NuMI Long-Baseline Off-Axis Oscillation Physics with Large Liquid Argon Detectors
Outline

- Physics Potential
- Progress towards realization of a large liquid Argon time projection chamber (LArTPC)
- R&D program to meet these goals

*This effort has been recognized and encouraged by FNAL management*
Long-baseline, off-axis oscillation physics provide next window into neutrino oscillation physics

hierarchy of the neutrino masses, structure of the mixing matrix, CP Violation in the neutrino sector

Take advantage of existing, high intensity NuMI beam!

Limiting factor in sensitivity for long-baseline neutrino physics is $\nu_e$ event rate and background rejection
Massive LArTPCs provide excellent means to do this physics

- Improved efficiencies and background rejection ameliorate statistics limitations of long-baseline neutrino physics
- Success of the ICARUS T600 proves technical feasibility for “small” detectors
- Study of massive liquid Argon detector designs shows a path for realizing larger detectors for long baseline, off-axis neutrino physics

There is a growing effort at Fermilab and a group of universities worldwide to pursue this technology for this physics.
Liquid Argon TPCs:
Fine-grained tracking, total absorption calorimeter

50,000 electrons/cm

Drift ionization electrons over meters of pure liquid argon to collection planes to image track
Signals on wire chamber planes

Arrange $E$ fields and wire spacing for total transparency for induction planes. Final plane collects charge.

ICARUS TM/2001-09
Allows for high resolution imaging like bubble chambers, but with calorimetry and continuous digital readout (no deadtime)
How good are these detectors at identifying $\nu_e$ interactions and rejecting NC interactions?
LArTPCs
• Total absorption calorimeter
• 5mm sampling
  -> 28 samples/rad length
• energy resolution

First pass studies using hit level MC show
\[ \sim 80 \pm 7 \% \nu_e \] efficiency and
NC rejection factor \( \sim 70 \)

(only need rejection factor of 20 to knock background
down to \( \frac{1}{2} \) the intrinsic \( \nu_e \) rate)

Studies from groups
working on T2K LAr indicate 85-95% \( \nu_e \) efficiency

in documents submitted to NuSAG
Electrons versus $\pi^0$'s at 1.5 GeV

Dot indicates hit
color indicates collected charge
green=1 mip, red=2 mips

**Electrons**

*Single track (mip scale)*
*starting from a single vertex*

Use both topology and dE/dx to identify interactions

Multiple secondary tracks can be traced back to the same primary vertex

Each track is two electrons – 2 mip scale per hit
Neutral current event with 1 GeV $\pi^0$

\[ v_\mu + n \rightarrow v_\mu + \pi^+ + \pi^- + \pi^0 + n \]

(1 GeV) $\pi^0 \rightarrow \gamma + \gamma$

3.5% $X_0$ samples in all 3 views

4 cm gap

12% $X_0$ samples alternating x-y
Efficiency and Rejection study

Analysis was based on a blind scan of 450 events, carried out by 4 undergraduates with additional scanning of “signal” events by experts.

- Neutrino event generator: NEUGEN3. Used by MINOS/NOvA collaboration. Hugh Gallagher (Tufts) is the principal author.
- GEANT 3 detector simulation: trace resulting particles through a homogeneous volume of liquid argon. Store energy deposits in thin slices.

Training samples:
50 events each of $\nu_e$CC, $\nu_\mu$CC and NC
- individual samples to train
- mixed samples to test training

Blind scan of 450 events scored from 1-5 with
- signal=5
- background=1

Tufts University Group
Overall efficiencies, rejection factors, and dependencies

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>pass</th>
<th>ε</th>
<th>η</th>
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<tr>
<td>NC</td>
<td>290</td>
<td>4</td>
<td>-</td>
<td>72.5</td>
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<tr>
<td>signal (\nu_e)</td>
<td>32</td>
<td>26</td>
<td>0.81</td>
<td>-</td>
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<tr>
<td>Beam (\nu_e): CC</td>
<td>24</td>
<td>14</td>
<td>0.58</td>
<td>-</td>
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<tr>
<td>NC</td>
<td>8</td>
<td>0</td>
<td>-</td>
<td>-</td>
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**Signal \(\nu_e\):**

Efficiency is substantial even for high multiplicity events

Efficiency is \(\sim 100\%\) for \(y<0.5\), and \(\sim 50\%\) above this

\[y = \frac{E_{\text{had}}}{E_\nu}\]
Given very high $\nu_\text{e}$ efficiency and NC background rejection well below $1/2$ of the intrinsic $\nu_\text{e}$ beam backgrounds, how sensitive are these detectors?

$$\text{Sensitivity} = \text{detector mass} \times \text{detector efficiency} \times \text{protons on target/yr} \times \text{# of years}$$
Three Neutrino Mixing Matrix:

\[ U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \]

From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

From Long Baseline Appearance Measurements

From Solar Neutrino Measurements

Chooz limit is \( \sin^2 2\theta_{13} \approx 0.1 \)

The CP Violation Parameter

Capability depends on \( \delta \) and \( \theta_{13} \)
Capability will also depend on the mass hierarchy
As an example: focus on recent paper by Mena and Parke

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<tr>
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<th>Medium</th>
<th>Large</th>
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<tbody>
<tr>
<td>NOvA</td>
<td>30kTon</td>
<td>30kton + PD or x5 det. mass</td>
<td>30kton + PD + x5 det. mass</td>
</tr>
<tr>
<td>LArTPC</td>
<td>8kton (90% ν\textsubscript{e} eff.)</td>
<td>40kton</td>
<td>40kton + PD</td>
</tr>
</tbody>
</table>

All sensitivities assume 3 years running each in ν and \(\bar{\nu}\) mode
Sensitivity to CP phase($\sin \delta$) vs $\sin^2 2\theta_{13}$ for

most restrictive:
$\cos \delta < 0$, normal hierarchy
$\cos \delta > 0$, inverted hierarchy

least restrictive:
$\cos \delta > 0$, normal hierarchy
$\cos \delta < 0$, inverted hierarchy
Can we build these detectors?
Technical Feasibility: History of prototype work on ICARUS


24 cm drift wires chamber


50 litres prototype 1.4 m drift chamber

1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

10 m³ industrial prototype

1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.
The success of the ICARUS T600 tested above ground in Pavia in 2001 now below ground in Gran Sasso.
Baseline concept: 15-50kTon vessel which builds on ICARUS wire plane readout
Many large LNG tanks in service

Excellent safety record

Last failure in 1940 understood
Overview

6 Wire Sectors, each containing 6 Wire Planes

7 Cathode Planes

Active volume Diameter: 40m Height: 30m

Scalable → 15-50 kTons 4 - 6 wire planes
Front View

- Attic Floor Support Structure
- Outer Tank Roof
- Attic Floor
- Flexible Joint
- Signal Read-Out Duct
- Access Door
- Access Platform
- Outer Tank Cylindrical Wall
- Insulation
- Inner Tank Cylindrical Wall
- Inner Tank Roof Support
- Cylindrical Wall Bottom Bracing

Dimensions:
- 30m
- 40m
Each wire plane:

- Vertical collect. plane
- +30° induction plane
- -30° induction plane

5mm spacing between planes

Wires are:
- 150 μm stainless steel
- 5mm pitch
- 38m at longest

Wire planes head on

2 wire readout

3 wire readout (overconstrained)
Drifting electrons over long distance (3m)?

Signal size for passing track: 55,000 electrons/cm

How many are drifted to the edge of the detector?

- drift velocity,
  \[ V_{\text{drift}} = 1.55 \text{mm/\mu s} \]
  for \( E = 500 \text{ V/cm} \)

- diffusion coefficient

- argon impurities
  - don't want \( O_2 \) to 'eat' electrons along the way
Argon purity/electron lifetime in ICARUS

Impurities concentration is a balance of
- Purification speed $t_c$
- Leaks $F_{in}(t)$
- Outgassing $A$, $B$

\[
\frac{dN}{dt} = - F_{out}(t) + F_{in}(t) = \frac{N(t)}{t_c} + F_{in}^0 + \frac{A}{(1 + t/t_0)^B}
\]

for the T600 module: achieved lifetime $> 13$ msec
for large LArTPCs: electron lifetime $\sim 10$ms
Argon purity, lessons for a very large detector

- Long electron lifetimes (~10ms)/drift distances (>3m) are achievable with commercial purification systems
- The main source of impurities are the surfaces exposed to the gaseous argon
- Increasing the ratio of liquid volume to the area of gaseous contact helps (dilution)
- Increasing the ratio of cold/warm surfaces helps (purification)
- Material selection and handling is the key
Wires fed through tensioning system and fastened by wrapping wire around itself (ICARUS method)

ICARUS has 50,000 wires attached in this fashion

no breakage
Readout Electronics

Readout electronics and data acquisition -- current technology:

Each wire is connected to a continuous wave-form digitizer with a pulse-height dynamic range of ~30 and a time bin of 0.5 microsecond.

Signal size per wire on collection plane is 22,000 e after full drift. Signal to Noise is ~10/1

The signals from the wires pass to the electronics via ~80 chimneys in the top of the tank. Each chimney passes ~3000 signals.
Baseline Concept presented in two day “mini-Review”
Fermilab Particle Physics Division

No show stoppers in scaling up liquid argon technology as per Fermilab mechanical, cryogenic, and electronics engineers

Large detector can be built at a reasonable cost

Preliminary Costing

50 kton TPC ~100M
15 kton TPC ~54M
Can purity be achieved and maintained in a large detector?
Can very large wire chamber and cathode planes be assembled with high signal quality?
Can cosmic backgrounds be rejected for a surface detector?

Prototyping and R&D efforts underway with path to demonstrate that answers to these questions are yes
R&D efforts underway at FNAL, at Yale, at UCLA/CERN.
R&D path over the next year shaped by open questions for large detectors:

**Key Hardware Issues**

Technology transfer
- Test setup at FNAL
- Seeing tracks and light production at Yale

Understanding long drifts at UCLA/CERN

Purity tests in long drift vessel at Fermilab
- Introduction of impurities
- Test of detector and tank materials
- Test of filtering materials
- Purification rate

Very long electrode assembly/stability and readout

Design for detector to be assembled with industrial techniques
R&D path over the next year shaped by open questions for large detectors: (part2)

Key software, feasibility and infrastructure issues

Continuing Monte Carlo work – automated event reconstruction

Costing study

Growing a strong collaboration
  • FNAL group is growing
  • University involvement growing
  • Participation from groups on the ICARUS collaboration growing
This is a great, scalable technology that can enhance growing NuMI long baseline program!

Support from the community in pursuing new technologies:

2005 APS neutrino study
“The development of new technologies will be essential for further advances in neutrino physics”

Support from incoming director Pier Oddone

EPP2010 talk, May 2005
“We want to start a long term R&D program towards massive totally active liquid Argon detectors for extensions of NOvA”
Endorsement from NuSAG towards realization of very large liquid Argon TPCs will keep effort on time to contribute to Fermilab's NuMI long baseline program
Backup slides etc.
T2K efficiency studies in LArTPC

T2K studies also show excellent e/p0 separation:
automated reconstruction $\Rightarrow$ dE/dx in first 8 hit wires combined with scan to look for displaced vertex $\Rightarrow$ p0 inefficiency of 0.2%
p0 rejection improves with increasing energy (dE/dx only)

Overall $\nu_e$ efficiency: 85%-95%
topology topology + kinematics, PID
Signal size: how many electrons per 1 cm of a track?

- $(dE/dx)_{\text{mip}} = 2.13 \text{ MeV/cm}, W_{\text{ion}} = 23.6 \text{ eV}$
- $(dQ/dx)_0 = 90000 \text{ e/cm}$
- $(dQ/dx)_{\text{measured}} = R(dQ/dx)_0$
- $R$ – recombination factor:
  - Electric field
  - Ionization density
  - scintillation
- Experiment: $(dQ/dx) \sim 55,000 \text{ e/cm@400-500 V/m}$
Argon purity

Q: Oxisorb R20 filters have design purity level of <5 ppb. How come that the results are so good (<0.1 ppb)?
A: Specs refer to gaseous argon at NTP.

In a liquid phase impurities ‘freeze out’ at the vessel walls. The natural purification speed is limited by diffusion speed. (Related: B. Kephart, E706)

Electron lifetime improvement in ‘regular argon’

Degradation of argon purity is consistent with diffusion time

Slide needs work