First Neutrino Oscillation Results from T2K

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Outline

• Neutrino oscillations
• The T2K experimental setup
• Experimental method & potential
• Data-taking operations
• SuperK event reduction
• First (2010) oscillation analysis with 3.23E+19 POT (Run1) data
  • Methodology & results
• Prospects and summary
Neutrino Oscillations

\[
\begin{pmatrix}
    \nu_e \\
    \nu_\mu \\
    \nu_\tau
\end{pmatrix} =
\begin{pmatrix}
    U_{e1} & U_{e2} & U_{e3} \\
    U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
    U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
    \nu_1 \\
    \nu_2 \\
    \nu_3
\end{pmatrix}
\]

mass-eigenstates

propagation described by plane waves

\[|\nu_i(L)\rangle = e^{-im_i^2L/2E} |\nu_i(0)\rangle\]

production

weak-interaction eigenstates

detection
Neutrino oscillation \((v_\alpha \rightarrow v_\beta)\) probability

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

mixing matrix elements (determined experimentally)
squared neutrino mass splittings (determined experimentally)

Experiments match \(L / E\) to a particular range of \(\Delta m^2\)
What do measure in neutrino oscillation experiments?

- 3 mixing angles, $\theta_{12}$, $\theta_{23}$, $\theta_{13}$
- 1 CP violating phase $\delta$
- with 3 neutrinos, any 2 squared mass splittings $\Delta m^2$
1997-2010

**First age of neutrino-mixing exploration**

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

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

- multi-GeV mu-like (FC+PC)
  - Data
  - Predicted
  - numu-ntau osc.

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

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

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

- KamLAND data
  - no oscillation
  - best-fit osci.
  - accidental
  - $^{13}C(α,n)^{16}O$
  - best-fit Geo $\overline{\nu}_e$
  - best-fit osci. + BG
  - best-fit Geo $\overline{\nu}_e$

- MINOS Far Detector
  - Far detector data
  - No oscillations
  - Best oscillation fit
  - NC background
Results from the first age of neutrino-mixing exploration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best Fit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{21}^2$ $[10^{-5} \text{eV}^2]$</td>
<td>$\Delta m_{21}^2$ $[10^{-5} \text{eV}^2]$</td>
<td>$\frac{7.59 + 0.23}{0.18}$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m_{31}^2</td>
<td>$ $[10^{-3} \text{eV}^2]$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>$\sin^2 \theta_{12}$</td>
<td>$\frac{0.318 + 0.019}{0.016}$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$\sin^2 \theta_{23}$</td>
<td>$\frac{0.50 + 0.07}{0.06}$</td>
</tr>
</tbody>
</table>

- **23**: LBL accelerator & atmospheric
- **12**: LBL reactor & solar
- **13**: LBL accelerator & SBL reactor

- (solar)  
- (atmospheric)
Next big questions in neutrino physics...

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

Neutrino beam to Kamioka

Near detector (280m) pit

181 MeV

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
The neutrino beam-line

Graphite rod
diameter: 2.6 cm
length: 91.4 cm
(1.9 interaction length)

Horns
320 kA
2.1 T max B field
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

\(\nu_\mu \text{ CC}\)

\(\nu_e \text{ CC}\)
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: 0x80000007
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

**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

**POD (π0 detector)**
- Scintillator planes interleaved with lead and water layers
- 13 tons lead + 3 tons water
- Optimised for γ detection
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 \((v_\mu)\) disappearance' channel
- The \((v_e)\) appearance' channel
Disappearance channel: Extracting $\sin^2 2\theta_{23}$ and $\Delta m^2_{23}$

No oscillation

Oscillations with $\Delta m^2 = 2.4 \times 10^{-3}$ eV$^2/c^4$, $\sin^2 2\theta = 1$

Looking for:

Energy dependent depletion of muon-like events

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \left( \frac{\Delta m^2_{32} L}{4E_\nu} \right)$$
Disappearance channel: `Signal' process

Signal: $\nu_\mu$ CCQE

Determining the neutrino energy:
Conservation of energy comes to the rescue

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

- $m_N$: Neutron mass
- $E_\mu$: Muon energy
- $m_\nu$: Muon mass
- $p_\mu$: Muon momentum
- $\Theta_\mu$: Muon angle wrt beam
$\nu_\mu$ CC $\sigma/E$ per nucleon for isoscalar target (no nuclear effects)

$\nu_\mu$ flux at SuperK
Energy reconstruction for CCQE and non-CCQE

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

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

$\nu_\mu \text{ CCQE}$

$\nu_\mu \text{ CC1}\pi^+$

$\nu_\mu + \text{C12}$
Appearance channel: Extracting $\sin^2 2\theta_{13}$

$$\mathcal{I}(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left( \frac{\Delta m^2_{32} L}{4E_\nu} \right)$$

- **Background:**
  - intrinsic beam contamination
  - misidentified muon-neutrinos

- **Signal:** $\nu_e$ CCQE

- **Looking for:**
  - Energy-dependent excess of electron-like events

- \( \sin^2 2\theta_{13} = 0.1 \)
- \( \Delta m^2_{23} = 2.4 \times 10^{-3} \text{eV}^2 \)
- \( \sin^2 \theta_{23} = 1.0 \)

- Events/100 MeV/8.33x10^{21} POT
Appearance channel: Electron-neutrino beam contamination

\[ K^0_L \rightarrow \nu_e + \pi^- + e^+ \]
\[ K^0_L \rightarrow \nu_e + \pi^+ + e^- \]
\[ K^0_L \rightarrow \nu_\mu + \pi^- + \mu^+ \]
\[ K^0_L \rightarrow \bar{\nu}_\mu + \pi^+ + \mu^- \]
\[ K^+ \rightarrow \nu_\mu + \mu^+ \]
\[ K^+ \rightarrow \nu_e + \pi^0 + e^+ \]
\[ K^+ \rightarrow \nu_\mu + \pi^0 + \mu^+ \]
\[ K^- \rightarrow \bar{\nu}_\mu + \mu^- \]
\[ K^- \rightarrow \bar{\nu}_e + \pi^0 + e^- \]
\[ K^- \rightarrow \bar{\nu}_\mu + \pi^0 + \mu^- \]
\[ \mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+ \]
\[ \mu^- \rightarrow \bar{\nu}_e + \nu_\mu + e^- \]
\[ \pi^+ \rightarrow \nu_\mu + \mu^+ \]
\[ \pi^- \rightarrow \bar{\nu}_\mu + \mu^- \]
Appearance channel: Muon neutrino background

Signal: $\nu_e$ CCQE

Background: $\nu_\mu$ NC$\pi^0$

Super-Kamiokande IV

Charge (psi)

Super-Kamiokande IV

Times (ns)
$\nu_\mu$ NC $\pi^0$ (coherent) cross sections – Survey of models

$\nu_\mu + C12$
T2K ultimate (5 yrs x 750 kW) sensitivity

\( v_e \) appearance:
\[
\sin^2 2\theta_{13} < 0.008 \text{ (90\% CL)}
\]

\( v_\mu \) disappearance:
\[
\delta(\sin^2 2\theta_{23}) \sim 1E-2 \text{ (90\% CL)}
\]
\[
\delta(\Delta m^2_{23}) \sim 1E-4 \text{ eV}^2/c^4 \text{ (90\% CL)}
\]
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
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

**Run-2** *(Nov 2010 - ?):*
- 8 bunches / spill (~9E+13 PPP)
- 3.04 sec cycle
- 135-145 kW stable operation
- Integrated (Run1+2) exposure (physics): 1.459E+20 POT
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)
Secondary muon beam monitoring (MUMON) spill-by-spill.

Beam direction is controlled within 1 mrad

Secondary beam intensity stable to ~1%

- Stability of targeting & focusing
Neutrino beam monitoring

\[ p \quad \pi \quad \mu \quad \nu \]
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 live-time

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

Run-1
33 FC neutrino events candidates found
Accidental bkg 0.0094 +/- 0.0067
SuperK FC neutrino event candidate timing
SuperK FCFV event reduction

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

Run-1:
23 FCFV neutrino event candidates found
Accidental bkg 0.00112 +/- 0.00002
2010 oscillation analysis with Run-1 (3.23E+19 POT) data

- 23 FCFV events
  - 1-ring
  - multi-ring

- μ-like
- e-like

- Disappearance analysis
- Appearance analysis
Analysis Flow (2010)

- **External cross-section measurements (neutrino, charged-lepton, hadron probes)**
- **SuperK beam data**
- **SuperK prediction**
- **Oscillation measurement**

**SuperK neutrino flux**

**Neutrino cross-sections**

**SuperK detector response**

**Neutrino flux simulation**

- **Beam-line monitoring data**
- **INGRID**
- **NA61**

**ND280 MC (CC inclusive)**

**ND280 beam data (CC inclusive)**

- **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

fit

SuperK beam data

Oscillation measurement

SuperK prediction

Neutrino flux simulation

Beam-line monitoring data

NA61

INGRID

ND280 MC (CC inclusive)

vs

ND280 beam data (CC inclusive)

shape

normalization

Neutrino flux prediction
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

0-60 mrad
60-120 mrad
120-180 mrad
180-240 mrad

0-p at production point of $\pi^+$ producing $\nu_\mu$ @ SK

prelim 2007 thin target data
Neutrino flux tuning

$\nu_\mu$ at SuperK

$\nu_e$ at SuperK
Neutrino flux uncertainties

Dominant uncertainty:
• Low energies → Pion production
• High energies → Kaon production

Further improvement anticipated with recent NA61 data
Analysis Flow (2010)

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

SuperK neutrino flux

SuperK neutrino cross-sections

SuperK detector response

SuperK atm. neutrino & calibration data

SuperK beam data

fit

Oscillation measurement

SuperK prediction

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

SuperK neutrino flux

SuperK neutrino cross-sections

SuperK detector response

Shape

Normalization

Beam-line monitoring data

NA61

INGRID

Constrain normalisation

ND280 MC (CC inclusive)

ND280 beam data (CC inclusive)
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
- $\geq 1$ 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: $\sim 90\%$ $v_\mu$ CC ($\sim 50\%$ CCQE)
ND280: Inclusive muon-neutrino CC

\[ R_{DATA/MC} = 1.061 \pm 0.028 \text{ (stat)} ^{+0.044}_{-0.038} \text{ (det. syst)} \pm 0.039 \text{ (phys. model)} \]
Analysis Flow (2010)

- Oscillation measurement
- SuperK beam data
- SuperK prediction
- Neutrino flux simulation
- Neutrino cross-sections
- SuperK detector response
- ND280 beam data (CC inclusive)
- ND280 MC (CC inclusive)
- Beam-line monitoring data
- INGRID
- NA61

SuperK neutrino flux

SuperK neutrino flux simulation

Shape vs normalization

ND280 MC (CC inclusive) vs ND280 beam data (CC inclusive)
Muon neutrino disappearance
Muon-neutrino disappearance

- 1-ring muon-like sample:
  - No oscillation expectation: $22.42 \pm 4.74 \text{ (stat)} +3.58 -3.48 \text{ (syst)}$ events
  - Observed: 8 events
  - A 2.5σ 1-ring muon-like event deficit

<table>
<thead>
<tr>
<th>Error source</th>
<th>No Oscillation $\delta N_{SK}^{exp}/N_{SK}^{exp}$</th>
<th>MINOS best-fit $\delta N_{SK}^{exp}/N_{SK}^{exp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SuperK CCQE efficiency</td>
<td>±6.4%</td>
<td>±4.7%</td>
</tr>
<tr>
<td>SuperK CCnonQE efficiency</td>
<td>±4.3%</td>
<td>±8.4%</td>
</tr>
<tr>
<td>SuperK NC efficiency</td>
<td>±2.7%</td>
<td>±7.3%</td>
</tr>
<tr>
<td>SuperK $\nu_e$ CC efficiency</td>
<td>±0.0%</td>
<td>±0.0%</td>
</tr>
<tr>
<td>ND280 efficiency</td>
<td>+5.3% -4.8%</td>
<td>+5.3% -4.8%</td>
</tr>
<tr>
<td>Flux normalization</td>
<td>±9.7%</td>
<td>±6.0%</td>
</tr>
<tr>
<td>CCQE cross section</td>
<td>±4.1%</td>
<td>±2.4%</td>
</tr>
<tr>
<td>CC1pi/CCQE cross section ratio</td>
<td>+2.2% -2.0%</td>
<td>+0.5% -0.5%</td>
</tr>
<tr>
<td>CCoother/CCQE cross section ratio</td>
<td>+5.4% -4.8%</td>
<td>+4.2% -3.7%</td>
</tr>
<tr>
<td>NC/CCQE cross section ratio</td>
<td>±0.8%</td>
<td>±0.8%</td>
</tr>
<tr>
<td>FSI</td>
<td>±3.3%</td>
<td>±5.9%</td>
</tr>
<tr>
<td>Total</td>
<td>+15.7% -15.3%</td>
<td>+16.4% -16.1%</td>
</tr>
</tbody>
</table>

Consistent with MINOS / K2K
Muon-neutrino disappearance prospects

Run1 sensitivity

Run1 + Run2 (already on tape) sensitivity

MINOS-2011
Electron-neutrino appearance
SuperK electron-neutrino event selection

23 FCFV events

visible energy > 100 MeV

1-ring

2 e-like 1-ring events

ring has e-like PID

Data

MC

Signal $\nu_e$ ($\sin^2 2\theta_{13} = 0.1$)

Beam $\nu_\mu$

Beam $\nu_e$

Beam $\nu_\tau$

Accept

Accept

Accept

MC $\times$ 5
SuperK electron-like 1-ring events
Additional background reduction cuts - I

- Misidentified $\nu_\mu$ CC
  - $\mu \to e$
- Misidentified NC$\pi$
  - $\pi \to \mu \to e$

Data

MC

Signal $\nu_e$ ($\sin^2 2\theta_{13} = 0.1$)

Beam $\nu_\mu$

Beam $\nu_e$

Beam $\bar{\nu}_\mu$

1 candidate rejected

No decay electron

1 accept

# of decay electron

Number of Events
SuperK rejected electron-neutrino candidate

Initial neutrino event

Decay electron triggering SuperK 3.5 μs after the initial neutrino event
Additional background reduction cuts - II

POLfit (forces 2nd ring) reconstructed mass not π0-like

- Reduces NC π0 background

Reconstructed neutrino energy < 1.25 GeV

- Reduces intrinsic beam contamination from Kaon decays (contributing > 1 GeV)
- $v_\mu \rightarrow v_e$, $v_\mu$ flux peaks at 600 MeV
SuperK electron-neutrino candidate

1 candidate e-like event was found

<table>
<thead>
<tr>
<th></th>
<th>Expected (Fluka)</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BG total</td>
<td>$\nu_\mu$</td>
</tr>
<tr>
<td>Interactions</td>
<td>29.8</td>
<td>27.6</td>
</tr>
<tr>
<td>FCFV</td>
<td>15.6</td>
<td>14.1</td>
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<tr>
<td>$E_{vis} &gt; 100$ MeV</td>
<td>14.5</td>
<td>13.0</td>
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<tr>
<td>Single-ring</td>
<td>7.01</td>
<td>6.15</td>
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<tr>
<td>Electron-like PID</td>
<td>1.22</td>
<td>0.77</td>
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<tr>
<td>$N_{dxy} == 0$</td>
<td>0.94</td>
<td>0.57</td>
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<tr>
<td>POLfit mass &lt;105 MeV/c$^2$</td>
<td>0.39</td>
<td>0.15</td>
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<tr>
<td>Reconst. $\nu$ energy &lt;1250 MeV</td>
<td>0.28</td>
<td>0.12</td>
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<tr>
<td>Efficiency from Interactions [%]</td>
<td>0.94</td>
<td>0.45</td>
</tr>
<tr>
<td>Efficiency from FCFV [%]</td>
<td>1.8</td>
<td>0.87</td>
</tr>
</tbody>
</table>
### Expected number of events & systematics

**(Background-only hypothesis)**

<table>
<thead>
<tr>
<th>Error source</th>
<th>$N_{SK}^{\text{sig}}$</th>
<th>$N_{SK}^{\text{bkg}}$</th>
<th>$N_{SK}^{s+b}$</th>
<th>$N_{ND}$</th>
<th>$N_{SK}^{\text{bkg}}/N_{ND}$</th>
<th>$N_{SK}^{s+b}/N_{ND}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK Efficiency</td>
<td>± 7.60</td>
<td>± 15.81</td>
<td>± 9.47</td>
<td>± 0.0</td>
<td>± 15.81</td>
<td>± 9.47</td>
</tr>
<tr>
<td>ND Efficiency</td>
<td>± 0.00</td>
<td>± 0.00</td>
<td>± 0.00</td>
<td></td>
<td>+5.60</td>
<td>+5.60</td>
</tr>
<tr>
<td>Overall Norm.</td>
<td>± 0.00</td>
<td>± 0.00</td>
<td>± 0.00</td>
<td>± 0.00</td>
<td>-5.16</td>
<td>-5.16</td>
</tr>
<tr>
<td>Total</td>
<td>± 25.17</td>
<td>± 27.77</td>
<td>± 24.64</td>
<td></td>
<td>+22.23</td>
<td>+23.95</td>
</tr>
</tbody>
</table>

**Background only hypothesis:**

± 24% total systematic error

**Background:**

$0.30 \pm 0.07$ (syst)
Expected number of events & systematics
(Background + signal hypothesis)

<table>
<thead>
<tr>
<th>Error source</th>
<th>$N_{SK}^{sig}$</th>
<th>$N_{SK}^{bkg}$</th>
<th>$N_{SK}^{s+b}$</th>
<th>$N_{ND}$</th>
<th>$N_{SK}^{bkg}/N_{ND}$</th>
<th>$N_{SK}^{s+b}/N_{ND}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK Efficiency</td>
<td>± 7.60</td>
<td>± 15.81</td>
<td>± 9.47</td>
<td>± 0.0</td>
<td>± 15.81</td>
<td>± 9.47</td>
</tr>
<tr>
<td>ND Efficiency</td>
<td>± 0.00</td>
<td>± 0.00</td>
<td>± 0.00</td>
<td>± 0.00</td>
<td>+5.60</td>
<td>+5.60</td>
</tr>
<tr>
<td>Overall Norm.</td>
<td>± 0.00</td>
<td>± 0.00</td>
<td>± 0.00</td>
<td>± 0.00</td>
<td>-5.16</td>
<td>-5.16</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>± 25.17</td>
<td>± 27.77</td>
<td>± 24.64</td>
<td>±22.23</td>
<td>+23.95</td>
<td>+19.55</td>
</tr>
</tbody>
</table>

$\Delta m^2_{23} = 2.4 \times 10^{-3} \text{eV}^2$
$\sin^2 2\theta_{23} = 1.0$
$\sin^2 \theta_{13} = 0.1$
$\delta_{CP} = 0$

Background + signal hypothesis:
± 20% total systematic error

Normal hierarchy
$\Delta m^2_{23} = 2.4 \times 10^{-3} \text{eV}^2$
$\sin^2 2\theta_{23} = 1.0$
Excluded oscillation parameter region & sensitivity

\[ \Delta m_{23}^2 = 2.4 \times 10^{-3} \text{eV}^2 \]
\[ \sin^2 2\theta_{23} = 1.0 \]
Electron-neutrino appearance prospects

This measurement (2010 / Run1)

90% CL $\theta_{13}$ Sensitivity

MINOS

Full proposal

Data already on tape

Target for 2011 Jun (before quake)
Conclusions

• Reported oscillation results from an initial exposure of 3.23E+19 POT (Run1)
  • Electron-neutrino appearance:
    • Observed 1 single-ring electron-like event
    • Background ($\theta_{13} = 0$) = 0.30 ± 0.07
  • Muon neutrino disappearance:
    • Observed 8 single-ring muon-like events
    • 2.5 $\sigma$ deficit compared with null-hypothesis. Consistent with MINOS / K2K / SuperK-atm.

• In total 1.459E+20 (Run1+2) are currently on tape (estimate before quake was ~3E+20)

Nevertheless
• Probably the best limit on electron-neutrino appearance
• A competitive result on muon neutrino disappearance

• 2011 analysis in progress

Improvements:
• New results from NA61
• Exclusive CCQE measurement in ND280 + spectral information; F/N extrapolation
• CC$\pi$ fraction constrain from ND280
• NC$\pi$0 and beam $\bar{v}_e$ measurement from ND280
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 Sollan, Warsaw
- HNiewodniczanski
- U Warsaw
- U of Silesia
- Warsaw U
- Wroclaw 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

**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**
- INFN Bari
- INFN Roma
- Napoli U
- Padova U
- 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:

<table>
<thead>
<tr>
<th>Category</th>
<th>Error [%]</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 ) GeV) 20 (( E_{\nu} &gt; 2 ) GeV)</td>
</tr>
<tr>
<td>CC coherent ( \pi )</td>
<td>100</td>
</tr>
<tr>
<td>CC other</td>
<td>30 (( E_{\nu} &lt; 2 ) GeV) 25 (( E_{\nu} &gt; 2 ) GeV)</td>
</tr>
<tr>
<td>NC 1( \pi^0 )</td>
<td>30 (( E_{\nu} &lt; 1 ) GeV) 20 (( E_{\nu} &gt; 1 ) 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

\(~7\% at 500\ MeV\)

Uncertainties on the ratio relative to CCQE

FSI of pions in nuclei

Due to nuclear target diff. b/w near and far detector
Beam systematics

- Uncertainties in the neutrino flux prediction

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
<th>Change at Peak</th>
<th>Max Change (&lt;3 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pion Multiplicity</td>
<td>20%</td>
<td>16%</td>
<td>22%</td>
</tr>
<tr>
<td>Kaon Multiplicity</td>
<td>20-25%</td>
<td>1%</td>
<td>20%</td>
</tr>
<tr>
<td>Prod. Cross Sections</td>
<td>10-50%</td>
<td>7%</td>
<td>8%</td>
</tr>
<tr>
<td>Proton Beam</td>
<td>0.5mm, 0.3 mrad</td>
<td>3%</td>
<td>9%</td>
</tr>
<tr>
<td>$\nu$ Beam Direction</td>
<td>0.44 mrad</td>
<td>1%</td>
<td>8%</td>
</tr>
<tr>
<td>Target Alignment</td>
<td>1.3 mrad</td>
<td>&lt;1%</td>
<td>1%</td>
</tr>
<tr>
<td>Horn Alignment</td>
<td>1 mm</td>
<td>1%</td>
<td>3%</td>
</tr>
<tr>
<td>Horn Current</td>
<td>5 kA</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>Horn Field Asym</td>
<td>1.25%</td>
<td>0.5%</td>
<td>1%</td>
</tr>
</tbody>
</table>
Electron-neutrino appearance systematics

<table>
<thead>
<tr>
<th>Error source</th>
<th>(N^{\text{sig}}_{\text{SK}})</th>
<th>(N^{\text{bkg}}_{\text{SK}})</th>
<th>(N^{s+b}_{\text{SK}})</th>
<th>(N_{\text{ND}})</th>
<th>(N^{\text{bkg}}<em>{\text{SK}}/N</em>{\text{ND}})</th>
<th>(N^{s+b}<em>{\text{SK}}/N</em>{\text{ND}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK Norm.</td>
<td>(f_{\text{SK norm}})</td>
<td>(\pm 1.41)</td>
<td>(\pm 1.41)</td>
<td>(\pm 1.41)</td>
<td>(\pm 0.0)</td>
<td>(\pm 1.41)</td>
</tr>
<tr>
<td>SK Energy Scale</td>
<td>(f_{\text{Energy}})</td>
<td>(\pm 0.30)</td>
<td>(\pm 0.50)</td>
<td>(\pm 0.35)</td>
<td>(\pm 0.0)</td>
<td>(\pm 0.50)</td>
</tr>
<tr>
<td>SK Ring Counting</td>
<td>(f_{\text{N_{ring}}})</td>
<td>(\pm 3.90)</td>
<td>(\pm 8.40)</td>
<td>(\pm 5.03)</td>
<td>(\pm 0.0)</td>
<td>(\pm 8.40)</td>
</tr>
<tr>
<td>SK PID Muon</td>
<td>(f_{\text{PID}_{\mu}})</td>
<td>(\pm 0.0)</td>
<td>(\pm 1.00)</td>
<td>(\pm 0.25)</td>
<td>(\pm 0.0)</td>
<td>(\pm 1.00)</td>
</tr>
<tr>
<td>SK PID Electron</td>
<td>(f_{\text{PID}_{e}})</td>
<td>(\pm 3.80)</td>
<td>(\pm 8.10)</td>
<td>(\pm 4.88)</td>
<td>(\pm 0.0)</td>
<td>(\pm 8.10)</td>
</tr>
<tr>
<td>SK POLfit Mass</td>
<td>(f_{\text{POLfit}})</td>
<td>(\pm 5.10)</td>
<td>(\pm 8.70)</td>
<td>(\pm 6.01)</td>
<td>(\pm 0.0)</td>
<td>(\pm 7.70)</td>
</tr>
<tr>
<td>SK Decay Electron</td>
<td>(f_{\text{N_{decay}}})</td>
<td>(\pm 0.10)</td>
<td>(\pm 0.30)</td>
<td>(\pm 0.15)</td>
<td>(\pm 0.0)</td>
<td>(\pm 0.30)</td>
</tr>
<tr>
<td>SK (\pi^0) Efficiency</td>
<td>(f_{\text{\pi^0_{eff}}})</td>
<td>(\pm 0.00)</td>
<td>(\pm 5.90)</td>
<td>(\pm 1.49)</td>
<td>(\pm 0.0)</td>
<td>(\pm 5.90)</td>
</tr>
<tr>
<td>CC QE shape</td>
<td>(f_{\text{CCQE shape}})</td>
<td>(\pm 4.91)</td>
<td>(\pm 2.62)</td>
<td>(\pm 4.33)</td>
<td>(\pm 0.0)</td>
<td>(\pm 2.72)</td>
</tr>
<tr>
<td>CC (1\pi)</td>
<td>(f_{\text{CC1\pi}})</td>
<td>(\pm 4.28)</td>
<td>(\pm 3.76)</td>
<td>(\pm 4.15)</td>
<td>(\pm 5.93)</td>
<td>(\pm 2.10)</td>
</tr>
<tr>
<td>CC Coherent(\pi)</td>
<td>(f_{\text{CCcoherence}})</td>
<td>(\pm 0.32)</td>
<td>(\pm 0.23)</td>
<td>(\pm 0.30)</td>
<td>(\pm 3.29)</td>
<td>(\pm 3.06)</td>
</tr>
<tr>
<td>CC Other</td>
<td>(f_{\text{CCother}})</td>
<td>(\pm 0.07)</td>
<td>(\pm 0.35)</td>
<td>(\pm 0.14)</td>
<td>(\pm 4.77)</td>
<td>(\pm 4.43)</td>
</tr>
<tr>
<td>NC (1\pi^0)</td>
<td>(f_{\text{NC1\pi^0}})</td>
<td>(\pm 0.00)</td>
<td>(\pm 5.86)</td>
<td>(\pm 1.48)</td>
<td>(\pm 0.05)</td>
<td>(\pm 5.56)</td>
</tr>
<tr>
<td>NC Coherent(\pi)</td>
<td>(f_{\text{NCcoherence}})</td>
<td>(\pm 0.00)</td>
<td>(\pm 2.48)</td>
<td>(\pm 0.63)</td>
<td>(\pm 0.00)</td>
<td>(\pm 2.37)</td>
</tr>
<tr>
<td>NC Other</td>
<td>(f_{\text{NCother}})</td>
<td>(\pm 0.00)</td>
<td>(\pm 3.83)</td>
<td>(\pm 0.97)</td>
<td>(\pm 1.14)</td>
<td>(\pm 2.53)</td>
</tr>
<tr>
<td>(\sigma(\nu_e))</td>
<td>(f_{\sigma(\nu_e)})</td>
<td>(\pm 6.00)</td>
<td>(\pm 3.17)</td>
<td>(\pm 5.29)</td>
<td>(\pm 0.01)</td>
<td>(\pm 3.28)</td>
</tr>
<tr>
<td>FSI</td>
<td>(f_{FSI})</td>
<td>(\pm 3.83)</td>
<td>(\pm 10.34)</td>
<td>(\pm 5.47)</td>
<td>(\pm 0.00)</td>
<td>(\pm 10.32)</td>
</tr>
<tr>
<td>Beam Norm.</td>
<td>(f_{\text{SK/ND}} )</td>
<td>(\pm 21.97)</td>
<td>(\pm 18.12)</td>
<td>(\pm 20.49)</td>
<td>(\pm 19.83)</td>
<td>(\pm 9.17)</td>
</tr>
<tr>
<td>ND Efficiency</td>
<td>(f_{\text{ND}})</td>
<td>(\pm 0.00)</td>
<td>(\pm 0.00)</td>
<td>(\pm 0.00)</td>
<td>(\pm 5.60)</td>
<td>(\pm 5.60)</td>
</tr>
<tr>
<td>Overall Norm.</td>
<td>(f_{\text{norm}})</td>
<td>(\pm 0.00)</td>
<td>(\pm 0.00)</td>
<td>(\pm 0.00)</td>
<td>(\pm 5.16)</td>
<td>(\pm 5.16)</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>(\pm 25.17)</td>
<td>(\pm 27.77)</td>
<td>(\pm 24.64)</td>
<td>(\pm 22.23)</td>
<td>(\pm 23.96)</td>
</tr>
</tbody>
</table>

\(\Delta m^2_{23} = 2.4 \times 10^{-3} \text{eV}^2\)
\(\sin^2 2\theta_{23} = 1.0, \sin^2 2\theta_{13} = 0.1\)
\(\delta_{CP} = 0\)
Excluded oscillation parameter region & sensitivity

normal hierarchy

Run-1 measurement (90% CL)

Run-1 sensitivity (90% CL)

inverted hierarchy

Run-1 measurement (90% CL)

Run-1 sensitivity (90% CL)
SuperK event break-down

### SuperK event break-down

#### Appearance analysis

<table>
<thead>
<tr>
<th>Fully-Contained</th>
<th>33</th>
<th>54.5</th>
<th>24.6</th>
<th>0.0094</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial Volume, $E_{\text{vis}} &gt; 30\text{MeV}$</td>
<td>23</td>
<td>36.8</td>
<td>16.7</td>
<td>0.0011</td>
</tr>
<tr>
<td>Single-ring $\mu$-like ($P_\mu &gt; 200\text{MeV/c}$)</td>
<td>8 (8)</td>
<td>24.6 (24.5 ± 3.9)</td>
<td>7.2 (7.1 ± 1.3)</td>
<td>-</td>
</tr>
<tr>
<td>Single-ring $e$-like ($P_e &gt; 100\text{MeV/c}$)</td>
<td>2 (2)</td>
<td>1.9 (1.5 ± 0.7)</td>
<td>1.5 (1.3 ± 0.6)</td>
<td>-</td>
</tr>
<tr>
<td>Multi-ring</td>
<td>13</td>
<td>10.2</td>
<td>8.0</td>
<td>-</td>
</tr>
</tbody>
</table>

---

#### Disappearance analysis

- $\Delta m^2 = 2.4 \times 10^{-3} \text{eV}^2$
- $\sin^2 2\theta_{23} = 1.0$

---

### PID parameter

0 1 2 3 4 5 6

0 2 4 6

---

Science & Technology Facilities Council
\[ U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \]
\(\nu_\mu\) CCQE cross section – Survey of models

\[\sigma(E)\]

\[\frac{d\sigma(E,T_\mu)}{dT_\mu}\]

\(\nu_\mu + C_{12}\)
$\nu_\mu$ CC1$\pi$ cross section – Survey of models

$\sigma(E)$

$\nu_\mu + C12$

$\frac{d\sigma(E,T_\pi)}{dT_\pi}$
EARTHQUAKE
Full extend of impact to T2K still unknown
Final State Interactions (FSI)

$\nu_{\mu} + C12, 1 \text{ GeV}$

hadrons re-interacting

hadrons escaping without re-interaction

~ 2/3 of hadrons re-interact!
FSI effect on final state topologies

what was generated inside the nucleus

what we could see in a perfect detector

<table>
<thead>
<tr>
<th>Final-State</th>
<th>0πX</th>
<th>1π^0X</th>
<th>1π^+X</th>
<th>1π^-X</th>
<th>2π^0X</th>
<th>2π^+X</th>
<th>2π^-X</th>
<th>π^0π^+X</th>
<th>π^0π^-X</th>
<th>π^+π^-X</th>
</tr>
</thead>
<tbody>
<tr>
<td>0πX</td>
<td>293446</td>
<td>12710</td>
<td>22033</td>
<td>3038</td>
<td>113</td>
<td>51</td>
<td>5</td>
<td>350</td>
<td>57</td>
<td>193</td>
</tr>
<tr>
<td>1π^0X</td>
<td>1744</td>
<td>44643</td>
<td>3836</td>
<td>491</td>
<td>1002</td>
<td>25</td>
<td>1</td>
<td>1622</td>
<td>307</td>
<td>59</td>
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<tr>
<td>1π^+X</td>
<td>2590</td>
<td>1065</td>
<td>82459</td>
<td>23</td>
<td>14</td>
<td>660</td>
<td>0</td>
<td>1746</td>
<td>5</td>
<td>997</td>
</tr>
<tr>
<td>1π^-X</td>
<td>298</td>
<td>1127</td>
<td>1</td>
<td>12090</td>
<td>16</td>
<td>0</td>
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<td>34</td>
<td>318</td>
<td>1001</td>
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<tr>
<td>2π^0X</td>
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<td>2761</td>
<td>2</td>
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<td>7</td>
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<tr>
<td>2π^+X</td>
<td>57</td>
<td>5</td>
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<td>0</td>
<td>1</td>
<td>1999</td>
<td>0</td>
<td>136</td>
<td>0</td>
<td>12</td>
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<tr>
<td>2π^-X</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>134</td>
<td>0</td>
<td>31</td>
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<tr>
<td>π^0π^+X</td>
<td>412</td>
<td>869</td>
<td>1128</td>
<td>232</td>
<td>109</td>
<td>106</td>
<td>0</td>
<td>9837</td>
<td>15</td>
<td>183</td>
</tr>
<tr>
<td>π^0π^-X</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>73</td>
<td>0</td>
<td>8</td>
<td>5</td>
<td>1808</td>
<td>154</td>
</tr>
<tr>
<td>π^+π^-X</td>
<td>799</td>
<td>7</td>
<td>10</td>
<td>65</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>139</td>
<td>20</td>
<td>5643</td>
</tr>
</tbody>
</table>
Analysis Flow

SuperK beam data

SuperK prediction

fit

Oscillation measurement
Analysis Flow

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

SuperK prediction

fit
Analysis Flow

- SuperK neutrino flux
- Neutrino cross-sections
- SuperK detector response
- SuperK beam data
- ND280 neutrino flux measurement
- ND280→SuperK neutrino flux transfer function
- Oscillation measurement

SuperK prediction

fit
Analysis Flow

SuperK neutrino flux

Neutrino cross-sections

SuperK detector response

SuperK prediction

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 beam data
- Neutrino flux simulation
- ND280→SuperK neutrino flux transfer function
- ND280 beam data
- Neutrino cross-sections
- ND280 detector response

SuperK
- neutrino flux
- cross-sections
- detector response

Fit measurement

Oscillation

SuperK
- atmo. neutrino & calibration data

ND280
- calibration & test-beam data

NA61
- Beam-line monitoring data

INGRID
Analysis Flow

- External cross-section measurements (neutrino, charged-lepton, hadron probes)
- SuperK beam data
- SuperK neutrino flux
- Neutrino cross-sections
- SuperK detector response
- SuperK prediction
- Oscillation measurement

- ND280 neutrino flux measurement
- ND280→SuperK neutrino flux transfer function
- ND280 calibration & test-beam data
- Beam-line monitoring data
- INGRID
- Neutrino flux simulation
- ND280 beam data
- Neutrino cross-sections
- ND280 detector response
- NA61

- SuperK atmo. neutrino & calibration data
Analysis Flow (2010)

- External cross-section measurements (neutrino, charged-lepton, hadron probes)
- SuperK neutrino flux
- Neutrino cross-sections
- SuperK detector response
- SuperK beam data
- Oscillation measurement

2010 Analysis: Simplicity of inputs & robustness!