Norm Buchanan
Colorado State University
On behalf of the T2K Collaboration
Lake Louise Winter Institute
Feb 25, 2011
Neutrino Oscillations

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

SuperK, K2K, MINOS

Daya Bay
Double Chooz
T2K

\[\Delta m_{23}^2 \approx 2.4 \cdot 10^{-3} \text{ eV}^2\]
\[\theta_{23} \approx 45^\circ\]

\[\theta_{13} < 10^\circ \text{ Chooz}\]
\[\delta \text{ unknown}\]

\[\Delta m_{12}^2 \approx 7.7 \cdot 10^{-5} \text{ eV}^2\]
\[\theta_{12} \approx 34.5^\circ\]

\[\theta_{13}\] is the last neutrino mixing angle remaining to be measured (gateway to $\delta_{\text{CPV}}$)

Searches underway (T2K, MINOS and Double-Chooz) and near future (Daya Bay, Reno, Nova)

Accelerator experiments

Reactor experiments
$\frac{L}{E_\nu} = 492 \text{ km/GeV}$
<table>
<thead>
<tr>
<th>Country</th>
<th>Institutions</th>
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<tbody>
<tr>
<td>Canada</td>
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<td>H. Niewodniczanski, Cracow</td>
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<td><strong>Italy</strong></td>
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<td><strong>~500 Members, 61 Institutes, 12 Countries</strong></td>
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</table>
νμ disappearance

\[ P(ν_μ → ν_μ) ≈ 1 - \sin^2(2θ_{23})\sin^2(1.27Δm_{23}^2L/E) \]

How close to 45º is θ_{23}? (measure to ~1%)
Measure Δm_{23}^2 to higher precision (< 1×10^{-4})

νe appearance

\[ P(ν_μ → ν_e) ≈ \sin^2(θ_{23})\sin^2(2θ_{13})\sin^2(1.27Δm_{13}^2L/E) \]

Improve upper limit on θ_{13} by > order of magnitude
Determine if θ_{13} is large enough to measure δ_{CP}

Sensitivity down to 0.006 (Δm_{23}^2 = 2.4 × 10^{-3} \text{eV}^2)
Many measurements can be made with the near detector. Region around T2K beam energy not well measured.

**CCQE**
- Dominates T2K energy region
- Well understood - characterize $E_{beam}$

**NC $\pi^+$ and CC $\pi^+$**
- Background for disappearance measurement

**NC $\pi^0$**
- Largest physics background to appearance measurement at SuperK.

Yellow bands correspond to region around T2K beam peak energy.

**Interesting Results Elsewhere**
- For example – possible discrepancy between MiniBooNE and NOMAD CCQE cross-section measurements.
The J-PARC Facility

- KEK/JAEA facility
- Construction of accelerator chain (JFY 2001 - 2009)
The J-PARC Facility

Completed 2007

181 MeV LINAC

3 GeV Synchrotron
The J-PARC Facility

181 MeV LINAC
Completed 2008

3 GeV Synchrotron

30 GeV Main ring
Completed 2007
Completed 2008
The J-PARC Facility

181 MeV LINAC
Completed 2009

3 GeV Synchrotron

Neutrino beam

30 GeV Main ring
Completed 2007
Completed 2008
Completed 2009
T2K Beamline Monitoring

• Beam orbit tuned within 2 mm of design (important to minimize beam loss)

• Beam position on target <1 mm movement – long term operation
Delivered proton number (so far)

<table>
<thead>
<tr>
<th>Date</th>
<th>Delivered proton#</th>
<th>Physics run</th>
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<tbody>
<tr>
<td>1/1/2010</td>
<td>1.0 x 10^19</td>
<td>4.8592 x 10^19</td>
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<tr>
<td>3/1/2010</td>
<td></td>
<td></td>
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<tr>
<td>5/1/2010</td>
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<td>7/1/2010</td>
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<td>9/1/2010</td>
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<tr>
<td>11/1/2010</td>
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<tr>
<td>1/1/2011</td>
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Results discussed today

- 2010 summer shutdown
- v beam 6 bunches -> 8 bunches
- ECAL fully installed (ND280)

<table>
<thead>
<tr>
<th>Total</th>
<th>Physics</th>
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<tbody>
<tr>
<td>4.9315 x 10^19</td>
<td>4.8592 x 10^19</td>
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<tr>
<td>(23.7 kW x 10^7 s)</td>
<td>(23.3 kW x 10^7 s)</td>
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</table>

Data taken Jan-Dec 2010

Reached 1 x 10^20 delivered POT Feb 8!
Off Axis Beam

\[ E_{\nu} = \frac{m_{\pi}^2 - m_{\mu}^2}{2(E_{\pi} - p_{\pi}\cos\theta)} \]

Pure \( \nu_\mu \) beam with <1% \( \nu_e \) contamination

Nearly mono-energetic beam at oscillation maximum
Suppress high energy tail

"Iso-contours" of \( \theta_{OA} \)

(approximate)

Outer corner of P0D about 20% more off-axis than inner corner
Near Detector (ND280)

Goal: Characterize the $\nu_\mu$ beam before propagation to far detector

- View of off-axis detector from above (magnet half open)
- View of Ingrid on-axis monitor (vertical modules)
On Axis Beam Monitor (Ingrid)

Important to get rapid feedback from on-axis beam position to determine off-axis angle – i.e. off-axis beam energy

**Beam Profile**

- **Horizontal Profile**
  - $\chi^2 / \text{ndf} = 7.015 / 4$
  - Constant: $1.007 \times 10^4 \pm 58.9$
  - Mean: $0.0844 \pm 2.671$
  - Sigma: $43.2 \pm 6.472$

  ![Horizontal Profile Graph](image)

- **Vertical Profile**
  - $\chi^2 / \text{ndf} = 4.02 / 4$
  - Constant: $1.027 \times 10^4 \pm 60.84$
  - Mean: $-10.86 \pm 3.207$
  - Sigma: $464.1 \pm 5.81$

  ![Vertical Profile Graph](image)

**Beam Center Stability**

- **Profile Center X/cm**
  - Jan and Feb.
  - Mar.
  - Apr.
  - May (20th-)
  - May (20th+)

- **Profile Center Y/cm**
  - Jan and Feb.
  - Mar.
  - Apr.
  - May (20th-)
  - May (20th+)

![Beam Center Stability Graph](image)

**Measured off-axis angle**: $2.519 \pm 0.021$ degrees
**Magnet**
UA1 magnet
Nominal B=0.2T

**Side Muon Range Detector**
Cosmic trigger and $p_\mu$ measurement
Scintillator interleaved into magnet yoke
192 hor. and 248 vert. modules

**PiZero Detector**
Optimized for $\pi^0$ rate measurement
Measure beam $v_e$
40 layers of x-y scint. Bars w/ WS fibers
Water target + US/DS ECALs

**TPCs**
Detection of charged particles
Excellent PID (dE/dx)
Momentum resolution < 10% (@ 1 GeV/c)
Readout: MicroMegas (7mm x 10mm pads)

**Fine Grained Detectors**
Target mass for tracker
Fine grain scintillator bars (1cm x 1cm)
Capable of detecting recoil protons

**ECALs**
Capture $\gamma/e/\mu$ escaping P0D and tracker
Scintillating layers and Pb absorber
Neutrino interaction upstream of the 1st TPC

Another neutrino interaction (DIS) in 1st FGD

Resolution: 7.8%

Energy loss for negative particles with 400 MeV/c < p < 500 MeV/c

Energy loss as a function of momentum for positively charged particles in neutrino interactions

See M. Day’s talk on measuring electron neutrinos with ND280
Other ND280 Performance

Extremely low number of unusable channels

<table>
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<tr>
<th>Detector</th>
<th>Total Chan</th>
<th>Bad Chan</th>
<th>Bad Fraction</th>
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<tbody>
<tr>
<td>TPC</td>
<td>124,416</td>
<td>12</td>
<td>0.01%</td>
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<tr>
<td>FGD</td>
<td>8,448</td>
<td>32</td>
<td>0.4%</td>
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<tr>
<td>P0D</td>
<td>10,400</td>
<td>7</td>
<td>0.07%</td>
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<tr>
<td>DSECAL</td>
<td>3,400</td>
<td>11</td>
<td>0.3%</td>
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<tr>
<td>SMRD</td>
<td>4,016</td>
<td>3</td>
<td>0.07%</td>
</tr>
<tr>
<td>INGRID</td>
<td>8,360</td>
<td>8</td>
<td>0.1%</td>
</tr>
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</table>

P0D event rate (March 19 – May 1 2010)

FGD cluster timing
ND280 Events
Event Selection

No track in TPC 1

≥1 negative charge track in TPC 2 (or 3)

Track starts in FV of FGD1 or FGD2

TPC PID

Before PID cut

After PID cut

Track ionization vs momentum

All plots data

Selected events in time with beam

Selected events vs POT

events/(1e17 POT): (5.289 +/- 0.014)
CCQE Measurement with ND280 Off-Axis Tracker

All plots: data compared with MC

\[ R_{\text{data/MC}} = 1.061 \pm 0.028 \quad +0.044 \quad -0.038 \quad \pm 0.xxx \]

- statistical
- model uncert.
- detector systematic

under evaluation
Super-Kamiokande

22.5 kton fiducial vol. (50 kton total)
11,129 20” PMT (inner detector)
1,885 8” PMT (outer detector)

Excellent E resolution and $e/\pi^0$ discrimination
Synchronized to T2K beam via GPS
Dead-timeless front-end electronics (2008)
SuperK Event Selection

Timing coincidence with beam (+TOF)

Fully contained (no OD activity)

Vertex in fiducial vol. (>2m from wall)

$E_{\text{vis}} > 100$ MeV

$E_n < 1250$ MeV

$1 \, e$-like ring

No decay electron

Forced 2$^{\text{nd}}$ ring ($m_{\text{inv}} < 105$ MeV/$c^2$)

$E_{\nu}^{\text{reco}} < 1250$ MeV

$\nu_e$ appearance

$\nu_\mu$ disappearance

$E_{\text{vis}} > 30$ MeV

$1 \, \mu$-like ring

Unbiased selection – decided before start of run

Made possible by many years of experience. SuperK is a mature detector that has been extensively studied and is well understood.
SuperK Events

Cuts

<table>
<thead>
<tr>
<th>Cuts</th>
<th>Events</th>
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<tbody>
<tr>
<td>Fully contained</td>
<td>33</td>
</tr>
<tr>
<td>FC + fiducial volume cut +</td>
<td>23</td>
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<tr>
<td>$E_{\text{vis}} &gt; 30\text{ MeV}$</td>
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RMS 26 ns

No off-bunch FC events

Invariant mass (ring 1 + ring 2): 133.8 MeV/c$^2$ (close to $\pi^0$ mass)
Momentum: 148.3 MeV/c
Plan Going Forward

Goal: Average 150 kW operation
Nov 2010 – Jun 2011

Design goal:
3.75 MW \times 10^7 \text{s}
5 years

2011 goal:
150 kW \times 10^7 \text{s}

Tripled data set since November
T2K had a strong first run period (Jan – Jun 2010)
- Steady 50 kW operation – integrated $3.23 \times 10^{19}$ POT for 1st run
- Current run: steady operation at 125 kW (recently 135 kW)
- Detectors operating with near 100% data collection efficiency
- SuperK and ND280 detectors performing at or above specification

Beam and detector work during 2010 summer shutdown
- FX Kicker upgraded - 6 bunch to 8 bunch v beam spill structure
- P0D and barrel ECALs installed – analyses for current run will incorporate the full ECAL

Tripled data set since November 2010

Oscillation analyses using 2010 dataset are converging
- Expect full results soon
Supplementary Material
Neutrino Flux Predictions

![Graphs showing neutrino flux predictions for ND280 and SK experiments.](image-url)
Beam Power

PMR (8-bunch@30GeV) = 1.6 x PRCS / MRCYCLE
( ): Beam transfer ratio from RSC to MR

RCS POWER FOR MR ★ 0.72 MW

MR POWER AT 30GeV

6sec (2.7%)
3.52sec (4.5%)
3.2sec (5.0%)
2.47sec (6.5%)
2.23sec (7.2%)
1.0sec (16%)(maximum cycle with existing power supply)
$\theta_{13}$ sens. to $\delta_{CP}$ (NH and IH)

90% CL $\theta_{13}$ Sensitivity

Systematic Error Fraction
- 5% sys error
- 10% sys error
- 20% sys error

Normal Hierarchy

Inverted Hierarchy