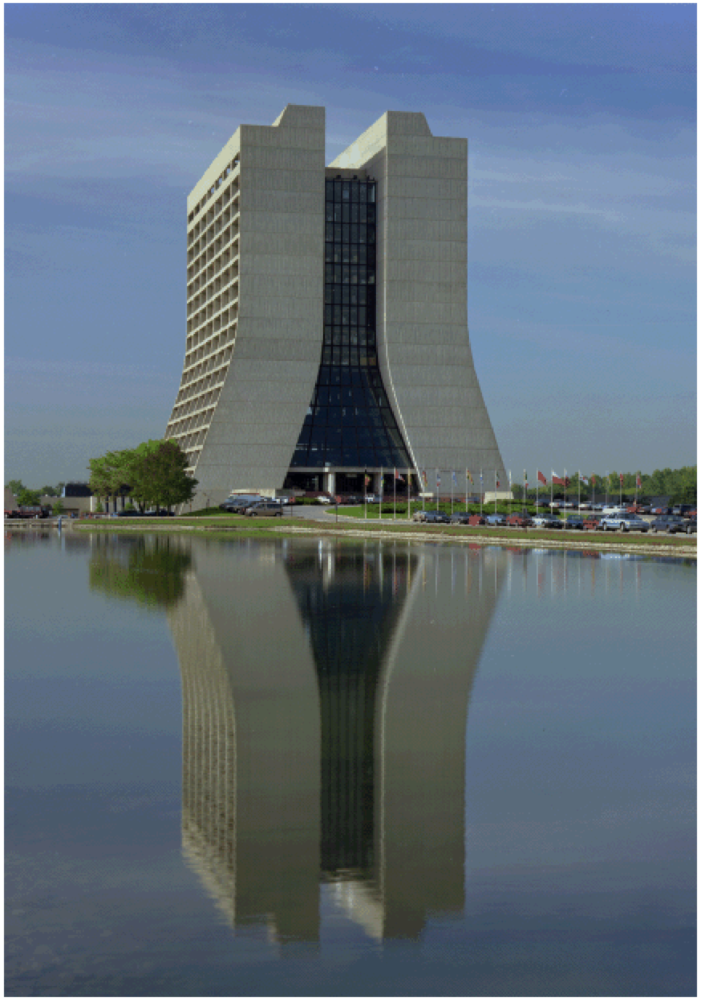
Future Long-baseline Neutrino Oscillation Program at Fermilab



Scott Menary

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Outline

- Issues in Neutrino Physics
- Experimental Solutions
- NOνA
- The Liquid Argon Time Projection Chamber (LArTPC)
- Progress towards realization of a large LArTPC
- Conclusions

Three Neutrino Mixing Matrix:

The CP Violation Parameter

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

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

From Long Baseline Appearance Measurements

From Solar Neutrino Measurements

At present only an upper limit on θ_{13}

In Vacuum the Oscillation Probability is:

- $P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$

$$P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\ \Delta m_{13}^2\ L/E)$$

$$P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\ \Delta m_{12}^2\ L/E)$$

$$P_3 = J \sin(\delta) \sin(1.27\ \Delta m_{13}^2\ L/E)$$

$$P_4 = J \cos(\delta) \cos(1.27\ \Delta m_{13}^2\ L/E)$$

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

$$\sin(1.27\ \Delta m_{13}^2\ L/E) \sin(1.27\ \Delta m_{12}^2\ L/E)$$

- The expression becomes even more complicated once matter effects are taken into account although this does introduce a difference depending on whether the beam consists of neutrinos or antineutrinos.
- Ultimately we measure:

$$P = f(\sin^2(2\theta_{13}),\delta,\mathrm{sign}(\Delta m_{13}^2),\Delta m_{12}^2,\Delta m_{13}^2,\sin^2(2\theta_{12}),\sin^2(2\theta_{23}),L,E)$$

The expression contains:

3 unknowns,

4 known "measured" quantities,

3 parameters under the experimenter's control – *L*, *E*, nu VS anti-nu beam

Goals of the Next Generation Neutrino Experiments

- Primary goal: Find evidence for $\nu_\mu \to \nu_e$ transitions determining effective value of $\sin^2(2\theta_{13})$.
- Longer term goal: Determine the mass hierarchy.
- Ultimate goal: Precision measurement of the CP-violating phase δ.

Sensitivity = mass x efficiency x protons on target/yr x # of years
{ detector } { accelerator } { funding! }

The ultimate limiting factor in sensitivity for long-baseline "superbeam" neutrino experiments is the intrinsic ν_e component of the beam.

Requirements to Achieve These Goals:

- High intensity, narrow-band ν_μ beam
- Detector highly efficient for ν_e events but with the capability to reject neutral current events (i.e., to differentiate electrons from π^0's)

New Initiatives: neutrinos

- Understanding the Neutrino matrix:
  - What is $sin^2 2\theta_{13}$
  - What is the Mass Hierarchy
  - What is the CP violation parameter δ
- Fermilab is in the best position to make vital contributions to answer these questions

P. Oddone September 12, 2005

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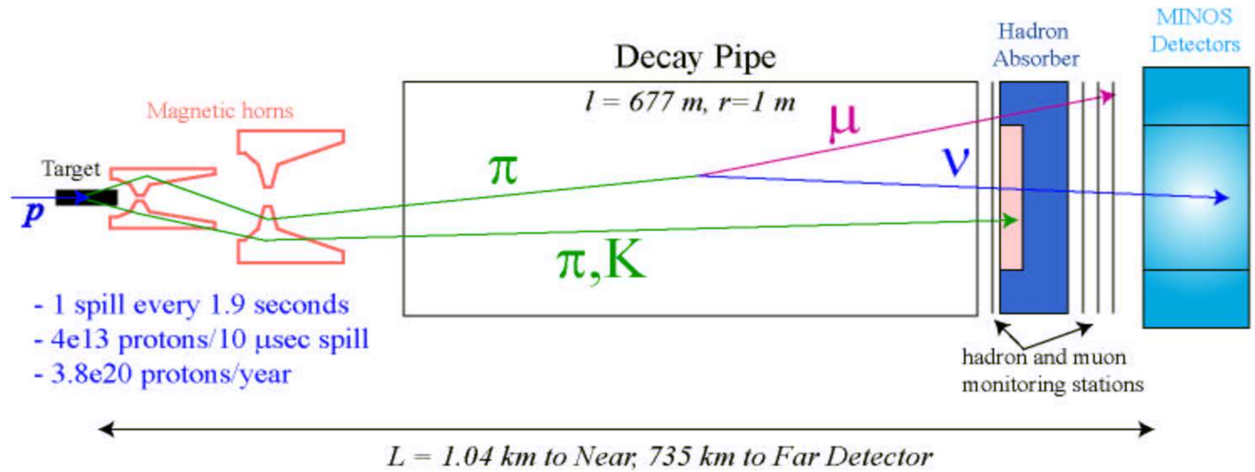
The Beam Already Exists!

The NuMI tunnel is complete and …

120 GeV/c protons strike graphite target

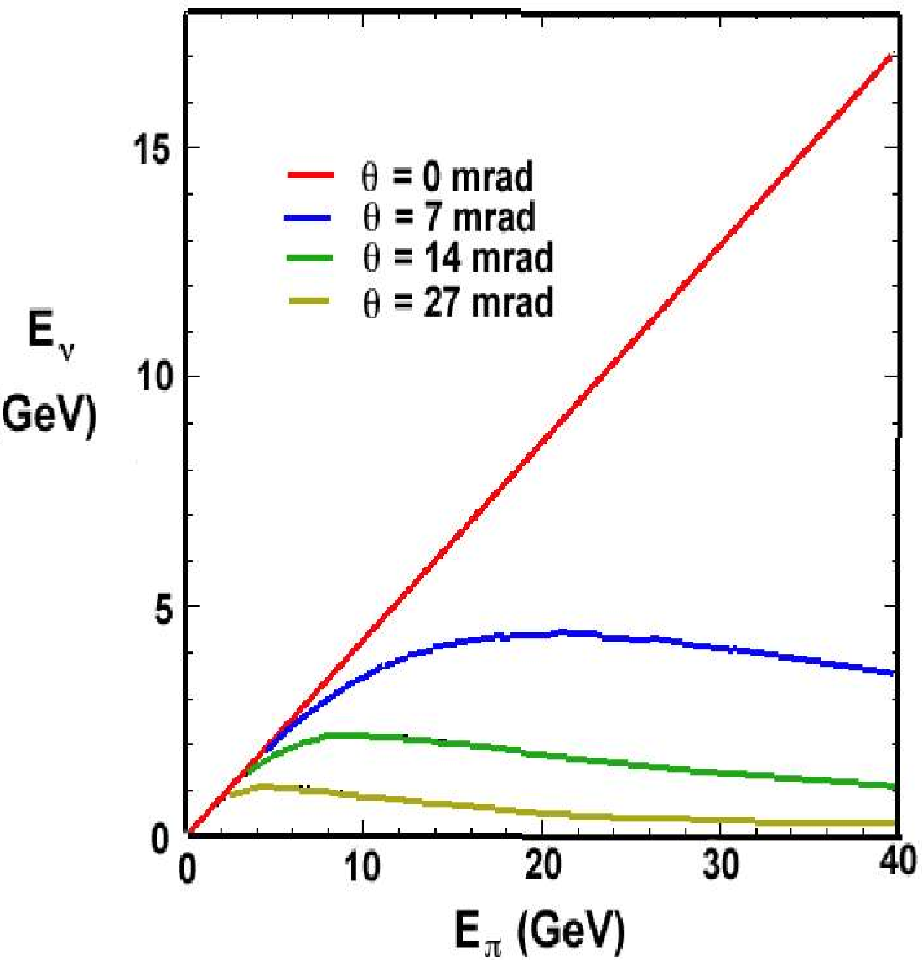
Magnetic horns focus charged mesons (pions and kaons)

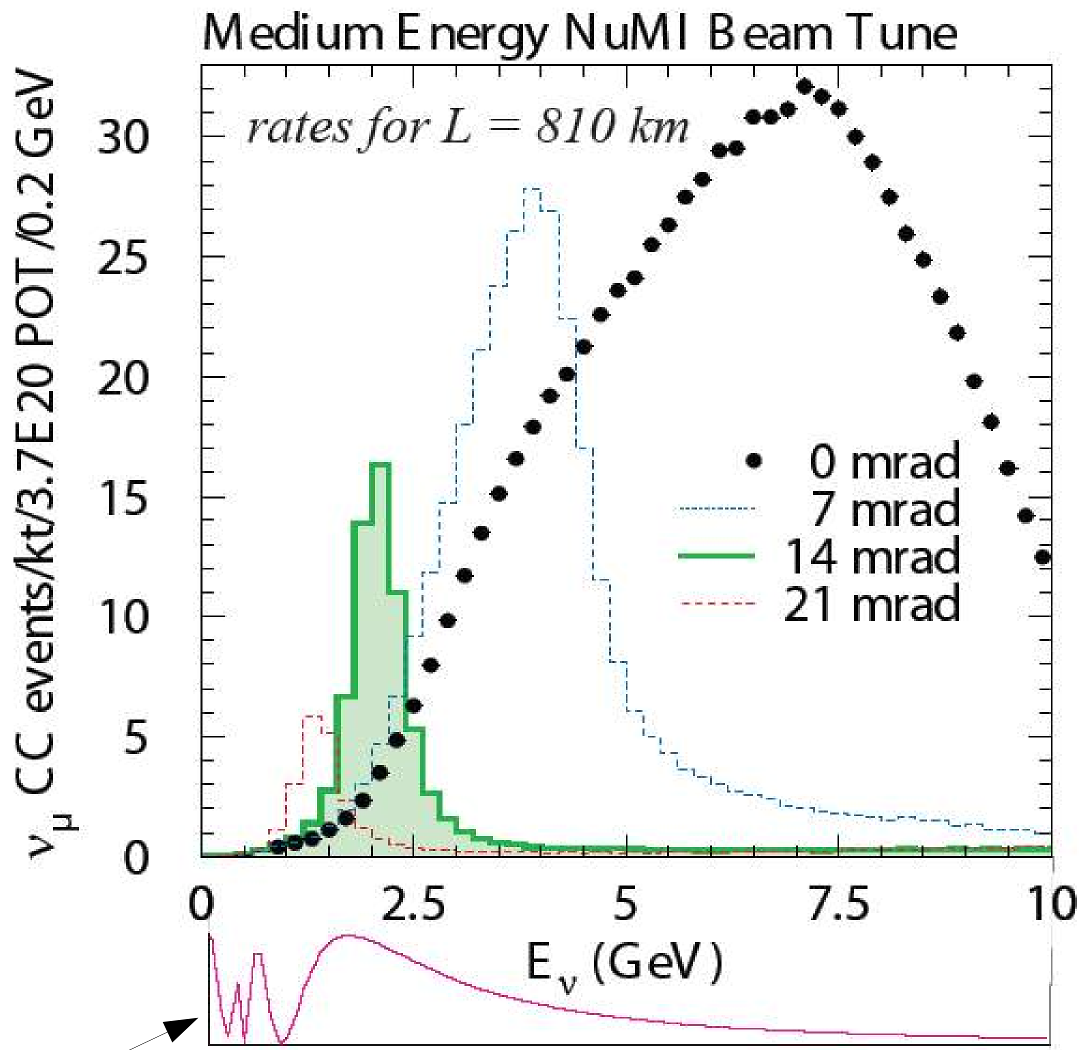
Pions and kaons decay giving neutrinos



… in January of last year the MINOS near detector saw its first neutrinos from the NuMI facility!

The "Off-axis" Beam

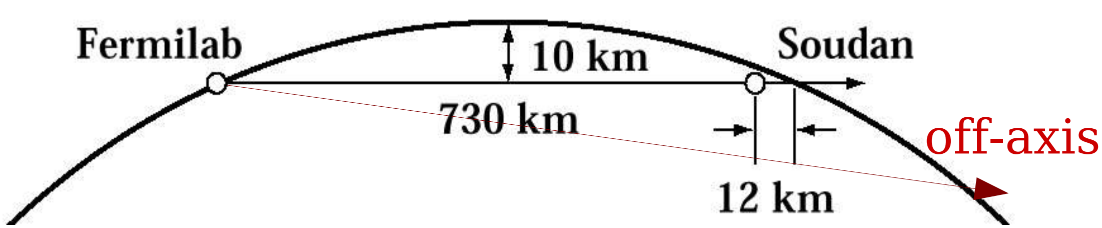




$\sin^2(1.27\ \Delta m_{13}^2\ L/E)$

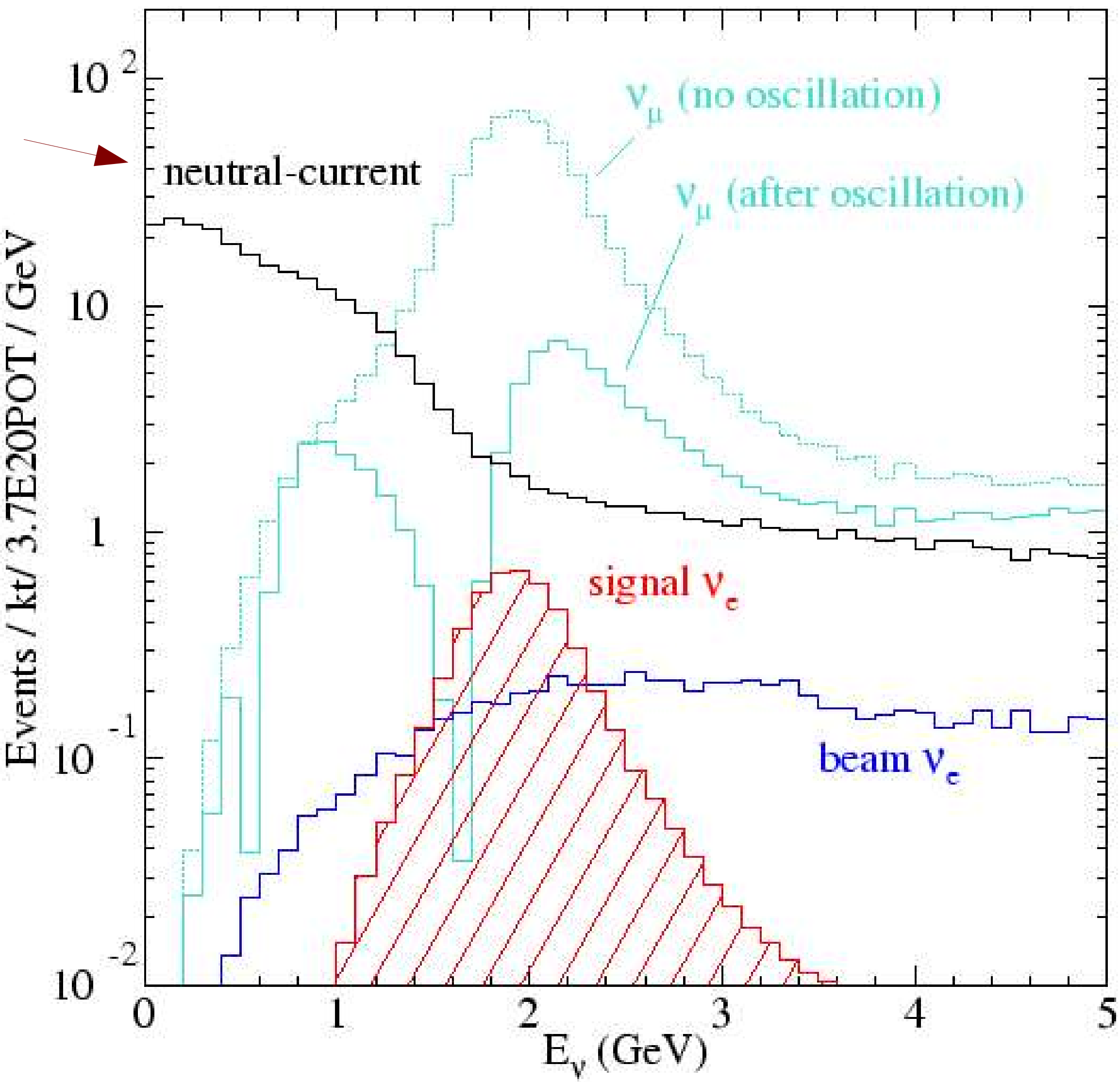
Assuming best current value for Δm_{13}^2, the oscillation maximum is related to baseline by L=500E.

=> L=1000 km for E=2 GeV



Rates and Spectra

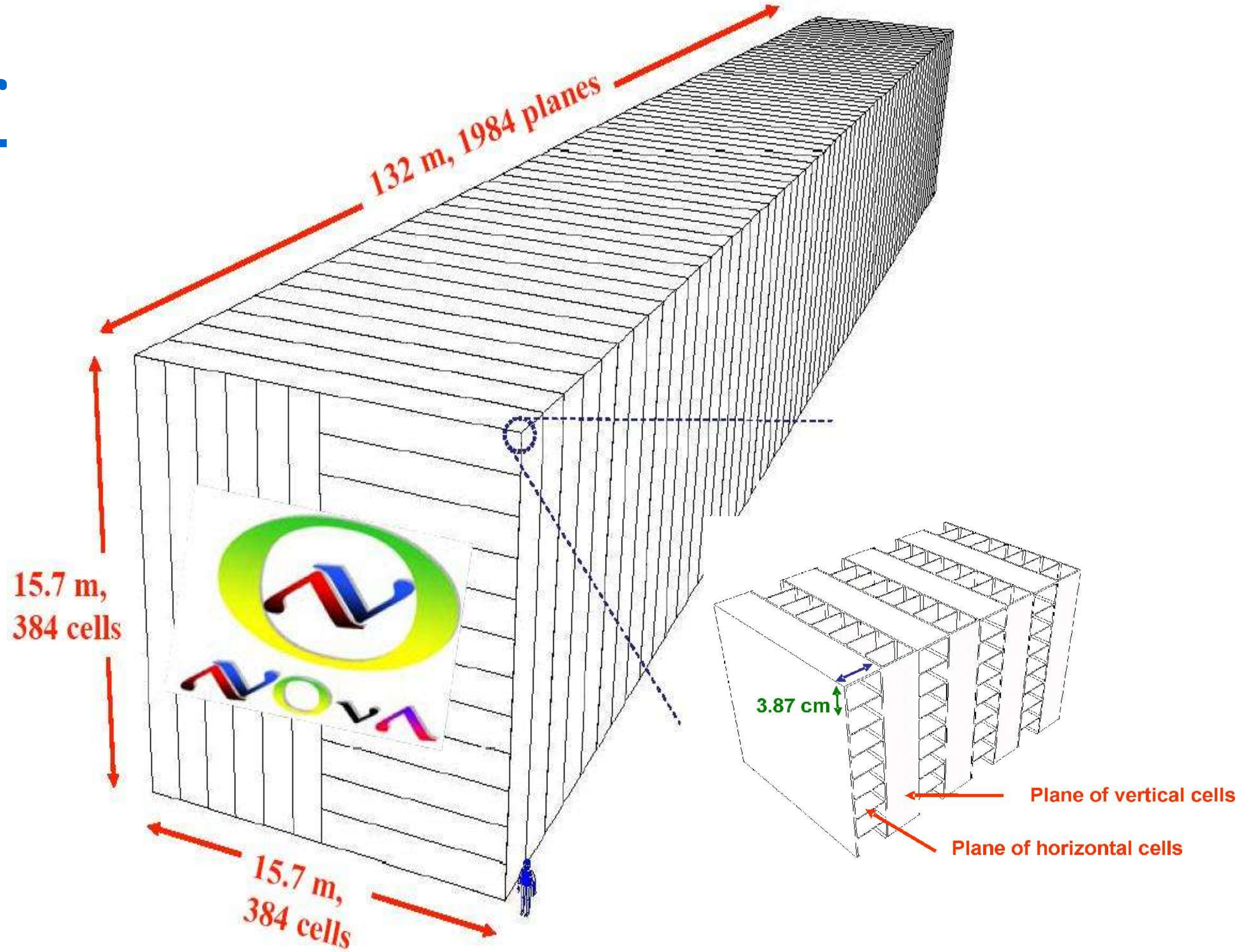
Source of π°'s to be cut



Simulated energy distributions for the ν_e oscillation signal, intrinsic beam ν_e events, neutral-current events and ν_μ charged-current events with and without oscillations. The simulation used $\Delta m^2_{32} = 2.5 \times 10^{-3}$ eV^2, $\sin^2(2\theta_{23}) = 1.0$, and $\sin^2(2\theta_{13}) = 0.04$. An off-axis distance of 12 km at 810 km was assumed.

NOνA Detector

- Revised Proposal (April 05)
  - "Totally Active" scintillator detector (75%)
- 30 kT
  - 24 kT liquid scintillator
  - 6 kT of cells
- Liquid scintillator cells
  - 3.9 cm x 6 cm x 15.7m
  - 0.15 X_0 sampling
  - 1984 planes of cells
- Cell walls
  - Extruded rigid PVC
  - 3 mm outer; 2 mm inner horizontal; vertical 4.5 mm outside
- Readout
  - U-shaped 0.8 mm WLS fiber : 27,000 km!
  - APDs (80% QE)



One Plane: 15 tonnes

Horizontal/vertical cells different for structural strength

Reconstruction

Two Algorithms:using a maximum likelihood analysis with the following variables

a) Total measured energy
b) Fraction of total energy carried by the electron
c) Mean pulse height near the origin of the electron
d) Pulse height per plane for the electron
e) Number of hits per plane for the electron
f) Energy upstream of the vertex
g)Curvature of the electron
h) Missing transverse momentum
i) Fraction of total electron energy contained in the first half of the electron track
j) rms deviation of electron hits from the fitted track
k) number of tracks identified as hadrons in the event

Cell width	Cell Depth	Relative FOM	Electron Energy
3.8	4.5	1.0	10.0%
3.8	6.0	1.02	10.7%
5.4	4.5	0.9	9.9%

Efficiency Typically 25-40%

Algorithms under development

FOM = Signal/Sqrt(Bkg)

Cost

	Contingency	Total Cost M$
Far Detector		
Active detector	30%	80
Electronics and DAQ	55%	13
Shipping	21%	7
Installation	43%	14
Near Detector	44%	3
Building and outfitting	58%	29
Project management	25%	5
Additional contingency		14
Total	50%	165

- Sensitive to price of crude oil!
  - We have understanding of how price depends on petroleum price: can make sensible estimates

Schedule

- Cannot start in FY2007 due to regulations on Congressional line items.
- Aiming for a FY2008 project start.
- Start of data taking October 2010
- Completion of the Far Detector July 2011

3 Feb 06: President's Budget: White House to Congress
High Energy Physics Program ($775.1 million)
This is a $58.4 million increase over FY 2006.

!!!!

Project engineering and design funding of $10.3 million is requested for the new Electron Neutrino Appearance project.

Importance of the Mass Ordering

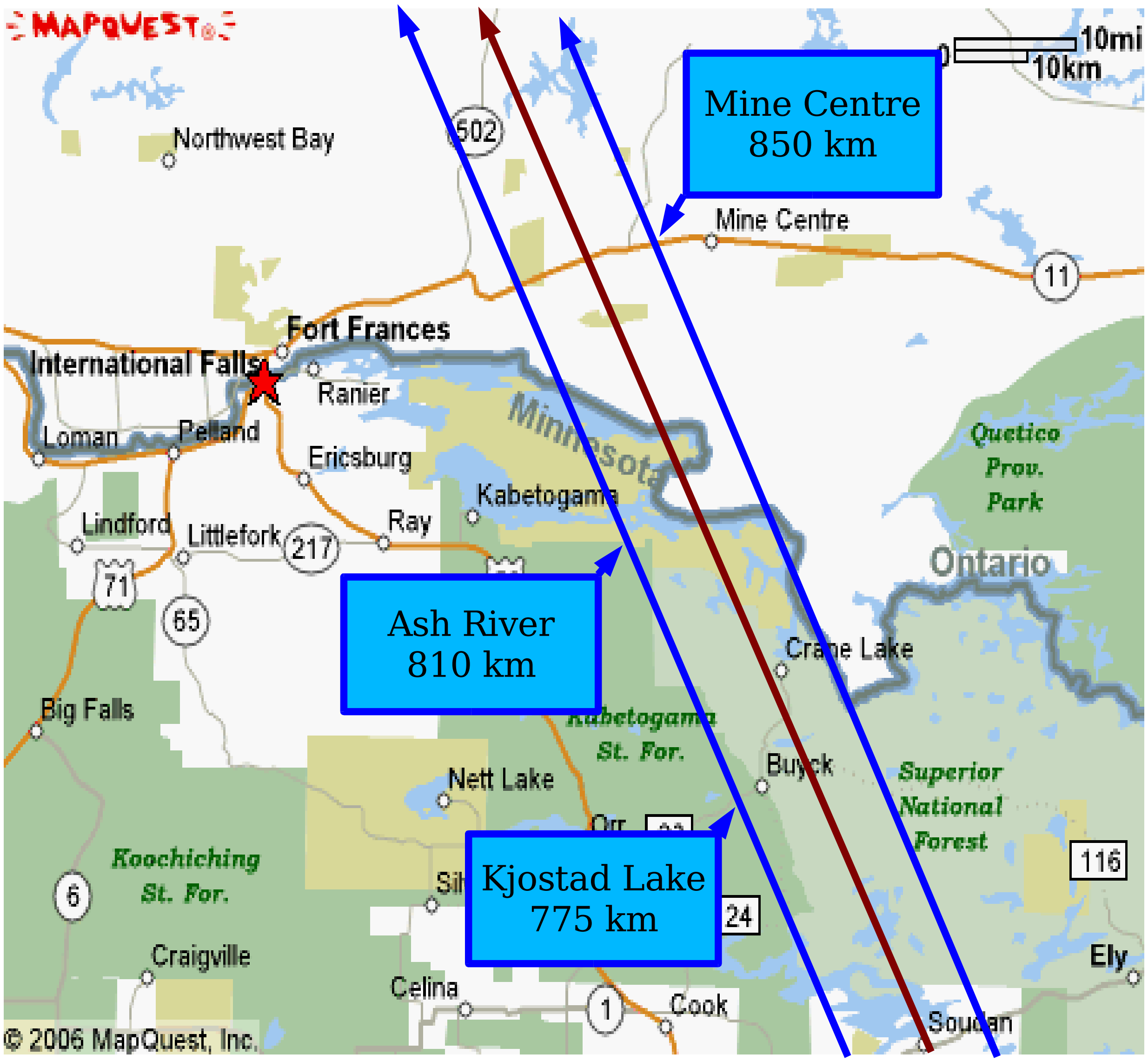
- Window on very high energy scales
  - Grand unified theories (mostly) favour the normal mass ordering but other approaches favour the inverted ordering
- The next generation of neutrinoless double beta decay experiment care about the mass ordering
  - If inverted ordering, can decide if the neutrino is its own antiparticle
  - If normal ordering, a negative result is inconclusive
- For CPV measurement we need to resolve the mass ordering
  - Matter effects contributes an apparent CP violation that must be corrected

Role of NOνA in Resolving the Mass Ordering

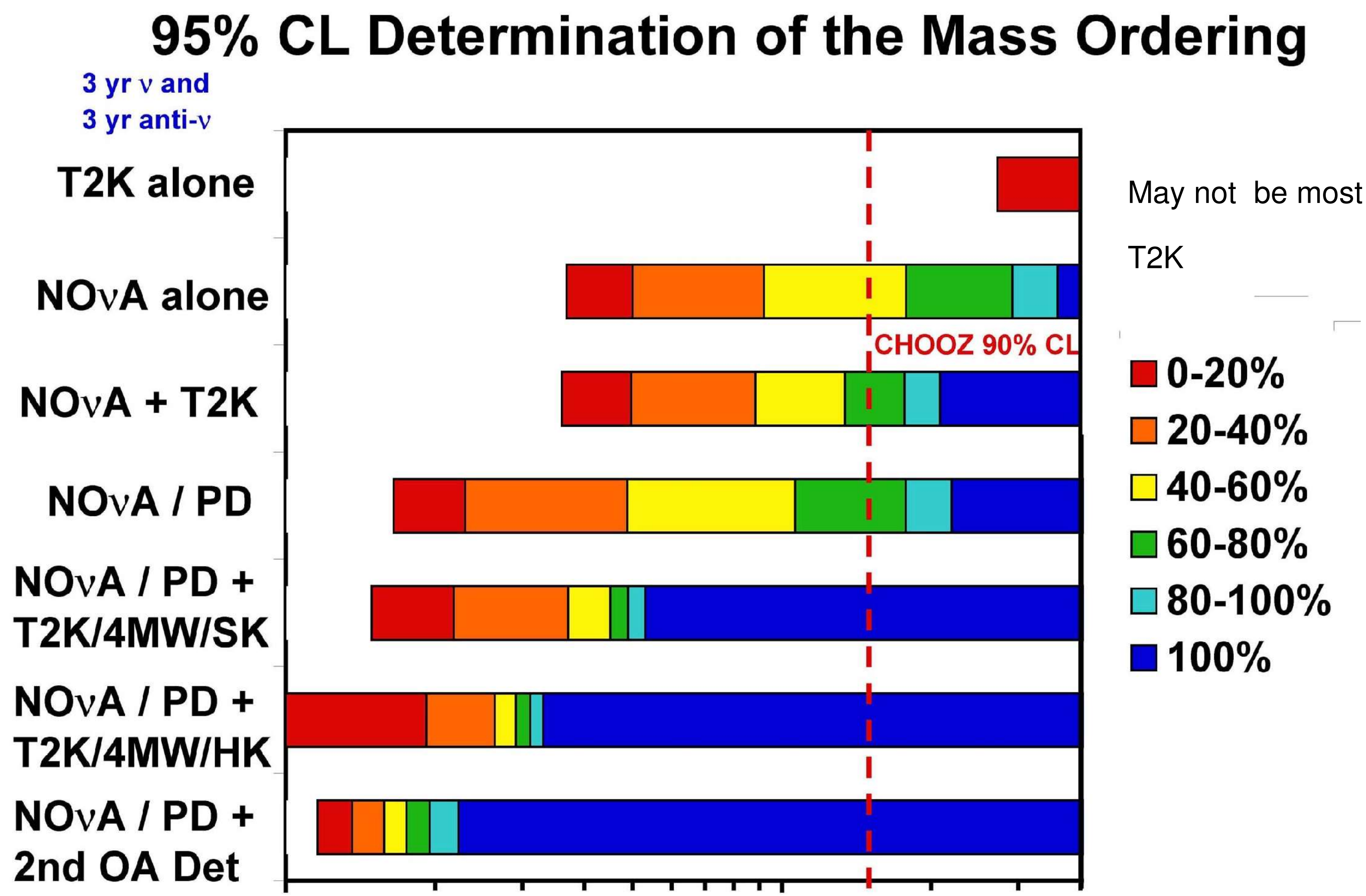
- The mass ordering can be resolved only by matter effects in the earth over long baselines
- NOνA is the only proposed experiment with a sufficiently long baseline to resolve the mass ordering
- The siting of NOνA is optimized for this measurement
- NOνA is the first step in a step-by-step program that can resolve the mass ordering in the region accessible to conventional neutrino beams

Far Detector Sites

- Ash River
  - Baseline site for **NOνA**
  - Resort area
- Kjostad Lake
  - Orr-Buyck Rd
  - Good backup site
- Mine Centre
  - Just off the Trans-Canada highway and railway
- Range of angles available at all sites



95% CL Resolution of the Mass Ordering

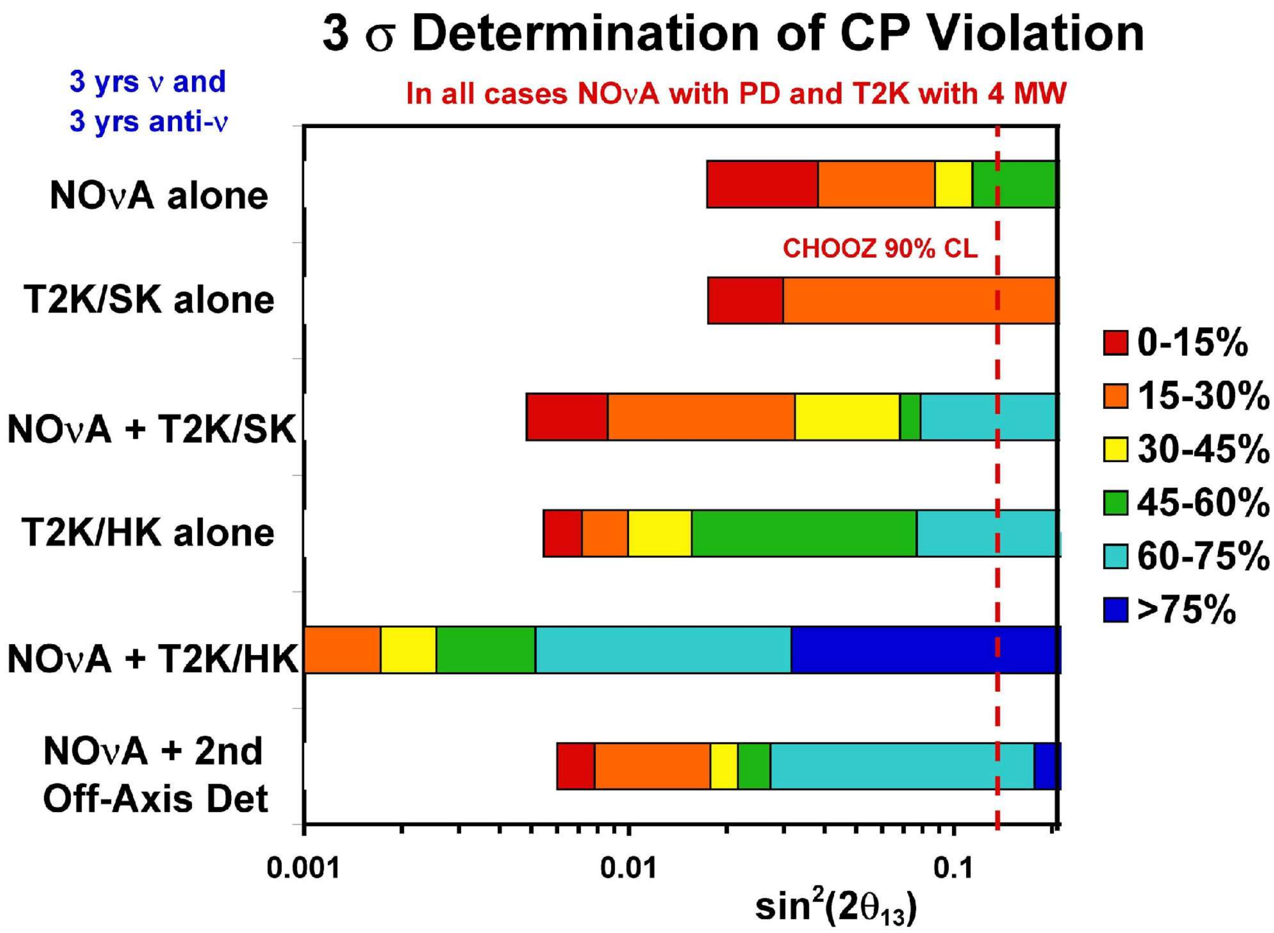


$\sin^2(2\theta_{13})$

May not be most recent for T2K

Fraction of δ covered

3 σ Determination of CP Violation



Fraction of δ covered

- Must have measurement errors < 30° (3σ=90°)
- Some values of δ (e.g. δ=0) not resolvable

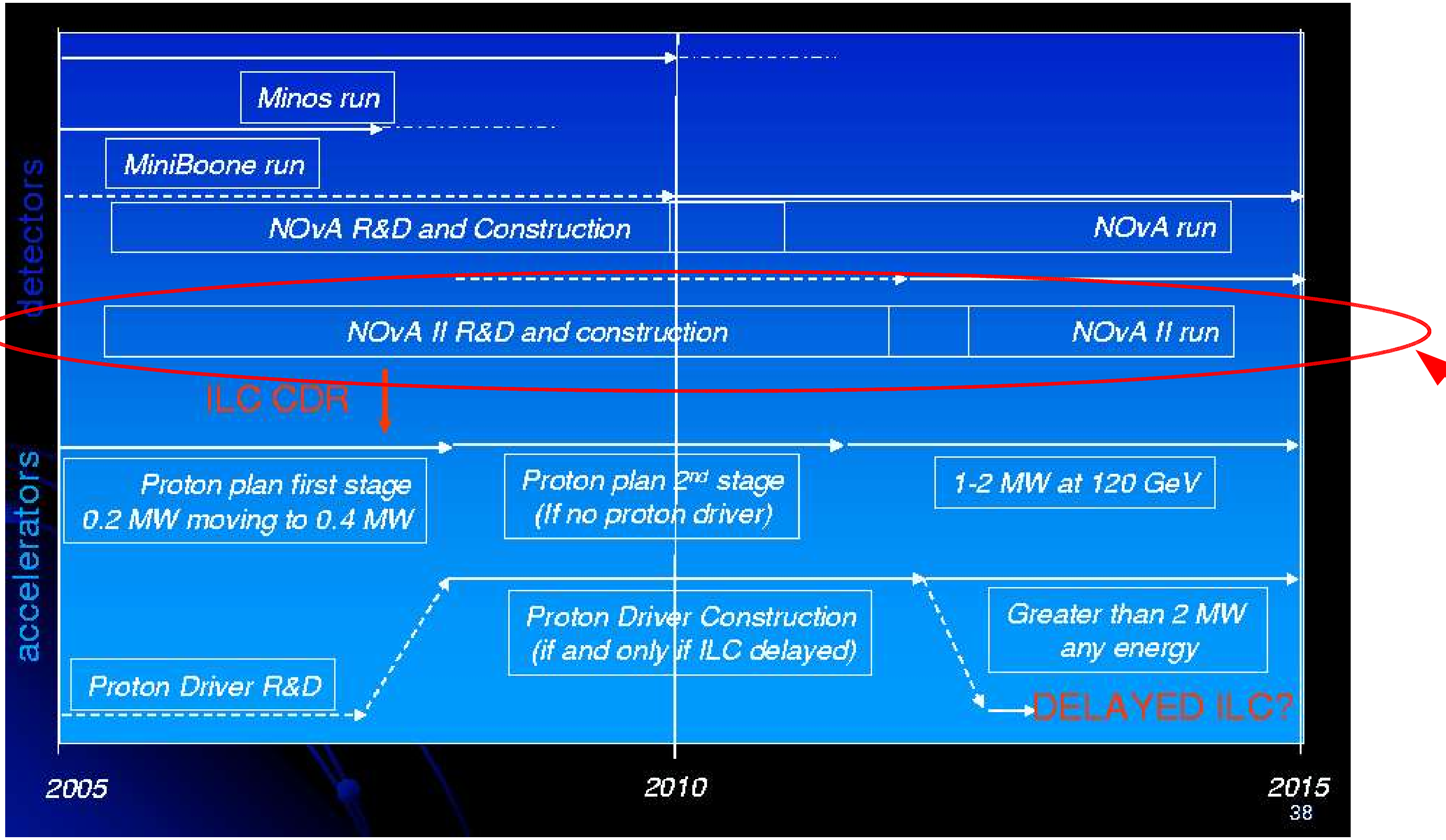
Main NOνA Detector Issue

- Primary problem is efficiency VS background rejection:
  - The particular background being,

    $$\pi^0 \rightarrow \gamma\gamma \rightarrow \text{electrons}$$

  - Look for "gap" from photons at beginning, followed by shower
  - Tradeoff of acceptance vs. shower fluctuations vs. background rate and ability to accurately model
  - Beam-Related backgrounds are measurable and small
- Lots to do, progress being made

According to the Director of Fermilab, the NuMI long-baseline program includes more than NOνA alone



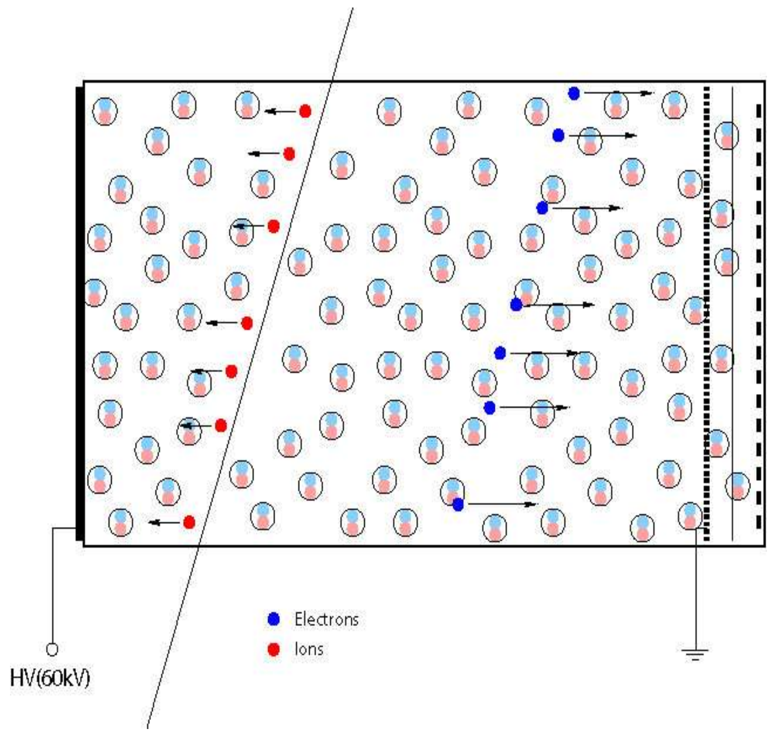
Large Liquid Argon TPC?

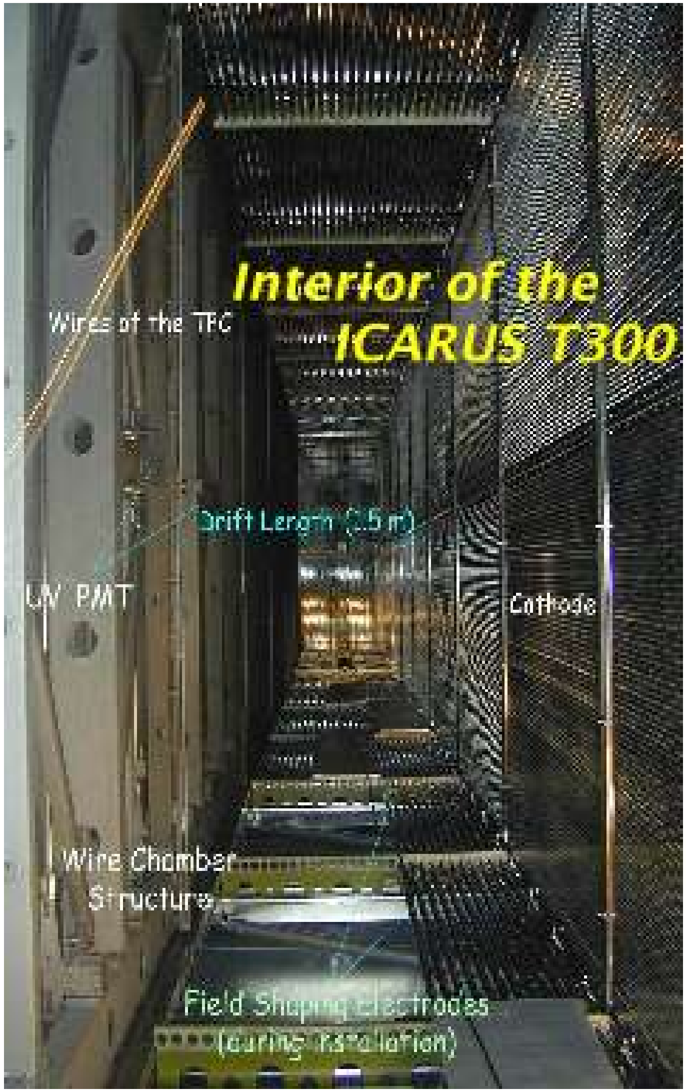
P. Oddone EPP2010 talk

Several North American university groups and Fermilab have embarked on R&D towards construction of a large Liquid Argon TPC (LArTPC) as the far detector.

The Liquid Argon Time Projection Chamber

Fine-grained tracking, total absorption calorimeter

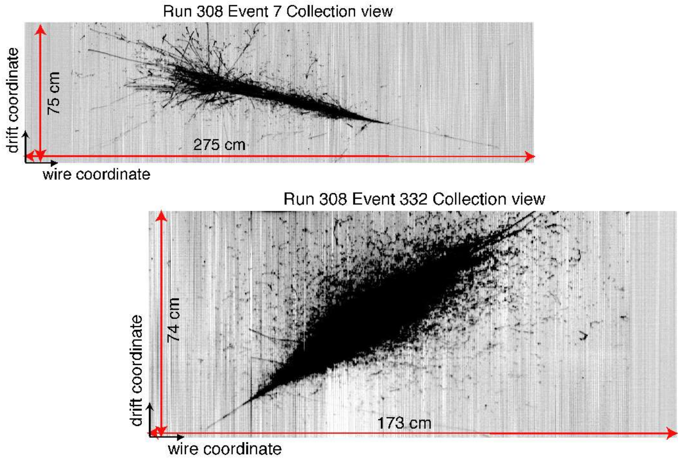


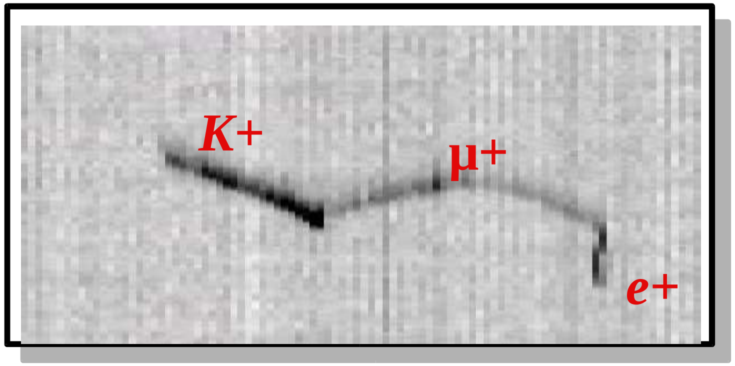


Drift ionization electrons over metres of pure liquid argon to collection planes to image track

- 50,000 electrons/cm

Allows for high resolution imaging like bubble chambers, but with calorimetry and continuous digital readout (no deadtime)





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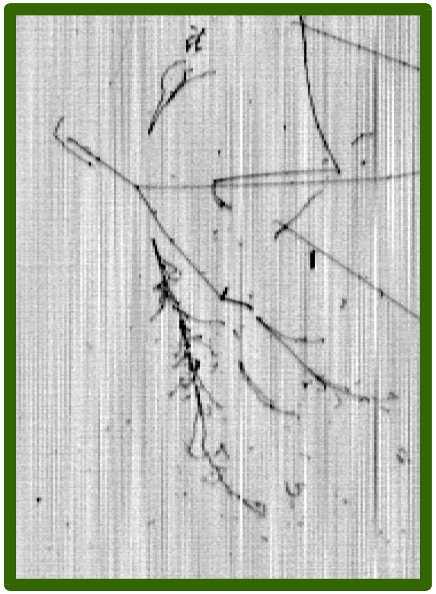
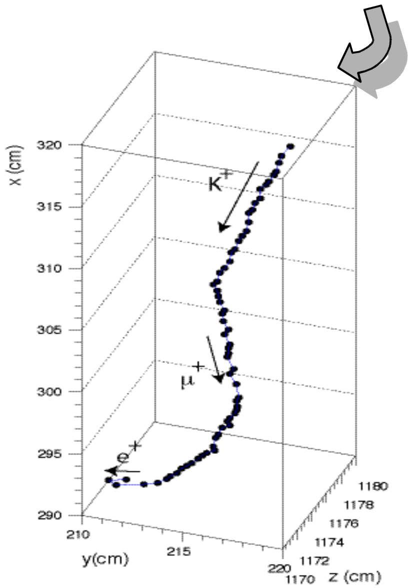
data



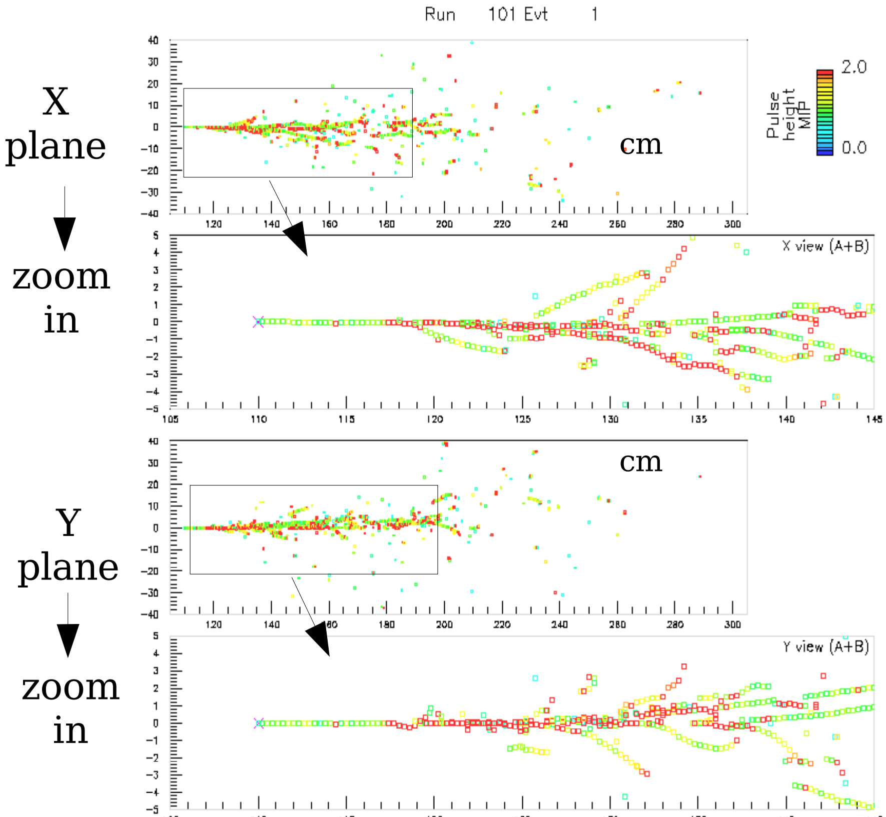


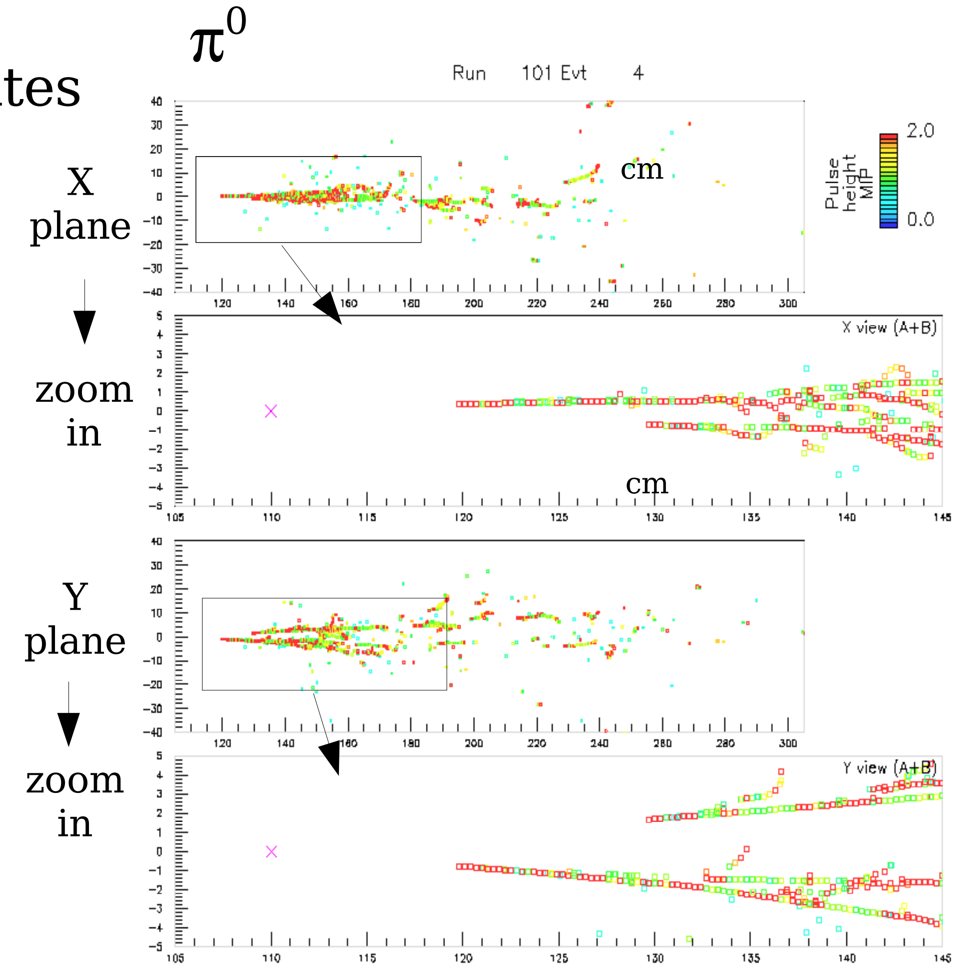
MC simulation

ICARUS images

The Promise of a LArTPC: Electrons versus π^0's at 1.5 GeV

Dot indicates hit while colour indicates collected charge with green=1 mip, red=2 mips





Electrons

Single track (mip scale) starting from a single vertex

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

Each track is two electrons – 2 mip scale per hit

Use both topology and dE/dx to identify interactions

Efficiency and Rejection Study

Tufts University Group

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 (and others) - Hugh Gallagher (Tufts) is the principal author.

GEANT 3 detector simulation (Hatcher, Para): trace resulting particles through a homogeneous volume of liquid argon. Store energy deposits in thin slices.

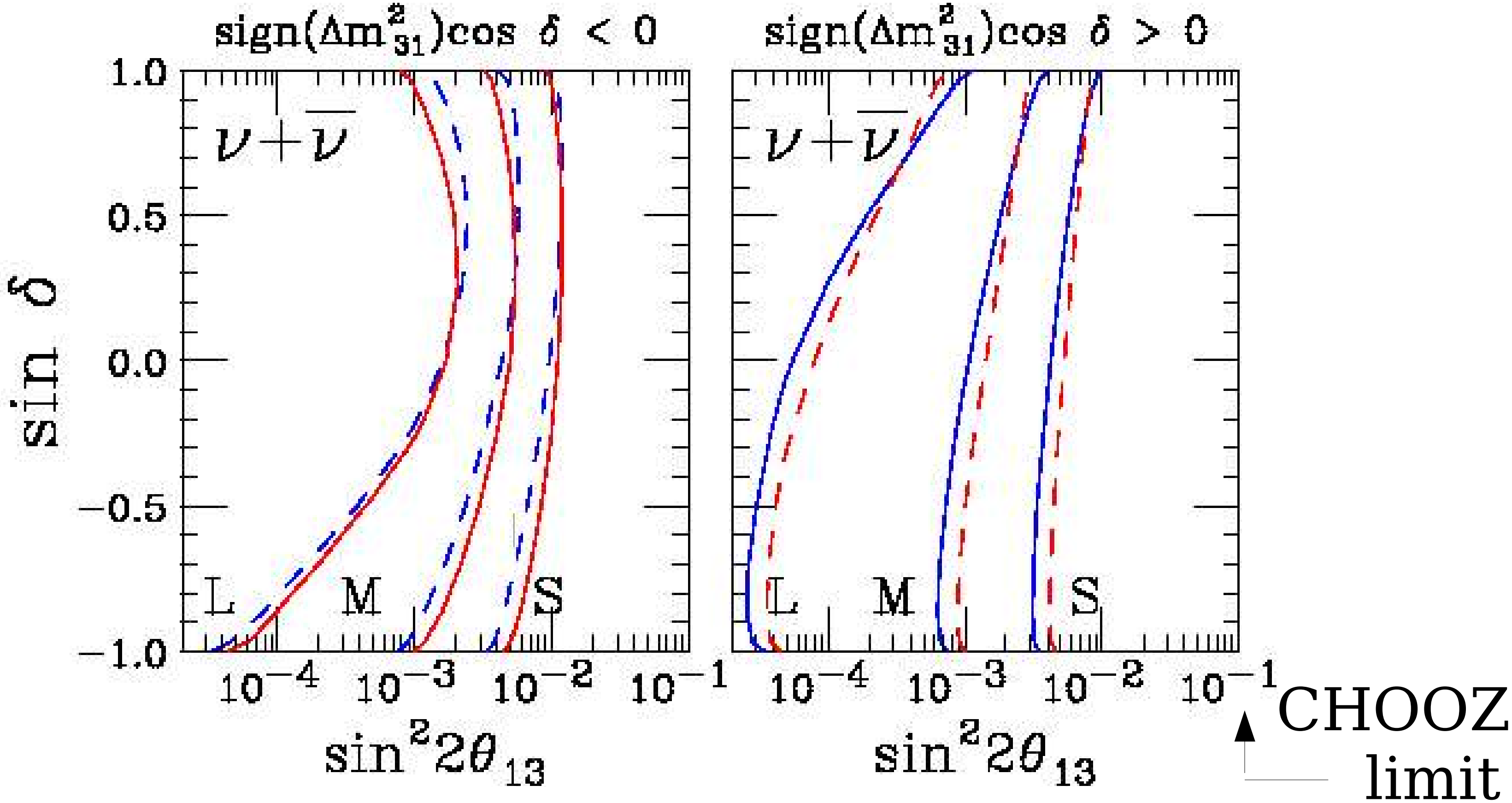
signal efficiency ***background rejection***

Event Type		N	pass	ϵ	η
NC		290	4	-	0.99±0.01
signal ν_e	CC	32	26	0.81±0.07	-
Beam ν_e	CC	24	14	0.58±0.10	-
Beam ν_e	NC	8	0	-	/
Beam $\overline{\nu}_e$	CC	13	10	0.77 ± 0.09	-
Beam $\overline{\nu}_e$	NC	19	0	-	/
ν_μ	CC	32	0	-	/
$\overline{\nu}_\mu$	CC	32	1	-	/

+ factor of 6 rejection on NC background from energy pre-selection ⇒ 99.8% NC rejection efficiency

Good signal efficiency (81+/- 7)%

Sensitivity to CP phase($\sin\delta$) vs $\sin^2 2\theta_{13}$ for

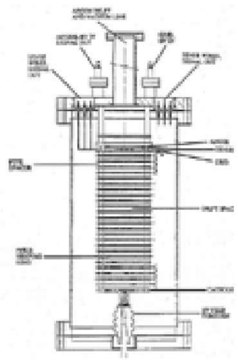


most restrictive: least restrictive:

$\cos\delta < 0$, normal hierarchy $\cos\delta > 0$, normal hierarchy

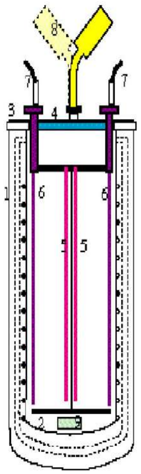
$\cos\delta > 0$, inverted hierarchy $\cos\delta < 0$, inverted hierarchy

Technical Feasibility: History of prototype work c



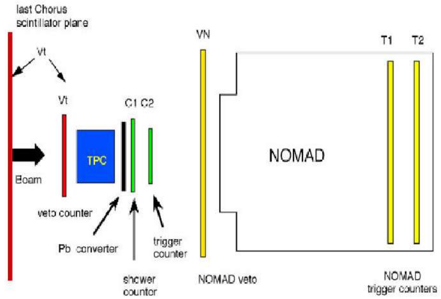
24 cm drift wires chamber

1987: First LAr TPC. Proof of principle. Measurements of TPC performances.



3 ton prototype

1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.



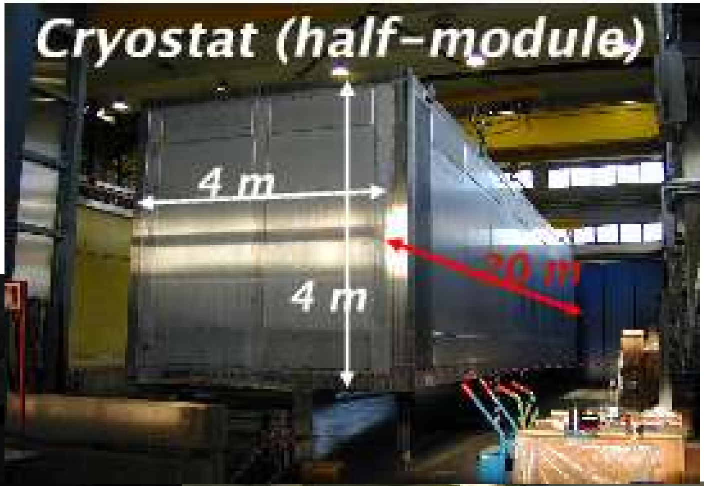
50 litres prototype 1.4 m drift chamber

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

10 m^3 industrial prototype

1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

The ICARUS T600



Tested above grou
in Pavia in 2001

Now below groun
Gran Sasso

LArTPC's report to NuSAG*

Fermilab Note: **FN-0776-E**

A Large Liquid Argon Time Projection Chamber for Long-baseline, Off-Axis
Neutrino Oscillation Physics with the NuMI Beam
Submission to NuSAG
September 15, 2005

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* *The* ***Neu****trino* ***S****cientific* ***A****ssessment* ***G****roup for the DOE/NSF*

A 15 to 50 ktonne LArTPC for NuMI off-axis Neutrino Physics

Basic concept follows ICARUS:

TPC, drift ionization electrons to 3 sets of wires (2 induction, 1 collection)

record signals on all wires with continuous waveform digitizing electronics

Differences aimed at making a multi-kton detector feasible

Construction of detector tank using industrial LNG tank as basic structure

Single device (not modular)

Long(er) signal wires

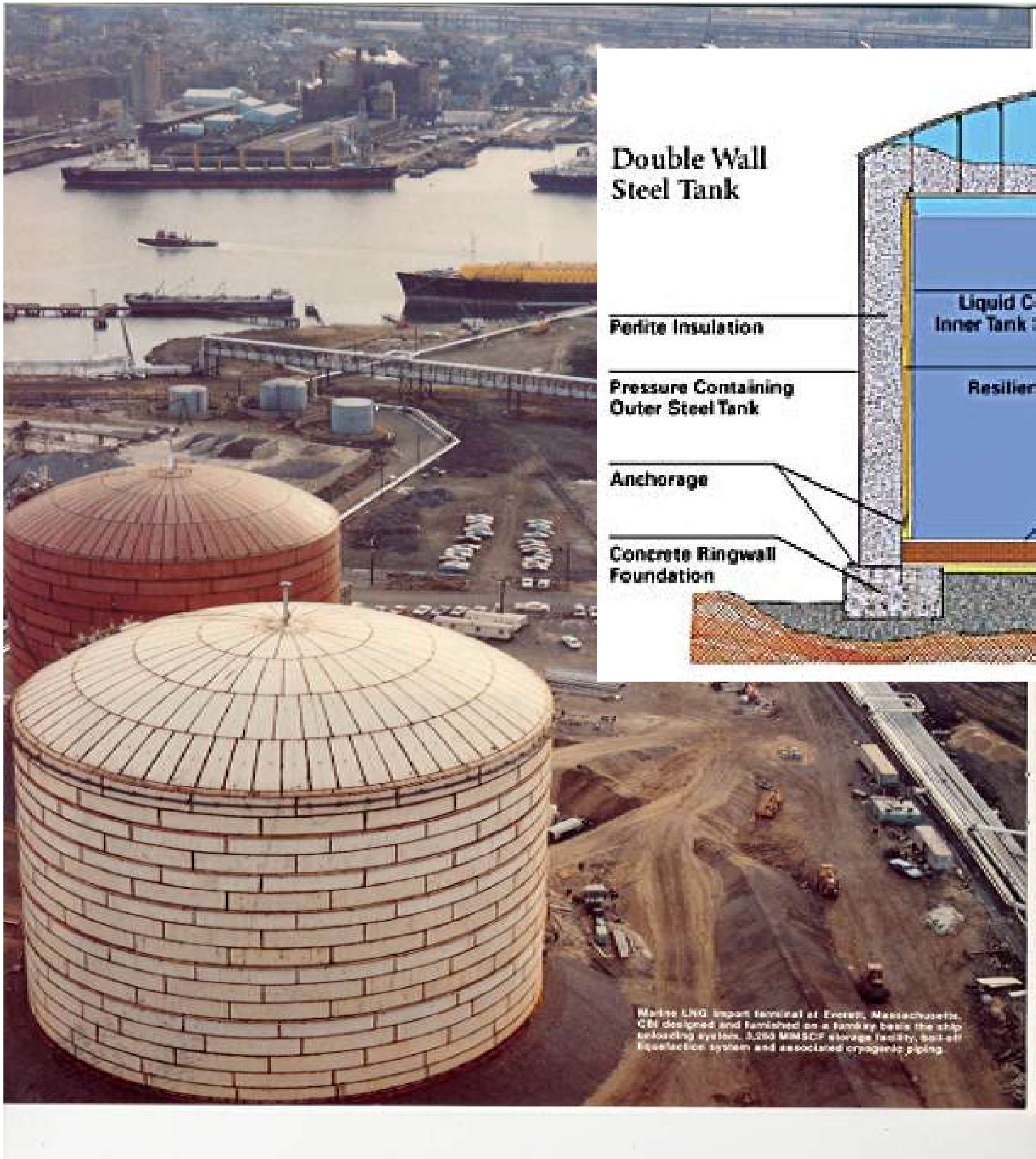
Basic parameters:

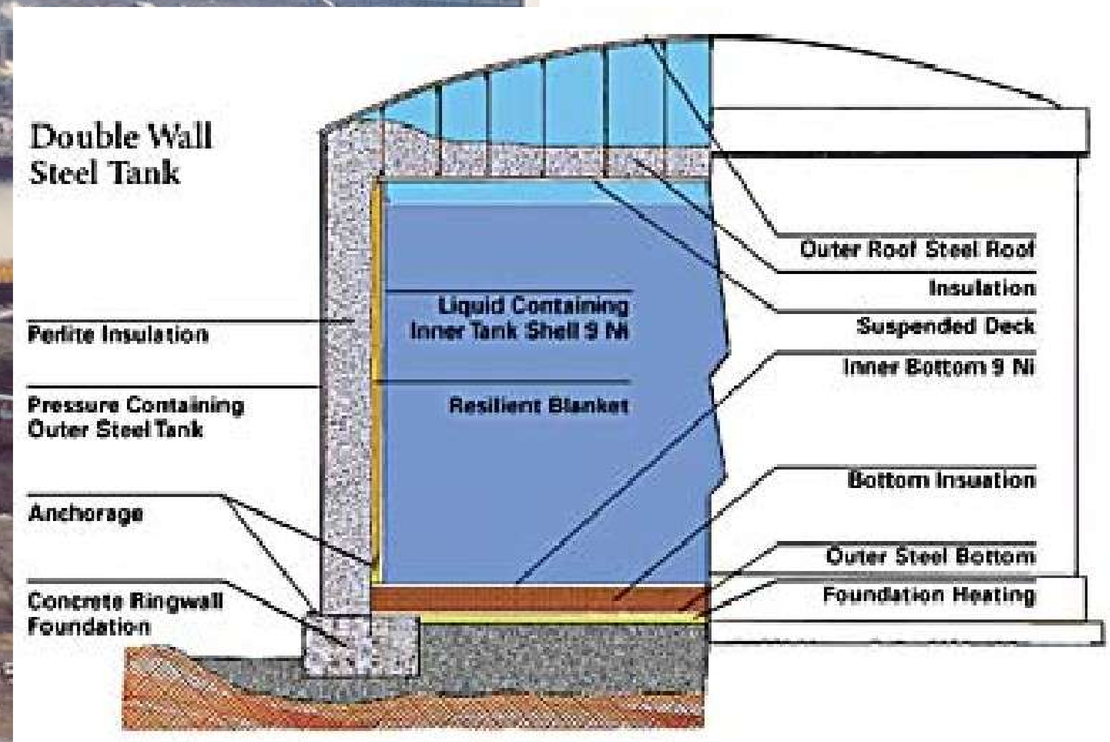
Drift distance - 3 meters; Drift field - 500 V/cm (gives v_{drift} = 1.5 m/ms)

High Voltage 150 kV

Wire planes - 3 (+/-30^0 and vertical); wire spacing 5 mm; plane spacing 5 mm

Number of signal channels ~ 100,000 (15kt), 220,000 (50kt)

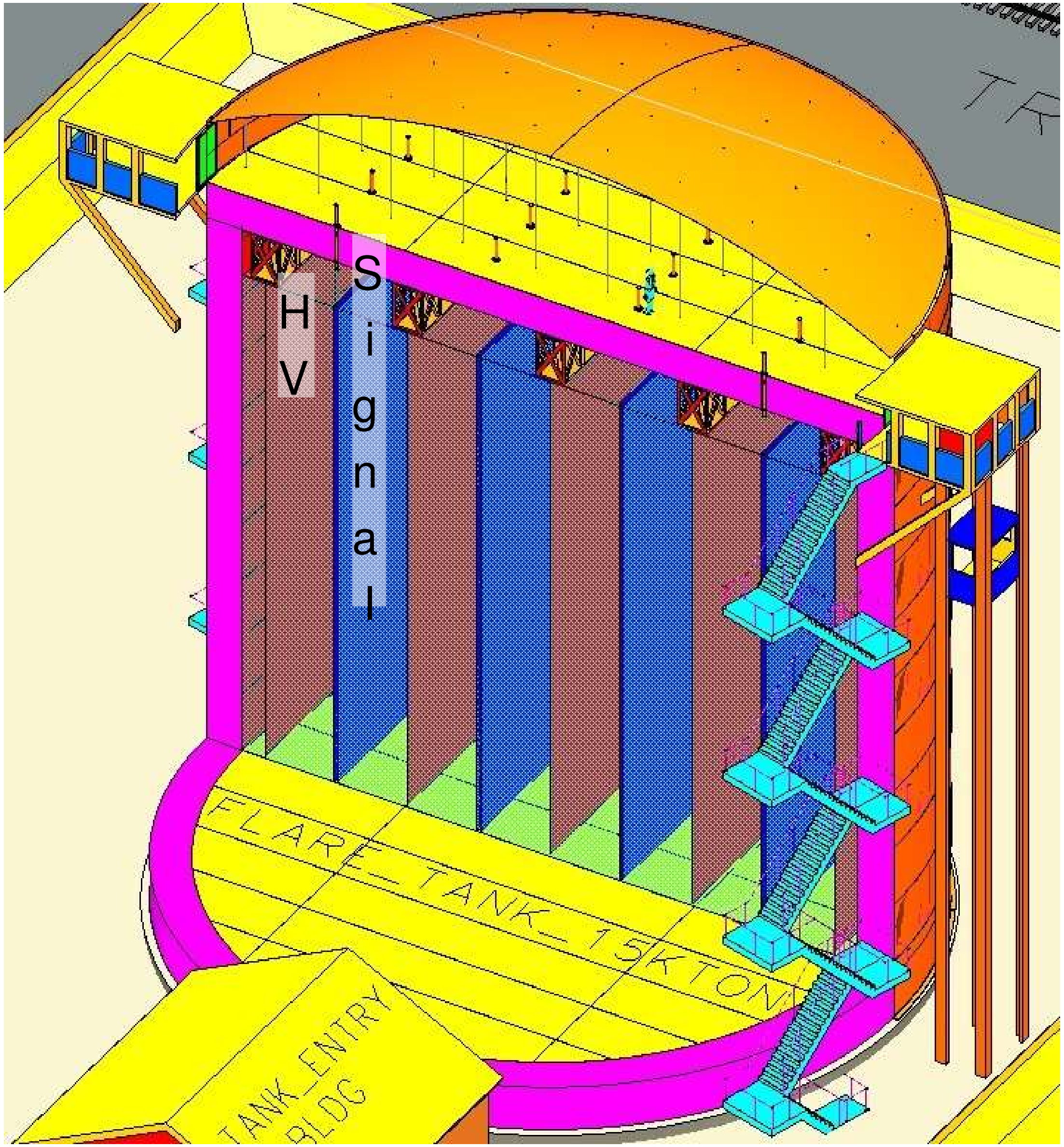




Many large LNG tanks
in service

Excellent safety record
Last failure in 1940
understood

Engineering has begun on a large multi- kton Device



A 15 kton Device

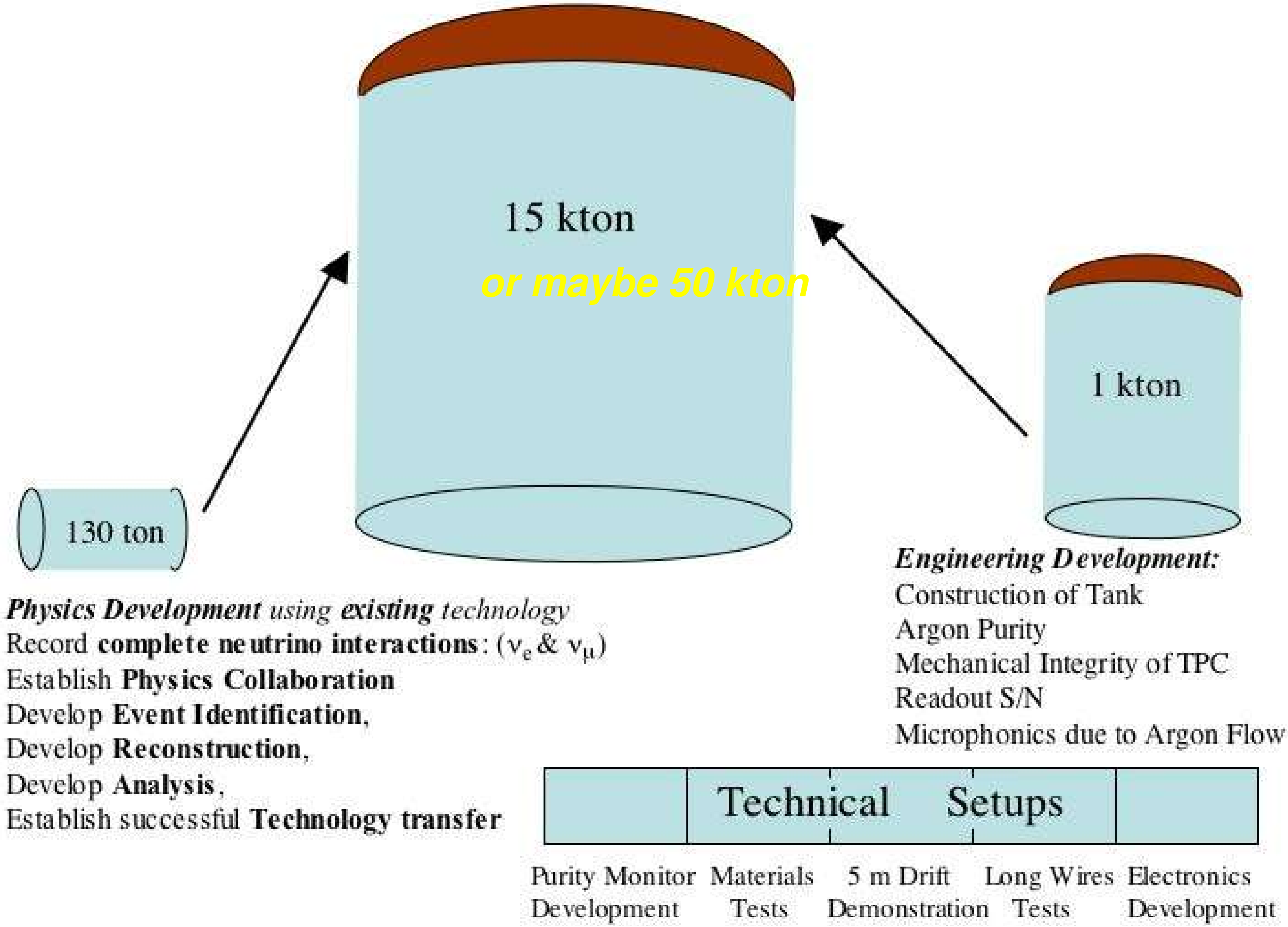
Inner tank dimensions:

26 m diameter by 21 m height

Changes from standard LNG tank:

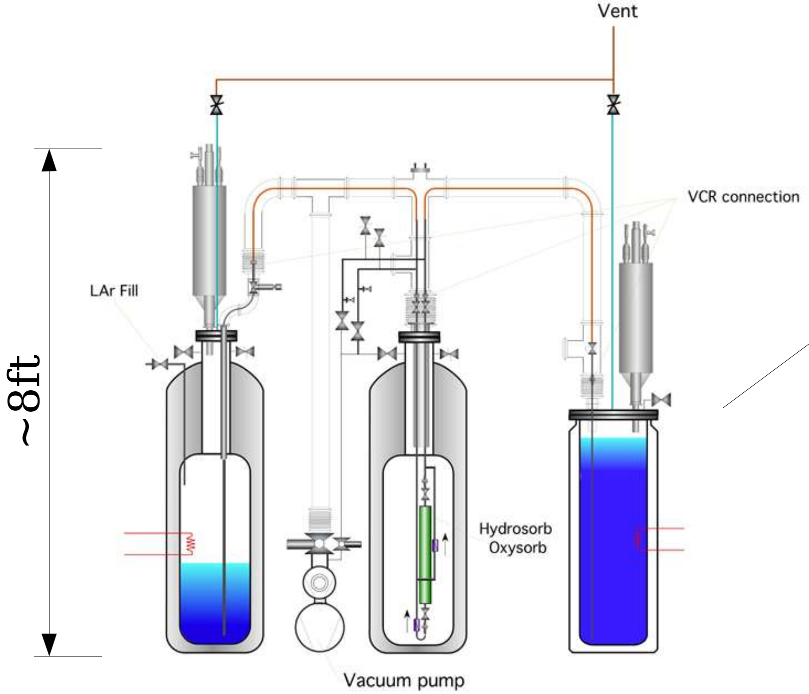
- *inner tank wall thickness increased*
  - *LAr is 2 x density of LNG;*
- *trusses in inner tank to take load of the wires;*
- *penetrations for signals from inner tank to floor supported from roof of outer tank.*

LArTPC Plan



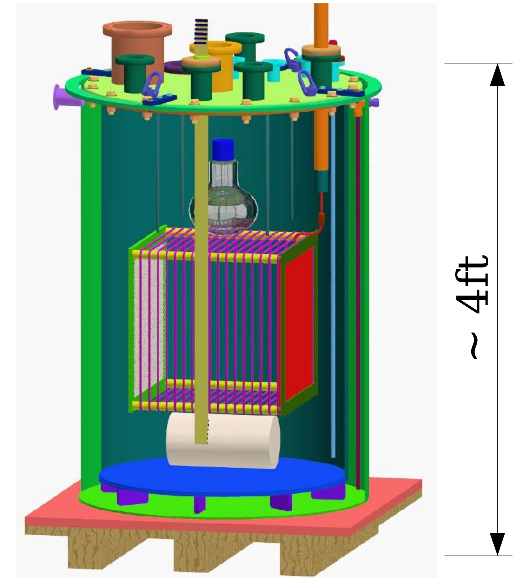
15 kton
or maybe 50 kton
1 kton
130 ton
Physics Development using existing technology
Record **complete neutrino interactions**: (ν_e & ν_μ)
Establish **Physics Collaboration**
Develop **Event Identification**,
Develop **Reconstruction**,
Develop **Analysis**,
Establish successful **Technology transfer**
Engineering Development:
Construction of Tank
Argon Purity
Mechanical Integrity of TPC
Readout S/N
Microphonics due to Argon Flow
Technical Setups
Purity Monitor Development
Materials Tests
5 m Drift Demonstration
Long Wires Tests
Electronics Development

R&D efforts underway

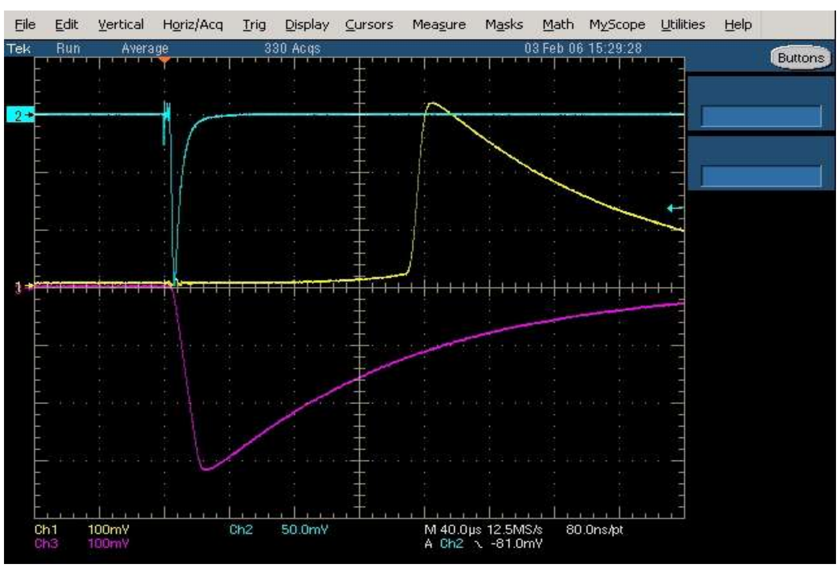


C.Kendziora 2.17.05

at FNAL



at Yale



at UCLA/ CERN

Conclusions

- Neutrino physics is at a very exciting stage. Measuring $P(\nu_\mu \rightarrow \nu_e)$ to get at $\sin^2(2\theta_{13})$, δ, and $\mathrm{sgn}(\Delta m_{13}^2)$ is one of the central goals of the next generation of experiments set to exploit the NuMI beam.
- The 30 kT "totally active" (75%) liquid scintillator NOνA detector located 810 km from Fermilab is competitive with T2K.
- ICARUS has demonstrated the viability of the Liquid Argon TPC (LArTPC) technique. The LArTPC is capable of observing ν_e CC events with high efficiency while allowing easy differentiation between electrons and π^0's leading to a large NC event rejection factor. The powerful combination of the NuMI off-axis ν_μ beam and a large LArTPC is perfectly suited for making a precise measurement of $P(\nu_\mu \rightarrow \nu_e)$.
- There is a group of group of scientists from North American universities and Fermilab who have proposed a path towards the realization of a large LArTPC (15-50 kton) located in the NuMI off-axis neutrino beam. There are plenty of interesting projects within this program for new groups.