Status and Prospects of Long Baseline ν experiments

Niki Saoulidou, Fermilab

Nufact08, 01-07-08, Valencia Spain
Outline

• Introduction

• Long Baseline $\nu$ Experiments
  *(Present, Near term and Long term Future):*
  - MINOS
  - OPERA
  - ICARUS
  - T2K
  - NOvA
  - Future Super Beam experiments

• Summary / Outlook
Introduction

• **Neutrinos** were invented in order to solve a “mystery” (energy non-conservation in beta decays)...

• Since their birth, they have created even more **mysteries** themselves ...
  - **Solar neutrino “problem”** ($\nu_e$'s from the Sun are less than expected)
  - **Atmospheric neutrino “problem”** (“Too few $\nu_\mu$ problem”)

• The “problem” of missing neutrinos can be nicely explained if they possess non-degenerate masses, in which case they can **oscillate** between the different flavors:
  - 3 active light ($m_\nu < M_Z/2$) (LEP/SLC)
  - n sterile (MiniBoone results do not see a signal in the allowed LSND region)

• **Non zero neutrino masses** is one (or the only) of the strongest experimental evidence we have so far for physics beyond the Standard Model!
**3-Flavor $\nu$ Oscillation Formalism**

If neutrinos oscillate, then the interaction eigenstates (or weak eigenstates, which is what we observe) can be expressed in terms of the mass eigenstates as follows:

$$\nu_{e(\mu)(\tau)} = \sum_{i=1}^{3} U_{e(\mu)(\tau)i}^* \nu_i$$

<table>
<thead>
<tr>
<th>Atmospheric</th>
<th>Cross Mixing</th>
<th>Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U = \begin{bmatrix} 1 &amp; 0 &amp; 0 \ 0 &amp; c_{23} &amp; -s_{23} \ 0 &amp; s_{23} &amp; c_{23} \end{bmatrix}$</td>
<td>$\begin{bmatrix} c_{13} &amp; 0 &amp; -s_{13}e^{-i\delta} \ 0 &amp; 1 &amp; 0 \ s_{13}e^{-i\delta} &amp; 0 &amp; c_{13} \end{bmatrix}$</td>
<td>$\begin{bmatrix} c_{12} &amp; s_{12} &amp; 0 \ -s_{12} &amp; c_{12} &amp; 0 \ 0 &amp; 0 &amp; 1 \end{bmatrix}$</td>
</tr>
</tbody>
</table>

- $c_{ij} = \cos \theta_{ij}$
- $s_{ij} = \sin \theta_{ij}$

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Why use accelerator $\nu$'s to study oscillations??

- Very wide neutrino flight length
- Wide neutrino energy
- Mixture of $\nu_\mu$, anti-$\nu_\mu$, $\nu_e$ and anti-$\nu_e$

- Single flight length
- Controlled neutrino energy
- Almost pure $\nu_\mu$ (or anti-$\nu_\mu$)

Initial discovery $\rightarrow$ Precise studies
MINOS Collaboration

MINOS Near Detector Surface Building

30 institutions
175 physicists

Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab
College de France • Harvard • IIT • Indiana •
Minnesota–Twin Cities • Minnesota–Duluth • Oxford • Pittsburgh • Rutherford
Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M
Texas–Austin • Tufts • UCL • William & Mary • Wisconsin

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MINOS (Main Injector Neutrino Oscillation Search) is a two detector long baseline $\nu$ oscillation experiment.

Basic Idea: 2 detectors “identical” in all their important features.

Cross Section ($\sigma$) & Beam Modeling ($\Phi_\nu$) uncertainties to high accuracy cancel out between the two Detectors.
MINOS Physics Goals

- Verify $\nu_\mu \rightarrow \nu_\tau$ mixing hypothesis and make a precise (<10%) measurement of the oscillation parameters \textit{Phys. Rev. Lett.} 97 (2006) 19180

- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations (not yet seen at this mass-scale)

- Search for/rule out exotic phenomena:
  - Sterile neutrinos
  - Neutrino decay

- Use magnetized MINOS Far detector to study neutrino and anti-neutrino oscillations (unique capability of MINOS experiment)
  - Test of CPT violation
  - Cosmic rays, hep-ex/0705.3815
Far Detector Neutrino Events
(\(CC\) like and \(NC\) like)

\[\begin{align*}
\nu \text{ Beam} & \quad \text{CC}_{\text{like}} \\
\nu \text{ Beam} & \quad \text{NC}_{\text{like}}
\end{align*}\]

Trk\(\text{RangeEnergy}\): 2.481  \(\text{RecoShwEnergy}\): 4.754
\(\text{Vtx}\): 2.18, 0.29, 4.11

Run: 37242, Snarl: 108753, Slice: 1/1, Event 1/1
Reco
\[#\text{Trks: 0}\]
\[#\text{Shws: 1}\]
\(q/p: 0.000 \, \pm 0.000, \, p/q: 0.000\)
\(\text{Trk\(\text{RangeEnergy}\): 0.000} \quad \text{Reco\(\text{ShwEnergy}\): 4.610 [4.610]}\)

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\[ \chi^2 = \sum_{nbins} (2(e_i - o_i) + 2 o_i \ln(o_i/e_i)) + \sum_{nsys} \frac{\Delta s_j^2}{\sigma^2 s_j} \]

**Systematic Uncertainties**

- Absolute hadronic energy scale: 10.3%
- Normalization: 4%
- NC contamination: 50%
$|\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3} \text{ eV}^2$ (68% C.L.)
\[ \sin^2(2\theta) > 0.90 \] (90% C.L.)

$\chi^2/\text{ndof} = 90/97$

Fit is constrained to the physical region.

Unconstrained:

$|\Delta m|^2 = 2.33 \times 10^{-3} \text{ eV}^2$
\[ \sin^2(2\theta) = 1.07 \]
$\Delta \chi^2 = -0.6$
Differentiating between neutrino oscillations and alternative hypothesis

**Decay:**

V. Barger *et al.*, PRL82:2640(1999)

$\chi^2/\text{ndof} = 104/97$

$\Delta \chi^2 = 14$

disfavored at $3.7\sigma$

**Decoherence:**


$\chi^2/\text{ndof} = 123/97$

$\Delta \chi^2 = 33$

disfavored at $5.7\sigma$
• Oscillation parameters are fixed (at MINOS best fit CC values)
• MC predictions, under $3 \nu$ model with $\theta_{13}=0$ and $\theta_{13}$ at the CHOOZ limit are shown.

$$\text{Sig.} = \frac{\text{Data} - \text{MC}}{\sqrt{\text{MC} + \sigma^2_{\text{sys}}}}$$

<table>
<thead>
<tr>
<th>Energy Range (GeV)</th>
<th>Data</th>
<th>MC $\theta_{13} = 0$</th>
<th>Sig. ($\sigma$) $\theta_{13} = 0$</th>
<th>MC $\theta_{13} = 0.21$ $\delta = 3\pi/2$</th>
<th>Sig. ($\sigma$) $\theta_{13} = 0.21$ $\delta = 3\pi/2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-3</td>
<td>100</td>
<td>115.16 ± 7.67</td>
<td>1.15</td>
<td>122.09 ± 8.42</td>
<td>1.56</td>
</tr>
<tr>
<td>0-5</td>
<td>165</td>
<td>175.92 ± 10.42</td>
<td>0.65</td>
<td>191.26 ± 11.88</td>
<td>1.42</td>
</tr>
<tr>
<td>0-120</td>
<td>291</td>
<td>292.63 ± 15.02</td>
<td>0.10</td>
<td>311.54 ± 16.28</td>
<td>0.89</td>
</tr>
</tbody>
</table>
4 Flavour Model : NC\textsubscript{like} Spectrum

Assume $\Delta m_{41}^2 = 0$

- Oscillation at single mass scale

- Oscillation probabilities simplify to:

\[
\begin{align*}
P_{\nu_\mu \to \nu_\mu} &= 1 - 4 \left| U_{\mu 3} \right|^2 \left( 1 - \left| U_{\mu 3} \right|^2 \right) \Delta_{31}^2 \\
P_{\nu_\mu \to \nu_e} &= 4 \left| U_{\mu 3} \right|^2 \left| U_{e 3} \right|^2 \Delta_{31}^2 \\
P_{\nu_\mu \to \nu_s} &= 4 \left| U_{\mu 3} \right|^2 \left| U_{s 3} \right|^2 \Delta_{31}^2 \\
P_{\nu_\mu \to \nu_\tau} &= 1 - P_{\nu_\mu \to \nu_\mu} - P_{\nu_\mu \to \nu_e} - P_{\nu_\mu \to \nu_s}
\end{align*}
\]

Far Detector $\Delta_{41} = 0$

- $|U_{e 3}|^2 = 0$
- $|U_{e 3}|^2 = 0.04$
- $|U_{\mu 3}|^2 = 0.50^{+0.16}_{-0.15}$
- $|U_{\mu 3}|^2 = 0.48^{+0.18}_{-0.12}$
- $|U_{s 3}|^2 = 0.14^{+0.18}_{-0.13}$
- $|U_{s 3}|^2 = 0.21^{+0.20}_{-0.12}$
Projected Sensitivity of MINOS

$\nu_\mu$ disappearance

MINOS Sensitivity as a function of Integrated POT

Monte Carlo, 90% C.L. contours, statistical errors only

With increased statistics:

- Improve precision on $\Delta m^2$ and $\sin^2(2\theta)$
- Set more stringent limits on alternative hypothesis (neutrino decay, sterile neutrinos)
- Make first measurement on $\theta_{13}$ or improve current best limit set by CHOOZ

MINOS Projected 90% Exclusion

$|\Delta m^2_{\odot}| = 2.4 \times 10^{-3} \text{ eV}^2$

$\sin^2(2\theta_{\odot}) = 1.0$

Pro\ jected Sensitivity of MINOS $\nu_\mu \rightarrow \nu_e$

$\nu_\mu \rightarrow \nu_s$

$|U_{\mu 3}|^2$

$|U_{s3}|^2$

$0.0$ $0.2$ $0.4$ $0.6$ $0.8$ $1.0$

$0.0$ $0.2$ $0.4$ $0.6$ $0.8$ $1.0$

$0.5$ $1.0$ $1.5$ $2.0$

$10^{-2}$ $10^{-1}$

PRELIMINARY

CHO0Z 90% CL

$3.25 \times 10^{20}$ POT $|\Delta m^2_{\odot}| > 0$ (2006, 10%)

$3.25 \times 10^{20}$ POT $|\Delta m^2_{\odot}| < 0$ (2006, 10%)

$6.5 \times 10^{20}$ POT (+ -1 year, 5%)

$9.5 \times 10^{20}$ POT (+ ~2 years, 5%)

Input Values

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The OPERA Collaboration
(13 Countries, 35 Institutions, ~200 members)

Belgium
IIHE(ULB-VUB) Brussels
Bulgaria
Sofia
Croatia
IFB Zagreb
France
LAPP Annecy, IPNL Lyon,
IRESE Strasbourg
Germany
Hamburg, Münster, Rostock
Israel
Technion Haifa
Italy
Bari, Bologna, LNF Frascati,
L’Aquila, LNGS, Naples Federico II,
Padova, Rome Sapienza, Salerno
Japan
Aichi, Nagoya, Kobe,
Toho, Utsunomiya
Korea
Gyeongsang Jinju
Russia
INR Moscow, LPI Moscow,
ITEP Moscow, SINPMSU Moscow,
JINR Dubna, Obninsk
Switzerland
Bern, Neuchâtel, ETHZ Zurich
Tunisia
UPHNE Tunis
Turkey
METU Ankara

CERN to Gran Sasso Neutrino Beam

Emulsion Cloud Chamber

A "hybrid" experiment at work

Electronic detectors
→ select ν interaction brick
→ μ ID, charge and p

Emulsion analysis
→ vertex search
→ decay search
→ e/μ ID, kinematics

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OPERA experiment: Goals

Physics goals:

- Verify oscillation of $\nu_\mu$ is to $\nu_\tau$
- Search for $\nu_e$ appearance

CNGS L/E = 0.04km/MeV (17GeV $E_\nu$)

October 2 2007: First neutrino interaction in the emulsion bricks of the OPERA Experiment! (Many more recorded since then)
**OPERA experiment: Emulsion Data**

<table>
<thead>
<tr>
<th>Bricks at the start of the run (5/10/07)</th>
<th>Bricks at the end of the run (29/10/07)</th>
<th>Integrated pot</th>
<th>In-Target events (bricks+scintillator+walls)</th>
</tr>
</thead>
<tbody>
<tr>
<td>57040</td>
<td>64060</td>
<td>8.24x 10^{17}</td>
<td>38 (31.5 expected)</td>
</tr>
</tbody>
</table>

**Event 179673325 QE-like topology**

...a charm candidate!

The visual inspection allows the observation of nuclear fragments and the classification of the event as DIS

Flight length: 3247.2 μm
θ_{lab}: 0.204 rad
P_{meson} = 3.9 (+1.7, -0.9) GeV
P_{μ}: 796 MeV (~ 606 MeV)

Two e. m. showers pointing to vertex
OPERA experiment: Status + Prospects

$\nu_\mu \rightarrow \nu_\tau$

10 events expected with 1 background after 5 yrs

(4.5 x $10^{19}$ pots/year, 1.35 kton target mass)

Full compliment soon, 87% done already

2008 CNGS Run: 2.4-2.6 x $10^{19}$ pots, 1.2 $\nu_\tau$ events expected!

<table>
<thead>
<tr>
<th>$\tau$ Decay Channels</th>
<th>$\Delta m^2 = 2.5 \times 10^{-3}$ (eV$^2$)</th>
<th>$\sin^2(2\theta) = 1$</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \mu$</td>
<td>2.9</td>
<td></td>
<td>0.17</td>
</tr>
<tr>
<td>$\tau \rightarrow e$</td>
<td>3.1</td>
<td></td>
<td>0.17</td>
</tr>
<tr>
<td>$\tau \rightarrow h$</td>
<td>3.5</td>
<td></td>
<td>0.24</td>
</tr>
<tr>
<td>$\tau \rightarrow 3h$</td>
<td>0.9</td>
<td></td>
<td>0.17</td>
</tr>
<tr>
<td>ALL</td>
<td>10.4</td>
<td></td>
<td>0.76</td>
</tr>
</tbody>
</table>

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**OPERA experiment: Status and Prospects**

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

(5 years of operation, 4.5 x 10^{19} pots/year, 1.35 kton target mass)

<table>
<thead>
<tr>
<th>( \theta_{13} )</th>
<th>SIGNAL [ \Delta m^2 = 2.5 \times 10^{-3} \text{ (eV}^2) ]</th>
<th>( \nu_\mu ) Beam</th>
<th>( \tau \rightarrow e )</th>
<th>( \nu_\mu ) CC</th>
<th>( \nu_\mu ) NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td>9.3</td>
<td>18</td>
<td>4.5</td>
<td>5.2</td>
<td>1.0</td>
</tr>
<tr>
<td>70°</td>
<td>5.8</td>
<td>18</td>
<td>4.5</td>
<td>5.2</td>
<td>1.0</td>
</tr>
<tr>
<td>50°</td>
<td>3.0</td>
<td>18</td>
<td>4.5</td>
<td>5.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

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ICARUS (T600) Experiment

- Ionization electrons drift (msec) over large distances (meters) in a volume of highly purified liquid Argon (0.1 ppb of O₂) under the action of an E field.

- With a set of wire grids (traversed by the electrons in ~ 2-3 µs) one can realize a massive, continuously sensitive electronic “bubble chamber”.

E = 500 V/cm

ICARUS COLLABORATION
25 INSTITUTIONS, 150 PHYSICISTS

ICARUS, LHC, CERN, HEV, UCLA, HEP, CERN, Granada

LAr used as ‘target’ and ‘detector’

Anode: multi-plane readout
3 wire planes at 0 and ± 60 deg

Wire separation = 3 mm

Collection
Induction 1
Induction 2

Minimum ionizing track: 88000 electron-ion pairs per cm
After recombination @ 500 V/cm: 55000 pairs/cm

Drift of electrons: ν

Drift of ions: ν’

ν’<ν ≈ 1.8 mm/µs @ 500 V/cm

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ICARUS (T600) Experiment: Goals

1) Prove a very promising detector technology for next generation neutrino oscillation and proton decay experiments...

2) ...While doing interesting physics
ICARUS (T600) Experiment
: Detector Capabilities

- **Tracking device**
  - Precise event topology
  - Momentum via multiple scattering

- **Measurement of local energy deposition dE/dx**
  - $e/\gamma$ separation (2%$X_0$ sampling)
  - Particle ID by means of dE/dx vs range measurement

- **Total energy reconstruction of the events from charge integration**
  - Full sampling, homogeneous calorimeter with excellent accuracy for contained events

**RESOLUTIONS**

- Low energy electrons: $\sigma(E)/E = 11% / \sqrt{E(\text{MeV})+2%}$
- Electromagn. showers: $\sigma(E)/E = 3% / \sqrt{E(\text{GeV})}$
- Hadron shower (pure LAr): $\sigma(E)/E \approx 30% / \sqrt{E(\text{GeV})}$
ICARUS T600: Data (cosmics & neutrino events in a small prototype @ CERN)

\[ \nu_\mu + X \rightarrow \mu^- + Shw \]
\[ \nu_\mu + n \rightarrow \mu^- + p \]

Muon bundle

EM shower

Hadronic interaction

Collection view

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ICARUS T600: Status and Prospects

Start taking Data within the coming year!!!
vews to come: What will they tell us in the Near Future?

What is the value of the “third” mixing angle? (the other two indicate nearly maximal mixing, the limit for the third indicates a pretty low value...) (Reactor experiments, NOVA, T2K)

- Is there CP violation in the neutrino sector? (which might explain why we are here!!) (NOVA + T2K)

Are there sterile neutrinos???
(MiniBoone)

What is after all, the neutrino MASS?? (absolute value not mass squared difference)
(Kinematics of beta decay)

- Do “man made” ν’s oscillate?

- What is “precisely” the mass squared difference and the mixing angle? (K2K)

- Are neutrinos and anti neutrinos the same?? (Majorana particles) (neutrino-less double beta decays)

- Which is the heaviest one? (NOVA, T2K)

DO NOT FORGET

Atmospheric
$\begin{bmatrix}
1 & 0 & 0 \\
0 & c_{23} & -s_{23} \\
0 & s_{23} & c_{23}
\end{bmatrix}$

Solar
$\begin{bmatrix}
c_{12} & s_{12} & 0 \\
- s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{bmatrix}$

$0
\nu\beta\beta$ decays
$\begin{bmatrix}
e^{ia_1/2} & 0 & 0 \\
0 & e^{ia_2/2} & 0 \\
0 & 0 & 1
\end{bmatrix}$

$U=$

$\begin{bmatrix}
c_{13} & 0 & -s_{13}e^{-is} \\
0 & 1 & 0 \\
s_{13}e^{-is} & 0 & c_{13}
\end{bmatrix}$
Degeneracies (ghost solutions) ...

Oscillation Probability depends on, at least, 3 parameters
\[ \theta_{13}, \delta_{cp}, \text{sign}(\Delta m^2_{31}) \]

Multiple Combinations of the 3 parameters can yield the “same” number of events, especially if parameters are “doing” similar things (like CPV and matter effects)

WHAT DO WE NEED :

a) Large Number of neutrinos since we know the effects are small (\( \theta_{13} < 11^0 \))

b) Multiple measurement of number of events as a function of energy, \( E \), and as a function of distance, \( L \).

c) Longer Baselines to enhance matter effects

d) Nature to be kind to us !!!

More on O. Mena’s talk
The T2K far detector is the 50 Kt SuperK detector, located ~2.50° off axis (JPARC beam), at a distance of ~300km.

T2K, due to the sorter baseline has no sensitivity to the mass hierarchy.

Hunt for a non-zero $\theta_{13}$: PHASE I
Accelerator Experiments: T2K (Japan)
Hunt for a non-zero $\theta_{13}$ (+more): PHASE I

**Accelerator Experiments**: NOvA

More on M. Ishitsuka’s talk

Start Data Taking ~2013

The NOvA far detector will be a 15 kT “totally active” liquid scintillator detector, located 14 mrad (12 km) off the NuMI beamline axis near Ash River, MN, 810 km from Fermilab.

Depending on the value of the third mixing angle NOvA could determine the neutrino mass hierarchy.

Best measurements and discovery potential will come from combination of T2K and NOvA.
PHASE II: Measure CPV, extend $\theta_{13}$ reach, extend neutrino mass hierarchy reach

Numerous studies world-wide over the past several years have studied strategies to achieve the goals of PHASE II and came to the same conclusions. One needs:

- Massive cost effective detectors that are larger than those of Phase I ($> 20$ KT)

- Intense neutrino beams with intensity possibly higher than that of Phase I ($> 700$ KW)

- The ability to break inherent degeneracies between genuine CP violation and “Fake CP violation” from matter effects.
Ingredients for achieving the goals of Phase II: Massive Detectors

Massive Detectors (Liquid Argon, Water Cherenkov, Liquid Scintillator, etc) that are scalable in the Multi Kt scale
Wide Band Neutrino Beam: Advantages

ON AXIS WBB: 1st and 2nd Oscillation Maxima 1 Detector

OFF AXIS NBB: 1st and 2nd Oscillation Maxima 2 Detectors

\[ \delta_{cp} = 0 \]

\[ \delta_{cp} = \pi/2 \]
Ingredients for achieving the goals of Phase II: Powerful Neutrino Beams, JPARC

**Plan for Improving Neutrino Beam Intensity by Main-Ring Upgrade**

- **Linac**: 181 MeV to 400 MeV
  - 0.60 MW
  - 0.28 Hz
  - 0.91 MW
  - 0.57 Hz
  - 1.66 MW
  - 0.52 Hz

- **RF system improvement**
- **BM power supply**

- **Achievements**:
  - Shorten acceleration time
  - More RF system
  - Magnet power system
  - More beam per pulse
  - Operation of 3 GeV RCS in harmonic number = 1

*Slide by A. Suzuki, KEK Roadmap Review Committee, March 2008*

*Assumed in most part of this talk*
Ingredients for achieving the goals of Phase II:
Longer Baseline  Tokai->Korea
Physics Reach: JPARC with two 0.27 Mton detectors in Kamioka and Korea

- 0.27 Mton fid. Mass at Kamioka and Korea (water Ch)
- 4 years $\nu$ beam + 4 years anti-$\nu$ beam, 4MW, 2.5 deg Off-axis

**Mass hierarchy**

**CP violation ($\sin\delta \neq 0$)**

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Ingredients for achieving the goals of Phase II: Powerful Neutrino Beams, US (FNAL)

Powerful $\nu$ beams of very high intensity Project X

More on A. Jansson and D. Harris talk

Two options for neutrino beams and experiment baselines exist:

Fermilab vision: The Intensity Frontier with Project X:

Great flexibility toward a very high power facility while simultaneously advancing energy-frontier accelerator technology.

- Project X = 8 GeV ILC-like Linac
- Recycler
- Main Injector

National Project with International Collaboration

From YKK

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Ingredients for achieving the goals of Phase II:
Longer Baseline FNAL->Ash River, FNAL-> DUSEL

(A) L ~ 800 Km and NuMI Off Axis Narrow Band Beam.

(B) L ~ 1300 Km (Fermilab->DUSEL)
New Wide Band Beam (On or off Axis)

Implications on ν beam:
New beam has to be designed and constructed (beginning design considerations)
Physics Reach: FNAL to DUSEL with 0.1 Mton LAr Detector

Reach in $\nu$ mass hierarchy well below $10^{-2}$!!
FNAL to DUSEL program

- Science goals for future long baseline neutrino experiments in the US endorsed by P5
- Strong consensus within the US neutrino community to form the Collaboration to accomplish the physics goals:
  - Neutrino oscillations
  - Proton Decay
  - Astrophysical neutrinos
- Science community is awaiting guidance from the funding agencies (DOE and NSF) for funding and management.
Summary and Conclusions

• So far the behavior of the “little neutral one” has been full of many “big” surprises…

• Running experiments enter a new era of precision physics regarding atmospheric and solar oscillations.

• Experiments starting up set the stage for the next generation of powerful neutrino detectors.

• Near and long term experiments worldwide aim to address many of the remaining important questions with respect to neutrino oscillations.

• Stay tuned for the fascinating views to come..
BACKUP SLIDES
...a charm candidate!

Flight length: 3247.2 μm
\( \theta_{\text{track}} \): 0.204 rad
\( P_{\text{daughter}} \): 3.9 (+1.7 -0.9) GeV
\( P_{T} \): 796 MeV (> 606 MeV)

Two e.m. showers pointing to vertex
Staged approach to achieve ultimate goals in US

1) Start with NuMI off Axis beam at 810 km (NOvA) and 700 KW

2) Upgrade detector, ie add 5kt LAr with NuMI on Axis Beam at 735 km and 700 KW (equivalent to increasing statistics. Equivalent to ~doubling NOvA, with the benefit of proving or not a promising detector technology that is scalable)

3) Increase Beam Power: Project X yields 2.3 MW, (SNUMI could yield 1.2 MW) (equivalent to increasing statistics)

4) Improve the Neutrino Beam (new WBB), Increase Detector Mass (equivalent to increasing statistics) and Increase Baseline
• Such beam does not exist, but is in the design phase.

• In general, design of target station and horns for beam power > 1 MW non trivial (R&D needed)
## OPERA experiment : Data

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![Graphical representation of OPERA experiment data]

**NC event**

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Longer baseline (>>L) AND a new Wide Band Beam

With new Wide Band Beam:

1) Increase "useful" flux (at first and second oscillation maxima)

2) With increasing L oscillation maxima "appear" in more "favourable" positions in the neutrino energy spectra

3) Thus study of first and second oscillation maxima is easier (one detector instead of two, higher rates, etc)

4) With increasing L matter effects increase and hence potential for mass hierarchy determination is increasing
NuMI Neutrino Beam: Capabilities & Advantages

- The Beam Exists and performs well
- There is a well defined upgrade plan
- The off-axis idea of obtaining a NBB is attractive: It reduces the NC background resulting from high energy neutrinos.
Detector Technology

MINOS Near and Far detectors are functionally identical: share same detector technology and granularity:

Scintillator strip

**Scintillator module**

M64 PMT

M16 PMT
Why Beam Modeling uncertainties Cancel (Beam Matrix Method)

Beam Matrices that correspond to quite different near detector spectra are very similar (spread in each column determined primarily by the geometry of the beamline).

NOTE: Red dotted bands are ± 5%.

Method: Use instead of LE010 185 kA Beam transfer Matrix the LE010 200kA Beam transfer Matrix.

These different matrices correspond to quite different “beams” as evident from the Near Detector Spectra.

However, Far Detector Prediction is quite accurate to within < 5%.
Why Cross Section Uncertainties Cancel
(Beam Matrix Method)

\[ \begin{align*}
&\text{ND Spectrum} \\
&\begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix} \times \begin{pmatrix} \sigma_a & 0 & 0 \\ 0 & \sigma_b & 0 \\ 0 & 0 & \sigma_c \end{pmatrix}^{-1} \times \begin{pmatrix} b_1 & 0 & 0 \\ 0 & b_2 & 0 \\ 0 & 0 & b_3 \end{pmatrix} \times \begin{pmatrix} \sigma_a & 0 & 0 \\ 0 & \sigma_b & 0 \\ 0 & 0 & \sigma_c \end{pmatrix} = \begin{pmatrix} e_1 \\ e_2 \\ e_3 \end{pmatrix}
\end{align*} \]

\[\text{ND Flux} \quad \Rightarrow \quad \text{FD Flux}\]

Cross Section matrices & Beam Matrix almost diagonal $\Rightarrow$ They Commute!

Their Product is I regardless of their values!
(In the limit where the Beam Matrix is diagonal)
Event catching: Timing and Triggering

- The elements of the timing system are as follows:
  - $74$ signal from Main Injector – tells kicker magnet (which extracts protons to NuMI) that it is in the queue to fire (which it does ~$220$ $\mu$s later).
  - $74$ signal sent to clock controller at ND & a spill gate (SGATE) window is opened (in hardware) for $13\mu$s around the time neutrinos hit the ND (with an offset of $-1.5\mu$s)
  - SpillServer process at FD informed when most recent spill occurred.
  - FD trigger farm queries SpillServer process every second. If a spill signal has been received and the Spill Trigger is enabled, the DAQ reads out $100\mu$s of previously buffered data around the predicted time that the neutrinos should have hit the FD
NuMI Alignment

Align the center of ν beam to the Far Detector in the Soudan mine. Goal is within 12 m.

• Fermilab to Soudan surface done using GPS
  • determined vector to 0.01 m horiz., 0.06 m vertical
• Soudan surface to 27th level
  • 0.7 m per coordinate
• Fermilab surface to underground
  • gyrotheodolite with 0.015 mrad precision
  • 11 m at Soudan
• Transverse alignment of baffle, target and horn at 0.5 mm

N.Saoulidou
Nufact08, 01-07-08, Valencia Spain
Effect of MC tuning on the measurement

- Using Beam Matrix Method, hadron production tuning does not affect the Unoscillated prediction (obtained from the ND data) by more than 1-2%.

- However, its use improves the MC (make it more similar to the data) and therefore uncertainties due to energy smearing-unsmearing and acceptance become smaller.
Beam Matrix Results RunI

N. Saoulidou
Nufact08, 01-07-08

MINOS Preliminary

RunI 1D $\Delta \chi^2$ Projections

RunI Data  MINOS Preliminary

Sensitivity

$|\Delta m^2_{32}|$ (eV$^2$/c$^4$) vs $\sin^2(2\theta_{23})$
Beam Matrix Results RunI

Oscillation Results for 1.27E20 POTs

MINOS Preliminary

Events per GeV

Reconstructed Neutrino Energy (GeV)

Ratio of Data / Prediction

Reconstructed Neutrino Energy (GeV)

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Beam Matrix Results RunIIa

N.Saoulidou

MINOS Preliminary

RunIIa 1D $\Delta \chi^2$ Projections

RunIIa Data
Sensitivity

MINOS Preliminary

RunIIa 1D $\Delta \chi^2$ Projections

RunIIa Data
Sensitivity

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Beam Matrix Results RunIIa

Oscillation Results for 1.23E20 POTs

- Un-Oscillated
- Best Fit
- NC
- Data

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Neutral Current Analysis: Near Detector NC-like Spectrum

- **Goal** is a NC spectrum measurement in the FD which is **Sensitive** to $\nu_\mu \rightarrow \nu_{\text{sterile}}$, $\nu$ decay signatures...

  - First step of this analysis is a measurement of the NC spectrum in the Near Detector.

  - Second step is the use of similar techniques to the CC analysis to extrapolate measured spectrum to the Far Detector and compare with the data

Use simple cuts to select NC events with high (93%) efficiency (CC contamination ~50%)

The agreement of NC Selection Variables between Data and MC is good.
Neutral Current Analysis: Near Detector NC-like Spectrum

• Unlike the Far Detector our Near Detector “sees” a lot of neutrinos per beam spill (event overlapping).

• To ensure that event overlapping is not affecting the NC-like spectrum we reconstruct we developed two independent methods to obtain clean samples of events for data/MC comparisons in the Near Detector:

  - Both are designed to reject events that overlap in time and space and/or are not well-reconstructed:

  1) High multiplicity selection: Uses timing & topological cuts (selects 860K NC-like events for 1.23e20 pot)

  2) Low multiplicity selection: Use only spills with 1 or 2 reconstructed events (selects 10472 NC-like events for 1.23e20 pot)

One near detector spill

Snarl 95980 Strip times in microseconds

Individual events

Time (us)
Neutral Current Analysis: Near Detector NC-like Spectrum cont’d

- **MC error band** includes contributions from beam, cross-section and energy scale uncertainties
- Both methods (high and low multiplicity data cleaning) give results consistent with each other and with expectations.