Recent Results from the Long Baseline Neutrino Oscillation Experiments

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Outline

1. Physics of Neutrino Oscillations

2. Current Long Baseline Experiments
   - The T2K Experiment
   - The NO\(\nu\)A Experiment
   - T2K and NO\(\nu\)A Joint Neutrino Oscillation Analysis
   - The MINOS and MINOS+ Experiments
   - Summary of LBL Results

3. Summary
Neutrinos have different weak and mass eigenstates, and they cannot be determined at the same time.

Weak eigenstates (interaction)

\[ \nu_e = \nu_1 + \nu_2 + \nu_3 \]

Mass eigenstates (propagation)

\[ \nu_\mu = \nu_1 + \nu_2 + \nu_3 \]

\[ \nu_\tau = \nu_1 + \nu_2 + \nu_3 \]
Neutrino Oscillation Probabilities

The (SM) $U_{PMNS}$ Matrix

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = U_{PMNS}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

(1)

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

(2)

where, $c_{ij} = \cos \theta_{ij}$, $s_{ij} = \sin \theta_{ij}$

Neutrino Oscillations are possible due to the fact that neutrinos are massive
This is the first evidence of physics beyond the SM

This makes neutrino physics one of the most interesting research fields
Neutrino Oscillation Parameters

Total of 6 independent neutrino oscillation parameters in SM:
\[ \theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}, \Delta m_{21}^2, \Delta m_{31}^2 \ (\Delta m_{32}^2 = \Delta m_{31}^2 - \Delta m_{21}^2) \]

The most important remaining unknowns are:

- The neutrino mass ordering, which is parametrized by the sign of \( \Delta m_{32}^2 \)
- The lepton CP-violating phase, \( \delta_{CP} \)
- The value for \( \theta_{23} \) mixing angle
Disappearance Channel Probability

This channel is most sensitive to the $\theta_{23}$ mixing angle and the value and sign of $\Delta m_{32}^2$

$$P\left(\nu_\mu \to \nu_\mu\right) \approx 1 - 4 \sin^2 \theta_{23} \cos^2 \theta_{13} M(1 - \sin^2 \theta_{23} \cos^2 \theta_{13}) \sin^2 \left(\frac{\Delta L}{E}\right)$$ (3)

Appearence Channel Probability

This is most sensitive to $\theta_{13}$, $\delta_{CP}$ and the sign and value of $\Delta m_{31}^2$

$$P\left(\nu_\mu \to \nu_e\right) \approx \sin^2 \theta_{23} \frac{\sin^2 2 \theta_{13}}{(A - 1)^2} \sin^2 \left(\frac{(A - 1) \Delta L}{E}\right) + \alpha^2 \cos^2 \theta_{23} \frac{\sin^2 2 \theta_{12}}{A^2} \sin^2 \left(\frac{A \Delta L}{E}\right)$$

$$\frac{\alpha J_{CP}}{A(1 - A)} \sin \left(\frac{A \Delta L}{E}\right) \sin \left(\frac{(A - 1) \Delta L}{E}\right) \left(\cot \delta_{CP} \cos \left(\frac{\Delta L}{E}\right) \pm \sin \left(\frac{\Delta L}{E}\right)\right)$$

Leading term, $\theta_{13}$

$$\Delta m_{ij}^2 = m_i^2 - m_j^2, \quad \alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}, \quad A = \sqrt{2} G_F N_e^m - \frac{2 E}{\Delta m_{31}^2}, \quad J_{CP} = \cos \theta_{13} \sin 2 \theta_{12} \sin 2 \theta_{23} \sin 2 \theta_{13} \sin \delta_{CP}$$

$$\sin^2 \theta_{13} = \frac{\sin^2 2 \theta_{13}}{2 \sin^2 \theta_{13} + (A - \cos 2 \theta_{13})^2}, \quad \Delta = \frac{\Delta m_{31}^2}{4}, \quad \Delta = \frac{\Delta m_{32}^2 + \Delta m_{21}^2 \sin^2 \theta_{12} + \Delta m_{21}^2 \cos \delta_{CP}}{4} \sin 2 \theta_{12} \sin \theta_{13} \tan \theta_{23}$$
Current Long Baseline (LBL) Neutrino Experiments

- Long Baseline neutrino experiments consist on near and far detectors, to which muon (anti-)neutrinos produced in accelerators are thrown.
- These experiments are design so the distance between the neutrino target and the far detector and the energy of the produced neutrinos so $L/E$ lies on and oscillation minimum (disappearance channel) or maximum (appearance channel).
- Long baseline experiments are looking into the main remaining unknown oscillation parameters, such as the $\theta_{23}$ octant, the neutrino mass ordering and, specially, the CP-violating phase.

Next, the current LBL experiments and their latest results are summarized.
The T2K Experiment

Dedicated to measure $\theta_{23}$, $\theta_{13}$ and $\delta_{CP}$
The T2K Beam

It uses the J-PARC beam to produce, mainly, $\nu_\mu$ ($\nu$-mode) or $\bar{\nu}_\mu$ ($\bar{\nu}$-mode). The mean beam power this year was of $\sim 485$ kW, achieving up to 500 kW.

$\nu$-mode $1.51 \times 10^{21}$ (47.83%)
$\bar{\nu}$-mode $1.65 \times 10^{21}$ (52.17%)

23 Jan. 2010 – 31 May 2018
POT total: $3.16 \times 10^{21}$
The T2K Beam

- The beam is $2.5^0$ off-axis with respect to the far detector
- T2K was the first experiment to implement the off-axis technique around
- This technique provides a narrower neutrino energy spectrum with its maximum at $E_\nu \sim 0.7$ GeV, at the disappearance minimum and appearance maximum

It has been agreed to extend (T2K phase-II) the operation of T2K to a second phase that will run until 2026 with the goal of $20 \cdot 10^{21}$ POT
Near Detector (ND280 and INGRID)

- At 280 m from the neutrino target

**ND280**
- $2.5^\circ$ off-axis
- The detector is composed of trackers, a combination of fine grained detectors (FGDs) and Ar TPCs
- Will be upgraded for phase-II to reduce systematics up to 4%

**INGRID:**
- On-axis
- Scintillation light detector made up by sixteen modules of iron plates and tracking scintillators

Used for cross-section studies and reduction of the systematic errors related to the neutrino flux and interactions at the far detector
Far Detector (Super-Kamiokande)

- 2.5$^\circ$ off-axis
- Water-Cherenkov detector with 50 kton of ultra-pure water
- 1000 m (2700 m.w.e.) of rock overburden (Kamioka mine)
- 11,143 20”-PMT facing inwards (inner detector) with 40% photocoverage
- 1,885 8”-PMT facing outwards (outer detector) and used for veto

- Being upgraded and refurbished for adding of Gd (SuperK-Gd), enhancing hugely its neutron-tagging capabilities (during phase-II)
- The NA61/SHINE hadron production experiment at CERN provides input for reducing the T2K flux uncertainties to $\sim 5\%$
Super-Kamiokande Neutrino Candidate Event Topologies

**μ-like event**

Super-Kamiokande I  
Run 1728 Sub 4 Ev 25171  
96-05-29 00:01:53  
Inner: 1094 hits, 7896 pE  
Outer: 4 hits, 22 pE (in-time)  
Trigger ID: 0x03  
D wall: 592.8 cm  
PC max-13m, p = 1012.9 MeV/c

**e-like event**

Super-Kamiokande I  
Run 1757 Sub 4 Ev 25716  
96-06-01 00:01:37  
Inner: 1248 hits, 9243 pE  
Outer: 4 hits, 56 pE (in-time)  
Trigger ID: 0x04  
D wall: 671.6 cm  
PC e-13m, p = 618.1 MeV/c
T2K Oscillation Analysis Results

Compare observed event rates at SK to predictions under oscillation hypothesis, with inputs from ND rates. Results are for, $\nu$-mode: $1.49 \cdot 10^{21}$ POT + $\bar{\nu}$-mode: $1.12 \cdot 10^{21}$ POT.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Prediction</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\delta_{CP} = -\pi/2$</td>
<td>$\delta_{CP} = 0$</td>
</tr>
<tr>
<td>FHC 1R(ing) $\mu$</td>
<td>268.5</td>
<td>268.2</td>
</tr>
<tr>
<td>RHC 1R(ing) $\mu$</td>
<td>95.5</td>
<td>95.3</td>
</tr>
<tr>
<td>FHC 1R e 0 decay-e</td>
<td>73.8</td>
<td>61.6</td>
</tr>
<tr>
<td>FHC 1R e 1 decay-e</td>
<td>6.9</td>
<td>6.0</td>
</tr>
<tr>
<td>RHC 1R e 0 decay-e</td>
<td>11.8</td>
<td>13.4</td>
</tr>
</tbody>
</table>
$\theta_{23}$ and $\Delta m_{32}^2$

T2K data with reactor experiments constraints

The normal mass ordering and the second octant of $\theta_{23}$ is preferred

The best fit values are:

<table>
<thead>
<tr>
<th>Normal Ordering</th>
<th>Inverted Ordering</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$0.536^{+0.031}_{-0.046}$</td>
</tr>
<tr>
<td>$\Delta m_{32}^2 (10^{-3} \text{eV}^2)$</td>
<td>$2.434 \pm 0.064$</td>
</tr>
</tbody>
</table>
$\delta_{CP}$ and $\theta_{13}$

T2K data with reactor constraints

CP-conserving values are disfavoured by more that 2σ

<table>
<thead>
<tr>
<th>Mass Ordering</th>
<th>$\delta_{CP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best Fit</td>
<td>NH (2.0σ)</td>
</tr>
</tbody>
</table>
The NOνA Experiment

Dedicated to the measurement of $\theta_{23}$ and $\delta_{CP}$
The NOνA Beam

NOνA uses the NuMI beam to produce mainly $\nu_\mu$ or $\bar{\nu}_\mu$

The beam is running at the design power, 700 kW, since January 2017

The highest power neutrino beam in the world

Accumulated $8.85 \cdot 10^{20}$ POT in $\nu$-mode and $6.91 \cdot 10^{20}$ POT in $\bar{\nu}$-mode
The NOνA beam

The mean neutrino energy is $\langle E_\nu \rangle \sim 1.9$ GeV. The beam is 14.6 mrad ($\sim 0.84^0$) off-axis with respect to the far and near detectors.
NOνA Detectors

The NOνA experiment is composed by two identical (except for the size) detectors and 810 km apart.
The detectors are made up of 344,000 cells of extruded and highly reflective plastic PVC filled with liquid scintillator.
Each cell of the detectors measures 3.9 cm wide, 6.0 cm deep.
It also contains wavelength shifting fiber (WLS) agents.
The fiber end readout is a single pixel of a 32 pixel avalanche photo diode (APD) array.
**NOνA Detectors**

- **Near Detector**
  - 290 ton detector
  - Cell length is 4 m
  - About 100 m underground
  - Placed at 1 km from the neutrino target
  - It reduces the systematic uncertainties related to the flux predictions and also conducts cross-section studies
NO\(\nu\)A Detectors

- Far Detector
  - 14 kton detector
  - Cell is 15 m long
  - The detector is placed on the surface with a concrete and barite overburden, stopping a significant part of the cosmic rays
NOνA Neutrino Candidate Event Topologies

νμ CC Signal

μ + p

νe CC Signal

e + p

NC Signal or Background

π0 + π + p
Despite being very different experiments, the NOνA and T2K analysis strategies are the same. The far detector event rates are compared with the oscillation predictions, and near detector data is used to reduce uncertainties related to the beam flux and the cross-section interactions.

<table>
<thead>
<tr>
<th>Beam Mode</th>
<th>Predictions</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$-mode</td>
<td>30-75</td>
<td>58</td>
</tr>
<tr>
<td>$\bar{\nu}$-mode</td>
<td>10-22</td>
<td>18</td>
</tr>
</tbody>
</table>
The data events agree with the current neutrino oscillation parameter measurements.

The plot shows the event rates predictions depending on the $\theta_{23}$ octant, the mass ordering and the $\delta_{CP}$.
\( \theta_{23} \) and \( \Delta m_{32}^2 \)

The normal mass ordering and the second octant of \( \theta_{23} \) are preferred.
Current Long Baseline Experiments

The NOνA Experiment

\[ \delta_{CP} \]

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

<table>
<thead>
<tr>
<th>Mass Ordering</th>
<th>( \sin^2 \theta_{23} )</th>
<th>( \Delta m^2_{32} \ \left(10^{-3} \text{ eV}^2\right) )</th>
<th>( \delta_{CP} )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Best Fit</strong></td>
<td>NH (1.8( \sigma ))</td>
<td>0.58 ± 0.03</td>
<td>( 2.51^{+0.12}_{-0.08} )</td>
</tr>
</tbody>
</table>
The two collaborations agreed to the formation of a working group to perform a combined analysis of the data in order to improve the sensitivity to the neutrino oscillation parameters. The full joint analysis is forseen for 2021.
The MINOS and MINOS+ Experiments

MINOS was dedicated to measure the atmospheric oscillation parameters and MINOS+ is more focused on the additional (sterile) neutrinos search.
The MINOS and MINOS+ Beam

They use the NuMI beam as the NO\(\nu\)A experiment

- MINOS period: \(\langle E_\nu \rangle \sim 3\) GeV, \(10.56 \cdot 10^{20}\) POT in \(\nu\)-mode and \(3.36 \cdot 10^{20}\) POT in \(\bar{\nu}\)-mode
- MINOS+ period: \(\langle E_\nu \rangle \sim 7\) GeV, \(9.69 \cdot 10^{20}\) POT in \(\nu\)-mode

![Total NuMI protons](image)

- Low energy neutrinos
- Low energy antineutrinos
- Medium energy neutrinos
The MINOS/MINOS+ Detectors

Both, near and far, detectors share the same technology and are aligned with the beam axis.

The detectors are composed by iron-scintillator tracking calorimeters. Both of them are magnetized, allowing for \( \nu - \bar{\nu} \) distinction and better energy reconstruction.

- Near Detector: 1 km from target, 1 kton mass, 100 m underground
- Far Detector: 735 km from target, 5.4 kton mass, 716 m underground (Soudan mine)
MINOS/MINOS+ Combined Oscillation Analysis Results

<table>
<thead>
<tr>
<th>Mass Ordering</th>
<th>$\sin^2 \theta_{23}$</th>
<th>$\Delta m^2_{32} \ (10^{-3} \text{ eV}^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best Fit</td>
<td>NH (slight pref.)</td>
<td>0.42</td>
</tr>
</tbody>
</table>
Summary of LBL Results

Normal mass ordering - Preliminary

- MINOS, MINOS+ combined analysis 90% CL (2018)
- MINOS, MINOS+ combined analysis best fit
- NOvA analysis 90% CL (2018)
- NOvA analysis best fit (2018)
- T2K with reactor constraint analysis 90% CL (2018)
- T2K with reactor constraint analysis best fit
- T2K analysis 90% CL (2017)
The three main LBL neutrino experiments (except OPERA) have been reviewed and their most important results shown

In terms of neutrino oscillation results,

- All three experiments show a preference for normal neutrino mass ordering
- NOνA and T2K data prefer the second octant of $\theta_{23}$ and large values of $\delta_{CP}$, disfavouring CP-conservation in the lepton sector
- MINOS and MINOS+ best fit is at the first octant of $\theta_{23}$, although compatible with second octant at $< 1\sigma$

T2K will keep taking data until 2026 with improved near and far detectors and the goal of $20 \cdot 10^{21}$ POT accumulated

The proposed joint fit of NOνA and T2K will improve the sensitivity for the neutrino oscillation parameters, specially for the CP phase
Thank you very much!
Veel Dank!