Latest Results and Future Prospects from T2K

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NuFact 2017 Uppsala Sweden
25 – 30 September 2017
Neutrino Oscillations

- Neutrino oscillation is a consequence of non-degenerate neutrino masses and flavour mixing. Flavour states are linear superpositions of mass states with a mixing matrix as:

\[ |\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}^* |\nu_i\rangle \]

- Neutrinos are produced and interact in the flavour states, and propagate as the mass states. Therefore, a neutrino can change its flavour in flight. → **Neutrino Oscillation!**

- Neutrino oscillations are observed in
  - solar and atmosphere neutrinos detected on Earth.
  - accelerator- or reactor-produced neutrino beam measured at detectors far from its production.
Tokai-to-Kamioka

- Long-baseline neutrino oscillation experiment in Japan.
- ~500 collaborators, 62 institutes, 11 countries.
T2K Design

Beam Facilities
T2K Design

Near Detectors
T2K Design

J-PARC 30GeV proton beam

target & 3horns

beam dump

muon monitor

30 GeV

π

μ

decay volume

Off-axis ND

Off-axis angle 2.5 deg.

On-axis ND (INGRID)

Super-K

beam axis

295 km

Far Detector
T2K Beam

- 30 GeV proton beam on graphite target to produce secondary particles.
- The secondary particles decay in the decay volume to produce neutrinos.
- Off-axis configuration (2.5 degrees).
T2K Near Detectors

- On-axis detector: INGRID
- Iron/Scintillator detectors.
- Measure beam profile and event rates on daily basis.
T2K Near Detectors

- Off-axis detector: ND280
- Detectors are enclosed in the magnet.
- Trackers
  - 3 Time Projection Chambers (TPCs)
  - 2 Fine-grained Detectors (FGDs)
- $\pi^0$-detector (P0D) is placed in front of the trackers.
- Electromagnetic calorimeters (ECAL) surround the trackers and P0D. Muon range detectors are installed in between the magnet.
T2K Far Detector

- 50 kiloton water-Cherenkov detector.
- Charged particles above Cherenkov threshold produce Cherenkov light detected by the PMTs.
- T2K signal: single ring events for charged-current quasi-elastic (CCQE) interactions of muon/electron neutrinos.
T2K Far Detector

- 50 kiloton water-Cherenkov detector.
- Charged particles above Cherenkov threshold produce Cherenkov light detected by the PMTs.
- T2K signal: single ring events for charged-current quasi-elastic (CCQE) interactions of muon/electron neutrinos.
POT History

- Data collected: protons on target (POT) history.

![Graph showing POT history](image)

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

Accumulated POT

$\times 10^{20}$

$\nu$ mode $14.7 \times 10^{20}$ POT

$\bar{\nu}$ mode $7.56 \times 10^{20}$ POT

Beam Power (kW)

Sep 26 2017
Oscillations at T2K
Oscillations at T2K

\[ P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{32} \]
\[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{32} \]
\[ P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1-x)\Delta_{31}]}{(1-x)^2} \]
\[ + \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(x \Delta_{31})}{x} \frac{\sin[(1-x)\Delta_{31}]}{(1-x)} \]
\[ (\sin \delta_{CP} \sin \Delta_{31} + \cos \delta_{CP} \cos \Delta_{31}) \]
\[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1+x)\Delta_{31}]}{(1+x)^2} \]
\[ + \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(x \Delta_{31})}{x} \frac{\sin[(1+x)\Delta_{31}]}{(1+x)} \]
\[ (\sin \delta_{CP} \sin \Delta_{31} + \cos \delta_{CP} \cos \Delta_{31}) \]

\[ \Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E_\nu}, \quad x = \frac{2\sqrt{2}G_F N_e E_\nu}{\Delta m_{31}^2} \]

Opposite signs for the matter effects terms and CP phase!

Neutrino/anti-neutrino oscillation probabilities with matter effects.

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Oscillations at T2K

\[ P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{32} \]
\[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{32} \]

\[ P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1-x)\Delta_{31}]}{(1-x)^2} \]
\[ + \left| \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \right| \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(x\Delta_{31})}{x} \frac{\sin[(1-x)\Delta_{31}]}{(1-x)} \left( -\sin \delta_{CP} \sin \Delta_{31} + \cos \delta_{CP} \cos \Delta_{31} \right) \]

\[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1+x)\Delta_{31}]}{(1+x)^2} \]
\[ + \left| \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \right| \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(x\Delta_{31})}{x} \frac{\sin[(1+x)\Delta_{31}]}{(1+x)} \left( +\sin \delta_{CP} \sin \Delta_{31} + \cos \delta_{CP} \cos \Delta_{31} \right) \]

\[ \Delta m_{32}^2 : \text{sign can be determined by the matter effect} \]
\[ \sin^2 \theta_{23} \text{ instead of } \sin^2 2\theta_{23} \]
\[ \sin^2 2\theta_{13}, \delta_{CP} \]
Oscillations at T2K

\[
P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{32}
\]

\[
P(\bar{\nu}_\mu \to \bar{\nu}_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{32}
\]

\[
P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1 - x)\Delta_{31}]}{(1 - x)^2}
\]

\[+ \left| \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \right| \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(x\Delta_{31}) \sin[(1 - x)\Delta_{31}]}{x(1 - x)} \left( -\sin \delta_{CP} \sin \Delta_{31} + \cos \delta_{CP} \cos \Delta_{31} \right) \]

\[
P(\bar{\nu}_\mu \to \bar{\nu}_e) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1 + x)\Delta_{31}]}{(1 + x)^2}
\]

\[+ \left| \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \right| \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(x\Delta_{31}) \sin[(1 + x)\Delta_{31}]}{x(1 + x)} \left( +\sin \delta_{CP} \sin \Delta_{31} + \cos \delta_{CP} \cos \Delta_{31} \right) \]

→ Joint Analysis: combine $\nu/\bar{\nu}$ oscillations
Analysis Overview

- Compare the neutrino events observed at SK to the MC predictions. The MC predictions involve modelling of the flux, the neutrino interactions and detection efficiency as:

\[ N_{SK}^{\text{prediction}} \sim \sum_{i} P(\nu_i \rightarrow \nu_k) \Phi_i^{SK} \sigma_k \epsilon_{SK} \] (predicted number of \( \nu_k \) at SK ; \( k = e, \mu \))

- ND280 measurements are used to constrain the flux and neutrino interaction uncertainties. Charged-current neutrino interactions are included in ND280 samples as:
  
  \( \nu \) mode: \( \mu^- \) CC0\( \pi \), \( \mu^- \) CC1\( \pi \), \( \mu^- \) CCN\( \pi \) in FGD1/2

  \( \bar{\nu} \) mode: \( \mu^+ \) 1-track, \( \mu^+ \) N-track, \( \mu^- \) 1-track, \( \mu^- \) N-track in FGD1/2

See more details on systematics in the analysis at Systematic Uncertainties in Neutrino Oscillation Measurements by D. Hadley; September 27th;
ND280 Fit

\[\mu^- \text{ CC0}\pi\]

\[\mu^+ \text{ 1-track}\]

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ND280 Fit

Flux Predictions
- proton beam properties/flux
- hadronic production on graphite
- propagation/decay of hadrons

Neutrino Interaction Models
- nuclear models
- axial mass $M^{QE}_A$
- 2p-2h contributions
- and other more...

Flux and neutrino interaction model parameters are fit to ND280 data.
→ constrain the parameters!
→ reduce the uncertainties!
ND280 Fit

\[ \mu^- \text{ CC0}\pi \]

\[ \mu^+ \text{ 1-track} \]

\[ \bar{\nu} \text{ mode} \]

\[ \nu \text{ mode} \]

Post-Fit
Flux parameters are updated after ND280 fit.
Post-fit parameters and covariance matrices are input to the oscillation analysis.
Cross-section parameters are updated after ND280 fit. Large changes to the cross-section models. Post-fit parameters and covariance matrices are input to the oscillation analysis.
SK Data

- Observed events at SK with neutrino beam.
- New fiducial volume and reconstruction algorithm!
  - 30 % more statistics with better purity/efficiency.
- Three samples:
  - $\nu_e$ CCQE (1e ring) (top-left)
  - $\nu_e$ CC$\pi^+$ (1e ring) (bottom-left)
  - $\nu_\mu$ CCQE (1$\mu$ ring) (top-right)
SK Data

- Observed events at SK with anti-neutrino beam.
- New fiducial volume and reconstruction algorithm!
  - 30% more statistics with better purity/efficiency.
- Two samples:
  - $\bar{\nu}_e$ CCQE (1e ring) (top-left)
  - $\bar{\nu}_\mu$ CCQE (1$\mu$ ring) (top-right)
- No single pion sample here due to $\pi^-$ absorption.
Results

- With reactor constraint:
  - $\sin^2 2\theta_{13} = 0.085 \pm 0.05$
- Consistent with maximal mixing.
- Preliminary contours. Update expected from neutrino interaction model uncertainties.

See more details at Oscillation results and plans from the T2K experiment by P. Dunne; September 27th;
Results: Possible Impact

Shift in the contours. Normal hierarchy is assumed.

(a) $\sin^2 \theta_{23} - \Delta m^2_{23}$

See more details at *The T2K cross-section results and prospects from the oscillation perspective* by K. Nakamura; September 26th;
Results

- With reactor constraint: $\sin^2 2\theta_{13} = 0.085 \pm 0.05$
- $\sin \delta_{CP} = 0$ is excluded at $2\sigma$.
- $2\sigma$ C.L. intervals are shown on the right plot.

See more details at *Oscillation results and plans from the T2K experiment* by P. Dunne; September 27th;
Cross sections at T2K
Neutrino Interactions

- Accurate knowledge of the neutrino interaction reduces uncertainties on the oscillation analysis.
- Probe the weak interaction.
- Probe nuclear effects.
  - Final State Interaction (FSI)
  - Multi-nucleon processes
Cross sections at T2K

- **Targets**: carbon and oxygen
- **Interaction Channels**: main signal at T2K is charged-current quasi-elastic (CCQE) scattering with significant backgrounds from Charged-current resonance (CCRES) which is sub-dominant channel at T2K energy.
Cross sections at T2K

- **Targets**: carbon and oxygen

- **Interaction Channels**: main signal at T2K is charged-current quasi-elastic (CCQE) scattering with significant backgrounds from Charged-current resonance (CCRES) which is sub-dominant channel at T2K energy. As we only can observe the interactions by final state particles, signals are defined as final state topology.
Cross sections at T2K

CCQE

Detector mis-reconstruction
FSI

CC0π (CCQE-like)

CC1π (CCRES-like)
Cross sections at T2K

- **Targets**: carbon and oxygen

- **Interaction Channels**: main signal at T2K is charged-current quasi-elastic (CCQE) scattering with significant backgrounds from Charged-current resonance (CCRES) which is sub-dominant channel at T2K energy. As we only can observe the interactions by final state particles, signals are defined as final state topology.
Cross sections at T2K

- Nuclear Correlations
- Multi-nucleon Currents
- Fermi Motion
- Final State Interactions (FSI)

Multi-nucleon ejection
Alter the CCQE kinematics

Main signal

Detector mis-reconstruction FSI

CCQE

CCRES

CC0π (CCQE-like)

CC1π (CCRES-like)
Cross sections at T2K

started looking at hadronic side to probe nuclear effects!

This talk will focus on the $CC0\pi$ and $CC0\pi Np$ measurements. See more details at *T2K recent results of cross section measurements* by C. Riccio; September 25th;
Results

- **CC0\(\pi\)** double-differential cross section in muon kinematics.

\[
\begin{align*}
0.00 &< \text{true } \cos\theta_\mu < 0.60 \\
\end{align*}
\]

**carbon**

arXiv:1602.03652

**oxygen**

T2K Preliminary
arXiv:1708.06771
Results

- CC0πNp differential cross section in **proton** related variables.
- Two analyses with different sets of variables.

Analysis I

- 3D Projection
- Reconstructed kinematics
- Inferred kinematics
- Difference

Reference:
Phys. Rev. C 94, 015503
arXiv:1512.05748

Analysis II

- ν Transverse Plane
- Reconstructed kinematics
- Inferred kinematics
- Difference

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Results

- CC0πNp  differential cross section in single transverse variables.
- Analysis I : Project proton/muon kinematics on the transverse plane of the neutrino beam.
- Shows interesting sensitivity to numerous nuclear effects.
Results

- CC0πNp  differential cross section in proton kinematic imbalance.

- Analysis II: Inferred proton kinematics from muon kinematics, and compared to the observed proton kinematics, expecting imbalance for any non-CCQE contributions.

- Momentum difference in different interaction modes.
  - Deviation for non-CCQE contributions.
  - CCQE distribution is centred at zero with some deviation due to FSI (e.g. proton re-scattering).

![NEUT Prediction graph with CCQE, CC1π+, and 2p2h distributions](image-url)
Future Perspectives

- Approved for $7.8 \times 10^{21}$ POT by 2021, and proposal (arXiv:1609.04111) to extend the operation for $20.0 \times 10^{21}$ POT with
  - Beam power upgrade: will be increased from 450 kW to 1.3 MW.
  - Possible near detector upgrade.
- Exclude CP conserving hypothesis at $3\sigma$.
- Reduce the systematic uncertainties.
Future Perspectives

- New near detector design is proposed to have better acceptance and more target.

- Keeping the main trackers and replace P0D with two horizontal TPCs and a horizontal scintillator detector.

See more details at *Upgrade of the T2K near detector ND280: effect on oscillation and cross-section analyses* by M. Lamoureux; September 29th;
Conclusions

- Combined neutrino and anti-neutrino analysis with doubled neutrino statistics and improved SK measurements has been shown.
- CP conservation is disfavoured at $2\sigma$ C.L.
- $CC0\pi$ measurements indicated the data is more in favour with multinucleon contributions. But we do not know how or how much it will contribute to the data.
  - started looking at hadronic side as well, moving to $CC0\pi Np$
- In addition to $CC0\pi$ measurements, there are also other cross-section measurements such as $\nu_\mu CC1\pi^+$, and $\bar{\nu}_\mu/\nu_e CC$ inclusive.
- Proposal to extend run until 2026 to collect 3 times more POT. It will achieve $3\sigma$ sensitivity.
Back Up
SK Updates

- Since 2016, there have been improvements on SK side.
  - New fiducial volume: ~ 30 % more statistics.
  - New sample: CC1π⁺ has been included.
    - Additional e-like ring is required for the michel electron.
    - Gain ~ 10 % more statistics.
    - Applied only to neutrino mode. For anti-neutrino mode, π⁻ is absorbed.
  - New reconstruction algorithm uses charge and time likelihood.
    - Selection efficiency and purity have been improved.
## SK Systematics

<table>
<thead>
<tr>
<th>Error Source</th>
<th>1R ( \mu )-Like</th>
<th>1R ( e )-Like</th>
<th>1R ( \mu )-Like</th>
<th>1R ( e )-Like</th>
<th>1R ( \mu )-Like</th>
<th>1R ( e )-Like</th>
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<tbody>
<tr>
<td></td>
<td>FHC</td>
<td>RHC</td>
<td>FHC</td>
<td>RHC</td>
<td>FHC CC1( \pi )</td>
<td>FHC/RHC</td>
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<tr>
<td>SK Detector</td>
<td>1.86</td>
<td>1.51</td>
<td>3.03</td>
<td>4.22</td>
<td>16.69</td>
<td>1.60</td>
</tr>
<tr>
<td>SK FSI+SI+PN</td>
<td>2.20</td>
<td>1.98</td>
<td>3.01</td>
<td>2.31</td>
<td>11.43</td>
<td>1.57</td>
</tr>
<tr>
<td>ND280 const. flux &amp; xsec</td>
<td>3.22</td>
<td>2.72</td>
<td>3.22</td>
<td>2.88</td>
<td>4.05</td>
<td>2.50</td>
</tr>
<tr>
<td>( \sigma(v_e)/\sigma(v_\mu) ), ( \sigma(v_e)/\sigma(v_\mu) )</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>
</tr>
<tr>
<td>NC1( \gamma )</td>
<td>0.00</td>
<td>0.00</td>
<td>1.08</td>
<td>2.59</td>
<td>0.33</td>
<td>1.49</td>
</tr>
<tr>
<td>NC Other</td>
<td>0.25</td>
<td>0.25</td>
<td>0.14</td>
<td>0.33</td>
<td>0.98</td>
<td>0.18</td>
</tr>
<tr>
<td>Total Systematic Error</td>
<td>4.40</td>
<td>3.76</td>
<td>6.10</td>
<td>6.51</td>
<td>20.94</td>
<td>4.77</td>
</tr>
</tbody>
</table>
Flux Simulation Inputs

- The proton beam properties measured at the beam monitor.
- Hadron production on graphite is simulated (FLUKA2011) with external data from NA61/SHINE.
- Propagation of hadrons is simulated with GEANT3.
- INGRID measures the neutrino beam direction/centre.
The overall uncertainties on the flux prediction is 8~12 %.

The main source of the uncertainties is hadron interaction modelling.
Systematics with Fit

Fractional uncertainties (%) on the observed neutrino events at SK.

<table>
<thead>
<tr>
<th></th>
<th>$\nu_\mu$</th>
<th>$\nu_e$</th>
<th>$\bar{\nu}_\mu$</th>
<th>$\bar{\nu}_e$</th>
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<tr>
<td>Pre-fit</td>
<td>7.6</td>
<td>8.9</td>
<td>7.1</td>
<td>8.0</td>
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<tr>
<td>Post-fit</td>
<td>2.9</td>
<td>4.2</td>
<td>3.4</td>
<td>4.6</td>
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<tr>
<td>Flux</td>
<td>7.7</td>
<td>7.2</td>
<td>9.3</td>
<td>10.1</td>
</tr>
<tr>
<td>Cross section</td>
<td>7.7</td>
<td>4.2</td>
<td>3.4</td>
<td>4.6</td>
</tr>
<tr>
<td>Total</td>
<td>12.0</td>
<td>5.0</td>
<td>5.4</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Systematics with Fit

Fractional uncertainties (%) on the observed neutrino events at SK.
ND280 Fitted Parameters

Correlation between parameters (flux and cross-section models) before ND280 fit.
ND280 Fitted Parameters

Correlation between parameters (flux and cross-section models) after ND280 fit.
Likelihood Function

\[-\ln(L) = \sum_{i}^{N_{SK\text{bins}}} N_{i}^{SK} (\bar{\theta}, \bar{p}) - M_{i}^{SK} + M_{i}^{SK} \ln[M_{i}^{SK}/N_{i}^{SK} (\bar{\theta}, \bar{p})] \]

Measured (M) and predicted (N) number of events at SK

\[+ \frac{1}{2} \sum_{i}^{N_{\text{const}}} \sum_{j}^{N_{\text{const}}} \Delta o_{i} (V_{ij}^{o})^{-1} \Delta o_{j} + \frac{1}{2} \sum_{i}^{N_{p}} \sum_{j}^{N_{p}} \Delta p_{i} (V_{ij}^{p})^{-1} \Delta p_{j} . \]

Penalty term due to oscillation parameter systematics

Penalty term due to model parameter systematics
Fakedata Studies

- Motivation: In ND280 fit, model and flux parameters are fitted simultaneously. What if there is 3p-3h in nature, not yet in MC?
  - Deficit in MC. ND280 fit can increase flux to overcome.
  - This fitted flux goes into SK and will alter the oscillation analysis.
- Fakedata studies examine any potential bias by a choice of cross-section models.
- Data-driven fakedata sets are generated to use. In MC, one of neutrino interaction modes are enhanced to account for the difference in data and model predictions.
  - ND280 and MINERvA data are used.
T2K-II POT Request

Assumed avg. MR beam power [kW]
Total Integrated POT by the end of JFY
Expected POT in Each T2K-Run Period (POT accumulated in Oct. ~ next Jun.)
# Main Ring Plan

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<tr>
<td>FX power [kW]</td>
<td>390</td>
<td>470</td>
<td>480-500</td>
<td>&gt; 500</td>
<td>700</td>
<td>800</td>
<td>900</td>
<td>1060</td>
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<tr>
<td>SX power [kW]</td>
<td>42</td>
<td>42</td>
<td>50</td>
<td>50-60</td>
<td>60-80</td>
<td>80</td>
<td>80-100</td>
<td>100</td>
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<tr>
<td>Cycle time of main magnet PS</td>
<td>2.48 s</td>
<td>2.48 s</td>
<td>1.3 s</td>
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<td>New magnet PS</td>
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<tr>
<td>High gradient rf system</td>
<td>Installation</td>
<td>Manufacture, installation/test</td>
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<td>2nd harmonic rf system</td>
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<td>Mass production installation/test</td>
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<td>Ring collimators</td>
<td>Add. collimators (2 kW)</td>
<td>Add. coll. (3.5 kW)</td>
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<tr>
<td>Injection system</td>
<td>Kicker PS improvement, Septa manufacture /test</td>
<td>Kicker PS improvement, FX septa manufacture /test</td>
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<td>FX system</td>
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<td>SX collimator / Local shields</td>
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<td>Ti ducts and SX devices with Ti chamber</td>
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<td>ESS</td>
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</table>
Neutrino Oscillations

- Neutrino mixing matrix in the standard 3-flavor mixing:

\[
U = \begin{pmatrix}
    c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
    -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\
    s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}
\end{pmatrix}
\]

where \(c_{12} = \cos \theta_{12}, s_{12} = \sin \theta_{12}\)

- There are six oscillation parameters: \(\Delta m_{21}^2, \Delta m_{32}^2, \theta_{12}, \theta_{23}, \theta_{13}, \delta_{\text{CP}}\)

- Global fits

<table>
<thead>
<tr>
<th>Parameter</th>
<th>best fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta m_{21}^2 (10^{-5} eV^2))</td>
<td>(7.54^{+0.26}_{-0.22})</td>
</tr>
<tr>
<td>(\Delta m_{32}^2 (10^{-3} eV^2))</td>
<td>(2.43 \pm 0.96 (2.38 \pm 0.06))</td>
</tr>
<tr>
<td>(\sin^2 \theta_{12})</td>
<td>(0.308 \pm 0.017)</td>
</tr>
<tr>
<td>(\sin^2 \theta_{23})</td>
<td>(0.437^{+0.033}<em>{-0.023} (0.455^{+0.039}</em>{-0.031}))</td>
</tr>
<tr>
<td>(\sin^2 \theta_{13})</td>
<td>(0.0234^{+0.0020}<em>{-0.0019} (0.0240^{+0.0019}</em>{-0.0022}))</td>
</tr>
</tbody>
</table>

- Open Questions
  - Mass hierarchy
  - CP violation phase
  - Dirac or Majorana
Cross-section Results

- **CC1π⁺** differential cross section in pion kinematics.

T2K Preliminary


- Carbon
- Oxygen
Cross-section Results

- Anti-neutrino CC inclusive on carbon.
- Differential cross section in muon kinematics.
Sensitivity to the Efficiency

Cross-section Extraction: $\nu_\mu$ inclusive CC cross-section measurement on C at T2K at NuInt 2017

Goal -> double-differential $(p_\mu, \cos\theta_\mu)$ cross section $\nu_\mu$ CC inclusive on plastic*  

*C[86%]H[7%]O[4%]

- Efficiency correction using NEUT 5.3.0 and GENIE 2.8.0 predictions.
  - Discrepancies for low momentum muons going forward (in RES and DIS channels).