The Ultimate Neutrino Detector

Adam Para, Fermilab

Experimental Seminar,
SLAC,
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Outline

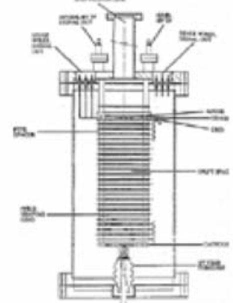
- Liquid Argon Time Projection Chamber: a mature technology
- Neutrino oscillations opportunities with the NuMI beam
- Liquid Argon detector for the NuMI off-axis experiment
- ‘Other’ physics with the LAr detector

Liquid Argon Time Projection Chamber

- Proposed in May 1976 at UCI (Herb Chen, FNAL P496). R&D enthusiastically endorsed by the PAC 50 L/100 L prototypes at UCI and Caltech,
  - ✓ Fermilab prototype (Sam Segler/Bob Kephart)
  - ✓ 10 ton prototype at Los Alamos (Herb Chen, Peter Doe)
- BARS spectrometer operating in Protvino (2 x 150 ton) (Franco Sergiampietri, S. Denisov)
- 25 years of pioneering efforts at CERN and INFN (Carlo Rubbia + countless others) + advances in technology
  - ✓ 50 l prototype in WANF beam
  - ✓ 3 ton prototype, 10 m^3 prototype
  - ✓ 300 ton detector operating in Pavia
  - ✓ 600 ton under commissioning in LNGS

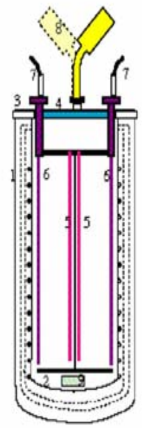
Many years of intense R&D

24 cm drift wires chamber



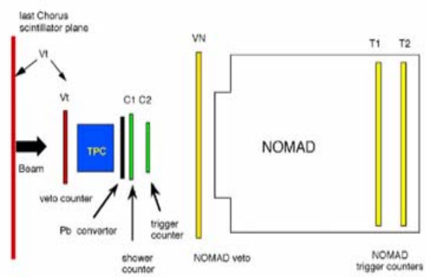
1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

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

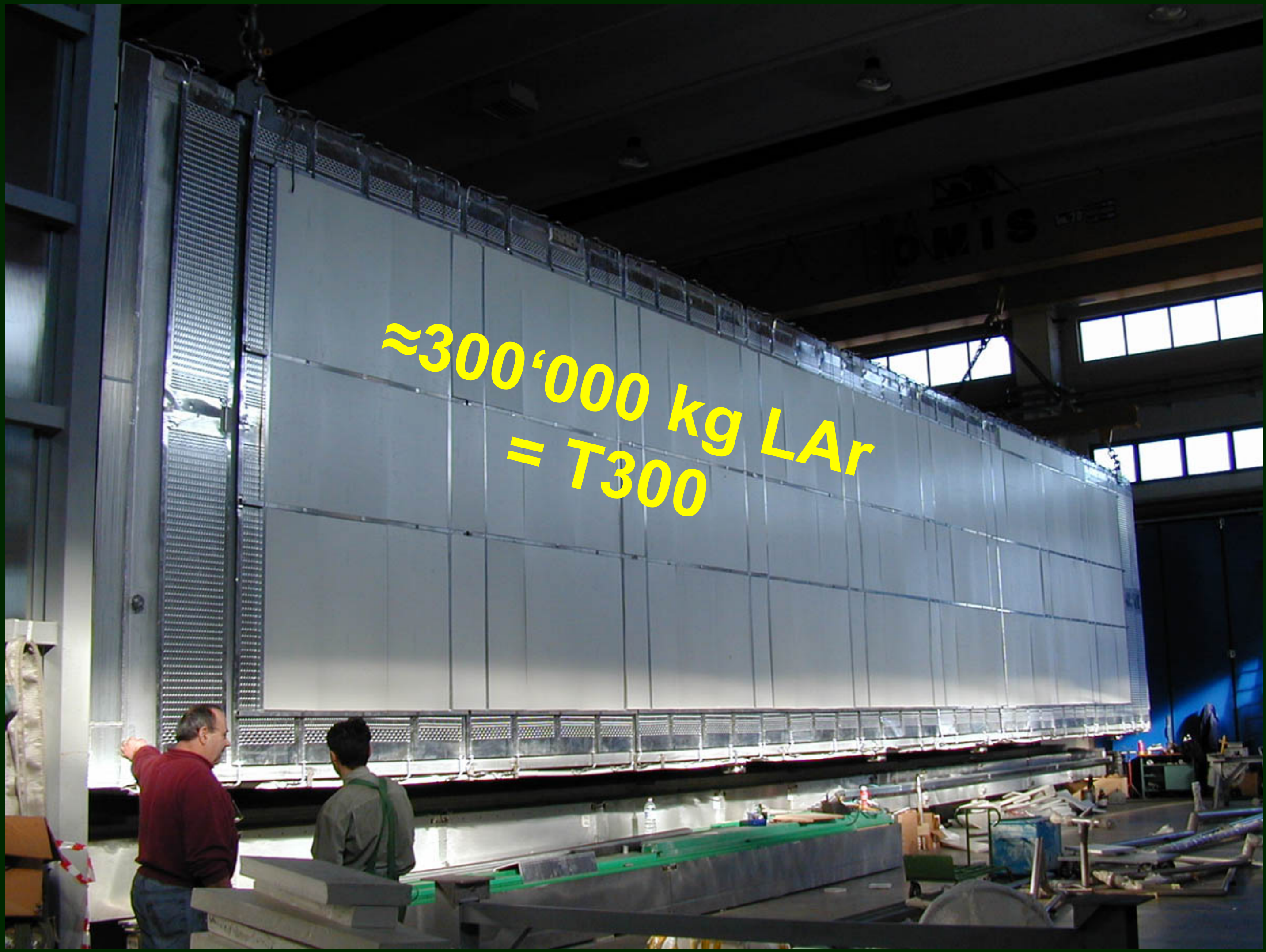


1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

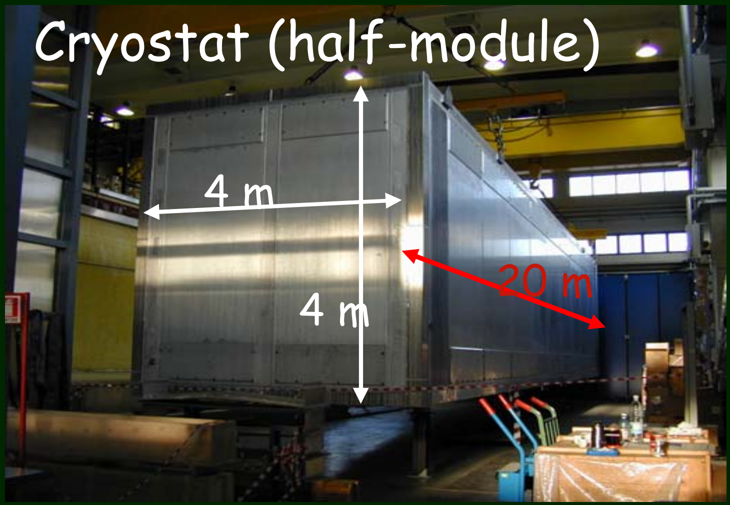
10 m3 industrial prototype

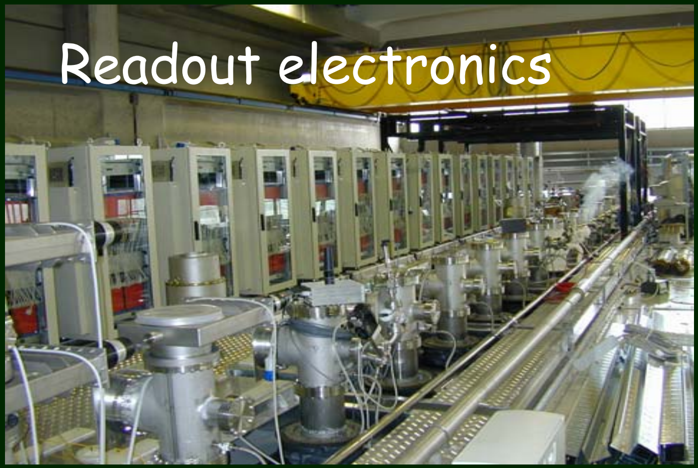
1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

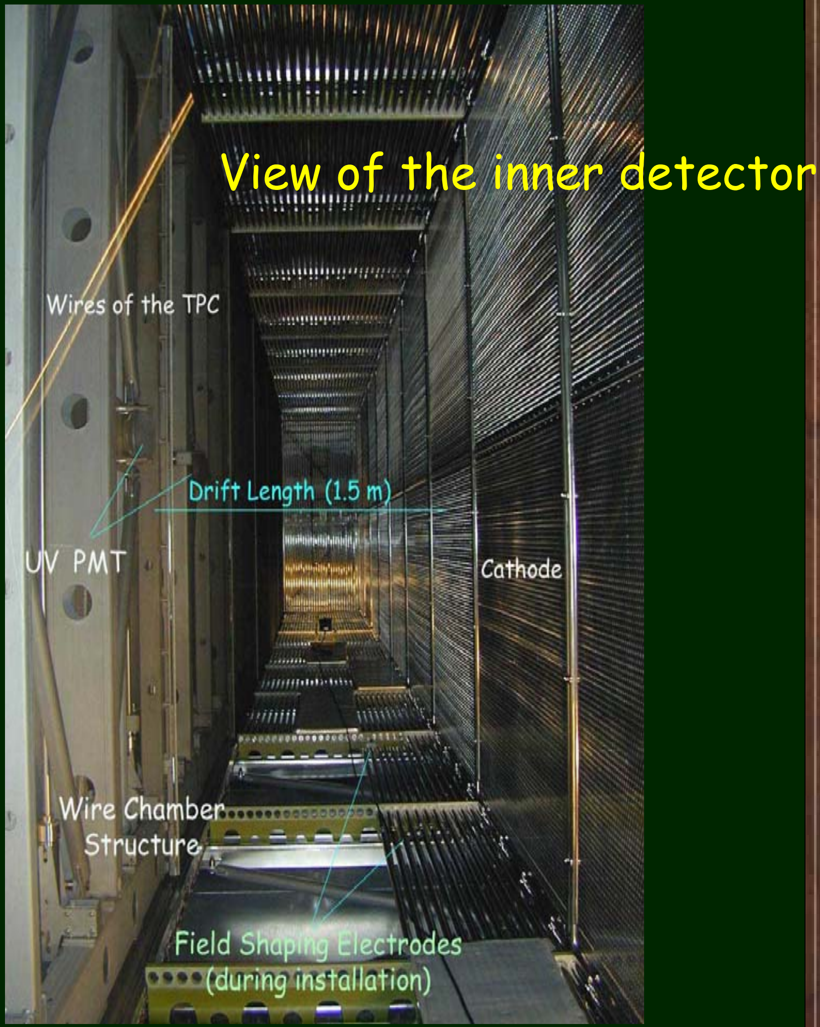
Leading to a large detector



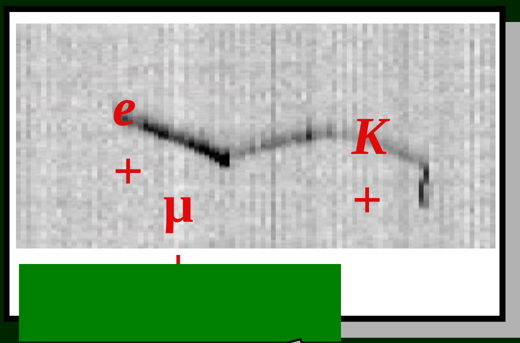
Inside and outside







It works!


e
μ
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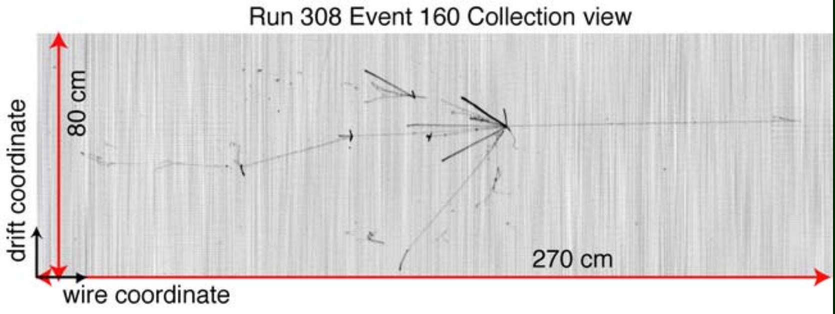
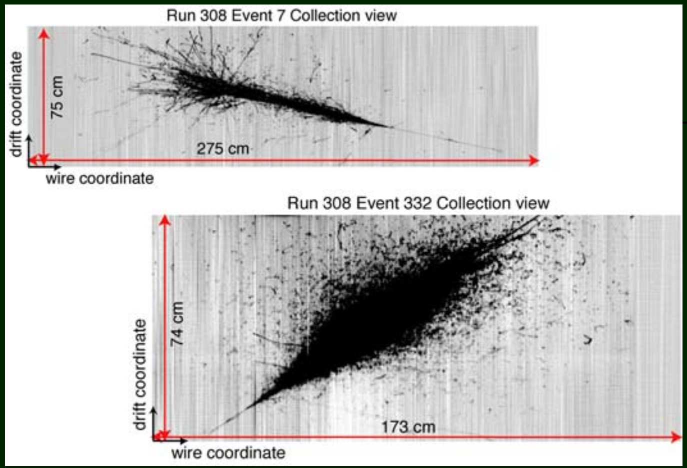
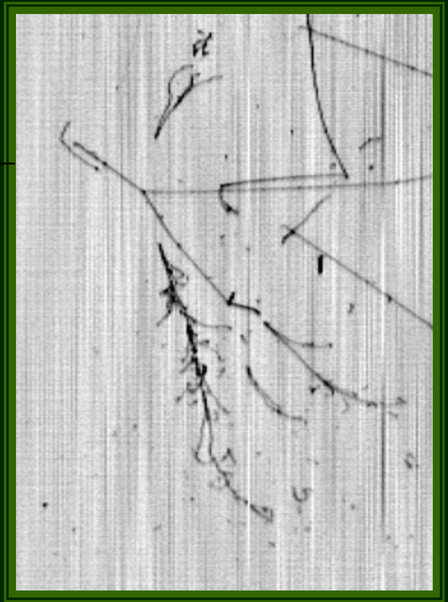
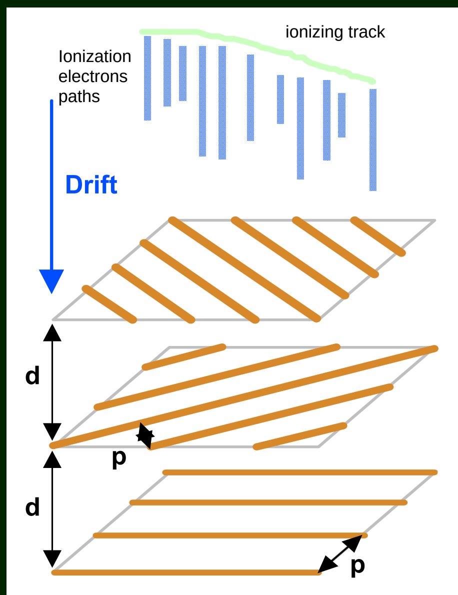
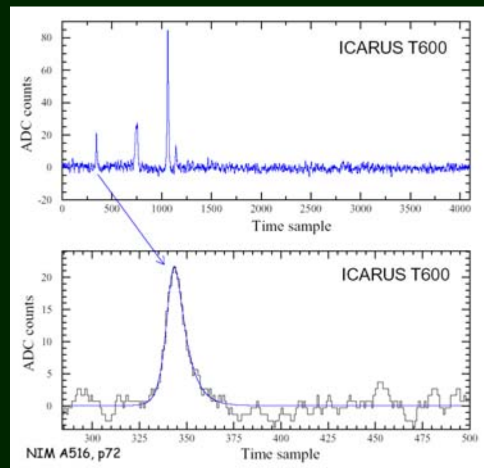

Run 308 Event 160 Collection view
80 cm
drift coordinate
270 cm
wire coordinate


Run 308 Event 7 Collection view
75 cm
drift coordinate
275 cm
wire coordinate
Run 308 Event 332 Collection view
74 cm
drift coordinate
173 cm
wire coordinate



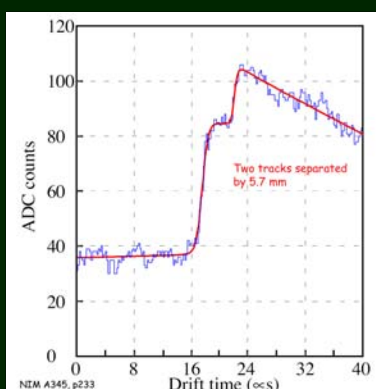
Time Projection Chamber I





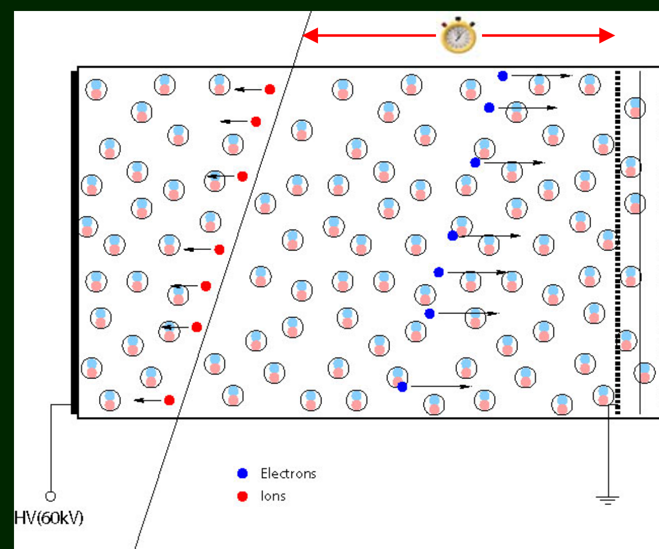
$$F(t) = B + A\frac{e^{-\frac{t-T_0}{\tau_2}}}{1+e^{-\frac{t-T_0}{\tau_1}}}$$

A: signal amplitude (dE/dx)
τ_1 : rise time (track angle, diffusion)
τ_2: fall time (front-end electronics)
B : baseline



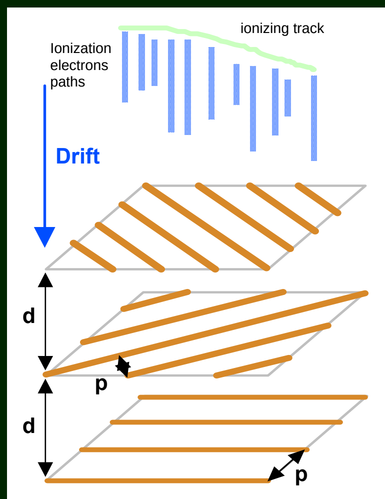
Uniform electric field:

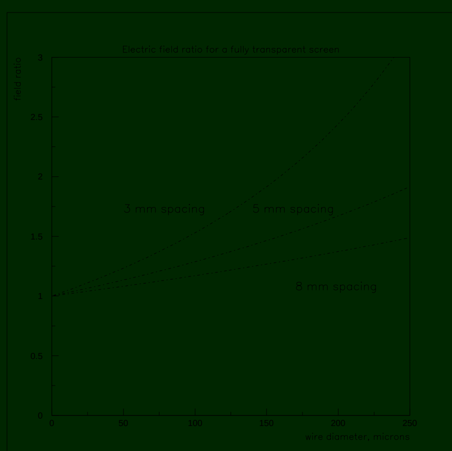
$(t-T_0) = v_{drift} * (x-x_{wire})$



a 2D projection 'only'

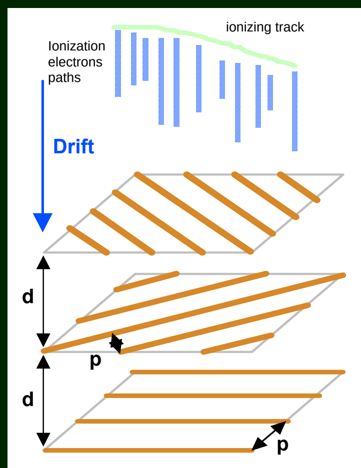
TPC II: the second/(third?) coordinate

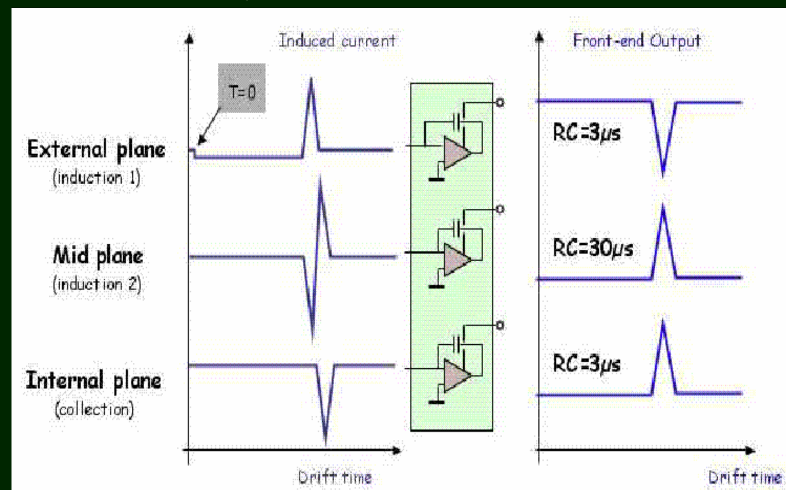


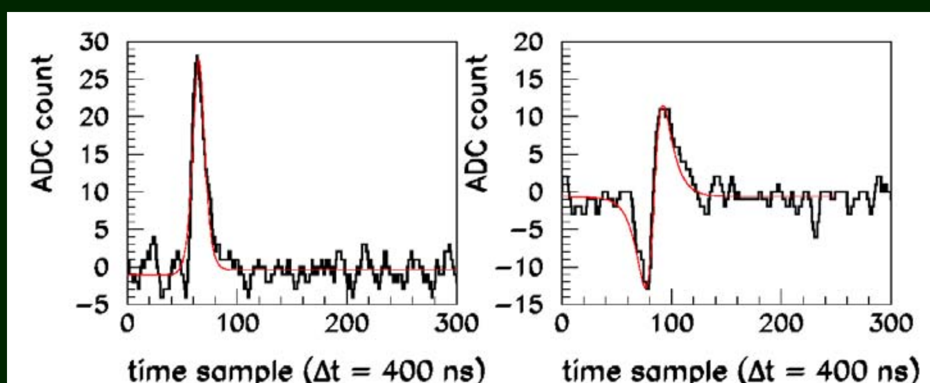


- A 'traditional' TPC: a set of pads behind the sense wire.
- Liquid Argon: add a plane(s) of grids in front of the collection wires
- Arrange the electric fields/wire spacing for a total transparency [Bunneman, Cranshaw,Harvey, Can. J. Res. 27 (1949) 191]
- Detect the signal induced by passing electrons, thus giving additional coordinates [Gatti, Padovini, Quartapelle,Greenlaw,Radeka IEEE Trans. NS-26 (2) (1979) 2910]
- Signals are strongly correlated: the arrival time and charge (module electronics noise)

TPC III: Induction wires signal in real life



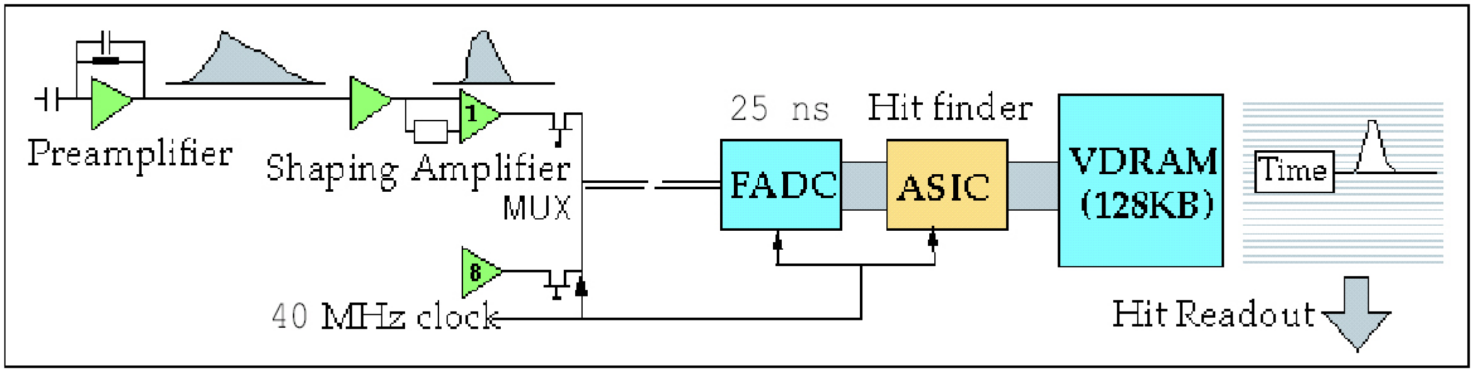




ICARUS TM/2001-09

Front-end electronics/pulse shaping determines the actual waveform: room for optimization

Front-end electronics issues

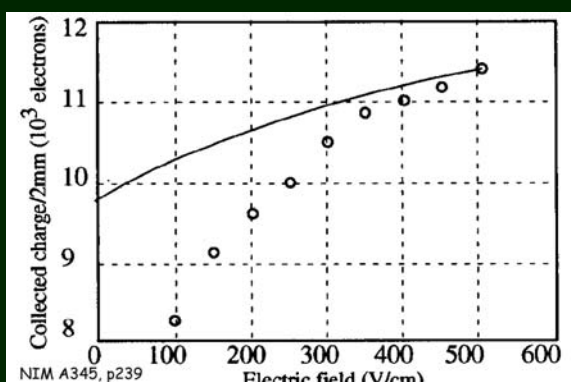


ICARUS TM/2001-09

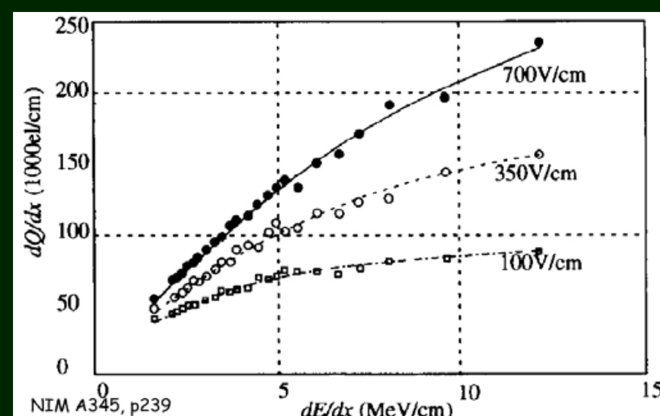
- Signal to noise:
  - ✓ Signal = 5,500 e * d (in mm)
  - ✓ JFET, shaping time ~ 1μsec: ENC = 500 + 2.6 C (C –detector capacitance)
    - Optimize detector design (wire spacing, cable length)
    - Better technology? SiGe? Bipolar?
- Cold vs warm (reliability vs feed-throughs, cables, noise)

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



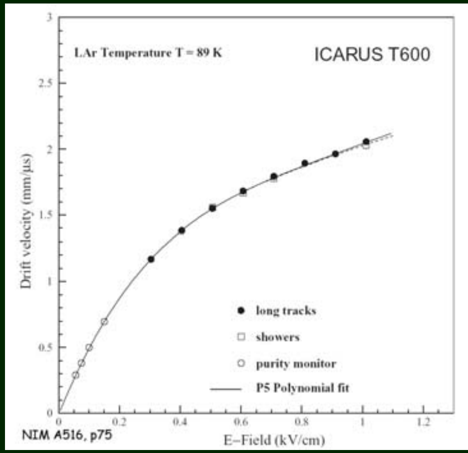
NIM A345, p239

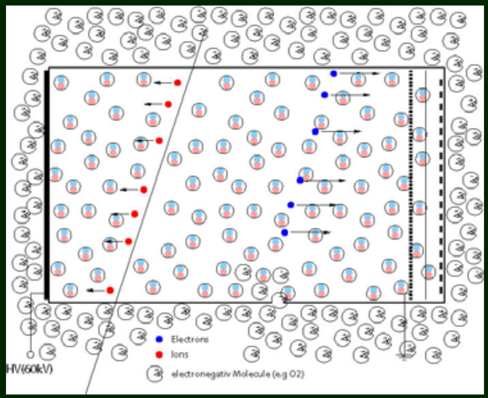


NIM A345, p239

Drifting electrons over long distance (3m)?

- Electron mobility 500 cm^2/Vs
- $V_{drift} = f(E)$. Use E= 500 V/cm
  - ✓ HV across the drift gap = 150 kV
  - ✓ V_{drift} = 1.55 mm/μsec
  - ✓ t_{drift} = 2msec
- Diffusion?
  - ✓ Diffusion coefficient, D=4.8 cm^2/s
  - ✓ $\sigma_d^2 = 2Dt = 9.6t$, σ_d= 1.4 mm for 3 m drift
- Number of collisions/sec ~10^{12}
  - ✓ 2×10^9 collisions along the longest path
  - ✓ 'none' of them must 'eat' an electron
  - ✓ Concentration of electronegative (O_2) impurities < **10^{-10}**





Measuring argon purity below 0.1 ppb ?

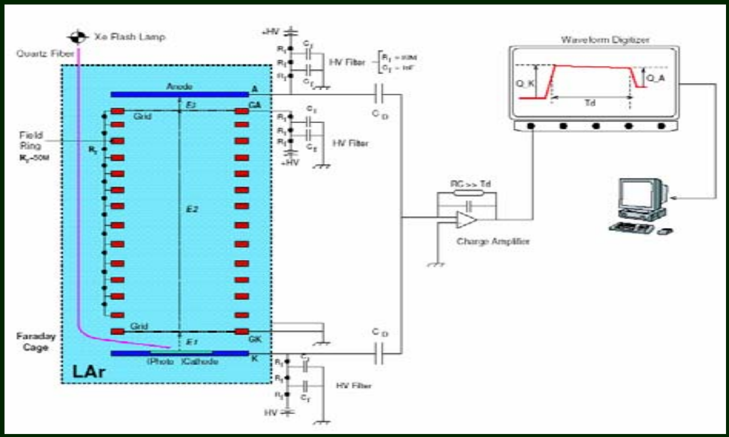
- Best commercial O_2 gauge: least count 0.2 ppb (not bad at all, but not good enough)
- How do you know that there are no other impurities, not detectable with your purity ,monitors, which absorb electrons (remember MarkII?)
- Electron lifetime detector

Carugno,Dainese,Pietropaolo,Ptohos

NIM A292 (1990) 580:

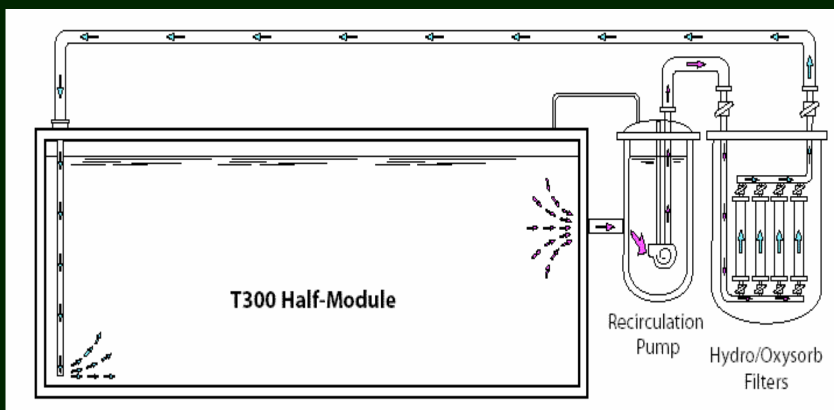
- ✓ Extract electrons from a cathode
- ✓ Drift over a certain distance
- ✓ Measure charge along the path

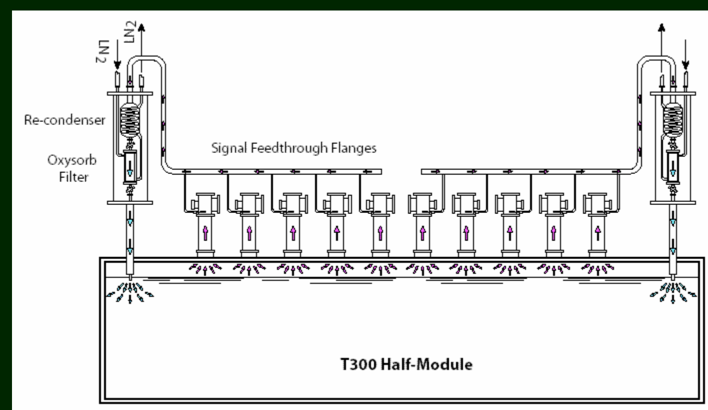
$$Q(t) = Q_0 e^{-\frac{t}{\tau}}$$



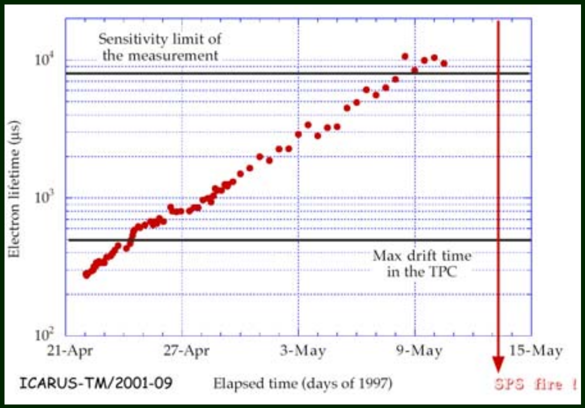
Argon purification: liquid and gas phase

- Re-circulate liquid/gaseous argon through standard Oxysorb/Hydrosorb filters (R20 Messers-Griesheim GmBH)
- ICARUS T600 module:
  - ✓ 25 Gar m^3/hour/unit
  - ✓ 2.5 Lar m^3/hour





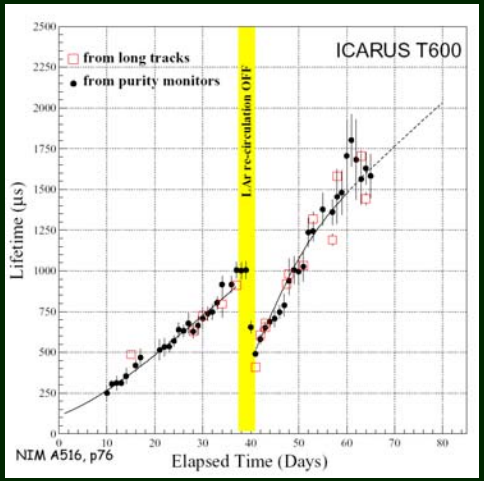
Argone purity/electron lifetime in real life ?



$$\frac{dN}{dt} = -\Phi_{out}(t) + \Phi_{in}(t) =$$

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

- Impurities concentration is a balance of
  - ✓ Purification speed τ_c
  - ✓ Leaks $\Phi_{in}(t)$
  - ✓ Outgassing A, B
- For a T600 module: asymptotic purity/lifetime > 13 msec



Argon purity, lessons for a very large detector

- Long electron lifetimes (~10ms)/drift distances (>3m) appear 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/handling (high vacuum technology) is the key

In the meantime..

Neutrino Physics has become a major source of excitement/surprises:

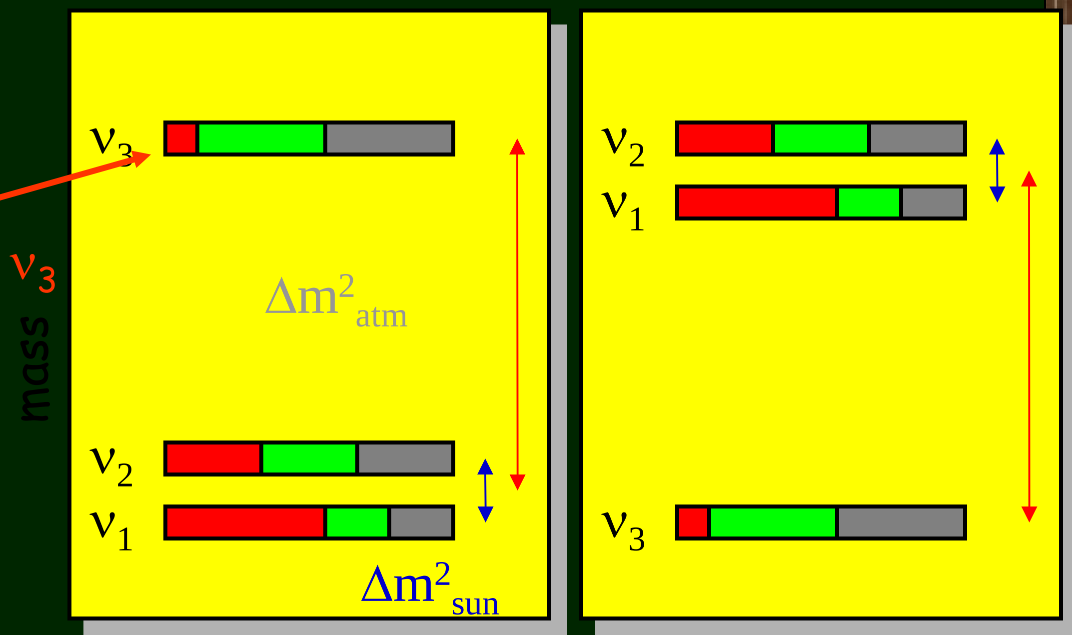
- Neutrinos have mass. First glimpse of physics beyond the Standard Model
- Neutrino mixing. Why so different from quark mixing??
- CP violation in the lepton sector?? Origin of matter-antimatter asymmetry in the Universe??

Neutrino experiments will be a significant component of our future physics program

Hint: we have a (super) beam.

What do we want to know AD2006 ?

1. Neutrino mass pattern: This ? Or that?



"Normal" mass hierarchy "Inverted" mass hierarchy

2. Electron component of ν_3
   ($\sin^2 2\theta_{13}$)

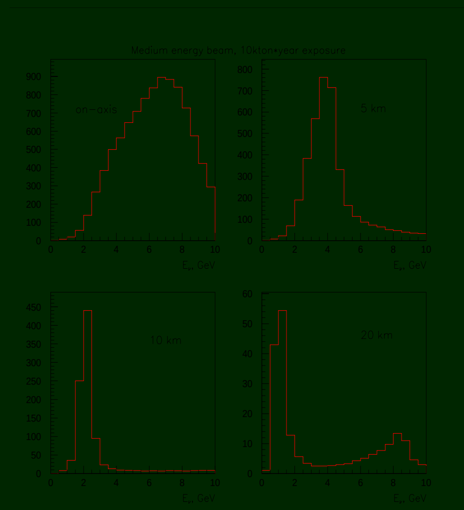
$$\begin{bmatrix} \nu_e & \nu_\mu & \nu_\tau \end{bmatrix} = \begin{pmatrix} B & B & s\,? \\ B & B & B \\ B & B & B \end{pmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

3. Complex phase of s(?) ←→
   CP violation in a neutrino sector ←→ (?) baryon number of the universe

Off-axis NuMI Experiment

NuMI neutrino beam: exists since Feb. 2005

- NuMI: intense neutrino (ν_μ) beam from Fermilab to Minnesota
- Initial motivation: precise determination of Δm^2. First results this Thursday!
- 'Current' motivation: ν_e appearance experiment



Off-axis 'narrow band' beams minimize NC background

NuMI Opportunity

$$P_{\mu\to e} \approx \left|A_{23} + A_{13}\right|^2 = P_{23} + 2\sqrt{P_{23}P_{13}}\cos\left(\Delta_{23} \pm \delta\right) + P_{13}$$

where:

$$P_{23} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$

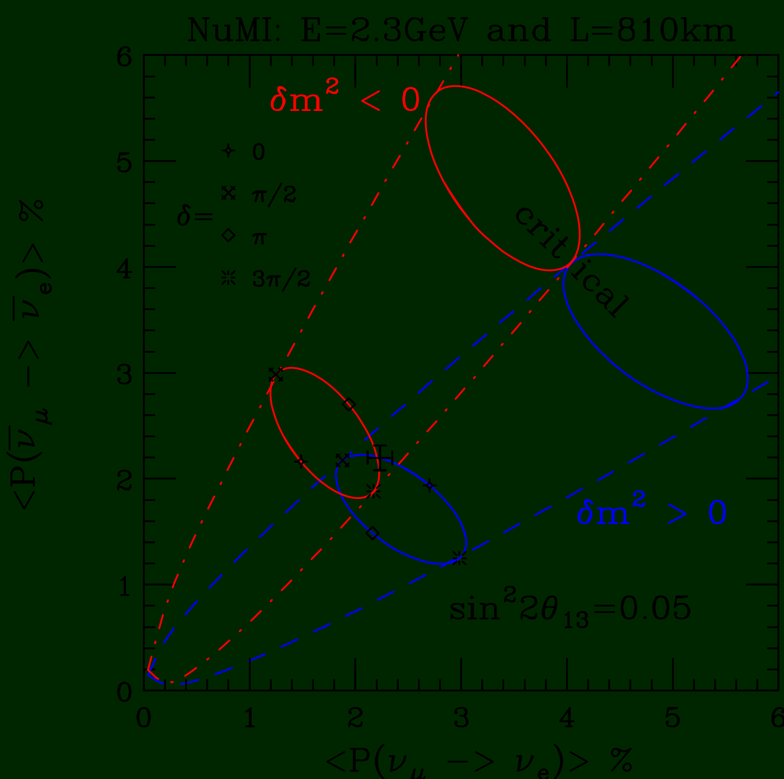
$$P_{13} = \cos^2\theta_{13}\cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2\Delta_{12}$$

$$\Delta_{ij} = \frac{1.27\,\delta m_{ij} L}{E}; \quad \textit{in matter}$$

$$\sin\Delta_{i1} \Rightarrow \frac{\Delta_{i1}}{\Delta_{i1} \mp aL}\sin(\Delta_{i1} \mp aL), i = 2,3$$

- Two amplitudes contribute
- One amplitude proportional to θ_{13}
- Relative phase, CP violating, δ changes sign from neutrinos to antineutrinos
- Matter effects have different sign for different mass hierarchies

Untangling the physics



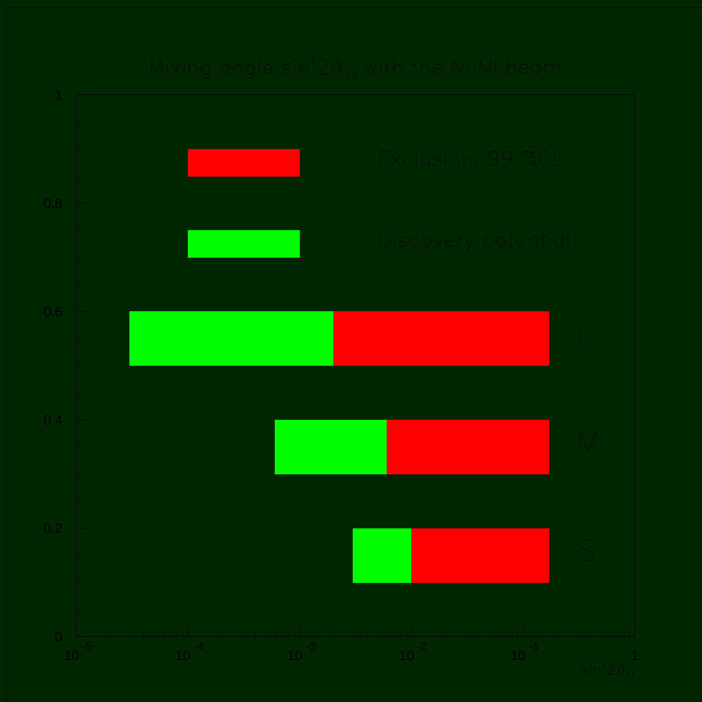
- Experiment measures two numbers: P_{nu} and P_{nubar}
- Distance from the origin: θ_{13}
- Distance from the diagonal: CP violation and mass hierarchy
- *All effects of the same order*
- *Ambiguities possible if* θ_{13} *small*

Physics potential of the NuMI beam (Mena+Parke,hep-ph/0505202)

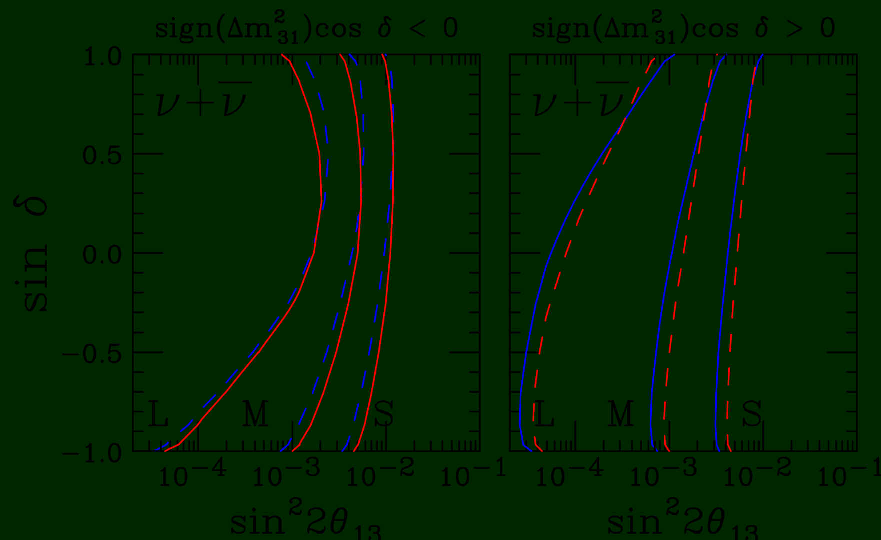
- To first order the physics potential of an off-axis experiment is determined by a product: $N_p \times M \times \varepsilon$
- Possible detectors:
  - ✓ Liquid Scintillator calorimeter (NOvA) – ε = 0.24
  - ✓ Liquid Argon TPC (FLARE) – ε = 0.9
- Three scenarios: S/M/L

S	30 kton NOvA	8 ktonFLARE
M	30 kton NOvA + Proton Driver	40 kton FLARE
L		40 kton FLARE + Proton Driver

A Quest for $\sin^2 2\theta_{13}$



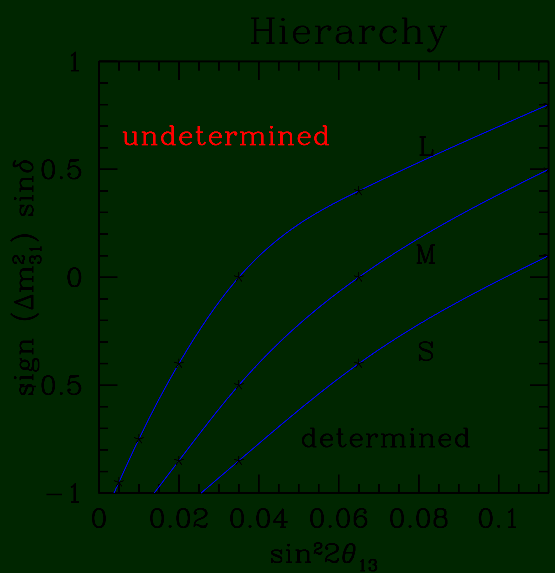
- Dependence on mass hierarchy and CP phase precludes unambiguous interpretation of a possible null result in terms of a limit on $\sin^2 2\theta_{13}$.
- Limits of 1×10^{-2} (2×10^{-3}) achievable with S (L) detectors

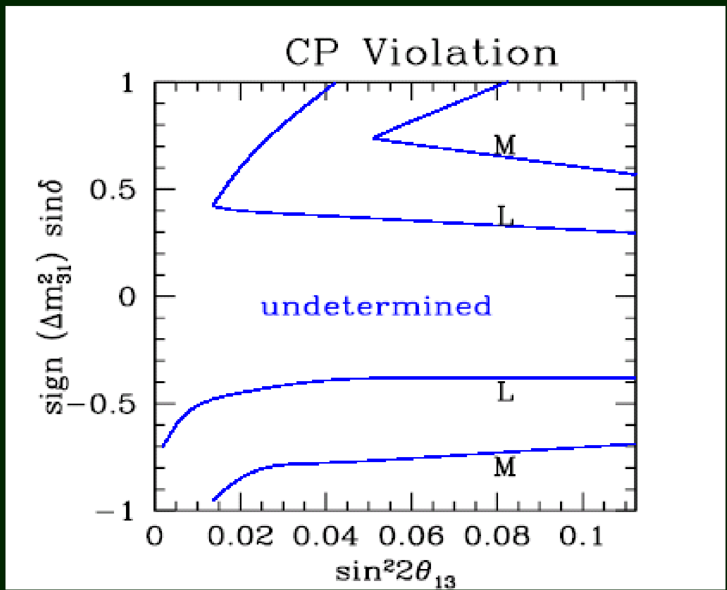


but it offers an increase of sensitivity beyond 10^{-4} level ! (some luck required)

Real Challenges: Mass Hierarchy and CP violation

- Required: $\sin^2 2\theta_{13}$>0.01 + favorable value of δ.
- Required amount of luck diminishes as the size of the experiment/beam intensity increases





Experimental Challenge

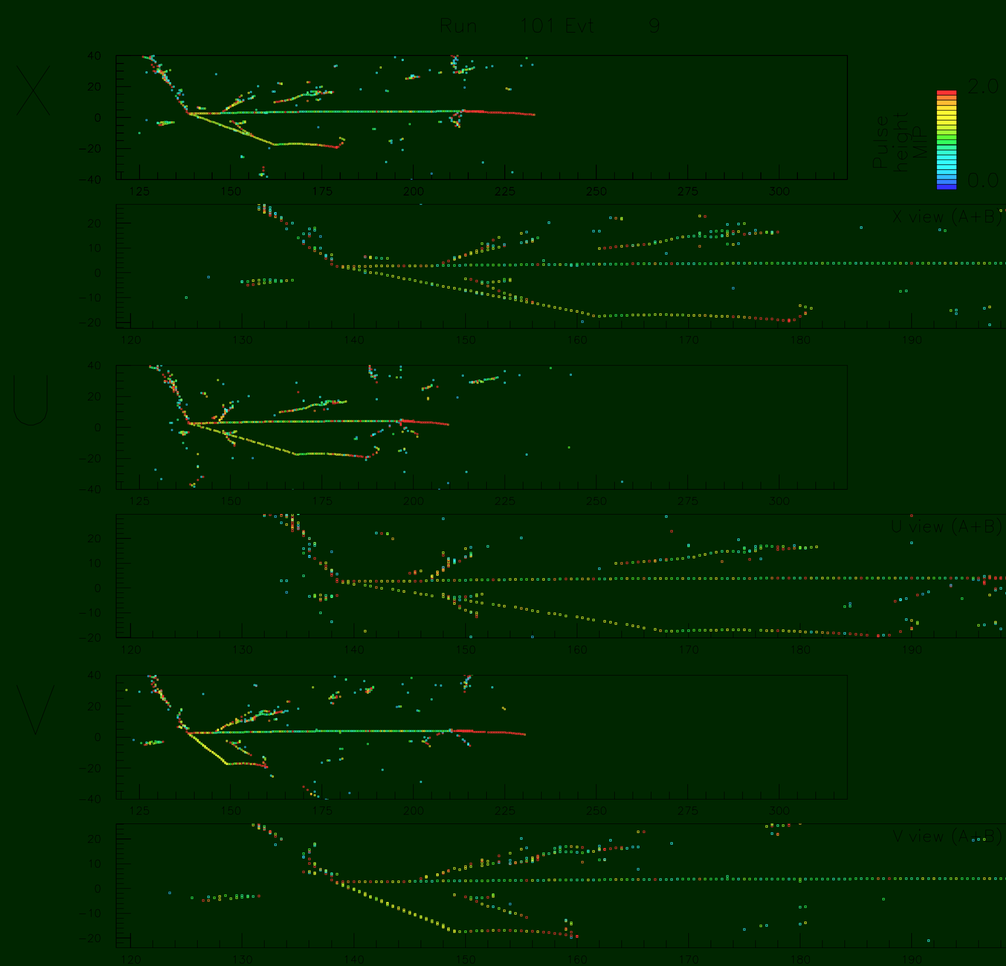
- Maximize M×ε

  Where:
  - M – detector mass
  - ε – efficiency for identification of ν_e CC events
- While maintaining η>20/ ε (to ensure NC bckg < 0.5 ν_e CC bckg)

  Where η is the rejection factor for NC events with observed energy in the signal region
- Why is it hard to achieve high ε
  - ✓ Y-distribution – electron energies ranging from 0 to E_ν
  - ✓ Low(er) electron energies emitted at large angles
- Why is it hard to achieve high η
  - ✓ π^0's produced in the hadronic shower, early conversions and/or overlap with charged hadrons
  - ✓ Coherent π^0 production

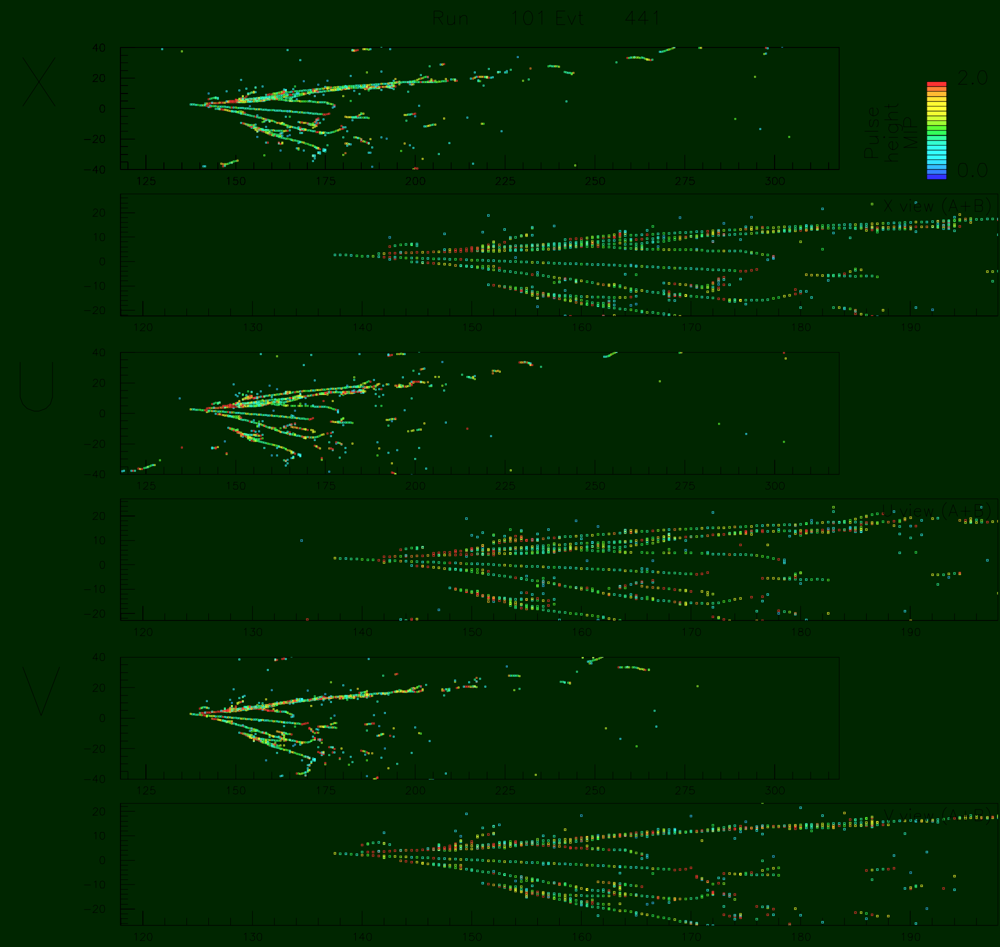
ν_e identification in LAr TPC

- Good particle identification using purely topological information
- Excellent spatial granularity an important asset
- High detection efficiency. The key: possibility to identify high-y events (low energy electrons at large angles)



Good NC background rejection

- Very fine longitudinal sampling: gamma conversions clearly separable from the primary vertex (often)
- Very good transverse graularity: gamma conversions clearly separable from charged tracks (often)
- Very good energy resolution: gamma conversions identifiable through dE/dx at the origin (usually)



Detector Performance

Blind scan of fully simulated detector (GEANT 3):

- electron neutrino CC identification efficiency = 81+-7%
- while NC background < 20% of the intrinsic nue component of the beam

Questions:

- can one build such a detector?
- can one afford such a detector?

Legacy of ICARUS (and other R&D efforts)

- One can drift electrons in argon over distance of several meters in argon purified with the standard commercial purifiers
- HV systems (power supply, noise filter, feedthrough, field shaping cage) can be made to operate reliably with voltages up to 150 kV
- Low noise electronics can be built (commercial!) and operated with adequate S/N ratio for detector capacitances up to ~ 600 pF for signals at the level of 15,000 electrons

Challenge of Scaling up ICARUS ?

- ICARUS modules 'work'. If you want a bigger detector why not build a necessary number of modules??
  - ✓ Not an optimal detector
  - ✓ Expensive
- Large detector concept:
  - ✓ A single cryogenic tank (~thousand tanks operational world-wide, excellent safety record)
  - ✓ industrial scale high performance argon purification

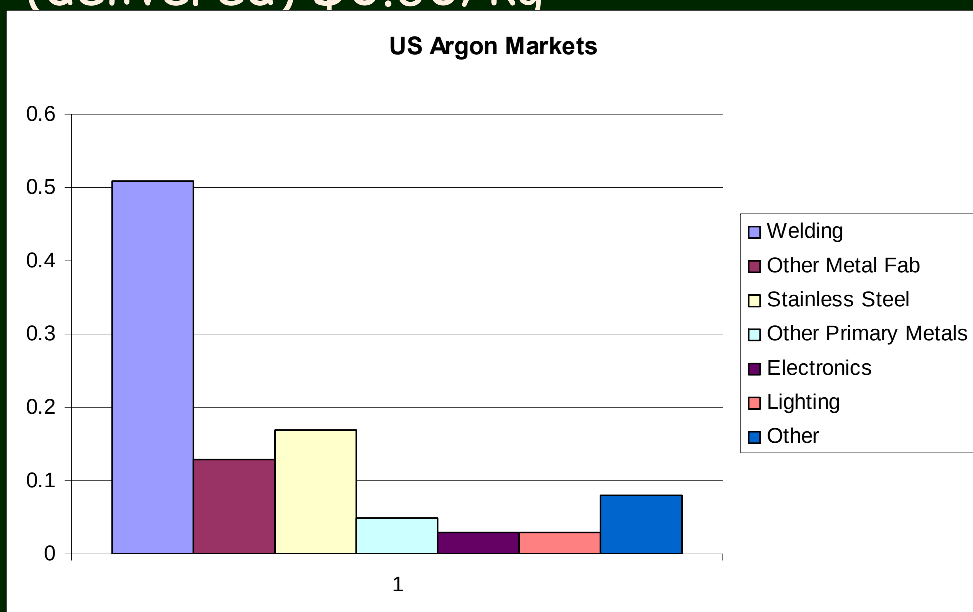
- 10,000 l/h (2,640 gph)
- 3 m H x 1.4 m W x 2 m D
- 2,500 Kg
- NEMA 4X cabinet
- 0°C to 40°C standard
- -20°C to 40°C option

Measured Performance		
Impurity	Inlet	Outlet
O_2	0.4 ppm	<0.1 ppb
H_2O		<0.2 ppb
N_2	2 ppm	<1 ppb
CH_4	1 ppm	<1 ppb
CO		<0.5 ppb
CO_2		<0.1 ppb

Liquid Argon as a commodity

G. Mullholland

- Byproduct of air liquefaction
- Annual production ~ 1,000,000 tons/year (mostly at the coasts, East Chicago) (tied to oxygen demand for steel production)
- Delivery: truck (20 t) or railroad car (70 t)
- Cost (delivered) $0.60/kg



Cryogenic storage tanks: a competitive industry. Example:

CBI
PRODUCTS

Refrigerated Storage
& Process Systems

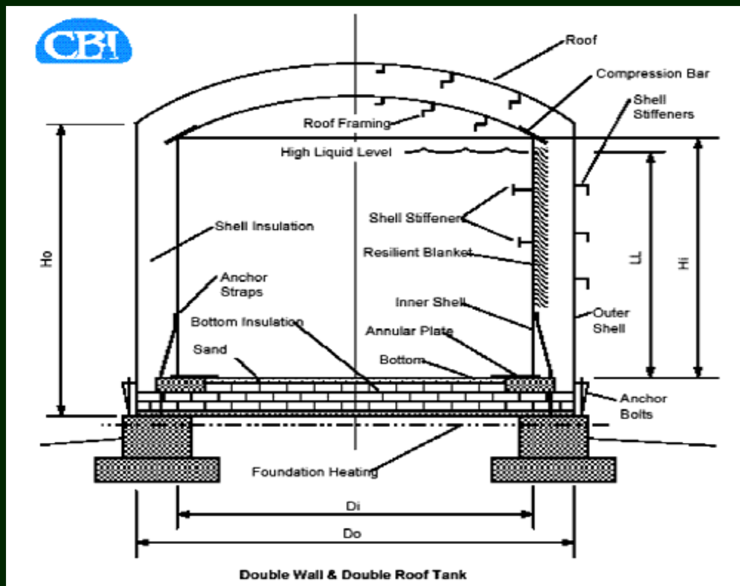
CB&I takes a total systems approach for low-temperature and cryogenic facilities as this results in the most operationally efficient and cost effective design for the owner. The efficiencies result from the storage solution, liquefaction and/or revaporizing systems design and the terminal facilities design all being considered together during the design and construction planning.

Design and construction of these facilities requires CB&I's traditional core competencies in steel structure design, fabrication, welding and field construction management combined with specialized knowledge in thermodynamics and in the physical properties of pure gases, fluid flow, heat transfer, chemical engineering and simply construction "know-how".

Refigerated storage tanks are highly specialized structures as they are storing liquids at temperatures as low as -450°F. Due to the extremely low temperatures and the volatile nature of these gases, the storage tanks all utilize special insulation and can be single wall, double wall or complete concrete containment tanks. CB&I utilizes a patented Horizontal Foamed In Place insulation on single wall tanks that provides the best performing and lowest cost solution for storing the less intensive cold applications.

Cryogenic storage is for temperatures less than -150°F and requires the use of special materials such as aluminum, stainless steel, and 5% and 9% nickel for the inner tank shell. These tanks are double wall with special perlite insulation in-between the two shells, and often have some form of concrete containment for safety reasons.

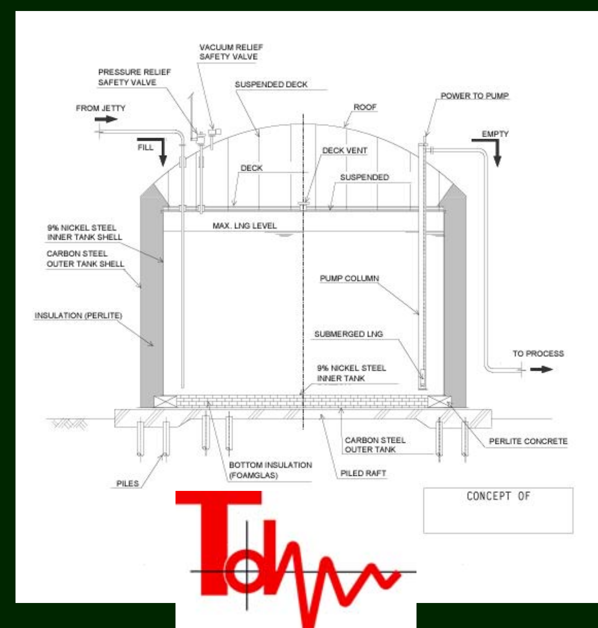
Competitive Industry



- CBI
- Technodyne
- Kawasaki
- Mitsubishi
- Hyundai
- Nissan

Refrigeration? And industrial problem too..Boil-off rate – 0.05%/d (25 t/day)

100 t/day argon re-liquifier, 1.8MW (Cosmodyne):



Thermal analysis of a 50 kT liquid argon tank

Rough analogy: big boiling pot

Vapor bubbles at the surface only (hydrostatic pressure)

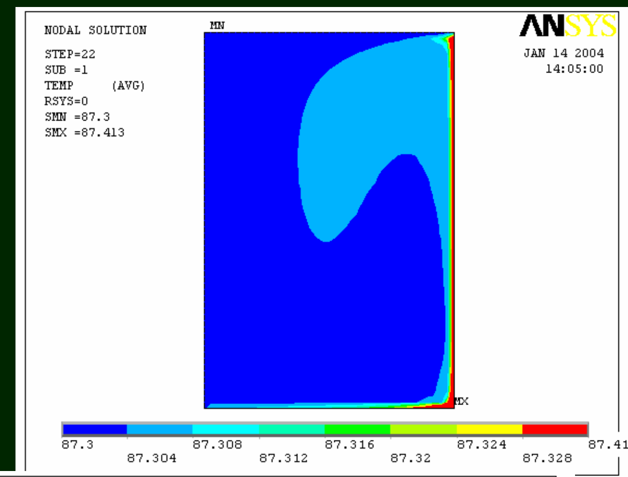
Total heat leak: 49 kW

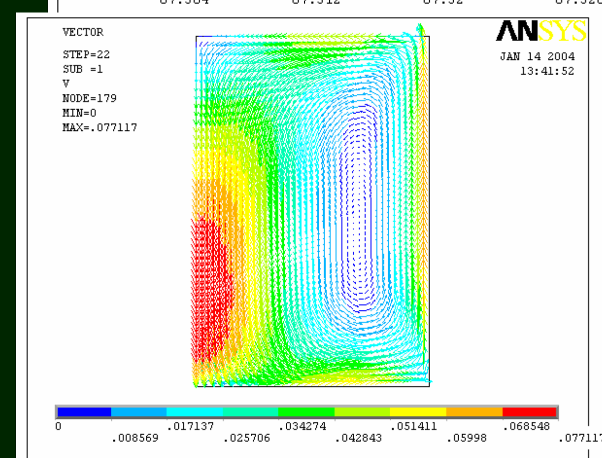
Maximal temperature diference ΔT_{max} = 0.1°C

Tempereture difference over most of the volume 0.01°C

Maximum flow velocity: 7.7 cm/s

Heat leak through a signal feed-through chimney 48W/chimney





Zhijing Tang, PPD

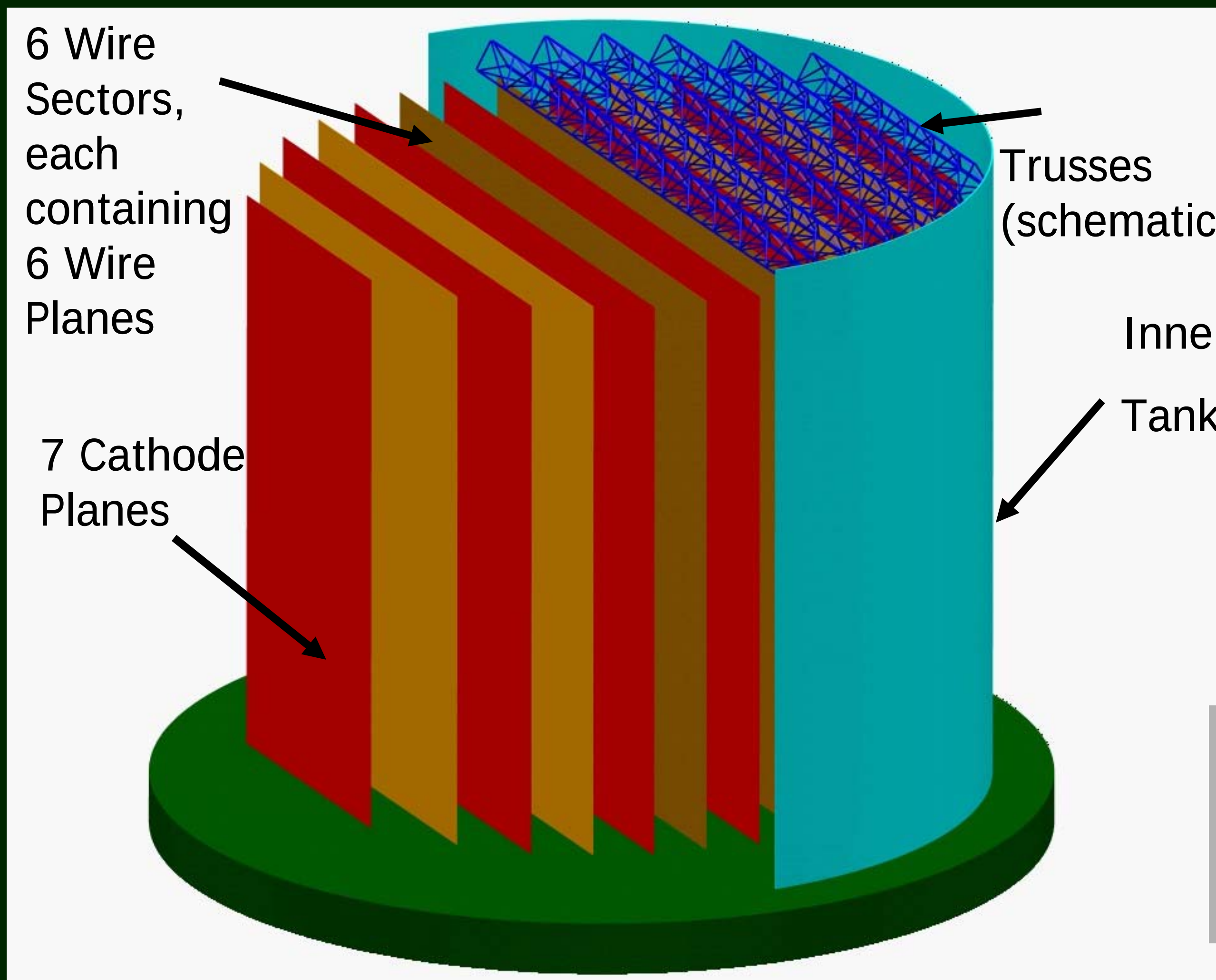
Fundamental parameter: signal/noise ratio

- Signal
  - ✓ Attenuated by impurities (➔ argon purity, ➔drift distance)
  - ✓ Shared between wires (➔ wire spacing)
  - ✓ Produced: 55,000 electrons/cm of the track
- Noise
  - ✓ JFET, shaping time ~ 1μsec: ENC = 500 + 2.6 *C* (*C* – detector capacitance) electrons

FLARE design:

- wire spacing 5 mm
- electron lifetime > 10 msec
- short signal cables, *C*<700 pF
- ➢ signal > 22,000 electrons.
- ➢ noise < 2500 electrons

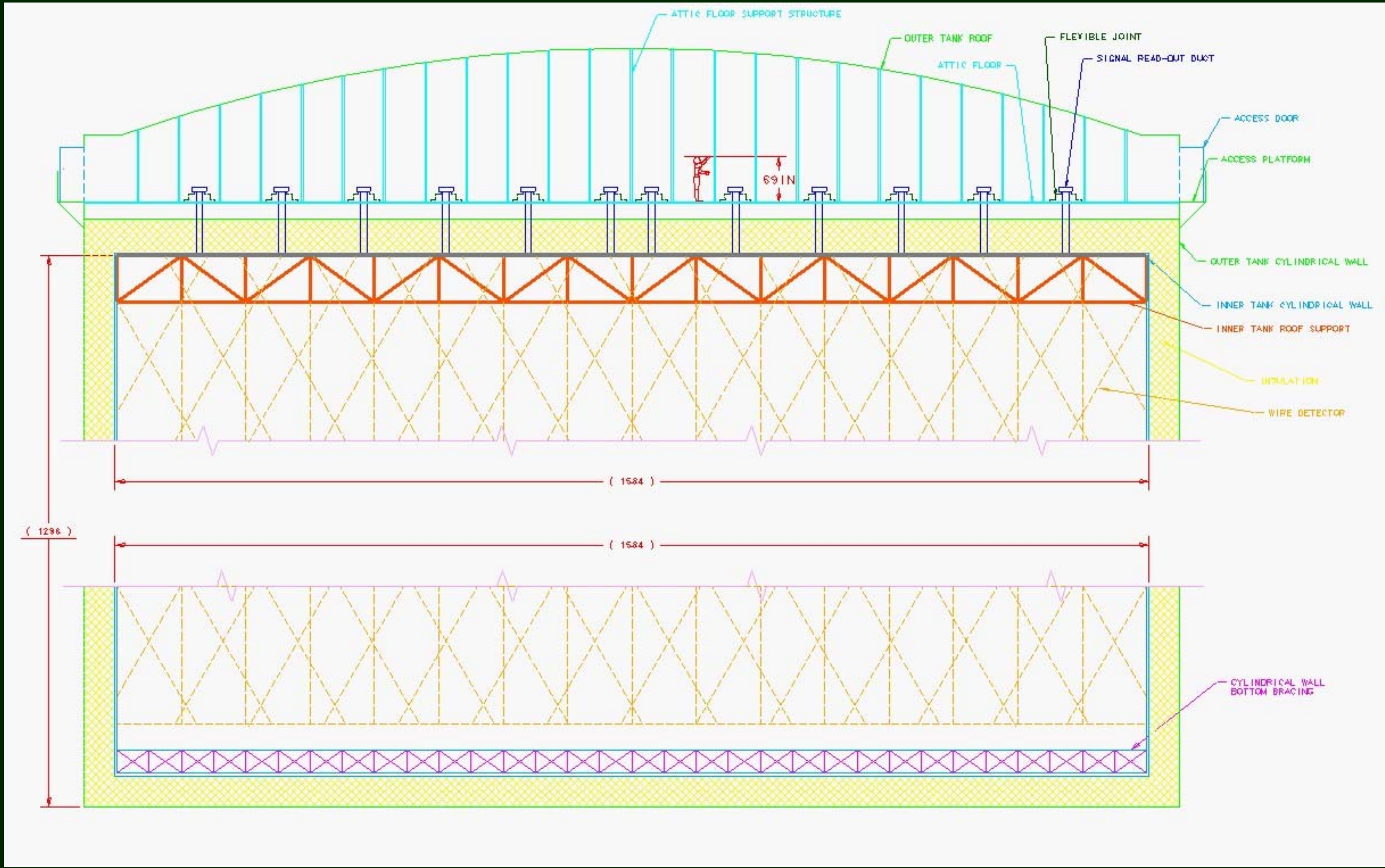
FLARE Detector



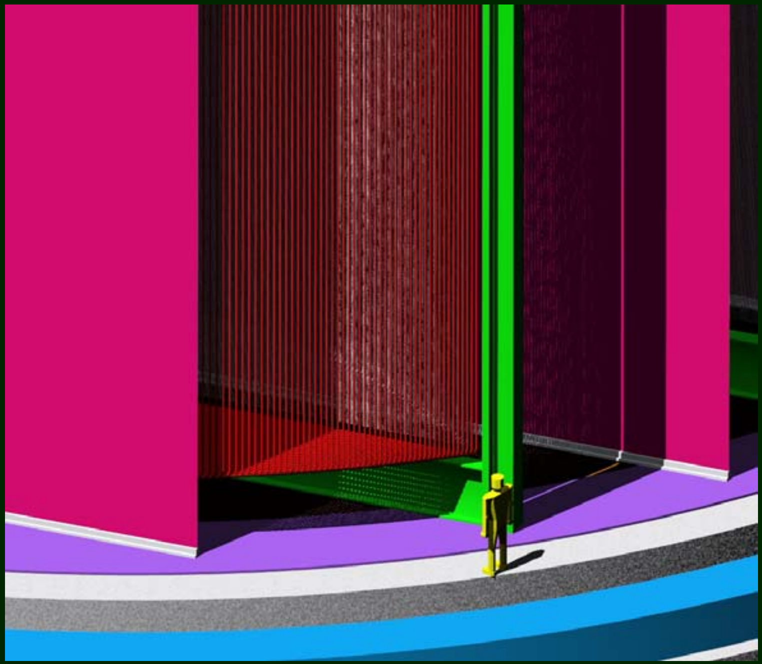
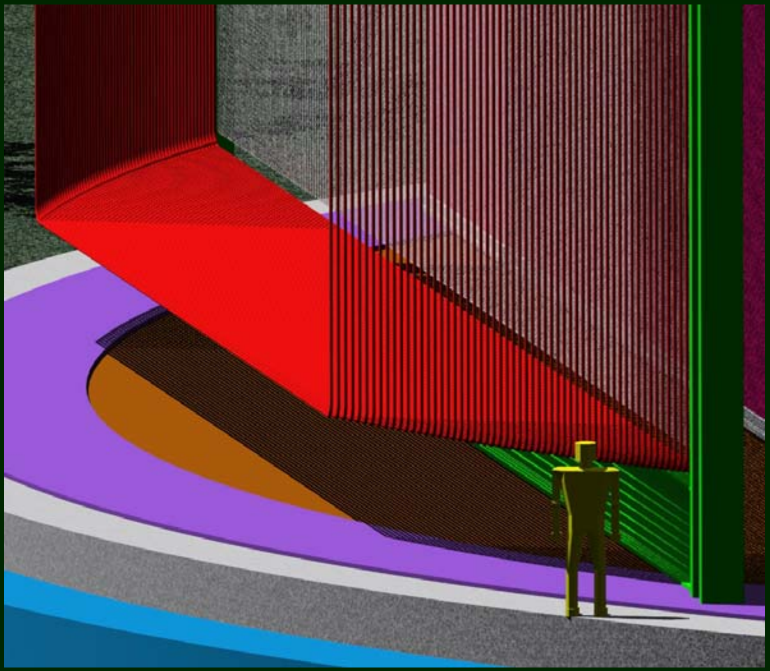
(Model by Chuck Grimm)

<u>Active volume</u>
Diameter: 40m
Height: 30m

FLARE detector, 2005



Field shaping in the drift region

L. Bartoszek

- A set of field shaping tubular electrodes grading the potential from 150 kV to 0V
- 5 cm steps : 2.5kV step 29 'picture frames' per drift volume. Copy of the ICARUS stetup. Likely on overkill.

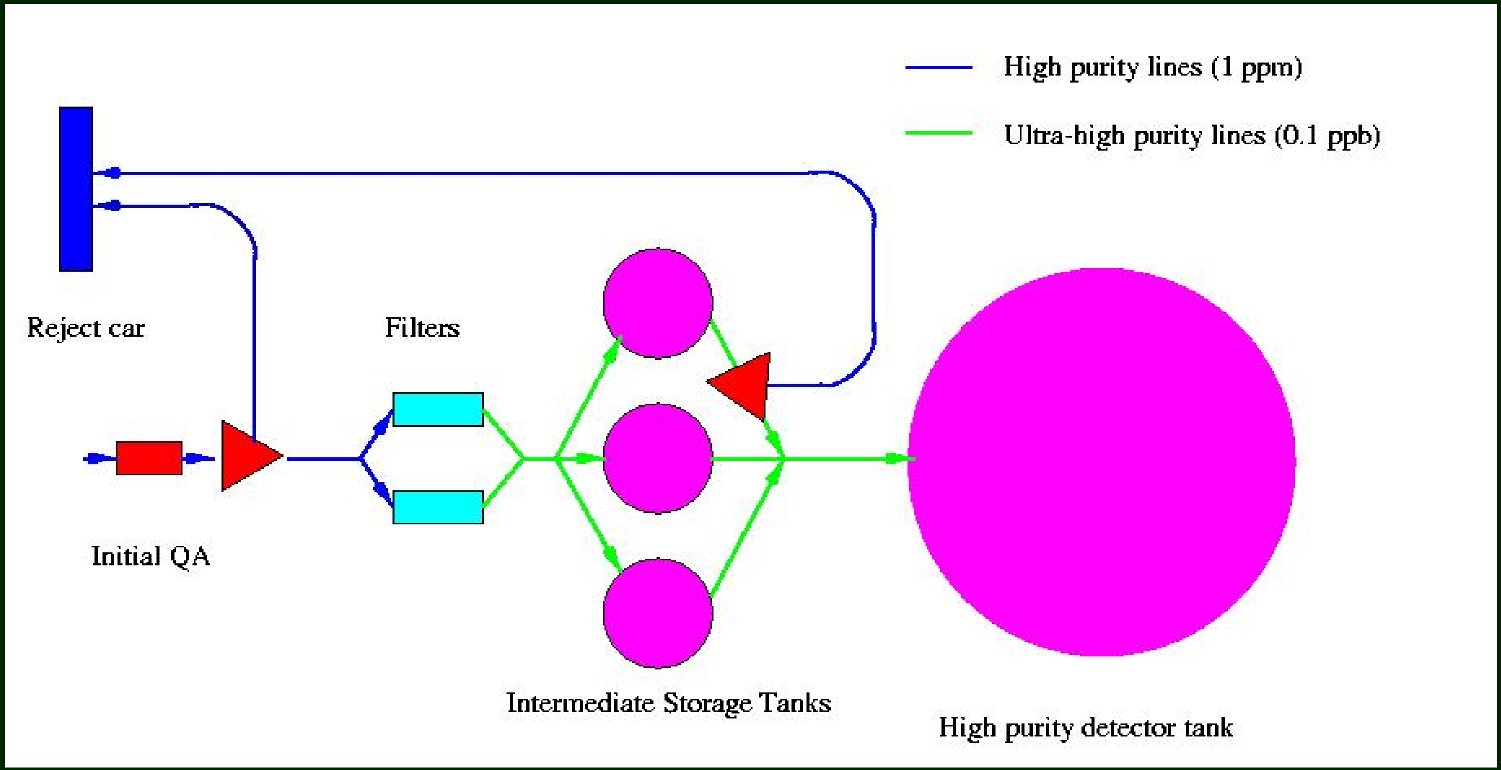
Wire chambers

- Very large up 30x40 m
- No gain, collection/induction only: thick wires, 150 μ stainless
- Wire spacing 5 mm
- 6 planes (UVX XVU) UV +- 30^{o} from vertical
- Wire tension ~10N, gravitational. Wires supported every 3 m
- Local loadad on the supporting truss 1.2t/m. 50 tons for the longest chamber.
- Total number of planes 36
- Total number of wires ~250,000
- Longest wire 35 m
- Wire capacitance 450-500 pF
- Signal ~ 25,000 electrons, Noise ~ 2,000 e
- Design S/N: 12. Improvements possible

Very Large Scale ← → Industrial Methods and Components wherever possible

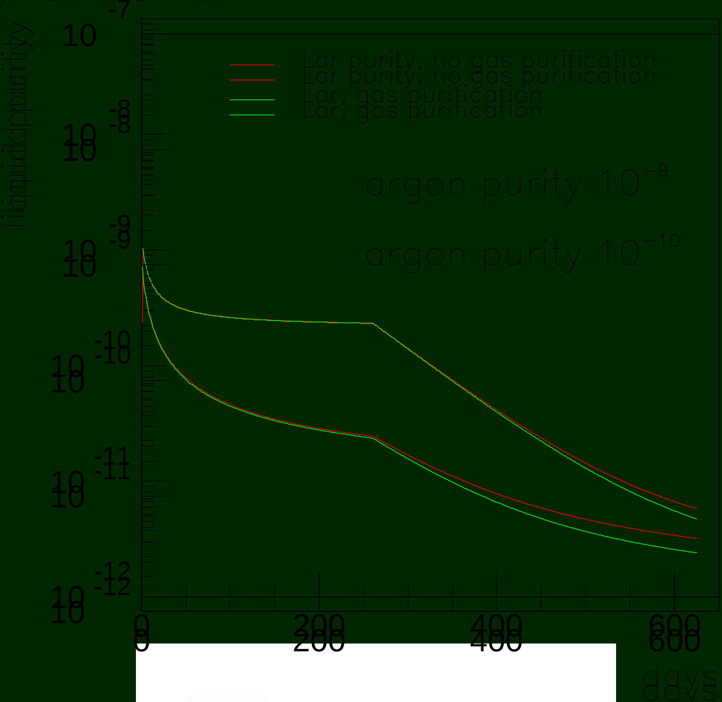
- Reliability ad robustness
- Safety of construction and operation
- Fault-proof and fault tolerant design

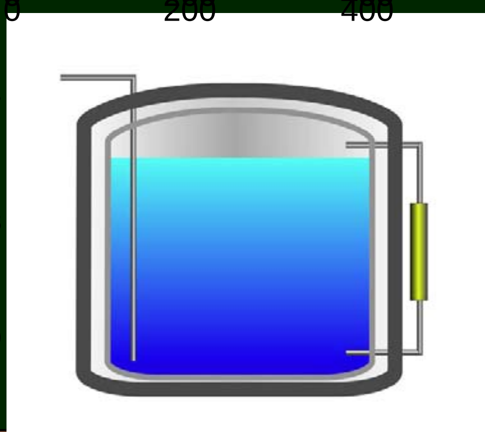
Initial purification system



- Design throughput: 200 t/day
- Oxygen load @1ppm delivered argon purity : 200 g/day. May be more. Probably will be less..
- 24/7 operation for 9 month

Main tank:28 t/hour re-circulation and purification system





Phase I: initial purge – 100-200 tons of LAr (~ 2 weeks) (vessel not evacuated)

- Very rapid volume exchange (several hours) => rapid purification
- Main issue: very large oxygen capacity required

➡ **Milestone: achieve >10 ms lifetime before continuing the fill process**

Phase II: filling

- Purity level determined by balance of the filtering vs. impurities introduced with the new argon

Phase III: operation

- Low rate of volume exchange (74 days)
- Removal (mainly) of the impurities introduced with argon
- Balance between purification and out-gassing
- In this phase out-gassing of tank walls, cables and other materials becomes a visible factor, although still very small.

50 kton detector

- Double wall cryogenic tank: H=30m, D=40 m
- Nitrogen re-liquefier of the boil-off
- 35,000 $m^3$of liquid argon
- 3 meter drift distance
- 7 cathode planes @ 150 kV
- 6 wire chambers, 6 planes of wires each (collection only, no gain, no high electric field) 225,000 wires
- Readout electronics
- Commercial re-circulation/purification system
- DAQ

Initial Engineering Studies → Cost

	15 kt, $M	50 kt, $M
Cryostat(tank)	19.4	32.1
Liquid Argon	12	37.0 (trucks)
Cryogenics/purification	4.0	6.5
HV/field shaping	4.0	5.7
Wire Chambers	4.0	(5.0)
Electronics , cabling	4.0	5.0
Data Acquisition	5.0	5.0
Site	-	???
TOTAL	52.4 +'Site'	96.3 + 'Site'

Challenge: Make a Convincing Case

- Are there any elements of technology which are not <u>really</u> known or demonstrated, or does one need some further R&D?
- What is the best way to collect/present the wealth of information available from industry/ICARUS/others
- What is a realistic, fully loaded, cost estimate of a (~fully) engineered detector?
- What are the risks associated with the construction and operation of a large cryogenic detector?

Possible (?) Scenario

Phase I: 15 kton detector

- superior to the 'S' detector of Mena/Parke
- factor 12 bigger than the ICARUS module under construction
- validation of LNG tank-based detector concept

Phase II: 50 kton (or larger) detector ('M')

Data rates

- 250,000 channels read out @ 2 Mhz
- A single time frame ('event') ~ 1 G 'pixels' – GIGApixel camera
- Take 40 bits/channel => 0.25 Tbyte/sec
- Most of the pixels are empty. Rate is dominated by cosmics. Cluster finding/zero suppression in FE electronics: factor ~ 1000
- Data rate 0.25 Gbytes/sec

Case E(asy): Neutrino beam

- Need to read out 2 msec time window (10 μsec + drift time)
- Data rate 0.5 Mbytes/sec, 5 Tbytes/year

Case C(hallenging): free running, continuously active detector

- Need LHC-class DAQ system
- 2.5 Pbytes/year data storage system
- Grid-like analysis (SETI, Prime search?)

Liquid Argon: the detector to differentiate supernova neutrino species

- Elastic scattering (ES)

  $\phi(\nu_e)+0.15\ \phi(\nu_\mu + \nu_\tau)$
  $\phi(\bar{\nu}_e)+0.34\ \phi(\bar{\nu}_\mu + \bar{\nu}_\tau)$

  $$\nu_x + e^- \rightarrow \nu_x + e^-$$
  $$\bar{\nu}_x + e^- \rightarrow \bar{\nu}_x + e^-$$

- Electron-neutrino absorption (CC)

  $\phi(\nu_e)$
  Q=5.885 MeV

  $$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$

- Electron-antineutrino absorption (CC)

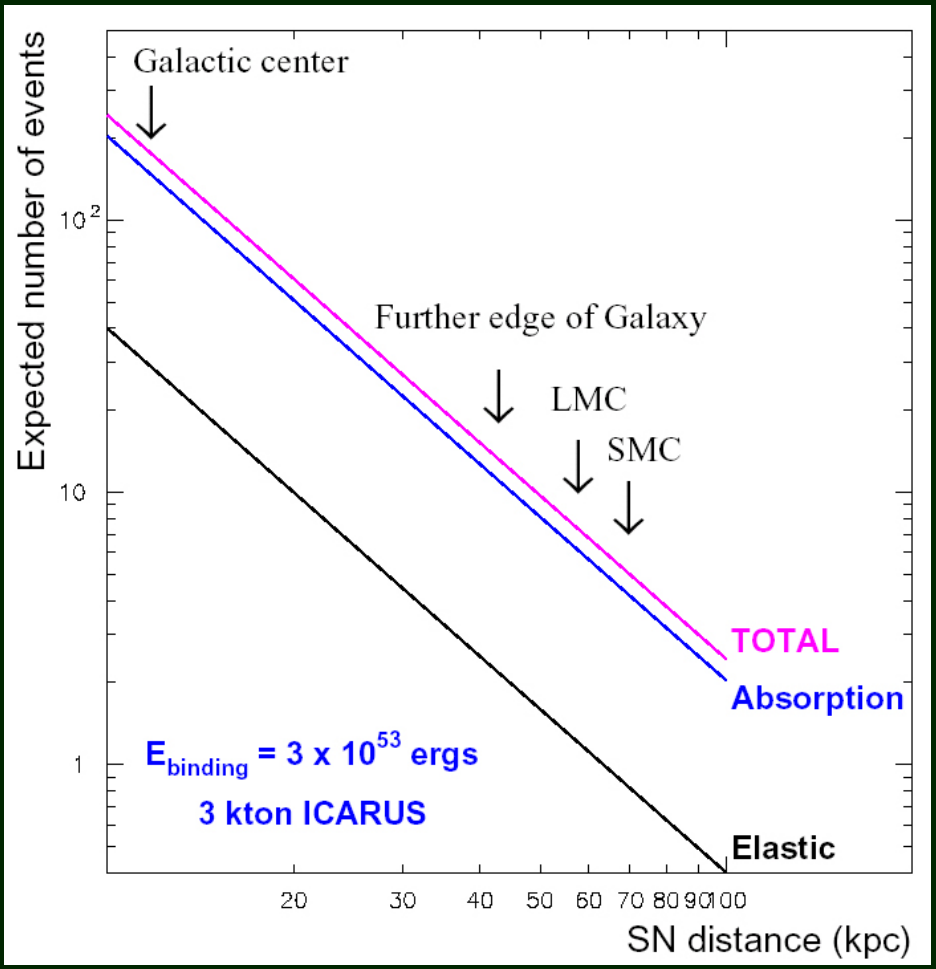
  $\phi(\bar{\nu}_e)$
  Q≈8 MeV

  $$\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$$

- K*/Cl* nuclear states identified by electromagnetic nuclear cascades (energy resolution!)

A. Bueno,I. Gil-Botella, A. Rubbia hep-ph/ 0307222

Supernova 201xA?



- These event rates are for 3 kt ICARUS
- Multiply by a factor 17 or so for NuMI off axis ➔ good measurement of energy and time distribution from not-too-distant supernova

Are protons forever?

Q: Why do protons do not decay?

A1: We do not know

A2: Because of baryon number conservation

Notice: A1 == A2, but A2 sounds better

SuperK: 50 ktons detector, several years of operation. Very stringent limits. Is there anything to add, short of a major increase of mass ?

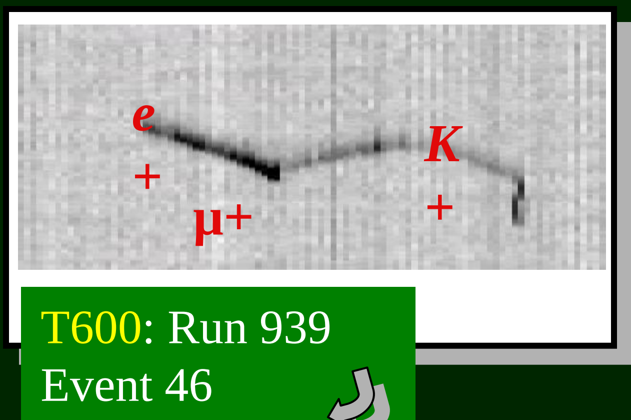
A: it depends on the postulated decay modes /supermultiplet assignment at the GUT scale. Perhaps the dominant decay mode is into K? (Weak spot of water Cerenkov due to Cerenkov thresold)

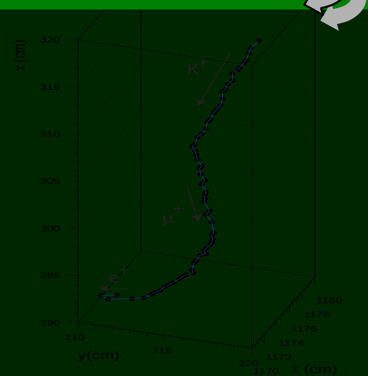
P-> Kν in LAr detector

K identification: dE/dx

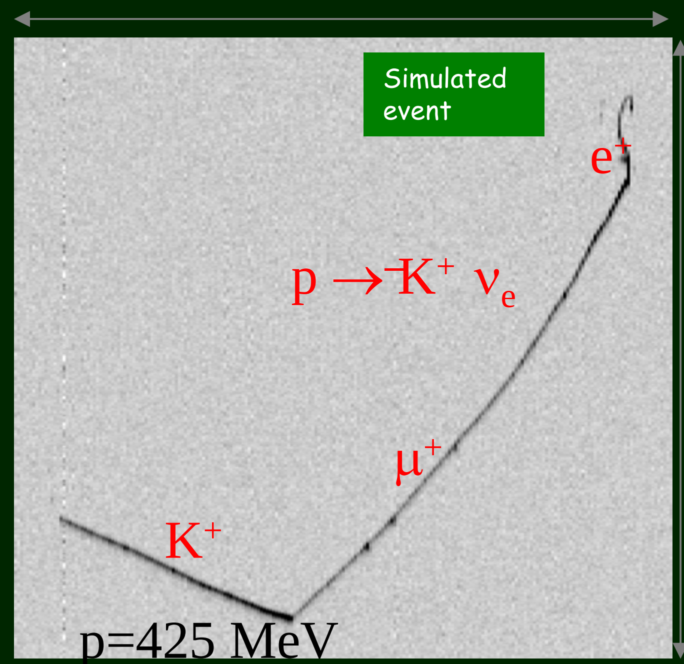
K/μ/e decay chain. Good energy determination from range

High efficiency, very low background





- Real event in a real detector
- K incoming from outside
- Imagine this happening in the middle of a big detector volume



Proton decay, expected limits: ICARUS

Channel		Eff. (%)	Observed (evts.)	Bkg. (evts.)	Exposure (kTon×yr)	τ/B limit (10^{32} yr)	Needed Exp. to reach SK (kTon×yr)
$p \to e^+ \pi^0$	SuperK	43	0	0.2	79	$50 \to 30$ [1 evt]	
	ICARUS	45	–	0.005	5	2.7	94
$p \to K^+ \bar{\nu}$	SuperK				79	$19 \to 13$ [1 evt]	
prompt $\gamma\, \mu^+$	SuperK	8.7	0	0.3		$10 \to 7$	
$K^+ \to \pi^+ \pi^0$	SuperK	6.5	0	0.8		$7.5 \to 5$	
	ICARUS	97	–	0.005	5	5.7	17
$p \to \mu^+ \pi^0$	SuperK	32	0	0.4	79	$37 \to 24$ [1 evt]	
	ICARUS	45	–	0.04	5	2.6	102

This is just an example: it takes ~17 kton years to reach the current limit of sensitivity

Low backgrounds, detailed kinematical reconstruction allow for a positive identification even with very small signal events

Proton decay with surface detector? Nuts??

- Exquisite spatial and temporal resolution/granularity (1 gigapixel x 1 msec
- Complete history of all incoming 'stuff' (3D movie)
- Very large volume (self-shielding for a major fraction of a detector, systematic checks, etc..)
- Primarily a computing/data storage problem (fun problem to have)
- Most serious source of a problem: nAr -> KΛ, Λ decays invisibly. Investigating… (Ed Kearns)
- T0 ??
  - T0 is an attribute of an object, not of an 'event'
  - cathode/wire plane crossing determines a T0
  - dE/dx from a small section of a track determines the drift distance

Challenges

- Are there any elements of technology which are not really yet demonstrated, or does one need some further R&D?
- What is a realistic cost estimate of a (~fully) engineered detector?
- Accelerator neutrino experiment is *given*, how realistic is a perspective of a surface-based nucleon decay/ supernova experiment?
- A very real possibility of a major savings in money and much shorter timescale for an experiment

Conclusions

- Newly developed technology of liquid argon imaging calorimetry offers a very attractive (and diversified) physics opportunities to establish/enrich our physics program
- We can make a Great Leap Forward by learning and using the technology developed by/for ICARUS
- 50 kton class Lar calorimeter in northern Minnesota/southern Canada is a very attractive avenue to take a lead in studies of neutrino oscillations in the US and establish this technology