Latest T2K results: leptonic CP violation in sight?

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Neutrino oscillations

- Neutrinos are neutral leptons that interact weakly
- Very big detectors to collect enough neutrino interactions
- A neutrino mass eigenstate can be described as a linear combination of neutrino flavor eigenstates
- Amount of each flavor varies in \( L(\text{distance}) \) / \( E(\text{energy}) \)

Amplitude: determined by mixing matrix \( U_{\alpha i} \)

Pontecorvo-Maki-Nakagawa-Sakata (PMNS)

Neutrinos oscillate \( (\Delta m^2_{ij} \neq 0) \) \( \rightarrow \) neutrinos have non-zero mass
\[ c_{ij} = \cos \theta_{ij} \]
\[ s_{ij} = \sin \theta_{ij} \]

\[ U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i \delta_{CP}} \\
0 & 1 & 0 \\
-s_{13} e^{i \delta_{CP}} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\[ \Delta m_{21}^2 \sim 2.5 \times 10^{-3} \text{ eV}^2 \]
\[ \Delta m_{32}^2 \sim 7.5 \times 10^{-5} \text{ eV}^2 \]

\[ \sin^2 \theta_{23} \sim 0.5 \]
\[ \sin^2 2\theta_{13} \sim 0.085 \]
\[ \sin^2 \theta_{12} \sim 0.85 \]

\[ |\Delta m_{32}^2| \sim 2.5 \times 10^{-3} \text{ eV}^2 \]

\[ \delta_{CP} \text{ not known} \]
\[ \text{MH not known} \]

**Mass hierarchy (MH):**
- Normal (NH): \( m_3 > m_2 > m_1 \) \( \rightarrow \Delta m_{32}^2 > 0 \)
- Inverted (IH): \( m_2 > m_1 > m_3 \) \( \rightarrow \Delta m_{32}^2 < 0 \)

**CP symmetry is violated in lepton sector if** \( \delta_{CP} \neq 0, \pi \)**
How to measure neutrino oscillations

- $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x)$: look for a deficit on the number of events consistent with an oscillatory pattern (disappearance)
- $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$: look for an excess of events consistent with an oscillatory pattern (appearance)

Monte Carlo (MINOS experiment)
(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35 \times 10^{-3}$ eV$^2$)
The T2K collaboration

~400 researchers, 59 institutes, 11 countries
The T2K experiment

- Intense muon (anti)neutrino beam from J-PARC to Super-Kamiokande (Japan) where oscillations occur (295 km from target production)
- Unoscillated neutrino flux is measured at the near detector (~280m)
- Precise measurements of
  - muon (anti)neutrino disappearance
  - electron (anti)neutrino appearance
Neutrino oscillations at T2K

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

- Precise measurement of \( \sin^2 2\Theta_{23} \)
- Test of CPT by comparing measured \( \nu_\mu \to \nu_\mu \) with \( \bar{\nu}_\mu \to \bar{\nu}_\mu \)

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

M. Freund, Phys.Rev. D64 (2001) 053003

- Leading term

**CP violating** \(- \alpha \sin \delta_{CP} \times \sin^2 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin \Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \)

**CP conserving** \( \alpha \cos \delta_{CP} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \cos \Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \) + \( O(\alpha^2) \)

\[ x = \frac{2\sqrt{2} G_F N_e E}{\Delta m_{31}^2} \] \[ \alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \sim \frac{1}{30} \] \[ \Delta = \frac{\Delta m_{31}^2 L}{4E} \]

- The leading term defines the octant \( \Theta_{23} > 45^\circ \) or \( \Theta_{23} < 45^\circ \)
- \( \Theta_{13} \) precisely measured by the reactor experiments
- Second order term can violate the CP symmetry if \( \delta_{CP} \neq 0,\pi \)

\( E \sim 0.6 \) GeV \n\( L \sim 295 \) km
Effect of CP violation at T2K

- $\delta_{CP} \neq 0, \pi$ ($\Theta_{13}$ is non-zero) $\rightarrow$ violate the CP symmetry
- Asymmetric effect on $P(\nu_{\mu} \rightarrow \nu_{e})$ and $P(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e})$:
  - $\delta_{CP} = -\pi/2 \rightarrow$ maximize $P(\nu_{\mu} \rightarrow \nu_{e})$ and minimize $P(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e})$
  - $\delta_{CP} = +\pi/2 \rightarrow$ minimize $P(\nu_{\mu} \rightarrow \nu_{e})$ and maximize $P(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e})$
- Mass Hierarchy enhanced by matter effects. Effect of $\sim 10\%$ on $\nu_{\mu} \rightarrow \nu_{e}$ and $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$
- T2K baseline not long enough to provide good sensitivity to Mass Hierarchy
- $\delta_{CP}$ and Mass Hierarchy have similar effects on $\nu_{\mu} \rightarrow \nu_{e}$ and $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$
Neutrino beam production

- Invert magnet polarity to produce a $\bar{\nu}_\mu$ beam
- $\nu_\mu$ and $\bar{\nu}_\mu$ produced by pion and Kaon decay:
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
- <1% $\nu_e$ contamination from $\mu$ and K decay
- Muon Monitor for stability of the beam
- 2.5° off-axis neutrino beam
  - spectrum peaked at 0.6 GeV, on the expected oscillation maximum

- 30 GeV proton beam on 90cm long graphite target
- L=295 km

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- 2.5º off-axis neutrino beam
  - spectrum peaked at 0.6 GeV, on the expected oscillation maximum
  - mainly Charged Current Quasi Elastic (CCQE)
    $\nu_\mu + n \rightarrow \mu^- + p$ and $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
- Large uncertainties on hadron production
Hadron production measurement with NA61/SHINE

- Theoretical models do not describe well the production of neutrino parents in forward direction because not perturbative QCD
- Large acceptance detector with very good capabilities of momentum, charge and mass measurements
- Cover almost the full T2K phase space
- Measure pions, protons and Kaons production with a 31 GeV/c proton beam on a carbon target
  - Thin 2cm target (4%\(\lambda_i\)) (Eur. Phys. J. C 76, 84 (2016))
  - T2K replica target (arXiv:1603.06774 accepted for publication in EPJC)

Located in the CERN North Area
Neutrino and AntiNeutrino flux prediction

- Thanks to the NA61/SHINE the hadron production measurements the flux systematic uncertainty is reduced from ~30% to ~10%
T2K near detector complex

**INGRID (on-axis)**
- Iron/scintillator tracking calorimeters
- 16 modules
- Measure the neutrino beam intensity and direction

**ND280 (2.5° off-axis)**
- 0.2T dipole magnet (recycled from UA1)
- Electromagnetic Calorimeter (ECal)
- $\pi^0$ detector (P0D)
- SMRD (Side Muon Range Detector)

- 2 Fine Grain Detectors (FGDs)
  - FGD1: only plastic scintillator
  - FGD2: 50%:50% water:scintillator
  - 1.6 ton fiducial mass for analysis
  - constrain water xsec at Super-K
- Time Projection Chamber (TPC)
  - better than 10% dE/dx resolution
  - 10% momentum resolution at 1GeV/c
• Now neutrino interactions are selected and measured both in carbon (FGD1) and water (FGD2)
• FGD2 - FGD1 subtraction provides the measurement of neutrino cross section in water. Better constraint for neutrino interactions at far detector (water)
• Also samples of wrong-sign background (i.e. $\nu_\mu$ contamination in $\bar{\nu}_\mu$ sample)
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T2K far detector: Super-Kamiokande

• Located in Mozumi mine
  - 2700 m.w.e overburden
• Water Cherenkov detector (50 kton)
• Fiducial mass 22.5 kton
• Inner detector
  - 11000 20-inch PMTs
• Outer veto detector
  - 1900 8-inch PMTs
  - determine fully contained events
• New DAQ system: no dead time
- Water Cherenkov detector (50 kton)
- The largest detector in the world
- Underground (screen cosmic rays)
- ~13000 PhotoMultipliers
Super-Kamiokande events

$\nu_\mu$ CCQE

- Low scattering
- Ring with sharp edge
- Protons below Cherenkov threshold

$\nu_e$ CCQE

- Multiple scattering
- EM shower
- Ring with “fuzzy” edge

Background

- EM shower from $\pi^0 \to \gamma\gamma$
- Can be misidentified as an electron
Particle Identification

- Excellent e/μ separation
- Probability to misidentify a muon as an electron is smaller than 1%
Strategy for oscillation analyses

\[ N_{ND} \sim \Phi(E_\nu) \sigma(E_\nu) \epsilon_{ND} \]
- Flux
- Cross Section
- Detector Efficiency

\[ N_{FD} \sim \Phi(E_\nu) \sigma(E_\nu) \epsilon_{FD} P(\nu_\mu \rightarrow \nu_e) \]
- Flux
- Cross Section
- Detector Efficiency
- Oscillation probability

INGRID & Beam monitor data
External data (NA61/SHINE)
ND280 data

Neutrino flux prediction
ND280 fit

ND280 detector model
Cross section model

Oscillation fit

Super-K detector model

Oscillation parameters
Where we were with only neutrino data

- $6.6 \times 10^{20}$ protons on target (POT) at Super-K of neutrino beam mode data
- Discovery of $\nu_\mu \rightarrow \nu_e$ appearance ($7.3\sigma$) (Phys. Rev. Lett. 112, 061802 (2014)) opens a window on the search for CP violation in leptonic sector
- Slight preference for $\delta_{CP} \sim -\pi/2$ and Normal Hierarchy

Phys. Rev. D 91, 072010

$\sin^2\theta_{13} = 0.0243 \pm 0.0026$

Best-fit:
- $\delta_{CP} = -1.601$
- normal hierarchy

Need to directly compare neutrino and anti-neutrino to infer $\delta_{CP}$
We collected mainly anti-neutrino data

- Beam power increased from 225 kW up to 420 kW between 2014 and 2016
- Collected almost same number of protons-on-target (POT) in neutrino and antineutrino beam mode

27 May 2016
POT total: $1.510 \times 10^{21}$

- $\nu$-mode POT: $7.57 \times 10^{20} (50.14\%)$
- $\bar{\nu}$-mode POT: $7.53 \times 10^{20} (49.86\%)$
Near Detector Fit

- Anti-neutrino samples: 1 $\mu^+$ candidates (CC0$\pi$) + CC other (CC-Ntracks)
- Neutrino samples: 1 $\mu^-$ candidates (CC0$\pi$) + 1$\pi^+$ (CC1$\pi$) + CC other
- Simultaneous analysis of neutrino and anti-neutrino data ($\mu$ momentum/angle)

Anti-neutrino best-fit distributions

Additional samples to measure wrong-sign background (~30% of $\nu_\mu$ contamination)
Near Detector Fit

Neutrino best-fit distributions
• Measure neutrino flux and cross-Section at ND280 in order to constrain the systematic uncertainties of the neutrino oscillation measurement at far detector

• Flux parameters increase by ~15%

• Cross sections ~ consistent with input value

• The p-value to the pre-fit prediction is acceptable (8.6%)

• Systematic uncertainties in neutrino oscillation analyses from 12-15% to 5-6%
\( \nu_\mu \) and \( \bar{\nu}_\mu \) CCQE candidates at Far Detector

1) Fully contained in fiducial volume rings

2) \( \mu \)-like PID

3) Single ring event

4) Momentum > 200 MeV

5) \# decay electron \( \leq 1 \)

- Well understood detector/selection
- Not magnetized detector: same selection for neutrino and antineutrino beam
$\nu_\mu$ and $\overline{\nu}_\mu$ CCQE predicted spectra at Far detector

$\sin^2\theta_{23} = 0.528$
$|\Delta m^2_{32}| = 2.509 \times 10^{-3} \text{eV}^2$
$\sin^2\theta_{13} = 0.0217$
$\delta_{CP} = -1.601$
Normal Hierarchy

<table>
<thead>
<tr>
<th>Beam mode</th>
<th>Expected Not Oscillated</th>
<th>Expected Oscillated</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutrino</td>
<td>521.8</td>
<td>135.8</td>
<td>135</td>
</tr>
<tr>
<td>anti-neutrino</td>
<td>184.8</td>
<td>64.2</td>
<td>66</td>
</tr>
</tbody>
</table>

- Reconstructed energy ($E_{\text{rec}}$) distributions assuming 2-body ("QE") kinematics
$\nu_e$ and $\bar{\nu}_e$ CCQE candidates at Far Detector

1) Fully contained in fiducial volume rings
2) E-like PID
3) Single ring event
4) $E_{\text{visible}} > 100$ MeV
5) $# \text{ decay } e^- = 0$
6) $0 < E_{\text{rec}} < 1250$ MeV
7) $\pi^0$ rejection cut

- Well understood detector/selection
- Not magnetized detector: same selection for neutrino and antineutrino beam
\( \nu_e \) and \( \bar{\nu}_e \) CCQE predicted spectra at Far Detector

\[ \sin^2 \theta_{23} = 0.528 \]
\[ |\Delta m^2_{32}| = 2.509 \times 10^{-3} \text{eV}^2 \]
\[ \sin^2 \theta_{13} = 0.0217 \]
\[ \delta_{CP} = -1.601 \ (\sim -\pi/2) \]

**Normal Hierarchy**

<table>
<thead>
<tr>
<th>True ( \delta_{CP} ) - Normal Hierarchy</th>
<th>-( \pi/2 )</th>
<th>0</th>
<th>( \pi )</th>
<th>+( \pi/2 )</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_e )</td>
<td>28.7</td>
<td>24.1</td>
<td>24.2</td>
<td>19.6</td>
<td>32</td>
</tr>
<tr>
<td>( \bar{\nu}_e )</td>
<td>6.0</td>
<td>6.9</td>
<td>6.8</td>
<td>7.7</td>
<td>4</td>
</tr>
</tbody>
</table>

- \( E_{rec} \) distributions assuming 2-body ("QE") kinematics
- \( \nu_e \) and \( \bar{\nu}_e \) cover quite different phase space:
  - constrain wrong sign background --> use lepton angle (\( \Theta_{lep} \))
- Three analyses: \( p_{lep} - \Theta_{lep} \), \( E_{rec} \) only, \( E_{rec} - \Theta_{lep} \)

Observe more \( \nu_e \) and less \( \bar{\nu}_e \) than predicted
Impact of systematic uncertainties

- Improvement given by measurements with ND280 data
- Low energy: mainly NC, not measured by ND280
Joint neutrino and antineutrino analysis

- Joint analysis of all the 4 samples at the far detector

\( \nu_\mu \) candidate

\( \nu_e \) candidate

\( \overline{\nu}_\mu \) candidate

\( \nu_e \) candidate
**sin^2\theta_{23} and Δm^2_{32}**

- Measurement of sin^2\theta_{23} and Δm^2_{32}
- \(\nu_\mu\) and \(\bar{\nu}_\mu\) candidate samples constrain sin^22\theta_{23}
- \(\nu_e\) and \(\bar{\nu}_e\) candidate samples define the θ_{23} octant
- Contours with constant \(\Delta \chi^2\) method (gaussian approximation)

Mass Hierarchy is fixed to either Normal or Inverted

Daya Bay measures Δm^2_{ee}

T2K data consistent with maximal mixing as in past analysis results

<table>
<thead>
<tr>
<th></th>
<th>NH</th>
<th>IH</th>
</tr>
</thead>
<tbody>
<tr>
<td>sin^2\theta_{23}</td>
<td>0.532</td>
<td>0.534</td>
</tr>
<tr>
<td></td>
<td>Δm^2_{32}</td>
<td>(x10^{-3} eV^2)</td>
</tr>
</tbody>
</table>
\[ \sin^2 \theta_{13} \text{ and } \delta_{CP} \]

- Mass hierarchy is fixed to either normal or inverted
- Contours with constant \( \Delta \chi^2 \) method (gaussian approximation)

**T2K only sensitivity (True \( \delta_{CP} = -1.601 \))**

- T2K data are in good agreement with the reactors measurement
- T2K only data (no constraint on \( \theta_{13} \) with reactors) reject region of \( \delta_{CP} \) at \( \sim +\pi/2 \)
- Confidence intervals are slightly tighter than expected ones

**Sensitivity assumption:**
\[ \sin^2 \theta_{23} = 0.528 \]
\[ |\Delta m^2_{32}| = 2.509 \times 10^{-3} \text{eV}^2 \]
\[ \sin^2 \theta_{13} = 0.0217 \ (PDG2015) \]
\[ \delta_{CP} = -1.601 \ (\sim -\pi/2) \]

Normal Hierarchy

\[ \sin^2 2\theta_{13} = 0.085 \pm 0.005 \ (PDG \ 2015) \]
Confidence intervals of $\delta_{CP}$

- Confidence intervals at 90% CL computed with Feldman-Cousins method (toys MC method that provides proper coverage)

- Best-fit: $\delta_{CP} = -1.885$, Normal Hierarchy
- $\delta_{CP} = 0$ is excluded at 2$\sigma$ CL while $\delta_{CP} = \pi$ is excluded at 90% CL
- CP conservation hypothesis is excluded at 90%CL
- Allowed 90% CL region:
  - Normal Hierarchy: [-3.13, 0.39]
  - Inverted Hierarchy: [-2.09, -0.74]

Constrain $\theta_{13}$ with reactors measurement

$\sin^2 2\theta_{13} = 0.085 \pm 0.005$ (PDG 2015)
Confidence intervals of $\delta_{CP}$

- Toys MC study to estimate the probability to observe such a data set

\[ -2\ln L(90\% \text{ CL}) \]

\[ \delta_{CP} = -\pi/2, \text{ NH} \]

- A few more $\nu_e$ candidates and a few less $\bar{\nu}_e$ candidates than predicted for $\delta_{CP} = -\pi/2$ and Normal Hierarchy that induces the largest asymmetry
- More than $\sim 5\%$ of toy MC experiments show stronger exclusion than T2K data
- If nature is $\delta_{CP} = -\pi/2$ and Normal Hierarchy:
  - probability to exclude $\delta_{CP} = 0$ at $2\sigma$ is $9.2\%$
  - probability to exclude $\delta_{CP} = \pi$ at $90\%$CL is $17.3\%$
Prospects for the future

- Continue to take data with high beam intensity (currently 420 kW)
- Plan to gradually increase the beam intensity up to ~1 MW in 2021
- Expect to reach the approved T2K statistic (7.8x10^{21} POT) around 2020
- Aiming for >1 MW intensity for 2021
- **T2K-II phase**: proposed to extend T2K run to 20x10^{20} POT by 2026 (Stage-I approved by JPARC PAC)
- Need accelerator and beam-line upgrade to reach 1.3 MW
Physics potential of T2K-II

Unknown hierarchy

- Exclude CP conservation hypothesis at $\sim 3\sigma$ if $\delta_{CP} \sim -\pi/2$
- Measure $\Theta_{23}$ with resolution of $\lesssim 1.7^\circ$
- Need to reduce systematic uncertainties!!!
Possibility of the ND280 upgrade

- Need to reduce the systematic uncertainties to reach the aimed sensitivities with T2K-II
- Discussions within the collaboration about a possible upgrade of the T2K near detector with the following goals:
  - improve the detector acceptance (high angle tracks)
  - reduce the neutrino cross section systematics
  - increase the fraction of water target mass

- Also possibility to build a water-Cherenkov intermediate detector (NuPrism)
Conclusions

- Steadily improving power with 420 kW achieved at end of FY 2015
  - accumulated up to \(\sim 7.5 \nu + 7.5 \bar{\nu} \times 10^{20} \text{ POT}\)
- First search of CP violation in the leptonic sector with a joint analysis neutrino / antineutrino data ever performed
  - \(\nu_\mu/\bar{\nu}_\mu\) disappearance, \(\nu_e/\bar{\nu}_e\) appearance
  - data continue to prefer maximal \(\nu_\mu/\bar{\nu}_\mu\) disappearance
  - CP conservation is excluded at 90% CL
  - \(\delta_{CP} = [-3.13, 0.39] \) (NH), \([-2.09, -0.74]\) (IH) @ 90% CL
- Working to include in the analysis the CC1\(\pi^+\) - \(\nu_e\) candidate sample soon
  - \(\sim 10\%\) expected additional statistic
- New papers on the latest results will come in the next months
- Plan to gradually increase the beam power up to \(\sim 1\) MW
- Proposal for extending T2K to reach 3\(\sigma\) sensitivity to \(\delta_{CP} \sim -\pi/2\)
  - running until \(\sim 2026\) to accumulate up to \(20 \times 10^{21} \text{ POT}\) (3x currently approved POT)
  - possibility of the ND280 upgrade (simulation studies ongoing)
Strategy for oscillation analyses

\[ N_{FD} \sim \Phi(E_{\nu})\sigma(E_{\nu})\epsilon_{FD}P(\nu_\mu \rightarrow \nu_e) \]

Fit the observed rate of \( \nu_e \) or \( \nu_\mu \) to determine the oscillation probability, \( P \). Depends on:

- Neutrino flux prediction
- Neutrino cross section model
- Far detector selection, efficiency

We reduce the error on the rate of \( \nu_\mu \) with the near detector:

\[ N_{ND} \sim \Phi(E_{\nu})\sigma(E_{\nu})\epsilon_{ND} \]

- Neutrino flux prediction
- Neutrino cross section model
- Near detector selection, efficiency
(Anti)Neutrino interactions at T2K

- Knowledge of (anti)neutrino cross section important for oscillations measurements
- Neutrino cross section is 2/3 times larger than antineutrino cross section

Charged Current
Quasi-Elastic (CCQE)

Neutrino energy from lepton momentum and angle:
- 2 body kinematics and assumes the target nucleon is at rest

Other processes:
- CCQE-like multinucleon interaction
- Charged current single pion production (CCπ)
- Neutral current single pion production (NCπ)
Previous T2K measurements of AntiNeutrino data

- About half of the current statistics: $4 \times 10^{20}$ POT at Super-K
- Results presented at main HEP conferences in 2015

No evidence for NueBar appearance (p-value to nuebar appearance = 0.26)

Agreement between Neutrino and AntiNeutrino data

Necessary step toward CP violation searches is the joint analysis of Neutrino and AntiNeutrino data (with more statistics)
Updated $\bar{\nu}_\mu$ disappearance results

- Previous analysis with $4.01 \times 10^{20}$ POT (2015) published in PRL116,181801
- Update with more anti-neutrino ($+3.5 \times 10^{20}$POT) + neutrino:
  - joint neutrino / antineutrino data (better constraint on systematic uncertainties)
  - fit different oscillation probabilities for neutrino and antineutrino samples
  - test of CPT theorem or Non Standard Interactions

CPT theorem:

$$P(\nu_\mu \rightarrow \nu_\mu) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$$

if $P(\nu_\mu \rightarrow \nu_\mu) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$

$\Rightarrow$ CPT theorem is violated

$\nu_\mu$ and $\bar{\nu}_\mu$ T2K data results are consistent

Good agreement with antineutrino data from other experiments
Updated $\bar{\nu}_e$ appearance results

Test of no NueBar appearance hypothesis:
- $\beta = 0$ --> no NueBar appearance
- $\beta = 1$ --> NueBar appearance PMNS

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \beta \times P_{\text{PMNS}}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

$\beta$ scales the NueBar appearance signal (purple component)

- No evidence of NueBar with new full data set (p-value to Bkg only = 0.0374)
- No NueBar appearance hypothesis is slightly favored
Joint neutrino and antineutrino analysis

• First search for leptonic CP violation by directly comparing neutrino and antineutrino oscillation

• Joint analysis of all the 4 samples at Super-K

Analysis frameworks

- Marginalization of nuisance parameters

• Frequentist with $\Delta \chi^2$ fit to
  - $E_{\text{rec}}/\theta_{\text{lep}}$ for $\nu_e/\bar{\nu}_e$
  - $E_{\text{rec}}$ for $\nu_\mu/\bar{\nu}_\mu$

• Bayesian with likelihood fit to
  - $p_{\text{lep}}/\theta_{\text{lep}}$ for $\nu_e/\bar{\nu}_e$
  - $E_{\text{rec}}$ for $\nu_\mu/\bar{\nu}_\mu$

• Bayesian with Markov Chain MC
  - $E_{\text{rec}}$ for all samples
  - simultaneous fit with near detector

• All the analyses are in good agreement. Extrapolation from near to far detectors consistent with simultaneous fit results
Muon monitor

![Graph showing event rate, horizontal beam direction, and vertical beam direction over different runs and years.](image)

**Event rate**
- Horn250kA
- Horn205kA
- Horn-250kA

**Horizontal beam direction**
- INGRID
- MUMON

**Vertical beam direction**
- INGRID
- MUMON

**Dates**
- T2K Run1: Jan. 2010 - Jun. 2010
- T2K Run2: Nov. 2010 - Mar. 2011
Oscillation parameters

\[ \sin^2 \theta_{23} = 0.528 \text{ (T2K)} \]
\[ \sin^2 2\theta_{13} = 0.085 \pm 0.005 \text{ (PDG 2015)} \]
\[ \sin^2 \theta_{12} = 0.846 \pm 0.021 \text{ (PDG 2015)} \]
\[ |\Delta m^2_{32}| = 2.509 \times 10^{-3} \text{ eV}^2 \text{ (T2K)} \]
\[ \Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2 \text{ (PDG 2015)} \]
\[ \delta_{\text{CP}} \text{ not known} \]
\[ \text{Mass Hierarchy not known} \]
NA61/SHINE

• Large acceptance detector with very good capabilities of momentum, charge and mass measurements
• 2 dipole magnets (max bending power = 9 Tm)
• 5 TPCs with high momentum resolution, $\sigma(p)/p^2 \sim 10^{-4}$ (GeV/c)$^{-1}$
• Good particle identification: $\sigma(dE/dx) / <dE/dx> \sim 0.04$
• 3 ToF ($\sigma_{ToF} \sim 120$ps, $\sigma_{ToFL/R} \sim 80$ps)
• New ToFF to fully cover the T2K acceptance

Data collected with “thin” (2 cm) and T2K replica (90 cm) carbon target
Flux prediction

- A very good knowledge of the neutrino flux is required in order to perform precise neutrino oscillation measurements
- Theoretical models don’t describe well the production of neutrino parents in forward direction because not perturbative QCD
- Need an experiment that measures the multiplicities of the hadron produced with the same configuration as at T2K and ~same phase space: NA61/SHINE at CERN

- Pilot run with low statistic was taken in 2007 to test the method
- New run in 2009 with ~ x 10 the statistics for precise measurements
Fit of ND280 event samples (wrong sign bkg AntiNu)

- Measure Flux and Cross-Section w/ unoscillated anti-neutrinos
- Select events with 1 muon candidates (CC0π) + other (CC-Ntracks)

~30% of wrong-sign background ($\nu_\mu$ contamination) --> measure it!
ND280 selected samples

Number of observed events in FGD2:

- neutrino mode: 25151
- antineutrino mode right-sign: 3499
- antineutrino mode wrong-sign: 1916

Number of observed events in FGD2:

- neutrino mode: 25558
- antineutrino mode right-sign: 3438
- antineutrino mode wrong-sign: 1990
ND280 samples in neutrino beam mode (FGD1)

**pre-ND280 fit**

- CC0π
- CC1π⁺
- CC-Other

**post-Nd280 fit**

- CC0π
- CC1π⁺
- CC-Other
ND280 samples in neutrino beam mode (FGD2)

PRELIMINARY

CC0πτ

Data
- CCQE
- CC 2p-2h
- CC Res 1τ
- CC Coh 1τ
- CC Other
- NC modes
- τ modes

PRELIMINARY

CC1πτ+

Data
- CCQE
- CC 2p-2h
- CC Res 1τ
- CC Coh 1τ
- CC Other
- NC modes
- τ modes

PRELIMINARY

CC-Other

Data
- CCQE
- CC 2p-2h
- CC Res 1τ
- CC Coh 1τ
- CC Other
- NC modes
- τ modes

PRELIMINARY

post-ND280 fit

PRELIMINARY

pre-ND280 fit

PRELIMINARY
ND280 samples in anti-neutrino beam mode ($\bar{\nu}_\mu$ FGD1)

**pre-ND280 fit**

**post-ND280 fit**

**CC-1track**

**CC-Ntracks**

PRELIMINARY
ND280 samples in anti-neutrino beam mode ($\bar{\nu}_\mu$ FGD1)

**Pre-ND280 Fit**

- CC-1track
- CC-Ntracks

**Post-ND280 Fit**

- CC-1track
- CC-Ntracks

PRELIMINARY
ND280 samples in anti-neutrino beam mode ($\nu_\mu$ FGD2)

pre-ND280 fit

post-ND280 fit

PRELIMINARY

CC-1track

CC-Ntracks

PRELIMINARY
Parameters are typically a ratio to NEUT nominal values, excepting the CC Other Shape parameter and the FSI parameters.
Importance of cross-sections

- CCQE
- Nieves 2p2h (x5)
- π-less Δ decay (x5)

**T2K preliminary**

E_{reco}^{QE} - E_{true} [GeV]

- Non-relativistic RPA correction
- Relativistic RPA correction

E_v = 8 GeV

- Charged-Current
- Quasi-Elastic (CCQE)
- 2 protons 2 holes (2p2h)

E_v / GeV
Predicted spectra and systematic uncertainties

<table>
<thead>
<tr>
<th>Fractional error on the number of expected events at SK</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Fraction of the number of expected events at SK</th>
<th>( \nu_\mu ), sample 1R( _{\mu} ), FHC</th>
<th>( \nu_e ), sample 1R( _{e} ), FHC</th>
<th>( \bar{\nu}_\mu ), sample 1R( _{\mu} ), RHC</th>
<th>( \bar{\nu}_e ), sample 1R( _{e} ), RHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu ) flux w/o ND280</td>
<td>7.6%</td>
<td>8.9%</td>
<td>7.1%</td>
<td>8.0%</td>
</tr>
<tr>
<td>( \nu ) flux with ND280</td>
<td>3.6%</td>
<td>3.6%</td>
<td>3.8%</td>
<td>3.8%</td>
</tr>
<tr>
<td>( \nu ) cross-section w/o ND280</td>
<td>7.7%</td>
<td>7.2%</td>
<td>9.3%</td>
<td>10.1%</td>
</tr>
<tr>
<td>( \nu ) cross-section with ND280</td>
<td>4.1%</td>
<td>5.1%</td>
<td>4.2%</td>
<td>5.5%</td>
</tr>
<tr>
<td>( \nu ) flux+cross-section</td>
<td>2.9%</td>
<td>4.2%</td>
<td>3.4%</td>
<td>4.6%</td>
</tr>
<tr>
<td>Final or secondary hadron int.</td>
<td>1.5%</td>
<td>2.5%</td>
<td>2.1%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Super-K detector</td>
<td>3.9%</td>
<td>2.4%</td>
<td>3.3%</td>
<td>3.1%</td>
</tr>
<tr>
<td>Total w/o ND280</td>
<td>12.0%</td>
<td>11.9%</td>
<td>12.5%</td>
<td>13.7%</td>
</tr>
<tr>
<td>Total with ND280</td>
<td>5.0%</td>
<td>5.4%</td>
<td>5.2%</td>
<td>6.2%</td>
</tr>
</tbody>
</table>
ND280 selected samples

### AntiNu

<table>
<thead>
<tr>
<th>Sample</th>
<th>Topology</th>
<th>MC composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC-inclusive</td>
<td>CC-0π</td>
<td>59.7%</td>
</tr>
<tr>
<td></td>
<td>CC-Nπ</td>
<td>21.6%</td>
</tr>
<tr>
<td></td>
<td>BKG</td>
<td>12.5%</td>
</tr>
<tr>
<td></td>
<td>External (OOFV)</td>
<td>6.2%</td>
</tr>
<tr>
<td>CC-1track</td>
<td>CC-0π</td>
<td>74.4%</td>
</tr>
<tr>
<td></td>
<td>CC-Nπ</td>
<td>14.5%</td>
</tr>
<tr>
<td></td>
<td>BKG</td>
<td>5.4%</td>
</tr>
<tr>
<td></td>
<td>External (OOFV)</td>
<td>5.7%</td>
</tr>
<tr>
<td>CC-Ntracks</td>
<td>CC-0π</td>
<td>8.8%</td>
</tr>
<tr>
<td></td>
<td>CC-Nπ</td>
<td>46.4%</td>
</tr>
<tr>
<td></td>
<td>BKG</td>
<td>37.0%</td>
</tr>
<tr>
<td></td>
<td>External (OOFV)</td>
<td>7.9%</td>
</tr>
</tbody>
</table>

### Nu

<table>
<thead>
<tr>
<th>Sample</th>
<th>Purity (%)</th>
<th>Fraction of events with respect to CC-inclusive (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FGD1</td>
<td>FGD2</td>
</tr>
<tr>
<td>CC-0-pion</td>
<td>70.4</td>
<td>67.4</td>
</tr>
<tr>
<td>CC-1-pion</td>
<td>54.1</td>
<td>53.5</td>
</tr>
<tr>
<td>CC-other</td>
<td>72.9</td>
<td>72.8</td>
</tr>
</tbody>
</table>

TO CHECK: not clear the efficiencies

---

**AntiNu Graph:**

- CC0π Efficiency
- CC0π Purity

**AntiNu Graph:**

- CCNπ Efficiency
- CCNπ Purity

---

67
Sensitivity

- th13 Vs dcp comparison with reactors

![Diagram showing sensitivity analysis with contours for different hierarchy and CP phases]
sin^2\Theta_{13} and \delta_{CP}

- Mass hierarchy is fixed to either normal or inverted
- Reactor constraint: \(\sin^2 2\Theta_{13} = 0.085 \pm 0.005\) (PDG 2015)

Contour with constant \(\Delta \chi^2\) method (gaussian approximation)
- Reactor constraint further shrinks the allowed regions
T2K Run1-7c preliminary

-2\ln L

-2lnL

-\delta_{CP} (\text{radians})

Sensitivity

Normal Hierarchy

Inverted Hierarchy

-2L_{\text{crit}} (90\% \text{ CL})

-2L_{\text{crit}} (2\sigma \text{ CL})

-2lnL

-\delta_{CP} (\text{radians})

T2K Run1-7c preliminary

Normal Hierarchy

Inverted Hierarchy

-2L_{\text{crit}} (90\% \text{ CL})

-2L_{\text{crit}} (2\sigma \text{ CL})
Bayesian posterior probabilities

- All the nuisance parameters are marginalised.
- Small dependence on the prior of $\delta_{\text{CP}}$ (flat in $\delta_{\text{CP}}$ Vs flat in $\sin \delta_{\text{CP}}$)

### T2K Run 1-7c preliminary

<table>
<thead>
<tr>
<th></th>
<th>$\sin^2 \theta_{23} &lt; 0.5$</th>
<th>$\sin^2 \theta_{23} &gt; 0.5$</th>
<th>Line total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverted hierarchy</td>
<td>0.10</td>
<td>0.14</td>
<td>0.25</td>
</tr>
<tr>
<td>Normal hierarchy</td>
<td>0.29</td>
<td>0.46</td>
<td>0.75</td>
</tr>
<tr>
<td>Column total</td>
<td>0.39</td>
<td>0.61</td>
<td>1</td>
</tr>
</tbody>
</table>

- Preference for Normal Hierarchy and $\Theta_{23} > \pi/4$
Confidence intervals of $\delta_{CP}$

- Observed a few more $\nu_e$ candidates and a few less $\bar{\nu}_e$ candidates than predicted for $\delta_{CP} = -\pi/2$ and Normal Hierarchy that induces the largest asymmetry

<table>
<thead>
<tr>
<th>Beam mode</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutrino</td>
<td>28.7</td>
<td>32</td>
</tr>
<tr>
<td>anti-neutrino</td>
<td>6.0</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>True $\delta_{CP}$ - Normal Hierarchy</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>-$\pi/2$</td>
<td>0</td>
<td>$\pi$</td>
<td>+$\pi/2$</td>
<td>32</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>6.0</td>
<td>6.9</td>
<td>6.8</td>
<td>7.7</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>True $\delta_{CP}$ - Inverted Hierarchy</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>-$\pi/2$</td>
<td>0</td>
<td>$\pi$</td>
<td>+$\pi/2$</td>
<td>32</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>6.5</td>
<td>7.4</td>
<td>7.4</td>
<td>8.4</td>
<td>4</td>
</tr>
</tbody>
</table>
Beam power improvement plan

- Increase the MR beam power up to 1.3MW
  - Power $\propto 30\text{GeV} \times \# \text{ of protons} \times \frac{1}{T_{\text{rep.}}}$
  - Upgrade MR for both shortening the repetition time ($T_{\text{rep.}}$) and increasing the number of protons per pulse

<table>
<thead>
<tr>
<th></th>
<th>Achieved</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam power [MW]</td>
<td>0.425</td>
<td>1.3</td>
</tr>
<tr>
<td># of protons per pulse</td>
<td>$2.2 \times 10^{14}$</td>
<td>$3.2 \times 10^{14}$</td>
</tr>
<tr>
<td>Rep. Time [sec]</td>
<td>2.48</td>
<td>1.16</td>
</tr>
</tbody>
</table>

- Improve the neutrino beam-line
  - Modest improvement to realize 1.3MW operation

- Increase the effective statistics (x1.5)
  - Horn current increase (250kA → 320kA) and data analysis improvement
MR upgrade status (1)

- Shorten $T_{\text{rep}}$ by:
  - Replacing magnet power supply (PS)
    - New PS was developed with energy recovery bank capacitor to suppress a power variation at AC main grid
    - Plan to start 1.3sec repetition in 2018 (budget has been approved from JFY2016)
  - Improve RF
    - High gradient RF cavity was developed (new type of magnetic alloy core, FT3L)
      - Under installing the new RF cavities (~2018)
    - Plan to upgrade the anode power supply for 1.16s repetition
Further improvement of # of protons

- High intensity beam study was performed in 2015 June
  - $6.82 \times 10^{13}$ protons per bunch x 2 bunch (single shot op.)
  - MR has capability to reach 1MW (although beam loss needs to be reduced)

<table>
<thead>
<tr>
<th></th>
<th>Measurement (2 bunch)</th>
<th>Estimation (8 bunch)</th>
<th>Estimation (8 bunch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam power [MW]</td>
<td>0.13</td>
<td>0.53</td>
<td>1.0</td>
</tr>
<tr>
<td>Rep. Time [sec]</td>
<td>2.48</td>
<td>2.48</td>
<td>1.3</td>
</tr>
<tr>
<td># of protons per pulse (equiv.)</td>
<td>$2.7 \times 10^{14}$</td>
<td>$2.7 \times 10^{14}$</td>
<td>$2.7 \times 10^{14}$</td>
</tr>
<tr>
<td>Beam loss [kW]</td>
<td>0.42</td>
<td>1.7</td>
<td>3.2</td>
</tr>
</tbody>
</table>

- Further improvement of # of protons per pulse up to $3.2 \times 10^{14}$ protons per pulse is planned with upgraded RF system, fast extraction kicker and optimized beam tune.
Other analyses in T2K

$\nu CC$ inclusive cross-section on C

$\nu CC0$

$\pi$ cross-section on

$\mu CC$ in the tracker

$H O$ in the P0D

$2 \sigma$ -38 $(10^{3} \text{cm}/\text{GeV}/\text{nucleon})$

$\theta dp \cos \theta dp$

$E_\nu$ (GeV)

$0.2 \leq \leq 0.4 \leq 0.6 \leq 0.8 \leq 1.2 \leq 1.6 \leq 2$

Other analyses in T2K

T2K is not only measuring neutrino oscillations!

Several cross-section analyses are being performed at ND280/INGRID