Recent development in T2K
Oscillation Analysis

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Stony Brook University

DPF – FNAL
July 31st, 2017
The T2K experiment

Super-Kamiokande
(ICRR, Univ. Tokyo)

J-PARC Main Ring
(KEK-JAEA, Tokai)

Near detectors

295 km

280 m

280 m

N

FNAL, DPF2017
The T2K experiment – beam
The T2K experiment – beam

- Narrow band neutrino beam peaked at oscillation maximum (~0.6 GeV)
- Reduces intrinsic $\nu_e$ contamination
- Reduces neutrinos with higher energy; enhances CCQE mode & suppress NC mode
The T2K experiment – near detectors

On-axis

Off-axis

Designed Beam center

~10m

1.5m

~10m
The T2K experiment – far detector

Super-Kamiokande

- 50 kilo-ton Water Cherenkov detector
- Outer detector to veto cosmic background
- Excellent $e/\mu$ separation
- Cannot separate $\nu/\bar{\nu}$
- Cannot detect particles below Cherenkov threshold

The T2K experiment
- Far detector
- Super-Kamiokande
- Particle ID parameter

\[ \nu_\mu \text{ CCQE} \]

\[ \nu_e \text{ CCQE} \]

\[ \nu_\alpha + n \rightarrow l^- \bar{\nu} + p \]

\[ \bar{\nu}_\alpha + p \rightarrow l^+ + n \]

- Energy reconstruction based on lepton kinematics → select CCQE-enriched samples

NC$1\pi^0$ background

T2K Signal

Atmospheric $\nu\%$ vs. $\nu$ 

MC

Data
T2K analysis – overview

- Near detector fit
  - Flux model
  - Near detector model
  - Cross-section model
  - Far detector model

- Far detector fit
  - ND280 data
  - Super-K data

- Oscillation parameters
  - ND + FD Bayesian analysis
  - ND → FD Frequentist analysis

- Other cross-section measurements
- Beam monitor & INGRID data
- NA61/SHINE hadron production measurements
Flux prediction and uncertainties

- FLUKA/Geant3-based neutrino beam simulation
  - “Wrong-sign” component
  - Significant $\nu$ component in $\bar{\nu}$ beam
  - $\sim 0.5\%$ intrinsic $\nu_e$($\bar{\nu}_e$)

SK: Neutrino Mode, $\nu_\mu$

- Hadron Interactions
- Proton Beam Profile & Off-axis Angle
- Horn Current & Field
- Horn & Target Alignment
- Material Modeling

$\Phi \times E_{\nu} \times$ Arb. Norm.

$\nu$ component in $\bar{\nu}$ beam

~0.5% intrinsic $\nu_e$($\bar{\nu}_e$)
Flux prediction and uncertainties

- FLUKA/Geant3-based neutrino beam simulation
  - “Wrong-sign” component
  - Significant $\nu$ component in $\bar{\nu}$ beam
  - $\sim 0.5\%$ intrinsic $\nu_e(\bar{\nu}_e)$

- Constrained by NA61/SHINE experiment
  - Thin carbon target and replica target
  - $\pi^\pm, K^\pm, K_S^0$ production

---

**Neutrino Mode Flux at SK**

**Antineutrino Mode Flux at SK**

**Hadronic interactions**

- Material Modeling
- Proton Beam Profile & Off-axis Angle
- Number of Protons
- Horn Current & Field
- Horn & Target Alignment
- $\Phi = E_\nu$, Arb. Norm.
- $13\text{av}1$ Error
- $11\text{bv}3.2$ Error
Flux prediction and uncertainties

- FLUKA/Geant3-based neutrino beam simulation
  - “Wrong-sign” component
  - Significant $\nu$ component in $\bar{\nu}$ beam
  - $\sim 0.5\%$ intrinsic $\nu_e(\bar{\nu}_e)$

In-situ measurements to constrain
- Proton beam profile
- Off-axis angle
- Horn/target alignment

Neutrino Mode Flux at SK

Antineutrino Mode Flux at SK

Fractional Error
Cross-section modeling

- **NEUT event generator**
- **CCQE**
  - Global Relativistic Fermi Gas (RFG) + Random Phase Approximation (RPA)
- **Multi-nucleon interactions**
  - ~10% relative to CCQE
  - 2p2h model by Nieves et al
- **Single resonant pion interactions**
  - Rein-Sehgal model with modified Delta form factor tuned to bubble chamber data
- **Final state interaction (FSI) and Secondary interaction (SI)**
  - Pion cascade model tuned by external pion scattering measurements
- **Extensive studies of analysis sensitivity to different cross-section models**

Tuned to MiniBooNE and MINERvA


PHYSICAL REVIEW C 70, 055503 (2004)


Near detector fit

- Select CC $\nu_\mu, \bar{\nu}_\mu$ interactions with vertex in either Fine-Grained Detectors (FGD)
  - FGD1: CH target
  - FGD2: 42% water by mass
- Event samples provide information on flux and cross-section

A likelihood fit to all ND samples is performed; tuned flux and cross-section parameters are provided to far detector analysis
Data sample

- Stable running at 470kW achieved during Run8
- Ongoing studies to further improve beam power

Results shown today are from T2K Run1-7 data analysis
- \(\nu\)-mode: \(7.48 \times 10^{20}\) POT
- \(\bar{\nu}\)-mode: \(7.47 \times 10^{20}\) POT

Run8: \(7.25 \times 10^{20}\) POT in \(\nu\)-mode
Results coming out soon!

<table>
<thead>
<tr>
<th>Run period</th>
<th>Dates</th>
<th>(\nu)-mode POT ((\times 10^{20}))</th>
<th>(\bar{\nu})-mode POT ((\times 10^{20}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>Jan. 2010 - Jun. 2010</td>
<td>0.323</td>
<td>--</td>
</tr>
<tr>
<td>Run 2</td>
<td>Nov. 2010 - Mar. 2011</td>
<td>1.108</td>
<td>--</td>
</tr>
<tr>
<td>Run 4</td>
<td>Oct. 2012 - May 2013</td>
<td>3.560</td>
<td>--</td>
</tr>
<tr>
<td>Run 5</td>
<td>May 2014 - Jun. 2014</td>
<td>0.242</td>
<td>0.506</td>
</tr>
<tr>
<td>Run 6</td>
<td>Nov. 2014 - Jun. 2015</td>
<td>0.190</td>
<td>3.505</td>
</tr>
<tr>
<td>Run 7</td>
<td>Feb. 2016 - May 2016</td>
<td>0.480</td>
<td>3.520</td>
</tr>
<tr>
<td>Run 8</td>
<td>Nov. 2016 - May 2017</td>
<td>7.252</td>
<td>--</td>
</tr>
<tr>
<td>Total</td>
<td>Jan. 2010 - May 2017</td>
<td>14.734</td>
<td>7.531</td>
</tr>
</tbody>
</table>
Far detector data samples

$\nu_\mu$ CC0$\pi$

$\nu_e$ CC0$\pi$

$\bar{\nu}_e$ CC1$\pi^+$

$v$-mode

Data: 135
MC: 137.8

Data: 32
MC: 28.6

Data: 66
MC: 68.3

Data: 5
MC: 3.1

$\nu$-mode

Data: 4
MC: 6.3

$\bar{\nu}$-mode

Data: 4
MC: 6.3

FNAL, DPF2017
Current Results – Joint Analysis $\theta_{23}$ & $\Delta m_{23}^2$

- T2K data favors maximal disappearance and are consistent with maximal mixing
- Consistent with results from other experiments

$\sin^2 \theta_{13} = 0.085 \pm 0.005$

* 5 samples frequentist analysis

<table>
<thead>
<tr>
<th>ID parameter constraints</th>
<th>NH</th>
<th>IH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$0.550^{+0.051}_{-0.085}$</td>
<td>$0.552^{+0.048}_{-0.083}$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m_{23}^2</td>
<td>\times 10^{-3} \text{eV}$</td>
</tr>
</tbody>
</table>
Current Results – Joint Analysis $\delta_{CP}$

- Data prefers largest CP asymmetry $\delta_{CP} = -\pi/2$, normal hierarchy
- CP conservation disfavored at 90% C. L.
- Normal hierarchy: $\delta_{CP} = [-2.978, -0.467]$ at 90% C.L.
- Inverted hierarchy: $\delta_{CP} = [-1.466, -1.272]$ at 90% C.L.
Recent developments

- SK fiducial volume is expanded
  - Use atmospheric neutrino data to estimate detector systematics in different detector regions
  - Optimize fiducial cut for each T2K sample for sensitivity to oscillations with systematics in different detector regions taken into account

<table>
<thead>
<tr>
<th>Sample</th>
<th>Towall cut (cm)</th>
<th>Wall cut (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCQE 1-ring e-like FHC</td>
<td>170</td>
<td>80</td>
</tr>
<tr>
<td>CCQE 1-ring $\mu$-like FHC</td>
<td>250</td>
<td>50</td>
</tr>
<tr>
<td>CC1$\pi$ 1-ring e-like FHC</td>
<td>270</td>
<td>50</td>
</tr>
<tr>
<td>CCQE 1-ring e-like RHC</td>
<td>170</td>
<td>80</td>
</tr>
<tr>
<td>CCQE 1-ring $\mu$-like RHC</td>
<td>250</td>
<td>50</td>
</tr>
</tbody>
</table>
Recent developments

- New reconstruction algorithm is used at SK
  - Enhanced $e/\mu$ separation
- Optimized event selection for sensitivity to oscillation parameters
  - All systematics taken into account
  - Maximize sensitivity to precision of $\sin^2 \theta_{23}$ for $\nu_\mu$ samples
    - Introduce $\mu/\pi$ separation cut in $\nu_\mu$ sample for the first time
  - Maximize sensitivity to reject $\delta_{CP} = 0$ for $\nu_e$ samples
- Total effective statistical improvement is **33%**
  - ~15% signal increase and ~50% NC background reduction in $\nu_\mu$
  - ~23% statistical increase in $\nu_e$ sample
  - ~33% signal increase and background reduction in $\nu_e$ CC1$\pi^+$ sample
Recent developments

- Run8 doubles $\nu$-mode statistics
- Improvements in cross-section modeling
  - Inclusion of RPA uncertainty
  - 2p2h normalization + shape uncertainties
  - New tuning of the uncertainties on single resonant pion production

![T2K sensitivity](image)

* 2017 analysis uses new samples

### Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Set A</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2_{21}$</td>
<td>$7.53 \times 10^{-5}$ eV$^2$</td>
</tr>
<tr>
<td>$\Delta m^2_{32}$</td>
<td>$2.509 \times 10^{-3}$ eV$^2$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.528</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$ ($\sin^2 2\theta_{12}$)</td>
<td>0.304 (0.846)</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$ ($\sin^2 2\theta_{13}$)</td>
<td>0.0219 (0.0857)</td>
</tr>
<tr>
<td>$\delta_{CP}$</td>
<td>-1.601</td>
</tr>
<tr>
<td>Earth matter density</td>
<td>2.6 g/cm$^3$</td>
</tr>
<tr>
<td>Baseline length</td>
<td>295 km</td>
</tr>
<tr>
<td>Mass hierarchy</td>
<td>Normal</td>
</tr>
</tbody>
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**2016 analysis**

Old reconstruction and Run1-7 statistics

**2017 analysis**

New reconstruction and Run1-8 statistics
Recent developments

- Run8 doubles $\nu$-mode statistics
- Improvements in cross-section modeling
  - Inclusion of RPA uncertainty
  - 2p2h normalization + shape uncertainties
  - New tuning of the uncertainties on single resonant pion production

T2K sensitivity
(w/ reactor constraint)

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*2017 analysis uses new samples*
Summary and future prospect

- So far T2K has analyzed data
  - \( \nu \)-mode: \( 7.48 \times 10^{20} \) POT
  - \( \bar{\nu} \)-mode: \( 7.47 \times 10^{20} \) POT
- **New results to be released soon**
  - \( \nu \)-mode: \( 14.75 \times 10^{20} \) POT
  - New reconstruction algorithm and expanded fiducial volume
- Short term target: \( 9 \times 10^{20} \) POT in \( \bar{\nu} \)-mode next year
- Beam power improvements
  - MR power supply upgrade etc. scheduled in 2019
  - To 750kW – repetition rate 2.48 sec → 1.3 sec
- T2K phase II
  - \( 7.8 \times 10^{21} \) POT → \( 20 \times 10^{21} \) POT
  - Near detector upgrade
  - 1.3MW beam
Data and Results will be shown at KEK seminar
August 4th 10:00 am JST
“New T2K Neutrino Oscillation Results”, C.K. Jung, DPF plenary Aug. 4th, 8:30am
The T2K Collaboration

~500 members, 63 Institutes, 11 countries

Canada
TRIUMF
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
Aachen

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tokyo Institute of Tech
Tokyo Metropolitan U.
U. Tokyo

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroclaw U.

Russia
INR

Spain
IFAE, Barcelona
IFIC, Valencia
U. Autonoma Madrid

Switzerland
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. Liverpool
U. Sheffield
U. Warwick

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

\[ P(\nu_\mu \to \nu_\mu) \approx 1 - (\cos^4 \theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23}) \cdot \sin^2 \frac{\Delta m_{31}^2 L}{4E} \]

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

- Leading including matter effect
- CP conserving
- CP violating
- Solar
- Matter effect (small)

\[ c_{ij} = \cos \theta_{ij}, s_{ij} = \sin \theta_{ij} \]

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

\[ a \approx 2\sqrt{2} G_F n_e E = 7.56 \times 10^{-5} \text{ eV}^2 \frac{\rho}{\text{ g/cm}^3} \frac{E}{\text{ GeV}} \]

replace \( \delta \) by \(-\delta\) and \( a \) by \(-a\) for \( P(\bar{\nu}_\mu \to \bar{\nu}_e) \)
Near Detector samples -- $\nu$-mode

CC0pi

CC1pi

CCother

FGD I

Data / Sim., Events/100 MeV/c

Reconstructed muon momentum (MeV/c)

$\gamma$-mode

Data / Sim., Events/100 MeV/c

Reconstructed muon momentum (MeV/c)

$\gamma$-mode

Data / Sim., Events/100 MeV/c

Reconstructed muon momentum (MeV/c)

$\gamma$-mode

Data / Sim., Events/100 MeV/c

Reconstructed muon momentum (MeV/c)

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FNAL, DPF2017
Near Detector samples -- $\bar{\nu}$-mode

$\bar{\nu}$ CC1track

$\bar{\nu}$ CCNtrack

FGD I
Near Detector samples -- $\bar{\nu}$-mode

$v$ CC1track  
$v$ CCNtrack

FGD I
Near Detector fit

Cross section parameter | Prefit | ND280 postfit
--- | --- | ---
$M_A^{QE}$ (GeV/c²) | 1.20 | 1.12 ± 0.03
$pF^{12C}$ (MeV/c) | 217.0 | 243.9 ± 16.6
2p2h $^{12C}$ | 100.0 | 154.5 ± 22.7
$E_b^{12C}$ (MeV) | 25.0 ± 9.00 | 16.5 ± 7.53
$pF^{16O}$ (MeV/c) | 225.0 | 234.2 ± 23.7
2p2h $^{16O}$ | 100.0 | 154.6 ± 34.3
$E_b^{16O}$ (MeV) | 27.0 ± 9.00 | 23.8 ± 7.61
$C_A^\lambda$ | 1.01 ± 0.12 | 0.80 ± 0.06
$M_A^{RES}$ (GeV/c²) | 0.95 ± 0.15 | 0.84 ± 0.04
$1_2$ background | 1.30 ± 0.20 | 1.36 ± 0.17
CC other shape | 0.00 ± 0.40 | -0.02 ± 0.21
CC coherent | 1.00 ± 0.30 | 0.86 ± 0.23
NC coherent | 1.00 ± 0.30 | 0.93 ± 0.30
2p2h $\bar{\nu}$ | 1.00 | 0.58 ± 0.18
NC other | 1.00 ± 0.30 | Not constrained
NC $1-\gamma$ | 1.00 ± 1.00 | Not constrained
$\nu_e/\nu_\mu$ ratio | 1.00 ± 0.02 | Not constrained
$\nu_e/\bar{\nu}_\mu$ ratio | 1.00 ± 0.02 | Not constrained
FSI elastic low-E | 1.00 ± 0.41 | Not constrained
FSI elastic high-E | 1.00 ± 0.34 | Not constrained
FSI pion production | 1.00 ± 0.50 | Not constrained
FSI pion absorption | 1.00 ± 0.41 | Not constrained
FSI charge exchange low-E | 1.00 ± 0.57 | Not constrained
FSI charge exchange high-E | 1.00 ± 0.28 | Not constrained
Near Detector fit

ND280 $\nu_e$, $\nu$ beam mode

ND280 $\nu_\mu$, $\nu$ beam mode

ND280 $\bar{\nu}_e$, $\nu$ beam mode

ND280 $\bar{\nu}_\mu$, $\nu$ beam mode
Near Detector fit

SK $\nu_\mu$, v beam mode

SK $\nu_e$, v beam mode

SK $\bar{\nu}_\mu$, v beam mode

SK $\bar{\nu}_e$, v beam mode

Pre-fit

Post-fit

Xiaoyue Li

FNAL, DPF2017
Effect of systematics uncertainties

**Source of uncertainty**

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\frac{\delta N_{SK}}{N_{SK}}$</th>
<th>$\frac{\delta N_{SK}}{N_{SK}}$</th>
<th>$\frac{\delta N_{SK}}{N_{SK}}$</th>
<th>$\frac{\delta N_{SK}}{N_{SK}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SKDet+FSI+SI</td>
<td>4.13%</td>
<td>4.47%</td>
<td>3.91%</td>
<td>4.47%</td>
</tr>
<tr>
<td>FSI+SI</td>
<td>1.47%</td>
<td>2.50%</td>
<td>2.05%</td>
<td>2.50%</td>
</tr>
<tr>
<td>SKDet</td>
<td>3.89%</td>
<td>2.45%</td>
<td>3.34%</td>
<td>2.45%</td>
</tr>
<tr>
<td>Flux</td>
<td>3.54%</td>
<td>3.60%</td>
<td>3.70%</td>
<td>3.66%</td>
</tr>
<tr>
<td>MEC (corr)</td>
<td>3.52%</td>
<td>3.90%</td>
<td>2.96%</td>
<td>3.90%</td>
</tr>
<tr>
<td>MECbar (corr)</td>
<td>0.21%</td>
<td>0.05%</td>
<td>1.82%</td>
<td>0.05%</td>
</tr>
<tr>
<td>NC 1gamma (uncorr)</td>
<td>0.00%</td>
<td>1.46%</td>
<td>0.00%</td>
<td>1.46%</td>
</tr>
<tr>
<td>XSec nue/numu</td>
<td>0.01%</td>
<td>2.63%</td>
<td>0.00%</td>
<td>2.63%</td>
</tr>
<tr>
<td>XSec Tot</td>
<td>4.07%</td>
<td>5.14%</td>
<td>4.16%</td>
<td>5.14%</td>
</tr>
<tr>
<td>Flux+XSec</td>
<td>2.90%</td>
<td>4.12%</td>
<td>3.30%</td>
<td>4.12%</td>
</tr>
<tr>
<td>Flux+XSec (Pre ND280)</td>
<td>10.90%</td>
<td>11.47%</td>
<td>11.84%</td>
<td>11.47%</td>
</tr>
<tr>
<td>Oscillations</td>
<td>0.02%</td>
<td>0.49%</td>
<td>0.03%</td>
<td>0.49%</td>
</tr>
<tr>
<td>All</td>
<td>5.08%</td>
<td>5.53%</td>
<td>5.19%</td>
<td>5.53%</td>
</tr>
<tr>
<td>All (Pre ND280)</td>
<td>12.25%</td>
<td>12.06%</td>
<td>12.88%</td>
<td>12.06%</td>
</tr>
</tbody>
</table>

**Effect of systematics uncertainties**

- **numu**
- **nue**
- **numubar**
- **nuebar**
- **Nue CCp+**
Current Results – Joint Analysis $\theta_{13}$

- T2K-only measurement consistent with reactor results
- Favors “small” $\sin^2 \theta_{13}$ and large CPV

\[ \sin^2 \theta_{13} = 0.085 \pm 0.005 \]