T2K: Status and Prospects

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(on behalf of T2K Collaboration)

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Exploration of Particle Physics and Cosmology with Neutrinos Workshop 2019

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The T2K Experiment:

Super-Kamiokande
(ICRR, Univ. Tokyo)

ND280

INGRID

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

295 km
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Ali Ajmi, Kyoto University
Far Detector: 
ν-Oscillation parameters
Near Detectors: Pre-Osc. Flux measurement, 
ν-Interaction/Cross-section measurement
\[
\frac{N_{\text{far}}}{N_{\text{near}}} \sim f(\sigma, \Phi, \text{Det})
\]
Measuring neutrino Cross Sections

\[ N(\vec{x}) = \Phi(E_\nu) \cdot \sigma(E_\nu, \vec{x}) \cdot \epsilon(E_\nu) \cdot P_{ab}(E_\nu, \Delta m^2_{ij}, \theta_{ij}) \]

- Systematic uncertainty important for precision in oscillation results.

- Events ratios at Near and Far detectors do not cancel systematics: owing to different Flux, Cross-sections, Detector-smearing, and Osc. Probability.

- \( \sigma(E_\nu, \vec{x}) \) relate \( E_\nu \) with observables

- Measurement of \( \sigma \) with minimal uncertainty
  \( \Rightarrow \) Reduced Systematics in Osc. analysis @FD
  \( \Rightarrow \) Better goals-designing of future OA experiments
  \( \Rightarrow \) Several measurements needed to constrain and develop \( \nu \)-interaction models

Flux-U.Details @poster: Lukas
The Cross-section Strategy:

- Nuclear & Detector effects obscure true interaction mode
- Sample w.r.t visible outgoing hadron ($\pi$) content
- Sample w.r.t. to #reconstructed tracks
- Measure in: Reconstructed muon momentum and direction.
- Multi-targets: CH and CH+H2O separately, Fe, H2O
- Multi-beam energy peaks: Off-axis: $2.5^\circ \sim 0.6$ GeV; On-axis: $0^\circ \sim 1$ GeV
- Phase space coverage: fwd, bwd, $4\pi$. 
Sample Selection:

- ND280 flux favors $\nu$-CCQE as a major fraction.
- Appropriate selections to ensure high purity of an int. mode. Altered criteria enrich other modes.
- Signal selection efficiency and purity ensuring crucial.
- Primarily: Event quality, total multiplicity, quality and fiducial origin cut, $\mu$-CID multiplicity check etc.
- Other cuts applied depending on the considered target.
As for example in the following sample in FGD1:

- Vetoing with TPC and FGD2 applied
- Additional constraints from the ECAL improve the selection, by reducing the p-bkg.
- Max. Signal efficiency/purity in the $p_{\mu}$ and $\cos \theta_{\mu}$ ensured

$\bar{\nu}$-CC inc.: T2K work in progress
Unfolding the Reconstructed Events:

- An unfolding method used aiming to remove the detector effects in the measurement.
- The flux-avg./int. xsec. is calculated from the unfolded events $N$ in each bin, $N_{\alpha\beta}$.

$$\langle \frac{\delta^2 \sigma}{\delta p_{\mu} \delta \cos \theta_{\mu}} \rangle_{\alpha\beta} = \frac{\hat{N}_{\alpha\beta}}{T \Phi \Delta p_{\mu,\alpha} \Delta \cos \theta_{\mu,\beta}}$$

And finally also obtain total cross section $\sigma$.

- So choice of the **Unfolding method** to be used must be checked to ensure min. MC bias, and convergence of the unfolding process.

- **Unfolding Techniques**: D’Agostini, SVD, TUnfold or binned-likelihood fit and many more available.

- Checks with lots of pseudo data sets. After lot of checks and reviews: unblind the data.

- Forward-folding techniques also used by some.
Cross Section Results from T2K:
CC Inclusive on CH (Off-axis):

- Fwd, Bwd, & High angle selections
- CCQE dominance,
  Flux-integrated Cross Section 
  \( \sim 6.9 \pm 0.7\% \text{ stat.} \pm 8.7\% \text{ fluxU.} \pm 1.8\% \text{ syst.} \times 10^{-39} \text{cm}^2\text{nucleon}^{-1} \)
- Binned likelihood fit,
  unregularised. Fit with both NEUT and GENIE as priors.
CC 0π on CH, H2O (Off-axis):

- CC0π \sim 80\% \text{ CCQE} + 12\% \text{ 2p2h}


- Unfolded with D’Agostini method, MC truth used as prior

- Flux-int. \sigma_{\nu_{\mu}}^{CC0\pi} _{H2O} = 0.95 \pm 8\% \text{ stat.}
  \pm 8\% \text{ fluxU.} \pm 10\% \text{ syst.}
  \times 10^{-38} \text{ cm}^2 \text{nuc}^{-1}

- Compared with other models. Better if 2p2h included.

PRD 97, 012001 (2018), PRD 93, 112012 (2016)
Many More Cross Section results:

- CC $0\pi^+ + p$ on CH (Off-axis, phasespace constraints boosting the efficiency; Standard Transverse variables introduced for probing p): PRD 98, 032003 (2018)

- CC Inclusive on CH, Fe, H2O (On-axis): Paper under prep.

- CC-$1\pi^+$ on CH, H2O (Off-axis): PRD 95 (2017) 012010

- CC$0\pi$ for $\bar{\nu}_\mu$ on H2O (Off-axis): Paper under prep.

- NC1$\pi^\circ$ and CC1$\pi^\circ$ (rate measured: PRD 97 032002 (2018), cross section ongoing).

- $\nu_e/\bar{\nu}_e$ in the FHC/RHC mode: coming soon.

- Several more analyses ongoing: $\bar{\nu}_\mu$ CC-Inc., NC1$\gamma$ etc. etc.
Newer Near Detectors: (Off-Axis)

- The **WAGASCI** detector at 1.5° Off-Axis taking data since 2017
- Cross Section measured with $\bar{\nu}_\mu$ on H2O, CH.

\[
\begin{align*}
\sigma_{\bar{\nu}_\mu}^{\text{H}_2\text{O}} &= [1.082 \pm 0.068\text{(stat.)}^{+0.145}_{-0.128}\text{(syst.)}] \times 10^{-39}\text{cm}^2 \\
\sigma_{\bar{\nu}_\mu}^{\text{CH}} &= [1.096 \pm 0.054\text{(stat.)}^{+0.132}_{-0.117}\text{(syst.)}] \times 10^{-39}\text{cm}^2 \\
\frac{\sigma_{\bar{\nu}_\mu}^{\text{H}_2\text{O}}}{\sigma_{\bar{\nu}_\mu}^{\text{CH}}} &= 0.987 \pm 0.078\text{(stat.)}^{+0.093}_{-0.090}\text{(syst.)} \\
\sigma_{\bar{\nu}_\mu + \nu_\mu}^{\text{H}_2\text{O}} &= [1.155 \pm 0.064\text{(stat.)}^{+0.148}_{-0.129}\text{(syst.)}] \times 10^{-39}\text{cm}^2 \cdot \text{nucleon}^{-1} \\
\sigma_{\bar{\nu}_\mu + \nu_\mu}^{\text{CH}} &= [1.159 \pm 0.049\text{(stat.)}^{+0.129}_{-0.115}\text{(syst.)}] \times 10^{-39}\text{cm}^2 \cdot \text{nucleon}^{-1} \\
\frac{\sigma_{\bar{\nu}_\mu + \nu_\mu}^{\text{H}_2\text{O}}}{\sigma_{\bar{\nu}_\mu + \nu_\mu}^{\text{CH}}} &= 0.996 \pm 0.069\text{(stat.)}^{+0.083}_{-0.078}\text{(syst.)}
\end{align*}
\]
Oscillation Studies at the FAR detector: T2K-SK

![Graph showing accumulated POT and beam power over years](image)

- Total Accumulated POT for Physics
- \(\nu\)-Mode Accumulated POT for Physics
- \(\bar{\nu}\)-Mode Accumulated POT for Physics
- \(\nu\)-Mode Beam Power
- \(\bar{\nu}\)-Mode Beam Power

\(\times 10^{20}\)
The Oscillation Measurements: Super-Kamiokande

(General details already covered in Roger’s talk)

- $\nu_\mu$ Disappearance: Precision measurement of $\theta_{23}$ and $\Delta m^2_{32}$
- $\nu_e/\bar{\nu}_e$ Appearance: $\delta_{CP}$

Octant degeneracy? CP violation?
Order of Mass Hierarchy?

The Analysis Strategy (Conceptual):

- Flux predictions
- Super-Kamiokande flux
- Geometry
- INGRID data
- Super-K atmospheric analysis
- Detector response
- Super-K beam data
- Super-K prediction

Phys. Rev. D 96, 011102
Analyses & Results:

- Improved reconstruction & classifier
- Expanded Fiducial Volume
- Select events with no pions ($\nu_e 1\pi^+$)

$$E_{QE}^\nu = \frac{m^2_p - m^2_n - m^2_\mu + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos \theta_\mu)}$$

- Fit is done simultaneously to all five data samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Predicted</th>
<th>Observed</th>
<th>Systematic uncertainty for prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ mode $\mu$-like</td>
<td>$\delta_\text{CP} = -\pi/2$</td>
<td>272.4</td>
<td>272.0</td>
</tr>
<tr>
<td>$\bar{\nu}$ mode $\mu$-like</td>
<td>$\delta_\text{CP} = 0$</td>
<td>139.5</td>
<td>139.2</td>
</tr>
<tr>
<td>$\nu$ mode $e$-like</td>
<td>$\delta_\text{CP} = +\pi/2$</td>
<td>74.4</td>
<td>62.2</td>
</tr>
<tr>
<td>$\bar{\nu}$ mode $e$-like</td>
<td>$\delta_\text{CP} = \pi$</td>
<td>17.1</td>
<td>19.4</td>
</tr>
<tr>
<td>$\nu$ mode $e$-like + 1$\pi^+$</td>
<td>$\delta_\text{CP} = -\pi/2$</td>
<td>7.0</td>
<td>6.1</td>
</tr>
</tbody>
</table>
Results from T2K-SK data:

- Focusing $\delta_{CP} \sim -\pi/2$, 2σ confidence interval

- Including reactor constrain, matches PDG2018 value: $\sin^2 \theta_{13} = 0.0212$

Maximal mixing favored

Ali Ajmi, Kyoto University 19 14 June, 2019
Status Summary and Prospects:

- T2K has added more new $\bar{\nu}$-data in the analyses.
- Oscillation Results updated; $2\sigma$ in deciding CP-violation.
- T2K-near detectors: on-axis, off-axis: Cross sections measured for several samples, several still on-going.
- T2K near detectors (ND280/WAGASCI/BABYMIND) and beamline upgrade to allow 750 kW–1.3 MW: to set for obtaining $3\sigma$ in deciding CP-violation.
Status Summary and Prospects: (contd...)  
- New off-axis WAGASCI already started  
- BABYMIND being integrated, to add charge id-capability to WAGASCI  
- Ongoing efforts to install the ND280-Upgrade very soon  

Details talked at Kenji/Giorgio posters

More@posters: Soichiro, Takuji, Yuki
Thank you!
Back ups:
We define for every bin $k$:

$$
\hat{N}_k = \sum_{j}^{n_r} U_{jk} (N_{j}^{sel} - B_{j}) / \epsilon_k.
$$  \hspace{1cm} (1)

- the selected events in reconstructed bin $j = 1, \ldots, n_r$: $N_{j}^{sel}$.
- the background events in reconstructed bin $j$: $B_{j}$.
- the generated events in true bin $k = 1, \ldots, n_t$: $N_{k}$.

The smearing matrix $S_{jk} = \text{the number of events generated in the } k\text{-th bin and reconstructed in the } j\text{-th bin.}$

- the probability to have an event reconstructed in the bin $j$ when it has been generated in the true bin $k$: $P(j|k) = \frac{S_{jk}}{N_k}$.

- the probability that an event was generated in the truth bin $k$ given that it was reconstructed in bin $j$: $U_{jk}$ (unfolding matrix)

$$
U_{jk} = \frac{S_{jk} \sum_{k} N_{k}}{\sum_{\alpha}^{n_t} (\frac{S_{j\alpha}}{N_{\alpha}} \sum_{\alpha} N_{\alpha})} = \frac{S_{jk}}{\sum_{\alpha}^{n_t} S_{j\alpha}}
$$  \hspace{1cm} (2)

$$
\epsilon_k = \frac{\sum_{j}^{n_r} S_{jk}}{N_k}
$$  \hspace{1cm} (3)
Effect of ND280-fit on SK-analyses:

<table>
<thead>
<tr>
<th>Sample</th>
<th>w/o ND280</th>
<th>w/ND280</th>
</tr>
</thead>
<tbody>
<tr>
<td>FHC 1R_μ</td>
<td>14.6%</td>
<td>5.1%</td>
</tr>
<tr>
<td>RHC 1R_μ</td>
<td>12.5%</td>
<td>4.5%</td>
</tr>
<tr>
<td>FHC 1R_e</td>
<td>16.9%</td>
<td>8.8%</td>
</tr>
<tr>
<td>RHC 1R_e</td>
<td>14.4%</td>
<td>7.1%</td>
</tr>
</tbody>
</table>
The Oscillation Probability:

\[
P(\nu_\mu \rightarrow \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31} \times \left( 1 \pm \frac{2a}{\Delta m_{31}^2} \left( 1 - s_{13}^2 \right) \right) \\
\qquad + 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos \delta - s_{12} s_{13} s_{23}) \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21} \\
\qquad \pm 8c_{13}^2 s_{13}^2 s_{23} \cos \Delta_{32} \sin \Delta_{31} \frac{a L}{4 E} (1 - 2s_{13}^2) \\
\qquad \pm 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin \delta \sin \Delta_{32} \sin \Delta_{31} \sin \Delta_{21} \\
\qquad + 4s_{12}^2 c_{13}^2 (c_{12} c_{23}^2 + s_{12}^2 s_{23}^2 - 2c_{12} c_{23} s_{12} s_{13} s_{23} \cos \delta) \sin^2 \Delta_{21}
\]

Leading term

CP Conserving

Matter effect

CP Violating

Solar term

\[c_{\nu} = \cos \theta_{\nu} \quad s_{\nu} = \sin \theta_{\nu} \quad \Delta_{31} = \Delta m_{31}^2 \frac{L}{4 E_{\nu}} \quad a = 2\sqrt{2} G_F n_e E\]

Disappearance

\[
P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \left( \cos^4 \theta_{13} \cdot \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \cdot \sin^2 \theta_{23} \right) \cdot \sin^2 \frac{\Delta m_{32}^2 \cdot L}{4 E_{\nu}}
\]