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

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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:

- $P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$
  - $P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\ \Delta m_{13}^2\ L/E)$
  - $P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\ \Delta m_{12}^2\ L/E)$
  - $P_3 = \quad J \sin(\delta) \sin(1.27\ \Delta m_{13}^2\ L/E)$
  - $P_4 = J \cos(\delta) \cos(1.27\ \Delta m_{13}^2\ L/E)$

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

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

- In matter, P_1 will be approximately multiplied by $(1 \pm 2E/E_R)$ and P_3 and P_4 will be approximately multiplied by $(1 \pm E/E_R)$, where the top sign is for neutrinos with the normal mass hierarchy and antineutrinos with the inverted mass hierarchy.
- Ultimately we measure:

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

The expression contains: 3 unknowns, 4 known "measured" quantities, and 3 parameters under experimenter's control

– L, E + neutrino VS antineutrino beam

Need several independent measurements to get to underlying physics parameters

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 = detector mass x efficiency x protons on target/yr x # of years

Limiting factor in sensitivity for long-baseline neutrino physics (after intrinsic beam ν_e component) is ν_e event rate (i.e., signal efficiency) and neutral current background rejection

Requirements to Achieve These Goals:

- High intensity, narrow-band ν_μ beam
- Detector highly efficient for ν_e events with large rejection factor for neutral current events

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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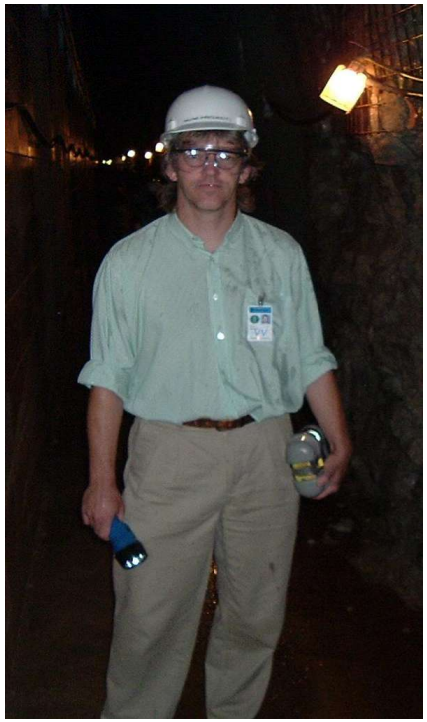
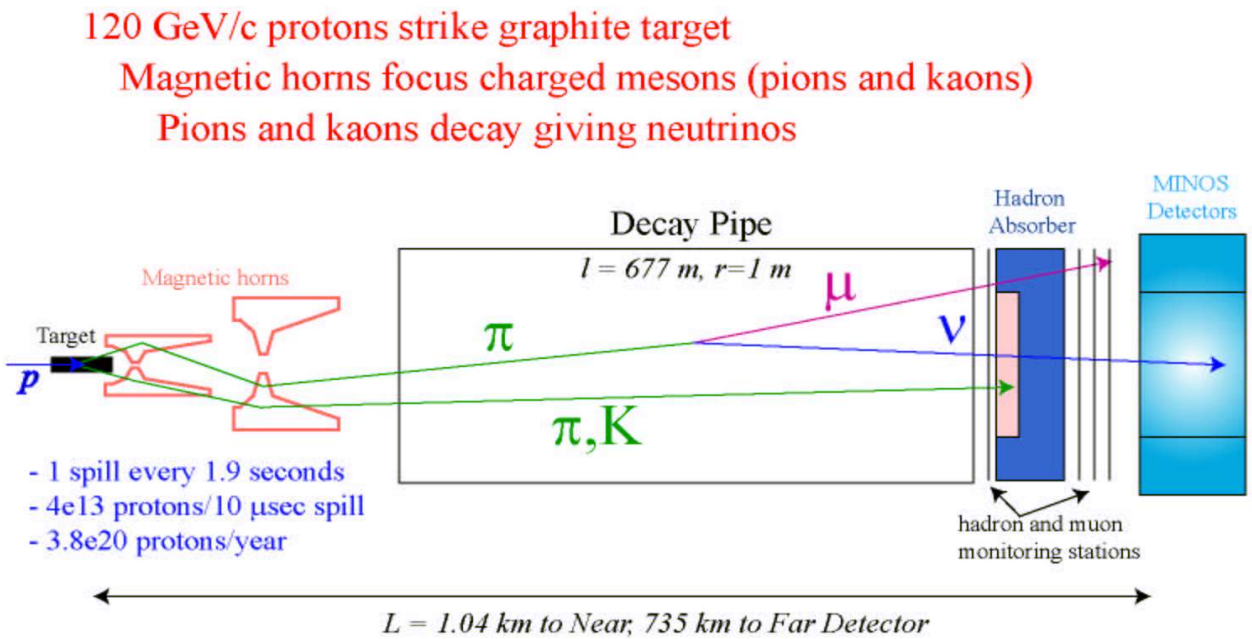
The Beam Already Exists!

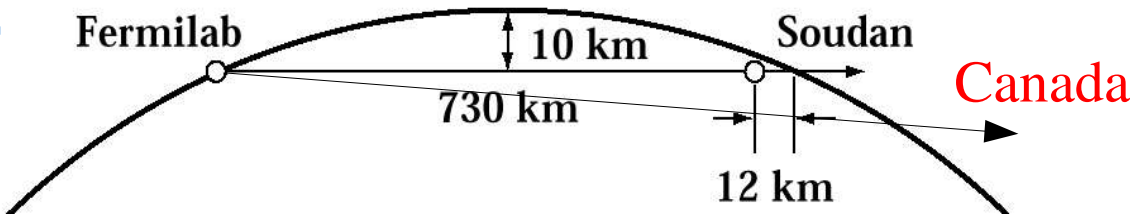
The NuMI tunnel is complete and …

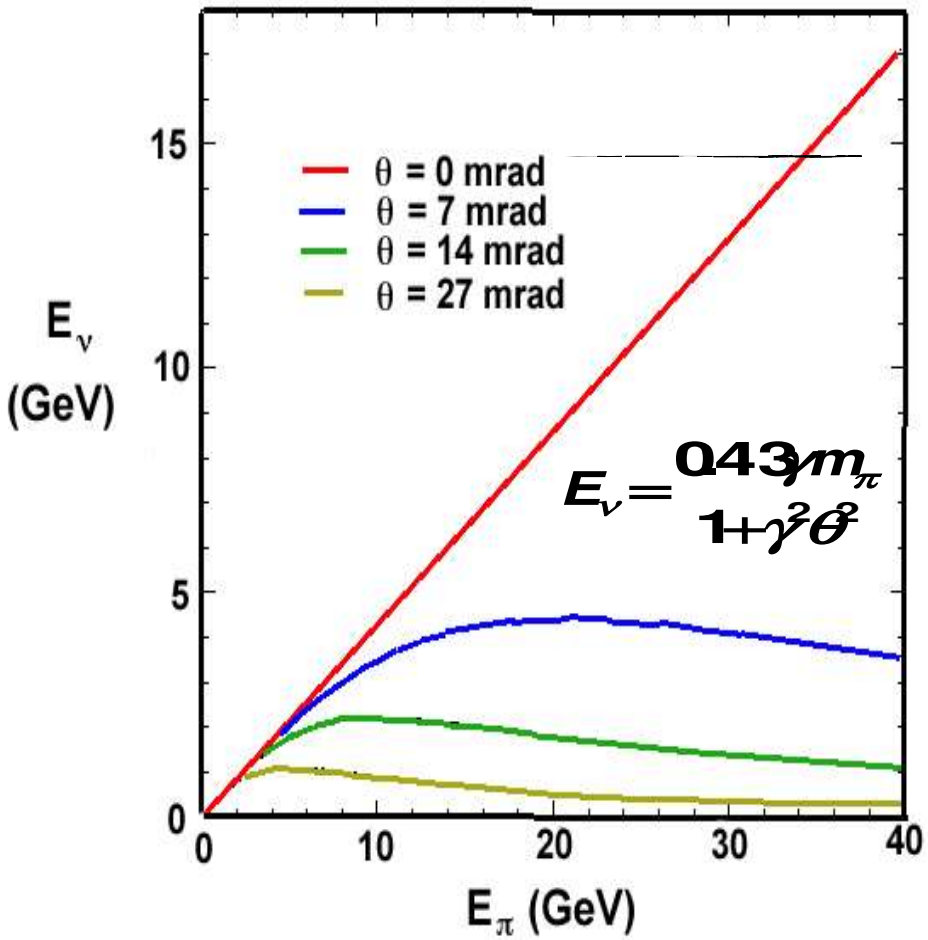


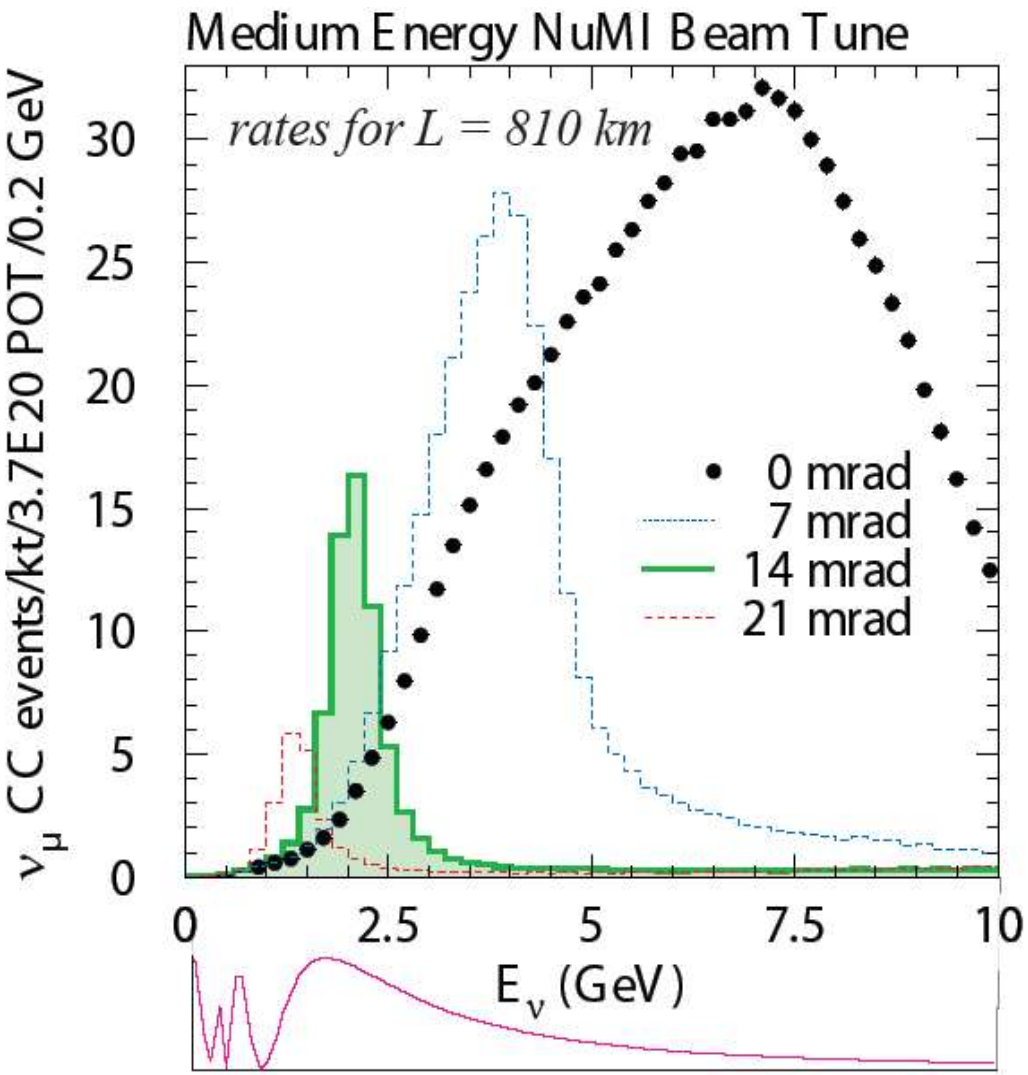


… in January of this year the MINOS near detector saw its first neutrinos from the NuMI facility!

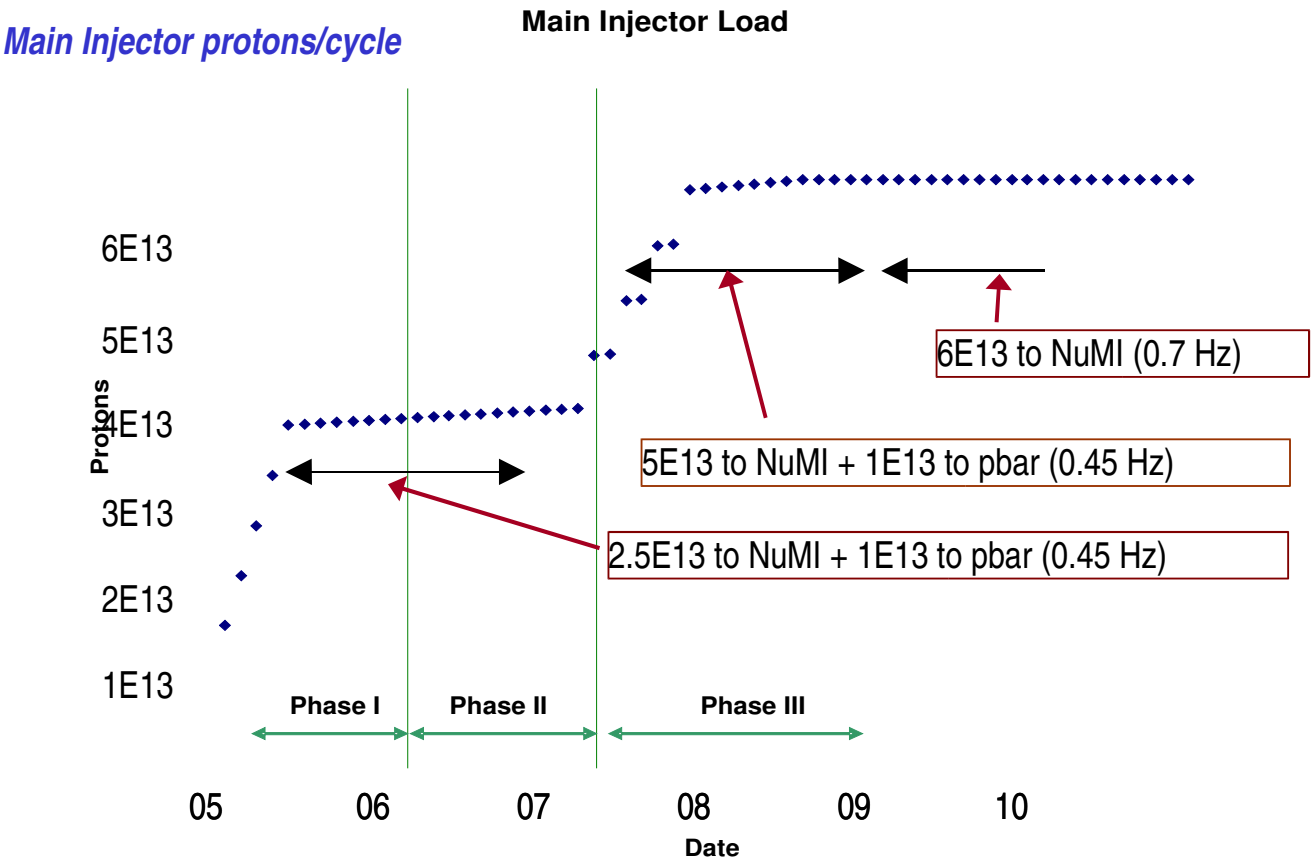
The "Off-axis" Beam







Main Injector Power Upgrades



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

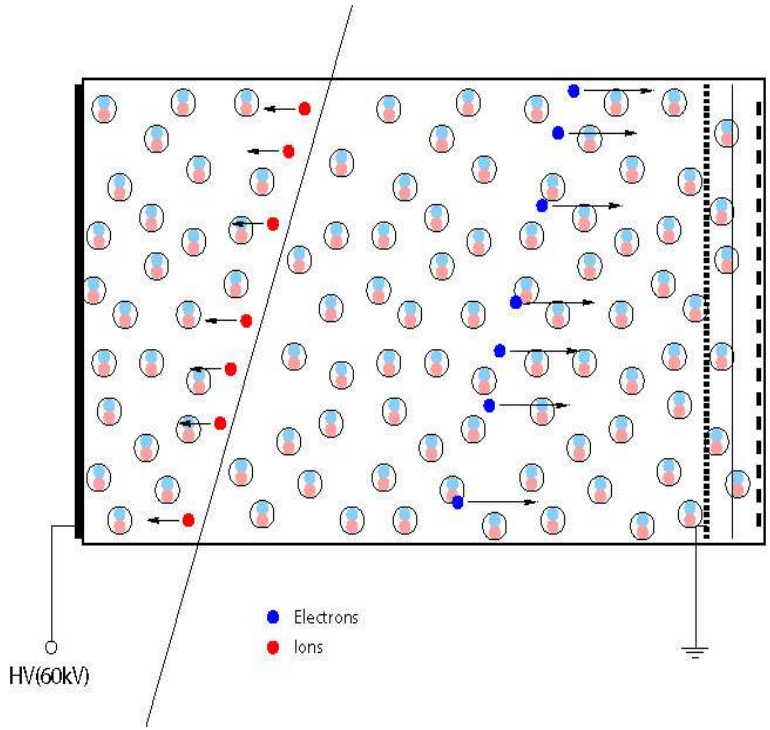
Proton Driver (new Linac) ~ 25 x 10^{20} - whenever PD exists

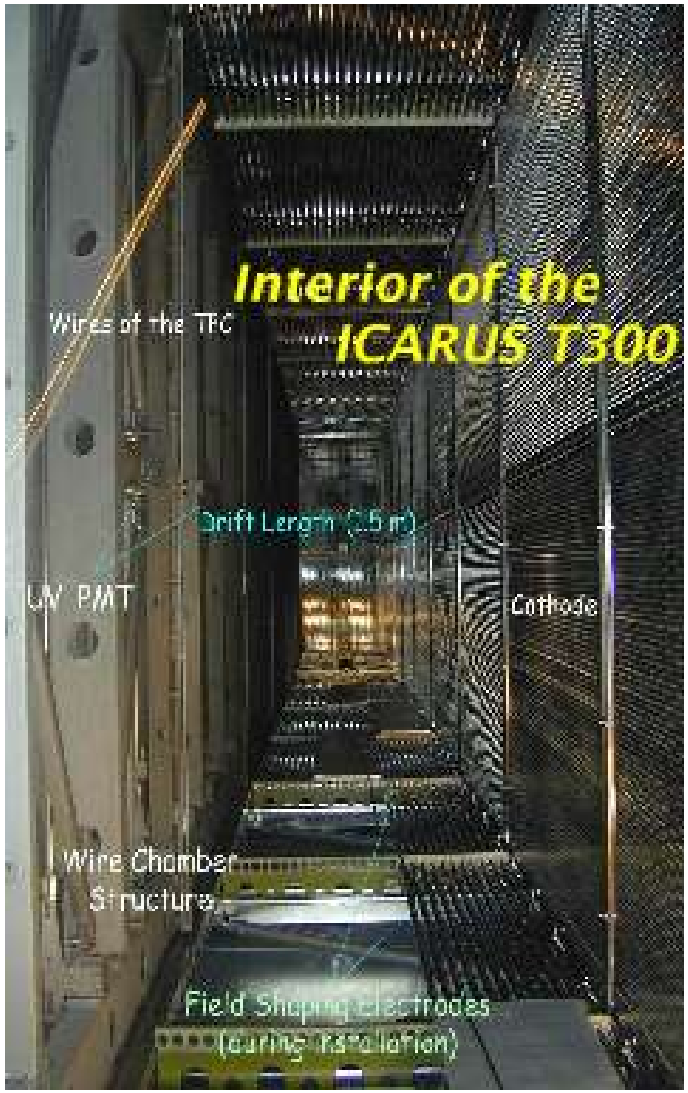
Detector Requirements

- *optimized for the neutrino energy range of 1 to 3 GeV*
- *detector on surface, must be able to handle raw rate and 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

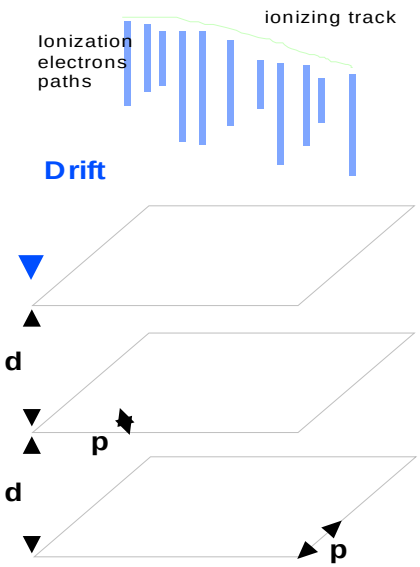




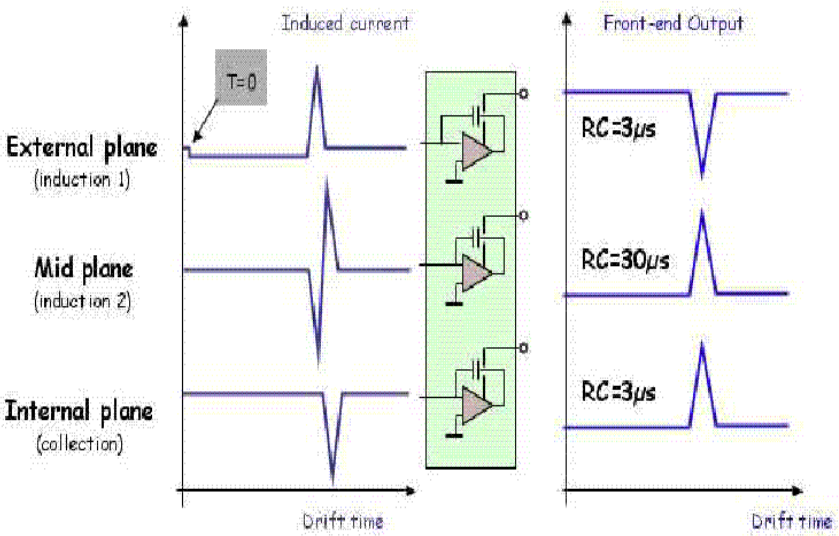
Drift ionization electrons over metres of pure liquid argon to collection planes to image track

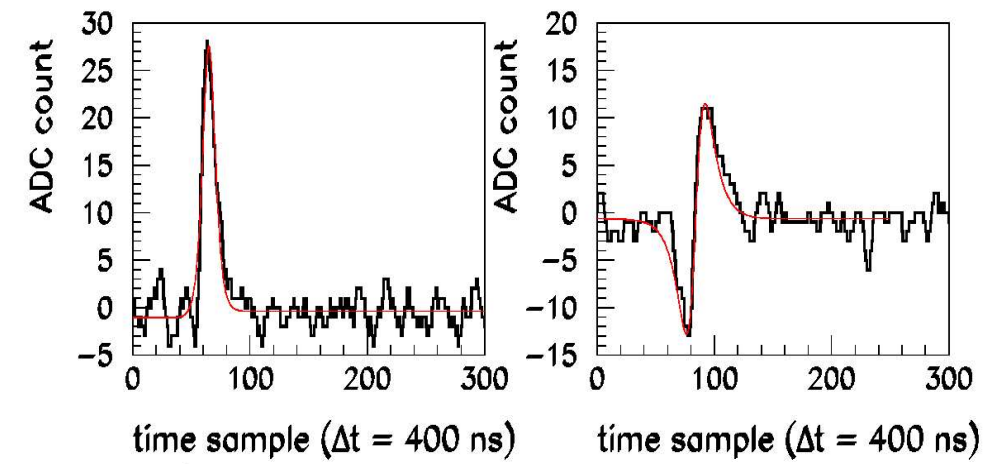
- 50,000 electrons/cm

Signals on Wire Chamber Planes



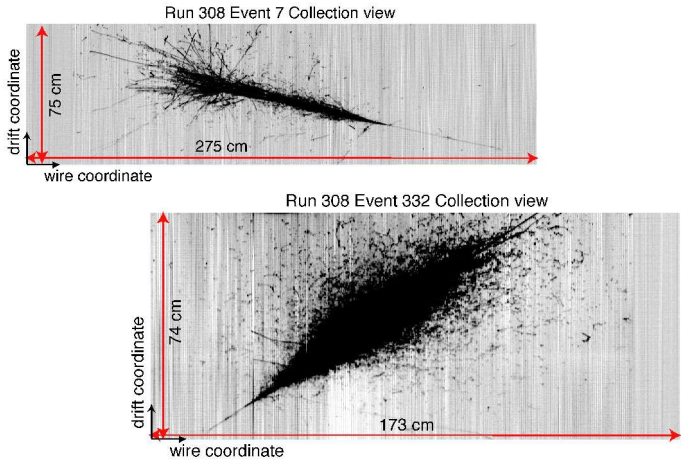
- Arrange E fields and wire spacing for total transparency for induction planes.
- Final plane collects charge.

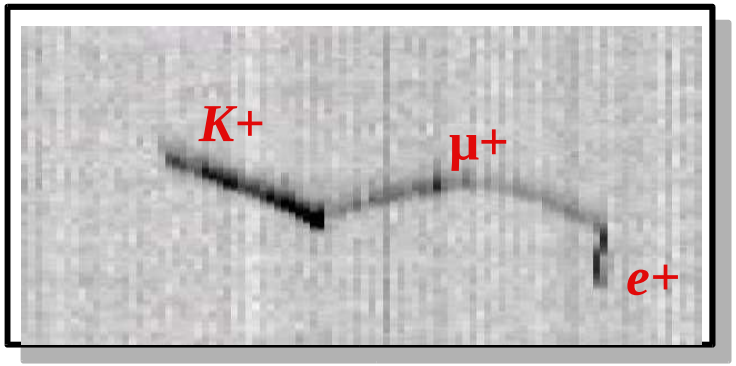




ICARUS TM/2001-09

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





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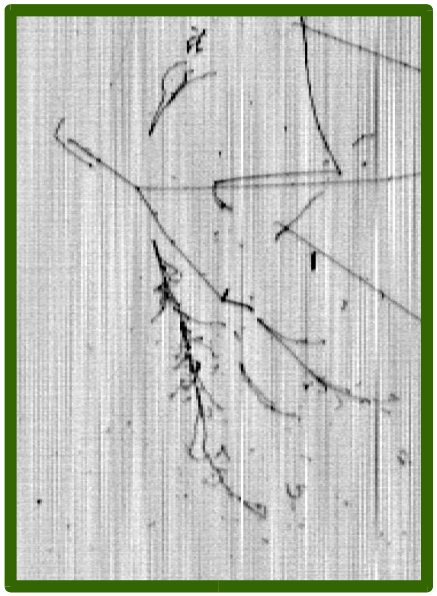
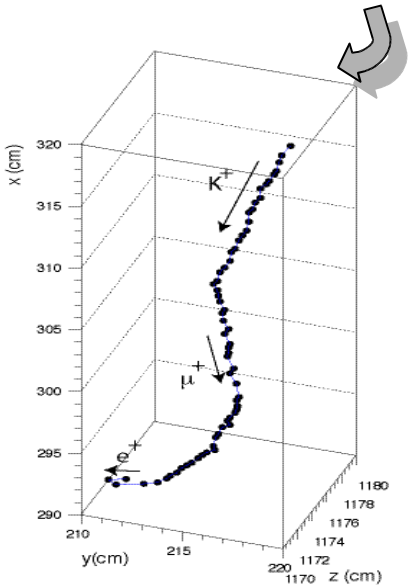




MC simulation

ICARUS images

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

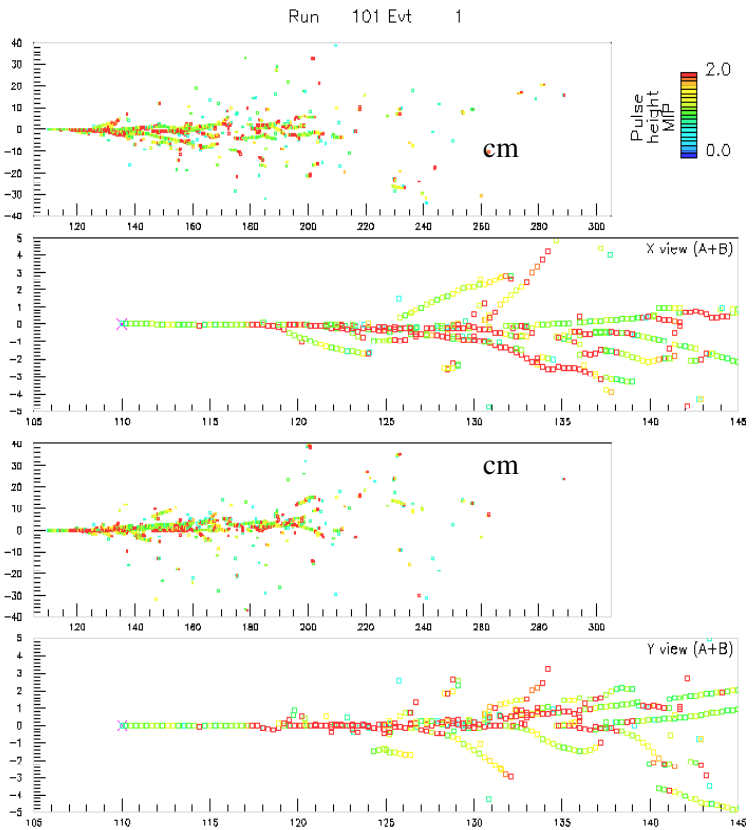
Dot indicates hit while colour indicates collected charge with green=1 mip, red=2 mips

X plane

zoom in

Y plane

zoom in

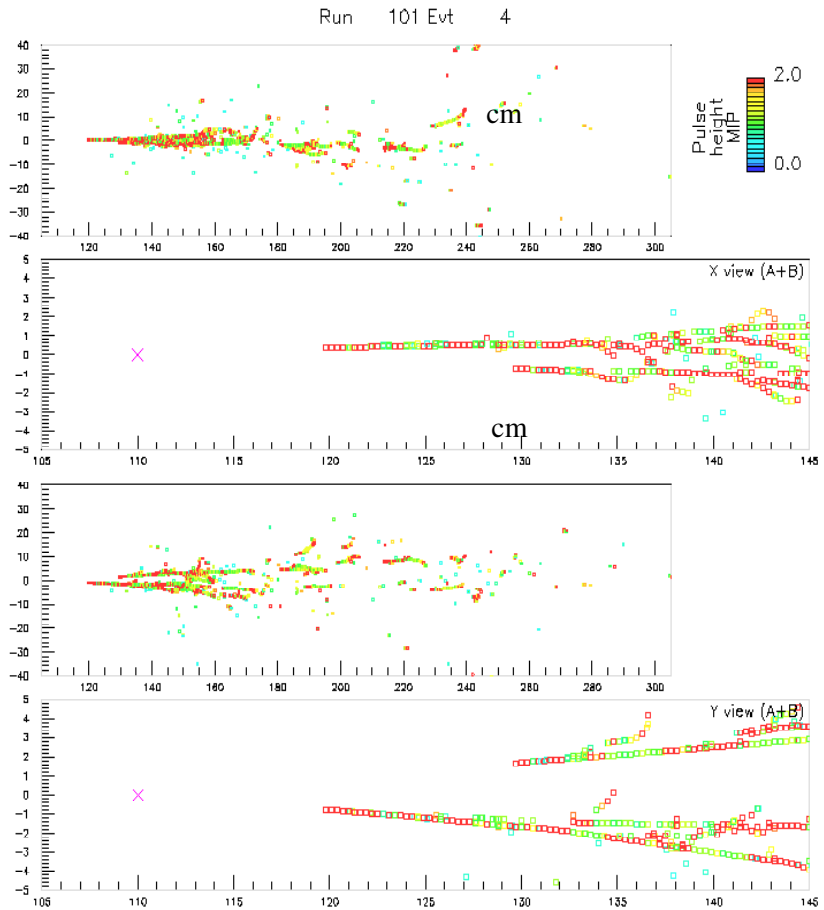


X plane

zoom in

Y plane

zoom in



π^0

0

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***

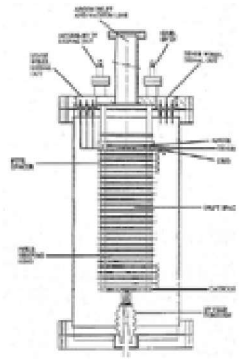
Event Type		N	pass	ϵ	η
NC		290	4	-	0.99±0.01
signal ν_e	CC	32	26	0.81±0.07	-
Beam ν_e	CC	24	14	0.58±0.10	-
Beam ν_e	NC	8	0	-	/
Beam $\overline{\nu}_e$	CC	13	10	0.77 ± 0.09	-
Beam $\overline{\nu}_e$	NC	19	0	-	/
ν_μ	CC	32	0	-	/
$\overline{\nu}_\mu$	CC	32	1	-	/

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

⇒ 99.8% NC rejection efficiency

Good signal efficiency (81±7)%

Technical Feasibility: History of prototype work on ICARUS

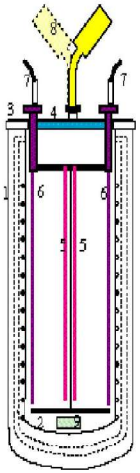


24 cm drift wires chamber

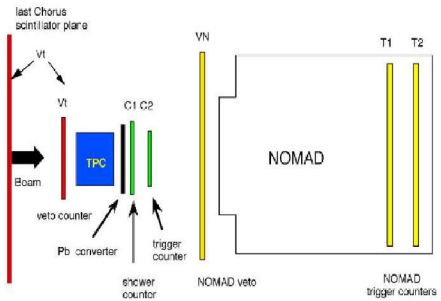
1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

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

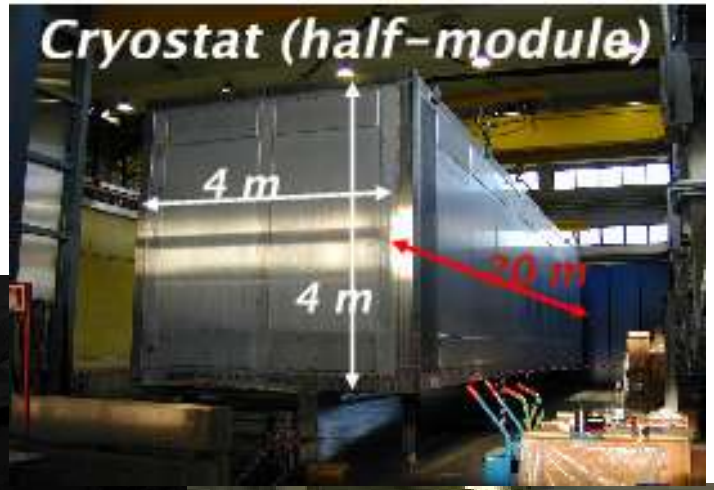


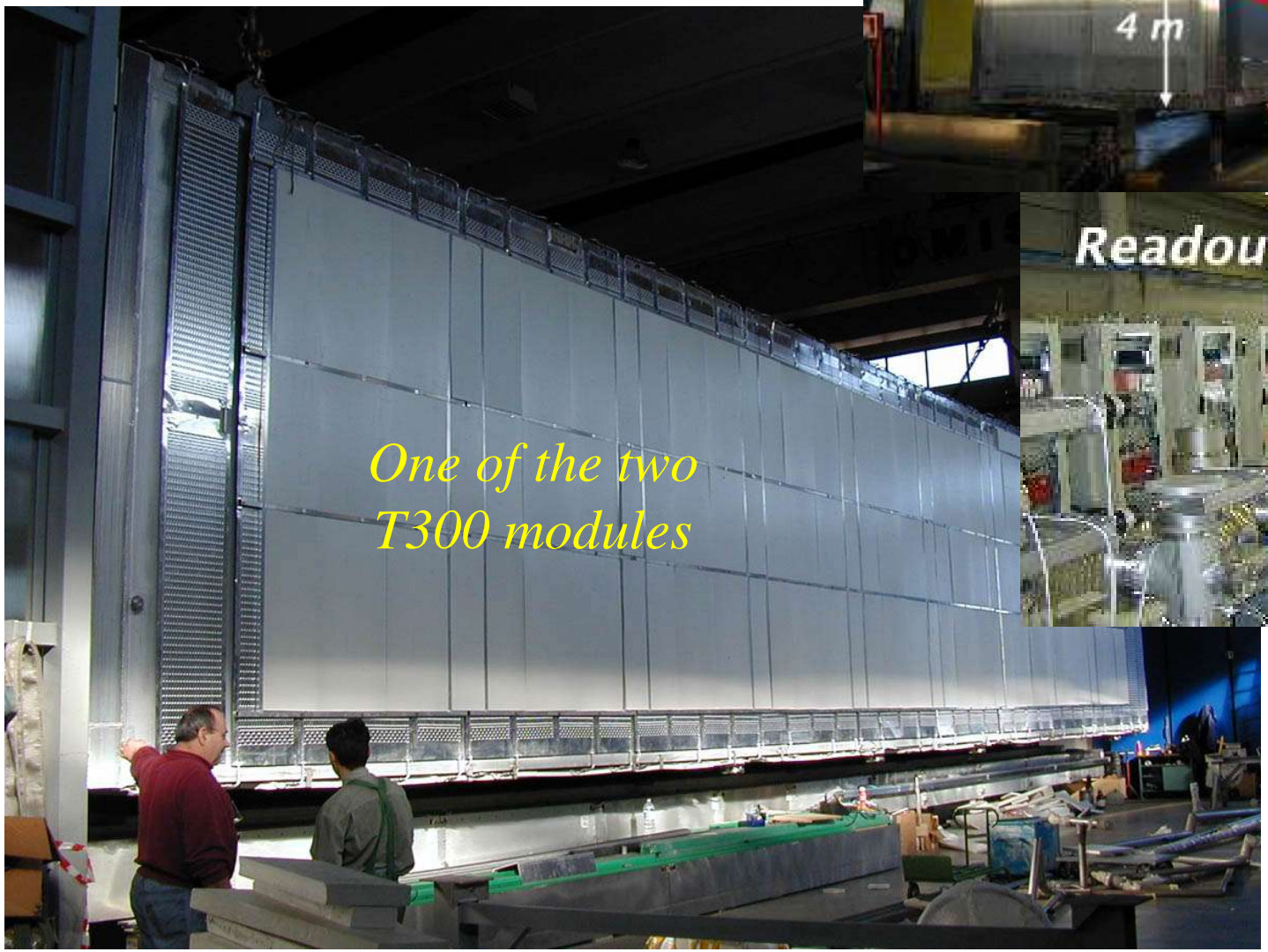
1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

10 m^3 industrial prototype

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

The ICARUS T600

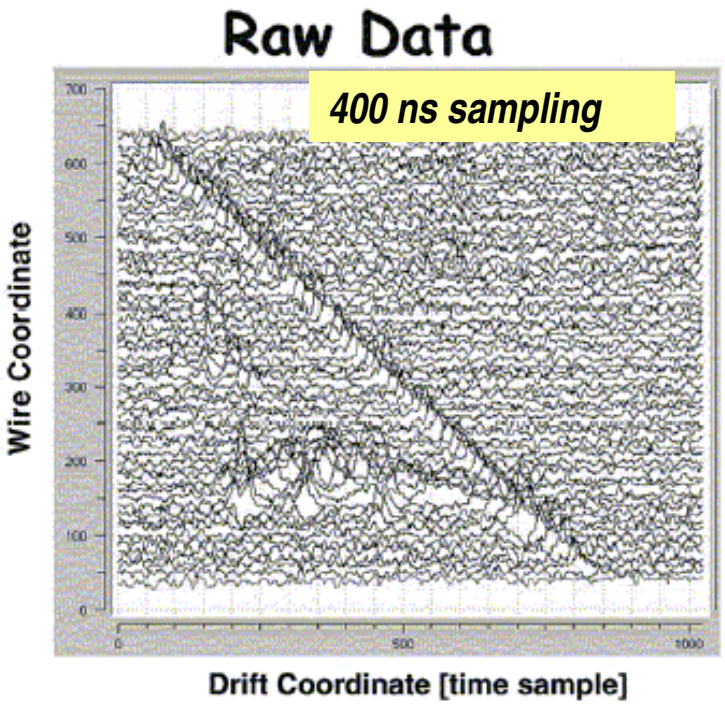


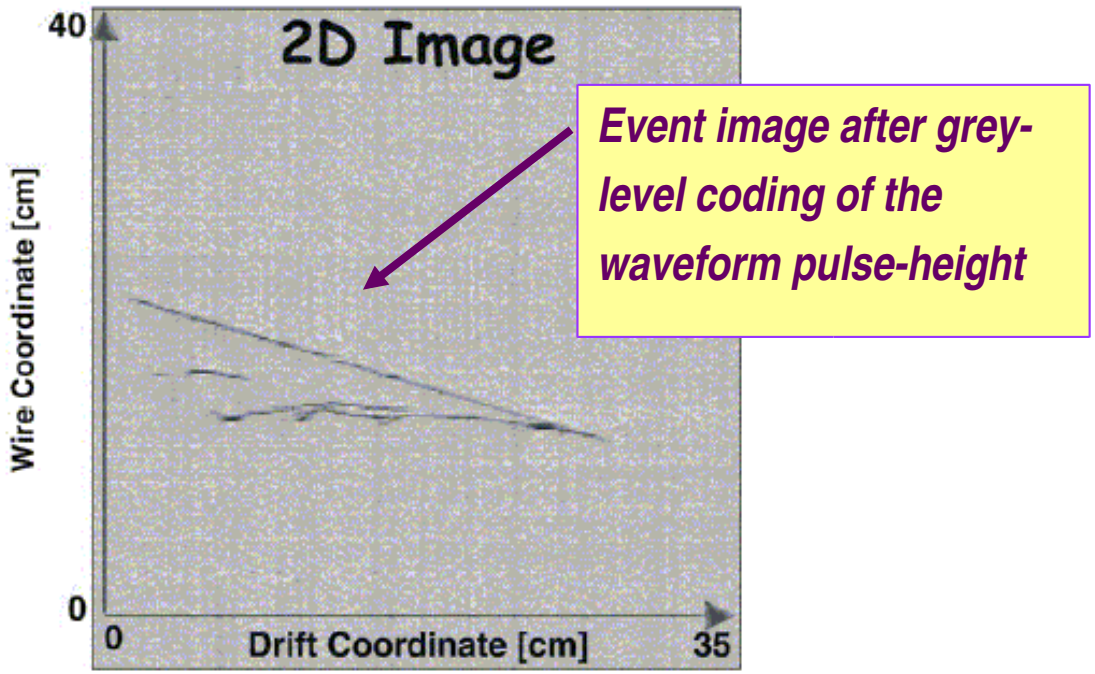


Tested above ground in Pavia in 2001

Now below ground in Gran Sasso

Lessons from ICARUS





- ***demonstration of 3D imaging reconstruction over massive detector volumes (~ 1 kton)***
  - *performance comparable to traditional bubble chambers, with the advantage of being continuously sensitive*
- ***calorimetric measurement, particle ID capabilities***
- ***possibility of absolute timing definition and internal trigger from Liquid Argon scintillation light detection***

Lessons from ICARUS continued

- **Importance of the cryostat design**
  - *have to not pollute Argon (no leaks)*
  - *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 (on Italian highways!)*
- **Long electron lifetimes (>5 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

Soon to be on the hep-ex preprint server

** The **N**e**U**trino **S**cientific **A**ssessment **G**roup for the DOE/NSF*

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

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

Long(er) signal wires

Single device (not modular)

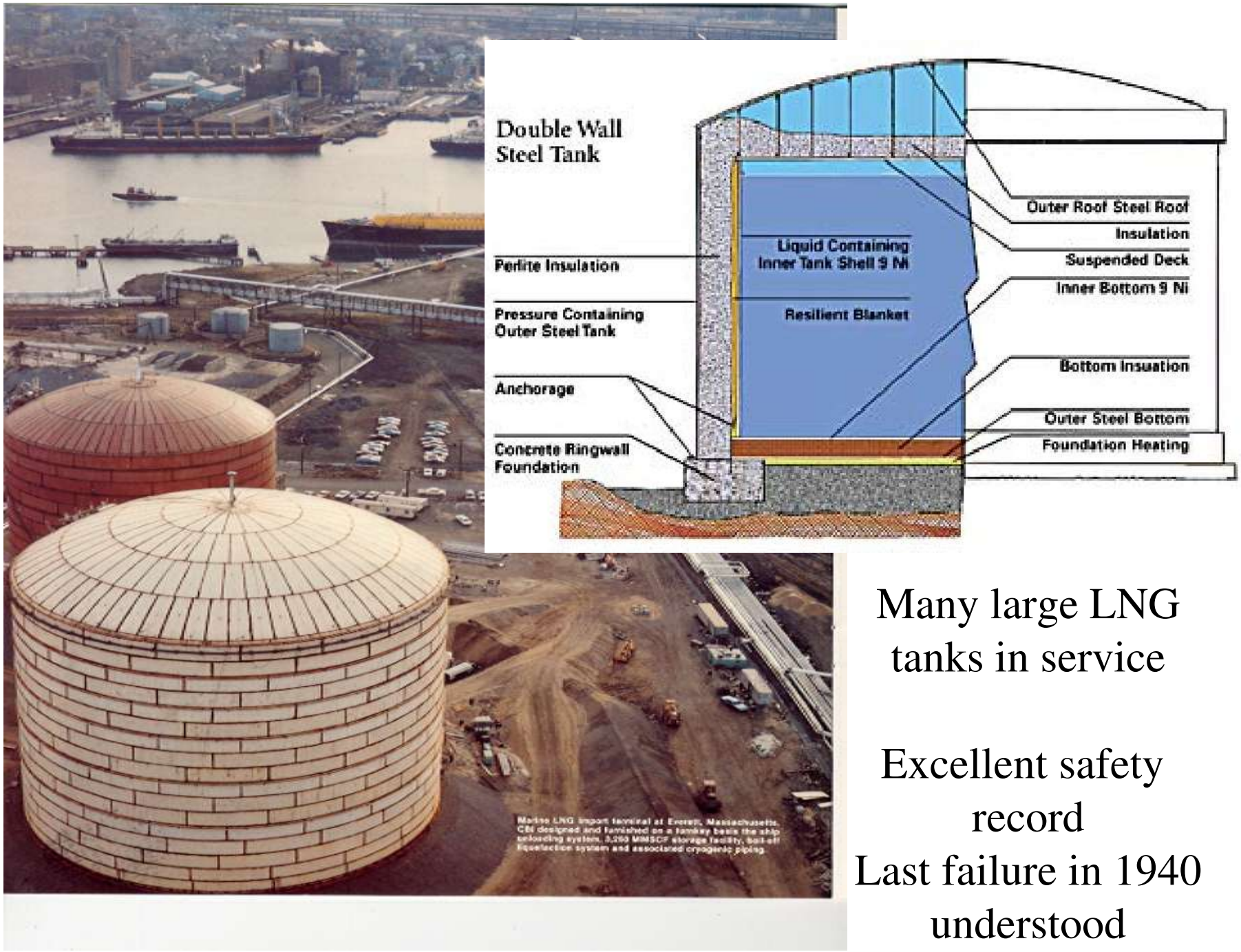
Basic parameters:

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)

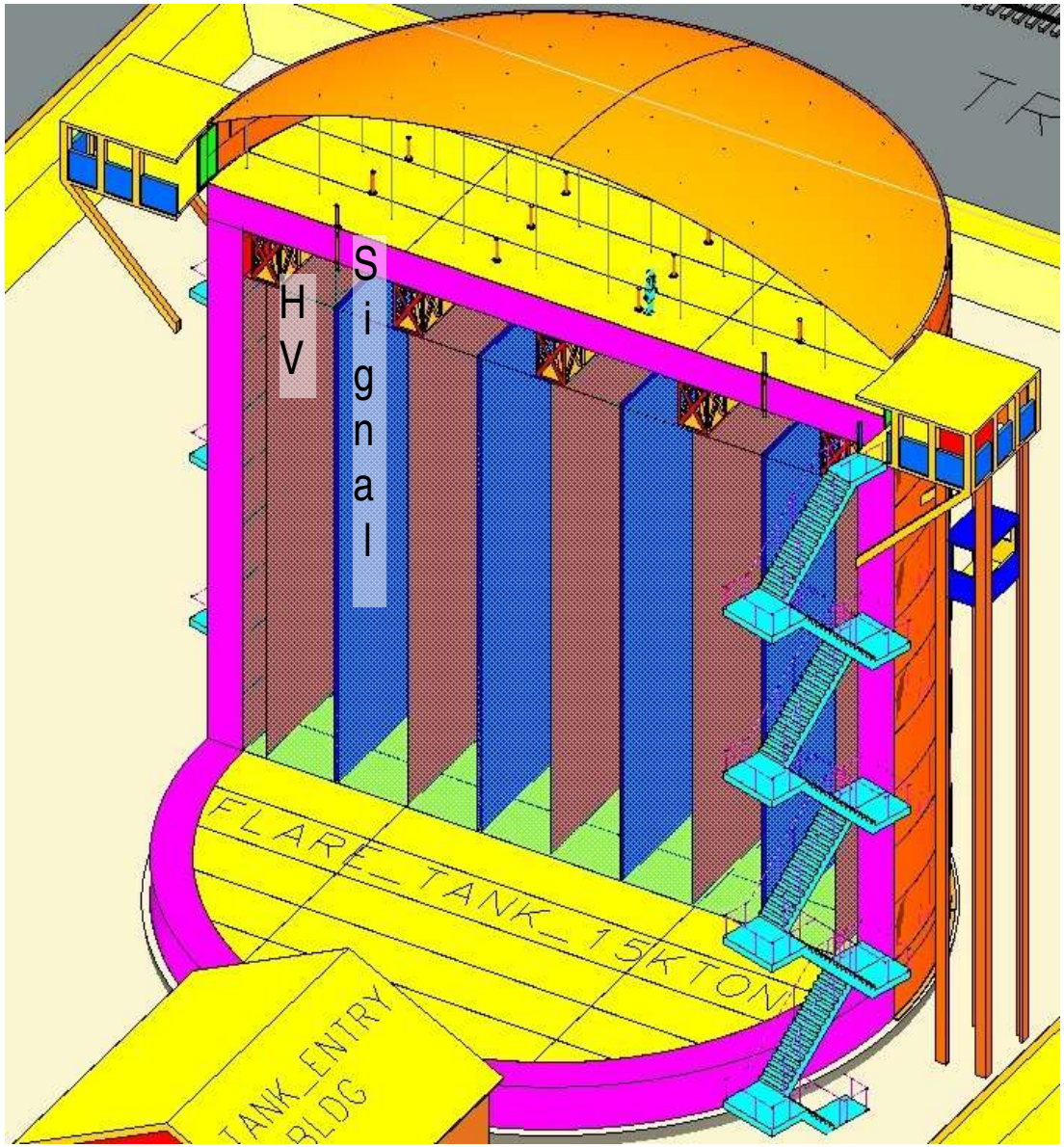


Many large LNG tanks in service

Excellent safety record

Last failure in 1940 understood

Engineering has begun on a large multi- kton Device



A 15 kton Device

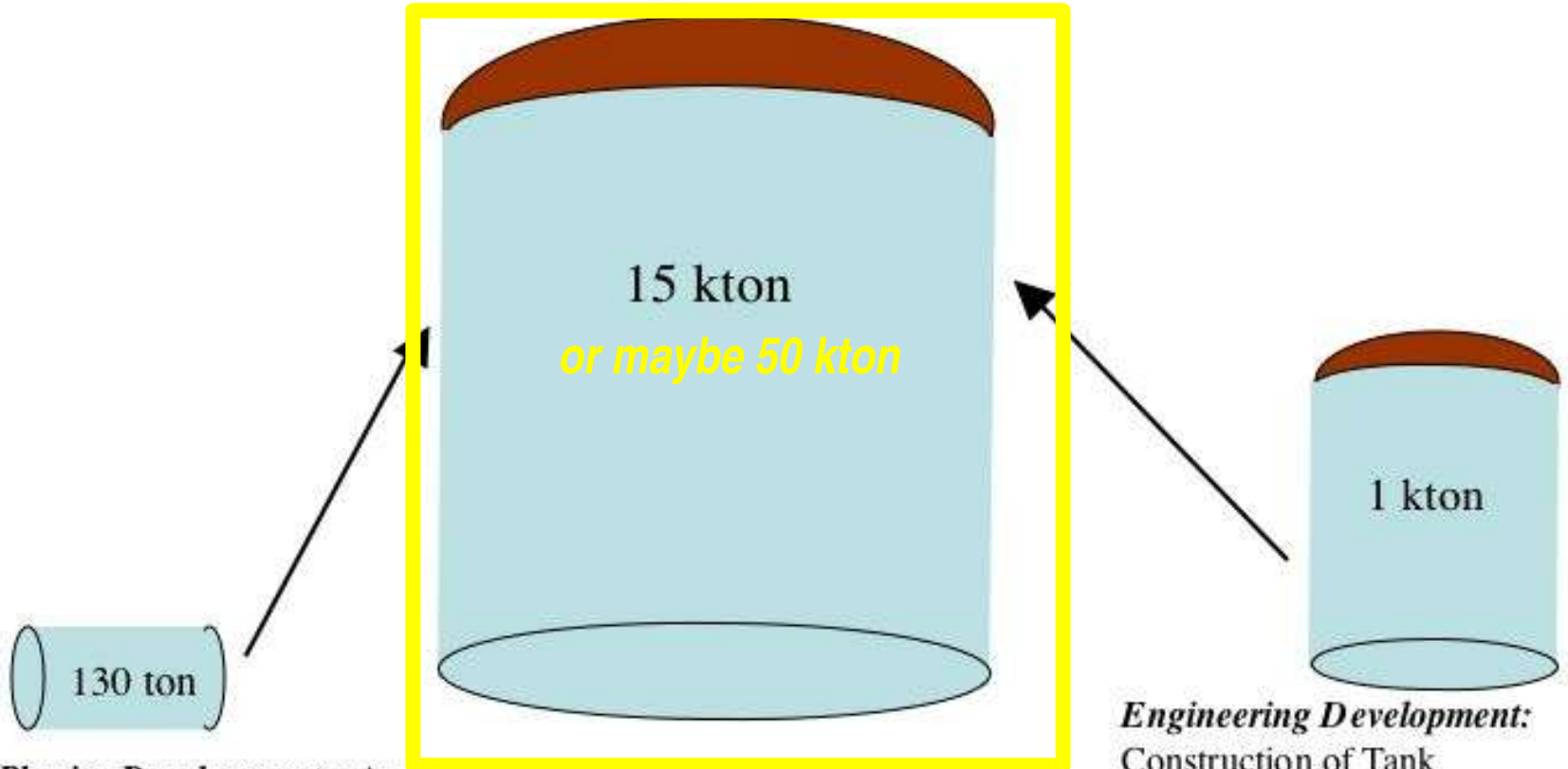
Inner tank dimensions:

26 m diameter by 21 m height

Changes from standard LNG tank:

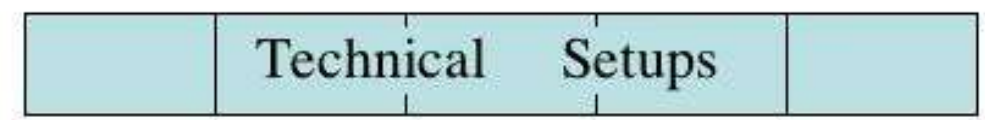
- *inner tank wall thickness increased*
  - *LAr is 2 x density of LNG;*
- *trusses in inner tank to take load of the wires;*
- *penetrations for signals from inner tank to floor supported from roof of outer tank.*

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



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

Conclusions

- Neutrino physics is at a very exciting stage. Measuring $P(\nu_\mu \rightarrow \nu_e)$ in several experiments with differing baselines is crucial in order to understand CP violation in the neutrino sector.
- 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. So 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. There is still lots of work to be done!

Backup slides

Neutral current event with 1 GeV π^0

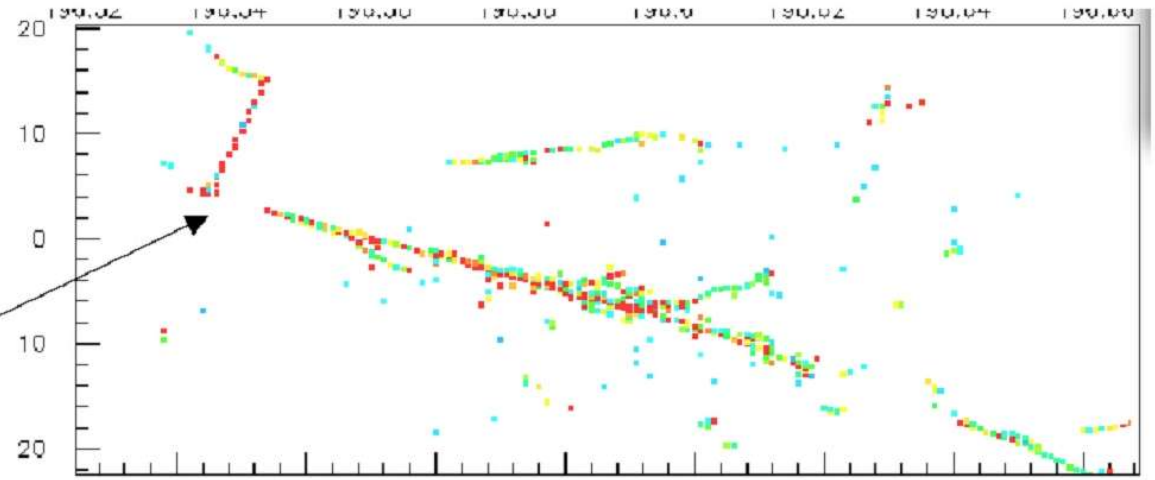
$$\nu_\mu + \mathrm{n} \rightarrow \nu_\mu + \pi^+ + \pi^- + \pi^0 + \mathrm{n}$$

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

3.5% X_0 samples

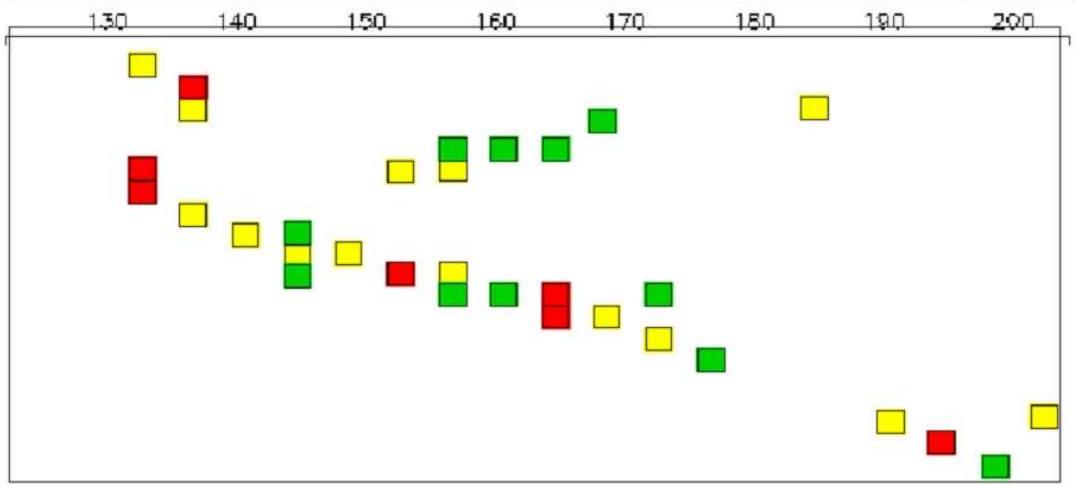
in all 3 views

4 cm gap



12% X_0 samples

alternating x-y

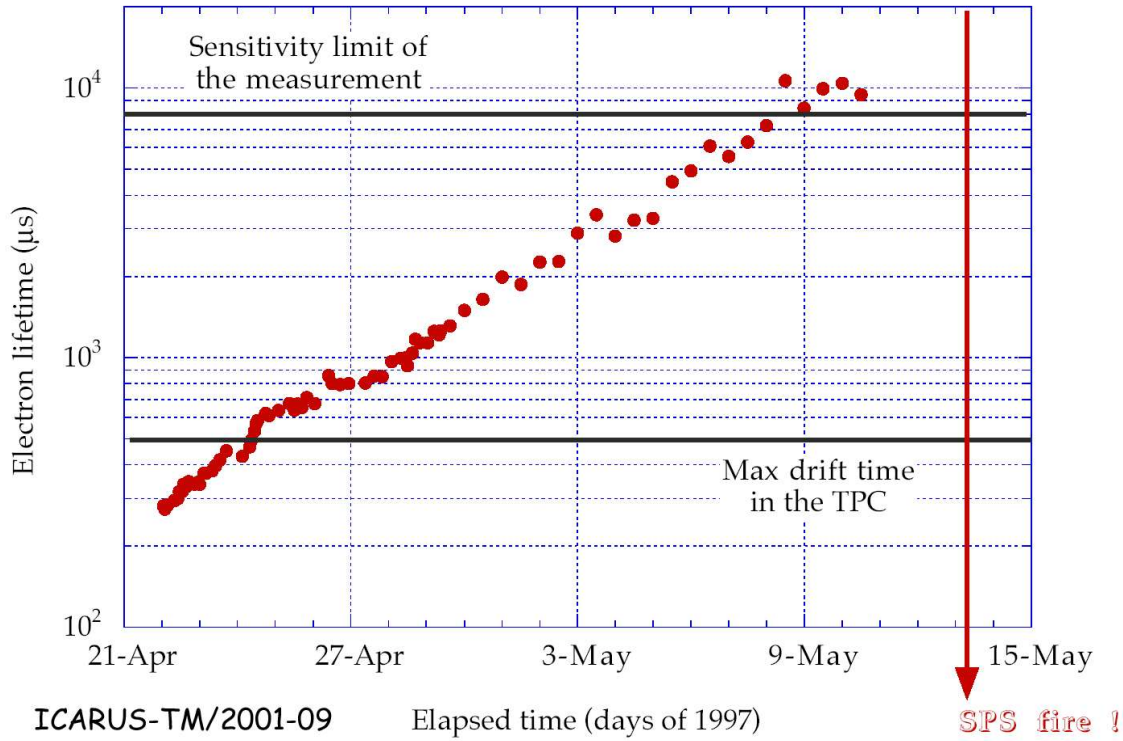


Argon Purity/Electron Lifetime in ICARUS

Impurities concentration is a balance of

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

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



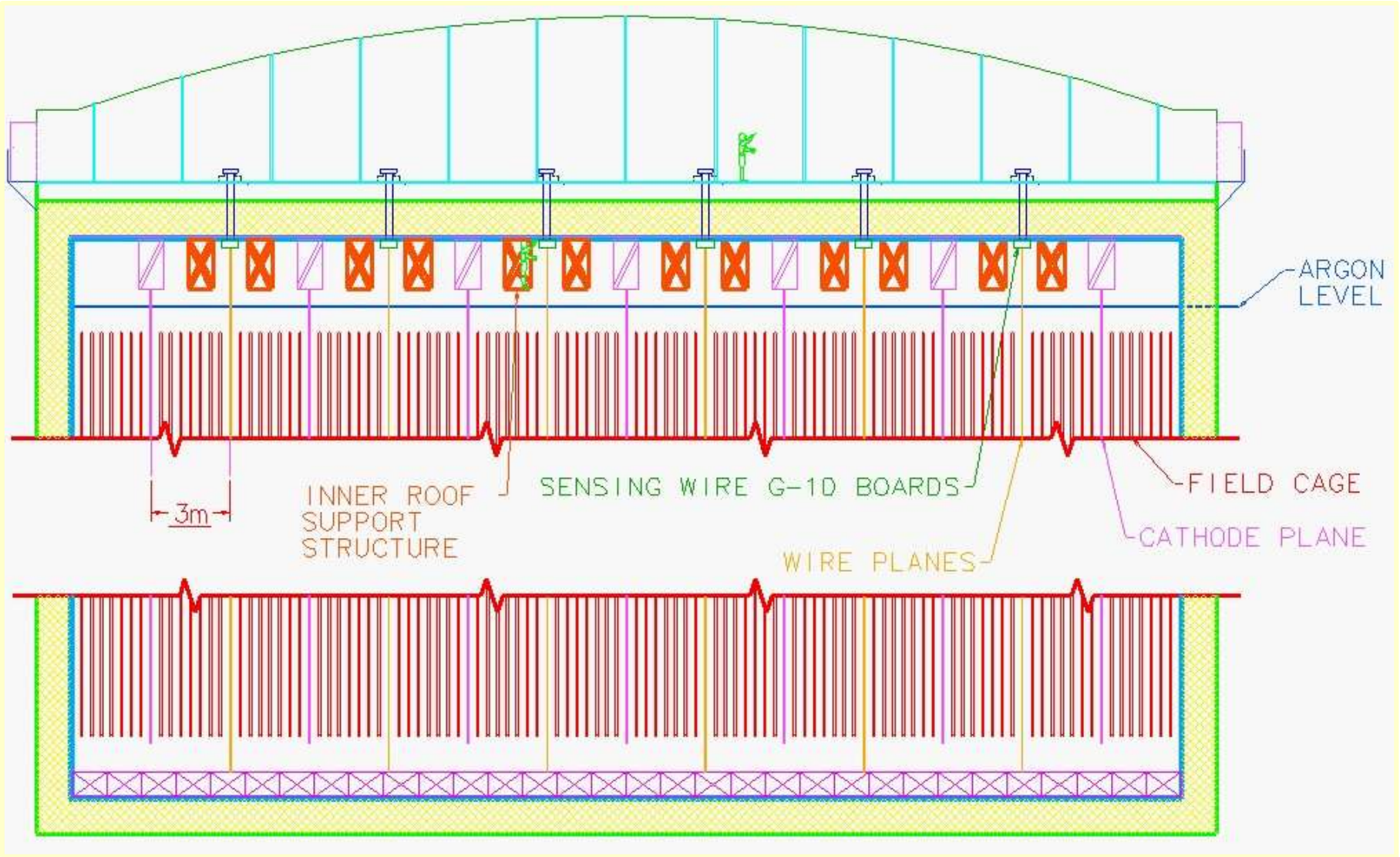
for the T600 module: achieved lifetime > 13 msec

for large LArTPCs : electron lifetime ~10ms is required

Argon Purity - Lessons for a Very Large Detector

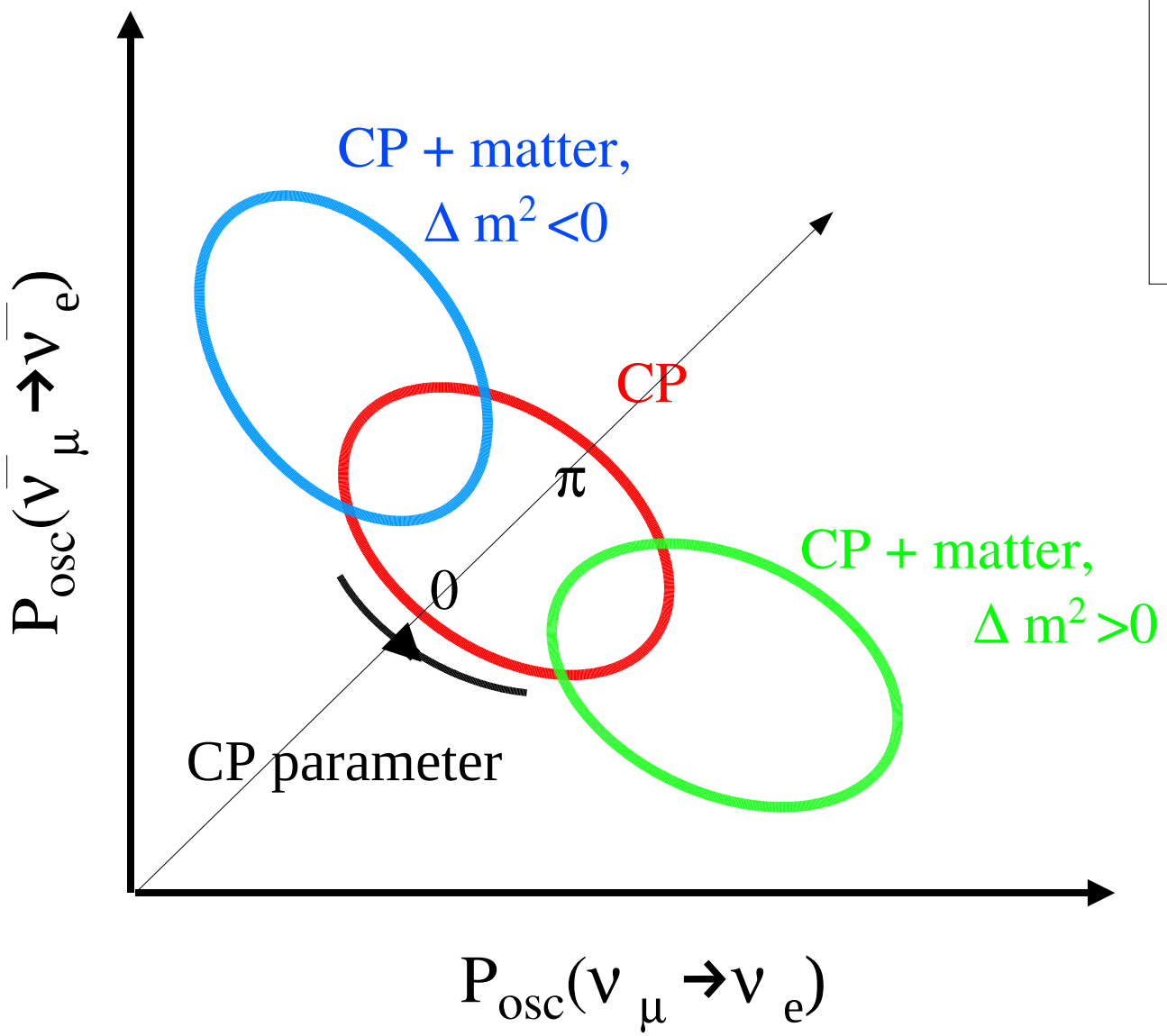
- Long electron lifetimes (~10ms)/drift distances (>3m) are achievable with commercial purification systems
- The main source of impurities are the surfaces exposed to the gaseous argon
- Increasing the ratio of liquid volume to the area of gaseous contact helps (dilution)
- Increasing the ratio of cold/warm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

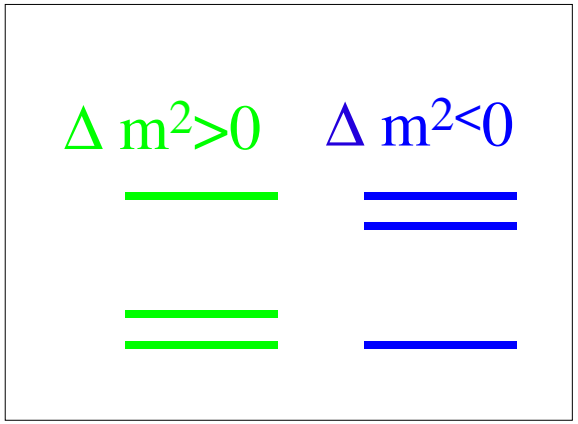
Engineering of Inside of Tank is Well Underway



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

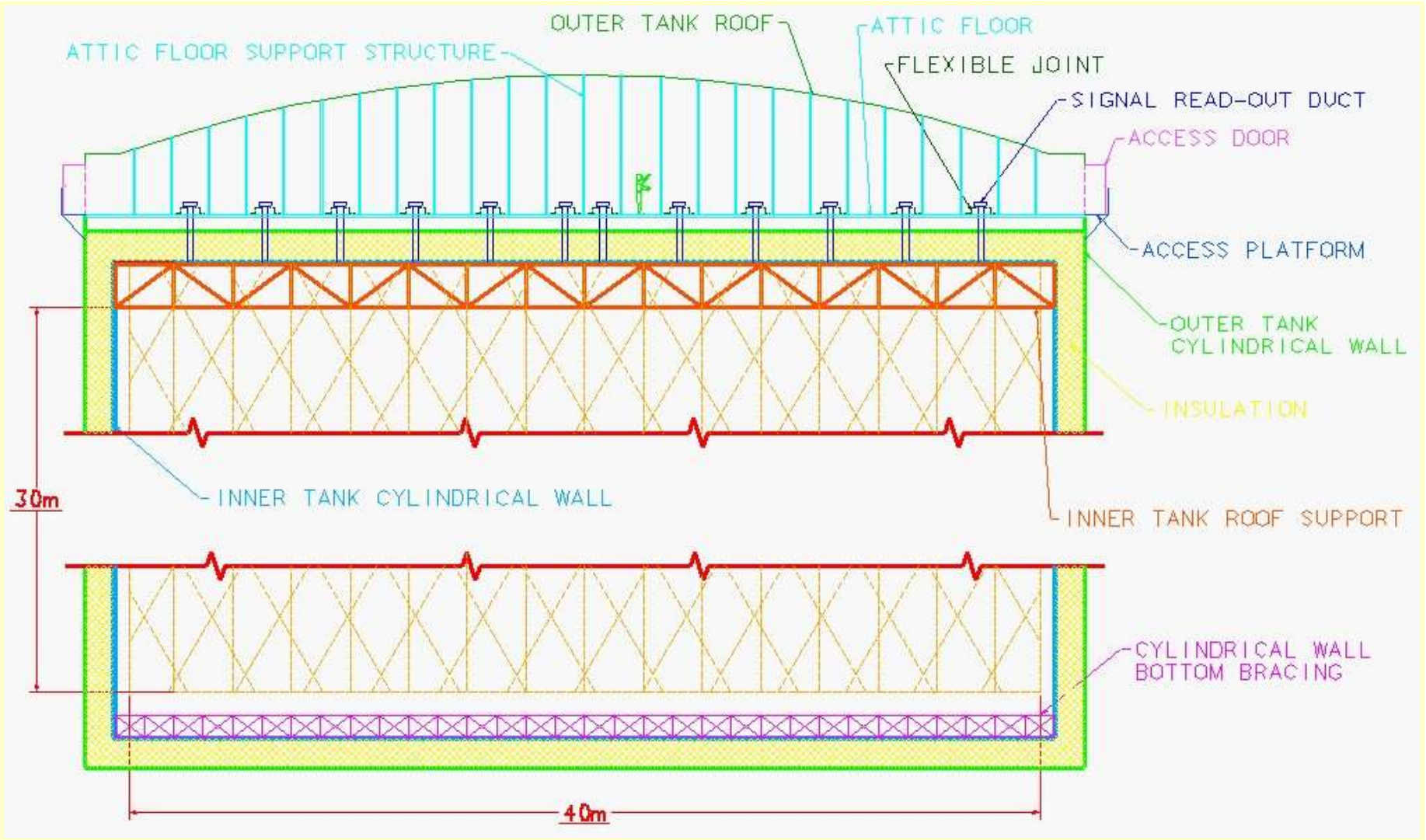
Capability will also depend on the mass hierarchy



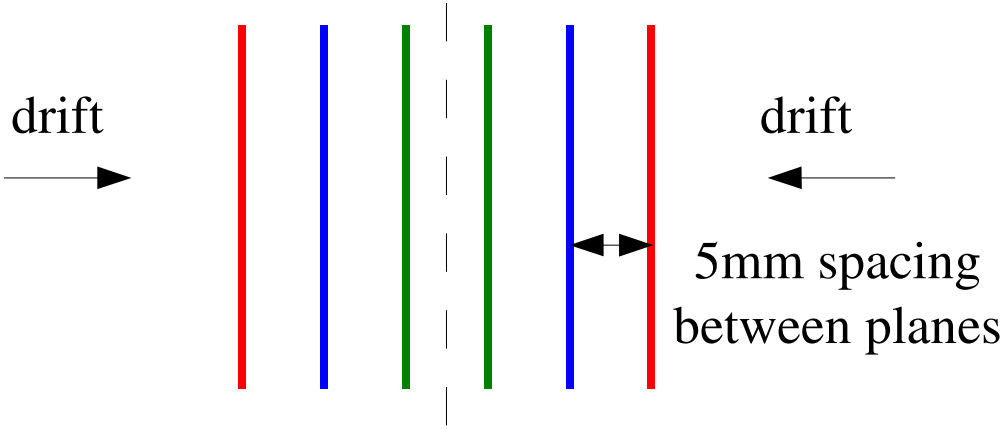


CP violation
+ matter effects

Front View

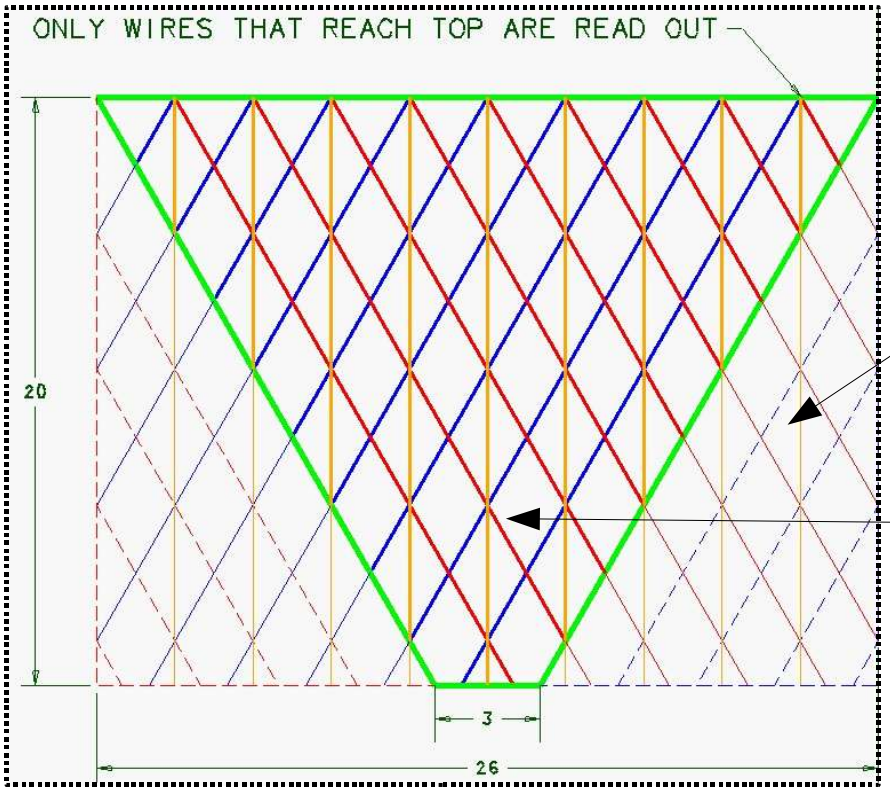

OUTER TANK ROOF
ATTIC FLOOR
ATTIC FLOOR SUPPORT STRUCTURE
FLEXIBLE JOINT
SIGNAL READ-OUT DUCT
ACCESS DOOR
ACCESS PLATFORM
OUTER TANK
CYLINDRICAL WALL
INSULATION
30m
INNER TANK CYLINDRICAL WALL
INNER TANK ROOF SUPPORT
CYLINDRICAL WALL
BOTTOM BRACING
40m

Each wire plane:



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

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



Wire planes
head on

2 wire readout

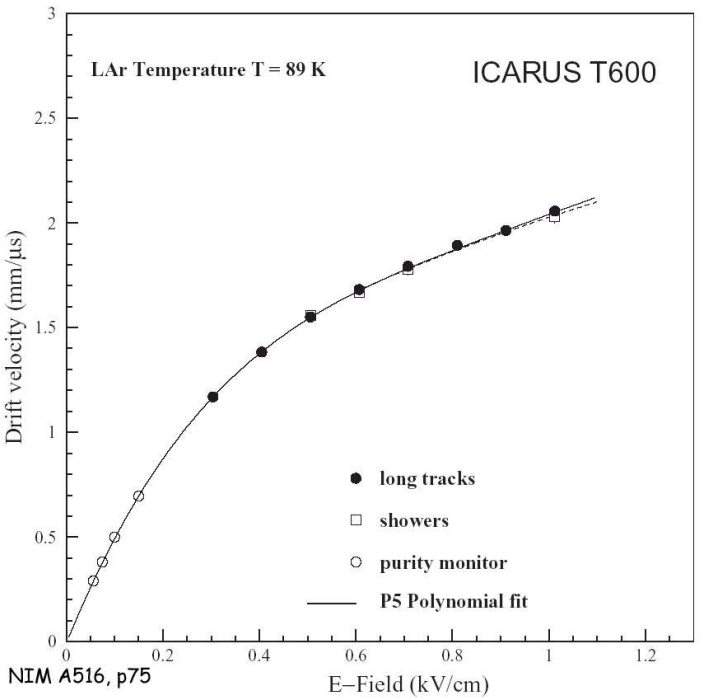
3 wire readout
(overconstrained)

Drifting electrons over long distance (3m)?

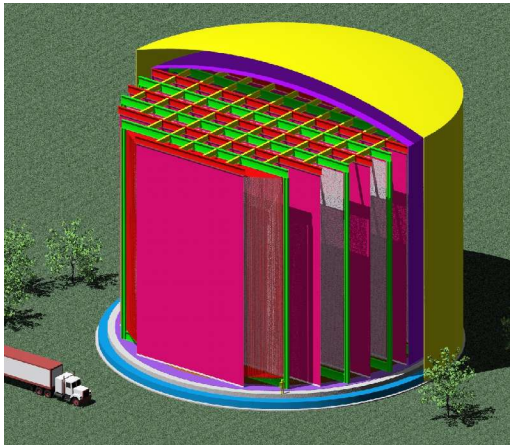
Signal size for passing track:
55,000 electrons/cm

How many are drifted to the edge of the detector?

- drift velocity,
  V_{drift}=1.55mm/ s
  for E=500 V/cm
- diffusion coefficient
- argon impurities
  - don't want 0_2 to 'eat' electrons along the way



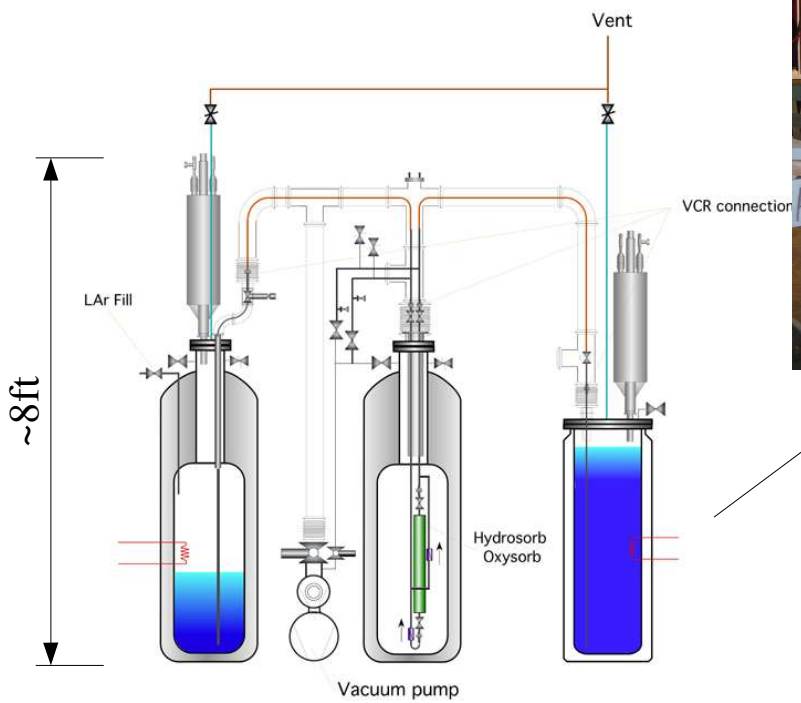
Great technology! ...What are the open questions in going to large scales? (15-50 kton?)



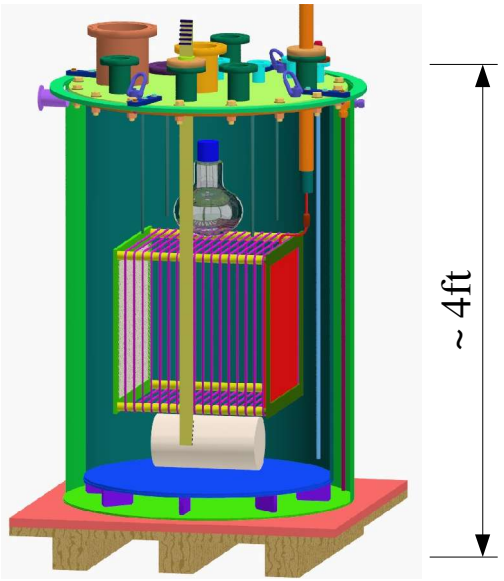
- Can purity be achieved and maintained in a large detector?
- Can very large wire chamber and cathode planes be assembled with high signal quality?
- Can cosmic backgrounds be rejected for a surface detector?

Prototyping and R&D efforts underway with path to demonstrating that answer to all these questions is yes!

R&D efforts underway



at FNAL



at Yale

at UCLA/ CERN