Oscillation results and plans from the T2K experiment

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NUFACT 2017
Outline

• The T2K Experiment
• Structure of T2K oscillation analysis
• New results from data to date
• Future prospects
The T2K Experiment

- Muon (anti) neutrino beam generated at J-PARC and sent to Super-K 295 km away
- Near detector complex 280m from target constrains flux and cross-section uncertainties
- Details in Jiae Kim’s plenary yesterday
Neutrino oscillations at T2K

- Muon (anti)neutrino disappearance
  - Location of dip determined by $\Delta m^2_{23}$
  - Depth of dip determined by $\sin^2(2\theta_{23})$

- Electron (anti)neutrino appearance
  - Leading term depends on $\sin^2(\theta_{23})$, $\sin^2(\theta_{13})$ and $\Delta m^2_{23}$
  - Sub-leading dependance on $\delta_{\text{CP}}$
    - $\delta_{\text{CP}} = \pi/2$: fewer neutrinos, more anti-neutrinos
    - $\delta_{\text{CP}} = -\pi/2$: more neutrinos, fewer anti-neutrinos
  - Matter effects give dependence on mass hierarchy
Beam operation

- Accumulated $14.7 \times 10^{20}$ protons-on-target (POT) in neutrino mode and $7.6 \times 10^{20}$ POT in antineutrino mode
  - 29% of approved T2K-I POT
- Previous results used $7.5 \times 10^{20}$ POT $\nu$-mode, $7.5 \times 10^{20}$ POT $\bar{\nu}$-mode
- Operated at stable beam power of 470 kW this year
  - Enabled doubling $\nu$-mode data
Changes for this year

• New fiTQun SK reconstruction algorithm has been used
  • Allows ~20% increase in fiducial volume (FV)

• This year we added a sample targeting CC1pi interactions
  • Require one electron ring and an additional decay electron
  • Last summer’s analysis used 4 samples all targeting CCQE

• Cross-section model updated
  • Improved uncertainties to multi-nucleon interactions (2p2h)
    and long range nucleon correlations (RPA)
  • Details in Keigo Nakamura’s talk yesterday
• Construct model to predict event rates and distributions
• Constrain models using appropriate data
• Add likelihood penalty for deviating from these constraints to fit
Fitting to data

Two approaches used for fitting:
1. Use ND data fit to constrain flux and cross-section models first then fit far detector
   • Computationally easier
   • Makes more assumptions
2. Perform simultaneous fit of both detectors
   • Computationally more demanding
   • Makes fewer assumptions
Fitting to data

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T2K analyses: Bayesian vs Frequentist

- T2K has three separate analysis frameworks: two frequentist, one Bayesian
- Bayesian analysis does joint near/far detector fit, frequentist analyses fit near detector first and propagate
- All three able to construct frequentist confidence intervals for comparisons
  - Very good agreement is seen

Bayesian analysis shows posterior probability density
(high values mean more likely this is the “correct” parameter value)

Frequentist analyses show $\Delta \chi^2$
(low values mean better agreement with the data for this parameter value)
Predicted and observed Super-K event rates

<table>
<thead>
<tr>
<th>Sample</th>
<th>Predicted Rates</th>
<th>Observed Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\delta_{CP} = -\pi/2$</td>
<td>$\delta_{CP} = 0$</td>
</tr>
<tr>
<td>CCQE 1-Ring e-like $\nu$-mode</td>
<td>73.5</td>
<td>61.5</td>
</tr>
<tr>
<td>CC1$\pi$ 1-Ring e-like $\nu$-mode</td>
<td>6.92</td>
<td>6.01</td>
</tr>
<tr>
<td>CCQE 1-Ring e-like $\bar{\nu}$-mode</td>
<td>7.93</td>
<td>9.04</td>
</tr>
<tr>
<td>CCQE 1-Ring $\mu$-like $\nu$-mode</td>
<td>267.8</td>
<td>267.4</td>
</tr>
<tr>
<td>CCQE 1-Ring $\mu$-like $\bar{\nu}$-mode</td>
<td>63.1</td>
<td>62.9</td>
</tr>
</tbody>
</table>

- Other oscillation parameters at previous best fits: maximal $\theta_{23}$
- Number of events observed generally agrees with oscillated predictions
  - e-like sample rates are most consistent with $\delta_{CP} = -\pi/2$ hypothesis
  - $\mu$-like sample rates consistent within statistical and systematic errors
  - CC$1\pi$ rate shows large upwards fluctuation
  - p-value for fluctuation of this size in at least 1 of 5 samples: 11.9%
## Size of systematic uncertainties

<table>
<thead>
<tr>
<th>Error Source</th>
<th>1R µ-like</th>
<th>1R e-like</th>
<th>1R e-like</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ν-mode</td>
<td>¯ν-mode</td>
<td>ν-mode</td>
</tr>
<tr>
<td>SK Detector</td>
<td>1.86</td>
<td>1.51</td>
<td>3.03</td>
</tr>
<tr>
<td>SK FSI+SI+PN</td>
<td>2.20</td>
<td>1.98</td>
<td>3.01</td>
</tr>
<tr>
<td>ND280 const. flux &amp; xsec</td>
<td>3.22</td>
<td>2.72</td>
<td>3.22</td>
</tr>
<tr>
<td>σ(ν&lt;sub&gt;e&lt;/sub&gt;)/σ(¯ν&lt;sub&gt;e&lt;/sub&gt;)</td>
<td>0.00</td>
<td>0.00</td>
<td>2.63</td>
</tr>
<tr>
<td>NC1γ</td>
<td>0.00</td>
<td>0.00</td>
<td>1.08</td>
</tr>
<tr>
<td>NC Other</td>
<td>0.25</td>
<td>0.25</td>
<td>0.14</td>
</tr>
<tr>
<td>Total Systematic Error</td>
<td>4.40</td>
<td>3.76</td>
<td>6.10</td>
</tr>
</tbody>
</table>

- Total error in the 4-7% range (except CC1π).
- Errors constrained by ND280 contribute 3-4% uncertainties.
- Error on ν-mode /¯ν-mode ratio 4.8%.
  - important for CP violation.
Set A sensitivity

Integrate out $\sin^2\theta_{13}$ dependence

Impose reactor constraint on $\sin^2(2\theta_{13})$ (PDG 2016)

Integrate out $\sin^2\theta_{13}$ dependence
Comparison to Summer 2016 sensitivity
Fake data

- Check robustness of results to neutrino interaction model by using our model to fit 
  `fake data` generated with two methods
  
  1. `Data-driven`: assign differences between current model and ND280 data to one interaction mode and refit
     - Effect seen on $\sin^2\theta_{23}$ and $\Delta m^2_{23}$
  
  2. Model choices: generate data using other models implemented in generator but not used in oscillation analysis and refit
Impact on $\delta_{CP}$

- Need to check how changes to $\Delta\chi^2$ from fake data studies affect statements on $\delta_{CP}$
- Take $\Delta\chi^2$ difference observed in fake data study (top plot) and shift observed $\Delta\chi^2$ in data (bottom plot) by that amount
- Impact on $\delta_{CP}$ intervals is small
- $\sin^2\theta_{23}$ and $\Delta m^2_{23}$ results presented with caveat that the systematic error model may be updated
Data results
Appearance parameter constraints

- T2K value for $\sin^2\theta_{13}$ is consistent with PDG 2016 average (0.0219)
Measurements of the CP violating phase $\delta_{CP}$ from T2K data only and combined with reactor constraints show that CP conserving values are outside the $2\sigma$ (95.4%) interval for the combined constraint.
Constraint vs sensitivity

- Observed constraint stronger than predicted sensitivity
- Studied how likely this was to happen
- Generated many toy data sets with statistical and systematic fluctuations around $\delta_{CP}=-\pi/2$, normal hierarchy (NH)
- Ran fits to these spectra to determine $\delta_{CP}$ constraint
- Observed constraint falls within 95.45% for most $\delta_{CP}$ points
- 30% of experiments exclude $\delta_{CP} = 0$ at 2$\sigma$
- 25% of experiments exclude $\delta_{CP} = \pi$ at 2$\sigma$
Octant and hierarchy preferences

- Bayesian framework has natural way to express preference for binary choices: Bayes factors
  \[ B = \frac{P(\text{option 1})}{P(\text{option 2})} \]
- Bayes factor for NH vs IH: 6.6
- Bayes factor for upper vs lower octant: 3.6
- Both classified as ”substantial/positive” on Jeffreys/Kass & Rafferty scale but not yet decisive
- Systematics may change due to fake data studies

<table>
<thead>
<tr>
<th>Posterior probabilities (T2K + reactor constraint)</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 $(\Delta m_{23}^2 &gt; 0)$</td>
<td>0.193</td>
<td>0.674</td>
<td>0.868</td>
</tr>
<tr>
<td>IH $(\Delta m_{23}^2 &lt; 0)$</td>
<td>0.026</td>
<td>0.106</td>
<td>0.132</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td><strong>0.219</strong></td>
<td><strong>0.781</strong></td>
<td><strong>1.00</strong></td>
</tr>
</tbody>
</table>
Future plans

T2K-II

• T2K target POT is $7.8 \times 10^{21}$
• T2K-II is a proposal to extend target to $20.0 \times 10^{21}$ POT by ~2026
  • Upgrade Main Ring power supply to increase from 0.4->1 Hz running
  • Beam power increase up to 1.3 MW

Other beam and detector upgrades

• Neutrino horns will run at 320 kA from next year
  • Reduces wrong sign contamination in antineutrino mode
• ND280 will be upgraded to improve high-angle acceptance
  • More similar to SK improving cross-section constraint
• SK will be refurbished during Summer 2018 to allow Gd addition in 2019/2020
  • Gd enables neutron tagging
T2K-II sensitivity

- If current preferred $\delta_{CP}$ is true T2K-II has potential for 3$\sigma$ discovery
- Size of systematic uncertainties has large effect on sensitivity
Summary

- **T2K neutrino mode data has doubled** since Summer 2016
- **SK reconstruction improved** and additional samples added
  - Increases number of events per POT by ~30%
- **With new analysis CP conserving values of \( \delta_{CP} \) are excluded** at 2\( \sigma \) in both Bayesian and frequentist frameworks
- **T2K-II proposal plans** to collect \( 20 \times 10^{21} \) POT
  - Gives 3\( \sigma \) sensitivity to favourable \( \delta_{CP} \) values
  - Actively looking for new groups to join
- **Exciting program of oscillation physics to look forward to!**
Super-K

- 50 kton water-Cherenkov detector
- 11,000 20” PMT inner detector
  - 40% photo-coverage
- 2,000 8” PMT outer detector
  - Cosmic veto/exiting particles
- Not magnetised
- Particle ID via Cherenkov ring pattern:
  - Muons produce sharp rings
  - Electrons scatter more → fuzzier rings
Near detectors

**INGRID**
- On-axis detector
- Monitors beam direction and constrains flux
- Design beam direction tolerance 1 mrad
- Achieved <0.5 mrad

**ND280**
- 2.5° off-axis (same as Super-K)
- Two fine-grained detector (FGD) targets
  - FGD1 – Active carbon target
  - FGD2 – Active carbon and passive water layers
- Magnet + three TPCs
  - Particle charge + momentum from curvature
  - Particle ID From dE/dx – 0.2% mis-ID rate
- Constrains cross-section and flux uncertainties
Off-axis beam concept

- Want as much flux as possible at oscillation peak (~0.6 GeV)
- Use 2.5° off-axis beam:
  - Off-axis phase space gives maximum energy for neutrinos from pion decay at a given angle
  - Gives narrower peak in flux
  - Removal of high-energy component suppresses NC backgrounds
Changes for this year – SK reconstruction

• Previous T2K analyses used “APFit” Super-K reconstruction algorithm
• For this result fitQun algorithm has been used
  • For each event chooses event kinematic/topology hypothesis that maximises likelihood
  • Full charge and time information in likelihood leads to improved signal/background discrimination
• Improved reconstruction performance enables increased fiducial volume
  • Previously required vertices to be >2m from detector wall
  • Now optimise cut on “wall” and “towall” for each sample to minimise statistical and systematic errors
  • Provides ~20% increase in fiducial volume (FV)
Changes since last summer – SK samples

- Last summer’s result used 4 Super-K samples
  - Neutrino mode:
    - 1 μ-like ring, ≤1 decay electron
    - 1 e-like ring, 0 decay electrons
  - Antineutrino mode:
    - 1 μ-like ring, ≤1 decay electron
    - 1 e-like ring, 0 decay electrons
  - All four samples target charged-current quasi-elastic (CCQE) interactions

- This year we also include neutrino mode sample targeting CC1π interactions
  - Neutrino mode: 1 e-like ring, 1 decay electron
  - No antineutrino mode due to π⁻ absorption

- Combination of new sample and increased FV equates to 30% increase in event rate for same POT in neutrino mode
Changes to model this year – Cross section

• NEUT neutrino interaction MC generator has been significantly improved in recent years:
  • New tune of pion production model to external hydrogen and deuterium data
  • Improvements to the CCQE model:
    Included the effect of long-range nucleus correlations (calculated using random phase approximation, RPA)

• This analysis includes new parametrisations of the uncertainties on 2p-2h and RPA modelling
more on $\nu_\mu$ disappearance

• $\nu_\mu$ disappearance probability in vacuum

\[
P(\nu_\mu \to \nu_\mu) = 1 - \left( c^4_{13} \sin^2 2\theta_{23} + s^2_{13} \sin^2 2\theta_{13} \right) \sin^2 \Delta_{atm} \\
+ \left\{ c^2_{13} \left( c^2_{12} - s^2_{12} s^2_{23} \right) \sin^2 2\theta_{23} + s^2_{12} s^2_{23} \sin^2 2\theta_{13} - c_{13} \sin 2\theta_{13} \sin 2\theta_{12} \cos \delta \right\} \\
\times \left\{ \frac{1}{2} \sin 2\Delta_{solar} \sin 2\Delta_{atm} + 2 \sin^2 \Delta_{solar} \sin^2 \Delta_{atm} \right\} \\
- \left\{ \sin^2 2\theta_{12} \left( c^2_{23} - s^2_{13} s^2_{23} \right)^2 + s^2_{13} \sin^2 2\theta_{23} \left( 1 - c^2_\delta \sin^2 2\theta_{12} \right) \\
+ 2 s_{13} \sin 2\theta_{12} \cos 2\theta_{12} \sin 2\theta_{23} \cos 2\theta_{23} c_{\delta} \\
- \frac{1}{2} c_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \cos \delta \left( s^2_{23} s^2_{12} \\
+ \sin^2 2\theta_{23} \left( c^2_{12} - s^2_{12} s^2_{13} \right) + s^2_{13} s^2_{23} \sin^2 2\theta_{13} \right) \right\} \times \sin^2 \Delta_{solar}
\] (26)

T2K: $L = 295$ km, $E_\nu$ peaks at $\sim 0.6$ GeV $\to$ $\sin^2 \Delta_{solar} \sim 0$, $\sin^2 \Delta_{atm} \sim 0$

$P(\nu_\mu \to \nu_\mu) \sim 1 - \left( \cos^4 \theta_{13} \cdot \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23} \right) \cdot \sin^2 \frac{\Delta m^2_{31} \cdot L}{4E}$

$\nu_\mu$ disapp. probability depends on $\sin^2 2\theta_{13} \sin^2 \theta_{23}$ to second order

$\to$ Can be used in combination with known $\sin^2 2\theta_{13}$ to resolve the $\theta_{23}$ octant
$\nu_e$ appearance probability 
with 1\textsuperscript{st} order matter effect

$$P(\nu_\mu \rightarrow \nu_e) \approx 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31} \left( 1 + \frac{2a}{\Delta m_{31}^2} \left( 1 - 2s_{13}^2 \right) \right)$$

$$+ 8c_{13}^2 s_{12} s_{13} s_{23} \left( c_{12} c_{23} \cos \delta - s_{12} s_{13} s_{23} \right) \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21}$$

$$- 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin \delta \sin \Delta_{32} \sin \Delta_{31} \sin \Delta_{21}$$

$$+ 4s_{12}^2 c_{13}^2 \left( c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta \right) \sin^2 \Delta_{21}$$

$$- 8c_{13}^2 s_{13}^2 s_{23}^2 \left( 1 - 2s_{13}^2 \right) \frac{aL}{4E} \cos \Delta_{32} \sin \Delta_{31}$$

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

$$\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E}$$

replace $\delta$ by $-\delta$ and $a$ by $-a$ for $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
Oscillation parameters used for predictions

- Evaluated sensitivity by fitting spectrum expected for certain oscillation parameters if no statistical or systematic fluctuations
- Define two sets of oscillation parameter values:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Set A</th>
<th>Set B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2\theta_{12}$</td>
<td>0.304</td>
<td>0.304</td>
</tr>
<tr>
<td>$\sin^2\theta_{23}$</td>
<td>0.528</td>
<td>0.45</td>
</tr>
<tr>
<td>$\sin^2\theta_{13}$</td>
<td>0.0219</td>
<td>0.0219</td>
</tr>
<tr>
<td>$\Delta m^2_{12}$</td>
<td>7.53x10^{-5} eV$^2$</td>
<td>7.53x10^{-5} eV$^2$</td>
</tr>
<tr>
<td>$\Delta m^2_{23}$</td>
<td>2.509x10^{-3} eV$^2$</td>
<td>2.509x10^{-3} eV$^2$</td>
</tr>
<tr>
<td>$\delta_{\text{CP}}$</td>
<td>-1.601</td>
<td>0</td>
</tr>
</tbody>
</table>
Set A: $\sin^2 \theta_{23} = 0.528$, $\delta_{CP} = -1.601$

Set B: $\sin^2 \theta_{23} = 0.45$, $\delta_{CP} = 0$
Triangle plots

T2K data only

T2K + reactor constraint
Dcp split by hierarchy - T2K+reactor

Normal hierarchy

Inverted hierarchy

T2K Run 1-8 preliminary

Posterior probability density

Posterior probability density

$\delta_{CP}$ (rad.)

$\delta_{CP}$ (rad.)
T2K data only disappearance parameters

![Graph showing Δm^2_{32} (eV^2) vs sin^2θ_{23} with 68% and 90% credible intervals, and a MaCh3 best fit.](image)
Biprobability plots

Final systematics pending

T2K Run1-8 Preliminary

- $\sin^2 \theta_{23} = 0.50$
- $\sin^2 \theta_{23} = 0.45$
- $\sin^2 \theta_{23} = 0.55$
- $\Delta m^2_{32} = 2.46 \times 10^{-3} \text{eV}^2/\text{c}^4$
- $\Delta m^2_{31} = -2.44 \times 10^{-3} \text{eV}^2/\text{c}^4$

- $\delta_{CP} = \pi$
- $\delta_{CP} = +\pi/2$
- $\delta_{CP} = 0$
- $\delta_{CP} = -\pi/2$

- Data (stat. errors only)
Spectra for each of the 5 samples at SK

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

\( \bar{\nu} \)-mode
\( \mu \)-like
Plan to deal with fake data

• Investigating further to see if differences seen between data and MC are a physical effect we should include an uncertainty for
  \[ \delta_{CP} \text{ results not affected} \]
• \( \sin^2 \theta_{23} \) and \( \Delta m^2_{23} \) results presented with caveat that the systematic error model may be updated

• In future we plan to address ambiguity between interaction modes with:
  • Use of 4\pi acceptance samples at ND280 to better match SK acceptance
  • Studies of hadronic recoil system through proton reconstruction
  • Near detector upgrades to improve model constraints