T2K neutrino oscillation results

Ciro Riccio
WIN2019 - The 27th International Workshop on Weak Interactions and Neutrinos
June 4th, 2019
Overview
Overview

• Neutrino oscillations
Overview

• Neutrino oscillations

• T2K experimental setup
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- Neutrino oscillations
- T2K experimental setup
- Oscillation analysis strategy
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• T2K latest results
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• T2K latest results

• Conclusions
Neutrino oscillations

Neutrino mixing described by the PMNS matrix: 3 mixing angles and 1 complex CPV phase

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\end{pmatrix} =
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Atmospheric and accelerator
\[\theta_{23} \sim 50^\circ\]
\[|\Delta m_{32}^2| \sim 2.5 \times 10^{-3} \text{ eV}^2\]

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Open questions: \[\delta_{CP}, \theta_{23} \text{ octant and mass ordering}\]

\[\Delta m_{ji}^2 = m_j^2 - m_i^2 \quad c_{ij} = \cos \theta_{ij} \quad s_{ij} = \sin \theta_{ij}\]
The T2K experiment

Super-Kamiokande

Near Detectors

J-PARC

Mt. Noguchi-Goro
2,924 m

Mt. Ikeno-Yama
1,360 m

1,700 m below sea level

295 km

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Physics goals:

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The T2K experiment

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- Precise measurement of $\theta_{23}, |\Delta m_{32}^2|$
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  • Determine $\theta_{13}$ and $\delta_{CP}$
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- $\nu$ cross section measurements at the near detectors
Oscillations measurements at T2K
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Long baseline accelerator-based experiments are sensitive to:
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- Atmospheric parameters ($\theta_{23}, \Delta m_{32}^2$) through $\nu_\mu$ disappearance

\[
P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E} \right)
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Oscillations measurements at T2K

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- ($\theta_{13}, \delta_{CP}$) depends on the $\nu_e/\bar{\nu}_e$ appearance

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In the case of T2K $\delta_{CP}$ change the appearance probability by ±30% while the mass ordering has a ~10% effects
30 GeV proton beam from J-PARC Main Ring extracted onto a graphite target producing hadrons (mainly pions and kaons)
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Hadrons are focused and selected in charge by 3 electromagnetic horns:
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Detectors 2.5° off the direction of the beam centered around 0.6 GeV. Off-axis method reduce high energy tail and maximize oscillation detection probabilities

$\sin^2 2\theta_{23} = 1.0$
$\sin^2 2\theta_{13} = 0.1$
$\Delta m^2_{32} = 2.4 \times 10^{-3} \text{ eV}^2$
The off-axis near detector (ND280)
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A large dipole magnet (UA1) produces 0.2 T.
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Side muon range detector (SMRD): plastic scintillators instrumenting the magnet iron slice

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- An electromagnetic calorimeter (ECal) is used to distinguish tracks from showers.

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Super-Kamiokande (SK)

SK is a 50 kton water Cherenkov detector
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Inner detector ~11000
20 inch PMTs

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Outer detector ~2000
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Very good $\mu/e$ separation

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Collected data

• Total proton on target (POT) collected: $3.1 \times 10^{21}$ POT: $1.5 \times 10^{21}$ POT in $\nu$ mode and $1.6 \times 10^{21}$ POT in $\bar{\nu}$ mode

• Beam power 500 kW!
Flux prediction:
proton beam measurements and
external hadron production
measurements

Neutrino interactions model:
tuned using external data
T2K oscillation analysis strategy

Flux prediction:
proton beam measurements and external hadron production measurements

ND280 measurements:
select CC $\nu_\mu$ and $\bar{\nu}_\mu$ interactions
constrain flux and cross sections

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ND280 measurements predict the expected events at SK

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**Extract oscillation parameters**
T2K oscillation analysis strategy

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Extract oscillation parameters

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Neutrino fluxes

SK: Neutrino Mode, $\nu_\mu$

SK: Antineutrino Mode, $\bar{\nu}_\mu$
Neutrino fluxes

Fluxes known with uncertainties smaller than 10% based on NA61/SHINE thin-target measurements
Neutrino fluxes

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Dominant systematics due to the hadron interactions modeling
Neutrino fluxes

It will be reduced to ~5% by using NA61/SHINE measurements of T2K replica target.

Fluxes known with uncertainties smaller than 10% based on NA61/SHINE thin-target measurements.

Dominant systematics due to the hadron interactions modeling.
Relevant $\nu$ interactions at T2K

\[ \sigma_{\nu_{\mu}CH}(E_\nu) \]

FHC $\nu_\mu$ Flux (arbitrary norm.)

- CC-Total
- CC-RES
- CC-1p1h+2p2h
- NC-Total
- NC-RES

\[ \frac{\sigma(E_\nu/E_\nu)(10^{38} \text{cm}^2 \text{nucleon}^{-1} \text{GeV}^{-1})}{E_\nu (\text{GeV})} \]

T2K: ND off-axis

[1707.01048] B.F. Super-K oscillated

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Relevant $\nu$ interactions at $\text{T2K}$

**CCQE**
(Charged-Current Quasi-Elastic)

$\nu_{\mu}$ Flux (arbitrary norm.)

$\nu_{\mu}$ ch $(E_{\nu})$

$\frac{\sigma(E_{\nu})/E_{\nu}}{(10^{38}\text{cm}^{2}\text{nucleon}^{-1}\text{GeV}^{-1})}$

$E_{\nu}$ (GeV)

$\nu_{\mu}$ to $\mu^-$

$W^+$

$n$ to $p$

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Relevant $\nu$ interactions at $T2K$.

**CCQEs**

- Charged-Current Quasi-Elastic (CCQE)
- Charged-Current Resonant pion production (CCRES)

**Fluxes**

- $\nu_\mu$ flux (arbitrary norm.)
- $\mu$ flux

**Relevant Events**

- CC-Totals
- CC-RES
- CC-1p1h+2p2h
- NC-Totals
- NC-RES

**Graphs**

- Graph showing the cross-section $\sigma(E_{\nu})/E_{\nu}$ in units of $10^{-38}$ cm$^2$ nucleon$^{-1}$ GeV$^{-1}$.
- Graph showing the $\nu_\mu$ and $\mu^-$ interactions with $W^+$ and $\pi^+$.

**References**

- NEUT 5.3.6, $\sigma_{\nu_{CH}}(E_{\nu})$
- FHC $\nu_\mu$ flux (arbitrary norm.)
- T2K ND off-axis
- [1707.01048] B.F. Super-K oscillated

**Author**

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Relevant $\nu$ interactions at T2K

**CCQE**
(Charged-Current Quasi-Elastic)

$\nu_\mu \rightarrow \mu^-$

$\nu_\mu \rightarrow \mu^- W^+$

$\nu_\mu \rightarrow \mu^- n \rightarrow \mu^- p + \Delta^{++} \pi^+$

$\nu_\mu \rightarrow \mu^- n \rightarrow \mu^- p + \pi^+$

**CCRES**
(Charged-Current Resonant pion production)

$\nu_\mu \rightarrow \mu^- W^+$

$\nu_\mu \rightarrow \mu^- n \rightarrow \mu^- p + \pi^+$

**CCDIS**
(Charged-Current Deep Inelastic Scattering)

$\nu_\mu \rightarrow \mu^- W^+$

$\nu_\mu \rightarrow \mu^- n \rightarrow \mu^- p + n, p + X$

--

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Nuclear effects
Nuclear effects

Nucleons bound in the nucleus $\Rightarrow$ Nuclear effect!
Nuclear effects

Nucleons bound in the nucleus $\implies$ Nuclear effect!
Nuclear effects

Nucleons bound in the nucleus $\rightarrow$ Nuclear effect!

Fermi motion

Nucleon correlations
Nuclear effects

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Fermi motion

Nucleon correlations

Final State Interaction (FSI)
Nuclear effects

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Neutrino Energy reconstructed using CCQE hypothesis
Nuclear effects

Nucleons bound in the nucleus $\Rightarrow$ Nuclear effect!

Fermi motion

Nucleon correlations

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Neutrino Energy reconstructed using CCQE hypothesis

Nuclear effects introduce a bias in neutrino energy reconstruction

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Detector acceptance

Nucleons bound in the nucleus \( \Rightarrow \) Nuclear effect!

Fermi motion

Nucleon correlations

Final State Interaction (FSI)
Detector acceptance

Nucleons bound in the nucleus ⇒ Nuclear effect!

Fermi motion

Nucleon correlations

Final State Interaction (FSI)

Limited detector acceptance
Detector acceptance

Nucleons bound in the nucleus \(\Rightarrow\) Nuclear effect!

Limited detector acceptance
Nucleons bound in the nucleus ⇒ Nuclear effect!

Detector acceptance

Limited detector acceptance

Fermi motion
Nucleon correlations
Final State Interaction (FSI)
Detector acceptance

Nucleons bound in the nucleus $\Rightarrow$ Nuclear effect!

- Fermi motion
- Nucleon correlations
- Final State Interaction (FSI)

$\nu_\mu \rightarrow W^+ \rightarrow \mu^-$

Detector acceptance

$\nu_\mu \rightarrow W^+ \rightarrow \mu^-$

P0D | FGD | FGD
---|---|---
ECal | TPC | ECal

Magnet | SMRD

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Detector acceptance

Nucleons bound in the nucleus $\Rightarrow$ Nuclear effect!

Increase acceptance and reduce the dependence from the cross-section modeling measuring interaction topologies
ND280 measurements: $\nu$ beam
ND280 measurements: $\nu$ beam

**CC-0\pi**

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<tr>
<td>TPC</td>
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</tr>
<tr>
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Events/(100 MeV/c)

Reconstructed muon momentum (MeV/c)

Data / Sim.

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ND280 measurements: $\nu$ beam

**CC-0\(\pi\)**

- Magnet
- SMRD
- FGD
- TPC
- ECAL

**CC-1\(\pi^+\)**

- Magnet
- SMRD
- FGD
- TPC
- ECAL

Events/(100 MeV/c)

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Reconstructed muon momentum (MeV/c)

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ND280 measurements: $\nu$ beam

CC-0$\pi$

CC-1$\pi^+$

CC-Other

Magnet 
SMRD

FGD $\mu^-$ FGD

TPC $p$

ECal

Events/(100 MeV/c)

Reconstructed muon momentum (MeV/c)

Data / Sim.

PRELIMINARY

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ND280 measurements: $\bar{\nu}$ beam
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CC-1Track

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ND280 measurements: $\bar{\nu}$ beam
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**CC-NTracks**

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$\bar{\nu}_\mu$ in $\bar{\nu}$ mode
int. in FGD1
CC-NTracks

![Graph showing data and simulated events vs. reconstructed muon momentum (MeV/c)]

Ciro Riccio, Naples U. & INFN | WIN2019
ND280 measurements: $\bar{\nu}$ beam

CC-1Track

CC-NTracks

Data / Sim.

Events/(100 MeV/c)

Reconstructed muon momentum (MeV/c)

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**ND280 fit results**

**Impact on SK:**

<table>
<thead>
<tr>
<th>Sample</th>
<th>w/o ND280</th>
<th>w/ ND280</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu 1\mu$</td>
<td>14.6%</td>
<td>5.1%</td>
</tr>
<tr>
<td>$\overline{\nu} 1\mu$</td>
<td>12.5%</td>
<td>4.5%</td>
</tr>
<tr>
<td>$\nu 1e$</td>
<td>16.9%</td>
<td>8.8%</td>
</tr>
<tr>
<td>$\overline{\nu} 1e$</td>
<td>14.4%</td>
<td>7.1%</td>
</tr>
<tr>
<td>$\nu 1e + 1\pi^+$</td>
<td>22.0%</td>
<td>18.7%</td>
</tr>
</tbody>
</table>
## Observed events at SK

<table>
<thead>
<tr>
<th></th>
<th>Observed</th>
<th>$\delta = -\pi/2$</th>
<th>$\delta = 0$</th>
<th>$\delta = +\pi/2$</th>
<th>$\delta = \pi$</th>
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</thead>
<tbody>
<tr>
<td>$e$-like $\nu$ mode</td>
<td>75</td>
<td>74.4</td>
<td>62.2</td>
<td>50.6</td>
<td>62.7</td>
</tr>
<tr>
<td>$e$-like+$1\pi^+$ $\nu$ mode</td>
<td>15</td>
<td>7.0</td>
<td>6.1</td>
<td>4.9</td>
<td>5.9</td>
</tr>
<tr>
<td>$e$-like $\bar{\nu}$ mode</td>
<td>15</td>
<td>17.1</td>
<td>19.4</td>
<td>21.7</td>
<td>19.3</td>
</tr>
<tr>
<td>$\mu$-like $\nu$ mode</td>
<td>243</td>
<td>272.4</td>
<td>272.0</td>
<td>272.4</td>
<td>272.8</td>
</tr>
<tr>
<td>$\mu$-like $\bar{\nu}$ mode</td>
<td>140</td>
<td>139.2</td>
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<td>139.5</td>
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Observed events at SK

<table>
<thead>
<tr>
<th>Neutrino mode</th>
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T2K data prefer $\delta_{CP} = -\pi/2$: maximize $\nu_e$ appearance and minimize $\bar{\nu}_e$ appearance
Observed events at SK

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T2K data prefer $\delta_{CP} = -\pi/2$: maximize $\nu_e$ appearance and minimize $\bar{\nu}_e$ appearance

In $\nu$-mode the deficit of $\mu$-like events is compatible with statistical and systematic uncertainties

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T2K oscillation analysis strategy

Flux prediction:
proton beam measurements and external hadron production measurements

ND280 measurements:
select CC $\nu_\mu$ and $\bar{\nu}_\mu$ interactions
constrain flux and cross sections

Neutrino interactions model:
tuned using external data

Prediction at the Far Detector:
ND280 measurements predict the expected events at SK

SK measurements:
Select CC $\nu_\mu/\bar{\nu}_\mu$ and $\nu_e/\bar{\nu}_e$ candidates
after the oscillations

Extract oscillation parameters

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T2K data prefer values of $\delta_{CP} \sim -\pi/2$ mostly driven by the large number of events observed in the $e$-like sample in neutrino mode.

C.L. | Normal hierarchy | Inverted hierarchy
--- | --- | ---
68% | \([-2.51, -1.26]\) | -
90% | \([-2.80, -0.84]\) | -
2$\sigma$ | \([-2.97, -0.63]\) | \([-1.78, -0.98]\)
**δ_{CP} measurement**

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2$\sigma$ | $[-2.97, -0.63]$ | $[-1.78, -0.98]$
Oscillation results ($\theta_{23}$, $|\Delta m^2_{32}|$, $\theta_{13}$, $\delta_{CP}$)

- **T2K data compatible with maximal mixing**

- **T2K Run1-9 Preliminary**

- **w/o reactor constraint**

### Table

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best Fit NH (HI)</th>
<th>$\pm 1\sigma$ NH (IH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2\theta_{32}$</td>
<td>0.54 (0.53)</td>
<td>[0.490,0.558] [0.496,0.560]</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m^2_{32}</td>
<td>$ ($10^{-3}$eV$^2$/c$^4$)</td>
</tr>
<tr>
<td>$\sin^2\theta_{13}$</td>
<td>0.0268 (0.0305)</td>
<td>[0.0222,0.0319] [0.0253,0.0369]</td>
</tr>
</tbody>
</table>
Conclusions

• T2K released results with $3.1 \times 10^{21}$ POT (50% $\nu$-mode, 50% $\bar{\nu}$-mode)

• With these data CP conserving values are excluded at more than $2\sigma$

• T2K data prefers maximal mixing

• Future improvements:
  • More data will come with many improvement in the analysis;
  • New antineutrino samples at the near detector;

Stay tuned!!!
Thank you for your attention
Backup
The on-axis near detector (INGRID)

Monitor the beam stability and direction day-by-day looking at $\nu$ ($\bar{\nu}$) interactions

14 modules arranged in a cross; two others placed at off-diagonal positions

1 extra module made of scintillators and water at the center of the cross

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As far as possible, use data to constrain systematics; e.g. use cosmic samples to evaluate inter-detector matching.

Dominant systematics are pion secondary interactions and out of fiducial volume events.
### Event generators: details

<table>
<thead>
<tr>
<th></th>
<th>NEUT 5.3.2</th>
<th>GENIE 2.8.0</th>
</tr>
</thead>
</table>
| **CCQE** | SF (Benhar et al., 2000)  
BBA05 (Bradford et al., 2005)  
\( M_{AQE} = 1.21 \text{ GeV/c}^2 \)  
\( p_F [^{12}\text{C}] = 217 \text{ MeV/c} \)  
\( E_B [^{12}\text{C}] = 25 \text{ MeV} \) | RFG (Bodek et al., 1981)  
BBA05 (Bradford et al., 2005)  
\( M_{AQE} = 0.99 \text{ GeV/c}^2 \)  
\( p_F [^{12}\text{C}] = 221 \text{ MeV/c} \)  
\( E_B [^{12}\text{C}] = 25 \text{ MeV} \) |
| **2p2h** | Nieves et al., 2011 | - |
| **CCRES** | \( W < 2 \text{ GeV} \)  
Rein-Sehgal, 1981  
FF (Graczyk et al., 2008) | \( W < 1.7 \text{ GeV} \)  
Rein-Sehgal, 1981  
FF (Kuzmin et al., 2016) |
| **CCDIS** | \( W > 1.3 \text{ GeV} \) (w/o single \( \pi \))  
GRV98 PDF (Glück et al. 1998)  
BY corr. at low \( Q^2 \) (Bodek et al. 2003) | \( W > 1.7 \text{ GeV} \) (for \( W < 1.7 \text{ GeV} \) is tuned)  
GRV98 PDF (Glück et al. 1998)  
BY corr. at low \( Q^2 \) (Bodek et al. 2005) |
| **Hadronization** | \( W < 2 \text{ GeV} \)  
KNO scaling (Koba et al. 1972)  
\( W > 2 \text{ GeV} \)  
PYTHIA/JETSET | \( W < 2.3 \text{ GeV} \)  
AGKY (Koba et al. 1972)  
2.3 GeV < \( W < 3 \text{ GeV} \)  
AGKY (Koba et al. 1972) + PYTHIA/JETSET  
\( W > 3 \text{ GeV} \)  
PYTHIA/JETSET |
| **FSI** | Intra-nuclear cascade | Intra-nuclear cascade (INTRANUKE hA) |
Expectation at SK

ND280 constraints are crucial for oscillation analysis precision

<table>
<thead>
<tr>
<th></th>
<th>μ-like</th>
<th>ν mode</th>
<th>μ-like</th>
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</tr>
</thead>
<tbody>
<tr>
<td>e-like</td>
<td>14.6%</td>
<td>16.9%</td>
<td>22.0%</td>
<td></td>
</tr>
<tr>
<td>e-like+1π⁺</td>
<td></td>
<td></td>
<td></td>
<td>4.5%</td>
</tr>
<tr>
<td>Total w/o ND280</td>
<td>5.1%</td>
<td>8.8%</td>
<td>18.7%</td>
<td>7.1%</td>
</tr>
<tr>
<td>Total w/ ND280</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
SK Samples

1 $\mu$-like ring

1 $e$-like ring

1 $e$-like + 1 Michel-$e$-like ring

$\nu$ sample

$\overline{\nu}$ sample

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SK reconstruction

- New reconstruction algorithm is used for SK
- It combines time and charge likelihood for a given ring hypothesis
- New definition of fiducial volume combining distance of the vertex from the wall and direction to the wall (previously only distance from the wall was used)
  - ~30% more statistics for ν-mode e-like samples
  - ~20% more statistic for ¯ν-mode e-like
  - Better purity for μ-like samples by reducing NC background

<table>
<thead>
<tr>
<th>Samples</th>
<th>New SK selection</th>
<th>Old SK selection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Purity</td>
<td>Purity</td>
</tr>
<tr>
<td>μ-like ν mode</td>
<td>80%</td>
<td>68%</td>
</tr>
<tr>
<td>e-like ν mode</td>
<td>81%</td>
<td>81%</td>
</tr>
<tr>
<td>e-like+1π⁺ ν mode</td>
<td>79%</td>
<td>72%</td>
</tr>
<tr>
<td>μ-like ¯ν mode</td>
<td>80%</td>
<td>71%</td>
</tr>
<tr>
<td>e-like ¯ν mode</td>
<td>62%</td>
<td>64%</td>
</tr>
</tbody>
</table>
**Future prospects: T2K-II**

**T2K was originally approved to collect $7.8 \times 10^{21}$ POT driven by sensitivity to $\theta_{13}$**

**Proposal for an extended to collect $20 \times 10^{21}$ POT**

**Increase beam power up to 1.3 MW and horn current up to $\pm 320$ kA**

**SK plan to start to dope water with Gadolinium from next year:**

- Enhance neutron detection capability
- Improves low energy antineutrino detection
- Provides wrong sign bkg constraint in T2K antineutrino data

*MR Power Supply upgrade*
Main ND280 limitations:

- Low efficiency in the “high-angle” region
- Reduced sensitivity to cross section models
- Low threshold for protons
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- Low efficiency in the “high-angle” region
- Reduced sensitivity to cross section models
- Low threshold for protons
T2K-II physics case

~3σ sensitivity to CP-violation for favorable (and currently favored) parameters

Important to reduce systematics with respect to what we have today

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FIG. 18: Distribution of CCQE and 2p2h contributions as a function of muon momentum in the angular range $\cos \theta = [0.7, 0.8]$ at ND280 (left) and Super-K (right) as predicted in the models of Martini et al. [68] (continuous line) and Nieves et al. [69, 70] (histogram).
T2K oscillation \((\theta_{23}, |\Delta m^2_{23}|)\)

- Atmospheric parameters \((\theta_{23}, \Delta m^2_{32})\) through \(\nu_\mu\) disappearance

\[
P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{32} L}{4E}\right)
\]

\(\sin^2 2\theta_{23}\) proportional to the depth of the dip (oscillation minimum)

\(\Delta m^2_{23}\) proportional to the position of the dip
**T2K oscillation \((\theta_{13}, \delta_{CP})\)**

- \((\theta_{13}, \delta_{CP})\) depends on the \(\nu_e/\bar{\nu}_e\) appearance

\[
P(\bar{\nu}_\mu \to \bar{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left( \frac{\Delta m^2_{32} L}{4E} \right) \mp O(\delta_{CP})
\]

In the case of T2K \(\delta_{CP}\) change the appearance probability by \(\pm 30\%\) while the mass ordering has a \(\sim 10\%\) effects

\(\sin^2 2\theta_{13}\) proportional to the oscillation maximum

\(\theta_{13}\) compatible with the one measured by experiments at reactors.