B.T.Fleming
Yale University
June 1st, 2005,NuSAG

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

Outline

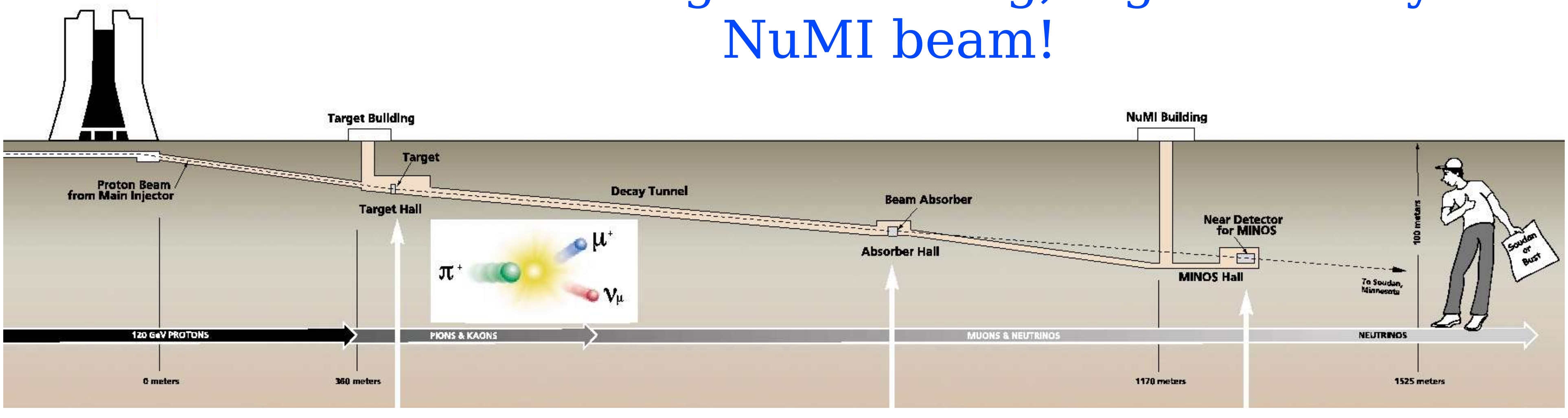
- Physics Potential
- Progress towards realization of a large liquid Argon time projection chamber (LArTPC)
- R&D program to meet these goals

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 ν_e event rate and background rejection

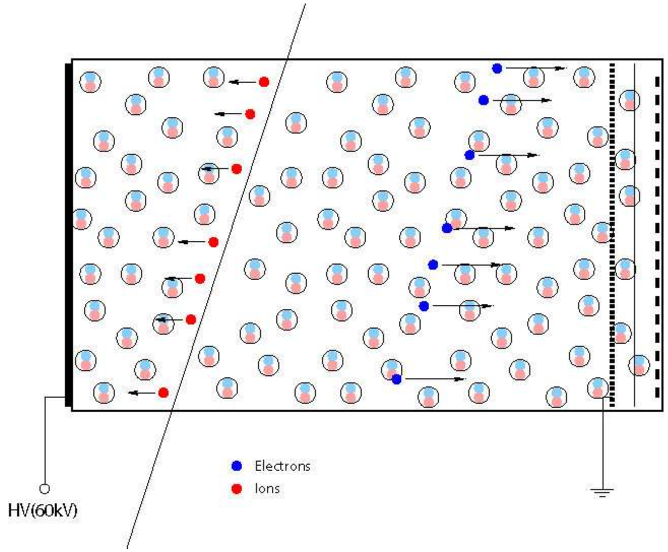
Massive LArTPCs provide excellent means to do this physics

- 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

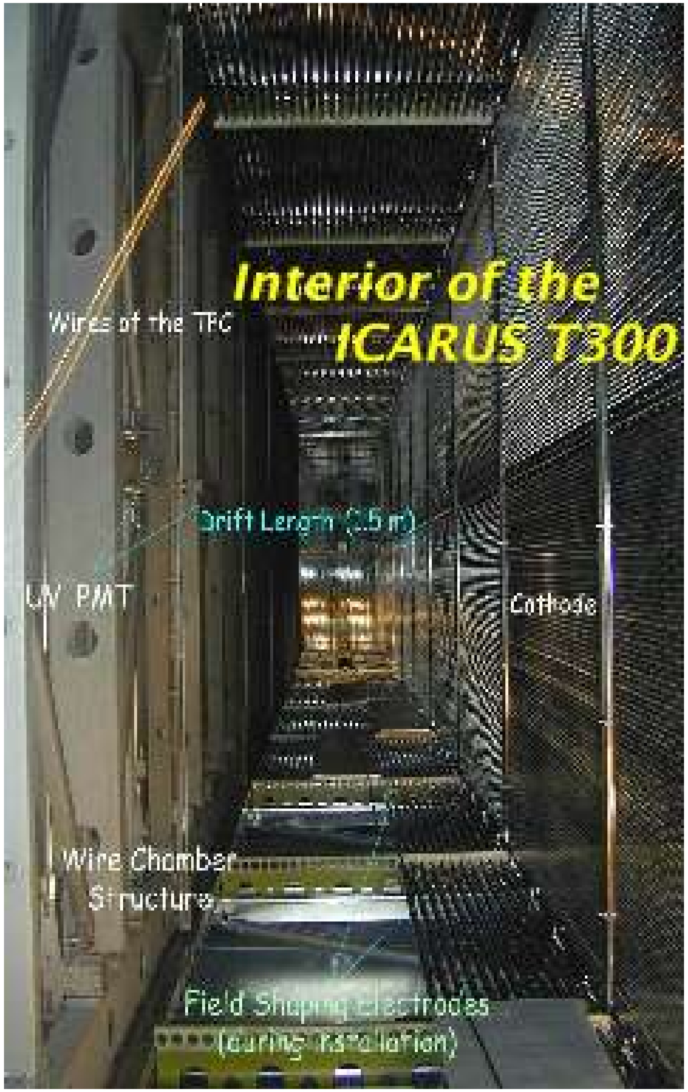
There is a growing effort at Fermilab and a group of universities worldwide to pursue this technology for this physics.

Liquid Argon TPCs:
Fine-grained tracking, total absorption calorimeter

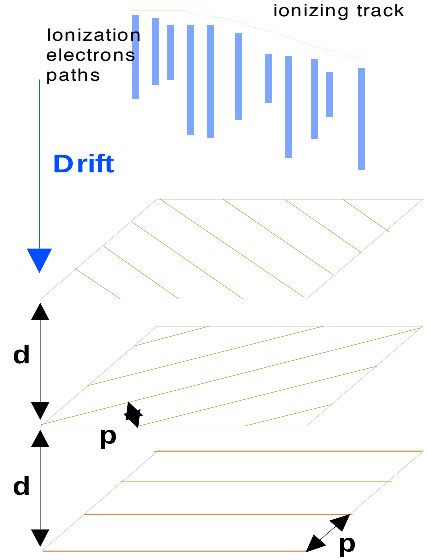
50,000 electrons/cm



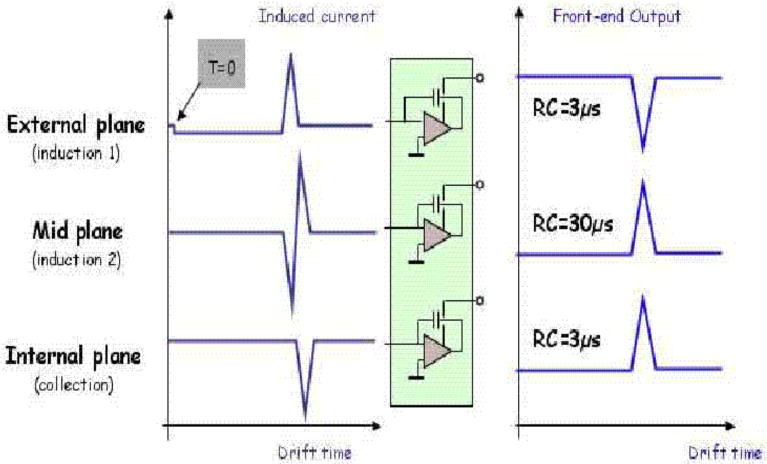
Drift ionization electrons over meters of pure liquid argon to collection planes to image track

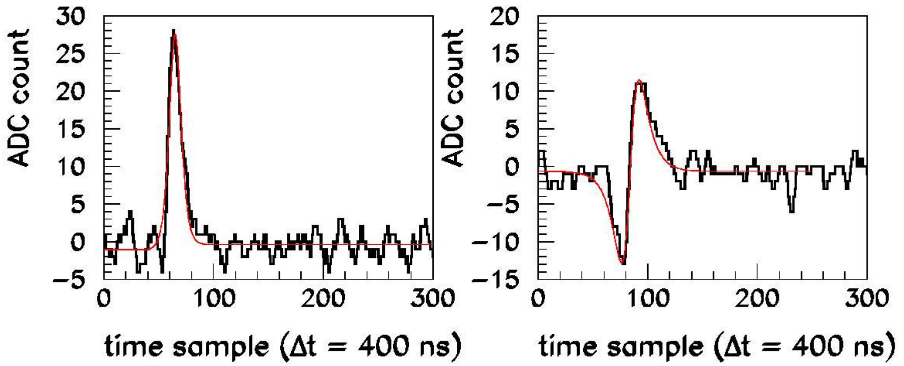


Signals on wire chamber planes



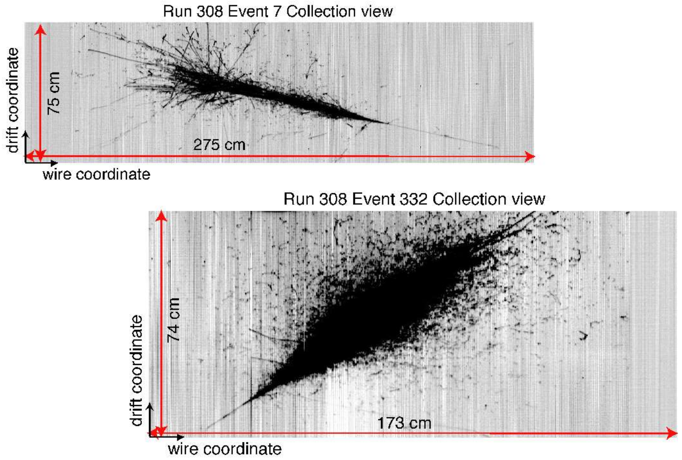
Arrange E fields and wire spacing for total transparency for induction planes. Final plane collects charge

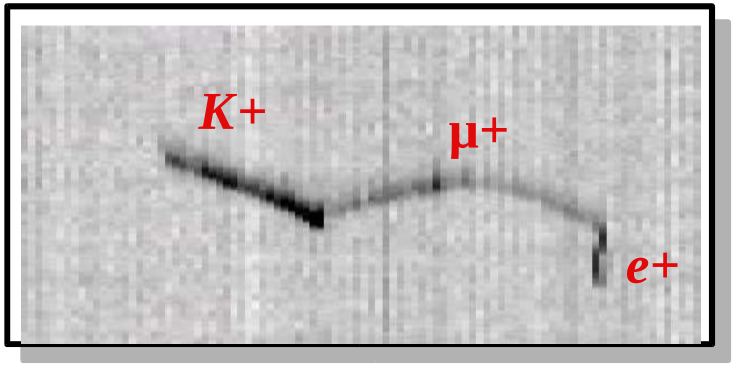




ICARUS TM/2001-09

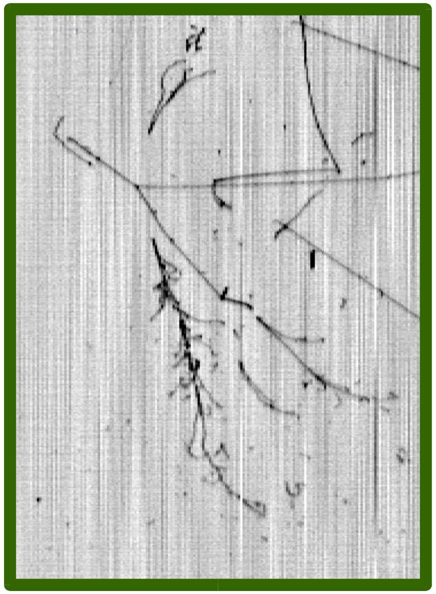
Allows for high resolution imaging like bubble chambers, but with calorimetry and continuous digital readout (no deadtime)

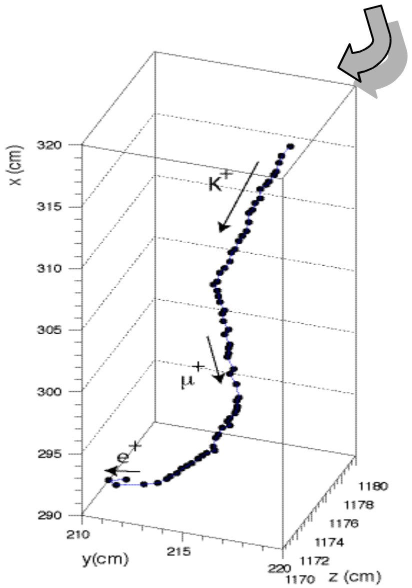




data

data





MC simulation

ICARUS images

How good are these detectors at identifying ν_e interactions

and

rejecting NC interactions?

LArTPCs

- Total absorption calorimeter
- 5mm sampling
  -> 28 samples/rad length
- energy resolution

→ ν_e efficiency
NC rejection

First pass studies using hit level MC show
~80 ± 7 % ν_e efficiency and
NC rejection factor ~70

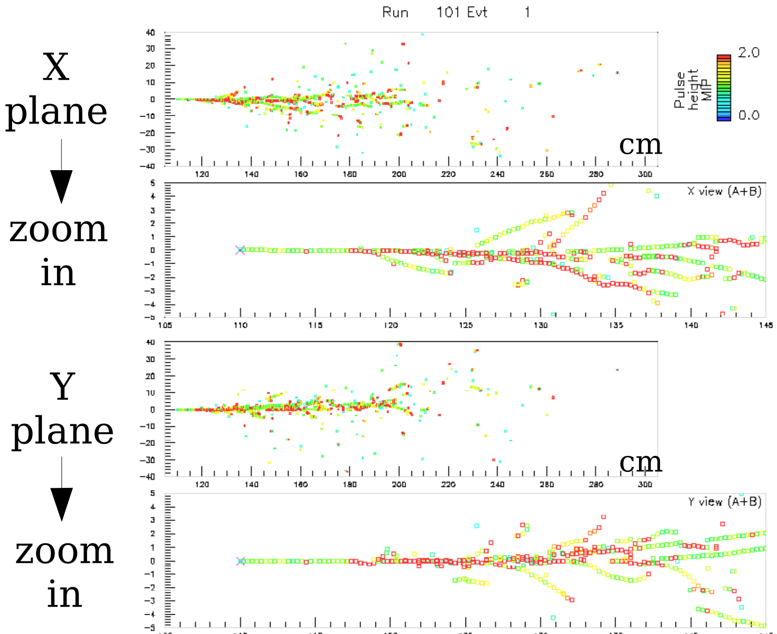
(only need rejection factor of 20 to knock background down to ½ the intrinsic ν_e rate)

Studies from groups working on T2K LAr indicate 85-95% ν_e efficiency

in documents submitted to NuSAG

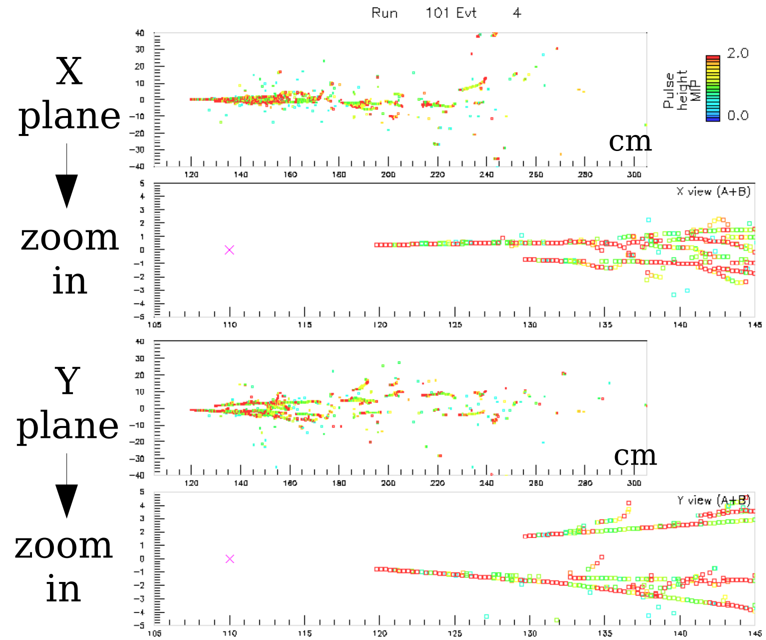
Electrons versus π^0's at 1.5 GeV

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



Electrons

Single track (mip scale) starting from a single vertex



π^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

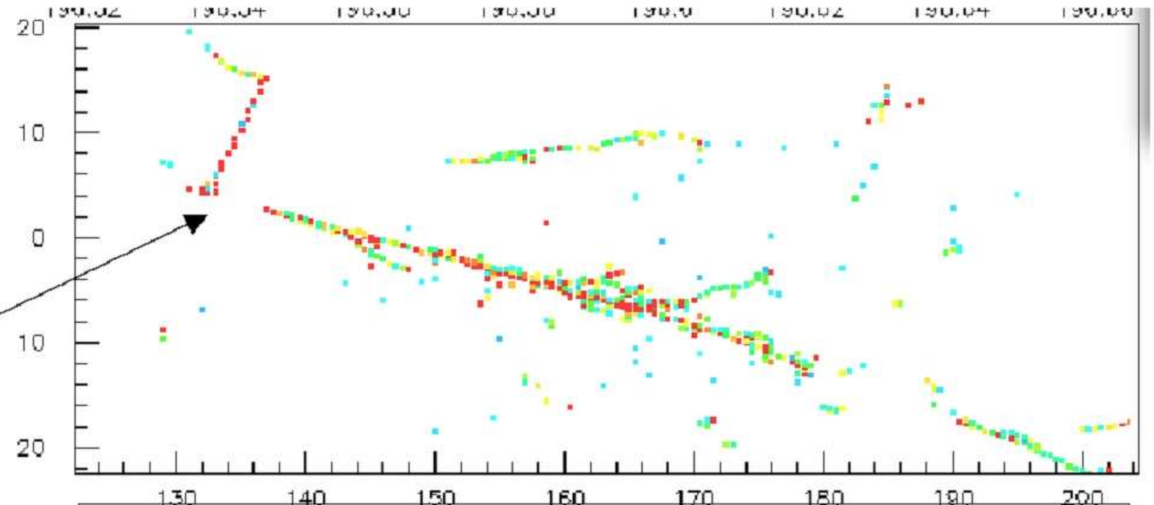
Neutral current event with 1 GeV π^0

$$\nu_\mu + \mathrm{n} \rightarrow \nu_\mu + \pi^+ + \pi^- + \pi^0 + \mathrm{n}$$
$$(1\ \mathrm{GeV})\ \pi^0 \rightarrow \gamma + \gamma$$

3.5% X_0 samples

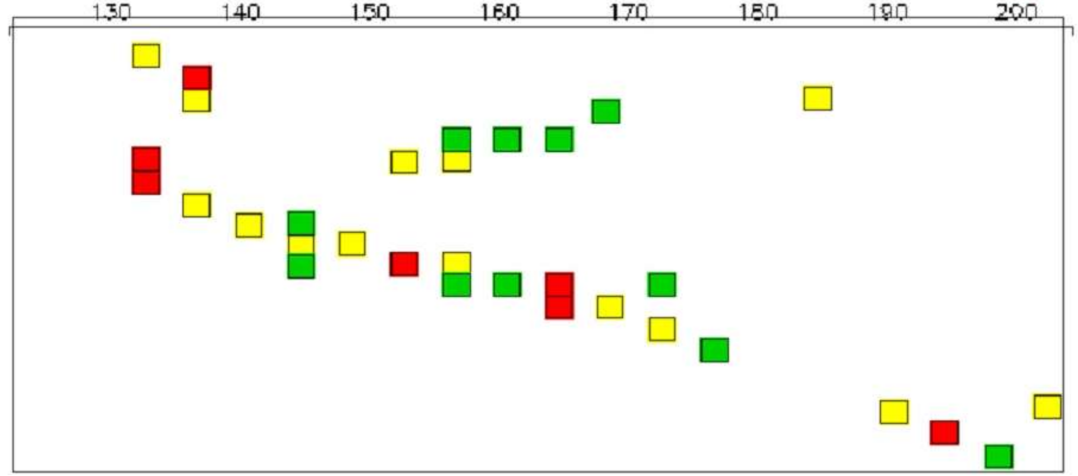
in all 3 views

4 cm gap



12% X_0 samples

alternating x-y



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.

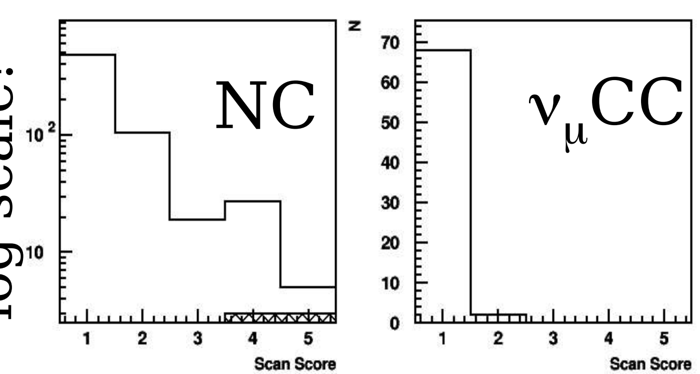
- Neutrino event generator: NEUGEN3. Used by MINOS/NOvA collaboration. Hugh Gallagher (Tufts) is the principal author.
- GEANT 3 detector simulation: trace resulting particles through a homogeneous volume of liquid argon. Store energy deposits in thin slices.

Training samples:

50 events each of ν_eCC, ν_μCC and NC

- individual samples to train
- mixed samples to test training

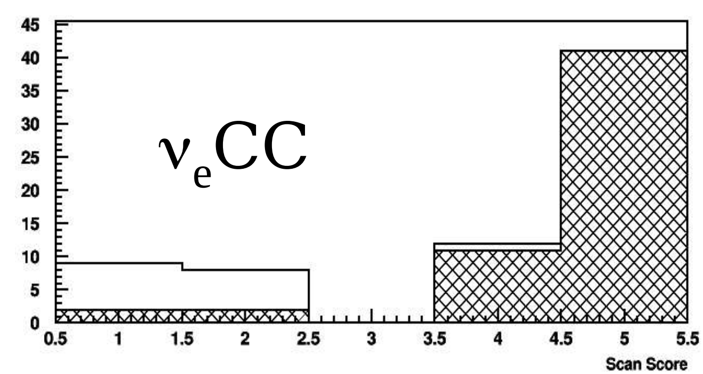
log scale!



Blind scan of 450 events scored from 1-5 with

- signal=5
- background=1

plain region: students
Hatched region: experts

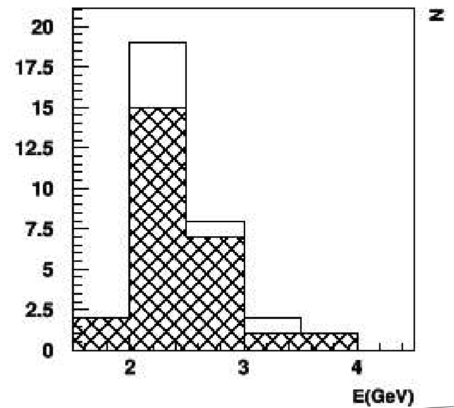


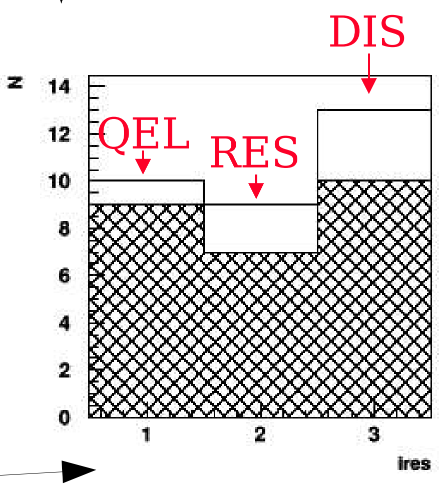
Tufts University Group

Overall efficiencies, rejection factors, and dependencies

	N	pass	ε	η
NC	290	4	-	72.5
signal ν_e	32	26	0.81	-
Beam ν_e: CC	24	14	0.58	-
NC	8	0	-	

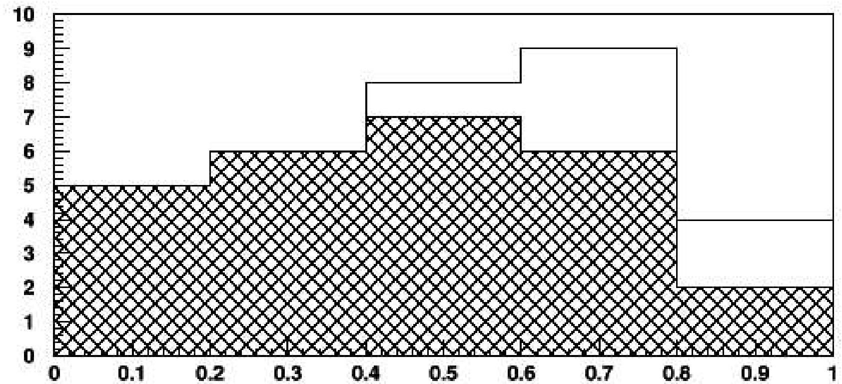
Signal ν_e:





Efficiency is substantial even for high multiplicity events

Efficiency is ~100% for $y<0.5$, and ~50% above this



$y=E_{had}/E_{\nu}$

Given very high ν_e efficiency and NC background rejection well below ½ of the intrinsic ν_e beam backgrounds, how sensitive are these detectors?

↓

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

Capability depends on δ and θ_{13}

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

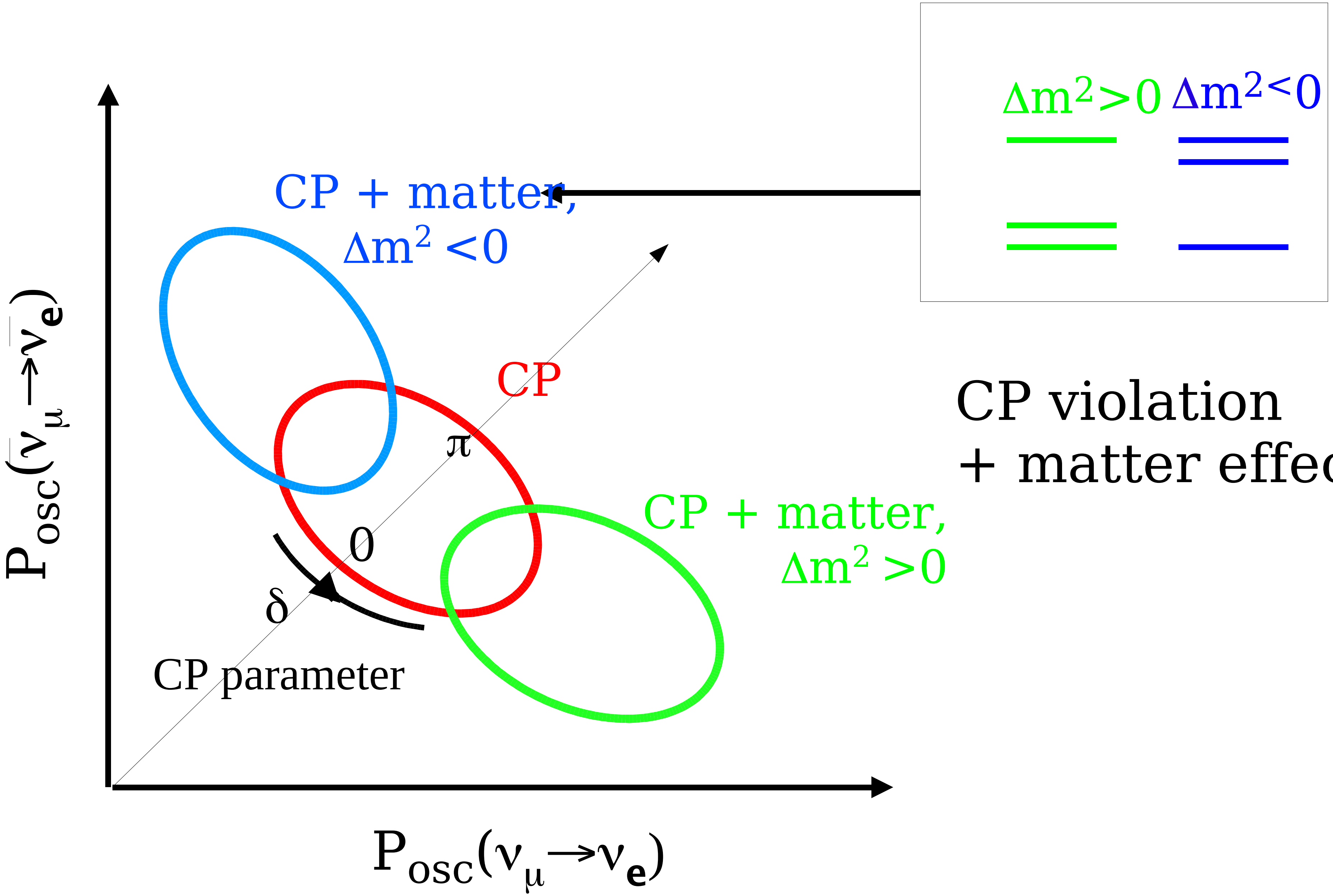
From Reactor Disappearance Measurements

From Long Baseline Appearance Measurements

From Solar Neutrino Measurements

Chooz limit is
$\sin^2 2\theta_{13} \sim 0.1$

Capability will also depend on the mass hierarchy



CP violation
+ matter effects

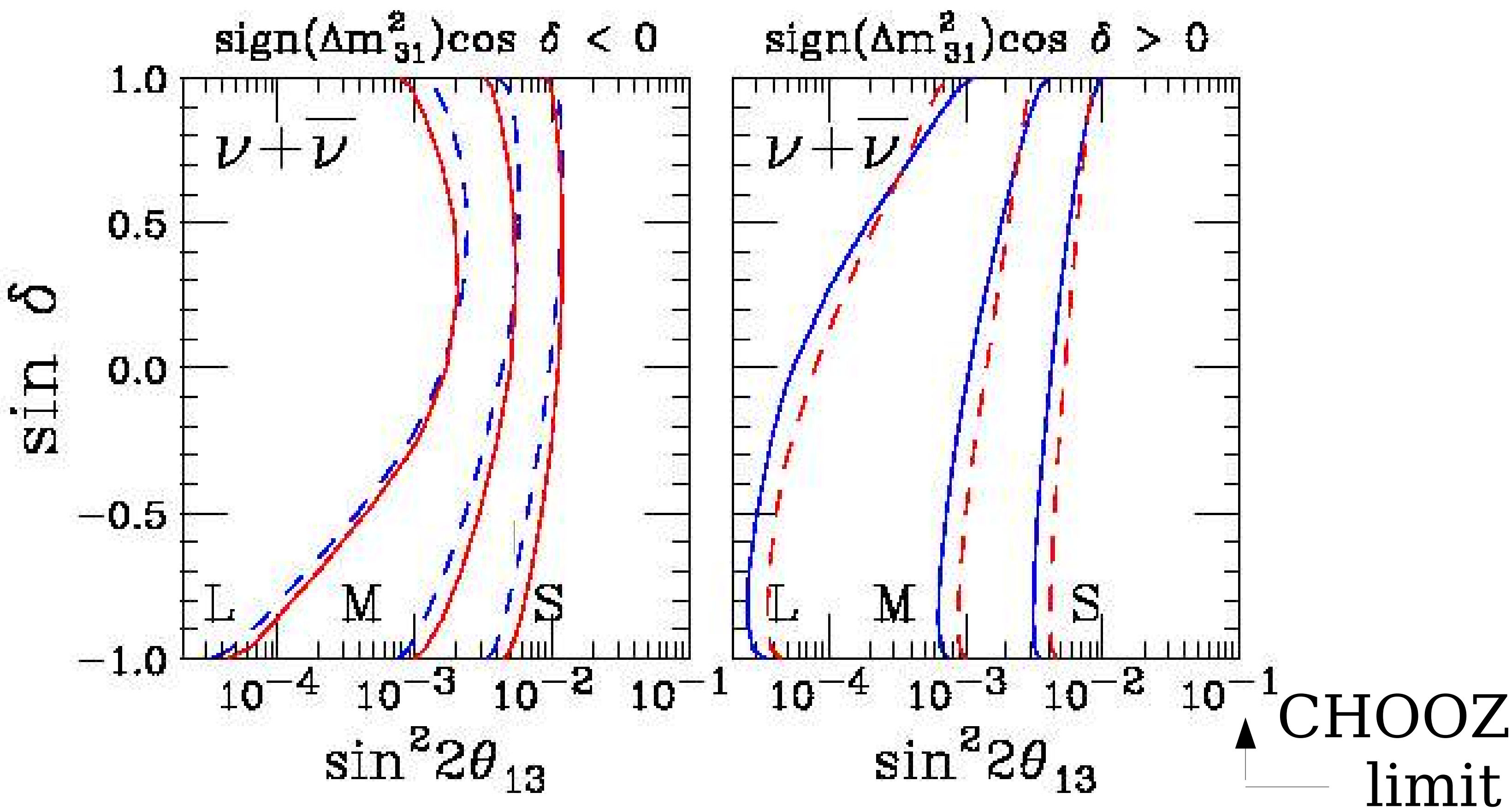
As an example: focus on recent paper by Mena and Parke

hep-ph/0505202

	Small	Medium	Large
NOvA	30kTon	30kton + PD or x5 det. mass	30kton + PD + x5 det. mass
LArTPC (90% ν_e eff.)	8kton	40kton	40kton + PD

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 δ <0, normal hiearchy

cos δ >0, inverted hiearchy

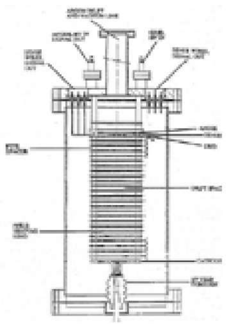
least restrictive:

cos δ >0, normal hiearchy

cos δ <0, inverted hiearchy

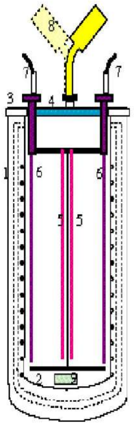
Can we build these detectors?

Technical Feasibility:
History of prototype work on ICARUS



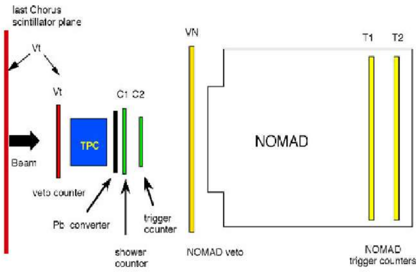
24 cm drift wires chamber

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.



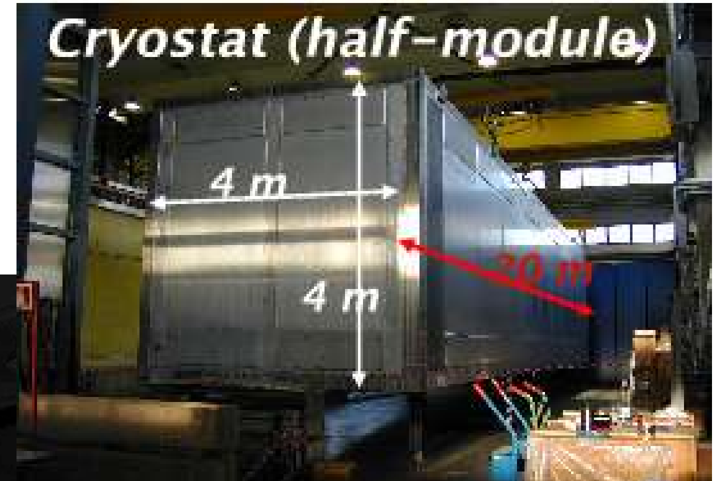
50 litres prototype 1.4 m drift chamber

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

10 m^3 industrial prototype

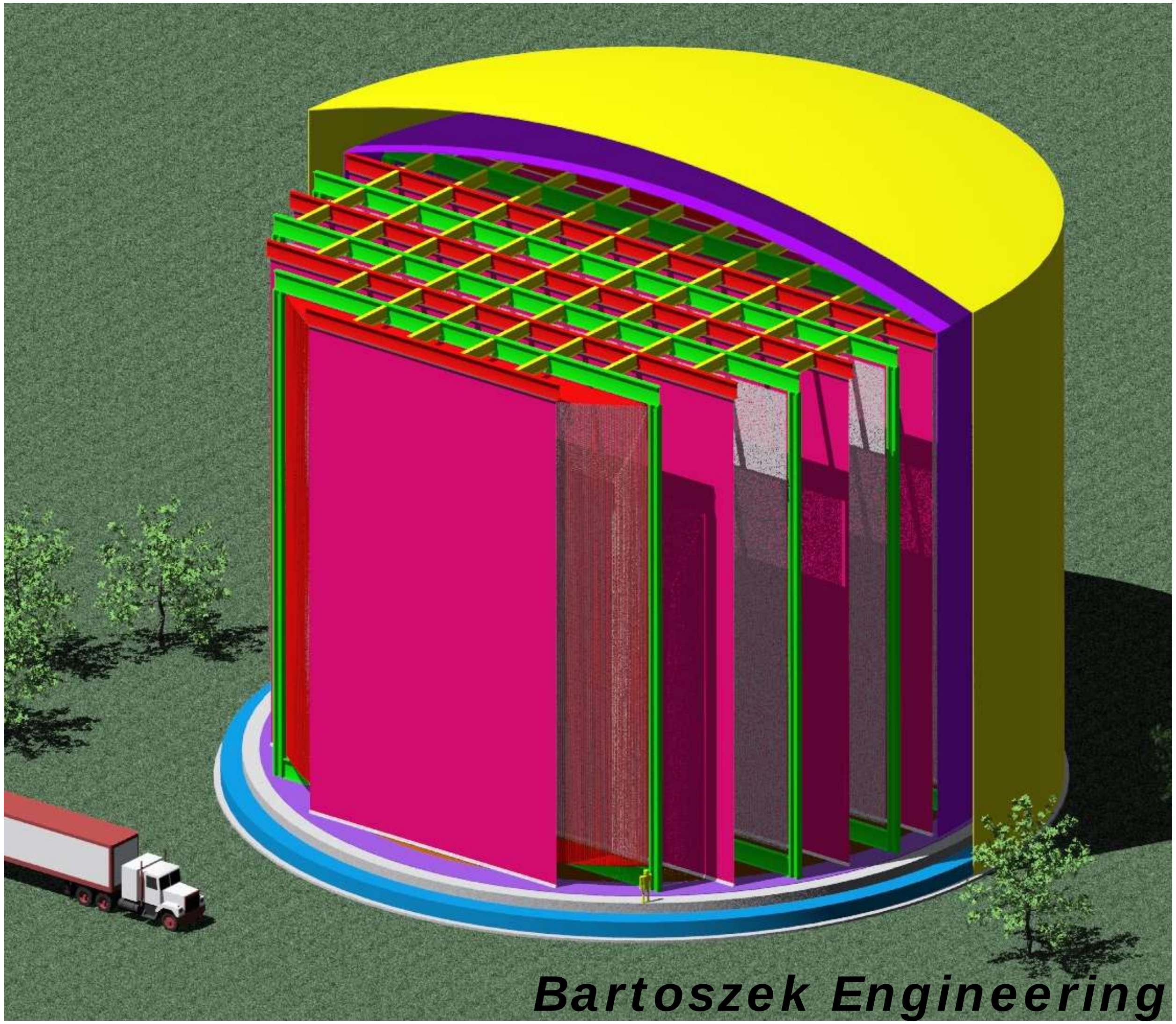
1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

The success of the ICARUS T600

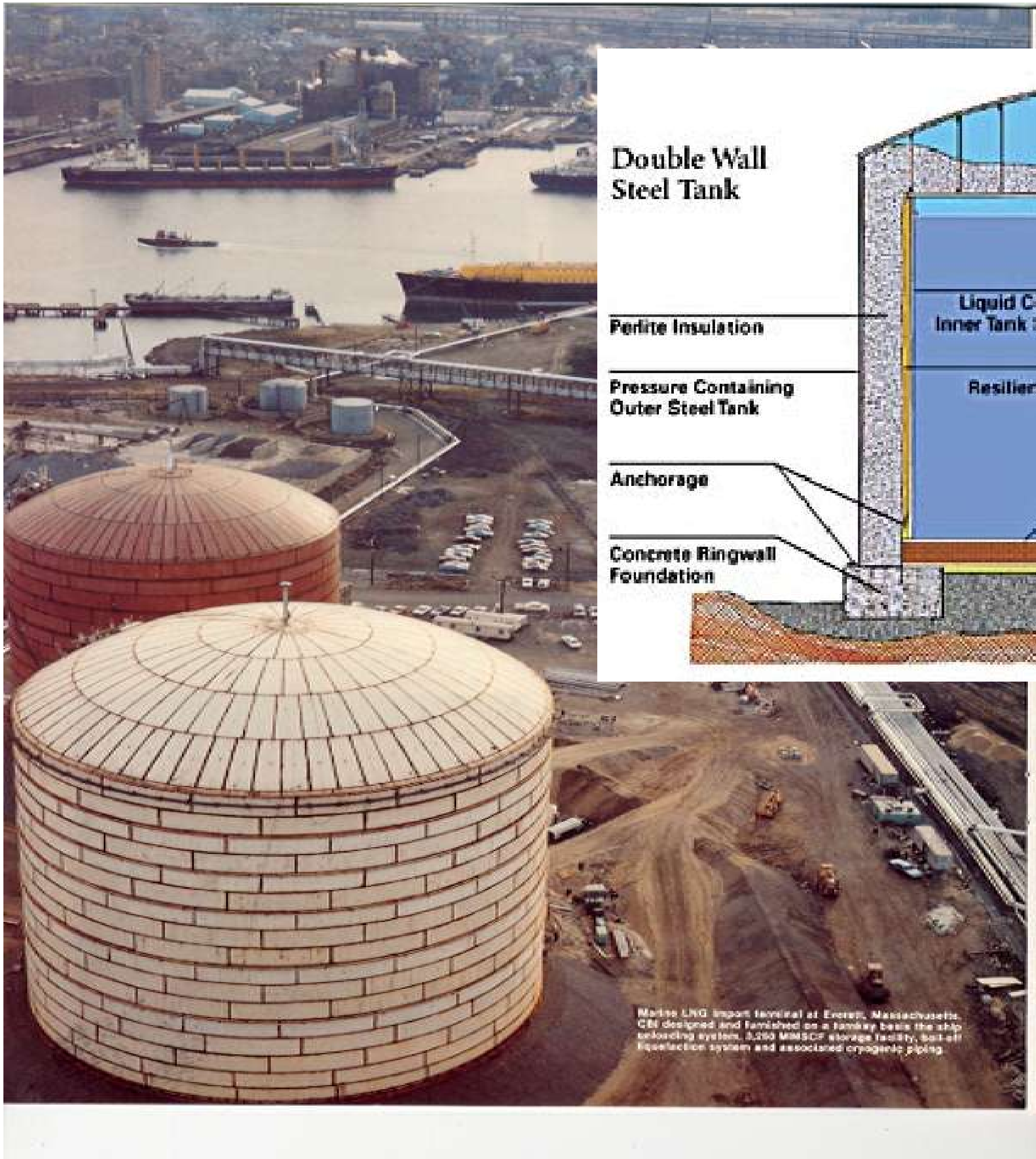


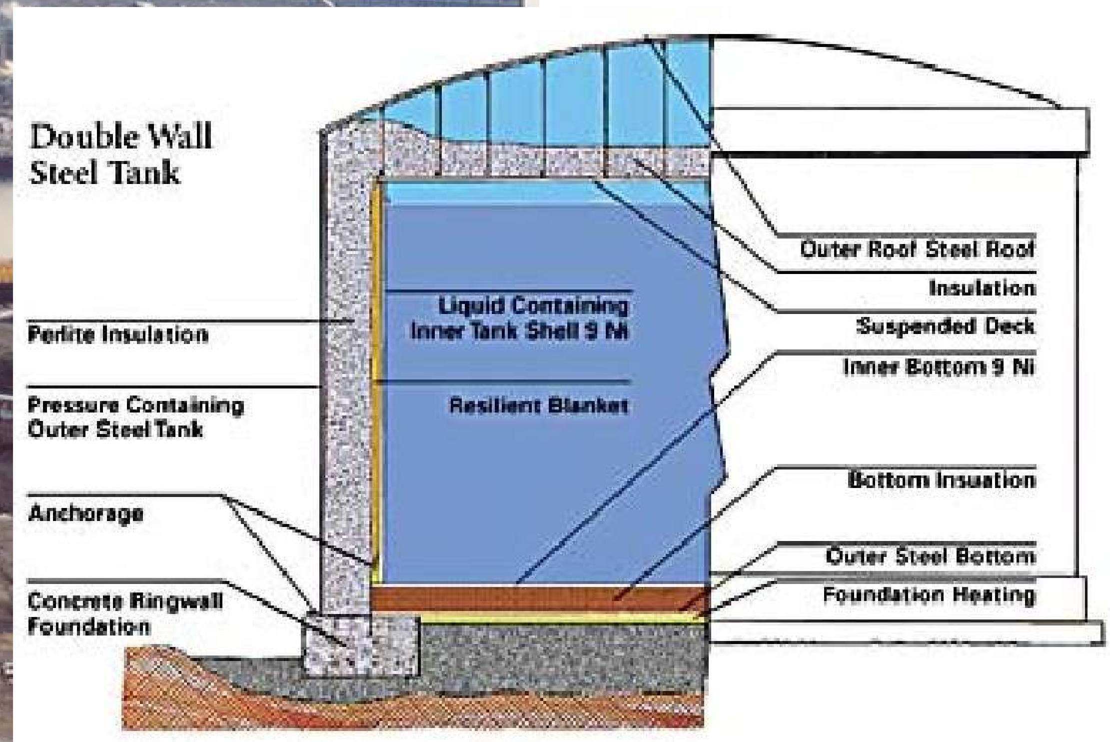
tested above ground in Pavia in 2001
now below ground in Gran Sasso

Baseline concept:
15-50kTon vessel which builds on ICARUS wire plane readout



50 kTon design



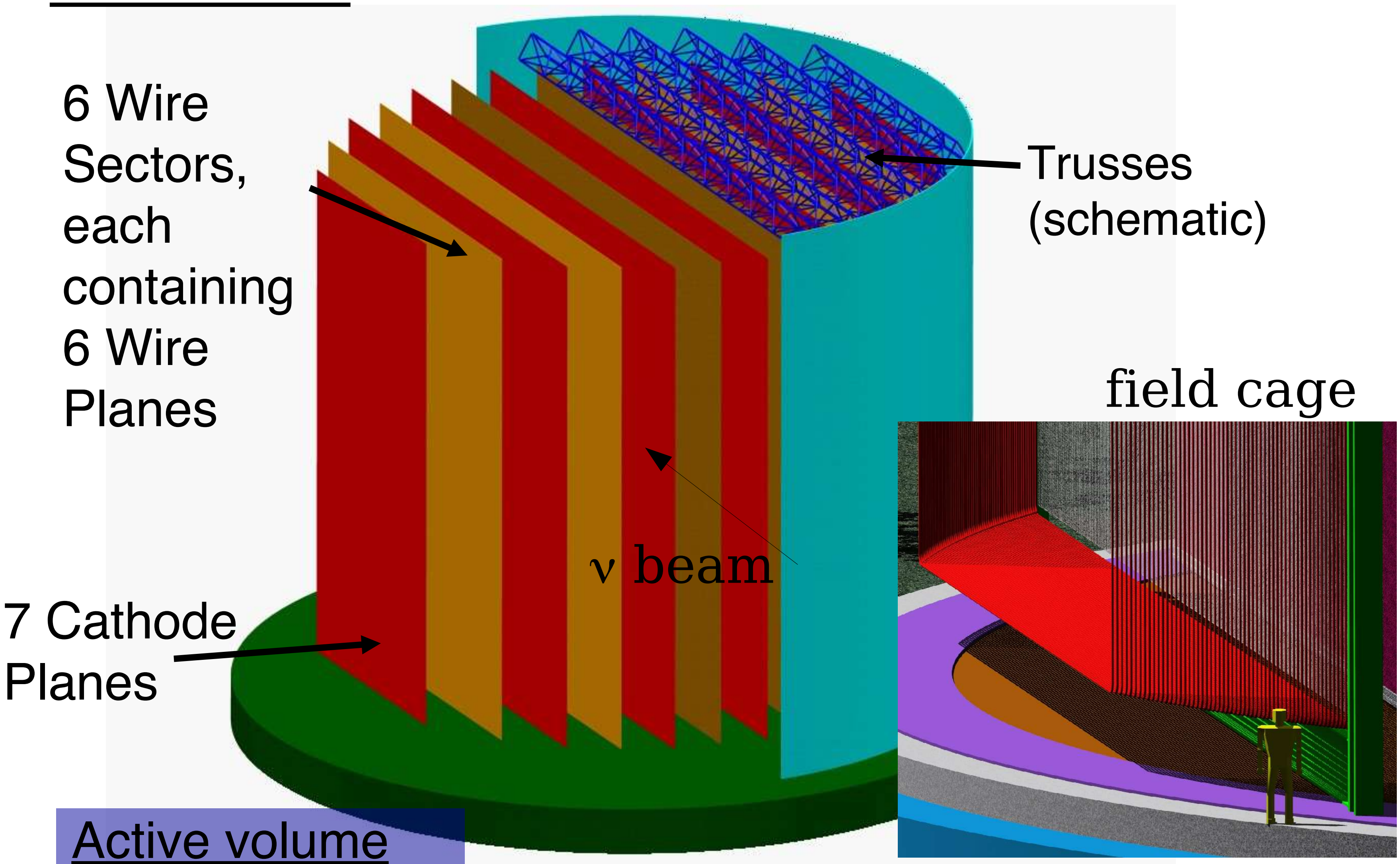


Many large LNG tanks in service

Excellent safety record

Last failure in 1940 understood

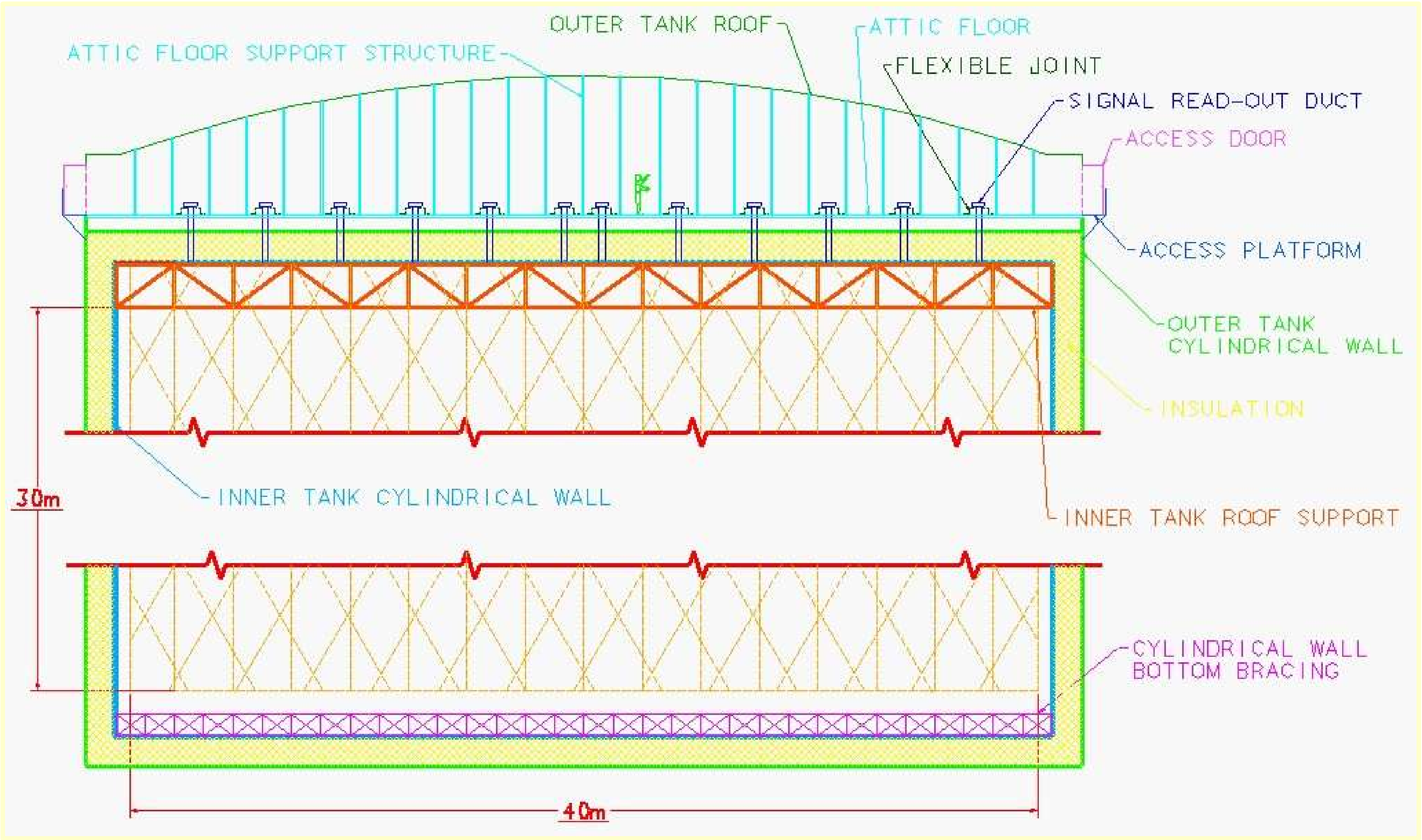
Overview



Active volume
Diameter: 40m
Height: 30m

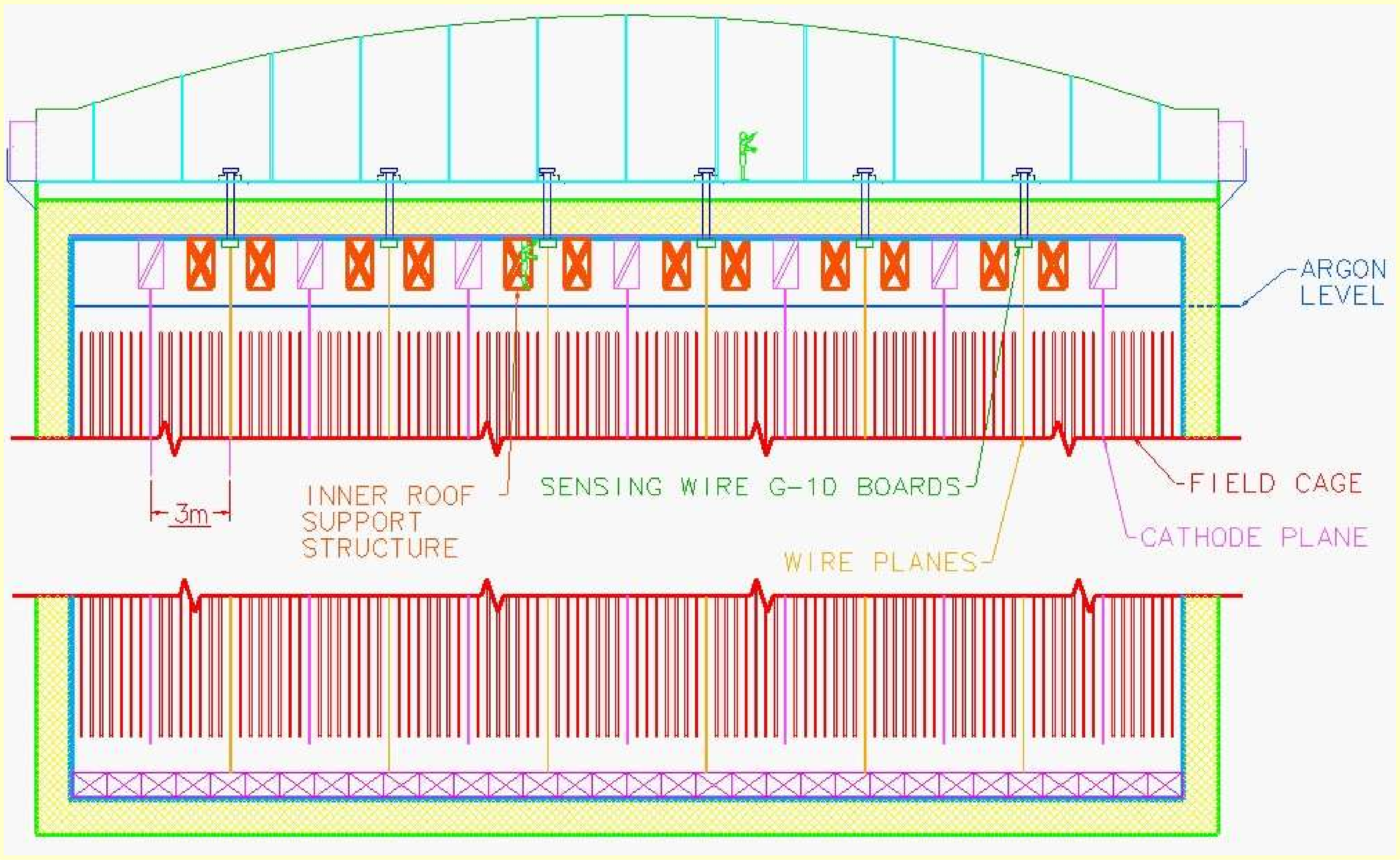
Scalable → 15-50 kTons
4 - 6 wire planes

Front View

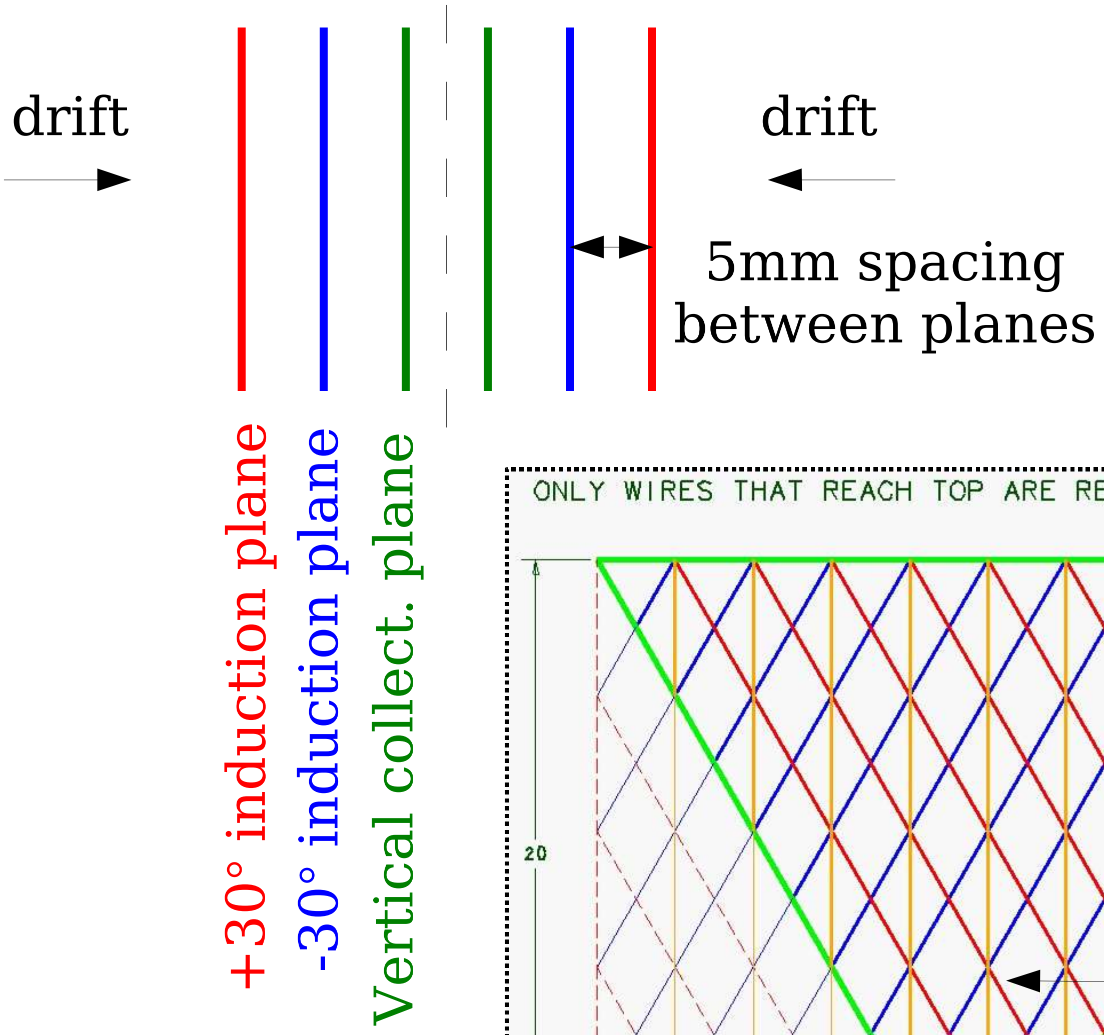


OUTER TANK ROOF
ATTIC FLOOR
ATTIC FLOOR SUPPORT STRUCTURE
FLEXIBLE JOINT
SIGNAL READ-OUT DUCT
ACCESS DOOR
ACCESS PLATFORM
OUTER TANK
CYLINDRICAL WALL
INSULATION
INNER TANK CYLINDRICAL WALL
INNER TANK ROOF SUPPORT
30m
CYLINDRICAL WALL
BOTTOM BRACING
40m

Side View

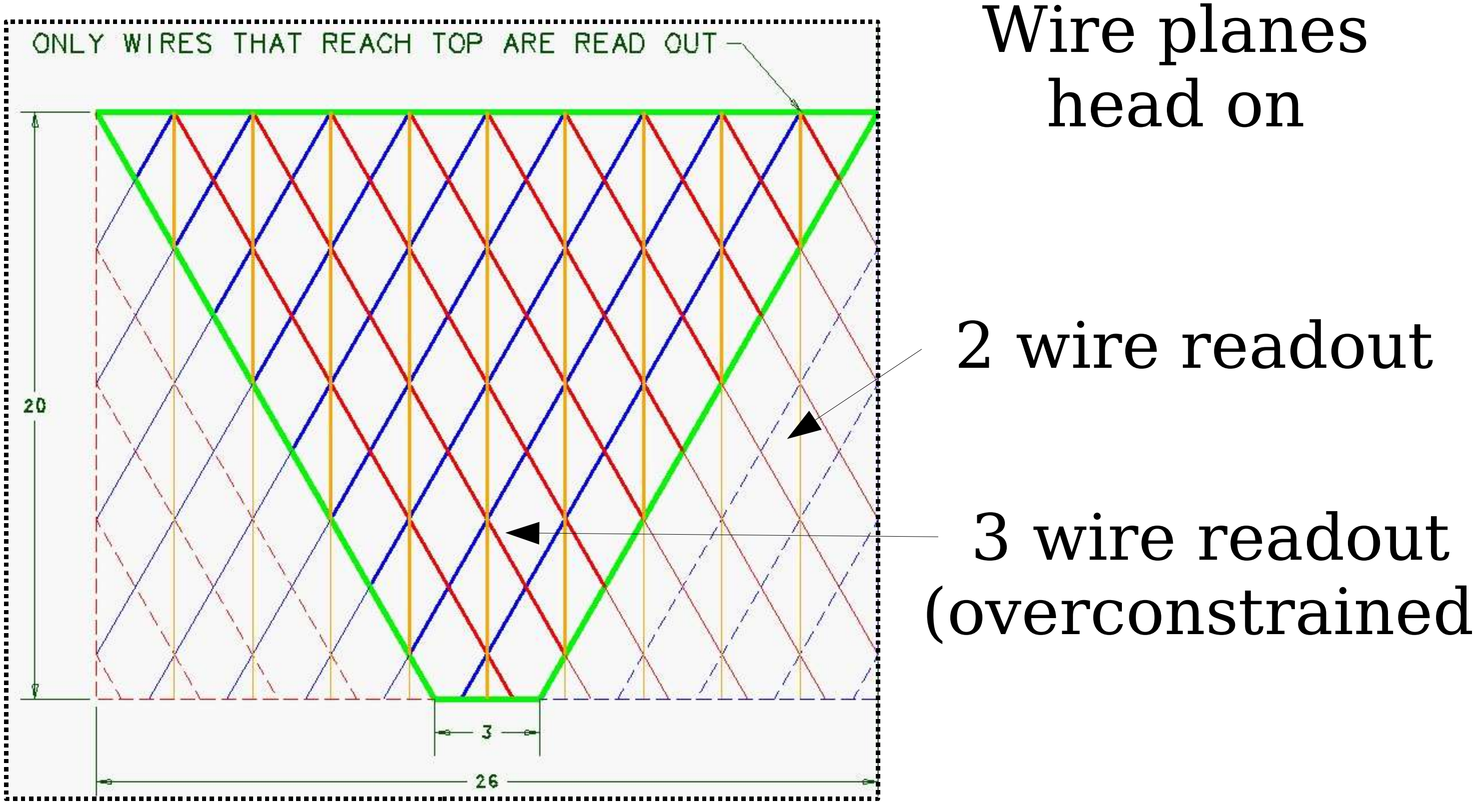

ARGON LEVEL
3m
INNER ROOF SUPPORT STRUCTURE
SENSING WIRE G-10 BOARDS
FIELD CAGE
CATHODE PLANE
WIRE PLANES

Each wire plane:



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

Wire planes head on

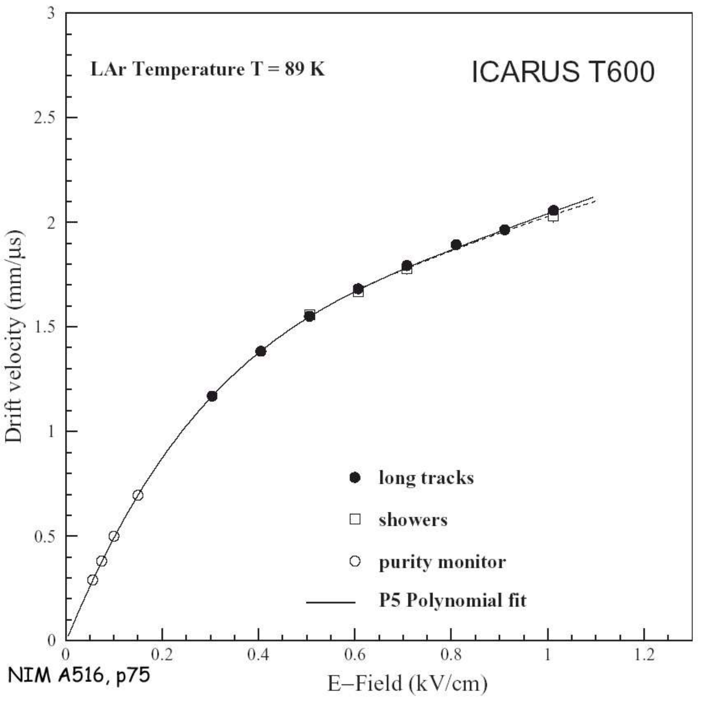


Drifting electrons over long distance (3m)?

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



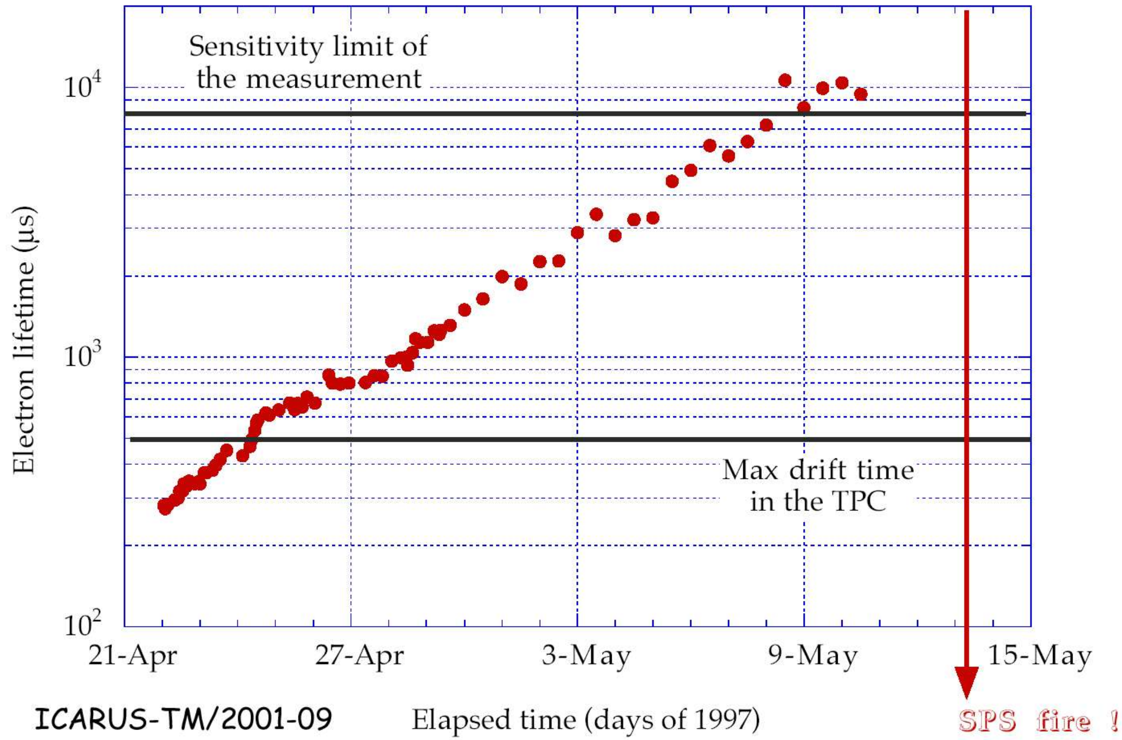
NIM A516, p75

Argone purity/electron lifetime in ICARUS

Impurities concentration is a balance of

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

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



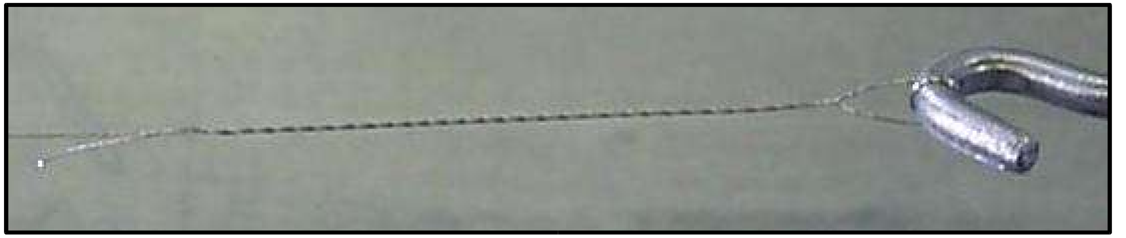
for the T600 module: achieved lifetime > 13 msec

for large LArTPCs : electron lifetime ~10ms

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

Wire Planes



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

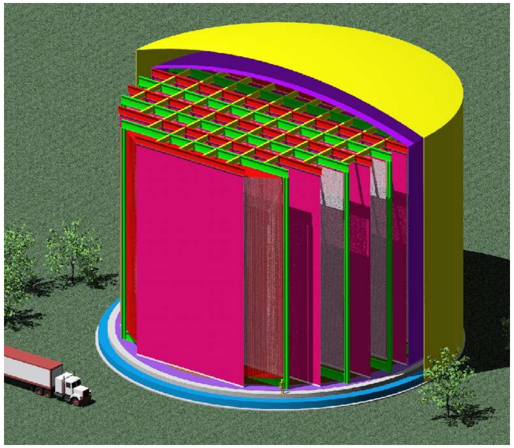
No show stoppers in scaling up liquid argon technology as per Fermilab mechanical, cryogenic, and electronics engineers

Large detector can be built at a reasonable cost

Preliminary Costing

50 kton TPC	~100M
15 kton TPC	~54M

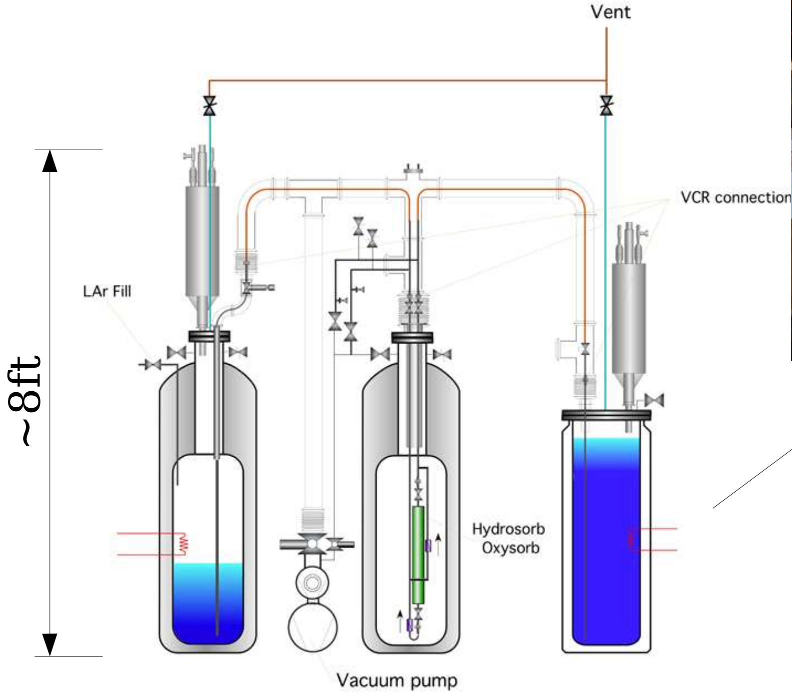
Great technology! ...What are the open questions in going to large scales? (15-50kton?)



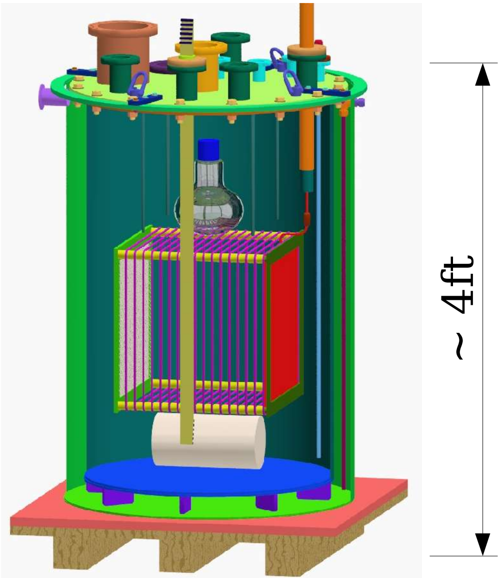
- Can purity be achieved and maintained in a large detector?
- Can very large wire chamber and cathode planes be assembled with high signal quality?
- Can cosmic backgrounds be rejected for a surface detector?

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 pursing new technologies:

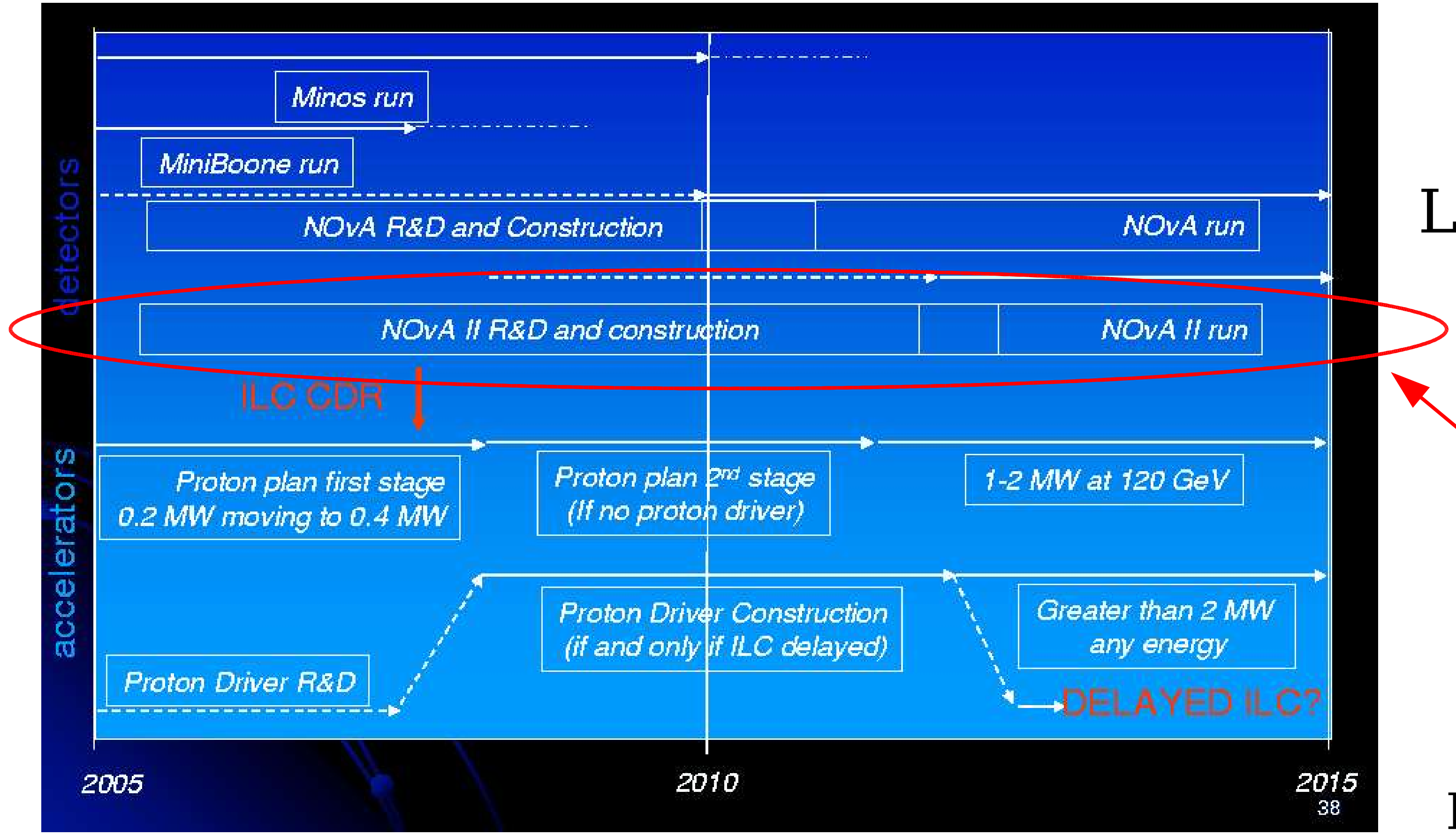
2005 APS neutrino study

"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"



Large liquid Argon TPCs for long baseline program

P. Oddone EPP2010 talk

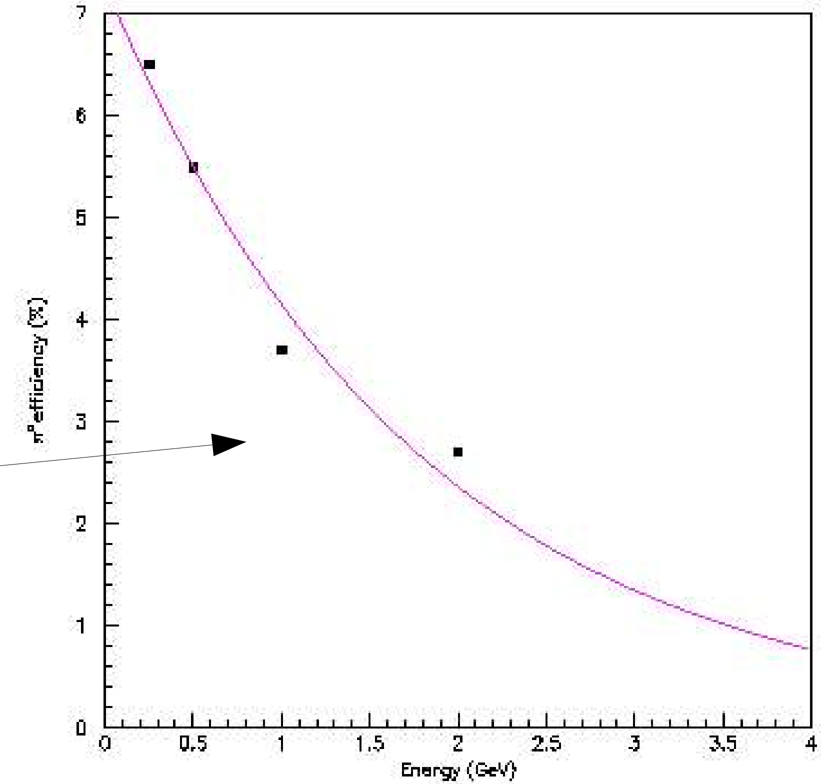
Endorsement from NuSAG towards realization of very large liquid Argon TPCs will keep effort on time to contribute to Fermilab's NuMI long baseline program

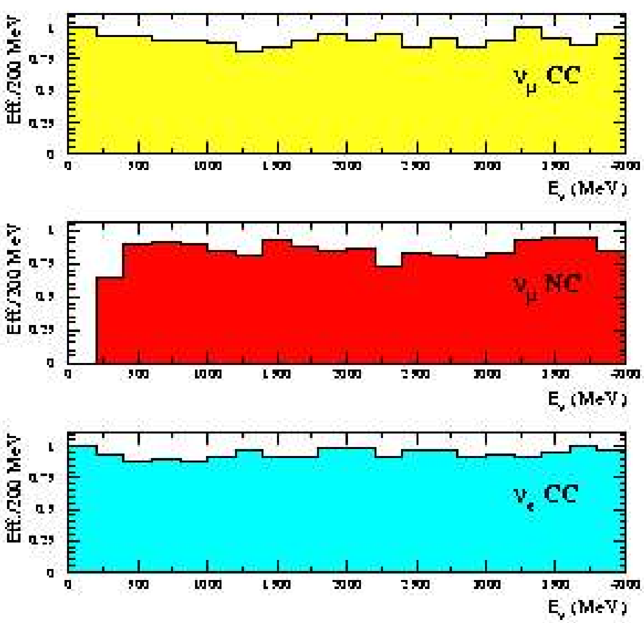
Backup slides etc.

T2K efficiency studies in LArTPC

T2K studies also show excellent e/p0 separation:
autmoated reconstruction -> dE/dx in first 8 hit wires combined with scan to look for displaced vertex -> p0 inefficiency of 0.2%

p0 rejection improves with increasing energy (dE/dx only)





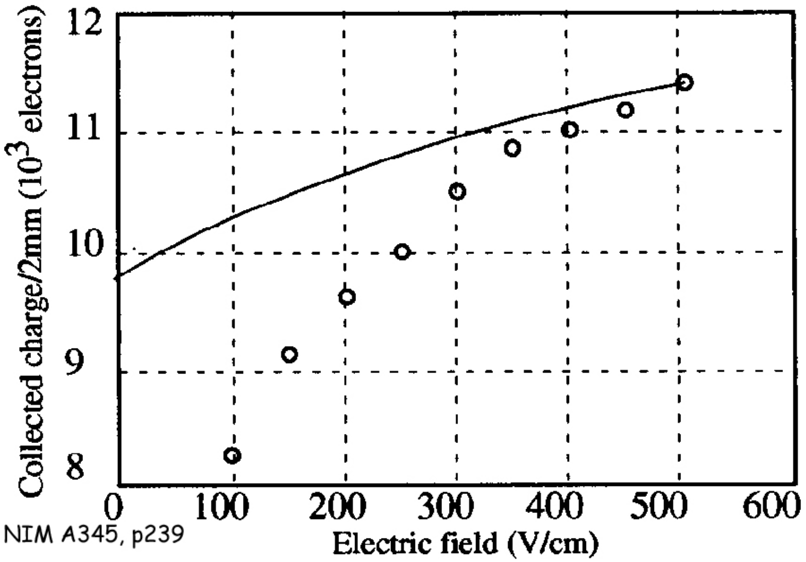
Overall ν_e efficiency:
85%-95%

topology

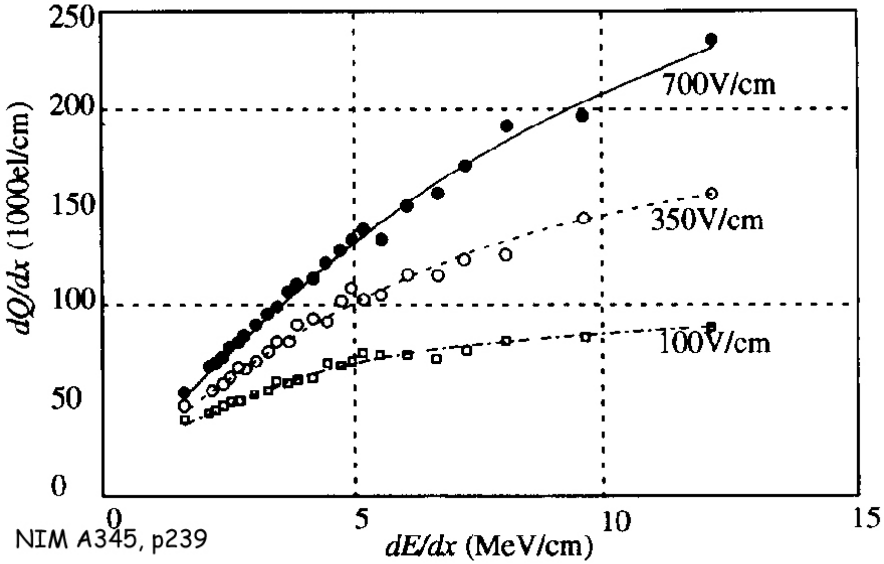
topology + kinematics, PID

Signal size: how many electrons per 1 cm of a track?

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



NIM A345, p239



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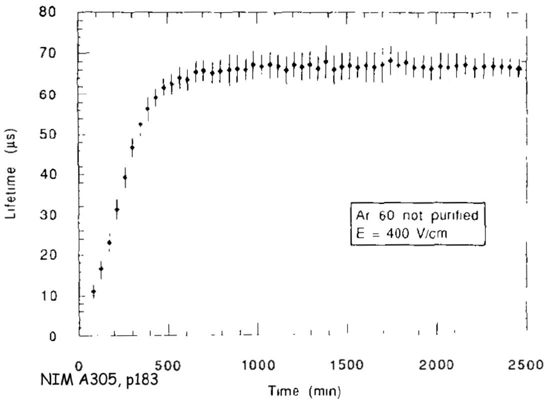
Argon purity

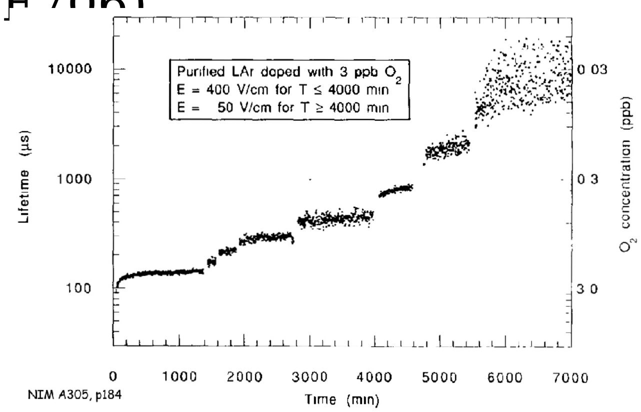
Q:Oxisorb R20 filters have design purity level of <5 ppb. How come that the results are so good (<0.1ppb)?

A: Specs refer to gaseous argon at NTP.

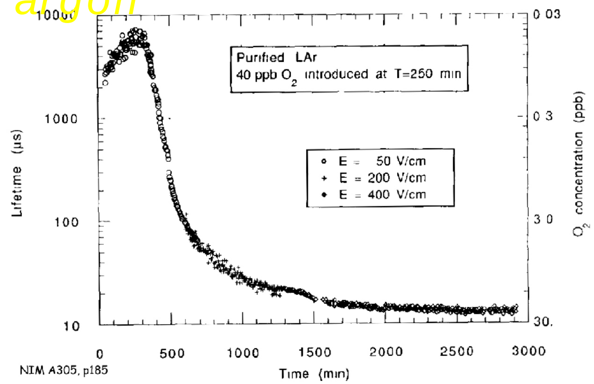
In a liquid phase impurities 'freeze out' at the vessel walls. The natural purification speed is limited by diffusion speed. (Related: B. Kephart, E706)



Electron lifetime improvement in 'regular argon'



Electron lifetime in ultra-pure argon doped with oxygen



Degradation of argon purity is consistent with diffusion time

Slide needs work