Long-Baseline Accelerator Neutrino Oscillations

Louise Suter, Fermilab
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Create ~100% muon-neutrino beam (or anti-neutrino beam)

Characterize beam with ND

Make precision measurements of PMNS neutrino mixing parameters
Investigate BSM physics: Non-standard Interactions, additional flavors of neutrinos
Neutrino mass mixing matrix factorizes into three terms

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\end{pmatrix} =
\begin{pmatrix}
1 & c_{13} & s_{13} e^{-i\delta} \\
c_{23} & s_{23} & 1 \\
-s_{23} & c_{23} & s_{13} e^{i\delta} \\
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} \\
-s_{12} & c_{12} \\
0 & 0 & 1 \\
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\end{pmatrix}
\]

\[\Delta m_{32}^2 \approx 2 \times 10^{-3} \text{eV}^2\]
\[\frac{L}{E} = 500 \text{ km/GeV}\]

\[\Delta m_{31}^2 \approx \Delta m_{32}^2\]
\[\Delta m_{21}^2 \approx 8 \times 10^{-5} \text{eV}^2\]
\[\frac{L}{E} = 15,000 \text{ km/GeV}\]

\[\nu_\mu \rightarrow \nu_\mu\]
\[\nu_\mu \rightarrow \nu_\tau\]

atmospheric and
long baseline

\[\nu_e \rightarrow \nu_e\]
\[\nu_\mu \rightarrow \nu_\mu + \nu_\tau\]

reactor and
long baseline

\[\nu_e \rightarrow \nu_\mu + \nu_\tau\]

\[\nu_e \rightarrow \nu_\mu + \nu_\tau\]

\[c_{\alpha\beta} = \cos \alpha \beta\]
\[s_{\alpha\beta} = \sin \alpha \beta\]
Neutrino mass mixing matrix factorizes into three terms

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\end{pmatrix}
\begin{pmatrix}
1 & c_{12} & s_{12} \\
-c_{12} & c_{12} & -s_{13}e^{i\delta} \\
-s_{12} & c_{12} & c_{13}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[\Delta m_{32}^2 \simeq 2 \times 10^{-3} \text{eV}^2\]
\[L/E = 500 \text{ km/GeV}\]

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\[\Delta m_{21}^2 \simeq 8 \times 10^{-5} \text{eV}^2\]

Long-Baseline experiments can probe

\[c_{\alpha\beta} = \cos\alpha_\beta \quad s_{\alpha\beta} = \sin\alpha_\beta\]
ν_μ \rightarrow ν_μ, \ ν_μ disappearance in a ν_μ beam

Can make precision measurements of the amplitude, atmospheric mixing angle, \(\sin^2(2θ_{23})\), and frequency, mass difference, \(Δm^2_{32}\)

\[
P(ν_μ \rightarrow ν_μ) \approx 1 - \sin^2(2θ_{23}) \sin^2 \left( \frac{1.27Δm^2_{32}[eV^2]L_ν[km]}{E_ν[GeV]} \right)
\]

First maxima, location of most LBL neutrino experiments

θ_{23} has been measured to be near 45 degrees indicating maximal mixing between ν_μ and ν_τ in the ν_3 mass state
$\nu_\mu \to \nu_\mu$, $\nu_\mu$ disappearance in a $\nu_\mu$ beam

Can make precision measurements of the amplitude, atmospheric mixing angle, $\sin^2(2\theta_{23})$, and frequency, mass difference, $\Delta m_{32}^2$

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2 \left( \frac{1.27 \Delta m_{32}^2 [eV^2] L [km]}{E_\nu [GeV]} \right)$$
Neutrino mass mixing matrix factorizes into three terms

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\end{pmatrix} =
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-s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & s_{13} e^{-i\delta} \\
-s_{13} e^{i\delta} & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} \\
-s_{12} & c_{12}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[
\Delta m^2_{32} \approx 2 \times 10^{-3} \text{eV}^2 \\
L/E = 500 \text{ km/GeV}
\]

\[
\Delta m^2_{31} \approx \Delta m^2_{32}
\]

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\Delta m^2_{21} \approx 8 \times 10^{-5} \text{eV}^2 \\
L/E = 15,000 \text{ km/GeV}
\]

\[
\nu_\mu \rightarrow \nu_\mu \\
\nu_\mu \rightarrow \nu_\tau \\
\nu_\mu \rightarrow \nu_e
\]

atmospheric and long baseline

\[
\nu_e \rightarrow \nu_e \\
\nu_e \rightarrow \nu_\mu
\]

reactor and long baseline

\[
\nu_e \rightarrow \nu_\mu + \nu_\tau
\]

solar and reactor

\[c_{\alpha\beta} = \cos\alpha\beta \quad s_{\alpha\beta} = \sin\alpha\beta\]
$\nu_\mu \rightarrow \nu_e$, $\nu_e$ appearance in a $\nu_\mu$ beam

To describe $\nu_e$ appearance must use full 3-flavor description and include effects of interaction of neutrinos with matter

$P(\nu_\mu \rightarrow \nu_e) \propto \theta_{23}, \Delta m^2_{13}, \theta_{13}, \delta_{cp}$

$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

$\theta_{13}$ well constrained from reactor experiments

Probe $\theta_{23}, \Delta m^2_{13}$, and $\delta_{cp}$

Has sensitivity to some of the biggest questions in the field
\( \nu_\mu \rightarrow \nu_e, \nu_e \) appearance in a \( \nu_\mu \) beam

To describe \( \nu_e \) appearance must use full 3-flavor description and include effects of interaction of neutrinos with matter.

No matter effects and CP conservation

\[
P(\nu_\mu \rightarrow \nu_e) \propto \theta_{23}, \Delta m_{13}^2, \theta_{13}, \delta_{\text{cp}}
\]

\[
P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)
\]

\( \theta_{13} \) well constrained from reactor experiments

Probe \( \theta_{23}, \Delta m_{13}^2, \) and \( \delta_{\text{cp}} \)

Has sensitivity to some of the biggest questions in the field
Neutrino Mass Hierarchy

Matter effect: Electron neutrinos experience additional interactions with electrons in the earth.
Charge Parity Violation

Do neutrinos conserve CP?
Observing CPV in neutrinos important step towards leptogenesis
$P(\nu_\mu \rightarrow \nu_e) \propto \theta_{23}, \Delta m^2_{13}, \delta_{CP}$

- Inverted Hierarchy
- Normal Hierarchy

$\sin^2 \theta_{23} = 0.5$

$\delta_{CP}$

- $\delta_{CP} = 0$
- $\delta_{CP} = \pi/2$
- $\delta_{CP} = \pi$
- $\delta_{CP} = 3\pi/2$

$E = 2$ GeV
w/ Matter Effects

$\sin^2 \theta_{23}$ provides amplitude of oscillation
Longest baseline of currently running experiments
Off-axis beam gives narrow band neutrino beam at 2 GeV
Huge, low-Z, 65% active, liquid scintillator tracking calorimeter

Designed to maximize electron neutrino selection efficiency
Low-Z to enhance electron pion separation
NuMI beam has been running excellently, regularly exceeding 700 kW designed power. Recently set a record for average power of 758 kW/hour.

Antineutrino data: $\sim 12.5 \times 10^{20}$ Protons-on-target

Neutrino data: $\sim 11 \times 10^{20}$ Protons-on-target collected to date, $8.85 \times 10^{20}$ POT used in current analysis
The modeling of neutrino beams and interactions with complicated nuclei create a challenge for oscillation measurements. Modeling and systematic uncertainties constrained using near detector.

NOvA used theoretical input and observed data-MC differences to improve its cross section model in both detectors.

Remaining data-mc differences in Near Detector data, due to flux and detector miss-modeling, used to correct Far Detector prediction.
NOvA is planning to run until 2025, results shown here represent about 30% of the total data to be collected.

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>Prediction (at best fit)</th>
<th>bkgd</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$</td>
<td>113</td>
<td>124</td>
<td>4.2</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>102</td>
<td>96</td>
<td>2.2</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>58</td>
<td>59</td>
<td>15</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>27</td>
<td>27</td>
<td>10.3</td>
</tr>
</tbody>
</table>

Antineutrinos: 12.33e20 Protons-on-target  
Neutrinos: 8.85e20 Protons-on-target

Greater than 4.4σ evidence of electron antineutrino appearance in long-baseline beam
CP phase, $\delta_{CP}$, and mass hierarchy

Best fit:
$$\sin^2 \theta_{23} = 0.56^{+0.11}_{-0.03}$$
$$\Delta m_{32}^2 = +2.48^{+0.11}_{-0.08}\times10^{-3} \text{eV}^2/c^4$$
$$\delta_{CP} = 0^{+1.3}_{-0.4}$$

$\theta_{13}$ set to world average from PDG

At 1.1$\sigma$ all values of $\delta_{CP}$ allowed normal hierarchy upper octant

For inverted hierarchy $\delta_{CP} = \pi/2$ ruled out at greater than 4 $\sigma$ for all values of $\theta_{23}$
NOvA atmospheric mixing angle limits, $\theta_{23}$

- Best fit in normal hierarchy and $\theta_{23}$ upper octant
  $\sin^2 \theta_{23} = 0.56^{+0.11}_{-0.03}$
  $\Delta m^2_{32} = +2.48^{+0.11}_{-0.06} \times 10^{-3}$ eV$^2$/c$^4$

- Lower octant, $\sin^2 \theta_{23} < 0.5$, disfavored at 1.6$\sigma$
- Maximal mixing, $\sin^2 \theta_{23} = 0.5$, disfavored at 1.5$\sigma$
Values used in bi-probability
- Inverted Hierarchy: $\Delta m^2_{32} = -2.54 \times 10^{-3}$ eV$^2$
- Normal Hierarchy: $\Delta m^2_{32} = +2.48 \times 10^{-3}$ eV$^2$
- Upper $\theta_{23}$ octant: $\sin^2 \theta_{23} = 0.56$
- Lower $\theta_{23}$ octant: $\sin^2 \theta_{23} = 0.48$

Total events - neutrino beam
- NOvA FD: $8.85 \times 10^{20}$ POT-equiv ($\nu$)
- $12.33 \times 10^{20}$ POT ($\bar{\nu}$)

Total events - antineutrino beam
- NOvA Preliminary
- 2019 best fit

\[ \sin^2 2\theta_{13} = 0.082 \]
\[ \sin^2 2\theta_{13} = 0.082 \]

**Inverted Hierarchy**

- \[ \delta_{\text{CP}} = 0 \]
- \[ \delta_{\text{CP}} = \pi/2 \]
- \[ \delta_{\text{CP}} = \pi \]
- \[ \delta_{\text{CP}} = 3\pi/2 \]

**Normal Hierarchy**

- \[ \sin^2 \theta_{23} = 0.56 \]
- \[ \sin^2 \theta_{23} = 0.48 \]

**Values used in bi-probability**

<table>
<thead>
<tr>
<th></th>
<th>Inverted Hierarchy</th>
<th>Normal Hierarchy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper octant</td>
<td>Disfavored 1.8σ</td>
<td>Best fit</td>
</tr>
<tr>
<td>( \sin^2 \theta_{23} &gt; 0.5 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower octant</td>
<td>Disfavored 2σ</td>
<td>Disfavored 1.6σ</td>
</tr>
<tr>
<td>( \sin^2 \theta_{23} &lt; 0.5 )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Within best fit region, Normal Hierarchy upper octant, all values of \( \delta_{\text{CP}} \) allowed at 1.1σ.
T2K
Super-Kamiokande detector

Credit: Kamioka Observatory, ICRR, The University of Tokyo
T2K: Off-axis long-baseline neutrino oscillation experiment

Off-axis beam gives narrow band neutrino beam at 600 MeV

Near Detectors: ND280 and INGRID

Far Detector, Super-Kamiokande

1,700 m below sea level

295 km
Challenge of Modeling Neutrino Interactions

The modeling of neutrino beams and interactions with complicated nuclei create a challenge for oscillation measurements. Modeling and systematic uncertainties constrained using near detector.

T2K selected samples in ND based on lepton plus number of pions or tracks which match samples which they select in Super-K.

Used large number of parameters to both fit near detector data to produce central value for Super-K prediction and to constrain the systematic uncertainties.
Steadily increasing beam power, beam nominally running now at 500 kW

Antineutrino data: \( \sim 15 \times 10^{20} \) Protons-on-Target

Neutrino data: \( \sim 31 \times 10^{20} \) Protons-on-Target collected to date
Far Detector, Super-Kamiokande, is a water Cherenkov detector
Stainless-steel tank, 39.3m diameter and 41.4m tall, filled with 50,000 tons of ultra pure water

Detector provides excellent $e/\mu$ separation and $\pi^0$ rejection.
Select 1-ring, Charged Current Quasi-Elastic enriched sample, and a CC1$\pi^+$ sample for $\nu_e$ appearance.
Super-Kamiokande events

<table>
<thead>
<tr>
<th>sample</th>
<th>$\delta = - \pi/2$</th>
<th>$\delta = 0$</th>
<th>$\delta = + \pi/2$</th>
<th>$\delta = \pi$</th>
<th>Data</th>
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<tr>
<td>neutrino $\mu$ CCQE</td>
<td>272.4</td>
<td>272.0</td>
<td>272.4</td>
<td>272.8</td>
<td>243</td>
</tr>
<tr>
<td>anti neutrino $\mu$ CCQE</td>
<td>139.2</td>
<td>139.2</td>
<td>139.5</td>
<td>139.9</td>
<td>140</td>
</tr>
<tr>
<td>neutrino $\nu$ CCQE</td>
<td>74.4</td>
<td>62.2</td>
<td>50.6</td>
<td>62.7</td>
<td>75</td>
</tr>
<tr>
<td>neutrino $\nu$ CC1+</td>
<td>7.02</td>
<td>6.10</td>
<td>4.94</td>
<td>5.87</td>
<td>15</td>
</tr>
<tr>
<td>anti-neutrino $\nu$ CCQE</td>
<td>17.1</td>
<td>19.4</td>
<td>21.7</td>
<td>19.3</td>
<td>15</td>
</tr>
</tbody>
</table>

Observed events at Super-K.
predictions assuming Normal
Hierarchy reactor constant on $\theta_{13}$

In neutrino mode the deficit of $\mu$-like
events is compatible with statistical
and systematic uncertainties

Muon neutrino: Charged current quasi-elastic sample

Muon antineutrino: Charged current quasi-elastic sample
Super-Kamiokande events

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<td>neutrino e CC1$\pi^+$</td>
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Electron antineutrino results

Expect 9.4 events in the case of no $\nu_e$ appearance, and observed 15 events.

No $\bar{\nu}_e$ appearance excluded at 2$\sigma$
T2K Atmospheric mixing angle limits, $\theta_{23}$

T2K data compatible with maximal mixing

<table>
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<tr>
<th>Parameter</th>
<th>Best Fit NH (IH)</th>
<th>±1σ NH (IH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2\theta_{32}$</td>
<td>0.54 (0.53)</td>
<td>[0.490,0.558] ([0.496,0.560])</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m^2_{32}</td>
<td>\times 10^{-3} eV^2/c^4$</td>
</tr>
<tr>
<td>$\sin^2\theta_{13}$</td>
<td>0.0268 (0.0305)</td>
<td>[0.0222,0.0319] ([0.0253,0.0369])</td>
</tr>
</tbody>
</table>
**CP phase, $\delta_{\text{CP}}$, at T2K**

The vertical lines show the corresponding allowed 95% confidence interval.

[T2K Run 1-9 Preliminary Diagram]

T2K data prefer values of $\delta_{\text{CP}} \sim -\pi/2$

Mostly driven by the large number of events observed in the e-like sample in neutrino mode.

No inverted hierarchy values allowed at < 2$\sigma$

**CP conservation** ($\delta_{\text{CP}} = 0, \pi$) disfavored at 2$\sigma$ for both mass hierarchies

<table>
<thead>
<tr>
<th>C.L.</th>
<th>Normal hierarchy</th>
<th>Inverted hierarchy</th>
</tr>
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<tbody>
<tr>
<td>68%</td>
<td>[-2.51, -1.26]</td>
<td>-</td>
</tr>
<tr>
<td>90%</td>
<td>[-2.80, -1.04]</td>
<td>-</td>
</tr>
<tr>
<td>2$\sigma$</td>
<td>[-2.97, -0.63]</td>
<td>[-1.78, -0.98]</td>
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Looking forward

Based on current analysis:
• Potential 3-5σ sensitivity to hierarchy with favorable parameters
• Possible >2σ sensitivity to CP violation

• Proposed accelerator and beam upgrade projects which will enable beam up to ~1 MW
• Test-beam program underway to improve detector modeling and reduce systematic uncertainties

NOvA will continue take data until ~2025
Plan to run 50% neutrino, 50% anti-neutrino going forward

\[ \sin^2 \theta_{23} = 0.45 \pm 0.60, \ \Delta m^2_{32} = +2.48 \times 10^{-3} \text{eV}^2, \ \sin^2 2\theta_{13} = 0.082 \]

\[ \chi^2 = \sigma^2 = \Delta \chi^2 \]

\[ \delta_{CP} = \begin{cases} 3\pi/2 & \text{for NH} \\ \pi & \text{for NH} \\ 0 & \text{for NH} \\ \pi/2 & \text{for NH} \end{cases} \]

\[ \nu_{\text{POT}}(2.0 \times 10^{20}) + 3.6 \times 10^{20} \text{ POT}(\nu) \text{ by 2025} \]
Looking forward

- Super-K undergoing Gd doping this summer, improves neutron detection capability and may provide wrong sign background constraint in T2K anti-electron data
- T2K initiated Near Detector upgrade project, aim to reduce systematics to 4%
- Approved beam upgrades allow 750 kW operation, with eventual upgrades to 1.3 MW (2021)
- Proposal to collect 8x more data by 2027 (when HK starts), total of $20 \times 10^{21}$ POT

Enables T2K to have up to 3σ CP violation sensitivity

Sensitivity improves beyond 3σ with reduced systematic errors
T2K and NOvA collaborations to produce joint neutrino oscillation analysis

January 30, 2019

The NOvA and T2K Collaborations are working towards the formation of a joint working group to enhance the measurements of neutrino oscillation parameters made by each collaboration individually. The projected timescale of the NOvA-T2K working group is for production of a full joint neutrino oscillation analysis by 2021.
Conclusions

- Exciting active program in long-baseline neutrino physics from both NOvA and T2K
- Both NOvA and T2K data have preference for Normal Hierarchy over Inverted Hierarchy
- NOvA and T2K best fit in upper octant of $\theta_{23}$, but at NOvA lower octant and maximal mixing only disfavored at $\sim 1.5\sigma$, and T2K results consistent with maximal mixing
- At T2K CP conservation ($\delta_{CP} = 0, \pi$) disfavored at $2\sigma$ for both mass hierarchies, for NOvA all $\delta_{CP}$ values in normal hierarchy upper octant allowed at $1.1\sigma$
- NOvA antineutrino results 4.4 observation for electron anti-neutrino appearance
- Both experiments have exciting upgrade programs in the works, and are aiming for joint results for 2021

Thanks for all the people I took plots and slides from, including Mayly Sanchez, Morgan Wascko, Ciro Riccio, Jeremy Wolcott and others