LArTPC: Large Liquid Argon TPC for the NuMI Off-axis Beam

Context:

Neutrinos and Fermilab etc

Status Report on LArTPC Activities

Synopsis

- This talk presents some of the efforts of the LArTPC group which is pushing the development of large liquid argon TPCs. Our small group is currently composed of 6 University groups and 6 Fermilab staff physicists, and the number of people is growing.

- Large neutrino detectors, including large liquid argon TPCs, clearly are needed for upcoming neutrino experiments and into the neutrino factory era.

ICARUS

- The LArTPC group recognizes that the technical concept and any possibility that such a detector may be feasible owes a huge debt to the work done by the ICARUS collaboration.

The Big Picture

Sensitivity =

detector mass x

detector efficiency x

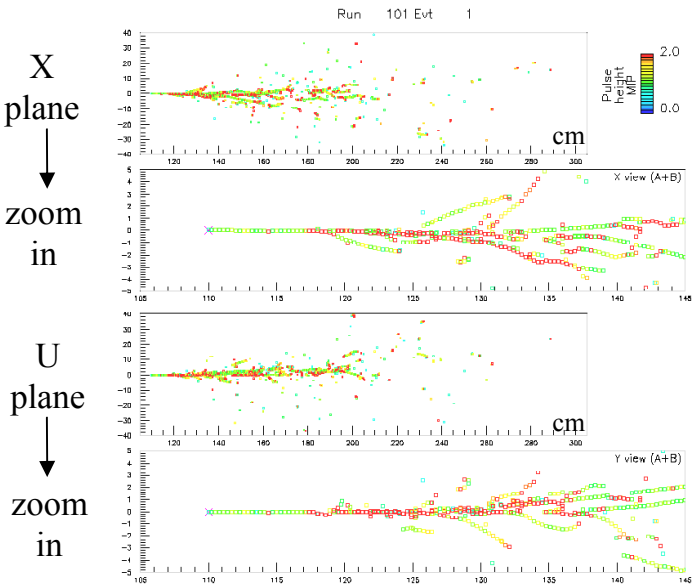
protons on target/yr x

# of years

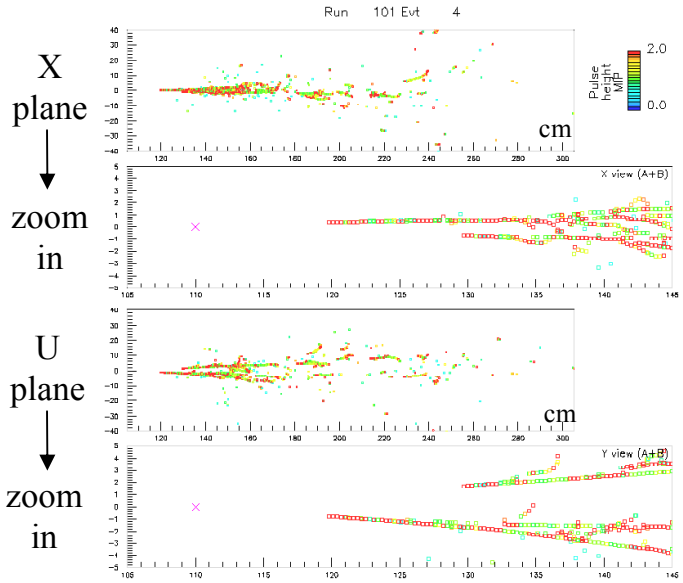
The promise of liquid argon

Electrons compared to π^0's at 1.5 GeV in LAr TPC

Dot indicates hit, color is collected charge
green=1 mip, red=2 mips (or more)



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



π^0

Multiple secondary tracks pointing 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

The promise of liquid argon

Neutral current event with 1 GeV π^0

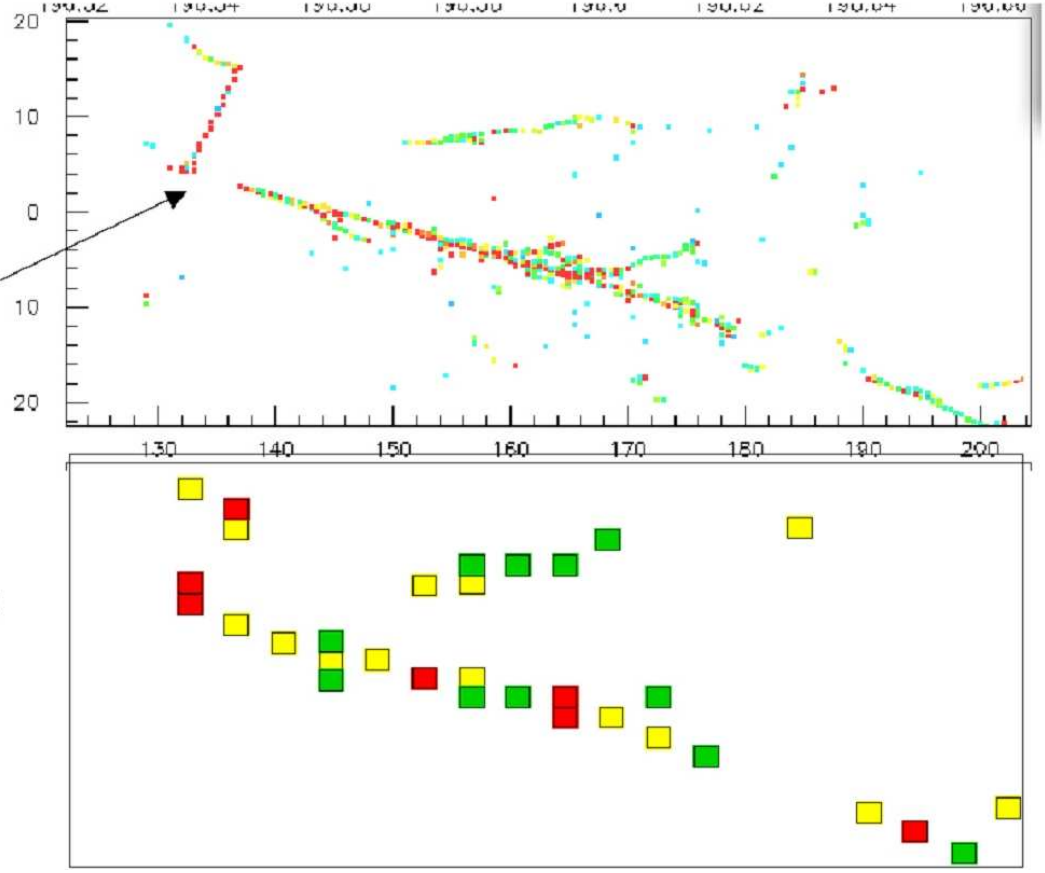
$$\nu_\mu + \mathrm{n} \rightarrow \nu_\mu + \pi^+ + \pi^- + \pi^0 + \mathrm{n}$$

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

3.5% X_0 samples

in all 3 views

4 cm gap



12% X_0 samples

alternating x-y

From Presentation by Jim Strait* to Fermilab PAC June 20, 2005

Liquid Argon TPC R&D

Massive LAr TPC provide a potential means to extend our reach in neutrino physics.

- Fine-grained tracking, total absorbtion calorimeter with improved electron efficiency and background rejection.
- ICARUS has demonstrated the technical feasibility of this technique in a "small" 600 T detector.
- Sketches and some preliminary engineering has been done that indicate a path for realizing larger detectors in the 10's kT range.

Substantial R&D must be done to demonstrate that this technology can be scaled to the masses of interest for long-baseline neutrino physics.

* Head of Particle Physics Division at Fermilab

Driven by physics

- Where the largest mysteries are:
  - We know next to nothing about the next accessible energy scale: witness the plethora of models
  - We know very little about the world of neutrinos
  - We are ignorant about what dark matter and dark energy are
- We have strong clues that these are the hunting grounds for major new discoveries
- We also believe there is a deep connection between all these areas

P. Oddone September 12, 2005

David Finley, Fermilab / Sept. 22, 2005 to ISS @ CERN/ A Large Liqud Argon TPC for the NuMI Off-axis Beam 8

While we develop the ILC….

- We must deliver on our "ships of the line":
  - The Tevatron Program: CDF and D0
  - LHC and CMS
  - The neutrino program: Minos and MiniBoone
- and maintain scientific vitality with a diverse program that includes:
  - Particle astrophysics
  - Theory and computing
  - Technology development

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David Finley, Fermilab / Sept. 22, 2005 to ISS @ CERN/ A Large Liqud Argon TPC for the NuMI Off-axis Beam 9

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 34

Neutrino Initiative: NOvA

- In addition to Beam power: detector mass and detector sensitivity: NOvA is 30 ktons, totally active
- NOvA is the only experiment sensitive to matter effects (hence the mass hierarchy).
  - We want to start a long term R&D program towards massive totally active liquid Argon detectors for extensions of NOvA.
  - Improvement is proportional to (Beam power) x (detector mass) x (detector sensitivity)

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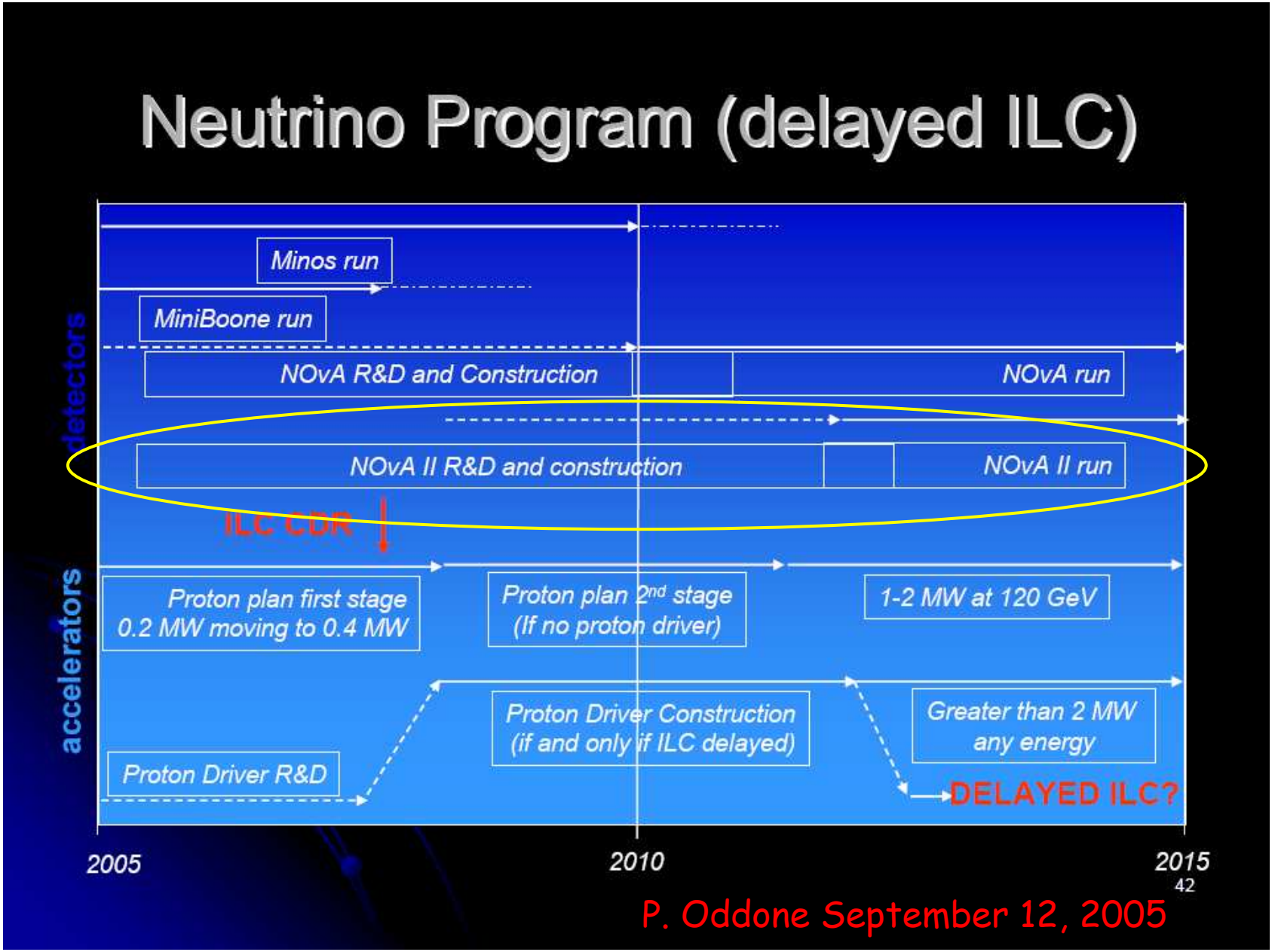
David Finley, Fermilab / Sept. 22, 2005 to ISS @ CERN/ A Large Liqud Argon TPC for the NuMI Off-axis Beam 11



A Large Liquid Argon TPC for the NuMI Off-axis Beam is part of a plan at Fermilab

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

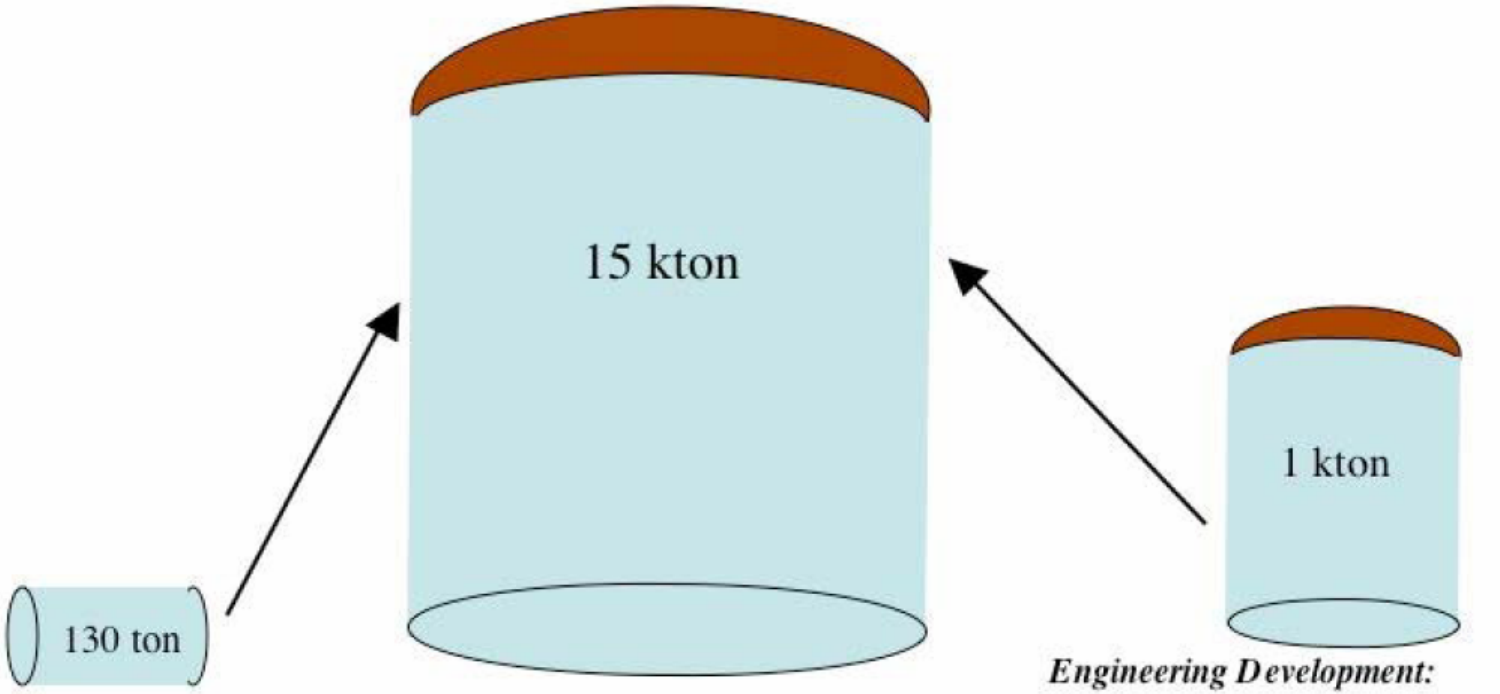
D. Finley, D. Jensen, H. Jostlein, A. Marchionni, S. Pordes, P. A. Rapidis
Fermi National Accelerator Laboratory, Batavia, Illinois
C. Bromberg
Michigan State University
C. Lu, K. T. McDonald
Princeton University
H. Gallagher, A. Mann, J. Schneps
Tufts University
D. Cline, F. Sergiampietri, H. Wang
University 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 Neutrino Scientific Assessment Group for the DOE/NSF

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

NuMI Liquid Argon TPC Overview



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

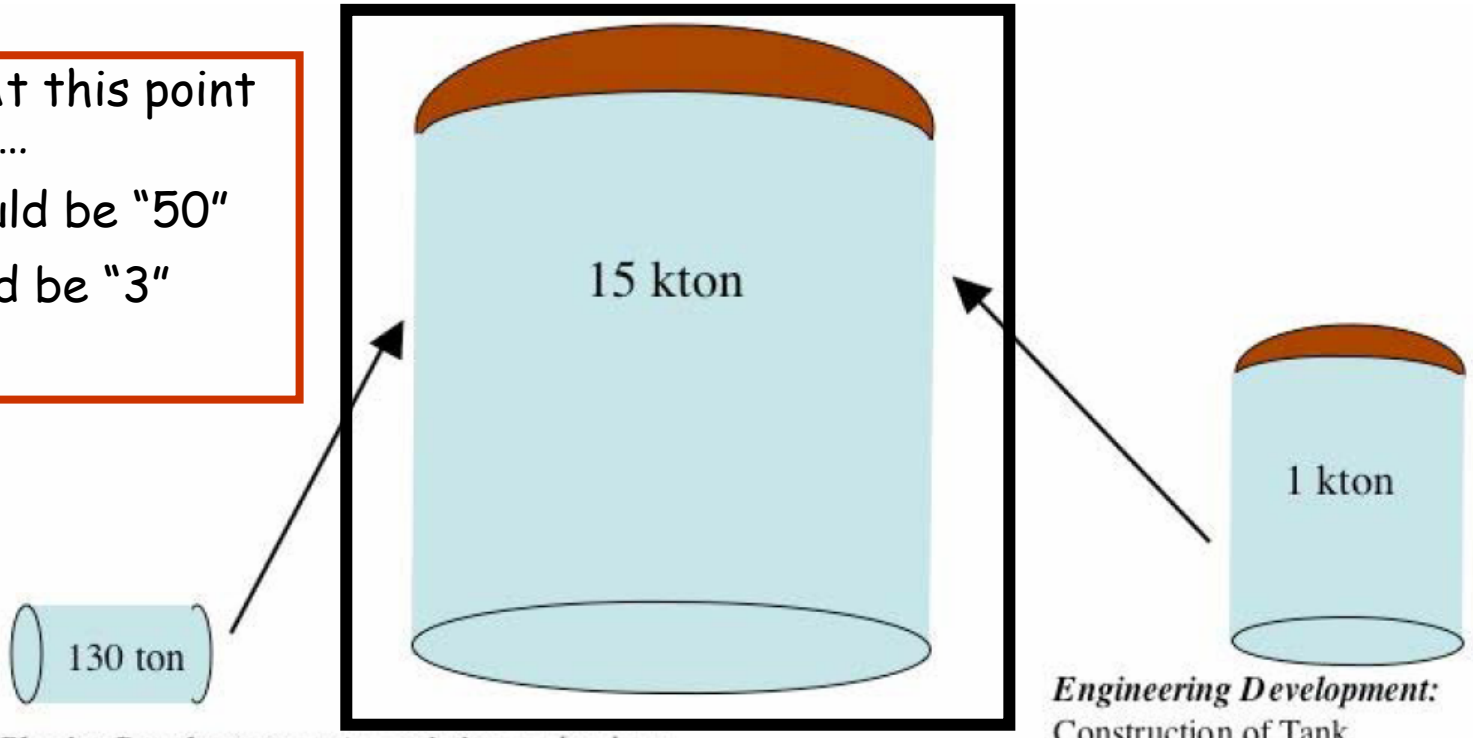
NuMI Liquid Argon TPC Overview

Note: At this point in time …

"15" could be "50"

"1" could be "3"

etc



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The Large Liquid Argon TPC

Aim is to produce a viable design for a 15 kt - 50 kt liquid argon detector.

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)

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)

$L_{Radiation}$ = 14 cm, dE/dx = 2.1 MeV/cm, 55,000 electrons/cm liberated

The Large Liquid Argon TPC

Some Specific challenges:

Argon: (long drift)

purification - starting from atmosphere (cannot evacuate detector tank)
- effect of tank walls & non-clean-room assembly process

Wire-planes:

long wires - mechanical robustness, tensioning, assembly, breakage/failure

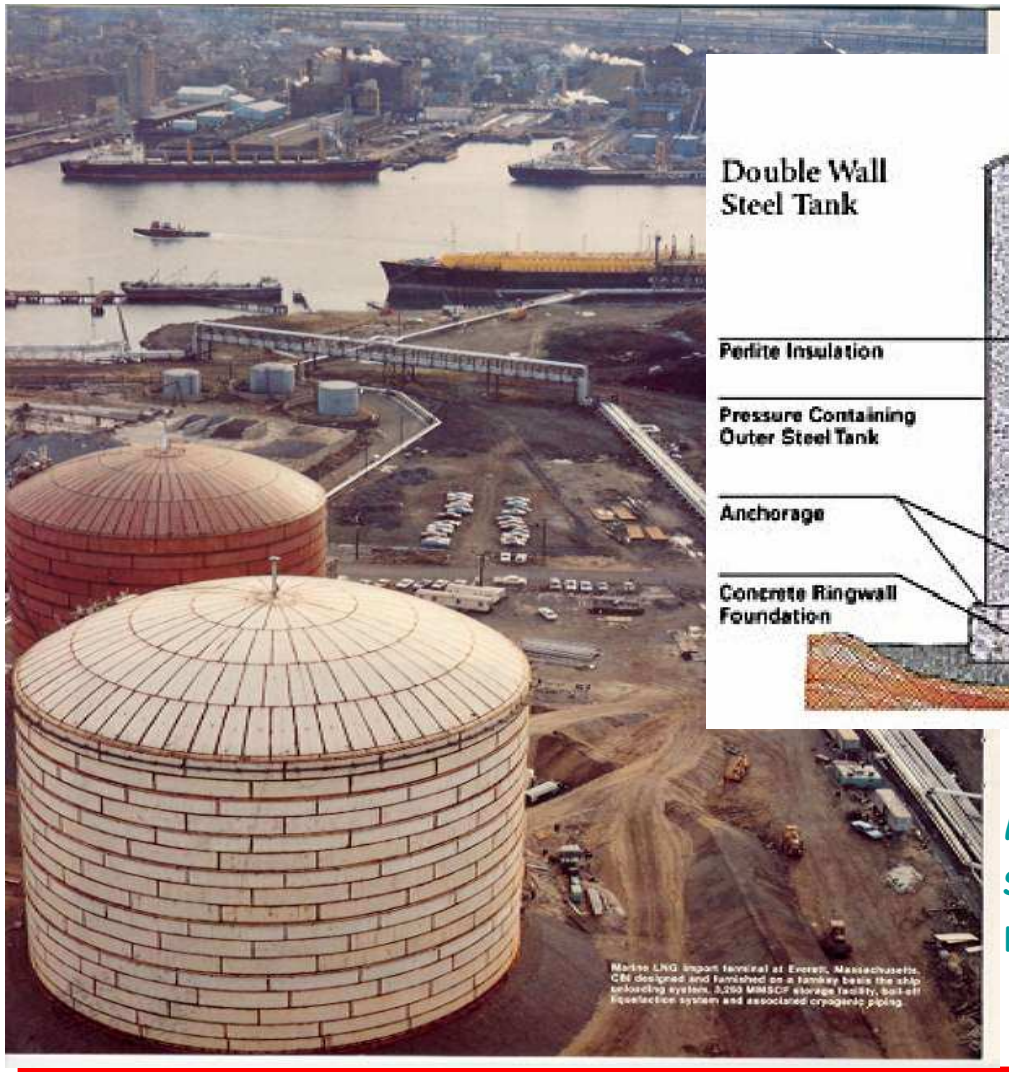
Signal processing:

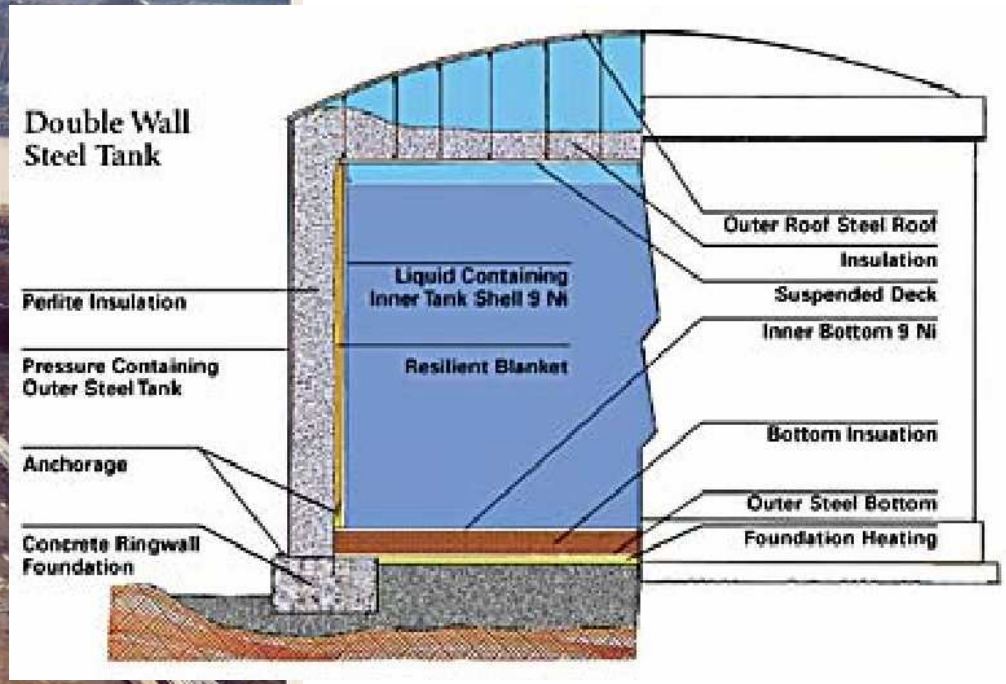
electronics - noise due to long wire and connection cables (large capacitance)

surface detector - data-rates,
- automated cosmic ray rejection
- automated event recognition and reconstruction

(and there are others for example, High Voltage)

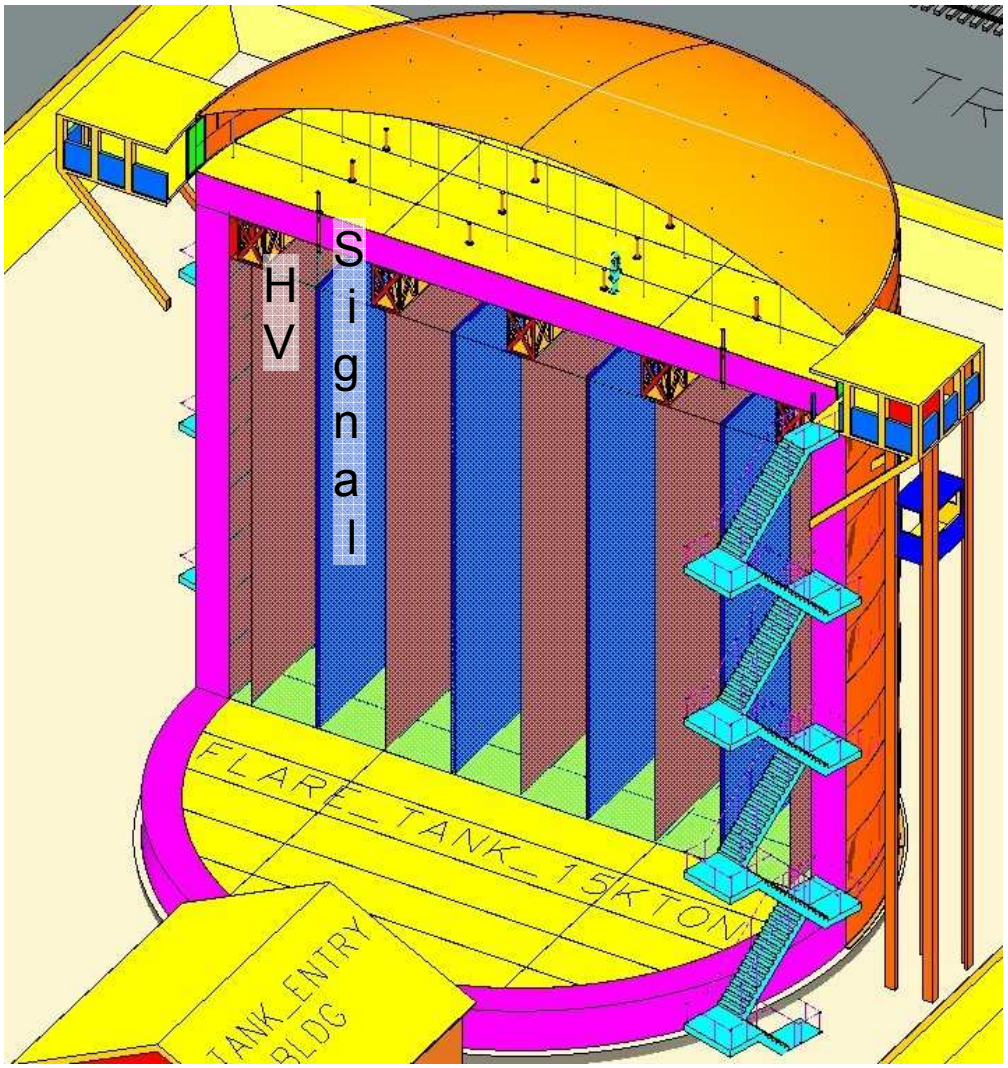
Detector Tank based on Industrial Liquefied Natural Gas (LNG) storage tanks





Many large LNG tanks in service. excellent safety record

The Large Liquid Argon TPC: Sketch



3D `Model' cutaway
15 kt detector

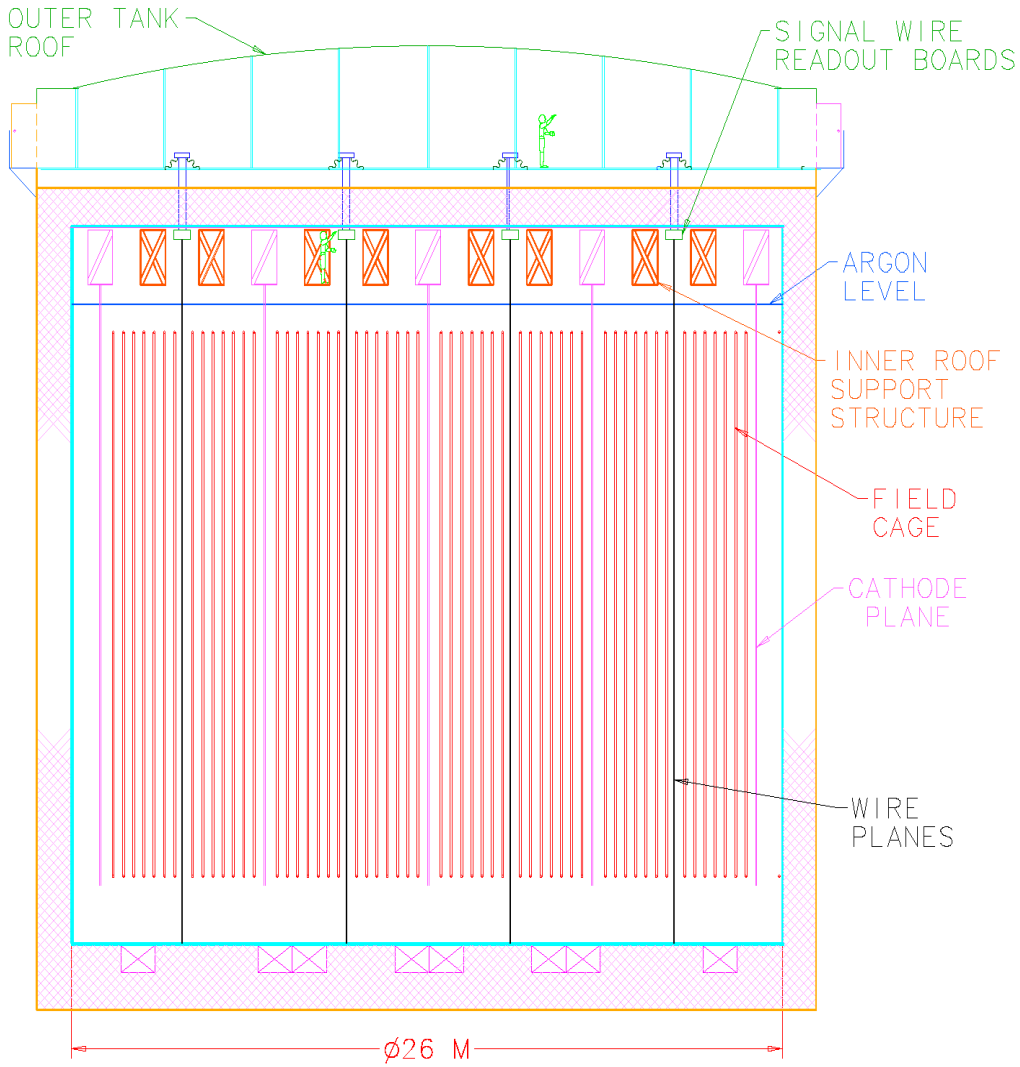
Changes from standard LNG tank:

inner tank wall thickness increased
- LAr is 2 x density of LNG;

trusses in inner tank to take load of the wires:

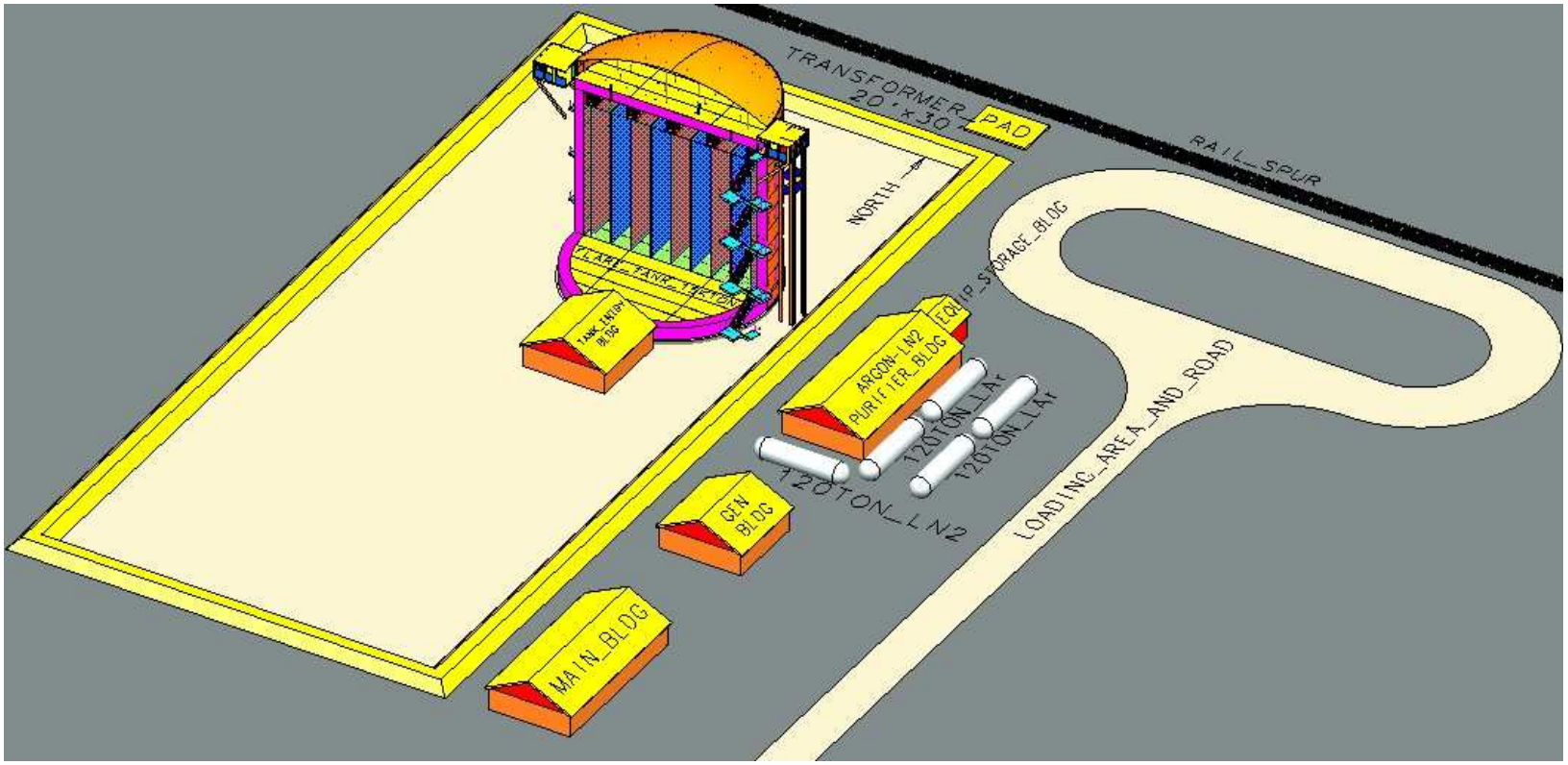
penetrations for signals from inner tank to floor supported from roof of outer tank;

The Large Liquid Argon TPC: Beam's Eye View



Beam's eye view showing the electrodes (cathode, field-cage and wires)

The Large Liquid Argon TPC: Site Features



Site Layout (very) Schematic –
showing some of the services needed

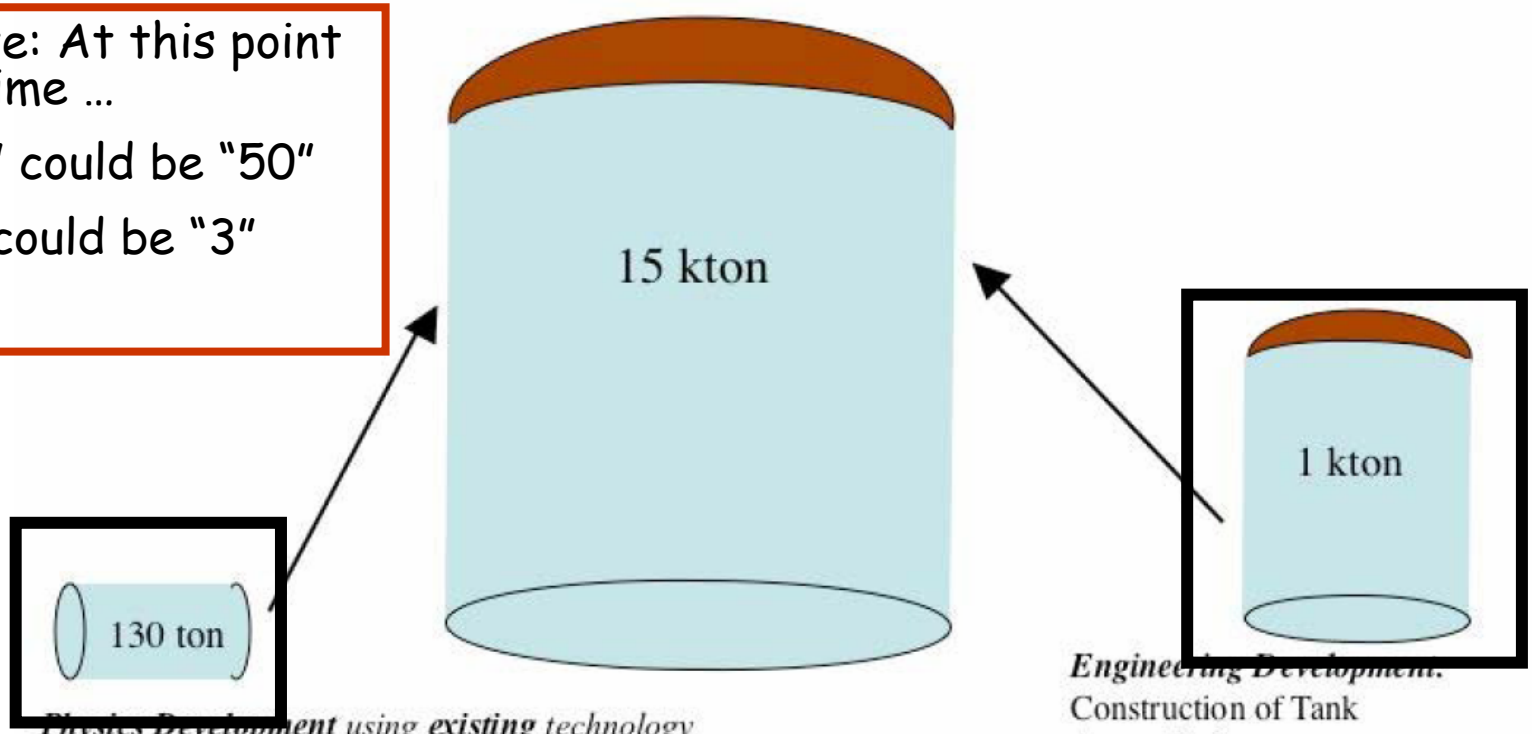
On the way to the Large Liquid Argon TPC

Note: At this point in time …

"15" could be "50"

"1" could be "3"

etc



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The Purposes of the “1 kton” tank

- Engineering Development to demonstrate scalability to large tank
  - Construction of tank with the same techniques to be used with the large tank
  - Demonstrate argon purity with the same techniques to be used with the large tank
  - Mechanical integrity of TPC
  - Readout signal / noise
  - Microphonics due to argon flow
  - Uncover whatever surprises there may be

The Purposes of the "130 ton" detector (50 ton fiducial)

- Physics development using existing technology
  - Record complete neutrino interactions (ν_μ and ν_e) in a high intensity beam
  - Establish physics collaboration by:
    - Developing event identification
    - Developing reconstruction
    - Developing analysis
  - Establish successful technology transfer

What Energy to pick?

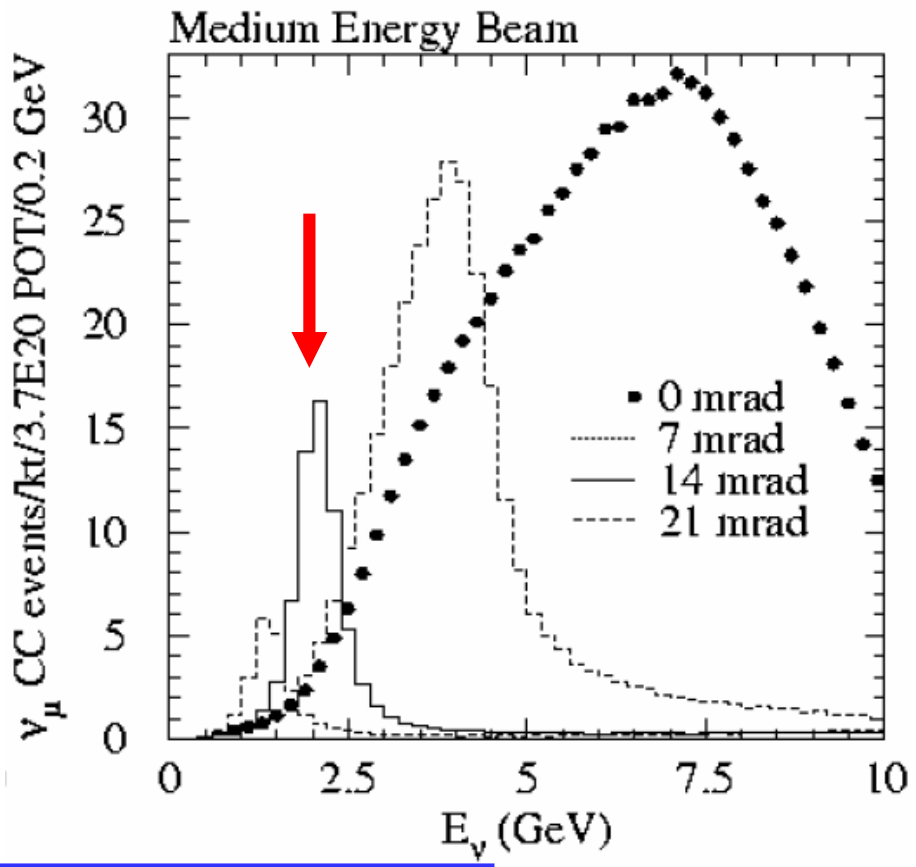
NuMI Off-axis Neutrino Energy

From the NOvA Proposal March 15, 2005

CC ν_μ event rate for:

- NuMI "medium" energy beam
- No-oscillation hypothesis
- 800 km from Fermilab for various off-axis angles

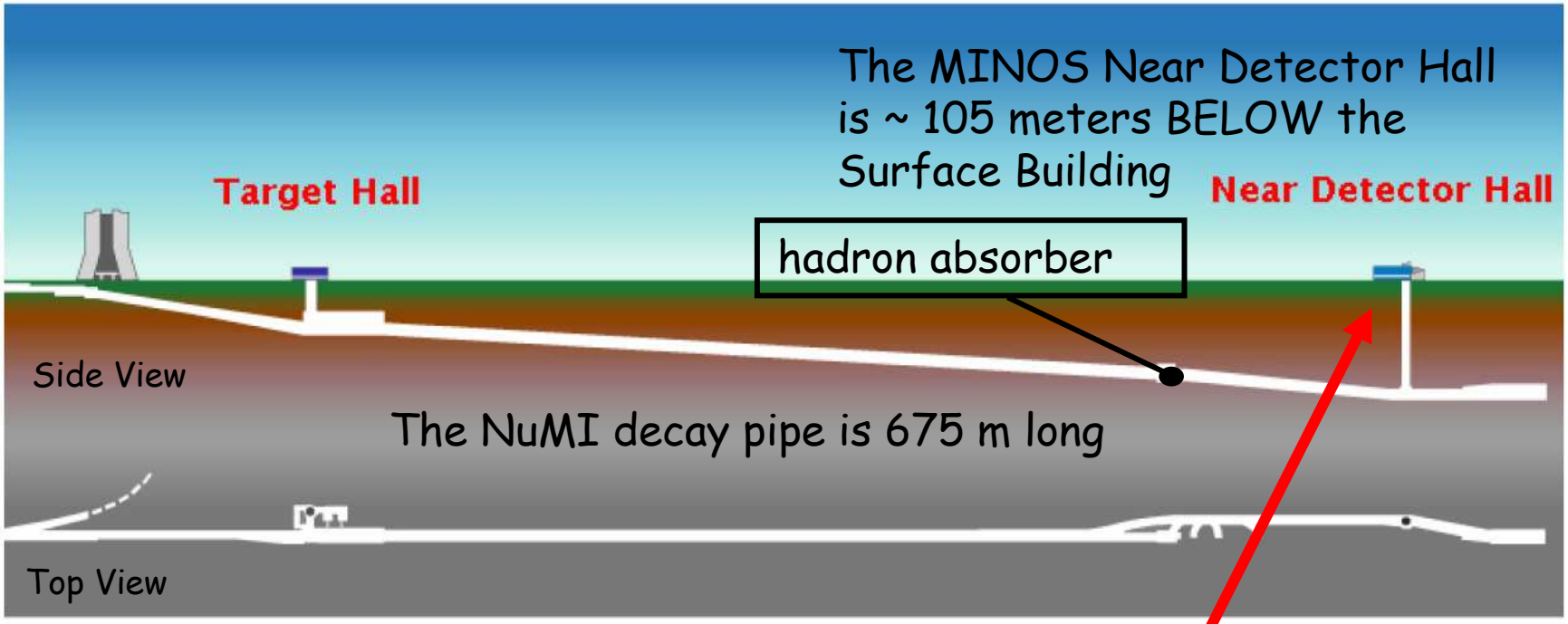
The event spectrum in the 14 mrad off-axis beam peaks at about 2 GeV, and there are more events than at 0 mrad.



Pick 2 GeV. Where can we get 2 GeV today?

NuMI Beamline and Surface Building

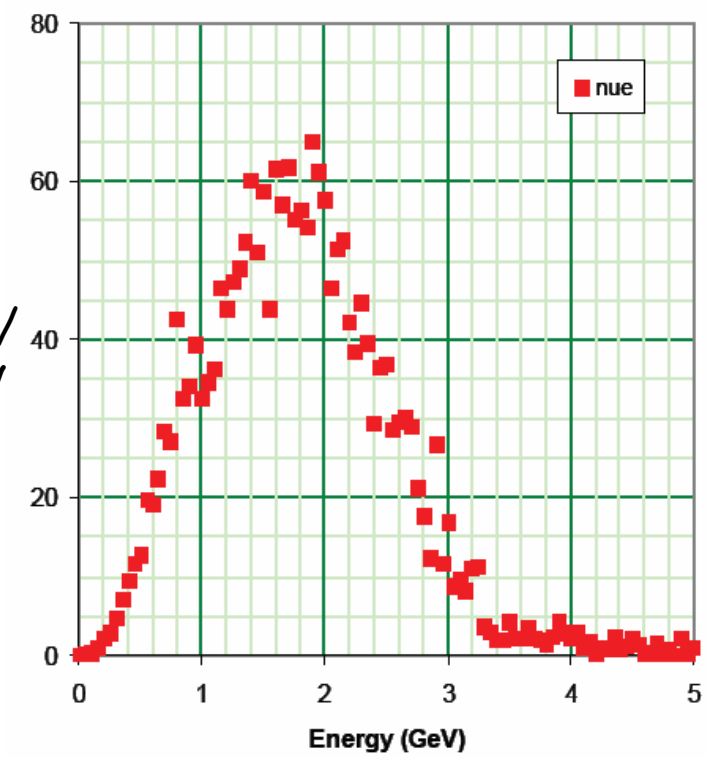
From the NOvA Proposal March 15, 2005



The 130 ton LArTPC detector would go in or near the MINOS Surface Building.

Electron Neutrinos in MINOS Surface Building

From the NOvA Proposal March 15, 2005



The charged current ν_e event spectrum in the MINOS surface building.

The ν_e event spectrum peaks just below 2 GeV.

There are ~2,000 ν_e events shown here for 6.5E20 POT and the 20.4 ton fiducial mass NOvA near detector.

NuMI is presently providing ~2E20 POT per year.

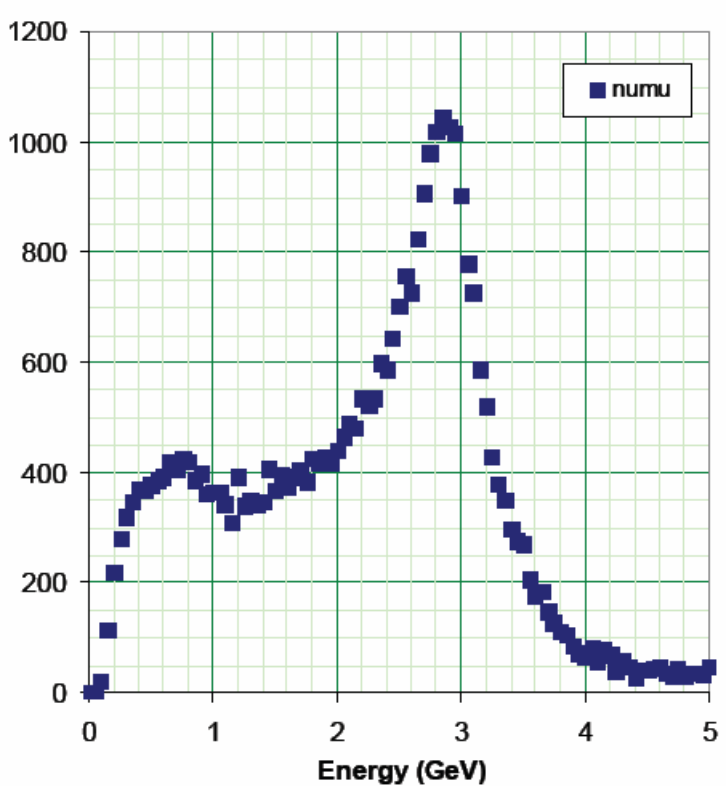
The 130 ton LArTPC has a 50 ton fiducial mass.

Thus … the LArTPC detector would get ~1600 ν_e events / year.

Muon Neutrinos in MINOS Surface Building

From the NOvA Proposal March 15, 2005

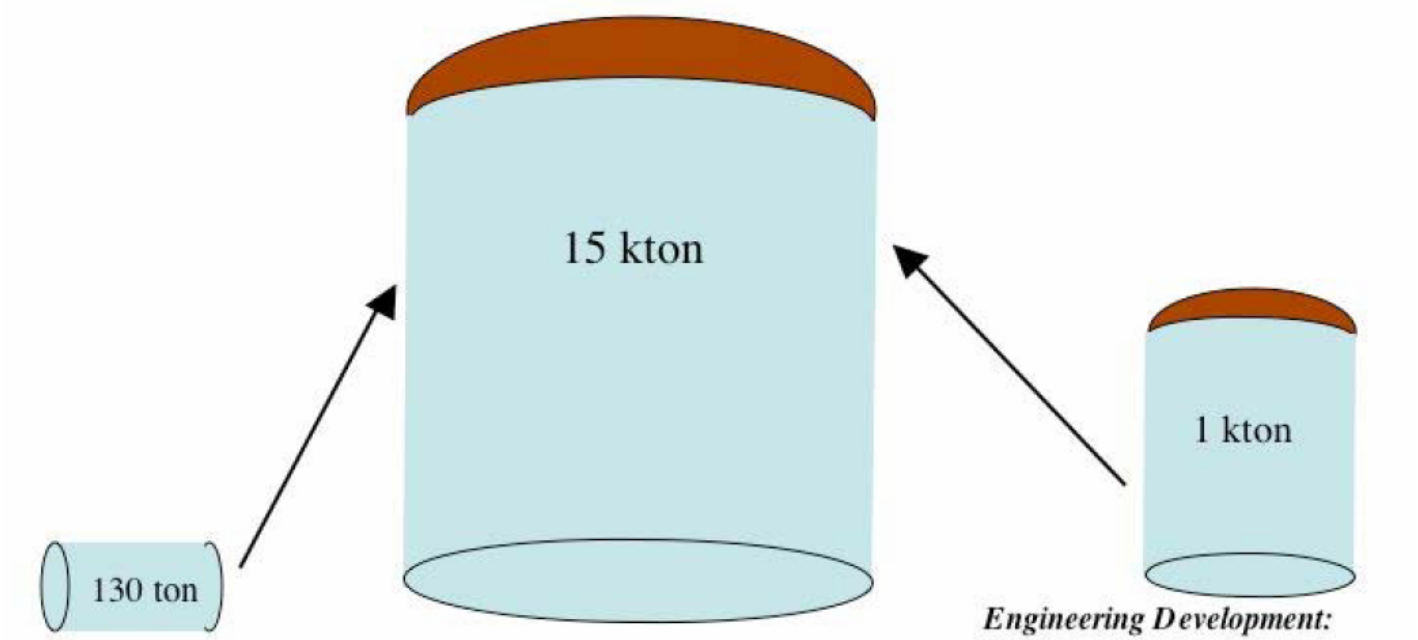
ν_μ CC events / 50 MeV



Same assumptions as previous slide, except this shows ~15,000 muon neutrinos.

The ν_μ peak at ~2.8 GeV is from Kaon decay.

NuMI Liquid Argon TPC: Getting Started



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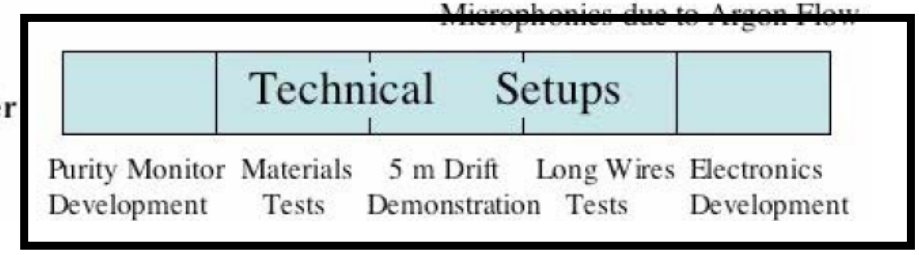
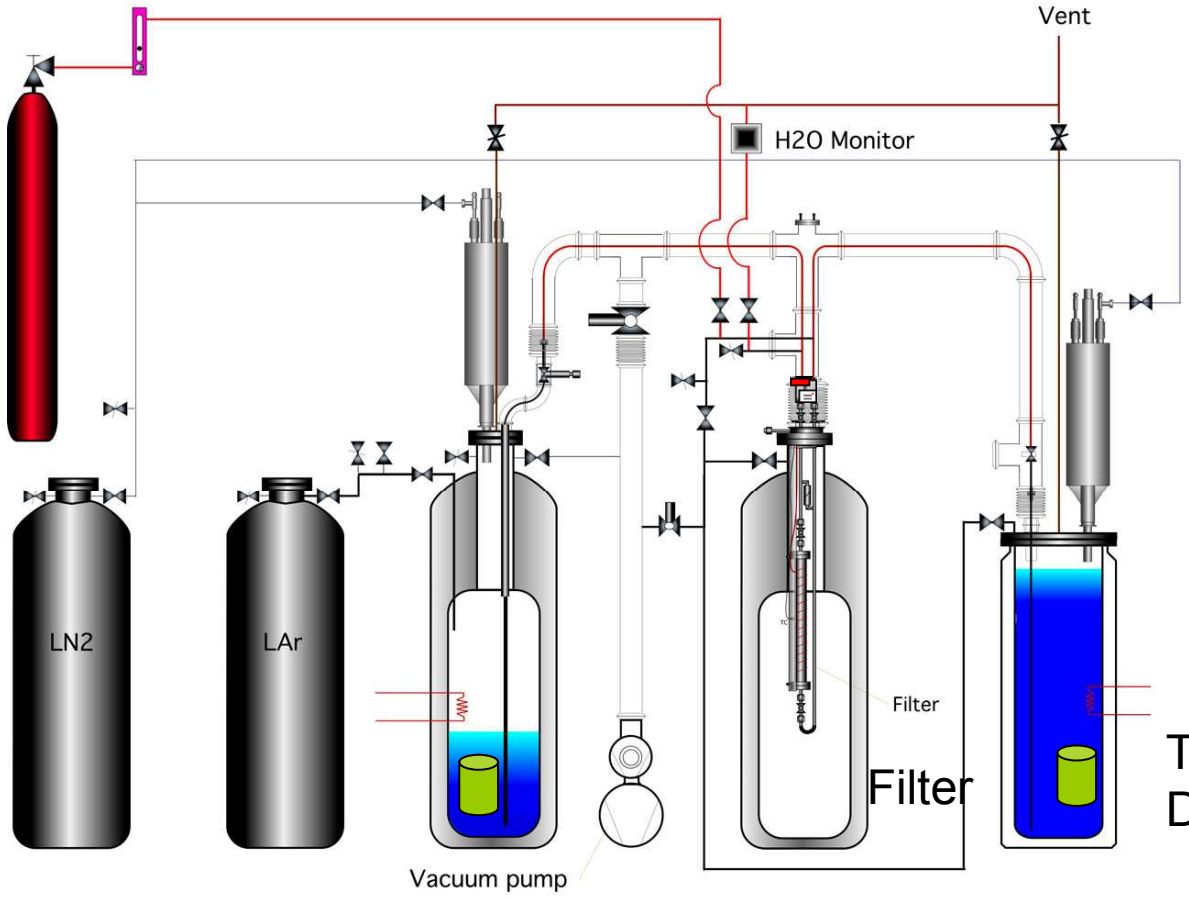


Materials Tests

System at Fermilab for testing filter materials and the contaminating effects of detector materials (e.g. tank-walls, cables)



ICARUS purity monitor

G. Carugno et al., NIM. A292 (1990

Test Samples Dewar

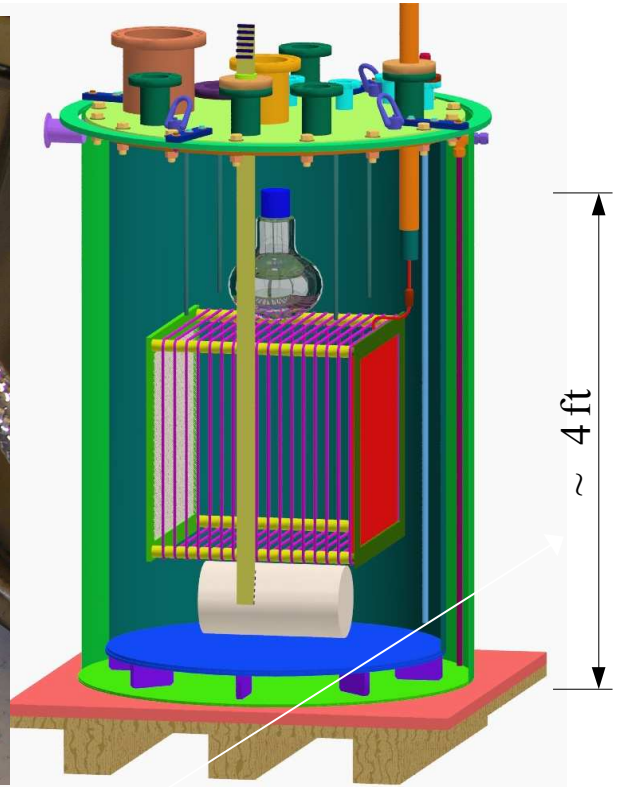
C.Kendziora6.13.05

Materials Tests

setup for lifetime measurements (effect of materials and effectiveness of different filters) under assembly at Fermilab.

LArTPC Test Setup at Yale

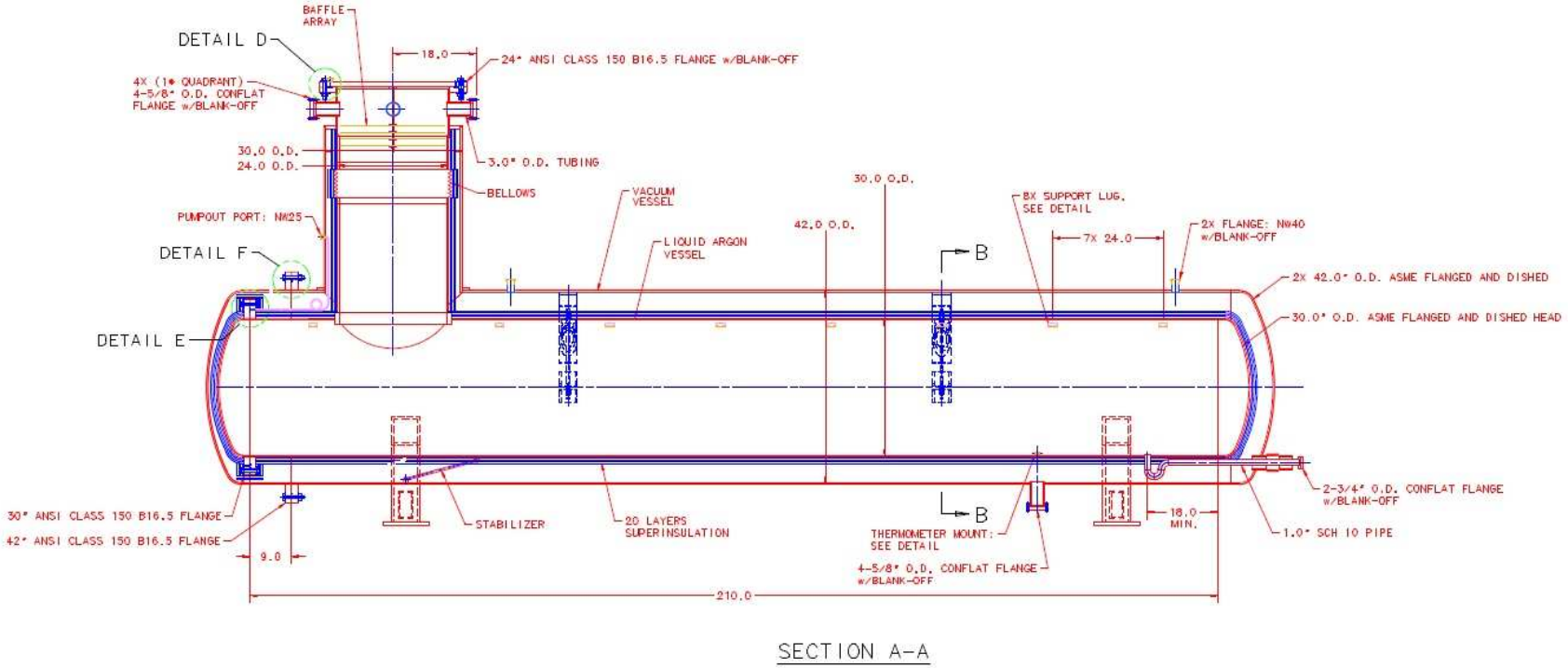
Purity monitor in liquid argon



Purity and light collection

5 m Drift Demonstration at Fermilab

Cryostat drawing for purchasing department



SECTION A-A

Long Wires Tests

- Wire Planes:
  - Induction (2 +/- 30) and Collection Planes spaced by 5 mm
  - 5mm pitch within planes
  - ~220,000 signal wires total (50 kTon), ~100,000 signal wires (15 kTon)
  - Longest wire ~35 meters (50 kTon) , ~ 23 meters (15 kTon)

- Need to be robust - no breakages
- Need practical assembly and installation procedure.

- Wire Material 150 micron Stainless

- Present Concept: (different from ICARUS)
  - Tension implemented by attaching a weight to each wire (~1kg) to avoid tension changes due to temperature changes.

R&D path shaped by open questions for large detectors (part 1):

Key Hardware Issues

Technology transfer

- Begin Technical Setups at Fermilab
- Seeing tracks and light production at Yale

Understanding long drifts (~5 m)

Purity tests setups at Fermilab

- Introduction of impurities, test of detector and tank materials
- Test of filtering materials, demonstrate purification rate

Very long wire electrode assembly/stability and readout

Design for detector to be assembled with industrial techniques

R&D path shaped by open questions for large detectors (part 2):

Key software issues

Simulation Monte Carlo(s)

Reconstruction / automated event reconstruction

Physics analysis

Key collaboration and physics issues

Developing defensible cost and schedule

Growing a strong collaboration

Navigating a global, developing, exciting neutrino physics program

Final Slide

Receiving support from Fermilab – both in engineering and with recently increased funding

Growing support from University groups in smaller technical setups, software efforts, etc

Receiving generous support for technology transfer from experts in Europe, and hoping to learn more from ongoing tests

Hoping for continued interest from the US Government for neutrino physics in general and LArTPCs in particular

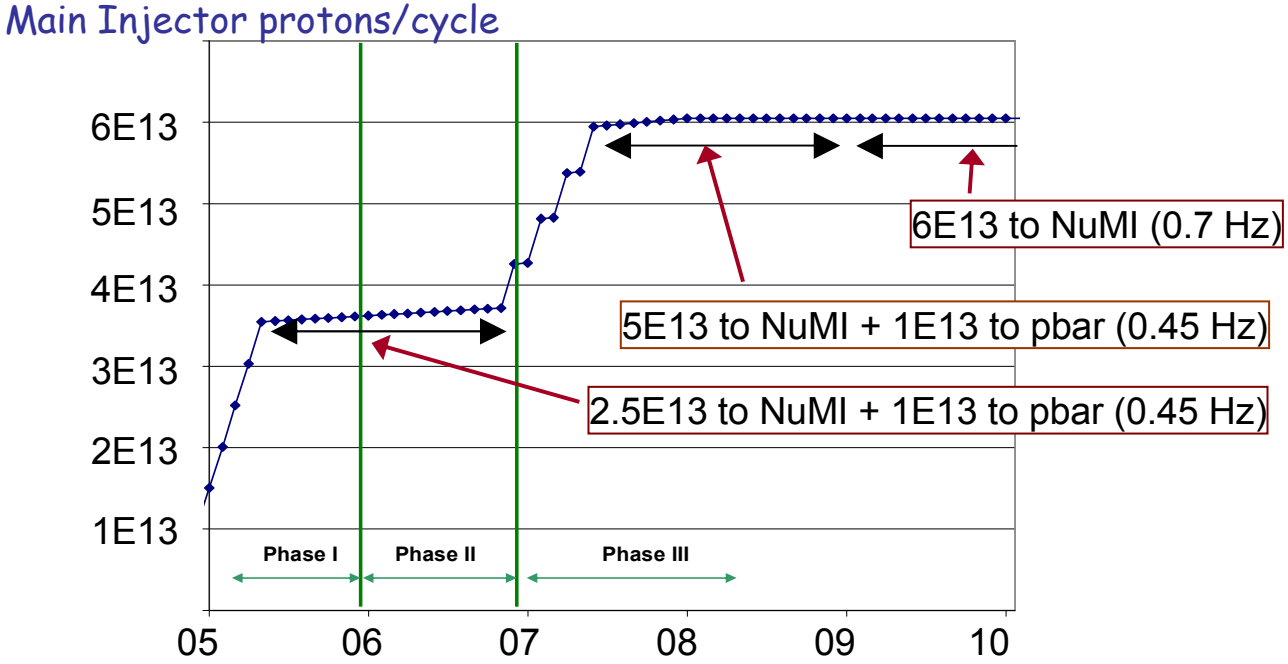
Continuing along the path to develop Large Liquid Argon TPCs - not only in the ongoing NuMI era, but also into the neutrino factory era, and for other physics

Would like to develop our efforts with wider participation

Back- ups, extras

towards a Large Liquid Argon TPC for the NuMI Off-axis Beam

Evolution of Beam Intensities and Rates to NuMI



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

`Proton Plan' (remove existing limitations) gives NuMI

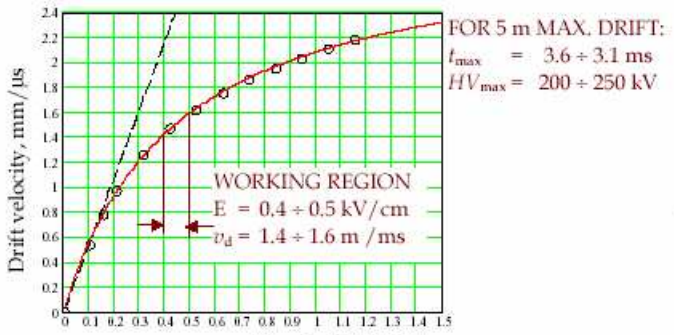
~ 4 x 10^{20} protons/year before collider turn-off in 2009

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

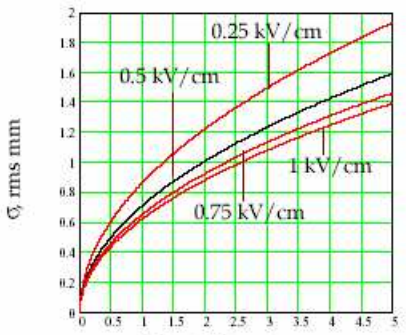
Proton Driver (new Linac) ~ 25 x 10^{20} - whenever PD exists

Large Liquid Argon TPC for the NuMI Off-axis Beam

everything about drifting in one fine slide



Drift velocity versus electric field in liquid argon



Longitudinal rms diffusion spread versus drift paths at different electric field intensities

$$\sigma_D = \sqrt{2 \cdot D \cdot \frac{x}{v_d}}$$

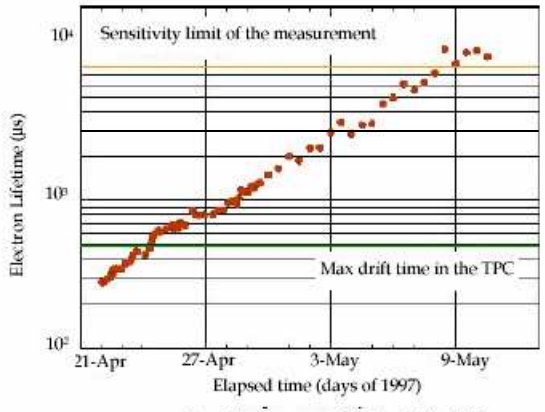
$D = 4.06\ \text{cm}^2/\text{s}$

$\sigma_D = 0.9\ \text{mm} \cdot \sqrt{T_D[\text{ms}]}$

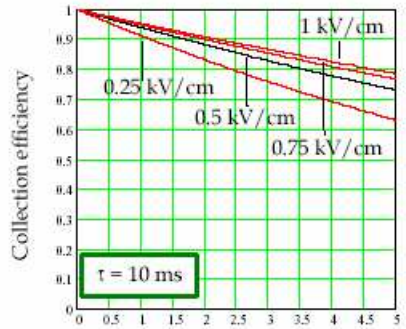
Longitudinal rms diffusion spread at 0.5 kV/cm

Average $\langle\sigma_D\rangle$ = 1.1 mm

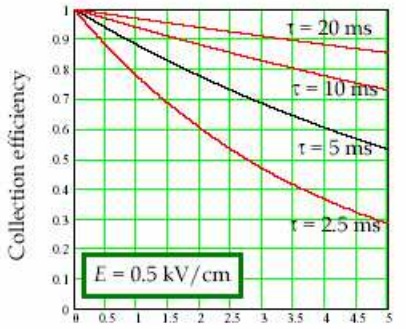
Maximum $\sigma_{D\,max}$ = 1.6 mm



Purification rate for the 50L TPC



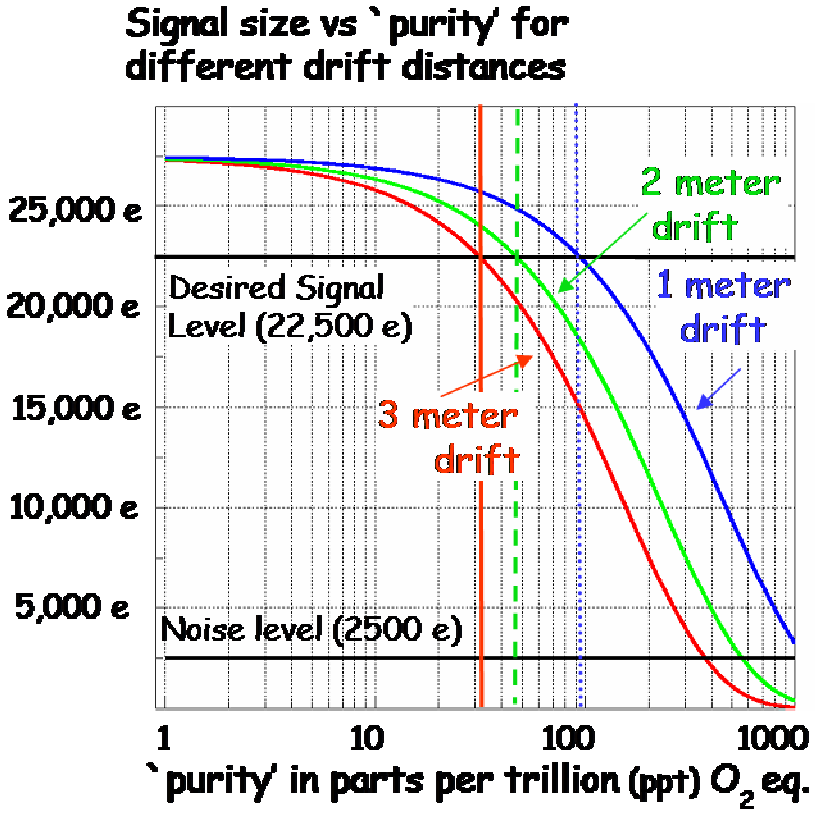
Drifting charge attenuation versus drift paths at different electric field intensities (τ = 10 ms)



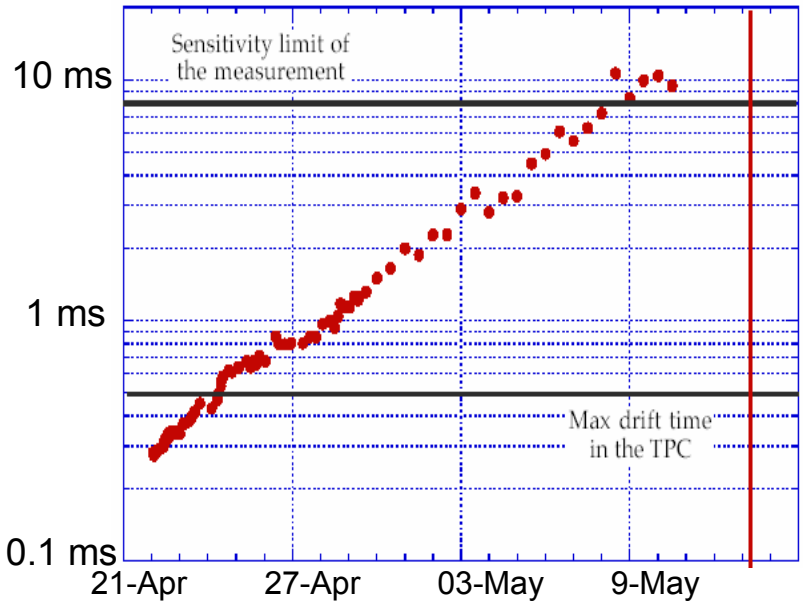
Drifting charge attenuation versus drift path at different electron lifetimes (E = 0.5 kV/cm)

towards a Large Liquid Argon TPC for the NuMI Off-axis Beam

Liquid Argon `purity' requirements



data from ICARUS T10 1997



`purity'/lifetime requirements for <20% signal loss

- 3m drift -> 10 ms lifetime = 30 ppt
- 2m drift -> 6 ms lifetime = 50 ppt
- 1m drift -> 3ms lifetime = 90 ppt

ICARUS achieved 10 ms in 1997
T600 lifetime evolution implies
>10 ms asymptotic value

towards a Large Liquid Argon TPC for the NuMI Off-axis Beam

Electronics and Data Acquisition Summary

Electronics:

ICARUS scheme - an intelligent waveform recorder on each wire:

Amplifier sensitivity achieved in existing custom devices for this capacitance

(S/N) =22,000 e / 2500 e = 8.5/1

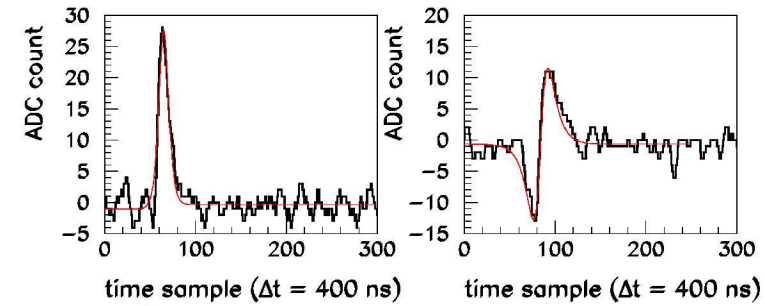
- digitize with commercial ADCs adequate performance, reasonable cost
- intelligence from commercial FPGAs adequate performance, reasonable cost.

Data Acquisition

Use commercial switches and multiplexors

Have a design to achieve 5 Gbyte/second into 200 PC's for reasonable cost.

Data Acquisition schematic



ICARUS TM/2001-09

Raw data rate = nwires x 2.5 MHz; need 2 bytes per sample

WFT (Wave Form Train) is all the digitizings

`Zero' suppression: *Cosmic ray rate is 200 kHz; each ray ~5000 signals,*

Set intelligent threshold in FPGA, pass next 40 samples

DAT (Data Above Threshold)

Processing each hit fully in FPGA to return pulse-height and time; requires 4 bytes/hit

FHP (Full Hit Processing)

50 kt data rates

Data Type & Data Rates	Spill Only* (bytes/sec)	Always Live (bytes/sec)
Wave Train	2×10^9	~~10^{12}~~
Data above threshold	8×10^7	~~4×10^{10}~~
Full hit processing	8×10^6	4×10^9

~~ exceeds bandwidth of 5 GB/sec

Note: Full hit processing allows for Always Live running

* Spill Only looks at 4 milliseconds (to see events plus any early cosmic rays) each spill (every 2 seconds)

Simulation Results

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

→ high ν_e efficiency
good NC rejection

First pass studies using hit level MC show 81 ± 7 % ν_ε efficiency and Neutral Current rejection factor ~70

(only need NC rejection factor of 20 to reduce NC background down to $\frac{1}{2}$ the intrinsic ν_ε rate)

Large Liquid Argon TPC for the NuMI Off-axis Beam

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.

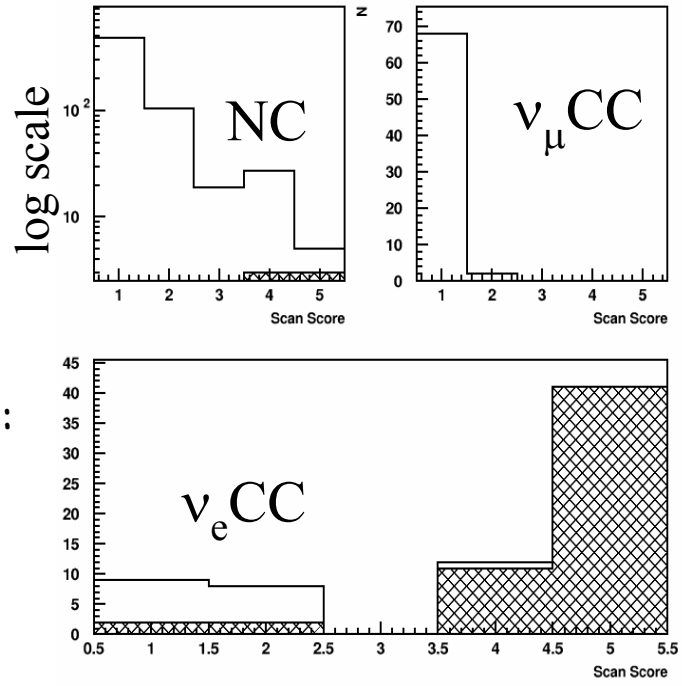
GEANT 3 detector simulation (Hatcher, Para): trace resulting particles through a homogeneous volume of liquid argon. Store energy deposits in thin slices.

Training samples:
50 events each of ν_eCC, ν_μCC 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

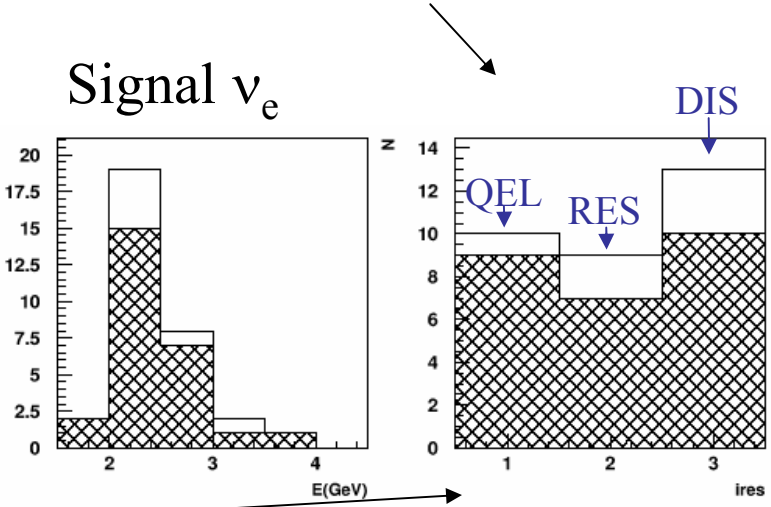


open region: students
hatched region: + experts

Large Liquid Argon TPC for the NuMI Off-axis Beam

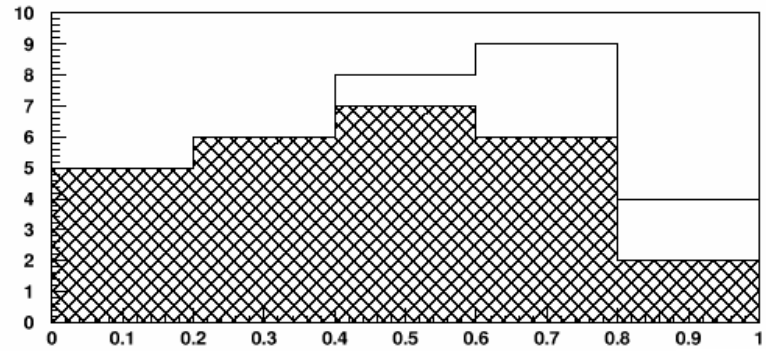
Overall efficiencies, rejection factors, and dependencies

Event type	N	pass	eff.	rej.
NC	290	4	-	72.5
signal ν_e	32	26	0.81	-
Beam ν_e: CC	24	14	0.58	-
NC	8	0	-	
Beam $\bar{\nu}_e$: CC	13	10	0.77	-
NC	19	0		



Efficiency is substantial even for high multiplicity (DIS) events

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



Overall efficiency 81% +/- 7%
Rejection of NC is 73 (+60,-30)

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

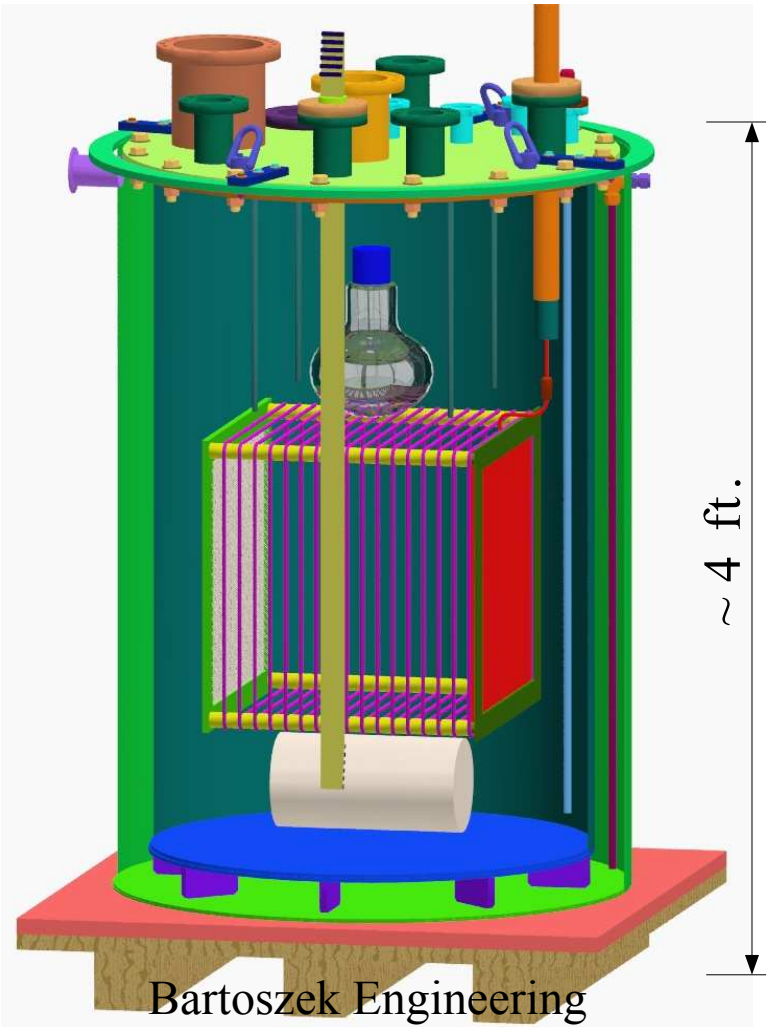
LArTPC work underway at Yale

How good are these detectors at IDing low (~1 GeV) energy ν interactions?

↓

- understand the technology
- purity studies
- understand detector response at very low energies
- study combination of charge and light production for particle ID

Constructing small prototype vessel this summer



Bartoszek Engineering

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