Recent results from T2K

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March. 5, 2013
Rencontres de Moriond
Content

• Introduction of T2K
• Results
  – $\nu_\mu$ disappearance: $\theta_{23}$ & $\Delta m_{32}$
    \textbf{(New results in this winter)}
  – $\nu_e$ appearance: $\theta_{13}$ (shown in ICHEP 2012)
• Summary

T2K collaboration
~500 people from 11 countries
Introduction: Neutrino mixing

3 flavor neutrino mixing:

Flavor (e,μ,τ)  
Eigenstate  

\[
\begin{align*}
V_e & = U_{PMNS} \times V_1 \\
V_\mu & = U_{PMNS} \times V_2 \\
V_\tau & = U_{PMNS} \times V_3
\end{align*}
\]

Mass (m_1,m_2,m_3)  
Eigenstate  

\[
U_{PMNS} = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13} e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

Current status

Solar and reactor (KamLAND)
\[\theta_{12} = 33.6^\circ \pm 1.0^\circ\]

Atmospheric, accelerator
\[\theta_{23} = 45^\circ \pm 6^\circ \quad (90\% CL)\]

Accelerator, reactor (DayaBay,DoubleChooz,RENO)
\[\theta_{13} = 9.1^\circ \pm 0.6^\circ\]

Remaining questions:

- Is \(\theta_{23} = \pi/4\)?
- CP phase (\(\delta\))?  
- Mass hierarchy  
  \(m_1 < m_2 < m_3\)? \(m_3 < m_1 < m_2\)?
Introduction: 2 modes in T2K

**ν\(_\mu\) disappearance**

\[ \text{Prob}(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin(1.27 \Delta m_{32}^2 L/E) \]

Precise measurement of \(\theta_{23}, \Delta m_{32}^2\)

**ν\(_e\) appearance**

\[ \text{Prob}(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin(1.27 \Delta m_{32}^2 L/E) + \text{CPV term} + \text{Matter term} + \ldots \]

*Evidence of ν\(_e\) appearance in 2012!*

To answer the remaining questions, precise measurement of all parameters are necessary.
Results Shown Today

• Data: from Jan 2010 to July 2012

3.01 × 10^{20} Protons On Target (POT)

~4% of T2K’s target POT (7.8 × 10^{21}POT)
Stable ν beam in whole period.

• Oscillation analysis results

  – Near detector measurement
  
  – ν_μ disappearance : θ_{23} & Δm_{32}
    (New results in this winter)
  
  – ν_e appearance: θ_{13} (shown in ICHEP 2012)
Experimental setup of T2K

- Secondary $\pi^+$ (and $K^+$) from 30 GeV protons focused by three E.M. horns
- $\nu_\mu$ beam (mainly $\pi^+ \rightarrow \mu^+ + \nu_\mu$)
- Off axis neutrino beam (2.5°)
  - Narrow band @ osc. max
  - Reduce BG from high energy
  - $\nu$ direction stability < 1 mrad

$\Delta m^2_{23} = 2.4 \times 10^{-3} eV^2$
$\theta_{23} = 1/4\pi$, $L=295 km$
$\sin^2 2\theta_{13} = 0.1$
ND280

*Off axis* neutrino detector

280m from target
ND280

*Off axis* neutrino detector

Signal:
Charged Current Quasi Elastic (CCQE) interaction

\[ \nu \rightarrow e \text{ or } \mu \]

Fine Grained Detector (FGD) with 1cm square plastic scintillators (1.6ton fiducial mass).

Tracker: FGD & TPC

TPC provides PID \((de/dx, \text{charge})\) and Momentum of each track.
ND280

*Off axis* neutrino detector

Event Display of CC like event
CCQE selection (one $\mu$ track selection)

- Good $\mu^-$ candidate in FV.
- Upstream TPC veto
- muon ID by TPC
- 1 FGD-TPC track
- No decay-e in FGD

For CCQE selection
40% eff. w/ 72% purity
Far Detector: Super-Kamiokande

20inch (~50cm) PMT

Fiducial volume is 2m from ID wall

= 22.5 kton
Particle ID technique

\[ \nu_e \text{ CC simulation} \quad \nu_e \]

\[ \nu_\mu \text{ CC simulation} \quad \nu_\mu \]

Miss-PID probability \( \sim 1\% \)!
$\nu_\mu$ disappearance

$\nu_\mu$ candidate

58 events observed
MC: 57.8 (osc.)
196.2 (no osc.)

$E_\nu$ can be reconstructed by $P_\mu$ & $\theta_\mu$

Signal (CCQE): 1 ring $\mu$-like

$\nu_\mu$ can be reconstructed by $P_\mu$ & $\theta_\mu$

CC1π

$\nu_\mu$ candidate

$\nu_\mu$ CC QE

$\nu_\mu$ CC non-QE

$\nu_e$ CC

NC

(MC w/ 2-flavor osc.)

$(\sin^2 2\theta_{23}, \Delta m_{23}^2) = (1.0, 2.4 \times 10^{-3} \text{eV}^2)$

Fiducial Volume

16$^\text{O}$

(Cherenkov threshold)
Method of $\nu$ oscillation analysis

**$\nu$ Flux prediction**
With external hadron production data especially from NA61@CERN

**Neutrino Cross section**
Model (NEUT), uncertainties developed with fits to external data

<table>
<thead>
<tr>
<th>ND280 Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum and angle of $\nu_\mu$ CCQE and CCnonQE</td>
</tr>
</tbody>
</table>

- Fit the ND280 Data to refine flux and $\nu$-int. model
- Verification with $\nu_e$ & $\pi^0$ data @ND280

**SK prediction**
Tuned MC based on ND280 measurement

**Comparison**

**SK Measurement**
$\nu_\mu$ disappearance: # of events and energy spectrum
Neutrino oscillation parameter fit

2 different methods

• Maximum likelihood method with reconstructed $E_\nu$

$$\mathcal{L}(\vec{\sigma}, \vec{f}) = \mathcal{L}_{\text{norm}}(\vec{\sigma}, \vec{f}) \times \mathcal{L}_{\text{shape}}(\vec{\sigma}, \vec{f}) \times \mathcal{L}_{\text{syst}}(\vec{f})$$

  – Where $\sigma$ and $f$ are $\nu$ oscillation parameters and systematic error parameters.

  – Vacuum oscillation is used (matter effect is small)

• Likelihood-ratio method with reconstructed $E_\nu$

$$\chi^2 = 2 \sum_{E} \left( N_{SK}^{\text{data}} \ln \frac{N_{SK}^{\text{data}}}{N_{SK}^{\text{exp}}} + (N_{SK}^{\text{exp}} - N_{SK}^{\text{data}}) \right) + (\vec{f} - \vec{f}_0)^T C^{-1} (\vec{f} - \vec{f}_0)$$

  – $N_{SK}$ is number of event in SK for each energy bin

  – $f_0$ is default systematic parameters, and $C$ is covariance.

  – Matter effect is taken into account.
ν osc. analysis (ν_μ disappearance)

Preliminary

Best fit spectrum
No osci. spectrum
Data (Run1-3)

World best precision of θ_{23}!
Effect of systematics

True oscillation parameter \((\sin^2 2\theta_{23}, \Delta m_{32}^2) = (1.0, 2.4 \times 10^{-3} \text{eV}^2)\)

<table>
<thead>
<tr>
<th>Error on # of event@SK</th>
<th>w/ ND280 Meas.</th>
<th>w/o ND280 Meas.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux (\times \nu \times\text{sec.})</td>
<td>21.7%</td>
<td>4.2%</td>
</tr>
<tr>
<td>Un-corr (\nu \times\text{sec})</td>
<td>6.2%</td>
<td></td>
</tr>
<tr>
<td>SK detector</td>
<td>10.5%</td>
<td></td>
</tr>
<tr>
<td>Final State Int.</td>
<td>3.5%</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>25.3%</td>
<td>13.5%</td>
</tr>
</tbody>
</table>

Error is still dominated by stat. error.
$v_e$ appearance
**νₑ appearance**

νₑ candidate

Signal (CCQE): 1 ring e-like

Fiducial Volume

νₑ

16O

p

(main below Cherenkov threshold)

Main NC BG

---

Number of Events

- 11 events
- p-value 0.08%
- 3.2 σ

Reconstructed Eν [MeV]
$\nu$ osc. analysis ($\nu_e$)

<table>
<thead>
<tr>
<th>Error on # of event at SK (%)</th>
<th>w/ ND280</th>
<th>w/o ND280</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux $\times$ $\nu$ cross section</td>
<td>24.4</td>
<td>5.7</td>
</tr>
<tr>
<td>Un-correlated $\nu$ cross section</td>
<td>7.4</td>
<td></td>
</tr>
<tr>
<td>SK +FSI+SI</td>
<td>3.9</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>25.9</td>
<td>10.3</td>
</tr>
</tbody>
</table>

Best fit: $\sin^22\theta_{13} = 0.094^{+0.053}_{-0.040} (0.116^{+0.063}_{-0.049})$ for N.H. (I.H.)

Assuming Normal H.

Assuming Inverted H.
Data taking status & prospect

Currently beam power:

230kW
(~150kW in last year)

*Very stable operation.*
*Almost double POT since Run3 (as of March)*

Expected P.O.T.
This year : $8 \times 10^{20}$
(5σ for $v_e$ appearance)
2014 : $12 \times 10^{20}$
2015 : $18 \times 10^{20}$
Goal : $78 \times 10^{20}$

Please look forward to more results from T2K!!
Summary

• T2K results are presented with $3.01 \times 10^{20}$ POT (~4% of ultimate POT)

• $\nu_\mu$ disappearance: World record on $\theta_{23}$!
  
  $(\sin^2 2\theta_{23}, \Delta m_{23}^2) = (1.00_{-0.068}^{+0.068}, 2.45 \pm 0.30 \times 10^{-3} \text{ eV}^2)$ 90% C.L.

• $\nu_e$ appearance: 3.2σ significance. Evidence!!
  
  $\sin^2 2\theta_{13} = 0.094^{+0.053}_{-0.040} (0.116^{+0.063}_{-0.049})$ for N.H. (I.H)

Prospect

• Keep stable data taking (current beam power ~230kW)

• $8 \times 10^{20}$ POT by this summer ($\rightarrow$ 5σ for $\nu_e$ app.)

• Aim to accumulate $12 \times 10^{20}$ POT (2014) and $18 \times 10^{20}$ POT (2015)
back up
Physics
CPV measurement

- CPV term in \( \text{Prob}(\nu_{\mu} \to \nu_e) \propto \sin \theta_{12} \cdot \sin \theta_{23} \cdot \sin \theta_{13} \cdot \sin \delta \)

Now we know \( \theta_{13} \) is not 0!

This has opened up the possibility to measure CPV in lepton sector

Note: The largest uncertainty is on \( \theta_{23} \)

Both \( \nu_e \) appearance and \( \nu_\mu \) disappearance are very important to for future CPV measurement
We want to understand the underlying physics to explain the structure of lepton mixing with precise measurements of parameters.
\( \nu_\mu \rightarrow \nu_e \) appearance

\[
P(\nu_\mu \rightarrow \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \frac{\Delta m_{21}^2 L}{4E} \right)
\]

\[
+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos \delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E}
\]

\[
-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin \delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}
\]

\[
+4S_{12}^2 C_{13}^2 \left\{ C_{12} C_{23}^2 + S_{12} S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos \delta \right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E}
\]

\[
-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} \left(1 - 2S_{13}^2 \right)
\]

Matter effect (small in T2K)

\(a \rightarrow -a, \delta \rightarrow -\delta\) for \(P(\nu_\mu \rightarrow \nu_e)\)

\(L=295\text{km}, \langle E_\nu \rangle \sim 0.6\text{GeV}\)

\[
a = 7.56 \times 10^{-5} \left[ \frac{eV^2}{g/cm^3} \right] \left( \frac{E}{\text{GeV}} \right)
\]

\(\sin^2 2\theta_{13} = 0.1, \delta = \pi/4\)
Mass hierarchy

(normal)  

(inverted)
Goal of T2K

First Goal
- Discovery of $\nu_\mu \rightarrow \nu_e$ ($\theta_{13}$ measurement)
  Achieved in 2012!

Ultimate Goal
- Precision measurement of $\nu_\mu$ disappearance
- Measurement (/indication/hint) of $\delta_{CP}$ and the mass hierarchy.
Beam line and monitors
Run1-2 (2010-2011): $1.43 \times 10^{20}$ Protons on target (p.o.t.)

Run3 (2012): $1.58 \times 10^{20}$ p.o.t.

- Confirmed that the beam quality is unchanged after the earthquake
- Achieved stable 200kW beam power operation.

Total number of protons is $3.01 \times 10^{20}$ p.o.t for this analysis
J-PARC neutrino beamline components

- Muon Monitor
- Horn
- Beam monitors
- Super-Conducting Magnets

Near Detector (at 280m from target)

Beam Dump
Decay Volume

νμ

π+

30GeV
MR

Target
Monitoring $\nu$ beam direction

Muon monitor
- consists of 49 Si sensors
- can check Spil by spil stability.
$$10^5 - 10^7 \mu/cm^2/bunch$$

INGRID
- consists of 16 modules of scintillator + Iron trackers.
- can check actual $\nu$ beam direction day by day.

For off axis beam $\rightarrow$ Beam direction monitors are very important
Secondary beam line monitor: Muon monitor (MUMON)

Detect decay $\mu$ from $\pi$

→ Indirect measurement of $\nu$ beam direction spill-by-spill.

Ion chamber array (7×7ch)

Silicon pin photo diode array (7×7ch)

Spill-by-spill $\mu$ beam profile by fitting with Gaussian.

Signal @ 1ch

Integrate $\times 49$ ch

2D profile

1D slice profile

ADC count

Integrate

x[cm]

1000 2000 3000 4000 5000

Time [ns]

-600 -400 -200 0 200 400

-80 -60 -40 -20 0 20 40 60

$\times 80$
1 mrad change makes the peak of ν spectrum by 2-3% (=error on Δm²)

INGRID also shows good stability of neutrino beam
~280m from target

INGRID
On axis neutrino detector
INGRID event selection

Select neutrino event in FV
- Coincident hits in X-Y plane & Timing cut → Reject accidental hits
- Reconstruct one track.
- Select vertex inside fiducial volume → Veto sand, muon, cosmic

Event timing

![Event timing graph showing # of events vs time from trigger in nsec]
Event display of INGRID

Neutrino event

Beam profile (~1 month data)
Neutrino event rate is stable within 1% @ INGRID

Beam center position by INGRID

± 1 mrad

X profile center

Y profile center

(a point ~ one month)

~ 280 m from target
Neutrino flux prediction

NA61/SHINE (@CERN) measured hadron production in \((p, \theta)\) using 30GeV protons and graphite target *

* \(\pi\) outside NA61 acceptance and production modeled with FLUKA

horn focusing, decay is simulated by GEANT3

\(\nu_\mu\) at SK

\(\nu_e\) of \(\mu\) decay is due to \(\pi\) decay → can accurately be predicted by NA61 \(\pi\) measurement

---

Graphs showing flux vs. energy for different categories of particles. The graphs are labeled for \(\nu_\mu\) at SK and \(\nu_e\) at SK.
CERN NA61/SHINE measurement

Measure hadron (π, K) yield distribution in 30 GeV p + C inelastic interaction
- thin target 4%λ (2cm)

π+ production: Two analysis for different momentum region

NA61/SHINE setup

Large acceptance spectrometer + TOF

detector performance
σ(p)/p^2 ≈ 2 × 10^{-3}, 7 × 10^{-3}, 3 × 10^{-2} (GeV/c)^{-1},
σ(dE/dx)/(dE/dx) ≈ 0.04
σ(TOF-F) ≈ 115 ps

for p > 5, p = 2, p = 1 GeV/c
Results of pion production from thin target (2007 data)

N. Abgrall et al., arXiv:1102.0983 [hep-ex]

Differential cross section for $\pi^+$ production
in 30GeV $p+C$

Error bars = stat. + syst. in quadrature

Systematic uncertainty was evaluated in each $(p, \theta)$ bin
typically 5-10%

The normalization uncertainty is 2.3% on the overall $(p, \theta)$

→ Propagate the systematic uncertainty in each $(p, \theta)$ bin into the expected number of events in T2K

→ Input to T2K neutrino beam simulation
## Near future operation plan of MR-FX

<table>
<thead>
<tr>
<th>Periods</th>
<th>Expected beam power</th>
<th>Improvements / Cycle time</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011. 6-11</td>
<td>shutdown</td>
<td>Ring collimator shields, 7th and 8th RF systems, New injection kicker</td>
</tr>
<tr>
<td>2011. 12 - 2012. 6</td>
<td>100 - 200 kW (RCS 300 kW eq.)</td>
<td>Cycle time 3.2 -&gt; 2.56 Beams loading compensation</td>
</tr>
<tr>
<td>2012. 7 – 9</td>
<td>shutdown</td>
<td>Ring collimator upgrade (0.45 -&gt; 2 kW) 9th RF system</td>
</tr>
<tr>
<td>2012. 10 – 2013. 7</td>
<td>&gt; 200 kW (2012.10~) (RCS 300-400 kW eq.)</td>
<td>Cycle time 2.48 -&gt; 2.4 s Second harmonic cavities</td>
</tr>
<tr>
<td>2013. 8 – 2013. 1</td>
<td>shutdown</td>
<td>Ring collimator upgrade (2 kW -&gt; 3.5 kW) Linac upgrade</td>
</tr>
<tr>
<td>2014. 2 – 2014. 6</td>
<td>&gt; 300 kW (RCS &gt; 600 kW eq.)</td>
<td>Cycle time 2.4 s</td>
</tr>
</tbody>
</table>

Koseki @ HK open meeting
http://indico.ipmu.jp/indico/getFile.py/access?contribId=13&sessionId=3&resId=0&materialId=slides&confId=7
Off-axis Near Detectors (ND280)

In present analysis,

2 fine grained detectors (FGDs)
  - Active target
  - 1.6t fiducial mass

3 time projection chambers (TPCs)
  - PID(by dE/dx), Momentum, Charge

Measure ν flux/spectrum before oscillation

Better than 10% dE/dx resolution

10% momentum resolution @1GeV/c
Constrain by ND280 fit

Cross section param. | Before ND280 Fit | After ND280 Fit
--- | --- | ---
Axial Mass for QE (GeV) | 1.21 ± 0.45 | 1.19 ± 0.19
Axial Mass for Resonance (non QE)(GeV) | 1.16 ± 0.11 | 1.14 ± 0.10
CCQE Norm 0-1.5 GeV | 1.00 ± 0.11 | 0.94 ± 0.09
CC1π Norm 0-2.5 GeV | 1.63 ± 0.43 | 1.67 ± 0.28
NC1π0 Norm. | 1.19 ± 0.43 | 1.22 ± 0.40

Cross section parameters are constrained by ND280 data! They are used for SK prediction.
$p_{\mu,\theta}@\text{ND280}$ Color: MC, Box: Data

CCQEsample

CCnQEsample

$\mu$ momentum [MeV/c]

$\cos(\mu\text{ angle})$
Beam $\nu_e$ measurement

**POD**

- Only one shower like track
- Energy threshold 1.5GeV

**TPC+FGD+ECAL**

- Largest negative track from FGD
- Largest track is e-like (TPC $dE/dx$, and Ecal shower like)

MC consistsents with data
POD NC$\pi^0$ measurements

- Main BG for nue appearance at SK

Selection
- no μ-like track
- 2 shower like track
- no μ-decay electron
- Forward tracks
- Track distance > 5cm

Data/MC = 0.84 ± 0.16 (stat) ± 0.18(sys)

MC consistent with data
CC Inclusive cross section

\[\langle \sigma_{CC} \rangle_\phi = (6.93 \pm 0.13 \text{(stat)} \pm 0.85 \text{(syst)}) \times 10^{-39} \text{ cm}^2 \text{ nucleons}\]
SK
$\nu_e$ signal and background at Super-K

- **Signal:** Single electron event
  - Mainly Charged Current Quasi Elastic (CCQE)
    \[ \nu_e + n \rightarrow e^- + p \]

- **Main background:**
  - Intrinsic $\nu_e$ (estimated from beam MC)
  - $\pi^0$ from Neutral Current interaction (NC$\pi^0$)
    - Overlap of 2$\gamma$s
    - Missing out on 1$\gamma$
      when one of $\gamma$ has very low energy

Oscillation
Proton is below Cherenkov Threshold
**ve appearance**

1. Events in the T2K beam timing and fully contained (FC) in ID
2. Fiducial volume cut
3. Single electron cut
   - Number of ring = 1 and e-like event
4. Visible energy > 100 MeV
   - Rejects low energy NC events and electrons from invisible $\mu$, $\pi$ decays
5. No decay electron
   - To eliminate non-CCQE, miss identified $\mu$ event
6. Invariant mass < 105 MeV
   - To eliminate NC $\pi^0$ background
7. Reconstructed energy (assuming CCQE) < 1250MeV
$\nu_\mu$ disappearance

- **Signal:** Single $\mu$ event
  - CCQE enriched sample for energy spectrum measurement.
- **Background:**
  - CC non-QE (ex. CC$1\pi$, etc.)
- **Selection criteria**
  - T2K beam timing & FCFV
  - Single ring $\mu$-like event
  - less than 2 decay electron (to reduce CC non-QE)
  - Reconstructed $\mu$ momentum $> 200$ MeV/c
Observed $\nu_e$ candidate event (No.1)
Observed $\nu_e$ candidate event (No.2)

Super-Kamiokande IV
T2K Beam Run 36 Spill 261731
Run 67886 Sub 289 Event 66474118
10-11-21:07:07:21
T2K beam dt = 8.2 ns
Inner: 2532 hits, 5837 pe
Outer: 2 hits, 1 pe
Trigger: 0x80000007
D_wall: 284.2 cm
e-like, p = 583.1 MeV/c

Charge (pe)
- >26.7
- 23.3-26.7
- 20.2-23.3
- 17.3-20.2
- 14.7-17.3
- 12.2-14.7
- 10.0-12.2
- 8.0-10.0
- 6.2-8.0
- 4.7-6.2
- 3.3-4.7
- 2.2-3.3
- 1.3-2.2
- 0.7-1.3
- 0.2-0.7
- < 0.2

0 mu-e decays

Times (ns)
demonstrate to reconstruct invariant mass using atmospheric $\nu$ data

SK atm. $\nu$ data and MC
(single + multi ring e-like event with T2K $\nu_e$ selection except for # of ring cut)
Systematic error on $\nu_e$ event selection at SK

- Evaluation using various control samples (atm $\nu$, cosmic $\mu$, ...)
- An example: NC$1\pi^0$ rejection efficiency

Real data electron ring (atm $\nu$, ...) + MC simulation $\gamma$ ring

- can produce the control sample w/ same topology as T2K NC$1\pi^0$
- compare the cut efficiency btw control sample data and its MC
\( \nu_e \) event selection at SK (cont’d)

6. Invariant mass of 2 \( \gamma \) rings forced to be found by the special fitter < 105 MeV/c^2

\( \checkmark \) rejects NC \( \pi^0 \) BG

\( \checkmark \) rejects NC \( \pi^0 \) BG

7. Reconstructed \( \nu \) energy < 1250 MeV

\( \checkmark \) rejects intrinsic beam \( \nu_e \) at high energy

After applying all criteria

BG rejection:

- >99.9% for \( \nu_\mu \) CC
- 77% for intrinsic beam \( \nu_e \) CC
- 99% for NC

Signal efficiency:

- 66% for \( \nu_\mu \rightarrow \nu_e \) CC
Pi0 mass cut

![Graph showing the number of events vs. invariant mass (MeV/c²) with different categories and cuts.]

- RUN1-3 data (3.010×10^{20} POT)
- Osc. $\nu_e$ CC
- $\nu_\mu + \bar{\nu}_\mu$ CC
- $\nu_e + \bar{\nu}_e$ CC
- NC

(MC w/ $\sin^22\theta_{13} = 0.1$)
Neutrino oscillation analysis
Main nu cross section parameters

Charged Current Quasi Elastic (CCQE)

Charged Current 1 \( \pi \) production (CC1\( \pi \))

Neutral Current 1 \( \pi^0 \) production (NC1\( \pi^0 \))

\[ \nu_l \rightarrow \ell \rightarrow n \rightarrow p \]

\[ \nu_l \rightarrow \ell \rightarrow n \rightarrow p \rightarrow \pi \]

\[ \nu_l \rightarrow \ell \rightarrow n \rightarrow p \rightarrow \pi^0 \rightarrow \gamma \]

\[ \nu_l \rightarrow \ell \rightarrow p(n) \rightarrow \pi^0 \rightarrow \gamma \]

\[ \nu_l \rightarrow \ell \rightarrow p(n) \rightarrow \pi^0 \rightarrow \gamma \]

\[ \nu_l \rightarrow \ell \rightarrow p(n) \rightarrow \pi^0 \rightarrow \gamma \]
Main nu cross section parameters

Charged Current Quasi Elastic (CCQE)

Charged Current 1 π production (CC1π)

Neutral Current 1 π⁰ production (NC1π⁰)

\[ M_{A_{QE}} \approx 1.2 \text{GeV} \]
\[ M_{A_{RES}} \approx 1.2 \text{GeV} \]
Main nu cross section parameters

Charged Current Quasi Elastic (CCQE)

Charged Current 1 π production (CC1π)

Neutral Current 1 π⁰ production (NC1π⁰)

\[ M_A^{QE} \sim 1.2 \text{GeV} \]
\[ M_A^{RES} \sim 1.2 \text{GeV} \]
\[ p_F \sim 200 \text{MeV/c} \]
Main nu cross section parameters

- Charged Current Quasi Elastic (CCQE)
- Charged Current 1\(\pi\) production (CC\(1\pi\))
- Neutral Current 1\(\pi^0\) production (NC\(1\pi^0\))

\[ \nu \rightarrow \ell \]

- \(M_A^{QE} \sim 1.2\text{GeV}\)
- \(M_A^{RES} \sim 1.2\text{GeV}\)
- \(p_F \sim 200\text{MeV/c}\)

- Nuclear Potential: Fermi Gas Model or Spectral function
Main nu cross section parameters

- Charged Current Quasi Elastic (CCQE)
- Charged Current 1 π production (CC1π)
- Neutral Current 1 π^0 production (NC1π^0)

- \( M_A^{QE} \sim 1.2 \text{GeV} \)
- \( M_A^{RES} \sim 1.2 \text{GeV} \)
- \( p_F \sim 200 \text{MeV/c} \)

- Nuclear Potential
- Final State Interaction (FSI)
Main nu cross section parameters

Charged Current Quasi Elastic (CCQE)

Charged Current 1 π production (CC1π)

Neutral Current 1 π^0 production (NC1π^0)

- $M_A^{QE} \sim 1.2$ GeV
- $M_A^{RES} \sim 1.2$ GeV
- $p_F \sim 200$ MeV/c

• Nuclear Potential
• Final State Interaction (FSI)
Signal prediction
(for example, $\nu_\mu$ disapp.)

Fit ND280 data
momentum and angle
distribution of
CCQE and CCnonQE
to tune the flux and $\nu$-
cross section parameters.
Sys on energy spectrum

8% at oscillation maximum

Reconstructed ν energy (GeV)

Fractional error
ND280フィット

Δχ² of Pseudo-experiments and Fit to Data

Δχ² From Fit to Data

Δχ² of Pseudo-experiments
Fitted χ² Distribution

Degrees of Freedom = 41.56 ± 0.20
Fit Probability = 0.45
Comparison w/ 2011 results

Best-fit + 68% C.L. error for individual run period

Results w/ Run3 only are consistent with Run1+2

Allowed region of $\sin^2 2\theta_{13}$ for each value of $\delta_{CP}$

This result is consistent w/ the 2011 (Run1+2) results and is improved
## Systematic error contribution to the predicted number of events in the oscillation analysis

<table>
<thead>
<tr>
<th>Error source</th>
<th>( \sin^2 2\theta_{13} = 0 ) w/o ND280 fit</th>
<th>( \sin^2 2\theta_{13} = 0 ) w/ ND280 fit</th>
<th>( \sin^2 2\theta_{13} = 0.1 ) w/o ND280 fit</th>
<th>( \sin^2 2\theta_{13} = 0.1 ) w/ ND280 fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam only</td>
<td>10.8</td>
<td>7.9</td>
<td>11.8</td>
<td>8.5</td>
</tr>
<tr>
<td>( M_A^{QE} )</td>
<td>10.6</td>
<td>4.5</td>
<td>18.7</td>
<td>7.9</td>
</tr>
<tr>
<td>( M_A^{RES} )</td>
<td>4.7</td>
<td>4.3</td>
<td>2.3</td>
<td>2.0</td>
</tr>
<tr>
<td>CCQE norm. ( (E_\nu &lt; 1.5 \text{ GeV}) )</td>
<td>4.6</td>
<td>3.7</td>
<td>7.8</td>
<td>6.2</td>
</tr>
<tr>
<td>CC1( \pi ) norm. ( (E_\nu &lt; 2.5 \text{ GeV}) )</td>
<td>5.3</td>
<td>3.7</td>
<td>5.5</td>
<td>3.9</td>
</tr>
<tr>
<td>NC1( \pi^0 ) norm.</td>
<td>8.1</td>
<td>7.7</td>
<td>2.4</td>
<td>2.3</td>
</tr>
<tr>
<td>CC other shape</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Spectral Function</td>
<td>3.1</td>
<td>3.1</td>
<td>5.4</td>
<td>5.4</td>
</tr>
<tr>
<td>( p_F )</td>
<td>0.3</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>CC coh. norm.</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>NC coh. norm.</td>
<td>2.1</td>
<td>2.1</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>NC other norm.</td>
<td>2.6</td>
<td>2.6</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>( \sigma_{\nu_e}/\sigma_{\nu_\mu} )</td>
<td>1.8</td>
<td>1.8</td>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td>W shape</td>
<td>2.0</td>
<td>2.0</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>pion-less ( \Delta ) decay</td>
<td>0.5</td>
<td>0.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>CC1( \pi ), NC1( \pi^0 ) energy shape</td>
<td>2.5</td>
<td>2.5</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>SK detector eff.</td>
<td>7.1</td>
<td>7.1</td>
<td>3.1</td>
<td>3.1</td>
</tr>
<tr>
<td>FSI</td>
<td>3.1</td>
<td>3.1</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>SK momentum scale</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>21.5</strong></td>
<td><strong>13.4</strong></td>
<td><strong>25.9</strong></td>
<td><strong>10.3</strong></td>
</tr>
</tbody>
</table>
T2K Far detector events at beam timing

Events at the T2K beam timing synchronized by GPS

\[ \Delta T_0 = T_{\text{GPS} @ \text{SK}} - T_{\text{GPS} @ \text{J-PARC}} - \text{TOF}(\sim 985 \mu\text{s}) \]
Fiducial volume cut (distance between recon. vertex and wall > 200cm)
Vertex distribution

**beam direction**

- Run 1+2 in FV
- Run 3 in FV
- non-FV

---

**p-values of several distribution are calculated w/ toy MC**

<table>
<thead>
<tr>
<th></th>
<th>RUN1+2</th>
<th>RUN3</th>
<th>RUN1+2+3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{wall}$</td>
<td>22.9%</td>
<td>94.7%</td>
<td>39.4%</td>
</tr>
<tr>
<td>$From_{wall}$ beam</td>
<td>1.34%</td>
<td>35.2%</td>
<td>6.05%</td>
</tr>
<tr>
<td>$R^2 + Z$</td>
<td>10.5%</td>
<td>74.6%</td>
<td>32.4%</td>
</tr>
</tbody>
</table>
Nue Selection

Number of rings

Number of events

RUN1-3 data

Osc. $\nu_e$ CC

$\nu^+ e^-$ CC

$\nu^- e^+$ CC

NC

(MC w/ sin$^2 \theta_{13} = 0.1$)

Number of events

RUN1-3 data

Osc. $\nu_e$ CC

$\nu^+ e^-$ CC

$\nu^- e^+$ CC

NC

(MC w/ sin$^2 \theta_{13} = 0.1$)

Number of events

RUN1-3 data

Osc. $\nu_e$ CC

$\nu^+ e^-$ CC

$\nu^- e^+$ CC

NC

(MC w/ sin$^2 \theta_{13} = 0.1$)

Visible energy (MeV)

Number of decay-e

S. Coleman - T2K Results

Inclusive energy (MeV)

Number of rings

Number of events

RUN1-3 data

Osc. $\nu_e$ CC

$\nu^+ e^-$ CC

$\nu^- e^+$ CC

NC

(MC w/ sin$^2 \theta_{13} = 0.1$)

Number of events

RUN1-3 data

Osc. $\nu_e$ CC

$\nu^+ e^-$ CC

$\nu^- e^+$ CC

NC

(MC w/ sin$^2 \theta_{13} = 0.1$)

Number of events

RUN1-3 data

Osc. $\nu_e$ CC

$\nu^+ e^-$ CC

$\nu^- e^+$ CC

NC

(MC w/ sin$^2 \theta_{13} = 0.1$)