Recent Results from T2K

Jonathan Perkin on behalf of the T2K collaboration
The T2K experiment

Tokai to Kamioka

$\nu_\mu \rightarrow \nu_e \quad \nu_\mu \rightarrow \nu_\mu$

~500 Collaborators
59 Institutions
11 Countries

Super-KAMIOKANDE

INGRID

ND280

Neutrino Facility to Super Kamiokande

Near Detectors

Pure $\nu_\mu$ beam

295 km
neutrino mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1}/2 & 0 & 0 \\ 0 & e^{i\alpha_2}/2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- flavour eigenstates $\neq$ mass eigenstates
- described by (decomposed) PMNS matrix
- analogous to mixing in quark sector [CKM]
  - however mixing angles are comparatively large
- neutrino mass hierarchy presently unknown
  - only mass splittings are measured

Note: $c_{ij} = \cos(\theta_{ij}), s_{ij} = \sin(\theta_{ij})$
T2K physics: $\nu + n(p) @ 0.1-2\text{GeV}$

- $\nu_\mu \rightarrow \nu_e$ appearance $\sim \sin^2 \theta_{23} \sin^2 \theta_{13} \sin^2 (\Delta m_{32}^2 L/4E)$
- $\nu_\mu \rightarrow \nu_\mu$ disappearance $\sim 1-\sin^2 \theta_{23} \sin^2 (\Delta m_{32}^2 L/4E)$

- CCQE dominates ($M_{A}^{QE}$)
- Also:
  - Resonant CC pion ($M_{A}^{Res}$)
  - minimal DIS
**JPARC beam apparatus**

- Japan Proton Accelerator Research Complex

- 30 GeV protons on graphite target
- Neutrinos from pion decay in flight
  \[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
- Magnetic horn for sign selection
- Novel 2.5° off-axis beam for oscillation
  - improves monochromaticity
  - close to oscillation maximum

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Muon Monitor (MuMon)

- Measure beam centre and energy

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[arxiv.org/1211.0469](http://arxiv.org/1211.0469)
On Axis Near Detector

- Interactive Neutrino Grid (INGRID)
  - 280m from target on beam axis
  - 16x iron/scintillator tracking calorimeters
  - 1x all-scintillator proton module
  - monitors beam centre, profile and $\text{CC}^{\text{inc}}$ rate

Near Detector @ 280m (ND280)

- 280m from target 2.5° from beam axis
- Upstream $\pi^0$ detector (P0D)
- 2x 0.8ton Fine Grained scintillation Detectors (FGD) with C and $\text{H}_2\text{O}$ target
- 3x Time Projection Chambers (TPC) for accurate $\text{dE}/\text{dx}$ based PID
- Hermetic lead/scintillator Electromagnetic Calorimeters (ECAL)
- 0.2T refurbished UA1/NOMAD magnet

Off Axis Near Detector
T2K Far Detector : Super-K

- **Super Kamioka Neutrino Detection Experiment**
  - 50 kiloton water Cherenkov detector with photomultiplier tube (PMT) based readout
  - 22.5 kiloton inner fiducial mass + outer detector

- Can observe several sources
  - Atmospherics
  - Beamline (T2K)
  - Solar
  - Supernovae
  - Geophysical

Inner detector: 11,129 20” PMTs
Outer detector: 1885 8” PMTs
T2K Far Detector : Super-K

- Event displays (data) [http://www.ps.uci.edu/~tomba/sk/tscan](http://www.ps.uci.edu/~tomba/sk/tscan)

**603 MeV muon** (162ns timescale)
- Low scattering - sharply defined ring

**492 MeV electron** (130ns timescale)
- Multiple scattering - fuzzy ring

**Pi0 decay** (photons)
- 2 rings reconstructed

• (MC)
T2K

latest results
• 6.63x10^{20} protons on target (POT) recorded
• <1mrad (~16MeV [2%]) beam stability for total period
• Achieved 1.2x10^{14} protons per pulse (WR)
• 8% of design goal POT so far
Near Detector Constraint

- Use ND280 to constrain flux and cross section parameters
  - propagate to Far Detector
- 2013 $CC^{inc} \nu_\mu$ selection is split into 3 subsamples
  - improves data/MC agreement
  - improves parameter errors

<table>
<thead>
<tr>
<th></th>
<th>efficiency</th>
<th>purity</th>
</tr>
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<tbody>
<tr>
<td>$CC0\pi$</td>
<td>50.1%</td>
<td>72.6%</td>
</tr>
<tr>
<td>$CC1\pi^+$</td>
<td>29.5%</td>
<td>49.4%</td>
</tr>
<tr>
<td>CCOther</td>
<td>35.2%</td>
<td>73.8%</td>
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</table>
Near Detector Constraint

• In 2012 analysis, increasing dataset (~x2POT) did not significantly improve parameter uncertainties

• New 2013 analysis reduces parameter uncertainties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2012 Analysis</th>
<th>2013 Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_A^{QE}$ (GeV)</td>
<td>1.33 ± 0.20</td>
<td>1.17 ± 0.09</td>
</tr>
<tr>
<td>$M_A^{RES}$ (GeV)</td>
<td>1.15 ± 0.10</td>
<td>0.97 ± 0.08</td>
</tr>
<tr>
<td>CCQE Norm.</td>
<td>0.96 ± 0.09</td>
<td>0.99 ± 0.08</td>
</tr>
<tr>
<td>CC1π Norm.</td>
<td>1.63 ± 0.29</td>
<td>1.18 ± 0.18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$\sin^2 2\theta_{13} = 0.1$</th>
<th>$\sin^2 2\theta_{13} = 0.0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>4.9%</td>
<td>6.5%</td>
</tr>
<tr>
<td>2013</td>
<td>3.5%</td>
<td>5.2%</td>
</tr>
</tbody>
</table>

oscillation parameter uncertainties

cross section parameters and uncertainties
Near Detector Constraint

- Far Detector $\nu_\mu$ and $\nu_e$ flux predictions constrained by 2013 analysis
  - Plots show central values and error bands for normalization parameters before and after the near detector constraint
  - Central values are changed from 2012 results: due to finer bins and new selection
Updated $\nu_\mu$ result

- 2012: $31\nu_\mu^{\text{obs}}$ vs $104\nu_\mu^{\text{exp}}$
  - best fit $\sin^2(2\theta_{23}) = 0.98$ and $|\Delta m^2_{32}| = 2.65 \times 10^{-3}$ eV$^2$
  - $\theta_{23} < \pi/4$ octant only

- 2013: 58 observed $\nu_\mu$ against expectation of $204.75 \pm 16.75^{\text{sys}}$
  - preliminary best fit for $\sin^2(2\theta_{23}) = 1$ is $|\Delta m^2_{32}| = 2.45 \times 10^{-3}$ eV$^2$ ($\theta_{23} < \pi/4$)
    - $2.44 \times 10^{-3}$ eV$^2$ ($\theta_{23} < \pi/4$)
  - shape of contour affected by octant – plot both
    - $\theta_{23} < \pi/4$ and $\theta_{23} > \pi/4$
T2K cross-sections and more

- Use ND280 $\nu_\mu$ oscillation analysis to extract $CC^{inc}$ cross section
  - 2010-11 data set (10.8x10$^{19}$POT)
  - carbon target (FGD fiducial mass)
  - flux prediction from MC + NA61/SHINE data

- Other analyses underway
  - NC $\pi^0$, CCQE, NC Elastic $CC\pi$ and $CC\pi^{coh}$
  - Anti neutrinos
  - Steriles and other exotica
  - …

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2013 T2K far detector reconstruction

- for a given event topology, create a PDF for charge and time at each PMT sensor
  - charge $\sim$ Light Yield $\times \int_{\text{track length}} \text{PMT solid angle} \times \text{PMT response} \times \text{Attenuation}$
    - Based on the algorithm used by MiniBooNE (NIM A608, 206 (2009))
    - no limitation on number of tracks in event
- given event PDFs select one with best fit likelihood
  - electron, muon, 1-ring, 2-ring, n-ring...
- Aids $\pi^0$ (dominant T2K FD background) rejection [70% more than 2012]
- Significant improvement on existing T2K Far Detector algorithms
\(\nu_e\) appearance

- Event selection:
  - Fully contained in fiducial volume
  - Only one reconstructed rings
  - Ring is electron like

![Graphs showing event selection criteria](image)
$\nu_e$ appearance

- Event selection:
  - Visible energy $> 100\text{MeV}$
  - No Michel Electrons
  - $(2013)2D \pi^0$ invariant mass : fiTQun likelihood cut
  - Reconstructed energy $< 1.25 \text{GeV}$
\( \nu_e \) appearance result

- Null oscillation hypothesis predicts \( 20.4 \pm 1.8 \, \nu_e \) events
  - \( \sin^2 2\theta_{13} = 0.1 \)
  - \( \sin^2 2\theta_{23} = 1 \)
  - \( \delta_c^p = 0 \)
- \( 4.64 \pm 0.53 \) background events also expected
- Oscillation parameters extracted from reconstructed neutrino kinematics
  - energy spectrum
  - momentum vs angle distribution
ν_e appearance result

• **28 events observed**
  - unoscillated expectation of **20.4±1.8** (for sin^2θ_{13}=0.1, sin^2θ_{23}=1, δ^{cp}=0)
• Comparing to null oscillation hypothesis gives a **7.5σ** significance for non-zero θ_{13}
Summary

- A total of $6.63 \times 10^{20}$ POT on tape
  - $6.39 \times 10^{20}$ POT accumulated by April 12th, 2013 now analysed
- With only 8% of the design POT $\theta_{13}=0$ is excluded with a significance of $7.5\sigma$ ($\delta_{CP}=0$, $\sin^2 2\theta_{23}=1$)
  - via observation of the $\nu_\mu \rightarrow \nu_e$ appearance channel
  - null oscillation hypothesis predicts 20 $\nu_e$
  - 28 $\nu_e$ are observed
- The $\nu_\mu$ disappearance contours are sensitive to the octant chosen
  - both contours are provided
  - via observation of the $\nu_\mu \rightarrow \nu_\mu$ disappearance channel
  - 58 $\nu_\mu$ observed vs unoscillated expectation of 204.75
- 2013 near detector constraints
  - significant improvement on parameter errors
- New T2K Far Detector reconstruction algorithm
  - 70% reduction of the $\pi^0$ background relative to the previous analysis
  - More improvement is expected as new algorithm becomes more fully integrated into T2K analyses
- Achieved steady operation of JPARC beam at 220 kW
  - further increases of beam power in future
Thank You!
Backup Slides
\( \nu_\mu \) oscillation at T2K – octant sensitivity

\[
P(\nu_\mu \rightarrow \nu_\mu) \approx \]
\[
1 - ( \cos^4 \theta_{13} \cdot \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \cdot \sin^2 \theta_{23} ) \cdot \sin^2 (\Delta m^2_{32} L/4E) + \text{other terms tending to 0 at } L=295\text{km and } E\approx600\text{MeV}
\]

- leading order and sub-leading order terms
  - sensitive to choice of octant \( \theta_{23} \leq \pi/4 \) or \( \theta_{23} \geq \pi/4 \)
T2K analysis concept

• $\nu_\mu \rightarrow \nu_x$ oscillation measurement
  • essentially a counting experiment
  1. measure source flux at near detector
  2. extrapolate flux to far detector and predict observed rate
  3. measure $\nu_\mu$ deficit at far detector
  4. use deficit to exclude null oscillation hypothesis

• sounds simple, but...
  • many inputs required
  • many sources of uncertainty
  • many correlations to consider
  • several competing analyses
T2K analysis strategy
Beam Stability (MuMon)
Beam Stability (INGRID)
Beam Stability (ND280)
**T2K Far Detector**

- Candidate events from last analysis run

**Super-Kamiokande IV**
T2K Beam Run 440058 Spill 11130074
Run 70557 Sub 236 Event 328624972
12-3-4-21-6-12-8-14-2-1
TK beam dt = 1154.0 μs
Inster: 2146 hits, 4590 p.e.
Others: 4 hits, 9 p.e.
Trigger: 5a8001007
E_electron: 760.0 MeV
\( E_{\text{miss}} = 466.0 \, \text{MeV} \)

**First reconstructed electron candidate following Tohoku earthquake**

![First reconstructed electron candidate following Tohoku earthquake](image)

**Figure 12: \( \nu_e \) candidate event #12**

**Super-Kamiokande IV**
T2K Beam Run 480017 Spill 7236603
Run 71066 Sub 1165 Event 289213499
12-04-10-21-12-9-2
TK beam dt = 1731.1 μs
Inster: 2302 hits, 3057 p.e.
Others: 4 hits, 3 p.e.
Trigger: 5a8001007
E_electron: 327.9 MeV
\( E_{\text{miss}} = 256.0 \, \text{MeV} \)

**Figure 31: \( \nu_e \) candidate event #31**
ND280 TPC

- dE/dx plots
Near Detector Constraint

**Neutrino Flux Model:**
- Data-driven: NA61/SHINE, beam monitor measurements
- Uncertainties: modeled by variation of normalization parameters \( b \) in bins of neutrino energy, flavor

**Neutrino Cross Section Model (NEUT):**
- Data-driven: External neutrino, electron, pion scattering data
- Uncertainties: modeled by variations of model parameters \((M_A, p_F, E_b)\) and ad-hoc parameters

**Constraint from ND280 Data:**
- Data Samples enhanced in CC interactions with 0, 1 or multiple pions
- Fit to data constrains flux, \( b \), and cross section, \( x=(M_A, p_F, E_b, \text{ad-hoc, etc.})\), parameters
- Constrained SK flux parameters and subset of cross section parameters are used to predict SK event rates
$\nu_e$ appearance

- vertex distributions
List of all publicized information in English

July 26 : Message from Director Ikeda of the J-PARC center
http://j-parc.jp/en/topics/20130726director_message.html

July 8 : J-PARC News - June 2013 (Issue #98)

June 27 : A delay in suspending the operation of the accelerator complex and a delay in turning off the ventilation fans at the Hadron Experimental Facility (HD Facility)

June 21 : Results of the individual does measurements from the radioactive material leak at the HD Facility

June 21 : Postponement of the 2nd International Symposium of Science at J-PARC (J-PARC 2013)
http://j-parc.jp/en/topics/20130621director_message.html

June 18 : 2nd Accelerator Facility Accident Report to Nuclear Regulation Authority - Full Version -

June 18 : Submission of the 2nd report on the radioactive material leak at the HD Facility of J-PARC

June 18 : On the establishment of an External Expert Panel to review the leak accident of radioactive material at the J-PARC HD Facility

June 13 : J-PARC News Special Issue

June 10 : Notification of Cancelation of Assigned Beamtime to the End of July 2013 due to the Accident at HD Facility
http://j-parc.jp/en/topics/20130610director_message.html

May 31 : Submission of the 1st report on the radioactive material leak at the HD Facility of J-PARC (Accelerator Facility Accident Report) - full version-

May 31 : A summary of the accident at HD Facility on May 23 2013 (based on the Japanese documents publicized at the J-PARC website on May 25 and May 29)

May 30 : Extension of the 2013B call for proposals deadline

May 29 : Message from Director of J-PARC Center
http://j-parc.jp/en/topics/20130529director_message.html

May 27 : Message from the Director of J-PARC Center to Users

May 25 : Accident of J-PARC Hadron Experimental Facility