3 Neutrino Model

• \( |\nu_i\rangle = \sum \alpha U_{\alpha i}^* \nu_\alpha \rangle \)

• Flavor composition of neutrinos change as they propagate

\[
U_{PMNS} = \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix} \times 
\begin{pmatrix}
\cos \theta_{13} & 0 & e^{-i \delta_{CP}} \sin \theta_{13} \\
0 & 1 & 0 \\
-e^{i \delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13}
\end{pmatrix} \times 
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

• \( \theta_{23} \approx 45^\circ \)
• Atmospheric, Accelerator
• Octant unknown

• \( \theta_{13} \approx 10^\circ \)
• Short-Baseline Reactor, Accelerator
• \( \delta_{CP} \) unknown

• \( \theta_{12} \approx 35^\circ \)
• Solar, Long-Baseline Reactor

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\( \nu_e \) Appearance

\[
P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 + \alpha \sin 2\theta_{13} \cos \delta \frac{\sin(aL) \sin(\Delta_{31} - aL)}{(aL)(\Delta_{31} - aL)} \cos \Delta_{32} - \alpha \sin 2\theta_{13} \sin \delta \frac{\sin(aL) \sin(\Delta_{31} - aL)}{(aL)(\Delta_{31} - aL)} \sin \Delta_{32}
\]

\[
a = G_F N_e \sqrt{2}
\]

\[
\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}
\]

- \( \sin^2(2\theta_{13}) \) determines size of event sample
- \( \delta_{CP} \) affects amplitude of oscillation
- \( \Delta_{31} \) affects frequency of oscillation
- MH affects both amplitude and frequency
Matter and CP Asymmetry

Matter asymmetry very important for long-baseline experiments!

Degeneracy between CP and matter asymmetry for 1st oscillation node at short baseline

\[ \delta_{\text{CP}} = -90^\circ, \text{IH} \]
\[ \text{or} \]
\[ \delta_{\text{CP}} = -20^\circ, \text{NH} \]
Matter and CP Asymmetry

Matter asymmetry very important for long-baseline experiments!

Longer baseline breaks degeneracy between CP and matter asymmetry.
Qualitative summary

- MH: Longer baseline is better
- CPV: Balancing act between long enough baseline to resolve degeneracy with MH and short enough baseline to accumulate statistics

Study with optimized beam design

1300 km a near optimal baseline
Long-Baseline Neutrino Experiment

- Neutrino beam from FNAL to SURF (1300 km baseline)
  - Protons from Main Injector
  - New $\mu$-neutrino beam line

- Massive underground far detector
  - LAr TPC
  - Integrated photon detection system
Sanford Underground Research Facility

Sanford Underground Research Facility (SURF) in the Black Hills of western South Dakota
Sanford Underground Research Facility (SURF) in the Black Hills of western South Dakota
LBNE Collaboration

- 372 members, 61 institutions, 5 countries (April 2013)
- Co-spokespersons: Milind Diwan (BNL), Bob Wilson (CSU)
LBNE Staging

- LBNE10
  - 10 kt LAr TPC
  - 700 kW, 120 GeV proton beam \((6 \times 10^{20} \text{ POT/year})\)
  - US DOE scope/cost approved, with the expectation that the scope of experiment will expand as the collaboration grows

- Higher exposure
  - Goal to have >10 kt LAr TPC in first phase of experiment
  - Proton beam upgradeable to 2.3 MW

- Underground physics
  - Goal to build first phase of experiment at 4850L - engineering/design efforts focusing on 4850L only
ν\textsubscript{e} Appearance Events

35 kt:

35 kton LAr @ 1300 km
5 yrs ν mode
sin\(^2\)2\(13\) = 0.09
Normal hierarchy

10 kt:

<table>
<thead>
<tr>
<th>Signal Events</th>
<th>Background Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>ν\textsubscript{e}</td>
<td>ν\textsubscript{μ} NC</td>
</tr>
<tr>
<td>Neutrino Normal Hierarchy</td>
<td>222</td>
</tr>
<tr>
<td>Neutrino Inverted Hierarchy</td>
<td>98</td>
</tr>
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<td>54</td>
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**ν_e Appearance Events**

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35 kton LAr @ 1300 km
5 yrs ν mode
\(\sin^2(2\theta_{13}) = 0.09\)
Inverted hierarchy

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<tr>
<td></td>
<td></td>
<td>Signal, (\delta_{CP} = 90^\circ)</td>
<td>(\nu_e) CC</td>
</tr>
<tr>
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10 kt:

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<th>(\nu_\mu) NC</th>
<th>(\nu_\mu) CC</th>
<th>(\nu_e) Beam</th>
<th>(\nu_\tau) CC</th>
<th>Total</th>
</tr>
</thead>
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<tr>
<td>Neutrino Normal Hierarchy</td>
<td>222</td>
<td>19</td>
<td>24</td>
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Parameter Measurements

\[ \delta_{\text{CP}} \text{ vs. } \sin^2(2\theta_{13}) \]

Project X Staging
1:1 \nu:\bar{\nu}, 1%/5% Signal/BG systematics

- True values
- 700 kW, 100 kt.yr
- + 1.1 MW, 200 kt.yr
- + 2.3 MW, 200 kt.yr

\[ \Delta m^2_{31} \text{ vs. } \theta_{23} \]

True values
- 700 kW, 100 kt.yr
- + 1.1 MW, 200 kt.yr
- + 2.3 MW, 200 kt.yr

\[ \delta_{\text{CP}} \text{ vs. } \sin^2(2\theta_{13}) \]

Fogli 2012 1\sigma bound on \sin^2(2\theta_{13})
Mass Hierarchy Determination

LBNE10, in combination with NOvA and T2K, will determine the mass hierarchy to $>3\sigma$ for all values of $\delta_{\text{CP}}$, for either hierarchy.
LBNE10 represents a major step forward in the search for leptonic CP violation. 3σ evidence for CPV could be found for many values of $\delta_{CP}$. A larger detector and higher beam power will accelerate $>5\sigma$ sensitivity.
LBNE10 could determine the $\theta_{23}$ octant at $>3\sigma$ if the true value of $\theta_{23}$ is within the $1\sigma$ Fogli 2012 bound. With higher exposure, it will be possible to determine the $\theta_{23}$ octant at $>3\sigma$ for true values of $\theta_{23}$ within a few degrees of 45°.
Atmospheric Neutrinos

MH sensitivity independent of true $\delta_{CP}$!
Non-standard interactions:
NC NSI discovery reach (3σ C.L.)

\[ \sin^2 2\theta_{13} = 0.094 \]
only one \( \varepsilon \neq 0 \) at a time
Left/right edges: Best/worst arg(\( \varepsilon \))

\[ L = 1300 \text{ km}, \ E_{\text{beam}} = 80 \text{ GeV} \]

Current bounds
LBNE sensitivity
- 700 kW, 50+50 kt yrs
- 1100 kW, 100+100 kt yrs
- 2300 kW, 100+100 kt yrs

GLoBES 2013

Proton decay:
\( \nu K^+ \) mode

Supernova burst neutrinos:
Livermore model
- 10 kpc
- 35 kt LAr
Summary

- FNAL & SURF provide an ideal baseline and excellent facilities to address many of the unanswered questions in neutrino physics
- LBNE10:
  - MH determined at $>3\sigma$ for all values of $\delta_{CP}$
  - CP violation detected at $>3\sigma$ for $\sim40\%$ of $\delta_{CP}$ values
  - $\theta_{23}$ octant determined at $>3\sigma$ ($\theta_{23}$ within $1\sigma$ of Fogli 2012 best fit)
  - LBNE has approval to begin this program
- Clear path forward for detector and accelerator upgrades
- Potential to significantly expand LBNE physics reach in first phase of the experiment
  - Building an international collaboration
  - Good experiment can become great experiment
- Long-term program: decades of precision neutrino oscillation measurements to come!
Best-fit Neutrino Parameters

- $\delta m^2 = 7.5 \times 10^{-5} \text{ eV}^2$ (3%)
- $\Delta m^2 = 2.4 \times 10^{-3} \text{ eV}^2$ (3%)
- $\sin^2(\theta_{12}) = 0.31$ (5%)
- $\sin^2(\theta_{23}) = 0.39$ (14%)
- $\sin^2(\theta_{13}) = 0.02$ (10%)
- $\delta_{CP} = ?$
- $M_H = ?$

Fit shows some preference for $\delta_{CP}$ near $-\pi$ and no $M_H$ preference.