Reactor measurements of $\theta_{13}$ CP violation, and current long-baseline experiments
**PMNS Matrix**

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

\[ c_{ij} = \cos \theta_{ij}; \; s_{ij} = \sin \theta_{ij} \]

- \( \theta_{12} = 33.44^\circ + 0.78^\circ - 0.75^\circ \)
- \( \theta_{23} = 49.0^\circ + 1.1^\circ - 1.4^\circ \)

- \( \Theta_{12} \) and \( \Theta_{23} \) are large ("maximal" mixing)
- Angle \( \Theta_{13} \) is small and mixes \( \nu_e \) with \( \nu_3 \)
- CPV term (\( \delta \)) \( \propto \Theta_{13} \)
- Look for \( \nu_e \) mixing driven by \( \Delta m^2_{32} \)

\[ \Delta m^2_{32} = 2.4 \times 10^{-3} \text{ eV}^2 \]
\[ \Delta m^2_{21} = 7.8 \times 10^{-5} \text{ eV}^2 \]
Daya Bay reactor
“Reactor” Oscillations

“Survival probability” for anti-$\nu_e$ from the reactor ($E \approx 3$ MeV)

$$\Delta m_{21}^2 = 7.8 \times 10^{-5} \text{ eV}^2$$

$$\Delta m_{32}^2 = 2.4 \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\theta_{13}) \sin^2 \left( 1.27 \frac{\Delta m_{32}^2 \text{[eV}^2\text{]}L\text{[km]}}{E\text{[GeV]}} \right)$$

J. Ling, Neutrino 2020
Daya Bay Layout

Far Hall
- 1540 m from Ling Ao I
- 1910 m from Daya Bay
- 324 m overburden

Ling Ao Near Hall
- 470 m from Ling Ao I
- 558 m from Ling Ao II
- 100 m overburden

Daya Bay Near Hall
- 363 m from Daya Bay
- 93 m overburden

- 17.4 GWth power
- 8 operating detectors
- 160 t total target mass
Daya Bay detectors

Each of the 8 detectors is 20 tons.

Inverse $\beta$ decay

$$\bar{\nu}_e + p \rightarrow n + e^+$$
Original $\theta_{13}$ measurements (Far/Near)

Double Chooz with only a far detector (Nov. 2011)

Daya Bay (March 2012)

RENO (April 2012)

$\sin^2 2\theta_{13} = 0.086 \pm 0.041\text{(stat)} \pm 0.030\text{(syst)}$

$\sin^2 2\theta_{13} = 0.092 \pm 0.016\text{(stat)} \pm 0.005\text{(syst)}$

$\sin^2 2\theta_{13} = 0.103 \pm 0.013\text{(stat)} \pm 0.011\text{(syst)}$

M.He, NNN
$\theta_{13}$ measurement (Daya Bay)

\[ \sin^2 2\theta_{13} = 0.0856 \pm 0.0029 \]

Daya Bay: 621 days
PMNS Matrix

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

\[c_{ij} = \cos \theta_{ij}; \quad s_{ij} = \sin \theta_{ij}\]

\[\theta_{12} = 33.44^\circ \pm 0.78^\circ \]

\[\theta_{23} = 49.0^\circ \pm 1.1^\circ \pm 1.4^\circ\]

- Small angle $\theta_{13}$ mixes $\nu_e$ with $\nu_3$
- Look for $\nu_e$ mixing driven by $\Delta m^2_{32}$
- Reactor: anti-$\nu_e$ disappearance
- Accelerator: $\nu_e$ appearance in $\nu_\mu$ beam
  \[\rightarrow\text{ sensitive to } \theta_{13} \text{ and } \delta\]

$\Delta m^2_{32} = 2.4 \times 10^{-3} \text{ eV}^2$

$\Delta m^2_{21} = 7.8 \times 10^{-5} \text{ eV}^2$
The CKM matrix is almost diagonal, while the PMNS matrix is almost uniform.
Matter and Anti-matter

Paul Dirac

Dirac equation predicts anti-particle states (1928)

\[
\left( \beta mc^2 + \sum_{k=1}^{3} \alpha_k p_k c \right) \psi(x, t) = i\hbar \frac{\partial \psi(x, t)}{\partial t}
\]

Positron discovered by C.D. Anderson in 1932
Matter-antimatter asymmetry (“CP violation”)

- A tiny ($\approx 10^{-10}$) asymmetry between particle and anti-particles led to our matter dominated universe
- One of the conditions for this asymmetry is violation of CP symmetry
- The observation of CP violation involving neutrinos could provide support for a theory called Leptogenesis

1. Baryon number violation
2. CP violation
3. Departure from thermal equilibrium

Born: 21 May 1921, Moscow, Russia
CP violation

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

\[c_{ij} = \cos \theta_{ij}; s_{ij} = \sin \theta_{ij}\]

- A 2x2 "rotation" matrix is real, whereas a 3x3 rotation matrix is imaginary (phase \(\delta\)).
- CP violation (the difference between a process and its CP conjugate) is only possible when the matrix is imaginary (3 generations!).

14
• The same is true for the CKM matrix, where CP violation has been observed for quark processes.
• CP violation in the quark sector is too small to describe the matter dominance in the Universe.
• Discovery of CP violation with neutrinos would lend support to the Leptogenesis model – Leptogenesis would happen at large scales, e.g. through a heavy right-handed neutrino $N_R$ (see-saw mechanism).
CKM vs PMNS – an aside

\[ U_{\text{PMNS}} = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix} \begin{pmatrix}
1 & 0 & 0 \\
0 & e^{i\alpha_1} & 0 \\
0 & 0 & e^{i\alpha_2}
\end{pmatrix} \]

- Neutrinos differ from quarks (Dirac particles), as they can be their own anti-particles (Majorana particles).
- This gives rise to additional complex phases in the PMNS matrix.
- These complex phases appear on the diagonal of the matrix so they have no impact on neutrino oscillations.
As neutrinos are neutral, they cannot be focused, and a magnetic horn is thus used to focus the pions.

Invented by Simon van der Meer at CERN
Fermilab NuMI beam
Making a neutrino beam

Pion decay at rest:

\[ E^{*}_\nu = \frac{m^2_\pi - m^2_\mu}{2m_\pi} = 29.8 \text{ MeV} \]

Boost into lab system:

\[ E_\nu = \frac{m_\pi E^{*}_\nu}{E_\pi - p_\pi \cos \theta} = \frac{E^{*}_\nu}{\gamma_\pi (1 - \beta_\pi \cos \theta)} \]

\[ E_\pi = 9 \text{ GeV at } \theta = 0 : \]

\[ \gamma_\pi = 64.5 \implies E_\nu = 3.8 \text{ GeV} \]
Forward/Reverse Horn Current

NOvA Simulation

Neutrinos from NuMI beam

"Antineutrino mode"

Fermilab

Ash River

Near

Far

10 km

810 km
Finding the oscillation maximum

Typical neutrino beam energy is around 2.5 GeV

Baseline/Neutrino energy
Optimizing L/E for neutrino oscillations

\[
\frac{\Delta m^2_{31} L}{4E} \approx \frac{\pi}{2}
\]

L \approx 300 \text{ km}

- L/E = 300 km /0.6 GeV = 500 km/GeV
- no matter effects; first oscillation maximum.
- use narrow width neutrino beam (off axis) with E < 1 GeV

L = 1300 km

- L/E = 1300 km/2.5 GeV = 500 km/GeV (1\text{st} max),
- L/E = 1300 km/0.8 GeV = 1700 km/GeV (2\text{nd} max)
- matter effects; first and second oscillation maximum.
- use broad-band neutrino beam (on axis).

Water Cherenkov (T2K,HK)

Liquid argon (DUNE)
Off-axis vs on-axis beams

T2K at 2.5 degrees

DUNE on-axis beam
Off-axis vs on-axis beams

T2K at 2.5 degrees

DUNE on-axis beam
How to measure LBL neutrino oscillations

• Measure flavour change as a function of energy over a long distance.
• Starting with a muon-neutrino beam, we observe muon-neutrino disappearance and electron-neutrino appearance.
• We measure event rates and not the flux directly.
• Measurement is a convolution of the oscillation probabilities $P$, the neutrino flux $\Phi$, the cross sections $\sigma$, and the detector response $T$.

$$\frac{N_{\nu_i}^{FD}(E_{\text{rec}})}{N_{\nu_\mu}^{ND}(E_{\text{rec}})} = \frac{\int \Phi_{\nu_\mu}^{FD}(E_\nu) \cdot P_{\nu_\mu \rightarrow \nu_i}(E_\nu) \cdot \sigma_{\nu_i}^{Ar} \cdot T_{\nu_i}^{FD}(E_\nu, E_{\text{rec}}) \, dE_\nu}{\int \Phi_{\nu_\mu}^{ND}(E_\nu) \cdot \sigma_{\nu_\mu}^{X} \cdot T_{\nu_\mu}^{ND}(E_\nu, E_{\text{rec}}) \, dE_\nu}$$
Neutrino sources, flux, and cross sections

C. Spiering, arXiv:1207.4952

Neutrino-nucleon interaction

Elastic scattering
\( \nu_l \nu_l \rightarrow Z n n \)

Quasi-elastic scattering
(lowest energies)
\( \nu_l l^- \rightarrow W n p \)

Resonance
(Energies \( \sim 1 \) GeV)
\( \nu_l l^- \rightarrow W \Delta^{++} p \)

Hadrons
Deep inelastic scattering
(Highest energies \( (>1 \) GeV))
\( \nu_l l^- \rightarrow W p \rightarrow \text{hadrons} \)
At lower energies, quasi-elastic dominates.

At higher energies, resonance production and deep-inelastic scattering.

An important systematic limitation for long-baseline neutrino experiments.

Interaction modelling will affect energy reconstruction.
Measuring neutrino cross sections with MINER$\nu$A

- Muon neutrinos

MINOS Near Detector (Muon Spectrometer)

- Liquid Helium Target 0.29t
- Nuclear Target Region (C, Pb, Fe, H2O)
- Active Tracker Region 8.3 tons total
- Electromagnetic Calorimeter 15 tons
- Hadronic Calorimeter 30 tons
- Side ECAL 0.6 tons
- Side HCAL 116 tons

Steel Shield
Scintillator Veto Wall

(Coming Soon)
MINER$\nu$A $\nu_\mu$ quasi-elastic interaction

Quasielastic scattering

$n \quad p$

$\nu_\mu \quad \mu^-$

Proton

Muon
MINER$\nu$A $\nu_\mu$ quasi-elastic interaction

Quasielastic scattering

$\nu_\mu \rightarrow \mu^+$

$W$

$p \rightarrow n$

Neutron

Antimuon

MANCHESTER
MINER$\nu$A deep inelastic scattering event
Another Complication

Need to understand nuclear effects – which are messy!

Some effects can be mitigated by use of same nuclear targets
Operating Long-baseline experiments

NOvA Detectors

NOvA baseline: 810 km

T2K baseline: 295 km
T2K Experiment

- Muon (anti) neutrino beam generated at J-PARC
- Beam travels 295 km to large SK far detector to be measured after oscillations
- Near detector complex, ND280 constrains beam flux and interaction cross-section before oscillation
- Important to constrain non-oscillation parts of model to avoid bias
Super-Kamiokande

- 50,000 tons of water surrounded by 11,000 PMTs (20 inch).
- 1 km rock overburden
- 39.3m in diameter and 41.4m in height

Cherenkov cone
Super-Kamiokande – electron or muon ring?
Super-Kamiokande – electron or muon ring?

\[ \nu_\mu + X \rightarrow \mu^- + X' \]

\[ \nu_e + X \rightarrow e^- + X' \]
The T2K Near Detector (ND280)

Different technology/target for near and far detector.
• **NuMI beam:** $\nu_\mu$ or $\bar{\nu}_\mu$
• 2 functionally identical, tracking calorimeter detectors
  - Near: 300 T underground
  - Far: 14 kT on the surface
  - Placed off-axis to produce a narrow-band spectrum
• **810 km baseline**
  - Longest baseline of current experiments.
NOvA is on the surface...

- 14 kt Far Detector
- Equivalent Near Detector
- Liquid scintillator (oil)
- Readout by APDs
NOvA uses Convolutional Neural Networks (CVNs) to reconstruct images.
$\nu_\mu$ and $\bar{\nu}_\mu$ disappearance at the NOvA Far Detector

211 events, 8.2 background

105 events, 2.1 background
$\nu_e$ and $\bar{\nu}_e$ appearance at the NOvA Far Detector

**ν-beam**

**NOvA Preliminary**

<table>
<thead>
<tr>
<th>Low PID</th>
<th>High PID</th>
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<td>Core</td>
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<td>Total Bkgd.</td>
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**ν̅-beam**

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<td>Total Bkgd.</td>
<td>14.0</td>
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>4σ evidence of $\bar{\nu}_e$ appearance

Alex Himmel, Neutrino 2020
$\nu_\mu$ and $\bar{\nu}_\mu$ disappearance at the T2K Far Detector (SK)

Muon-like rings
$\nu_e$ and $\bar{\nu}_e$ appearance at the T2K Far Detector (SK)

$\nu_e$

$\bar{\nu}_e$

electron-like rings ($0 \pi^0$)
Extracting the Information

How many $\nu_\mu$s are left? ("$\nu_\mu$ disappearance")

100s of km

How many $\nu_e$s show up? ("$\nu_e$ appearance")
Extracting the Information

Simultaneous fits of

- Data samples in Near and Far Detector
- Flux model, incl. beam monitor and hadron production (NA61-SHINE)
- Cross section models
- Detector models for Near and Far Detector
- Error correlation matrix
- Oscillations Parameters

J. Wolcott
To give you a “flavour”

\[
P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_23 \sin^2 2\theta_13 \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 \\
+ \sin 2\theta_23 \sin 2\theta_13 \sin 2\theta_12 \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin(aL)}{aL} \Delta_{21} \cos(\Delta_{31} - \delta) \\
+ \cos^2 \theta_23 \sin^2 2\theta_12 \frac{\sin(aL)}{aL} \Delta_{21}^2
\]

\[
a = \frac{G_F N_e}{\sqrt{2}} \\
\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}
\]

- Electron-neutrino appearance is sensitive to the CP phase.
- Mass ordering effect depends on electron density \(N_e\).
- Simultaneous determination of mass ordering and CP phase only possible with long-baselines by fitting the energy dependence of the flux modulation (unless we add atmospheric data).
CP Violation Phase

- Sensitivity to combination of CP phase and mass ordering.
- Normal ordering slightly preferred (1σ)
- Exclude IO, $\delta = \pi/2$ at $>3\sigma$
- Disfavour NO, $\delta = 3\pi/2$ at $\sim 2\sigma$

- CP conversation $(0, \pi)$ excluded at 90% confidence level
- Normal ordering preferred
The Status Quo

- Current data are inconclusive – expect some improvements with further running
- Need next-generation experiments to discover CPV and resolve mass ordering