A Large Liquid Argon TPC for Off-axis NuMI Neutrino Physics

Scott Menary

YORK UNIVERSITÉ UNIVERSITY

Outline

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

The CP Violation Parameter

Three Neutrino Mixing Matrix:

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

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

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:

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

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

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

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

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

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:

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

The expression contains: 3 unknowns, 4 known "measured" quantities, and 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 $\nu_\mu \rightarrow \nu_e$ 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 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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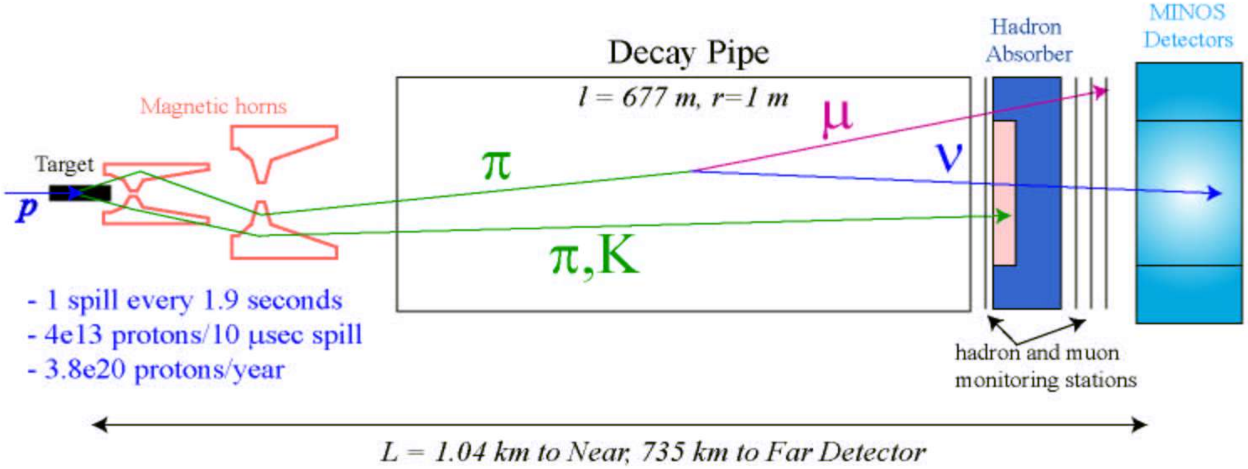
The Beam Already Exists!

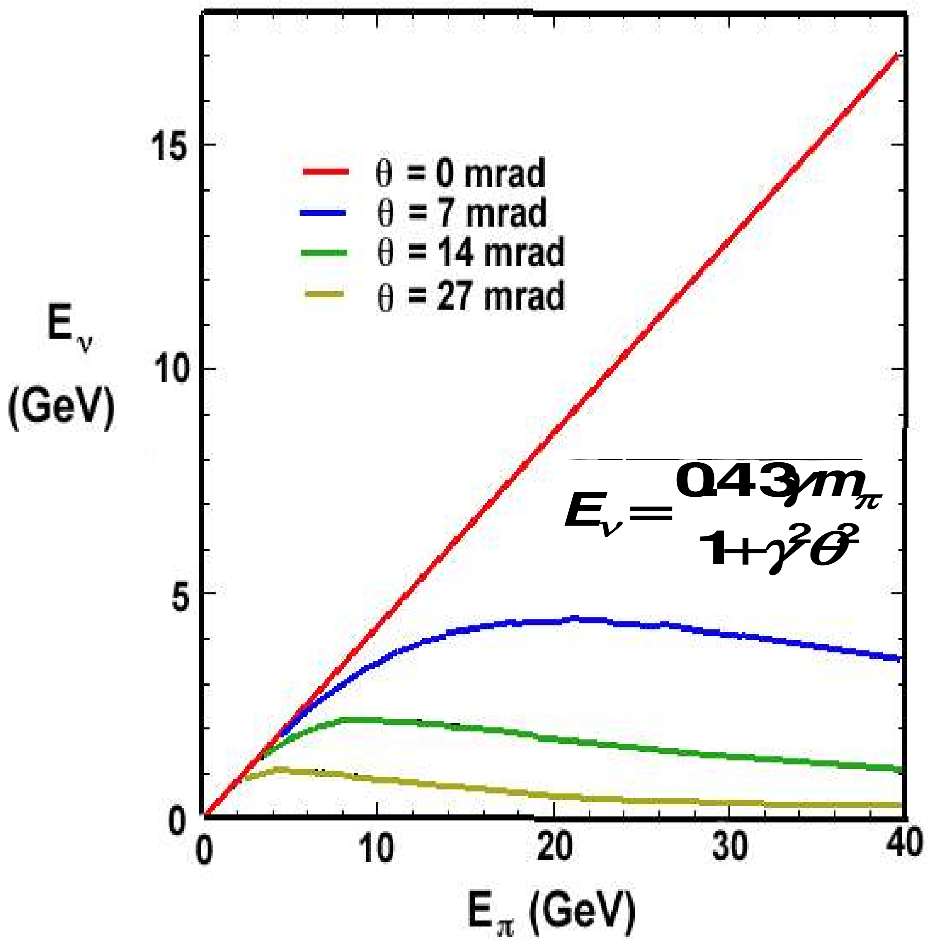
The NuMI tunnel is complete and …

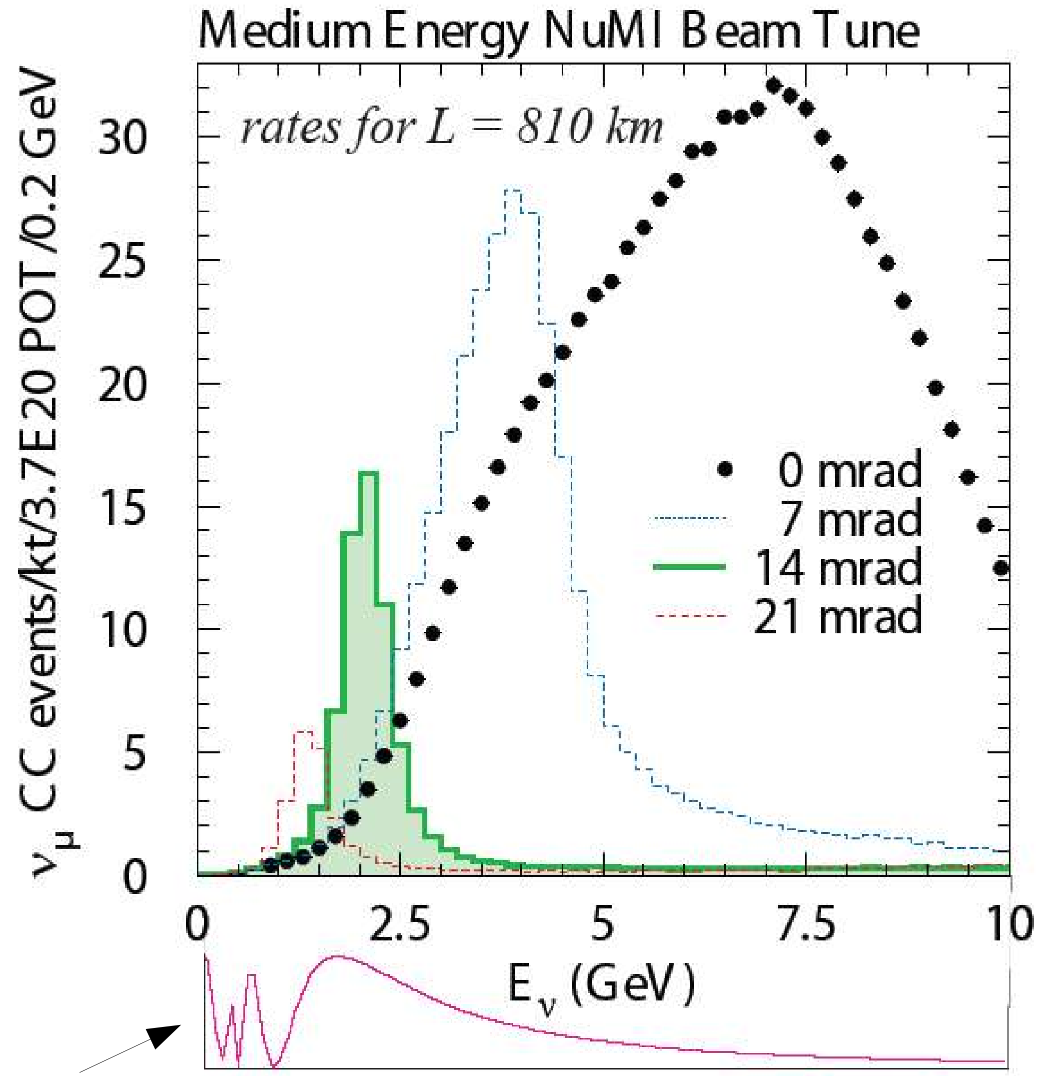
120 GeV/c protons strike graphite target
Magnetic horns focus charged mesons (pions and kaons)
Pions and kaons decay giving neutrinos



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

The “Off-axis” Beam

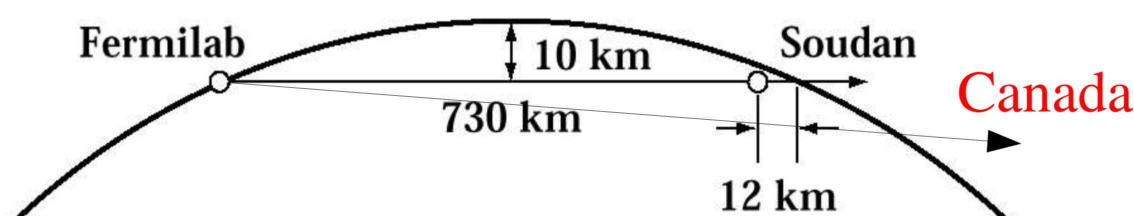




$\sin^2(1.27\ \Delta m_{13}^2\ L/E)$

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

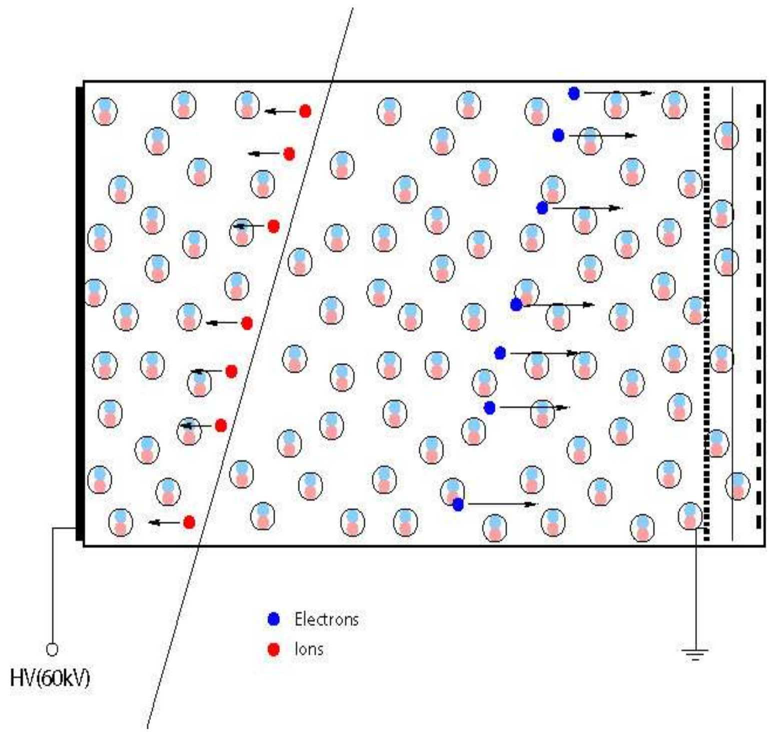


Detector Requirements

- *optimized for the neutrino energy range of 1 to 3 GeV*
- *detector on surface, must be able to handle raw rate/background from cosmic rays*
- *very large mass (10's kton range)*
- *identify with high efficiency* ν_e *charged interactions*
- *good energy resolution to reject* ν_e*'s from background sources*
  - ν_e *background has a broader energy spectrum than the potential signal*
- *provide adequate rejection against* ν_μ *NC and CC backgrounds*
  - *e/*π^0 *separation*
    - *fine longitudinal segmentation, much smaller than* X_0
    - *fine transverse segmentation, finer than the typical spatial separation of the 2* γ*'s from* π^0 *decay*
  - *e/*μ*,h separation*

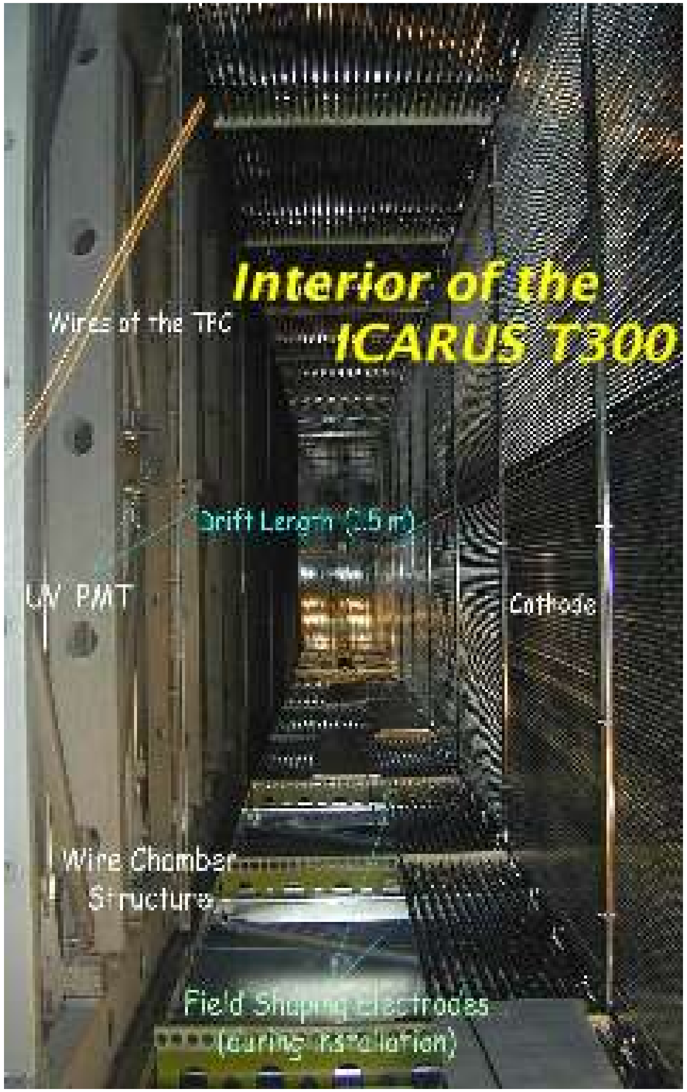
The Liquid Argon Time Projection Chamber

Fine-grained tracking, total absorption calorimeter

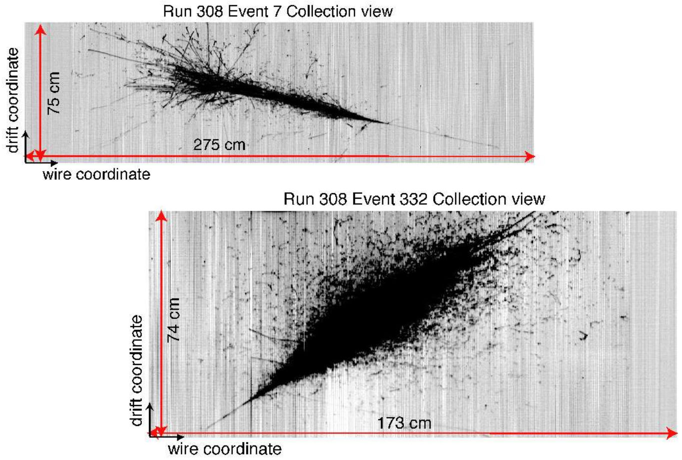


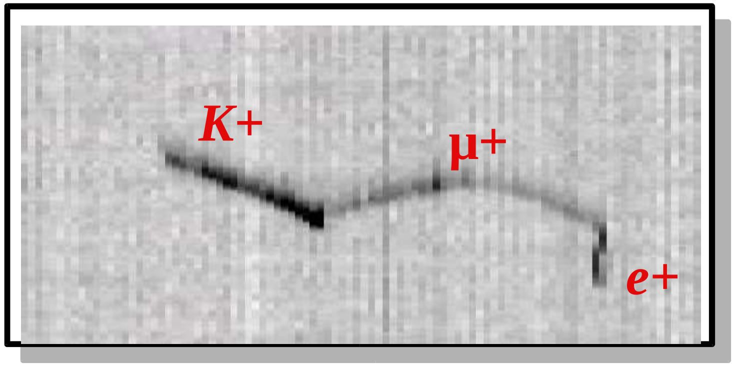
Drift ionization electrons over metres of pure liquid argon to collection planes to image track

- 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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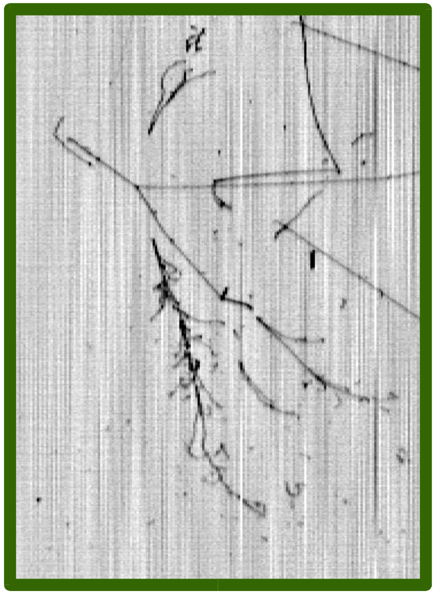
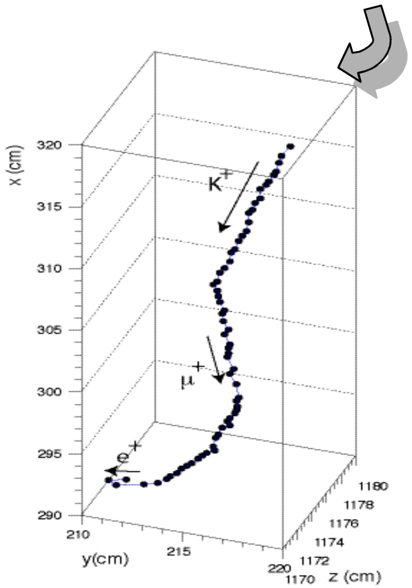




MC simulation

ICARUS images

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

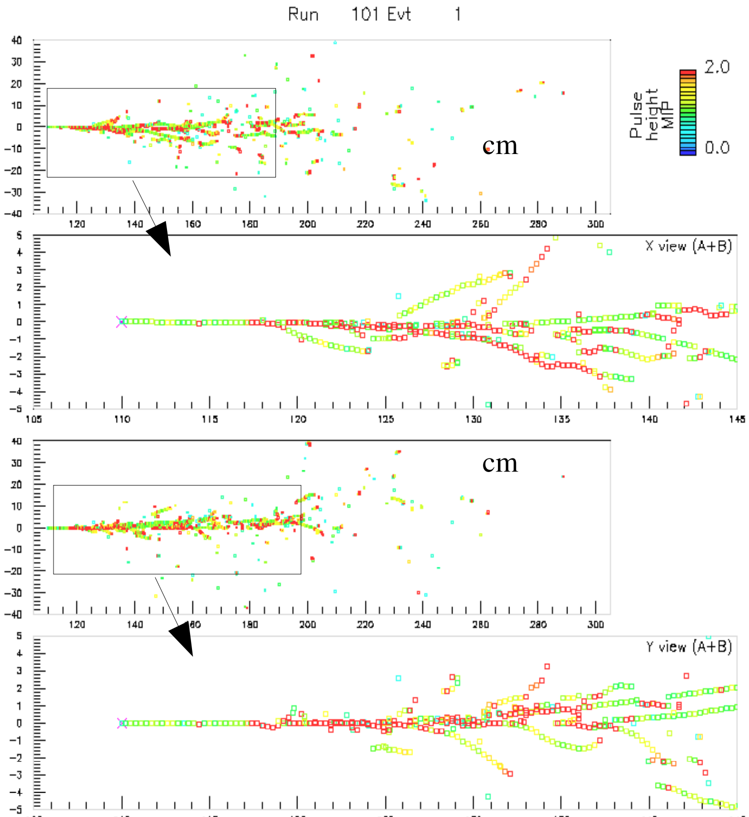
Dot indicates hit while colour indicates collected charge with green=1 mip, red=2 mips

X plane

↓ zoom in

Y plane

↓ zoom in



Electrons

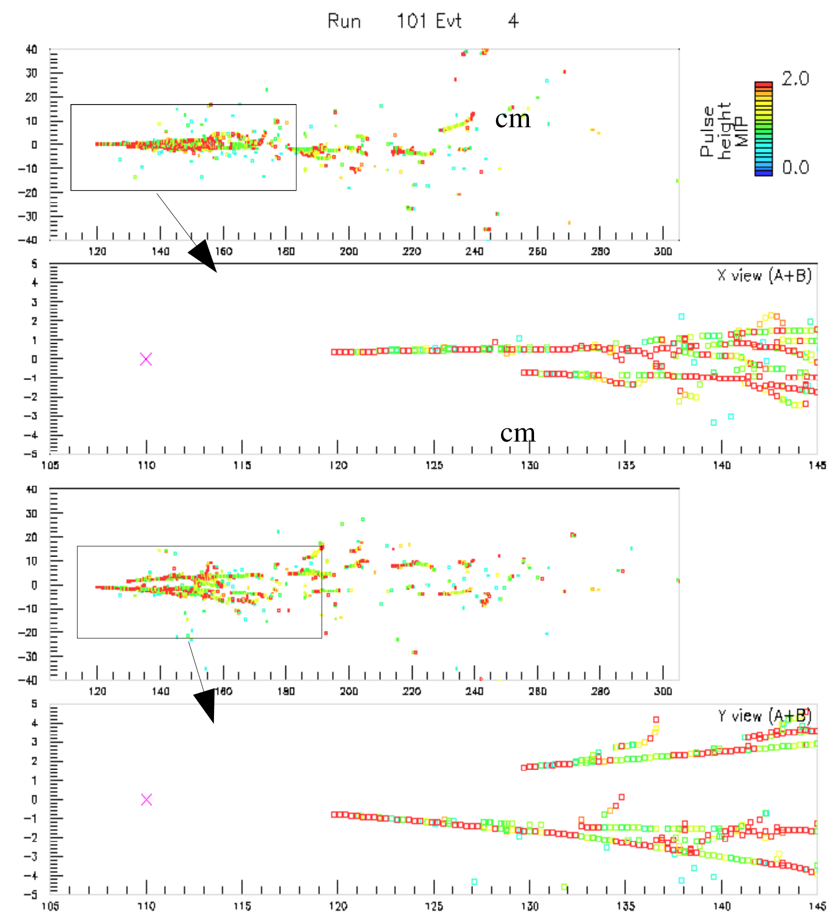
Single track (mip scale) starting from a single vertex

X plane

↓ zoom in

Y plane

↓ zoom in



π^0 *0*

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 → ϵ ***background rejection*** → η

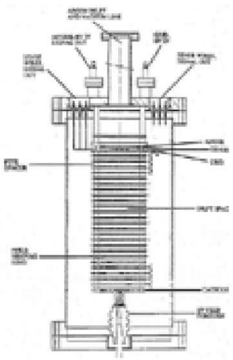
Event Type		N	pass	ϵ	η
NC		290	4	-	0.99 ± 0.01
signal ν_e	CC	32	26	0.81 ± 0.07	-
Beam ν_e	CC	24	14	0.58 ± 0.10	-
Beam ν_e	NC	8	0	-	/
Beam $\overline{\nu}_e$	CC	13	10	0.77 ± 0.09	-
Beam $\overline{\nu}_e$	NC	19	0	-	/
ν_μ	CC	32	0	-	/
$\overline{\nu}_\mu$	CC	32	1	-	/

+ factor of 6 rejection on NC background from energy pre-selection

⇒ 99.8% NC rejection efficiency

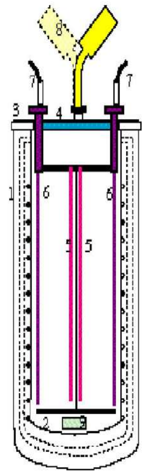
Good signal efficiency (81±7)%

Technical Feasibility: History of prototype work on ICARUS



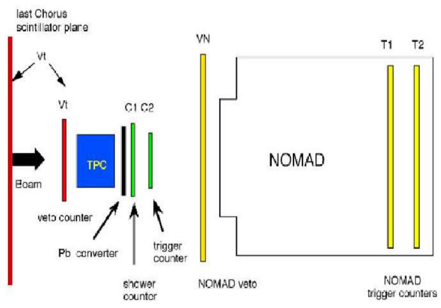
24 cm drift wires chamber

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.



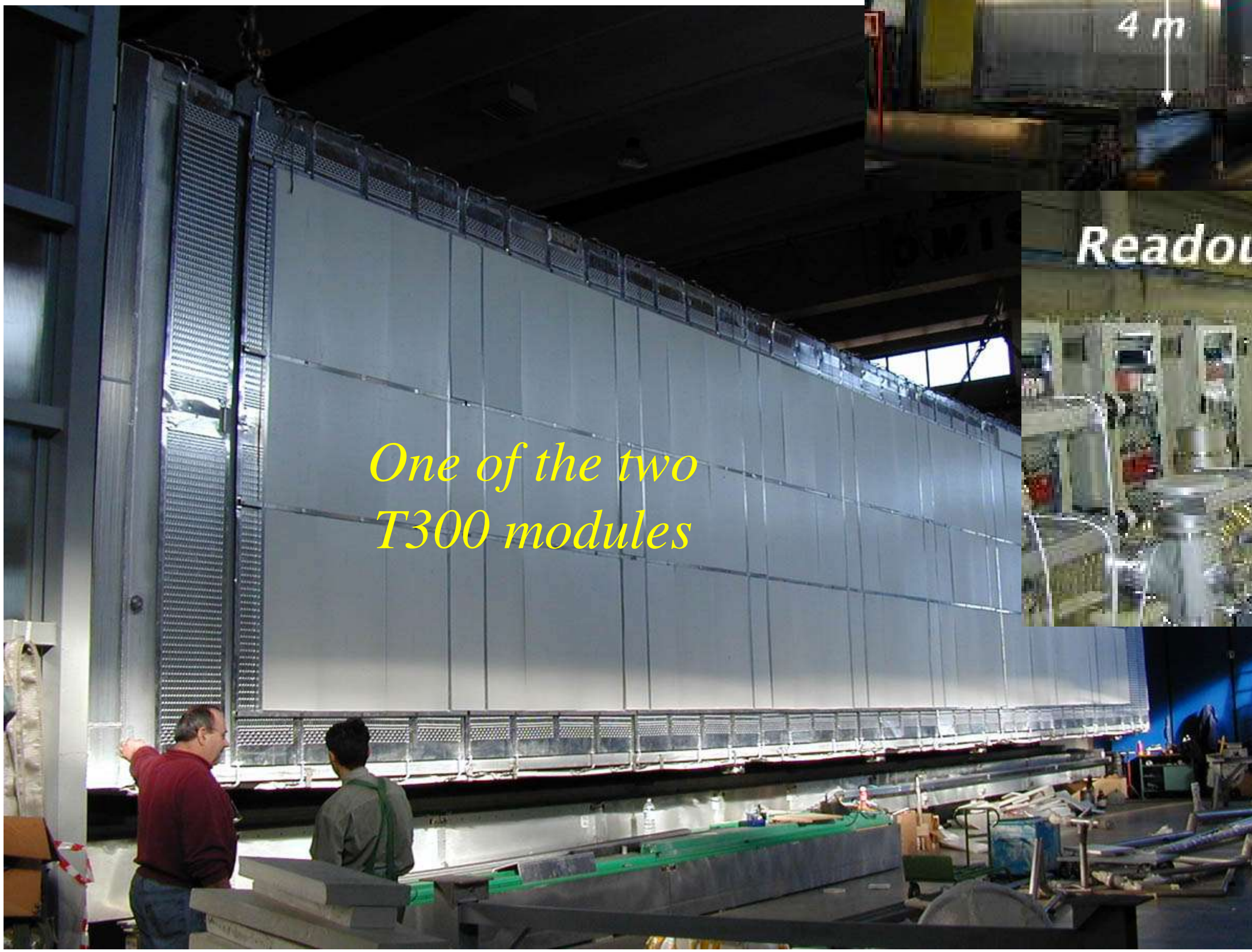
50 litres prototype
1.4 m drift chamber

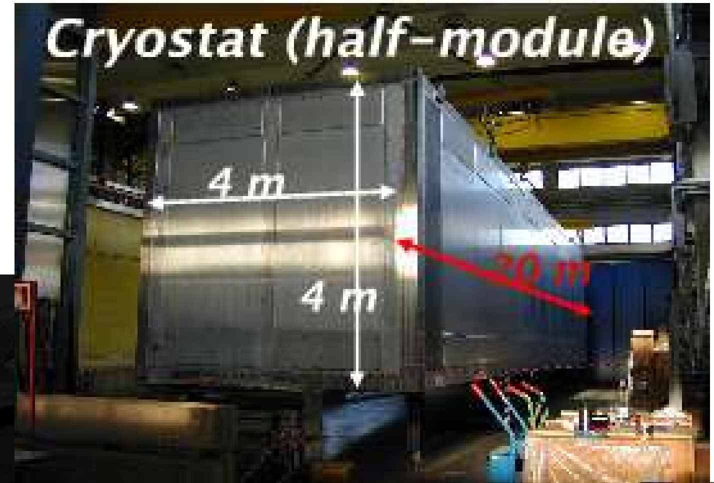
1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

10 m^3 industrial prototype

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

The ICARUS T600

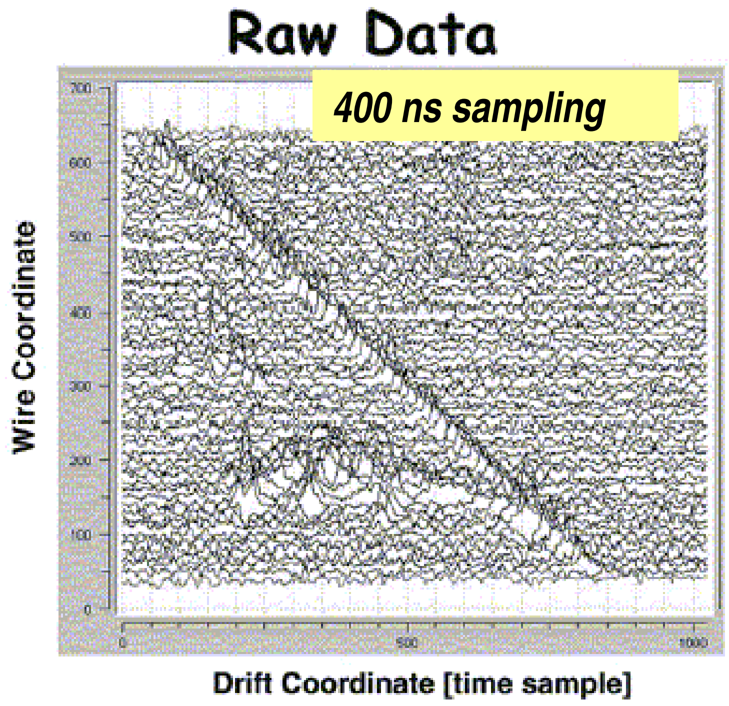


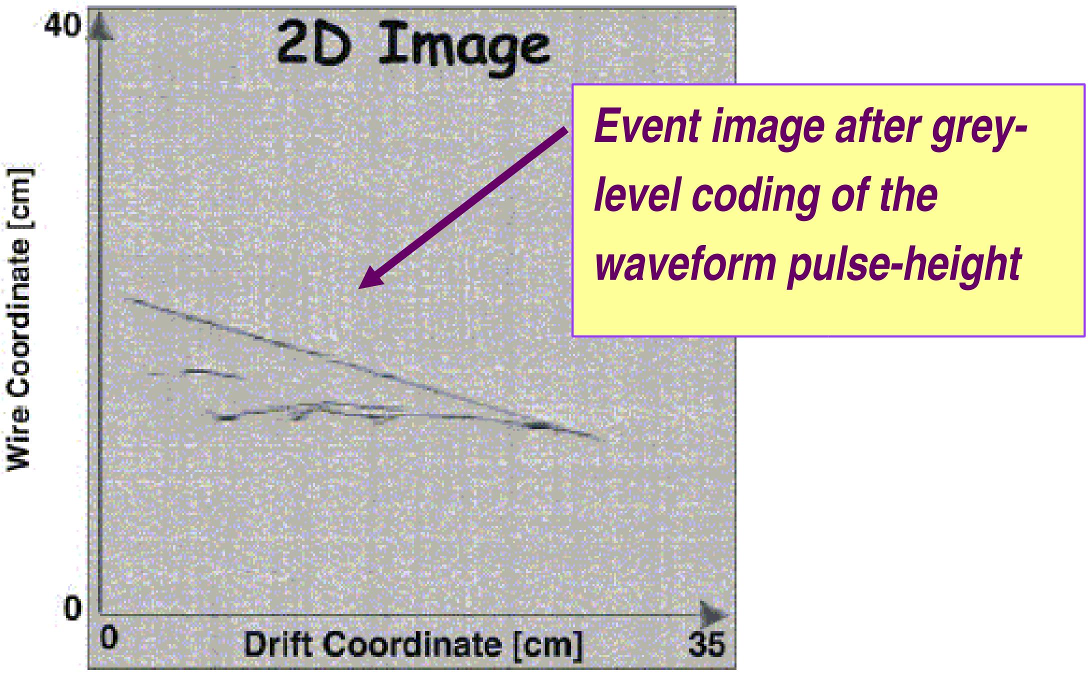


Tested above ground in Pavia in 2001

Now below ground in Gran Sasso

Lessons from ICARUS





- ***3D imaging capability demonstrated for detector masses of the order of a kton***
  - ***performance comparable to traditional bubble chambers, with the advantage of being continuously sensitive***
- ***calorimetric measurement, particle ID capabilities***

Lessons from ICARUS continued

- ❖ **Importance of the cryostat design**
  - *have to not pollute Argon (no leaks or electronegative comtaminants)*
  - *have to maintain stable thermodynamic conditions (good insulation)*
- ❖ **Possibility to safely employ high voltages up to 150 kV**
- ❖ **Reliability of the chamber design** *… no broken wires during the transportation of the T600 module from Pavia to Gran Sasso*
- ❖ **Long electron lifetimes (~10 ms)/drift distances (~ 3 m) appear achievable**
  - *after the initial phase, main sources of impurities are the surfaces exposed to the gaseous Argon*
  - *better volume/surface ratio in a larger detector*
  - *both Gaseous and Liquid Argon recirculation systems are needed*

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

D. Finley, D. Jensen, H. Jostlein, A. Marchionni, S. Pordes, P. A. Rapidis
Fermi National Accelerator Laboratory, Batavia, Illinois
C. Bromberg
Michigan State University
C. Lu, K. T. McDonald
Princeton University
H. Gallagher, A. Mann, J. Schneps
Tufts University
D. Cline, F. Sergiampietri, H. Wang
University of California at Los Angeles
A. Curioni, B. T. Fleming
Yale University
S. Menary
York University

Contact Persons: B. T. Fleming and P. A. Rapidis

Soon to be on the hep-ex preprint server

* The **N**e**u**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

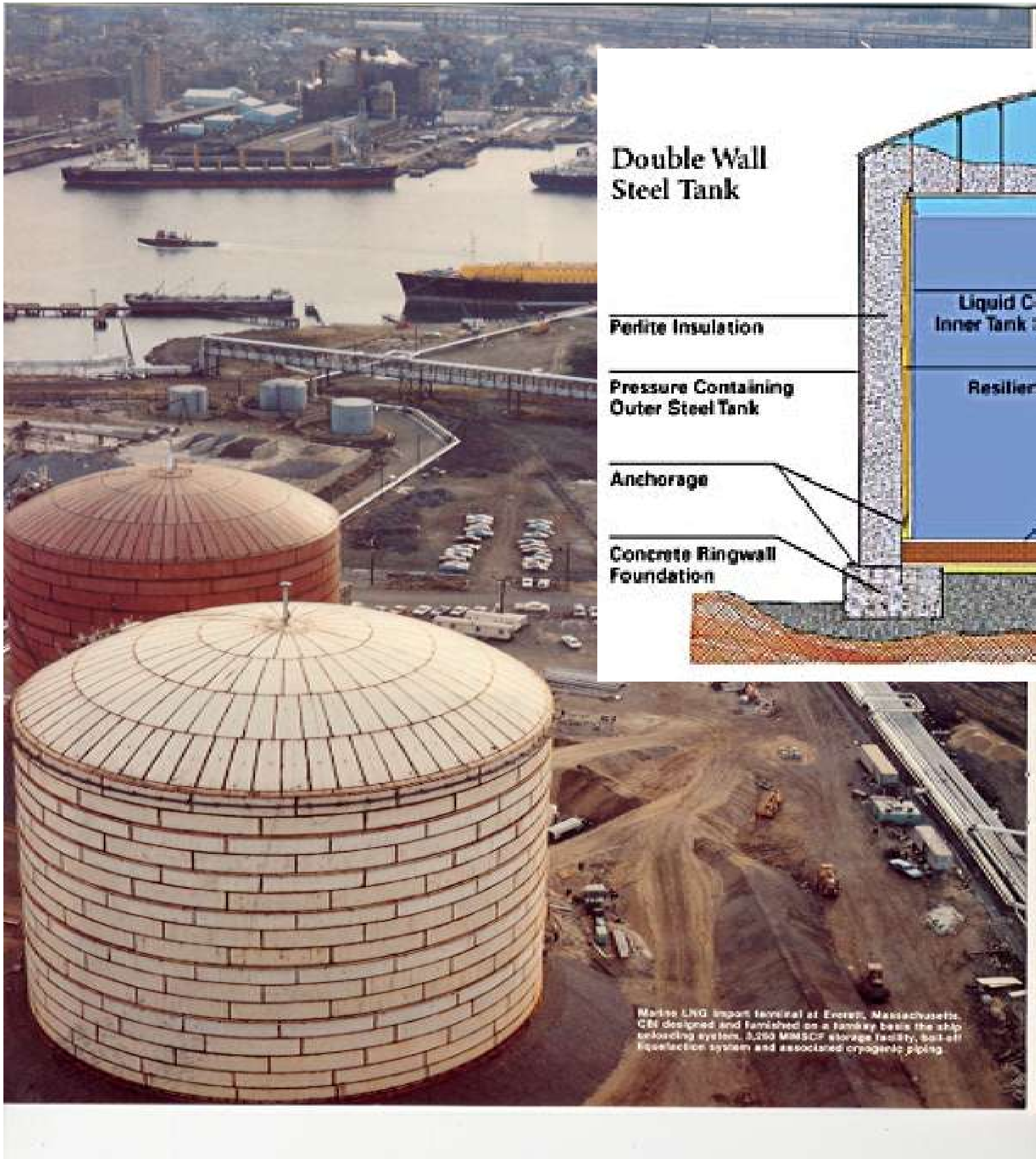
Basic parameters:

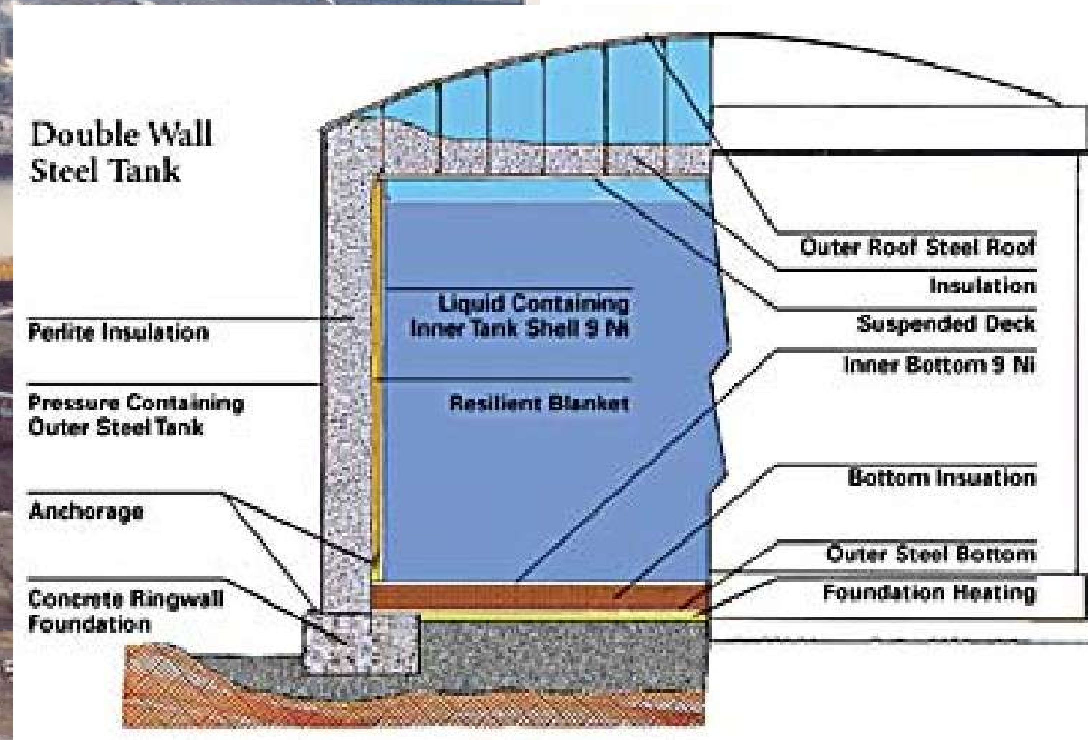
Drift distance - 3 meters; Drift field - 500 V/cm (gives v_{drift} = 1.5 m/ms)

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)

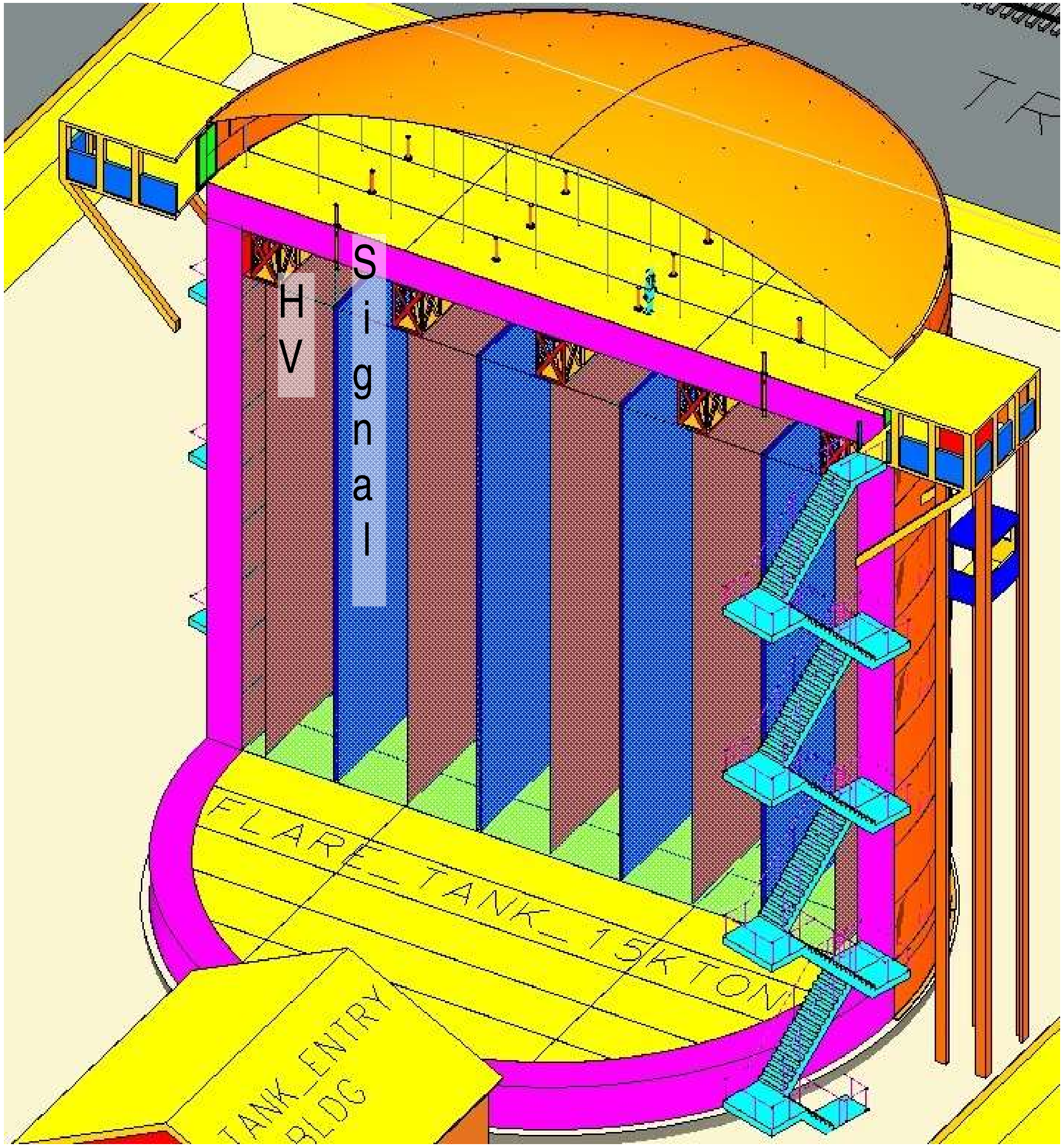




Many large LNG tanks
in service

Excellent safety record
Last failure in 1940
understood

Engineering has begun on a large multi- kton Device



A 15 kton Device

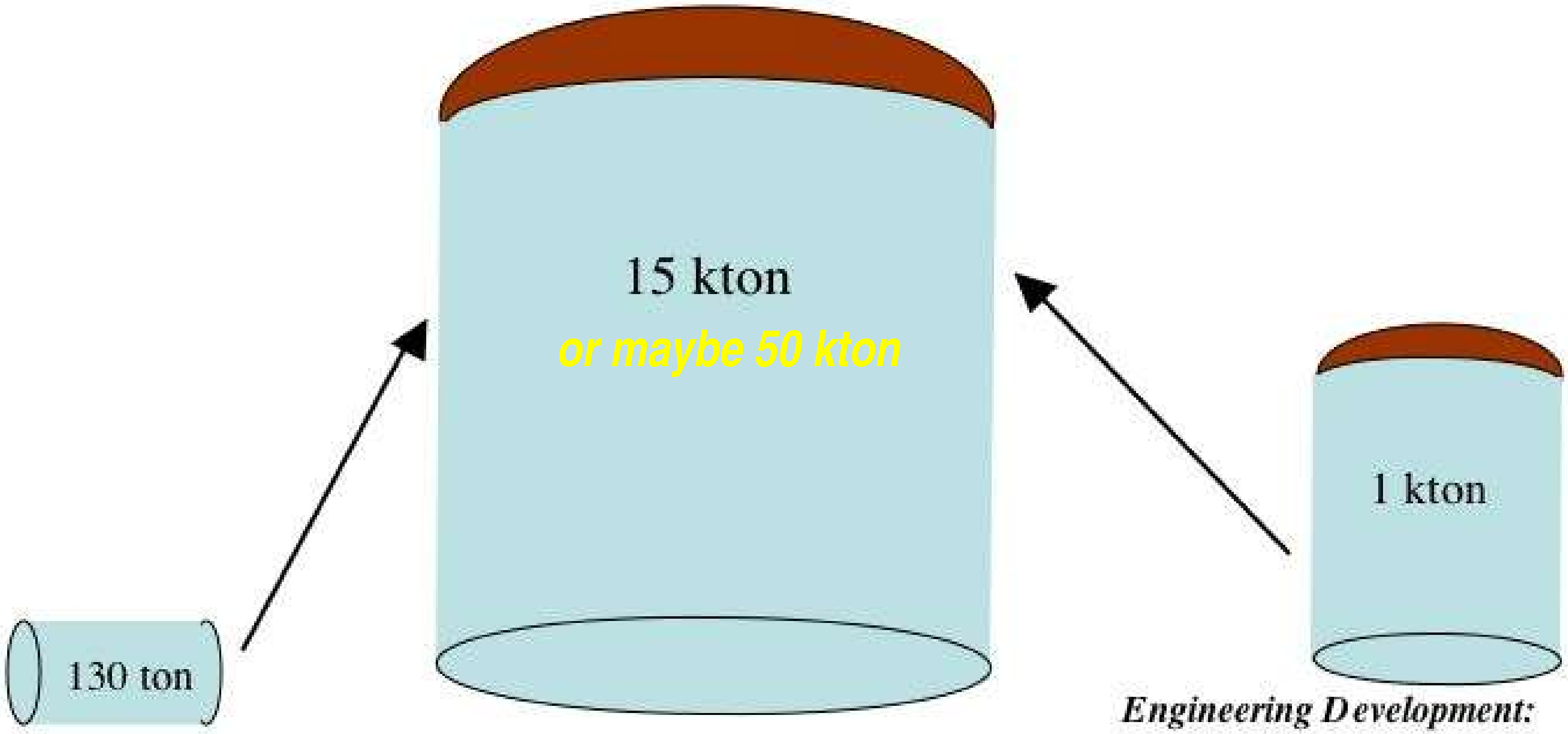
Inner tank dimensions:

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



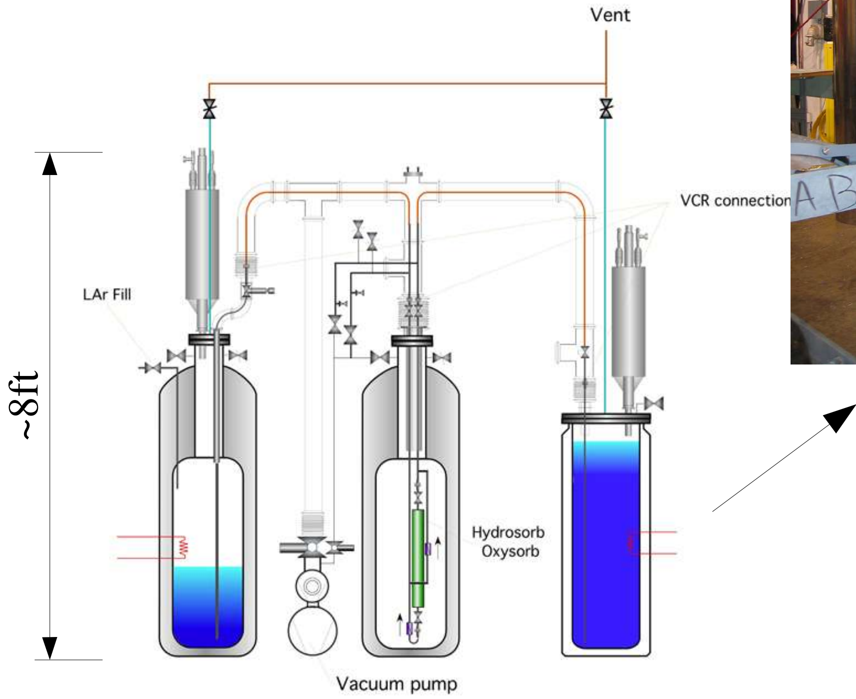
***Physics Development** using **existing** technology*
Record **complete neutrino interactions**: (ν_e & ν_μ)
Establish **Physics Collaboration**
Develop **Event Identification**,
Develop **Reconstruction**,
Develop **Analysis**,
Establish successful **Technology transfer**

Engineering Development:
Construction of Tank
Argon Purity
Mechanical Integrity of TPC
Readout S/N
Microphonics due to Argon Flow

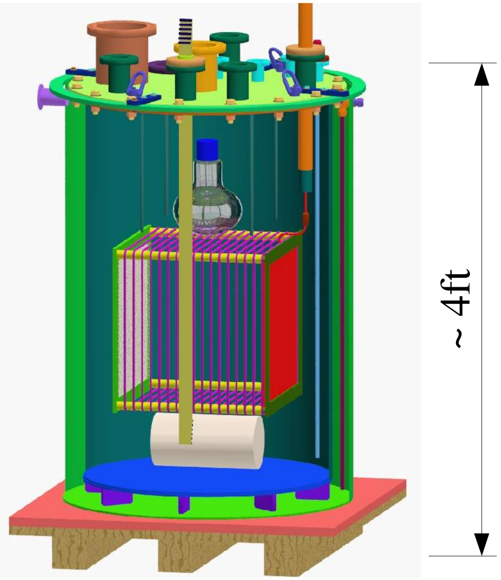
Technical Setups

Purity Monitor Development	Materials Tests	5 m Drift Demonstration	Long Wires Tests	Electronics Development

R&D efforts underway



at FNAL



at Yale

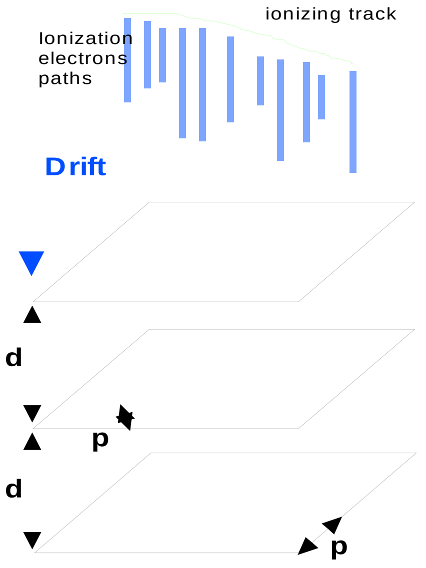
at UCLA/ CERN

Conclusions

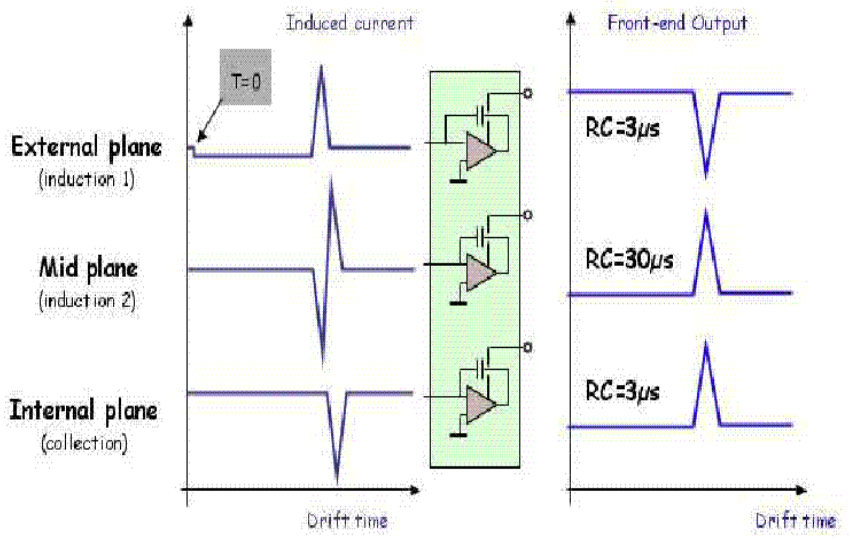
- Neutrino physics is at a very exciting stage. Measuring $P(\nu_\mu \to \nu_e)$ to get at $\sin^2(2\theta_{13})$, δ, and $\mathrm{sgn}(\Delta m_{13}^2)$ is one of the central goals of the next generation of experiments.
- ICARUS has demonstrated the viability of the Liquid Argon TPC (LArTPC) technique. 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 $P(\nu_\mu \to \nu_e)$.
- 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. There is lots of work to be done so new collaborators welcome!

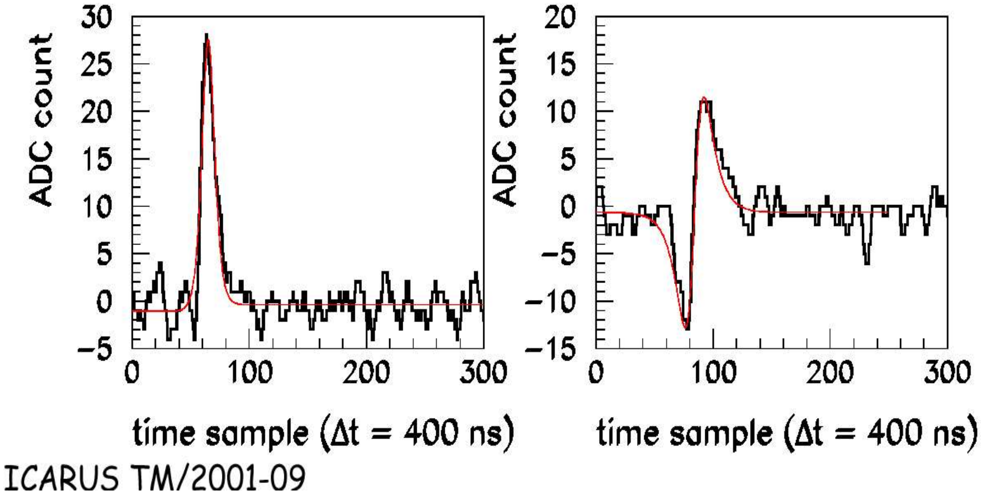
Backup slides

Signals on Wire Chamber Planes



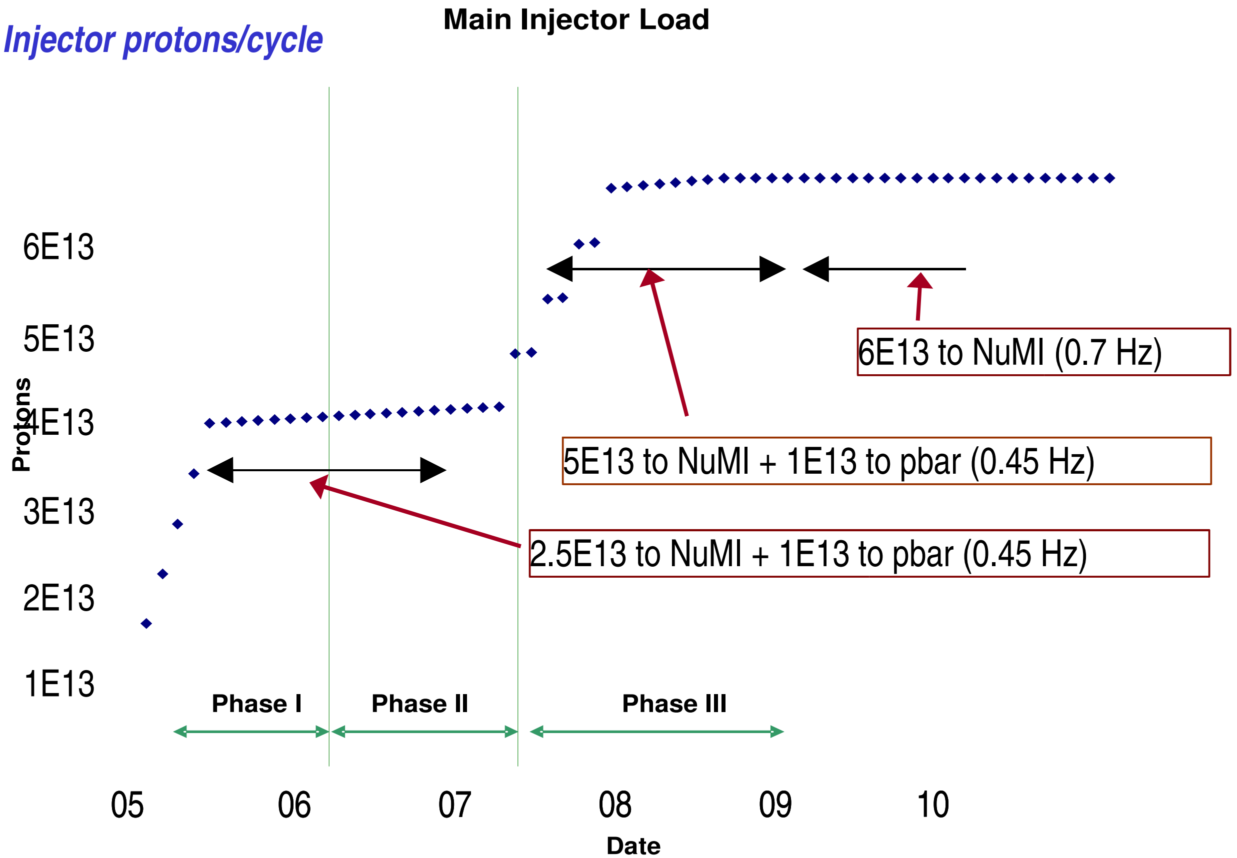
- Arrange E fields and wire spacing for total transparency for induction planes.
- Final plane collects charge.





Main Injector Power Upgrades

Main Injector protons/cycle



NuMI flux to MINOS ~ 2 x 10^{20} protons/year (now)

'Proton Plan' (remove existing limitations) gives NuMI

~ 4 x 10^{20} protons/year before collider turn-off in 2009

~ 6 x 10^{20} protons/year after collider turn-off in 2009

Proton Driver (new Linac) ~ 25 x 10^{20} - whenever PD exists

Neutral current event with 1 GeV π^0

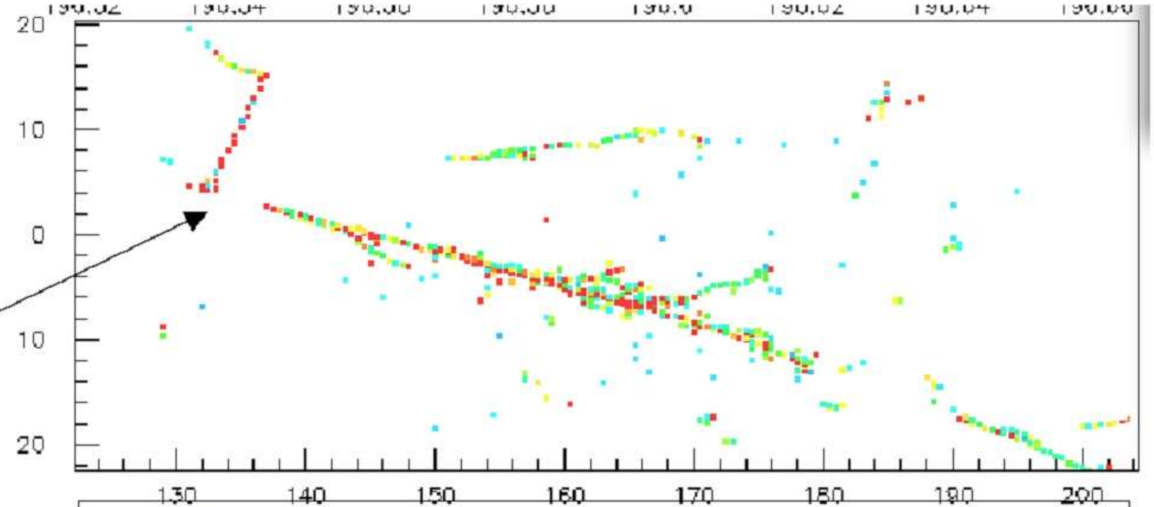
$$\nu_\mu + n \rightarrow \nu_\mu + \pi^+ + \pi^- + \pi^0 + n$$

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

3.5% X_0 samples

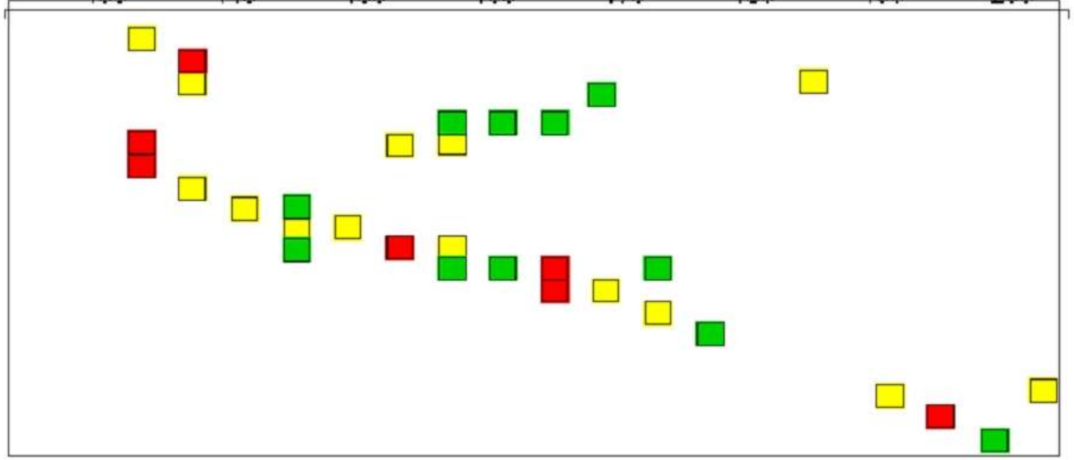
in all 3 views

4 cm gap



12% X_0 samples

alternating x-y

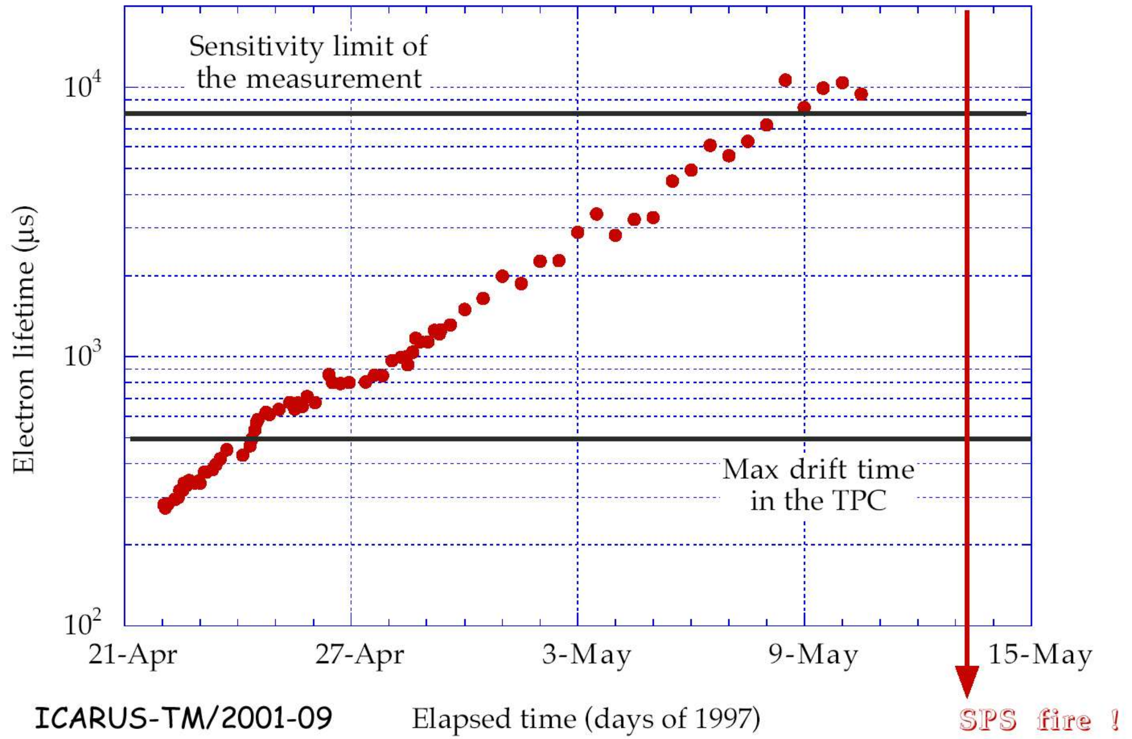


Argon Purity/Electron Lifetime in ICARUS

Impurities concentration is a balance of

- Purification speed t_c
- Leaks $F_{in}(t)$
- Outgassing A, B

$$\frac{dN}{dt} = -\Phi_{out}(t) + \Phi_{in}(t) = -\frac{N(t)}{\tau_c} + \Phi_{in}^{0} + \frac{A}{(1+t/t_0)^B}$$



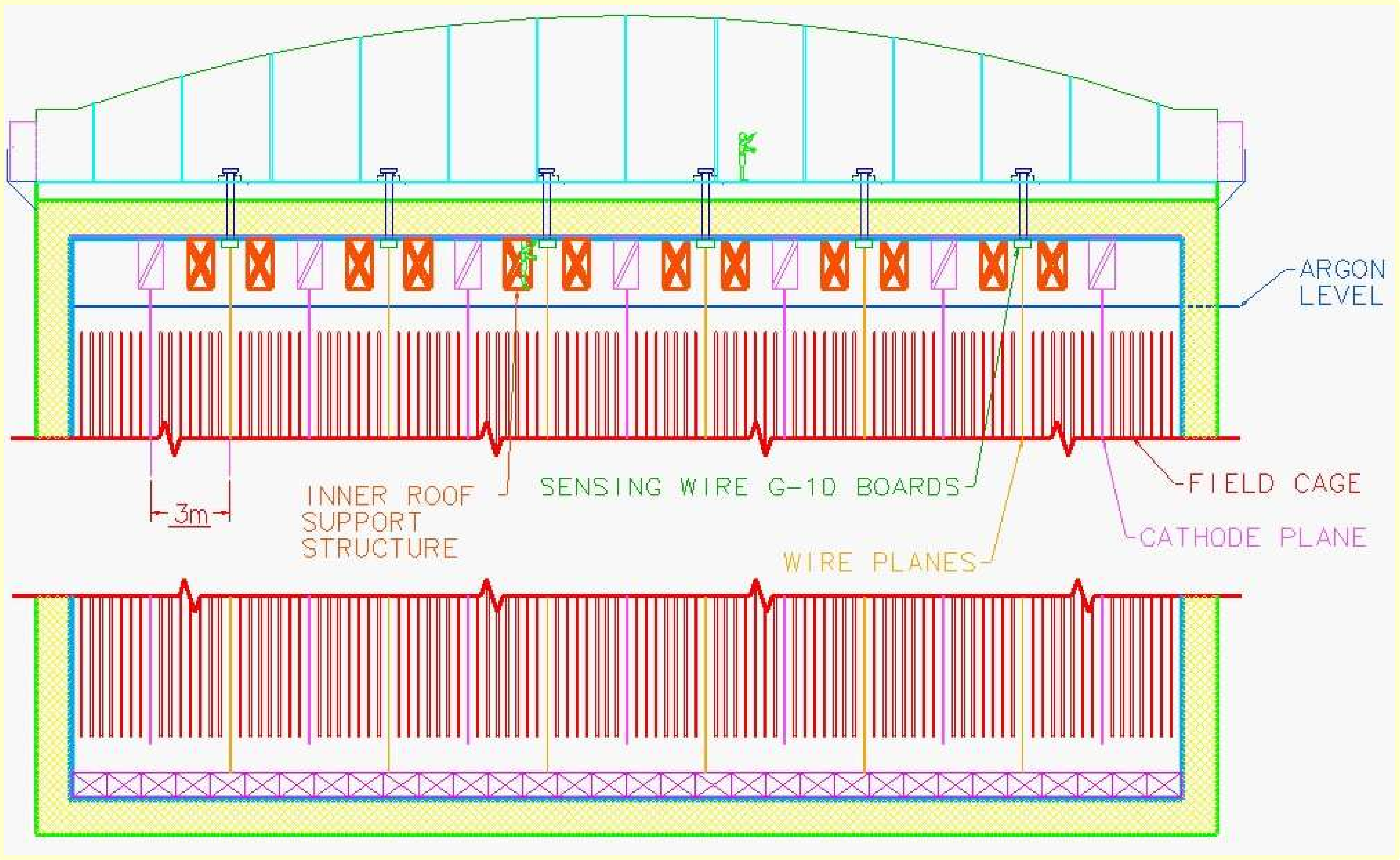
for the T600 module: achieved lifetime > 13 msec

for large LArTPCs : electron lifetime ~10ms is required

Argon Purity - Lessons for a Very Large Detector

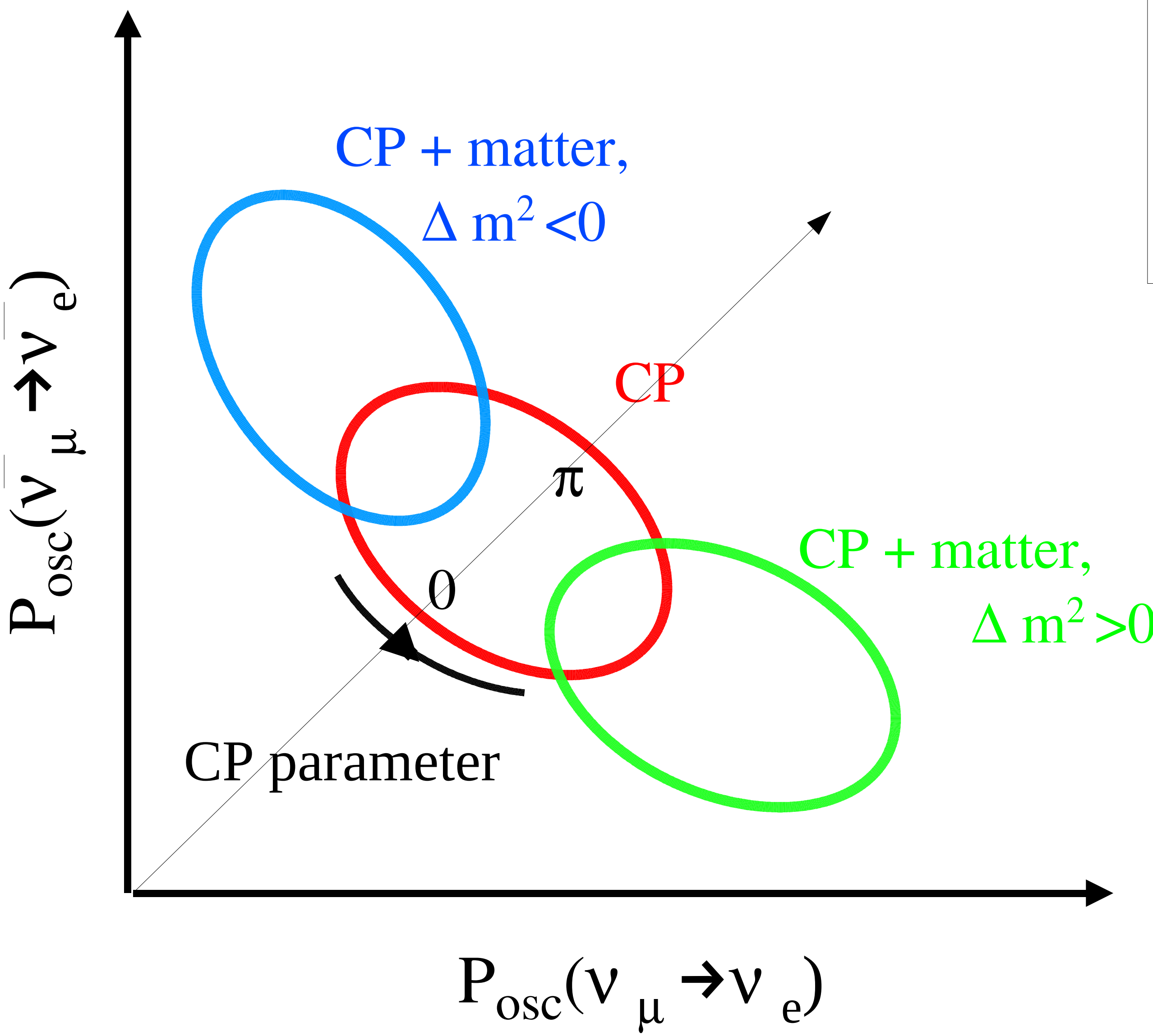
- Long electron lifetimes (~10ms)/drift distances (>3m) are achievable with commercial purification systems
- The main source of impurities are the surfaces exposed to the gaseous argon
- Increasing the ratio of liquid volume to the area of gaseous contact helps (dilution)
- Increasing the ratio of cold/warm surfaces helps (purification)
- Material selection and handling is the key

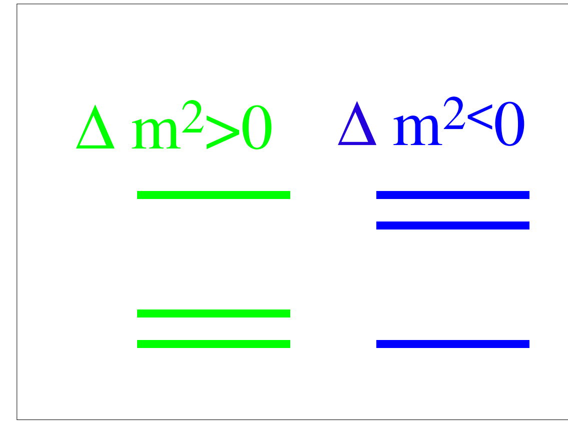
Engineering of Inside of Tank is Well Underway



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

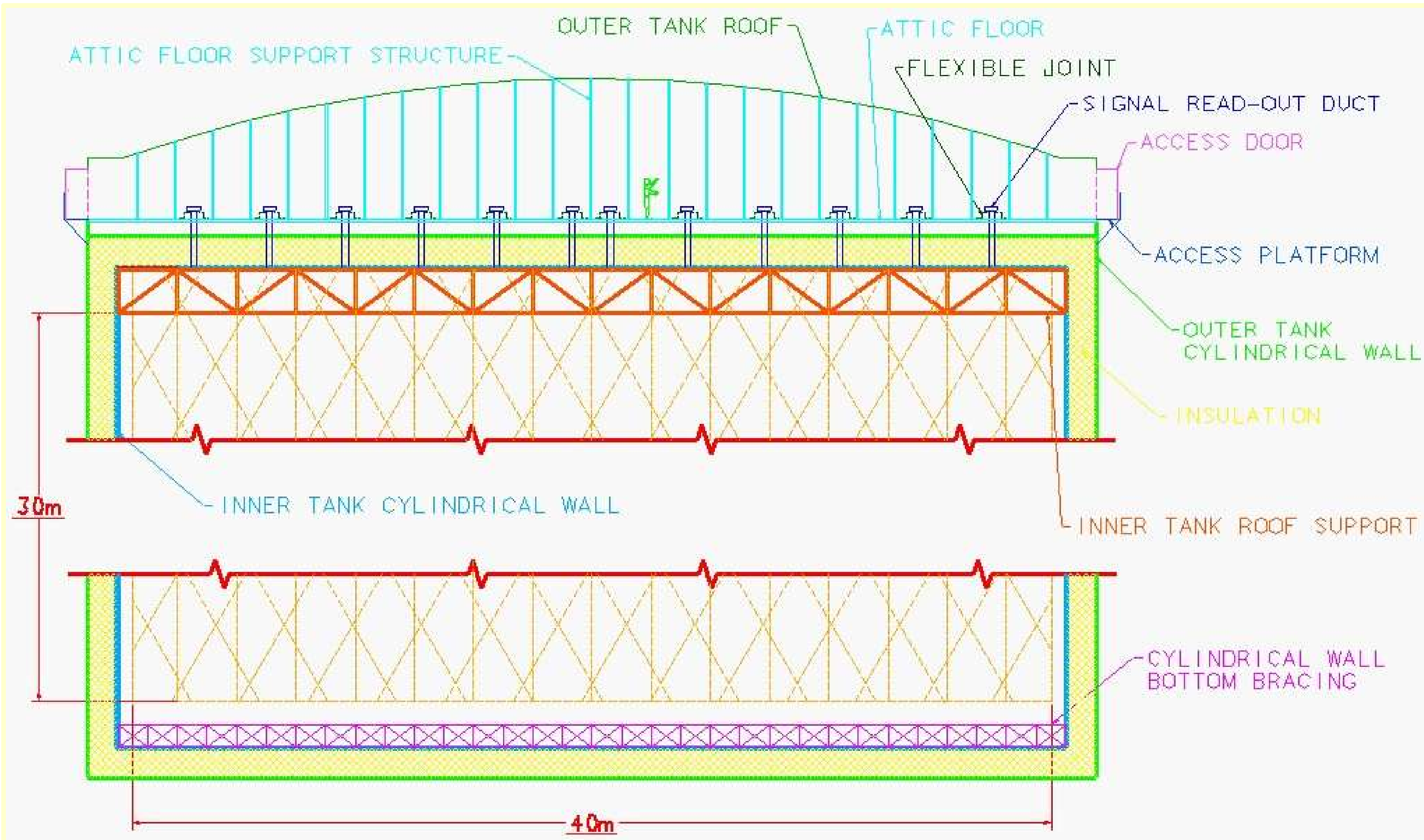
Capability will also depend on the mass hierarchy





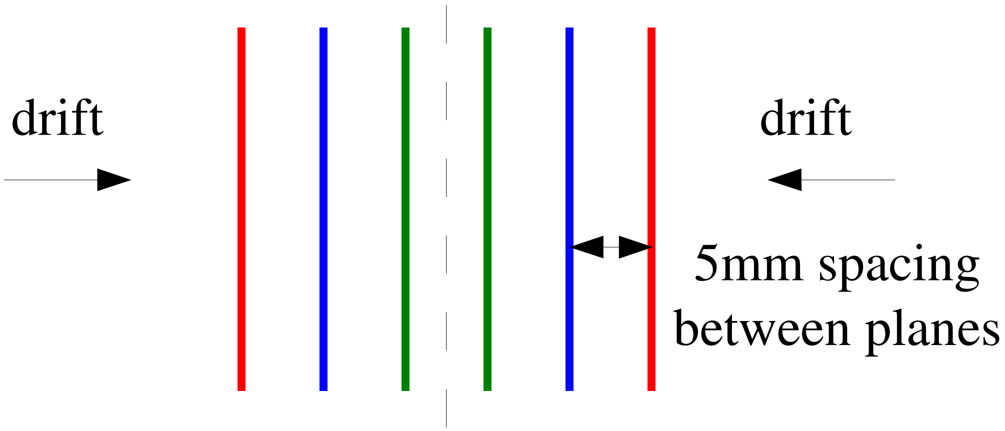
CP violation
+ matter effects

Front View



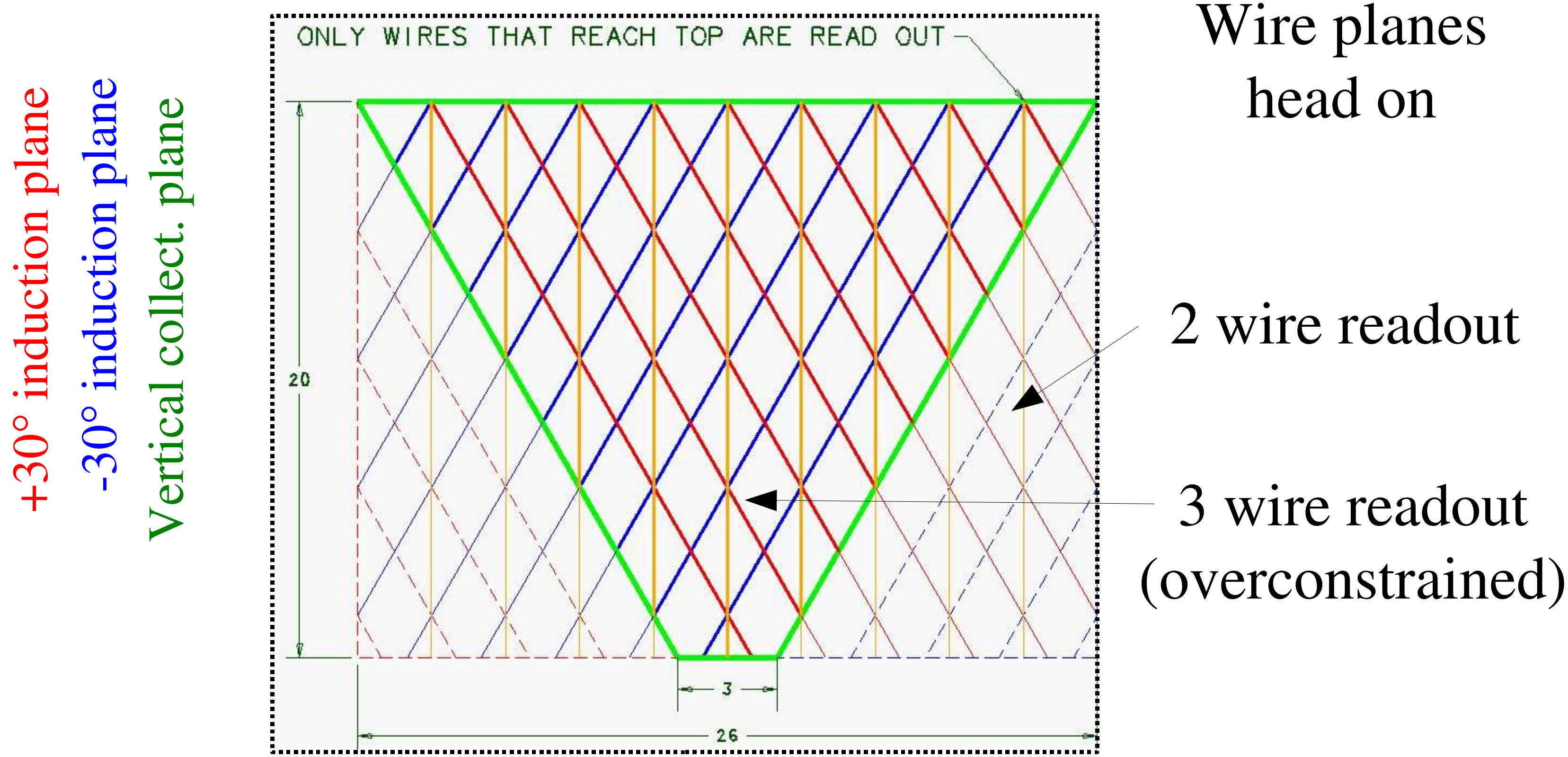
OUTER TANK ROOF
ATTIC FLOOR
ATTIC FLOOR SUPPORT STRUCTURE
FLEXIBLE JOINT
SIGNAL READ-OUT DUCT
ACCESS DOOR
ACCESS PLATFORM
OUTER TANK CYLINDRICAL WALL
INSULATION
30m
INNER TANK CYLINDRICAL WALL
INNER TANK ROOF SUPPORT
CYLINDRICAL WALL BOTTOM BRACING
40m

Each wire plane:



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

Wire planes head on



Drifting electrons over long distance (3m)?

Signal size for passing track:

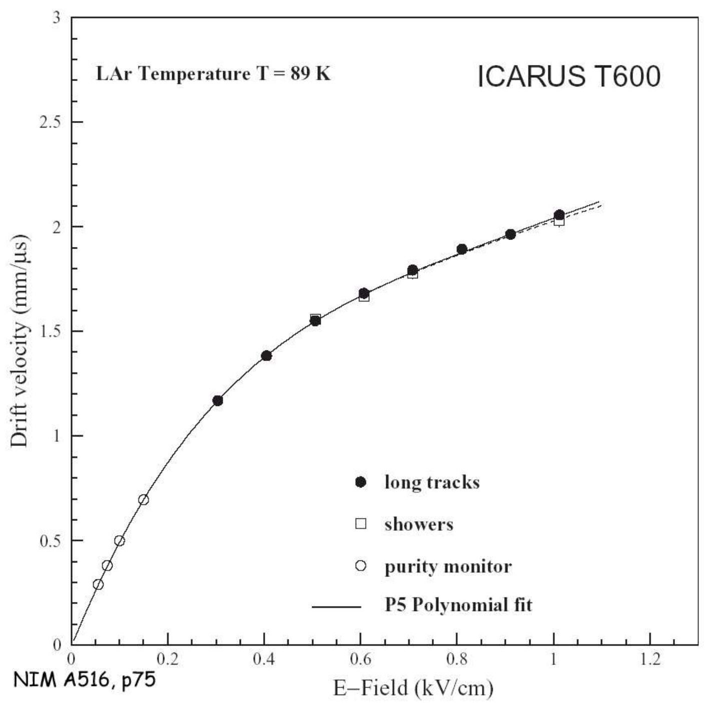
55,000 electrons/cm

How many are drifted to the edge of the detector?

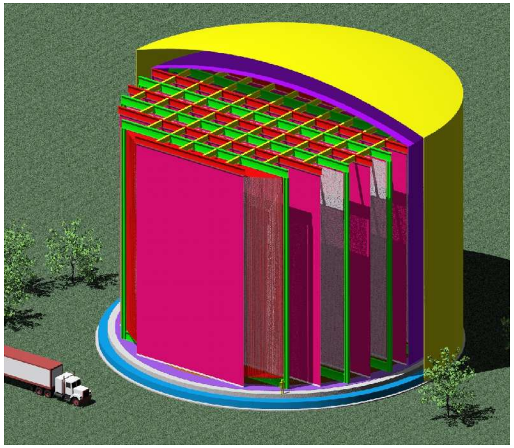
- drift velocity,

  V_{drift}=1.55mm/ s

  for E=500 V/cm
- diffusion coefficient
- argon impurities
  - don't want 0_2 to 'eat' electrons along the way



Great technology! ...What are the open questions in going to large scales? (15-50 kton?)



•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 demonstrating that answer to all these questions is yes!