Neutrinos with FLARE -
Fermilab Liquid ARgon Experiments

http://www-off-axis.fnal.gov/flare

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and Particle Physics Conference
The Banff Centre
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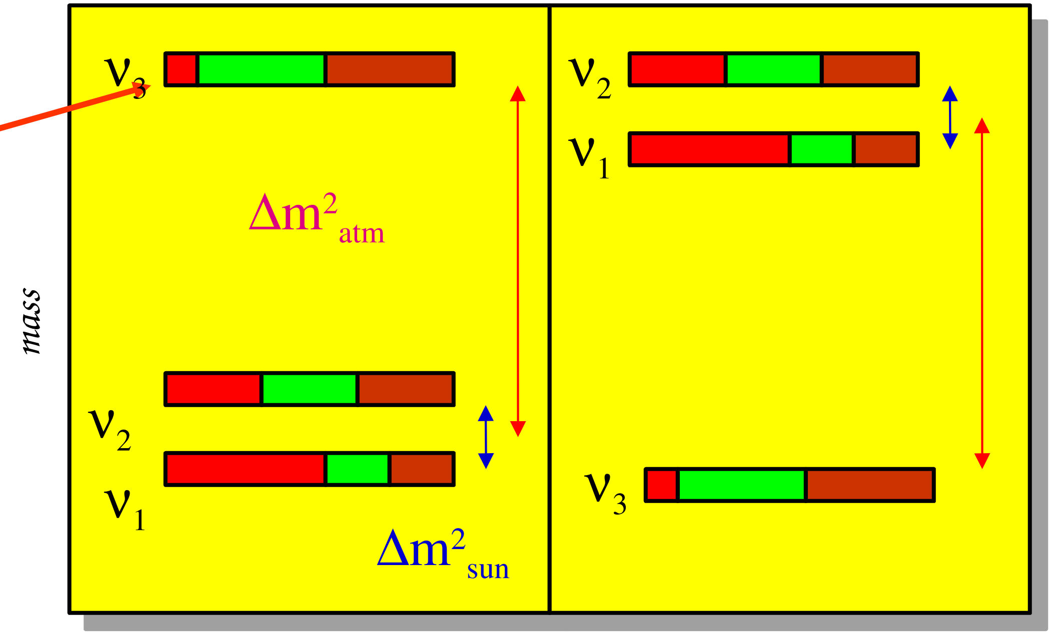
What Do We Want to Know?

1. Neutrino mass pattern: *This ?* *Or this?*

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



"Normal" mass hierarchy *"Inverted" mass hierarchy*

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

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

$P(\nu_\mu \rightarrow \nu_e)$ (in Vacuum)

- $P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$
  - $P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\ \Delta m_{13}^2\ L/E)$
  - $P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\ \Delta m_{12}^2\ L/E)$
  - $P_3 = m\ J \sin(\delta) \sin(1.27\ \Delta m_{13}^2\ L/E)$
  - $P_4 = J \cos(\delta) \cos(1.27\ \Delta m_{13}^2\ L/E)$

where $J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23}) \times$

$\sin(1.27\ \Delta m_{13}^2\ L/E) \sin(1.27\ \Delta m_{12}^2\ L/E)$

$P(\nu_\mu \rightarrow \nu_e)$ (in Matter)

- **In matter, P_1 will be approximately multiplied by $(1 \pm 2E/E_R)$ and P_3 and P_4 will be approximately multiplied by $(1 \pm E/E_R)$, where the top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy.**

$$E_R = \frac{\Delta m^2_{13}}{2\;\,2G_F\rho_e} \approx 11\,\text{GeV for the earth's crust.}$$

About a ±23% effect for NuMI, but only a ±10% effect for JPARC .

The Key: $\nu_\mu \rightarrow \nu_e$ Appearance

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

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

Oscillation at the 'atmospheric' frequency

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

Oscillation at the 'solar' frequency

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

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

Interference of these two amplitudes ➔ CP violation

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

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

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

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

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

3 unknowns, 2 parameters under control L,E + ν_μ */anti-* ν_μ

Need several independent measurements to learn about underlying physics parameters

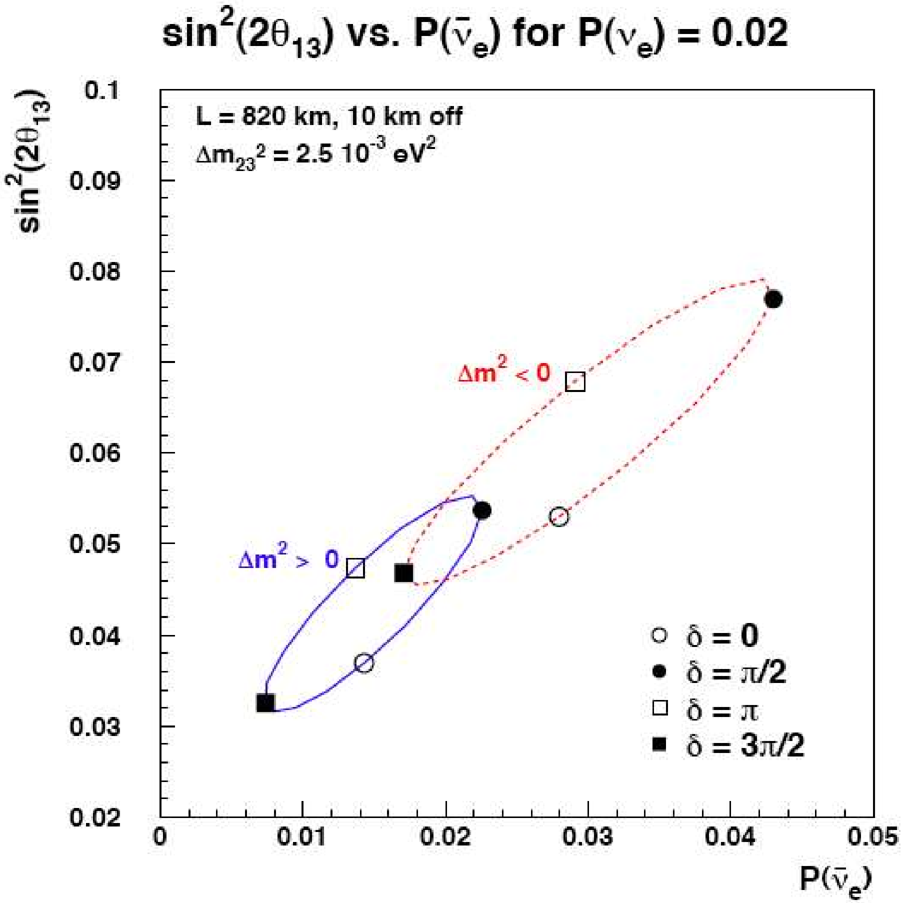
Magnitudes

- For long-baseline $\nu_\mu \rightarrow \nu_e$ oscillations, P_1, P_3, P_4, and the matter effects are all the same order of magnitude.
- A measurement of $P(\nu_\mu \rightarrow \nu_e)$ measures "$\sin^2(2\theta_{13})_{eff}$" which is only a crude estimate of $\sin^2(2\theta_{13})$.
- Reactor experiments measure $\sin^2(2\theta_{13})$ directly, but have no sensitivity to sign(Δm_{13}^2) or δ.

Probability Plots

- **Probability plots assumes a particular result for a measurement of $P(\nu_\mu \rightarrow \nu_e)$ and show**
  - **The possible values of $\sin^2(2\theta_{13})$, sign(Δm_{13}^2), and δ consistent with this measurement, and**
  - **How another another measurement would discriminate among them.**

$P(\nu_\mu \rightarrow \nu_e) = 0.02$ at 820 km



Note

(2) Effect of cos(δ) term

(3) Ambiguities

(Hidden ambiguity: P1 ∝ $\sin^2(\theta_{23})$; if $\sin^2(2\theta_{23}) = 0.95$, $\sin^2(\theta_{23}) = 0.39$ or 0.61)

(9) Rough equivalence of reactor and antineutrino measurements

Goals of the Next Generation Neutrino Experiments

- Primary goal: Find evidence for $\nu_\mu \rightarrow \nu_e$ transitions, determining $\sin^2(2\theta_{13})$ to a factor of 2.
- Longer term goal: Determine the mass hierarchy.
- Ultimate goal: Precision measurement of the CP-violating phase δ.

Off-Axis Rationale

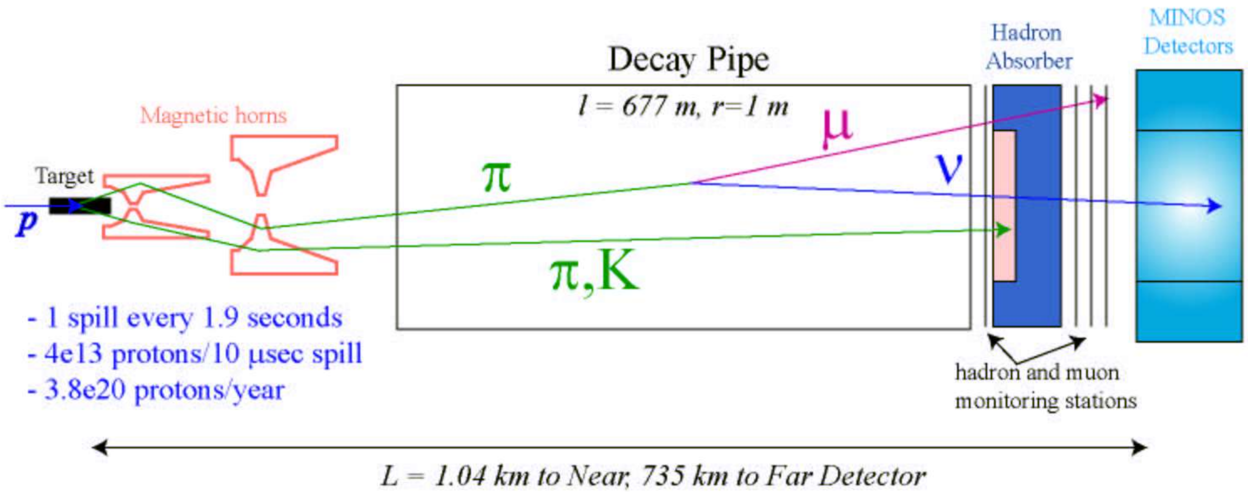
- Want low-energy narrow-band beams at the Dm^{2}_{13} » Dm^{2}_{23} oscillation maximum:
  - ν_e appearance maximum
  - ν_μ CC disappears
  - Higher-energy NC disappears
- Want increases in beam flux times detector mass
- ⇒ NuMI Off-axis Experiment
- Want detectors optimized for ν_e detection
- ⇒Liquid Argon Time Projection Chamber

NuMI – Neutrinos at the Main Injector

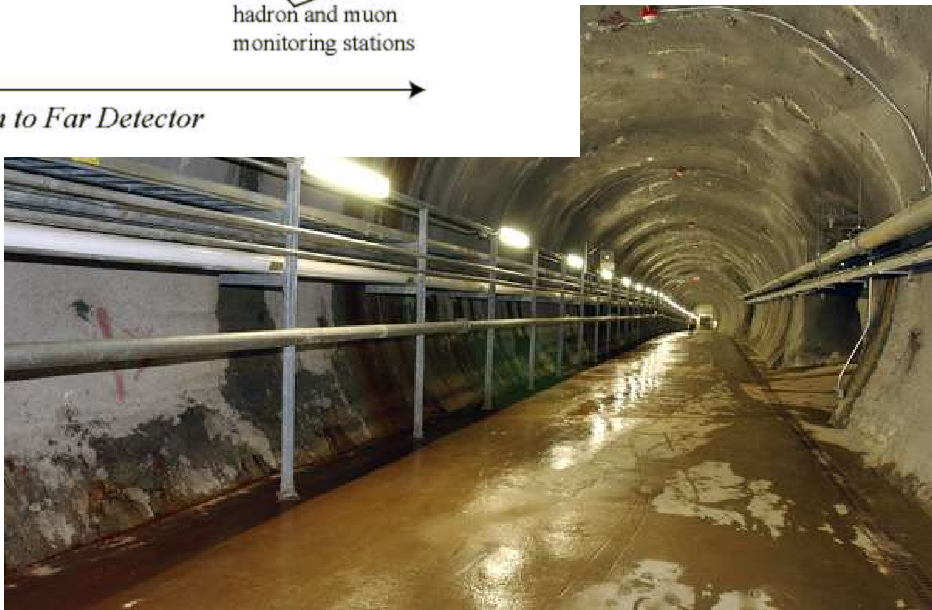
120 GeV/c protons strike graphite target

Magnetic horns focus charged mesons (pions and kaons)

Pions and kaons decay giving neutrinos



The NuMI tunnel is complete and …

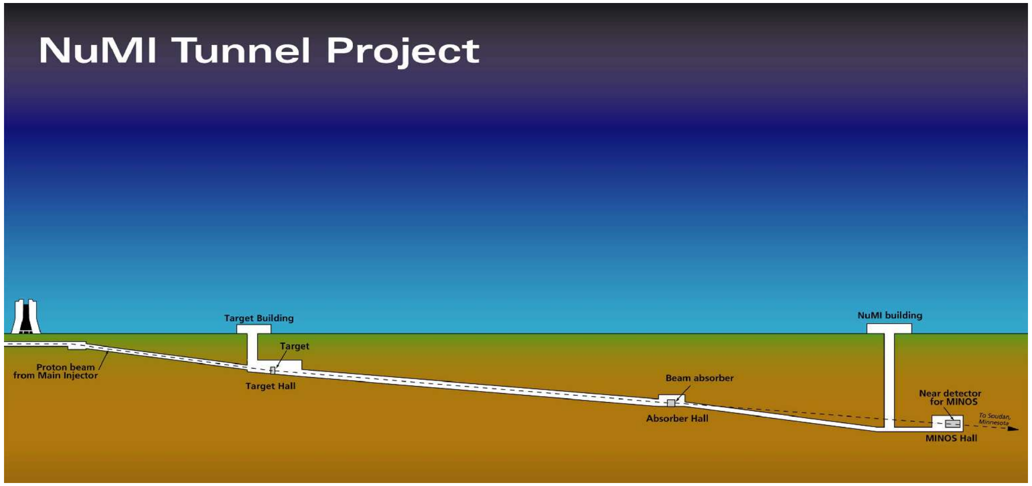


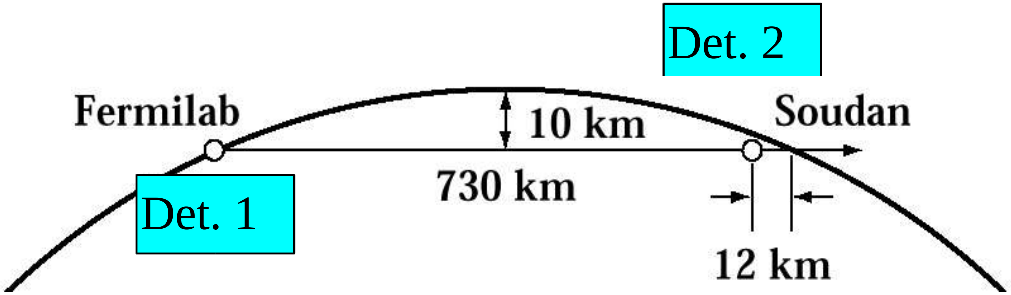
NuMI – Neutrinos at the Main Injector

Fermilab *Today*

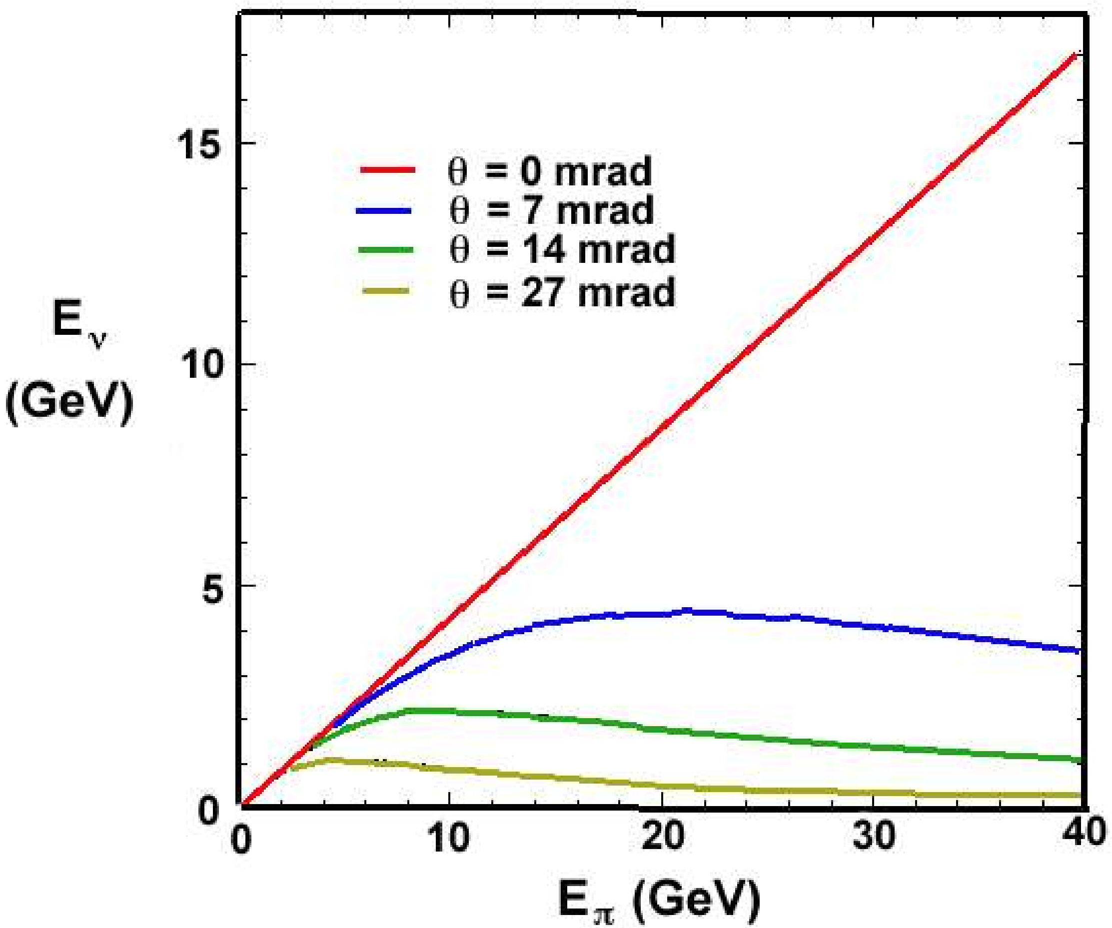
… last month the MINOS near detector saw its first neutrinos from the NuMI facility!

NuMI Beam to MINOS Experiment in Soudan Mine



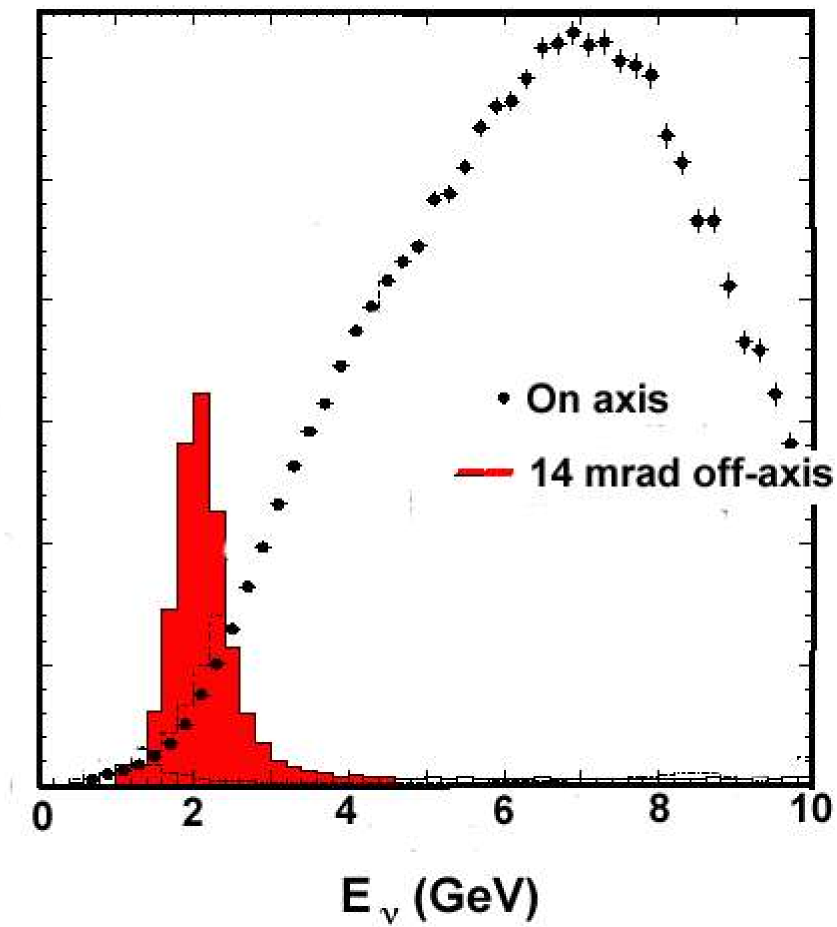


Off-Axis Kinematics



$$E = \frac{0.43\, g m_p}{1+g^2 q^2}$$

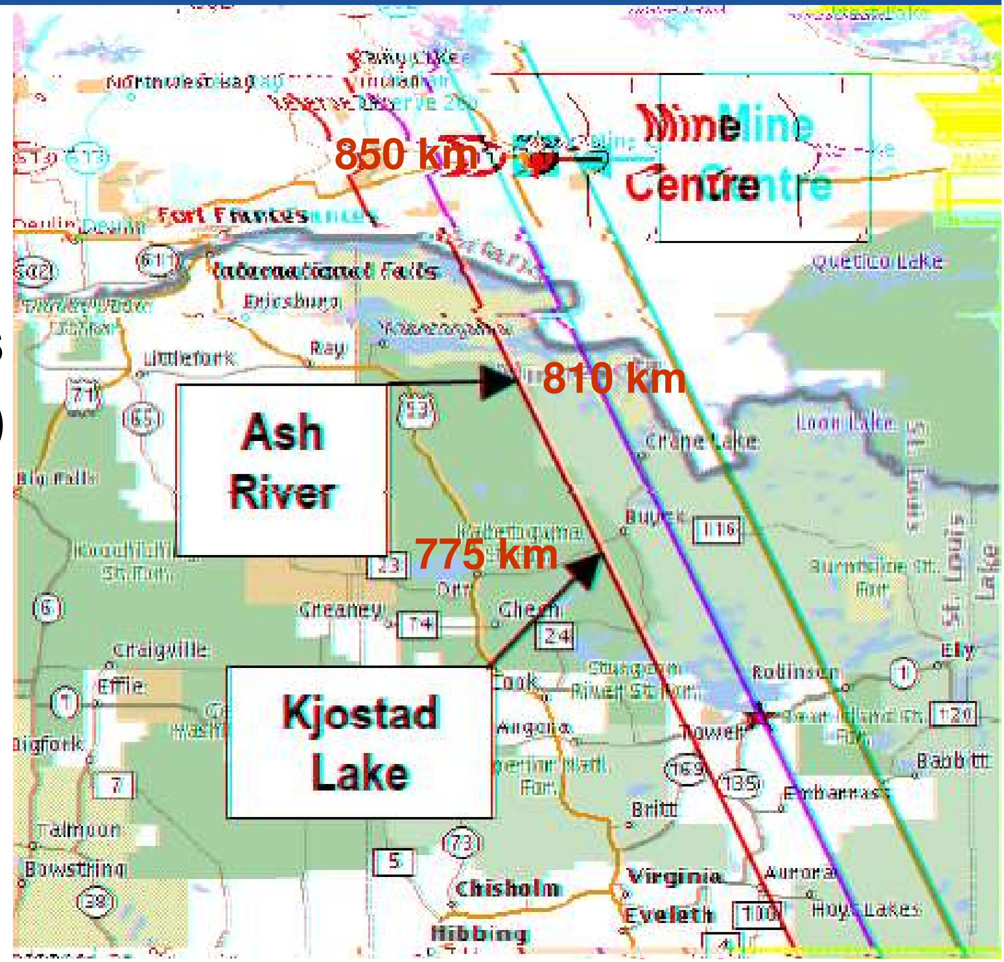
Off-Axis Spectrum (No oscillations)



Possible Sites

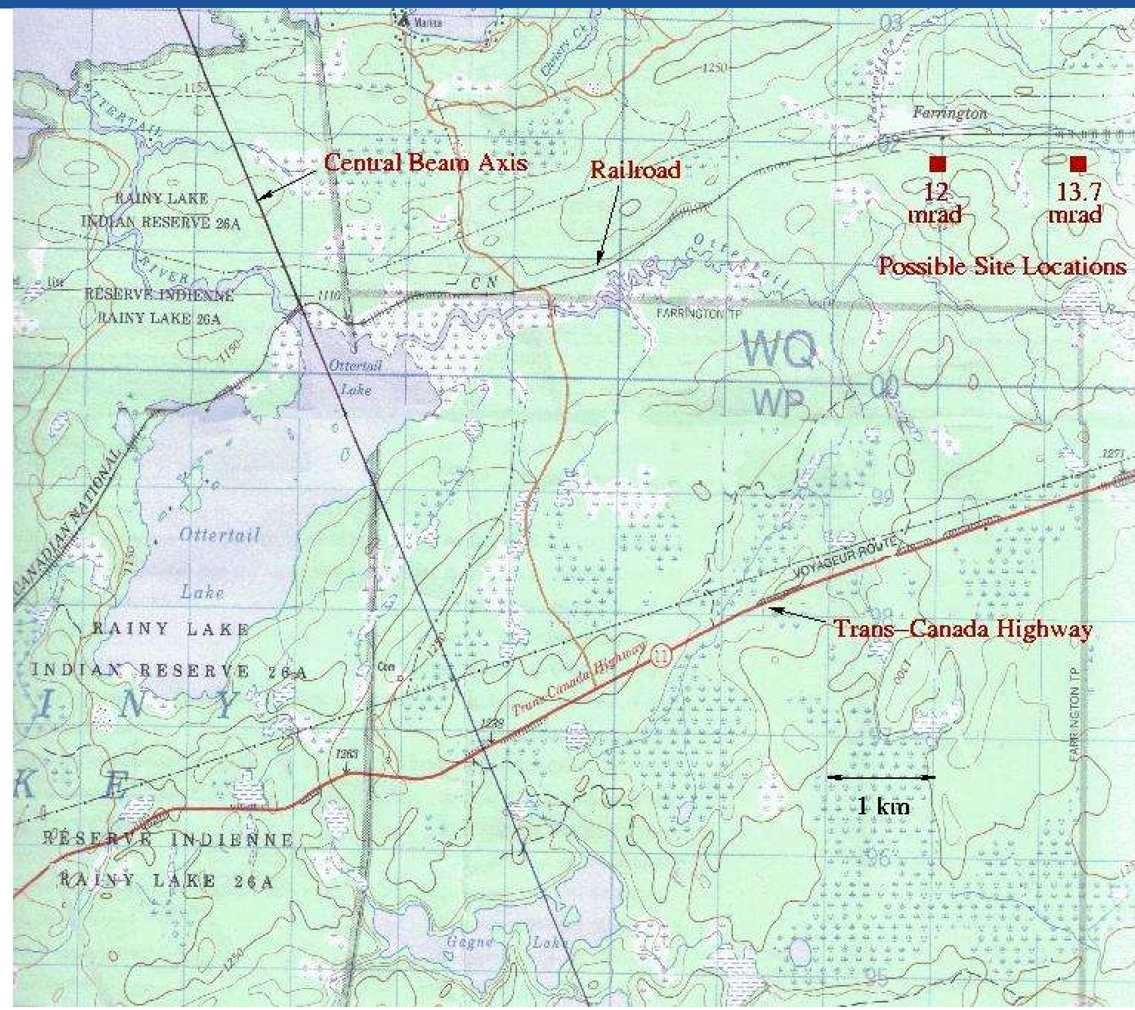
- There are a number of possible sites.

- The 14 mrad off-axis NuMI beam (E=2 GeV) results in an oscillation maximum at L=850-900 km
$\Rightarrow$ Canada



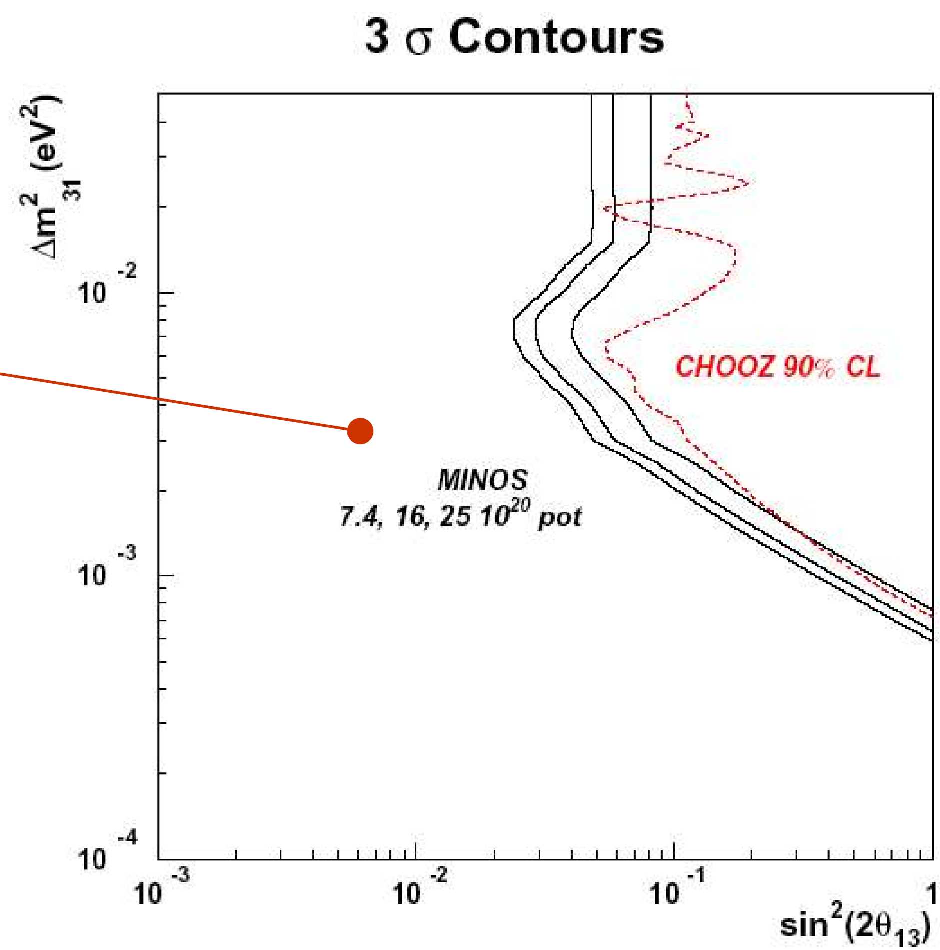
Canadian Site is the Official FLARE Site!

- Rail access
- Close to national hwy
- geologically stable
- choice of off-axis angles
- far, but not too far, from populated areas



MINOS Sensitivity to $\nu_\mu \rightarrow \nu_e$ at 3σ Discovery

Off-Axis Goal



Off-Axis Detector Requirements

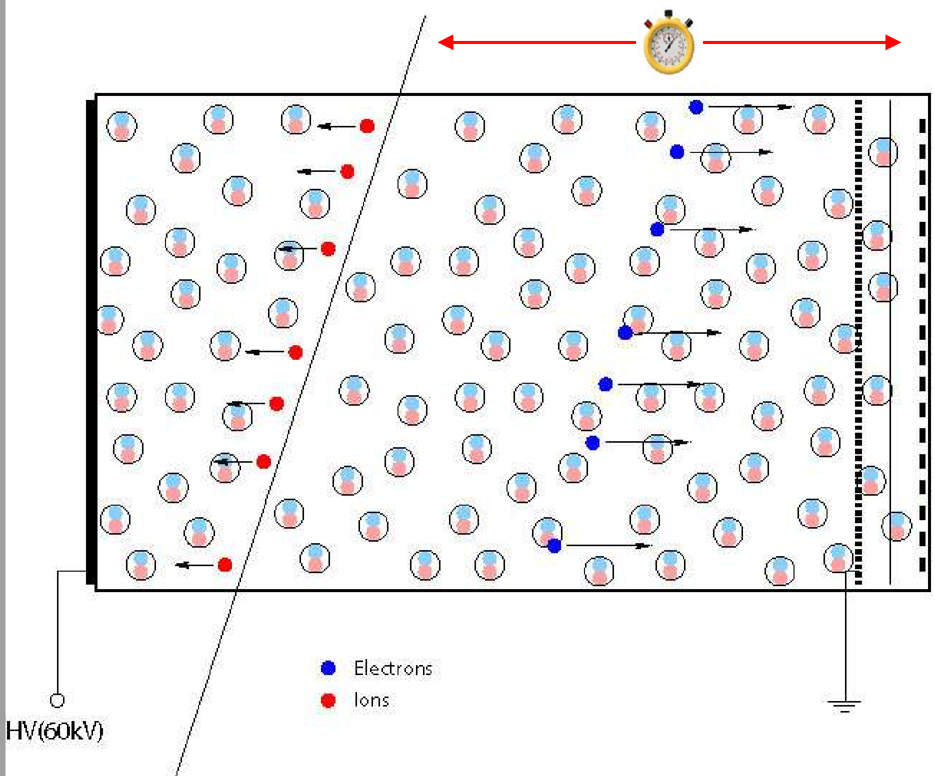
Require

- Very High Efficiency for ν_e events
- Rejection of NC and CC (π^0) background ~ beam ν_e

This technology exists – The Liquid Argon Time Projection Chamber

- e/π^o – 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

Principles of the Liquid Argon TPC

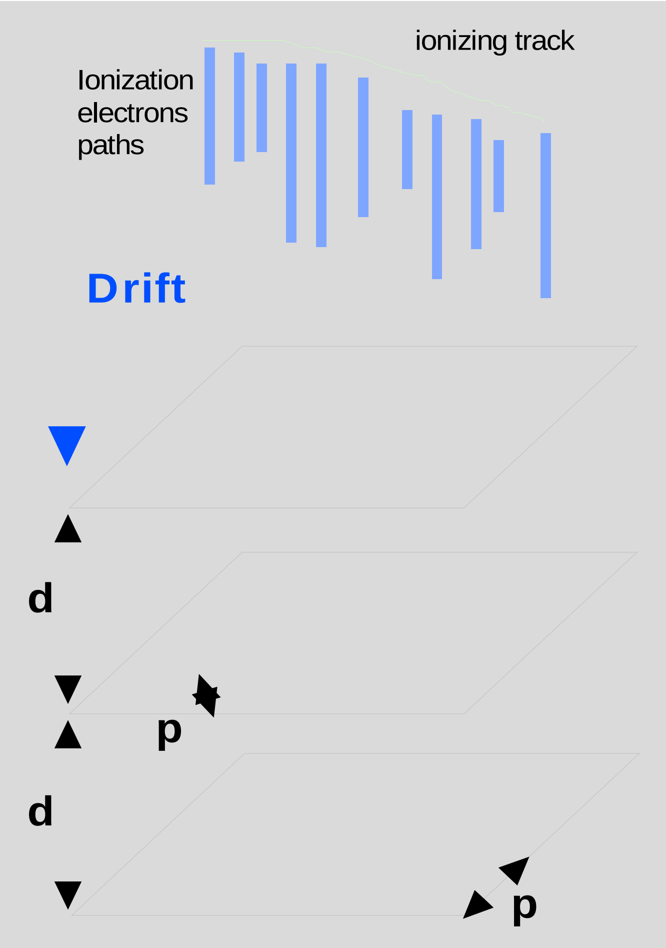


Uniform electric field:

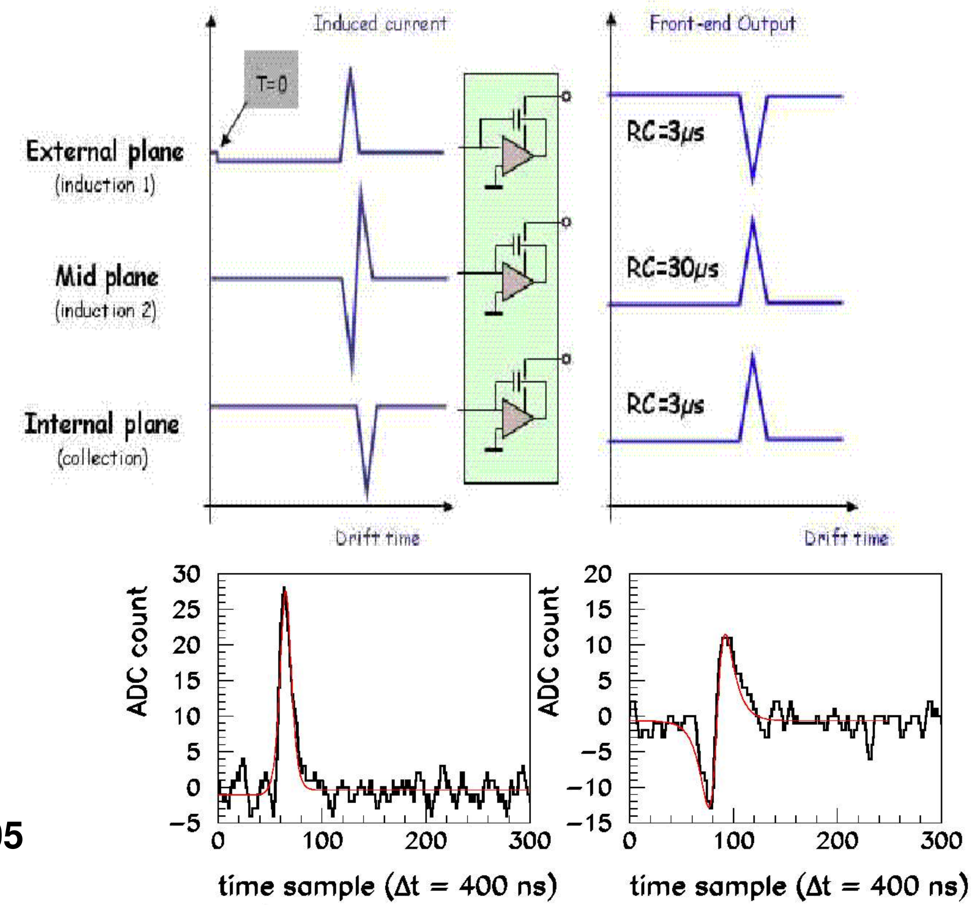
$(t-T_0) = v_{drift} * (x-x_{wire})$

- 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)

Principles of the Liquid Argon TPC



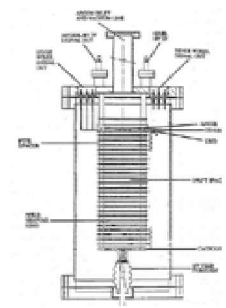
Read out the induced signals on two planes in order to get the "third" co-ordinate.



ICARUS TM/2001-09

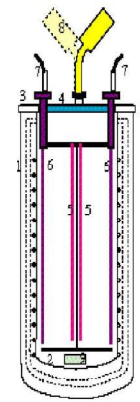
Many Years of R&D

Proposed in May 1976 at UCI (Herb Chen, FNAL P496).



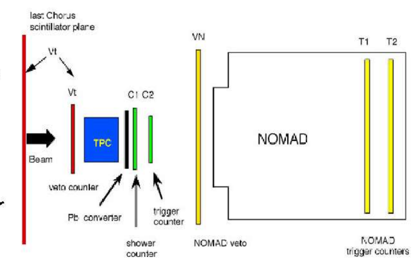
24 cm drift wires chamber

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.



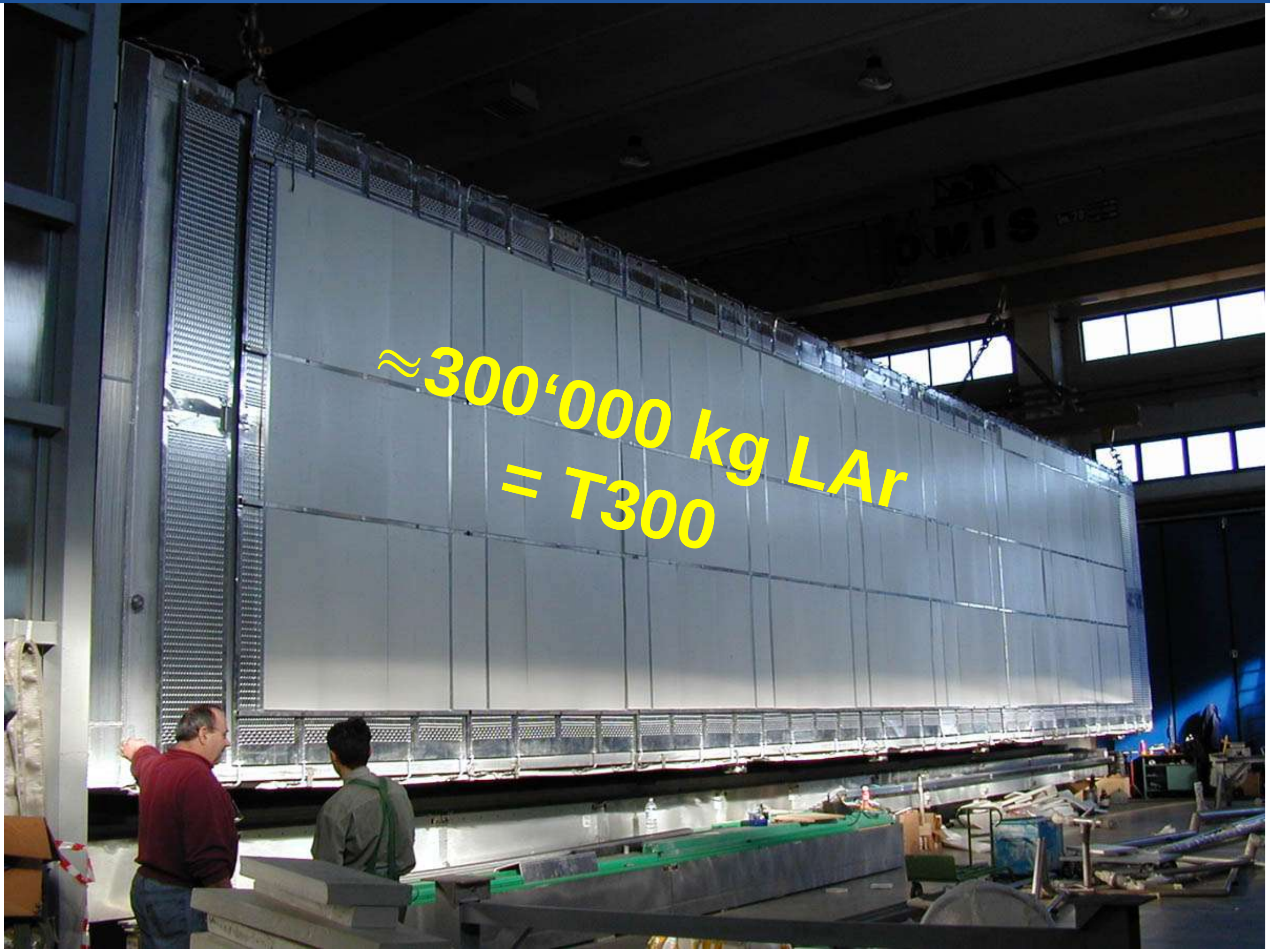
50 litres prototype 1.4 m drift chamber

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

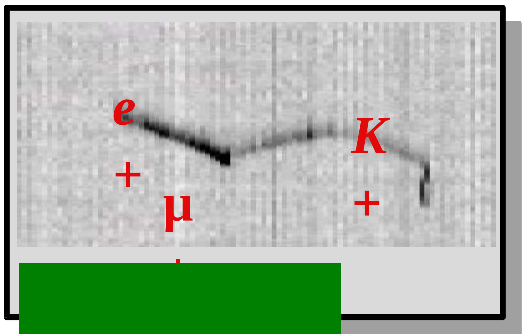
10 m^3 industrial prototype

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

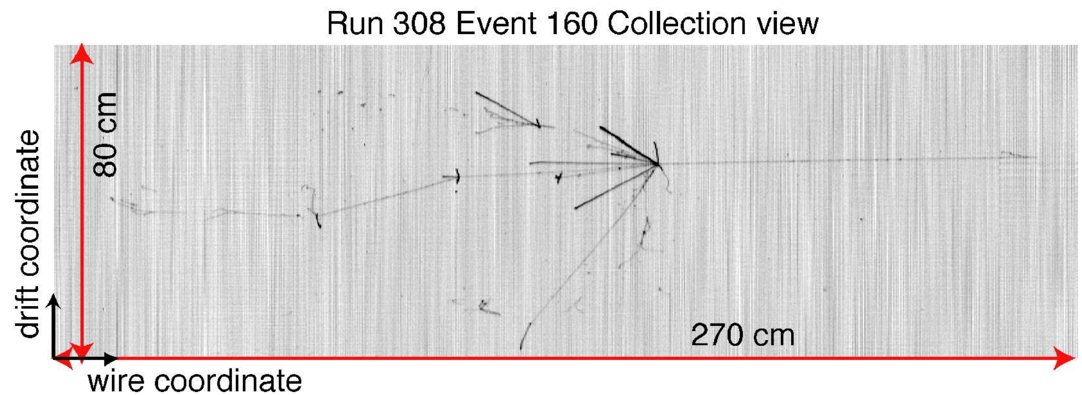
Leading to a Large Detector



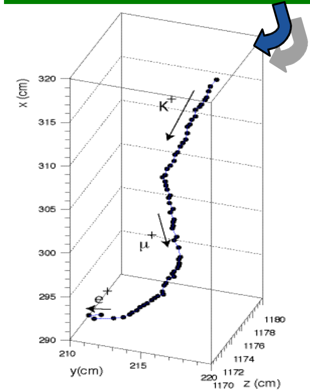
And it works!



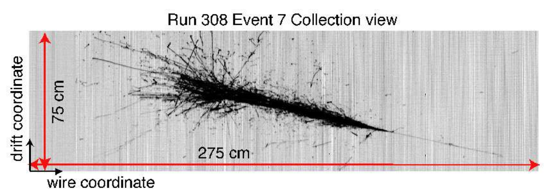
e
+
μ
K
+



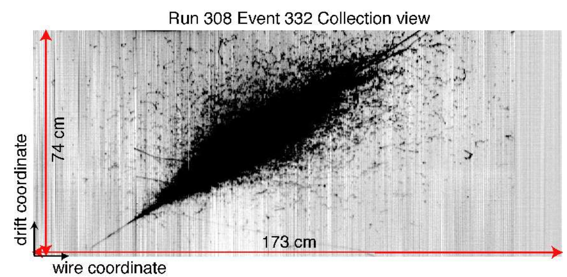
Run 308 Event 160 Collection view
80 cm
drift coordinate
270 cm
wire coordinate



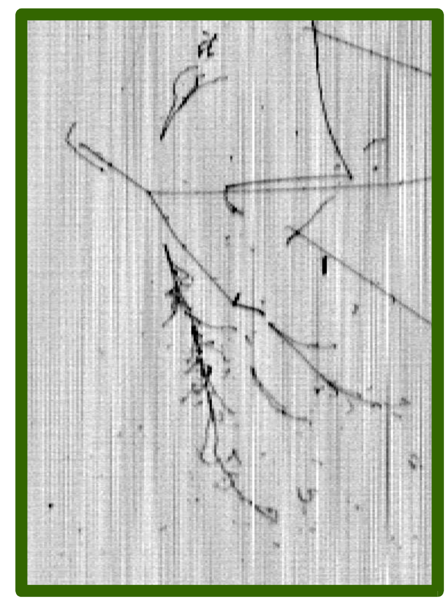
x (cm)
K+
μ+
e+
y(cm)
z (cm)



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

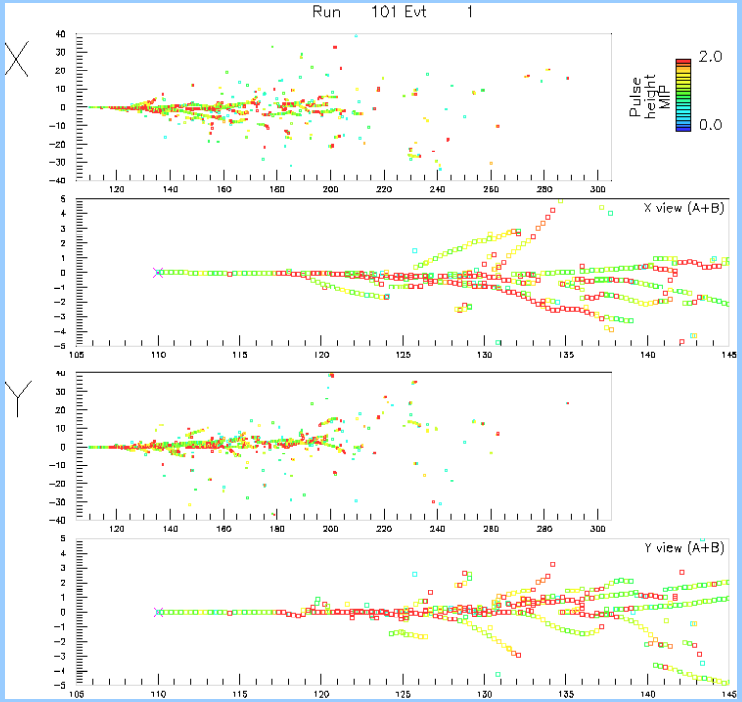


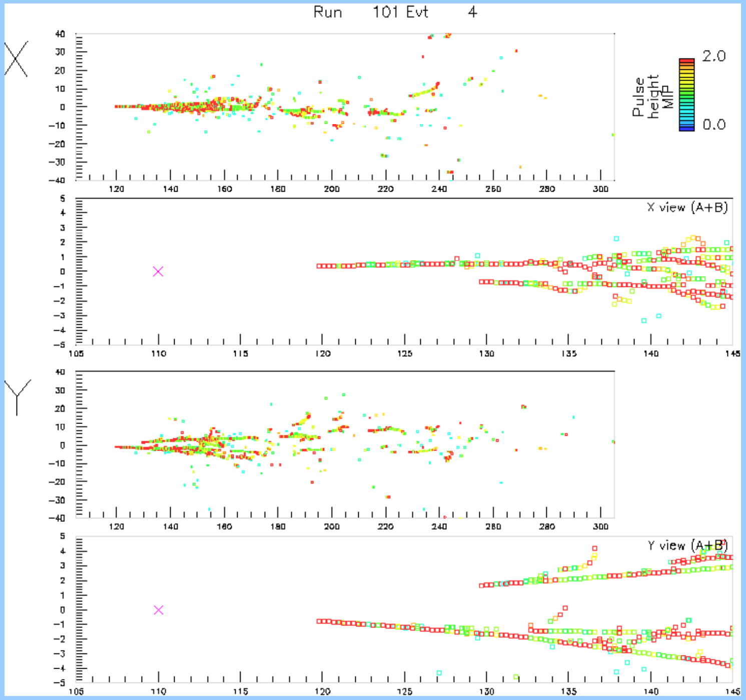
Run 308 Event 332 Collection view
drift coordinate
74 cm
173 cm
wire coordinate



Electrons vs π^0's (1.5 GeV) in a LArg TPC

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





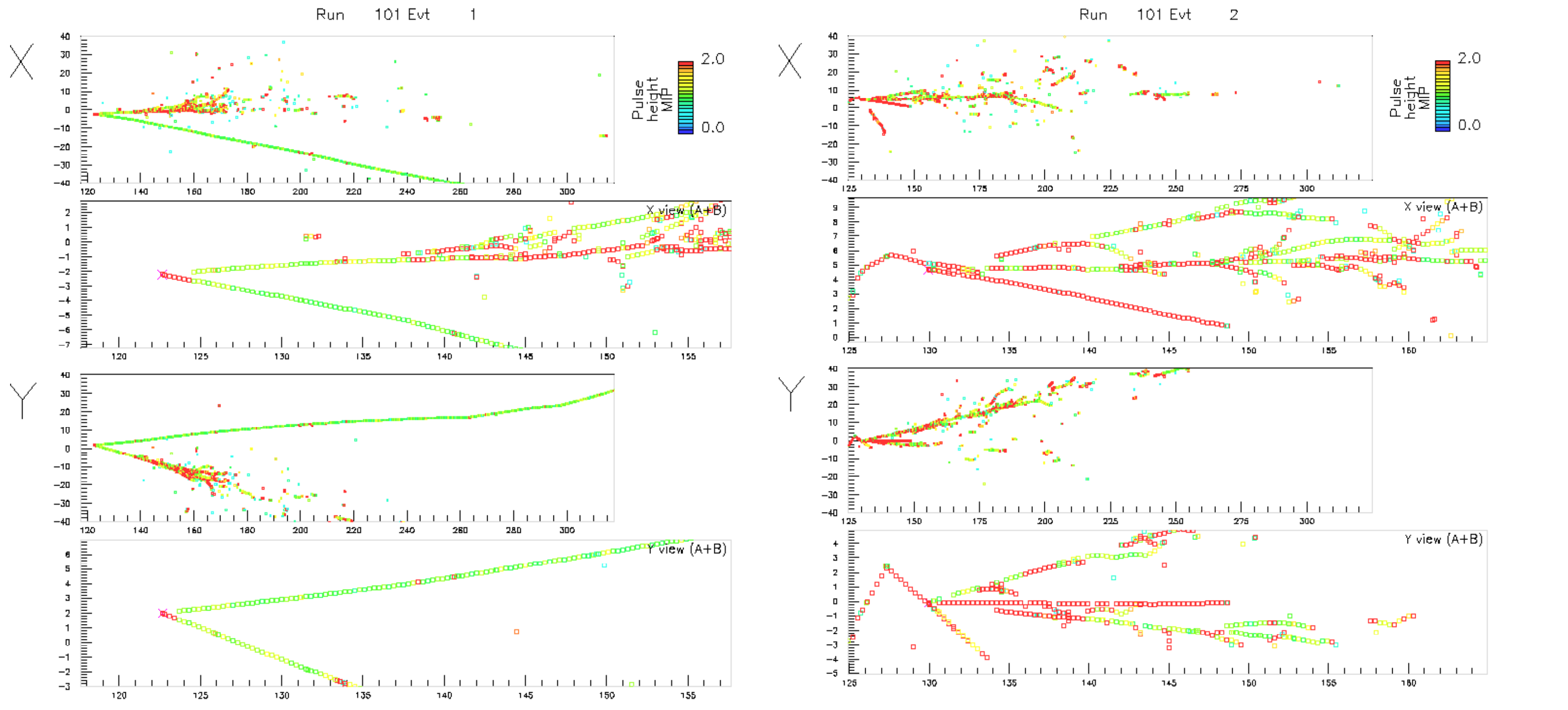
-Track starts at the vertex

-Single track (green) over first few cm

-Two conversion points detached from the vertex

-Two tracks(red) at the conversion point

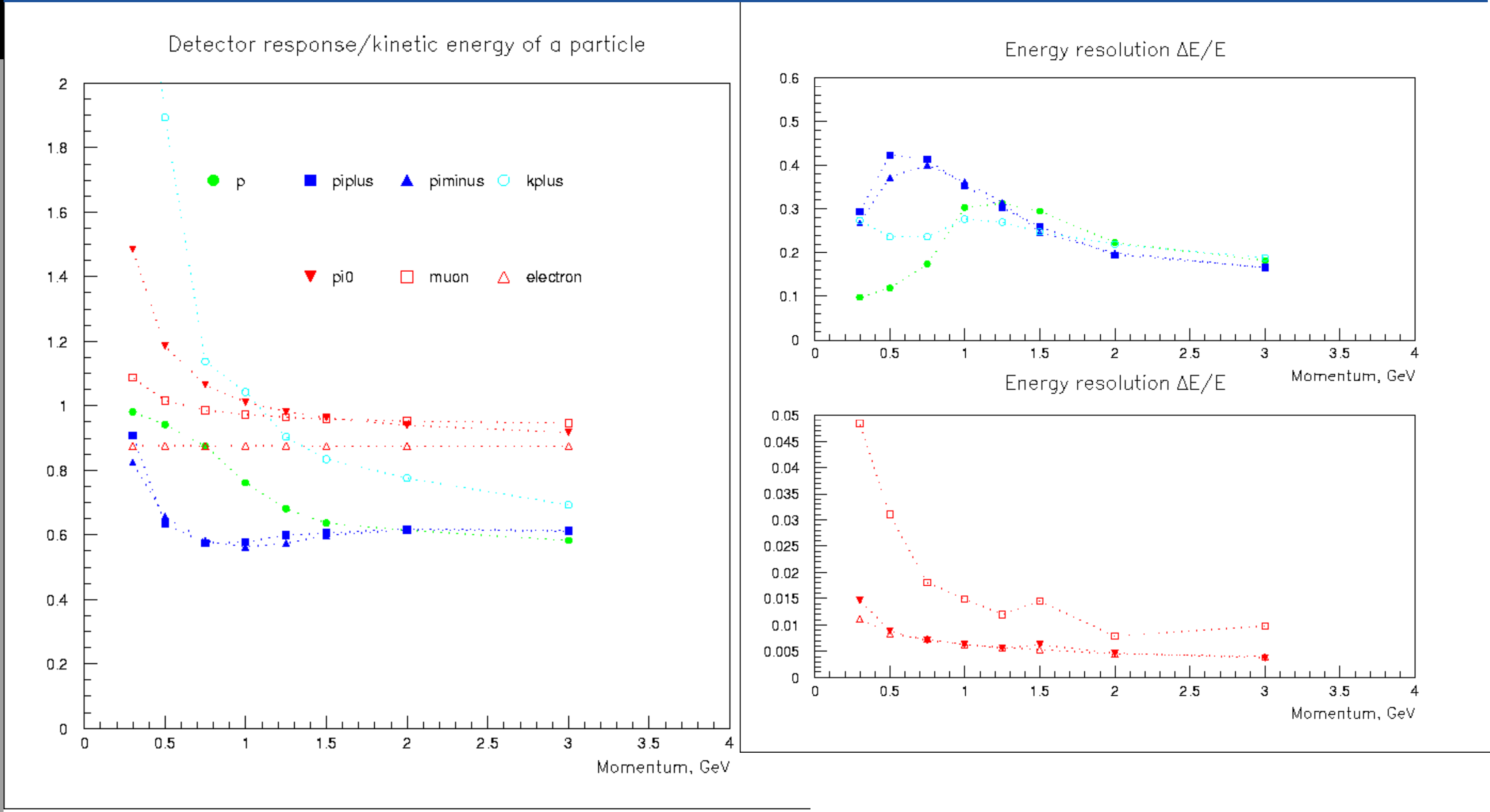
1.5 GeV ν_e CC events



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

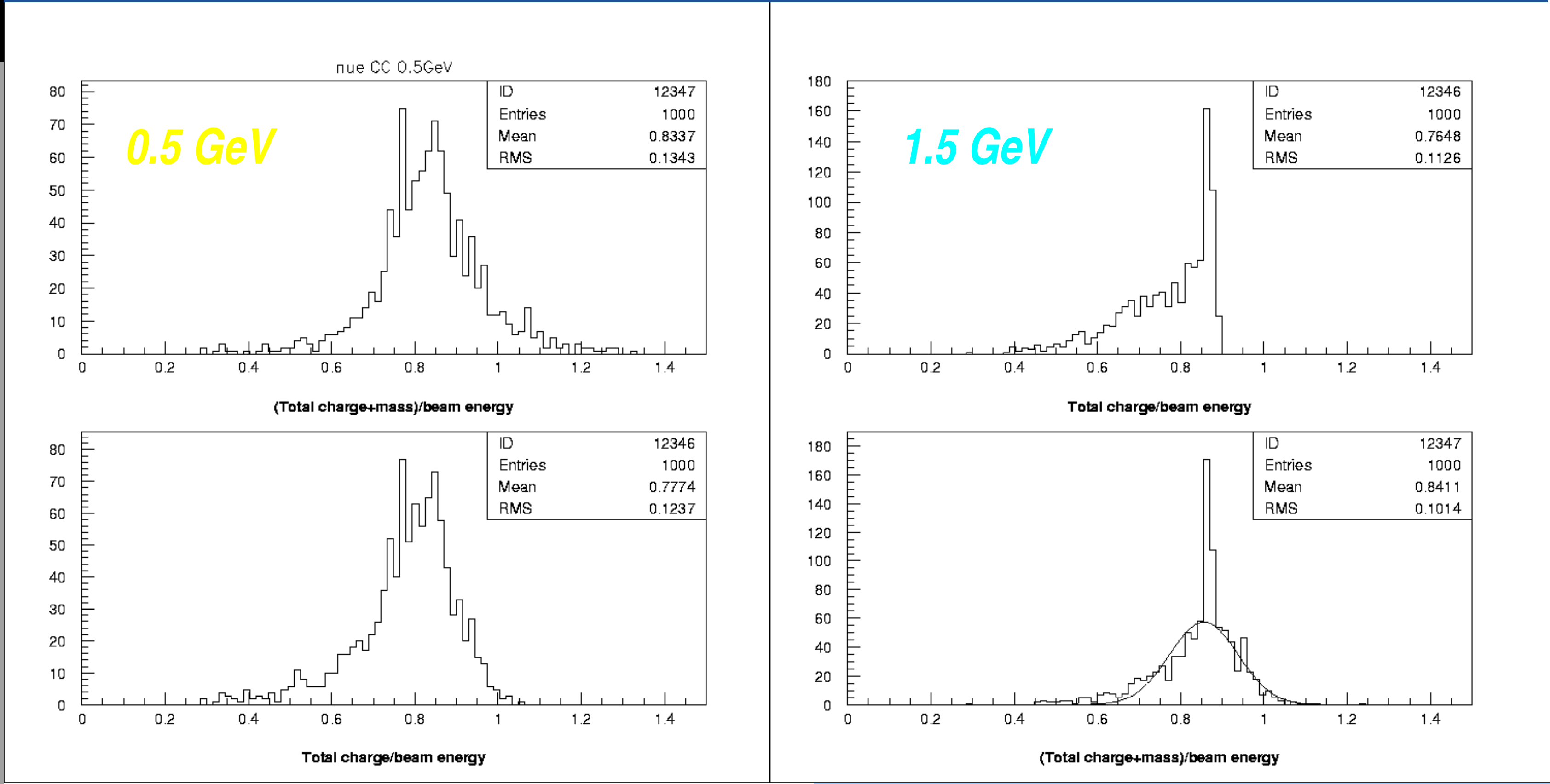
Extra bonus: particle ID and calorimetry at low energies, 0-2 GeV region



e/π° – resolution <1%/sqrt(E), μ – resolution ~1% above 0.7 GeV

Hadronic Resolution 30%/sqrt(E) asymptotically, better at very low energies (range-out), worse around the threshold for inelastic collisions

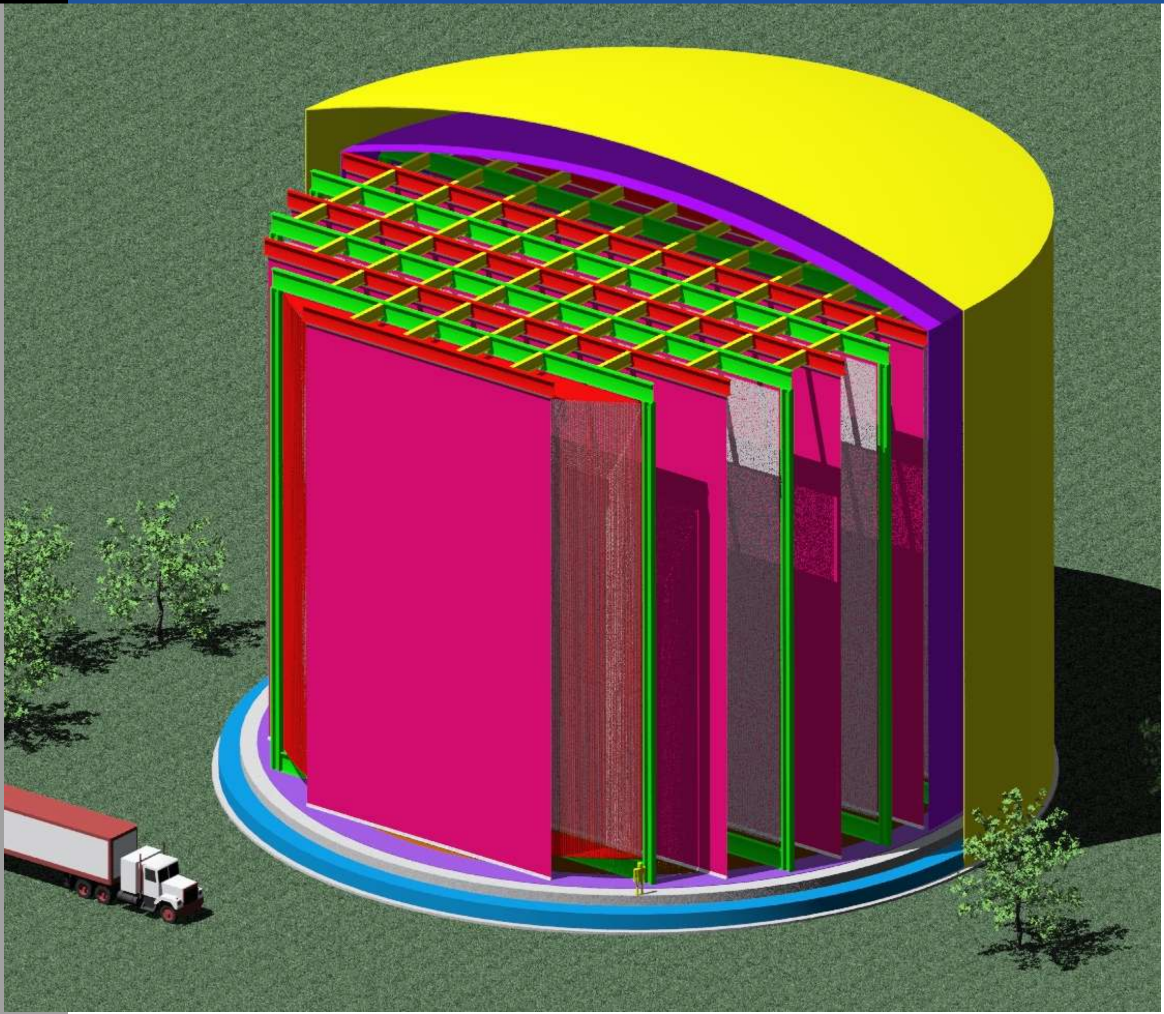
What really counts: Neutrino (CC) energy resolution



- 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

Off-Axis Detector



- Double wall cryogenic tank which is 30 m high and 40 m diameter
- 7 HV cathode planes (150 kV) – each 6 m apart
- 6 planes of wires per cathode: UVX XUV each
- 250,000 channels of electronics
- 50 kton of liquid argon
- DAQ

Thermal Analysis of a 50 kT Liquid Argon Tank

Rough analogy: big boiling pot

Vapor bubbles at the surface only (hydrostatic pressure)

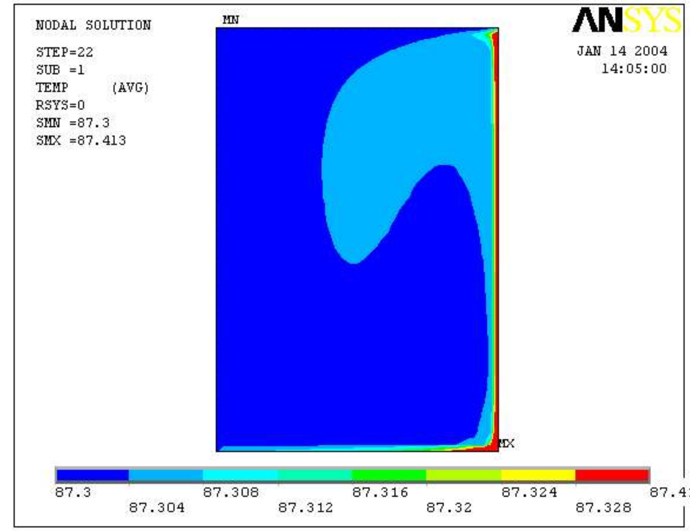
Total heat leak: 49 kW

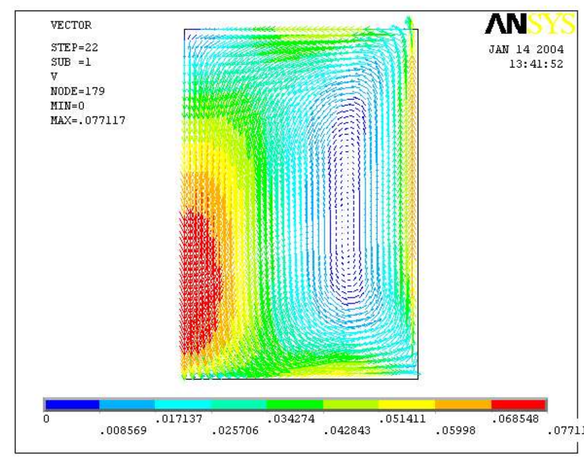
Maximal temperature difference $\Delta T_{max} = 0.1^{o}C$

Temperature difference over most of the volume $0.01^{o}C$

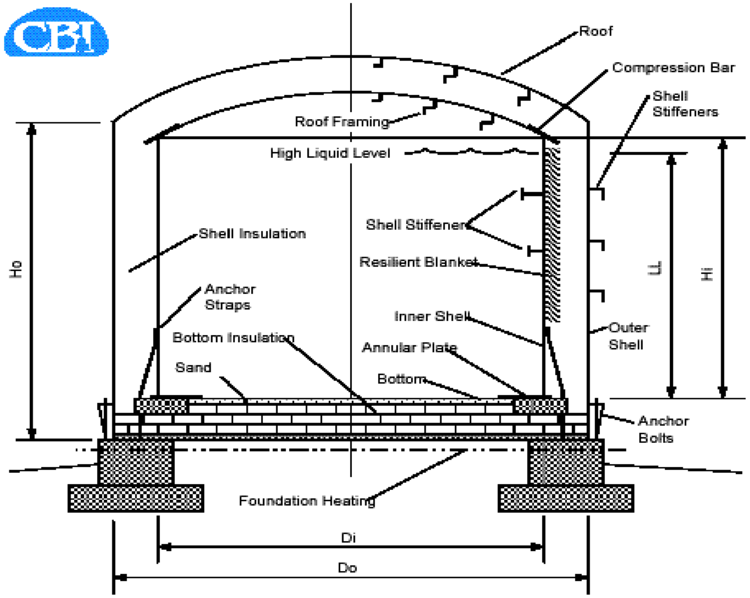
Maximum flow velocity: 7.7 cm/s

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





Cryogenic Storage Tanks – a Competitive Industry

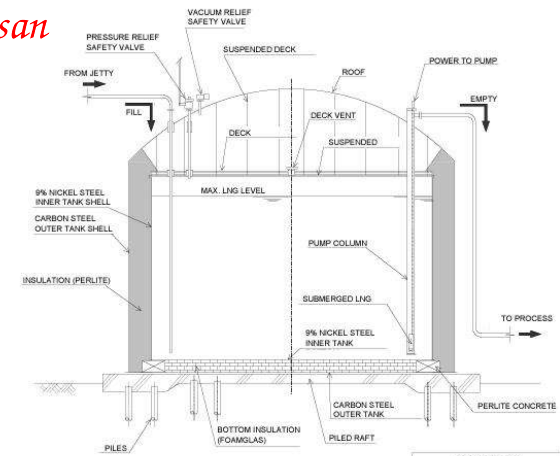


Double Wall & Double Roof Tank

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

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

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



Cryogenic Storage Tanks – an Industrial Example (CB&I)

CBI PRODUCTS

Refrigerated Storage & Process Systems

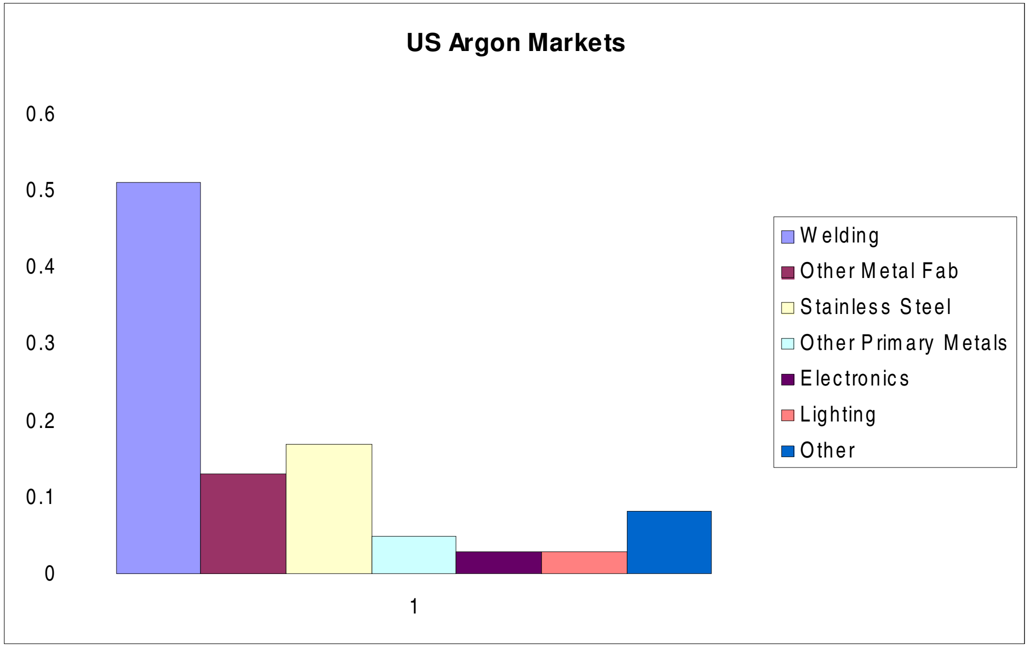
- CB&I takes a total systems approach for low-temperature and cryogenic facilities as this results in the most operationally efficient and cost effective design for the owner. The efficiencies result from the storage solution, liquefaction and/or revaporizing systems design and the terminal facilities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

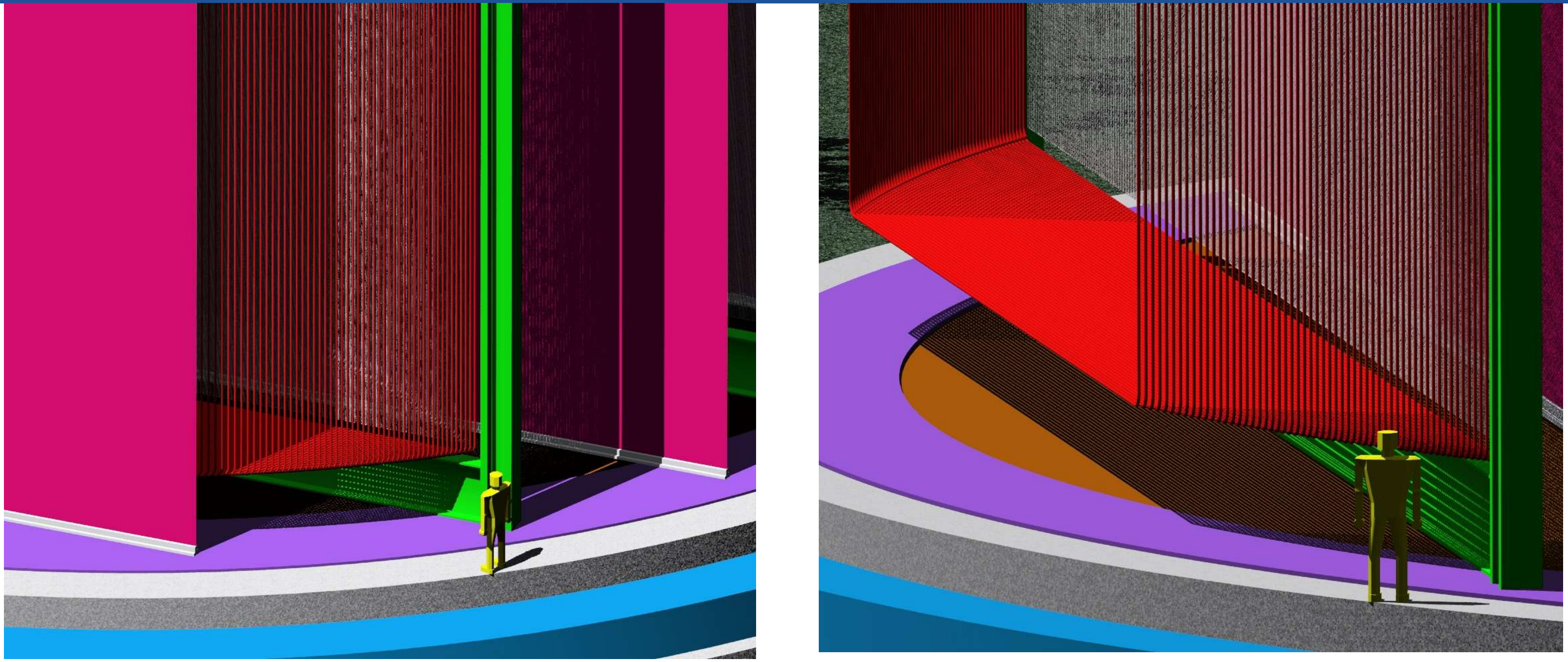
- *Byproduct of air liquefaction*
- *Annual production ~ 1,000,000 tons/year - tied to oxygen demand for steel production)*

- Delivery: truck (20 t) or railroad car (70 t)

- *Cost (delivered) $0.60/kg*



Field Shaping in the Drift Region



- 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

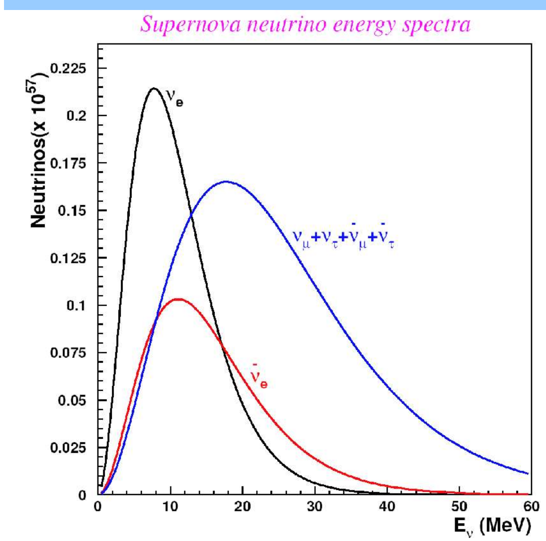
How Much?

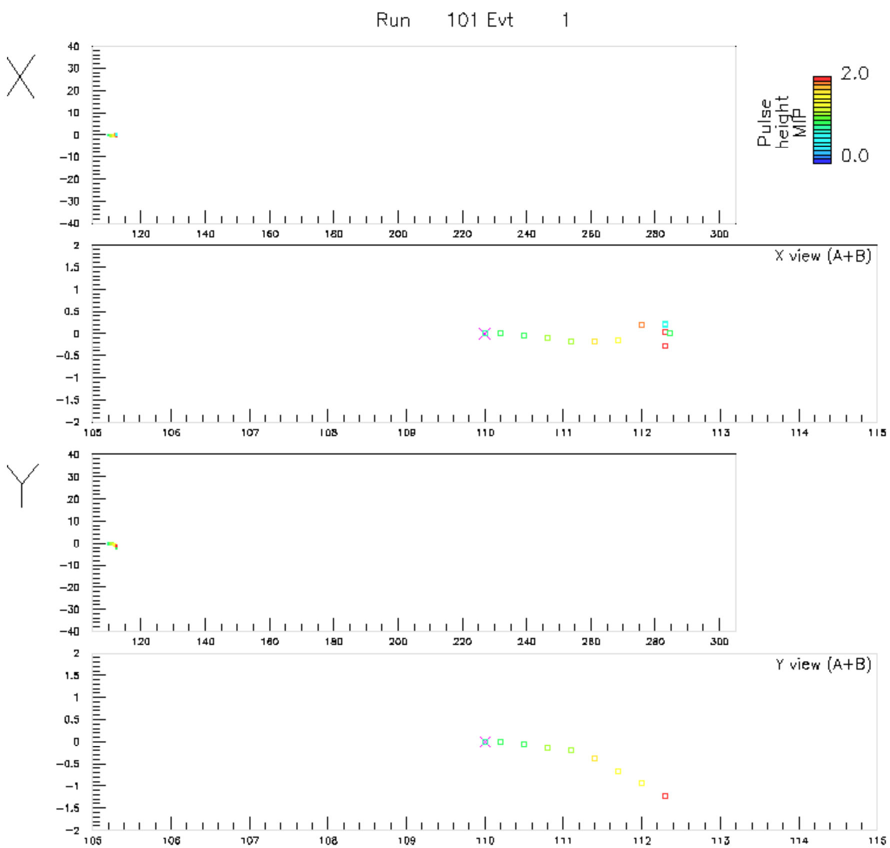
	M US$
• Cryostat (Industry: Liquified gases)	11
• Liquid Argon (delivered)	30
• Cryogenics/purification	12
• HV/field shaping	5.7
• Wire Chambers	5 (?)
• Electronics , cabling	5
• Data Acquisition/handling	5
• Structure/site	37.7
total	111.4 M US$

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

Supernova(s) 201x[A,B,C,…]?

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





FLARE can Differentiate Supernova Neutrino Species

- **Elastic scattering (ES)**

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

$\phi(\nu_e)+0.15\ \phi(\nu_\mu + \nu_\tau)$

$\phi(\nu_e)+0.34\ \phi(\nu_\mu + \nu_\tau)$

- **Electron-neutrino absorption (CC)**

$\phi(\nu_e)$

Q=5.885 MeV

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

- **Electron-antineutrino absorption (CC)**

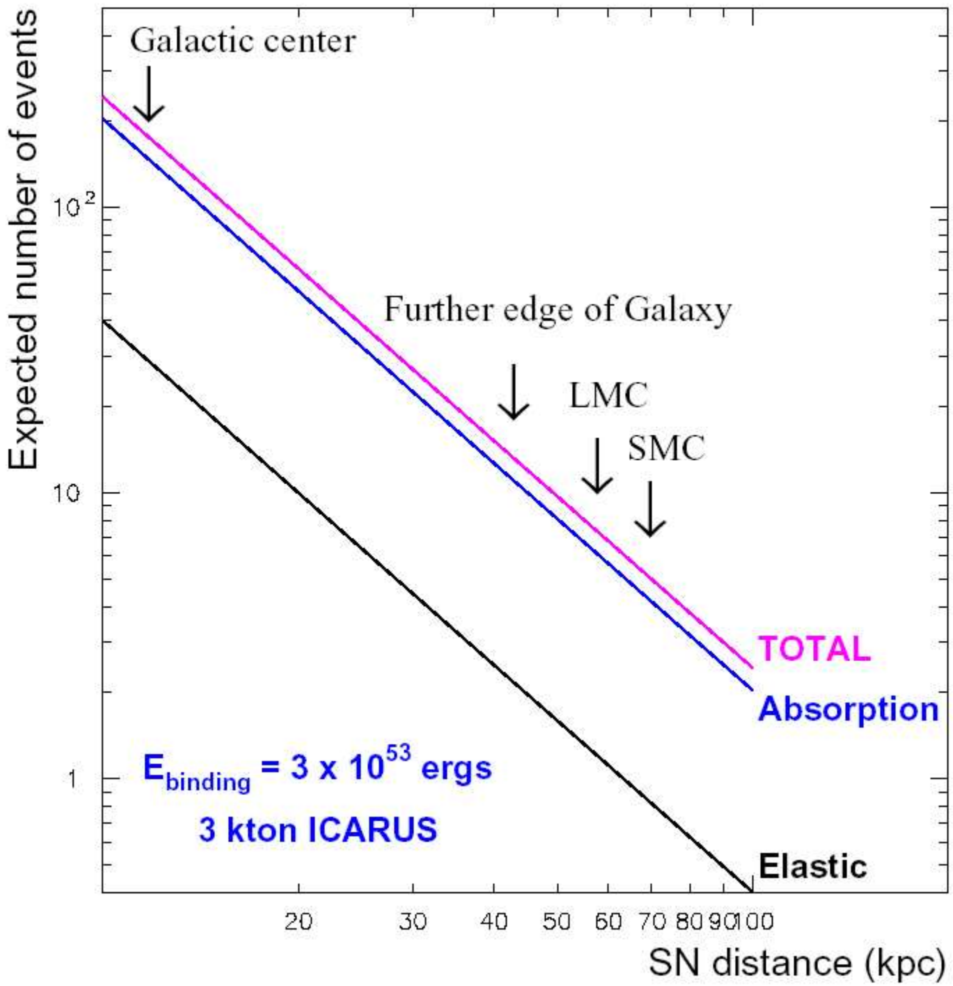
$\phi(\nu_e)$

Q≈8 MeV

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

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

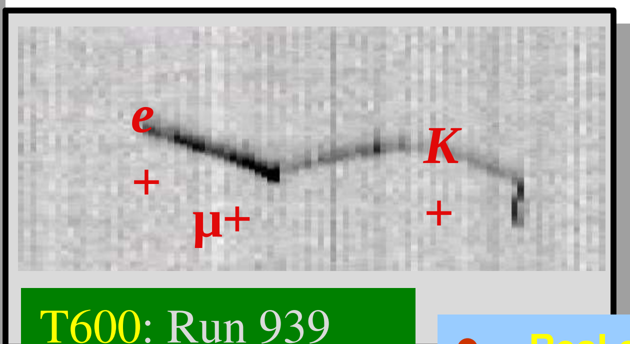
Supernova 201xA?



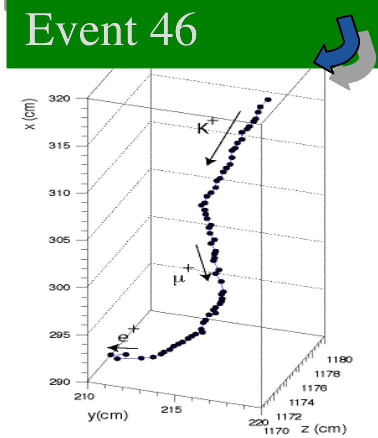
- These event rates are for 3 kT ICARUS
- Multiply by a factor 17 or so for NuMI off axis ➔ good measurement of the energy and the time distribution from a not-too-distant supernova

Remember Proton Decay?
How About P-> Kν ?

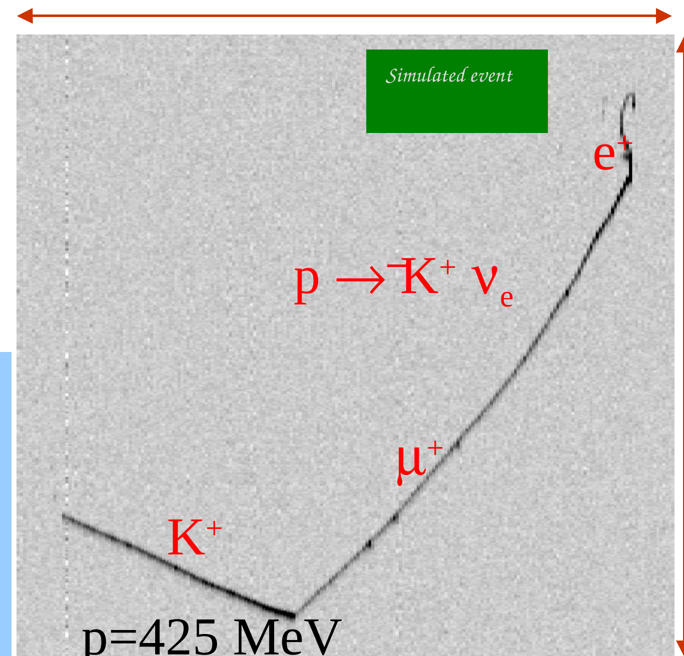
- **Not accessible to water Cerenkov detectors**
- *K/μ/e decay chain. Good energy determination from range*
- *High Efficiency and low background*



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**



ICARUS Projected Limits

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 → 30 [1 evt]	
	ICARUS	45	–	0.005	5	2.7	94
$p \to K^+ \bar{\nu}$	SuperK				79	19 → 13 [1 evt]	
prompt $\gamma\ \mu^+$	SuperK	8.7	0	0.3		10 → 7	
$K^+ \to \pi^+ \pi^0$	SuperK	6.5	0	0.8		7.5 → 5	
	ICARUS	97	–	0.005	5	5.7	17
$p \to \mu^+ \pi^0$	SuperK	32	0	0.4	79	37 → 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

Status and Prospects

- Proposal
  - Letter of Intent Submitted 2004
- Interest in neutrino oscillations has greatly increased during the past year
  - HEPAP APS study
  - Fermilab Long-Range Planning committee sees neutrino oscillations as a major part of Fermilab's future program
  - US Secretary of Energy lists a neutrino superbeam as one of four high-energy projects in "Facilities for the Future of Science."
  - Proton Driver studies given a boost by the Linear Collider technology decision

Conclusions

- The Liquid Argon TPC is a fantastically powerful detector which is not a fantasy – large working versions have been built and operated.
- FLARE proposes using a 50 kton LArg TPC as the ideal off-axis NuMI detector to study $\nu_\mu \Rightarrow \nu_e$ oscillations. Many engineering studies are required but much of the R&D is done.
- The FLARE physics program is very rich including proton decay and supernova observations as well as placing smaller detectors closer to neutrino beamlines for high-statistics studies of neutrino interactions.
- The future promises to be very exciting!

Liquid Argon Time Projection Chamber History

- 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)
- 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)