Recent results from the T2K experiment

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Outline

• Neutrino oscillations
• T2K experiment
• Oscillation analysis
• Recent results
• Future plans
• Summary
Neutrino oscillations

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Neutrino oscillations

Current efforts:
- Precise measurement of the oscillation parameters ($\theta_{23}$ octant, $\theta_{13}$)
- Neutrino mass hierarchy
  - $m_1 < m_2 < m_3$ or $m_3 < m_1 < m_2$
- Presence of CP violation and value of $\delta_{cp}$
- “Sterile neutrino”? Exotics?

Neutrino oscillations parameterized with:
- Three mixing angles:
  $\theta_{23} \sim 45^\circ$, $\theta_{13} \sim 9^\circ$, $\theta_{12} \sim 34^\circ$
- Two squared mass differences
  $\Delta m_{21}^2 \approx 7.5 \times 10^{-5} \text{eV}^2$,  
  $|\Delta m_{32}^2| \approx 2.5 \times 10^{-3} \text{eV}^2$,  
  $\Delta m_{ij}^2 = m_i^2 - m_j^2$
- CP violating phase $\delta_{cp}$  

PDG 2016

Atmospheric and accelerator
$\begin{pmatrix} 
\nu_e \\
\nu_\mu \\
\nu_\tau 
\end{pmatrix} = 
\begin{pmatrix} 
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23} 
\end{pmatrix} \begin{pmatrix} 
\cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13} 
\end{pmatrix} \begin{pmatrix} 
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1 
\end{pmatrix} \begin{pmatrix} 
\nu_1 \\
\nu_2 \\
\nu_3 
\end{pmatrix}$

Accelerator and reactor
Flavor eigenstates

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) – neutrino mixing matrix

Reactor and solar
Mass eigenstates

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RECENT RESULTS FROM THE T2K EXPERIMENT
• Neutrino oscillations
• T2K experiment
• Oscillation analysis
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• Summary
T2K experiment

Super-Kamiokande

Japan

295 km

J-PARC

3 GeV

Materials and Life Science Facility

Linac

J-PARC

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RECENT RESULTS FROM THE T2K EXPERIMENT
Neutrino oscillations in T2K

- T2K studies neutrino and antineutrino oscillations
  - $\nu_\mu \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_e$
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- Appearance channel: $\theta_{13}$, CP violation, $\theta_{23}$ octant, mass hierarchy

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m^2_{32} L}{4E_\nu}\right) \left(1 + \frac{2a}{\Delta m^2_{31}}(1 - 2\sin^2 \theta_{13})\right)$$

- For antineutrino oscillations ($P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$) $\delta$ turns into $-\delta$ and $a$ to $-a$

- Disappearance channel: measure $\theta_{23}$ and $|\Delta m^2_{32/1}|$

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - (\cos^2 \theta_{13} \sin^2 2\theta_{23}) \sin^2 \left(\Delta m^2_{32} \frac{L}{4E}\right)$$

$\alpha \equiv 2\sqrt{2} G_F n_e E$

Matter effect
Off-axis beam
- Far detector and complex of near detectors
- Neutrino energy peak at ~0.6 GeV
  \( L = 295 \text{ km, tuned for } 1^{\text{st}} \text{ osc. maximum} \)
- High-purity intense neutrino (antineutrino) beam
  - \( \nu/\bar{\nu} \) beam production by reversing current in magnetic horns
  - Reduced background from intrinsic \( \nu_e \) and high energy tail

\[ N_{ND} \approx \Phi_{\nu_D} \times \sigma_{ND} \times \epsilon_{ND} \]
\[ N_{FD} \approx \Phi_{\nu_D} \times \sigma_{FD} \times \epsilon_{FD} \times P_{\text{osc}} \]
**Near detectors**

**INGRID:**
- On-axis detector
- Iron\scintillator modules
- Beam direction and rate stability monitor
- Day-by-day measurements

**ND280:**
- Off-axis detector
- Sub-detectors in 0.2 T magnetic field:
  - Fine-Grained detectors (FGD)
  - Time-Projection Chambers (TPC)
- Used to constrain flux and cross-section uncertainty

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**RECENT RESULTS FROM THE T2K EXPERIMENT**
Far detector

- 50 kt water-Cherenkov detector
- 1 km underground
  (~2700 m of water equivalent)
- No magnetic field

- Analysis samples: TOTAL: 5 samples!
  - CCQE – μ – like and e – like events for ν and ν̅ mode
  - CC1π – 1 e-like ring and 1 delayed decay electron
    (~ 10% of events)

Good separation between e and μ events
• Neutrino oscillations
• T2K experiment
• Oscillation analysis
• Recent results
• Future plans
• Summary
Stable operation at ~ 470 kW

Total 22.54 × 10^{20} POT
* POT – Protons On Target

- 14.93 × 10^{20} POT in neutrino mode and 7.62 × 10^{20} POT in antineutrino mode
- Neutrino statistics doubled during 2016-2017 data taking period
**T2K analysis strategy**

- Hadron production data from NA61/SHINE
- INGRID/Beam monitor data
- ND280 model
- ND280 data
- Flux model
- Cross section model
- Cross-section data from other experiments
- Super-Kamiokande model
- Super-Kamiokande data

**Oscillation Fit**

- **Oscillation parameters**
  - Frequentist and Bayesian approaches
  - Good agreement between results
• Neutrino oscillations
• T2K experiment
• Oscillation analysis

• Recent results
• Future plans
• Summary
Analysis results: $|\Delta m_{32}^2|$ and $\theta_{23}$

- **2016 analysis:**
  - results comparable with other experiments
  - consistent results in neutrino and antineutrino modes $\rightarrow$ CPT conservation
- **2017 analysis:**
  - pending final systematics
Analysis results: $\theta_{13}$

- T2K results consistent with reactor experiments’ data
  - PDG’16: $\sin^2 \theta_{13} \approx 0.0210 \pm 0.0011$
- T2K data favor normal mass hierarchy
- Result may be used to put constrain on $\delta_{cp}$
Analysis results: CP violation

- Joint analysis with reactor constraint applied
  - *Best fit*: $\delta_{\mathrm{cp}} = -1.833$
  - Normal mass hierarchy preferred
  - CP conservation excluded at the 2σ level
  - $\delta_{\mathrm{cp}}$ (at 2σ):
    - $[-2.981; -0.600]$ normal mass hierarchy
    - $[-1.531; -1.184]$ inverted mass hierarchy

Reactor constraint $\sin^2 2\theta_{13} = 0.085 \pm 0.005$
• Neutrino oscillations
• T2K experiment
• Oscillation analysis
• Recent results
• **Future plans**
• Summary
Future plans

- Increase $\nu_\mu/\bar{\nu}_\mu$ statistics
  - $7.8 \times 10^{21}$ POT by ~ 2021
  - T2K II proposal to operate until 2026
- Possibly exclude CP conservation at 3σ level
- Reduction of systematic uncertainties is crucial
  - 18% (2011) → 9% (2014) → 6% (2016) → 4% (2020..)?
- Near detector upgrade
- Improve precision for atmospheric parameters
Summary

- By summer 2017 accumulated $22.54 \times 10^{20}$ POT
- $\theta_{13}$ and $\theta_{23}$ measurements are consistent with other experiments’ data
- Excluded CP conservation @2$\sigma$ level
  - Data favor normal mass hierarchy and the best fit is close to $\delta_{cp} = -\pi/2$

Plans:
- Continue data taking
- T2K II proposal: run until 2026
  - Beam line upgrade to reach power $\sim 1$MW
  - Near detector upgrade to further improve understanding of neutrino interactions
Backup
T2K Collaboration
~500 members, 63 institutes, 11 countries

<table>
<thead>
<tr>
<th>Country</th>
<th>Institutes</th>
</tr>
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<tr>
<td>U. Regina</td>
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Recent publications

- First measurement of the $\nu_\mu$ charged-current cross section without pions in the final state on a water target (arXiv:1708.06771)
- Measurement of neutrino and antineutrino oscillations by the T2K experiment including a new additional sample of $\nu_e$ interactions at the far detector (arXiv:1707.0148)
- Measurement of $\bar{\nu}_\mu$ and $\nu_\mu$ charged current inclusive cross sections and their ratio with the T2K off-axis near detector (Phys.Rev. D96 (2017) no.5, 052001)
- Measurement of the single $\pi^0$ production rate in neutral current neutrino interactions on water (arXiv:1704.07467)
- Updated T2K measurements of muon neutrino and antineutrino disappearance using $1.5 \times 10^{21}$ protons on target (Phys.Rev. D96 (2017) no.1, 011102)
- Search for Lorentz and CPT violation using sidereal time dependence of neutrino flavor transitions over a short baseline (Phys.Rev. D95 (2017) no.11, 111101)
T2K Neutrino flux prediction

- Simulation: FLUKA, GCALOR and GEANT3
- External data: hadron production from NA61/SHINE (CERN)
  - Reduction of uncertainties: ~30% to ~10%
  - Background from $\nu_e$ fraction at ~0.5% level
ND280 analysis samples: $\nu_\mu$-mode

- CC0$\pi$ – muon 0 pions in final state
- CC1$\pi$ – 1 pion and muon in final state
- CC-Other – all other CC interactions
ND280 analysis samples: $\bar{\nu}_\mu$-mode

- CC-1-track and CC-N-tracks samples
ND280 in oscillation analysis

<table>
<thead>
<tr>
<th>Total $N_{SK}$ Fraction Uncertainty, %</th>
<th>$\nu_\mu$</th>
<th>$\nu_e$</th>
<th>anti-$\nu_\mu$</th>
<th>anti-$\nu_e$</th>
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<tbody>
<tr>
<td>Flux</td>
<td>W/O ND280</td>
<td>7.6</td>
<td>8.9</td>
<td>7.1</td>
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<td>Cross section</td>
<td>W/O ND280</td>
<td>7.7</td>
<td>7.2</td>
<td>9.3</td>
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<tr>
<td>Flux and cross section</td>
<td>W/ ND280</td>
<td>2.9</td>
<td>4.2</td>
<td>3.4</td>
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<tr>
<td>Final/sec. hadronic interactions</td>
<td>-</td>
<td>1.5</td>
<td>2.5</td>
<td>2.1</td>
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<tr>
<td>Far detector</td>
<td>-</td>
<td>3.9</td>
<td>2.4</td>
<td>3.3</td>
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<tr>
<td>Total</td>
<td>W/O ND280</td>
<td>12.0</td>
<td>11.9</td>
<td>12.5</td>
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<tr>
<td>Total</td>
<td>W/ ND280</td>
<td>5.0</td>
<td>5.4</td>
<td>5.2</td>
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</table>

- Fit to ND280 data constrains flux and cross section model
- Significant reduction of systematic uncertainties for oscillation analysis
  - $\approx 12\% \rightarrow \approx 6\%$
Total systematics uncertainties

Systematic uncertainties (%) used in 2017 analysis

<table>
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<tr>
<th>Error Source</th>
<th>1Rmu FHC</th>
<th>1Rmu RHC</th>
<th>1Re FHC 1 d. e.</th>
<th>FHC/RHC</th>
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<td>1.9</td>
<td>1.6</td>
<td>16.5</td>
<td>1.6</td>
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<tr>
<td>SK FSI+SI+PN</td>
<td>2.2</td>
<td>2.0</td>
<td>11.3</td>
<td>1.6</td>
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<tr>
<td>SK Detector+FSI+SI+PN</td>
<td>2.9</td>
<td>2.5</td>
<td>19.2</td>
<td>2.1</td>
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<tr>
<td>ND280 const. flux &amp; xsec</td>
<td>3.3</td>
<td>2.7</td>
<td>4.1</td>
<td>2.5</td>
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<tr>
<td>$\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}<em>e)/\sigma(\bar{\nu}</em>\mu)$</td>
<td>0.0</td>
<td>0.0</td>
<td>2.6</td>
<td>3.1</td>
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<tr>
<td>NC1$\gamma$</td>
<td>0.0</td>
<td>0.0</td>
<td>0.3</td>
<td>1.5</td>
</tr>
<tr>
<td>NC Other</td>
<td>0.3</td>
<td>0.3</td>
<td>1.0</td>
<td>0.2</td>
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<tr>
<td>Syst. Total</td>
<td>4.4</td>
<td>3.8</td>
<td>19.6</td>
<td>4.7</td>
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SK analysis samples

RECENT RESULTS FROM THE T2K EXPERIMENT
New analysis sample in SK: CC1π

- 1 e-like ring and 1 decay electron
- Applied only for ν-mode running
  - Gain ~10% more statistics (MC)
  - 15 events observed
- Five samples available for T2K analysis
Event rates

<table>
<thead>
<tr>
<th>Sample</th>
<th>Predicted Rates</th>
<th>Observed Rates</th>
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<tbody>
<tr>
<td></td>
<td>$\delta_{cp}=-\pi/2$</td>
<td>$\delta_{cp}=0$</td>
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<tr>
<td>CCQE 1-Ring e-like FHC</td>
<td>73.5</td>
<td>61.5</td>
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<td>CC$1_\pi$ 1-Ring e-like FHC</td>
<td>6.92</td>
<td>6.01</td>
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<tr>
<td>CCQE 1-Ring e-like RHC</td>
<td>7.93</td>
<td>9.04</td>
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<tr>
<td>CCQE 1-Ring $\mu$-like FHC</td>
<td>267.8</td>
<td>267.4</td>
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<tr>
<td>CCQE 1-Ring $\mu$-like RHC</td>
<td>63.1</td>
<td>62.9</td>
</tr>
</tbody>
</table>

- Largely in line with the prediction for $\delta_{cp} = -\pi/2$
- More observed e-like $CC1\pi$ events**15** than maximum expectation **6.92**

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RECENT RESULTS FROM THE T2K EXPERIMENT

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Robustness of T2K analysis results

- Neutrino interaction modelling is a rapidly developing media
  - Study potential bias in the T2K oscillation analysis due to the choice of neutrino interaction model and investigate variations that are not yet implemented in the fit model
  - Produce fake data studies by varying parts of the interaction model
  - Fit using the model without the variations
  - Evaluate biases in the fitted oscillation parameters
- Use different data sets:
  - Discrepancies between models and data that may indicate deficiencies in models
  - Planned improvements to models not yet available in oscillation fitting framework
**Analysis results: $|\Delta m_{32}^2|$ and $\theta_{23}$**

- **Best fit for normal mass hierarchy:**
  - $|\Delta m_{32}^2| \approx 2.462^{+0.081}_{-0.084} \times 10^{-3} \text{ eV}^2/c^4$
  - $\sin^2 \theta_{23} = 0.532^{+0.046}_{-0.068}$

- **Best fit for inverted mass hierarchy:**
  - $|\Delta m_{32}^2| \approx 2.51^{+0.081}_{-0.083} \times 10^{-3} \text{ eV}^2/c^4$
  - $\sin^2 \theta_{23} = 0.534^{+0.043}_{-0.07}$

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**Posterior Bayesian probability**

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<tr>
<th></th>
<th>$\sin^2 \theta_{23} &lt; 0.5$</th>
<th>$\sin^2 \theta_{23} &gt; 0.5$</th>
<th>Sum</th>
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<tr>
<td>Normal mass hierarchy</td>
<td>0.193</td>
<td>0.674</td>
<td>0.868</td>
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<td>Inverse mass hierarchy</td>
<td>0.026</td>
<td>0.106</td>
<td>0.132</td>
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<tr>
<td>Sum</td>
<td>0.219</td>
<td>0.781</td>
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*Pending final systematics*
Fake data studies in T2K

- Use different data sets:
- Data-driven variation generated based on the pre-fit data/prediction discrepancy in ND280 (and external data, e.g. Minerva)
- Variations produced with different assumptions of the axial form factor
- Variations that cover discrepancies in pion spectrum observed in ND280
- Variations to probe new pion production model
Example of ND280 data-driven fake data studies

- Use excess of data over prediction prior to ND280 fitting
- Assign observed access to three different interactions
  - CCQE enhanced
  - 2p2h with intermediate $\Delta$ resonate ($2p2h-\Delta$)
  - Pure nucleon-nucleon correlations ($2p2h$-non$\Delta$)

- Use excess to predict event rates in ND280 and Super-Kamiokande
Example of ND280 data-driven fake data studies

- Example studies for the fake-data studies produced for Asimov data sample

<table>
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<th>Parameter(s)</th>
<th>Asimov A</th>
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<td>$\sin^2 \theta_{23}$</td>
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<tr>
<td>$\sin^2 \theta_{13}$ reactors</td>
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<td>$\sin^2 \theta_{12}$</td>
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<tr>
<td>$</td>
<td>\Delta m^2_{32}</td>
</tr>
<tr>
<td>$\Delta m^2_{21}$</td>
<td>$7.53 \times 10^{-5}$ eV$^2$/c$^4$</td>
</tr>
<tr>
<td>$\delta_{CP}$</td>
<td>-1.601</td>
</tr>
<tr>
<td>Mass Hierarchy</td>
<td>Normal</td>
</tr>
</tbody>
</table>

- Used in analysis to get sensitivity values
- Values set to PDG-2016 data and best fit values from the previous T2K analysis
Fake data studies

Effect on “atmospheric” parameters

- Bias of $\Delta m^2_{23}$ to lower values and $\sin^2\theta_{23}$ to max mixing
- Narrow contour obtained for fake data studies
- Studying whether should incorporate these effects of variations as an additional systematic uncertainty
- No conclusive statement yet
Fake data-studies
Effect on $\delta_{CP}$

- Right: Compare nominal MC and the fake data
- Left: shift data $\Delta \chi^2$ according to difference observed in fake data study
- Max change/shift to the confidence interval/mean point: $\approx 2\%$
  - Small effect on $\delta_{CP}$ limits
Impact of data samples on $\delta_{CP}$

- Take data samples out 1 at a time and replace with nominal Monte Carlo prediction → check the change on limits
- Largest effect from e-like CC1π sample
ND280 Upgrade

Current ND280 configuration

Reference ND280 configuration

Alternative ND280 configuration

Angle reconstruction efficiency