High Energy Neutrino Detectors

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Nufact'04 Summer Institute
July 21, 2004

Outline of this Lecture

- Introduction
  - What are the goals?
  - Particle Interactions in Matter
- Detectors
  - Fully Active
    - Liquid Argon Time Projection
    - Cerenkov (covered in previous talk)
  - Sampling Detectors
    - Overview: Absorber and Readout
    - Steel/Lead Emulsion
    - Scintillator/Absorber
    - Steel-Scintillator

For Each Detector

- Underlying principle
- Example from real life
- What do ν events look like?
  - Quasi-elastic Charged Current
  - Inelastic Charged Current
  - Neutral Currents
- Backgrounds
- Neutrino Energy Reconstruction
- What else do we want to know?

All detector questions are far from answered!

Detector Goals

$$P = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- Identify flavor of neutrino
  - Need charged current events!
  - Lepton Identification (e,μ,τ)
- Measure neutrino energy
  - Quasielastics
    - Lepton energy ~ ν energy
    - Corrections due to
      - P,n motion in nucleus
      - U,d motion in nucleon

$$\bar{\nu} p \rightarrow l^+ n$$

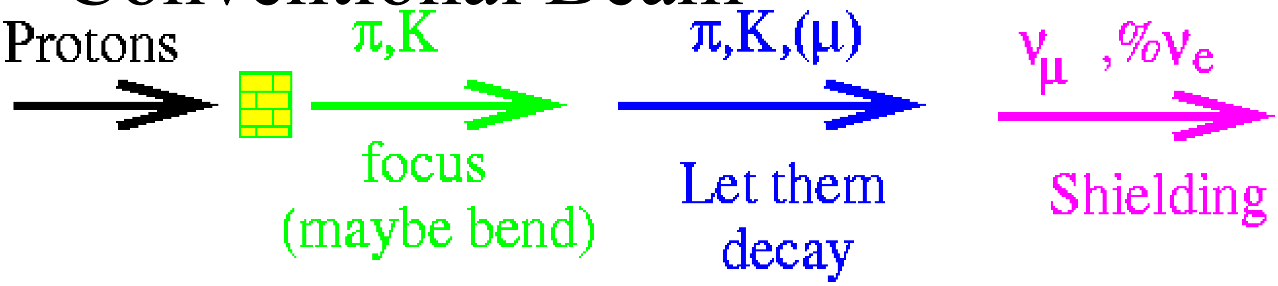
$$\nu n \rightarrow l^- p$$

  - Everything Else
    - Need to measure energy of lepton and of X!

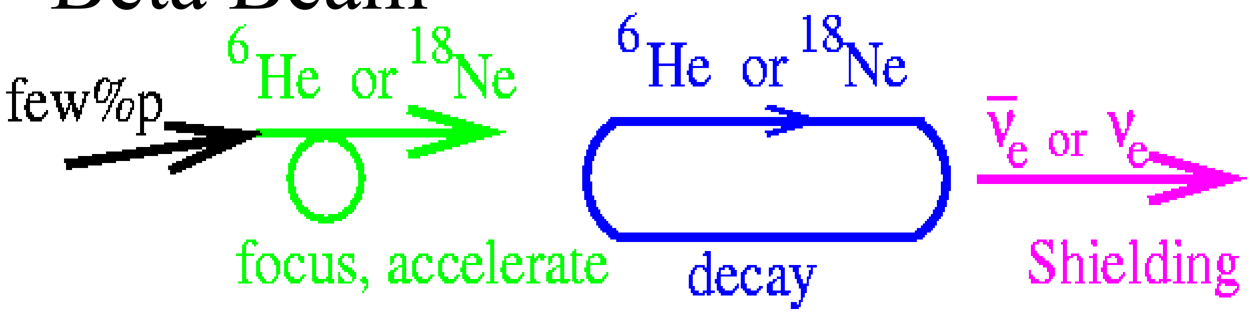
$$\nu N \rightarrow l X$$

Making a Neutrino Beam

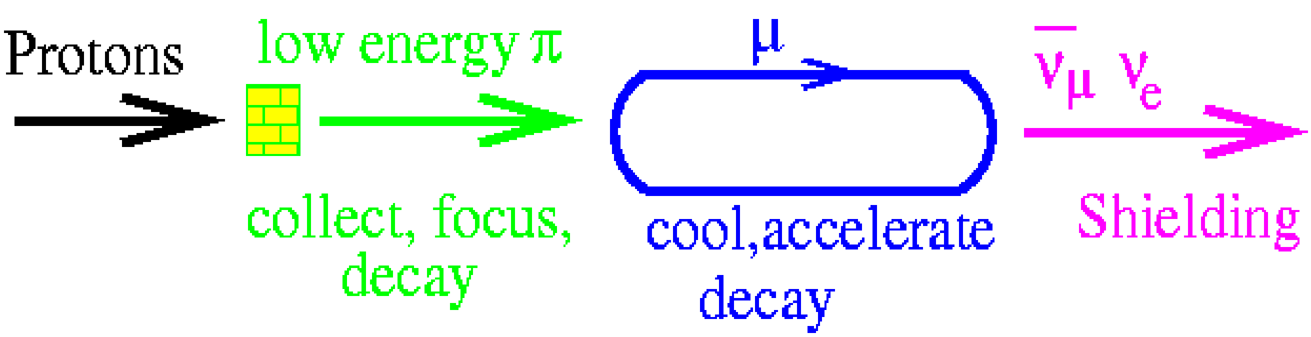
- Conventional Beam



- Beta Beam



- Neutrino Factory



For each of these beams,
ν flux (Φ) is related to
boost of
parent particle (γ)

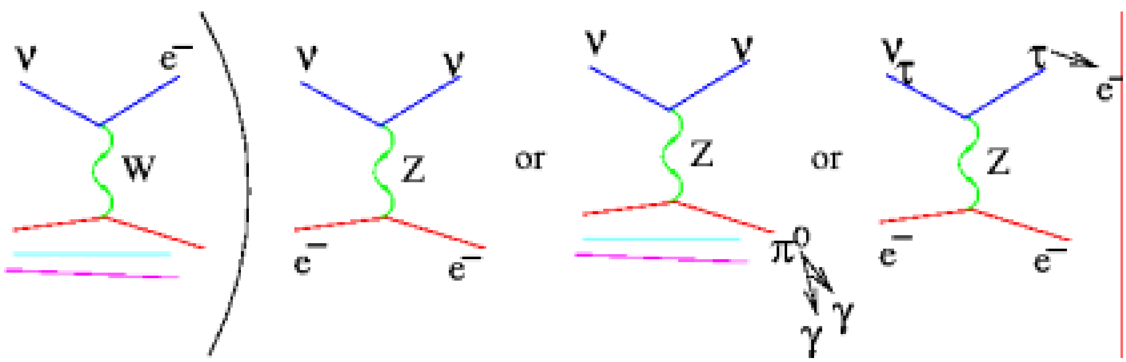
$$\Phi_\upsilon \propto \left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2$$

Goals vs ν Beams

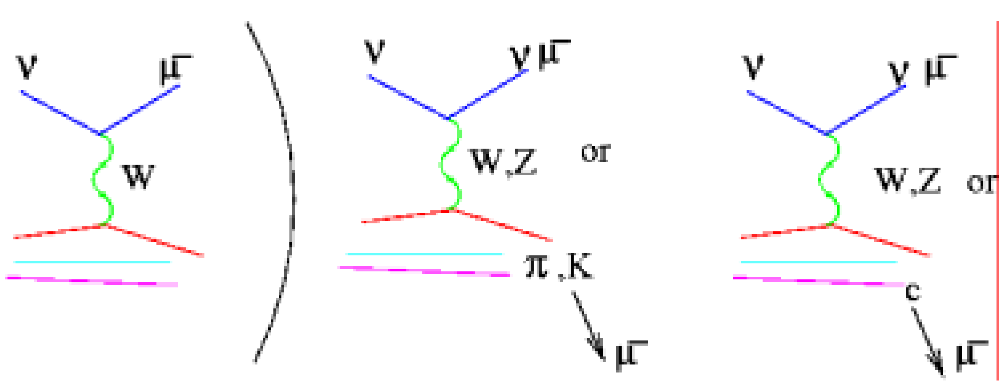
- Conventional Beams (ν_μ, $\%\nu_e$)
  - Identify muon in final state
  - Identify electron in final state, subtract backgrounds
  - Energy regime: 0.4GeV to 17GeV
- β beams (all ν_e)
  - Idenify muon or electron in final state
  - Energy regime: <1GeV for now
- Neutrino Factories (ν_μ, $\bar{\nu}_e$)
  - Identify lepton in final state
  - Measure Charge of that lepton!
    - Charge of outgoing lepton determines flavor of initial lepton
  - Energy regime: 5 to 50GeV ν's

Next Step in this field: appearance!

- Θ_{13} determines
  - If we'll ever determine the mass hierarchy
  - The size of cp violation
- How do backgrounds enter?
  - Conventional beams:
    - Already some ν_e in the beam
    - Detector-related backgrounds:



  - Neutrino Factories:
    - No beam-related backgrounds
    - Detector-related backgrounds:



Why do detector efficiencies and background rejection levels matter?

Assume you have a convenional neutrino beamline which produces:

- 1000 ν_μ CC events per kton (500NC events)
- 5 ν_e CC events per kton

- Which detector does better

  (assume 1% ν_μ-ν_e oscillation probability)

  – 5 kton of
    - 50% efficient for ν_e
    - 0.25% acceptance for NC

Background: (5*.5 ν_e + 500*.0025NC)x5=19

Signal: (1000*.01*.5)x5=25, S/sqrt(B+S)=3.8

  – 15kton of
    - 30% efficient for ν_e
    - 0.5% acceptance for NC events?

Background: (5*.3 ν_e + 500*.005NC)x15=60

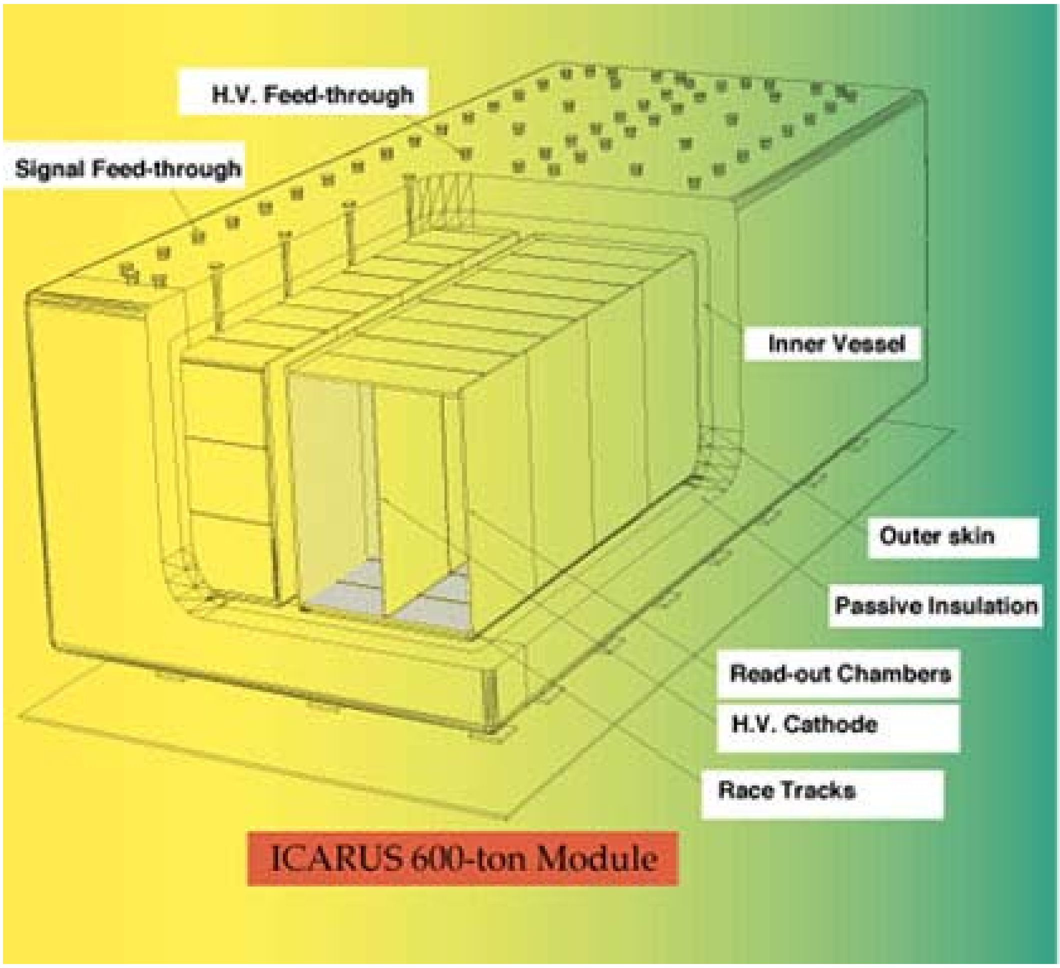
Signal: (1000*.01*.3)x15=45, S/sqrt(B+S)=4.4

Particles passing through material

Particle	Characteristic Length	Dependence
Electrons	Radiation length (X_o)	Log(E)
Hadrons	Interaction length (λ_{INT})	Log(E)
Muons	dE/dx	E
Taus	Decays first	$\gamma ct = \gamma 87 \mu m$

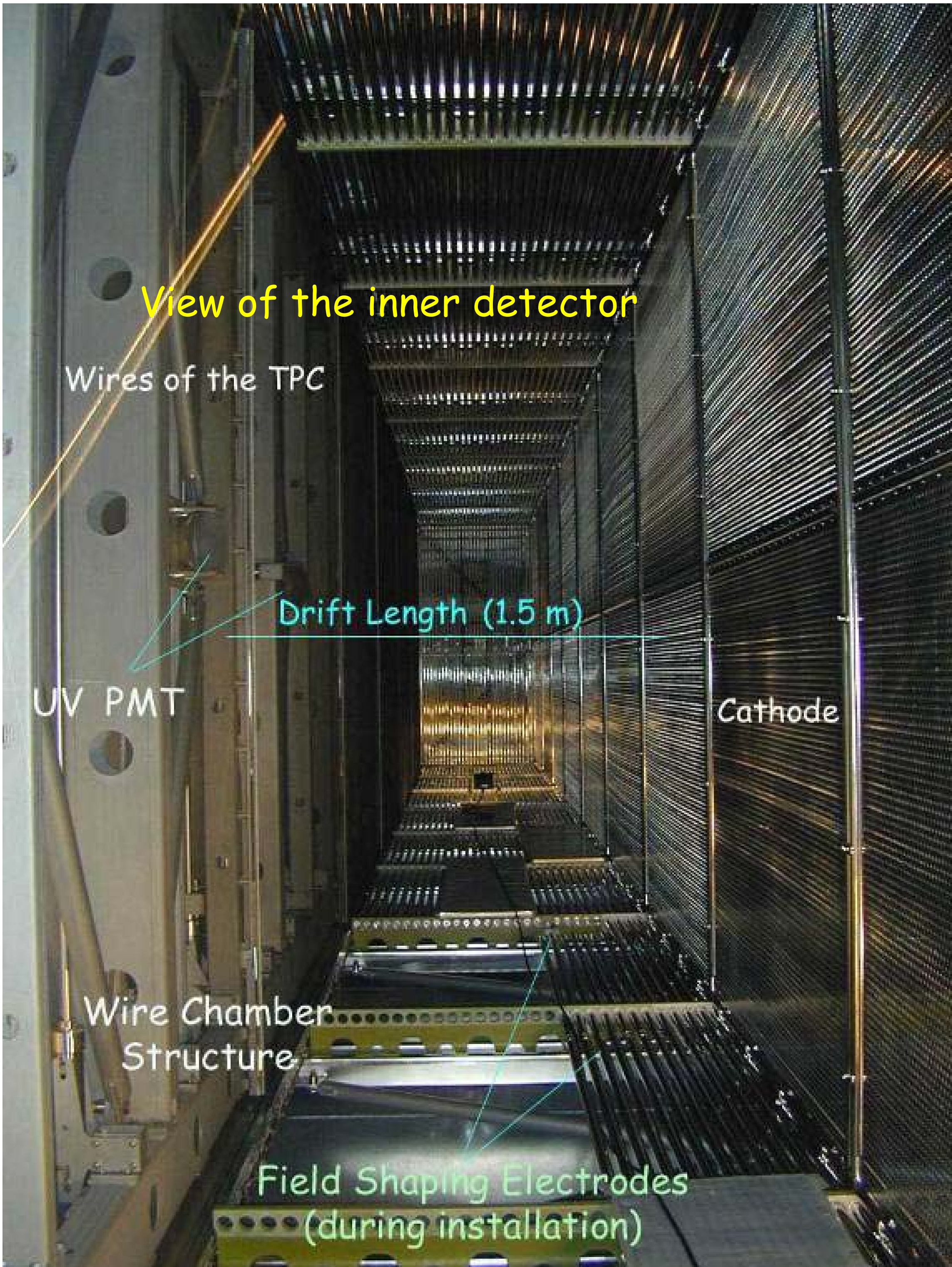
Material	X_o (cm)	λ_{INT}(cm)	dE/dx (MeV /cm)	ρ (g/cm^3)
L.Argon	14	83.5	2.1	1.4
Water	1	83.6	2.0	1
Steel	1.76	17	11.4	7.87
Scintillator	42	~80	1.9	1
Lead	0.56	17	12.7	11.4

Liquid Argon TPC (ICARUS)

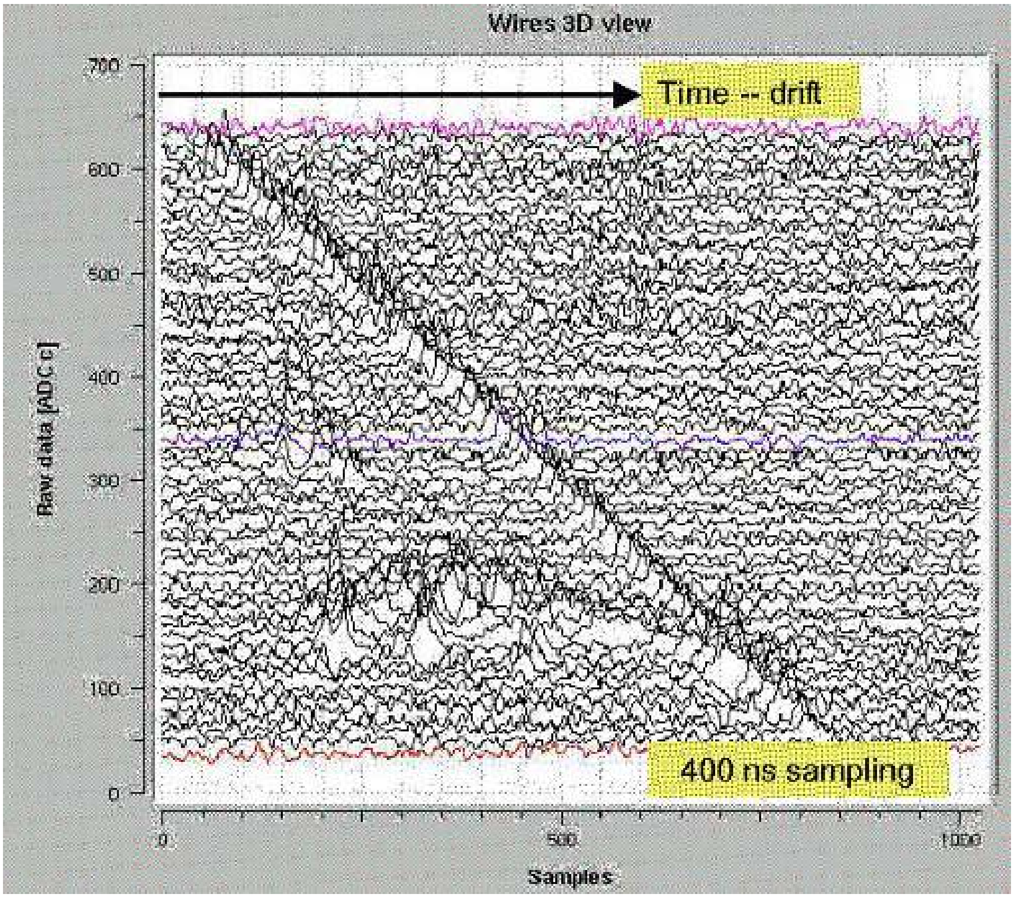


- Electronic Bubble chamber
- Planes of wires (3mm pitch) widely separated (1.5m) 55K readout channels!
- Very Pure Liquid Argon
- Density: 1.4, Xo=14cm λ_{INT} =83cm
- 3.6x3.9x19.1m^3 600 ton module (480fid)

Half Module of ICARUS

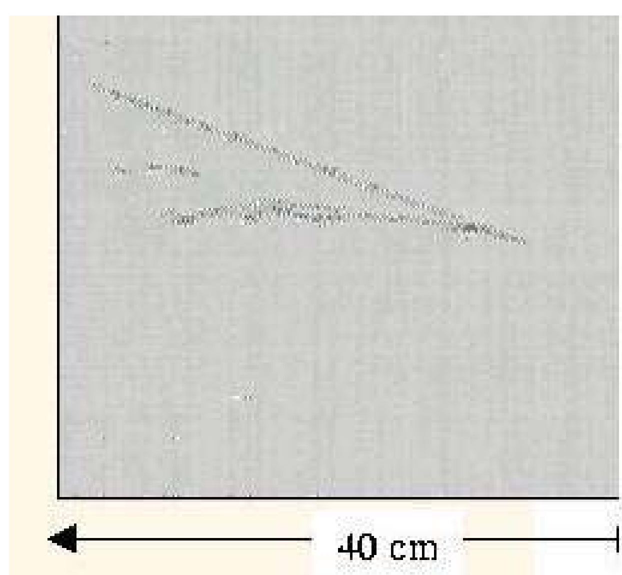


Liquid Argon TPC

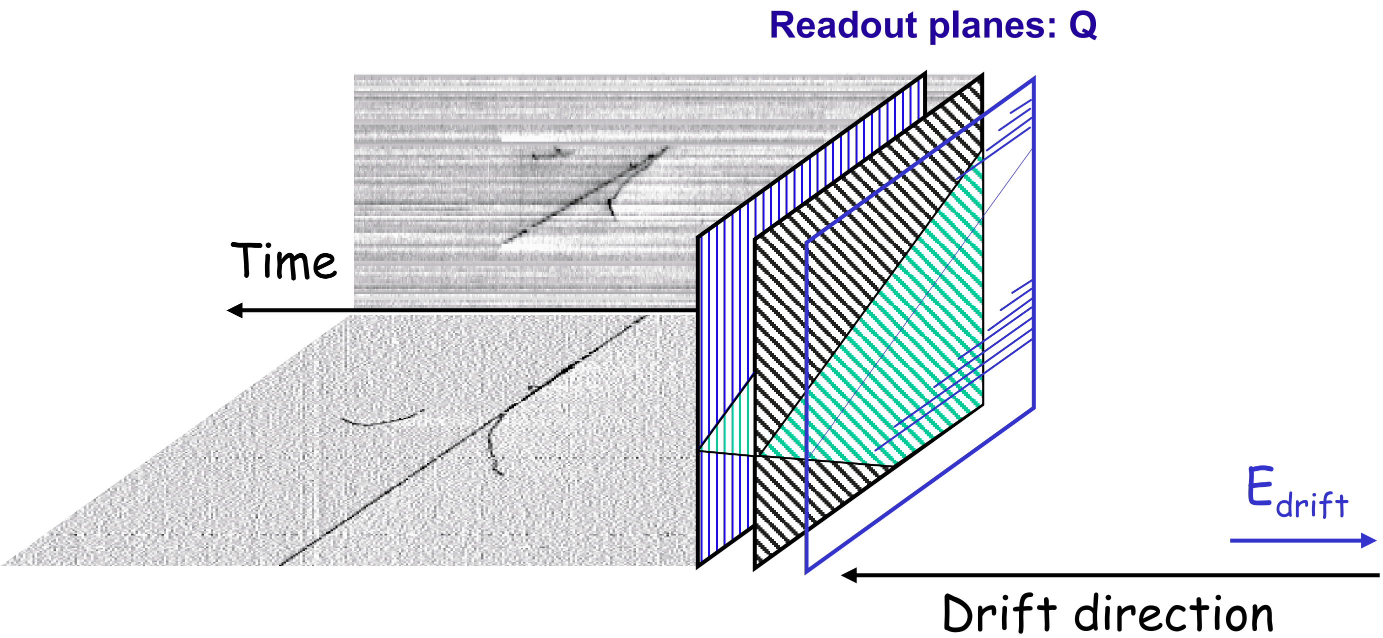


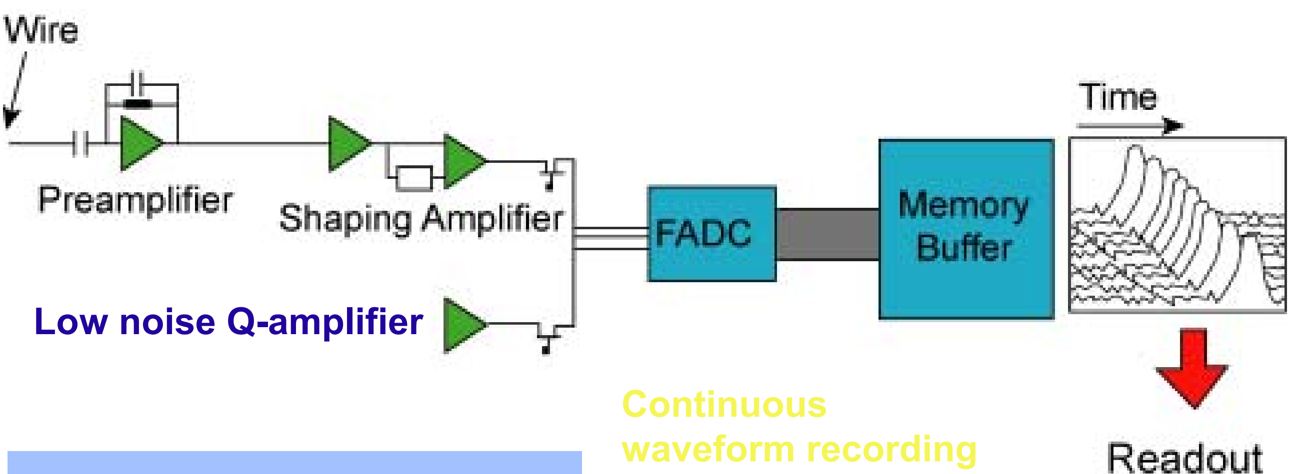
Raw Data to Reconstructed Event

- Because electrons can drift a long time (>1m!) in very pure liquid argon, this can be used to create an "electronic bubble chamber"



Principle of Liquid Argon TPC

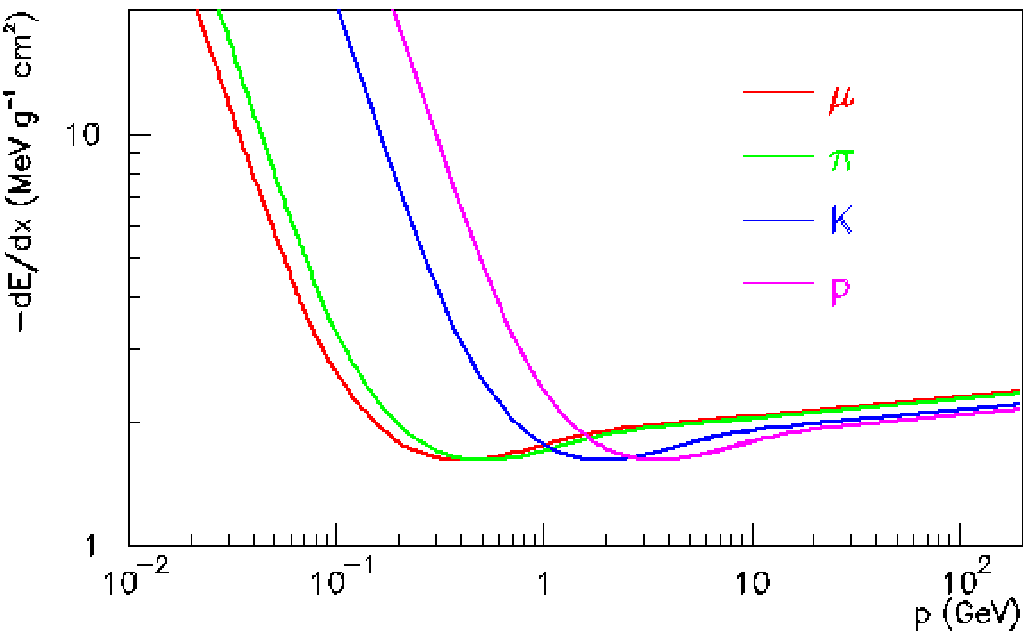




- High density
- Non-destructive readout
- Continuously sensitive
- Self-triggering
- Very good scintillator: T_0

dE/dx(mip) = 2.1 MeV/cm
T=88K @ 1 bar
$W_e \approx 24$ eV
$W_\gamma \approx 20$ eV
Charge recombination (mip) @ E = 500 V/cm ≈ 40%

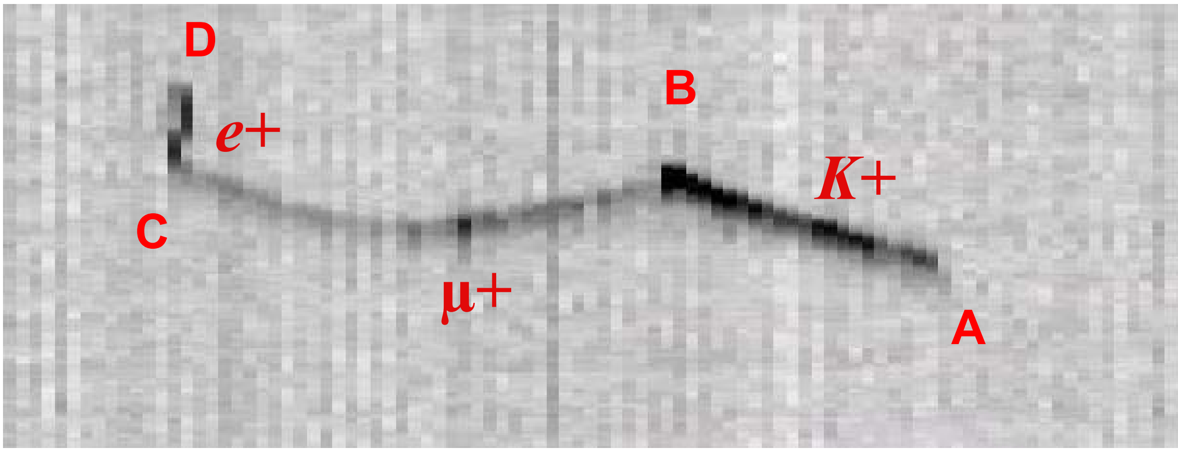
dE/dx in Materials

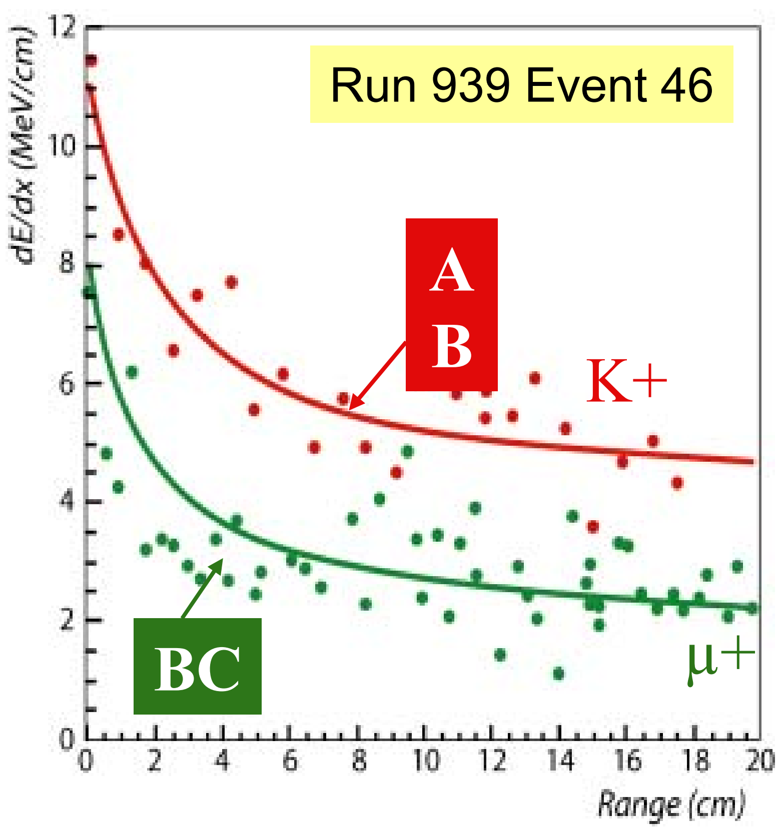


$$\frac{dE}{dx} \propto z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \frac{\ln 2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$

- Bethe-Block Equation
- x in units of g/cm^2
- Energy Loss Only f(β)
- Can be used for Particle ID in range of momentum

Bethe-Block in practice

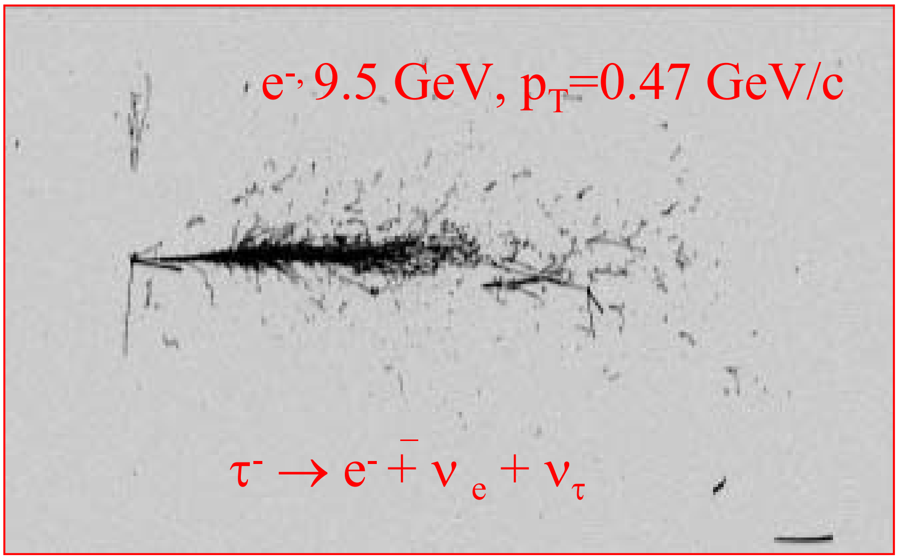




- From a single event, see dE/dx versus momentum (range)

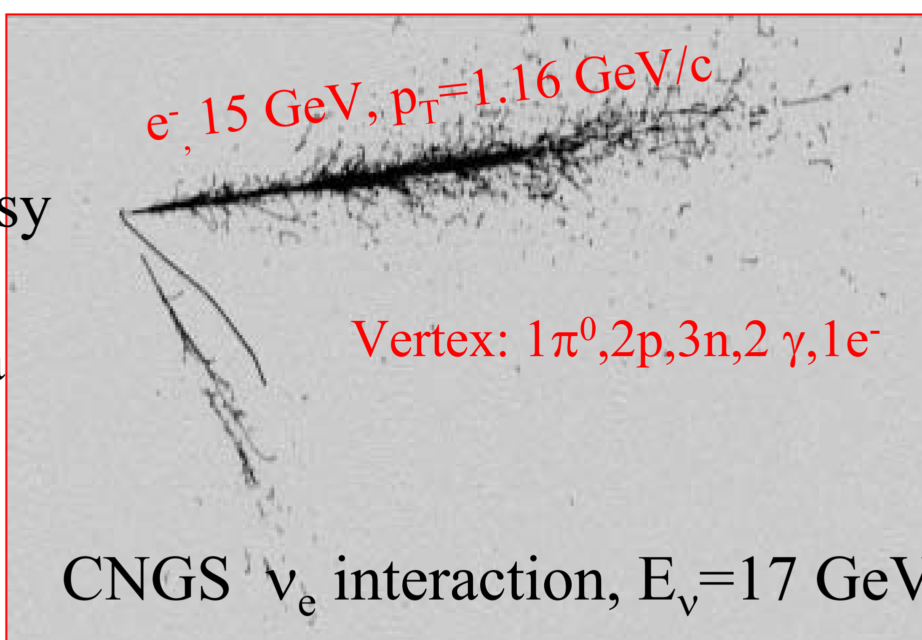
Examples of Liquid Argon Events

- Lots of information for every event…



- Primary τ tag: $\tau \rightarrow e$ decay
- Exclusive τ tag: $\tau \rightarrow \rho$ decay
- Primary Bkgd: Beam ν_e

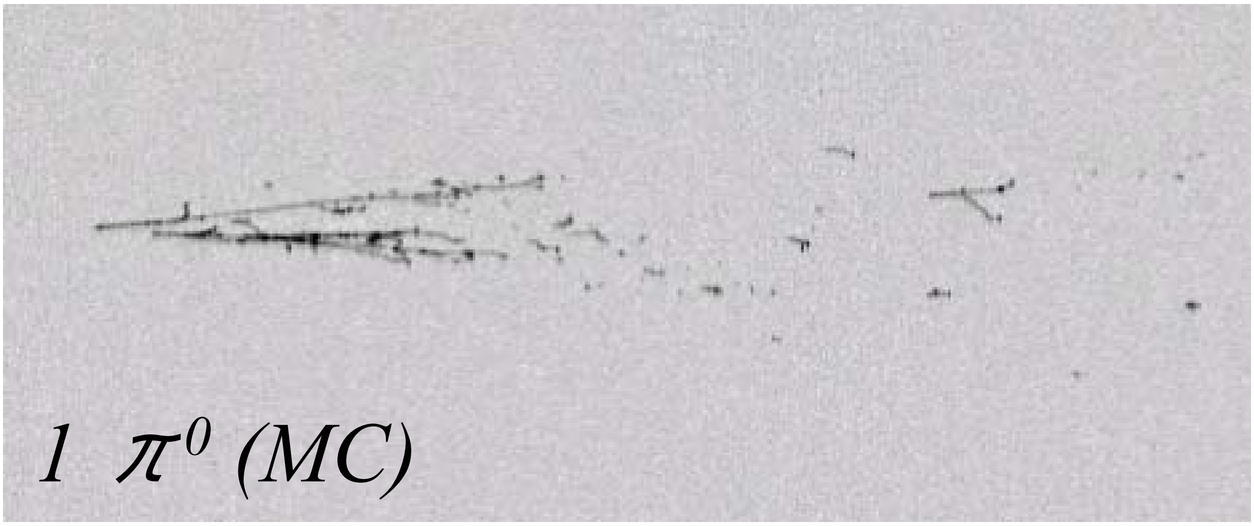
CNGS ν_τ interaction, E_ν=19 GeV



CNGS ν_e interaction, E_ν=17 GeV

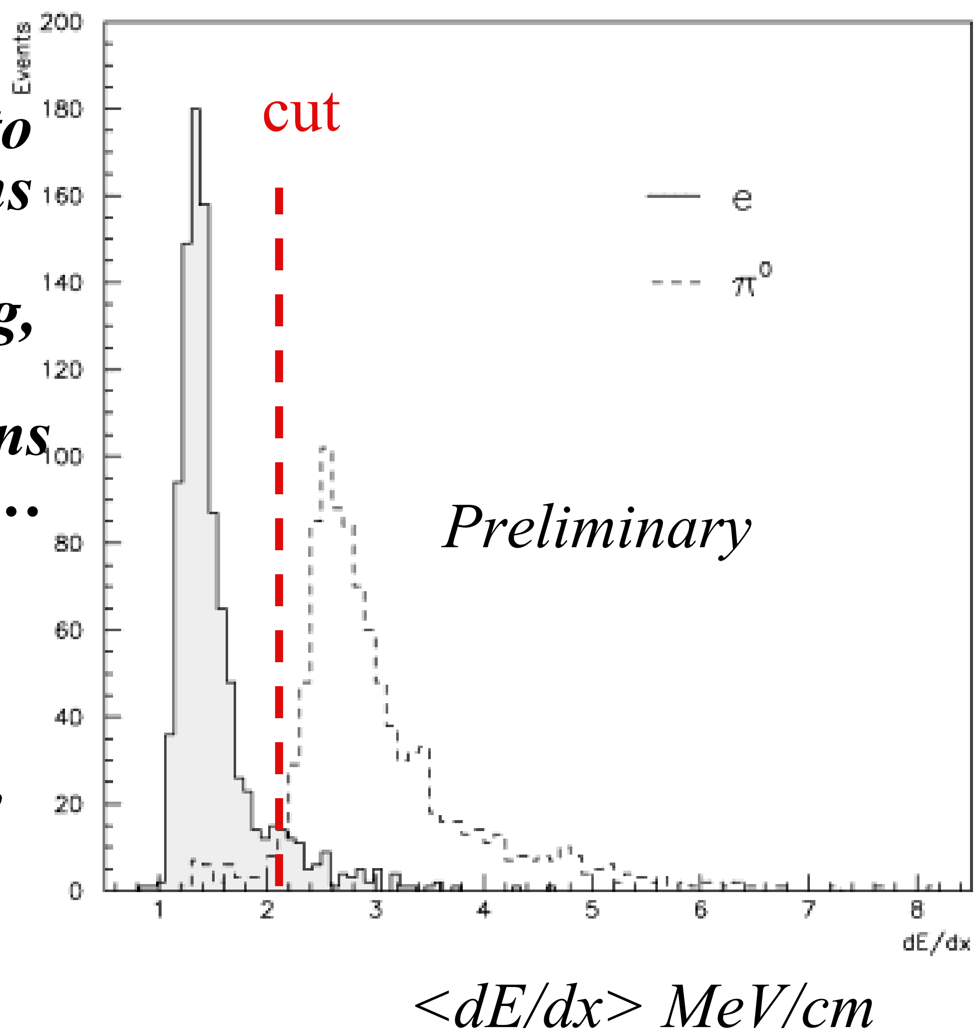
Courtesy André Rubbia

π^0 identification in Liquid Argon



One photon converts to 2 electrons before showering, so dE/dx for photons is higher…

Imaging provides ≈2×10-3 efficiency for single π^0



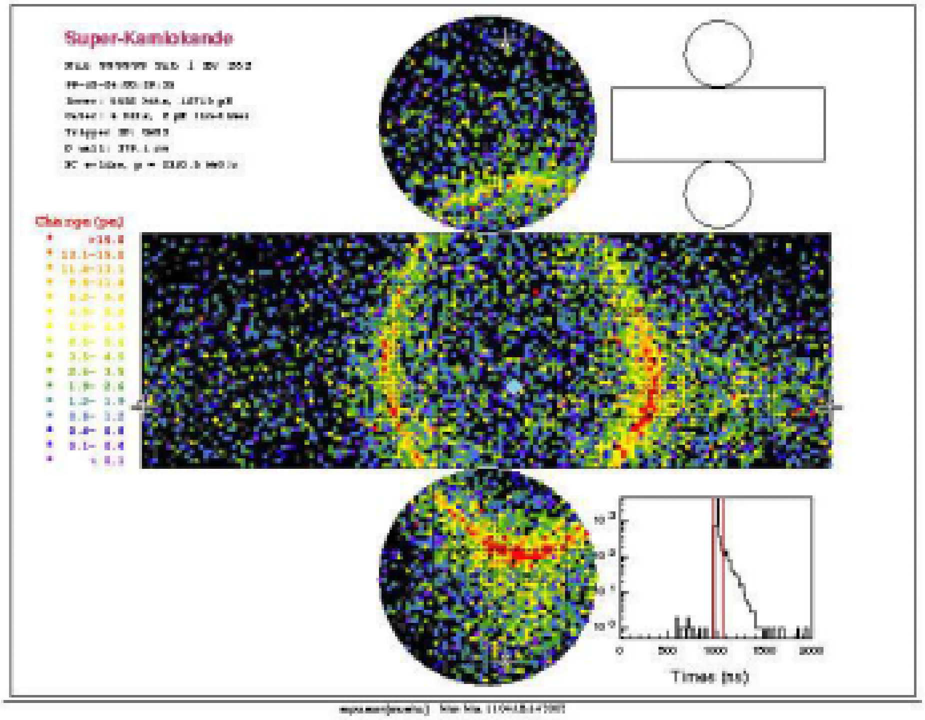
Oustanding Issues

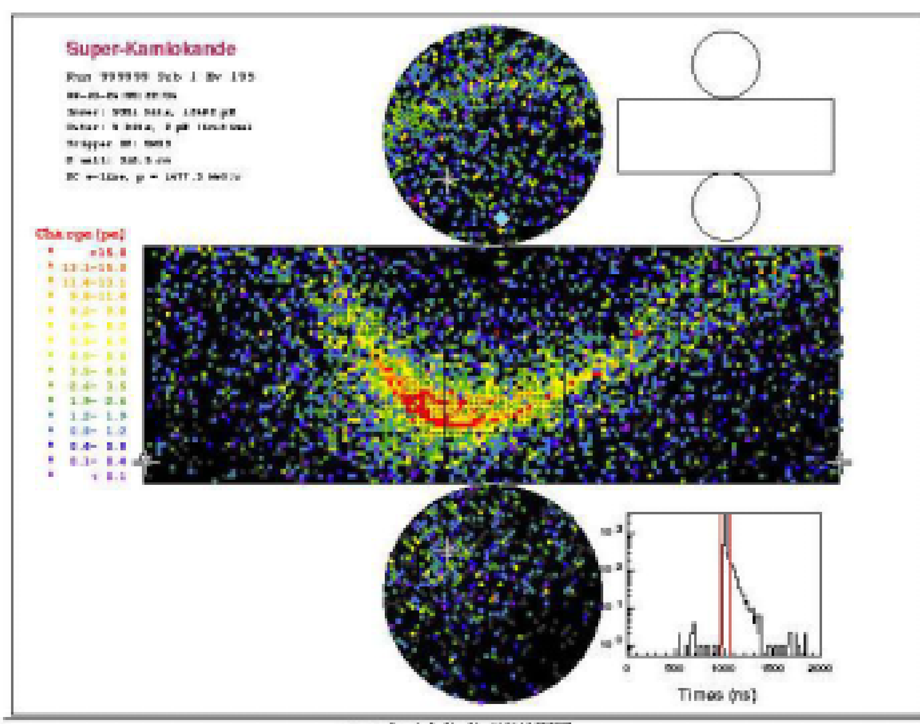
Liquid Argon
Time Projection Chamber

- Do Simulations agree with data (known incoming particles)
- Can a magnetic field be applied
- Both could be answered in CERN test beam program
- Is neutral current rejection that good?
- How large can one module be made?

- What is largest possible wire plane spacing?

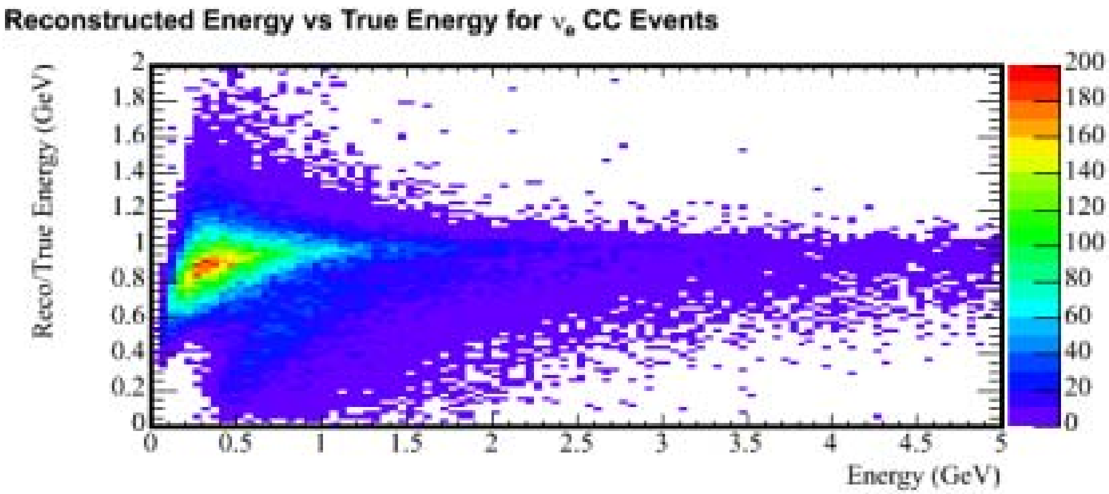
Water Cerenkov
at High (>1GeV) Energies



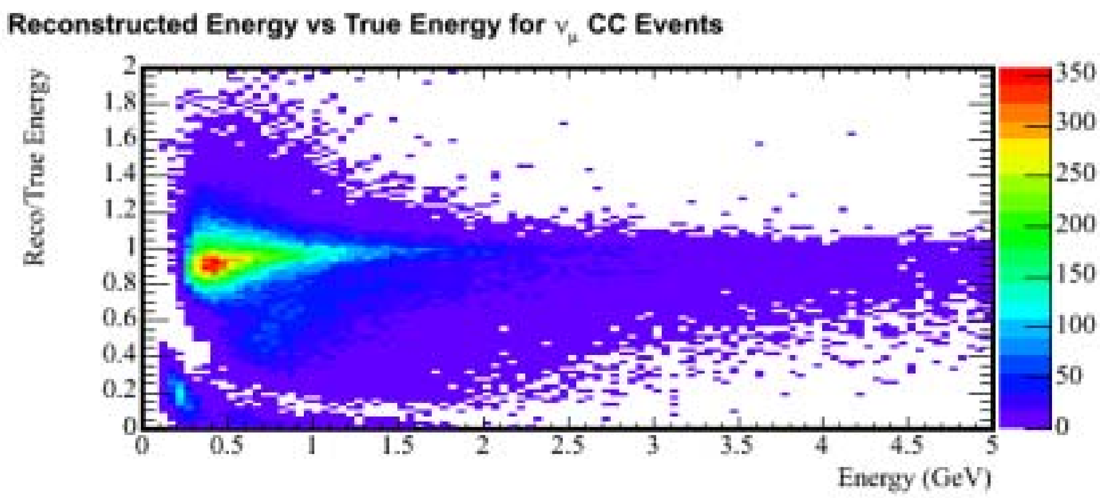


Courtesy Mark Messier: one is ν_e signal, one is π^0 background

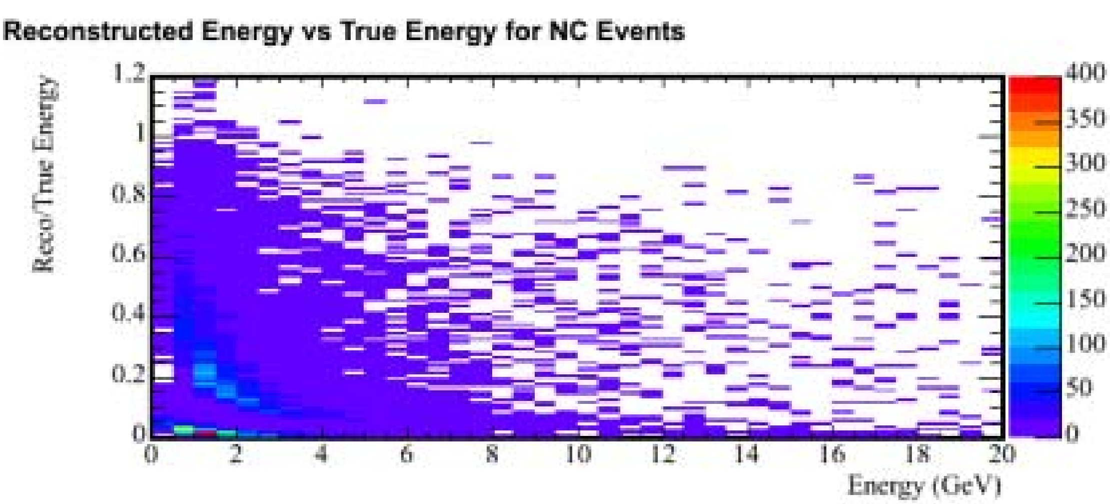
$\sigma(E\nu)$ of Water Cerenkov vs E_ν



ν_eCC

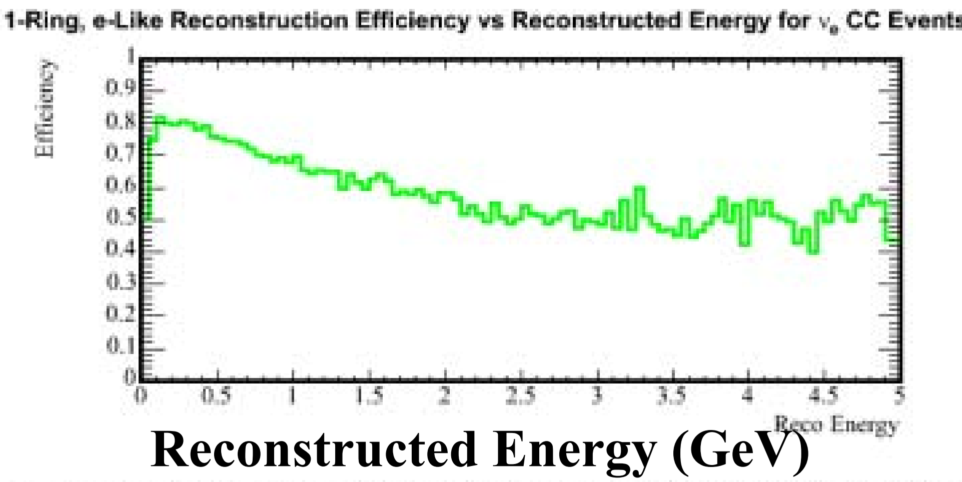


ν_μCC

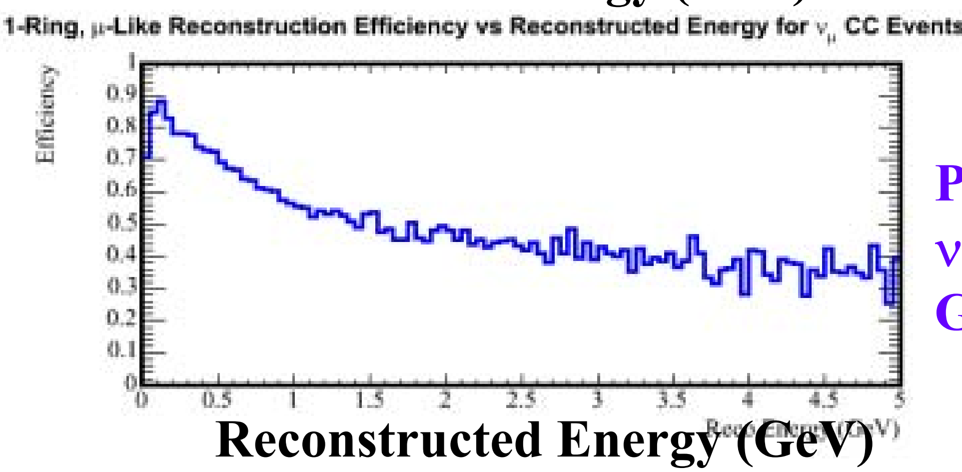


νNC

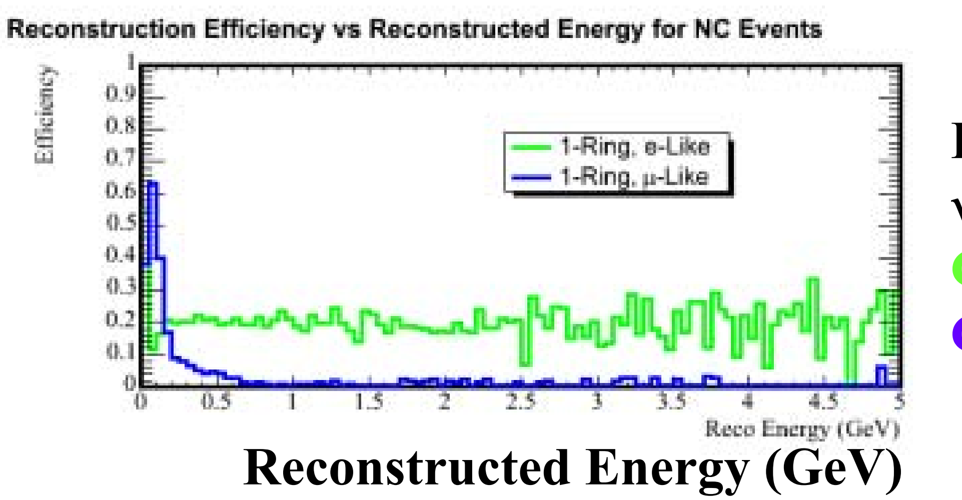
$\varepsilon(E_{recon})$ for Water Cerenkov



Probability of
ν_e CC
Giving 1 e-like ring



Probability of
ν_μ CC
Giving 1 μ-like ring



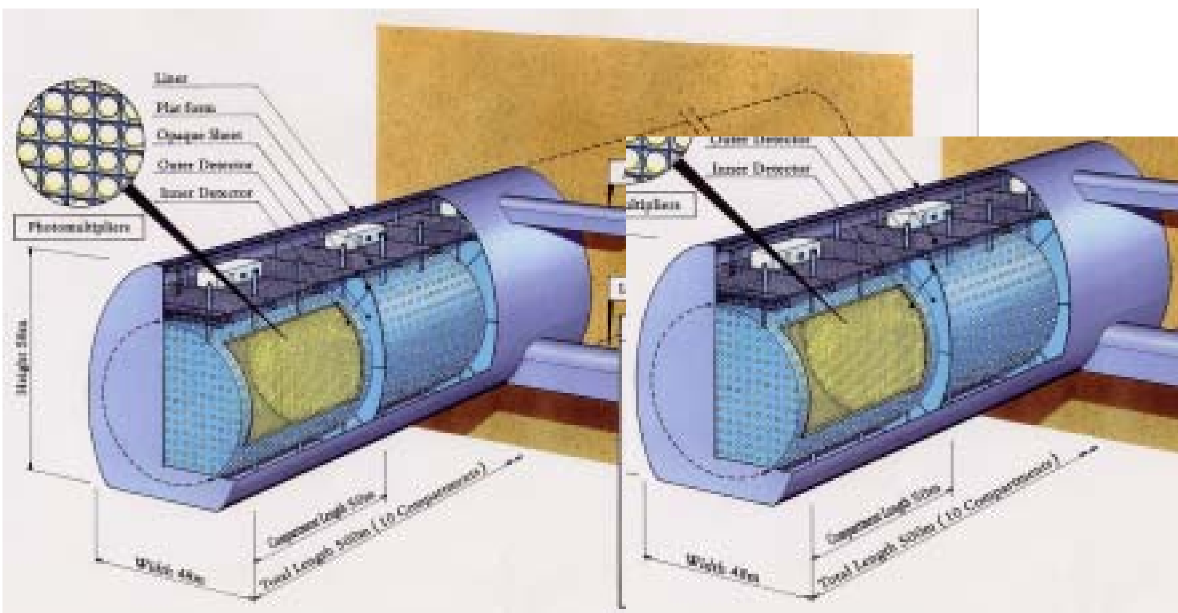
Probability of
ν NC
Giving 1 e-like ring
Giving 1 μ-like ring

- Again, courtesy Mark Messier, for FeHo Study

Oustanding Issues

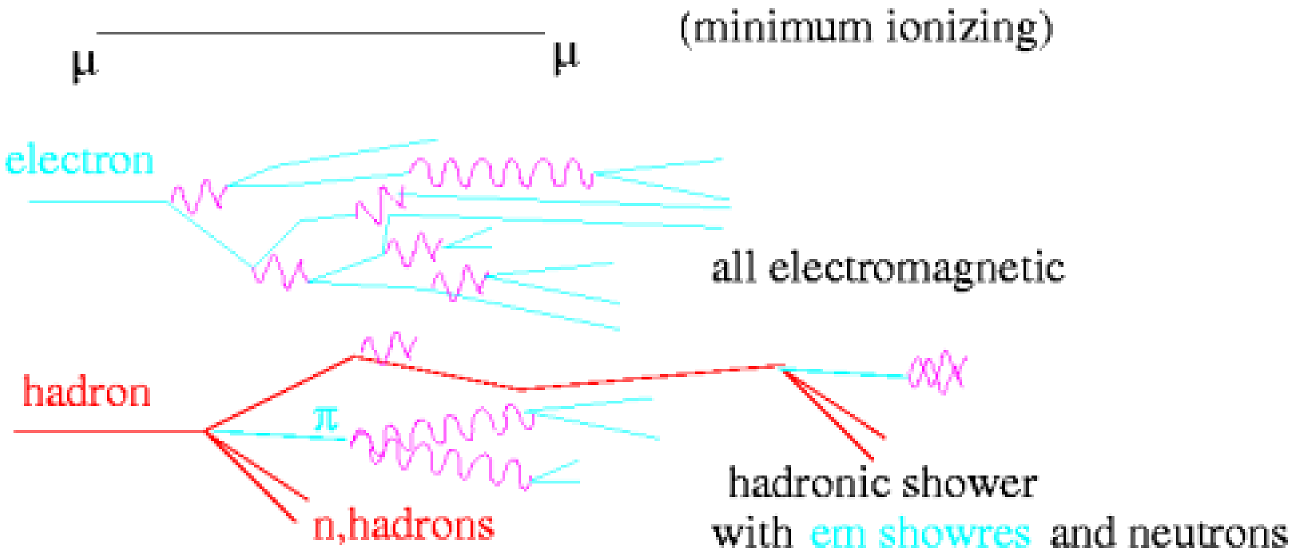
Cerenkov Detectors

- What is largest vessel that can be made? (48mx58mx250m?)

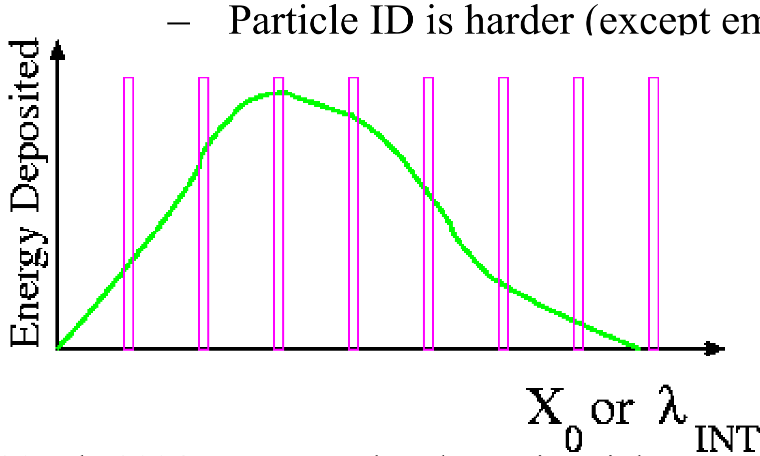


- What is highest energy regime that is possible, with better electronics,photo-detectors, etc?
- Water Cerenkov clearly the cheapest per kton

From Fully Active to Sampling



- Advantages to Sampling:
  - Cheaper readout costs
  - Fewer readout channels
  - Denser material can be used
    - More N, more interactions
    - Could combine emulsion with readout
  - Can use magnetized material!
- Disadvantages to Sampling
  - Loss of information
  - Particle ID is harder (except emulsion for taus in final state)

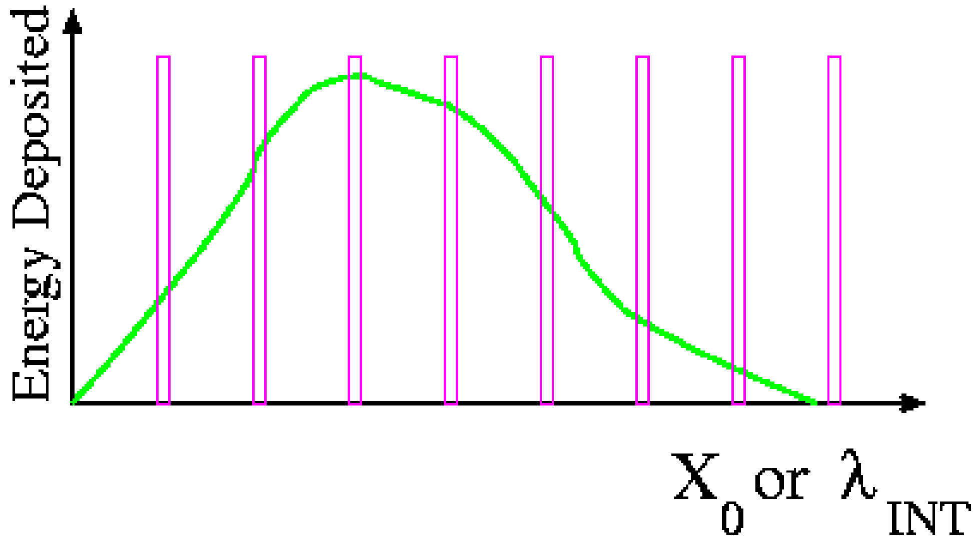


$$\frac{\delta E}{E} \propto \frac{1}{\sqrt{N}}, N = samples$$

$$\frac{\delta E(hadron)}{E(hadron)} \propto \sqrt{\frac{\lambda_{INT}}{N}}$$

$$\frac{\delta E(electron)}{E(electron)} \propto \sqrt{\frac{X_0}{N}}$$

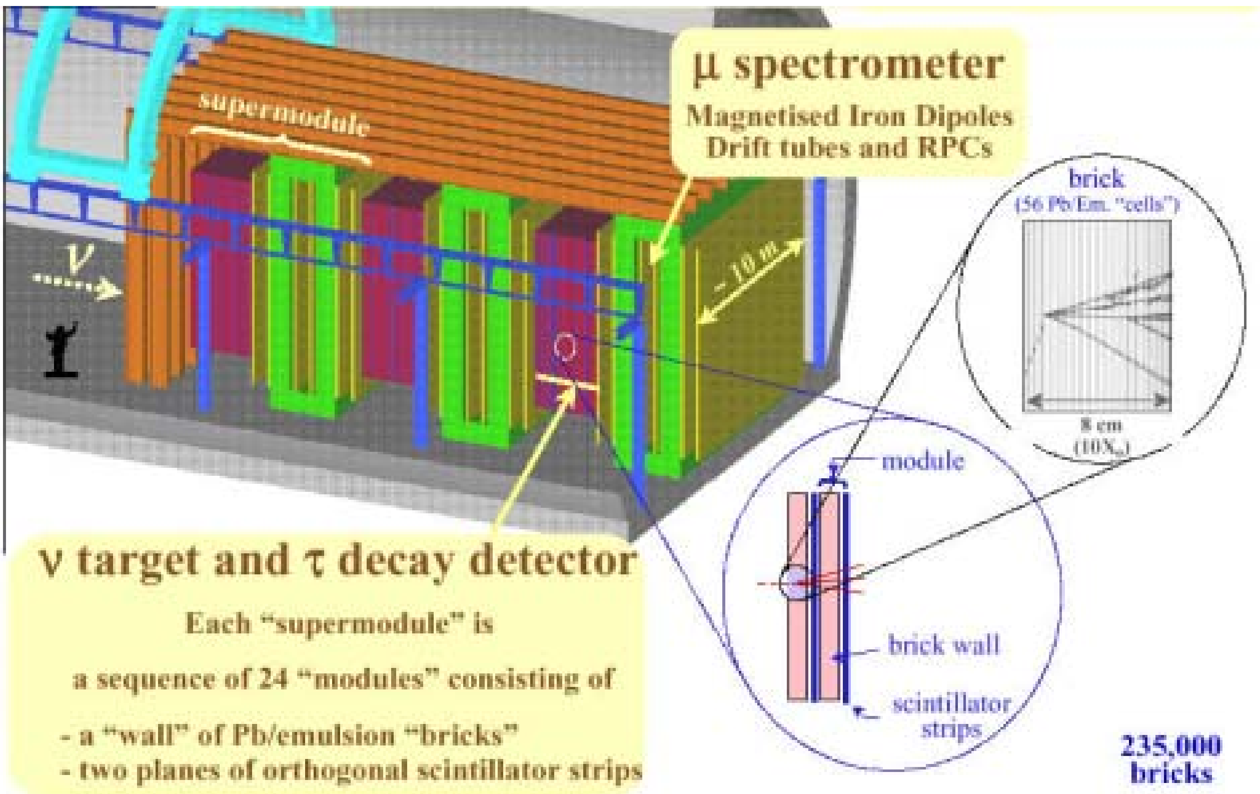
Sampling calorimeters



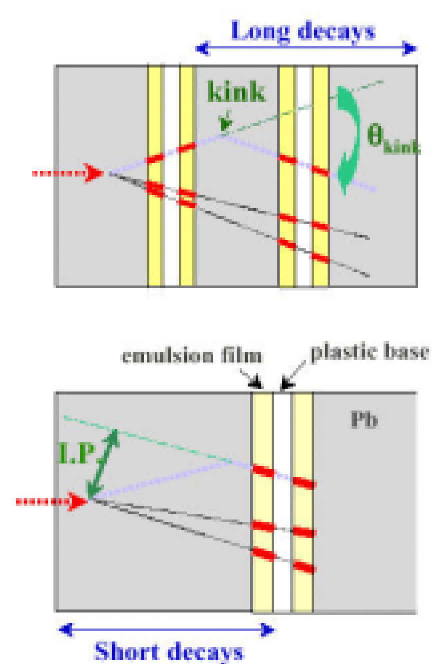
Material	X_o (cm)	l_{INT}(cm)	Sampling (X_o	X_o (g/cm²)
L.Argon	14	83.5	.2 (ICARUS)	20
Water	1	83.6	.33 (NuMI OA)	36
Steel	1.76	17	1.4 (MINOS)	14
Scintillator	42	~80	.33 (NOνA)	40
Lead	0.56	17	.2 (OPERA)	6

- High Z materials:
  - mean smaller showers,
  - more compact detector
  - Finer transverse segmentation needed
- Low Z materials:
  - more mass/X_0 (more mass per instrumented plane)
  - Coarser transverse segmentation
  - "big" events (harsh fiducial cuts for containment)

ν_τ detection (OPERA)



- Challenge: making a Fine-grained and massive detector to see kink when tau decays to something plus ν_τ

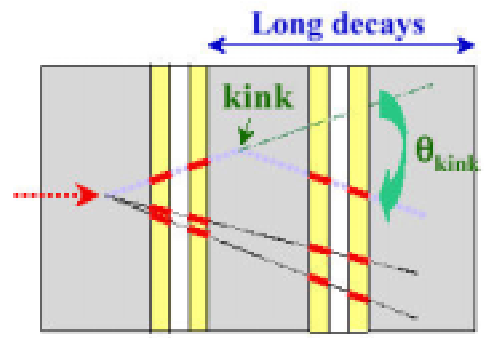


ν_τ detection (OPERA)

➢ **"Long" decays**

kink angle $\theta_{kink} > 20$ mrad

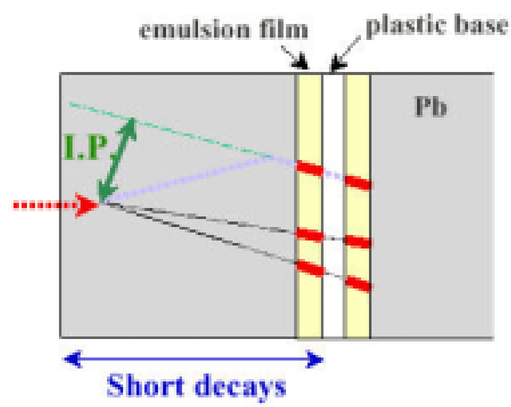
$\tau \rightarrow e$	Progr. Rep.	1999
$\tau \rightarrow \mu$	Progr. Rep.	1999
$\tau \rightarrow h\ (n\pi^0)$	Proposal	2000
$+\ \rho$ search		<u>2001</u>



➢ **"Short" decays**

impact parameter I.P. > 5 to 20 μm

$\tau \rightarrow e$	Proposal	2000
$\tau \rightarrow \mu$		<u>2001</u>



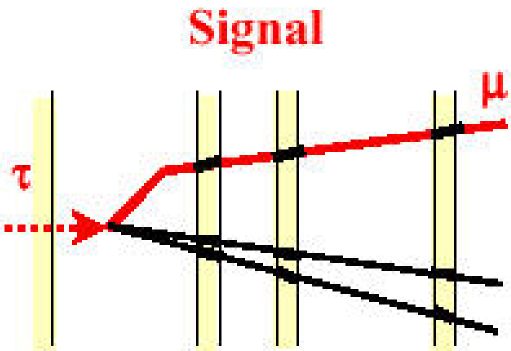
- Detection Efficiency

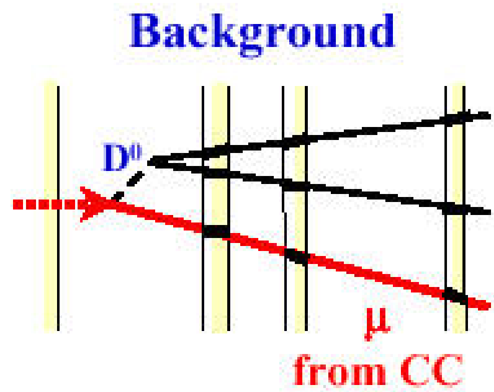
	DIS long	*QE long*	*DIS short*	*Overall**
$\tau \rightarrow e$	2.7	2.3	1.3	3.4
$\tau \rightarrow \mu$	2.4	2.5	0.7	2.8
$\tau \rightarrow h$	2.8	3.5	-	2.9
Total	8.0	8.3	1.3	9.1 (8.7)

* weighted sum of DIS and QE events

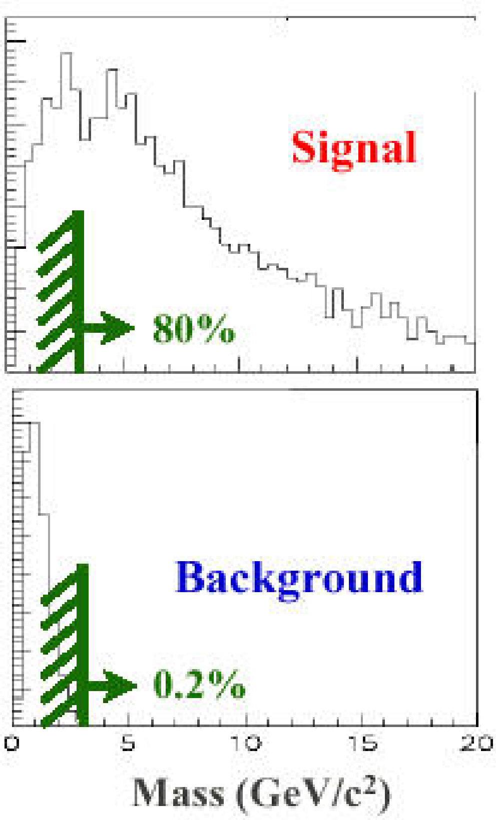
Efficiency given in the Proposal

ν_τ backgrounds





- **Main background**
  - charmed particle decay vertex mistaken as primary vertex
  - μ from ν_μ CC faking $\tau \to \mu$ because of its large IP

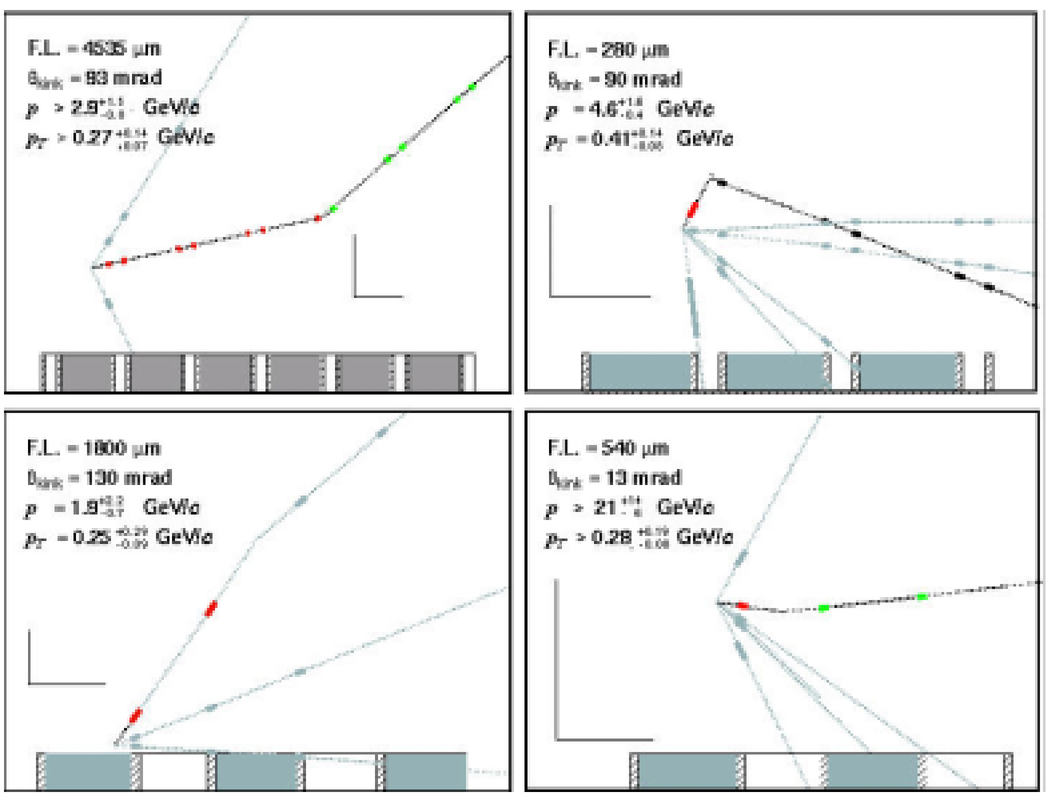


		$\tau \to e$	$\tau \to \mu$	$\tau \to h$	Total
LONG DECAYS	Charm production	0.14	0.03	0.14	0.31
	ν_e CC and π^0	0.01	-	-	0.01
	Large angle μ scattering		0.10	-	0.10
	Hadron reinteractions	-	-	0.10	0.10
	ν_μ CC		$\boxed{0.06}$		0.06
	ν_μ NC		$\boxed{0.10}$		0.10
	Total	0.15	0.29	0.24	0.67
SHORT DECAYS	Charm production	0.03	0.02	-	0.05
	Large angle μ scattering	-	0.02	-	0.02
	ν_e CC and π^0	≈ 0.01	-	-	≈ 0.01
	Total	0.03	0.04	-	0.07
Total		0.18	0.33	0.24	0.75

- Cut on invariant mass of primary tracks

ν_τ events expected (OPERA)

Decay mode	*Signal 1.2*10–3*	*Signal 2.4*10-3*	*Signal 5.4*10-3*	*Bkgnd.*
$\tau \rightarrow e$ *long*	0.8	3.1	15.4	0.15
$\tau \rightarrow \mu$ *long*	0.7	2.9	14.5	0.29
$\tau \rightarrow h$ *long*	0.9	3.4	16.8	0.24
$\tau \rightarrow e$ *short*	0.2	0.9	4.5	0.03
$\tau \rightarrow \mu$ *short*	0.1	0.5	2.3	0.04
Total	2.7	10.8	53.5	0.75



- Comparison: 4 ν_τ events over 0.34 background at DONUT .27kton

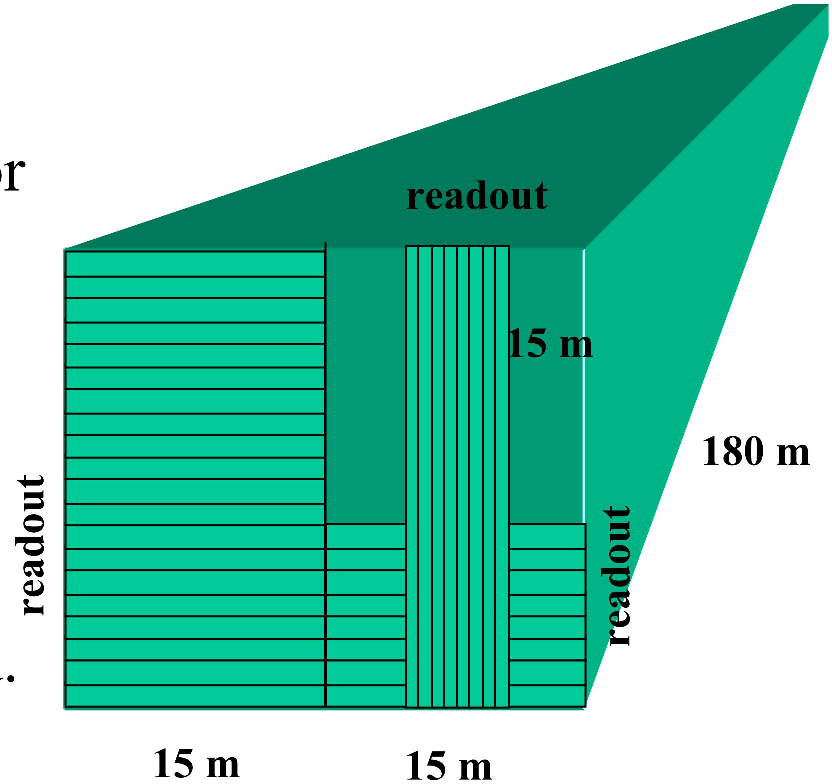
Outstanding Issues

Emulsion Sampling

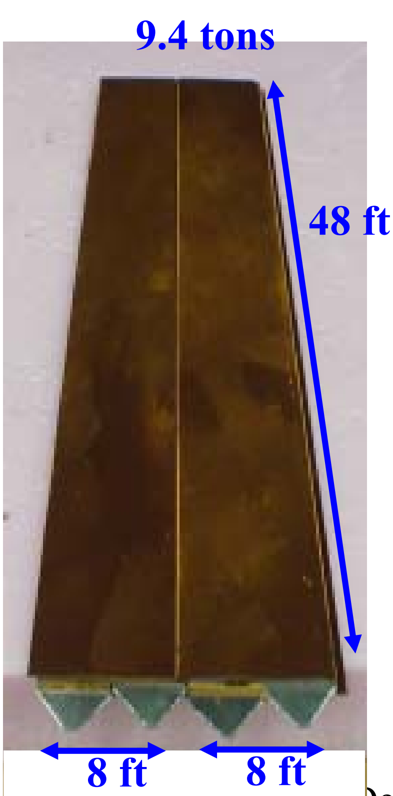
- If LSND signature is oscillations, ν_τ appearance will be much more important in the future: but need to understand if/how magnetic field can be made?
- Any way to make this detector more massive?

Scintillator + Wood

- Alternating horizontal and vertical scintillator planes
- Passive material: particle Board (density .6 - .7 g/cm^3)
- Sampling: 1/3 rad. length



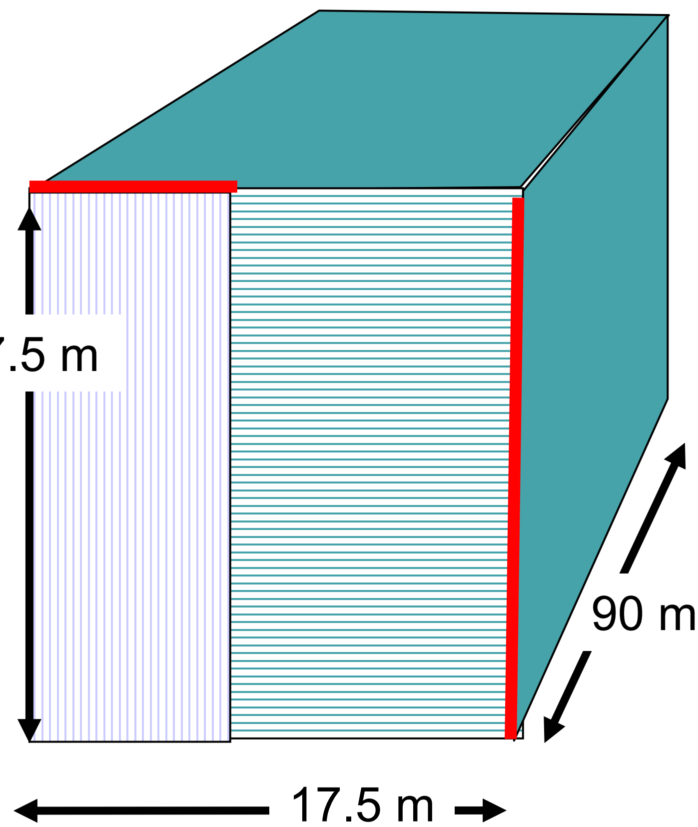
885 planes = detector



Scintillator modules

All Scintillator Detector

- Similar PVC extrusions
  - thicker cells along the beam
    - 4.5 cm vs. 2.56 cm (more light)
  - Longer extrusions
    - 17.5 m long vs. 48 ft (less light)
  - 32 cells wide vs. 30 cells
- All Liquid Scintillator
  - **85% scintillator, 15% PVC**
  - **~Same price implies a detector with ½ the mass**



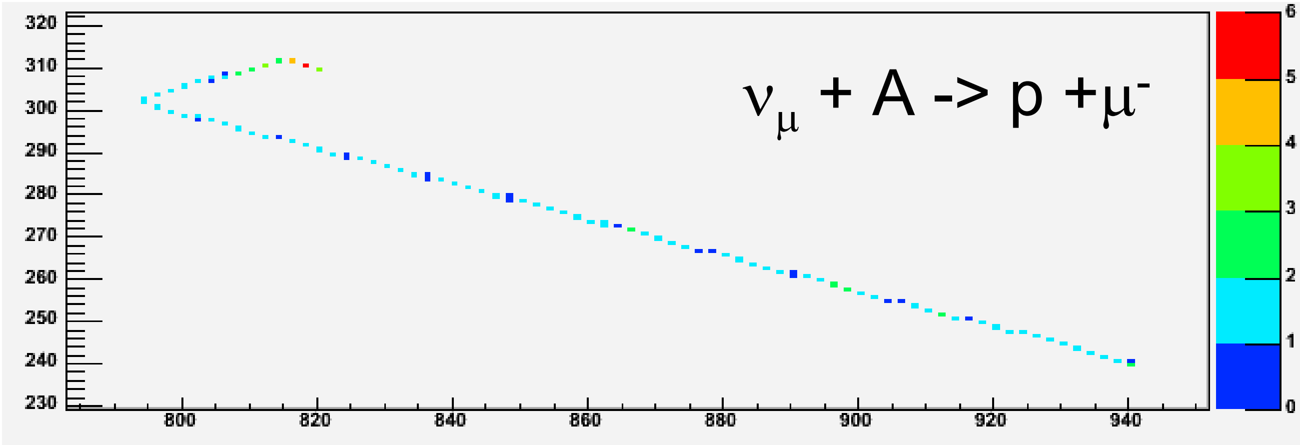
APD readout on TWO edges

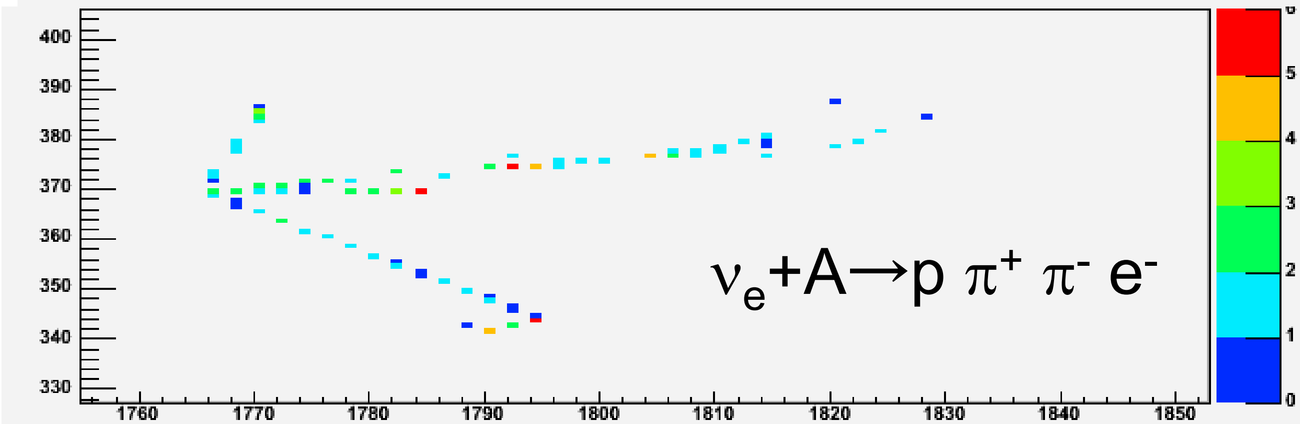
Detector is wider & taller, but shorter along the beam

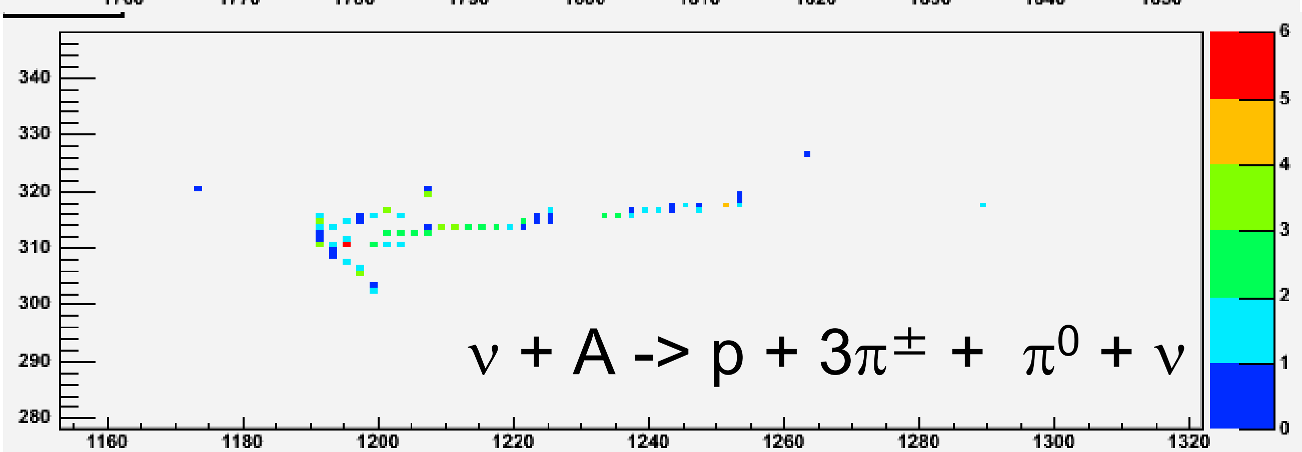
No crack down the center

Least light areas are at the left And bottom edges

Scintillator Events (2GeV)



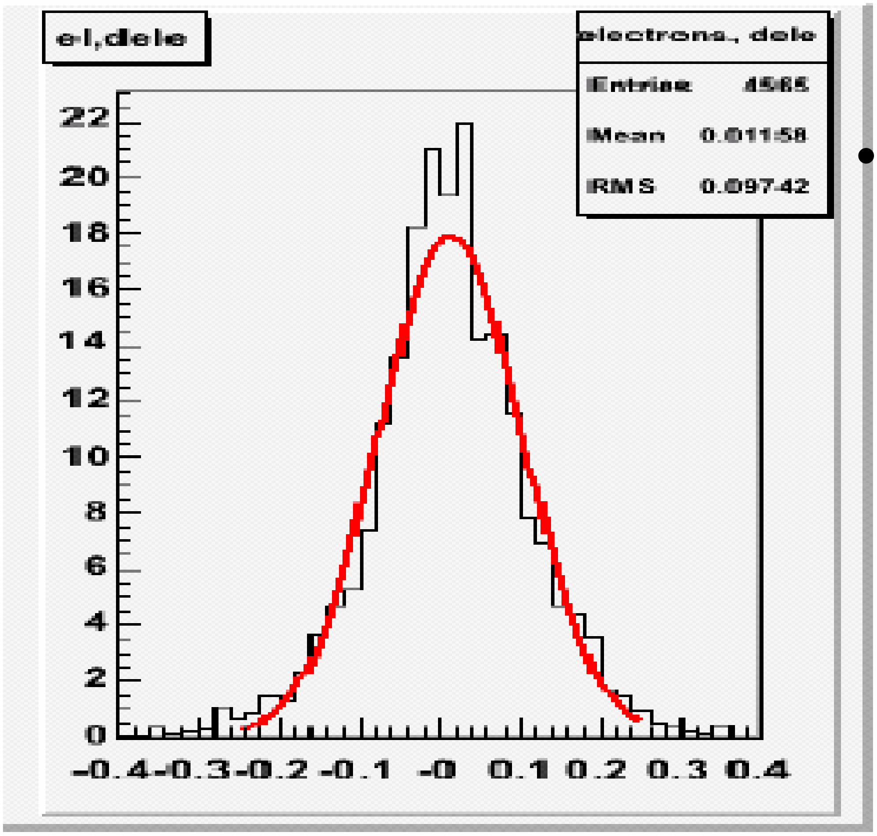




One unit is 4.9 cm (horizontal)
4.0 cm (vertical)

particularly "fuzzy" e's
long track, not fuzzy (μ)
gaps in tracks (π^0 ?)
large energy deposition
(proton?)

Energy Resolution

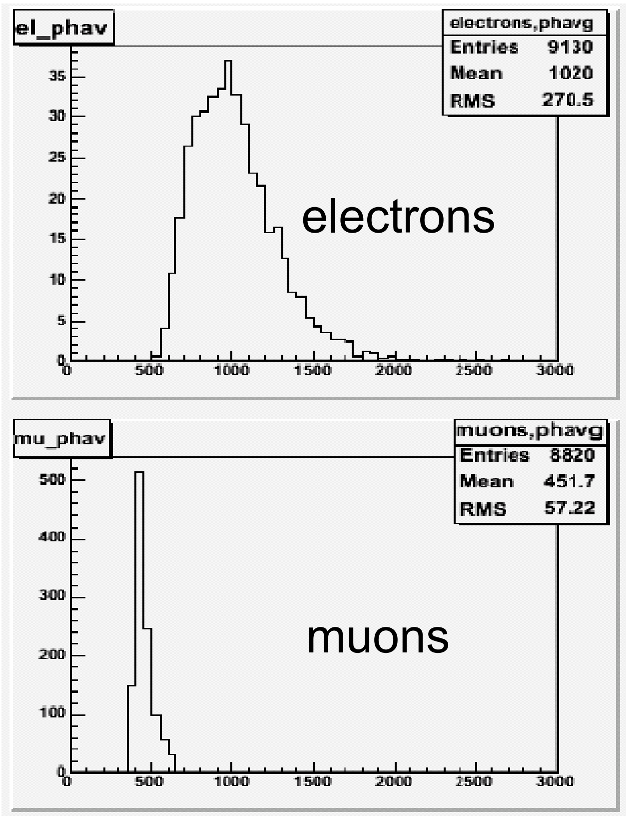


Measured – true energy divided by square root of true energy

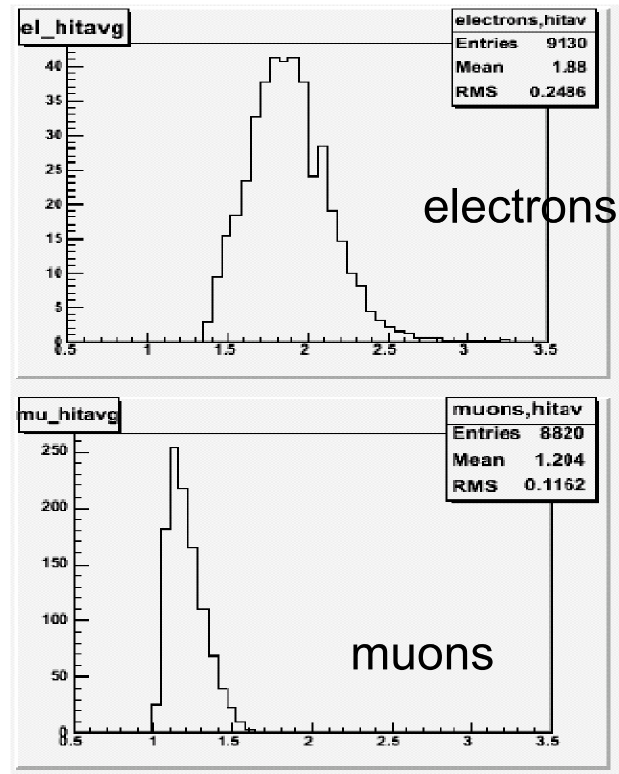
- For ν_e CC events with a found electron track (about 85%), **the energy resolution is 10% / sqrt(E)**

- This helps reduce the NC and ν_μ CC backgrounds since they do not have the same narrow energy distribution of the oscillated ν_e's (for the case of an Off Axis beam)

All Scintillator
μ / e separation



Average **pulse height** per plane



Average **number of hits** per plane

- This is what it means to have a “fuzzy” track
  - Extra hits, extra pulse height
- Clearly ν_μ CC are separable from ν_e CC

Outstanding Issues

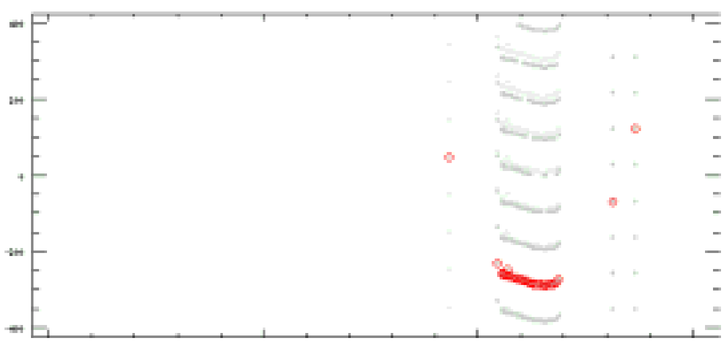
Fine Grained Scintillator/Something Sampling

- How cheaply can this be made?
- Do you need any passive absorber?
- What is best choice for readout?
- Must have confidence in ability to reduce Neutral Current Backgrounds

Steel/Scintillator Detector (MINOS)

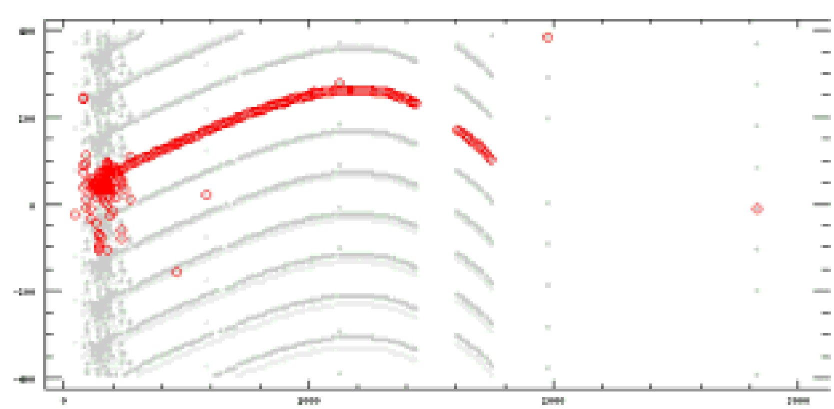
- 8m octagon steel & scintillator calorimeter
  - Sampling every 2.54 cm
  - 4cm wide strips of scintillator
  - 5.4 kton total mass
- 486 planes of scintillator
  - 95,000 strips

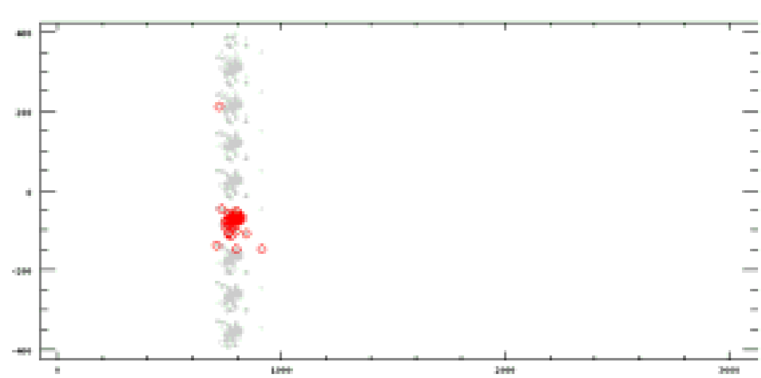
(simulated) Events at MINOS



2.4GeV ν_μCC

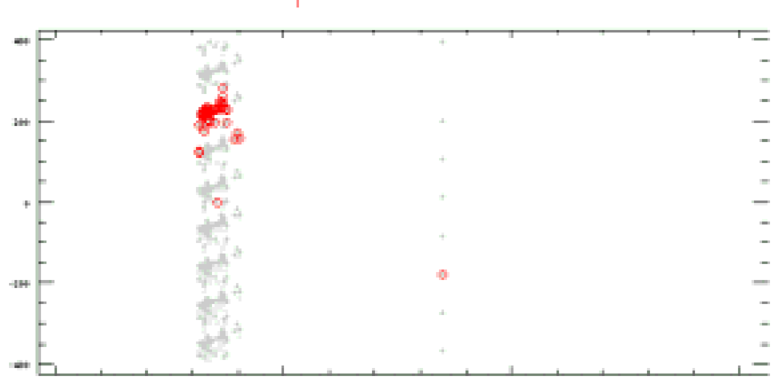
25GeV ν_μCC





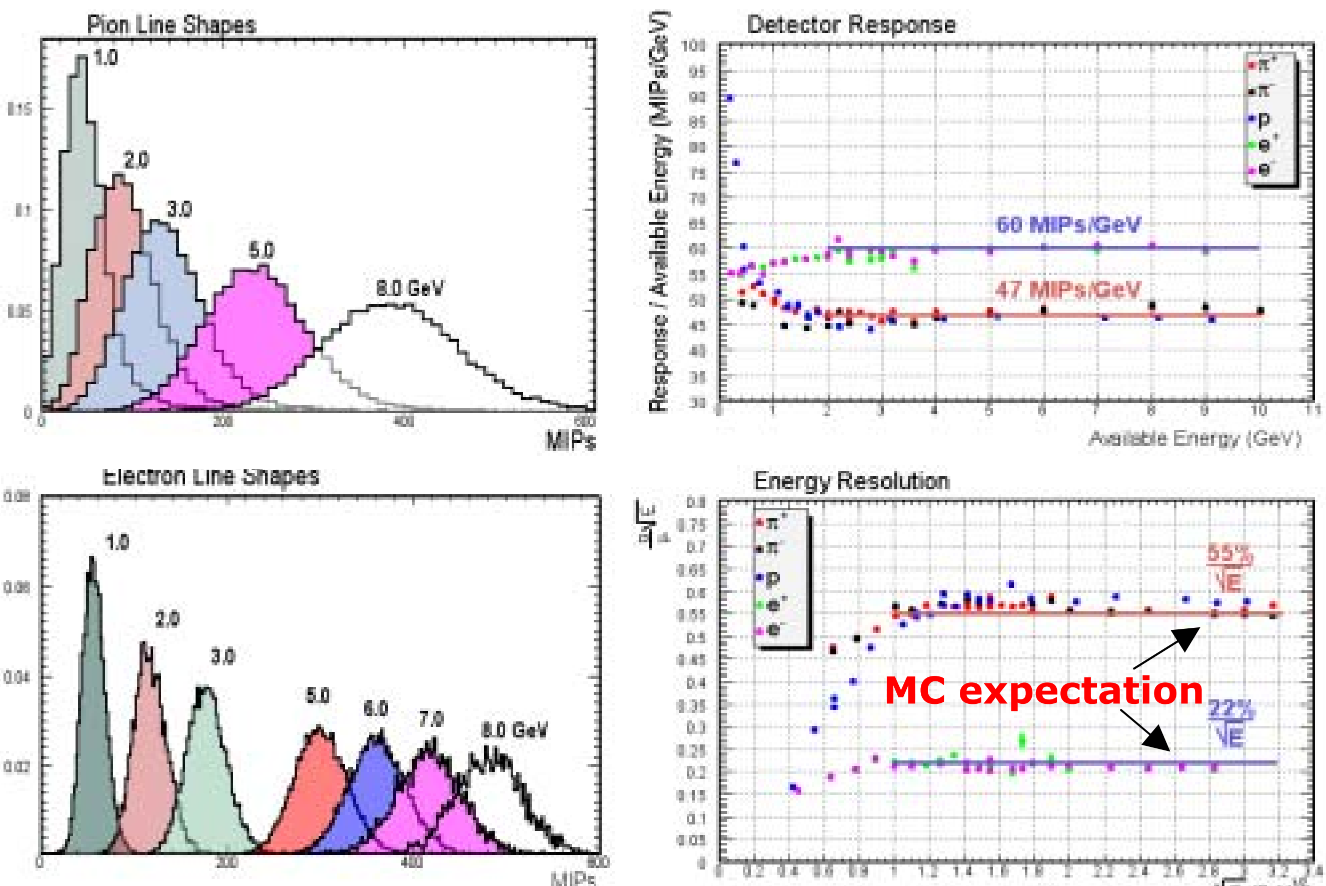
8.5GeV ν_eCC

10GeV νNC



Steel Scintillator Response

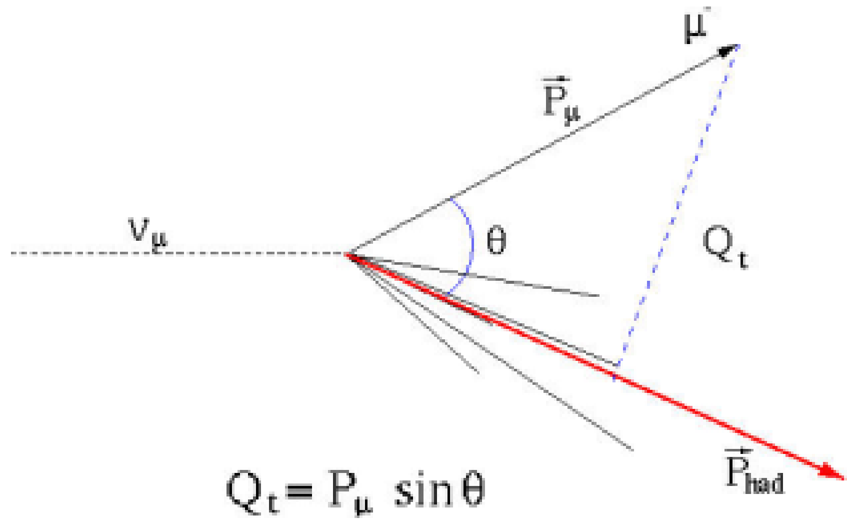
Response measured in CERN test beam using a MINI-MINOS (1mx1m)

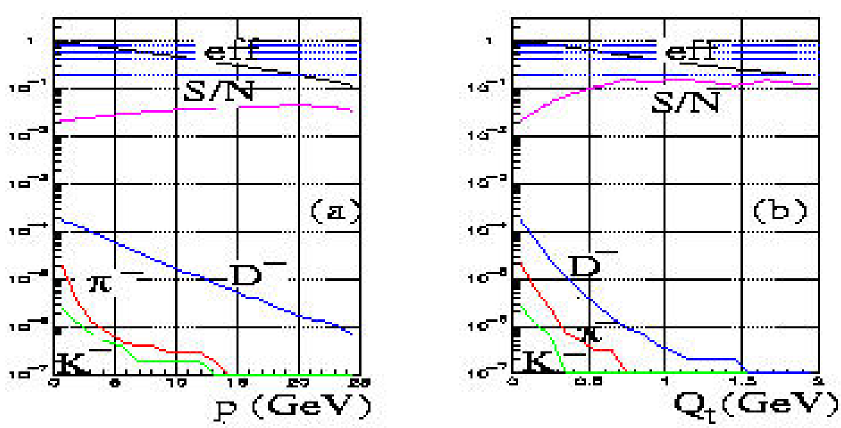


★Provides calibration information
★Test of MC simulation of low energy hadronic interactions

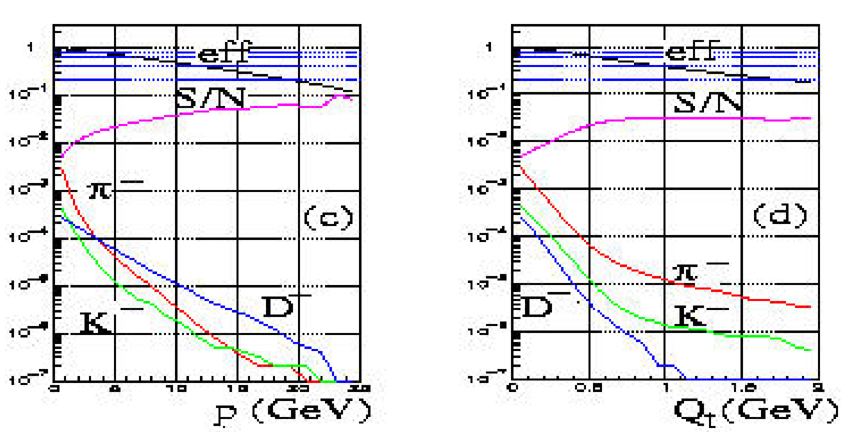
★Question: why might EM response be higher than hadronic response?

Backgrounds in ν Factories

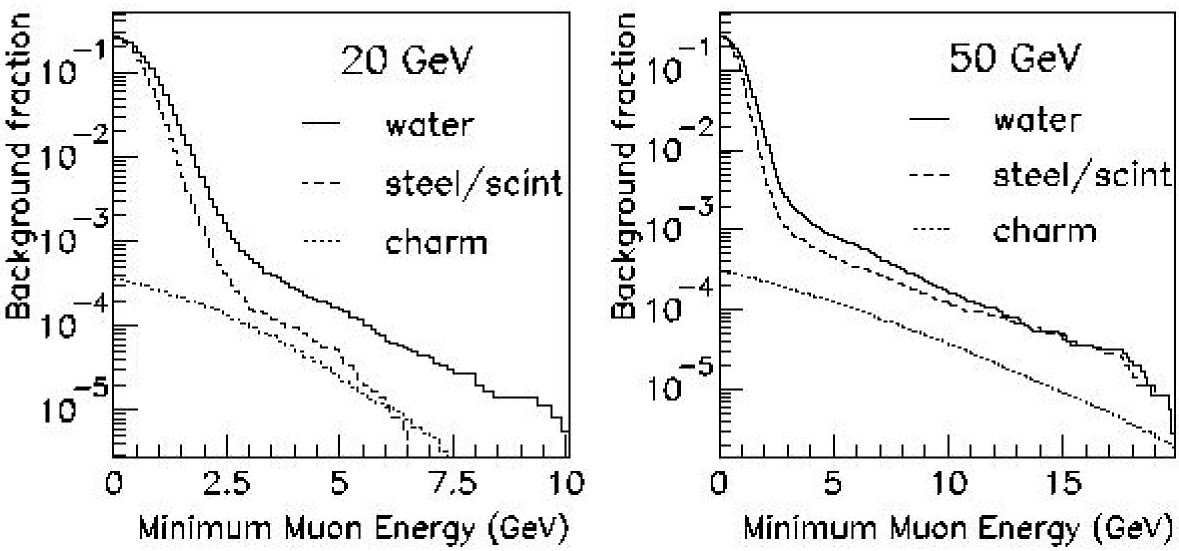




$\bar{\nu}_\mu$ Neutral Currents



Detector-Dependence



- The denser the detector, the more likely the meson in the hadronic shower will interact before decaying…

Outstanding Issues

Steel/Scintillator

- For Neutrino factory Application: what transverse and longitudinal segmentation is needed?
- Any way to make this detector cheaper?

Conclusions

Detector Scorecard

Detector Technology	Largest Mass to Date (kton)	Event by Event Identification			+/-?	Ideal Neutrino Energy Range
		ν_e	ν_μ	ν_τ		
LAR TPC	0.6	✓	✓		Not yet	huge
Water Cerenkov	50	✓	✓			<2GeV
Emulsion/Pb/Fe	0.27	✓	✓	✓		>.5GeV
Scintillator++	1 or less	✓	✓			huge
Steel/Scint.	5.4		✓		✓	>.5GeV

There are huge detector demands on the next generation of detectors

1. Size*signal efficiency
2. Background rejection (NC)
3. "Ability to do other physics"

Water Cerenkov the most popular choice for next generation experiments, but we must keep working on ways to do better at high neutrino energies!