Results from the T2K neutrino experiment

Kendall Mahn, TRIUMF
The Standard Model

**Fermions**

- **Quarks**
  - $u$: up
  - $c$: charm
  - $t$: top
  - $d$: down
  - $s$: strange
  - $b$: bottom

**Bosons**

- $\gamma$: photon
- $Z$: Z boson
- $W$: W boson
- $g$: gluon
- Higgs boson

**Leptons**

- $e$: electron
- $\mu$: muon
- $\tau$: tau
- $\nu_e$: electron neutrino
- $\nu_\mu$: muon neutrino
- $\nu_\tau$: tau neutrino

**Protons, neutrons**

**Electrons**

**Photons**

AAAS graphic

4/22/13

K Mahn, UC Davis
The Standard Model

Protons, neutrons

Electrons

Neutrinos!

AAAS graphic

Photons

Protons, neutrons
What we now know about neutrinos

- Three flavors: $\nu_e$, $\nu_\mu$, $\nu_\tau$
What we now know about neutrinos

- Three flavors: $\nu_e$, $\nu_\mu$, $\nu_\tau$
- Neutral
- Interact via the weak force

Neutral Current (NC)

Charged Current (CC)

Leptons
- $\nu_e$ electron neutrino
- $\nu_\mu$ muon neutrino
- $\nu_\tau$ tau neutrino

Force carriers
- $Z$ boson
- $W$ boson

$\nu_e \rightarrow e$
$\nu_\mu \rightarrow \mu$
$\nu_\tau \rightarrow \tau$
What we now know about neutrinos

- Three flavors: $\nu_e$, $\nu_\mu$, $\nu_\tau$
- Neutral
- Interact via the weak force

At neutrino energy ($E_{\nu}$) $\sim 1$ GeV, $\sigma_{CC} \sim 10^{-38}$ cm$^2$

Mean free path through lead is 1 light year
What we now know about neutrinos

- Three flavors: $\nu_e$, $\nu_\mu$, $\nu_\tau$
- Neutral
- Interact via the weak force
- Abundant
What we now know about neutrinos

- Three flavors: $\nu_e$, $\nu_\mu$, $\nu_\tau$
- Neutral
- Interact via the weak force
- Abundant

The majority of these are Big Bang neutrinos
$\sim 300 \, \nu / \text{cm}^3$
What we now know about neutrinos

- Three flavors: $\nu_e$, $\nu_\mu$, $\nu_\tau$
- Neutral
- Interact via the weak force
- Abundant

The amount of neutrinos and antineutrinos affects the formation of elements in the early universe:

$$\nu_e + n \rightarrow e^- + p$$

$$\bar{\nu}_e + n \rightarrow e^+ + n$$

CSIRO graphic
What we now know about neutrinos

- Three flavors: $\nu_e$, $\nu_\mu$, $\nu_\tau$
- Neutral
- Interact via the weak force
- Abundant
- Massive

The mass of the neutrino is small but it has a big impact in the early universe

At early times, neutrinos behave like radiation
At late times, neutrinos behave like matter

Affects large scale structure formation
Neutrino mass is SMALL

While we know neutrinos have mass, we don’t know the origin of neutrino mass
- Neutrinos are unlike other particles in the Standard Model because they are neutral and only interact with the weak force (and gravity)

**Why is neutrino mass non-zero?**

**Why is it so much smaller than the other particles?**
Neutrino mass

The “see saw mechanism” explains the lightness of the neutrino mass by adding a (very heavy) neutrino which doesn’t interact

If we have one neutrino which interacts in the Standard Model ($m_D$) and a heavy partner ($m_R$) then:

\[ m_1 \approx \frac{(m_D)^2}{m_R} \ll m_D, \]
\[ m_2 \approx m_R, \]

To get the observed neutrino mass, then $m_2 \sim m_R$ is very heavy ($10^{15}$ GeV)
How do we explain the observed matter-antimatter asymmetry in the universe?

- To create this asymmetry, we need: non-thermal equilibrium, CP violation and baryon number violation
- So far, there is no sufficient source of CP violation in the Standard Model

If there is CP violation with neutrinos, CP violating decays of the heavy neutrino can create the baryon number violation

*Searching for CP violation with neutrinos may lead to insights about this mechanism*
Why study neutrinos?

New source of CP violation?

Impact on cosmology

$\nu$ mass as a window to physics at much higher energies (GUT scale)?
What is neutrino oscillation?

We know neutrinos have mass because of we observe neutrino “oscillation”: the interference between the flavor and mass eigenstates of the neutrino.

If we start with two neutrino flavor ($\nu_e$, $\nu_\mu$) and two mass states ($\nu_1$, $\nu_2$), then:

$$
\begin{pmatrix}
\nu_e \\
\nu_\mu
\end{pmatrix}
= 
\begin{pmatrix}
\cos \theta & \sin \theta \\
-sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
$$

The flavor state evolution in time is like an elliptically polarized wave:

$$
|\nu_e(t)\rangle = \cos \theta \ e^{-iE_1t} \ |\nu_1\rangle - \sin \theta \ e^{-iE_2t} \ |\nu_2\rangle
$$
What is neutrino oscillation?

The flavor state evolution in time is like an elliptically polarized wave:

\[ |\nu_e(t)\rangle = \cos \theta \ e^{-iE_1 t} |\nu_1\rangle - \sin \theta \ e^{-iE_2 t} |\nu_2\rangle \]

Starting polarized along the x-axis (like starting in \(\nu_\mu\) state) then:
- Some time later polarization is along y-axis (\(\nu_e\))
- Or back to the x-axis (\(\nu_\mu\))

No mass, no oscillation
Neutrino oscillation

\[ P_{\mu e} = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2_{ij} L}{E} \right) \]

Probability to observe \( \nu_\mu \) after starting in flavor state \( \nu_e \) depends on:
- \( \theta \): Mixing angle
- \( L \text{ (km)} \): Distance the neutrino has travelled
- \( E \text{ (GeV)} \): Energy of the neutrino
- \( \Delta m^2 \text{ (eV}^2\text{)} \): mass splitting

Difference of the square of the mass eigenvalues

\[ \Delta m^2_{ij} = m_i^2 - m_j^2 \]

If neutrinos have no mass, or degenerate masses, no interference is possible
Open questions about neutrino mixing

Unitary PMNS mixing matrix

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

Mass eigenstates (definite mass)

Flavor eigenstates (coupling to the W)

Three observed flavors of neutrinos (\(\nu_e, \nu_\mu, \nu_\tau\)) means \(U\) is represented by three independent mixing angles (\(\theta_{12}, \theta_{23}, \theta_{13}\)) and a CP violating phase \(\delta\)

\[
\theta_{12} = 33.6^\circ \pm 1.0^\circ \\
\theta_{23} = 45^\circ \pm 6^\circ \quad (90\% \text{CL}) \\
\theta_{13} = 9.1^\circ \pm 0.6^\circ
\]

Is \(\theta_{23}\) mixing maximal (45°?)
Open questions about neutrino mixing

Flavor eigenstates (coupling to the W):
\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Mass eigenstates (definite mass):

Three observed flavors of neutrinos ($\nu_e$, $\nu_\mu$, $\nu_\tau$) means $U$ is represented by three independent mixing angles ($\theta_{12}$, $\theta_{23}$, $\theta_{13}$) and a CP violating phase $\delta$.

Quark mixing angles are small:

Neutrino mixing angles are large:

Why are quark and lepton mixing so different?
Open questions about neutrino mixing

Flavor eigenstates (coupling to the W)

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

Mass eigenstates (definite mass)

Unitary PMNS mixing matrix

Three observed flavors of neutrinos ($\nu_e$, $\nu_\mu$, $\nu_\tau$) means $U$ is represented by three independent mixing angles ($\theta_{12}$, $\theta_{23}$, $\theta_{13}$) and a CP violating phase $\delta$

$$\delta_{CP} = ??$$

Is there CP violation in the neutrino sector? Is it large?
Three neutrino mass eigenstates mean two independent mass differences

Two observed mass “splittings”, determined from atmospheric and solar neutrino experiments, respectively

- $\Delta m^2_{\text{atmospheric}} = |\Delta m^2_{32}| \sim 2.4 \times 10^{-3} \text{ eV}^2$
- $\Delta m^2_{\text{solar}} = \Delta m^2_{21} \sim 7.6 \times 10^{-5} \text{ eV}^2$
The sign of $\Delta m^2_{32}$, or the “mass hierarchy” is still unknown

- Normal “hierarchy” is like quarks ($m_1$ is lightest, $\Delta m^2_{32} > 0$)
- Inverted hierarchy has $m_3$ lightest ($\Delta m^2_{32} < 0$)
$\Delta m^2_{32} >> \Delta m^2_{21}$, producing high frequency and low frequency oscillation terms

$$P_{\alpha \beta} = \delta_{\alpha \beta} - 4 \sum_{i > j} \text{Re} \left[ U_{\beta i} U^*_{\alpha i} U_{\beta j} U^*_{\alpha j} \right] \sin^2 \left( \frac{\Delta m^2_{ij} L}{4E} \right) + 2 \sum_{i > j} \text{Im} \left[ U_{\beta i} U^*_{\alpha i} U_{\beta j} U^*_{\alpha j} \right] \sin \left( \frac{\Delta m^3_{ij} L}{2E} \right)$$

If choose $L$, $E$, such that $\sin^2(\Delta m^2_{32} L/E)$ is of order 1, then $\Delta m^2_{21}$ terms will be small. Then...

$\nu_\mu$ “disappear” into $\nu_e$, $\nu_\tau$

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \left( \frac{\Delta m^2_{32} L}{4E} \right)$$

A small fraction of $\nu_e$ will “appear”

$\Delta m^2_{31} \sim \Delta m^2_{32}$

Only leading order term shown

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left( \frac{\Delta m^2_{31} L}{4E} \right)$$
Antineutrino disappearance from (a group of) reactors

Measure rate with inverse beta decay:

\[
\bar{\nu}_e + p \rightarrow e^+ + n.
\]

Determine \(\theta_{13}\) from difference between near and far detectors from the reactor complex

\[
P(\nu_e \rightarrow \nu_{x\neq e}) \approx \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right)
\]
Antineutrino disappearance from (a group of) reactors

Measure rate with inverse beta decay:

\[ \bar{\nu}_e + p \rightarrow e^+ + n. \]

\[ \theta_{13} = 9.1^\circ \pm 0.6^\circ \quad \text{PDG2012} \]

Daya Bay, RENO, Double Chooz collaborations
Disappearance measurements

Can also use reactor sources to measure solar mixing parameter (KamLAND)

Complementary to solar neutrino experiments (e.g. SNO)

Determine $\Delta m^2_{21}, \theta_{12}$ from the distorted energy spectrum

$\Delta m^2_{21} = 7.6 \times 10^{-5} \text{ eV}^2$

$\theta_{12} = 33.6^\circ \pm 1.0^\circ$  

PDG2012
Disappearance with atmospheric sources

Muon neutrino disappearance from atmospheric neutrinos

Cosmic rays (protons, He, etc) hit nuclei in atmosphere:
- Produces muon neutrinos, muon antineutrinos and electron neutrinos

Need a large detector and time:
- MINOS
- IceCube
- Super-Kamiokande
Detecting atmospheric neutrinos

Detect neutrino interactions with charged current interactions

Charged Current (CC)
\[ \nu \rightarrow \text{lepton} \]

- \[ \nu_e \rightarrow e \]
- \[ \nu_\mu \rightarrow \mu \]
- \[ \nu_\tau \rightarrow \tau \]

Super-Kamiokande: 22.5kton fiducial volume water Cherenkov detector

Charged particles emit Cherenkov light
- Ring is imaged by 11,129 PMTs; ring is used to determine the lepton direction and momentum
- Entering (non-neutrino) events are rejected by outer veto region
- Select \[ \nu_e \] or \[ \nu_\mu \] events from ring shape and topology
Oscillation probability changes with L:
- Distance from production to detector
- As a function of angle from the zenith \( \cos(\theta) \)

\[
P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \left( \frac{1.27\Delta m_{32}^2 L}{E} \right)
\]
Oscillation probability changes with L:
- Distance from production to detector
- As a function of angle from the zenith \( \cos(\theta) \)

\[
P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \left( \frac{1.27 \Delta m^2_{32} L}{E} \right)
\]

Determine \( |\Delta m^2_{32}| \), \( \theta_{23} \) from atmospheric and accelerator neutrinos:

\[
\Delta m^4_{32} = 2.35 \times 10^{-3} \text{ eV}^2
\]

\[
\theta_{23} = 45^\circ \pm 6^\circ
\]
Advantages of an accelerator-based neutrino source:

1. >99% muon neutrino flavor, small $\nu_e$ component from muon, kaon decay
2. Intensity of proton beam increases neutrino rate
3. Switch magnetic horn polarization to focus $\pi^-$ and produce an antineutrino beam
4. Tunable neutrino energy spectrum optimized for oscillation
Disappearance with accelerator sources

\[ P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \left( \frac{\Delta m^2_{32} L}{4E} \right) \]

Typical experimental setup:

- Measure \( \nu_\mu \) rate at \( L=0 \)
- Measure \( \nu_\mu \) rate at \( L \approx \) oscillation maximum
- Infer oscillation parameters from rate change (\( \theta_{23} \)) and distortion of spectrum (\( \Delta m^2_{32} \))
Appearance with accelerator sources

\[ P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) \]

Typical experimental setup:
- Measure \( \nu_\mu \) rate* at \( L=0 \)
  *In practice also measure any \( \nu_e \) background rates at \( L=0 \)
- Measure \( \nu_e \) rate at \( L=\text{oscillation maximum} \)
- Infer oscillation parameters from rate change (\( \theta_{13} \))
Appearance with accelerator sources

\[ P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) \]

Subleading terms of $\nu_\mu$ to $\nu_e$ appearance depend on $\delta_{CP}$, mass hierarchy

Requires precision measurements of:
\[ \Delta m_{32}^2, \theta_{23}, \Delta m_{21}^2, \theta_{12} \text{ and } \theta_{13} \]

Measurements of $\nu_\mu$ to $\nu_e$ appearance are sensitive to new or exotic physics
Why do we want to make precision measurements of neutrino oscillation?

Probe of new or exotic physics
- Is there CP violation with neutrinos?
- Is $\theta_{23}$ maximal?
- Is our picture of neutrino mixing complete?

Understanding of relationship between quarks and leptons
The Tokai-to-Kamioka (T2K) experiment

``Long baseline” (L~ 295km) neutrino experiment designed to measure
\( \nu_e \) appearance (\( \theta_{13} \)) and \( \nu_\mu \) disappearance (\( \Delta m^2_{32}, \theta_{23} \))

Far detector
Super-Kamiokande

Near detectors
ND280

Neutrino beam
Peak \( E_\nu \approx 0.6 \) GeV
At $E_\nu \sim 0.6$ GeV, most neutrino interactions are Charged Current Quasi Elastic (CCQE)

- Neutrino flavor determined from flavor of outgoing lepton

\[
\nu_e \rightarrow e \\
\nu_\mu \rightarrow \mu
\]
At $E_\nu \sim 0.6$ GeV, most neutrino interactions are Charged Current Quasi Elastic (CCQE)

- Neutrino flavor determined from flavor of outgoing lepton
- Infer neutrino properties from the muon (or electron) momentum and angle:

$$E_{\nu}^{QE} = \frac{m_p^2 - m'_n - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos \theta_\mu)}$$

2 body kinematics
Assumes the target nucleon is at rest
Other interactions important for T2K analysis:

- Charged current single pion production (CC\(\pi\))
  - Lepton and pion (charged or neutral) produced
- Neutral current single pion production (NC\(\pi^0\))
  - No lepton in final state (happens for all flavors)
  - Only neutral pion (\(\pi^0\)) produced in detector
  - Can mimic \(\nu_e\) signal at Super-Kamiokande

\[\sigma/E (10^{-38} \text{cm}^2/\text{GeV})\]
$N(\nu_e) = \Phi(E_{\nu}) \sigma(E_{\nu}) \epsilon P(\nu_\mu \rightarrow \nu_e)$

Fit the observed rate to determine $\sin^2 2\theta_{13}$. Also depends on:

- Neutrino flux prediction
- Neutrino cross section model
- Far detector selection, efficiency
\[ N(\nu_e) = \Phi(E_{\nu}) \sigma(E_{\nu}) \epsilon P(\nu_\mu \rightarrow \nu_e) \]

Fit the observed rate to determine \( \sin^2 2\theta_{13} \). Also depends on:

- Neutrino flux prediction
- Neutrino cross section model
- Far detector selection, efficiency

We reduce the error on the rate of \( \nu_e \) with the near detector:

\[ N(\nu_\mu) = \Phi(E_{\nu}) \sigma(E_{\nu}) \epsilon \]

- Neutrino flux prediction
- Neutrino cross section model
- Near detector selection, efficiency

Challenge as osc analysis co-convener:

*correlate the physics, coordinate the students, convince the physicists*
Near detectors (ND280)

Measure unoscillated $\nu_\mu$ (CC) rate:
Select nothing coming in (neutrino) and muons coming out ($\nu_\mu$)

Analysis this year relies on “Tracker”, constructed at TRIUMF
- 2 scintillator based tracking detectors (FGDs)
- 3 time projection chambers (TPCs)
- Placed inside the UA1 magnet

Additional detectors include:
- P0D ($\pi^0$ detector)
- Electromagnetic calorimeters
- Muon range detectors

T2K experiment
NIM A 624, 591 (2010)
Selecting CC $\nu_\mu$ interactions

Measure unoscillated $\nu_\mu$(CC) rate

1. Neutrino interaction in FGD1
   - Veto events with TPC1 tracks
   - Events within FGD1 fiducial volume

2. Select highest momentum, negative curvature track as $\mu^-$ candidate
   - Energy loss of the track in TPC also consistent with muon hypothesis
Selecting CC $\nu_\mu$ interactions

Measure unoscillated $\nu_\mu$ (CC) rate

1. Neutrino interaction in FGD1
   - Veto events with TPC1 tracks
   - Events within FGD1 fiducial volume

2. Select highest momentum, negative curvature track as $\mu^-$ candidate
   - Energy loss of the track in TPC also consistent with muon hypothesis

Further separate sample into two categories to increase sensitivity to cross section:

CCQE enhanced:
   - 1 TPC-FGD matched track
   - no decay electron in FGD1

CCnonQE enhanced:
   - all other CC interactions
Near detector rate constraint

Tune flux, cross section models with a likelihood fit

- $p$-$\theta$ distribution is sensitive to rate ($\Phi \times \sigma$)

$$E_{\nu}^{QE} = \frac{m_p^2 - m_n^2 - m_{\mu}^2 + 2m_n E_{\mu}}{2(m_n - E_{\mu} + p_{\mu} \cos \theta_{\mu})}$$

- Fit includes information on flux, cross sections from external measurements (e.g. beam monitors, neutrino cross section measurements)

- Shared flux, similar CC cross section composition of near and far detector selections

\[
\begin{align*}
N(\nu_e) &= \Phi(E_{\nu}) \sigma(E_{\nu}) \epsilon P(\nu_{\mu} \rightarrow \nu_e) \\
N(\nu_{\mu}) &= \Phi(E_{\nu}) \sigma(E_{\nu}) \epsilon.
\end{align*}
\]
- Rate changed by no more than 10% across all energies
- CC cross sections, $\nu_\mu$ flux uncertainties reduced substantially
- $\Delta \chi^2 = 29.1$, $p=0.925$
Expected number of $\nu_e$ candidates

After ND280 tuning, expect $\sim 11$ events with $\nu_\mu$ to $\nu_e$ oscillation, 3 without

- Rate, p-\(\theta\) kinematics of events distinguishes signal from background

<table>
<thead>
<tr>
<th>Signal ($\nu_\mu$ to $\nu_e$ osc)</th>
<th># events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$@\sin^22\theta_{13}=0.1,\delta cp=0$</td>
<td>8.2</td>
</tr>
<tr>
<td>$\nu_e$ signal@$\Delta m^2_{32}=2.4 \times 10^{-3} \text{ eV}^2, \sin^22\theta_{23}=1.0$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Background</th>
<th># events</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam $\nu_e + \bar{\nu}_e$</td>
<td>1.8</td>
</tr>
<tr>
<td>$\nu_\mu + \bar{\nu}_\mu$ (mainly NC)</td>
<td>1.3</td>
</tr>
<tr>
<td>background</td>
<td></td>
</tr>
<tr>
<td>osc through $\theta_{12}$</td>
<td>0.2</td>
</tr>
<tr>
<td>total:</td>
<td>3.3±0.4(sys)</td>
</tr>
</tbody>
</table>
• 11 candidate events observed for background of $3.3\pm0.4$
• Probability to see 11 events or more for $\sin^2 2\theta_{13}=0$ is 0.0009 (3.1σ equivalent)
• Fit assumes $|\Delta m^2_{32}| = 2.4 \times 10^{-3} \text{ eV}^2$ and $\sin^2 2\theta_{23} = 1$
• For normal hierarchy, best fit:
  \[
  \sin^2 2\theta_{13} = 0.088 \pm 0.049 -0.039
  \]
Implications of a large $\theta_{13}$

Long baseline (LBL) appearance depends on all the mixing parameters, including $\delta_{CP}$, $\theta_{13}$

G. Fogli, Neutrino 2012

$\Delta m_{32}^2 > 0$
- 68% CL
- 90% CL
- Best fit

$\Delta m_{32}^2 < 0$
- 68% CL
- 90% CL
- Best fit

4/22/13
Implications of a large $\theta_{13}$

G. Fogli, Neutrino 2012

Reactor experiments are a pure measurement of $\theta_{13}$
Implications of a large $\theta_{13}$

G. Fogli, Neutrino 2012

SK atmospheric “3 flavor” fit $|\Delta m^2_{32}|$, $\theta_{23}$ and $\theta_{13}$ with different E, L than accelerator experiments
Implications of a large $\theta_{13}$

Sensitivity to new physics in appearance depends on knowledge of other mixing parameters:

$$\theta_{12} = 33.6^\circ \pm 1.0^\circ$$
$$\theta_{23} = 45^\circ \pm 6^\circ \quad (90\%\text{CL})$$
$$\theta_{13} = 9.1^\circ \pm 0.6^\circ$$

*Need precision measurements of $\Delta m^2_{32}$ and $\theta_{23}$*
Disappearance distorts energy spectrum and rate of $\nu_\mu$ candidates

- Select CCQE $\nu_\mu$ candidates at SK
- Reconstruct neutrino energy from muon kinematics
- Apply same near detector tuning as for $\nu_e$ appearance

$$P(\nu_\mu \rightarrow \nu_{x\neq\mu}) \approx \sin^2 2\theta_{23} \sin^2 \left( \frac{\Delta m_{32}^2 L}{4 E} \right)$$
$\nu_\mu$ disappearance results

World’s best measurement on $\sin^2 2\theta_{23}$

- Best fit is consistent with maximal mixing ($\theta_{23} = 45^\circ$)
- Expect to ~double statistics with this year’s data set ending in July
Why T2K?

Evidence for $\nu_e$ appearance is the first step towards searches of CP violation in the lepton sector

- Do we see hints of new physics?

New world’s best limits on $\theta_{23}$ from $\nu_\mu$ disappearance

- Will $\theta_{23}$ continue to be maximal?
- If not, what is the $\theta_{23}$ octant?
What is needed to measure $\delta_{CP}$?

Compare $\nu_e$ appearance to $\bar{\nu}_e$ appearance to determine an asymmetry:

$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \approx \frac{\Delta m_{12}^2 L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin \delta$$

With $\theta_{13}$ “large”, then $A_{CP}$ is small (~20-30%), so the measurement of $\delta_{CP}$ need systematic uncertainties of <5% or better

- T2K’s current statistics: 11 events ($\nu_e$ appearance probability)
- Need more raw event rate, with a larger detector
Hyper-Kamiokande

~1Mton detector, approximately 25x Super-Kamiokande

- 99,000 inner PMTs, 25,000 veto region PMTs (10 compartments)
- Same neutrino beamline as T2K, different cavern
- Other physics reach: solar neutrinos, atmospheric neutrinos, astrophysical neutrinos (supernova), geo-neutrinos and proton decay
Hyper-Kamiokande

~1Mton detector, approximately 25x Super-Kamiokande

- 99,000 inner PMTs, 25,000 veto region PMTs (10 compartments)
- Same neutrino beamline as T2K, different cavern
- Other physics reach: solar neutrinos, atmospheric neutrinos, astrophysical neutrinos (supernova), geo-neutrinos and proton decay

That’s a lot of PMTs!

Efforts at ICRR, TRIUMF, UC Davis to characterize the PMTs and explore modifications to collect more light or reduce cost
With <5% overall systematic uncertainty, HK could observe evidence of nonzero $\delta_{CP}$

- Statistical uncertainty ~2%
- Improved control of systematic uncertainties corresponds to increased physics impact
How do we achieve <5% systematics?

<table>
<thead>
<tr>
<th>Uncertainties</th>
<th>$v_e$ sig+bkrd</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v$ flux+xsec (constrained by ND280)</td>
<td>±5.7%</td>
</tr>
<tr>
<td>$v$ xsec (unconstrained by ND280)</td>
<td>±7.5%</td>
</tr>
<tr>
<td>Far detector</td>
<td>±3.9%</td>
</tr>
<tr>
<td>Total</td>
<td>±10.3%</td>
</tr>
</tbody>
</table>

The largest systematic uncertainties currently on the T2K $v_e$ appearance analysis are neutrino interaction model uncertainties:

- Disagreements between data and neutrino interaction model with other neutrino experiments (e.g. MiniBooNE, SciBooNE)
- Differences between alternate interaction models than those currently used by T2K

Also challenges faced by LBNE, LBNO, other proposed long baseline neutrino experiments
1) Incorporate alternate or updated neutrino interaction models into our simulations
   - Validate existing models with electron, pion scattering data
   - Add new models which help resolve disagreements with neutrino data to MC

\[ \sigma_{\text{appx}} \approx \frac{\sigma_{\text{QE}(\text{rel+RPA})}}{(A-Z)} \]
T2K’s efforts to reduce cross section uncertainties

2) Test the agreement of new models with ND280, as ND280-XSEC co-convener:
   - Detailed information (particle type, kinematics) out of the interaction
   - Provide cross section measurements for community to further develop models
     
     *Produced T2K’s first cross section measurement (CC inclusive)*
     
     *Accepted for publication in PRD*

   - ND280 performance, limitations important to determine what is needed for a HK near detector program
What will neutrinos tell us in the next 10 years?

Is there CP violation?
Other new physics?
*T2K has shown us the door and will help us walk through it*

What is the nature of neutrino mass and mixing?
*New T2K results on $\Delta m^2_{32}$, $\theta_{23}$*
Detecting atmospheric neutrinos

Select $\nu_e$ or $\nu_\mu$ events from ring shape and topology

Charged Current (CC)

$\nu_e \rightarrow e$
$\nu_\mu \rightarrow \mu$
$\nu_\tau \rightarrow \tau$

C. Walter, INSS2012
Selecting CC $\nu_e$ interactions

**Signal:** CC $\nu_e$ from $\nu_\mu$ to $\nu_e$ oscillation

**Background:** CC $\nu_e$  
Irreducible beam $\nu_e$

**Background:** NC $\pi^0$ $\nu_\mu$  
Mimics CC $\nu_e$

A $\pi^0$ from a NC interaction will decay to two photons (two electron-like rings)

- Search for 2$^{nd}$ ring
- Calculate invariant mass
- Reject events consistent with $\pi^0$ invariant mass

**MC event:**
- electron
- $\pi^0$
Fine Grained Detectors (FGDs)

Scintillation light (from charged particles) is sent down a wavelength shifting fibre connected to a multi-pixel-photon-counter (MPPC)
- MPPCs function in a magnetic field
- First large scale use

X and Y scintillator layers can be used for 3D tracking
1cm² bar size provides detailed vertex information

P.-A. Amaudruz et al,
“The T2K fine-grained detectors”,
Time projection chambers (TPCs)

Charged particle ionizes gas; electrons drift to readout plane (E~25kV)
``Wireless” TPC: Use of bulk micromegas detectors in readout

3D tracks are reconstructed provided drift velocity in the gas and timing of entry from other subdetectors
Momentum of the particle can be determined from curvature
- 0.2T B field; $p_\mu \sim 1$ GeV/c has <10% momentum resolution

Built DQ system, alignment convener
Overall systematic uncertainty

After ND tuning, systematic uncertainties reduced to ~10% on signal+ background

- Overall uncertainty halved with use of the near detector data

<table>
<thead>
<tr>
<th>Background</th>
<th># events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal (ν_μ to ν_e osc)</td>
<td># events</td>
</tr>
<tr>
<td>@sin²2θ₁₃=0.1,δcp=0</td>
<td>7.81</td>
</tr>
<tr>
<td>Beam ν_e + ν̄_e</td>
<td>1.73</td>
</tr>
<tr>
<td>ν_μ + ν̄_μ (mainly NC)</td>
<td>1.31</td>
</tr>
<tr>
<td>Osc through θ₁₂</td>
<td>0.18</td>
</tr>
<tr>
<td>Total</td>
<td>3.22 ±0.43(sys)</td>
</tr>
</tbody>
</table>

ν_e signal@Δm²_{32} = 2.4 x 10⁻³ eV², sin²2θ_{23}=1.0

<table>
<thead>
<tr>
<th>Uncertainties</th>
<th>ν_e bkrd</th>
<th>ν_e sig+bkrd</th>
</tr>
</thead>
<tbody>
<tr>
<td>ν flux+xsec (constrained by ND280)</td>
<td>±8.7%</td>
<td>±5.7%</td>
</tr>
<tr>
<td>ν xsec (unconstrained by ND280)</td>
<td>±5.9%</td>
<td>±7.5%</td>
</tr>
<tr>
<td>Far detector</td>
<td>±7.7%</td>
<td>±3.9%</td>
</tr>
<tr>
<td>Total</td>
<td>±13.4%</td>
<td>±10.3%</td>
</tr>
</tbody>
</table>

No ND measurement: 26% 22%
Hyper-K timeline

Schedule
assuming budget being approved from JPY2016

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>-4</td>
<td>-3</td>
<td>-2</td>
<td>-1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

- Construction start
- Tunnels
- Cavity excavation
- Concrete, liner
- PMT support, PMT installation
- Photo-sensor R&D
- Prep. for glass valve, PMT production
- PMT production
- Water filling
- Operation

A. Minamino
NuInt12
Appearance measurements: atmospheric nu

Electron neutrino rate is altered by $\nu_\mu$ to $\nu_e$ appearance and survival probability of $\nu_e$

- Contours of equal probability as a function of $E_\nu$ and $\cos(\theta)$

Appearance probability depends on all mixing parameters, including $\delta_{CP}$, $\theta_{13}$

- $\theta_{23} < 45$ degrees amplifies lower energy $\nu_e$ rate through the Earth’s core
- normal hierarchy ($\Delta m^2_{32} > 0$) increases higher energy $\nu_e$ rate through Earth’s core

Super-Kamiokande collaboration
Phys Rev D81 092004, 2010
**Hyper-K and mass hierarchy**

**Delta \( \chi^2 \) for the true normal hierarchy (left) and inverted (right) for HK (atmospheric nu alone, ~3sigma across most of par space, better with T2HK)**

- Nova resolves mass hierarchy at ~2 sigma for 40% of all values of delta
- Proposed Daya Bay II reactor experiments can be sensitive toMH
- PINGU 20: 3-11 sigma, depending on par space, systematics after 5 yrs
- Cosmology, or neutrinoless double beta decay may also provide indications
Vertex distribution of $\nu_e$ candidates

2011 analysis (Run 1+2, black points) had a discrepancy in radial distribution of event candidates.

Radial distribution of new data (Run 3, pink) appears normal.

KS test of radial distribution:
- Run 1+2: 10%
- Run 3: 74.6%
Separating signal and background

**Additional separation of signal, background events with CC $\nu_e$ candidate kinematics**

- **CC $\nu_e$ backgrounds** come from higher energy neutrinos and populate signal and higher momentum region
- **NC backgrounds** are due to misID’d photons that reconstruct as electrons at low momentum and low angle (as well as the signal region)
Basic neutrino event selection (Run 1+2)

Basic neutrino selection (precuts)

- Event time within beam window
- No activity in the veto
- Visible E > 30 MeV
- Reconstructed vertex >2m from wall
- Single reconstructed ring

Beam Time via GPS

- RUN1+2 (1.43 x 10^{26} POT)
- RUN3  (1.125 x 10^{26} POT)

Graphs:

- Number of events vs. Vertex R² (cm²)
- Number of events vs. Vertex Z (cm)
- Number of events vs. ΔT₀ (nsec)
MC simulates neutrino interactions upstream of the detector (e.g. $\pi^0$ production)

- Only 1 $\nu_e$ event cut by FV selection (no excess of $\nu_e$ events outside FV)
- Dedicated sample of events entering tank (with activity in veto) agree
- No bias to radial distribution of atmospheric sample under T2K $\nu_e$ selection

**Beam backgrounds at high radius (Run 1+2)**

**Vertex in FV, activity in veto**

**Fully contained events**

**$\nu_e$ selection**

**SK-IV atmospheric neutrino data**

**MC** simulates neutrino interactions upstream of the detector (e.g. $\pi^0$ production)

- Only 1 $\nu_e$ event cut by FV selection (no excess of $\nu_e$ events outside FV)
- Dedicated sample of events entering tank (with activity in veto) agree
- No bias to radial distribution of atmospheric sample under T2K $\nu_e$ selection
On-axis Interactive Neutrino GRID (INGRID)

- 16 modules arranged in a cross
- X-Y iron-scintillator layers, 7.1 tons each
- Count neutrino interactions in each module to determine neutrino rate vs. position
- Extract beam direction better than 0.5 mrad
- Monitor of neutrino beam vs. time
  - $\sim 1.5 \nu / 10^{14}$ protons on target
  - $\sim 10,000$ events / day
Neutrino beam stability

Neutrino rate at INGRID (1 point / day)

Beam direction (x and y) with the muon monitor
Stable to <1 mrad

Beam dir. stability < 1 mrad

Run 1 (2010 Jan. - 2010 Jun.)
Run 2 (2010 Nov. - 2011 Mar.)
Run 3 (2012 Mar. -)

- X center
- Y center
± 1 mrad

Data with horn 250kA
Data with horn 200kA
Mean with horn 250kA
Mean with horn 200kA
Select $\nu_e$ candidates at ND280 with TPC PID to check rate of intrinsic beam $\nu_e$

Additional backgrounds to $\nu_e$ selection, measured via control samples
- $\mu$ misidentified as $e$
- $e$ from photon conversion (photons emitted in $\nu_\mu$ interactions in FGD and other subdetectors)

Ratio of observed $\nu_e$ / $\nu_\mu$ events is consistent with untuned prediction

\[
\frac{N(\nu_e)}{N(\nu_\mu)} = R(e: \mu) = 1.0\% \pm 0.7\% \text{ (statistics)} \pm 0.3\% \text{ (systematics)}
\]

\[
\frac{R(e: \mu, \text{ data})}{R(e: \mu, \text{ MC})} = 0.6 \pm 0.4 \text{ (statistics)} \pm 0.2 \text{ (systematics)}
\]

Improvements to the analysis:
- Improved rejection of backgrounds with ECals
- More data: $2.88 \times 10^{19}$ POT shown here
Select high energy CC $\nu_e$ candidates within the P0D:

- Reconstructed track matched in $x,y$ with vertex in FV consistent with an single EM shower (reject $\pi^0$ multiple photon showers and muons)
- Primary backgrounds are HE $\pi^0$ events

Consistent with current untuned MC:

\[
\frac{\text{data-bkrd(MC)}}{\text{sig(MC)}} = R = 1.19 \pm 0.15\text{(statistics)} \pm 0.26\text{(systematics)}
\]
Neutrino flux prediction

FLUKA/Geant3 beam simulation

Unoscillated flux at SK:
- $\nu_\mu$ from $\pi^+, K$ decay
- $\sim 1\%$ $\nu_e$ from $\mu, K$ decay

Prediction and uncertainties determined by external or in-situ measurements of:
- proton beam
- $\pi, K$ production from NA61 experiment
- alignment and off-axis angle
**Neutrino flux at ND and SK**

<table>
<thead>
<tr>
<th>Neutrino Mode</th>
<th>Trkr. $\nu_\mu$</th>
<th>Trkr. $\nu_\mu$</th>
<th>SK $\nu_e$</th>
<th>SK $\nu_e$</th>
<th>SK $\nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CCQE</td>
<td>CCnQE</td>
<td>Sig.</td>
<td>CC intrinsic Bgd.</td>
<td>NC Bgd.</td>
</tr>
<tr>
<td>$\pi^+ \rightarrow \nu_\mu + \mu^+$</td>
<td>82.2%</td>
<td>45.8%</td>
<td>99.3%</td>
<td>1.1%</td>
<td>70.3%</td>
</tr>
<tr>
<td>$\mu^+ \rightarrow \nu_e + e^+ + \bar{\nu}_\mu$</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
<td>&lt;0.1%</td>
<td>66.0%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>$K^{+,0} \rightarrow \nu_e + X$</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
<td>&lt;0.1%</td>
<td>33.0%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>$K^{+,0} \rightarrow \nu_\mu + X$</td>
<td>17.4%</td>
<td>53.4%</td>
<td>0.7%</td>
<td>–</td>
<td>29.7%</td>
</tr>
</tbody>
</table>

ND samples represent $\nu_\mu$ flux
- $\nu_\mu$ from $\pi$ decay: CCQE, CCnQE samples
- $\nu_\mu$ from $K$ decay: CCnQE sample

\[ \pi^+ \rightarrow \nu_\mu + \mu^+ \]
\[ \mu^+ \rightarrow \nu_e + e^+ + \bar{\nu}_\mu \]
\[ K^{+,0} \rightarrow \nu_e + X \]
\[ K^{+,0} \rightarrow \nu_\mu + X \]
### Neutrino flux at ND and SK

<table>
<thead>
<tr>
<th>Neutrino Mode</th>
<th>Trkr. $\nu_\mu$</th>
<th>Trkr. $\bar{\nu}_\mu$</th>
<th>SK $\nu_e$</th>
<th>SK $\nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CCQE</td>
<td>CCnQE</td>
<td>Sig.</td>
<td>CC intrinsic Bgnd.</td>
</tr>
<tr>
<td>$\pi^+ \rightarrow \nu_\mu + \mu^+$</td>
<td>82.2%</td>
<td>45.8%</td>
<td>99.3%</td>
<td>1.1%</td>
</tr>
<tr>
<td>$\mu^+ \rightarrow \nu_e + e^+ + \bar{\nu}_\mu$</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
<td>&lt;0.1%</td>
<td>66.0%</td>
</tr>
<tr>
<td>$K^{+,0} \rightarrow \nu_e + X$</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
<td>&lt;0.1%</td>
<td>33.0%</td>
</tr>
<tr>
<td>$K^{+,0} \rightarrow \nu_\mu + X$</td>
<td>17.4%</td>
<td>53.4%</td>
<td>0.7%</td>
<td>-</td>
</tr>
</tbody>
</table>

SK signal and NC background events come from $\nu_\mu$ flux directly measured at ND.

- $\pi^+$, $\mu^+$, $\nu_\mu$: $p$, $\theta$ out of target

- $p$-\(\theta\) of pions which produce $\nu_e$ from $\nu_\mu$ oscillations in SK

- $p$-\(\theta\) of pions which produce $\nu_\mu$ in ND
Neutrino flux at ND and SK

<table>
<thead>
<tr>
<th>Neutrino Mode</th>
<th>Trkr. $\nu_\mu$</th>
<th>Trkr. $\bar{\nu}_\mu$</th>
<th>SK $\nu_e$</th>
<th>SK $\bar{\nu}_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CCQE</td>
<td>CCnQE</td>
<td>Sig.</td>
<td>CC intrinsic Bgd.</td>
</tr>
<tr>
<td>$\pi^+ \rightarrow \nu_\mu + \mu^+$</td>
<td>82.2%</td>
<td>45.8%</td>
<td>99.3%</td>
<td>1.1%</td>
</tr>
<tr>
<td>$\mu^+ \rightarrow \nu_e + e^+ + \bar{\nu}_\mu$</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
<td>&lt;0.1%</td>
<td>66.0%</td>
</tr>
<tr>
<td>$K^{+,0} \rightarrow \nu_e + X$</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
<td>&lt;0.1%</td>
<td>33.0%</td>
</tr>
<tr>
<td>$K^{+,0} \rightarrow \nu_\mu + X$</td>
<td>17.4%</td>
<td>53.4%</td>
<td>0.7%</td>
<td>–</td>
</tr>
</tbody>
</table>

CC background from beam $\nu_e$ is strongly correlated with $\nu_\mu$ flux at ND:

$p$-\(\theta\) of pions which produce muons which decay to $\nu_e$

$p$-\(\theta\) of pions which produce $\nu_e$ in ND
CCQE and CC1π are the largest interaction mode in ND, SK samples

- Separation of CCQE and CCnQE ND samples gives additional power for fit to constrain cross section models
- Need to account for acceptance difference between ND (forward going selection) and SK (4π selection) for identical changes to cross section to correlate the two samples

*From experience with SciBooNE/MiniBooNE joint analysis, developed machinery to alter the cross section for each simulated event*
Neutrino interactions at ND and SK

<table>
<thead>
<tr>
<th>Interaction Mode</th>
<th>Trkr. $\nu_\mu$ CCQE</th>
<th>Trkr. $\nu_\mu$ CCnQE</th>
<th>SK $\nu_e$ Sig.</th>
<th>SK $\nu_e$ Bgdnd.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCQE</td>
<td>76.6%</td>
<td>14.6%</td>
<td>85.8%</td>
<td>45.0%</td>
</tr>
<tr>
<td>CC$1\pi$</td>
<td>15.6%</td>
<td>29.3%</td>
<td>13.7%</td>
<td>13.9%</td>
</tr>
<tr>
<td>CC coh.</td>
<td>1.9%</td>
<td>4.2%</td>
<td>0.3%</td>
<td>0.7%</td>
</tr>
<tr>
<td>CC other</td>
<td>4.1%</td>
<td>37.0%</td>
<td>0.2%</td>
<td>0.7%</td>
</tr>
<tr>
<td>NC</td>
<td>1.5%</td>
<td>5.3%</td>
<td>-</td>
<td>39.7%</td>
</tr>
</tbody>
</table>

- Indirect constraint on NC ($1\pi^0$) through CC$1\pi$ in ND measurement
- Additional ND selection of NC$\pi^0$ with P0D detector to cross check rate prediction

Data
NC$\pi^0$ signal + background
Background only
Flux parameterization: $f_i$
Normalization on $E_\nu$ bin $i$ for SK and ND samples

Correlations in flux covariance are shared hadron production uncertainties

Flux covariance built from measurements of beam or external data (e.g. NA61)
T2K neutrino flux uncertainties

$\nu_\mu$ flux fractional uncertainties

Fractional Error

- Total
- Pion Production
- Kaon Production
- Secondary Nucleon Production
- Hadronic Interaction Length
- Proton Beam, Alignment and Off-axis Angle
- Horn Current & Field

$E_\nu$ (GeV)
Cross section parameterization: $x_k$

Model parameters:
- MAQE and MARES (modify $Q^2$ distribution of QE and resonant 1pi cross sections)
- Fermi momentum ($p_F$) provides low $Q^2$ handle, and is target dependant (C vs. O)
- Spectral function – RFG model-model difference is also target dependant

Normalizations provide overall scaling independent of $Q^2$ on a particular interaction

Apply cross section to observables at ND, SK using reweighting techniques

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_A^{QE}$ (GeV)</td>
<td>1.21 ± 0.45</td>
<td>1.19 ± 0.19</td>
</tr>
<tr>
<td>$M_A^{RES}$ (GeV)</td>
<td>1.162 ± 0.110</td>
<td>1.137 ± 0.095</td>
</tr>
<tr>
<td>CCQE Norm. 0-1.5 GeV</td>
<td>1.000 ± 0.110</td>
<td>0.941 ± 0.087</td>
</tr>
<tr>
<td>CCQE Norm. 1.5-3.5 GeV</td>
<td>1.00 ± 0.30</td>
<td>0.92 ± 0.23</td>
</tr>
<tr>
<td>CCQE Norm. &gt;3.5 GeV</td>
<td>1.00 ± 0.30</td>
<td>1.18 ± 0.25</td>
</tr>
<tr>
<td>CC1π Norm. 0-2.5 GeV</td>
<td>1.63 ± 0.43</td>
<td>1.67 ± 0.28</td>
</tr>
<tr>
<td>CC1π Norm. &gt;2.5 GeV</td>
<td>1.00 ± 0.40</td>
<td>1.10 ± 0.30</td>
</tr>
<tr>
<td>NC1π$^0$ Norm.</td>
<td>1.19 ± 0.43</td>
<td>1.22 ± 0.40</td>
</tr>
<tr>
<td>$p_F$ (MeV/c)</td>
<td>217 ± 30</td>
<td>224 ± 24</td>
</tr>
<tr>
<td>Spectral Function</td>
<td>0(off) ± 1(on)</td>
<td>0.04 ± 0.21</td>
</tr>
<tr>
<td>CC Other Shape (GeV)</td>
<td>0.00 ± 0.40</td>
<td>-0.05 ± 0.35</td>
</tr>
</tbody>
</table>

Parameter value, uncertainty is determined from MiniBooNE single pion samples

Parameter value, uncertainty is extrapolated to SK sample
ND280 likelihood

\[-2\ln L = 2 \sum_{i}^{p,\theta \text{ bins}} N_{i}^{pred}(\vec{f}, \bar{x}, \bar{d}) - N_{i}^{data} + N_{i}^{data} \ln[N_{i}^{data} / N_{i}^{pred}(\vec{f}, \bar{x}, \bar{d})]\]

Likelihood function, with Poisson statistics

\[E_{\nu} \text{ bins } E_{\nu} \text{ bins}\]
\[+ \sum_{j} \sum_{k} (1 - f_{j})(V_{f}^{-1})_{j,k}(1 - f_{k})\]

\[xsec \text{ pars } xsec \text{ pars}\]
\[+ \sum_{l} \sum_{m} (x_{nom} - x_{l})(V_{x}^{-1})_{l,m}(x_{nom} - x_{m})\]
\[p,\theta \text{ bins } p,\theta \text{ bins}\]
\[+ \sum_{i} \sum_{n} (1 - d_{i})(V_{d}^{-1})_{i,n}(1 - d_{n})\]
\[+ ln\left(\frac{|V_{d}(\vec{f}, \bar{x})|}{|V_{d}^{nom}|}\right)\]

Fit CCQE, CCnQE $p_{\mu} - \theta_{\mu}$ distribution (20x2 bins)
Sensitive to to rate ($\Phi \times \sigma$) changes:

\[E_{\nu}^{QE} = \frac{m_{p}^{2} - m_{n}^{2} - m_{\mu}^{2} + 2m_{n}\bar{E}_{\mu}}{2(m_{n} - \bar{E}_{\mu} + p_{\mu} \cos \theta_{\mu})}\]
\[-2\ln L = 2 \sum_{p,\theta \text{ bins}} N_i^{\text{pred}}(\vec{f}, \vec{x}, \vec{d}) - N_i^{\text{data}} + N_i^{\text{data}} \ln \left[ \frac{N_i^{\text{data}}}{N_i^{\text{pred}}(\vec{f}, \vec{x}, \vec{d})} \right]\]

\[\sum_{E_\nu \text{ bins}} \sum_{E_\nu \text{ bins}} (1 - f_j)(V_f^{-1})_{j,k}(1 - f_k)\]

\[\sum_{x\text{sec pars}} \sum_{x\text{sec pars}} (x_{\text{nom}} - x_l)(V_x^{-1})_{l,m}(x_{\text{nom}} - x_m)\]

\[\sum_{p,\theta \text{ bins}} \sum_{p,\theta \text{ bins}} (1 - d_i)(V_d^{-1})_{i,n}(1 - d_n)\]

\[\ln \left( \frac{|V_d(f, \vec{x})|}{|V_d^{\text{nom}}|} \right)\]

Prior constraint terms for flux, cross section parameters
- $V_f$ and $V_x$ are covariance matrices
- Determined using in-situ and external datasets: beam monitors, NA61, MiniBooNE
\[ -2\ln L = 2 \sum_{i} \left( N_i^{\text{pred}}(\vec{f}, \vec{x}, \vec{d}) - N_i^{\text{data}} + N_i^{\text{data}} \ln \left[ N_i^{\text{data}} / N_i^{\text{pred}}(\vec{f}, \vec{x}, \vec{d}) \right] \right) \]

\[ + \sum_{j} \sum_{k} (1 - f_j)(V_f^{-1})_{j,k}(1 - f_k) \]

\[ + \sum_{l} \sum_{m} (x_{\text{nom}} - x_l)(V_x^{-1})_{l,m}(x_{\text{nom}} - x_m) \]

\[ + \sum_{i} \sum_{n} (1 - d_i)(V_d^{-1})_{i,n}(1 - d_n) \]

\[ + \ln \left( \frac{|V_d(\vec{f}, \vec{x})|}{|V_d^{\text{nom}}|} \right) \]

Prior constraint likelihood terms for detector systematic errors

- Also includes uncertainties (e.g. FSI) which could not be otherwise easily parameterized
- Determined from control samples, calibration data, and external pion scattering data
Detector systematic errors

ND CCQE sample

$0.94 < \cos(\theta_\mu) < 1$

Fractional systematic uncertainty for vs. momentum
Flux parameters change after ND measurement

- Flux parameters without ND measurement and with ND measurement

 Flux parameters at ND

 Flux parameters at SK

 Flux parameters at ND

 Flux parameters at SK
Effect of ND measurement on $\nu_e$ signal, background

- Rate of $\nu_e$ signal and backgrounds without ND measurement and with ND measurement
- Uncertainty envelope from constrained flux, cross section parameters
- Includes correlation between flux and cross section at ND, SK

**Signal:** CC $\nu_e$

**Background:** CC $\nu_e$

**Background:** NC $\nu_\mu$