Neutrino Experiments in Project X

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DOE Briefing
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Fermilab ν Program
Fermilab ν Program

• The Fermilab Long Baseline Neutrino Oscillation Program tries to understand the whole oscillation picture in stepwise fashion

  • MINOS - verify oscillations, measure parameters in the atmospheric sector
  • NOvA - measure $\sin^2(2\theta_{13})$ (or set much better limits) and make first attempt at mass hierarchy
  • LBNE - better sensitivity to mass hierarchy, first attempt at CP violation
  • Project X - extend the reach for mass hierarchy and CP violation to lower values of $\sin^2(2\theta_{13})$; builds on infrastructure of LBNE
Fermilab $\nu$ Program

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- For their goals, the last three programs must focus on the subdominant channel $\nu_\mu \rightarrow \nu_e$ (and charge conjugate process)
Neutrino CP Violation and the Universe

The universe contains nucleons, but practically no antinucleons, making it safe for life.

The development of this matter-antimatter asymmetry requires CP violation (matter and antimatter must behave differently).

The observed quark CP violation cannot explain the cosmic nucleon-antinucleon asymmetry.

But a hypothesized neutrino CP violation can do so.

CP violation in light-neutrino oscillation would establish leptonic CP violation, and make leptogenesis more plausible.
Geography

NuMI and LBNE

Project X

LBNE: New beamline
Use of recycler

Project X: x3 Intensity
New Injector
LBNE Experiment

• Next generation neutrino experiments will require large number of events
• This is true for CP investigation even if $\sin^22\theta_{13}$ relatively large

$$N_{\text{evt}} = \sigma \times \text{flux} \times \text{efficiency} \times \text{mass} \times \text{time}$$

  • flux - from 700 kW proton beam
  • time - 5 yrs with neutrinos, 5 yrs with antineutrinos
  • mass - 100-200 kt Water Cerenkov (WC) or 17-34 kt LAr
  • efficiency - LAr $\sim$6 times better for $\nu_e$ channel at $\sim$3GeV

• We are already pushing the limits
More about Detectors
More about Detectors

An ArgoNeut neutrino event from the NuMI beam
More about Detectors

An ArgoNeut neutrino event from the NuMI beam

First accelerator neutrino event in SuperK (T2K beam)
More about Detectors

The 100 kt WC is comparable in height to Wilson Hall.

But

It has to be built deep underground.

An ArgoNeut neutrino event from the NuMI beam

First accelerator neutrino event in SuperK (T2K beam)
Current Status
Current Status

Fractional Flavor Content varying $\cos \delta$

O. Mena and S. Parke, hep-ph/0312131
Current Status

Know to some extent

Fractional Flavor Content varying $\cos \delta$
Current Status

Know to some extent

\[ \sin^2 \theta_{23} \quad \cos \delta = 1 \]

\[ \Delta m_{\text{atm}}^2 \quad \Delta m_{\text{sol}}^2 \]

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Fractional Flavor Content varying \( \cos \delta \)
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Know to some extent

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Fractional Flavor Content varying $\cos \delta$
Typical LBNE Sensitivity

$\sin^2(2\theta_{13}) = 0.08, 0.04, 0.02, 0.01$

Solid: normal hierarchy; dashed: inverted
Ideal detector assumed in all cases
Error bars indicate 3$\sigma$; statistics only
Typical LBNE Sensitivity

As $\theta_{13}$ increases ellipses move out

As $\theta_{13}$ decreases, the two sets of ellipses become less separated

The statistical significance of CP violation is independent of the value of $\sin^2(2\theta_{13})$

But for low values of $\sin^2(2\theta_{13})$ there is ambiguity between hierarchy and $\delta_{CP}$
Fitting for 3 Parameters
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- One fits the energy spectra for $\nu_\mu \rightarrow \nu_e$ for:
  - $\sin^2(2\theta_{13})$
  - mass hierarchy
  - CP violation phase $\delta_{CP}$
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- The other oscillation parameters ($\theta_{12}, \theta_{23}, \Delta m_{12}^2, \Delta m_{23}^2$) are kept constant at their best measured values
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  - mass hierarchy
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- The other oscillation parameters ($\theta_{12}$, $\theta_{23}$, $\Delta m^2_{12}$, $\Delta m^2_{23}$) are kept constant at their best measured values

- Later on one might be able to add additional constraints, e.g., value of $\theta_{13}$ from reactors or from NOvA or T2K
Energy Spectra (700kW)
Energy Spectra (700kW)

ν_e spectrum

5 yrs ν running
normal hierarchy

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

34 kton LAr

- Signal+Bkgd, \( \delta_{CP} = 0 \)
- Signal+Bkgd, \( \delta_{CP} = 90^\circ \)
- Signal+Bkgd, \( \delta_{CP} = -90^\circ \)

- All Bkgd
- Beam \( \nu_e \)

Events/0.25 GeV

Reconstructed Neutrino Energy (GeV)

Plots by Lisa Whitehead
Energy Spectra (700kW)


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Beam \( \nu_e \)

200 kton WC

\[ \nu_e \] spectrum

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All Bkgd

Beam \( \nu_e \)

Plots by Lisa Whitehead
1 kt of LAr gives comparable sensitivity as 6 kt of H₂O mainly due to reduction of NC background
Sensitivity for $\sin^2(2\theta_{13})$
Sensitivity for $\sin^2(2\theta_{13})$
Sensitivity for $\sin^2(2\theta_{13})$

- Project X can extend $\sin^2(2\theta_{13})$ reach by $\sim 2$
- This will address predictions of a number of models

![Graph](image)

- Limits of sensitivity of the next generation of reactor experiments
- Chooz limit
- $\theta_{13}$ sensitivity ($3\sigma$)
- 5 yrs $\lor$ 5 yrs $\lor$
- 200 kton WC

Sensitivity of NOvA and T2K "wiggles" around this value
Theoretical Predictions

Note factor of 4 difference from previous plot in horizontal scale

By relationships with other parameters:
\[ \theta_{12} - \theta_{13} \cos(\delta) = \sqrt{1/3} \]
but there are many such examples.

This will require precision measurements of
\[ \sin^2 \theta_{13}, \sin^2 \theta_{12}, \sin^2 \theta_{23} \text{ and } \delta_{CP} \]
Sensitivity for Mass Hierarchy

MH sensitivity (95% CL)

- 5 yrs $\nu$ + 5 yrs $\bar{\nu}$
- 200 kton WC

Increase in reach by $\sim 2$ over LBNE

accessible to NOvA

L. Whitehead
CP Violation Sensitivity
CP Violation Sensitivity

Increase in $\delta_{CP}$ coverage by 2-2.5 over LBNE coverage
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CP/Hierarchy Ambiguity
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As seen earlier, for low values of $\sin^2(2\theta_{13}) \sim < 0.03$, the two ellipses in the DUSEL beam begin to overlap affecting CP and mass hierarchy determination.
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• Resolving this ambiguity is a significant experimental challenge
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- Resolving this ambiguity is a significant experimental challenge
  - Interesting possibility: study 2nd maximum ($\delta_{\CP} = 3\pi/2$) CP effects there $\sim 3$ times larger, matter effects smaller
Ellipses for Low Energy

Preliminary - 1st look

Relatively small difference between 2 mass hierarchies
For this beam statistics are poor in this limited energy region
The efficiency difference between WC and LAr is less here
Energy Spectra (700kW)
Energy Spectra (700kW)

\[ \nu_e \text{ spectrum} \]

5 yrs \( \nu \) running inverted hierarchy
\[ \sin^2(2\theta_{13}) = 0.04 \]

Events/0.25 GeV

200 kton WC

Reconstructed Neutrino Energy (GeV)

Signal+Bkgd, \( \delta_{CP} = 0 \)

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All Bkgd

Beam \( \nu_e \)

Plots by Lisa Whitehead
Energy Spectra (700kW)

\( \nu_e \) spectrum

- 5 yrs \( \nu \) running inverted hierarchy
- \( \sin^2(2\theta_{13}) = 0.04 \)

\( \bar{\nu}_e \) spectrum

- 5 yrs \( \bar{\nu} \) running normal hierarchy
- \( \sin^2(2\theta_{13}) = 0.04 \)

Plots by Lisa Whitehead
The statistics at 2nd maximum are rather poor and the backgrounds quite high.
ν beam from 8 GeV p’s
ν beam from 8 GeV p’s

plots by Mary Bishai
ν beam from 8 GeV p’s

Advantages

- CC/NC ratio higher by ~50
- Hence NC background down
- Optimized beam design could decrease νₑ background from μ decays by ~3-4

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• CC/NC ratio higher by ~50
• Hence NC background down
• Optimized beam design could decrease ν_e background from μ decays by ~3-4

So far no detailed studies exist of this option

My “back-of-the-envelope” calculations indicate that for 1MW, 200 kt and 3 yrs one might see ~30-40 ν_e events with low background for sin²(2θ_{13})=0.01
Other Project X Opportunities

• Near Detector Physics
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  - Copious source of neutrinos in the 1-4 GeV range (exotica?)
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• Experiments based on 3 and/or 8 GeV proton beams (versatility of Project X)
Other Project X Opportunities

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  • Investigation of LSND/MiniBooNE anomaly
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- Near Detector Physics
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  - Possibilities for specialized experiments in front of Near Detector
- Experiments based on 3 and/or 8 GeV proton beams (versatility of Project X)
  - Investigation of LSND/MiniBooNE anomaly
- Not much work in this area so far
Non-$v_e$ Oscillation Physics

What is the deep underlying principle that determines the mass splittings and the mixing angles?

We might get some insight into this question by looking for patterns and symmetries eg is $\sin^2(2\theta_{23})$ exactly $=1$? (analogy: Mendeleev Table)
Non-ν_e Oscillation Physics

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Mixing angles seem to exhibit a pattern - “tri-bimaximal mixing”

Current experimental pattern:

\[
\begin{align*}
\sin^2 \theta_{13} &< 0.04 \\
|\sin^2 \theta_{12} - \frac{1}{3}| &< 0.04 \\
|\sin^2 \theta_{23} - \frac{1}{2}| &< 0.12
\end{align*}
\]

\[
U_{TBM} = \begin{pmatrix}
\frac{2}{\sqrt{3}} & \frac{1}{\sqrt{3}} & 0 \\
-\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\
\frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}}
\end{pmatrix}
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The high intensity of the Project X will allow us to probe this question with higher accuracy

after S.Parke, Neutrino 2010
Summary
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- Project X can probe a factor of ~2 beyond LBNE (alternatively finish program in 3 yrs) in:
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  • mass hierarchy
Summary

- Project X can probe a factor of \( \sim 2 \) beyond LBNE (alternatively finish program in 3 yrs) in:
  - \( \sin^2(2\theta_{13}) \)
  - mass hierarchy
  - CP violation
Summary

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• Potential of beams based on 3 and 8 GeV protons needs to be explored and quantified
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• It can improve our knowledge of other oscillation parameters

• Potential of beams based on 3 and 8 GeV protons needs to be explored and quantified

• Its versatility will undoubtedly provide a number of other, unexplored opportunities
Backup Slides
A Deep Underground Science and Engineering Laboratory
Long Baseline Neutrino Experiment

- Near Detector Hall 400 Feet Deep
- Muon Absorber Region 1147 Feet Long
- Absorber Hall 250 Deep
- Decay Pipe Tunnel 620 Feet Long
- Target Hall 170 Feet Deep
- Proton Beamline from Main Injector 1900 Feet Long
- Main Injector Accelerator
Transition Probability
Transition Probability

\[ P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2 \left(1.27 \Delta m_{31}^2 \frac{L}{E} \right) + \text{Main “atmospheric” term} \]

\[ \sin^2(2\theta_{12}) \cos^2(\theta_{23}) \sin^2 \left(1.27 \Delta m_{21}^2 \frac{L}{E} \right) + \text{Solar term} \]

\[ \sin(2\theta_{13}) \sin(2\theta_{23}) \sin(2\theta_{12}) \sin \left(1.27 \Delta m_{31}^2 \frac{L}{E} \right) \sin \left(1.27 \Delta m_{21}^2 \frac{L}{E} \right) \cos \left(1.27 \Delta m_{32}^2 \frac{L}{E} \pm \delta_{CP} \right) \]

Interference term
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- Transition depends on \( \theta_{12}, \Delta m_{21}^2, \Delta m_{31}^2, \theta_{23}, \text{mass hierarchy, } \theta_{13}, \delta_{\text{CP}} \)
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- Transition depends on \( \theta_{12}, \Delta m_{21}^2, \Delta m_{31}^2, \theta_{23}, \) mass hierarchy, \( \theta_{13}, \delta_{\text{CP}} \)
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- \( \sin^2 \theta_{23} \) is only known to \(~10\%-15\%\)
- mass hierarchy, \( \theta_{13} \) and \( \delta_{\text{CP}} \) are unknown (\( \theta_{13} \) small)
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- \( \sin^2\theta_{23} \) is only known to ~10-15%
- mass hierarchy, \( \theta_{13} \) and \( \delta_{CP} \) are unknown (\( \theta_{13} \) small)
- Interference term proportional to \( \sin(2\theta_{13}) \), not \( \sin^2(2\theta_{13}) \)
A natural mechanism to explain the very small mass of the neutrinos is to postulate a *very heavy neutrino* and a see-saw mechanism.

CP violation in early-universe decays of these *very heavy neutrinos* creates a *lepton-antilepton* asymmetry.

Standard-Model processes convert part of this *lepton-antilepton* asymmetry to a *nucleon-antinucleon* asymmetry.
Leptogenesis and light-neutrino oscillation are connected.

Although possible, it would be unnatural for there to be leptogenesis but no light-neutrino CP violation.

CP violation in light-neutrino oscillation would establish leptonic CP violation, and make leptogenesis more plausible.
Graphical Representation
Possible LBNE

\[
\sin^2(2\theta_{13}) = 0.08, 0.04, 0.02, 0.01
\]

Solid: normal mass hierarchy; dashed: inverted
Ideal detector assumed in all cases
Error bars indicate 3\(\sigma\); statistics only
Possible LBNE

1300km, 5yr ν, 5yr ν-bar, 700kW, 40kT $\epsilon=1$.  

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Solid: normal mass hierarchy; dashed: inverted  
Ideal detector assumed in all cases  
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Project X

1300km, 5yr ν, 5yr ν-bar, 2300kW, 40kT $\epsilon=1$.  

$\sin^2(2\theta_{13}) = 0.08, 0.04, 0.02, 0.01$
$\sin^2 \theta_{23}$ dependence
\[ \sin^2 \theta_{23} \] dependence

1300km, 5yr \( \nu \), 5yr \( \bar{\nu} \)-bar, 700kW, 40kT \( \in = 1 \).

\[ \sin^2 \theta_{23} = \begin{array}{c} 0.465 \\ 0.500 \\ 0.535 \end{array} \]

- \text{normal}
- \text{inverted}

Plot by Gina Rameika
sin^2 \theta_{23} dependence

CP sensitivity not affected much by this uncertainty
nu/nubar ratio stays relatively constant as sin^2 \theta_{23} is varied

\begin{align*}
\sin^2 \theta_{23} &= 0.465 \\
&= 0.500 \\
&= 0.535
\end{align*}
NOvA Reach

95% CL Resolution of the Mass Ordering

$\delta (\pi)$

NOvA + T2K

3 years for each $\nu$ and $\bar{\nu}$
NOvA at 700 kW,
1.2MW, and 2.3MW
+ T2K 6 years of $\nu$
at nominal, x2, and x4

$L = 810$ km, 15 kT
$\Delta m_{32}^2 = 2.4 \times 10^{-3} \text{eV}^2$
$\sin^2(2\theta_{23}) = 1$
$\Delta m^2 > 0$
Reconstructed Neutrino Energy (GeV)

- 0
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8

Events/0.25 GeV

- 0
- 50
- 100
- 150
- 200
- 250

ν_e spectrum

5 yrs ν running
normal hierarchy
\( \sin^2(2\theta_{13}) = 0.04 \)

- 200 kton WC
- 2 MW
- Signal+Bkgd, \( \delta_{CP} = 0 \)
- Signal+Bkgd, \( \delta_{CP} = 90^\circ \)
- Signal+Bkgd, \( \delta_{CP} = -90^\circ \)
- All Bkgd
- Beam \( \nu_e \)

- 34 kton LAr
- 2 MW
- Signal+Bkgd, \( \delta_{CP} = 0 \)
- Signal+Bkgd, \( \delta_{CP} = 90^\circ \)
- Signal+Bkgd, \( \delta_{CP} = -90^\circ \)
- All Bkgd
- Beam \( \nu_e \)
T2K and NOvA Sensitivities
T2K: Assumes 5 years at 750 kW, 22.5 kton fiducial volume
**T2K**: Assumes 5 years at 750 kW, 22.5 kton fiducial volume

**NOvA**: Assumes 3 years ν + 3 years anti-ν, 10% systematic, at 700 kW

The long distance (810 km) gives it some sensitivity to mass hierarchy
Spectra at 2 MW

5 yrs running
normal hierarchy
sin^2(2\theta_{13}) = 0.04

200 kton WC
2 MW

34 kton LAr
2 MW

ν_e spectrum

Events/0.25 GeV

Reconstructed Neutrino Energy (GeV)

ν_e spectrum

Reconstructed Neutrino Energy (GeV)