A Dream Detector Come True?

Adam Para

Outline

- What is the detector and how does it work?
- How does it fit into our long range plan and why is it much better than alternatives?
- Can it be built and how much will it cost?
- How does it fit into a grand picture (a.k.a. roadmap)?
- What are the additional physics opportunities offer by this detector?
- What other experiments can profit from this detector technology?

Not all issues of physics and technology can be presented in this talk. This is hopefully not the last talk on this subject.

(Incomplete) Credits

- Flavio Cavanna, Andre Rubbia, Antonio Ereditato, Francesco Pietropaolo, Franco Sergiampietri
- Dave Cline, Kirk McDonald, George Mulholland, John Learned
- Alberto Marchionni, Hans Jostlein, Mario Campanelli, Liz Buckley, Tom Ferbel, Robert Hatcher, Rich Kadel, Carl Bromberg, Stan Wojcicki, Aseet Mukherjee, Elena Aprile, Bonnie Fleming, Stephen Pordes, Petros Rapidis, Bruce Hanna, Olga Mena, Bob Kephart, Bill Willis
- Velko Radeka, Charlie Nelson, Ray Yarema
- Larry Bartoszek, Karen Kephart, Rich Schmitt, Zhijing Tang, Bob Wands
- + many, many others

Important papers/sources

- Gatti,Padovini,Quartapelle,Greenlaw,Radeka *Considerations for the design of a time projection liquidn argon ionization chamber*, IEEE Trans. NS-26, No2, (1979) p.2910
- F. Sergiampietri *On the Possibility to Extrapolate Liquid Argon Technology to a Supermassive Detector for a Future Neutrino Factory*, NuFact01
- Cline,Sergiampietri,Learned,McDonald LANNDD, *A Massive Liquid Argon Detector for Proton Decay, Supernova and Solar Neutrino Studies* astro-ph/0105442
- Mulholland(ACT) *A LANNDD Investigation*

Selected recent ICARUS publications I

- "Design, construction and tests of the ICARUS T600 detector"
- "Study of electron recombination in liquid Argon with the ICARUS TPC"
- "Measurement of the muon decay spectrum with the ICARUS T600 liquid Argon TPC"
- "Detection of Cerenkov light emission in liquid Argon", Nucl. Inst. Meth., A516 (2004) 348-363
- "Analysis of the liquid Argon purity in the ICARUS T600 TPC", Nucl. Inst. Meth., A516 (2004) 68-79
- "Observation of long ionizing tracks with the ICARUS T600 first half-module", Nucl. Inst. Meth., A508 (2003) 287-294
- "Performance of the 10 m3 ICARUS liquid argon prototype", Nucl. Inst. Meth., A498 (2003) 292-311
- "Determination Of Through-Going Tracks' Direction By Means Of Delta-Rays In The ICARUS Liquid Argon Time Projection Chamber", Nucl. Instrum. Meth. A449 (2000) 42

Selected recent ICARUS publications II

- "First Observation Of 140-cm Drift Ionizing Tracks In The ICARUS Liquid-Argon TPC", Nucl. Instrum. Meth. A449 (2000) 36
- "Study of Solar Neutrinos with the 600 ton liquid argon ICARUS detector", Nucl. Instr. and Meth. A 455 (2000), 378
- "Detection Of Scintillation Light In Coincidence With Ionizing Tracks In A Liquid Argon Time Projection Chamber", Nucl.Instrum.Meth.A432 (1999) 240
- "Performance Evaluation of a Hit Finding Algorithm for the ICARUS Detector", Nucl. Instr. and Meth. A 412, 2-3 (1998), 440.
- "A neural network approach for the TPC signal processing", Nucl.Instr. and Meth. A 356, (1995), 507.
- "On atmospheric Ar39 And Ar42 Abundance", Nucl. Instr. and Meth. A 356, (1995), 526.
- "Performance of a three-ton liquid argon time projection chamber", Nucl. Instr. and Meth. A 345, (1994), 230.
- A 3-D image chamber for the liquid argon TPC based on multi-layer printed circuit board", Nucl.Instr. and Meth. A 346, (1994), 550.
-

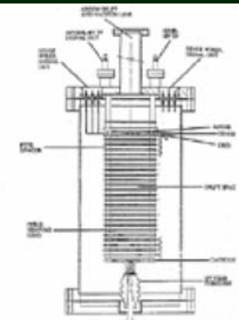
Selected recent ICARUS publications III

- "The ICARUS R&D program and results", Nucl. Instr. and Meth. A 327, (1993), 173.
- "A Simple and Effective Purifier for Liquid Xenon", Nucl.Instr. and Meth. A329, (1993), 567.
- "Detection of energy deposition down to the keV region using liquid xenon scintillation", Nucl. Instr. and Meth. A 327 (1993), 203.
- "A three-ton liquid argon time projection chamber", Nucl.Instr. and Meth. A 332, (1993), 395.
- "Argon purification in the liquid phase", Nucl. Instr. and Meth. A 333, (1993), 567.
- "The ICARUS liquid argon TPC: a complete imaging device for particle physics", Nucl.Instr. and Meth. A 315, (1992), 223.
- "A Study of The Factors Affecting The Electron Life Time in Ultra-Pure Liquid Argon", Nucl.Instr. and Meth. A305, (1991), 177.
- "A study of the Electron Image due to ionizing events in a two-dimensional liquid argon TPC with a 24 cm drift gap", Nucl. Instr. and Meth. A286, (1990), 135.

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
  - ✓ 600 ton detector operating in Pavia
  - ✓ 2x1200 ton detectors under construction for GS (ICARUS)

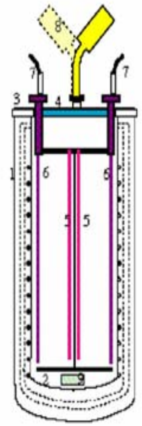
Many years of intense R&D



24 cm drift wires chamber

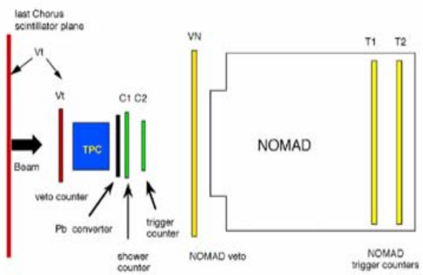
1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

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

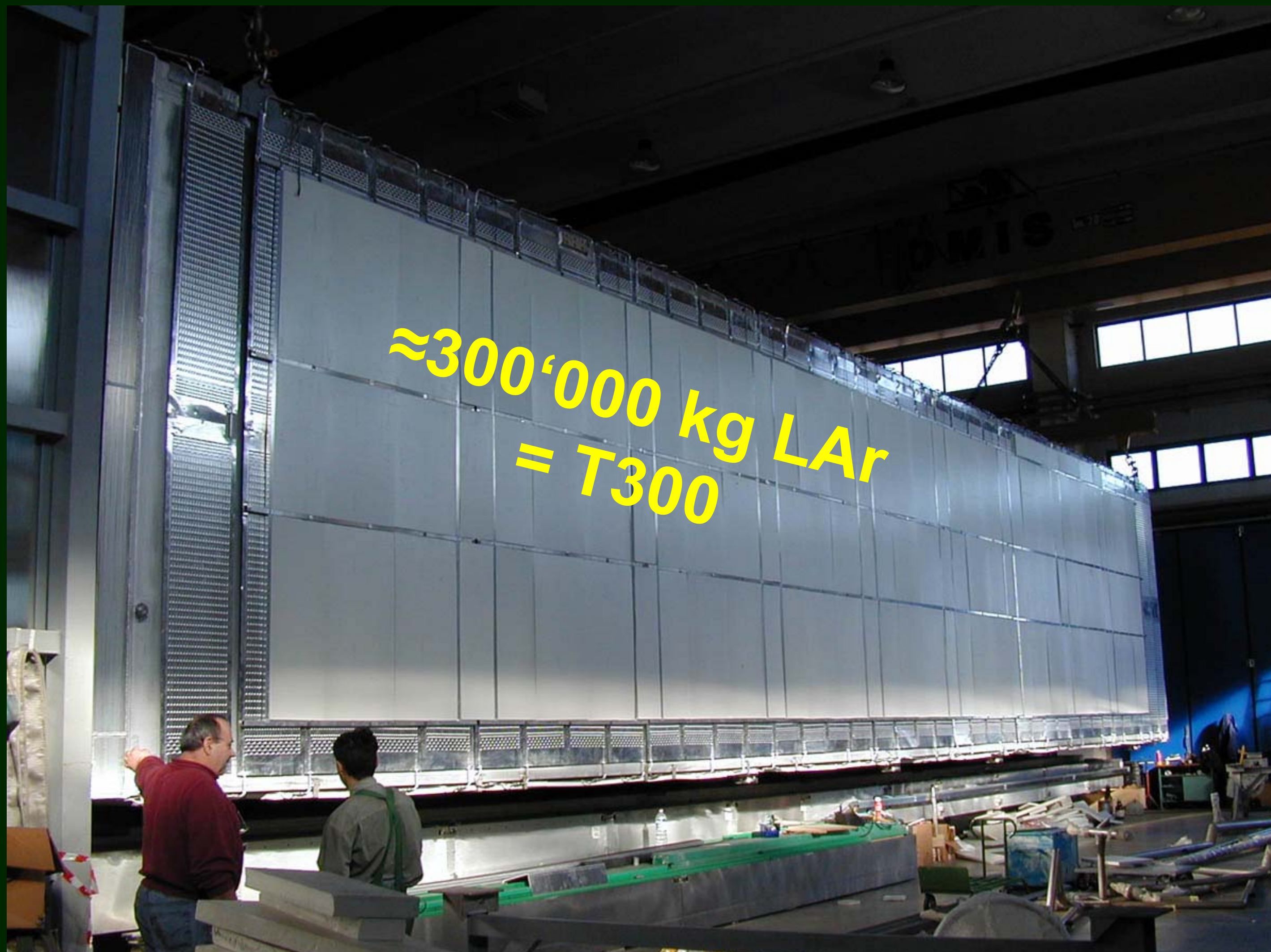


1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

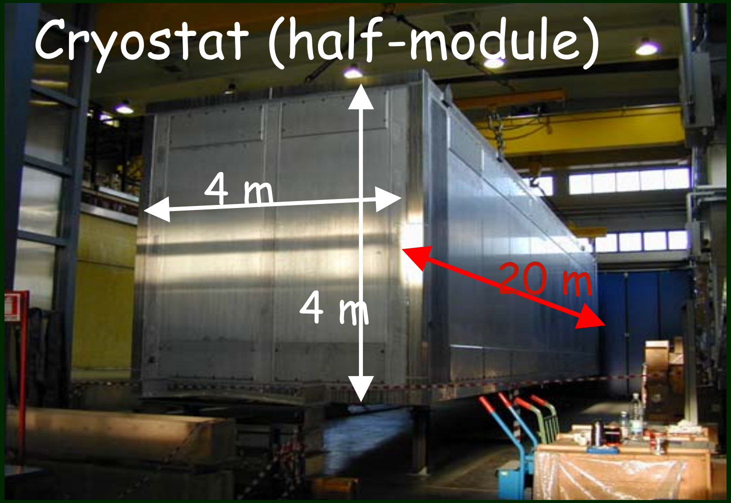
10 m^3 industrial prototype

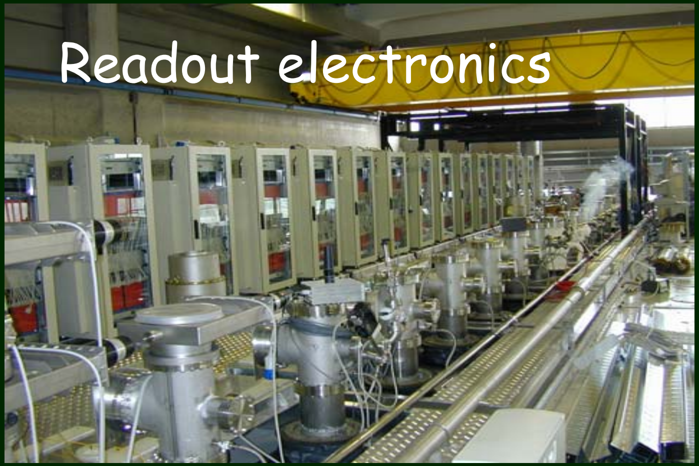
1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

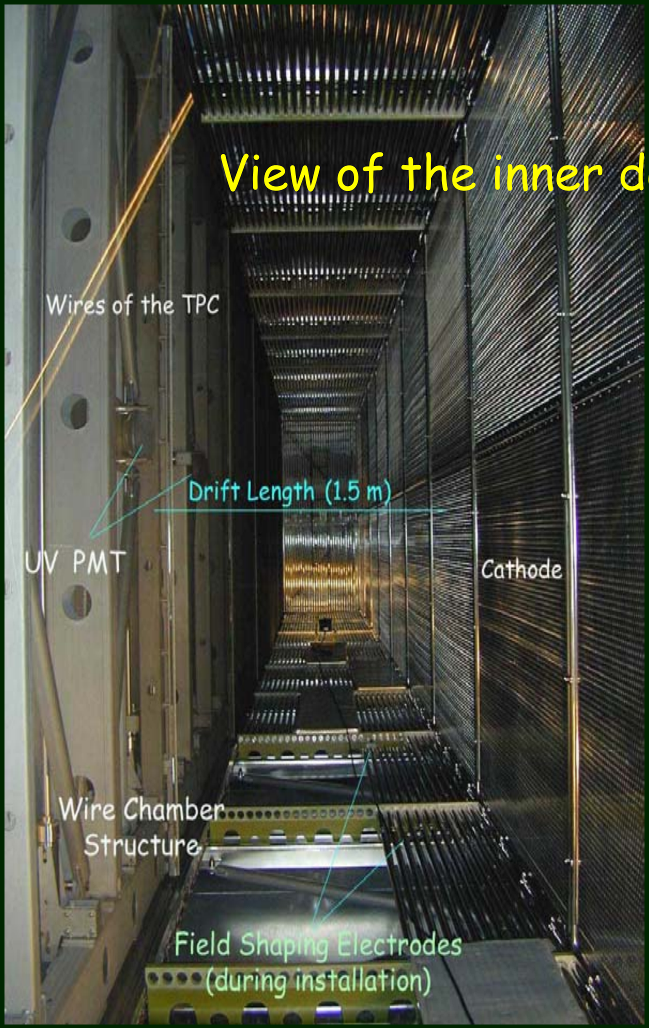
Leading to a large detector



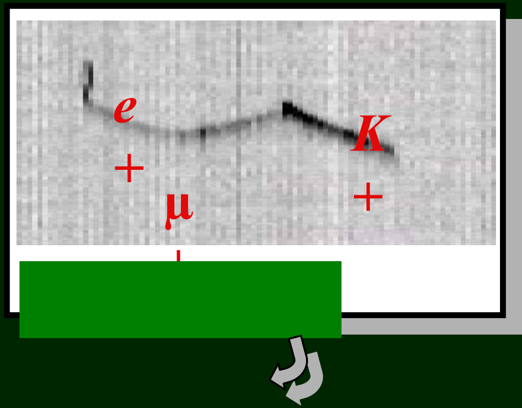
Inside and outside







It works!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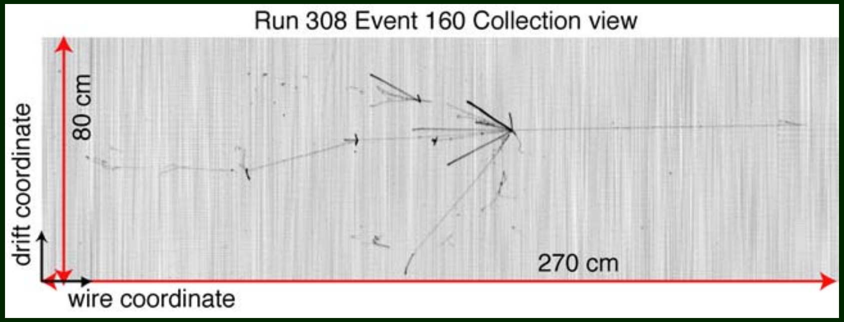
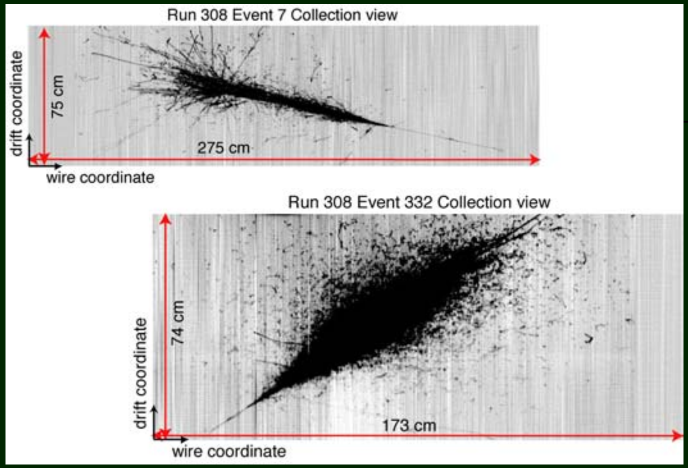
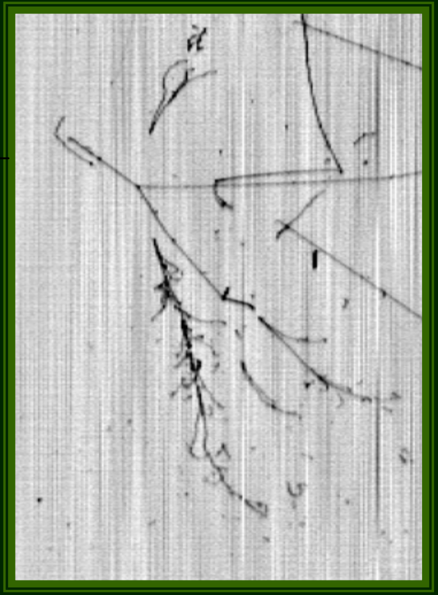
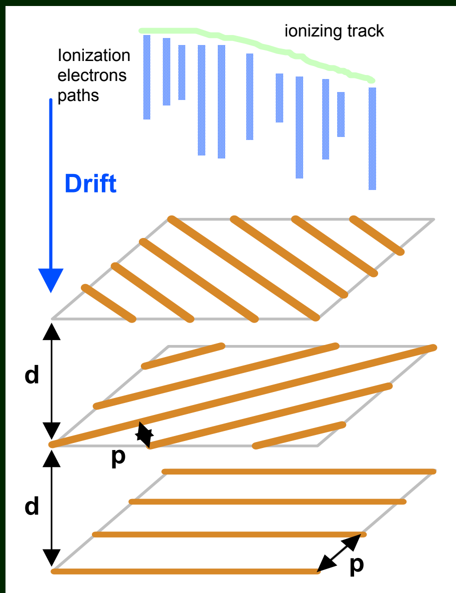
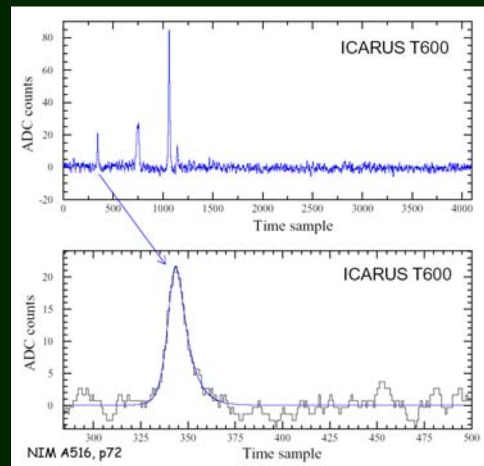

Run 308 Event 160 Collection view
80 cm
drift coordinate
270 cm
wire coordinate


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



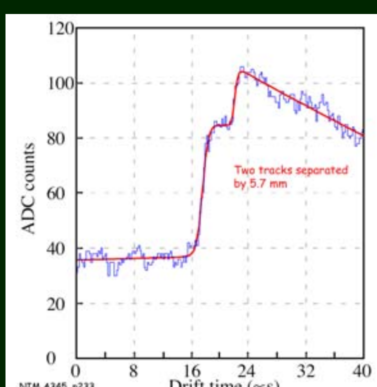


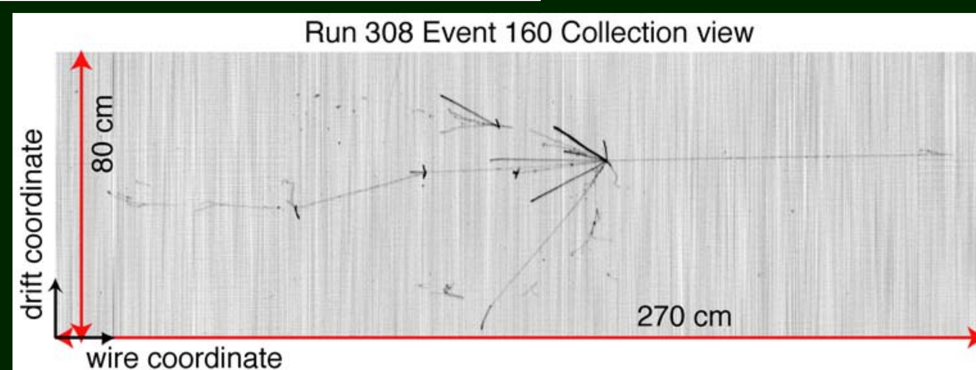
$$F(t) = B + A\frac{e^{-\frac{t-T_0}{\tau_2}}}{1+e^{-\frac{t-T_0}{\tau_1}}}$$

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

Uniform electric field:

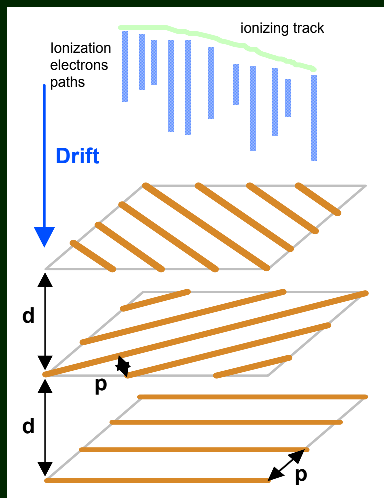
$(t-T_0) = v_{drift} * (x-x_{wire})$

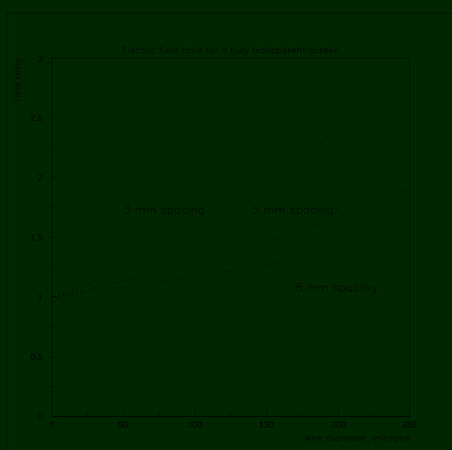




a 2D projection 'only'

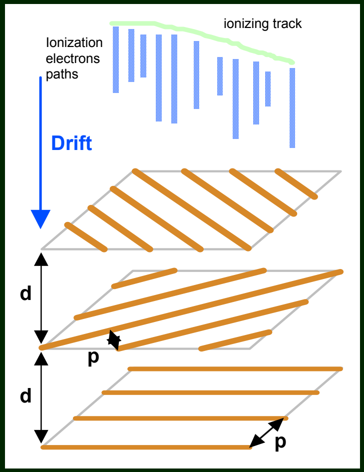
TPC II: the second/(third?) coordinate

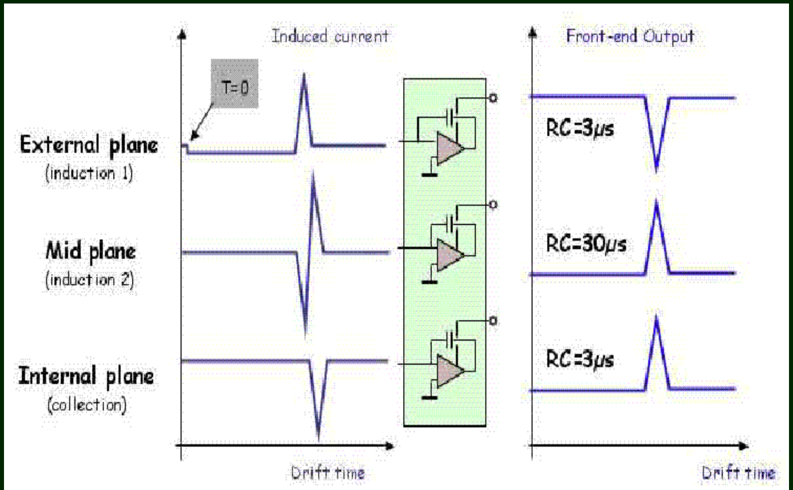


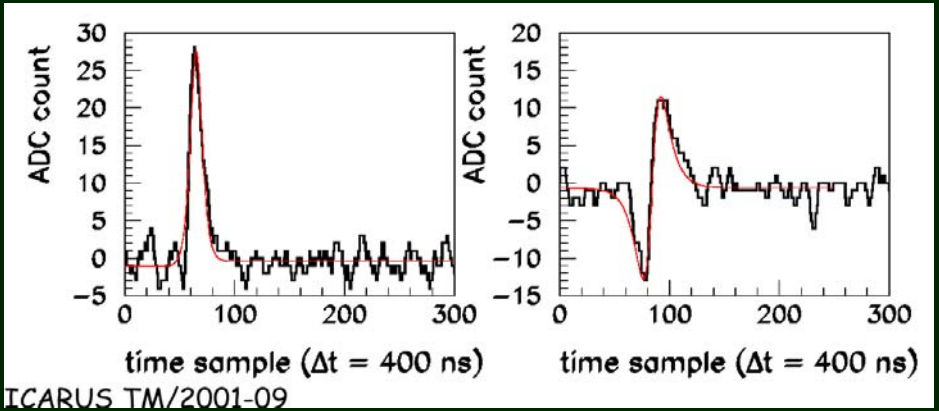


- A 'traditional' TPC: a set of pads behind the sense wire.
- Liquid Argon: add a plane(s) of grids in front of the collection wires
- Arrange the electric fields/wire spacing for a total transparency [Bunneman, Cranshaw,Harvey, Can. J. Res. 27 (1949) 191]
- Detect the signal induced by passing electrons, 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

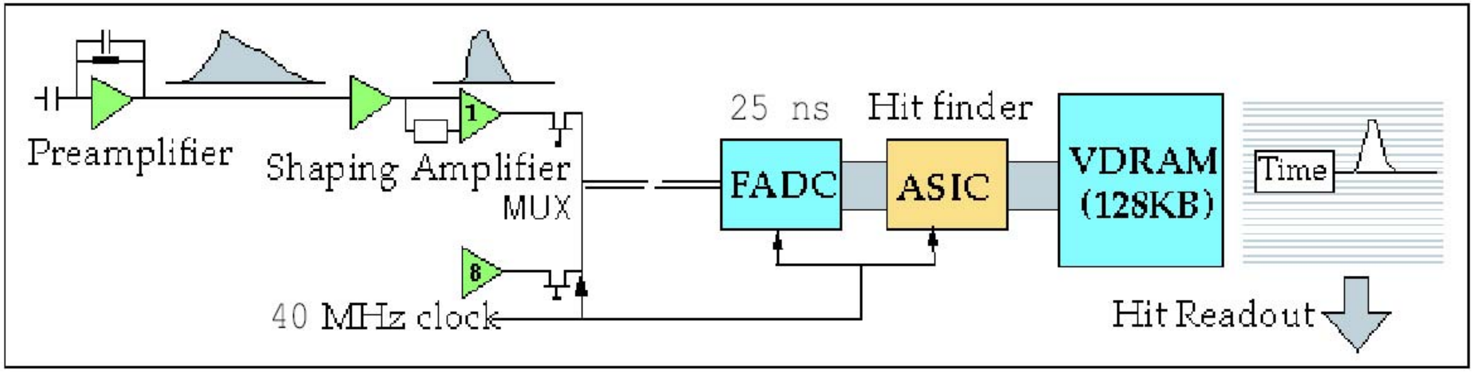






Front-end electronics/pulse shaping determines the actual waveform: room for optimization

Front-end electronics issues

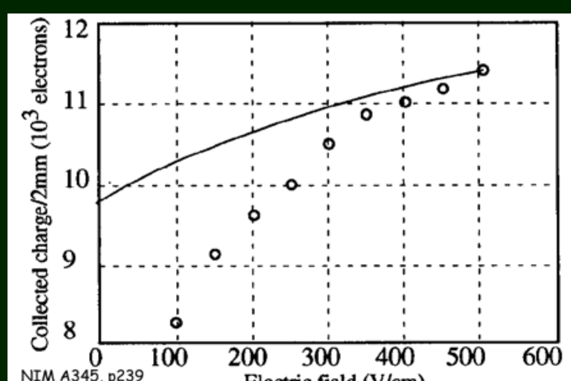


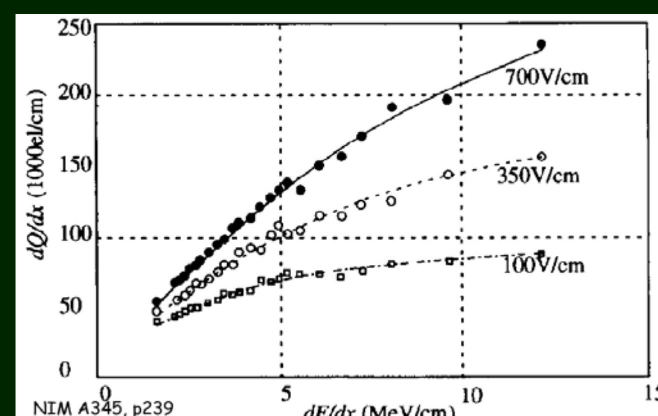
ICARUS TM/2001-09

- 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)

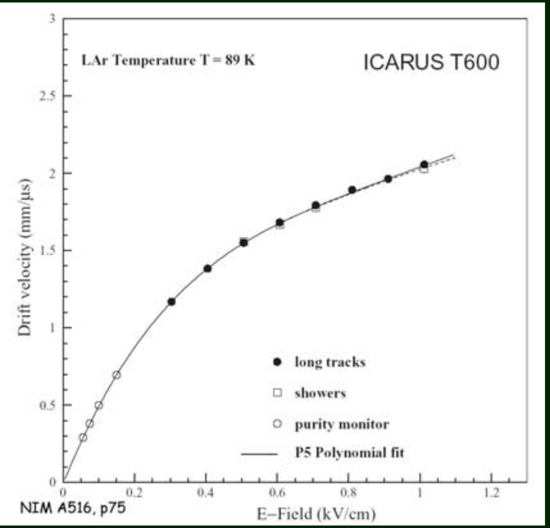
Signal size: how many electrons per 1 cm of a track?

- $(dE/dx)_{mip}$ = 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





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
  - ✓ σ_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 ?

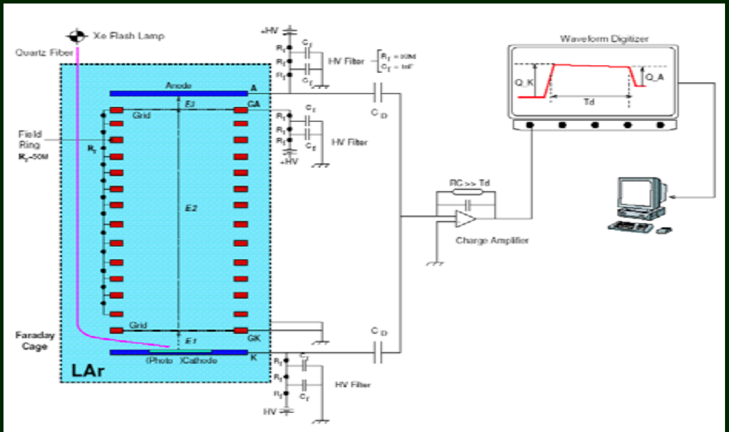
- Best commercial O_2 gauge: least count 0.2 ppb (not bad at all, but nut good enough)
- How do you know that there are no other impurities, not detectable with your purity ,monitors, which absorb electrons (remember MarkII?
- Electron lifetime detector

Carugno,Dainese,Pietropaolo,Ptohos

NIM A292 (1990) 580:

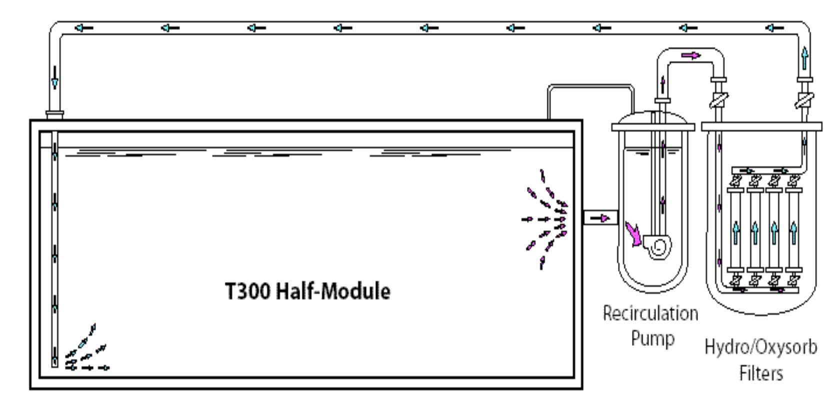
- ✓ Extract electrons from a cathode
- ✓ Drift over a certain distance
- ✓ Measure charge along the path

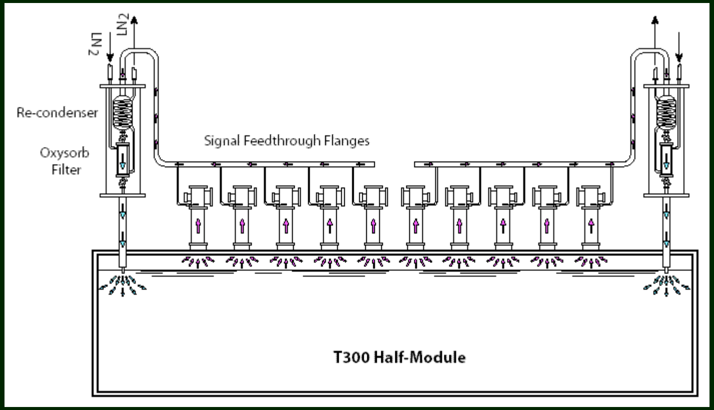
$$Q(t) = Q_0 e^{-\frac{t}{\tau}}$$



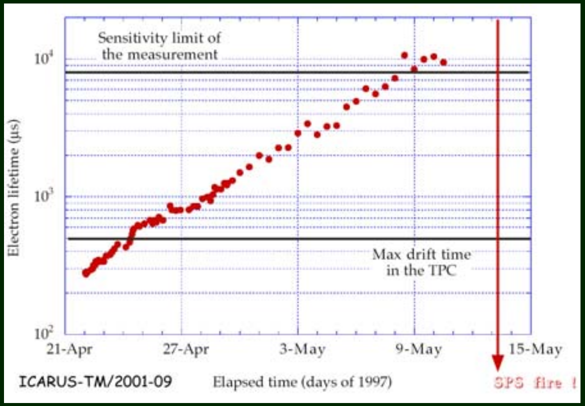
Argon purification: liquid and gas phase

- 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



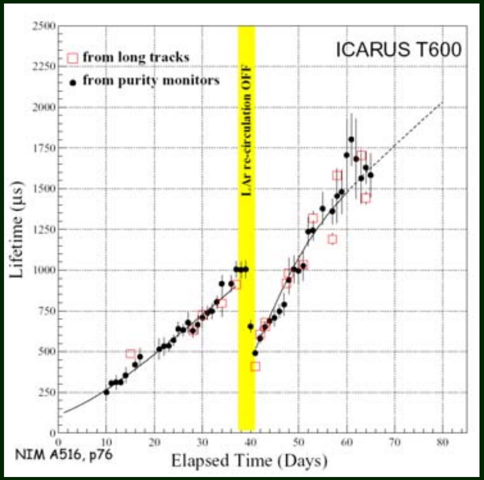


Argone purity/electron lifetime in real life ?



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

- 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

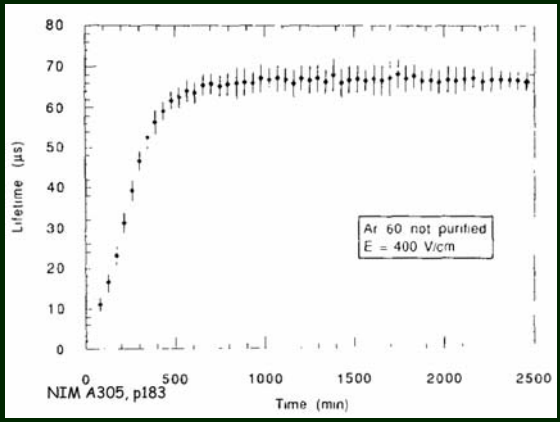


Argon purity, ctnd.

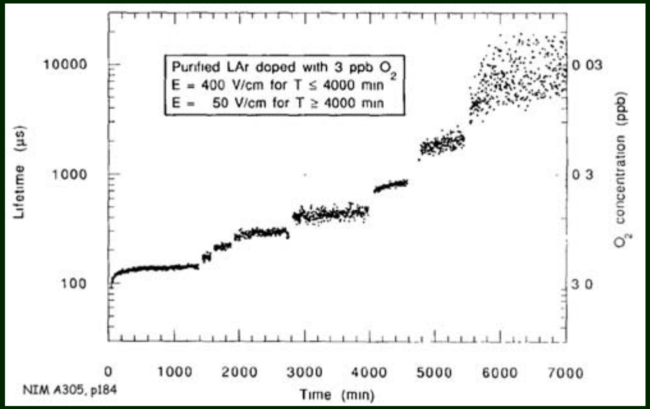
Q:Oxisorb R20 filters have design purity level of <5 ppb. How come that the results are so good (<0.1ppb)?

A: Specs refer to gaseous argon at NTP.

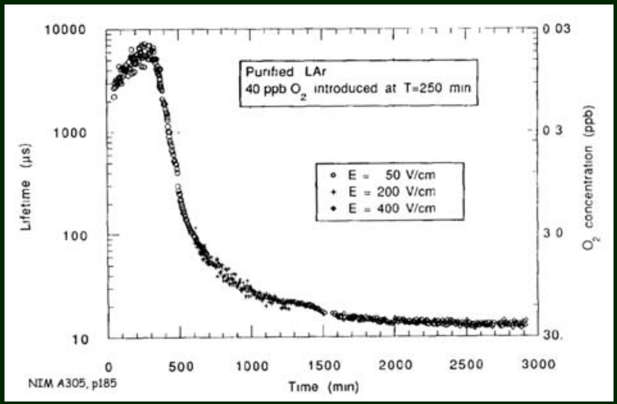
In a liquid phase impurities 'freeze out' at the vessel walls. The natural purification speed is limited by diffusion speed. (Related: B. Kephart, E706)



Electron lifetime improvement in 'regular argon'



Electron lifetime in ultra-pure argon doped with oxygen



Degradation of argon purity is consistent with diffusion time

Argon purity, lessons for a very large detector

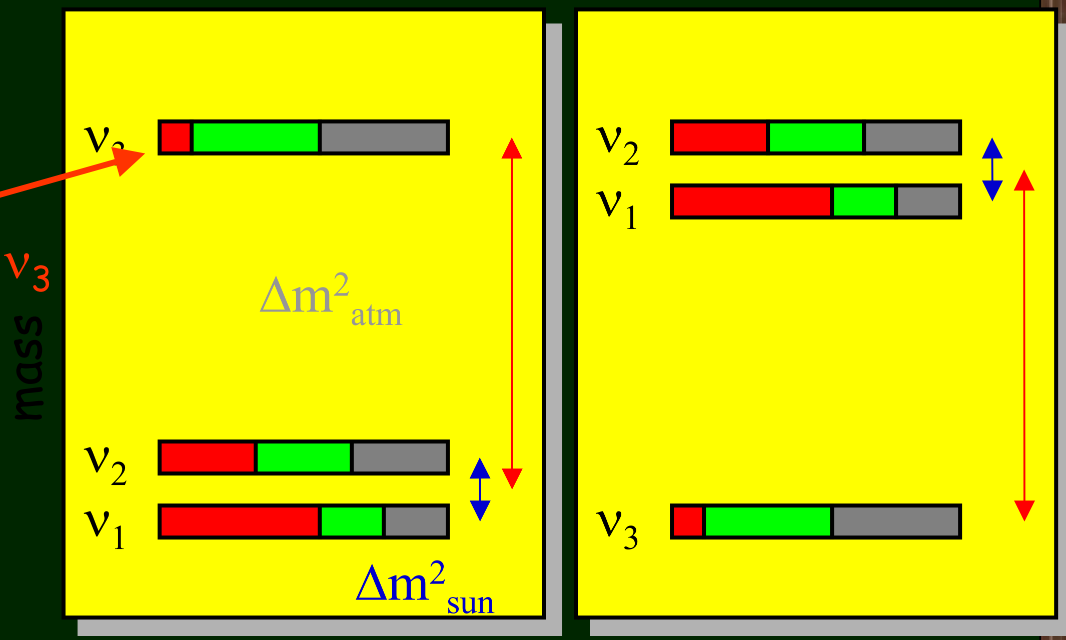
- Long electron lifetimes (~10ms)/drift distances (>3m) appear achievable with commercial purification systems
- The main source of impurities are the surfaces exposed to the gaseous argon
- Increasing the ratio of liquid volume to the area of gaseous contact helps (dilution)
- Increasing the ratio of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

Neutrino Physics is a major component of our future physics program

- Off-axis experiment
- Proton driver
- Neutrino scattering experiments

What do we want to know

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

The key: $\nu_\mu \Rightarrow \nu_e$ appearance

$$P(\nu_\mu \to \nu_e) = P_1 + P_2 + P_3 + P_4$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E_\nu};$$

$$A = \sqrt{2} G_F n_e;$$

$$B_\pm = \left| A \pm \Delta_{13} \right|;$$

$$J = \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

$$P_1 = \sin^2\theta_{23} \sin^2\theta_{13} \left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2}$$

Oscillation at the 'atmospheric' frequency

$$P_2 = \cos^2\theta_{23} \sin^2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2}$$

Oscillation at the 'solar' frequency

$$P_3 = J\cos\delta \left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right) \cos\frac{\Delta_{13} L}{2} \sin\frac{AL}{2} \sin\frac{B_\pm L}{2}$$

$$P_4 = J\sin\delta \left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right) \sin\frac{\Delta_{13} L}{2} \sin\frac{AL}{2} \sin\frac{B_\pm L}{2}$$

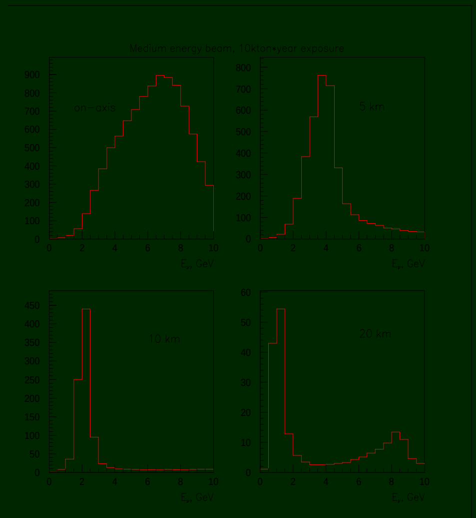
Interference of these two amplitudes ➔ CP violation

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

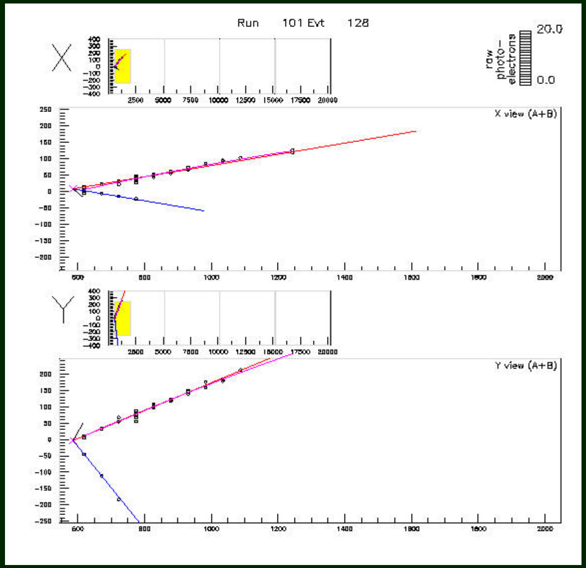
3 unknowns, 2 parameters under control L, E, neutrino/antineutrino <u>Need several independent measurements to learn about underlying physics parameters</u>

Off-axis NuMI Experiment

NuMI neutrino beam



Off-axis 'narrow band' beams minimize NC background



Low Z sampling calorimeter to detect/identify electrons

NuMI and JPARC experiments in numbers

- Low density sampling calorimeter (NuMI)
- Assume P_{osc}=0.05 (~ CHOOZ limit)

	NuMI Off-axis 50 kton, 85% eff, 5 years, 4×10^{20} pot/y		JHF to SK Phase I, 5 years	
	all	After cuts	all	After cuts
ν_μ CC (no osc)	28348	6.4	10714	1.8
NC	7032	17.2	4080	9.3
Beam ν_e	604	23.7	292	11
Signal (Δm^2_{23}=2.4/3 $\times 10^{-3}$, NuMI/JHF)	677.4	237.1	302	123
FOM (signal/$\sqrt{\text{bckg}}$)		34.6		26.2

Can we do better? Or much better?

$$FOM = \frac{S}{\sqrt{B}}$$

No signal, set limit

$$FOM = \frac{S}{\sqrt{B+S}}$$

Signal observed, measure probability

$$FOM \propto \sqrt{M}$$

Sampling calorimeter limitation:

- Efficiency ~0.3
- NC and CC (π^0) background ~ beam ν_e

Imagine, just imagine: a detector with ~ 90% efficiency and no π^0 background:

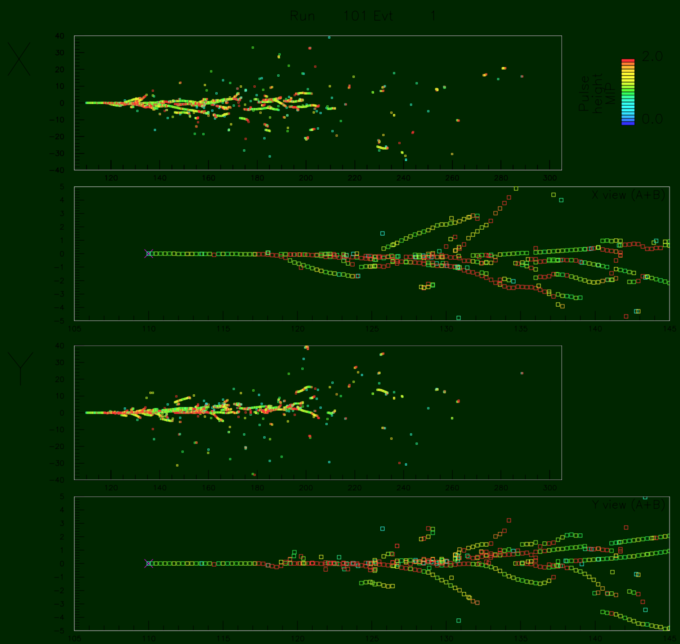
$$FOM' = \frac{3S}{\sqrt{\frac{3}{2}B}} = \sqrt{6}\frac{S}{\sqrt{B}}$$

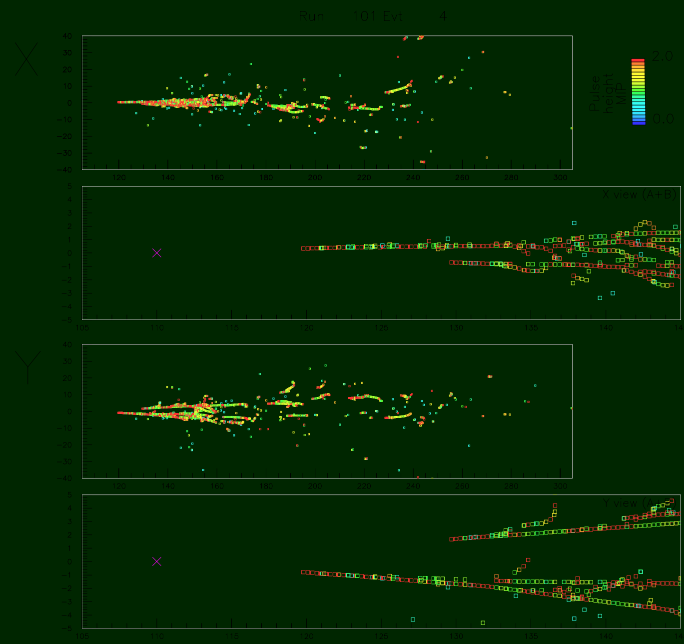
$$FOM' = \frac{3S}{\sqrt{3(S+B)}} = \sqrt{3}\frac{S}{\sqrt{S+B}}$$

Gain a factor 3-6 in an effective mass of a detector. Better use of preciuos commodity: <u>protons</u>

Electrons vs π^0's (1.5 GeV) in LAr

Pulse height scale : mip=green, 2mip=red





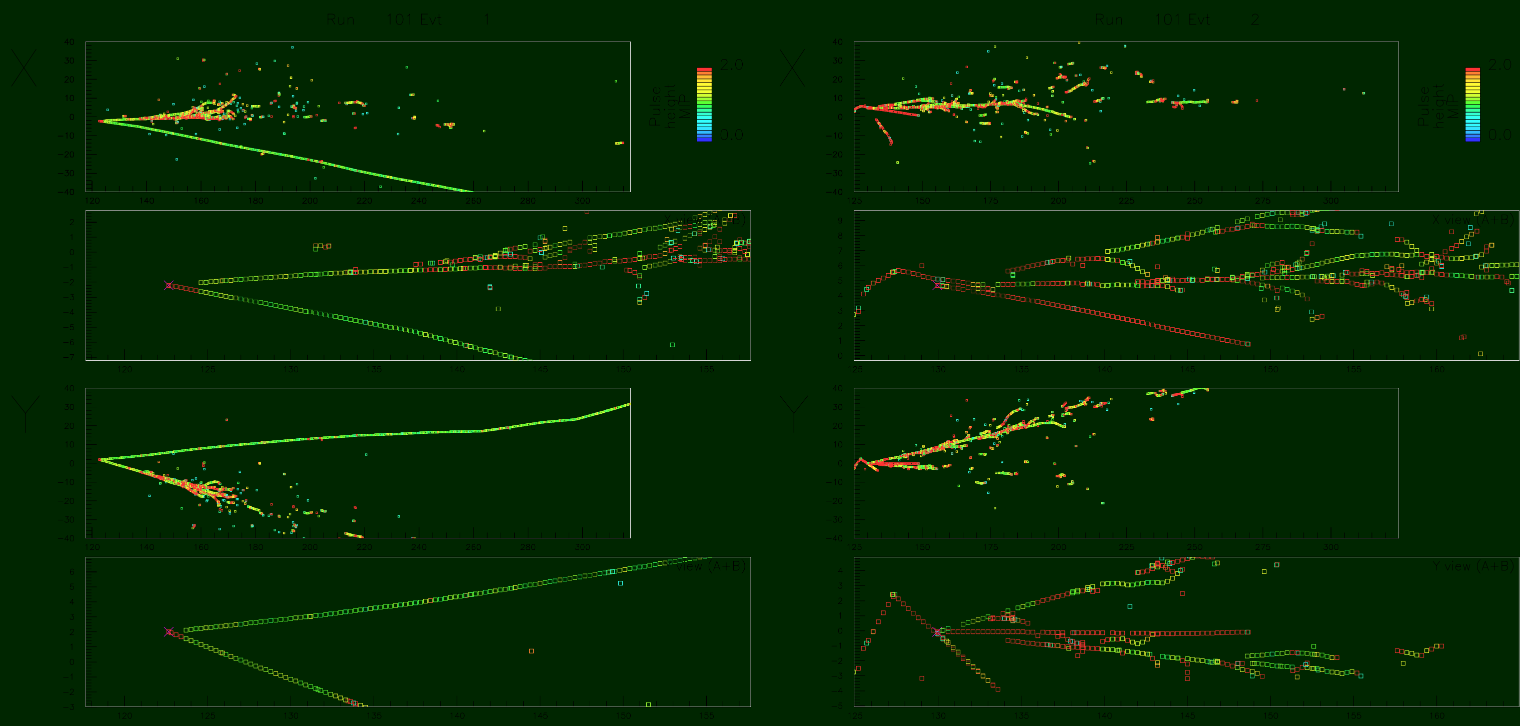
Electron:

- Track starts at the vertex
- Single track (green) over first few cm

π^0:

- Two conversion points detached from the vertex
- Two tracks(red) at the conversion point

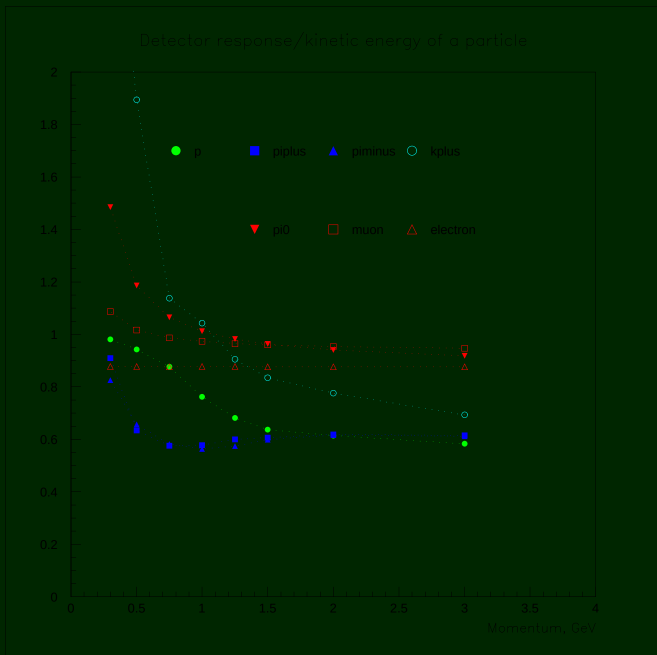
1.5 GeV ν_e CC events

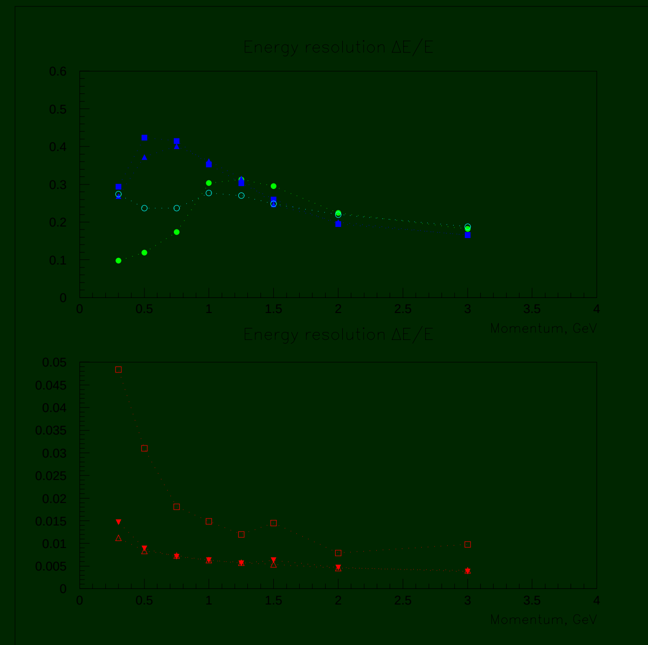


Visual scan:

- ~80% ν_e events easily recognizable, no NC background
- e/π^0 likelihood should be a powerful tools
- 90% efficiency should be achievable
- Topological information only, ultimate spatial resolution not important

Extra bonus: particle ID and calorimetry at low energies, 0-2 GeV region

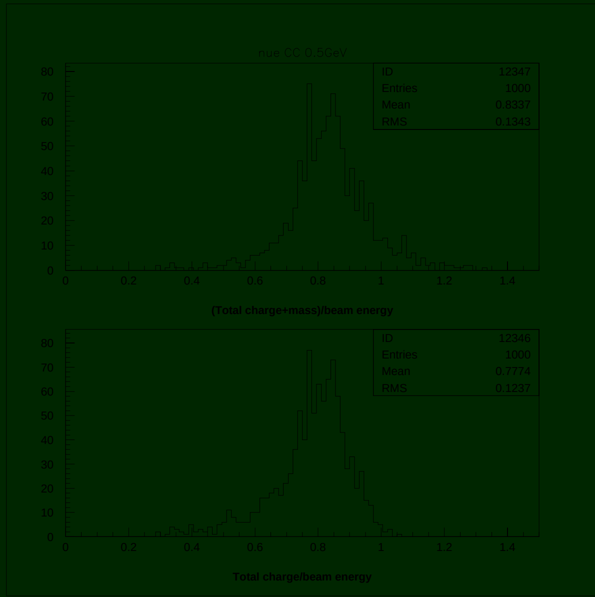




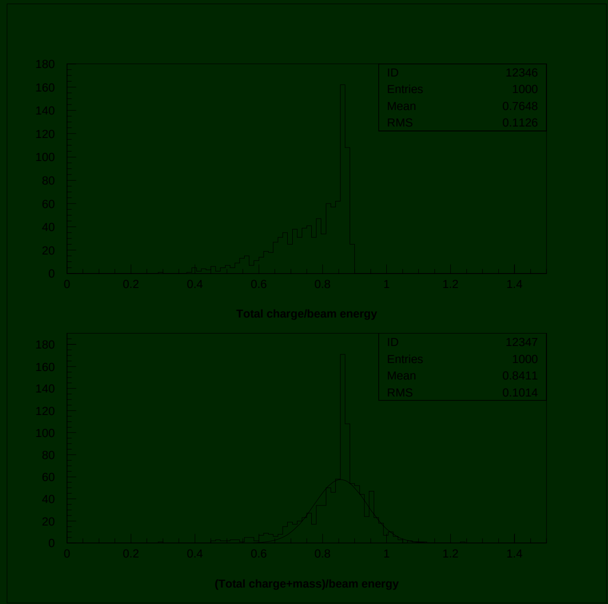
- e/π^0 – resolution <1%/sqrt(E), μ – resolution ~1% above 0.7 GeV
- Hadrons:
  - ✓ response depends on particle type, h/e~0.6 above 2 GeV
  - ✓ Resolution 30%/sqrt(E) asymptotically, better at very low energies (range-out), worse around the threshold for inelastic collisions

What really counts: Neutrino (CC) energy resolution

0.5 GeV



1.5 GeV

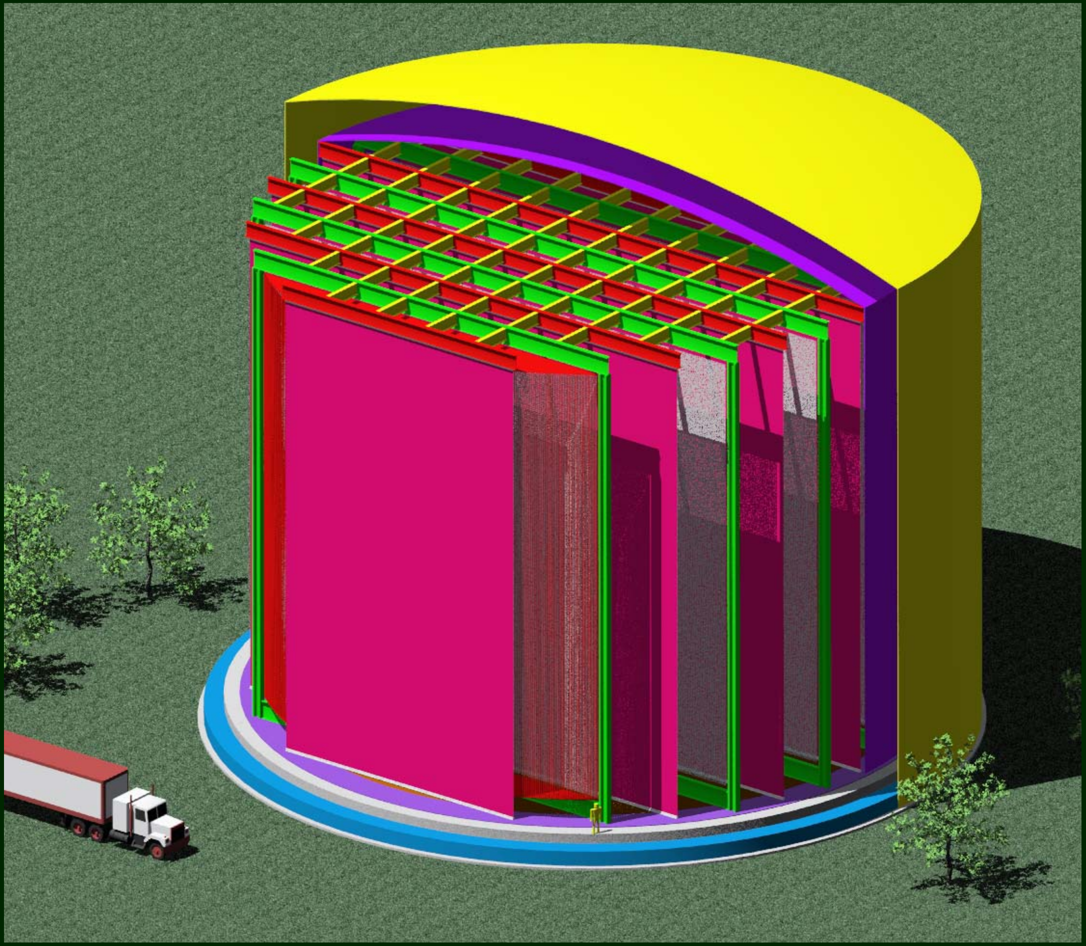


- Mostly quasi-elastic interactions, e+N in the final states
- Energy resolution, DE/E ~ 10%, dominated by Fermi motion and nuclear effects

- Mostly inelastic interactions
- Kinematical effects (rest masses of produced particles) contribute to energy resolution => need particles count
- Energy resolution, $\Delta E/E \sim 10\%$, once masses are added

$\Delta E/E \sim 1\text{-}2\%$ for QE

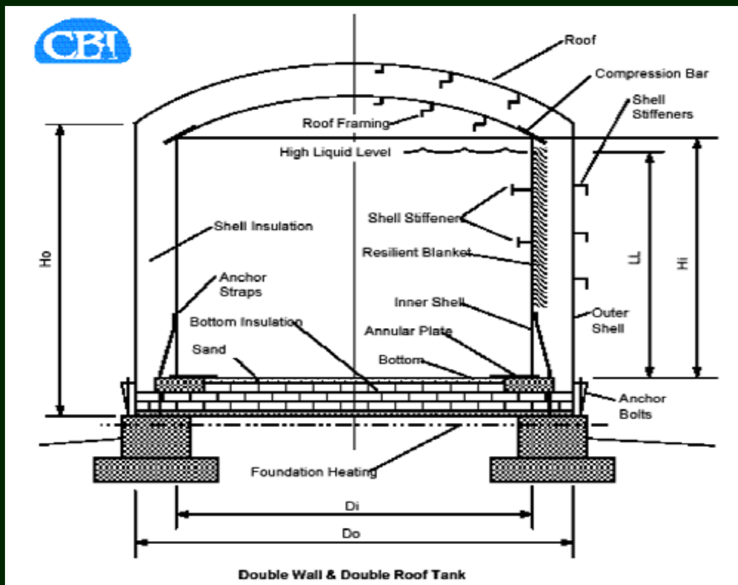
Off-Axis detector



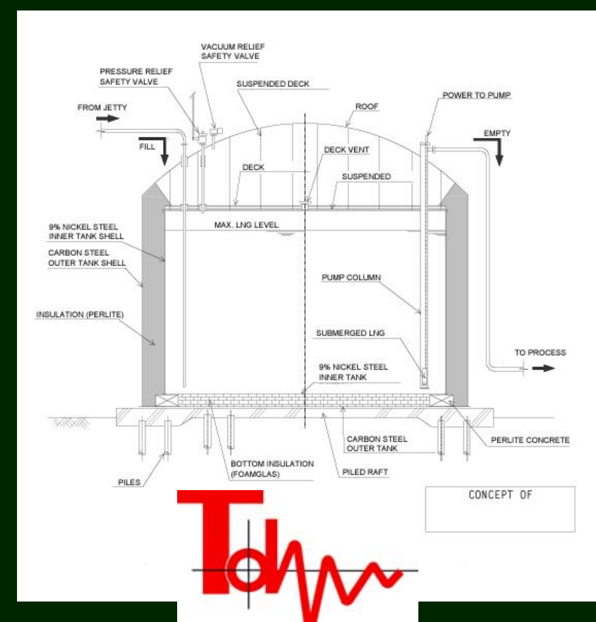
L. Bartoszek

- Double wall cryogenic tank
- 7 HV cathode planes (150 kV)
- 6 planar wire chambers (6 planes of wires: UVX XUV each)
- HV/signal feed throughs
- 250,000 channels of electronics
- Liquid argon
- DAQ

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):

$2.9M + $5000/day (probably an overkill [R. Schmitt])

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.

Liquid Argon as a commodity

G. Mullholland

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

grade	O2 content [ppm]	application
C	20.	General Industrial, shield gas
D	10.	Heat treating, sintering
E	5.	High purity applications
F	2.	Semiconductor applications

Thermal analysis of a 50 kT liquid argon tank

Rough analogy: big boiling pot

Vapor bubbles at the surface only (hydrostatic pressure)

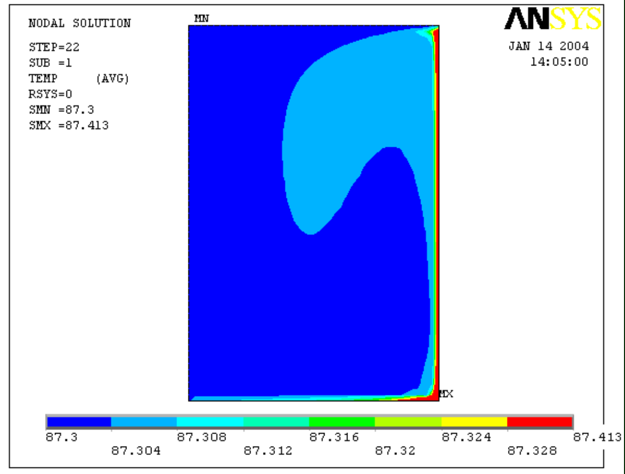
Total heat leak: 49 kW

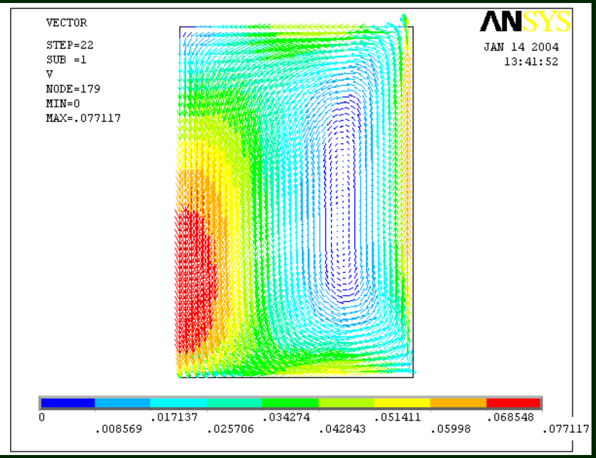
Maximal temperature diference ΔT_{max} = 0.1°C

Tempereture difference over most of the volume 0.01°C

Maximum flow velocity: 7.7 cm/s

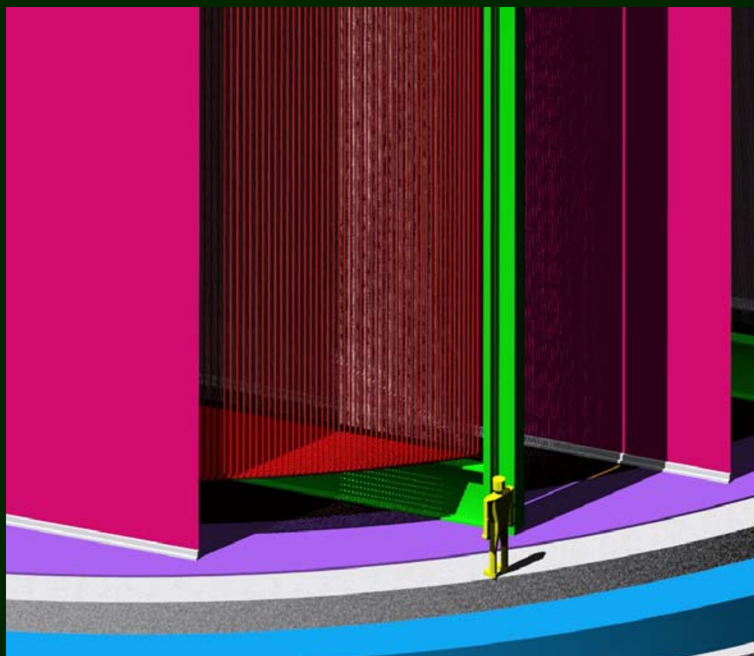
Heat leak through a signal feed-through chimney 48W/chimney

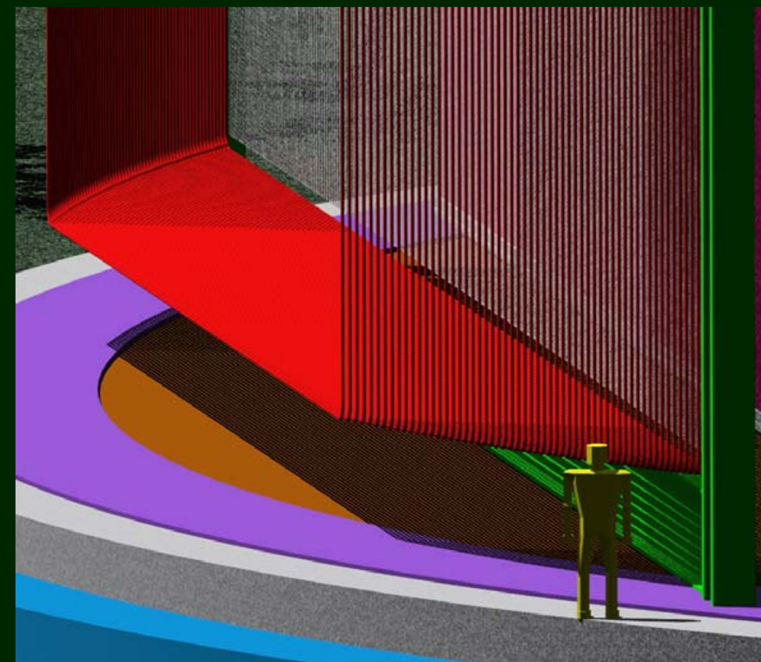




Zhijing Tang, PPD

Field shaping in the drift region





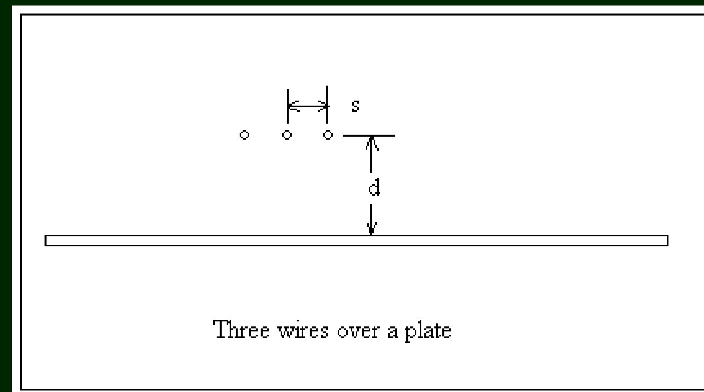
L. Bartoszek

- 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

Wire chamber optimization: an example

Zhijing Tang

- Increase wire/plane spacing:
  - ✓ Reduce capacitance
  - ✓ Increase signal
  - ✓ Reduce number of channels
  - ✓ Reduce the field to ensure full transparency
  - ✓ Loose topological information about the event
- 5mm wire and plane spacing: 28% reduction of the wire capacitance



15.871

Central wire capacitance, pF/m

s \d (mm)	3	5	8
3	15.871	14.603	13.845
5	12.528	11.437	10.722
8	12.442	11.232	10.390

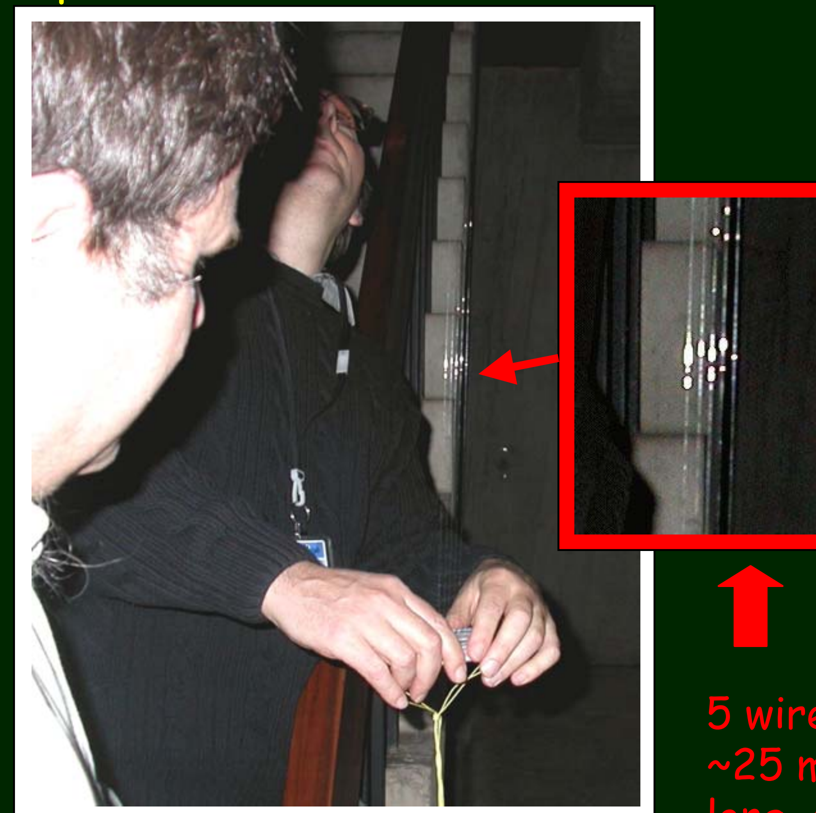
Wire chambers

- 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° from vertical
- Wire tension ~10N, wires supported every 5 m
- Compressive load on the chamber frame 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

How large chambers can you string???

String(ing) Sextet: L. Bartoszek, B. Fleming, H. Jostlein (in absentia), K.Kephart, A. Para, P. Rapidis

WH 15 floor



WH 6 floor

5 wires, ~25 m long, 4 mm spacing

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?)

50 kton detector

- Cryogenic tank: H=30m, D=40 m (Standard size, Chicago Bridge and Iron)
- 35,000 m^3 of liquid argon
- 3 meter drift distance
- 6 cathode planes @ 150 kV
- 6 wire chambers (collection only, no gain, no high electric field) 250,000 wires
- Readout electronics
- Commercial re-circulation/purification system
- DAQ

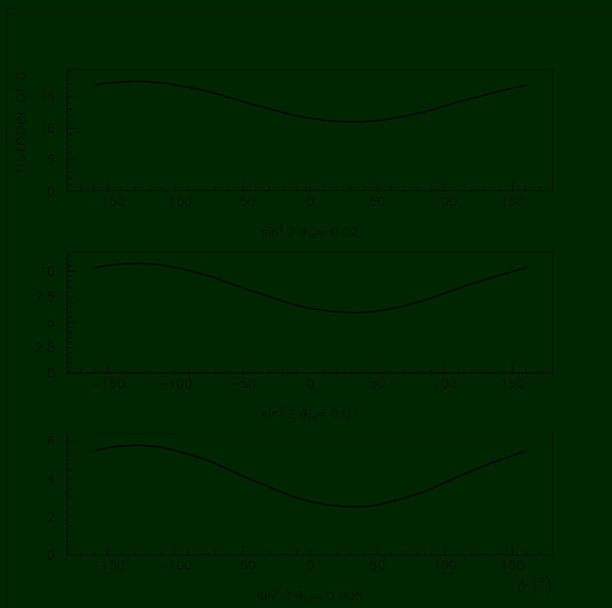
How much?

• Cryostat (Industry: Liquified gases)	$11M
• Liquid Argon (delivered)	$30M
• Cryogenics/purification	$10M
• HV/field shaping	$ 5M
• Wire Chambers	$10M (?)
• Electronics , cabling	$ 5M
• Data Acquisition/handling	$10 M
• Other costs/stategic reserve	$19 M
total	$100M

Observation: cost dominated by commodities/industrial products (Lar, tank, cryogenics)

Sensitivity of an off-axis experiment

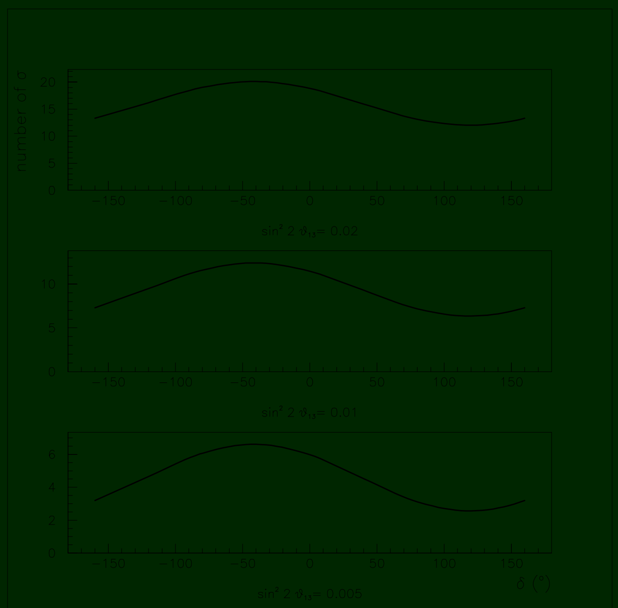
Common mis-perception: One should wait with an off-axis experiment for a positive signal from faster, cheaper, cleaner, more sensitive new reactor experiment



6xCHOOZ

12xCHOOZ

25xCHOOZ



Inverted hierarchy

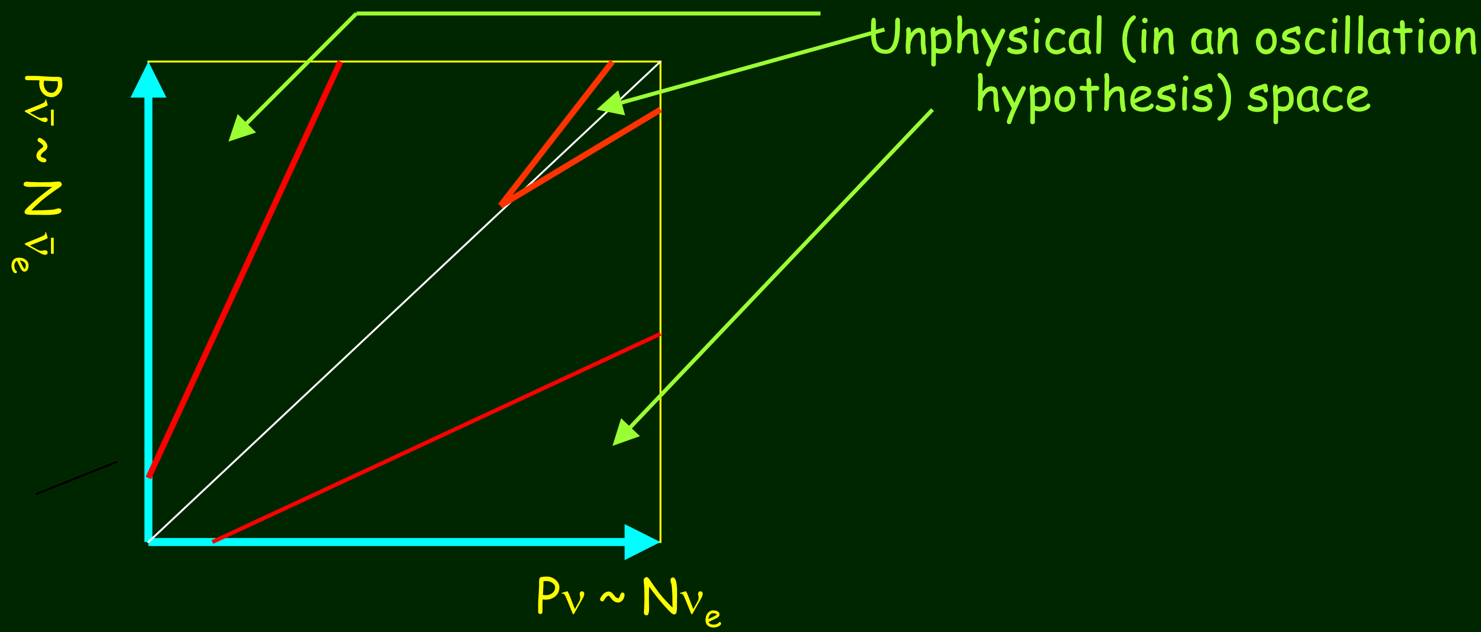
Normal hierarchy

5-6 years of running with a nominal NuMI beam yields 10-20 σ effects for a scenario where a realistic reactor experiment may set a limit.

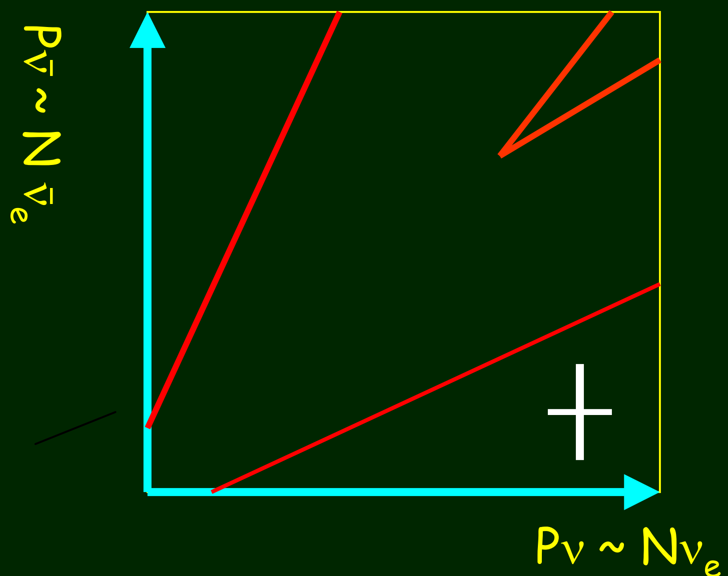
Even for $\sin^2 2\theta = 0.005$ we have 3-6 σ effect (Olga Mena)

How do you study oscillations by measuring (just?) two numbers ?? (a.k.a. long term plan/roadmap)

How does Liquid Argon TPC provide/fit to a long term neutrino oscillations study program?

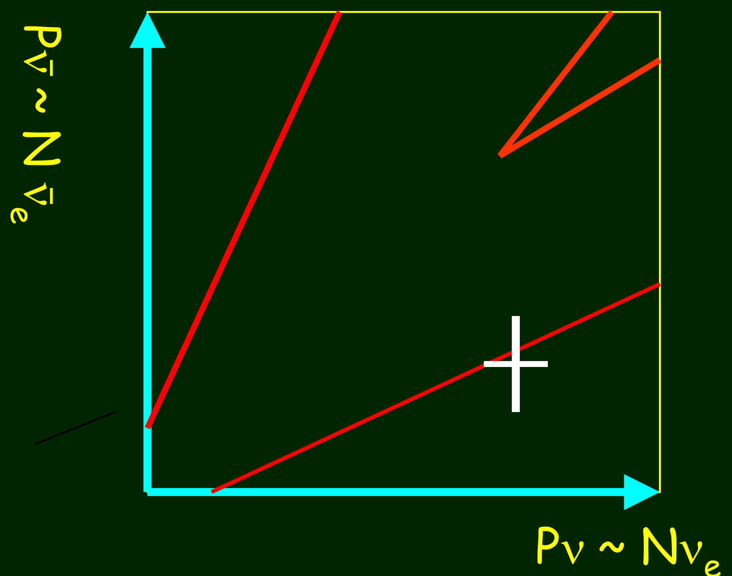


Possible case A: outside the 'physical region'



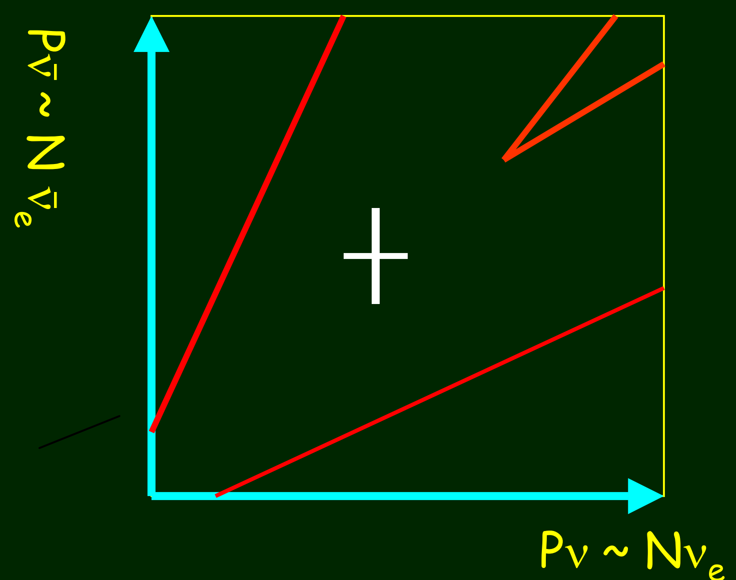
- Our 'understanding' is wrong (sounds familiar? ☺)
- Something new is happening
- Need detailed information about the interactions (Lar imaging)
- Need more events (proton driver)

Possible case B: at the boundary of the physical region



- Neutrino masses follow normal (or inverted, dependent on the result) hierarchy
- Nearly maximal CP violation occurs in Nature
- Need more events (proton driver, more detectors) to reduce the error on $\sin^2 2\theta_{13}$ and δ

Possible case C: well inside the physical region

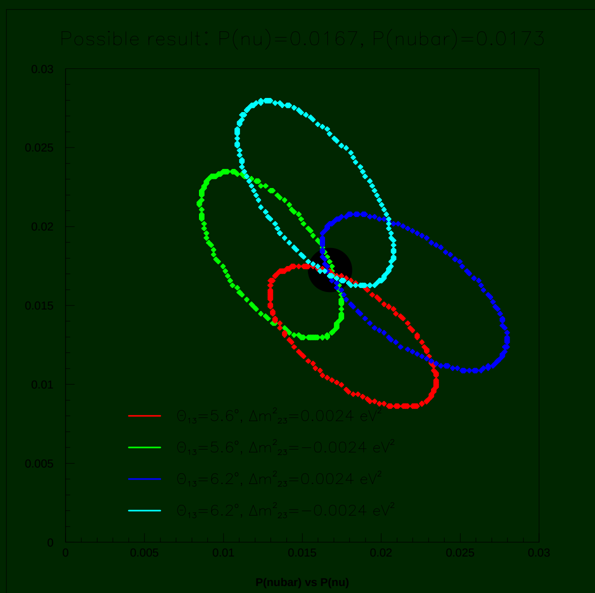


- Discovered ν_μ to ν_e oscillations
- Determine θ_{13} to about 10%
- (perhaps) determine neutrino mass hierarchy
- (perhaps) get some bounds on CP phase δ

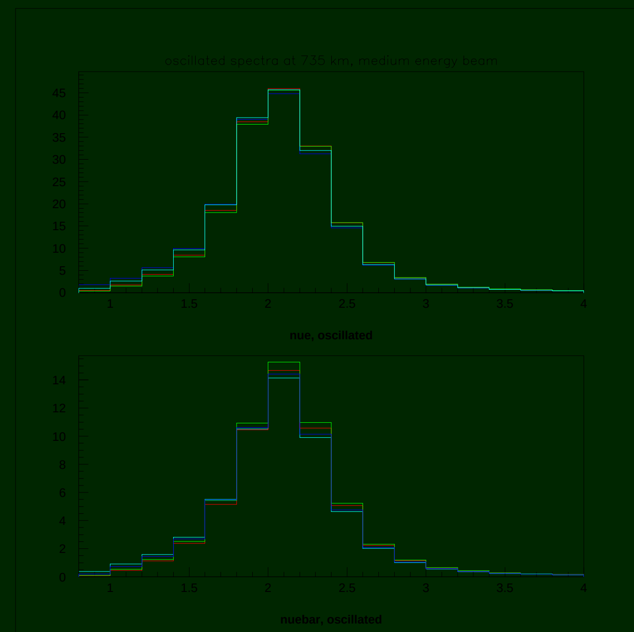
This may be a likely outcome, let's look in more deails .. .

An example: P_{ν}=0.0167, $P_{\nu bar}$=0.0173

- More and more precise measurements reduces a size of allowed parameters space
- No increase of statistics can sort out ambiguities

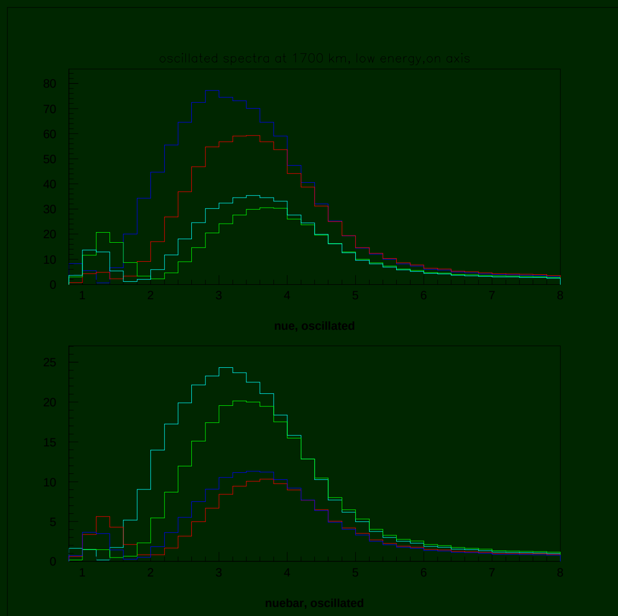


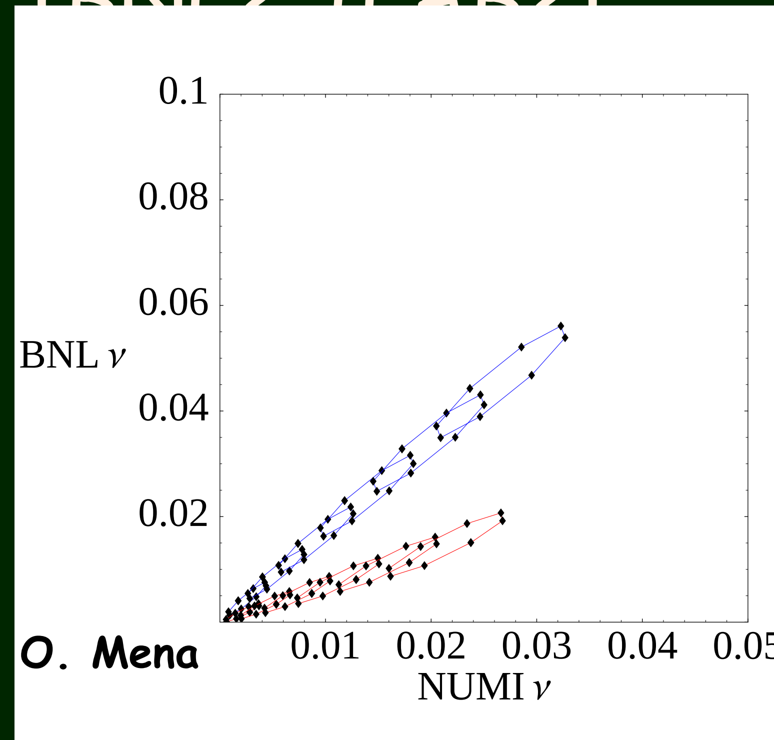
Q: can we infer some information from the energy spectrum of the observed signal?



A: NO

Long baseline neutrino beam from some sister Laboratory (BNL? JLAB?)

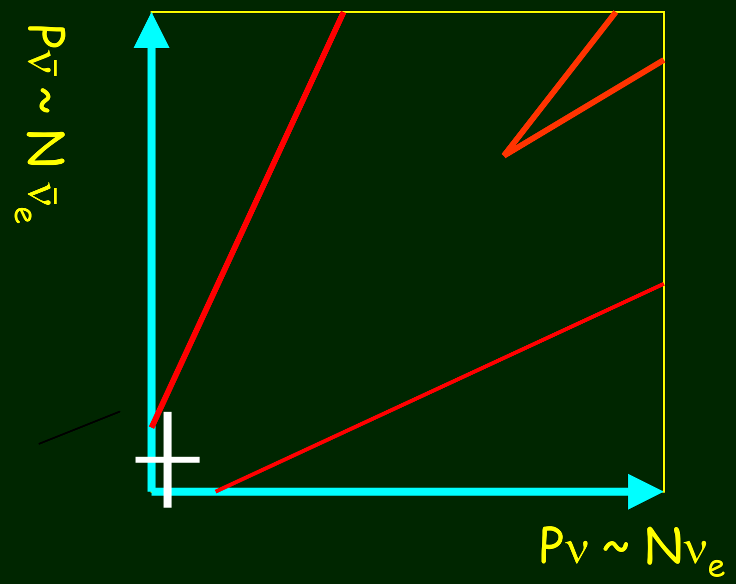




- Energy spectrum of oscillated neutrinos and antineutrinos differentiates between ambiguous solutions

- Oscillation rates differ because of large matter effects
- Determination of neutrino mass hierarchy

Possible case D: no signal observed

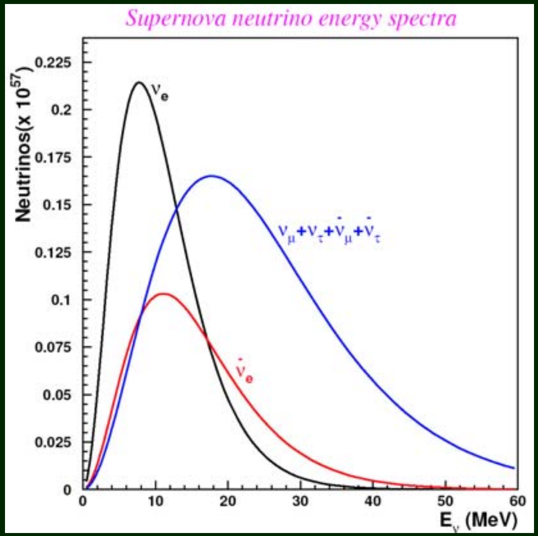


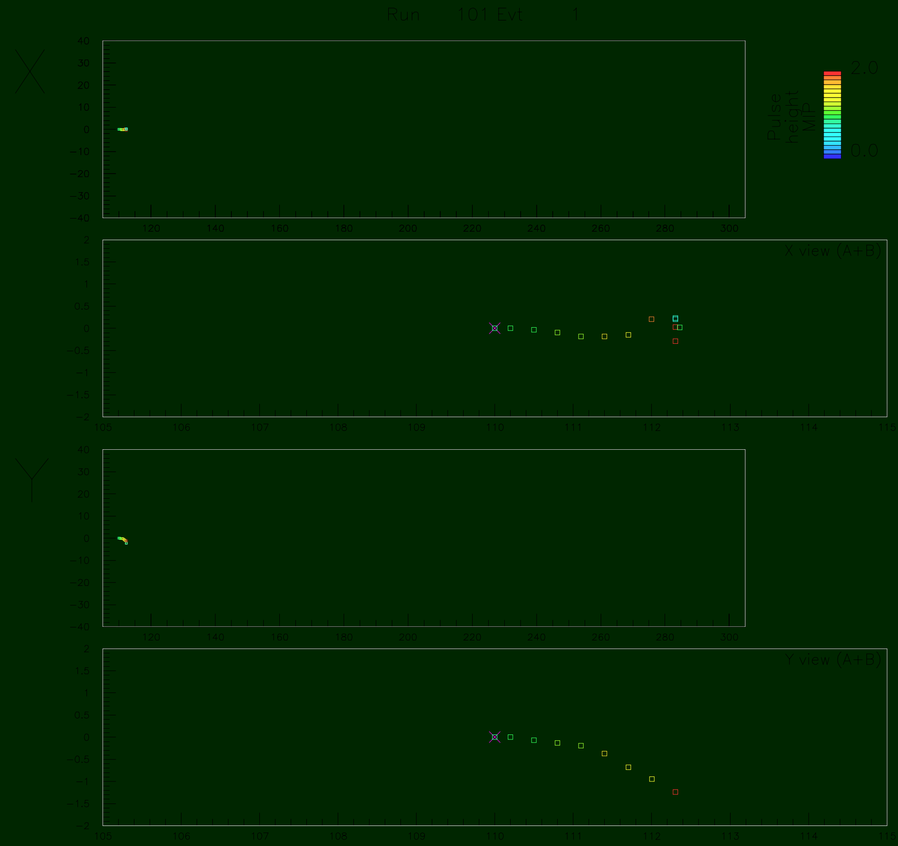
- Try harder: proton driver, more detectors [very big advantage of Lar: no NC background, high ID efficiency: equivalent to 6x bigger conventional detector]
- Get very good limit on mixing angle (~0.001-0.002)
- Great result, although a bit disappointing…

Unless.. In the meantime

Supernova(s) 201x[A,B,C,...]?

- Initial burst (~10 msec?) of ν_e's
- Followed by a stream of all neutrinos (~few secs)
- Energies 5 - 40 MeV, spectra depend on the Supernova modelling <u>and</u> neutrino oscillations





10 MeV electron in LAr

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)

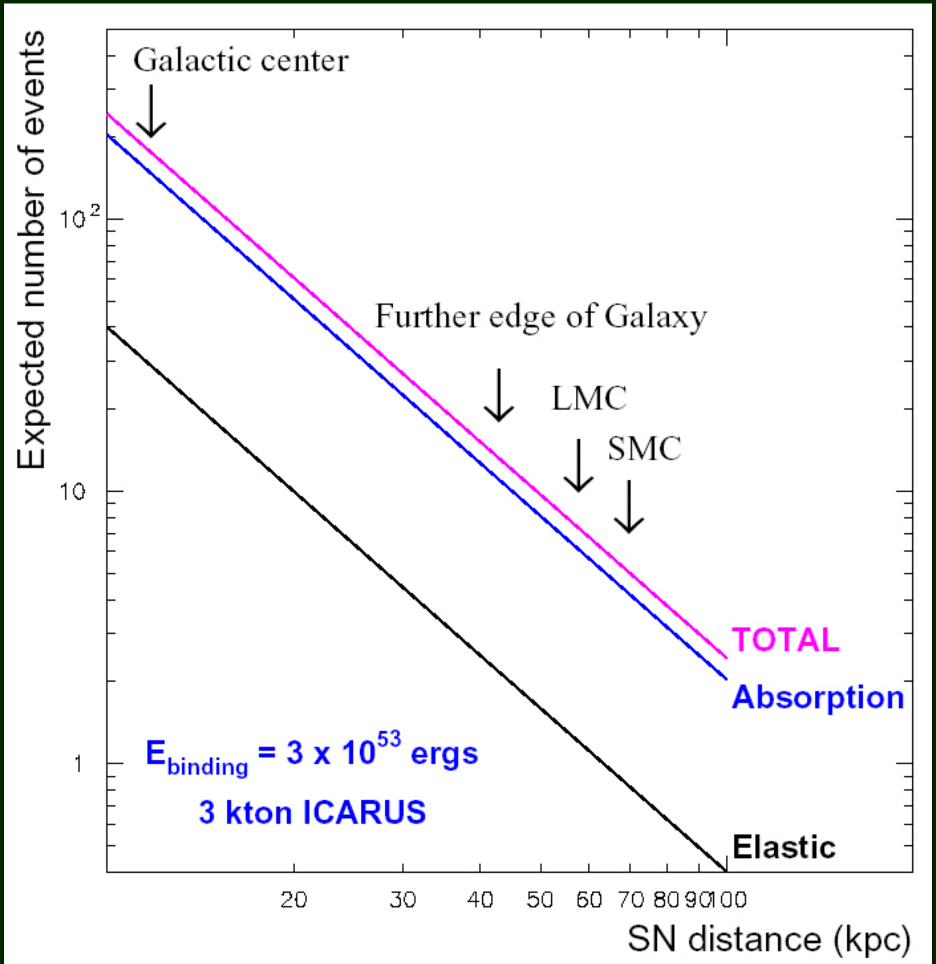
  $\phi(\bar{\nu}_e)$
  Q≈8 MeV

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

- 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 ?

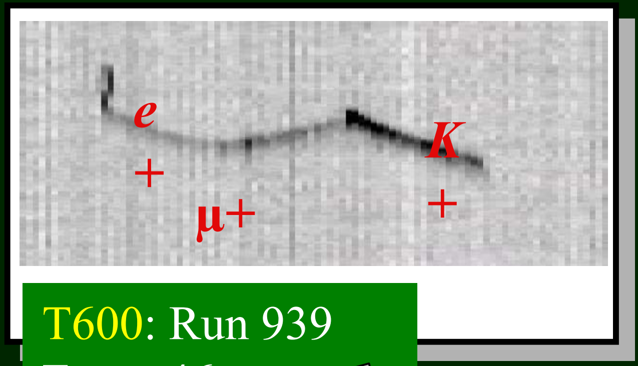
A: it depends on the postulated decay modes /supermultiplet assignment at the GUT scale. Perhaps the dominant decay mode is into K? (Weak spot of water Cerenkov due to Cerenkov thresold)

P-> Kν in LAr detector

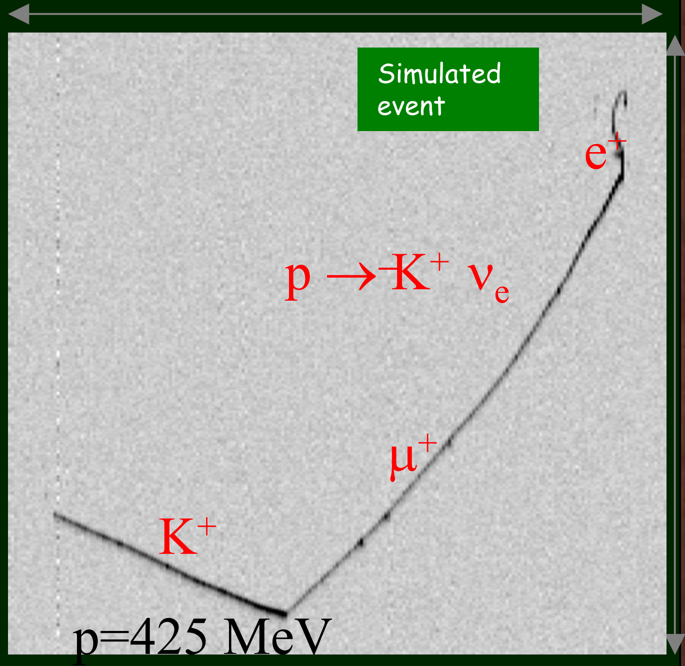
K identification: dE/dx

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

High efficiency, very low background



T600: Run 939
Event 46



- 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

The technology appears to be mature. Any other applications? (testing/learning ground?)

- Near detector for JPARC? (most? serious proposal)
- FINESSE:
  - ✓ Strange formfactor: detection/measurement of low energy protons
  - ✓ Neutrino magnetic moment: detection/energy measurement of very low energy electrons
- MINERνA = study of neutrino interactions at low energies:
  - ✓ Particle identification
  - ✓ Energy measurement
  - ✓ Kinematical reconstruction of relatively complex final states
- Serious design studies of T40-class detector at the Fermilab site (F. Sergiampietri, R. Schmitt)

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
- Sounds like a plan ? Let's do it !