B. T. Fleming
March 6th, 2006
FNAL/BNL Long
Baseline Wkshp

Liquid Argon Detectors for Long Baseline Neutrino Physics

Long-baseline $\nu_\mu \Rightarrow \nu_e$ neutrino oscillation physics:

structure of the mixing matrix, CP Violation in the neutrino sector, hierarchy of the neutrino masses

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

Outline:

What we know, and don't know about:

The promise of LAr detectors for this physics
The feasibility of building these detectors
- on the surface
- underground

Discussed in the context of:
LArTPCs for extensions to NOvA
LArTPCs with a wide-band beam
LArTPCs in an underground lab

Goals for this study......

Looking for just a handful of oscillated ν_es

Need a detector to well identify signal and background!

Physics Requirements:

- optimized for 1-10 GeV neutrinos
- high statistics
  - very large mass (~10's ktons)
  - identify with high efficiency ν_e charged current interactions
- good energy resolution for background rejection
  - ν_e intrinsic background has a broader energy spectrum than oscillation signal
- good event topology for background rejection
  - e/π^0 separation
  - e/μ,h separation
- For surface detectors: appropriate shielding for
  - reasonable data rates
  - appropriate background rejection

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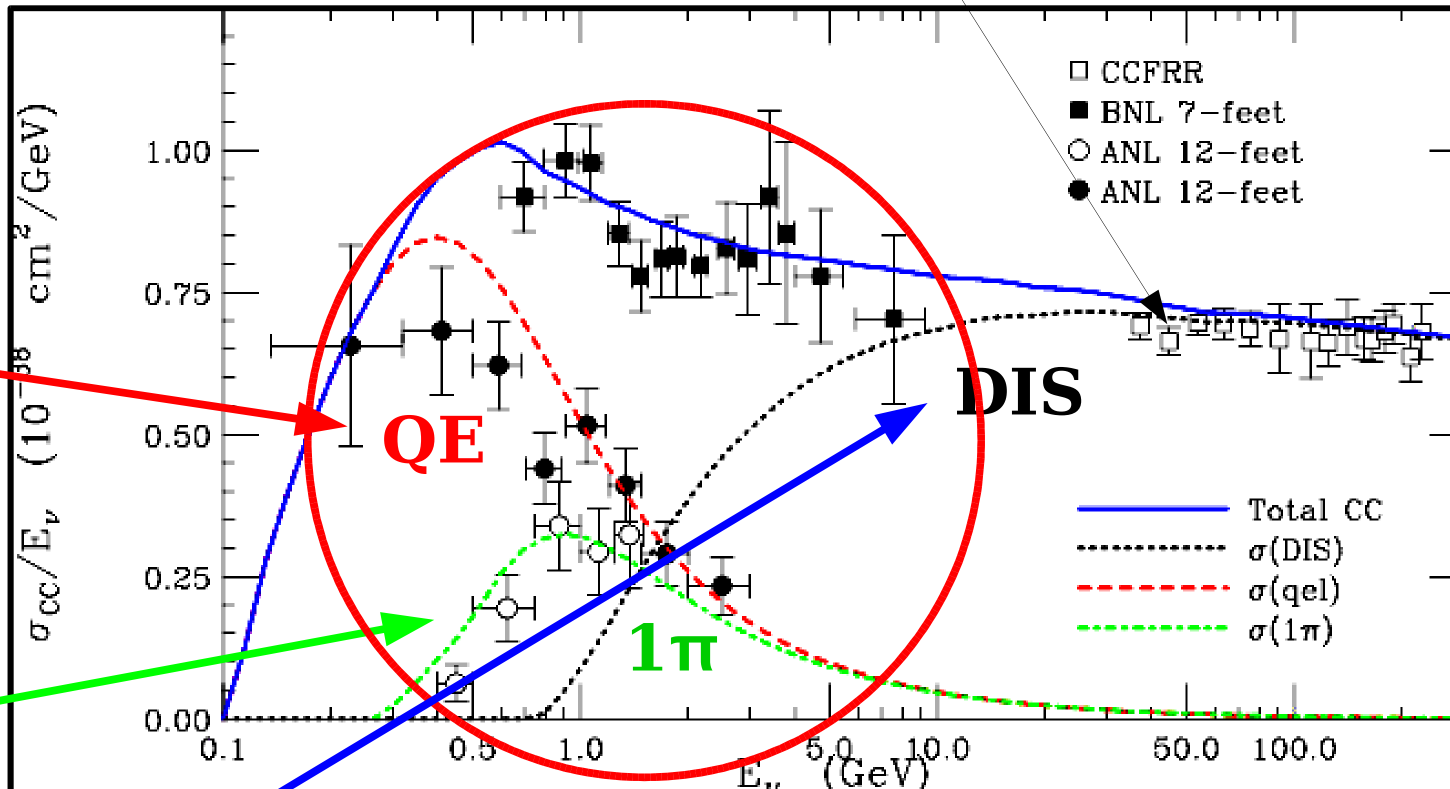
Neutrino Scattering

Elastic Scattering

Quasi-Elastic



Single Pion Production

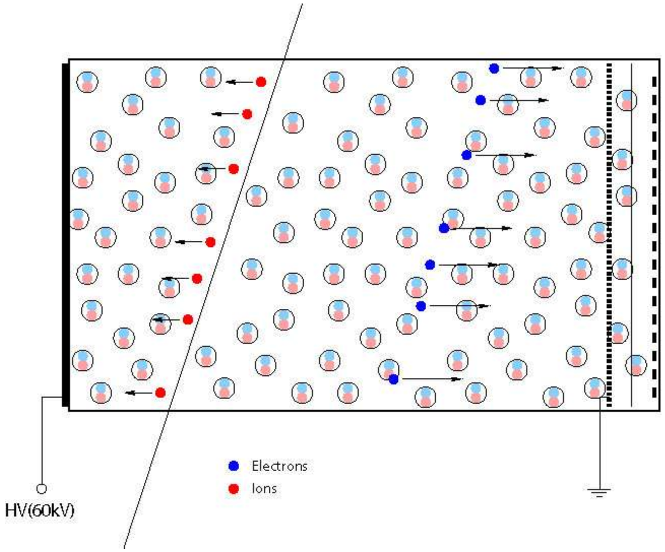
Deep Inelastic Scattering

1-10 GeV neutrinos
-> dynamic region with xsecs
turning on and off....

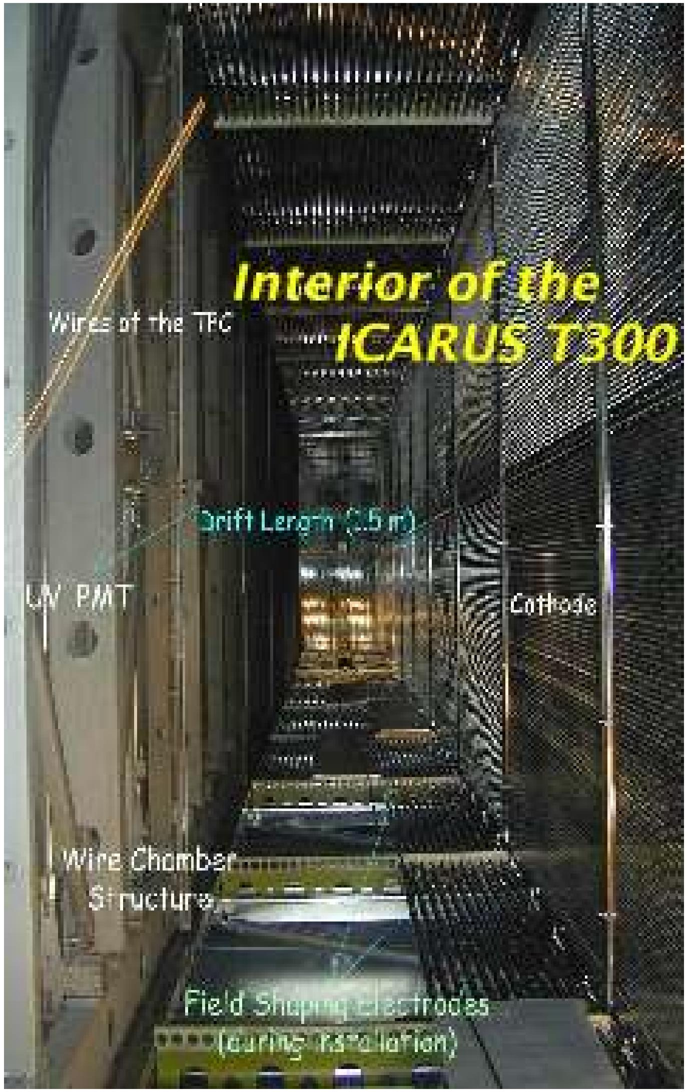
need to differentiate ν_e CC interactions
from backgrounds -> fine-grained detector

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

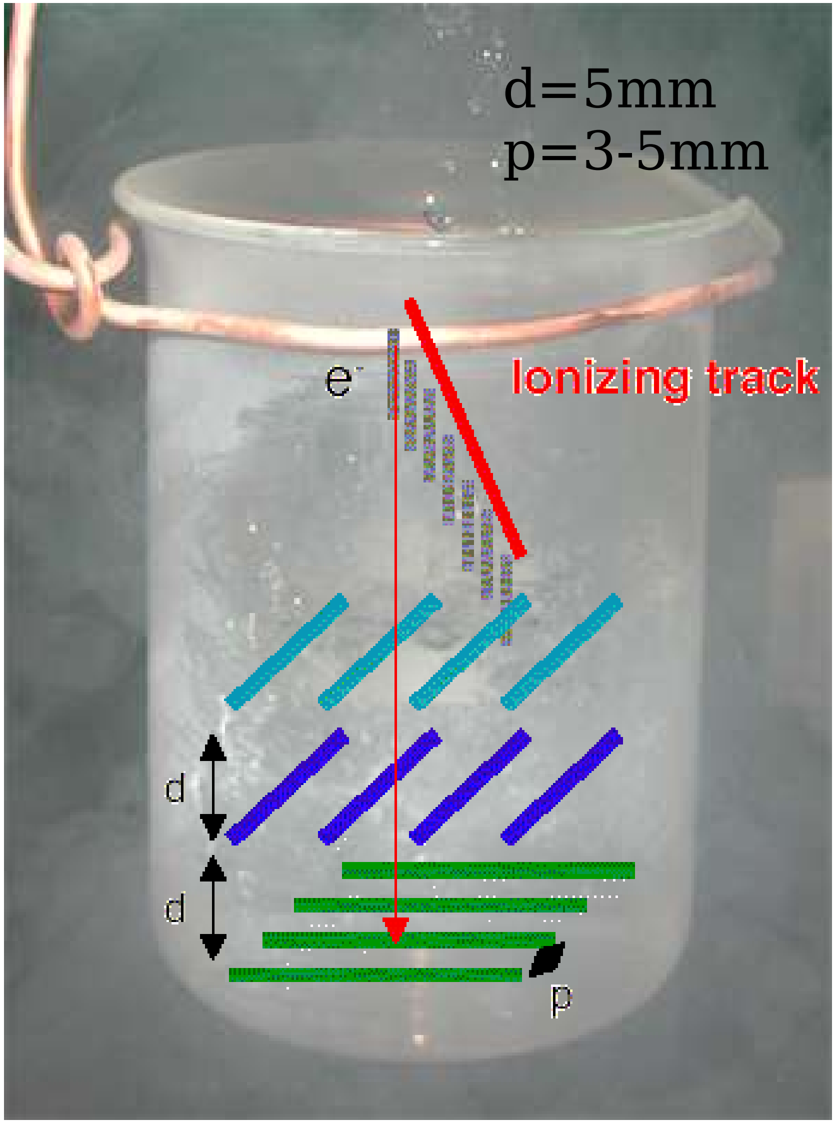
55,000 electrons/cm

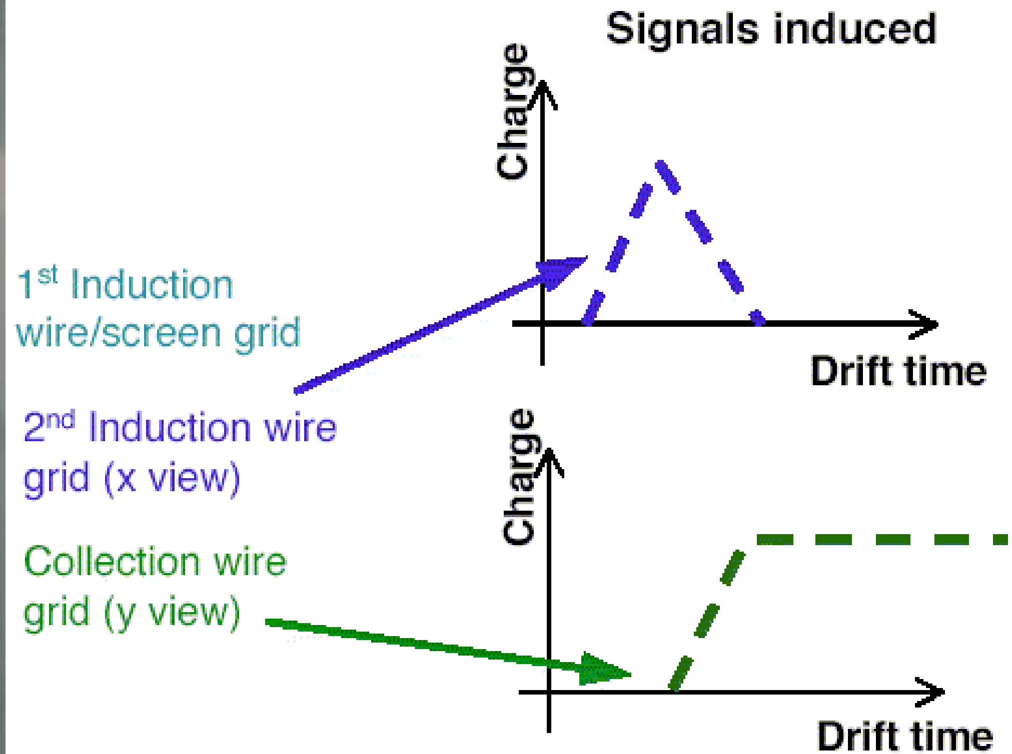


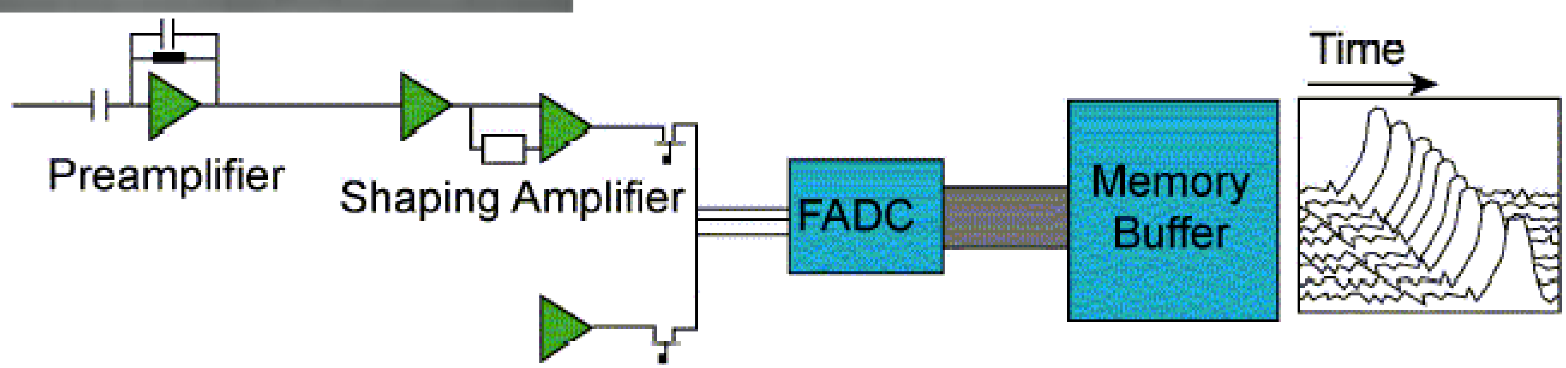
Drift ionization electrons over meters of pure liquid argon to collection planes to image track



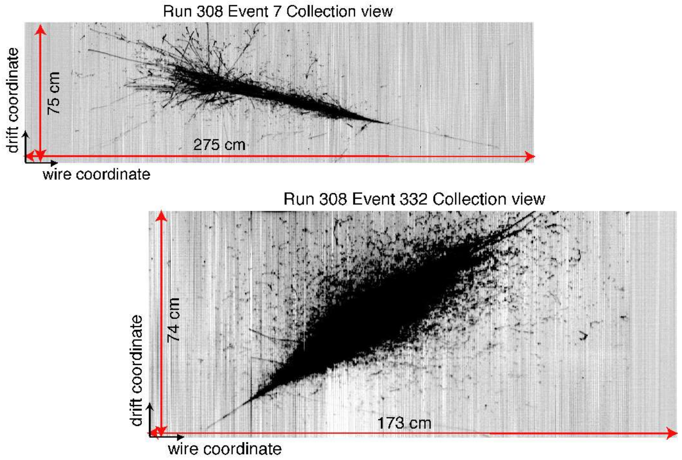
Liquid Argon TPC

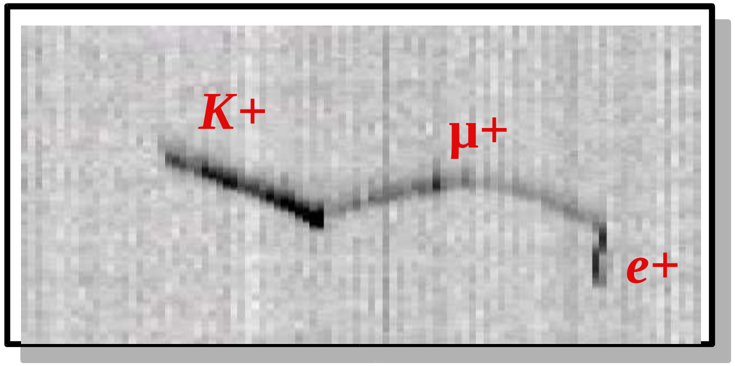






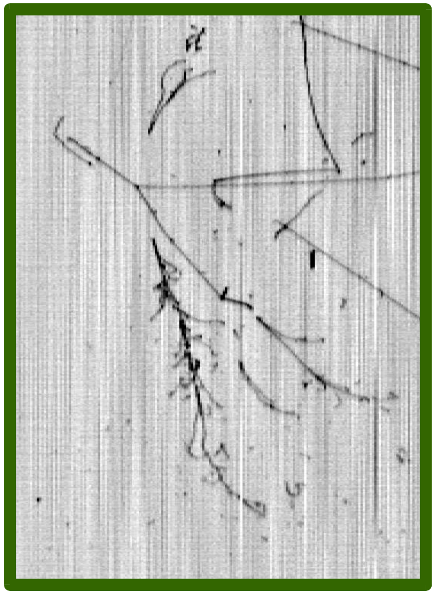
Allows for high resolution imaging like bubble chambers, but with calorimetry and continuous digital readout (no deadtime)

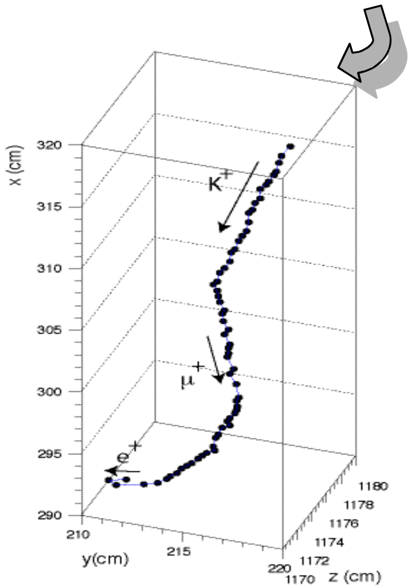




data

data





3D representation of data event

ICARUS images

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 (99 ± 1% eff.)

(only need NC 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

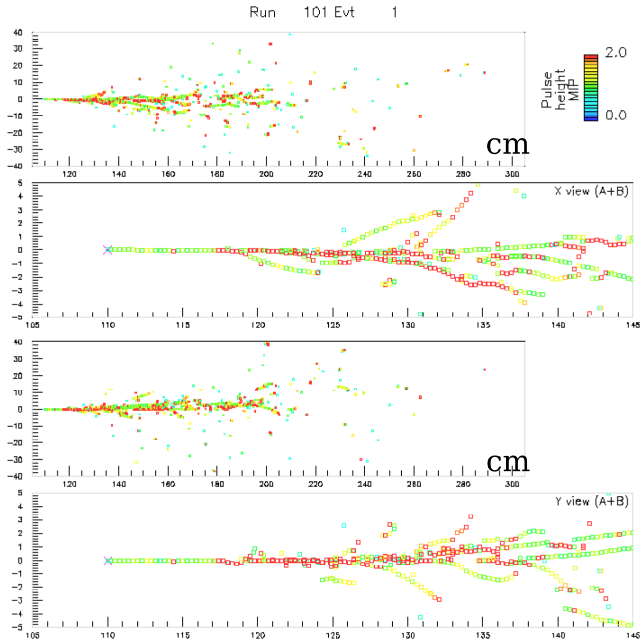
in documents submitted to NuSAG

Electrons versus π^0's at 1.5 GeV

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

X plane → zoom in

Y plane → zoom in

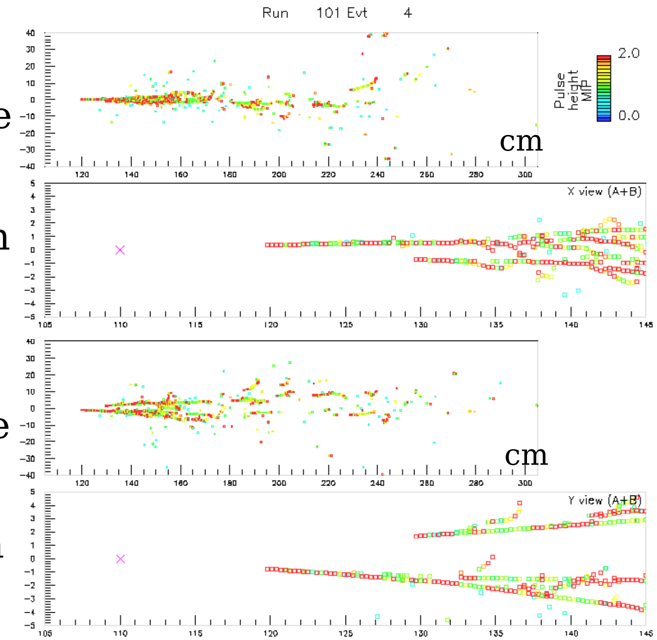


Electrons

Single track (mip scale) starting from a single vertex

X plane → zoom in

Y plane → zoom in



π^0

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

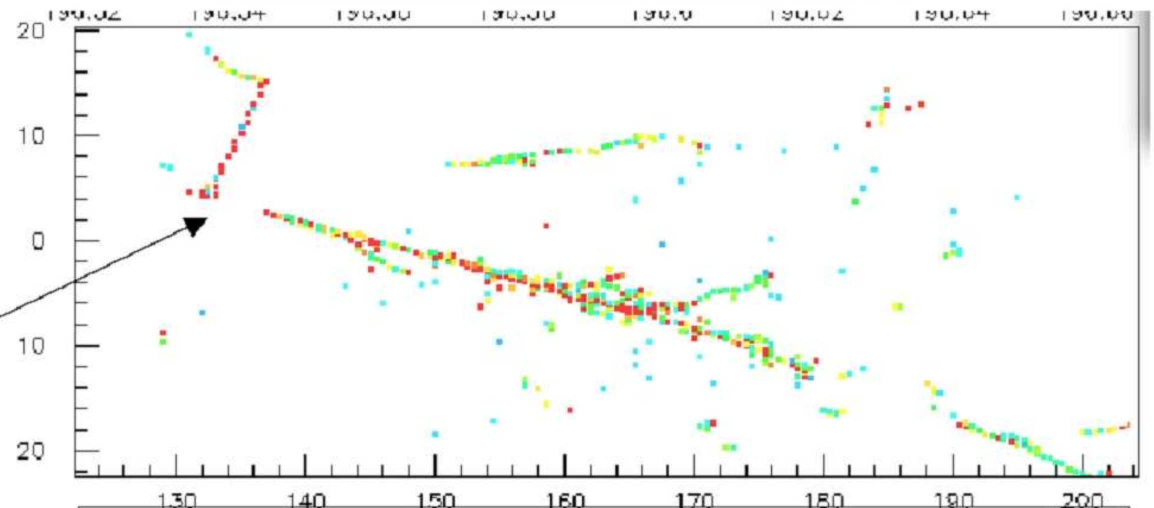
$$\nu_\mu + \mathrm{n} \to \nu_\mu + \pi^+ + \pi^- + \pi^0 + \mathrm{n}$$

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

3.5% X_0 samples

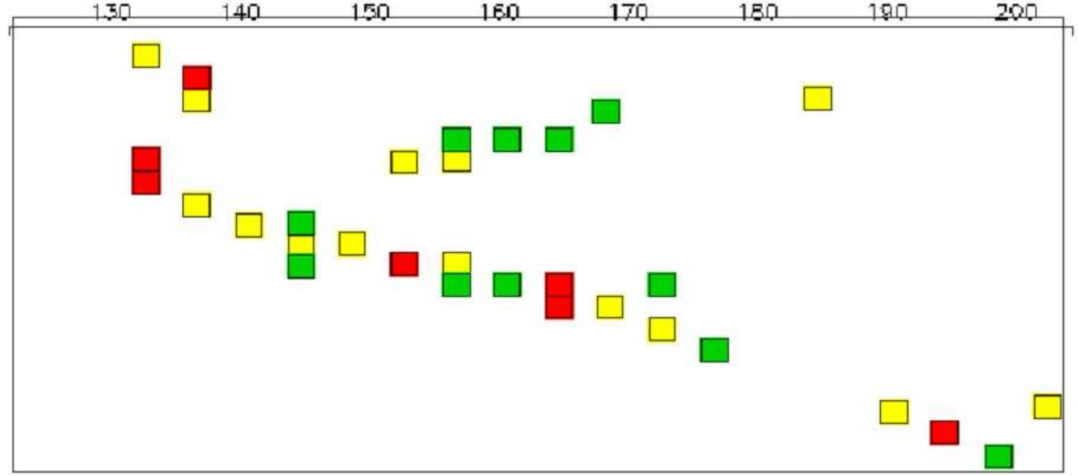
in all 3 views

4 cm gap



12% X_0 samples

alternating x-y



Efficiency and Rejection study

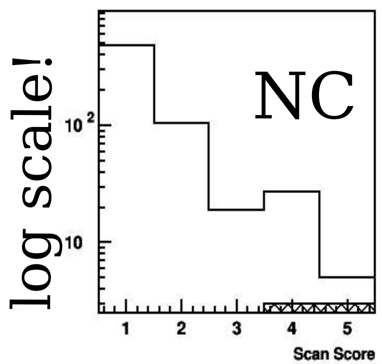
Analysis was based on a blind scan of 450 events, carried out by 4 undergraduates with additional scanning of “signal” events by experts.

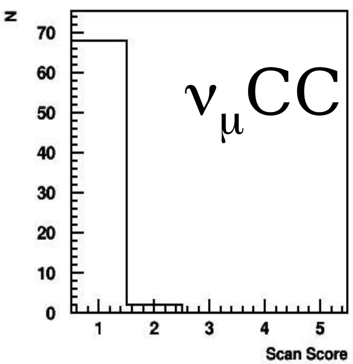
- Neutrino event generator: NEUGEN3. Used by MINOS/NOvA collaboration. Hugh Gallagher (Tufts) is the principal author.
- GEANT 3 detector simulation: trace resulting particles through a homogeneous volume of liquid argon. Store energy deposits in thin slices.

Training samples:

50 events each of ν_eCC, ν_μCC and NC

- individual samples to train
- mixed samples to test training

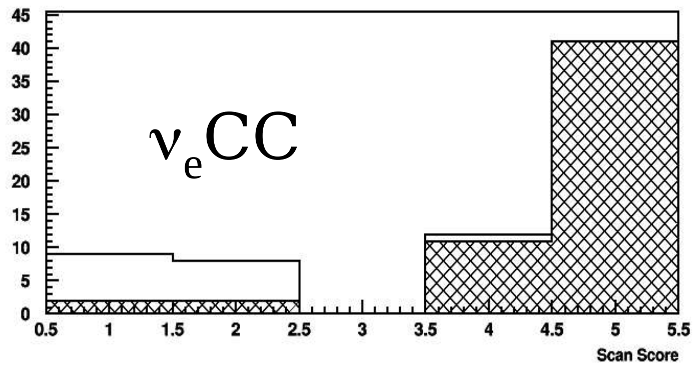




Blind scan of 450 events scored from 1-5 with

- signal=5
- background=1

plain region: students
Hatched region: experts

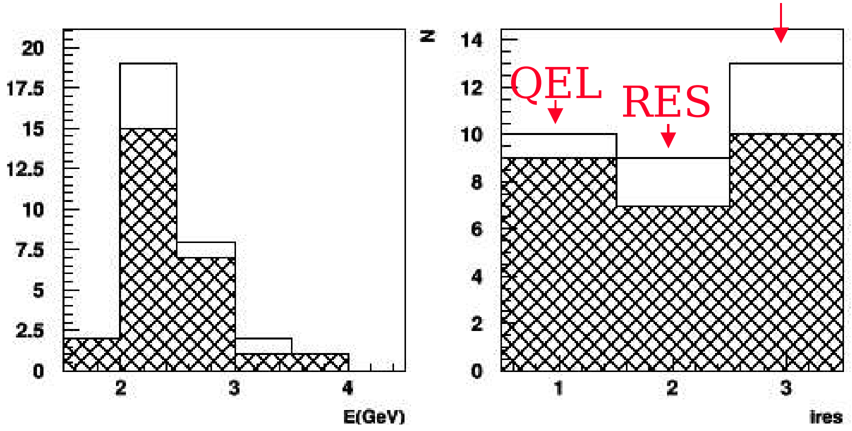


Tufts University Group

Overall efficiencies

	N	pass	ε	η
NC	290	4	-	99
signal ν_e	32	26	0.81	-
Beam ν_e: CC	24	14	0.58	-
NC	8	0	-	

Signal ν_e:



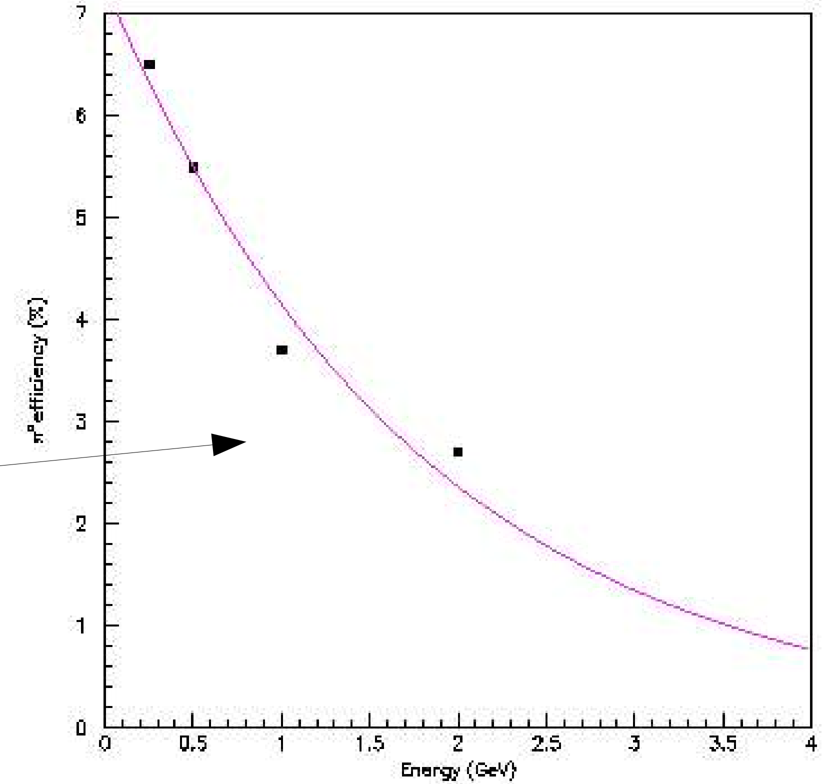
Efficiency is substantial even for high multiplicity events

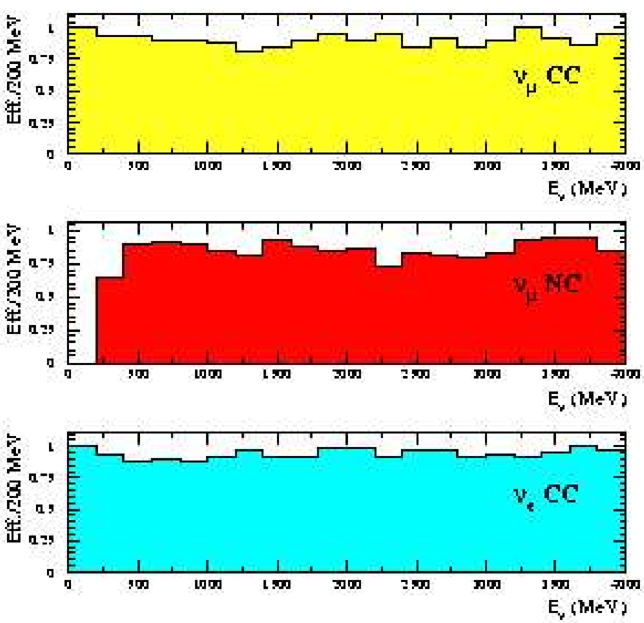
This is the first step towards detailed MC studies including automated reconstruction, noise, etc.
Focus of this study: advance this work

T2K efficiency studies in LArTPC

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

NC pion rejection improves with increasing energy (dE/dx only)





A. Rubbia
from T2K 2km NuSAG submission

Overall ν_e efficiency:
85%-95%

topology

topology +
kinematics, PID

What is beyond NOvA…

- larger 2nd detector at the 1st oscillation maximum
- 2nd detector placed at the 2nd oscillation maximum
- Wide band beam option

- physics sensitivity
- technical feasibility

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

How does this technology compare to conventional technologies?

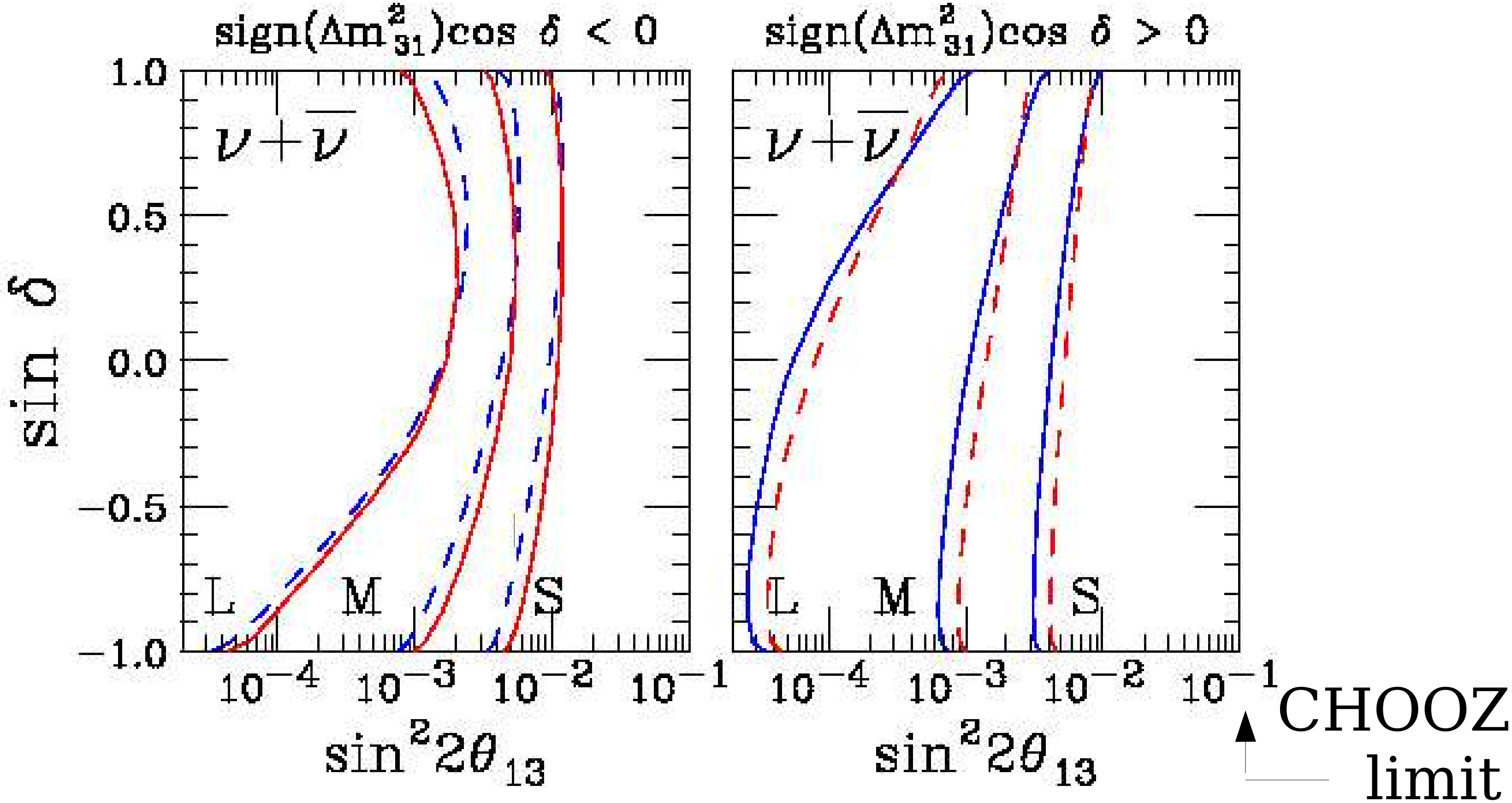
As an example: focus on paper by Mena and Parke

hep-ph/0505202

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

All sensitivities assume 3 years running each in ν and $\bar{\nu}$ mode

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



most restrictive:

cos δ <0, normal hierarchy

cos δ >0, inverted hierarchy

least restrictive:

cos δ >0, normal hierarchy

cos δ <0, inverted hierarchy

2^{nd} Maximum experiment

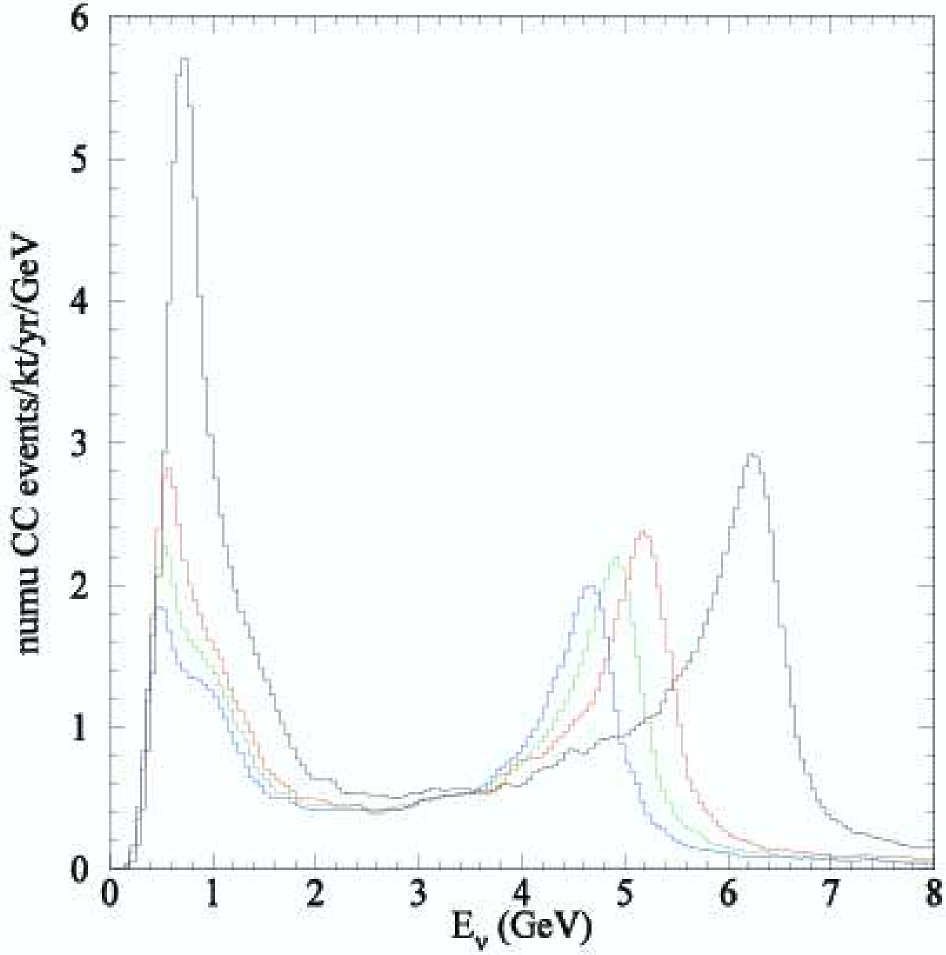
Mark has produced beam spectra that peak near the second maximum (525 MeV at 810 km)

30 km off-axis

36 km off-axis

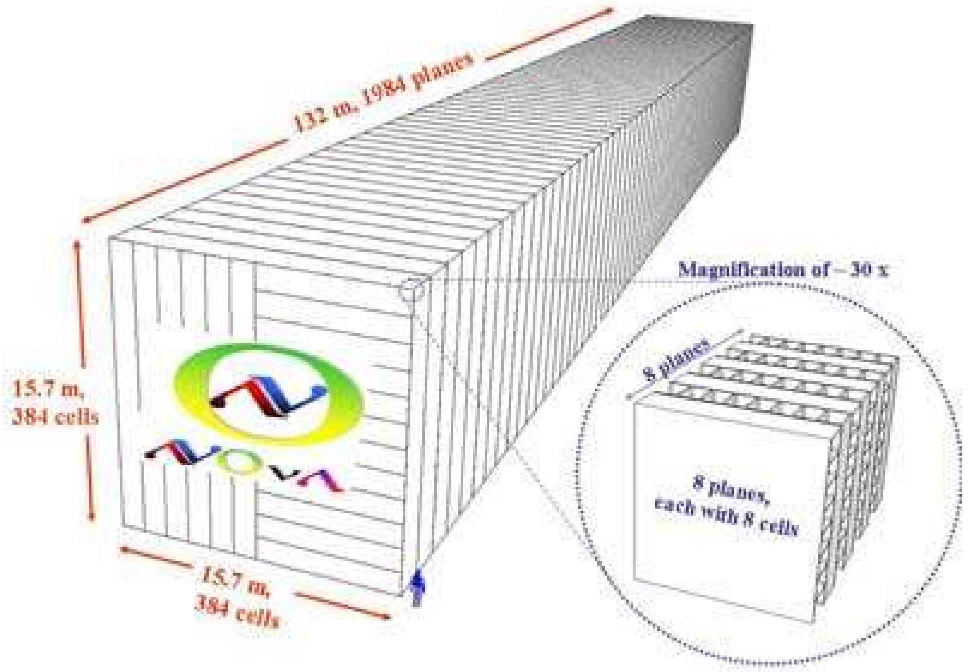
38 km off-axis

40 km off-axis



slide from Peter Litchfield

NOvA at the 2nd maxima:



- alternating xy cells of liquid scintillator
- cells: 15.7m x 3.87cm x 6.0 cm
- 0.8mm looped WLS fiber in each cell for light collection
- WLS fibers read-out by APDs
- 80% active material

for 2nd detector location:

- scale to 100kton
- detector at 735km
- 5 year neutrino run

1st pass of efficiencies in NOvA-like detector indicate .....

2^{nd} maximum experiment

I ran my selection program with the variables and cuts I used to examine the Booster 8 GeV beam in Nova and a very minimum of tuning (~2 hours)

Parameters: 100kton detector, 5 years run, 3.7 10^{20} pot at 735km
m^2=0.0025 eV^2, $sin^2 2\ _{23}$=1, $sin^2 2\ _{13}$=0.1

km	E_{osc} after energy cut	Selected e_{osc}		nc	e_{beam}	FOM
30	292	55	10	69	15	5.9
36	223	51	3	49	11	6.4
38	188	43	2	43	10	5.8
40	156	36	1	39	10	5.1

compare to FOM of ~25 for NOvA on axis

slide from Peter Litchfield

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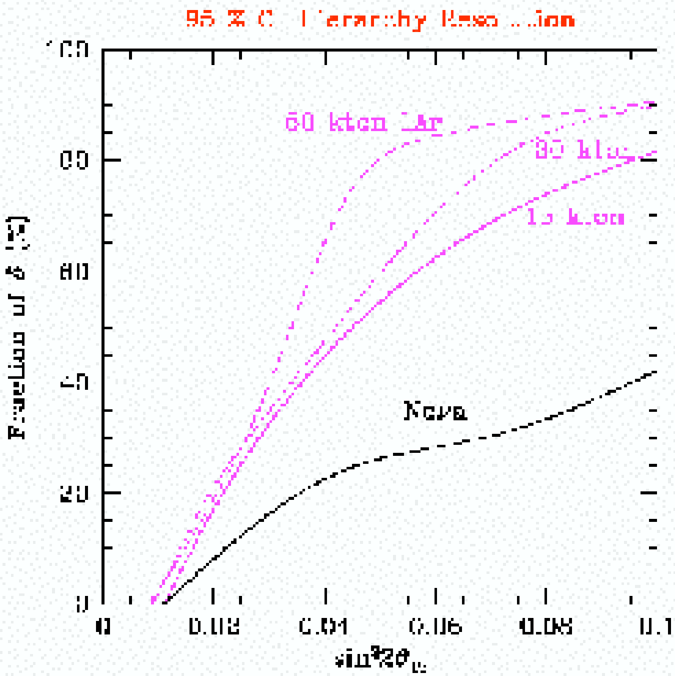
40	156	36	1	39	10	5.1
LAr at 36	223	178		5	38	27

compare to FOM of ~25 for NOvA on axis

slide from Peter Litchfield

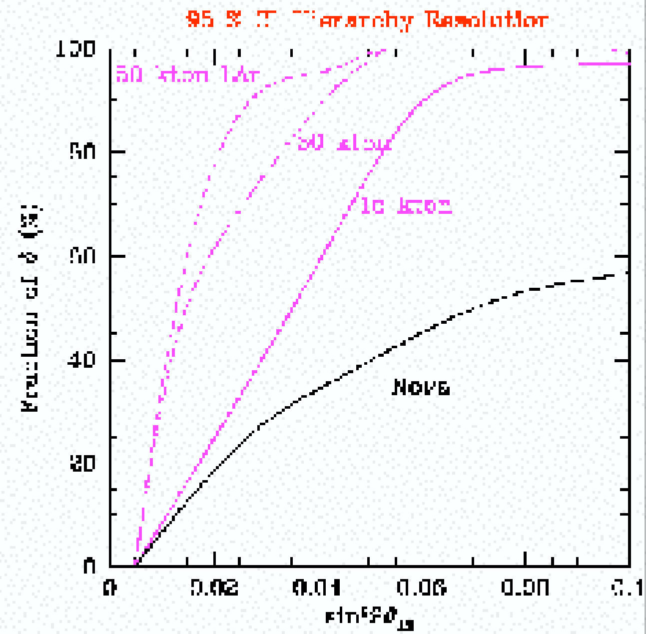
SuperNOvA sensitivities with LAr.....

O.M, S.Palomares-Ruiz and S.Pascoli, ``Determining the neutrino mass hierarchy and CP Violation in Nova with a second off-axis detector,'' hep-ph/0510182



Liquid Argon
Fid. Vols +
90% eff

NOvA
30 ktons
24% eff



6.5 e20 pot/yr

Exposure (yrs):
Far: 3 nu + 3 nubar
Near + Far: 6 nu + 2 nubar

Proton Driver: 25e20 pot/yr

Exposure (yrs):
Far: 3 nu + 3 nubar
Near + Far: 3 nu + 1 nubar

Efficiencies and purities
in NOvA-like detector
make expt. at 2nd oscillation max
difficult/impossible

Efficiencies for LAr at lower energies (~800 MeV)
is the same or better than at higher energies (>80%)

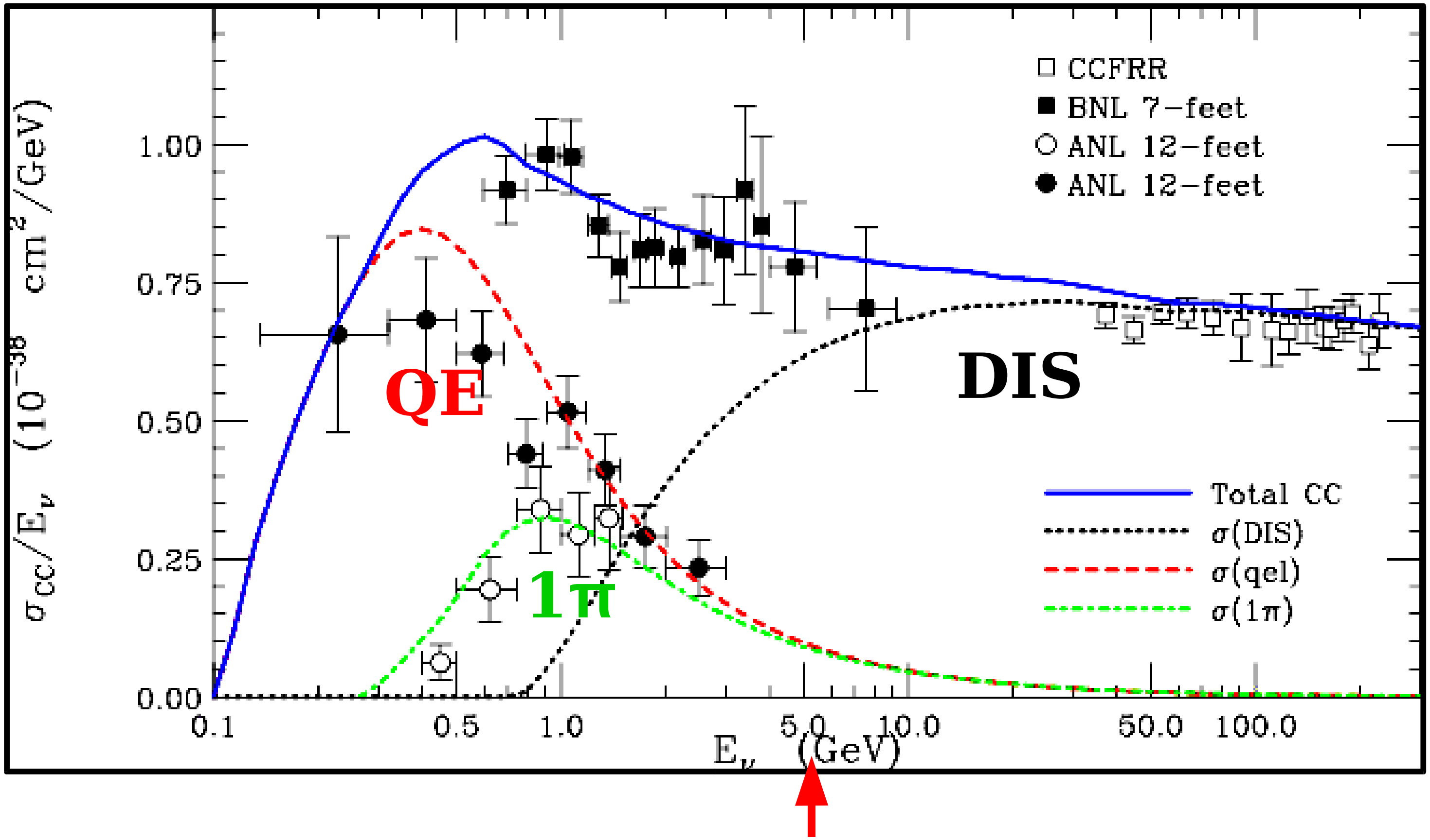
(T2K LAr study demonstrates 90% efficiency for
800 MeV off-axis T2K beam at 2km)

preliminary sensitivity studies
using GLOBES underway....
(Scott Menary)

simple GEANT3 MC to
understand energy resolutions,
backgrounds, etc...

*Efficiencies and purities in LAr
at these energies need further study
(need to be more quantitative)*

What about going to a wideband beam?



Need to differentiate ν_e's from background up to 5 GeV

backgrounds from 1π and DIS go up...

resolving interactions via topology -> suggest LAr very good in this regime

needs further study!

How good is the energy resolution at these energies?
How does this affect sensitivity?

For all possible scenarios....

Cosmic Backgrounds....

↓

Necessary Overburden....

What overburden (if any) is necessary to reduce backgrounds for ν_e appearance searches?

-beam timing helps

-reconstruction helps

needs further study

What physics gain is there with significant overburden?

-> proton decay

Getting above 10^{34}y

- Massive water Cerenkov detectors in the megaton range: Hyper Kamiokande
- Liquid Argon detectors in the 100 kton range (evolution of ICARUS in the "Dewar" concept)

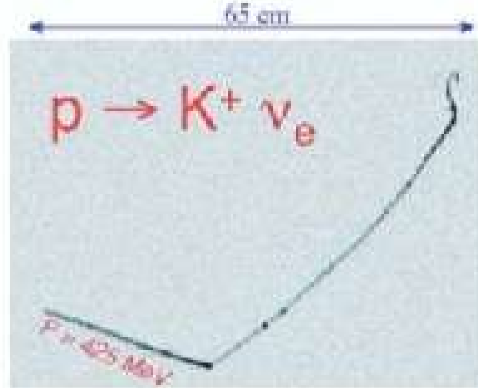
2 Sep 2005

The liquid Argon TPC: a powerful detector for future neutrino experiments and proton decay searches

A. Ereditato[a] and A. Rubbia[b]

[a]Istituto Nazionale di Fisica Nucleare, INF

[b]Institut für Teilchenphysik, ETHZ, CH-8



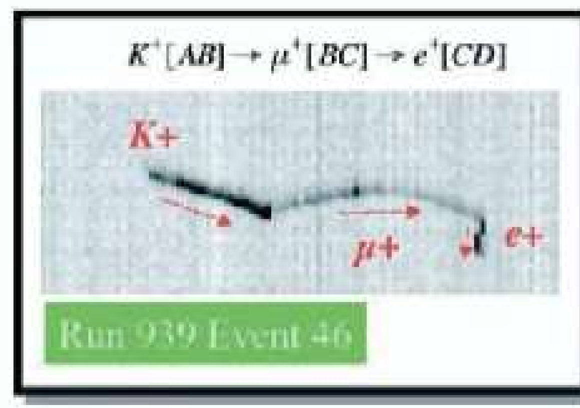
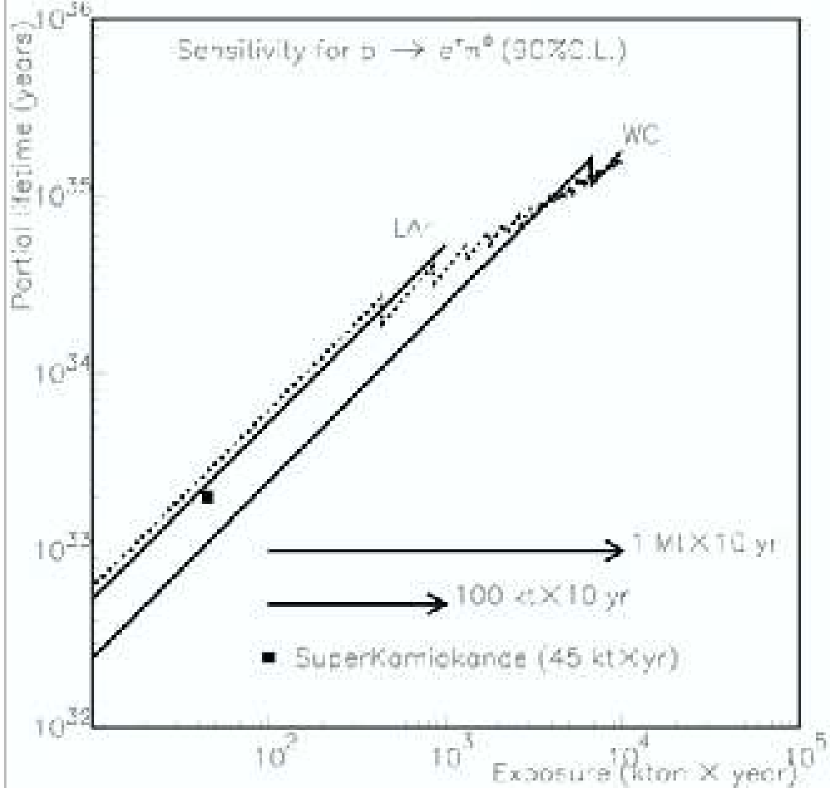


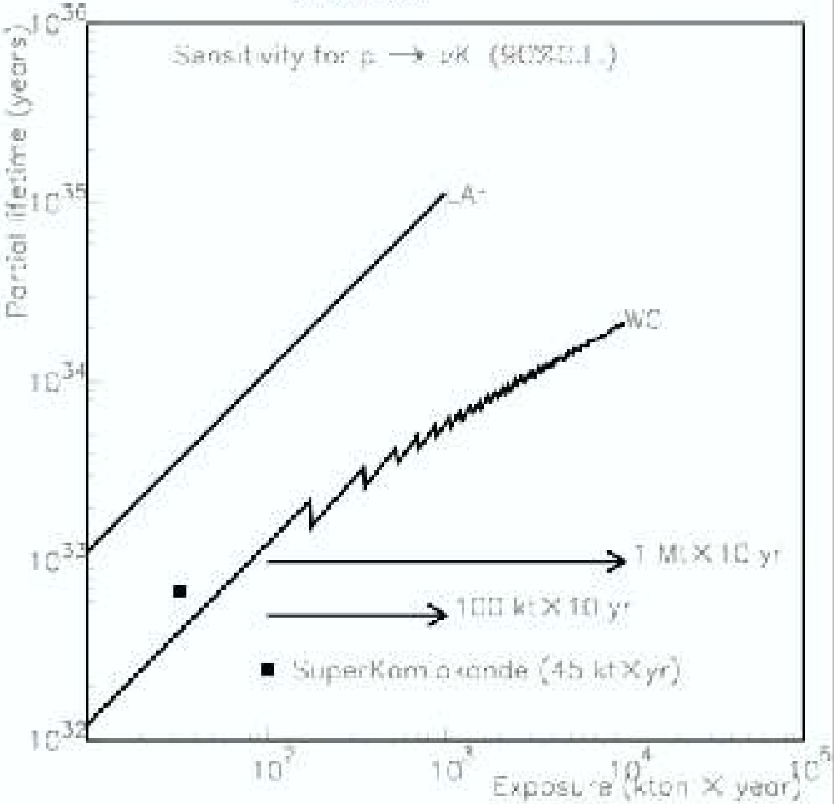
Figure 6: (left) MC event of $p \to K^+\nu$ in a liquid Argon TPC. (right) Real event collected in ICARUS T600 cosmic run performed on surface with a stopping kaon topology

Discovery potential of Water Cerenkov and Liquid Argon technologies

Very massive underground detectors for proton decay searches[1]

A. Rubbia





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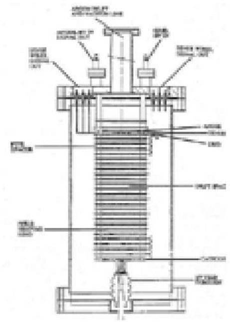
Can we build these detectors?

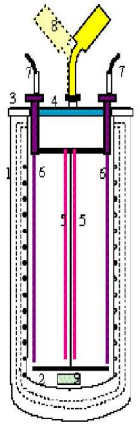
Technical Feasibility:
History of prototype work on ICARUS



24 cm drift
wires chamber

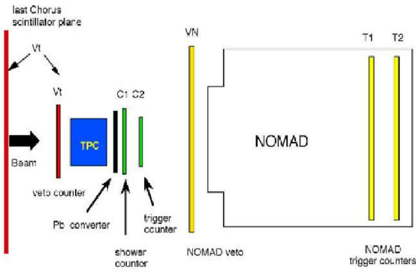
1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

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

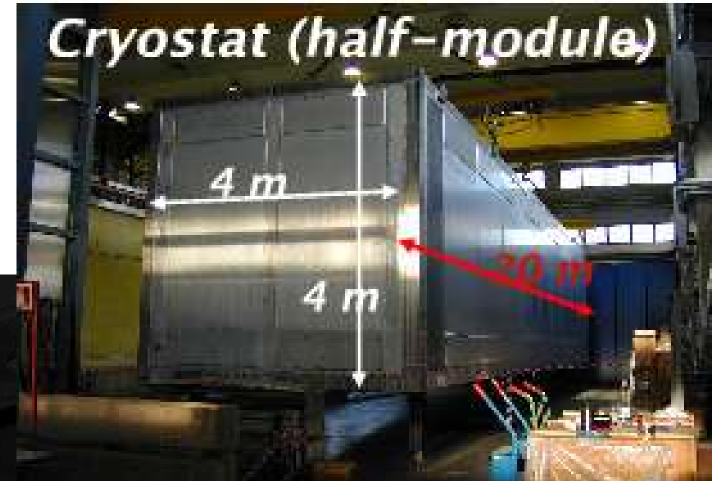


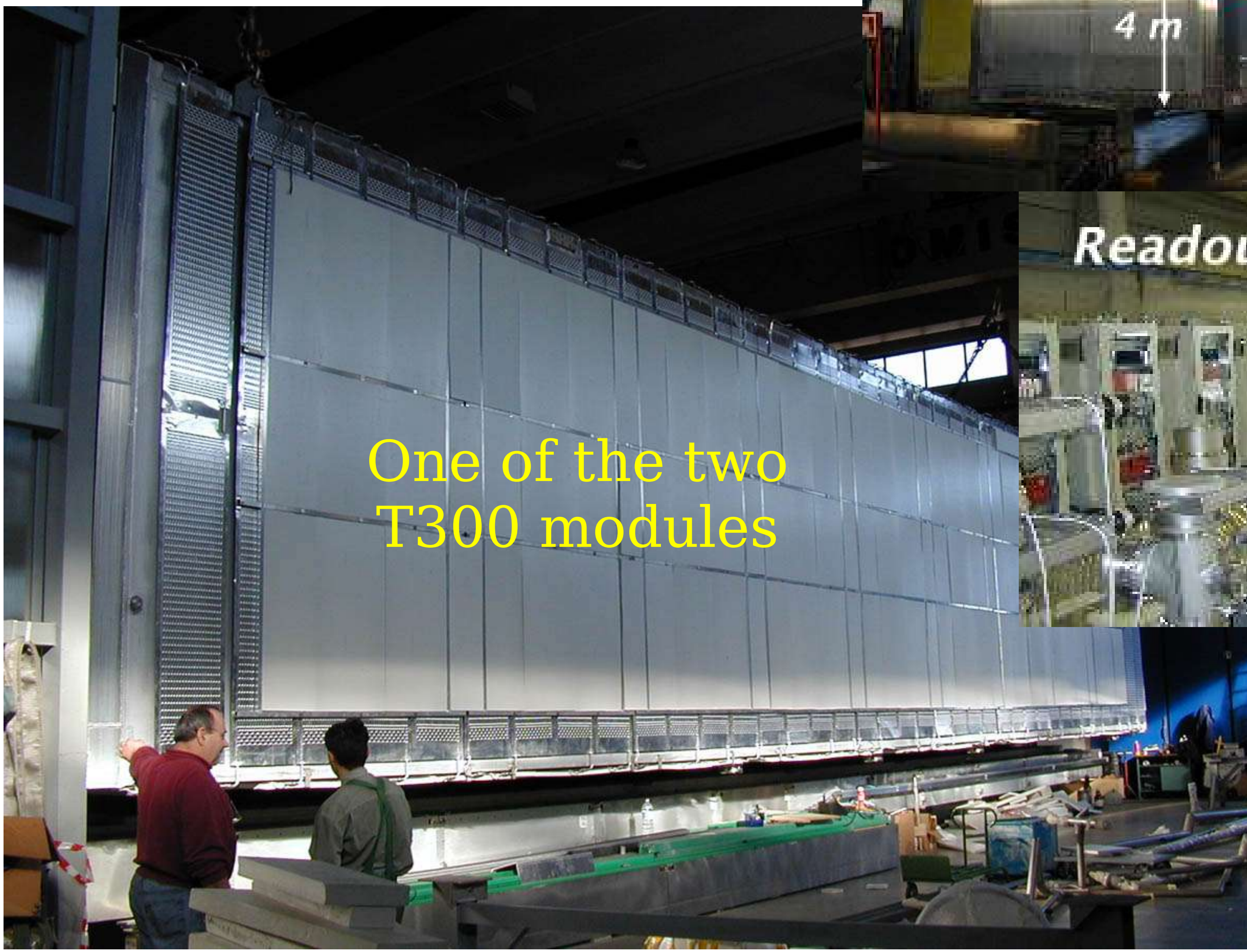
1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

10 m^3 industrial prototype

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

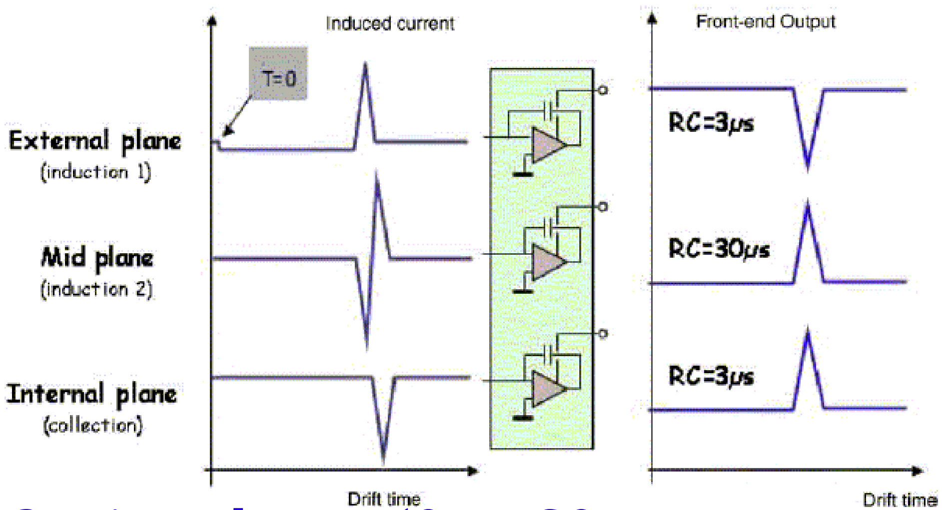
The success of the
ICARUS T600

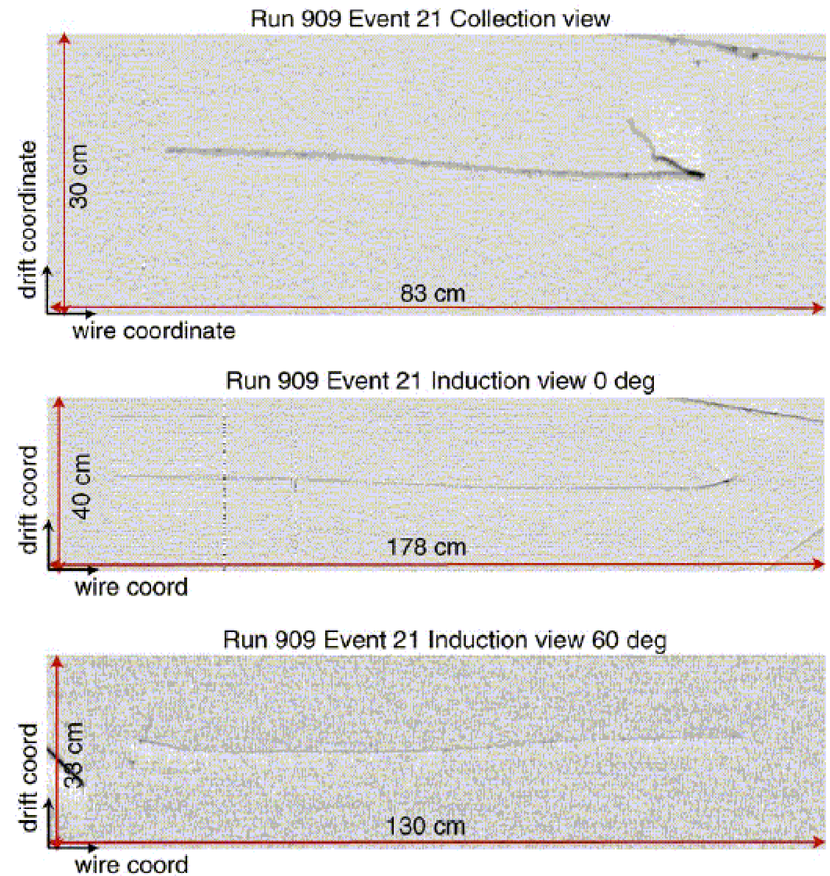




tested above
ground in Pavia
in 2001
now below
ground in
Gran Sasso

Signals and event reconstruction from T300

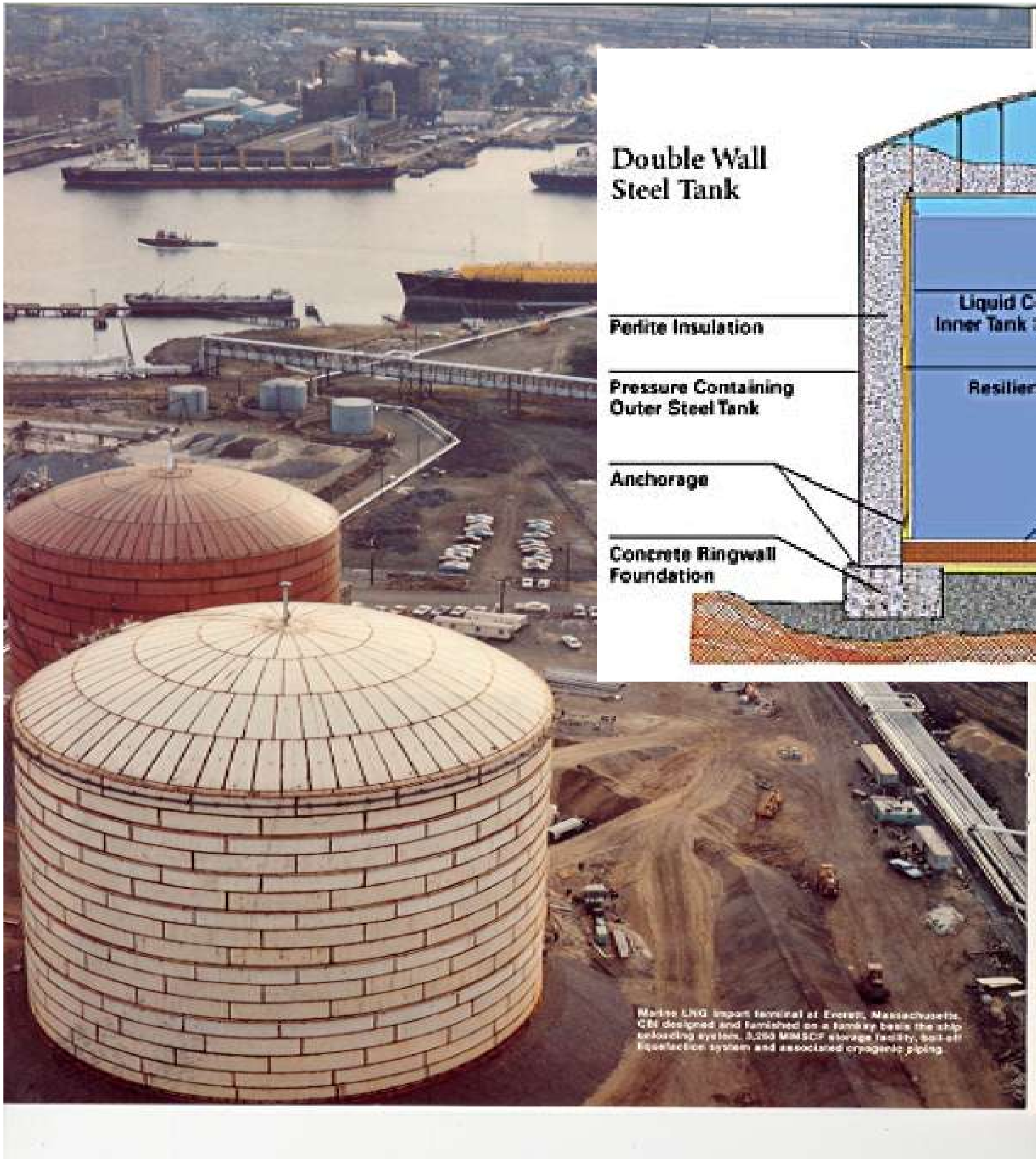


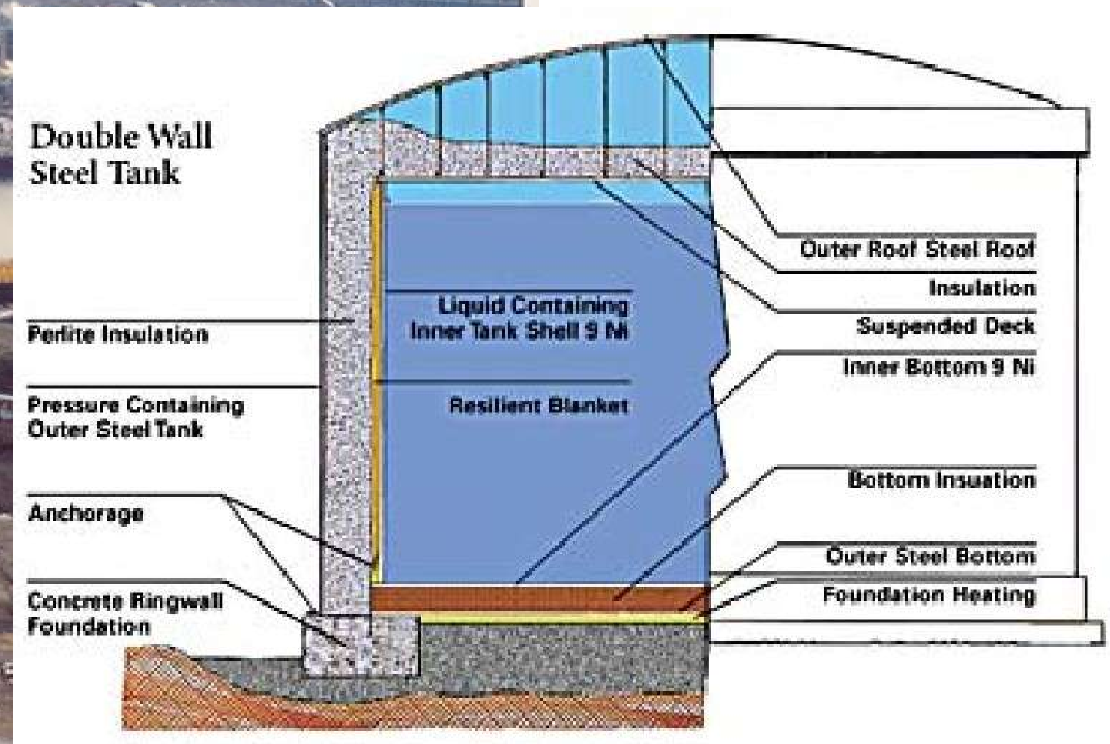


- 3 wire planes (0°, ±60°)
- 3mm wire pitch, 3mm distance b/t wire planes
- 0° **wires**: 9.4 m long, ±60° wires: 3.8m long
- Input capacitance (wire+cable)
0° **wires**: ~400 pF, ±60° wires: ~200 pF

- Ionization signal: 55,000 e/cm @ 500 V/cm (before atten.)
- Signal/Noise ratio ~10
- each wire digitized at 2.5 MHz by a 10 bit flash ADC

Can we scale up to more
massive detectors?
15-50ktons?

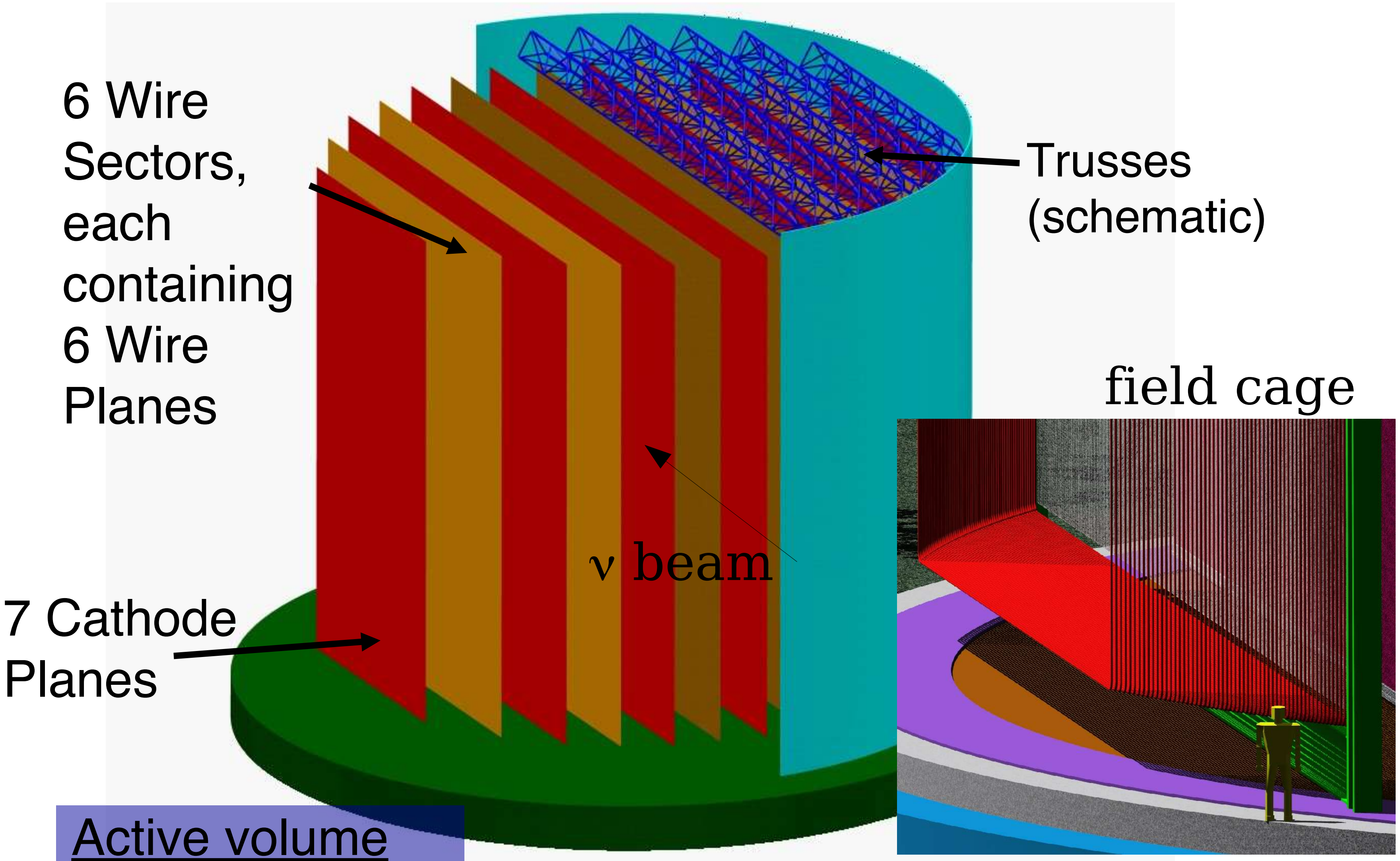




Many large LNG tanks in service

Excellent safety record
Last failure in 1940 understood

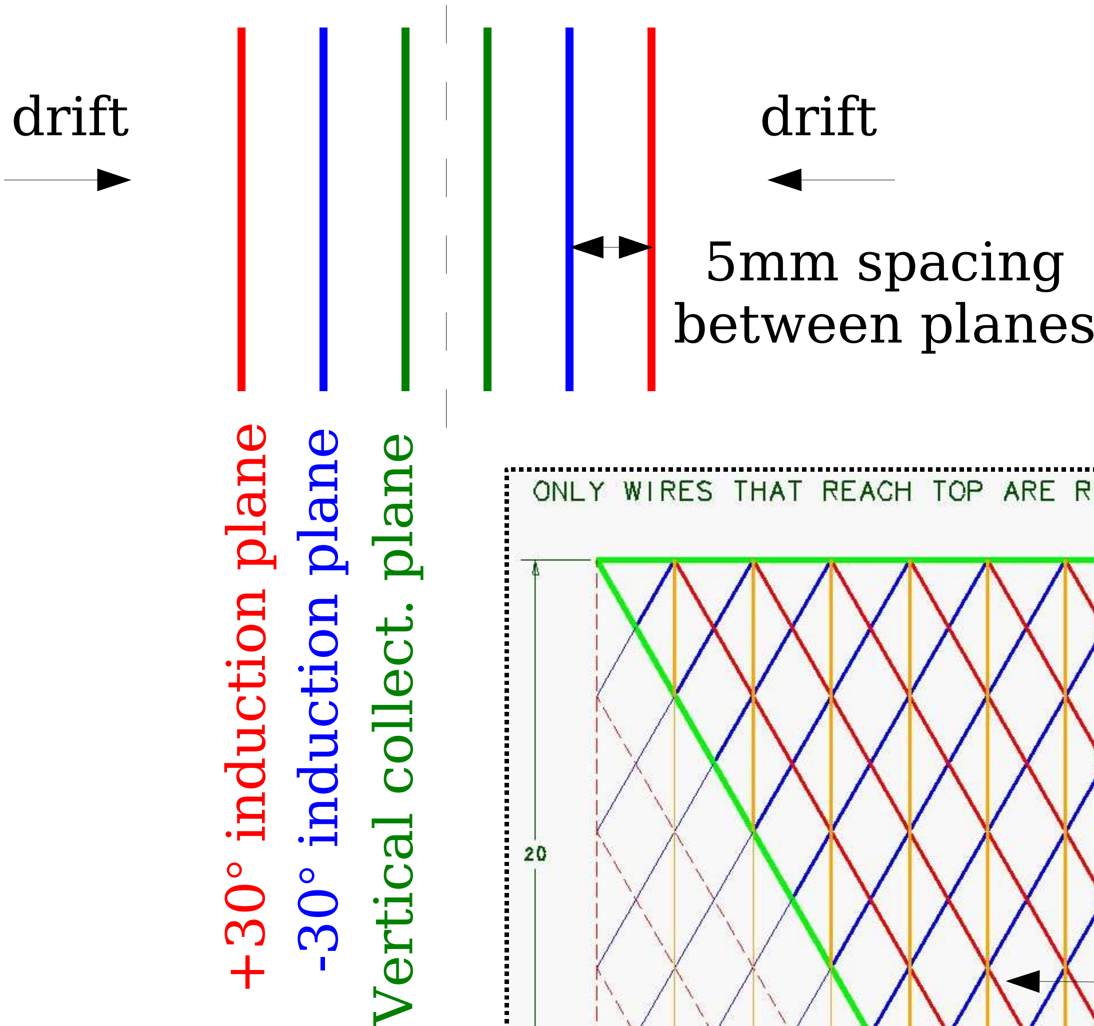
Modularized drift regions inside tank



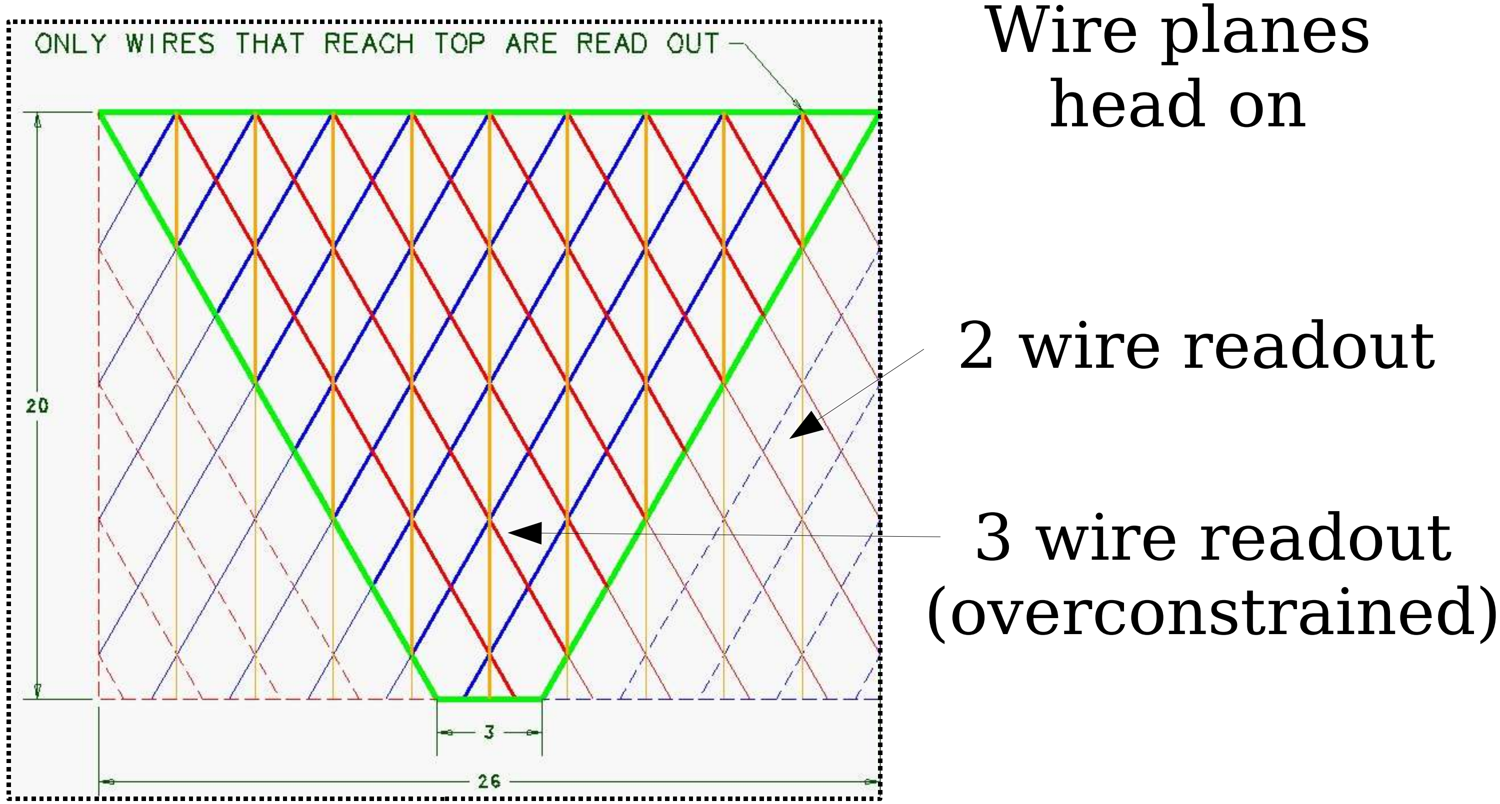
Active volume
Diameter: 40m
Height: 30m

Scalable → 15-50 kTons
4 - 6 wire planes

Each wire plane:

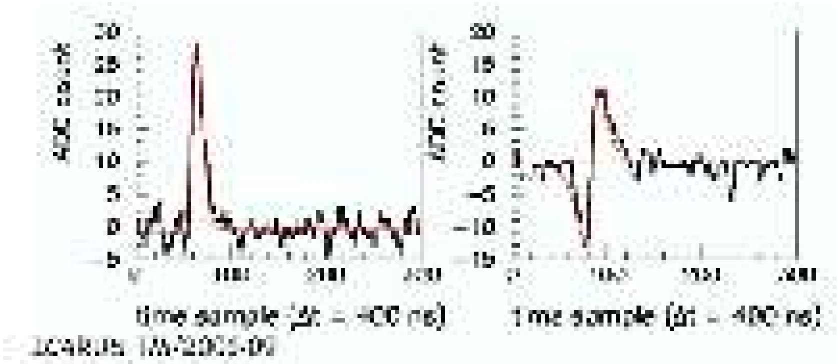


Wires are
- 150 μm stainless steel
- 5mm pitch
- 23m long (15kton)
  35m (50kton)
- 100K total (15kton)
  220K (50kton)



Electrons drift 1.5m/ms (150kV field) over 3m drift region

Electronics and Data Acquisition



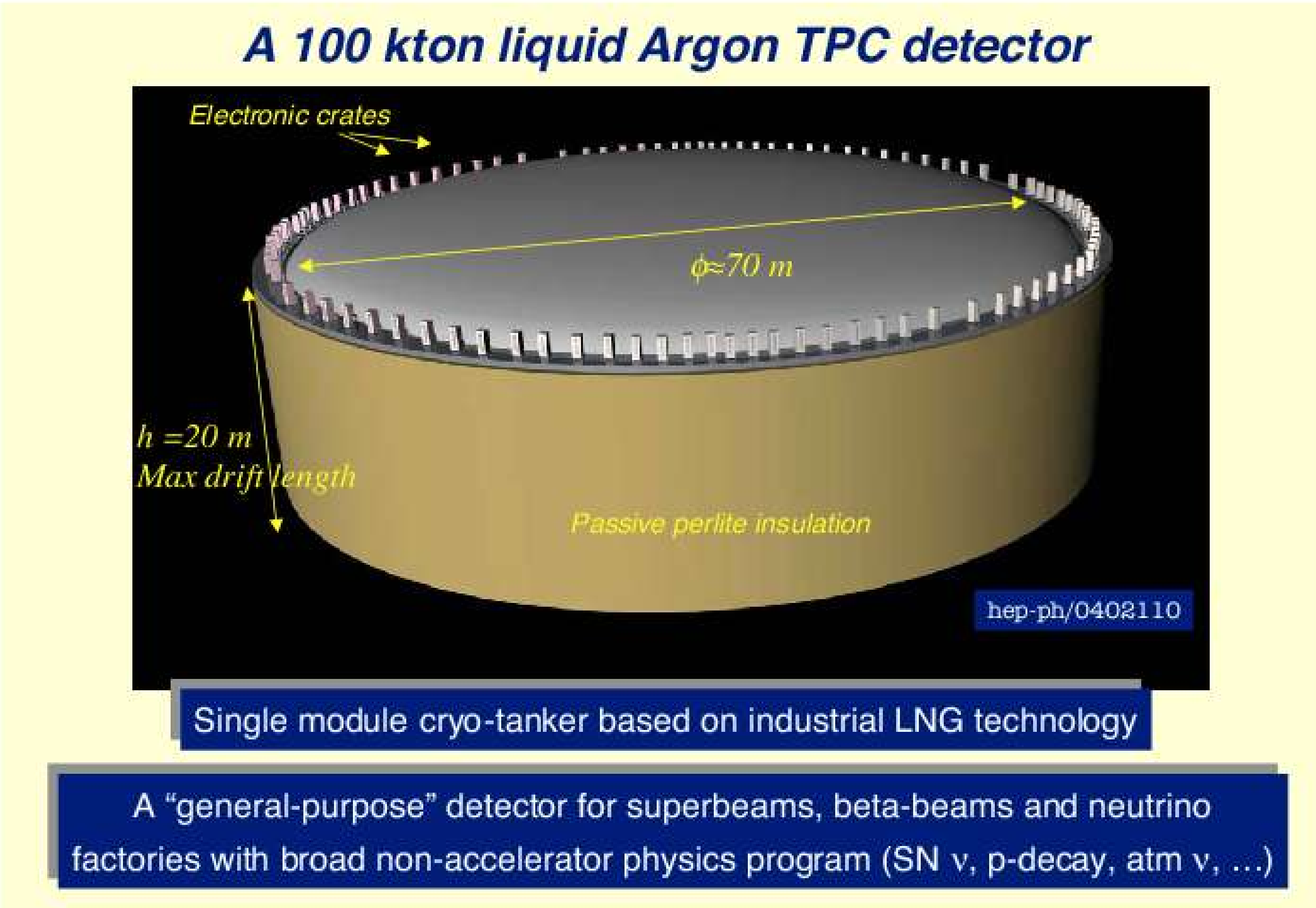
Electronics:

ICARUS scheme: an intelligent waveform recorder on each wire: (S/N = 8.5/1)

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

Data acquisition

- Use commercial switches and multiplexors
- Have a design to achieve 5 Gbytes/sec



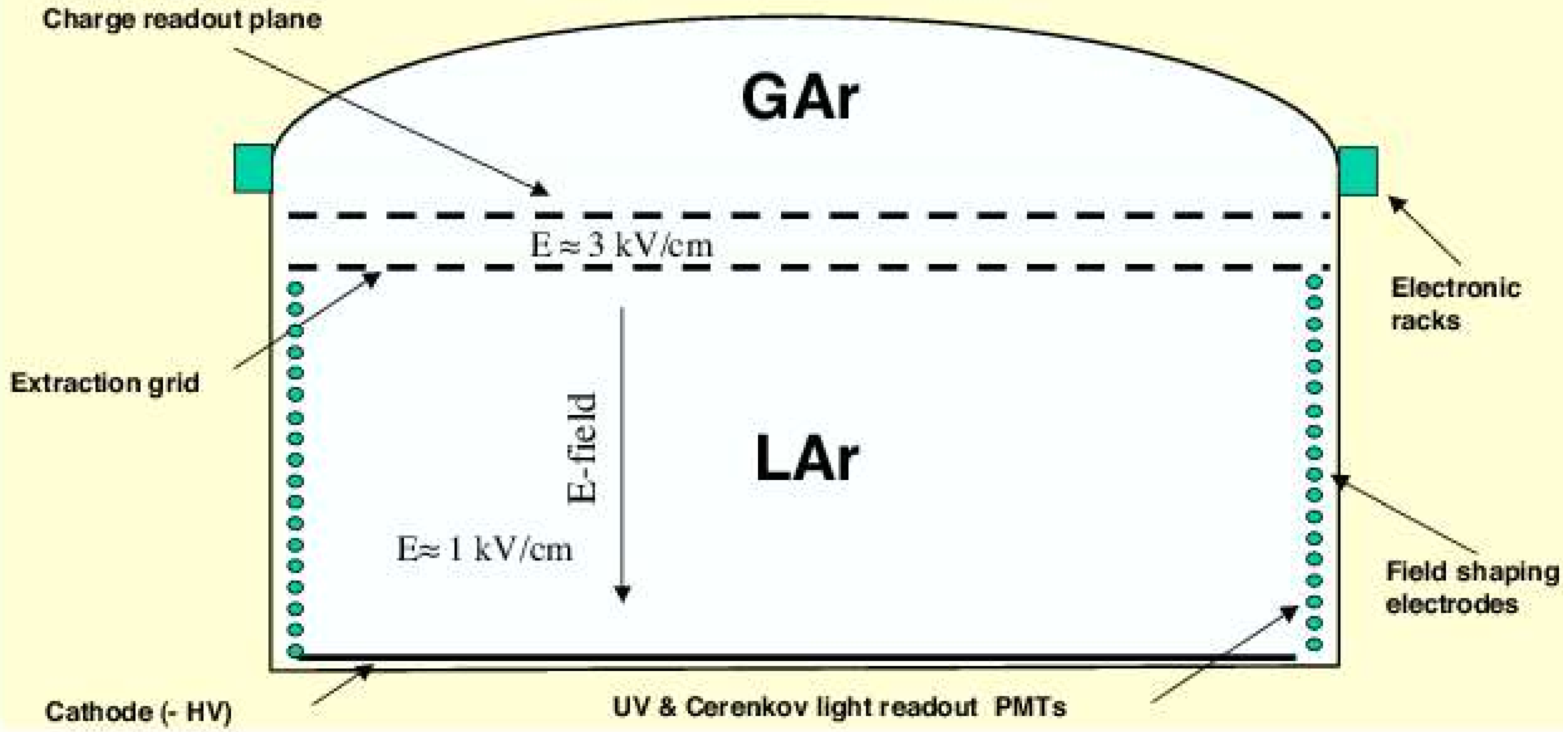
from A. Rubbia's talk at NuFACT05

What are the advantages/disadvantages of this design?

A tentative detector layout

Single detector: charge imaging, scintillation, Cerenkov light

Dewar	$\phi \approx 70$ m, height ≈ 20 m, perlite insulated, heat input ≈ 5 W/m^2
Argon storage	Boiling Argon, low pressure (<100 mbar overpressure)
Argon total volume	73000 m^3, ratio area/volume $\approx 15\%$
Argon total mass	102000 tons
Hydrostatic pressure at bottom	3 atmospheres
Inner detector dimensions	Disc $\phi \approx 70$ m located in gas phase above liquid phase
Charge readout electronics	100000 channels, 100 racks on top of the dewar
Scintillation light readout	Yes (also for triggering), 1000 immersed 8" PMTs with WLS
Visible light readout	Yes (Cerenkov light), 27000 immersed 8" PMTs of 20% coverage, single γ counting capability



magnetized LAr?

from A. Rubbia's talk at NuFACT05

Challenges for massive "multi-drift region" detector

Purity:

3 m drift in LAr

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*

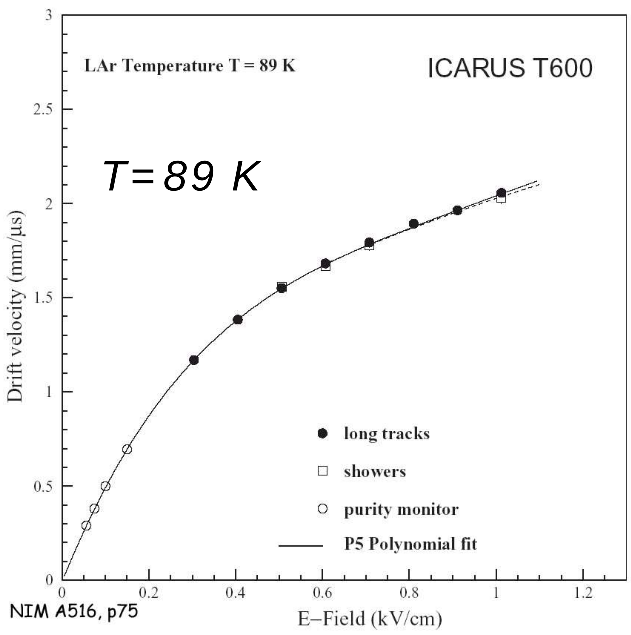
Signal processing:

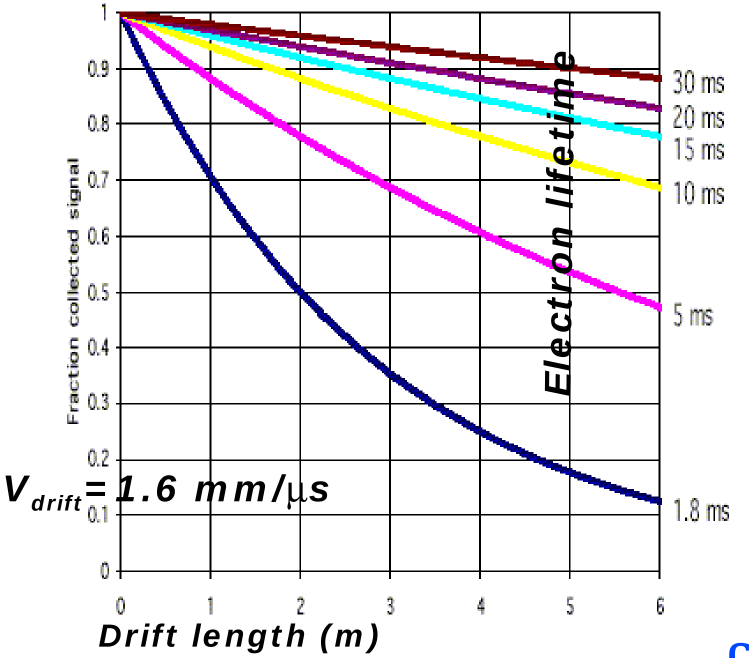
electronics *- noise due to long wire and connection cables (large capacitance)*

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

Can we drift over over long distances (3m) ?

Experience from ICARUS:
Max HV: 150kV
(E=1kV/cm in T600)
v_{drift} = 1.55±0.02 mm/μs
@ 500 V/cm



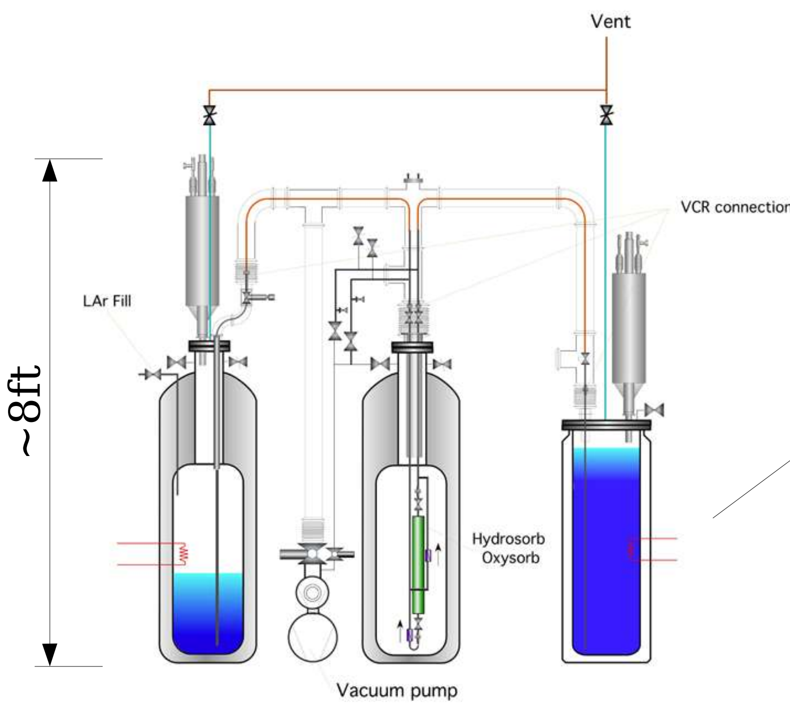


To drift over macroscopic distances -> very pure LAr

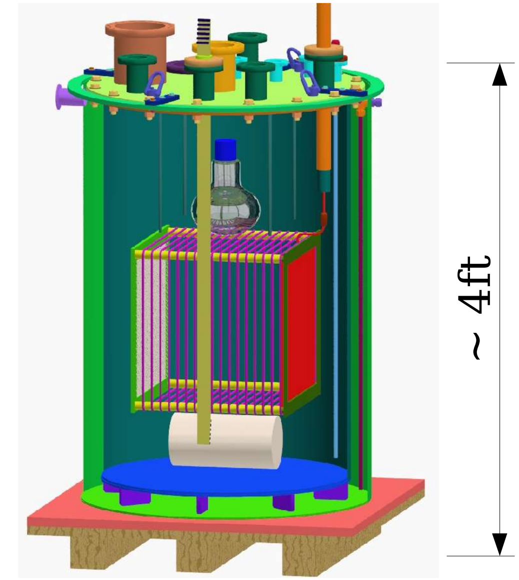
- a concentration of 0.1 ppb Oxygen equivalent gives an electron lifetime of 3ms

for 3m drift and <20% signal loss -> electron lifetime of 10ms

R&D efforts underway



at FNAL

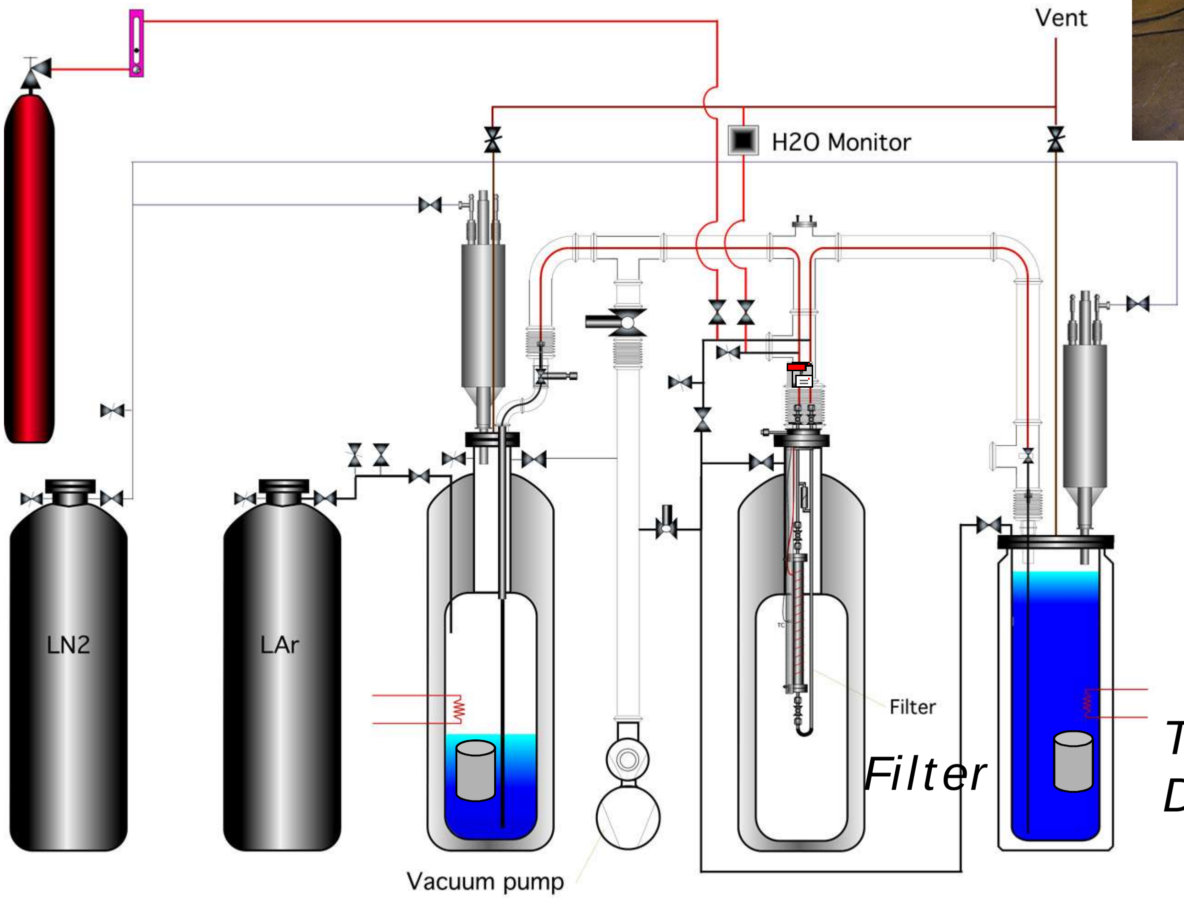


at Yale

at UCLA/
CERN

Material tests

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



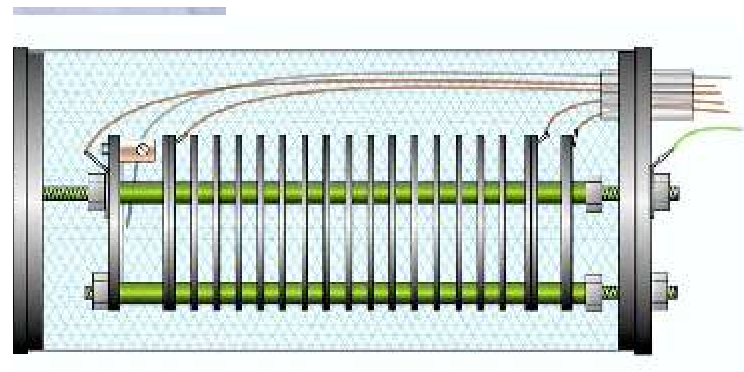
ICARUS purity monitor

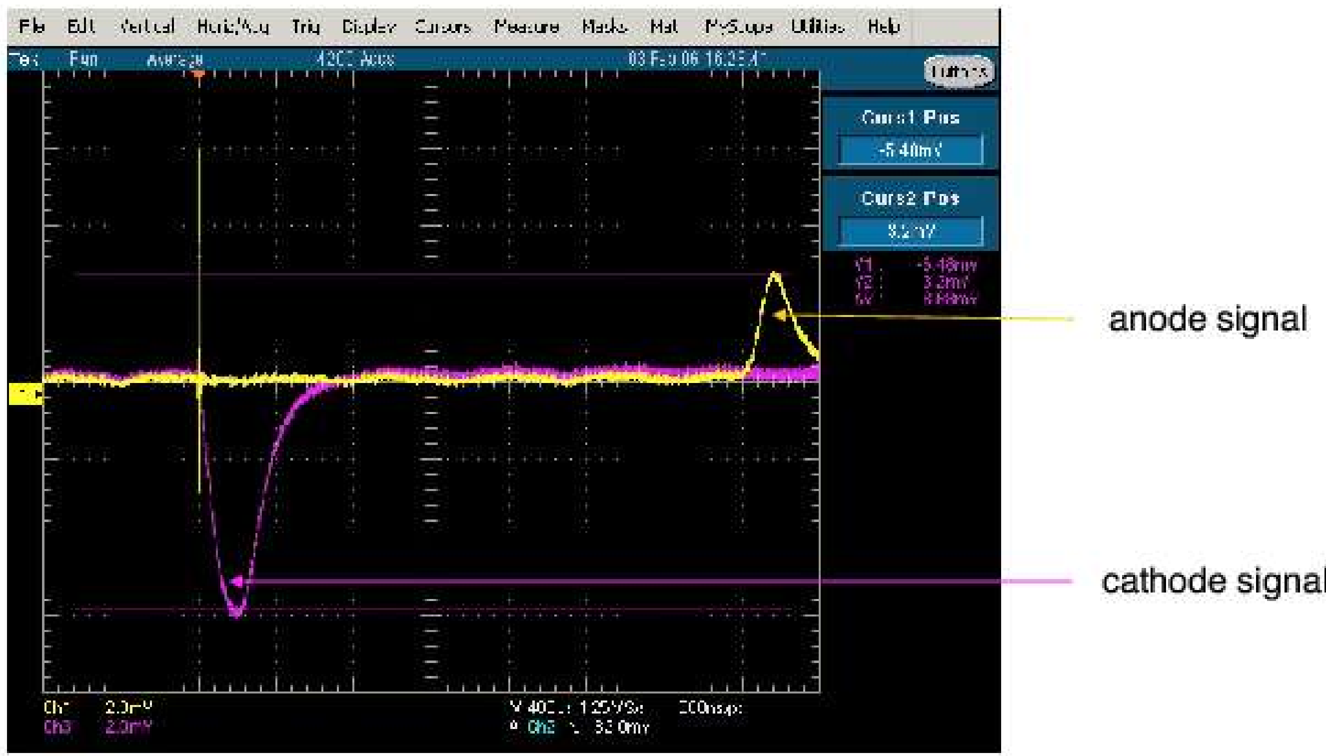
G. Carugno et al., NIM. A292 (1990

Test Samples Dewar

C.Kendziora6.13.05

purity monitor measures transmission of electrons from cathode to anode



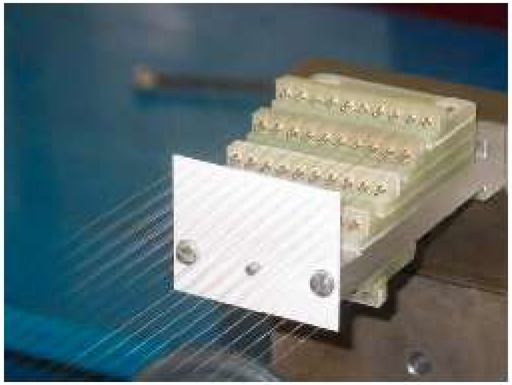


a 2.8 millisecond drift, $Q_{anode}/Q_{cathode} \sim 0.4$ (*)

(*) peaks need some correction for cathode signal rise-time

Long wire tests (ultimately in a LN_2 vessel)

A first setup in air of 20 meter long wires to study noise (microphonics) and have a first stab at electronics.

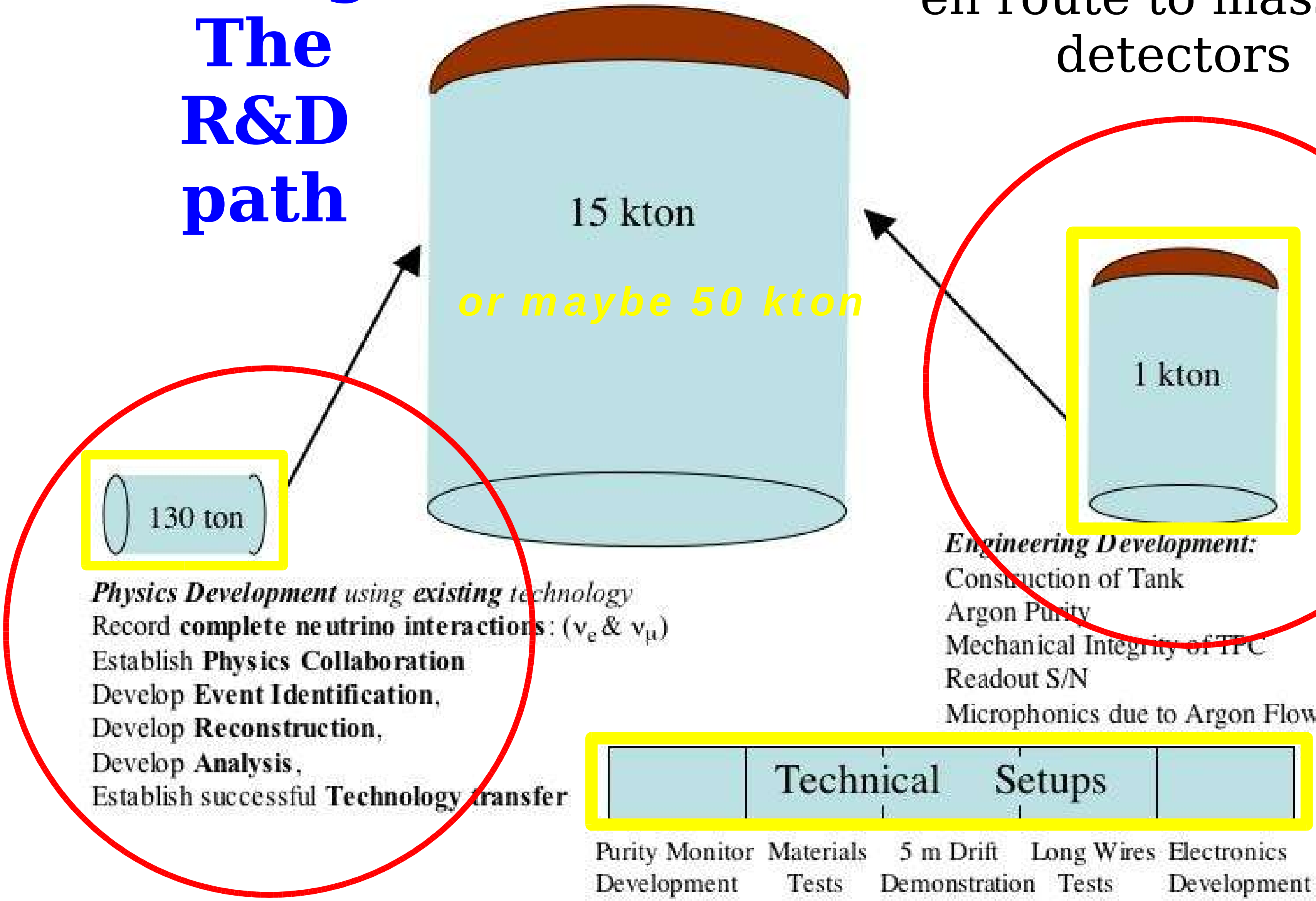


Long wires tests

- ***measurements of the mechanical properties of the wires both at room temperature and in LAr***
  - *100 μ and 150 μ Stainless Steel 304V*
- ***develop wire holders that work at cryogenic temperature and do not pollute LAr***
- ***determination of wire tension***
  - *electrostatic stability*
  - *wire supports*
- ***study of noise on long wires***
  - *mechanical vibrations (i.e. induced by LAr flow)*
  - *measure damping effect of LAr on wire oscillations*
  - *study of electronics coupled to long wires (large input capacitance !)*

Addressing the challenges: The R&D path

must move beyond small technical setups en route to massive detectors



How large a detector is needed for

-Physics R&D?

-Engineering R&D?

What are the added challenges of going underground?

-underground construction
-space constraints
-safety considerations
  -LAr spill containment

Conclusions:

Goals for this study......

Its clear that the efficiencies and purities in
LAr detectors are great for this physics....

need to be more quantitiative:
backgrounds from π^0s vs energy
backgrounds at higher energies (DIS)
cosmic backgrounds (determine overburden)
ν_e efficiencies (can be adjusted for by fid volume)

Quantitative studies for
2nd off-axis detector options
wide band options

fold in issues related to technical feasibility
how to best address these isssues