking so far!
Latest T2K far detector data set

SK Data

Predictions with: $\sin^2\theta_{13}=0.0212$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.51\times10^{-3}$, NH

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\delta_{CP}=\pi/2$</th>
<th>$\delta_{CP}=0$</th>
<th>$\delta_{CP}=\pi/2$</th>
<th>$\delta_{CP}=\pi$</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>FHC 1$\mu_\mu$</td>
<td>272.4</td>
<td>272.0</td>
<td>272.4</td>
<td>272.8</td>
<td>243</td>
</tr>
<tr>
<td>RHC 1$\mu_\mu$</td>
<td>139.5</td>
<td>139.2</td>
<td>139.5</td>
<td>139.9</td>
<td>140</td>
</tr>
<tr>
<td>FHC 1$\mu_e$</td>
<td>74.4</td>
<td>62.2</td>
<td>50.6</td>
<td>62.7</td>
<td>75</td>
</tr>
<tr>
<td>RHC 1$\mu_e$</td>
<td>17.1</td>
<td>19.4</td>
<td>21.7</td>
<td>19.3</td>
<td>15</td>
</tr>
<tr>
<td>FHC 1 decay e</td>
<td>7.0</td>
<td>6.1</td>
<td>4.9</td>
<td>5.9</td>
<td>15</td>
</tr>
</tbody>
</table>
Model of single muon events (CC0π) are constrained to data. This is very effective for $\nu_\mu$. Additional errors remain for $\nu_e$ -- interplay of lepton mass, thresholds and nuclear effects.
T2K flux + near detector event rates are used to predict the event rates at far detector for any set of oscillation parameters within syst. errors

% Errors on Predicted Event Rates

<table>
<thead>
<tr>
<th>Error source</th>
<th>1-Ring $\mu$ FHC</th>
<th>1-Ring $\mu$ RHC</th>
<th>1-Ring $e$ FHC 1 d.e.</th>
<th>All Systematics</th>
<th>All with osc</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK Detector</td>
<td>2.40</td>
<td>2.01</td>
<td>13.15</td>
<td>5.12</td>
<td>5.12</td>
</tr>
<tr>
<td>SK FSI+SI+PN</td>
<td>2.21</td>
<td>1.98</td>
<td>11.43</td>
<td>8.81</td>
<td>9.19</td>
</tr>
<tr>
<td>Flux + Xsec constrained</td>
<td>3.27</td>
<td>2.94</td>
<td>4.09</td>
<td>8.81</td>
<td>9.19</td>
</tr>
<tr>
<td>$E_b$ (binding energy)</td>
<td>2.38</td>
<td>1.72</td>
<td>2.95</td>
<td>5.12</td>
<td>5.12</td>
</tr>
<tr>
<td>$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$</td>
<td>0.00</td>
<td>0.00</td>
<td>2.61</td>
<td>5.12</td>
<td>5.12</td>
</tr>
<tr>
<td>NC1$\gamma$</td>
<td>0.00</td>
<td>0.00</td>
<td>0.33</td>
<td>0.81</td>
<td>0.81</td>
</tr>
<tr>
<td>NC Other</td>
<td>0.25</td>
<td>0.25</td>
<td>0.99</td>
<td>1.63</td>
<td>1.63</td>
</tr>
<tr>
<td>Osc</td>
<td>0.03</td>
<td>0.03</td>
<td>0.77</td>
<td>0.81</td>
<td>0.81</td>
</tr>
</tbody>
</table>
| **FHC (Forward Horn Current)** $\rightarrow$ $(h^+ \text{ focus}) \rightarrow \text{neutrino beam}$
| **RHC (Reverse Horn Current)** $\rightarrow$ $(h^- \text{ focus}) \rightarrow \text{anti-neutrino beam}$
| 1-ring = quasi-elastic interaction
| 1-ring + 1 decay electron = CC1$\pi$ candidate
| Binding energy effect is constrained by $\nu_\mu$ events at ND280, but not for $\nu_e$

Alain Blondel T2K latest results and prospects
Full 3-family analysis on all channels

- CL contours for $\nu_\mu \rightarrow \nu_\mu$ disappearance parameters, including reactor constraint on $\sin^2 \theta_{13}$
- Best fit points:
  $\sin^2 \theta_{23} = 0.532$
  $\Delta m^2_{32} = 2.452 \times 10^{-3}$ eV$^2$
- T2K data compatible with maximal mixing
  ($\sin^2 \theta_{23} = 0.52$)
- Stronger $\sin^2 \theta_{23}$ constraint in data than expected from sensitivity studies
  (due to a deficit of observed $\nu_\mu$)
Latest T2K CP Violation Search Result

Data Fit:

- Preference for values of $\delta_{CP} \sim -\pi/2$
- Sensitivity improved due to lower value of $\sin^2 \theta_{13} = 0.0212$
- Note: data-fit result gives a stronger constraint than the sensitivity
T2K Search for $\delta_{CP}$

- T2K fit with reactor constraint on $\sin^2 \theta_{13}$:
  - Best fit point: $\delta_{CP} = -1.885$ radians in Normal Hierarchy
  - $\delta_{CP}$ 2$\sigma$ CL confidence interval:
    - Normal mass hierarchy: $[-2.966, -0.628]$ radians
    - Inverted mass hierarchy: $[-1.799, -0.979]$ radians
  - CP conserving values ($0, \pi$) fall outside of the 2$\sigma$ CL intervals!
    - Still fall within the 3$\sigma$ CL intervals
    - Suggestive result, but need more data

Sensitivity  
Data (2$\sigma$ CL)
New T2K $\bar{\nu}_e$ Appearance Result

- Search for $\bar{\nu}_e$ appearance
- Compare consistency with PMNS $\bar{\nu}_e$ appearance ($\beta=0$) and no $\bar{\nu}_e$ appearance ($\beta=1$): $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \beta \times P_{PMNS}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

Rate+shape analysis

Blue: expected # of $\bar{\nu}_e$ events w/ NO $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation ($\beta=0$, 9.4 evts)
Red: expected # of $\bar{\nu}_e$ events w/ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation ($\beta=1$, 17.2 evts)

- For rate+shape, the $\beta = 0$ hypothesis is excluded by 2$\sigma$
- Result statistically not conclusive yet – need more data

<table>
<thead>
<tr>
<th>Analysis</th>
<th>P-value for $\beta = 0$ ($\sigma$ excl.)</th>
<th>P-value for $\beta = 1$ ($\sigma$ excl.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate only</td>
<td>0.0686 (1.82$\sigma$)</td>
<td>0.246 (1.16$\sigma$)</td>
</tr>
<tr>
<td>Rate+shape</td>
<td>0.0244 (2.25$\sigma$)</td>
<td>0.261 (1.12$\sigma$)</td>
</tr>
</tbody>
</table>
**FUTURE PROSPECTS ... LOTS!**

<table>
<thead>
<tr>
<th>Event</th>
<th>Timeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2K + Wagasci-Baby-MIND full detector to run</td>
<td>spring 2019</td>
</tr>
<tr>
<td>SK was open in 2018 starts again in March 2019</td>
<td></td>
</tr>
<tr>
<td>filling with Gd for improved ν vs ¯ν rejection (atmo, beam)</td>
<td>2020</td>
</tr>
<tr>
<td>ND280 upgrade construction (approved as CERN NP07)*</td>
<td>2019-2021</td>
</tr>
<tr>
<td>JPARC power converter upgrade (double. rep rate)</td>
<td>2021</td>
</tr>
<tr>
<td>restart with high power (&gt;750 kW)</td>
<td>2022</td>
</tr>
<tr>
<td>RF power upgrade power → 1.3 MW</td>
<td>2023-25</td>
</tr>
<tr>
<td>Also requires upgrades in neutrino beam infrastructure</td>
<td></td>
</tr>
<tr>
<td>aim at &gt; 3σ (expected, δ=-π/2) by start of HyperK</td>
<td></td>
</tr>
<tr>
<td>HyperK! seed-funded in 2019 pledged start of construction in</td>
<td>2020</td>
</tr>
<tr>
<td>Full data taking starts in ~2027</td>
<td></td>
</tr>
<tr>
<td>Also proposed:</td>
<td></td>
</tr>
<tr>
<td>New Intermediate Water Cherenkov detector</td>
<td></td>
</tr>
<tr>
<td>Second far detector in Korea</td>
<td></td>
</tr>
</tbody>
</table>

*) CERN will become member of T2K
Accelerator-based neutrino program in Japan: **K2K → T2K → HyperK**

- **Beam**
  - 2000: KEK-PS (5kW)
  - 2010: J-PARC (470kW → >750kW)
  - 2030: J-PARC (1.3MW)

- **Detectors**
  - Super-Kamiokande
  - ND280
  - ND280-Upgraded
  - Hyper-K

- **Neutrino Experiments**
  - K2K
  - T2K
  - T2K-II
  - J-PARC & Hyper-K

**Hyper-Kamiokande (260kt)**
Super-K Refurbishment for SK-Gd

- Super-K tank was opened summer 2018 (first time since 2006)
- Refurbishment work ongoing in preparation for Gd loading:
  - Cleaning + water sealing reinforcement
  - Improvement of tank piping
  - Replacement of defective PMTs
- Currently re-filling water + finishing work at top of tank + taking data with ~90% filled tank
- Gd loading schedule will be decided w/ input from T2K/J-PARC
  - Tentatively plan to add 0.01% Gd in late 2019/early 2020
  - Will then load with 0.1% Gd later
Super-K Tank Open Work
Near detector upgrade

motivations:
1. $\theta_{13}$ is large! → syst. dominate
2. Lots learned from running!

- missing: good coverage of large angle leptons
- also $e/\gamma$ separation and PID within target

→ replace upstream part of detector include large angle TPCs surrounding a 3D readout
fine grain scintillator detector SFGD (keep FGDs and forward TPCs)
→ allows full scattering angle coverage with magnetic tracking
→ SFGD target performance should allow $e/\gamma$ separation
  + investigation of low momentum protons and neutrons

beautiful test beam in 2018→
Submitted to JPARC PAC and CERN SPSC
→ approved (NP07 at CERN)
installation to start in 2021
to take data with upgraded beam in 2022.
SuperFGD R&D for ND280 Upgrade

- Many R&D items ongoing for ND280 upgrade
- SuperFGD is a major new component
  - 2,000,000 1x1x1 cm$^3$ scintillator cubes
  - 3D readout by wavelength shifting fibers
- Muon tracking efficiency significantly improved for high-angle tracks
Comments:
-- if 3.4σ NH evidence persists, T2K-II + NOvA will not be far from 5σ by 2026

-- HK saturation at 8σ driven by assumptions on systematic errors.
  ➔ strong effort and support to reduce these
  -- ND280 upgrade,
  -- Further NA61 measurements
  -- New IWC near detector (E61)
Take advantage of pion decay kinematics to probe neutrino interactions as a function of neutrino energy

\[ E_v = \frac{m^2_\pi - m^2_\mu}{2E_\pi (1 - \beta_\pi \cos \theta)} \]

1. By combination of fluxes taken at different angles, generate a quasi-monochromatic beam
2. By the same combination of data, generate the Energy Response Function
Hyper-K 2nd Detector in Korea

KNO
Korean Neutrino Observatory

1~3 deg. off-axis

The J-PARC v beam comes to Korea.

By K. Hagiwara, N. Okamoura, K. Senda

see hep-ph/0504061
1.49 \times 10^{21} \text{ POT } \nu + 1.63 \times 10^{21} \text{ POT } \bar{\nu}

\begin{align*}
\text{MC assumption:} & \\
\delta_{CP} &= -\pi/2 \\
\text{Normal Hierarchy} & \\
\sin^2 \theta_{23} &= 0.528 \\
\sin^2 \theta_{13} &= 0.0212
\end{align*}

<table>
<thead>
<tr>
<th>\text{MC assumption}</th>
<th>\mu-\text{like exp.}</th>
<th>\mu-\text{like meas.}</th>
<th>\text{e-}\text{like exp.}</th>
<th>\text{e-}\text{like meas.}</th>
</tr>
</thead>
<tbody>
<tr>
<td>\bar{\nu} Previous</td>
<td>92.7</td>
<td>102</td>
<td>11.7</td>
<td>9</td>
</tr>
<tr>
<td>\bar{\nu} Updated</td>
<td>139.5</td>
<td>140</td>
<td>17.1</td>
<td>15</td>
</tr>
<tr>
<td>\nu Updated</td>
<td>272.4</td>
<td>243</td>
<td>74.4(7.0cc1\pi)</td>
<td>75(15cc1\pi)</td>
</tr>
</tbody>
</table>
Baysesian analysis (Markov Chain)

T2K Run 1-9d Preliminary

All T2K Oscillation results in one slide!

A. Kaboth

A. Kaboth
nuphys18

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