T2K results and plans
ICPPA 2018

Andy Chappell
for the T2K Collaboration
23 October 2018
3-flavour neutrino oscillations

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

- $c_{ij} = \cos \theta_{ij}$
- $s_{ij} = \sin \theta_{ij}$

- Long baseline experiments can measure:
  - $\theta_{23}$ and $\Delta m^2_{32}$ via disappearance channel
  - $\theta_{13}$ and $\delta_{CP}$ via appearance channel
  - Mass ordering

Andy Chappell - University of Warwick
The T2K experiment

- Long baseline neutrino oscillation experiment in Japan
  - $\nu_\mu$ beam produced at J-PARC, Tokai
  - Near detectors at J-PARC, 280m downstream of target
  - Super-Kamiokande (SK) far detector, 295km downstream of target in Kamioka
  - Off-axis beam produces energy spectrum peaked at 0.6 GeV
- Precision measurements of $\nu_\mu$ disappearance
- Originally designed to discover $\nu_e$ appearance
- Currently searching for CP-violation
Neutrino beamline

- Three horn magnets focus $\pi$ to produce $\nu$-mode or $\bar{\nu}$-mode beam
- Stable beam running at 485kW
- Delivered $3.16 \times 10^{21}$ total protons on target (POT)
- Analysis presented uses $2.65 \times 10^{21}$ POT

Analysis presented uses $2.65 \times 10^{21}$ POT

23 Jan. 2010 – 31 May 2018
POT total: $3.16 \times 10^{21}$
$\nu$-mode $1.51 \times 10^{21}$ (47.83%)
$\bar{\nu}$-mode $1.65 \times 10^{21}$ (52.17%)

Andy Chappell - University of Warwick
Analysis approach

- Neutrino flux model
  - Simulation and NA61 and T2K replica target data on $\pi$ and $K$ yields
- Neutrino cross-section model
  - Simulation and external data on $\nu/e/h$ interactions
- Detector model
  - Simulation and calibration and test beam data
- Make predictions at ND280 and SK
  - Parametrise cross-section and flux model
  - Constrain cross-section and flux by tuning ND280 prediction to observation
- Extract oscillation physics
  - Perform simultaneous fits of the 5 SK samples to measure oscillation parameters
ND280 data fit

- 3 ND280 $\nu$ topologies:
  - $\nu_\mu$ CC0$\pi$, $\nu_\mu$ CC1$\pi^+$, $\nu_\mu$ CC other
- 4 ND280 $\bar{\nu}$ topologies:
  - $\bar{\nu}_\mu$ CC 1-track, $\bar{\nu}_\mu$ CC N-track
  - Wrong sign $\nu_\mu$ CC 1-track, $\nu_\mu$ CC N-track

- INGRID (on-axis)
  - Fit reduces flux and interaction model uncertainties at SK
  - Also use ND280 to measure $\nu$-nucleus cross-sections

ND280 (2.5° off-axis)

Andy Chappell - University of Warwick
ND280 data fit

\[ \nu_\mu \text{ CC0}\pi \text{ data fit} \]

**Pre-fit Error (%)**

<table>
<thead>
<tr>
<th>Group</th>
<th>Pre-fit Error (%)</th>
<th>Post-fit error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_\mu ) sample</td>
<td>14.05</td>
<td>2.88</td>
</tr>
<tr>
<td>( \bar{\nu}_\mu ) sample</td>
<td>11.46</td>
<td>2.68</td>
</tr>
<tr>
<td>( \nu_e ) sample</td>
<td>14.92</td>
<td>3.02</td>
</tr>
<tr>
<td>( \bar{\nu}_e ) sample</td>
<td>12.00</td>
<td>2.86</td>
</tr>
<tr>
<td>( \nu_e ) sample with decay electron</td>
<td>12.02</td>
<td>3.82</td>
</tr>
</tbody>
</table>
Super-Kamiokande far detector

- 50kt water Cherenkov detector
- Inner detector instrumented with 11000 PMTs for 40% photo coverage
- Excellent $\nu_e/\nu_\mu$ separation and good reconstruction at T2K energy

(a) $\mu$-like ring  (b) $e$-like ring

![Diagram of Super-Kamiokande detector with data plots and ring images]

Andy Chappell - University of Warwick
Neutrino oscillation at SK

- 2.5° off-axis beam produces flux peak in the region of the oscillation maximum
Recent analysis improvements

- Additional neutrino-nucleus effects in cross-section model
- Addition of $\nu_e$ CC1$\pi$ sample adds $\sim 10\%$ to $\nu_e$ sample
- Increase in SK fiducial volume:
  - Used to cut all vertices $< 2\text{m}$ from detector wall
  - Now consider particle trajectory to define $t_{\text{wall}}$
  - Variables tuned to each sample, but now have $t_{\text{wall}} \sim 2\text{m}$, $\text{wall} \sim 50\text{cm}$
  - Increases statistics by 15-20%
- Total increase in statistics of $\sim 30\%$
SK data fit

(a) $\nu$-mode e-like

(b) $\bar{\nu}$-mode e-like

(c) $\nu$-mode CC1$\pi^+$-like

(d) $\nu$-mode $\mu$-like

(e) $\bar{\nu}$-mode $\mu$-like
# SK event rates

<table>
<thead>
<tr>
<th></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>$\nu_{\mu}$-like sample</td>
<td>268.525</td>
<td>268.232</td>
<td>268.494</td>
<td>268.880</td>
<td>243</td>
</tr>
<tr>
<td>$\nu_{e}$-like sample</td>
<td>73.780</td>
<td>61.615</td>
<td>50.072</td>
<td>62.238</td>
<td>75</td>
</tr>
<tr>
<td>$\bar{\nu}_{\mu}$-like sample</td>
<td>95.528</td>
<td>95.306</td>
<td>95.529</td>
<td>95.770</td>
<td>102</td>
</tr>
<tr>
<td>$\bar{\nu}_{e}$-like sample</td>
<td>11.753</td>
<td>13.403</td>
<td>14.899</td>
<td>13.250</td>
<td>9</td>
</tr>
<tr>
<td>$\nu_{e}$ CC1$\pi^{+}$-like sample</td>
<td>6.928</td>
<td>6.009</td>
<td>4.869</td>
<td>5.788</td>
<td>15</td>
</tr>
</tbody>
</table>

- $\sin^2 \theta_{12} = 0.304$
- $\Delta m^2_{21} = 7.530 \times 10^{-5}$ eV$^2$ c$^{-4}$
- $\sin^2 \theta_{23} = 0.528$
- $\Delta m^2_{32} = 2.509 \times 10^{-3}$ eV$^2$ c$^{-4}$
- $\sin^2 \theta_{13} = 2.19 \times 10^{-2}$
- Normal ordering
$\Delta m^2$ vs $\sin^2 \theta_{23}$

### (a) Data

- Normal
- Inverted

### (b) Data

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

### (c) MC

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th>Inverted</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$0.536^{+0.031}_{-0.046}$</td>
<td>$0.536^{+0.031}_{-0.041}$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m^2</td>
<td>(10^{-3} \text{ eV}^2)$</td>
</tr>
</tbody>
</table>
\[ \delta_{CP} \text{ vs } \sin^2 \theta_{13} \]

(a) Data (T2K-only)

(b) Data (T2K + reactor)

- Sensitivity assumptions:
  - \( \sin^2 \theta_{13} = 0.0219 \) (PDG 2016)
  - \( \sin^2 \theta_{23} = 0.528 \)
  - \( \delta_{CP} = -1.601 \)

- Data constraint stronger than sensitivity

(c) MC (T2K-only)
\( \delta_{CP} \)

- CP conservation is rejected at 2\( \sigma \)
- 19% of toys exclude CP conservation at 2\( \sigma \) (both \( \delta_{CP} = 0 \) and \( \delta_{CP} = \pi \))
Mass ordering and octant

- T2K also performs a Bayesian analysis, used to express our confidence about the mass ordering and octant

<table>
<thead>
<tr>
<th></th>
<th>$\sin^2 \theta_{23} \leq 0.5$</th>
<th>$\sin^2 \theta_{23} &gt; 0.5$</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>0.204</td>
<td>0.684</td>
<td>0.888</td>
</tr>
<tr>
<td>Inverted</td>
<td>0.023</td>
<td>0.089</td>
<td>0.112</td>
</tr>
<tr>
<td>Sum</td>
<td>0.227</td>
<td>0.773</td>
<td>1</td>
</tr>
</tbody>
</table>

- We see a preference for normal ordering with a Bayes factor of 7.9
- We see a preference for the upper octant with a Bayes factor of 3.4
- Bayes factor between 3.16 and 10 corresponds to ‘substantial’ on the Jeffreys scale, but no strong statistical conclusions
\( \bar{\nu}_e \) appearance

- Two hypotheses:
  - Standard 3-flavour \( \bar{\nu}_e \) appearance (\( \beta = 1 \))
  - No \( \bar{\nu}_e \) appearance (\( \beta = 0 \))

- Rate + shape analysis:

<table>
<thead>
<tr>
<th>( \beta )</th>
<th>Hypothesis</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta = 0 )</td>
<td>No appearance</td>
<td>( p = 0.233 )</td>
</tr>
<tr>
<td>( \beta = 1 )</td>
<td>Appearance</td>
<td>( p = 0.0867 )</td>
</tr>
</tbody>
</table>

- No strong statistical conclusion yet

Data \( \Delta \chi^2 = -1.67 \)
Recent developments

- WAGASCI and BabyMIND near detectors recently installed
- WAGASCI:
  - Measures neutrino interaction cross-sections on hydrocarbon and water
  - On-axis modules taking data since 2016, with off-axis modules installed this year
- BabyMIND:
  - Magnetised spectrometry and charge ID for WAGASCI, with plastic scintillators made at INR, Russia
  - Constructed at CERN and installed in ND280 complex this year
SK Gadolinium upgrade

- Super-Kamiokande tank is open for maintenance and repairs
- This will be followed by Gadolinium doping
- Gadolinium has a high neutron capture cross-section and produces a delayed 8 MeV photon cascade allowing $\bar{\nu}$ tagging
  - Initial phase 0.02% $Gd$ for 50% neutron capture rate
  - Later phase 0.2% $Gd$ for 90% neutron capture rate
- Greater CP-Violation sensitivity due to charge discrimination

Andy Chappell - University of Warwick
T2K run extension

- T2K’s primary goal is now observation of CP-violation in the neutrino sector
- Propose to collect $2 \times 10^{22}$ POT by $\sim 2026$ (arXiv:1609.04111)
- Provides up to $3\sigma$ CP-violation sensitivity
ND280 upgrade

- As part of the run extension aim to reduce systematics to $\sim 4\%$
  - Full polar angle acceptance
  - Fiducial mass of a few tonnes
  - High efficiency for short tracks
  - Good timing to determine track direction
- Submitted proposal to CERN SPSC (http://cds.cern.ch/record/2299599)
- TDR by end of year
- Aim to install 2021
Conclusion

- Significant increase to data set with addition of Run 9a-9c, with $2.61 \times 10^{21}$ total POT
- Ongoing analysis including Run 9d will see this increase to $3.16 \times 10^{21}$ total POT
- CP-conservation excluded at $2\sigma$
- Preference for normal mass ordering with a Bayes factor of 7.9
- Various upgrades allow for the possibility of observing evidence for CP-violation with current generation experiments
Backup
## Systematic errors

<table>
<thead>
<tr>
<th>Error source</th>
<th>1-Ring $\mu$</th>
<th>1-Ring $\ell$</th>
<th>$\nu$</th>
<th>$\bar{\nu}$</th>
<th>$\nu$</th>
<th>$\bar{\nu}$</th>
<th>$\nu$ 1 d.e.</th>
<th>$\nu/\bar{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK Detector</td>
<td>2.40</td>
<td>2.01</td>
<td>2.83</td>
<td>3.79</td>
<td>13.16</td>
<td>1.47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SK Final State and Secondary Interactions</td>
<td>2.20</td>
<td>1.98</td>
<td>3.02</td>
<td>2.31</td>
<td>11.44</td>
<td>1.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flux + Xsec constrained</td>
<td>2.88</td>
<td>2.68</td>
<td>3.02</td>
<td>2.86</td>
<td>3.82</td>
<td>2.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Binding energy</td>
<td>2.43</td>
<td>1.73</td>
<td>7.26</td>
<td>3.66</td>
<td>3.01</td>
<td>3.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$</td>
<td>0.00</td>
<td>0.00</td>
<td>2.63</td>
<td>1.46</td>
<td>2.62</td>
<td>3.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NC1$\gamma$</td>
<td>0.00</td>
<td>0.00</td>
<td>1.07</td>
<td>2.58</td>
<td>0.33</td>
<td>1.49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NC Other</td>
<td>0.25</td>
<td>0.25</td>
<td>0.14</td>
<td>0.33</td>
<td>0.99</td>
<td>0.18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Osc</td>
<td>0.03</td>
<td>0.03</td>
<td>3.86</td>
<td>3.60</td>
<td>3.77</td>
<td>0.79</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All Systematics</td>
<td>4.91</td>
<td>4.28</td>
<td>8.81</td>
<td>7.03</td>
<td>18.32</td>
<td>5.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All with osc</td>
<td>4.91</td>
<td>4.28</td>
<td>9.60</td>
<td>7.87</td>
<td>18.65</td>
<td>5.93</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>