Recent results from long baseline neutrino experiments

Kendall Mahn
TRIUMF
What physics is beyond the Standard Model?

Massive neutrinos

as determined from neutrino oscillation experiments
What is neutrino oscillation?

Neutrino oscillation, the mixing between flavor and mass states, has been observed through deficits relative to expectation of different neutrino flavors. Evidence from:

- Electron neutrinos ($\nu_e$) from the Sun
- Electron antineutrinos (anti-$\nu_e$) from reactors
- Muon ($\nu_\mu$) neutrinos from the atmosphere

Sudbury Neutrino Observatory (SNO) experiment measured the flux of $\nu_e$ from the Sun

- $\nu_e$ flux determined through charged current interactions (CC) where flavor of the neutrino corresponds to the final state lepton
- Total flux of $\nu_e$, $\nu_\mu$, $\nu_\tau$ determined from neutral current interactions (NC)

Clear deficit of $\nu_e$ flux “$\nu_e$ disappearance”
Clear increase of $\nu_\mu$, $\nu_\tau$ flux “appearance”

June 16, 2014
K Mahn, CAP2014
Neutrino oscillation, the mixing between flavor and mass states, has been observed through deficits relative to expectation of different neutrino flavors. Evidence from:

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- Electron antineutrinos (anti-νₑ) from reactors
- Muon (νµ) neutrinos from the atmosphere

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- νₑ flux determined through charged current interactions (CC) where flavor of the neutrino corresponds to the final state lepton
- Total flux of νₑ, νµ, ντ determined from neutral current interactions (NC)

Clear deficit of νₑ flux “νₑ disappearance”

Clear increase of νµ, ντ flux “appearance”

Evidence* consistent with three active flavors of neutrinos

Do we directly observe neutrino oscillation through CC flavor tagging (νµ to νₑ, ντ “appearance”)

Do we observe the same transitions for neutrinos as for antineutrinos? Is there CP violation in neutrino oscillations?

*Excluding outstanding questions about sterile neutrinos
Neutrino oscillation between three active flavors is described by the PMNS mixing matrix, $U$, which is unitary and contains three mixing angles: $\theta_{12}$, $\theta_{23}$, $\theta_{13}$, and two mass splittings:

- $\Delta m^2_{\text{atmospheric}} = |\Delta m^2_{32}| \sim 2.4 \times 10^{-3}$ eV$^2$
- $\Delta m^2_{\text{solar}} = \Delta m^2_{21} \sim 7.6 \times 10^{-5}$ eV$^2$

The matrix also contains an unknown CP violating phase $\delta_{CP}$. The ordering of the mass eigenstates (mass hierarchy) is also unknown: $\Delta m^2_{32} > 0$ or $\Delta m^2_{32} < 0$?
\( \nu_\mu \) to \( \nu_e \) appearance probability:

\[
\alpha = \frac{\Delta m_{32}^2}{\Delta m_{31}^2} \ll 1
\]

\[
\Delta = \frac{\Delta m_{32}^2 L}{4E_\nu}
\]

\[
A = 2\sqrt{2}G_FN_e \frac{E_\nu}{\Delta m_{32}^2}
\]

\[
P_{\nu_\mu \rightarrow \nu_e} = \frac{1}{(A-1)^2} \sin^22\theta_{13} \sin^2\theta_{23} \sin^2[(A-1)\Delta]
\]

\[
-(+)\frac{\alpha}{A(1-A)} \cos\theta_{13} \sin2\theta_{12} \sin2\theta_{23} \sin2\theta_{12} \times
\sin\delta_{CP} \sin\Delta \sin A\Delta \sin[(1-A)\Delta]
\]

\[
+\frac{\alpha^2}{A^2} \cos\theta_{23} \sin^22\theta_{12} \sin^2 A\Delta
\]

Depends on \( \delta_{CP} \), mass hierarchy through matter effects (A)

*Measurements of \( \nu_\mu \) to \( \nu_e \) appearance are sensitive to new or exotic physics provided information on \( \Delta m_{32}^2 \), \( \theta_{23} \), \( \Delta m_{21}^2 \), \( \theta_{12} \) and \( \theta_{13} \)*

*Measurements of \( \nu_\mu \) disappearance determine \( \Delta m_{32}^2 \) and \( \theta_{23} \)*
Neutrinos are produced as a tertiary beam:
1. Protons hit a target, producing pions and kaons which decay to neutrinos

Advantages of an accelerator-driven neutrino source for precision studies of neutrinos and antineutrinos:
1. >99% muon neutrino flavor, small $\nu_e$ component from muon, kaon decay
2. “Known”, scalable source (intensity of proton beam increases neutrino rate)
3. Switch magnetic horn polarization to focus $\pi^-$ and produce an predominantly antineutrino beam (with a ~30% neutrino component)
Accelerator-based sources also are tunable as the neutrino energy spectrum depends on:

- Proton beam energy
- Position of the detector relative to the proton beam direction

"On axis" or "Wide band beam" is along proton beam direction

"Off axis" or "Narrow band beam" is at an angle to the proton beam

- Concept developed at TRIUMF
The oscillation probability, \( P \), for \( \nu_\mu \) to oscillate is sinusoidal and depends on the distance \( L \) (km) the neutrinos travel and their energy \( E \) (GeV):

\[
P(\nu_\mu \rightarrow \nu_\mu) \equiv 1 - \sin^2 \left( \frac{1.27 \Delta m^2_{32} L}{E} \right) \left[ \sin^2 2\theta_{23} \cos^4 \theta_{13} + \sin^2 \theta_{23} \sin^2 2\theta_{13} \right]
\]

Tokai To Kamioka (T2K) experiment:
Ev(peak) \( \sim 0.6 \text{GeV} \), \( L=295 \text{km} \)

MINOS experiment:
Ev(peak) \( \sim 3 \text{ GeV} \), \( L=735 \text{km} \)

"long baseline experiments" require
\( \Delta m^2_{32} \sim 3 \times 10^{-3} \text{ eV}^2 \), want \( \sin^2(\Delta m^2 L/E) \) to be of order 1
The oscillation probability, $P$, for $\nu_{\mu}$ to oscillate is sinusoidal and depends on the distance $L$ (km) the neutrinos travel and their energy $E$ (GeV):

$$P(\nu_{\mu}) \propto \sin^2 (1.27 \Delta m^2 L)$$

Recent long baseline measurements:
- **T2K**: $\nu_e$ appearance, $\nu_{\mu}$ disappearance
- **MINOS**: $\nu_e$, anti-$\nu_e$ appearance, $\nu_{\mu}$, anti-$\nu_{\mu}$ disappearance
- **OPERA**: $\nu_\tau$ appearance

Near term long baseline measurements:
- **T2K**: anti-$\nu_e$ appearance, anti-$\nu_{\mu}$ disappearance
- **NOvA**: $\nu_e$, anti-$\nu_e$ appearance, $\nu_{\mu}$, anti-$\nu_{\mu}$ disappearance

“long baseline experiments” require
$\Delta m^2_{32} \sim 3 \times 10^{-3}$ eV$^2$, want $\sin^2 (\Delta m^2 L/E)$ to be of order $1$
Tokai-mura to Kamioka (295km)
Off-axis beam (2.5°) produced at JPARC
\( E_\nu(\text{peak}) \approx 0.6\ \text{GeV} \)

**T2K physics run:**
Operating from 2010 onward
Neutrinos: \(6.57 \times 10^{20}\ \text{POT} \)
Antineutrinos: test run ongoing

**Measurements of:**
\(\nu_\mu\) disappearance
\(\nu_e\) appearance
Oscillation probability depends on neutrino energy
For T2K’s neutrino spectrum, dominant process is Charged Current Quasi-Elastic:

\[
P(\nu_\mu \rightarrow \nu_\mu) \cong 1 - \sin^2 \left( \frac{1.27 \Delta m_{32}^2 L}{E} \right) \left[ \sin^2 2\theta_{23} \cos^4 \theta_{13} + \sin^2 \theta_{23} \sin^2 2\theta_{13} \right]
\]

Infer neutrino properties from the lepton 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 and assumes the target nucleon is at rest

Background processes are:

- Charged current single pion production (CCπ)
- Neutral current single pion production (NCπ⁰)
Select CC $\nu_\mu$ candidates prior to oscillations in an off axis tracking detector (ND280)

- Neutrino interacts on scintillator tracking detector
- Muon momentum determined from curvature in magnetic field (with TPCs)
- Events separated based on presence of charged pion in final state ($CC0\pi$, $CC1\pi$, CC other)

Select CC $\nu_e$ and $\nu_\mu$ candidates after oscillations, in a 50kton water Cherenkov detector (Super-Kamiokande)

- Select single ring events, determine lepton flavor from ring shape and topology
- Reject CC nonQE interactions using ring multiplicity and decay electron tagging
- NC events with $\pi^0$ removed based on invariant mass
Use of near detectors on T2K

Expected number of events at the far detector is modified based on near detector information; provides a substantial constraint on the uncertainties of $\nu_e$ and $\nu_\mu$ events:

$$FD(\nu_e) = \Phi \times \sigma \times \epsilon \times P(\nu_\mu \rightarrow \nu_e)$$

$$ND(\nu_\mu) = \Phi \times \sigma \times \epsilon_{ND}$$

<table>
<thead>
<tr>
<th>uncertainties for $\nu_e$ appearance</th>
<th>$\nu_e$ sig+bkrd</th>
<th>$\nu_e$ bkrd</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ flux+xsec (before) after ND constraint</td>
<td>(25.9%) ±2.9%</td>
<td>(21.7%) ±4.8%</td>
</tr>
<tr>
<td>$\nu$ unconstrained xsec</td>
<td>±7.5%</td>
<td>±6.8%</td>
</tr>
<tr>
<td>Far detector</td>
<td>±3.5%</td>
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</tr>
<tr>
<td>Total</td>
<td>(27.2%) ±8.8%</td>
<td>±11.1%</td>
</tr>
</tbody>
</table>

After ND: expect 21.6 $\nu_e$ candidates (background only: 4.92)

After ND: expect 124.8 $\nu_\mu$ events (background only: 49.2)
28 candidate $\nu_e$ events observed

- First observation of CC $\nu_e$ appearance!
- Transition depends on all mixing parameters ($\Delta m^2_{32}, \theta_{23}, \theta_{13}$ and $\delta_{\text{CP}}$, mass hierarchy and $\Delta m^2_{21}, \theta_{12}$)

120 candidate $\nu_\mu$ events observed

- Determine $\Delta m^2_{32}, \sin^2\theta_{23}$ from distortion to neutrino energy spectrum

Fit both $\nu_e$ and $\nu_\mu$ samples simultaneously
Include solar, reactor determinations of $\Delta m^2_{21}, \theta_{12}, \theta_{13}$
Markov Chain Monte Carlo-based analysis

- Simultaneous fit to near detector $\nu_\mu$, far detector $\nu_\mu$, $\nu_e$ samples
- Includes correlations between $\nu_\mu$, $\nu_e$ samples

T2K data favors maximal disappearance

- Provides best constraint on $\theta_{23}$ to date
- Consistent with maximal ($45^\circ$) mixing
- Caveat: Baysian analysis, credible regions are shown with confidence intervals from other experiments

- T2K CL are similar to CI regions
Assumes equal probability for either hierarchy

Comparison of probabilities for each combination of $\theta_{23}$ octant, mass hierarchy:

<table>
<thead>
<tr>
<th>Probability</th>
<th>$\Delta m_{32}^2 &gt; 0$</th>
<th>$\Delta m_{32}^2 &lt; 0$</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{23} \leq 0.5$</td>
<td>18%</td>
<td>8%</td>
<td>26%</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23} &gt; 0.5$</td>
<td>50%</td>
<td>24%</td>
<td>74%</td>
</tr>
<tr>
<td>Sum</td>
<td>68%</td>
<td>32%</td>
<td></td>
</tr>
</tbody>
</table>
The MINOS (and MINOS+) experiments

FNAL to Soudan, MN (735km)
On-axis beam, two main configurations:
$E_\nu$(peak) $\approx$ 3 GeV
Also can detect atmospheric neutrinos

MINOS physics run:
 Operated from: 2003-2011
Neutrinos: $10.71 \times 10^{20}$ POT
Antineutrinos: $3.36 \times 10^{20}$ PO

Measurements of:
$\nu_\mu$, anti-$\nu_\mu$ disappearance
$\nu_e$, anti-$\nu_e$ appearance

MINOS plots from
A. Sousa, Neutrino2014
Event selection at MINOS

Near and far detectors are magnetized steel-scintillator tracking detectors

- Momentum of the muon is determined by curvature, sign indicates $\nu$ or anti-$\nu$
- Multivariate analysis techniques used to select $CC \nu_\mu$, $CC \nu_e$ candidates

- Reconstructed neutrino energy is determined from muon and/or hadronic shower information
- $CC \nu_e$ selection has substantial backgrounds due to NC interactions
MINOS results: $\Delta m_{32}^2$, $\sin^2\theta_{23}$

Fit includes:
- MINOS neutrino, antineutrino beam data sets
- Also includes atmospheric neutrino data set

MINOS provides the best constraint on $|\Delta m_{32}^2|$
- Consistent with T2K
The OPERA experiment

On-axis beam (E$_\nu$≈17 GeV)  
CERN to Gran Sasso, Italy (730km)

OPERA physics run:  
Operated from 2008-2012  
Neutrinos: 1.8x10$^{20}$ POT

Measurements of:  
$\nu_T$ appearance

OPERA plots from S. Dusini, Neutrino2014
**OPERA $\nu_\tau$ appearance results**

- Emulsion film + lead form “bricks”
  - Scintillator planes and magnetic spectrometer are used to identify likely neutrino interaction bricks
  - Bricks removed and scanned to determine $\tau$ decay candidate interactions

$\nu_\tau$ appearance expected signal $2.10 \pm 0.4$, background $0.23 \pm 0.04$

Observed 4 candidate events (no oscillation excluded at $4.2\sigma$)
Near term experiments: NOvA

FNAL to Ash River, MN (810km)
Off-axis (0.8°deg) beam ($E_\nu \approx 2$ GeV)

NOvA physics run:
Neutrinos since Feb 2014

Planned measurements of:
$\nu_\mu$, anti-$\nu_\mu$ disappearance
$\nu_e$, anti-$\nu_e$ appearance
Matter effects alter the appearance oscillation probability, depending on the sign of $\Delta m^2_{32}$, the mass hierarchy

- NOvA’s higher energy and longer baseline relative to T2K give NOvA more sensitivity to the mass hierarchy through matter effects
- Combinations of the two measurements exploit the different dependency of $\delta_{CP}$ and the mass hierarchy in the oscillation probability
To measure CP violation, future experiments propose to compare $\nu_e$ appearance to anti-$\nu_e$ appearance to determine an asymmetry:

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

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

- T2K’s current statistics: 28 events ($\nu_e$ appearance probability)
- Need more raw event rate, with a larger detector and/or intense beam
T2HK: same neutrino beamline and off-axis angle as T2K
Would use a new detector (Hyper-Kamiokande) in a different cavern

- Event rate enhanced over T2K’s with a much larger ~1Mton far detector (approximately 25x T2K’s current far detector)
- Technique requires mass hierarchy is known, assuming determined from cosmology, $0\nu\beta\beta$, atmospheric neutrinos, or T2K-NOvA combination

Hyper-Kamiokande LOI: arXiv:1109.3262
Wide band (on-axis) beams can be used to directly test energy dependence of oscillation and determine the mass hierarchy and $\delta_{CP}$ simultaneously.

- LBNE: 1300km distance (FNAL to South Dakota),
- LBNO/LAGUNA: 2300km distance (CERN to Finland)
- Both are considering LAr-based far detector technology of ~20-50kton size

M. Bass, NuInt2014
Neutrino oscillation physics is entering the precision era with accelerator driven long-baseline neutrino experiments:

From T2K:
- Discovery of CC $\nu_e$ appearance
- World’s best measurement of $\theta_{23}$

From MINOS:
- World’s best measurement of $\Delta m^2_{32}$

From OPERA
- Discovery of CC $\nu_\tau$ appearance

The next few years test our assumptions about three-flavor oscillation with:
- Improved measurements of $\nu_\mu$ and anti-$\nu_\mu$ mixing (T2K, NOvA)
- Searches for CC anti-$\nu_e$ appearance (T2K, NOvA)
- Combinations of different long baseline experiments, and atmospheric neutrino measurements may provide hints of the mass hierarchy

Future long baseline experiments (T2HK, LBNE, LBNO) propose to search for CP violation with enormous detectors and powerful beams
Backup: flux errors and how they affect the spectrum
Complementary results of MINOS+?
T2K observed event distributions

28 candidate $\nu_e$ events observed
- First observation of CC $\nu_e$ appearance!

120 candidate $\nu_\mu$ events observed
- Determine $\Delta m^2_{32}$, $\sin^2\theta_{23}$ from distortion to neutrino energy spectrum
Comparison of joint and standalone disap analyses

PRELIMINARY

Normal Hierarchy

\[ |\Delta m^2_{32}| (10^{-3} \text{ eV}^2/\text{c}^4) \]

\[ \sin^2 \theta_{23} \]

- T2K joint OA (with reactor constraint)
- Const. $\Delta \chi^2$
- T2K disappearance FC (2014) [arXiv:1403.1532]

PRELIMINARY

Inverted Hierarchy

\[ |\Delta m^2_{13}| (10^{-3} \text{ eV}^2/\text{c}^4) \]

\[ \sin^2 \theta_{23} \]

- T2K joint OA (with reactor constraint)
- Const. $\Delta \chi^2$
- T2K disappearance FC (2014) [arXiv:1403.1532]

PRELIMINARY

| Reactor constraint | Hierarchy | $|\Delta m^2_{32}| (NH)$ | $|\Delta m^2_{13}| (IH)$ | $\sin^2 \theta_{23}$ | $\sin^2 2\theta_{13}$ | $\delta_{CP}$ | $N_{\mu}^{1R_{\mu}}_{obs}$ | $N_{\mu}^{1R_{\mu}}_{exp}$ | $N_{e}^{1R_{e}}_{obs}$ | $N_{e}^{1R_{e}}_{exp}$ | $\Delta(\chi^2)$ |
|-------------------|-----------|--------------------------|--------------------------|-------------------|-------------------|----------------|-----------------------------|----------------------|-------------------|-------------------|--------------|
| NO                | NH        | 2.512                    | 0.524                    | 0.162             | 1.909             |               | 120                    | 119.915             | 28                | 27.999            | 0.01         |
| NO                | IH        | 2.488                    | 0.523                    | 0.187             | 1.005             |               | 120                    | 119.948             | 28                | 27.998            | -            |
| YES               | NH        | 2.509                    | 0.527                    | 0.0967            | -1.554            |               | 120                    | 120.383             | 28                | 25.870            | -            |
| YES               | IH        | 2.481                    | 0.533                    | 0.0984            | -1.556            |               | 120                    | 121.204             | 28                | 23.571            | 0.864        |
MCMC joint analysis results

- Constraints on $\nu_\mu$ disappearance parameters

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<td>16</td>
<td>20</td>
<td>36</td>
</tr>
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<td>$\sin^2 \theta_{23} &gt; 0.5$</td>
<td>29</td>
<td>35</td>
<td>64</td>
</tr>
<tr>
<td>Sum</td>
<td>45</td>
<td>55</td>
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T2K-Only Model Probabilities

With Reactor Constraint

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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

MP: TPC commissioning, data quality system and alignment
Selecting CC $\nu_\mu$ interactions

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

1. Neutrino interaction in FGD1
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   - Energy loss of the track in TPC also consistent with muon hypothesis

Further separate sample into three categories based on final state: CC0$\pi$ / CC1$\pi$ / CC other to increase sensitivity to cross section:

- FGD track: decay electron / $\pi$-p dE/dx
- TPC-FGD matched track: $\pi$-p dE/dx
- Electrons identify $\pi^0$ (often from DIS events)
Shared flux, similar CC cross section composition of near and far detector selections result in substantial reduction to CC cross sections, \( \nu_\mu \) flux uncertainties

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\[
N(\nu_e) = \Phi(E_\nu) \sigma(E_\nu) \epsilon P(\nu_\mu \rightarrow \nu_e)
\]

\[
N(\nu_\mu) = \Phi(E_\nu) \sigma(E_\nu) \epsilon
\]
Expected number of $\nu_e$ candidates

After ND280 tuning, expect 21.6 events with expected $\nu_\mu$ to $\nu_e$ oscillation
- 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$^2$2$\theta_{13}$=0.1, $\delta CP$=0</td>
<td>16.7</td>
</tr>
</tbody>
</table>

$\nu_e$ signal@$\Delta m^2_{32}$=2.4 $\times$ 10$^{-3}$ eV$^2$, sin$^2$2$\theta_{23}$=1.0
Excludes $\theta_{12}$ component

<table>
<thead>
<tr>
<th>Background</th>
<th># events</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam $\nu_e$</td>
<td>3.2</td>
</tr>
<tr>
<td>$\nu_\mu$ (mainly NC) background</td>
<td>1.1</td>
</tr>
<tr>
<td>osc through $\theta_{12}$</td>
<td>0.6</td>
</tr>
<tr>
<td>total assuming sin$^2$2$\theta_{13}$=0</td>
<td></td>
</tr>
</tbody>
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### CC $\nu_e$ signal

![CC $\nu_e$ signal graph](image1)

### CC $\nu_e$ background

![CC $\nu_e$ background graph](image2)
NBB (NoVA) sensitivity improves with combination of different beam energy and atmospheric neutrino statistics.