New (*) Neutrino Oscillation Results from T2K

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(*) Run1+2 (1.431E+20 protons on target) dataset
Outline

• Neutrino oscillations
• The T2K experimental setup → arXiv:1106.1238v2, accepted for publication by Nucl.Instrum.Meth. A
• Measuring oscillation parameters at T2K
• Data-taking operations (Physics Runs 1+2, January 2010 – March 2011)
• Data reduction & Oscillation analysis strategy (2010)
• Muon-neutrino disappearance results → Phys.Rev.Lett. in preparation
• Summary
Neutrino Oscillations

production

weak-interaction (flavour) eigenstates

mass-eigenstates

\[
\begin{pmatrix}
    \nu_e \\
    \nu_\mu \\
    \nu_\tau \\
\end{pmatrix} =
\begin{pmatrix}
    U_{e1} & U_{e2} & U_{e3} \\
    U_{\mu1} & U_{\mu2} & U_{\mu3} \\
    U_{\tau1} & U_{\tau2} & U_{\tau3} \\
\end{pmatrix}
\begin{pmatrix}
    \nu_1 \\
    \nu_2 \\
    \nu_3 \\
\end{pmatrix}
\]

propagation described by plane waves

\[
|\nu_i(L)\rangle = e^{-im_i^2L/2E}|\nu_i(0)\rangle
\]
Neutrino oscillation \((v_\alpha \rightarrow v_\beta)\) probability

\[
P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{i > j} \text{Re}\left[ U_{\beta i} U_{\alpha i}^* U_{\beta j}^* U_{\alpha j} \right] \sin^2 \left( \frac{\Delta m^2_{ij} L}{4E} \right) + 2 \sum_{i > j} \text{Im}\left[ U_{\beta i} U_{\alpha i}^* U_{\beta j}^* U_{\alpha j} \right] \sin \left( \frac{\Delta m^2_{ij} L}{2E} \right)
\]

depends on:

- **Mixing matrix elements**
  (determined experimentally)

- **Squared neutrino mass splittings**
  (determined experimentally)

Sensitivity to oscillations by matching the \(L / E\) (baseline to energy) ratio to a particular \(\Delta m^2\)
What do measure in neutrino oscillation experiments?

- With 3 neutrinos, **any 2** squared mass splittings $\Delta m^2$
- 3 mixing angles, $\theta_{12}$, $\theta_{23}$, $\theta_{13}$
- 1 CP violating phase $\delta$

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu_1} & U_{\mu_2} & U_{\mu_3} \\ U_{\tau_1} & U_{\tau_2} & U_{\tau_3} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

- “23” sector probed mainly by atmospheric and LBL accelerator expts
- “13” sector probed mainly by SBL reactor (not $\delta$) and LBL accelerator expts
- “12” sector probed mainly by LBL reactor and solar expts
- Majorana phases
1997-2010

First age of neutrino-mixing exploration

... the atmosphere (SuperK, Soudan, ...)

- multi-GeV mu-like (FC+PC)

... the Sun (SNO, SuperK, ...)

- Neutrino oscillations now firmly established
  studying neutrinos from ...

... nuclear reactors (KamLAND, ...)

- nuclear reactors

... accelerators (K2K, MINOS, ...)

- accelerators

Reconstructed neutrino energy (GeV)
Results from the first age of neutrino-mixing exploration

“23” : LBL accelerator & atmospheric

“12” : LBL reactor & solar

“13” : LBL accelerator & SBL reactor

<table>
<thead>
<tr>
<th>parameter</th>
<th>best fit</th>
<th>~</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{21}^2$ [10^{-5}eV^2]</td>
<td>$7.59^{+0.23}_{-0.18}$</td>
<td>~ 3%</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m_{31}^2</td>
<td>[10^{-3}eV^2]$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>$0.318^{+0.019}_{-0.016}$</td>
<td>~ 6%</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$0.50^{+0.07}_{-0.06}$</td>
<td>~ 14%</td>
</tr>
</tbody>
</table>

(solar) →

(atmospheric) →
Next big questions in neutrino physics...

- $\theta_{13}$ non-zero?
- $\theta_{23}$ maximal?
- CP violation in the neutrino sector?
- Mass hierarchy?
- Dirac or Majorana?
- Absolute mass scale?

T2K
T2K Experiment Overview

Almost pure $\nu_\mu$ beam
Peak at 600 MeV.
L/E tuned to the `atmospheric' $\Delta m^2$ scale.

Super-Kamiokande
50 kton water-Cherenkov detector

J-PARC
30 GeV proton beam
(design) power of 750 kW
J-PARC facility (KEK / JAEA)

RCS: 3 GeV synchrotron
(2 bunches / 25 Hz)

Fast extraction
3.3E+14 p/spill
cycle: ~0.3 Hz
8 bunches/spill
bunch interval: 581 nsec
bunch width: 58 nsec

Neutrino beam to Kamioka
Near detector (280m) pit

Linac
181 MeV

Secondary beam
Target area

30 GeV Main Ring
(8 bunches)
The neutrino beam-line

Magnetic Horns
- 320 kA
- 2.1 T max B field

Target
- A long graphite rod
- Diameter: 2.6 cm
- Length: 91.4 cm (1.9 interaction length)

Simon van der Meer (1925-2011)
CERN 1962

The neutrino beam-line
The `off-axis' trick

T2K is first accelerator neutrino experiment employing the `off-axis' trick.

Exploit kinematical properties of pion decay to create a narrow neutrino beam peaked at a particular energy (chosen to maximise oscillation probability at the SuperK location)
Super-K (IV)

50 kt Water Cherenkov detector
(22.5 kt fiducial mass)

Overburden (shielding): 2700 mwe

Inner detector: 11,129 20'' PMTs
(40% photo-cathode coverage)

Outer detector: 1,885 8'' PMTs

DAQ: No dead-time

Energy threshold: ~4.5 MeV
Water Cherenkov imaging

$\nu_\mu$ CC  "CRISP"

Super-Kamiokande IV
T2K Beam run 0 spill 2.204
Run 66481 Sub 416 Event 95433122
10-05-2009 020910

$\nu_\mu$ CC

Charge (pe)
- >26.7
- 25.3-26.7
- 23.5-25.3
- 21.7-23.5
- 19.9-21.7
- 18.1-19.9
- 16.3-18.1
- 14.5-16.3
- 12.7-14.5
- 10.9-12.7
- 9.1-10.9
- 7.3-9.1
- 5.5-7.3
- 3.7-5.5
- 1.9-3.7
- 0.1-1.9

$v_\mu < 0.2$

Super-Kamiokande IV
T2K Beam run 0 spill 2.204
Run 66481 Sub 416 Event 95433122
10-05-2009 020910

$\nu_e$ CC  "FUZZY"

Charge (pe)
- >26.7
- 25.3-26.7
- 23.5-25.3
- 21.7-23.5
- 19.9-21.7
- 18.1-19.9
- 16.3-18.1
- 14.5-16.3
- 12.7-14.5
- 10.9-12.7
- 9.1-10.9
- 7.3-9.1
- 5.5-7.3
- 3.7-5.5
- 1.9-3.7
- 0.1-1.9

$v_\mu < 0.2$
First T2K neutrino event at SuperK

Super-Kamiokande IV
T2K Beam Run 0 Spill 1143942
Run 66498 Sub 160 Event 37004533
10-02-24:06:00:06
T2K beam dt = 2362.3 ns
Inner: 1265 hits, 2344 pe
Outer: 2 hits, 1 pe
Trigger: 0x80000000
D_wall: 650.8 cm

[ 1st ring + 2nd ring ]
Invariant mass: 133.8 MeV/c²
(close to $\pi^0$ mass)
Momentum: 148.3 MeV/c
280m Near Detector complex
280m Near Detector complex

On-axis near detector (INGRID)
Monitor neutrino beam direction

Off-axis near detector (ND280)
Neutrino flux spectrum characteristics
Neutrino cross sections
Off-axis near detector (ND280)

Upstream target region: Pi0 Detector (P0D)
Optimised for pi0 measurement

Downstream target region: Tracker
Optimised for charged particles
Off-axis near detector (ND280)

**SMRD (Side Muon Range Detector)**
- Scintillator planes in magnet yoke
- Veto + CR trigger + aid in momentum measurement

**P0D (π0 detector)**
- Scintillator planes interleaved with lead and water layers
- 13 tons lead + 3 tons water
- Optimised for γ detection

**UA1 magnet (0.2 T)**

**Tracker**
- 2 FGDs (Fine Grained Detectors)
  - Active target mass
  - FGD1: 1.0 ton scintillator
  - FGD2: 0.5 ton scintillator + 0.5 ton water

**3 TPCs (Time Projection Chambers)**
- Momentum measurement of charged particles
- PID via dE/dx

**P0D, Barrel and Downstream ECAL**
- E/M showers from inner detector
ND280 off-axis detector event (in the Tracker)
ND280 off-axis detector event (in the Tracker)
ND280 off-axis detector event (in the Tracker)
ND280 off-axis detector event (in the P0D)
On-axis near detector (INGRID)

- 10 m x 10 m beam coverage
- ~700 neutrino interactions day at 50 kW
- Monitor neutrino beam direction
  - Off-axis angle precision goal < 1 mrad
  - 1 mrad → 2% SuperK flux change at peak energy

16 modules:
- 7 horizontal
- 7 vertical
- 2 off-cross

Each module:
- 7 tons - alternating scintillator / iron planes
Measuring oscillation parameters at T2K

- The `(νμ) disappearance' channel
- The `(νe) appearance' channel
Disappearance channel: Measuring $\sin^2 2\theta_{23}$ and $\Delta m^2_{23}$

Looking for:

Energy dependent depletion of muon-like events

$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{32} L}{4E_\nu}\right)$
Appearance channel: Measuring $\sin^2 2\theta_{13}$

$P(\nu_\mu \rightarrow \nu_\theta) \approx \sin^2 2\theta_{13} \cdot \sin^2 \theta_{23} \cdot \sin^2 \left(1.27\Delta m^2_{13} \frac{L}{E}\right)$

Looking for:
- $\sin^2 2\theta_{13} = 0.1$
- $\Delta m^2_{23} = 2.4 \times 10^{-3} \text{eV}^2$
- $\sin^2 \theta_{23} = 1.0$

Background:
- intrinsic beam contamination
- misidentified muon-neutrinos

Energy-dependent excess of electron-like events
T2K ultimate (5 yrs x 750 kW) sensitivity

$\nu_e$ appearance:

$\sin^2 2\theta_{13} < 0.008$ (90% CL)

$\nu_\mu$ disappearance:

$\delta (\sin^2 2\theta_{23}) \sim 1E-2$ (90% CL)

$\delta (\Delta m^2_{23}) \sim 1E-4$ eV$^2$/c$^4$ (90% CL)
Data-taking operations & beam stability
T2K data-taking operations

Run-1
- January 2010: Start of Run-1
  - February 24, 2010: First event seen in SuperK
  - June 26, 2010: End of Run-1

Run-2
- November 16, 2010: Start of Run-2
  - December 25, 2010: Start of end-of-year shutdown
  - January 20, 2011: End of end-of-year shutdown
  - March 11, 2011: Earthquake
    - data-taking stopped
  - July 1, 2011: Scheduled end of Run-2

3.23E+19 POT on tape!
Additional 1.136E+20 POT on tape!
Total on tape: 1.459E+20 POT
Estimated total at end of Run-2 was ~3E+20 POT

Expect to restart data-taking operations late in 2011 / early in 2012
Number of protons delivered by MR

Run-1 (Jan-Jun 2010):
- 6 bunches / spill (~3E+13 PPP)
- 3.52 sec cycle
- 50 kW stable operation
  - 100 kW trials
- Integrated exposure (physics): 3.23E+19 POT

- 8 bunches / spill (~9E+13 PPP)
- 3.04 sec cycle
- 135-145 kW stable operation
- Integrated (Run1+2) exposure (physics): 1.459E+20 POT

- Physics run
- Delivered proton#
- Proton per pulse (for physics run)
- Proton per pulse (all runs)
Primary proton beam monitoring

Beam intensity / loss monitoring:
- 5 Current Transformers (CT)
- 50 Beam Loss Monitors (BLM)

Beam position & profile monitoring:
- 21 Electro-static monitor (ESM)
- 19 Segmented Secondary Emission monitor (SSEM)
- 1 Optical Transition Radiation detector (OTR)

Run1+2: Stable primary proton beam
Secondary muon beam monitoring (MUMON) spill-by-spill.

Detector intrinsic resolution < 1.5 mm

Beam direction is controlled within 1 mrad

Secondary beam intensity stable to ~1%

Run1+2: Stable targeting & focusing systems
Neutrino beam monitoring

Run1+2: Stable neutrino intensity & direction verified by INGRID
T2K-SuperK event reduction
SuperK – Beam spill time synchronization

Record all hits in +/- 500 μs window around the beam spill arrival to SuperK.

GPS synchronization for J-PARC and SuperK times
SuperK good spill selection

- SK DAQ alive
- DAQ error check

Checking dark counts in ID and OD
- GPS error check
- Detector status check
- Pre-activity cut

No activity in the 100 μs before beam arrival.
Removes accidental contamination

SuperK live-time

Integrated exposure:
- “Beam” good spills → 1.446E+20 POT
- “SK & Beam” good spills → 1.431E+20 POT

SuperK live fraction (for physics) > 99%
SuperK FC (fully contained) event reduction

2 off-timing FC events. Expectation: 1.9 events

121 FC neutrino event candidates found

Expected accidental bkg (from dummy spill data): 0.023 events
SuperK FC neutrino event candidate timing

Neutrino beam structure seen with SuperK event candidates!
SuperK FCFV event reduction

FC event candidates
* In fiducial volume (more than 2m away from the ID wall)
* Visible energy > 30 MeV

FC (Fully Contained) FV (Fiducial Volume)
(event candidates
(events used for physics analysis)

Run-1+2:
88 FCFV neutrino event candidates found

Estimated (from atmospheric neutrino rate)
accidental background: 0.0028 events
2010 oscillation analysis with Run-1+2 (1.431E+20 POT) data

- 88 FCFV events
- 1-ring
  - μ-like
  - e-like
- multi-ring
- $\nu_\mu$ disappearance analysis
- $\nu_e$ appearance analysis
Oscillation Analysis Strategy (2010)

External cross-section measurements (neutrino, charged-lepton, hadron probes)

SuperK neutrino flux

SuperK neutrino flux simulation

Neutrino cross-sections

SuperK detector response

SuperK atmo. neutrino & calibration data

SuperK beam data (1-ring e-like, 1-ring μ-like)

fit

Oscillation measurement

shape

normalization

ND280 MC (CC inclusive) vs ND280 beam data (CC inclusive)

Beam-line monitoring data

NA61

INGRID

Neutrino flux simulation

ND280 MC (CC inclusive)

SuperK prediction

External cross-section measurements (neutrino, charged-lepton, hadron probes)
Oscillation Analysis Strategy (2010)

- External cross-section measurements (neutrino, charged-lepton, hadron probes)
- SuperK beam data (1-ring e-like, 1-ring μ-like)
- SuperK prediction
- Oscillation measurement

- SuperK neutrino flux
- Neutrino cross-sections
- SuperK detector response

- Neutrino flux simulation

- ND280 MC (CC inclusive) vs ND280 beam data (CC inclusive)

- Beam-line monitoring data
- INGRID
- NA61
NA61 / SHINE experiment

NA61/SHINE Setup:

- Large acceptance spectrometer
- 5 TPCs
- 2 dipole magnets
- 3 ToFs
- Good PID and momentum resolution

30 GeV p+C particle yields in
- thin target
- T2K replica target

NA61:
- Large acceptance spectrometer
- 5 TPCs
- 2 dipole magnets
- 3 ToFs
- Good PID and momentum resolution

PID methods
NA61 / SHINE measurements

Full coverage of T2K phase space

(~5-10% systematic error and similar statistical error)
Neutrino flux tuning

$\nu_\mu$ at SuperK

$\nu_e$ at SuperK

 Flux [10$^{-2}$/POT/cm$^2$/50MeV] vs. $E_\nu$ (GeV)

Reweighting factor vs. $E_\nu$ (GeV)
Oscillation Analysis Strategy (2010)

**External cross-section measurements (neutrino, charged-lepton, hadron probes)**

- **SuperK neutrino flux**
- **Neutrino cross-sections**
- **SuperK detector response**

**SuperK beam data** (1-ring e-like, 1-ring μ-like)

**SuperK prediction**

**Oscillation measurement**

**ND280**
- **MC** (CC inclusive)
- **beam data** (CC inclusive)

**Beam-line monitoring data**

**NA61**

**INGRID**

**Neutrino flux simulation**

**shape**

**normalization**
ND280: Inclusive muon neutrino CC analysis

Robust analysis using low-level reconstructed objects (FGD hits and tracks in single TPC)

- No tracks in TPC-1
- >= 1 track in TPC-2 with vertex in FGD-1
- No tracks in TPC-2? Repeat with TPC-3 and FGD-2
- Select track with highest momentum
- TPC dE/dx cuts to select muon candidates

High purity: ~90% $\nu_\mu$ CC (~50% CCQE)
ND280: Inclusive muon-neutrino CC

\[
\frac{N_{\text{ND}}^{\nu_{\mu,\text{DATA}}}}{N_{\text{ND}}^{\nu_{\mu,\text{MC}}}} = 1.036 \pm 0.028 \text{ (stat.)} ^{+0.044}_{-0.037} \text{ (det. syst.)} \pm 0.038 \text{ (phys. syst.)}
\]
Electron-neutrino appearance results
**SuperK $v_e$ event selection: Strategy**

Selecting $v_e$ CCQE events. A water-Cherenkov detector sees a single e-like (fuzzy) ring.

**Main backgrounds**

Intrinsic $v_e$ component in beam

$$
\begin{align*}
K_L^0 & \rightarrow \nu_e + \pi^- + e^+ \\
K_R^0 & \rightarrow \bar{\nu}_e + \pi^+ + e^- \\
K_L^0 & \rightarrow \nu_\mu + \pi^- + \mu^+ \\
K_R^0 & \rightarrow \bar{\nu}_\mu + \pi^+ + \mu^- \\
K_L^0 & \rightarrow \nu_\mu + \pi^+ + e^- \\
K^+ & \rightarrow \nu_\mu + \mu^- \\
K^- & \rightarrow \bar{\nu}_\mu + \mu^+ \\
K^- & \rightarrow \bar{\nu}_e + \pi^0 + e^- \\
K^- & \rightarrow \bar{\nu}_\mu + \pi^0 + \mu^- \\
\mu^+ & \rightarrow \bar{\nu}_\mu + \nu_e + e^+ \\
\mu^- & \rightarrow \nu_e + \nu_\mu + e^- \\
\pi^+ & \rightarrow \nu_\mu + \mu^- \\
\pi^- & \rightarrow \nu_\mu + \mu^-
\end{align*}
$$

$\nu_\mu$ NC $\pi^0$ with a missed $\gamma$

- Intrinsically invisible
- Mis-reconstructed
SuperK $\nu_e$ event selection: Cut overview

Cuts to isolate 1-ring e-like event sample & suppress $\nu_\mu \rightarrow \nu_e$ backgrounds

- Event has 1-ring
- Ring has e-like PID
- Visible energy > 100 MeV
- Decay electron cut
- Invariant mass cut
- Reconstructed energy cut

All cuts were defined **before** the data-taking operations

\[?\]

$\nu_e$ event candidates
SuperK $\nu_e$ event selection

(1) Event has 1-ring

(41 events left after cut)

(2) Ring has e-like PID

(8 events left after cut)
SuperK $\nu_e$ event selection

(3) Event has visible energy $> 100$ MeV
- Cut removes 14% of NC, 30% of $\nu_\mu$ CC bkg
- 98% signal efficiency

(4) No delayed decay-electron signal
- Rejects events with invisible or mid-ID'ed $\mu$ or $\pi$
- Cut removes 85% of $\nu_\mu$ CC bkg
- 90% signal efficiency

1 candidate rejected

1 candidate rejected
SuperK $\nu_e$ event selection

(5) Invariant mass cut ($< 105$ MeV/c$^2$)
[2-ring assumption, forced 2$^{nd}$ ring]
- Suppresses NC $\pi^0$ background.
- Cut removes 71% of NC background
- 91% signal efficiency

(6) Reconstructed energy cut ($< 1250$ MeV)
- Reduces intrinsic beam contamination from K decays
  (signal: $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu$ flux peaks at 600 MeV)
- Cut removes 36% of intrinsic beam $\nu_e$
- 98% signal efficiency
SuperK $\nu_e$ event selection

6 $\nu_e$ event candidates were found after all cuts!

Signal efficiency: ~66%
Background rejection:
• ~77% for intrinsic beam $\nu_e$
• ~99% for $\nu_\mu$ NC
MC predicts 1.5 background events
Background-only hypothesis: Systematic study

<table>
<thead>
<tr>
<th>Error source</th>
<th>( N_{ND} )</th>
<th>( N_{SK} )</th>
<th>( N_{SK}/N_{ND} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK Norm. ( f_{SK\text{norm}} )</td>
<td>± 0.0</td>
<td>± 1.4</td>
<td>± 1.4</td>
</tr>
<tr>
<td>SK Energy Scale ( f_{\text{Energy}} )</td>
<td>± 0.0</td>
<td>± 1.1</td>
<td>± 1.1</td>
</tr>
<tr>
<td>SK Ring Counting ( f_{N_{\text{ring}}} )</td>
<td>± 0.0</td>
<td>± 8.1</td>
<td>± 8.1</td>
</tr>
<tr>
<td>SK PID Muon ( f_{PID\mu} )</td>
<td>± 0.0</td>
<td>± 0.9</td>
<td>± 0.9</td>
</tr>
<tr>
<td>SK PID Electron ( f_{PIDe} )</td>
<td>± 0.0</td>
<td>± 7.8</td>
<td>± 7.8</td>
</tr>
<tr>
<td>SK POLfit Mass ( f_{POL\text{fit}} )</td>
<td>± 0.0</td>
<td>± 8.5</td>
<td>± 8.5</td>
</tr>
<tr>
<td>SK Decay Electron ( f_{N_{\text{dec}}} )</td>
<td>± 0.0</td>
<td>± 0.3</td>
<td>± 0.3</td>
</tr>
<tr>
<td>SK ( \pi^0 ) Efficiency ( f_{\pi^0\text{eff}} )</td>
<td>± 0.0</td>
<td>± 3.4</td>
<td>± 3.4</td>
</tr>
<tr>
<td>CC QE shape ( f_{CC\text{QE shape}} )</td>
<td>± 0.0</td>
<td>± 3.1</td>
<td>± 3.1</td>
</tr>
<tr>
<td>CC 1( \pi ) ( f_{CC\pi} )</td>
<td>± 5.9</td>
<td>± 3.7</td>
<td>± 2.2</td>
</tr>
<tr>
<td>CC Coherent( \pi ) ( f_{CC\text{coh}} )</td>
<td>± 3.3</td>
<td>± 0.2</td>
<td>± 3.1</td>
</tr>
<tr>
<td>CC Other ( f_{CC\text{other}} )</td>
<td>± 4.7</td>
<td>± 0.3</td>
<td>± 4.4</td>
</tr>
<tr>
<td>NC 1( \pi^0 ) ( f_{NC\pi^0} )</td>
<td>± 0.1</td>
<td>± 5.4</td>
<td>± 5.3</td>
</tr>
<tr>
<td>NC Coherent( \pi ) ( f_{NC\text{coh}} )</td>
<td>&lt; 0.1</td>
<td>± 2.3</td>
<td>± 2.3</td>
</tr>
<tr>
<td>NC Other ( f_{NC\text{other}} )</td>
<td>± 1.1</td>
<td>± 3.5</td>
<td>± 2.3</td>
</tr>
<tr>
<td>( \sigma(\nu_e) ) ( f_{\sigma(\nu_e)} )</td>
<td>&lt; 0.1</td>
<td>± 3.4</td>
<td>± 3.4</td>
</tr>
<tr>
<td>FSI ( f_{FSI} )</td>
<td>± 0.0</td>
<td>± 10.1</td>
<td>± 10.1</td>
</tr>
<tr>
<td>Beam Norm. ( f_{SK/ND} )</td>
<td>± 15.4</td>
<td>± 16.1</td>
<td>± 8.5</td>
</tr>
<tr>
<td>ND Efficiency ( f_{\text{ND}} )</td>
<td>+5.6</td>
<td>± 5.2</td>
<td>± 5.6</td>
</tr>
<tr>
<td>Overall Norm. ( f_{\text{norm}} )</td>
<td>± 0.0</td>
<td>± 0.0</td>
<td>± 2.7</td>
</tr>
<tr>
<td>Total</td>
<td>± 18.4</td>
<td>± 25.6</td>
<td>± 22.7</td>
</tr>
</tbody>
</table>

Uncertainty on background: ~23%

Expect: \( 1.5 \pm 0.3 \) (syst) events

SuperK detector systematics
(dominated by uncertainties in ring-counting, e-like PID and \( \pi^0 \) mass cut efficiency)

Cross-section systematics
(dominated by NC\( \pi^0 \) production uncertainties and FSI effects)

Flux systematic
(dominated by hadron-production uncertainties)

\( \Delta m^2_{23} = 2.4 \cdot 10^{-3} \text{eV}^2 \)

\( \sin^2 2\theta_{23} = 1.0 \)
Further $v_e$ candidate event checks

**Large $R$ clustering?**

Checked events outside the ID fiducial volume and in OD

→ No indication of unmodelled background

Checked events outside the K.S. test on $R^2$

→ p-value 0.03
Background fluctuation?

Distribution of observed number of events
Background-only hypothesis ($\sin^2 2\theta_{13} = 0$)

$\sin^2 2\theta_{13} = 0$ excluded to 99.34% level (2.48$\sigma$)

(Normal hierarchy)

$\Delta m_{23}^2 = 2.4 \cdot 10^{-3} \text{eV}^2$

$\sin^2 2\theta_{23} = 1.0$
Number of $v_e$ events allowing for $v_\mu \rightarrow v_e$

$\delta_{CP}$

$6$ events

$\Delta m^2_{23} = 2.4 \cdot 10^{-3} eV^2$

$\sin^2 2\theta_{23} = 1.0$
Allowed regions of $\sin^2 2\theta_{13}$ as function of $\delta_{\text{CP}}$

$\Delta m^2_{23} > 0$

$\delta_{\text{CP}} = 0$:
- best-fit $\sin^2 2\theta_{13} \sim 0.11$
- $\sin^2 2\theta_{13}$ 90% CL $\sim [0.03 - 0.28]$

$\Delta m^2_{23} < 0$

$\delta_{\text{CP}} = 0$:
- best-fit $\sin^2 2\theta_{13} \sim 0.14$
- $\sin^2 2\theta_{13}$ 90% CL $\sim [0.04 - 0.34]$

$\Delta m^2_{23} = 2.4 \times 10^{-3} \text{eV}^2$

$\sin^2 2\theta_{23} = 1.0$
Muon neutrino disappearance results
Selecting $\nu_\mu$ CCQE events. A water-Cherenkov detector sees a single $\mu$-like (crisp) ring

Main background: $\nu_\mu$ CC$\pi$ with unidentified $\pi$

(Background oscillates too, but energy reconstruction is systematically off due to unaccounted $\pi$)
SuperK $\nu_\mu$ event selection: Cut overview

All cuts were defined before the data-taking operations

- Event has 1-ring
- Ring has $\mu$-like PID
- $\mu$ momentum > 200 MeV/c
- 0 or 1 delayed electron signals

88 FCFV events

31 $\nu_\mu$ event candidates

Expected sample composition: CCQE(61%) CCnQE (32%), NC(6%), $\nu_e$ (<1%)
In absence of oscillations, expect: \(103.6 \pm 10.2\) (stat) \(^{+13.8}_{-13.4}\) (syst) 1-ring \(\mu\)-like events
$\nu_\mu$-disappearance: Best-fit spectrum

2 independent fitting methods

- Likelihood ratio, w/o systematic param fitting
  \[ \sin^2(2\theta_{23}) = 0.98, |\Delta m_{23}^2| = 2.6 \times 10^{-3} \text{ eV}^2/c^4 \]

- Ext. max. likelihood ratio, w systematic param fitting
  \[ \sin^2(2\theta_{23}) = 0.99, |\Delta m_{23}^2| = 2.6 \times 10^{-3} \text{ eV}^2/c^4 \]

Repeated the analysis with 2 different neutrino MC generators (GENIE and NEUT):
Very different cross-section model

Very good consistency between all fits.

A very robust oscillation result!
$\nu_\mu$-disappearance: Confidence regions

(and comparison with latest MINOS and SuperK results)

Both T2K analyses used the Feldman-Cousins method to construct confidence regions.
Conclusions

Reported results from an initial exposure of 1.431E+20 POT (just ~2% of expected final exposure)

• **Electron-neutrino appearance:**
  - **Observed 6 single-ring electron-like event**
  - **Background \((\theta_{13} = 0) = 1.5 \pm 0.3\)**
  - \(\theta_{13} = 0\) excluded to 2.5\(\sigma\) level
    - First strong indication for a non-zero \(\theta_{13}\)

• **3-flavour fit-results**
  For Normal (Inverted) hierarchy, \(\delta_{CP} = 0\) and global best-fit values of “23”-sector params:
  - Best-fit value: \(\sin^2 2\theta_{13} = 0.11\) (0.14), 90% CL: \(0.03 < \sin^2 2\theta_{13} < 0.28\)
  - 90% CL: \(0.03\) (0.04) < \(\sin^2 2\theta_{13}\) < 0.28 (0.34)

• **Muon-neutrino disappearance:**
  - **Observed 31 single-ring muon-like events.**
  - **Without oscillations, expect \(\sim 103.6 \pm 17.2\) events (a \(\sim 4\sigma\) deficit)**
  - Consistent with MINOS / K2K / SuperK (atmospheric neutrinos).

• **Effective 2-flavour fit-results:**
  - Best-fit values: \(\sin^2 2\theta_{23} = 0.98, |\Delta m^2_{23}| = 2.6 \times 10^{-3}\) eV\(^2/c^4\)
  - 90% CL: \(\sin^2 2\theta_{23} > 0.84, 2.1 \times 10^{-3}\) eV\(^2/c^4 < |\Delta m^2_{23}| < 3.1 \times 10^{-3}\) eV\(^2/c^4\)
Back-up slides
T2K Collaboration

59 institutions in 12 countries

Canada
TRIUMF
U of Alberta
U of B Columbia
U of Regina
U of Toronto
U of Victoria
York U

Korea
Chonnam Nat'l U
Dongshin U
Seoul Nat'l U

Spain
IFIC, Valencia
U.A. Barcelona

Poland
A Soltan, Warsaw
HNiewodniczanski
T U Warsaw
U of Silesia
Warsaw U
Wrocław U

Switzerland
Bern
ETH Zurich
U of Geneva

UK
U of Oxford
Imperial C London
Lancaster U
Queen Mary U of L
Sheffield U
STFC/RAL
STFC/Daresbury
U of Liverpool
U of Warwick

Japan
ICRR Kamioka
ICRR RCCN
KEK
Kobe U
Kyoto U
Miyagi U of Ed
Osaka City U
U of Tokyo

Italy
INFN Bari
INFN Roma
Napoli U
Padova U

USA
Boston U
BNL
Colorado State U
Duke U
Louisiana State U
Stony Brook U
U of California, Irvine
U of Colorado
U of Pittsburgh
U of Rochester
U of Washington

Germany
RWTH Aachen U
\( \nu \) interaction uncertainty

- Estimated from parameter variations in MC models and comparisons with data (K2K, MiniBooNE, SciBooNE, MINOS)

For electron appearance analysis:

| Category      | Error [%]                       
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CC QE</td>
<td>Depends on true neutrino energy</td>
</tr>
<tr>
<td>CC 1( \pi )</td>
<td>30 ( (E_\nu &lt; 2 \text{ GeV}) ) 20 ( (E_\nu &gt; 2 \text{ GeV}) )</td>
</tr>
<tr>
<td>CC coherent ( \pi )</td>
<td>100</td>
</tr>
<tr>
<td>CC other</td>
<td>30 ( (E_\nu &lt; 2 \text{ GeV}) ) 25 ( (E_\nu &gt; 2 \text{ GeV}) )</td>
</tr>
<tr>
<td>NC 1( \pi^0 )</td>
<td>30 ( (E_\nu &lt; 1 \text{ GeV}) ) 20 ( (E_\nu &gt; 1 \text{ GeV}) )</td>
</tr>
<tr>
<td>NC coherent</td>
<td>30</td>
</tr>
<tr>
<td>NC other</td>
<td>30</td>
</tr>
<tr>
<td>FSI error</td>
<td>Depends on reconst. neutrino energy</td>
</tr>
</tbody>
</table>

\( \sigma(\nu_e)/\sigma(\nu_\mu) \): 6%

Most errors considered correlated b/w near and far detectors
Neutrino flux uncertainties

SK $\nu_\mu$ Fractional Error

SK $\bar{\nu}_\mu$ Fractional Error

- Pion Production
- Kaon Production
- Other Hadronic Interactions
- Align., Beam Dir. & Horn Curr.
- Total
Neutrino flux uncertainties

SK $\nu_e$ Fractional Error

Pion Production
Kaon Production
Other Hadronic Interactions
Align., Beam Dir. & Horn Curr.
Total

SK $\bar{\nu}_e$ Fractional Error

Pion Production
Kaon Production
Other Hadronic Interactions
Align., Beam Dir. & Horn Curr.
Total
Energy reconstruction for CCQE and non-CCQE

\[ E_\nu = \frac{m_N E_\mu - m_\nu^2 / 2}{m_N - E_\mu + p_\mu \cos(\Theta_\mu)} \]

- \( m_N \): Neutron mass
- \( E_\nu \): Muon energy
- \( m_\nu \): Muon mass
- \( p_\mu \): Muon momentum
- \( \Theta_\mu \): Muon angle wrt beam
Cross sections – Survey of models

\[ \nu_\mu \text{ CCQE} \]

\[ \nu_\mu \text{ CC1}\pi^+ \]

\[ \nu_\mu + \text{C12} \]
$\nu_{\mu}$ CCQE cross section – Survey of models

$\sigma(E)$

$\nu_{\mu} + C12$

$\frac{d\sigma(E,T_{\mu})}{dT_{\mu}}$
$\nu_\mu \text{ CC1}\pi \text{ cross section} – \text{Survey of models}$

$$\sigma(E)$$

$$d\sigma(E, T_\pi)/dT_\pi$$

$\nu_\mu + \text{C12}$
$\nu_\mu$ NC $\pi^0$ (coherent) cross sections – Survey of models

$\nu_\mu$ + C12
Final State Interactions (FSI)

\[ \nu_{\mu} + C_{12}, 1 \text{ GeV} \]

- "signal" → "bkg"
- "bkg" → "signal"

\[ ~2/3 \text{ of hadrons re-interact!} \]
FSI effect on final state topologies

what we could see in a perfect detector

what was generated inside the nucleus

<table>
<thead>
<tr>
<th>Final-State</th>
<th>(0\pi X)</th>
<th>(1\pi^0 X)</th>
<th>(1\pi^+ X)</th>
<th>(1\pi^- X)</th>
<th>(2\pi^0 X)</th>
<th>(2\pi^+ X)</th>
<th>(2\pi^- X)</th>
<th>(\pi^0\pi^+ X)</th>
<th>(\pi^0\pi^- X)</th>
<th>(\pi^+\pi^- X)</th>
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<tbody>
<tr>
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<td>22033</td>
<td>3038</td>
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<td>1001</td>
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<tr>
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<tr>
<td>(2\pi^- X)</td>
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<td>0</td>
<td>1</td>
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<td>0</td>
<td><strong>134</strong></td>
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<td>0</td>
</tr>
<tr>
<td>(\pi^0\pi^+ X)</td>
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<td>183</td>
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<tr>
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<td>1</td>
<td>0</td>
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<td>0</td>
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<tr>
<td>(\pi^+\pi^- X)</td>
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<td>0</td>
<td>139</td>
<td>20</td>
<td><strong>5643</strong></td>
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</tbody>
</table>
T2K allowed regions of $\sin^22\theta_{13}$ as function of $\delta_{\text{CP}}$:

Comparison with upper limits from MINOS and CHOOZ.
Analysis Flow

- SuperK beam data
- SuperK prediction
- Oscillation measurement

Flow:
1. SuperK beam data → fit
2. SuperK prediction → fit → Oscillation measurement
Analysis Flow

- SuperK neutrino flux
- Neutrino cross-sections
- SuperK detector response
- SuperK beam data

Oscillation measurement

Fit
Analysis Flow

SuperK neutrino flux

Neutrino cross-sections

SuperK detector response

SuperK beam data

fit

Oscillation measurement

ND280 neutrino flux measurement

ND280→SuperK neutrino flux transfer function

SuperK prediction
Analysis Flow

SuperK neutrino flux

Neutrino cross-sections

SuperK detector response

SuperK beam data

fit

Oscillation measurement

ND280 neutrino flux measurement

ND280→SuperK neutrino flux transfer function

ND280 beam data

Neutrino cross-sections

ND280 detector response

Neutrino flux simulation
Analysis Flow

- External cross-section measurements (neutrino, charged-lepton, hadron probes)
- SuperK neutrino flux
- Neutrino cross-sections
- SuperK detector response
- SuperK beam data
- Fit
- Oscillation measurement
- ND280 neutrino flux measurement
- ND280→SuperK neutrino flux transfer function
- ND280 beam data
- Neutrino cross-sections
- ND280 detector response
- Neutrino flux simulation
- Beam-line monitoring data
- INGRID
- NA61
- ND280 calibration & test-beam data
Analysis Flow

- External cross-section measurements (neutrino, charged-lepton, hadron probes)
- SuperK beam data
- SuperK atmo. neutrino & calibration data
- Neutrino flux simulation
- ND280 neutrino flux measurement
- ND280→SuperK neutrino flux transfer function
- SuperK neutrino flux
- SuperK detector response
- Neutrino cross-sections
- ND280 beam data
- ND280 detector response
- Neutrino cross-sections
- ND280 calibration & test-beam data
- Beam-line monitoring data
- INGRID
- Oscillation measurement
- fit
Analysis Flow (2010)

External cross-section measurements (neutrino, charged-lepton, hadron probes)

SuperK neutrino flux

Neutrino cross-sections

SuperK detector response

SuperK atmo. neutrino & calibration data

SuperK beam data

Fit

Oscillation measurement

SuperK prediction

Neutrino flux simulation

Beam-line monitoring data

INGRID

NA61

shape

normalization

ND280 MC (CC inclusive)

VS

ND280 beam data (CC inclusive)

2010 Analysis: Simplicity of inputs & robustness!