Lecture 2 Outline

- **Three neutrinos**
  - Oscillation probability
  - Matter effects

- **Experimental Techniques**
  - Signals and ambiguities for measuring $\theta_{13}$ and $\delta_{CP}$ and the neutrino mass hierarchy
  - Understanding sensitivity calculations
  - Experiment baseline
  - Neutrino beam configurations

- **Experimental Landscape**
  - *Reactor Experiments*: $\bar{\nu}_e$ disappearance (Ed Blucher lecture)
  - $\nu_e$ appearance: T2K, NOvA, LBNE
  - Experiment Timelines
Lecture 2 Outline cont.

- Beyond conventional beams?
- New results to keep an eye on
- Conclusions

Lot’s of the plots and numbers in this lecture are for demonstration/education purposes only and don’t represent official calculations or status of any particular experiment.

Always check with an experiment’s official documentation to get the most up to date information.
Three neutrinos: $\theta_{13}$ and $\delta_{CP}$
Features of the matrix

- Two component mixing
- Complex phase $\delta$ and $\theta_{13}$

Now consider the case of all three neutrinos:

$$
\begin{bmatrix}
    v_e \\
    v_\mu \\
    v_\tau
\end{bmatrix} =
\begin{pmatrix}
    U_{e1} & U_{e2} & U_{e3} \\
    U_{\mu1} & U_{\mu2} & U_{\mu3} \\
    U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{bmatrix}
    v_1 \\
    v_2 \\
    v_3
\end{bmatrix}
$$
Current state of knowledge

<table>
<thead>
<tr>
<th>$\Delta m^2_{12}$</th>
<th>$7.59 \pm 0.02 \times 10^{-5} \text{eV}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2_{23}$</td>
<td>$2.43 \pm 0.13 \times 10^{-3} \text{eV}^2$</td>
</tr>
<tr>
<td>$\sin^2 2\theta_{12}$</td>
<td>$0.87 \pm 0.03$</td>
</tr>
<tr>
<td>$\sin^2 2\theta_{23}$</td>
<td>$&gt; 0.92$</td>
</tr>
<tr>
<td>$\sin^2 2\theta_{13}$</td>
<td>$&lt; 0.19$ (90%CL)</td>
</tr>
</tbody>
</table>

$\Delta m^2_{12} \ll \Delta m^2_{23}$

Neutrino Mass Squared

<table>
<thead>
<tr>
<th>$\nu_e$</th>
<th>$\nu_\mu$</th>
<th>$\nu_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2_{ee}$</td>
<td>$\sin^2 \theta_{23}$</td>
<td></td>
</tr>
<tr>
<td>$\Delta m^2_{em}$</td>
<td>$\sin^2 \theta_{13}$</td>
<td></td>
</tr>
<tr>
<td>$\Delta m^2_{ee}$</td>
<td>$\sin^2 \theta_{12}$</td>
<td></td>
</tr>
</tbody>
</table>

NORMAL

$\Delta m^2_{13} \cong \Delta m^2_{23}$

$\Delta m^2_{13} \approx \Delta m^2_{23}$

$\frac{m_1}{m_2}$

Fractional Flavor Content

INVERTED

$\nu_e$ OR $\nu_\mu$
Oscillation Probability with 3 flavors

\[ \alpha, \beta = e, \mu, \tau \]

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U_{\alpha i}^* U_{\beta j} U_{\alpha j}^* U_{\beta j}^*) \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4E} \right) + 2 \sum_{i>j} \Im(U_{\alpha i}^* U_{\beta i} U_{\alpha j}^* U_{\beta j}^*) \sin \left( \frac{\Delta m_{ij}^2 L}{2E} \right)
\]

\[
P(\nu_\alpha \rightarrow \nu_\beta) = P_{\alpha\beta} \left( \Delta m_{21}^2, \Delta m_{31}^2, \theta_{12}, \theta_{13}, \theta_{23}, \delta; E, L \right)
\]
3- \( \nu \) Oscillation Probability

\[
P(\nu_\alpha \rightarrow \nu_\beta) = P_{\alpha\beta}(\Delta m_{21}^2, \Delta m_{31}^2, \theta_{12}, \theta_{13}, \theta_{23}, \delta; E, L) \quad \alpha, \beta = e, \mu, \tau
\]

Ignore the small \( \Delta m_{21}^2 \)

\[
P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta_{23} \cos^4 (\theta_{13}) \sin^2 (\Delta m_{32}^2 L / 4E)
\]

\[
P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta_{13} \sin^2 (\theta_{23}) \sin^2 (\Delta m_{32}^2 L / 4E)
\]

\[
P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta_{13} \sin^2 (\theta_{23}) \sin^2 (\Delta m_{32}^2 L / 4E)
\]

\[
P(\nu_\tau \rightarrow \nu_e) = \sin^2 2\theta_{13} \cos^2 (\theta_{23}) \sin^2 (\Delta m_{32}^2 L / 4E)
\]
3- ν Oscillation Probability

\[ P(\nu_\alpha \rightarrow \nu_\beta) = P_{\alpha\beta}(\Delta m^2_{21}, \Delta m^2_{31}, \theta_{12}, \theta_{13}, \theta_{23}, \delta; E, L) \quad \alpha, \beta = e, \mu, \tau \]

And small \( \theta_{13} \)

\[ P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta_{23} \cos^2(\theta_{13}) \sin^2(\Delta m^2_{32} L / 4E) \]

\[ P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2(\theta_{23}) \sin^2(\Delta m^2_{32} L / 4E) \]

\[ P(\nu_\tau \rightarrow \nu_\mu) = \sin^2 2\theta_{13} \sin^2(\theta_{23}) \sin^2(\Delta m^2_{32} L / 4E) \]

\[ P(\nu_\tau \rightarrow \nu_e) = \sin^2 2\theta_{13} \cos^2(\theta_{23}) \sin^2(\Delta m^2_{32} L / 4E) \]

But we need to ask how small \( \theta_{13} \) really is? Can we measure it?
Probabilities with $\theta_{13}$

In vacuum

\[ P(\nu_\mu \rightarrow \nu_\tau) = P1 + P2 + P3 + P4 \]

\[ P1 = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 (\Delta m^2_{32} L / 4E) \]
\[ P2 = \cos^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 (\Delta m^2_{21} L / 4E) \]
\[ P3 = \mp J \sin \delta \sin (\Delta m^2_{32} L / 4E) \]
\[ P4 = J \cos \delta \cos (\Delta m^2_{32} L / 4E) \]

\[ J = \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin (\Delta m^2_{32} L / 4E) \sin (\Delta m^2_{21} L / 4E) \]
Recall….

"see" the electrons in the Earth which affects the oscillation probability

And the probability equation is quite complicated………

There are a number of different ways that it can be expressed using approximations and expansions....
A popular approximation

\[ P(\nu_\mu \to \nu_\tau) \equiv \sin^2 2\theta_{13} T_1 - \alpha \sin 2\theta_{13} T_2 + \alpha \sin 2\theta_{13} T_3 + \alpha^2 T_4 \]

\[ \alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \sim 1/30 \quad \Delta = \frac{\Delta m_{31}^2 L}{4E} \quad x = 2\sqrt{2} G_F N_e / \Delta m_{31}^2 \]

\[ T_1 = \sin^2 \theta_{23} \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \]

\[ T_2 = \sin \delta \sin 2\theta_{12} \sin 2\theta_{23} \sin \Delta \frac{\sin(x\Delta) \sin[(1-x)\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \]

\[ T_3 = \cos \delta \sin 2\theta_{12} \sin 2\theta_{23} \cos \Delta \frac{\sin(x\Delta) \sin[(1-x)\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \]

\[ T_4 = \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2} \]


Anti-neutrinos
\[ \delta \rightarrow -\delta; \ x \rightarrow -x \]

Easiest way to understand it – code it up and make some plots......
\[ P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 \]
\[ + \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin(aL)}{aL} \Delta_{21} \cos(\Delta_{31} + \delta) \]
\[ + \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2 \]
\[ \Delta_{ab} = \Delta m_{ab}^2 \frac{L}{4E} \approx 1.27 \Delta m_{ee}^2 (eV^2) \frac{L(km)}{E(GeV)} \]
\[ a = G_F N_c / \sqrt{2} \]

Code it up and plot it....

Nunokawa, Parke, Valle
CP Violation and Neutrino Oscillations
\[ \nu_\mu \rightarrow \nu_e \] appearance probability

\[ L = 1300 \text{ km} \]

From the “solar” term

1\textsuperscript{st} and 2\textsuperscript{nd} oscillation maximum
Experimental Implications

Is $\theta_{13} \neq 0$?

Ambiguities

Sensitivity Calculations

The Experiment Baseline

Neutrino Beam Configurations
Can an experiment determine if $\theta_{13} \neq 0$?

- What would we expect to measure if $\theta_{13} = 0$? (null)
  - Intrinsic $\nu_e$ in the beam
  - $\nu_e$ from the $\theta_{12}$ mixing
  - Background events that fake $\nu_e$

- Calculate what we would expect to measure for a particular value of $\theta_{13}$ and $\delta$

- Need a significance of events above the null expectation

\[ \chi^2 = \frac{(N_{null} - N_{pred})^2}{\sigma^2} \]

Statistical and systematic uncertainty in the prediction
The Experimental Landscape for measuring $\theta_{13}$

**REACTOR EXPERIMENTS**

**ACCELERATOR LONG BASELINE:**

**T2K, NOVA**
Reactor Experiments

- **Measure** $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$

- $P_{\text{ext}} = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} - \cos^2 \theta_{12} \sin^2 2\theta_{13} \sin^2 \Delta_{31}$

Independent of $\delta$ and $\theta_{23}$
Double Chooz, Northeast France
Daya Bay, China
RENO – Yonggwang, Korea

Figure 1. A schematic layout of the RENO experiment.
Double Chooz sensitivity

A positive result from Double Chooz $\sin^2 2\theta_{13}$ is relatively large
Long-baseline experiments

T2K AND NOVA
Off-axis Beams

Recall, the neutrinos come from pion decay...

\[ E_\nu = \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2} \]

\[ \gamma = \frac{E_\pi}{m_\pi} \]

Neutrino energy is relatively independent of the parent pion energy: enhances low energy, suppresses high energy
Why Off-Axis Beams?

$L = 285 \text{km}$  JPARC 2 Super-K

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

$\nu$ energy spectrum
(\text{Flux} \times \text{x-section})

Medium Energy NuMI Beam Tune

rates for $L = 810 \text{ km}$

$\nu_{\mu}$ CC events/kt/3.7E20 POT/0.2 GeV
Signals and Backgrounds

NOvA

![Graph showing signals and backgrounds](image)

- $\nu_\mu$ (no oscillation)
- $\nu_\mu$ (after oscillation)
- Signal $\nu_e$
- Beam $\nu_e$

Events / kt / 3.7E20POT / GeV
Tokai to Kamiokande : T2K
T2K

90% C.L. sensitivity
(0.75 kW beam x 5yr)

$\Delta m_{13}^2$ (eV$^2$)

$10^{-1}$

$10^{-2}$

$10^{-3}$

$10^{-4}$

$\sin^2 2\theta_1$

$\sin^2 2\theta_{13} \sim 0.008$ ($\delta_{CP} = 0, \pi$)

T2K Discovery Potential on $\nu_\mu \rightarrow \nu_e$ as a Function of Integrated Power

Excluded by CHOOZ

Line: 3σ Discovery

Dot: 90% C.L. Upper Bound

2009: MINOS

2010: D.CHOOZ (disappearance)

2013: OPERA

2012: NOVA

2012: D.CHOOZ (disappearance)

2010 July

0.5MW x 2 years = 0.33MW x 3 years

Integrated Power (10^7 Mw-sec; ~1Mw x Effective 1 Year Experimental Period)

T2K
Full Proposal
NOvA
14 kilotons Liquid scintillator in PVC extrusions
Under construction at Ash River

Commissioning in 2012-13; data 2013 - 2019
Sensitivity to $\sin^2 2\theta_{13} \neq 0$

90% CL Sensitivity to $\sin^2 (2\theta_{13}) \neq 0$

$\delta (\pi)$

$2 \sin^2 (\theta_{23}) \sin^2 (2\theta_{13})$

3 years at 700 kW, 1.2 MW, and 2.3 MW for each $\nu$ and $\bar{\nu}$

- $\Delta m^2 > 0$
- $\Delta m^2 < 0$

L = 810 km, 15 kT
$\Delta m^2 = 2.4 \times 10^{-3} \text{eV}^2$
$\sin^2 (2\theta_{23}) = 1$

Dotted lines $\Rightarrow$ intensity upgrades (more neutrinos) that probably won’t happen
Experiment Timelines for limits on $\theta_{13}$


If $\sin^2 2\theta_{13} > 0.01$ the current “Phase I” experiments should be able to determine this.

Figure 18. Evolution of the $\theta_{13}$ sensitivity limit as a function of time (90% CL), i.e., the 90% CL limit which will be obtained if the true $\theta_{13}$ is zero. The four curves for Daya Bay correspond to different assumptions on the achieved systematic uncertainty, from weakest to strongest sensitivity: 0.6% correlated among detector modules at one site, 0.38% correlated, 0.38% uncorrelated among modules, 0.18% uncorrelated.
Bottom line

- $\theta_{13}$ needs to be non-zero in order to have a CP-violating phase $\delta$.
- Measuring determining that $\delta$ has a value (not 0 or $\pi$) such that $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$, says that neutrinos violate $CP$ which may have a connection to $CP$ violation in the early universe, and hence to the observed matter-anti-matter asymmetry......
- Experimental challenge – we want to measure the parameter, $\delta$. 
Beyond $\theta_{13}$

MATTER EFFECTS

MASS HIERARCHY

AMBIGUITIES AND $\delta_{CP}$
Matter Effects and CP

Normal hierarchy

$$\sin^2(2\theta_{13}) = 0.04$$

\[ \delta = 0 \]

Vacuum, $\delta = 0$

CP effect

$\gamma$'s

anti-$\gamma$'s
Matter and the hierarchy

Neutrinos – blue
Anti-neutrinos - red

Oscillation Probability - 1250 km (nor)

Neutrinos – enhanced
Anti-neutrinos - suppressed

Oscillation Probability - 1250 km (inv)

Anti-neutrinos – enhanced
Neutrinos - suppressed
Neutrino vs. anti-neutrino bi-probability plots

\[ \sin^2 2\theta_{13} = 0.04 \quad L = 810 \text{ km} \]

\[ E = 2 \text{ GeV} \]

\[ \frac{P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{d} \]

\[ P(\nu_\mu \rightarrow \nu_e) \]
Include matter effects

\[ \sin^2 2\theta_{13} = 0.04 \quad L = 810 \text{ km} \]

Decreases

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

Increases

Normal

Vacuum

Matter
Plot for the inverted mass hierarchy

\[ \Delta m_{32}^2 (inverted) = -|\Delta m_{32}^2| (normal) \]

\[
\sin^2 2\theta_{13} = 0.04 \quad L = 810 \text{ km}
\]

\[ P(\nu_\mu \rightarrow \nu_e) \]
Overlapping probabilities $\Rightarrow$ ambiguities.

$$\sin^2 2\theta_{13} = 0.04 \ L = 810 \text{ km}$$

- Normal\[\begin{align*}
\text{vacuum} & \quad \text{matter}
\end{align*}\]
- Inverted\[\begin{align*}
\text{vacuum} & \quad \text{matter}
\end{align*}\]

- $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ increases
- $P(\nu_\mu \rightarrow \nu_e)$ decreases
Probabilities ➔ Event rate
Calculate Event Numbers!

Suppose you observe 20 neutrino events:
there are 4 ambiguous solutions

Get a beam Spectrum... (i.e. NOvA)

$L = 810, \sin^2 2\theta_{13} = 0.02$
Solid = normal; dashed = inverted

Ambiguity in $\delta$ and the hierarchy

Suppose you observe 20 neutrino events:
there are 4 ambiguous solutions
NO\text{\textcopyright}A Sensitivity to the Mass Hierarchy

\begin{align*}
\delta (\pi) & \quad 2 \\
\delta (\pi) & \quad 1.8 \\
\delta (\pi) & \quad 1.6 \\
\delta (\pi) & \quad 1.4 \\
\delta (\pi) & \quad 1.2 \\
\delta (\pi) & \quad 1 \\
\delta (\pi) & \quad 0.8 \\
\delta (\pi) & \quad 0.6 \\
\delta (\pi) & \quad 0.4 \\
\delta (\pi) & \quad 0.2 \\
\delta (\pi) & \quad 0 \\
\end{align*}

$2 \sin^2(\theta_{23}) \sin^2(2\theta_{13})$

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

$\sin^2(2\theta_{23}) = 1$

$\Delta m^2 > 0$

$L = 810 \text{ km, } 15 \text{ kT}$

$3 \text{ years for each } \nu \text{ and } \bar{\nu}$

NO\text{\textcopyright}A at 700 kW,

1.2 MW, and 2.3 MW

\begin{align*}
L & = 810 \text{ km, } 15 \text{ kT} \\
\Delta m_{32}^2 & = 2.4 \times 10^{-3} \text{ eV}^2 \\
\sin^2(2\theta_{23}) & = 1 \\
\Delta m^2 & < 0 \\
\end{align*}

NO\text{\textcopyright}A
Interpreting NO$
u$A Sensitivity to the Mass Hierarchy

If $\sin^2 2\theta_{13} = 0.15$, for 50% of the possible values of $\text{TM}_{CP}$ the mass hierarchy can be determined at 95%CL.
Interpreting

A Sensitivity to the Mass Hierarchy

If $\sin^2 \theta_{13} = 0.10$, for 36% of the possible values of $\sin^2 \theta_{23}$, the mass hierarchy can be determined at 95%CL.
If $\sin^2 \theta_{13} = 0.07$, for 24\% of the possible values of $\tan^2 \theta_{CP}$ the mass hierarchy can be determined at 95\%CL.
NO\text{A} 95\% \text{ CL sensitivity to the Mass Hierarchy}

50\% @ the Chooz limit

700\text{kW for 6 years}

\sin^{2}2\theta_{13}
A 95% CL sensitivity to the Mass Hierarchy

No sensitivity below 0.05

700kW for 6 years

$\sin^2 2\theta_{13}$
Take away - 1

- Reactor disappearance
  - A positive result from Double Chooz will indicate a “good” value for $\theta_{13}$.
  - Limit results from Reno and Daya Bay (several years from now) will indicate that $\sin^2 2\theta_{13}$ is not larger than $\sim 0.01$.

- T2K appearance
  - Prompt results from T2K will begin to shed light on the question and help guide the way for future long baseline experiments needing to use a non-zero $\theta_{13}$ (mass hierarchy and CP violation).
NOvA has a baseline of 810 km, which is long enough to exhibit matter effects in the appearance probability $\nu_\mu \rightarrow \nu_e$.

However, for half the possible values of $\delta$, the effect is not large enough to resolve the ambiguities which arise among $\theta_{13}$, $\delta$, and the hierarchy.

Nor, for values of $\sin^2 2\theta_{13} < 0.05$ can the ambiguity be resolved.

Though $\sin^2 2\theta_{13}$ can be observed for values to approaching $\sim 0.01$. 
Resolving the mass hierarchy
A longer baseline

**Straight Through the Earth**

<table>
<thead>
<tr>
<th>MINOS</th>
<th>Soudan Mine, MN</th>
<th>2340 ft deep</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOvA</td>
<td>Ash River, MN</td>
<td>Surface level</td>
</tr>
<tr>
<td>LBNE</td>
<td>Homestake Mine, SD</td>
<td>4850 ft deep</td>
</tr>
</tbody>
</table>

- Lead, South Dakota, 800 miles
- Ash River, Minnesota, 500 miles
- Fermilab

(Proposed)
What happens at the longer baseline?

- Oscillation maxima are moved to higher energy
- Matter effects are significantly larger

Plot by Niki Saoulidou
$\sin^2 2\theta_{13} = 0.04$

1300, 1400, 1700 km probabilities (vacuum)
1300, 1400, 1700 km including matter affect

Neutrinos, normal hierarchy, Delta = 0
Dramatic matter and $\delta$ effects at 2500 km

$\delta: \text{solid} \rightarrow 0, \text{dashed} \rightarrow \frac{\pi}{2}, \pi, \frac{3\pi}{2}$
Wide Band Beam covering multiple nodes
Beam Spectra and Probability

Not very useful.....
Reducing Ambiguities

\[
\sin^2 2\theta_{13} = 0.04 \times 30 \times 10^{20} \nu, 30 \times 10^{20} \nu \text{-bar}, 15kT \Rightarrow 1.
\]

\[L = 1300 \text{km}\]
Resolving the mass hierarchy

\[ \sin^2 2\theta_{13} = 0.04 \times 30 \times 10^{20} \nu, \ 30 \times 10^{20} \nu\text{-bar}, \ 30kT \ \epsilon = 1. \]
Mass hierarchy at 1300 km baseline

\[ \sin^2 2\theta_{13} > 0.03 \] can determine for all values of \( \delta \) during running time.
s2theta13 = 0.10 18e20, 18e20, 20kT LAr
$s_{2\theta 13} = 0.06 \, 18e20, \, 18e20, \, 20kT \, \text{LAr}$
s2theta13 = 0.04 18e20, 18e20, 20kT LAr
s2theta13 = 0.01 18e20, 18e20, 20kT LAr
Long Baseline Neutrino Experiment
A deep underground laboratory
A new neutrino beam at Fermilab

Long Baseline Neutrino Experiment
Very Large Detectors

50,000 PMTs
Why so large?

- Significance of a signal: \( \sigma \sim \frac{N_{\text{signal}}}{\sqrt{N_{\text{background}}}} \)

- Two Detector Dependent factors:
  
  - Signal efficiency: \( N_{\text{signal}}^{\text{observed}} = N_{\text{signal}}^{\text{produced}} \times \text{efficiency} \)
  
  - Rejection on non-intrinsic backgrounds depends on detector resolutions
What events occur in a detector of this size?

Event spectra by Roxanne Guenette, Yale U. LBNE LB Physics Working Group
Real appearance signal
Observed Signal and Background events
Background Subtraction ➔ small stats

Spectrum for water cherenkov detector (100kt) for 3 years, nue mode, $\sin^2 2\theta_{13}=0.03$

- Signal $\nu_e$ (for $\delta_{\text{CP}} = -45$)
- Signal $\nu_e$ (for $\delta_{\text{CP}} = 0$)
- Signal $\nu_e$ (for $\delta_{\text{CP}} = +45$)
Can we improve efficiency?

Liquid Argon Time Projection Chamber may offer 5-6 times the detection efficiency of a Water Cerenkov detector, allowing for a significantly smaller detector.
"Equivalent" # of signal events

Spectrum for liquid argon detector (17.6kt) for 3 years, $\nu_e$ mode, $\sin^2 2\theta_{13} = 0.03$

- Signal $\nu_e$ (for $\delta_{CP} = -45$)
- Signal $\nu_e$ (for $\delta_{CP} = 0$)
- Signal $\nu_e$ (for $\delta_{CP} = +45$)
Efficiency is high and background is small

Spectrum for liquid argon detector (17.6kt) for 3 years, $\nu_e$ mode, $\sin^2 2\theta_{13} = 0.03$
What’s the best approach?

- Need to evaluate pro’s and con’s
- Performance
- Cost, risk, time to build
- Other physics potential
- ....
- Community wide evaluation underway
A quick lesson in “Project Speak”

- New Department of Energy Project’s must pass through a “Critical Decision” process: CDs
- CD-0
  - Approval to think (and do conceptual design)
- CD-1
  - What can you do, and for how much $$? When could you do it?
- CD-2
  - How much does it really cost and how long will it really take?
- CD-3
  - What are you really going to build and are you really ready to build it?
- CD-4
  - Does it work? Did we get what we paid for?
LBNE Milestones/Timeline

- Department of Energy CD-0
  - January 2010
- CD-1 Review and Approval
  - January-May 2011
- CD-2 (Cost and Schedule Baseline)
  - 2013
- CD-3 : Start Construction!
  - 2015
- CD-4 : Start Operations !
  - 2020-2021 (if all goes well)
What’s the big gain?

SENSITIVITY TO CP-VIOLATION

MEASURING PARAMETERS
Sensitivity to $\delta \neq 0, \pi \Rightarrow P(\nu_\mu \rightarrow \nu_x) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x)$

Curves like this are used to show an experiment’s Sensitivity to measuring CP-violation
LBNE Sensitivity to $\delta_{CP}$

$\delta \neq 0, \pi$, WC 2000kT-yr, 700kW (dash: 4000 kT-yr)

$\delta \neq 0, \pi$, WC 2000kT-yr, 700kW (dash: 4000 kT-yr)

200 kT WC for 10 (or 20) years of Beam exposure
At 0.01, we can just barely distinguish $\delta$ at its maximum and minimum.
Doubling Exposure

Where will you be in 2040?

Your graduate student may be defending one of these points in their thesis!
Some tough questions

- What if we don’t know how big $\theta_{13}$ is?
- What if we think it’s $(\sin^2 2\theta_{13}) \sim 0.01$?
- Are conventional beams the only route to this physics?
Neutrino Factory
Unique signature

Need to be able to tell + from –
⇒ magnetized detector:
MINOS like?
Magnetize NOvA?
Magnetize LAr?
Potential sensitivity to very small $\theta_{13}$

Martinez, et.al.
Phys.Rev. D.
81,073010(2010)

Consideration of a low energy neutrino factory
New Results to Keep an Eye On

Neutrino 2010 (http://www-numi.fnal.gov/PublicInfo/; SSI talk by M. Sanchez)

MINOS Anti-neutrinos

Neutrino 2010
New Results to Keep an Eye On

Neutrino 2010 (R. Vandewater; SSI talk by Eric Zimmerman)
MiniBooNE Anti-neutrinos

Results for \text{5.66E20 POT}

• Best Fit Point
  \((\Delta m^2, \sin^2 2\theta) = (0.064 \text{ eV}^2, 0.96)\)
  \(\chi^2/\text{NDF} = 16.4/12.6\)
  \(P(\chi^2) = 20.5\%\)
Take-away

- The third mixing angle $\theta_{13}$ has not yet been measured and it is known to be small.
- Results are expected from both reactor and accelerator experiments (T2K and NOvA) within ?(few) years.
- A non-zero value of $\theta_{13}$ is required to determine the neutrino mass hierarchy and observe the CP phase $\delta$ using $\nu_\mu \rightarrow \nu_e$ oscillations.
- A long baseline experiment ($\gg L \sim 1000$) with massive and/or highly efficient detectors and a conventional neutrino beam offers an opportunity to determine the mass hierarchy and measure $\delta$ provided $\sin^2 2\theta_{13} \sim 0.01$ or larger.

This is a tricky number......
Thank you!