Recent results from T2K

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on behalf of the T2K collaboration

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Neutrino mixing and oscillations

mixing of flavor and mass eigenstates → PMNS matrix

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

+ Majorana phases

\[\theta_{23} = 45.8 \pm 3.2^\circ\]
\[\theta_{12} = 33.4 \pm 0.85^\circ\]
\[\theta_{13} = 8.88 \pm 0.39^\circ\]

\[\Delta m^2_{21} = (7.53 \pm 0.18) \cdot 10^{-5} \text{ eV}^2\]
\[|\Delta m^2_{32}| = (2.44 \pm 0.06) \cdot 10^{-3} \text{ eV}^2\]
\[\delta_{CP} = [-\pi \div 0.14\pi] \text{ and } [0.87\pi \div \pi] \text{ (90\% interval)}\]

- mass hierarchy, CPV phase (and Majorana phases) still unknown

long-baseline experiments only
T2K experiment

- searches for $\nu$ oscillations in high purity $\nu_\mu$ beam
- other measurements: cross sections, sterile $\nu$ search
- **off-axis** technique
  - CC quasi-elastic sample enhanced
  - backgrounds reduced
    - $\delta OA \sim 1$ mrad $\rightarrow \delta E/E \sim 2\%$ at far detector
- collaboration: $\sim 500$ members, 59 institutes, 11 countries
The near detectors (280m)

• INGRID (on axis)
  ▶ iron/scintillator tracking calorimeters, 16 modules
  ▶ 1 all-scintillator proton module
  ▶ direction, profile, rate of CC interactions

• ND280 (off axis)
  ▶ $\nu_\mu$ and $\nu_e$ flux measurement
  ▶ non-oscillation analyses

TPC
  • momentum measurement
  • particle identification (dE/dx measurement)

FGD
  • active target mass (2*0.8t)
  • recoil protons detection

SMRD
  improvement of muon identification
The far detector: Super-Kamiokande

- water Cherenkov detector
  - total mass 50 kt, fiducial mass 22.5kt
  - >11000 PMTs in inner detector
- $\Delta E/E \sim 10\%$ for 2-body kinematics
- very good $\mu/e$ separation
  - muons misidentified as electrons: <1%
- $\pi^0$ detection (2 e-like rings)

![Signal for $\nu_\mu$ disappearance](image1)

![Signal for $\nu_e$ appearance](image2)

![Background for $\nu_e$ appearance](image3)
Data taking

- antineutrino beam mode from 2014
  - looking for any differences between $\nu$ and $\bar{\nu}$ oscillations
  - potentially measure $\delta_{\text{CP}}$ (T2K data only)

- $7.0 \cdot 10^{20}$ POT delivered in $\nu$ mode,
  $2.3 \cdot 10^{20}$ POT in $\bar{\nu}$ mode (till March 12)
- beam stability <1 mrad

Analyses in T2K

- $\nu_e$ appearance
  - $\sin^2\theta_{13}$ measurement
- $\nu_\mu$ disappearance
  - $\sin^2\theta_{23}$ measurement
- joint $\nu_e + \nu_\mu$ analysis
  - first $\delta_{CP}$ constraints
- $\nu_\mu$ disappearance
  - $\sin^2\theta_{23}$ measurement

- cross section and other measurements at near detector

workflow:

1. INGRID+beam monitor data
2. NA61/SHINE data
3. flux model
4. cross section model
5. ND280 prediction
6. fit to ND280 data to reduce the flux and cross section uncertainties
7. fit to data
8. tuning of simulation parameters
9. the tuned parameters are then used to predict spectra in FD

Additional data:

- SK data
- oscillation fit
- SK detector model
- external data
- ND280 data
- ND280 detector model
Near detector analysis

- $\nu_\mu$ CC selection in tracker
  - subsamples $\leftrightarrow$ presence of pions in final state
  - sensitivity to different energy ranges and interactions (CC quasi-elastic, resonant, deep inelastic scattering)
- fit of spectra to reduce flux and cross section uncertainties

CC0 sample

CC1 sample

CCOther sample

muon momentum (pre-fit)
Near detector constraints

- reduced uncertainties on the cross section and flux parameters
- significant reduction of the far detector event rate errors

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

\[ \nu_e \text{ sample} \]

T2K $\nu_\mu$ flux at FD

- Prior to ND280 Constraint (including NA61 measurements)
- After ND280 Constraint

T2K $\nu_e$ flux at FD

- Prior to ND280 Constraint
- After ND280 Constraint
$\nu_\mu + \nu_e$ joint analysis (T2K only)

- we consider both T2K $\nu_\mu$ and $\nu_e$ spectra simultaneously
- extended maximum likelihood fit:

\[
L = L_{\text{nue}} \times L_{\text{numu}} \times L_{\text{sys}}
\]

\[
L_{\text{nux}} = L_{\text{norm}} \times L_{\text{shape}}
\]

- $\sin^2 \theta_{23}$ favours maximal mixing – world best precision
- $\sin^2 \theta_{13}$ compatible with reactor measurements

$\sin^2 \theta_{23} = 0.524^{+0.057}_{-0.059} \text{ (NH)}$  $0.523^{+0.055}_{-0.065} \text{ (IH)}$

$\sin^2 \theta_{13} = 0.042^{+0.013}_{-0.021} \text{ (NH)}$  $0.049^{+0.015}_{-0.021} \text{ (IH)}$
\( \nu_\mu + \nu_e \) joint analysis (+reactor)

- include results from reactor experiments:
  - extra constraint term in the likelihood
  - improves precision on \( \sin^2 \theta_{23} \) and \( \Delta m^2_{23} \)
  - frequentist and Bayesian approaches

Hints towards CP violation

- 90\% C.L. excluded region of \( \delta_{CP} \):
  - \( \frac{1}{6} \pi < \delta_{CP} < \frac{5}{6} \pi \) (NH)
  - \( -\frac{1}{6} \pi < \delta_{CP} < \frac{1}{6} \pi \) (IH)

Posterior probabilities (Bayesian)

<table>
<thead>
<tr>
<th>( \sin^2 \theta_{23} )</th>
<th>NH</th>
<th>IH</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \leq 0.5 )</td>
<td>0.179</td>
<td>0.078</td>
<td>0.257</td>
</tr>
<tr>
<td>( &gt; 0.5 )</td>
<td>0.505</td>
<td>0.238</td>
<td>0.743</td>
</tr>
<tr>
<td>Sum</td>
<td>0.684</td>
<td>0.316</td>
<td>1.0</td>
</tr>
</tbody>
</table>

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Antineutrino beam mode
Changes in 2015 analysis

- new NA61 data used in the beam MC simulation (uncertainty reduced by 4% in the energy peak)
- new neutrino MC model with multinucleon interactions
- new constraints on CC QE from MiniBooNE and Minerva
- before ND fit the MC underestimates CC0π and CCother samples, overestimates CC1π+ sample

External data is somewhat in tension, so errors are inflated to account for that tension
Near detector constraints for $\bar{\nu}$ beam mode

- additional samples for antineutrino beam mode

- $\nu_\mu$

- flux and cross section parameters after fit to ND280 data
Predicted $\bar{\nu}_\mu$ spectrum at SK

- expected spectrum obtained using the oscillation parameters from neutrino beam results
- 19.9 events expected with oscillation and 59.8 without oscillation
  - dominated by CCQE events
- systematic errors dominated by uncertainties on the difference between interactions on C (ND280) and O (Super-K)

<table>
<thead>
<tr>
<th>Systematic</th>
<th>without ND280</th>
<th>with ND280</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux and cross section</td>
<td>common to SK/ND280</td>
<td>9.2%</td>
</tr>
<tr>
<td></td>
<td>SK only</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>all</td>
<td>13%</td>
</tr>
<tr>
<td>FSI/SI</td>
<td></td>
<td>2.1%</td>
</tr>
<tr>
<td>SK detector</td>
<td></td>
<td>3.8%</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>14.4%</td>
</tr>
</tbody>
</table>
The best-fit $\bar{\nu}_\mu$ spectrum

- expectation:
  - 19.9 events with oscillation
  - 59.8 without oscillation
- 17 events observed
  - clear evidence of oscillation in data
- maximize the likelihood:

$$\mathcal{L} = \mathcal{L}_{\text{Poisson}} \times \mathcal{L}_{\text{Syst}}$$

- all oscillation parameters except $\sin^2 \theta_{23}$ and $\Delta m_{32}^2$ fixed, based on T2K neutrino data and PDG 2014
The oscillation parameters

best-fit point near maximal disappearance

comparison to T2K neutrino data
- still much larger contours
- results consistent with no difference between neutrinos and antineutrinos

comparison to MINOS
(beam and cosmic combined)
- T2K contours smaller in $\sin^2 \theta_{23}$
- MINOS saw non-maximal best-fit point, but results compatible
Other results: cross sections and sterile neutrino search

Search for short-baseline $\nu_e$ disappearance with the T2K near detector


Measurement of the $\nu_\mu$ CC QE cross section on carbon with the T2K on-axis neutrino beam

● 4 papers on cross-section published before 2015
● Measurement of the $\nu_e$ CC Interaction Rate on water with the T2K ND280 $\pi^0$ Detector (Accepted in PRD)
● more will come!

Measurement of the $\nu_\mu$ CC QE cross section on carbon with the ND280 detector at T2K

submitted to PRD

submitted to PRD
Conclusions

- recent T2K oscillation analyses:
  - combined $\nu_\mu + \nu_e$ analysis with reactor constraint
  - preference for values of $\delta_{CP}$ around $-\pi/2$
  - weakly favored normal hierarchy and octant $\sin^2\theta_{23} > 0.5$
  - first $\nu_\mu$ disappearance result
    - consistent with T2K $\nu_\mu$ disappearance measurements
    - and MINOS $\bar{\nu}_\mu$ disappearance result
  - analysis of $\bar{\nu}_e$ appearance is underway

- many cross section measurements at the near detector
- T2K continued to take data till end of May (statistics with antineutrino beam mode doubled)
T2K collaboration

Near & Far sites:

KEK/SAEC, ICRR
Additional slides
Beam stability

- Interaction rate normalized by POT
- Event rate
- Horizontal beam direction
- Vertical beam direction
- Much better than 1 mrad
$\bar{\nu}_\mu$ disappearance

- effect of systematic uncertainties: nearly identical contours
- the analysis is dominated by statistical errors

- three different analyses: different methods of maximizing likelihood
- all are in very good agreement
Event selection in SuperK

- beam timing and minimal activity in outer detector
- fully contained in fiducial volume (>200cm from wall)
- one reconstructed ring (QE-like)
  - muon-like ring
  - muon momentum >200MeV
  - one or fewer decay electrons
- electron-like ring
  - visible energy >100 MeV
  - no Michel (delayed) electrons
  - cut on $\pi^0$ invariant mass and likelihood ratio
  - reconstructed neutrino energy <1.25 GeV
Future sensitivity

- $7.8 \times 10^{21}$ POT $\rightarrow$ resolution of $0.050(0.054)$ on $\sin^2 \theta_{23}$ and $0.040(0.045) \times 10^{-3}$ eV$^2$ on $\Delta m^2_{32}$
  - for 100%(50%) neutrino beam mode running
  - assuming $\sin^2 \theta_{23} = 0.5$ and $\Delta m^2_{32} = 2.40 \times 10^{-3}$ eV$^2$
- sensitivity to $\delta_{\text{CP}}$ at 90% C.L. or better over a significant range.
  - if $\sin^2 \theta_{23} = 0.5 \rightarrow -115^\circ < \delta_{\text{CP}} < -60^\circ$ (NH);
    $+50^\circ < \delta_{\text{CP}} < +130^\circ$ (IH)
- combination of results from two experiments at different baselines (T2K + NOvA) will further improve the sensitivity

$\nu_\mu$ disappearance

full 3-$\nu$ oscillation framework

- with ND280 constraint

$0.514^{+0.055}_{-0.056} (0.511 \pm 0.055)$


<table>
<thead>
<tr>
<th>Source of uncertainty (number of parameters)</th>
<th>$\delta n_{SK}^{exp} / n_{SK}^{exp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND280-independent cross section (11)</td>
<td>4.9%</td>
</tr>
<tr>
<td>Flux and ND280-common cross section (23)</td>
<td>2.7%</td>
</tr>
<tr>
<td>SK detector and FSI+SI systematics (7)</td>
<td>5.6%</td>
</tr>
<tr>
<td>$\sin^2(\theta_{13})$, $\sin^2(\theta_{12})$, $\Delta m_{21}^2$, $\delta CP$ (4)</td>
<td>0.2%</td>
</tr>
<tr>
<td>Total (45)</td>
<td>8.1%</td>
</tr>
</tbody>
</table>
\( \nu_e \) appearance

- expected number of events in T2K FD:
  \[ 20.4 \pm 1.8 \]
- for \( \sin^2 2\theta_{13} = 0.1, \sin^2 2\theta_{23} = 1.0, \delta_{CP} = 0 \), normal mass hierarchy
- expected background:
  \[ 4.64 \pm 0.53 \]
  - 0.4 – \( \nu_e \) signal (solar term)
  - 0.9 – \( \nu_\mu \) background
  - 3.2 – \( \nu_e \) background
  - 0.3 – anti-\( \nu \) background
- 5.5\( \sigma \) sensitivity to exclude \( \theta_{13} = 0 \)

- 2 independent analyses:
  - neutrino energy spectrum
  - electron momentum and angle distribution
$\nu_e$ appearance result

- **28** events observed
- **7.3\sigma** significance for non-zero $\theta_{13}$

**First ever observation (>5\sigma) of $\nu$ appearance**


**NOTE**: These are 1D contours for various value of $\delta_{CP}$, not 2D contours