Long Baseline Experiments - a review of accelerator based neutrino physics

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Thank you to the organizers for the opportunity to speak today!

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Takeaways from today’s talk:

Long baseline experiments are broad scientific programs with opportunities to test our understanding of the universe.

The future is bright, with exciting long baseline results, starting with the current program, Tokai-to-Kamioka (T2K) and NuMI Off-axis $\nu_e$ Appearance (NOvA) experiments.
Evidence of neutrino mass from neutrino oscillation experiments leads to important questions:

*Is there new physics? CP violation in neutrinos?*

*What is the neutrino mass ordering?*

*Is our understanding complete? Are there sterile neutrinos? Non unitarity?*
Evidence of neutrino mass from neutrino oscillation experiments:

- Electron neutrinos from the Sun

Deficit in $\nu_e$ from charged current (CC):

$\nu \rightarrow W^\pm /$ lepton

$\nu_e \rightarrow e$

$\nu_\mu \rightarrow \mu$

$\nu_\tau \rightarrow \tau$
Evidence of neutrino mass from neutrino oscillation experiments:

- Electron neutrinos from the Sun


Deficit in $\nu_e$ from charged current (CC):

Total of all flavors matches expectation measured with neutral current (NC):

Electron neutrinos from the Sun

Evidence of neutrino mass from neutrino oscillation experiments:

- Electron neutrinos from the Sun

Oscillation is the transition of one flavor to another

Here, electron neutrinos have oscillated into muon and tau flavors


Borexino latest results - see talk Thurs by A. Re
Evidence of neutrino mass from neutrino oscillation experiments:

- Muon neutrinos from an accelerator

Example: KEK to Kamioka “Long baseline” experiment

250km from accelerator source to “far” detector

https://neutrino.kek.jp/intro/k2k.html
Evidence of neutrino mass from neutrino oscillation experiments:

- Muon neutrinos from an accelerator

\[ \nu_\mu \] “disappearance” into other flavors (\( \nu_e, \nu_\tau \))

- The spectrum is distorted and the rate reduced
- Oscillation depends on L (baseline) and E (energy of neutrinos)
Evidence of neutrino mass from neutrino oscillation experiments:

- Muon neutrinos from an accelerator

Example: OPERA experiment

Beam from CERN to Gran Sasso (732km)

https://proj-cngs.web.cern.ch/
Evidence of neutrino mass from neutrino oscillation experiments:

- Muon neutrinos from an accelerator

$\nu_\tau$ “appearance” from predominantly muon neutrino flavor beam

*Phys. Rev. Lett. 120, 211801 (2018)*
Evidence of neutrino mass from neutrino oscillation experiments:

- Electron neutrinos from the Sun, and electron antineutrinos from reactors
- Muon (anti) neutrinos from accelerators and atmosphere

Atmospheric (and astrophysical neutrino) results - see talk Thurs by S. Klein

Future reactor results with JUNO - see parallel talk and E. Worcester plenary Friday
Evidence of neutrino mass from neutrino oscillation experiments:

- Electron neutrinos from the Sun, and electron antineutrinos from reactors
- Muon (anti) neutrinos from accelerators and atmosphere

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

\textit{Pontecorvo-Maki-Nakagawa-Sakata matrix (PMNS)}

Assuming unitary matrix:

- Three mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$
- CP violating phase: $\delta_{\text{CP}}$
- Two Majorana phases - not accessible by osc experiments

\textit{see S. Mertens talk on 0n2b Thurs}
Evidence of neutrino mass from neutrino oscillation experiments:

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\]

Assuming unitary matrix:

- Three mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$
- CP violating phase: $\delta_{CP}$

Open questions:

- What is the CPV phase?
- Precision measurements of mixing angles (and $U$)
  - Is $\theta_{23}$ maximal? If not, what is the octant?
- Is our understanding complete?

See Thurs talks by P. Machado and J. Valle
Evidence of neutrino mass from neutrino oscillation experiments:

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\begin{pmatrix}
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\]

Three mass states, two mass splittings:
Evidence of neutrino mass from neutrino oscillation experiments:

- Electron neutrinos from the Sun, and electron antineutrinos from reactors
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\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\(\Delta m^2_{21}\) is known to be positive from solar experiments

\(\Delta m^2_{21} = m^2_2 - m^2_1\)
Evidence of neutrino mass from neutrino oscillation experiments:

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\]

Is \( \Delta m^2_{32} > 0 \) (\( m_3^2 > m_2^2 \)?)

“Normal ordering”
Or, is $\Delta m^2_{32} > 0$ ($m^2_3 > m^2_2$?)
“Inverted ordering”

What is the neutrino mass hierarchy?
Measure elements of U via appearance and disappearance experiments:

What do we learn from long baseline experiments?

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U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[
P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re}\left[U_{\beta i} U_{\alpha i}^* U_{\beta j}^* U_{\alpha j}\right] \sin^2\left(\frac{1.27 \Delta m_{ij}^2 L}{E}\right) + 2 \sum_{i>j} \text{Im}\left[U_{\beta i} U_{\alpha i}^* U_{\beta j}^* U_{\alpha j}\right] \sin\left(\frac{2.54 \Delta m_{ij}^2 L}{E}\right)
\]
Measure elements of U via appearance and disappearance experiments:

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    \nu_\tau
\end{pmatrix}
= 
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\[
P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re} [U_{\beta i} U_{\alpha i}^* U_{\beta j}^* U_{\alpha j}] \sin^2 \left( \frac{1.27 \Delta m_{ij}^2 L}{E} \right) + 2 \sum_{i>j} \text{Im} [U_{\beta i} U_{\alpha i}^* U_{\beta j}^* U_{\alpha j}] \sin \left( \frac{2.54 \Delta m_{ij}^2 L}{E} \right)
\]

\[
P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \left( \frac{1.27 \Delta m_{32}^2 L}{E} \right) + \ldots
\]
Muon neutrino and antineutrino disappearance

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

\[ \sin^2 \theta_{23} = 0.5 \]
\[ \Delta m_{32}^2 = 2.5 \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2 2\theta_{13} = 0.085 \]

Phys. Rev. D 88 3, 032002
Muon neutrino and antineutrino disappearance

- Frequency determines mass splitting ($\Delta m^2$)

\[
P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{1.27 \Delta m_{32}^2 L}{E}\right) + \ldots
\]
Muon neutrino and antineutrino disappearance

- Frequency determines mass splitting ($\Delta m^2$)
- **Amplitude** gives mixing angle (e.g. $\theta_{23}$)

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

- Sensitive to all oscillation parameters - include information from reactor, solar measurements, including $\delta_{\text{CP}}$ and mass hierarchy

\[ P(\nu_\mu \rightarrow \nu_e) \]
Electron neutrino and antineutrino appearance

- Sensitive to all oscillation parameters - include information from reactor, solar measurements, including $\delta_{CP}$ and mass hierarchy

Changing $\delta_{CP}$ increases or decreases neutrino appearance
Electron neutrino and antineutrino appearance

- Sensitive to all oscillation parameters - include information from reactor, solar measurements, including $\delta_{CP}$ and mass hierarchy

Changing $\delta_{CP}$ increases or decreases neutrino appearance

Changing from normal to inverted hierarchy decreases neutrino appearance
Electron neutrino and antineutrino appearance

- Sensitive to all oscillation parameters - include information from reactor, solar measurements, including $\delta_{CP}$ and mass hierarchy

Changing $\delta_{CP}$ has an anticorrelated effect in neutrinos vs. antineutrinos
Infer oscillation parameters from event rates

Intense, accelerator-based neutrino flux ($\Phi$)

Neutrino interaction cross section ($\sigma$)

Detection efficiency ($\epsilon$)

$$N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD}P(\nu_\mu \to \nu_e)$$
Near detector data improves event rate prediction through shared sources of systematic uncertainty

Intense, accelerator-based neutrino flux ($\Phi$)

Neutrino interaction cross section ($\sigma$)

Detection efficiency ($\epsilon$)

\[
N_{ND} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{ND}
\]

\[
N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD}P(\nu_\mu \rightarrow \nu_e)
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Near detector data improves event rate prediction through shared sources of systematic uncertainty

Intense, accelerator-based neutrino flux ($\Phi$)

Neutrino interaction cross section ($\sigma$)

$N_{ND} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{ND}$

$N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD}P(\nu_\mu \rightarrow \nu_e)$
How a long baseline experiment works: examples from T2K and NOvA

See T. Doyle talk on Tues, T2K status and plans

See A. Sztuc talk on Tues, latest results from NOvA
How a long baseline experiment works: examples from T2K and NOvA

Intense, accelerator-based neutrino flux ($\Phi$)

$$N_{FD} \sim \Phi(E_\nu) \sigma(E_\nu) \epsilon_{FD} P(\nu_\mu \rightarrow \nu_e)$$
How a long baseline experiment works: accelerator based neutrino source
How a long baseline experiment works: accelerator based neutrino source

99% pure muon flavor

*T2K flux prediction*
*Phys. Rev. D 87, 012001 (2013)*
How a long baseline experiment works: accelerator based neutrino source

Select neutrino or antineutrino!
How a long baseline experiment works: accelerator based neutrino source

Tunable energy

T2K near detector flux (2.5 degrees ‘off-axis’)

T2K near detector flux (off-axis)

30 GeV Proton beam

Credit: L. Pickering
How a long baseline experiment works: interactions in massive detectors

\[ N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD}P(\nu_\mu \rightarrow \nu_e) \]
How a long baseline experiment works: interactions in massive detectors

See S. M. Lakshmi talk on Monday for selection details

Credit: Super-Kamiokande collaboration

\[ N_{FD} \sim \Phi(E_\nu) \sigma(E_\nu) \epsilon_{FD} P(\nu_\mu \rightarrow \nu_e) \]
How a long baseline experiment works: interactions in massive detectors

\[ N_{FD} \sim \Phi(E_\nu) \sigma(E_\nu) \epsilon_{FD} P(\nu_\mu \rightarrow \nu_e) \]
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How a long baseline experiment works: interactions in massive detectors

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Recent results from T2K and NOvA

T2K preliminary 2020 results:
\[ \nu\text{-mode POT: } 1.851 \times 10^{21} \]
\[ \bar{\nu}\text{-mode POT: } 1.651 \times 10^{21} \]

NOvA preliminary 2020 results:
\[ \nu\text{-mode POT: } 1.36 \times 10^{21} \text{ (equivalent)} \]
\[ \bar{\nu}\text{-mode POT: } 1.25 \times 10^{21} \]

protons on target = POT
Recent results from T2K

$$P(\nu_\mu \rightarrow \nu_\mu) \equiv 1 - \sin^2 2\theta_{23} \sin^2 \left( \frac{1.27 \Delta m_{32}^2 L}{E} \right) + \ldots$$
Recent results from T2K

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

NOvA preprint: arxiv.org/abs/2108.08219
Recent results from NOvA
Recent results ... in good agreement across beam, atmospheric data
Appearance results*

*Actually, we analyze disappearance and appearance samples together

Recall the event rate depends on all oscillation parameters ($\delta_{CP}$, $\theta_{23}$, $\theta_{13}$, $\Delta m^2$ and mass hierarchy)

\[ N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD}P(\nu_\mu \rightarrow \nu_e) \]
Appearance results - NOvA

Excellent signal/background separation

\[
N_{FD} \sim \Phi(E_\nu) \sigma(E_\nu) \epsilon_{FD} P(\nu_\mu \rightarrow \nu_e)
\]
Appearance results - NOvA

Best fit in normal ordering and $\theta_{23}$ upper octant
Appearance results - T2K

Data currently has an excess of electron neutrino events, and a deficit of electron antineutrino events.
Preference for maximal CPV, normal ordering

Exclude 35% of $\delta_{CP}$ values at $3\sigma$ (marginalized over both hierarchies)
Appearance results - T2K
Global picture is complex - these are statistics limited experiments!

$1\sigma$ contours have regions of overlap
Global picture is to be clarified with combined analysis of NOvA-T2K, T2K-SK

**T2K @0.6 GeV, 295km**
- *CP effect: 32%*
- Matter effect: 9%

**NOvA @2 GeV, 810km**
- *CP effect: 22%*
- Matter effect: 29%

Credit: M. Hartz, *Minimum difference of sin(δcp)=0 and sin(δcp)=±1, neutrinos and antineutrinos*
Future plans of T2K and NOvA - operate through 2026

Significant improvements to T2K underway:

- Gd doping at far detector

NOvA will reduce largest systematics with results from test beam program
Not just long baseline physics: exotic physics tests

- Intense neutrino source x multiple detectors = searches for new physics!
  - Light dark matter
  - Sterile neutrinos - MINOS, MINOS+, T2K, NOvA
  - Heavy neutral leptons - T2K
  - Lorentz violation - MINOS, T2K
  - Large extra dimensions - MINOS+

See MicroBooNE talks, D. Caratelli for short baseline program
Sterile neutrinos with NOvA

Phys. Rev. Lett. 127, 201801

\[ \theta_{13} = 8.48^\circ, \sin^2 \theta_{23} = 0.542 \]
\[ \Delta m^2_{32} = 2.52 \times 10^{-3} \text{eV}^2 \]
\[ \delta_{CP} = 1.37\pi \]
Sterile neutrinos with NOvA

Antineutrino Beam  NOvA Preliminary

No significant suppression of NC rate due to sterile mixing

\[ \theta_{13} = 8.48^\circ, \sin^2 \theta_{23} = 0.542, \Delta m^2_{32} = 2.44 \times 10^{-3} \text{ eV}^2, \delta_{CP} = 1.37 \pi \]

\[ \text{NOvA Fit, } 12.51 \times 10^{30} \text{ POT} \]

\[ \sin^2 \theta_{23} = 0.542, \Delta m^2_{32} = 2.44 \times 10^{-3} \text{ eV}^2, \]

\[ \delta_{13} = 1.37 \pi \]

\[ 68\% \text{ C.L., } 90\% \text{ C.L.} \]

\[ \text{Phys. Rev. Lett. 127, 201801} \]
Heavy neutral lepton search on T2K

Production of heavy neutral leptons (N) from kaon decay

- Use large volume, low mass TPCs to identify signal
Heavy neutral lepton search on T2K

Production of heavy neutral leptons (N) from kaon decay

- Competitive high mass limits on coupling N to from $\mu, e$
- Complementary search to dedicated measurements - see talk Tues, R. Wanke
Long baseline experiments are broad scientific programs with opportunities to test our understanding of the universe

● Neutrino oscillation open questions: mass hierarchy, CPV and $\theta_{23}$ octant
● Searches for exotic physics phenomena, neutrino interaction physics
Long baseline experiments are broad scientific programs with opportunities to test our understanding of the universe

- Neutrino oscillation open questions: mass hierarchy, CPV and $\theta_{23}$ octant
- Searches for exotic physics phenomena, neutrino interaction physics

The future will be exciting with new long baseline results:

- Combined analysis of NOvA, T2K and atmospheric (Super-K) data sets exploits complementary information
- T2K and NOvA are statistics limited - *both plan to continue running*
- Beyond that, DUNE and HK will make precision measurements of oscillation physics, and more - see E. Worcester talk on future experiments on Friday
Backup
Results: deficit in disappearance spectra

1) Overall rate is underpredicted: 318 1Rmu in data, ~346 predicted

2) Deficit is covered by uncertainties, but this question has motivated model scrutiny:
   a) Example: HE process is overpredicted, then post oscillation, there is a MC excess over data.

3) Postfit spectrum is acceptable; fit to 2 flavor case where $\sin^2 2\theta_{23}$ is allowed to go larger than 1 ($\alpha > 1$, unphysical) includes PMNS ($\alpha < 1$) space.