Updated Results from the T2K Experiment with $3.13 \times 10^{21}$ Protons on Target

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For the T2K Collaboration

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Outline

- Neutrino Oscillations
- The Tokai to Kamioka Long Baseline Neutrino Oscillation Experiment (T2K)
- T2K Analysis Method and Systematic Errors
- T2K Latest Results
- Future Long-Baseline Neutrino Oscillation Physics Prospects
Neutrinos and Neutrino Oscillation
Neutrinos and Neutrino Oscillation

- There are (at least) three types of neutrinos (“neutrino flavors”):
  \[ \nu_e, \nu_\mu, \nu_\tau \] (+ 3 anti-neutrinos: \( \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau \))

- Neutrinos are very light \( (< 4 \times 10^{-6} m_e) \) and very weakly interacting

- When neutrinos propagate, they can change flavor (or oscillate): i.e. \( \nu_\mu \rightarrow \nu_e \) or \( \nu_\mu \rightarrow \nu_\tau \)
  - This is because neutrinos propagate in a mass eigenstate, which is a mixture of lepton flavor eigenstates
  - However, they are produced and interact in the flavor eigenstate

- So, you can think of neutrinos in two ways:
  - either as associated with a charged lepton \( (\nu_e, \nu_\mu, \text{ and } \nu_\tau) \), or with a specific mass \( (\nu_1, \nu_2, \text{ and } \nu_3) \)
  - Mass states \( \nu_1, \nu_2, \text{ and } \nu_3 \) are made up of some combination of \( \nu_e, \nu_\mu, \text{ and } \nu_\tau \)
  - The neutrino oscillation probability depends on the neutrino’s energy, distance it has traveled, mass splittings, and oscillation parameters given by the PMNS mixing matrix
Current Understanding of the Neutrino Oscillation Parameters

Neutrino oscillation can be described by the PMNS (Pontecorvo-Maki-Nakagawa-Sakata) mixing matrix:

\[
U_{PMNS} = \begin{pmatrix}
1 & 0 & 0 \\
0 & +C_{23} & +S_{23} \\
0 & -S_{23} & +C_{23}
\end{pmatrix}
\begin{pmatrix}
+C_{13} & 0 & +S_{13}e^{-i\delta_{CP}} \\
0 & 1 & 0 \\
-S_{13}e^{i\delta_{CP}} & 0 & +C_{13}
\end{pmatrix}
\begin{pmatrix}
+C_{12} & +S_{12} & 0 \\
-S_{12} & +C_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\( (C_{ij} = \cos \theta_{ij}, \ S_{ij} = \sin \theta_{ij}) \)

Precisely measure all parameters to fully understand neutrino oscillation

- \( \theta_{12} = 33.6^\circ \pm 0.8^\circ \) – solar \( \nu \)'s
- \( \theta_{23} = 45.6^\circ \pm 2.3^\circ \)
  - is \( \theta_{23} \) maximal?
- \( \theta_{13} = 8.3^\circ \pm 0.2^\circ \) – recent reactor \( \bar{\nu}_e \) disappearance measurements

\( \delta_{CP} \) unknown \( \rightarrow \) possibility of CP violation in the lepton sector

\( \rightarrow \) May be able to help explain the dominance of matter over anti-matter in the Universe

- MH completely unknown
Oscillation Probabilities

- Long-baseline $\nu_\mu \to \nu_e$ appearance probability depends most strongly on $\sin^2 2\theta_{13}$ and $\delta_{CP}$
  - (But also depends on $\theta_{23}$ and other parameters)

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \Phi_{31} \left(1 + \frac{2a}{\Delta m_{31}^2} (1 - 2S_{13}^2) \right) \quad \rightarrow \text{Leading, matter effect}$$
$$+ 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos \delta - S_{12} S_{13} S_{23}) \cos \Phi_{32} \sin \Phi_{31} \sin \Phi_{21} \quad \rightarrow \text{CP conserving}$$
$$- 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin \delta \sin \Phi_{32} \sin \Phi_{31} \sin \Phi_{21} \quad \rightarrow \text{CP violating}$$
$$+ 4S_{12}^2 C_{13}^2 (C_{12} C_{23}^2 + S_{12} S_{23} S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos \delta) \sin^2 \Phi_{21} \quad \rightarrow \text{Solar}$$
$$- 8C_{13}^2 S_{13}^2 S_{23}^2 (1 - 2S_{13}^2) \frac{aL}{4E} \cos \Phi_{32} \sin \Phi_{31} \quad \rightarrow \text{Matter effect}$$

$$\text{(C}_{ij} = \cos \theta_{ij}, S_{ij} = \sin \theta_{ij}, \Phi_{ij} = \Delta m_{ij}^2 L/4E)$$

- Long-baseline $\nu_\mu \to \nu_\mu$ disappearance probability depends most strongly on $\sin^2 2\theta_{23}$ and $\Delta m_{32}^2$
  - (But degeneracy is broken by $\sin^2 2\theta_{13}$)

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \left( \cos^4 \theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23} \right) \sin^2 \Delta m_{31}^2 L/4E$$
  - Leading Term
  - Next-to-Leading
The Tokai to Kamioka Long-Baseline Neutrino Oscillation Experiment
The T2K Experiment

- Primarily $\nu_\mu$ or $\bar{\nu}_\mu$, 2.5° off axis neutrino beam produced at J-PARC
- ND280 Near Detector – 280 m from $\nu$ source
  - Constrains systematic errors
  - Measures $\nu$ cross sections and beam backgrounds
- Neutrino interactions detected at the Super-Kamiokande (SK) far detector – 295 km from $\nu$ source
  - Cherenkov detector filled with 50kT of ultra-pure water
  - Good performance of $\nu_e/\nu_\mu$ particle ID for sub-GeV energy $\nu$’s
  - $\nu_e$ appearance and $\nu_\mu$ disappearance $\nu$ oscillation information
The T2K collaboration has \(~500\) members from 66 institutes in 12 countries.
Slam high-intensity 30GeV proton beam into 90-cm carbon target

Focus outgoing hadrons (pions, kaons, etc.) in 3 electro-magnetic focusing horns
  - Switch between $\nu$- or $\bar{\nu}$-mode by changing the horn polarity

Pions decay to muons and $\nu_\mu$'s in 100-m-long decay volume

Stop interacting particles in beam dump; neutrinos continue on to near and far detectors
  - Monitor $>5$GeV muon beam by Muon Monitor in beam dump

Number of neutrinos is proportional to number of protons
  → Increase beam power to increase neutrino flux
• T2K was the first-ever neutrino experiment to use an “off-axis” beam:
  • The T2K far detector is not sitting at the center of the neutrino beam – instead it is 2.5° off-axis
  • The “off-axis” beam concept gives a smaller range of neutrino energies
    • Can choose the peak energy to be at the oscillation maximum
  • Precise control of the beam parameters is very important
J-PARC Accelerator

- J-PARC = Japan Proton Accelerator Research Complex
- Accelerates proton beam to 30 GeV by:
  - 400 MeV Linac (linear accelerator) → 3 GeV RCS (Rapid Cycling Synchrotron) → 30 GeV MR (Main Ring)
- MR design beam power: 750 kW (currently ~485 kW)
J-PARC Neutrino Beamline
INGRID On-Axis Near Detector

• 14 identical modules arranged in a cross
• Each module consists of sandwiched iron plates and tracking scintillator planes
• Used to measure the neutrino beam stability and direction
• Also used to measure cross sections/neutrino interactions
ND280 Off-Axis Near Detector

Consists of many parts:

- In a magnet, so can sign-select charged particles
- P0D ($\pi^0$ Detector) – Measures pions ($\pi^0$’s), water target
- TPCs (Time Projection Chambers) – Track particles, particle identification
- FGDs (Fine-Grain Detectors) – Act as detector target, include interaction vertex information
- ECALs (Electromagnetic Calorimeters) – Detect and identify particles exiting the detector, such as $\gamma$’s, $\pi^0$’s

→ ND280 upgrades underway

ND280 is used to constrain the neutrino flux and measure neutrino cross sections
The Super Kamiokande Far Detector

- Super Kamiokande is a huge water Cherenkov detector – cylindrical tank holding 50 ktons of ultra-pure water
  - Walls lined with photo-sensors (PMTs) to detect Cherenkov light
  - \( \sim 11,000 \) 20” PMTs in inner detector (40% photo coverage)
- Deep underground (2700mwe) – very low background event rate
- Neutrinos passing through SK may interact with the water stored inside the tank and produce muons or electrons, which then produce Cherenkov light while passing through the water
Super Kamiokande Neutrino Detection

- Use Cherenkov light to reconstruct the particle energy, direction, etc.
- Can distinguish between muons (produced by $\nu_\mu$) and electrons (produced by $\nu_e$) at T2K beam energies for CC interactions:

  Muon Neutrino Detected
  Electron Neutrino Detected

\[\begin{align*}
\nu_\mu & \quad \mu \\
\nu_e & \quad \text{electron shower}
\end{align*}\]
Some Important T2K Results

- 2011: first ever indication of $\nu_e$ appearance from a $\nu_\mu$ beam (2.5$\sigma$)
- 2013: made world’s first observation of $\nu_e$ appearance from a $\nu_\mu$ beam (7.3$\sigma$)
- 2014: similar dataset used to show very first 90% CL hint of $\delta_{CP} \neq 0$
- 2014: started taking first $\bar{\nu}$-mode data
  - Aim to observe $\bar{\nu}_e$ appearance, measure $\delta_{CP}$ by T2K w/out external constraint on $\sin^2 \theta_{13}$
- 2015~2016: continue to improve statistical significance of $\nu$ and $\bar{\nu}$ results
- 2017: increased SK fiducial volume, added new SK $\nu_e$CC1π sample, etc...
  - Stronger hint of CP violation in neutrinos (CP conserving values of $\delta_{CP}$ are outside of 2$\sigma$ CL)
T2K Latest Dataset
T2K Data-Taking Status

- Jan. 20 2010 ~ May 31 2018
- $3.16 \times 10^{21}$ Protons On Target (POT) accumulated so far
  - $1.51 \times 10^{21}$ POT $\nu$-Mode + $1.65 \times 10^{21}$ POT $\bar{\nu}$-Mode
- Latest oscillation results based on :
  - $3.13 \times 10^{21} = \sim 1.49 \times 10^{21} \nu + \sim 1.63 \times 10^{21} \bar{\nu}$ POT
  - 40% of the total approved T2K statistics ($7.8 \times 10^{21}$ POT)
Last year (2017~2018) was our best year for datataking so far!

(Thanks to J-PARC center members !)
Neutrino Beam Stability

- INGRID + Muon Monitor stability – neutrino beam event rate and off-axis angle are stable with time
FHC = $\nu$-mode
RHC = $\bar{\nu}$-mode

### Super-Kamiokande Stability

- SK running with very high efficiency ($\sim 1\%$ inefficiency)
- Stable event rate in both modes
- Event timing as expected

**FC event rate (HFC)**

\[ \chi^2 / \text{ndf} = 22.27 / 27 \]
\[ p_0 = 8.233 \pm 0.235 \]

**FC event rate (RHC)**

\[ \chi^2 / \text{ndf} = 7.585 / 12 \]
\[ p_0 = 3.515 \pm 0.147 \]
Major Updates Since Last T2K Result

- Increased $\bar{\nu}$-mode dataset $1.12 \times 10^{21} \rightarrow 1.63 \times 10^{21}$ POT
  - $\sim 45\%$ increase

- Updated the reactor constraint to match PDG2018 values:
  - Old: PDG2016 value – $\sin^2 \theta_{13} = 0.0219 \pm 0.0012$ ($\sin^2 2\theta_{13} = 0.086$)
  - New: PDG2018 value – $\sin^2 \theta_{13} = 0.0212 \pm 0.0008$ ($\sin^2 2\theta_{13} = 0.083$)
Oscillation Analysis and Systematic Errors
Neutrino Oscillation Analysis Method

Number of neutrino events observed:

\[
N^{\text{far}} = \sum_i E_{\nu i} \sum_{\text{bins}} \sum_{\text{flavors}} P_{\nu_i \rightarrow \nu_k} \Phi^\text{far}_j \sigma^\text{far}_k \epsilon^\text{far} M^\text{far}_{\text{det}} \\
N^{\text{near}} = \sum_i E_{\nu i} \sum_{\text{bins}} \sum_{\text{flavors}} \Phi^\text{near}_j \sigma^\text{near}_k \epsilon^\text{near} M^\text{near}_{\text{det}}
\]

- Compare observed rates at far detector (after neutrino oscillation) to predictions under oscillation hypothesis
- Constrain by observed rates at near detector (before neutrino oscillation)
- Depends on:
  - Oscillation probabilities
  - Neutrino flux
  - Neutrino interaction cross sections
  - Detection efficiency
  - Detector resolution
The $\nu$ flux is predicted by simulations which take into account:

- Hadron interactions inside + outside the production target
  - Simulated by Fluka+GEANT3 and tuned to external measurements by NA61/SHINE experiment at CERN, etc
- Proton beam current, position, angle, profile
  - Measured by proton beam monitoring
- Neutrino beam off-axis angle
  - Measured by proton beam monitoring, confirmed by INGRID on-axis near detector
- Horn current, field, horn and target alignment, etc...
- Predicted fluxes at Super Kamiokande
- $<1\%$ intrinsic beam $\nu_e$'s at peak energy
- Wrong-sign component ($\nu$'s in $\bar{\nu}$ mode) is larger in $\bar{\nu}$-mode
Largest uncertainties on the neutrino flux come from hadron interactions, then the proton beam profile + $\nu$ beam off-axis angle.

Note, flux errors mostly cancel when we do our near/far fit.
  - However, reducing flux errors can help reduce errors on cross section measurements.

Analysis improvements to include NA61/shine replica target data will be ready very soon.
  - Will significantly reduce hadron interaction errors.
Neutrino Cross Sections

- Main interaction at T2K neutrino energies is Charged Current Quasi-Elastic (CCQE)
  - $\nu_\mu + n \rightarrow \mu^- + p$
  - Can reconstruct $\nu$ energy using mass, energy, momentum, scattering angle of outgoing charged lepton:
    $$E_{\nu}^{\text{rec}} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e \cos \theta_e)}$$
- Charged Current single pion (CC1$\pi$) sample also contributes
  - $\nu_\mu + n/p \rightarrow \mu^- + \pi^+ + n/p$
- Charged Current multinucleon (scattering on correlated pair of nucleons) can mimic CCQE – uncertainty on model for this scattering process
- Neutral Current (NC) and Deep Inelastic Scattering (DIS) interactions can be additional backgrounds

→ Observe interactions + constrain cross sections by Near Detector
• Data fit to simulation for $CC0\pi$ samples shown above
• Currently using a subset of T2K full dataset to constrain flux and cross section errors
  • Now working to update to use full Near Detector dataset
• Errors on SK event rates reduced by Near Detector fit:
  • $\nu$-mode 1-ring CCQE $\mu$-like 14.6% $\rightarrow$ 5.1%
  • $\nu$-mode 1-ring CCQE e-like 16.9% $\rightarrow$ 8.8%
  • $\bar{\nu}$-mode 1-ring CCQE $\mu$-like 12.5% $\rightarrow$ 4.5%
  • $\bar{\nu}$-mode 1-ring CCQE e-like 14.4% $\rightarrow$ 7.1%
FHC = $\nu$-mode  
RHC = $\bar{\nu}$-mode  
1 d.e. = CC1$\pi$ sample

## T2K Systematics

% Errors on Predicted Event Rates

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- SK detector errors – dominate for new-ish CC1$\pi$ sample
T2K Systematics

% Errors on Predicted Event Rates

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- SK Final State Interaction + Secondary Interaction + Photo-Nuclear effect errors – pion-nucleon interaction modeling
FHC = $\nu$-mode  
RHC = $\bar{\nu}$-mode  
1 d.e. = CC1$\pi$ sample  

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- Flux and cross section errors constrained by ND280
T2K Systematics

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<tr>
<td>All with osc</td>
<td>5.12</td>
<td>4.45</td>
<td>9.19</td>
<td>7.57</td>
<td>18.51</td>
<td>6.03</td>
</tr>
</tbody>
</table>

- Nuclear binding energy error – uncertainties related to scattering on nucleons bound in nucleus
\[ \text{FHC} = \nu-\text{mode} \]
\[ \text{RHC} = \bar{\nu}-\text{mode} \]
\[ 1 \text{ d.e.} = \text{CC1}\pi \text{ sample} \]

T2K Systematics

% Errors on Predicted Event Rates

<table>
<thead>
<tr>
<th>Error source</th>
<th>1-Ring $\mu$</th>
<th>1-Ring $e$</th>
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<tr>
<td></td>
<td>FHC</td>
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<td>SK Detector</td>
<td>2.40</td>
<td>2.01</td>
</tr>
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<tr>
<td>$E_b$</td>
<td>2.38</td>
<td>1.72</td>
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<tr>
<td>$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>NC1$\gamma$</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>NC Other</td>
<td>0.25</td>
<td>0.25</td>
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- Uncertainties on $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ arise since $\nu_e$, $\bar{\nu}_e$ cross sections are not precisely measured at ND280
FHC = \nu\text{-mode}
RHC = \bar{\nu}\text{-mode}
1 d.e. = CC1\pi sample

T2K Systematics

% Errors on Predicted Event Rates

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- Uncertainties on neutral current modes not constrained by ND280
% Errors on Predicted Event Rates

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- Error due to uncertainties on the oscillation parameter values (solar + $\theta_{13}$)
FHC = $\nu$-mode  
RHC = $\bar{\nu}$-mode  
1 d.e. = CC1\pi sample

% Errors on Predicted Event Rates

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- Total systematic errors $\sim 4\sim 9\%$ for 4 dominant samples
T2K Latest Results
Previous T2K Dataset (~Dec 2017)

Reconstructed energy distributions at Super-K

\[ \sim 1.49 \times 10^{21} \, \nu + \sim 1.12 \times 10^{21} \, \bar{\nu} \, \text{POT} \]
Latest T2K Dataset (~May 2018)

\[ \sim 1.49 \times 10^{21} \nu + \sim 1.63 \times 10^{21} \bar{\nu} \text{ POT} \]

### 1-ring CCQE-\(\mu\)-like

<table>
<thead>
<tr>
<th>Number of Events</th>
<th>(e^\nu \rightarrow \mu \nu)</th>
<th>(e^\nu \rightarrow \mu \nu) NC intrinsic</th>
<th>(\nu^\nu) intrinsic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Previous</td>
<td>92.7</td>
<td>102</td>
<td>11.7</td>
</tr>
<tr>
<td>Updated</td>
<td>139.5</td>
<td>140</td>
<td>17.1</td>
</tr>
<tr>
<td>(\nu) Updated</td>
<td>272.4</td>
<td>243</td>
<td>74.4(7.0cc1(\pi))</td>
</tr>
</tbody>
</table>

### 1-ring CCQE-e-like

### 1-ring CC1\(\pi\)-e-like

### MC assumption:

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

Normal Hierarchy

\[ \sin^2 \theta_{23} = 0.528 \]

\[ \sin^2 \theta_{13} = 0.0212 \]
New T2K $\bar{\nu}_e$ Appearance Data

Full Dataset (~May 2018):
- Lepton angle vs reconstructed energy for $\bar{\nu}$-mode 1-ring CCQE-e-like events
- Distribution of new points looks more like $\bar{\nu}_e$-signal
- Better constraint on possible $\bar{\nu}_e$ appearance
- Note: main backgrounds are $\nu_\mu \rightarrow \nu_e$ and beam intrinsic $\bar{\nu}_e + \nu_e$

Previous Dataset (~Dec 2017):
- Shape of $\bar{\nu}_e$ signal
- Shape of mis-ID BGs
New T2K $\bar{\nu}_e$ Appearance Result

- Search for $\bar{\nu}_e$ appearance
- Compare consistency with PMNS $\bar{\nu}_e$ appearance ($\beta=1$) and no $\bar{\nu}_e$ appearance ($\beta=0$):

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

Rate-only analysis

Blue: expected # of $\bar{\nu}_e$ events w/ NO $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation ($\beta=0$, 9.4 evts)
Red: expected # of $\bar{\nu}_e$ events w/ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation ($\beta=1$, 17.2 evts)

- For rate-only analysis, data agrees with both hypotheses
- Result statistically not conclusive yet – need more data
New T2K $\bar{\nu}_e$ Appearance Result

- Search for $\bar{\nu}_e$ appearance
- Compare consistency with PMNS $\bar{\nu}_e$ appearance ($\beta=1$) and no $\bar{\nu}_e$ appearance ($\beta=0$):

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Red: expected # of $\bar{\nu}_e$ events w/ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation ($\beta=1$, 17.2 evts)

- For rate+shape, the $\beta = 0$ hypothesis is excluded by $2\sigma$
- Result statistically not conclusive yet – need more data

<table>
<thead>
<tr>
<th>Analysis</th>
<th>P-value for $\beta = 0$ ($\sigma$ excl.)</th>
<th>P-value for $\beta = 1$ ($\sigma$ excl.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate only</td>
<td>0.0686 ($1.82\sigma$)</td>
<td>0.246 ($1.16\sigma$)</td>
</tr>
<tr>
<td>Rate+shape</td>
<td>0.0244 ($2.25\sigma$)</td>
<td>0.261 ($1.12\sigma$)</td>
</tr>
</tbody>
</table>
T2K $\nu_\mu$ Results (~May 2018)

- CL contours for $\nu_\mu \rightarrow \nu_\mu$ disappearance parameters, including reactor constraint on $\sin^2 \theta_{13}$
- Best fit points:
  $\sin^2 \theta_{23} = 0.532$
  $\Delta m_{32}^2 = 2.452 \times 10^{-3}$ eV$^2$
- T2K data compatible with maximal mixing ($\sin^2 \theta_{23} = 0.52$)
- Stronger $\sin^2 \theta_{23}$ constraint in data than expected from sensitivity studies
Latest T2K CP Violation Search Result

T2K-only sensitivity:

- Preference for values of $\delta_{CP} \sim -\pi/2$
- Sensitivity improved due to lower value of $\sin^2 \theta_{13} = 0.0212$
- Note: data-fit result gives a stronger constraint than the sensitivity
T2K Search for $\delta_{CP}$

- T2K fit with reactor constraint on $\sin^2 \theta_{13}$:
  - Best fit point: $\delta_{CP} = -1.885$ radians in Normal Hierarchy
  - $\delta_{CP}$ $2\sigma$ CL confidence interval:
    - Normal mass hierarchy: $[-2.966, -0.628]$ radians
    - Inverted mass hierarchy: $[-1.799, -0.979]$ radians
  - CP conserving values $(0, \pi)$ fall outside of the $2\sigma$ CL intervals!
    - Still fall within the $3\sigma$ CL intervals
    - Suggestive result, but need more data

Sensitivity

Data ($2\sigma$ CL)
T2K Search for $\delta_{CP}$ – Bayesian Analysis

Both Hierarchies

- **T2K excludes CP conservation at 2$\sigma$, but not 3$\sigma$**
- **Most probable value, marginalized over hierarchy, is $\delta_{CP} = -1.74$**
Other T2K Measurements

• T2K also has a rich program of non-oscillation physics
  • Many many world-leading cross section measurements
  • Exotic physics searches (sterile neutrinos, heavy neutrinos, etc..)

Some recent xsec results :
• CC-inclusive on CH, Fe, H₂O
• CC0π on CH, H₂O, ...
• CC1π on CH, H₂O
• NC1π⁰

Some ongoing xsec analyses :
• CC inclusive $\bar{\nu}_\mu$, on Ar
• CC0π $\nu + \bar{\nu}$, C+O, C+Pb, ...
• CC1π $\nu_\mu$ on H₂O and C
• NC1π⁰, CC1π⁰ on H₂O, CH
• NC1γ
• + many others!

Example new result : $\nu_\mu$ CC inclusive on CH

(PRD 98, 012004 (2018))
Future Long-Baseline Neutrino Oscillation Physics Prospects
Super Kamiokande : SK-Gd Upgrade

- Super Kamiokande now undergoing SK-Gd upgrade!
- Gd loading to capture thermal neutrons → delayed gamma signal
- Can be used to tag $\bar{\nu}_e$
- SK-Gd physics targets:
  - Supernova relic neutrino ($3\sigma$ discovery after 10 years)
  - Improve pointing accuracy for galactic supernovae
  - Nearby supernova Si-burning precursor detection
  - Reduction of solar $\nu$ BG
  - Reactor neutrinos
  - Reduce proton decay background
  - $\nu/\bar{\nu}$ discrimination
- No negative impact on water quality, high-energy background, etc.
- May help T2K $\nu/\bar{\nu}$ discrimination
Super-K Refurbishment for SK-Gd

- Super-K tank was opened summer 2018 (first time since 2006)
- Refurbishment work ongoing in preparation for Gd loading:
  - Cleaning + water sealing reinforcement
  - Improvement of tank piping
  - Replacement of defective PMTs
- Currently re-filling water + finishing work at top of tank + taking data with ~90% filled tank
- Gd loading schedule will be decided w/ input from T2K/J-PARC
  - Tentatively plan to add 0.01% Gd in late 2019/early 2020
  - Will then load with 0.1% Gd later
Super-K Tank Open Work
- Proposal for extension of T2K:
  - May have $3\sigma$ sensitivity to $\delta_{CP} \neq 0$ by around 2026
  - $20 \times 10^{21}$ POT by 2027~2028
  - Target beam power: 1.3 MW
  - Increase effective statistics
    - More new SK event samples
    - 320kA horn current
  - Reduce sys. error $\sim 9\% \rightarrow \sim 4\%$
- KEK/J-PARC Stage-1 status
J-PARC Beam Power Upgrades

- Currently: 485 kW with 2.48 s repetition rate
  - 500+ kW achieved during beam tests
- Plan to upgrade MR power supplies in 2020/2021 to reach 1.3 s repetition rate
  - RF improvements can allow for further decrease to 1.16 s
- Plan to improve beam stability, reduce MR beam losses to increase number of protons per pulse
- Upgrades to J-PARC neutrino beamline needed to accept high power beam
J-PARC Neutrino Beamline Upgrades

- Upgrades to the neutrino beamline necessary to accommodate the high power proton beam
  - + Others to improve T2K datataking
- Primary beamline upgrades:
  - Upgrade to semi-remote handling at most downstream part of beamline
  - Upgrades to beam profile monitoring
  - Upgrades to monitor readout electronics and beam interlock system
  - etc..
- Secondary beamline upgrades:
  - Increase horn current
  - Upgrades to target and horn cooling
  - Upgrades to radioactive water disposal scheme
  - etc..
- Beamline upgrade TDR under review now
- Necessary upgrades to be completed by 2021
• Reduce ND systematics to $< 4\%$
  • Improve acceptance for high-angle and backwards tracks
• Replace P0D with: superFGD + 2 High-Angle TPCs + TOF
• CERN joined upgrade team in 2018
• Upgrade TDR under review now
• Plan to install in late 2021
SuperFGD R&D for ND280 Upgrade

- Many R&D items ongoing for ND280 upgrade
- SuperFGD is a major new component
  - 2,000,000 1x1x1cm$^3$ scintillator cubes
  - 3D readout by wavelength shifting fibers
- Muon tracking efficiency significantly improved for high-angle tracks

+ Stopping muons in superFGD
Conclusion

• Latest T2K result is very exciting!
• Rate + shape analysis gives $2\sigma$ hint of $\bar{\nu}_e$ appearance from a $\bar{\nu}_\mu$ beam
  • Need more $\bar{\nu}$-mode data for T2K measurement of $\bar{\nu}_e$ appearance
• CP conserving values of $\delta_{CP} (0, \pi)$ fall outside of the $2\sigma$ CL intervals!
  • However, constraint is tighter than sensitivity – need more $\nu$-mode data to make a reliable/precise measurement
• May reach 99% CL for CP violation in the very near future!
  • Need more data!
• T2K extended running proposed to improve sensitivity
• Various upgrades underway for increased beam power + improved systematics
• T2K data compatible with maximal mixing ($\sin^2 \theta_{23} = 0.52$)

• Contours slightly narrower than expected for maximal mixing

T2K $\nu_{\mu}$ Results (~Dec 2017)