Current Long Baseline Neutrino Experiments

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The neutrino 3x3 mixing matrix

Different L/E values pick up different $\Delta m^2$ pairs, probing different parts of mixing matrix.

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

Atmospheric $\nu$'s: $\theta_{23} \approx 46^\circ$

Maximal mixing! (?)

Short baseline reactor $\nu$'s: $\theta_{13} \approx 9^\circ$

Small, quark-like mixing

Solar $\nu$'s: $\theta_{12} \approx 33^\circ$

Large, non-maximal mixing

Compare to identical parameterization of CKM matrix ...

$\theta_{23} \approx 2.4^\circ$  $\theta_{13} \approx 0.2^\circ$  $\theta_{12} \approx 13^\circ$
Mass Hierarchy

Currently unknown:
• value of $\delta_{\text{CP}}$
• sign of the mass hierarchy

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

$\Delta m^2_{21} = 7.5 \times 10^{-5} \text{ eV}^2$
Off-Axis $\nu_\mu$ Beam

Off-axis beam: more flux near peak oscillation energy, less flux at higher energies where $\nu_e$ backgrounds are produced.
LBL signature #1: $\nu_\mu$ disappearance

Starting from

$$P_{\nu_\mu \rightarrow \nu_\mu}(L, E) = \sum_{j,k} U_{aj}^* U_{bj} U_{ak} U_{bk}^* e^{-i \frac{\Delta m_{32}^2 L}{2E}}$$

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E} \right)$$
$$- \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E} \right)$$
$$\approx 1 - \sin^2 2\theta_{23} \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E} \right)$$

Sensitive to $\Delta m_{32}^2$ and $\theta_{23}$. Same formula for neutrinos and for antineutrinos, if CPT holds.
LBL signature #2: $\nu_e$ appearance

$$P(\nu_\mu \to \nu_e) \sim \frac{\sin^2 2\theta_{13} \times \sin^2 \theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}}{\frac{\sin \Delta \frac{\sin[x\Delta]}{x} \sin[(1-x)\Delta]}{(1-x)}} \times \frac{\sin \Delta \frac{\sin[x\Delta]}{x} \sin[(1-x)\Delta]}{(1-x)}$$

$$x = 2\sqrt{2}G_FN_e \frac{E_\nu}{\Delta m^2} \quad \Delta \equiv \frac{\Delta m^2_{31} L}{4E_\nu}$$

Dominant term corresponds to a $\sim 5\%$ transition probability at the oscillation maximum
LBL signature #2: $\nu_e$ appearance

\[ P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta_{13} \times \sin^2 \theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \times \sin \Delta \frac{\sin x\Delta}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \]

\[ x = 2\sqrt{2}G_F N_e \frac{E_\nu}{\Delta m^2_{31}} \]

\[ \Delta \equiv \frac{\Delta m^2_{31} L}{4E_\nu} \]

Terms containing $\delta$ are sensitive to CP phase. The $\delta$'s flip sign for antineutrinos.

The $\kappa$ parameter (matter effect) also flips sign for antineutrinos. The matter effect is subdominant at T2K due to low beam energy, but larger at NOνA.
CP, T, and CPT for neutrinos

$P(\nu_a \rightarrow \nu_b) \xleftarrow{\text{CP}} P(\overline{\nu}_a \rightarrow \overline{\nu}_b)$

$P(\nu_a \rightarrow \nu_b) \xleftarrow{\text{T}} P(\nu_b \rightarrow \nu_a)$

$P(\nu_a \rightarrow \nu_b) \xleftarrow{\text{CPT}} P(\overline{\nu}_b \rightarrow \overline{\nu}_a)$

$P(\nu_a \rightarrow \nu_a) \xleftarrow{\text{CPT}} P(\overline{\nu}_a \rightarrow \overline{\nu}_a)$

If CPT holds in neutrino sector, neutrino survival probability equals antineutrino survival probability.

As a result CP violation is observable only in appearance channels, in which the flavour of the appearing lepton is detected. This is why LBL neutrinos are interesting!
CP and three-flavour mixing

\[ V_\mu \quad V_\tau \quad \bar{V}_e \]

CP violation affects the mix of flavours that results from the oscillation
Leptogenesis

CP violation in quark sector not enough to explain observed matter-antimatter asymmetry in universe.

Neutrino mixing provides another possible source of CPV.

- **Standard Leptogenesis**: decays of RH neutrinos (CPV in decay)
  
  Quantum interference of tree diagram and one-loop diagram

Usual scenario: decay of heavy Majorana neutrinos

Many alternates, eg. leptogenesis with only Dirac $\nu$'s

Relation of $\delta_{\text{CP}}$ to leptogenesis is model-dependent, but observation of leptonic CP violation is an important milestone.
Matter Effects and $\nu_e$ Appearance

Matter effects modify the oscillation formula. Because the Earth is made of electrons and not heavier leptons, the effective “index of refraction” for $\nu_e$ is different than that for $\nu_\mu$. At the oscillation maximum, the $\nu_e$ appearance probability changes to:

$$P(\nu_\mu \rightarrow \nu_e) \approx \left(1 + 2 \frac{E}{E_R}\right) P_{\text{vac}}(\nu_\mu \rightarrow \nu_e)$$

where

$$E_R = \frac{\Delta m^2_{32}}{2 \sqrt{2} G_F N_e} = \pm 11 \text{ GeV}$$

The sign of the matter effect is opposite for neutrinos and anti-neutrinos, and depends on the sign of $\Delta m^2$ as well.
JAPAN PROTON ACCELERATOR RESEARCH COMPLEX (J-PARC): Tokai, Japan
30 GeV proton synchrotron design power: 0.75MW (upgradable to >1MW)
Super-Kamiokande: 50 ktonne water Cherenkov detector

off-axis beam
295 km baseline
~99% $\nu_\mu$, ~1% $\nu_e$

Oscillation Prob. @ $\Delta m^2 = 3.0 \times 10^{-3}$

$v$ energy spectrum (Flux $\times$ x-section)

OA0°
OA2°
OA2.5°
OA3°
Sophisticated on-axis and off-axis near detectors 280m from proton target.
Super-Kamiokande

Water Cherenkov detection.

Primary signal channel is CCQE single-ring events. Reconstruct $\nu$ energy in CCQE hypothesis from lepton kinematics.
Side Muon Range Detectors (in yoke)

Tracker = 3 TPC modules + 2 FGD modules

UA1 magnet: 0.188 T field

Downstream ECAL

Solenoid Coil

P0D ECAL

Barrel ECAL

neutrino beam

Off Axis Near Detector
Additional constraint from ND280 data allows us to refine the SK prediction.

T2K Oscillation Analysis Structure
νμ disappearance results

**Neutrino mode**

<table>
<thead>
<tr>
<th>Beam mode</th>
<th>Sample</th>
<th>Exp. Not Osc</th>
<th>Exp. δCP = 0 (NH)</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutrino</td>
<td>μ-like</td>
<td>521.8</td>
<td>135.5</td>
<td>135</td>
</tr>
<tr>
<td>antineutrino</td>
<td>μ-like</td>
<td>184.8</td>
<td>64.1</td>
<td>66</td>
</tr>
</tbody>
</table>

7.5 x 10^{20} protons on target of ν data
+ 7.5 x 10^{20} protons on target of anti-ν data
\( \nu_e \) appearance results

<table>
<thead>
<tr>
<th>( \nu_e )</th>
<th>( \delta_{CP} = -\pi/2 )</th>
<th>( \delta_{CP} = 0 )</th>
<th>( \delta_{CP} = \pi/2 )</th>
<th>( \delta_{CP} = \pi )</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \nu_e )</td>
<td>28.7</td>
<td>24.2</td>
<td>19.6</td>
<td>24.1</td>
<td>32</td>
</tr>
<tr>
<td>( \bar{\nu}_e )</td>
<td>6.0</td>
<td>6.9</td>
<td>7.7</td>
<td>6.8</td>
<td>4</td>
</tr>
<tr>
<td>Inverted</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \nu_e )</td>
<td>25.4</td>
<td>21.3</td>
<td>17.1</td>
<td>21.3</td>
<td>32</td>
</tr>
<tr>
<td>( \bar{\nu}_e )</td>
<td>6.5</td>
<td>7.4</td>
<td>8.4</td>
<td>7.4</td>
<td>4</td>
</tr>
</tbody>
</table>
The best-fit CP phase is close to $-\pi/2$: maximal CP effect. Formally speaking $\delta_{CP}=0$ is excluded at 90% CL.

Caveat: the result is primarily driven by very high $\nu_e$ appearance rate at T2K, beyond expectations of model. In other words, limit is better than expected sensitivity.
NOvA

FNAL to Ash River: 810km as the neutrino flies

- 14 kt liquid scintillator tracker
- 290t near detector
- 0.8 deg off axis
- ~2 GeV beam, up to 700 kW
NOνA vital characteristics

Flavour ID with NC sensitivity

Reconstruction informed by computer vision, machine learning

Beam energy of ~2GeV more sensitive than T2K to hadronic production. Energy estimation is more calorimetric than T2K, where hadrons usually are below detection threshold. (But hadrons are harder to model.)
NO\text{\textgreek{v}}A matter effect sensitivity

\[ P(\overline{\nu}_e) \approx P(\nu_e) \approx 1 + 2 \frac{E}{E_R} P_{\text{vac}}(\nu_\mu \rightarrow \nu_e) \]

Higher energy gives NO\text{\textgreek{v}}A better sensitivity to matter effects than T2K
NOνA Oscillation Results

33 $\nu_e$ events on background of $8.2 \pm 0.8$
Maximal mixing disfavoured at $2.6\sigma$

NOvA sterile neutrinos results

Neutral current sensitivity is unique capacity for NOvA. A convolutional neural network is used to distinguish events with no charged lepton.

If neutrinos mix to a sterile state, then the NC rate may be less than expected.

Recent NOvA arXiv submission 1706.04592 saw 95 events where $83.5 \pm 9.7 \text{(stat)} \pm 9.4 \text{(syst)}$ were predicted assuming mixing only occurs between active neutrino species.
Global oscillation parameter fits
(www.nu-fit.org)
T2K+NOνA combined sensitivity

Regions for which $\delta_{CP} = 0$ is rejected at 90% CL (for normal hierarchy)

Regions for which the wrong mass hierarchy is rejected at 90% CL (for normal hierarchy)

Proposal to continue running T2K until ~2025, with beam power and near detector upgrades, with an aim to achieve 3σ sensitivity to non-zero $\delta_{CP}$.

arXiv: 1609.04111
Conclusions

Long baseline neutrino experiments with flavour sensitivity are the only window we have on CP violation in the neutrino sector.

T2K and NO\text{v}A results are consistent with each other and PMNS paradigm. First limits on CP violation, although still statistically weak, favour maximal CP effect.

LBL experiments dominate $\Delta m_{32}^2$ and $\theta_{23}$ determination.

See parallel session talks by Mark Scott (T2K—Tuesday, 17:15, Neutrino 4), Nicoletta Mauri (OPERA—Tuesday, 17:00, Neutrino 4) and Kirk Bays (NO\text{v}A, Wednesday, 13:00, Neutrino 5) for details.
Backup Slides
CP Violation and $\nu_e$ Appearance

CP symmetry requires $P(\nu_\mu \to \nu_e) = P(\bar{\nu}_\mu \to \bar{\nu}_e)$

For $\nu_e$ appearance at $\Delta m^2_{32}$:

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

This may be a big asymmetry!

SO WHAT?

- Our universe is made of matter but not anti-matter.
- A cosmological asymmetry requires CP violation.
- Regular quark CP violation not enough---is this the missing piece?
OPERA

Beam from CERN to Gran Sasso, looking primarily for $\nu_{\tau}$ appearance using emulsion technology.

Five $\nu_{\tau}$ candidates seen on a background of $0.25 \pm 0.05$, & a claimed significance of $5.1\sigma$.

Flavour Oscillation

Because a flavour eigenstate produced by a weak interaction is a mix of mass eigenstates which, if $m_1 \neq m_2$, propagate with different kinematics, oscillation can occur.

$$|\nu(t=0)\rangle = |\nu_e\rangle = \cos \theta |\nu_1\rangle + \sin \theta |\nu_2\rangle$$

$$|\nu(t)\rangle = e^{i \sqrt{p^2 + m_1^2} t} \cos \theta |\nu_1\rangle + e^{i \sqrt{p^2 + m_2^2} t} \sin \theta |\nu_2\rangle$$

$$\text{Prob}(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta) \sin^2 \left( \frac{1.27 \Delta m^2 L}{E} \right)$$

Units: [L] = km; [E] = GeV; $\Delta m^2 = [\text{eV}^2]$
Neutrino interactions at $\sim 1$ GeV

T2K looks for final-state leptons from charged-current interactions
Cross-sections not well measured – need to use near detector to normalize.
The basic neutrino-nucleon interaction model is the dipole form factor model

- For CCQE interactions, this depends on a single physical parameter, the axial mass $M_A$.

CCQE interactions are particularly useful as the energy depends only on the outgoing lepton kinematics $p_\mu$, $\theta_\mu$

- This is the main signal for T2K

$$E_{\text{reco}} = \frac{m_p^2 - (m_n - E_b)^2 - m_{\mu}^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos \theta_\mu)}$$
Nuclear Effects

Dipole form factor model is sufficient for interactions with nucleons – not nuclear targets. In a nucleus there is binding energy, and Fermi motion of nucleons (no longer at rest). A simplistic nuclear model is used:

**Relativistic Fermi Gas**

Simple model of nuclear effects for CCQE interactions

- Nucleus is modeled as a Fermi gas of non-interacting neutrons and protons

Uses two nucleus-dependent parameters

- $E_B$ : the nucleon binding energy
- $p_F$ : the Fermi momentum
- Different for each nucleus

**Random Phase Approximation**

Correction to the RFG model

- Includes first-order nucleon-nucleon correlations not found in the RFG model

Models long range correlations between nucleons at low energies

- Not strongly nucleus dependent
Modelling CCQE interactions

Axial form factor for nucleon-neutrino interactions modelled by dipole parametrization:

$$F_A(Q^2) = g_A \left( 1 + \frac{Q^2}{M^2_A} \right)^{-2}$$

Measurements of the axial mass from different experiments are all over the map!

- World average: $1.012 \pm 0.031 \pm 0.060$ GeV
- Deuterium experiments: $0.99 \pm 0.04$ GeV
- MiniBooNE (carbon): $1.35 \pm 0.17$ GeV
- K2K (carbon): $1.20 \pm 0.12$ GeV

It looks like other effects confound the free nucleon form factor.
Other multinucleon correlations are not covered in the RFG + RPA model

- These interactions can produce multiple protons or neutrons in the final state – difficult to identify separately from CCQE
- Irreducible experimental background

T2K models 2p-2h interactions, where two particle – hole pairs are propagated through the nucleus

- Can produce two nucleons in the final state
- If not modeled, can have a significant effect on axial mass measurement: originally introduced to solve tensions between the axial mass measured with MiniBooNE and global averages
- T2K uses the Nieves 2p-2h model in the NEUT generator
Reactor neutrinos & $\theta_{13}$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{1.27 \Delta m_{31}^2 L}{E} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{1.27 \Delta m_{21}^2 L}{E} \right)$$

Daya Bay, RENO, Double CHOOZ look for disappearance of reactor neutrinos at ~1km baseline.

Daya Bay
How To Make A Neutrino Beam

30 GeV protons hit graphite target

3 magnetic horns focus $\pi^+$, defocus $\pi^-$. 

$\pi^+ \rightarrow \mu^+ + \nu_\mu$ in 110m long decay pipe

$\mu$ monitor at far end of beam dump: fluence: $10^8 \mu$/cm$^2$/spill at full power

T2K's 90cm graphite target
Inside the decay volume
↑
← The 2$^{\text{nd}}$ focusing horn
T2K data collection

27 May 2016
POT total: $1.510 \times 10^{21}$

$\nu$-mode POT: $7.57 \times 10^{20}$ (50.14%)
$\bar{\nu}$-mode POT: $7.53 \times 10^{20}$ (49.86%)
T2K: Flux prediction (Beam MC)

Simulate hadron production on target using FLUKA simulation

Model pion and kaon propagation and decay through horns and beamline

Get flux predictions at near detector and SK

Particle production cross sections tuned to external data from NA61 and others.
Backgrounds to $\nu_e$ Appearance

Intrinsic beam $\nu_e$:
- reduce with E cut
- measure at ND

$\pi^0$ production, with one $\gamma$ from event not detected at Super-K:
- better ID algorithms
- measure at ND
- measure $\pi^0$ in SK

The intrinsic beam events are a more significant background.
K2K & MINOS

Consistency between atmospheric and long-baseline $\nu$ oscillation results.
Atmospheric Neutrinos

Incident proton strikes atmosphere, making pion

\[ \pi \rightarrow \mu + \nu_\mu \]
\[ \rightarrow e + \nu_\mu + \nu_e \]

Two muon neutrinos produced for each electron neutrino!

Super-Kamiokande detector
Super-K atmospheric $\nu$ results

Deficit of upward-going $\nu_\mu$ relative to downward-going.

No deficit for $\nu_e$.

Seems like $\nu_\mu \rightarrow \nu_\tau$.

PRL 93:101801, 2004
PRD 71:112005, 2005
NuPRISM concept

New concept to exploit the variation in neutrino energy with off-axis angle: tall water Cherenkov near detector spanning range of off-axis angles.

Data taken at different angles can directly predict neutrino interactions with arbitrary neutrino fluxes, including effects from oscillation.

Main proposal to Canadian government under review.
Hyper-K

New technical design report: 187kton fiducial volume tank with enhanced photosensor coverage.

Proposal to locate a second detector in Korea at the second oscillation maximum.

High sensitivity for $\delta_{CP}$

arXiv: 1611.06118

arXiv: 1502.05199
Very long baseline experiment aiming at CP violation using liquid argon TPCs as the detector technology.

Higher energy and baseline than Hyper-K.