The NuMI Off-Axis Experiment

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It is clear that the next generation of experiments will concentrate on $\nu_e \leftrightarrow \nu_x$ oscillations, which are needed for
- $\sin^2(2\theta_{13})$
- $\text{sign}(\Delta m_{13}^2)$
- $\bar{\nu}$
Off-Axis Rationale

- Want low-energy narrow-band beams at $\Delta m_{13}^2$ and $\Delta m_{23}^2$ oscillation maximum:
  - $\nu_e$ appearance maximum
  - $\nu$ CC disappears
  - Higher-energy NC disappears
- Want detectors optimized for $\nu_e$ detection
- Want increases in beam flux times detector mass
- Off-axis Experiment Proposal
Off-Axis Kinematics

\[ E_\nu = \frac{0.43 \sqrt{m_\nu}}{1 + \frac{m_\nu^2}{2}} \]

\[ (\text{GeV}) \]

\[ (\text{GeV}) \]

\[ \theta = 0 \text{ mrad} \]
\[ \theta = 7 \text{ mrad} \]
\[ \theta = 14 \text{ mrad} \]
\[ \theta = 27 \text{ mrad} \]
Off-Axis Spectrum (No oscillations)
The Off-Axis experiment is proposed to be

- 50 kT
- Medium-Z sandwich detector
  - Particle board absorber
  - Liquid scintillator strip detectors with APD readout
  - Glass RPC detectors fallback option
- 810 km baseline, about 12 km off-axis (Ash River, MN)
- Current cost estimate about 150 M$
Possible Sites

We are now focusing on the Ash River site.

- Vermilion Bay, Ontario: ~950 km, 15.6 km up
- Fort Frances, Ontario: ~875 km, 9 km up
- Ash River, MN: 825 km, 5 km up
- Buyck, MN: 775 km, 2 km up
Monolithic structure

Liquid:
1.2 m x 3 cm x 14.4 m
30-cell extrusions,
24 extrusions/plane,
797 planes
= 19,128 extrusions
= 573840 channels
Electron Track

Hits per plane > 1

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Muon track

Hits per plane ~1

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NC with leading $\bar{\phi}^0$

Two tracks with different starting points leading to a “gap”
Detail of NC with leading $\Delta^0$

gap
NC Backgrounds

- NC backgrounds can be rejected by a likelihood analysis based on topological parameters

Signal Likelihood

NC Likelihood

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\[ P(\frac{\Delta m_{12}^2}{2L/E}) = P_1 + P_2 + P_3 + P_4 \]

- \( P_1 = \sin^2(\frac{\Delta m_{23}^2}{2}) \sin^2(2\theta_{13}) \sin^2(1.27 \frac{\Delta m_{13}^2}{2L/E}) \)
- \( P_2 = \cos^2(\frac{\Delta m_{23}^2}{2}) \sin^2(2\theta_{12}) \sin^2(1.27 \frac{\Delta m_{12}^2}{2L/E}) \)
- \( P_3 = \mp J \sin(\theta_{13}) \sin(1.27 \frac{\Delta m_{13}^2}{2L/E}) \)
- \( P_4 = J \cos(\theta_{13}) \cos(1.27 \frac{\Delta m_{13}^2}{2L/E}) \)

where \( J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23}) \times \)

\[ \sin(1.27 \frac{\Delta m_{13}^2}{2L/E}) \sin(1.27 \frac{\Delta m_{12}^2}{2L/E}) \]
P(ν₁ → νₑ)  
(in Matter)

- In matter, P₁ will be approximately multiplied by 
  \((1 \pm 2E/E_R)\) and P₃ and P₄ will be approximately 
  multiplied by \((1 \pm E/E_R)\), where the top sign is for 
  neutrinos with normal mass hierarchy and 
  antineutrinos with inverted mass hierarchy.

\[
E_R = \frac{\sqrt{m_{13}^2}}{2\sqrt{2}G_F} \quad 11 \text{ GeV for the earth's crust.}
\]

About a ±23% effect for NuMI, but only a ±10% 
effect for JPARC.
Magnitudes

- For long-baseline $\nu_\mu - \nu_e$ oscillations, $P_1$, $P_3$, $P_4$, and the matter effects are all the same order of magnitude.

- A measurement of $P(\nu_\mu - \nu_e)$ measures "$\sin^2(2\theta_{13})_{\text{eff}}$" which is only a crude estimate of $\sin^2(2\theta_{13})$.

- Reactor experiments measure $\sin^2(2\theta_{13})$ directly, but have no sensitivity to $\text{sign}(\Delta m_{13}^2)$ or $\Delta m_{13}^2$. 
Probability Plots

- Probability plots assume a particular result for a measurement of $P(\theta_\text{me})$ and show:
  - The possible values of $\sin^2(2\theta_{13})$, $\text{sign}(m_{13}^2)$, and $\theta_{13}$ consistent with this measurement, and
  - How another measurement would discriminate among them.
P(\bar{\nu}_e) = 0.02 at 820 km

\[ \sin^2(2\theta_{13}) \text{ vs. } P(\bar{\nu}_e) \text{ for } P(\nu_e) = 0.02 \]

Note

(1) Effect of \( \cos(\square) \) term

(2) Ambiguities

(Hidden ambiguity: \( P_1 \mu \sin^2(\square_{23}) \); if \( \sin^2(2\square_{23}) = 0.95, \sin^2(\square_{23}) = 0.39 \text{ or } 0.61 \))

(1) Rough equivalence of reactor and antineutrino measurements
$P(\theta_1, \theta_2, \theta_e) = 0.05, 0.02, 0.01, \text{ and } 0.005 \text{ at } 820 \text{ km}$
$P(\overline{\nu}_e) = 0.02$

at 820 and 295 km

$\sin^2(2\theta_{13})$ vs. $P(\overline{\nu}_e)$ for $P(\nu_e) = 0.02$

$L = 820$ km, 10 km off
$\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV$^2$

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

$\delta = 0$
$\delta = \pi/2$
$\delta = \pi$
$\delta = 3\pi/2$

$\sin^2(2\theta_{13})$ vs. $P(\overline{\nu}_e)$ for $P(\nu_e) = 0.02$

$L = 295$ km, on 1st oscillation max
$\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV$^2$

$\Delta m^2 < 0$
$\delta = 0$
$\delta = \pi/2$
$\delta = \pi$
$\delta = 3\pi/2$
\( P(\mu, e) = 0.02 \) at 820 km

Note ambiguities between normal hierarchy and inverted hierarchy.

Can combining JPARC and NuMI data help?
$P(n \neq n_e) = 0.02$ at 820 km vs. $P(n \neq n_e)$ at 295 km.

Ambiguous points are still fairly close together.
A 2nd Detector at the 2nd Maximum?

\[ \sin^2(2\theta_{13}) \text{ vs. } P_{2\text{nd max}}(\nu_e) \text{ for } P(\nu_e) = 0.02 \]

- \( L = 820 \text{ km}, 10 \text{ km off} \)
- \( L^* = 710 \text{ km}, 30 \text{ km off} \)
- \( \Delta m_{23}^2 = 2.5 \times 10^{-3} \text{ eV}^2 \)

\[ \Delta m^2 < 0 \]
\[ \Delta m^2 > 0 \]

- \( \delta = 0 \)
- \( \delta = \pi/2 \)
- \( \delta = \pi \)
- \( \delta = 3\pi/2 \)
Goals of the Off-Axis Experiment

- Primary goal: Find evidence for $\nu_\tau \neq \nu_e$, determining $\sin^2(2\theta_{13})$ to a factor of 2.
- Longer term goal: Determine the mass hierarchy.
- Ultimate goal: Precision measurement of the CP-violating phase $\delta$. 
3 \( \sigma \) Discovery Potential for \( \Delta m_{\nu}^2 \)

\[ L = 820 \text{ km, } 10 \text{ km off} \]
\[ \Delta m_{\nu}^2 = 2.5 \times 10^{-3} \text{ eV}^2 \]
MINOS Sensitivity to $\Delta m^2_{31}$ at 3σ Discovery

Off-Axis Goal

3σ Contours

$\Delta m^2_{31}$ (eV$^2$)

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

MINOS 7.4, 16, 25 $10^{20}$ pot

CHOZ 90% CL
To consider sensitivities, I consider one experiment (or one set of experiments) with the expected results and calculate 1, 2, and 3 $\sigma$ contours based on $\Delta\chi^2$'s, assuming 5% systematic error on the background.
Study Points

\[ \sin^2(2\theta_{13}) \text{ vs. } P(\bar{\nu}_e) \text{ for } P(\nu_e) = 0.02 \]

- \( L = 820 \text{ km}, 10 \text{ km off} \)
- \( \Delta m_{31}^2 = 2.5 \times 10^{-3} \text{ eV}^2 \)

- \( \Delta m^2 > 0 \):
  - \( \delta = 0 \)
  - \( \delta = \pi/2 \)
  - \( \delta = \pi \)
  - \( \delta = 3\pi/2 \)

- \( \Delta m^2 < 0 \):
  - \( \delta = 0 \)
  - \( \delta = \pi/2 \)
Point 1: NuMI 3 yr \(0\), 3 yr\(1\) 4 \(10^{20}\) and 20 \(10^{20}\) pot/yr

1, 2, 3 \(\sigma\) Contours for Starred Point, Neg \(\Delta m^2\)

\[
\begin{align*}
\sin^2(2\theta_{13}) & = 0.18 \\
\Delta m^2_{32} & = 2.5 \times 10^{-3} \text{ eV}^2 \\
12 \ 10^{20} \text{ pot } \nu, 12 \ 10^{20} \text{ pot } \bar{\nu}
\end{align*}
\]

L = 820 km, 10 km off

\[
\begin{align*}
\sin^2(2\theta_{13}) & = 0.18 \\
\Delta m^2_{32} & = 2.5 \times 10^{-3} \text{ eV}^2 \\
60 \ 10^{20} \text{ pot } \nu, 60 \ 10^{20} \text{ pot } \bar{\nu}
\end{align*}
\]

Proton Driver
NuMI 3 yr, 3 yr
4 $10^{20}$ and 20 $10^{20}$ pot/yr

1, 2, 3 σ Contours for Starred Point, Pos $\Delta m^2$

$L = 820$ km, 10 km off
$\Delta m_{23}^2 = 2.5 \times 10^{-3}$ eV$^2$
12 $10^{20}$ pot $\nu$, 12 $10^{20}$ pot $\bar{\nu}$

Proton Driver
NuMI 3 yr $\square$, 3 yr$\square$, 20 $10^{20}$ pot/yr and JPARC, Phase 1

1, 2, 3 $\sigma$ Contours for Starred Point, Pos $\Delta m^2$

- L = 820 km, 10 km off
- $\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2$
- 60 $10^{20}$ pot $\nu$, 60 $10^{20}$ pot $\bar{\nu}$

Without JPARC Phase 1

With JPARC Phase 1

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NuMI 3 yr $\mathbb{I}$, 3 yr $\mathbb{I}$, 20 $10^{20}$ pot/yr
and JPARC Phase 2, 2 yr $\mathbb{I}$, 2 yr $\mathbb{I}$
1, 2, 3 $\sigma$ Contours for Starred Point, Pos $\Delta m^2$

$\Delta m^2_{23} = 2.5 \times 10^{-3} \text{ eV}^2$

- $L = 820 \text{ km, 10 km off}$
- $L = 710 \text{ km, 9 km off}$
- $6 \times 10^{20} \text{ pot } \nu, 6 \times 10^{20} \text{ pot } \bar{\nu}$

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

$\delta (\pi)$
95% CL Resolution of the Mass Hierarchy

$L = 820 \text{ km, } 10 \text{ km off}$
$\Delta m^2_{23} = 2.5 \times 10^{-3} \text{ eV}^2$

*Each $\nu$ and $\bar{\nu}$*

- Blue: $12 \times 10^{20} \text{ pot, } \Delta m^2 > 0$
- Red: $12 \times 10^{20} \text{ pot, } \Delta m^2 < 0$
- Blue dotted: $60 \times 10^{20} \text{ pot, } \Delta m^2 > 0$
- Red dotted: $60 \times 10^{20} \text{ pot, } \Delta m^2 < 0$

(Proton Driver)
95% CL Resolution of the Mass Hierarchy with 2 Detectors

2 $\sigma$ Resolution of the Mass Hierarchy

$L = 820$ km, 10 km off
$L = 710$ km, 30 km off
$\Delta m_{23}^2 = 2.5 \times 10^{-3}$ eV$^2$

Each $\nu$ and $\bar{\nu}$
- $60 \times 10^{20}$ pot, $\Delta m^2 > 0$
- $60 \times 10^{20}$ pot, $\Delta m^2 < 0$
  (Proton Driver)
Proposed Recommendations

- That Fermilab proceed with the Off-Axis experiment as part of a step-by-step program to eventually measure all of the neutrino mixing parameters.
- That Fermilab proceed with the construction of a proton driver to provide a 2 MW 120 GeV beam.