Detector Technologies

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Goal of this talk

- I hope to give you enough information so you can understand what goes into designing detectors
- Maybe you’ll understand your own detector better, or at least your friends’ detectors
- Maybe you’ll have an easier time designing/building/using the next generation of detectors
- Okay, this is a tall order…

Outline

- Introduction
  - What are neutrino detector goals?
  - Neutrino Interactions: what particles are we trying to detect?
- Speedy review of particle interactions in matter
    - Energy loss by ionization
    - Electromagnetic Showers
    - Hadronic Showers
- Detectors

Oscillation Detector Goals

- Identify flavor of neutrino

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

  - Need charged current events!
  - Accelerator sources: Lepton Identification (e,μ,τ)
- Measure neutrino energy
  - Charged Current Quasi-elastic Events
    - In principle, all you need is the lepton angle and energy

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

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

  - Everything Else
    - Need to measure energy of lepton and of X, where X is the hadronic shower, the extra pion(s) that is (are) made..

$$\nu N \longrightarrow l X$$

Neutrino Oscillation Goals vs ν Sources

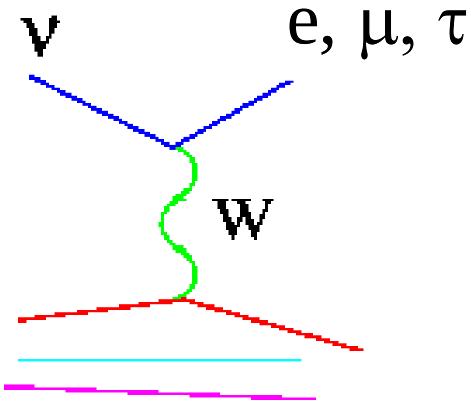
- Conventional Beams (ν_μ, %ν_e)
  - Identify muon in final state
  - Identify electron in final state, subtract backgrounds
- β beams (all $\bar{\nu}_e$ or all ν_e)
  - Idetnify muon or electron in final state
- Neutrino Factories ($\overline{\nu_\mu,}$ ν_e)
  - Identify lepton in final state
  - Measure Charge of that lepton!
    - Charge of outgoing lepton determines flavor of initial lepton
- Reactors (all $\bar{\nu}_e$)
  - Neutrino energy too low to make μ or τ
  - Need to identify $\bar{\nu}_e$ only, can only get e energy

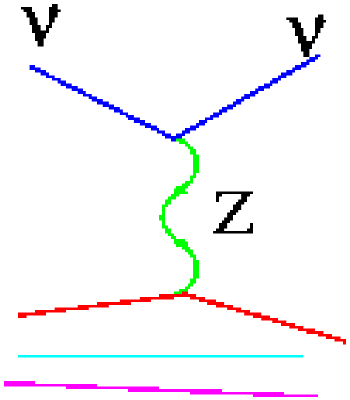
Neutrino Interaction Measurement Goals

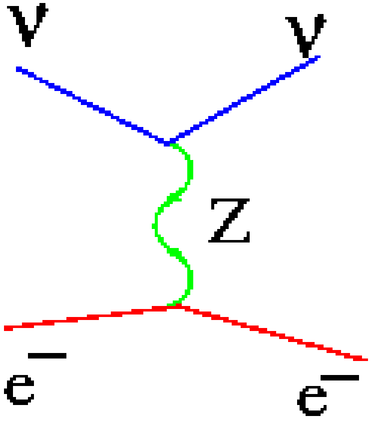
- Want to see lots of different interaction channels
- Want to measure total energy of event as well as possible
  - Means seeing all final state particles
- Need to know in one way or another whether it's a neutrino or an anti-neutrino
- Also need to see what the initial nucleus is, if you are looking for nuclear effects

What gets produced when a neutrino interacts?

- Charged Current Interactions
  - Final state lepton
  - Outgoing hadrons: neutrons, protons, charged and neutral pions
  - The more energy the incoming neutrino has, the more particles that can get produced in the final state
- Neutral Current Interactions
  - If scattering off a nucleon: can see only final state hadrons
  - If scattering off an electron: signal is a single final state electron

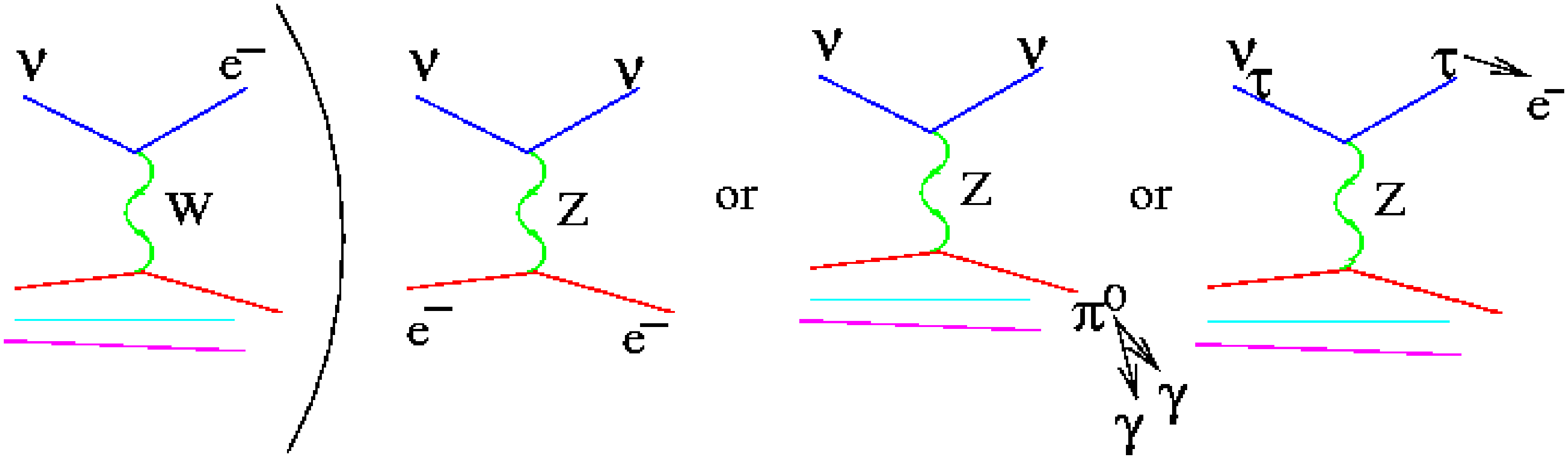






Detectors and Backgrounds…

- Depending on your detector, you may see lots of things that look like signal but aren't…



Why does detector performance matter?

Assume you have a convenional neutrino beamline which produces:

•1000 ν_μ CC events per kton (400NC 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 + 400*.0025NC)x5=17.5

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 + 400*.005NC)x15=52.5

Signal: (1000*.01*.3)x15=45, S/sqrt(B+S)=4.6

Now for a ν Factory…

Assume you have a neutrino factory which produces:

- 500 ν_μ CC events per kton (200NC)
- 1000 ν_e CC events per kton (400NC)

Again, assuming 1% oscillation probability, but now the backgrounds are 10^{-4} (for all kinds of interactions), the signal efficiency is 50%, and again you have 15kton of detector (because it's an easy detector to make)…

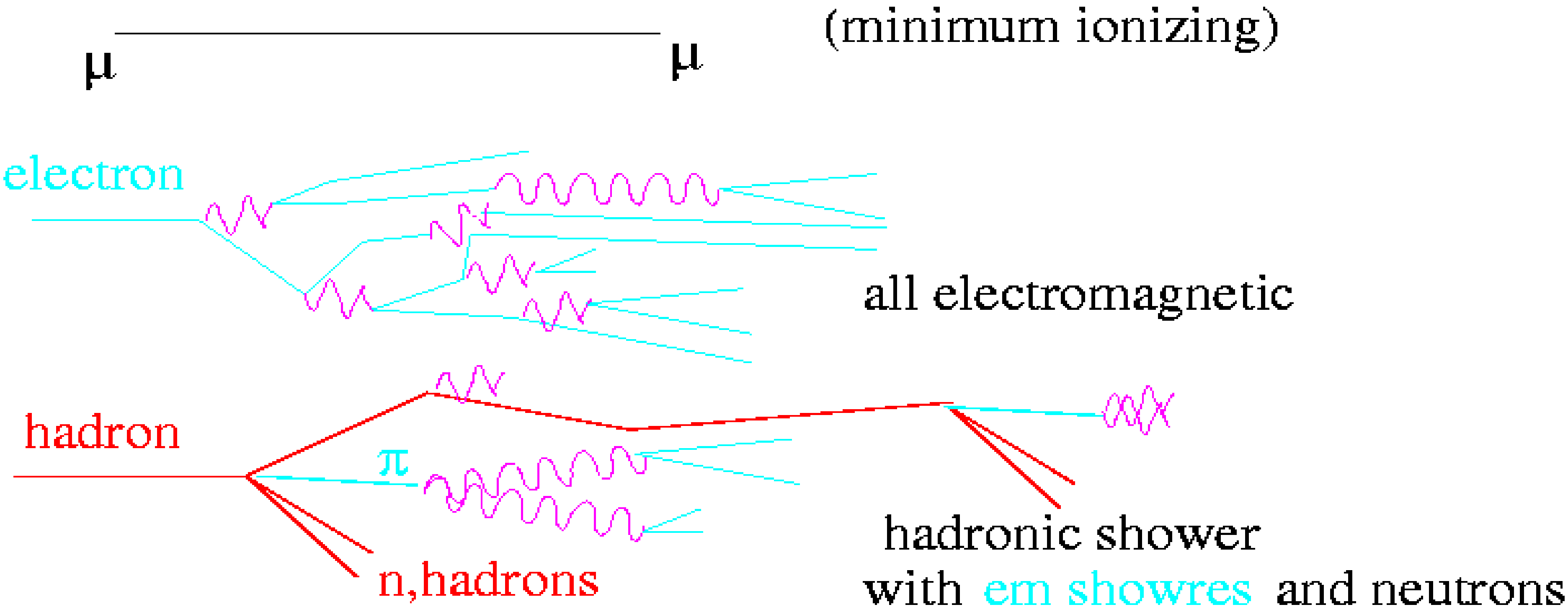
Background: (.0001*2100(CC+NC))x15=3

Signal: (1000*.01*.5)x15=150, S/sqrt(B+S)=12

Get a "figure of merit" of 12 instead of 3 or 4…
which is like getting a 12σ result instead of a 4σ result,
or being sensitive at 3σ
to a 10 times smaller probability!

Note: as muon energy increases, you get more ν/kton for a ν factory!

Three kinds of particle signatures



μ μ (minimum ionizing)

electron

all electromagnetic

hadron

π

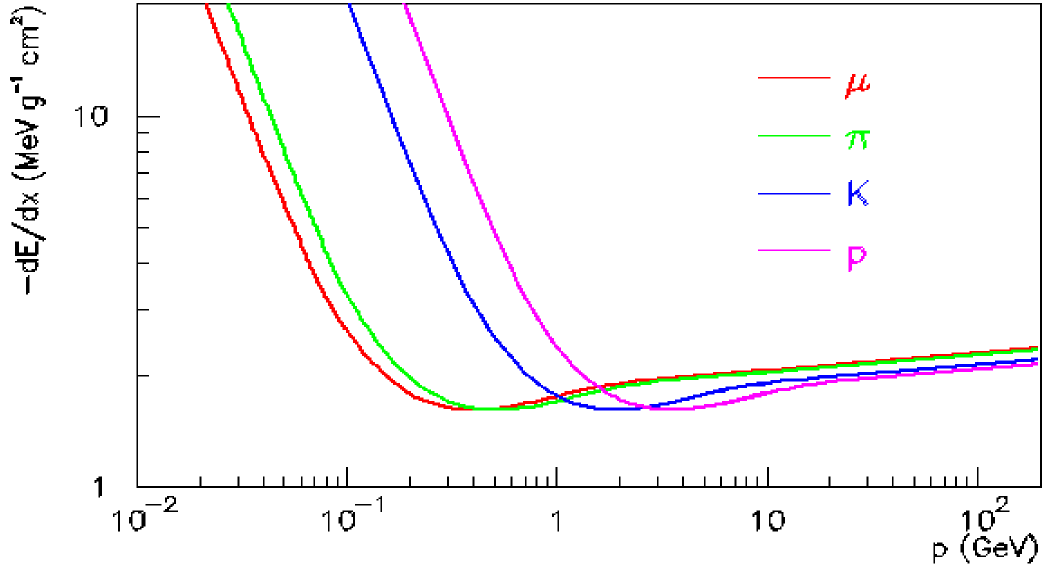
n,hadrons

hadronic shower
with em showres and neutrons

- Three fundamentally different signatures
- Question to you: how do you expect energy resolution to change with energy for these three?

Ionization Loss

- Primary mechanism for muon in energies of modern neutrino experiments
- If a particle is too low to start producing showers, it will loose energy through ionization
  - For Hadron: range<λ_{INT}
  - For Electron: range<X_0
- Bethe-Bloch Equation
- Typical value: 2MeV*cm^2/g
- x in units of g/cm^2
- Energy Loss Only f(β)



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

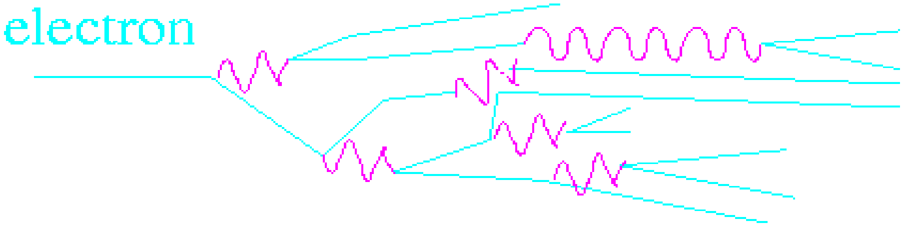
- Can be used for Particle ID in range of momentum

dE/dx in common detector materials

- These values determine how long an event will be in one's detector
- Determines how big one's near detector might need to be
- Example: T2K: to contain a 700MeV muon, need 350cm of water or scintillator, 65cm of steel

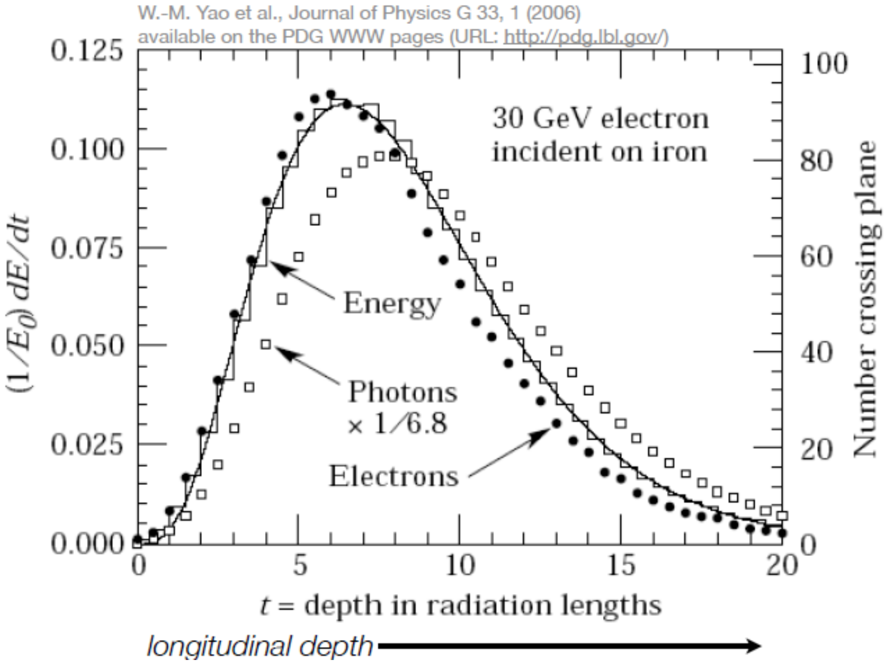
Material	Minimum Ionizing dE/dx (MeV/cm)
Liquid Argon	2.1
Water	2.0
Steel	11.4
Scintillator (CH)	1.9
Lead	12.7

Electromagnetic Showers



- For electrons above the critical energy, they will create photons through Bremsstrahlung which then go on to produce e^+e^- pairs
- As those produced e^+ and e^-'s travel, they also will create photons
- Eventually the energy of particles in the shower goes below the critical energy, then particles lose energy by bremsstrahlung

$$E_C = \frac{800 \text{ MeV}}{Z + 1.2}$$

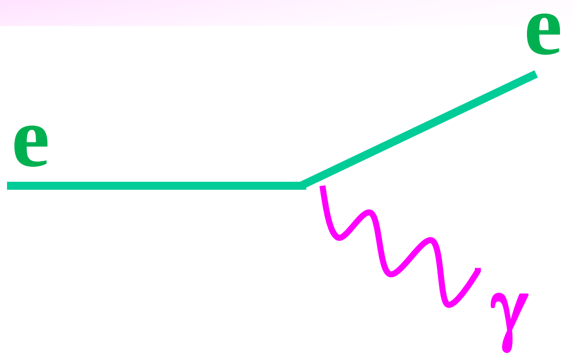

W.-M. Yao et al., Journal of Physics G 33, 1 (2006) available on the PDG WWW pages (URL: http://pdg.lbl.gov/)

Shower Maximum:

$$t_{max} = \ln \frac{E_0}{E_C} + C_i$$

C_e = -0.5, C_γ =0.5

Radiation Length



- Radiation length (X_0) defined as: distance over which electrons lose 1/e of their energy by radiation
- This also means that roughly, every X_0 a electron will emit a photon through brem
- Distance over which photons will pair produce is related: $\lambda=9/7\ X_0$

$$X_0 = \frac{716.4A}{Z(Z+1)\ln(287/\sqrt{Z})}\left[\frac{\mathrm{g}}{\mathrm{cm}^2}\right]$$

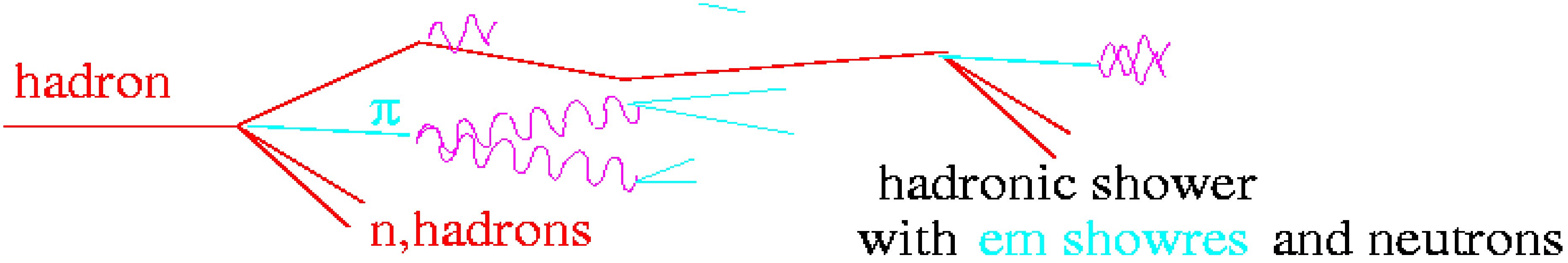
- Transverse EM shower development: determined by Moliere radius

$$R_M = X_0\frac{21.2\ \mathrm{MeV}}{E_C}$$

Material	X_o (cm)
Liquid Argon	14
Water	37
Steel	1.76
Scintillator (CH)	42
Lead	0.56

Hadronic Showers

- Similar to electromagnetic showers, but different underlying interaction means vital statistics are different

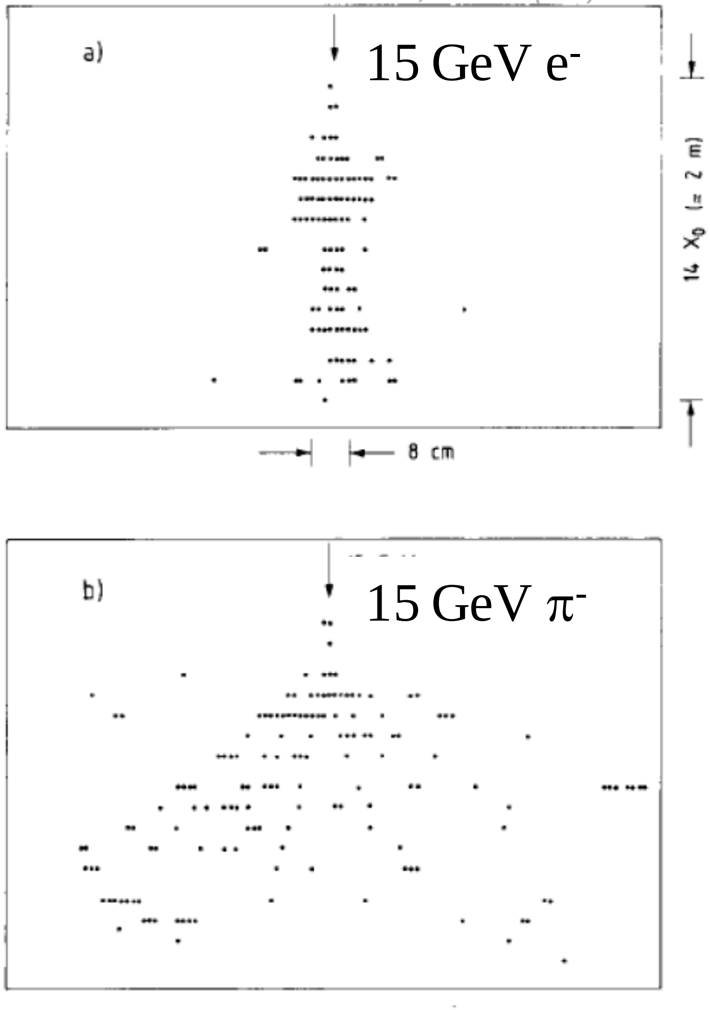


- Instead of a radiation length, now there is an interaction length, λ_I , defined by the average distance a hadron travels before it undergoes a strong (nuclear) interaction
- The catch: sometimes π^0's are produced which decay to photons which then proceed electromagnetically
- Another catch: sometimes neutrons are made in the shower, which then may show no visible energy in detector

Hadronic vs Electromagnetic Showers

- Radiation length always shorter than interaction length
  - EM showers are shorter
  - EM showers more narrow
- Dependence on materials:
  - Nuclear interaction probability f(A)
  - Radiation length is f(~A/Z^2)

Material	X_o (cm)	λ_{INT}(cm)
Liquid Argon	14	83.5
Water	37	83.6
Steel	1.76	17
Scintillator (CH)	42	~80
Lead	0.56	17



CHARM-II collaboration, NIM A277 (1989) 83-91.

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)	Density (g/cm^3)
Liquid Argon	14	83.5	2.1	1.4
Water	37	83.6	2.0	1
Steel	1.76	17	11.4	7.87
Scintillator (CH)	42	~80	1.9	1
Lead	0.56	17	12.7	11.4

Very Incomplete Survey of Neutrino Detectors

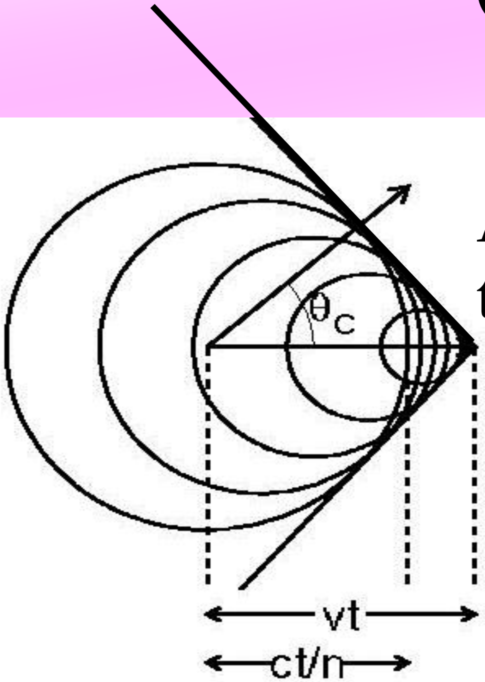
- Fully Active
  - Cerenkov
  - Scintillator
  - Liquid Argon Time Projection Chamber
- Sampling
  - Overview: Absorber and Readout
  - Steel/Lead Emulsion
  - Scintillator/Absorber
  - Steel-Scintillator

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!

Cerenkov Light



As particles move faster than the speed of light in that medium, they emit a “shock wave” of light

$$\beta \equiv \frac{v}{c} \qquad \beta > \frac{1}{n}$$

$$\theta_c = \cos^{-1}(1/n(\lambda))$$

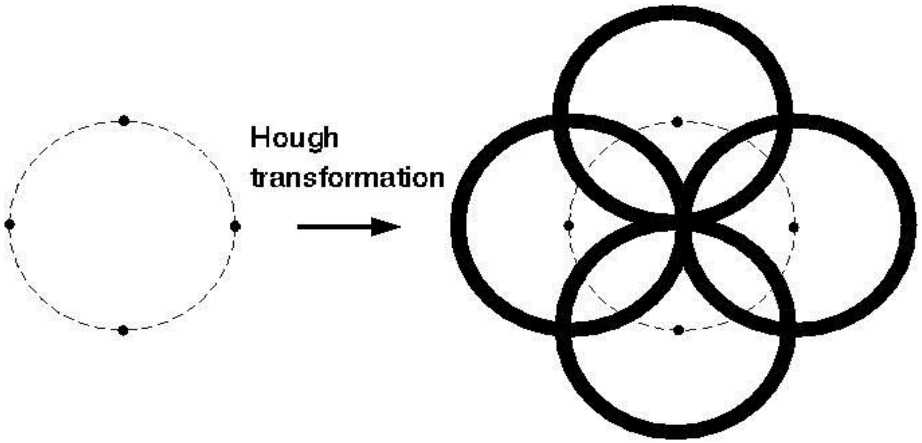
$$p_{threshold} = \frac{m}{\sqrt{n^2 - 1}}$$

particle	p (threshold)
e	660keV
μ	137MeV
$\pi^{\pm}$	175MeV
K	650MeV
p	1300MeV

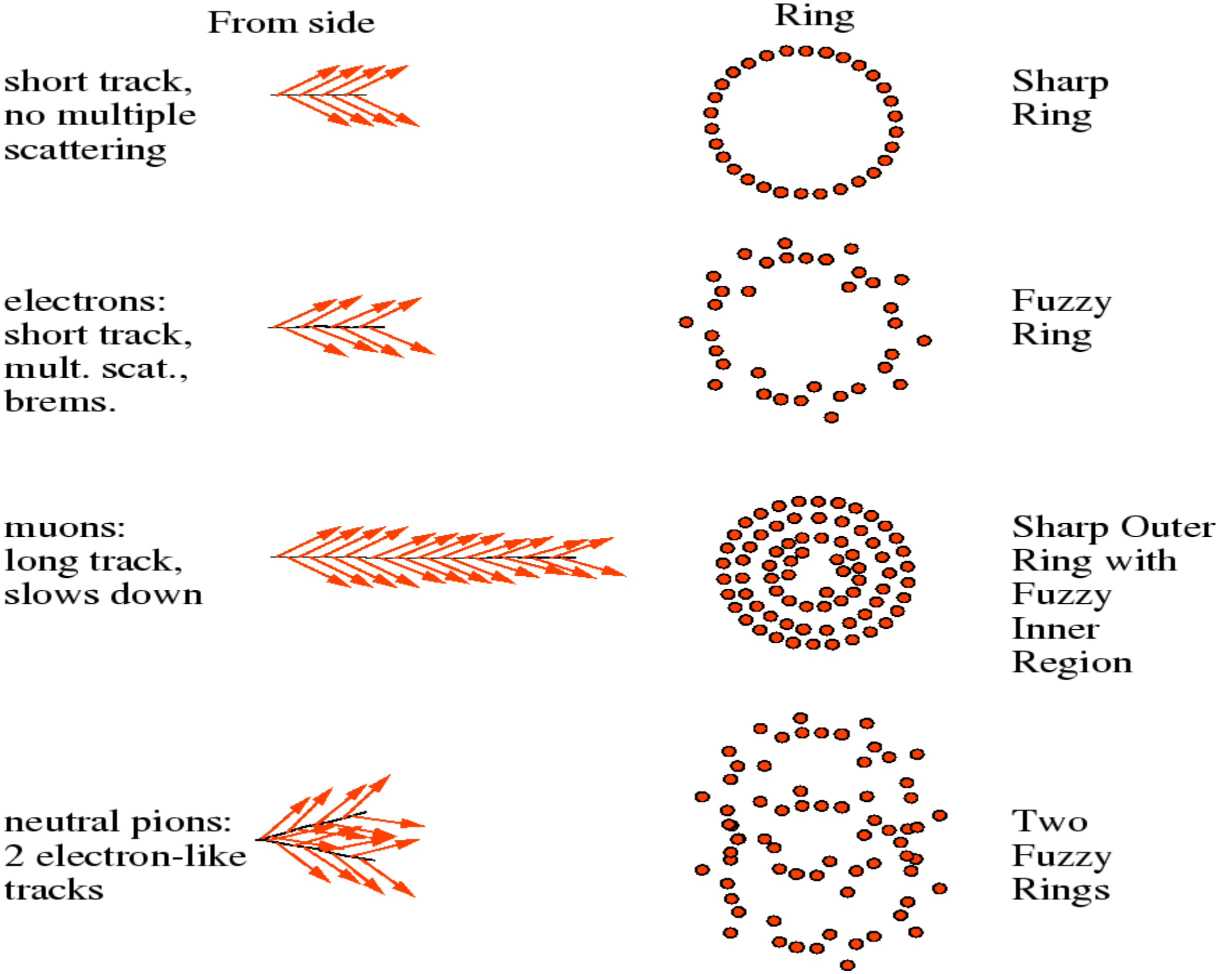
- For water, n(280-580nm)~1.33-6, so $p_{threshold} \approx 1.3 * mass$
- Threshold Angle: 42°
- **What is Threshold momentum for neutral pions?**

Event Reconstruction in Cerenkov Detector

- Vertex Point fit: time of flight should be as sharp as possible
- Define set of in-time tubes
- Use Hough Transform to find rings
- Look for rings until you're done
- Particle ID
- Corrections to Vertex
- Energy Reconstruction
- Decay Electron Finding



Particle ID Using Cerenkov Light



From side

Ring

short track,
no multiple
scattering

Sharp
Ring

electrons:
short track,
mult. scat.,
brems.

Fuzzy
Ring

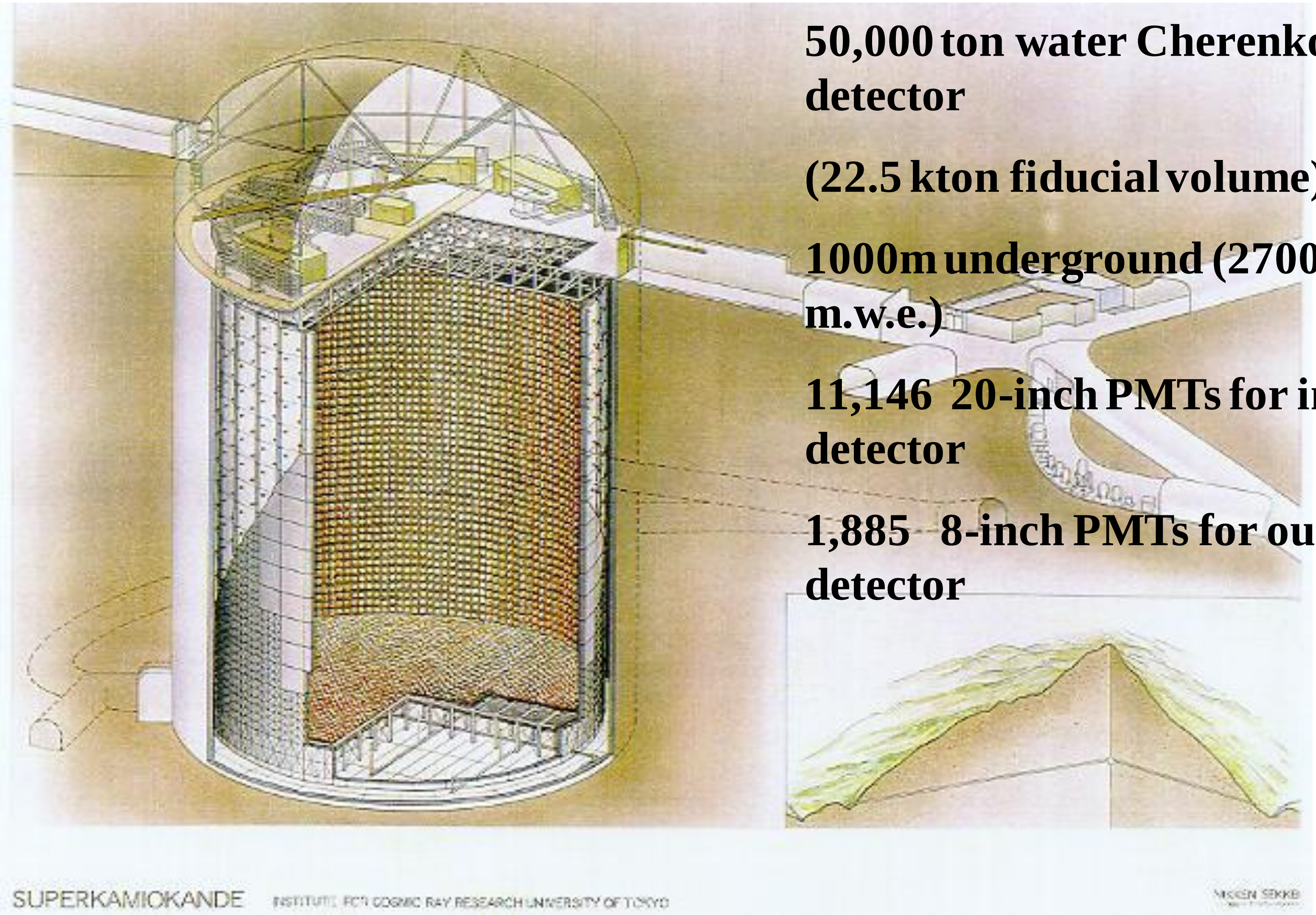
muons:
long track,
slows down

Sharp Outer
Ring with
Fuzzy
Inner
Region

neutral pions:
2 electron-like
tracks

Two
Fuzzy
Rings

Super-Kamiokande detector



50,000 ton water Cherenkov detector

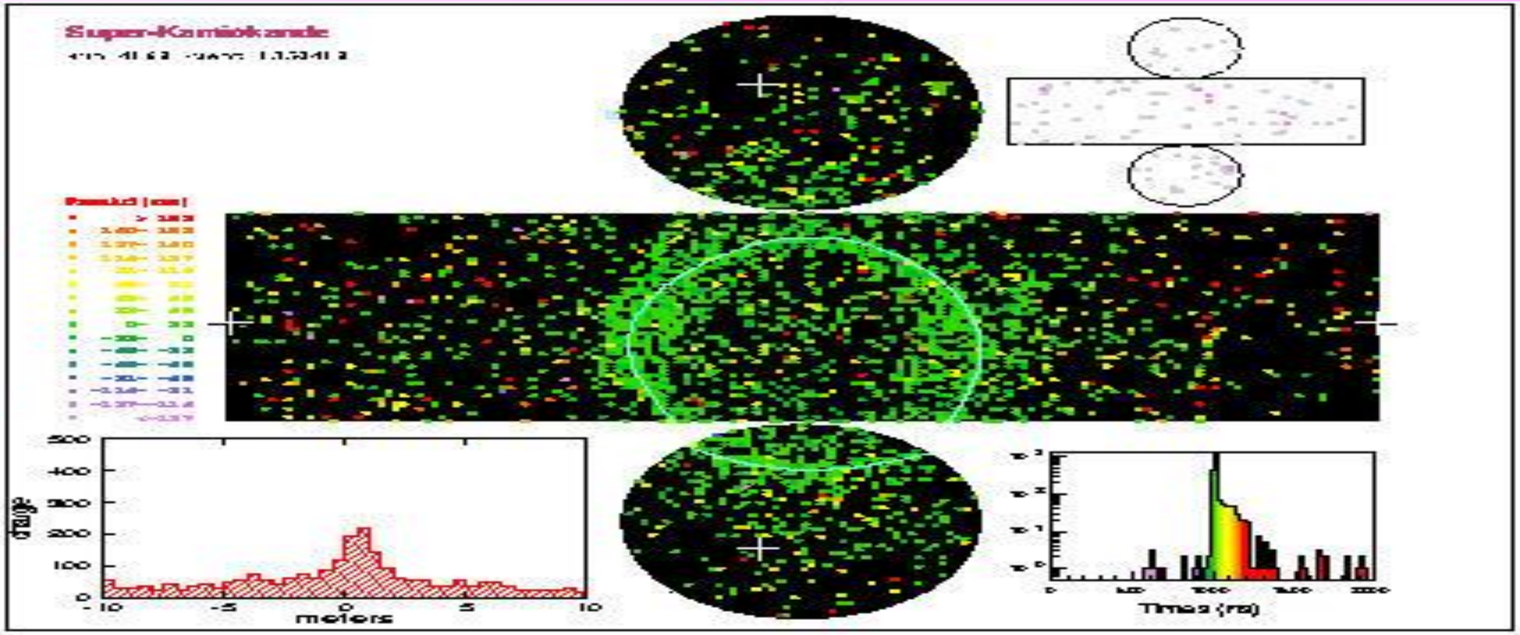
(22.5 kton fiducial volume)

1000m underground (2700 m.w.e.)

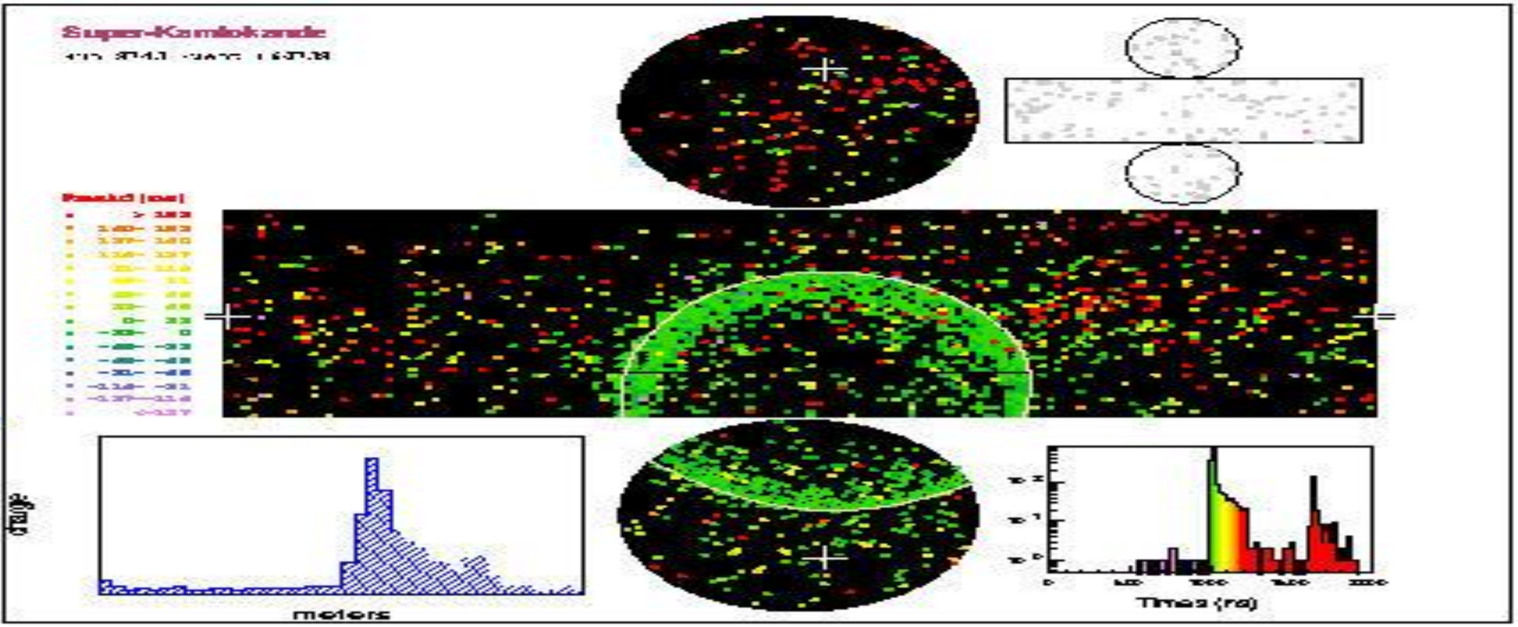
11,146 20-inch PMTs for inner detector

1,885 8-inch PMTs for outer detector

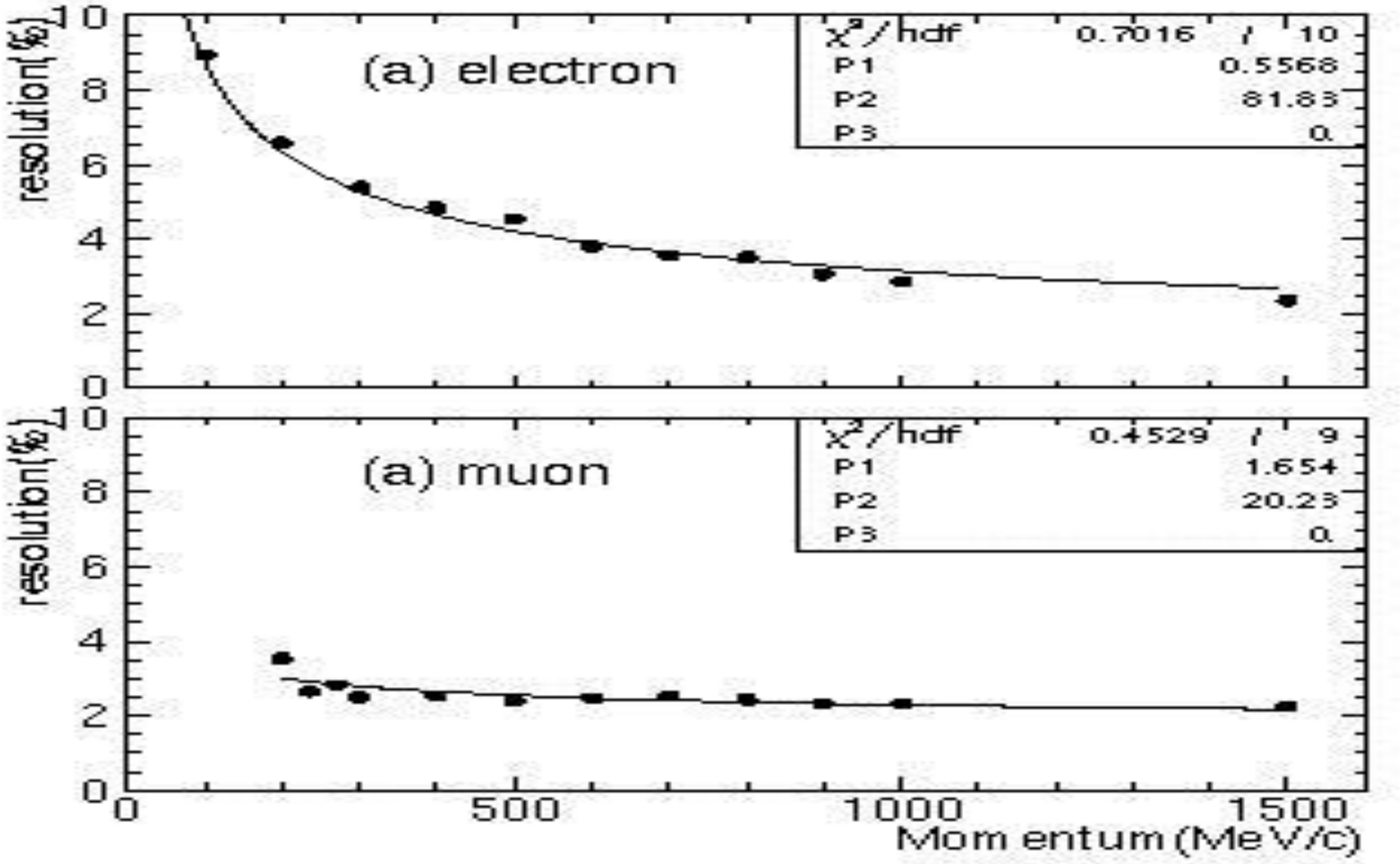
e-like


Super-Kamiokande
charge
500
400
300
200
100
0
-10
-5
0
5
10
meters
Times (ns)

μ-like


Super-Kamiokande
charge
meters
Times (ns)

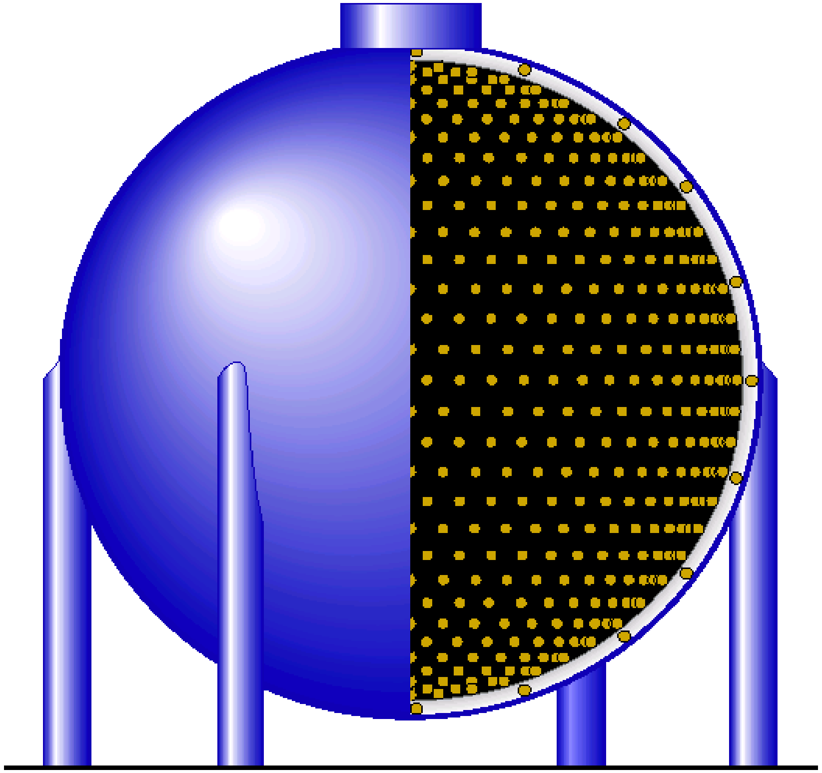
Single-Ring Energy Resolution

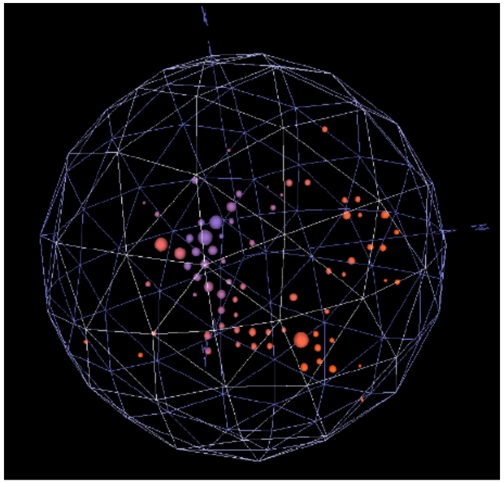


- Tested *in situ* with LINAC at KEK

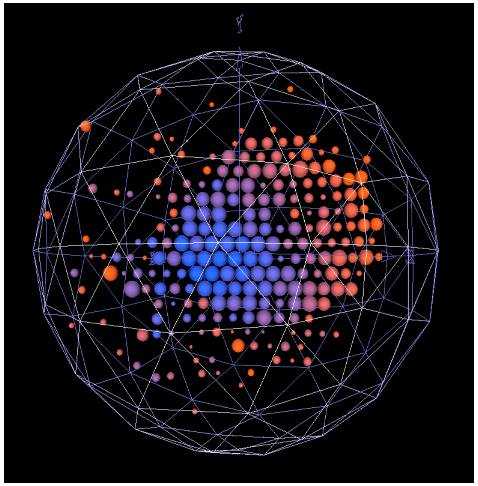
MiniBooNE detector:
Cerenkov with Mineral Oil

total volume: 800 tons (6 m radius)
fiducial volume: 445 tons (5m radius)
1280 PMTs in detector at 5.5 m radius
10% photocathode coverage
240 PMTs in veto





electron ring

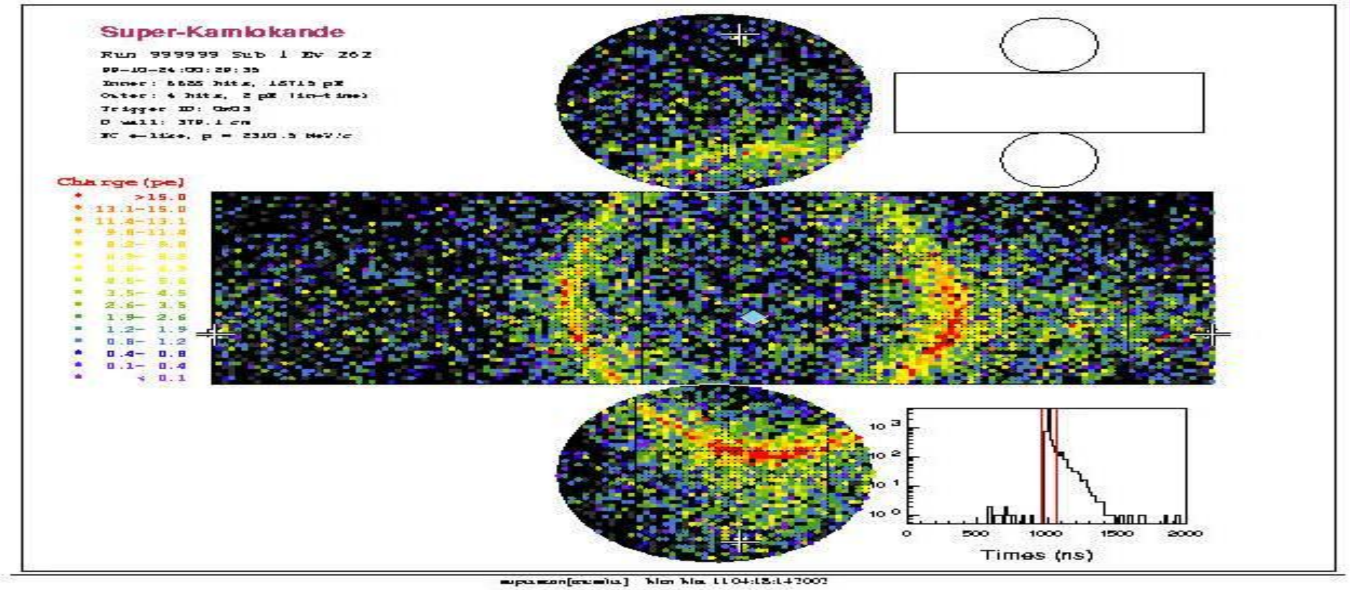


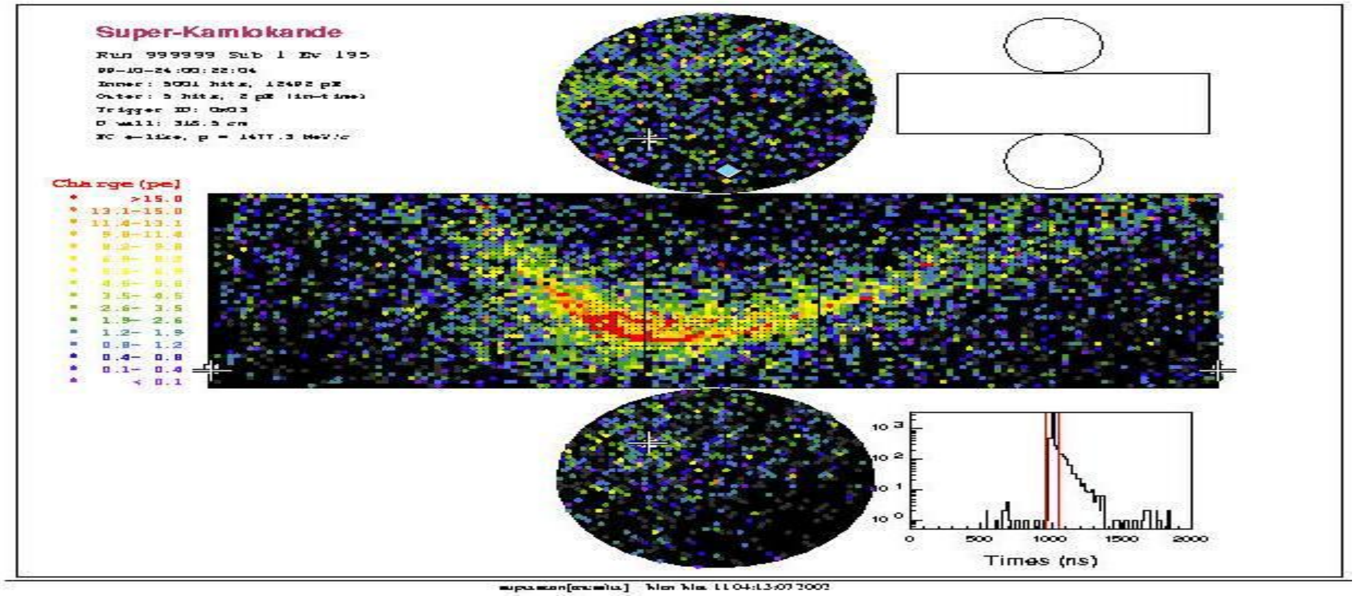
μ ring

Events courtesy G. Zeller

What about water Cerenkov at High (>1GeV) Energies???

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

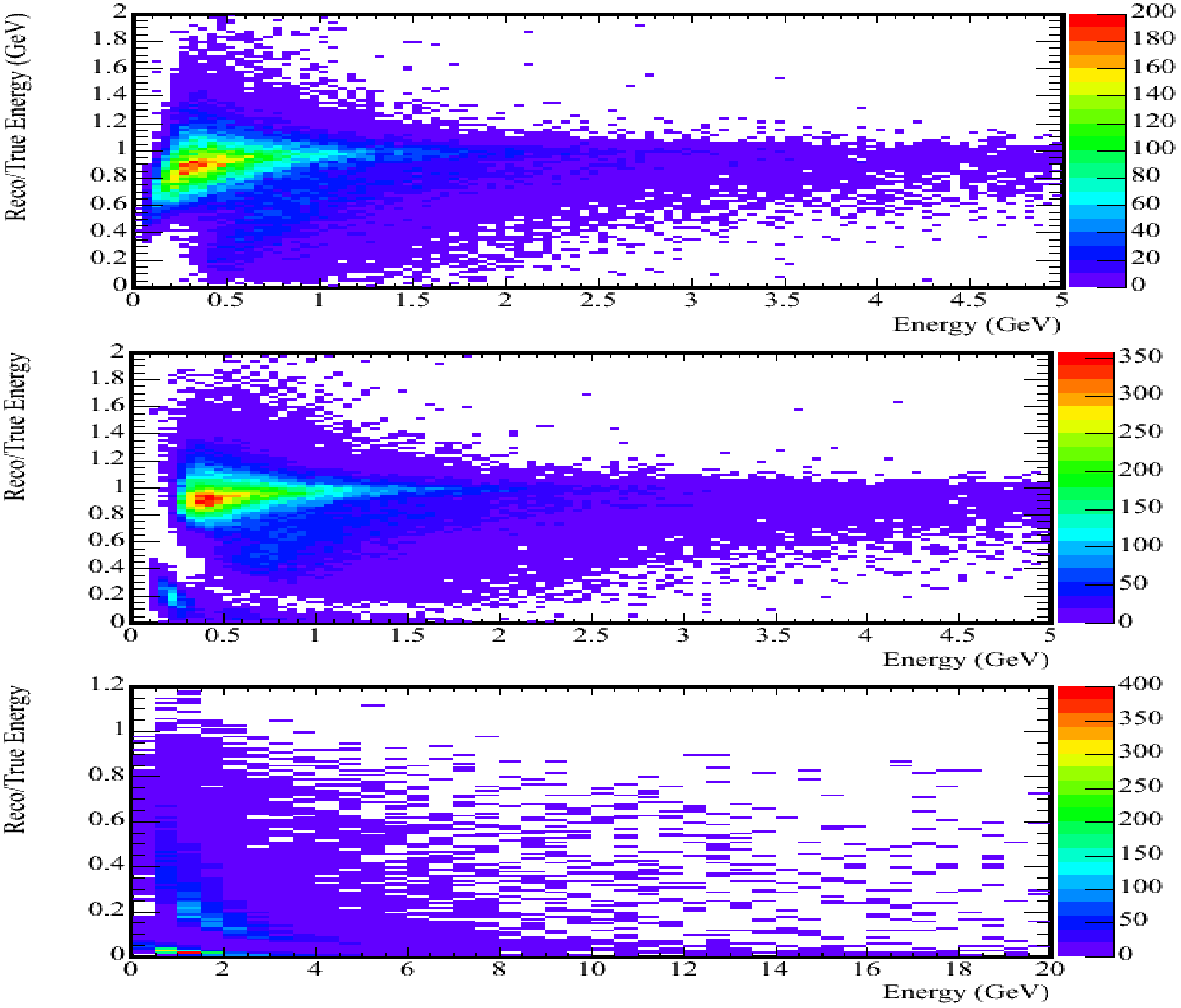




Visible Energy = 2GeV: One Is e^- One Is a π^0

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

Reconstructed/True Energy



ν_e CC

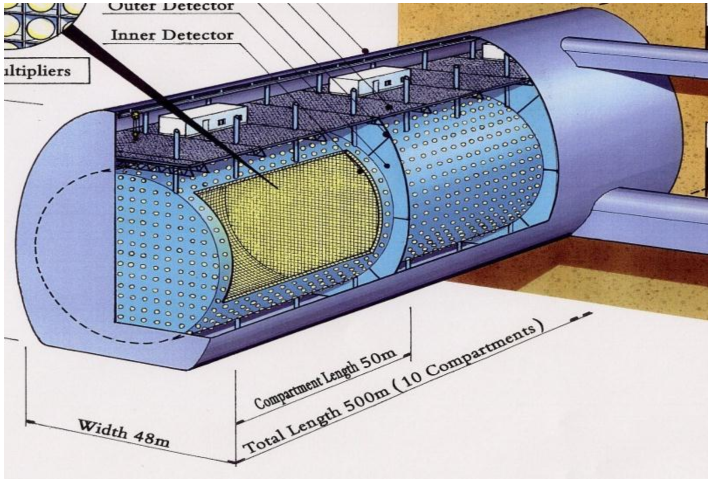
ν_μ CC

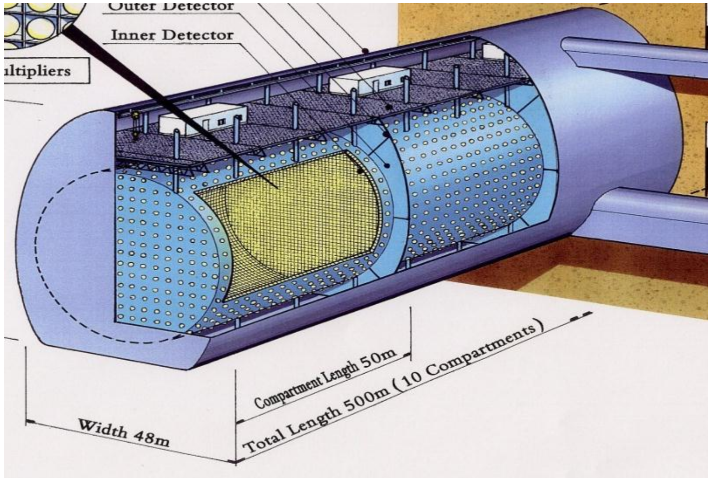
NC

Oustanding Issues

Cerenkov Detectors

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

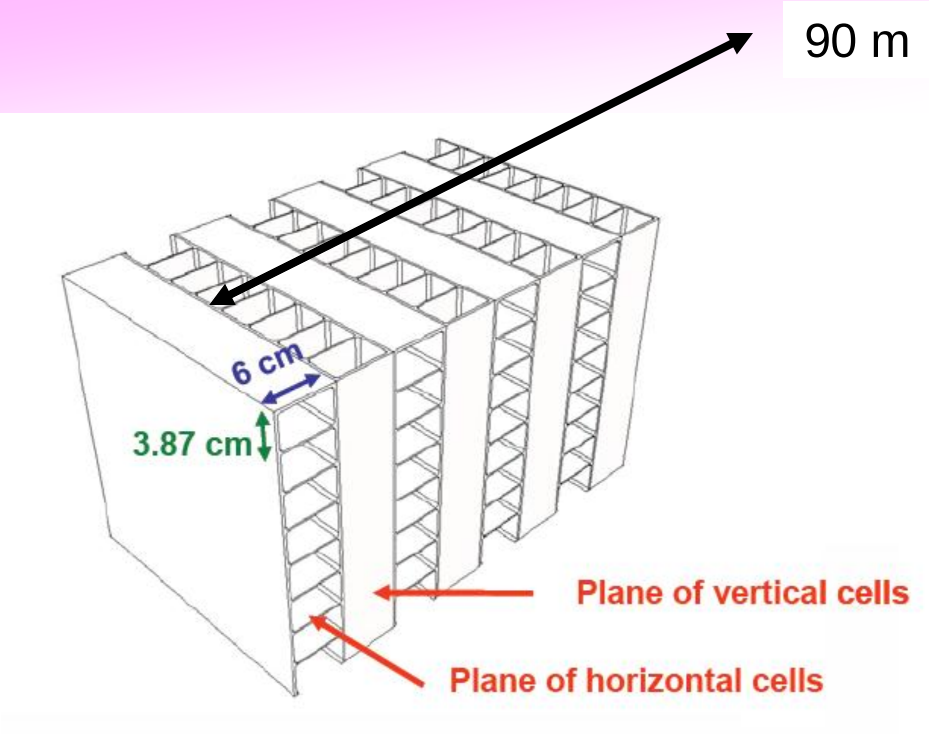




- What is highest energy regime that is possible, with better electronics,photo-detectors, etc?
- Water Cerenkov clearly the cheapest per kton

All Liquid Scintillator Detector

- PVC extrusions
  - 17m tallx17m widex90m long
  - 3.87 cm transverse, 6 cm wide in beam direction (more light)
  - 17.5 m long vs. 48 ft (less light)
- All Liquid Scintillator
  - 85% scintillator, 15% PVC
- Previous design: inactive (particle board) plus active (scintillator) material, but was less efficient at rejecting backgrounds

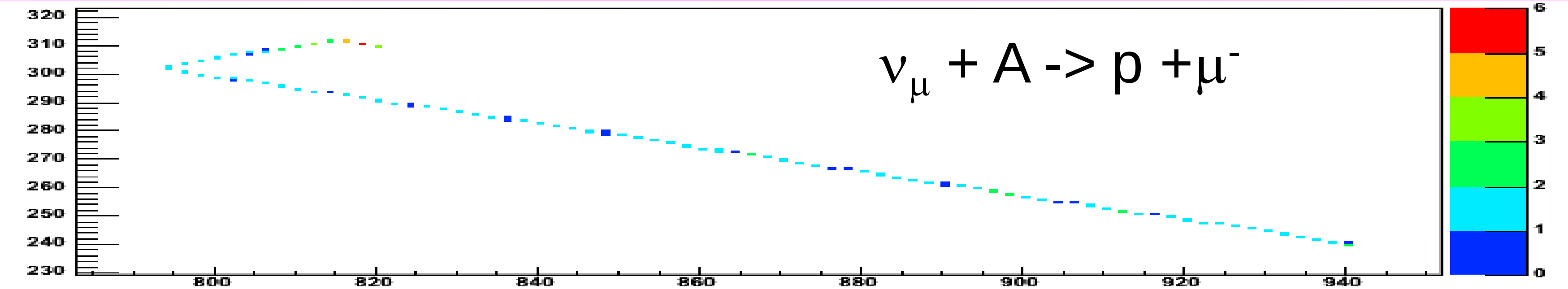


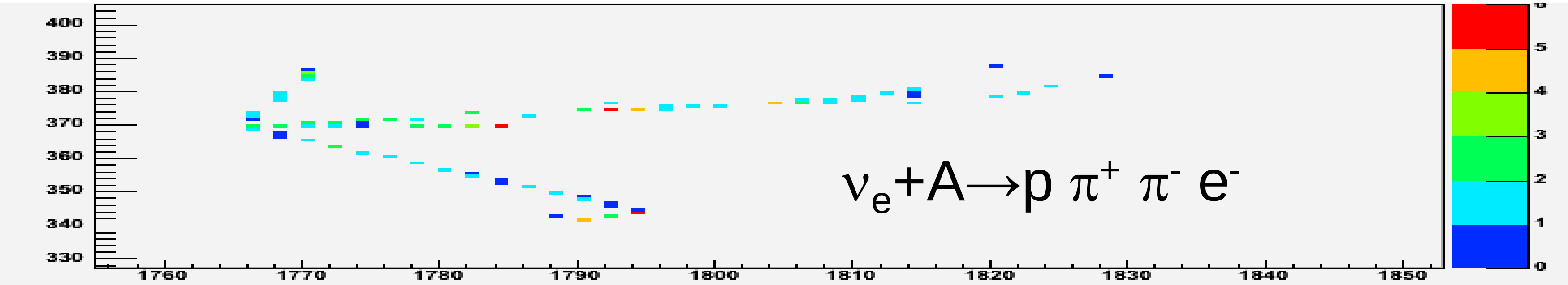
Read out on TWO edges

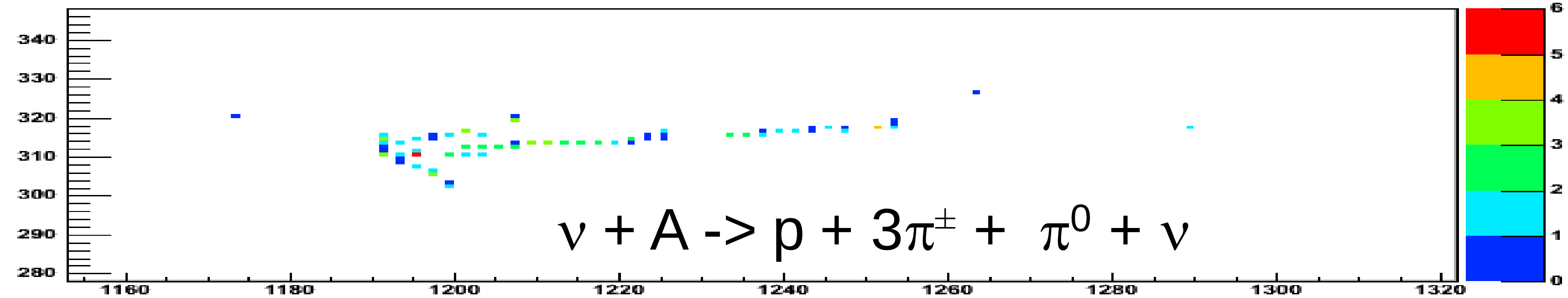
To Build:

Glue Planes of Extrusions together
Rotate them from horizontal to vertical
Fill Extrusions with Liquid Scintillator
Each box gets a WLS fiber loop (bent at far end)
Instrument WLS fibers with Advanced PhotoDiodes, repeat

Scintillator Events (2GeV)







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

Particle ID:

- particularly “fuzzy” e’s
- long track, not fuzzy (μ)
- gaps in tracks (π^0 ?)
- large energy deposition (proton?)

Detector Volume

- Scaling detector volume is not trivial

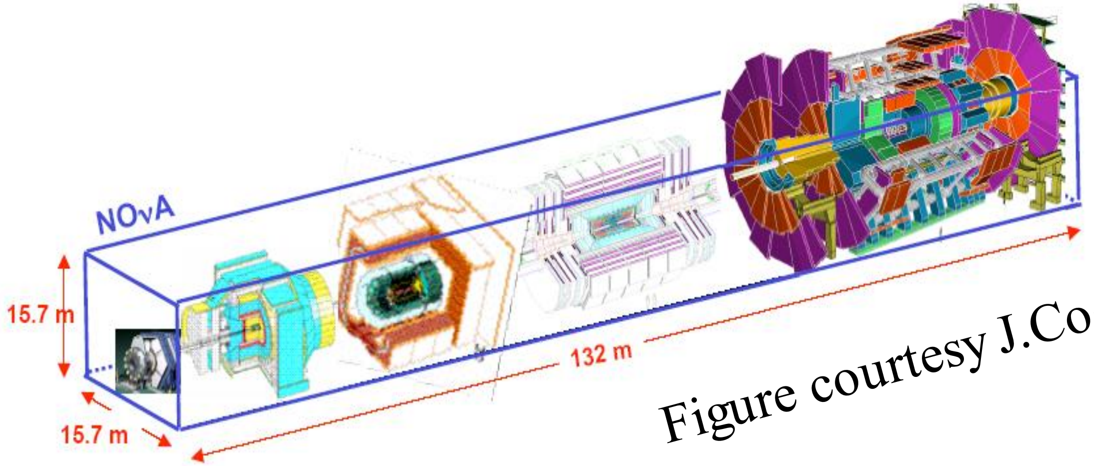
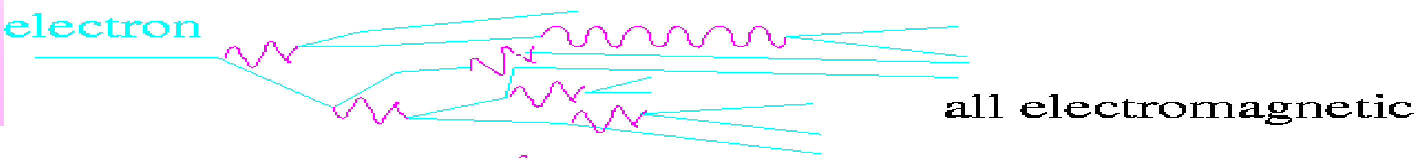
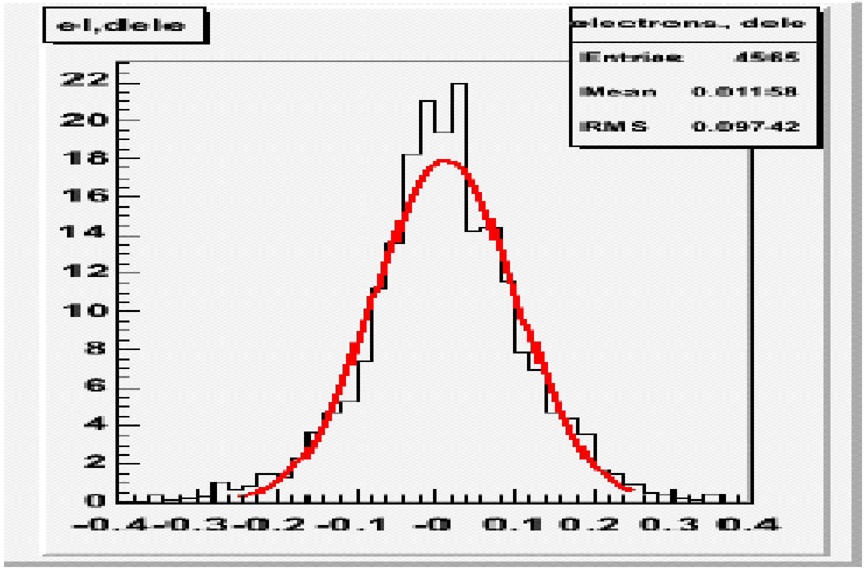


Figure courtesy J.Cooper

Energy Resolution





Measured – true energy divided by square root of true energy

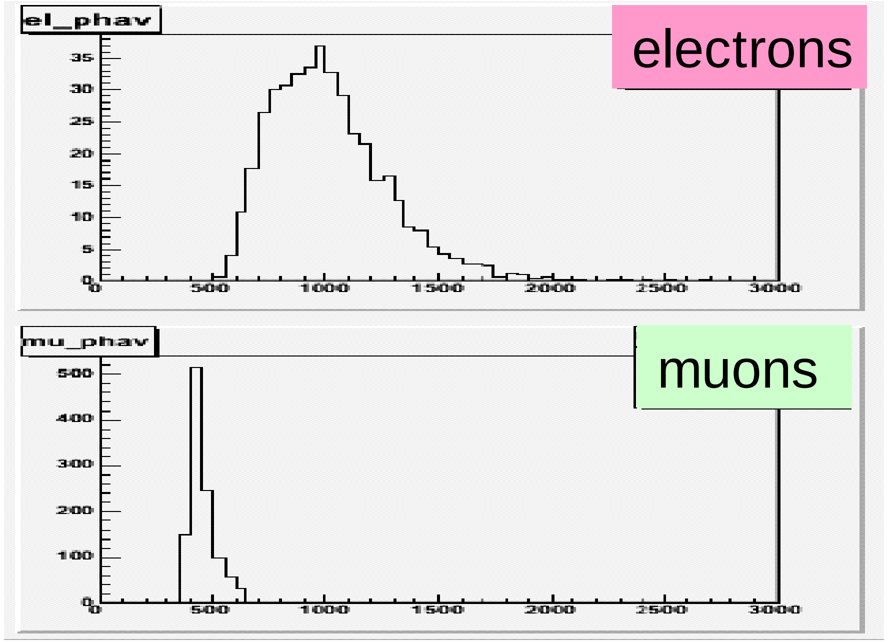
$$\frac{\delta E}{E} \propto \frac{1}{\sqrt{N}}, N = samples$$

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

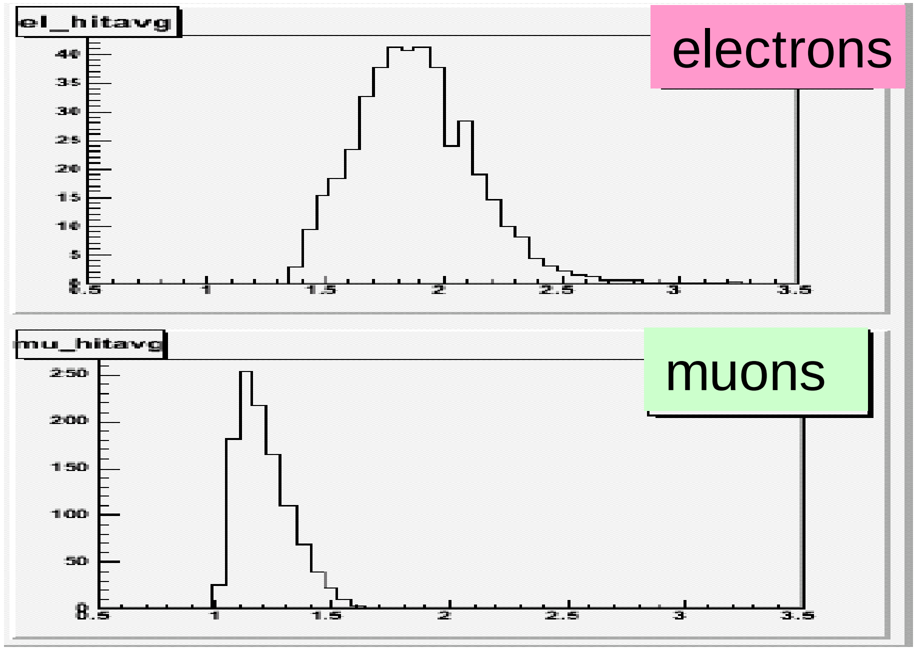
- For ν_e CC events with a found electron track (about 85%), **the energy resolution is 10% / sqrt(E)**

- 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

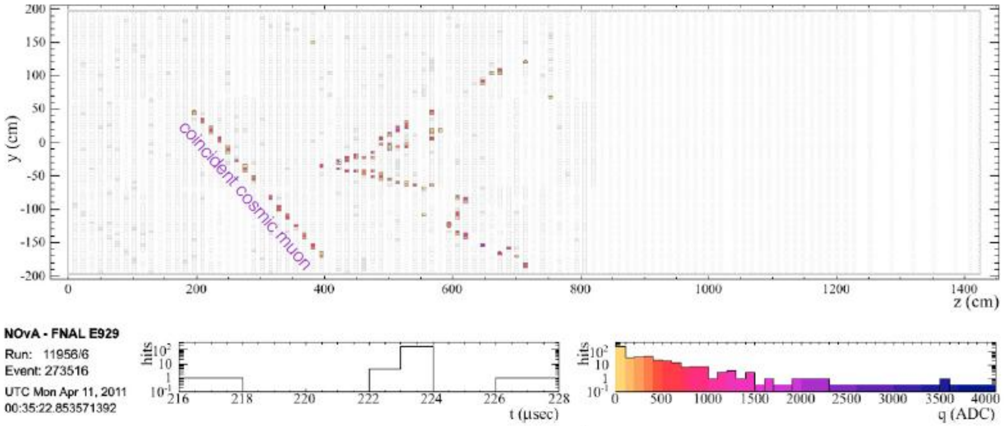


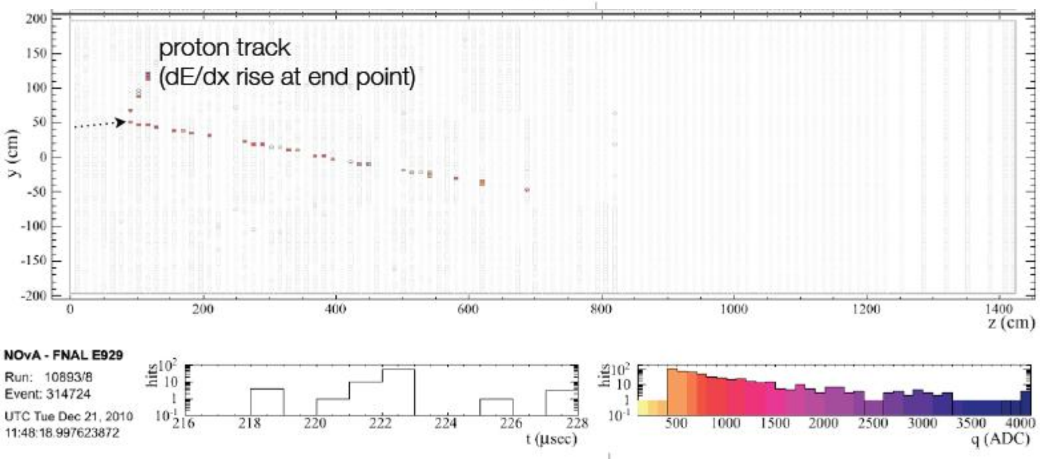
Average **number of hits** per plane

- 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

NOνA Event Displays

- Currently there is a near detector operating ~100 mrad from the NuMI beamline seeing 2GeV neutrinos from K decay



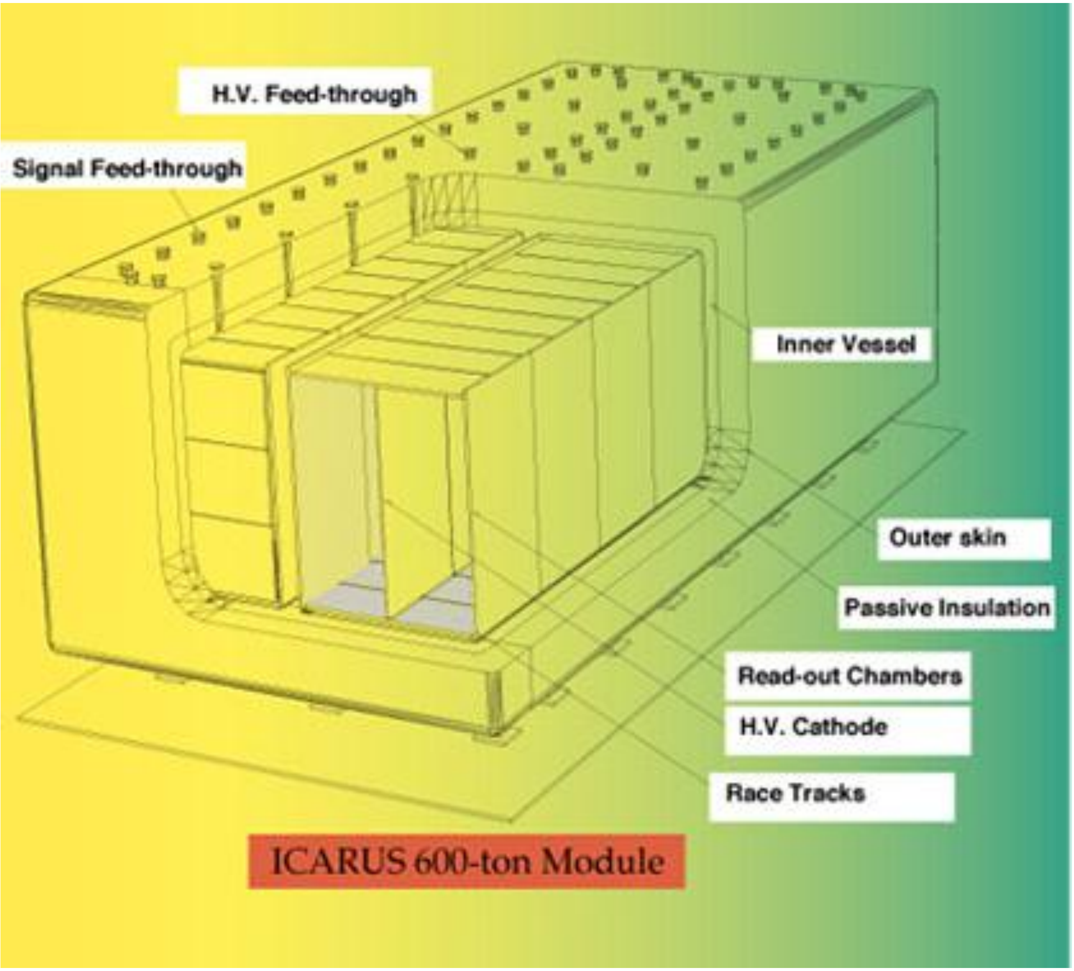


Outstanding Issues

Fine Grained Scintillator

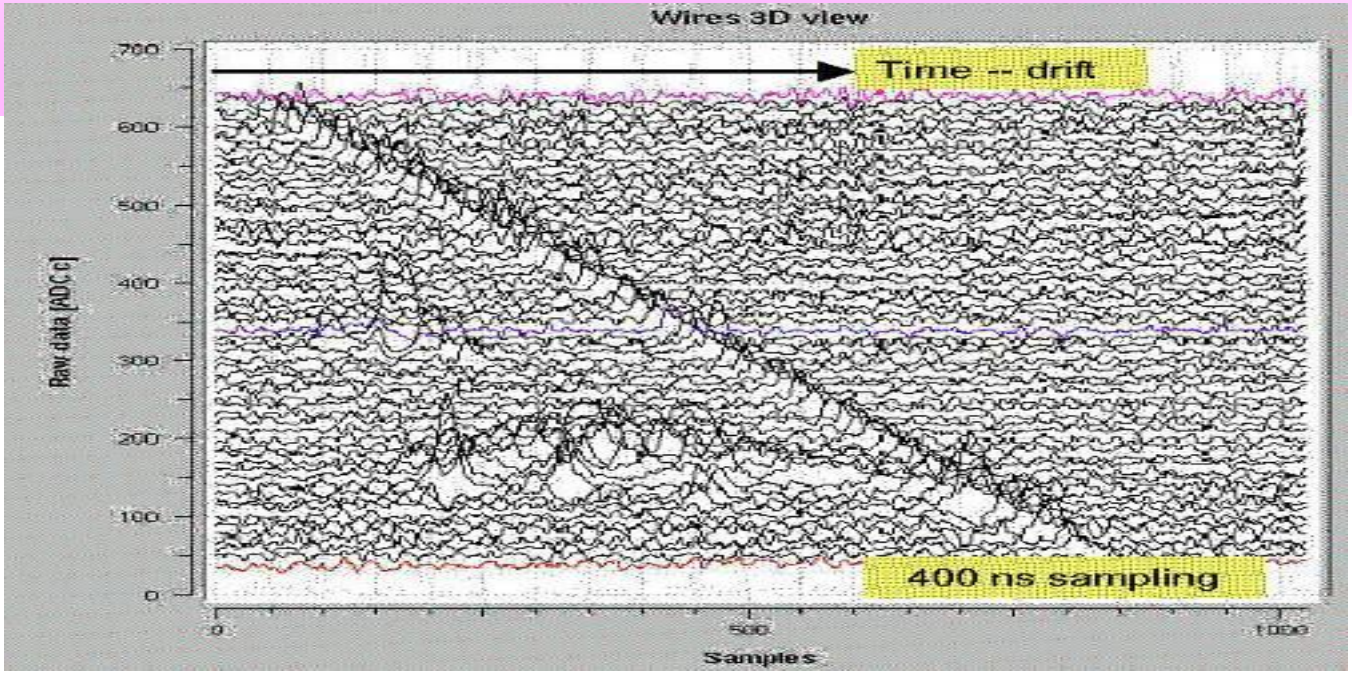
- How cheaply can this be made?
- Can you make something this large out of plastic?
- What is best choice for readout?
- What near detector is best for this?

Liquid Argon Time Projection Chamber



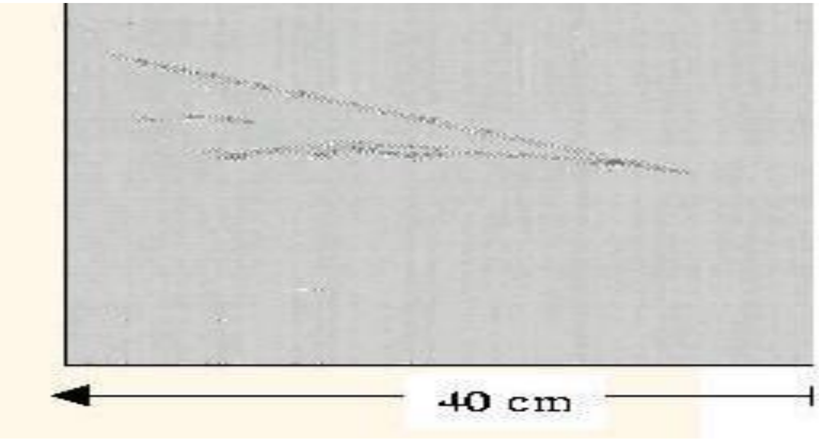
- Ingredients:
  - Very pure argon
  - Strong electric field
  - Several planes of wires where signal is induced when electrons drive
  - Electronics to read out wire planes
  - PMT's can be added to catch scintillation light, can provide trigger
- Argon Vital statistics:
  - Density: 1.4 g/cm^3
  - Xo=14cm
  - λ_{INT}=83cm

Liquid Argon TPC

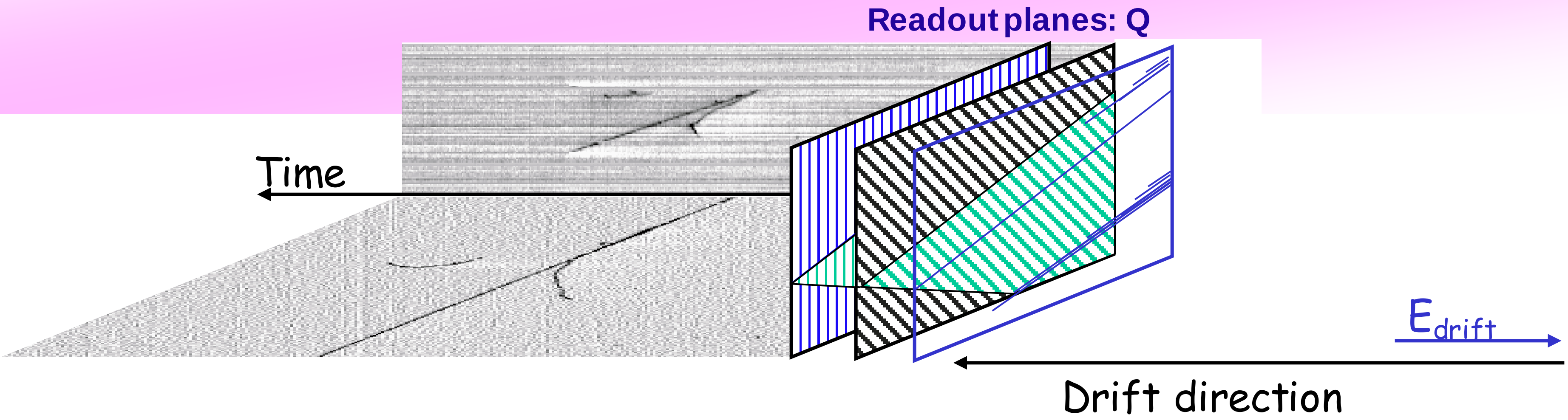


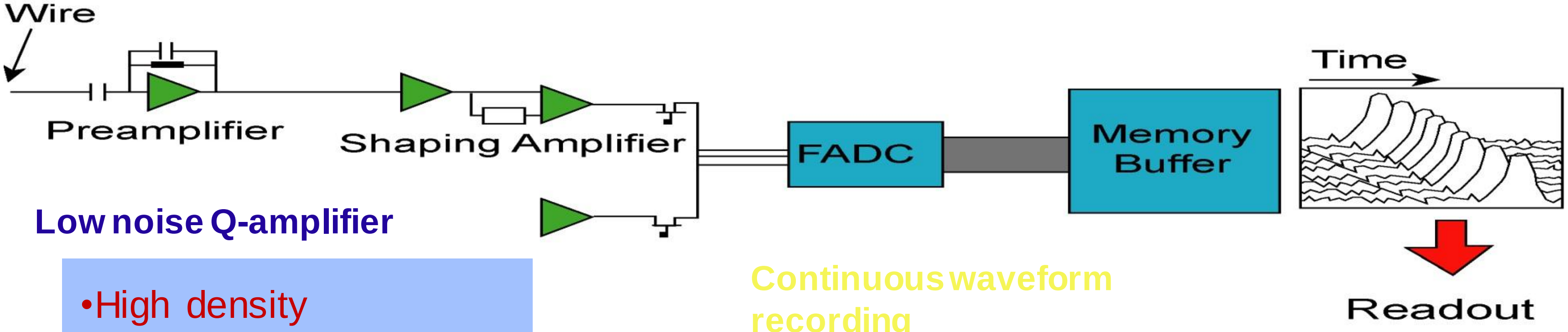
Raw Data to Reconstructed Event

- 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





Low noise Q-amplifier

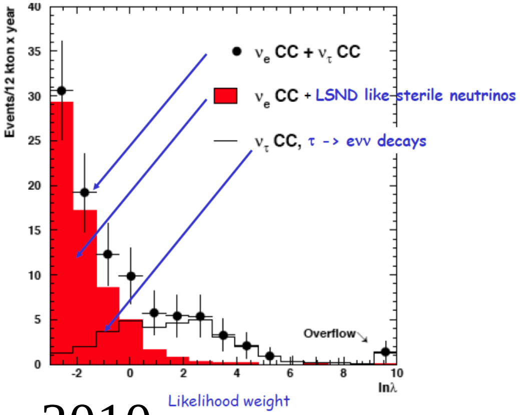
Continuous waveform recording

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

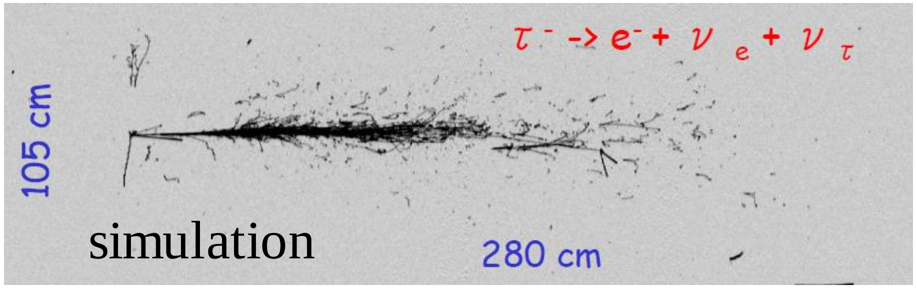
dE/dx(mip) = 2.1 MeV/cm
T=88K @ 1 bar
$W_e \approx 24$ *eV*
$W_\gamma \approx 20$ *eV*
Charge recombination (mip)
@ E = 500 V/cm ≈ 40%

ICARUS

- Active mass: 476 tons
- Total mass: 600 tons
- Wire spacing: 3mm
- Electron drift distance: 1.5m
- 54000 wires, 3 stereo angles
- 74 PMT's for scintillation light
- Statistical measurement of ν_τ appearance



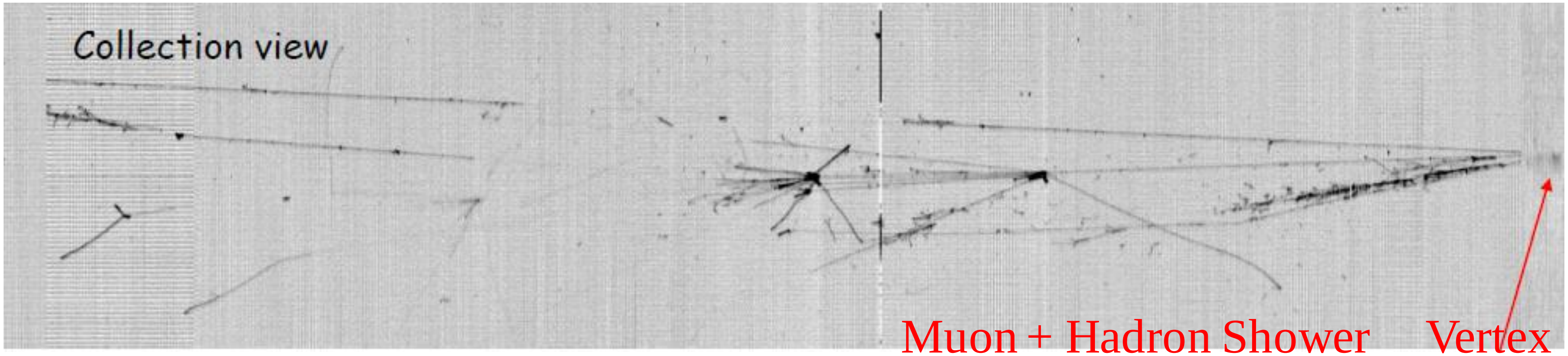
A. Guglielmi, ν2010



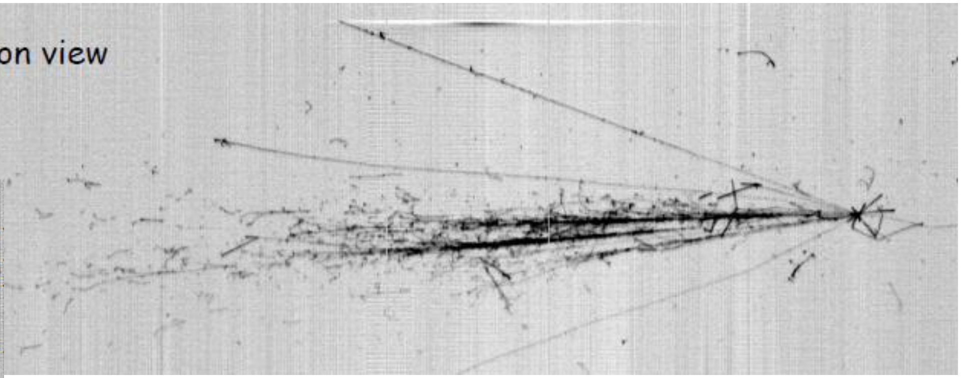
simulation

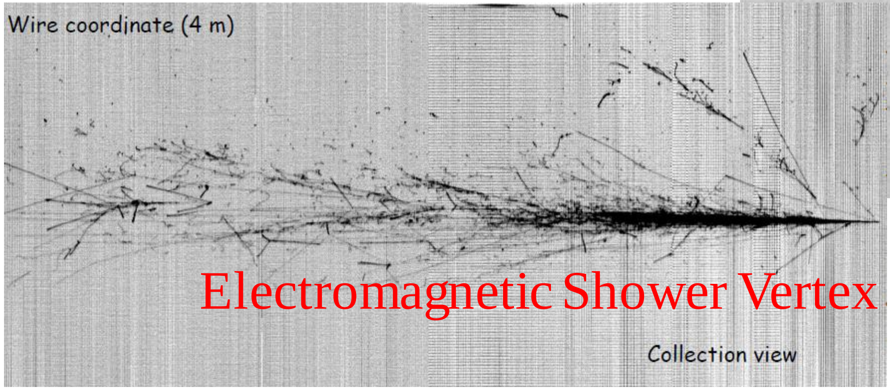
Expect 6 beam ν_e's, expect 12 ν_τ's

CNGS Beam events in ICARUS

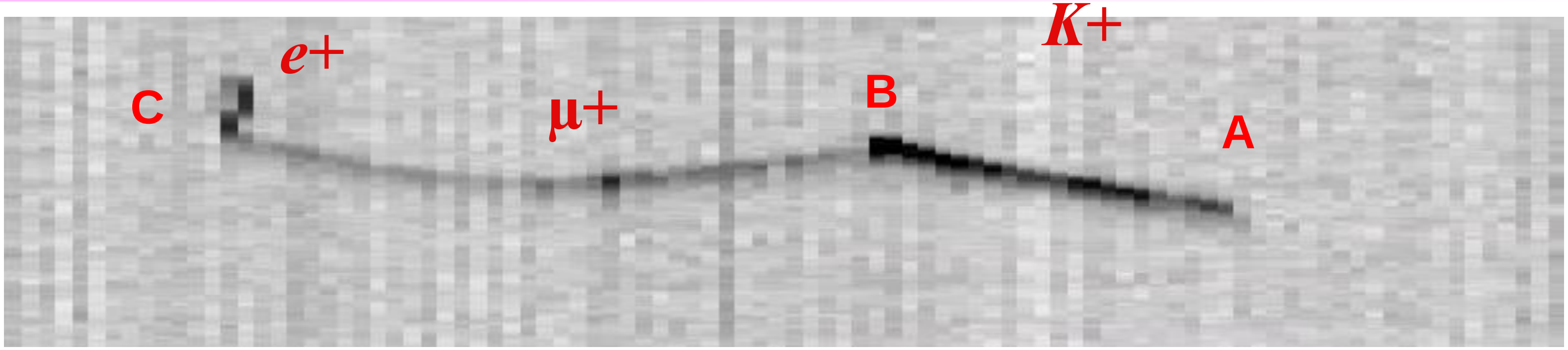


A. Guglielmi, ν2010

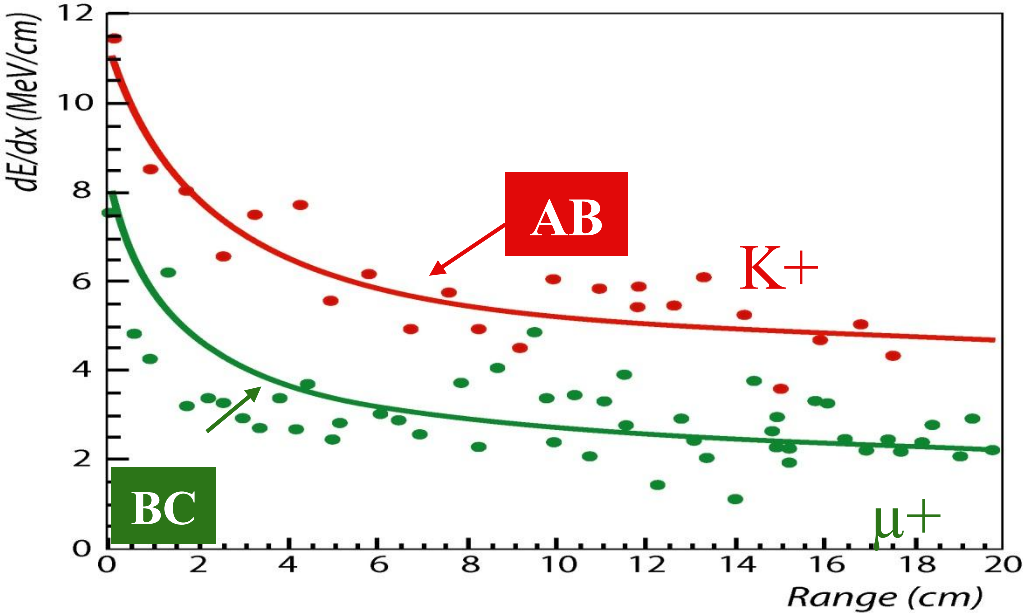




Bethe-Bloch in practice



Run 939 Event 46

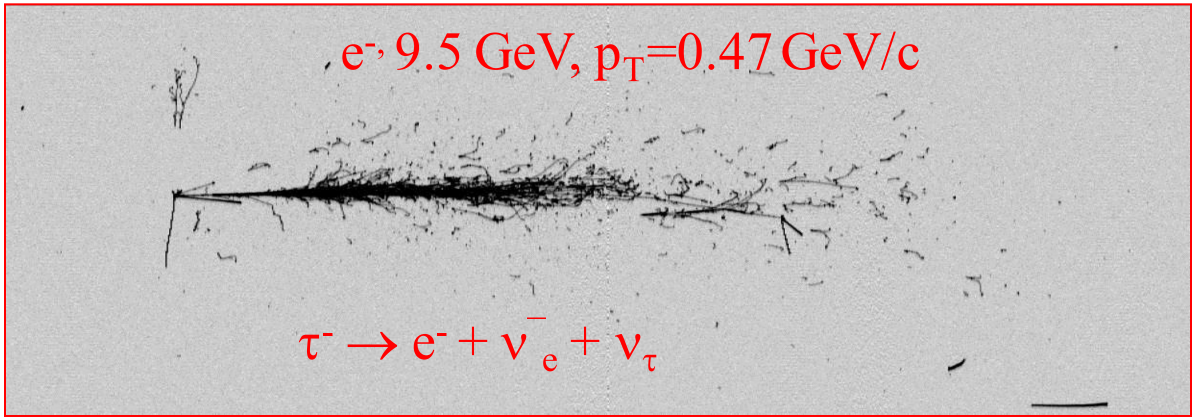


Question:
how would
This look different
for a π→μ event?

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

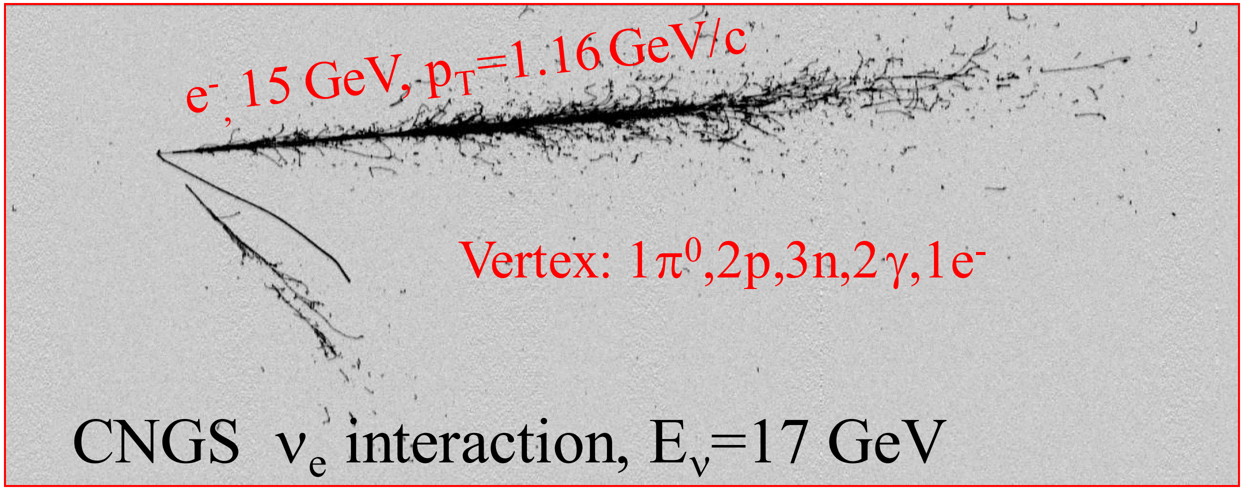
Examples of Liquid Argon (simulated) Events

- Lots of information for every event…



CNGS ν_τ interaction, E_ν=19 GeV

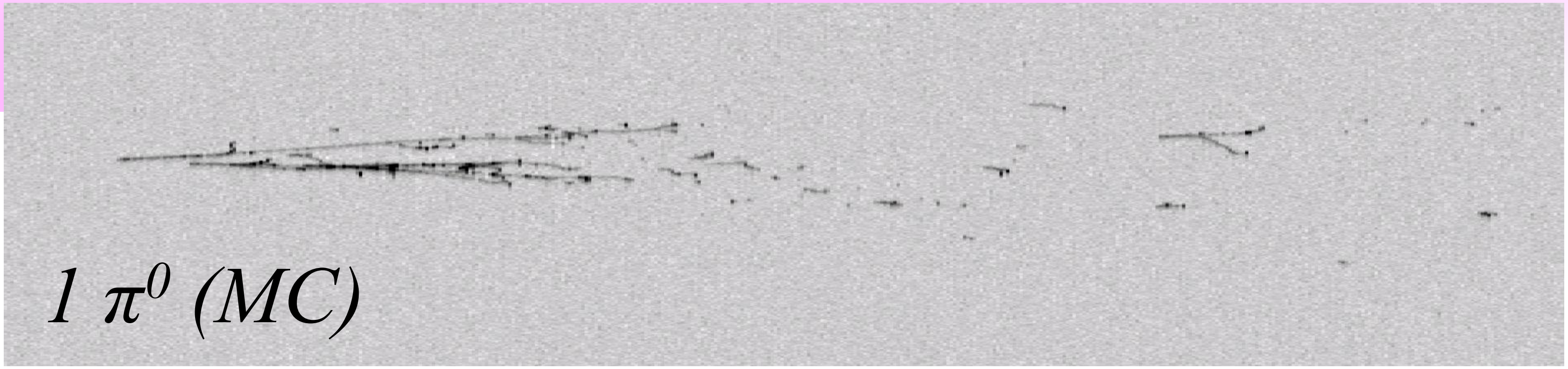
➢Primary τ tag:
$\tau \to e$ decay
➢Exclusive τ tag:
$\tau \to \rho$ decay
➢Primary Bkgd:
Beam ν_e



CNGS ν_e interaction, E_ν=17 GeV

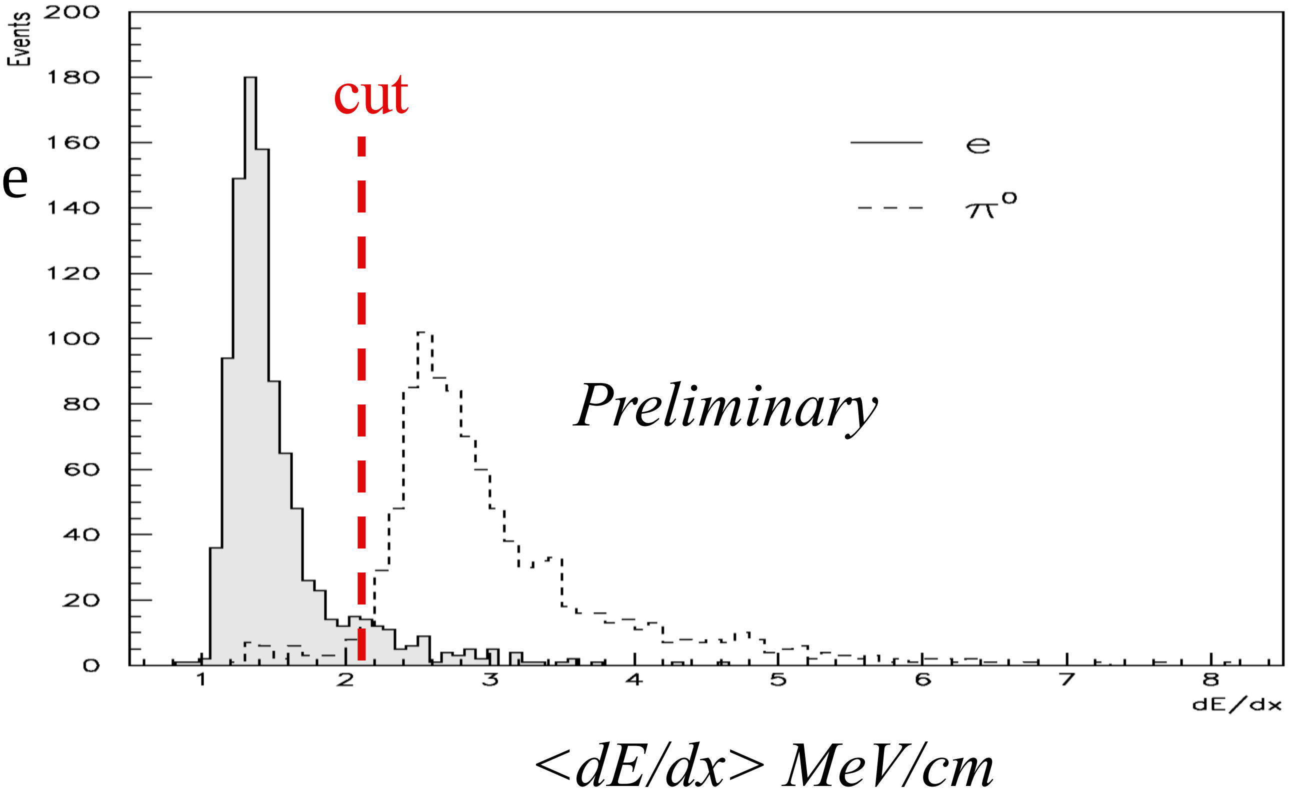
Courtesy
André
Rubbia

π^0 identification in Liquid Argon



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

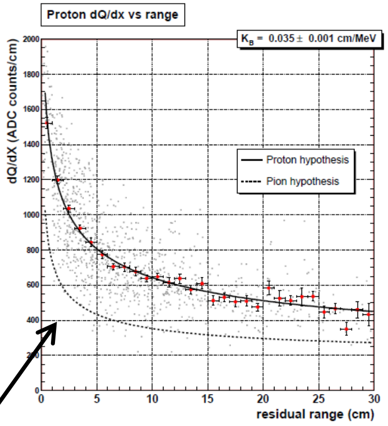
Imaging provides ≈2×10^{-3} efficiency for single π^0



Liquid Argon Development History

ICARUS 50 L @ CERN

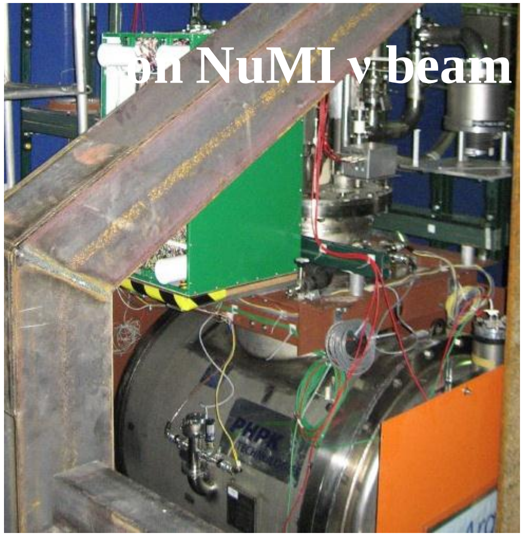
on WANF ν beam



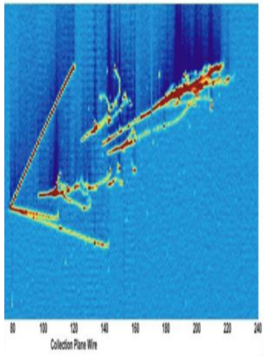
proton identification in ν interactions

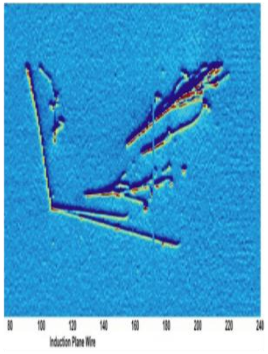
$$\nu_\mu n \rightarrow \mu^- \Delta^+ \rightarrow \mu^- p \pi^0$$

ArgoNeut 175 L @ FNAL



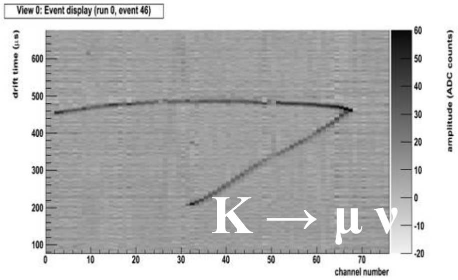
on NuMI ν beam



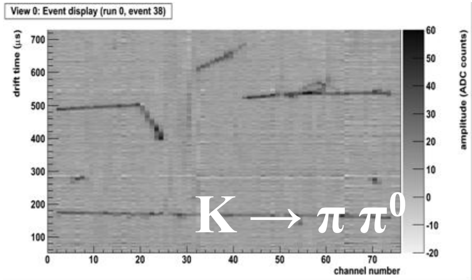


250 L @ KEK

on low energy Kaon beam @ J-PARC



K → μ ν



K → π π^0

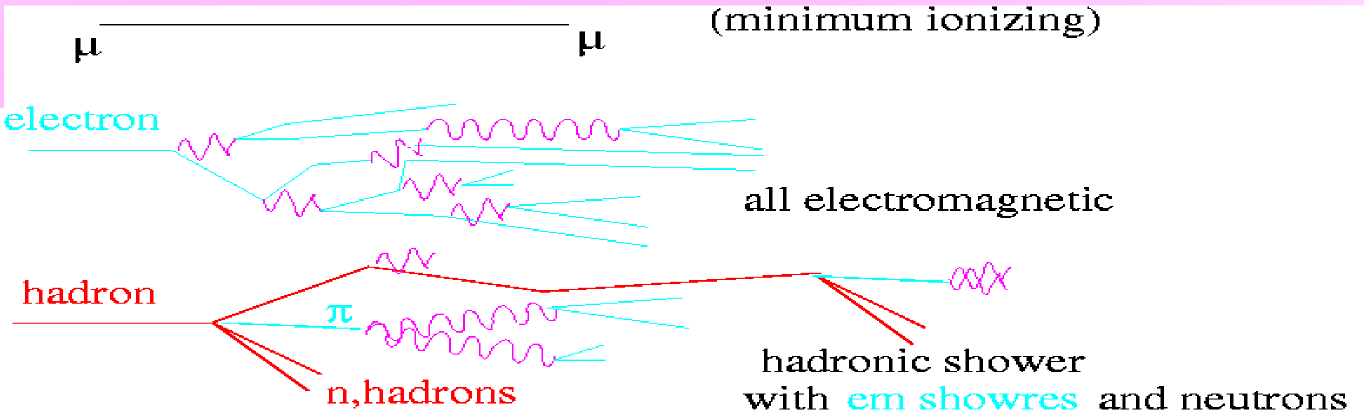
Oustanding Issues

Liquid Argon Time Projection Chamber

- Do Simulations agree with data (known incoming particles)
- Can a magnetic field be applied
- How well can neutral currents be rejected in practice?
- Can the electronics be put inside the cryostat?
- How large can one module be made?
- What is largest possible wire plane spacing?

Several R&D Efforts world-wide working to get >10kton detectors “on the mass shell”

From Fully Active to Sampling

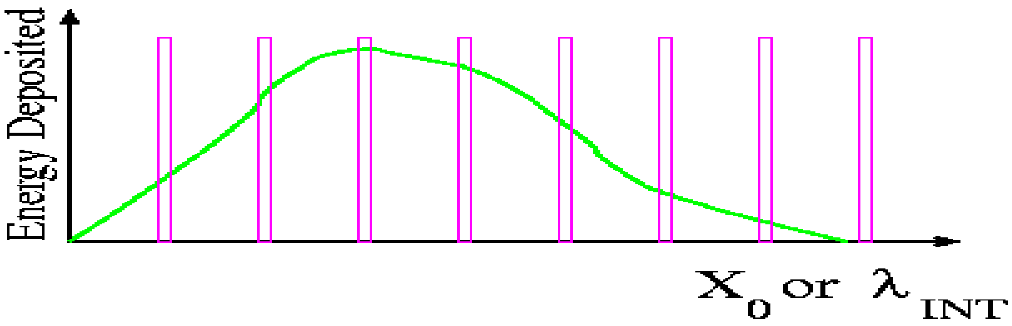


- Advantages to Sampling:
  - Cheaper readout costs
  - Fewer readout channels
  - Denser material can be used
    - More N, more interactions
    - Could combine emulsion with readout
  - Can use magnetized material!
- Disadvantages to Sampling
  - Loss of information
  - Particle ID is harder (except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

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

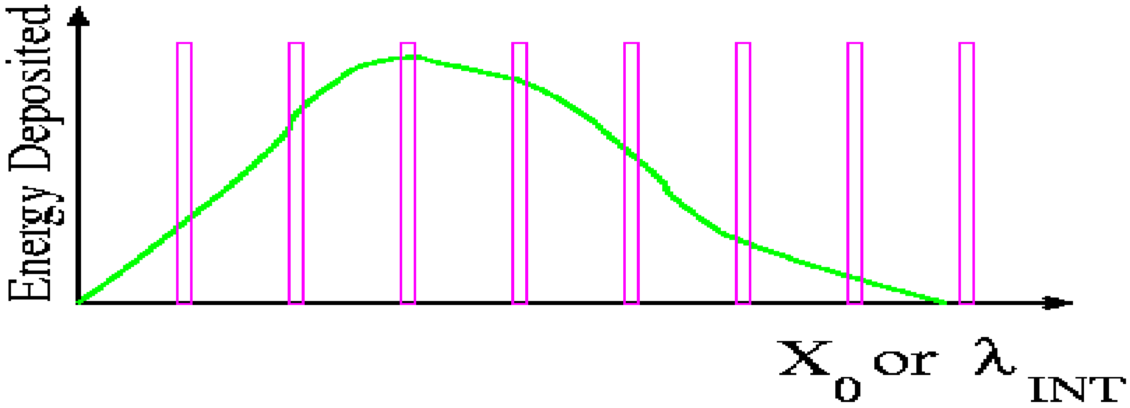
$$\frac{\delta E(hadron)}{E(hadron)} \propto \sqrt{\frac{\lambda_{INT}}{N}}$$

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



Sampling calorimeters

- 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)



Material	X_o (cm)	l_{INT} (cm)	Sampling (X_o)	X_o (g/cm^2)
L.Argon	14	83.5	0.02 (ICARUS)	20
Steel	1.76	17	1.4 (MINOS)	14
Scintillator	42	~80	0.13 (NOνA)	40
Lead	0.56	17	.2 (OPERA)	6

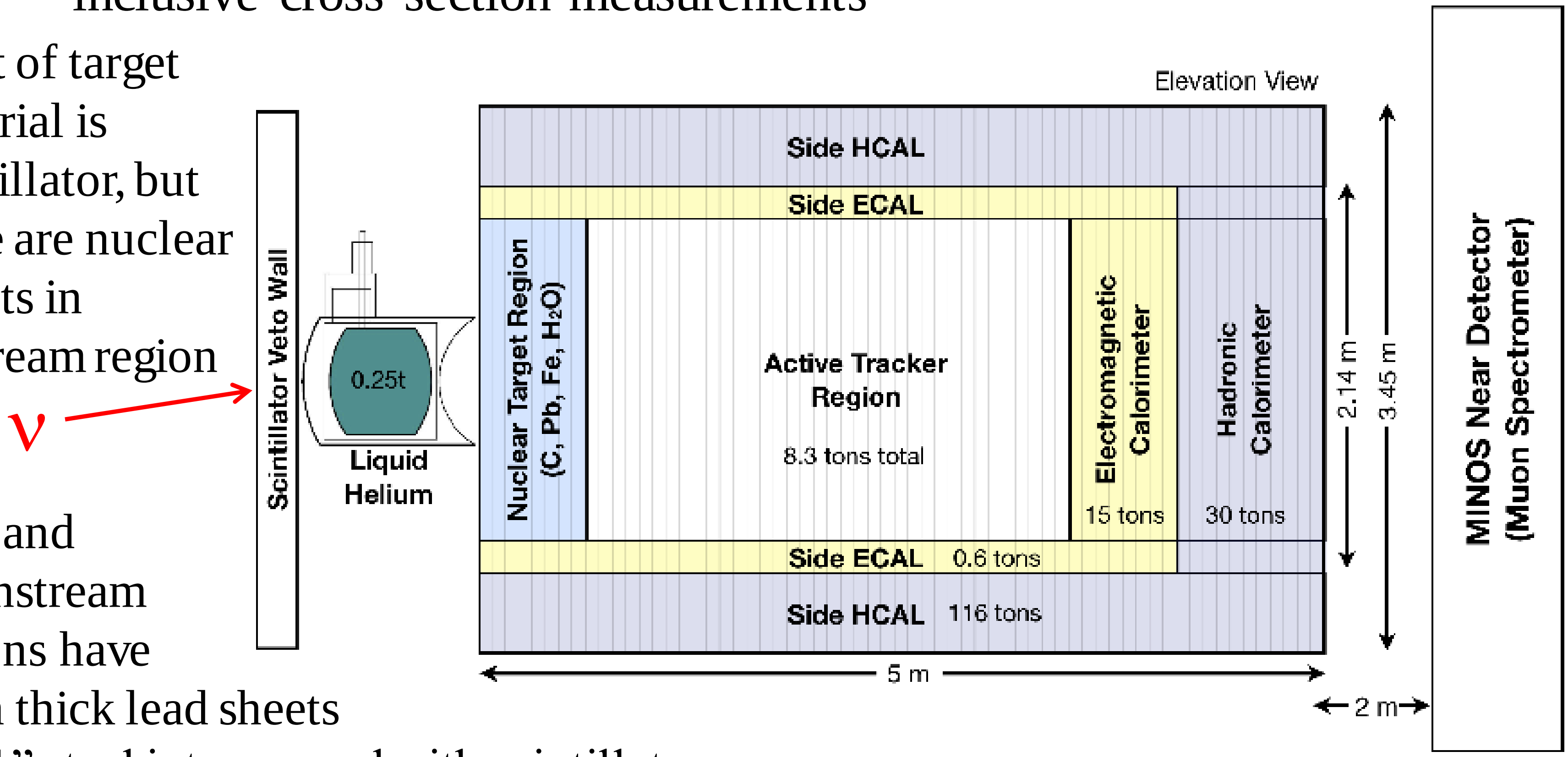
Recall Neutrino Interaction Measurement Goals

- Want to see lots of different interaction channels
- Want to measure total energy of event as well as possible
- Need to know in one way or another whether it’s a neutrino or an anti-neutrino
- Also need to see what the initial nucleus is, if you are looking for nuclear effects
- Result: hybrid detector, mix of totally active region surrounded by sampling detectors

MINERνA

- Dedicated neutrino interaction experiment, 1-20GeV ν's
- Goal of studying exclusive channels and also making total inclusive cross section measurements

Most of target material is scintillator, but there are nuclear targets in upstream region



Side and downstream regions have 2mm thick lead sheets and 1" steel interspersed with scintillator

MINERvA Sampling Fractions

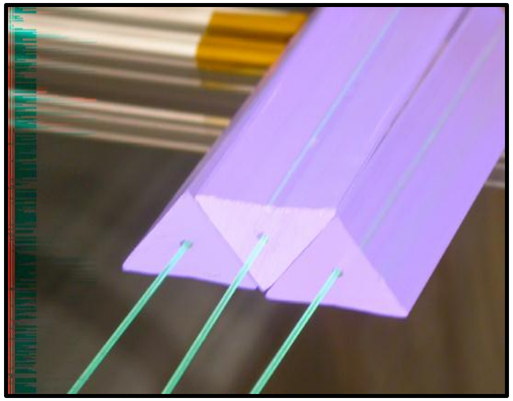
- Different functions call for different granularity

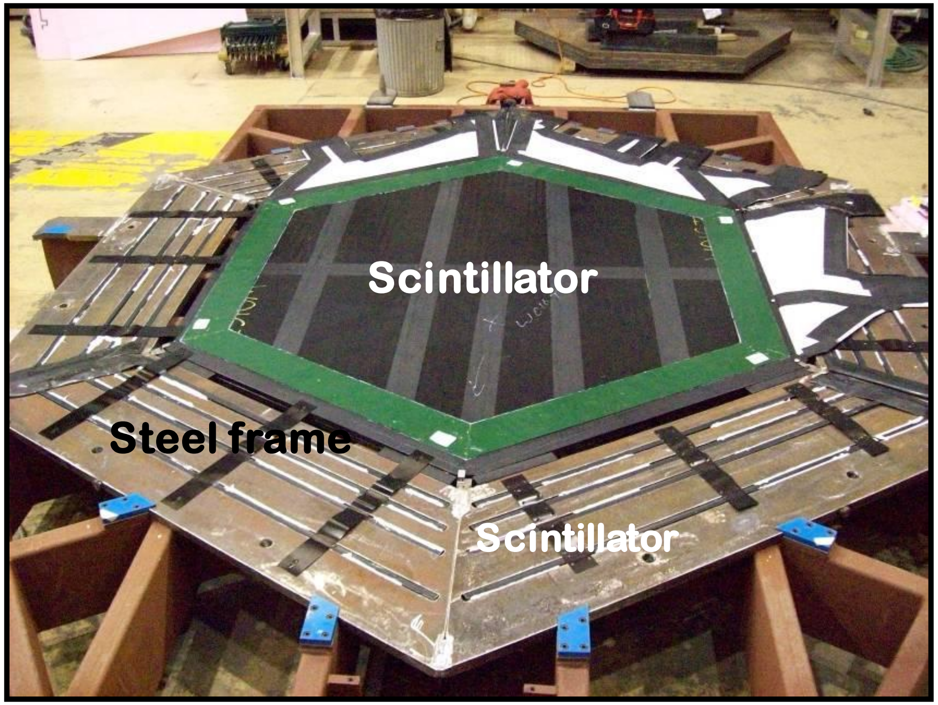
Material	X_o (cm)	l_{INT} (cm)	Sampling (X_o)	Sampling (l_{INT})	thickness (cm)
Steel	1.76	17	1.44	0.15	2.54
Scintillator	42	80	0.04	0.02	1.7
Lead	0.56	17	0.36	0.01	0.2
		ECAL	0.40	0.03	
		HCAL	1.48	0.17	

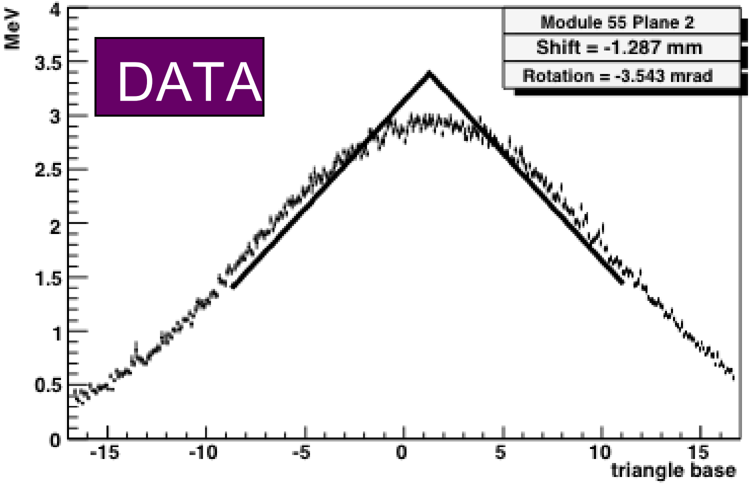
Recall: ICARUS: 0.02 X_0sampling, NOvA 0.13X_0 sampling

Building blocks of MINERvA

- 120 modules, some with (inactive) nuclear targets in them, some with lead and steel for sampling detector, 114 of them with at least 1 plane of scintillator

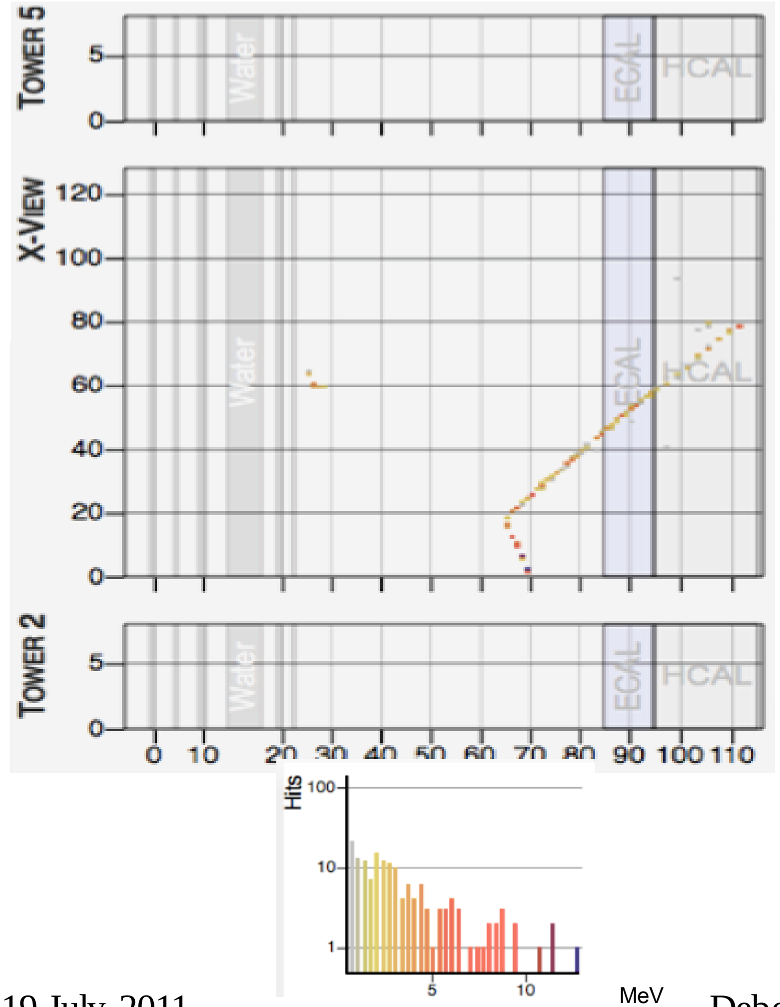




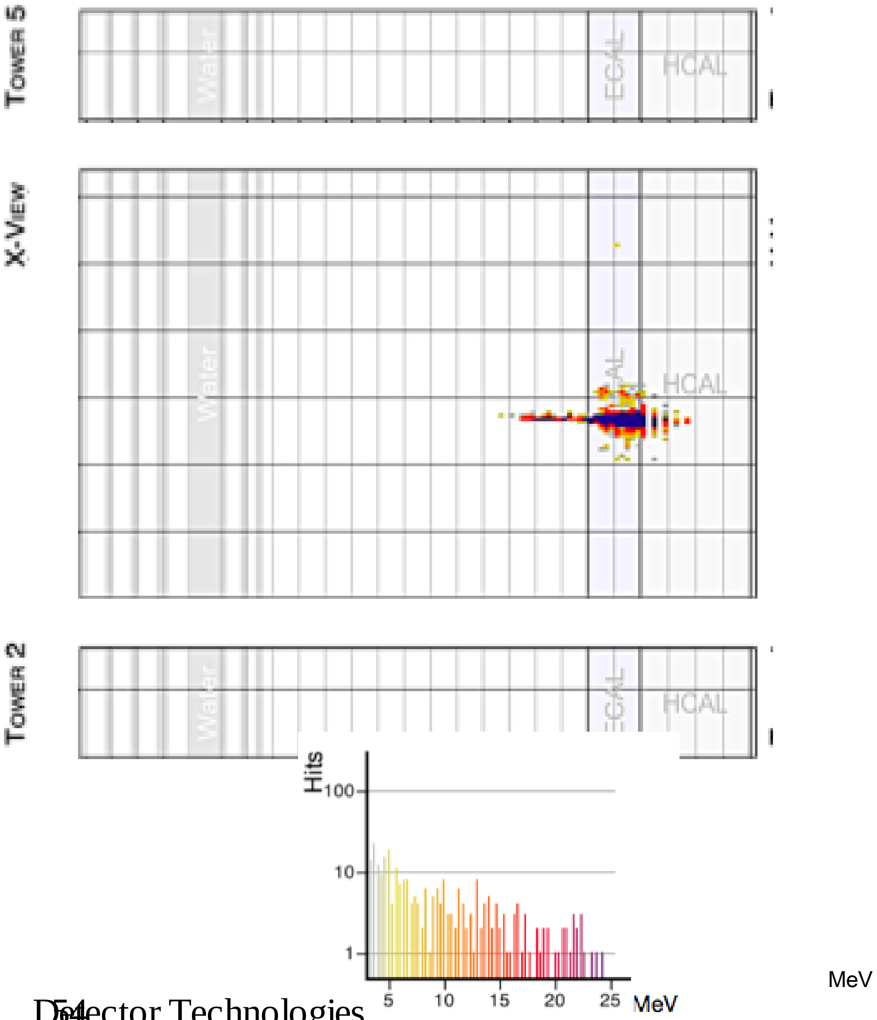


ν Events in MINERνA Data, I

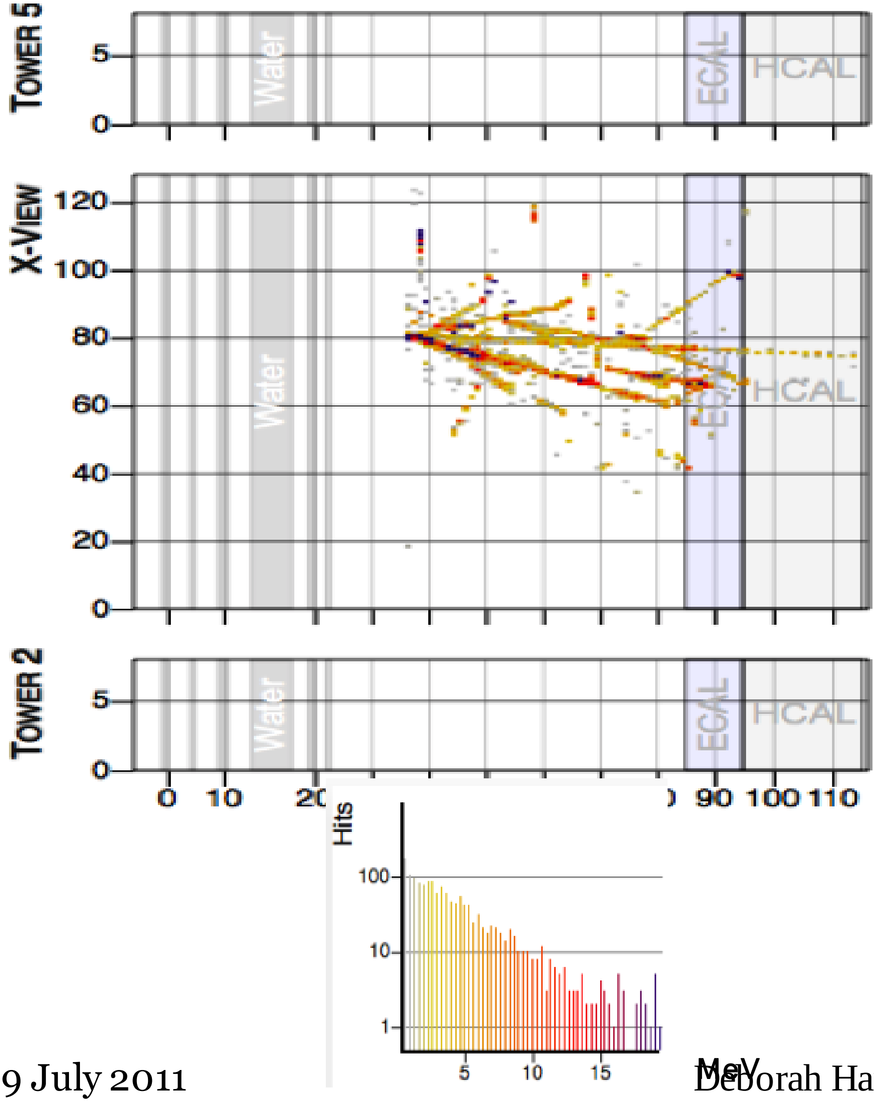
- anti-ν n→μ p Candidate

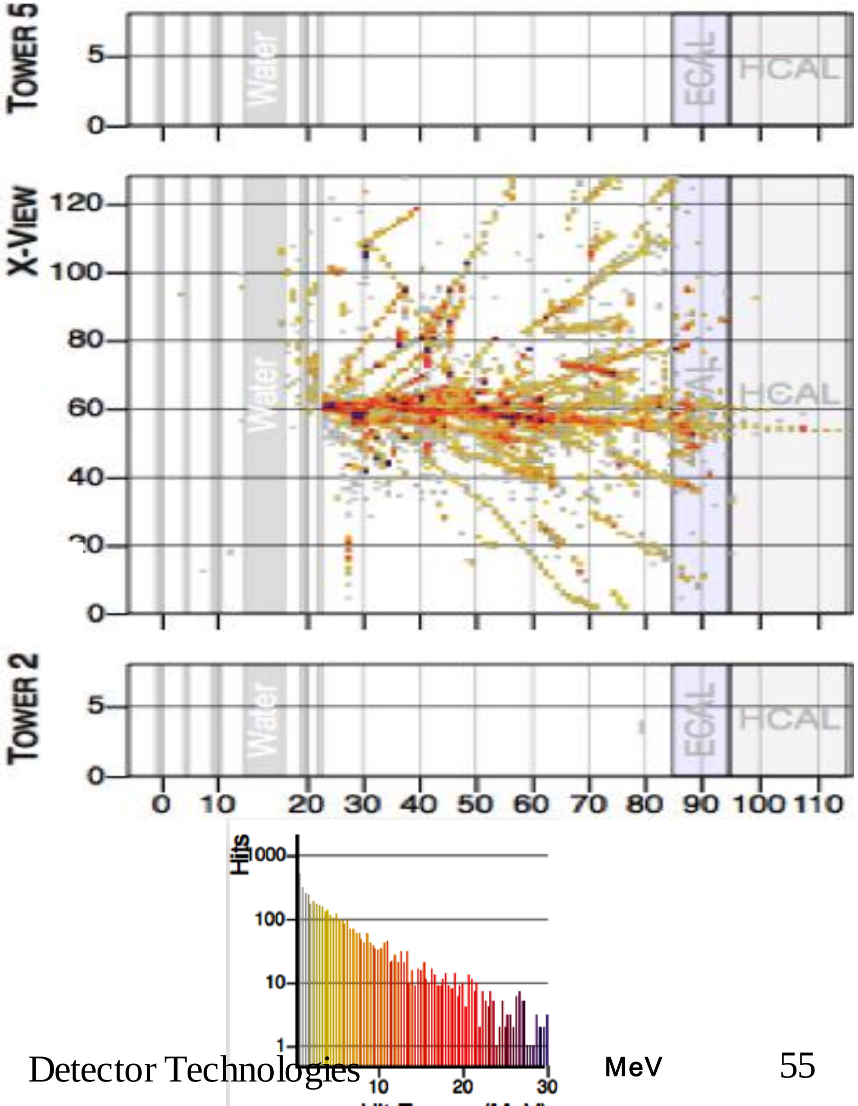


- Single Electron Candidate



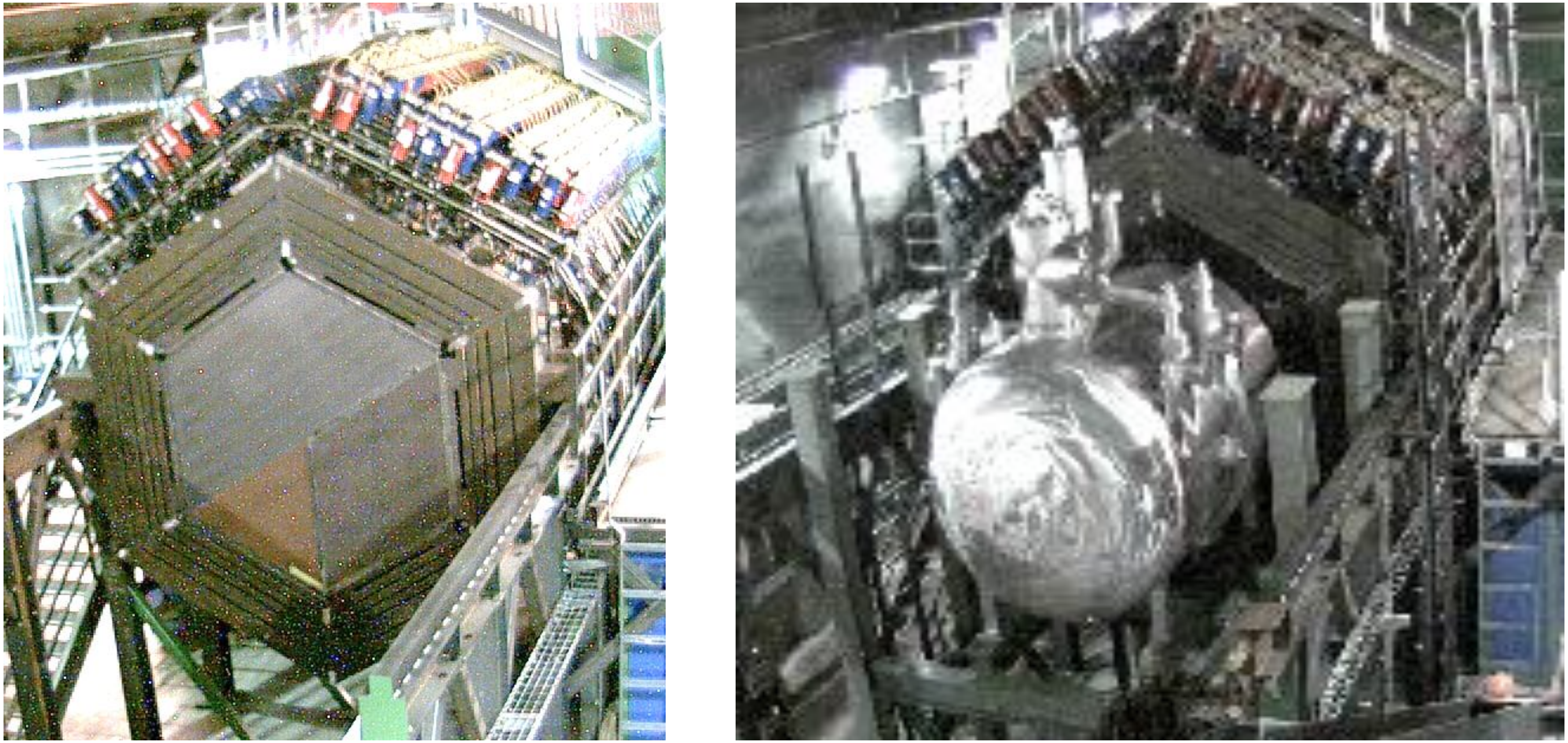
ν Events in MINERνA Data, II





Nuclear Targets at MINERvA

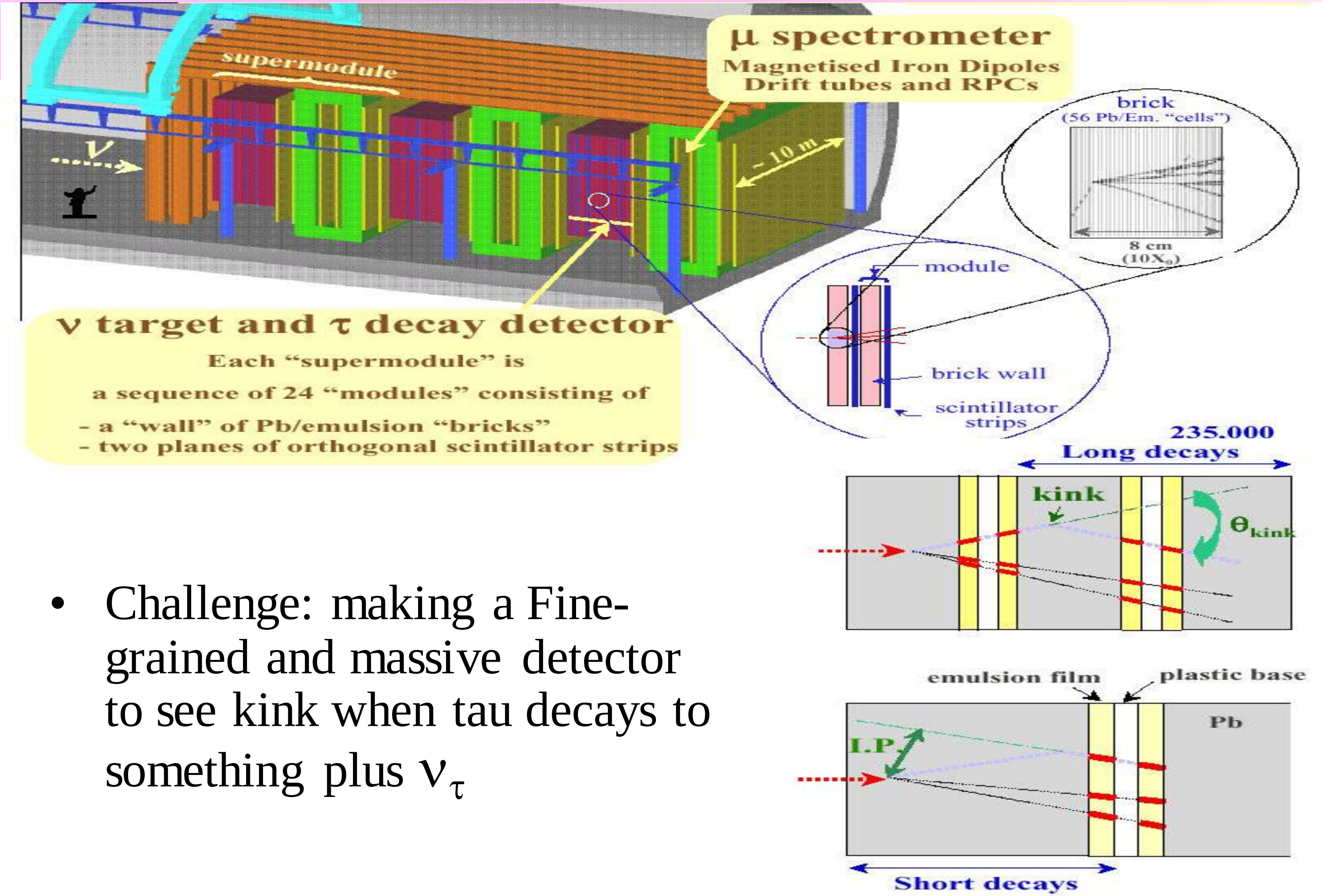
- Several different targets, different geometries



Outstanding Issues for solid scintillator

- How large can this technology detector be made?
  - I have seen talks where 15m tall MINERvA is assumed, right now it is ~2.5m tall
- Can this target be used in a magnetic field?
- How fine segmentation is really needed?
  - Remember the two limits: ranging out and showering particles

ν_τ detection (OPERA)



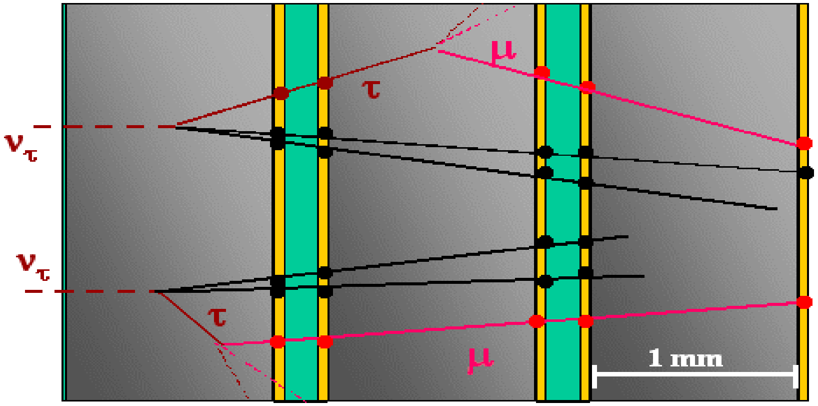
μ spectrometer
Magnetised Iron Dipoles
Drift tubes and RPCs

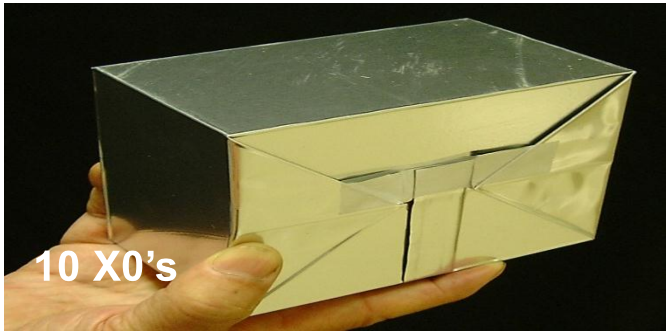
ν target and τ decay detector
Each "supermodule" is
a sequence of 24 "modules" consisting of
- a "wall" of Pb/emulsion "bricks"
- two planes of orthogonal scintillator strips

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

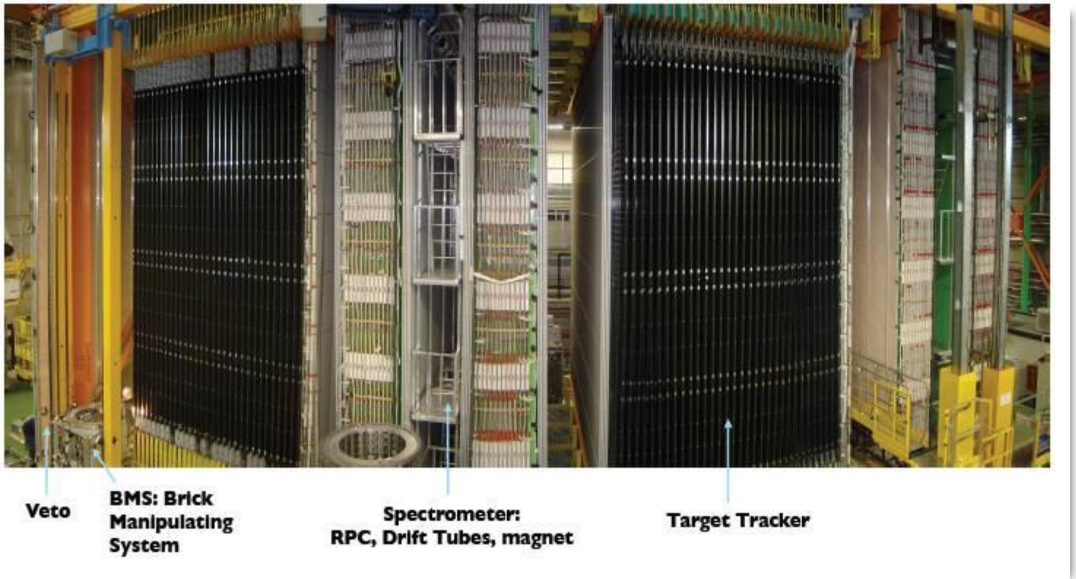
Lead-Emulsion Target

ν



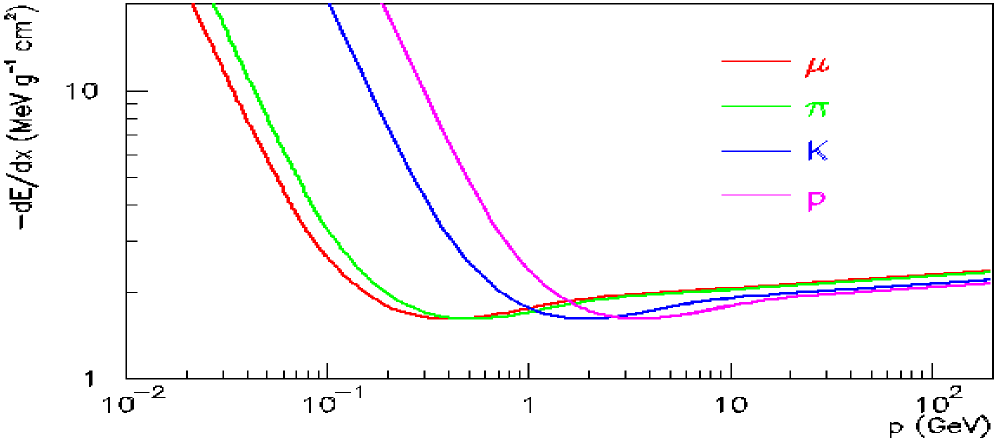


- 1.2kT emulsion detector
  - 146621 bricks, each 8.3kg
  - 56 (1mm) Pb sheets
  - 57 (300mm) FUJI emulsion layers
  - 2 (300mm) changeable sheets (CS)



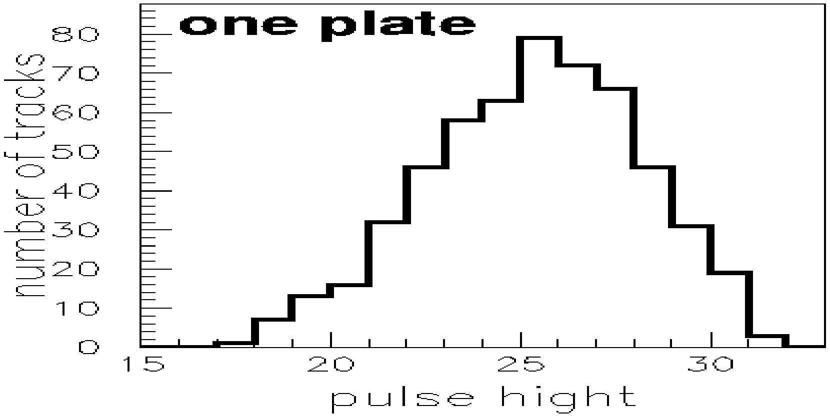
Particle ID in Emulsion

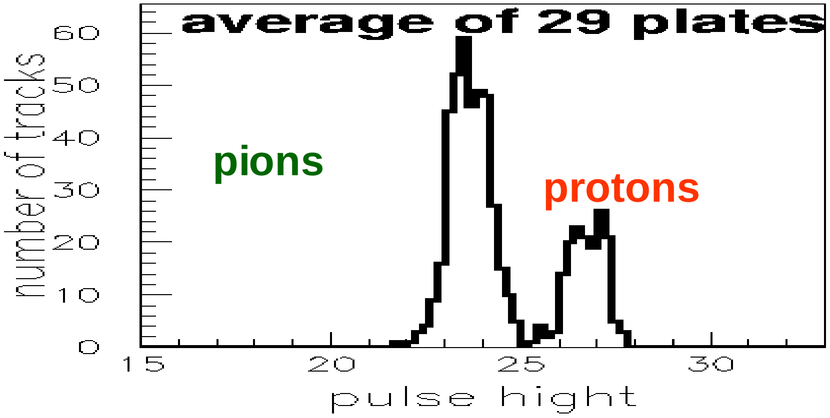
Grain density in emulsion is proportional to dE/dx



By measuring grain density as a function of the distance from the stopping point, particle identification can be performed.

Test exposure (KEK) : 1.2 GeV/c pions and protons, 29 plates

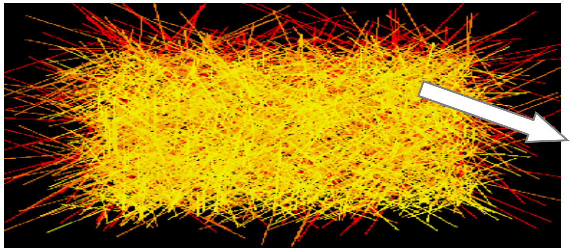




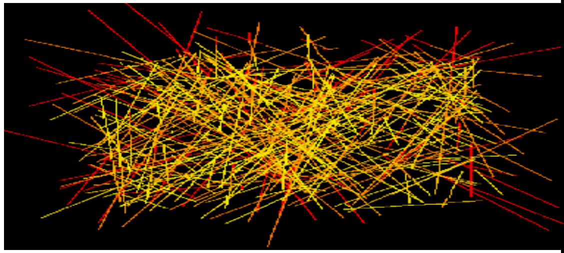
Plots courtesy M. DeSerio

One cannot live by Emulsion alone

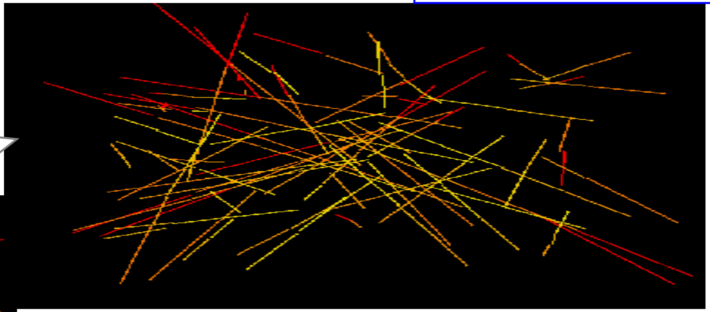
- Need to know when interaction has happened in a brick
- Electronic detectors can be used to point back to which brick has a vertex
- Take the brick out and scan it (don't forget to put a new brick in!)



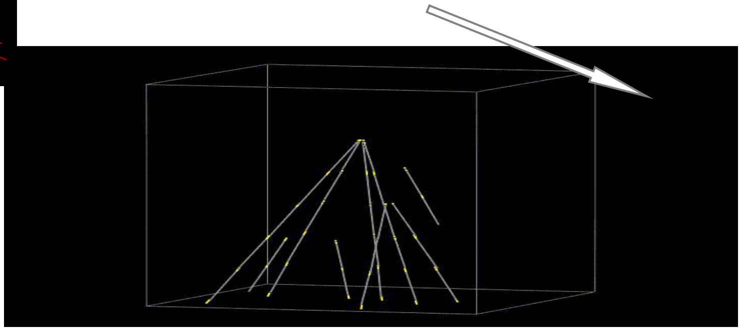
Track segments found in 8 consecutive plates



Connected tracks with >= 2 segments



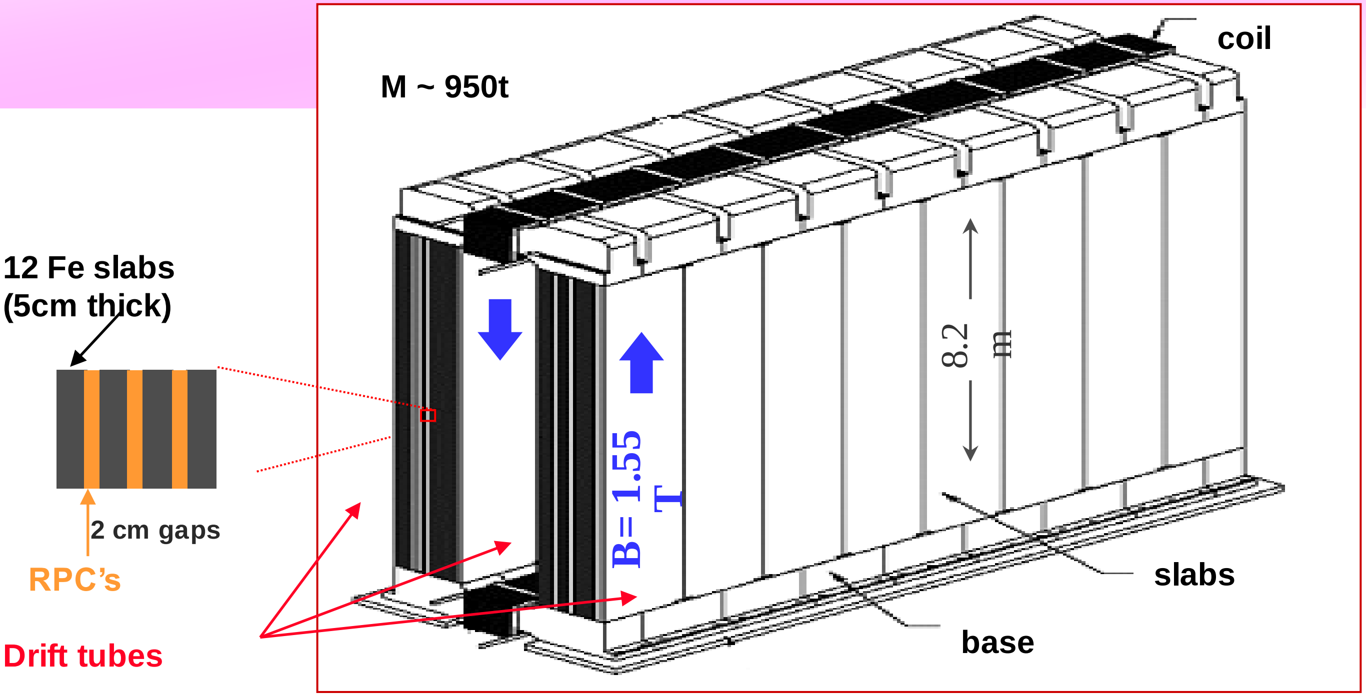
Passing-through tracks rejection



Vertex reconstructin

- Question: what can you use for the "electronic detectors" that point back to the brick?
- (Hint: you've used up most of the money you have to buy emulsion, you need something cheap that can point well anyway)

Muon Spectrometer w/RPC



$\Delta p/p < 20\%$,
$p < 50$ GeV/c

μ charge
Mis-id prob.
$\approx 0.1 \div 0.3\%$

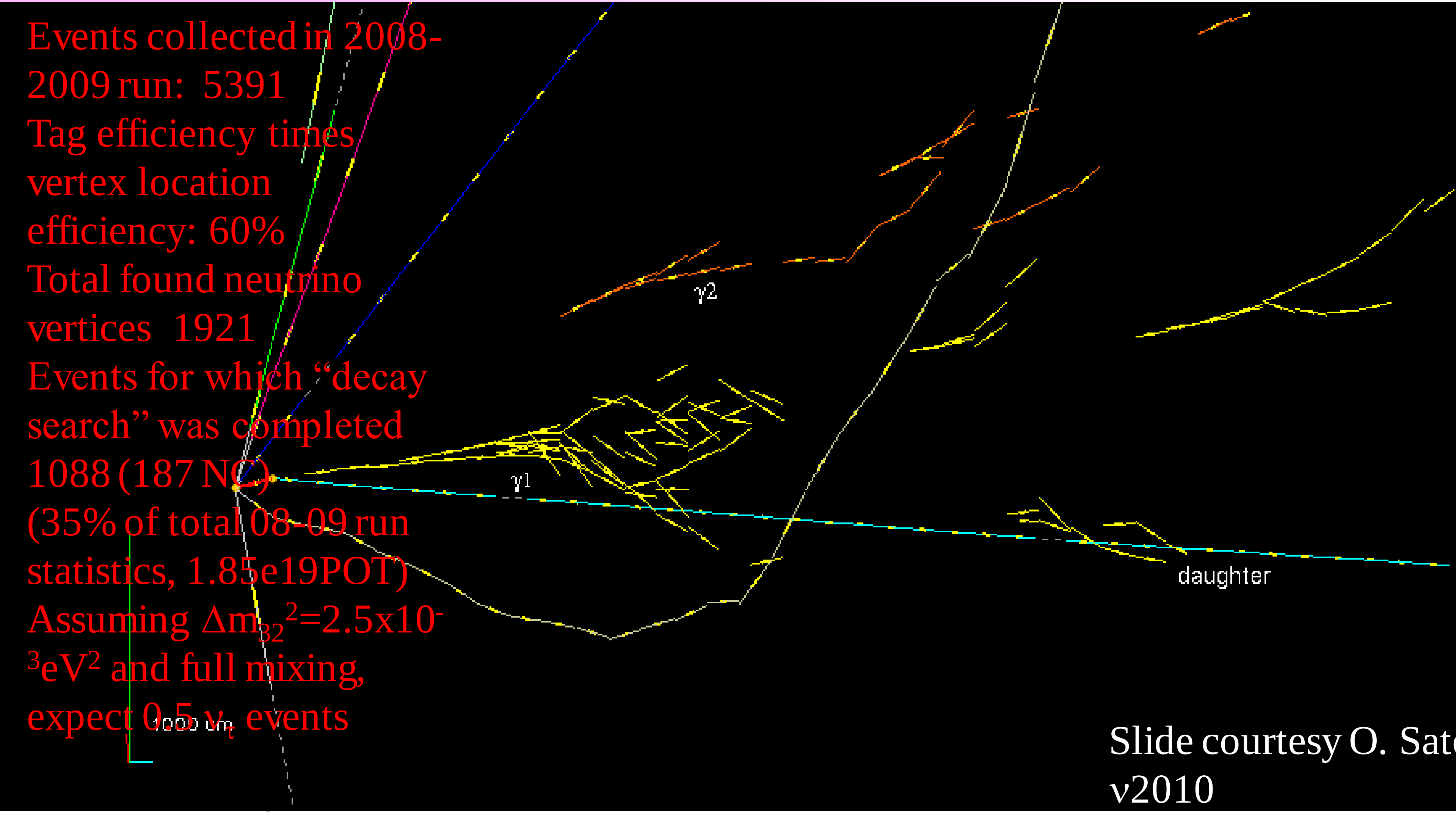
μidentification:
$\mu\varepsilon > 95\%$ (TT)

Precision tracker:
6 planes of drift tubes
diameter 38mm, length 8m
efficiency: ~99%
space resolution: ~300µm

Inner Tracker:
11 planes of RPC's
21 bakelite RPC's ($2.9 \times 1.1 m^2$) / plane
(~1,500m^2 / spectrometer)
pickup strips, pitch:
3.5cm (horizontal), 2.6cm (vertical)

RPC: gives digital information about track: has been suggested for use in several "huge mass steel detectors" (Monolith)

First Tau Neutrino Detected



Events collected in 2008-2009 run: 5391

Tag efficiency times vertex location efficiency: 60%

Total found neutrino vertices 1921

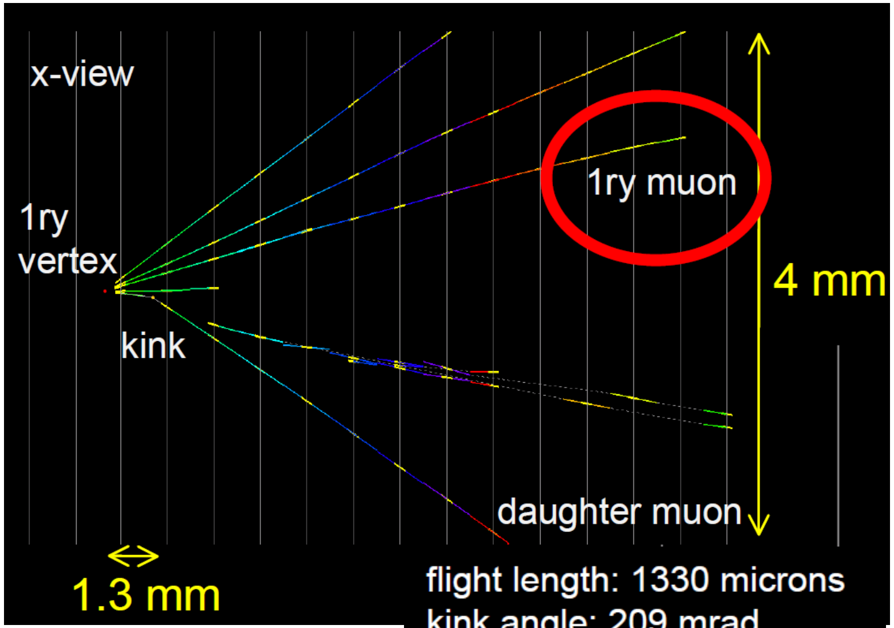
Events for which "decay search" was completed 1088 (187 NC) (35% of total 08-09 run statistics, 1.85e19POT)

Assuming $\Delta m_{32}^2 = 2.5\text{x}10^{-3}\text{eV}^2$ and full mixing, expect 0.5 ν_τ events

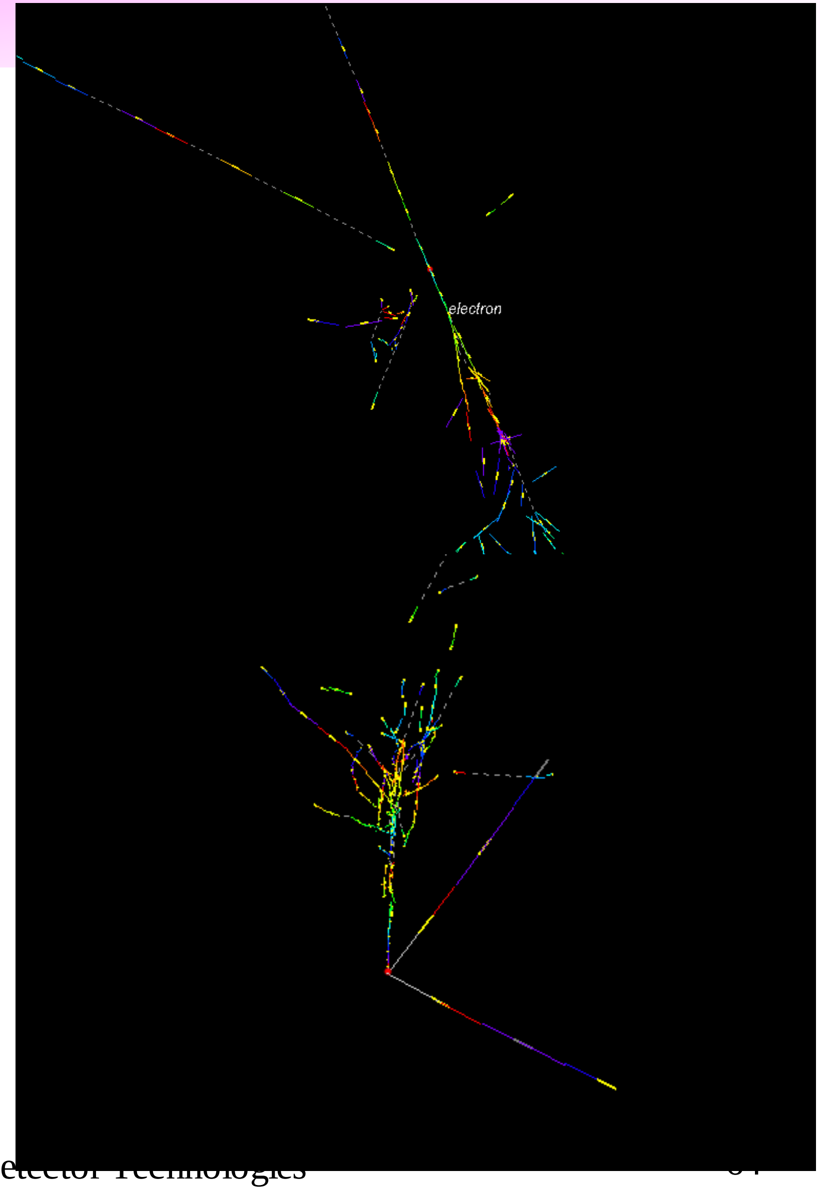
Slide courtesy O. Sat
ν2010

Other interesting events from OPERA

- Charm candidates, and 6 electron neutrino candidates out of 800 located vertices (2 at right)

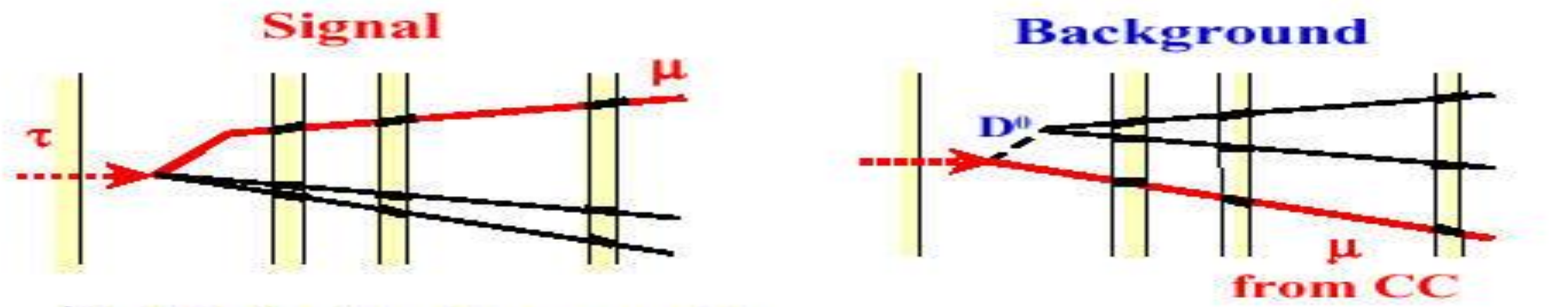


flight length: 1330 microns
kink angle: 209 mrad
IP of daughter: 262 microns
daughter muon: 2.2 GeV/c
decay Pt: 0.46 GeV/c

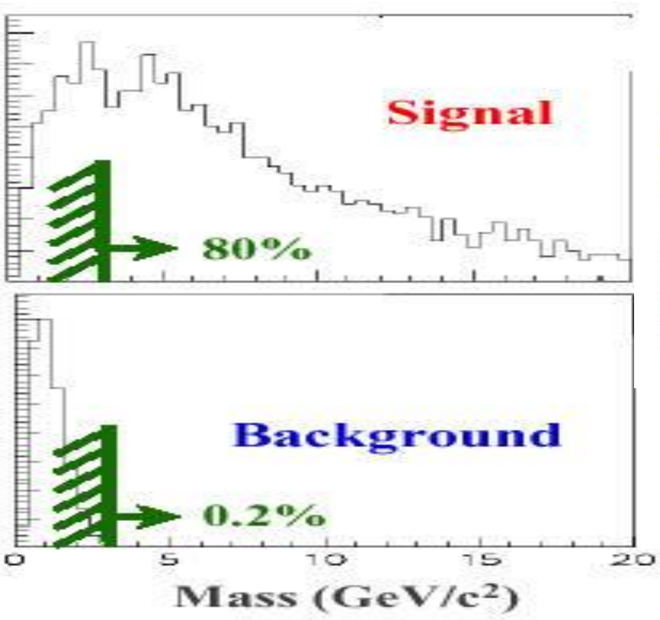


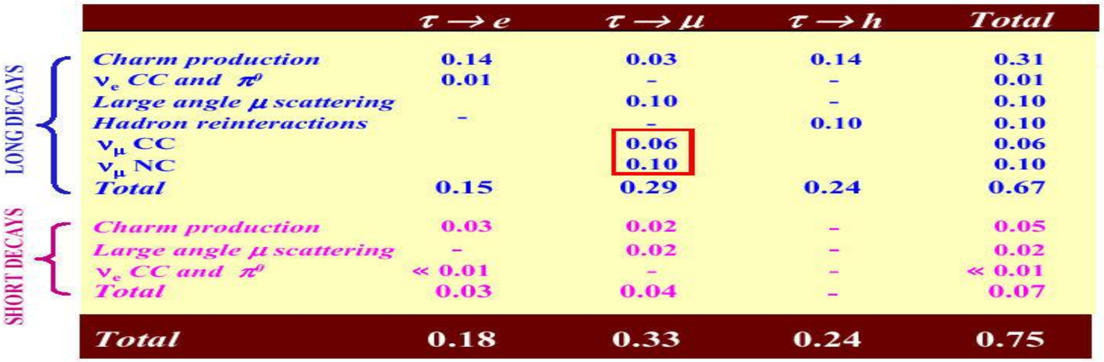
O. Sato, ν2010

ν_τ backgrounds



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





		$\tau \rightarrow e$	$\tau \rightarrow \mu$	$\tau \rightarrow h$	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		0.06		0.06
	ν_μ NC		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

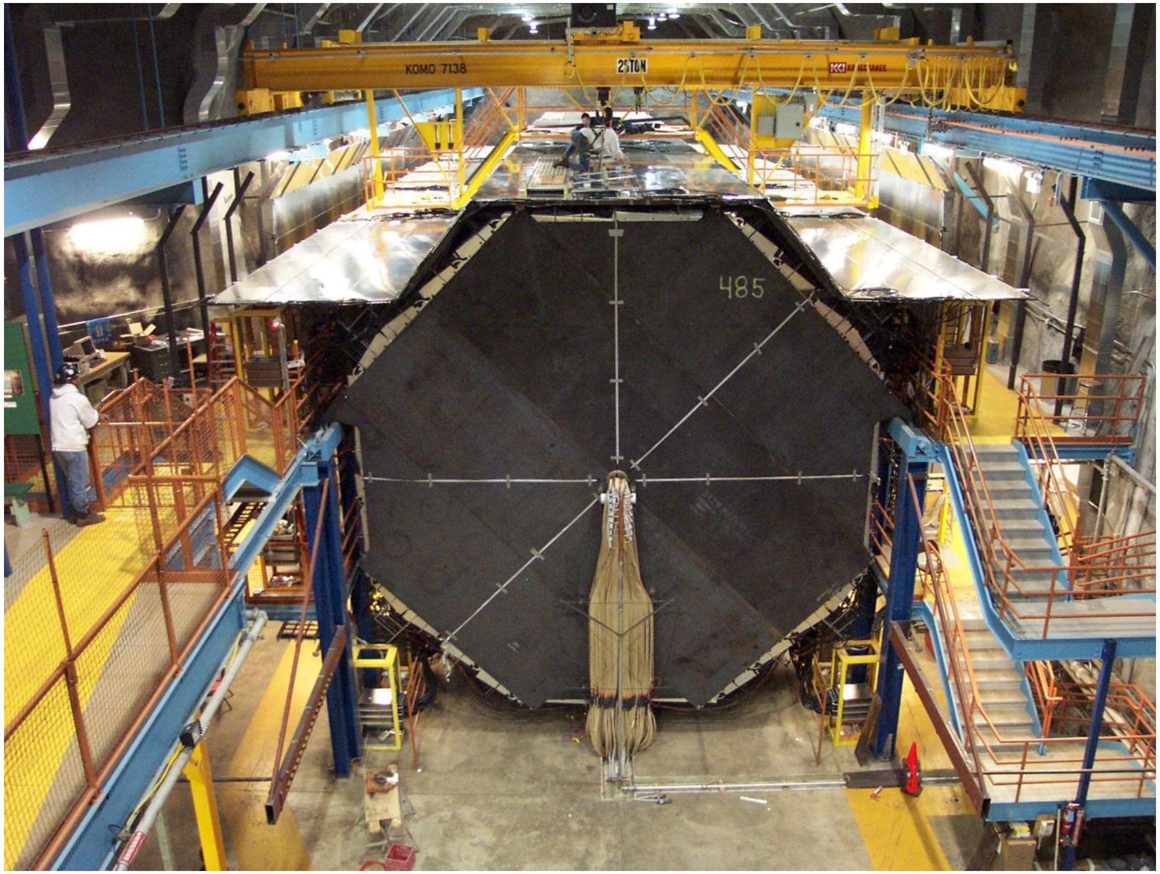
- Cut on invariant mass of primary tracks

Outstanding Issues

Emulsion Sampling

- For future neutrino factory experiments, could study $\nu_e \rightarrow \nu_\tau$
- For either of these topics, need to understand if/how magnetic field can be made…
- Any way to make this detector more massive and still affordable?

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

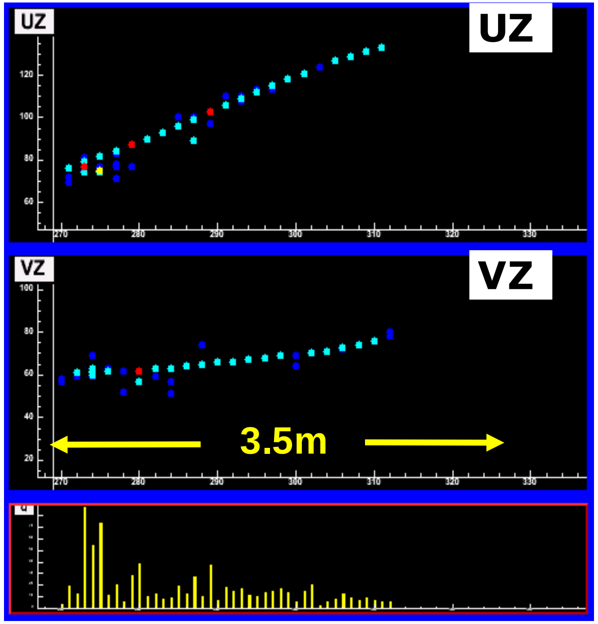
MINOS Detector Components

Detector module with 20 scintillator strips

Assembled plane ready to be lifted

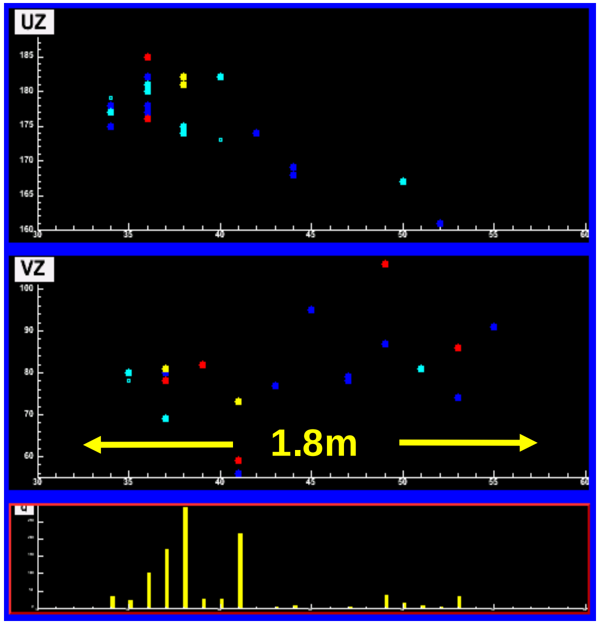
Simulated MINOS Events

ν_μ CC Event



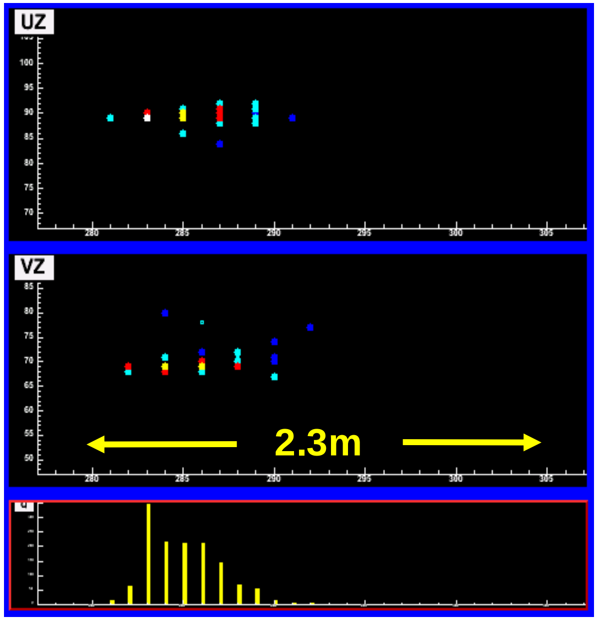
- Long muon track + hadronic activity at vertex

NC Event



- Short showering event, often diffuse

ν_e CC Event



- Short event with typical EM shower profile

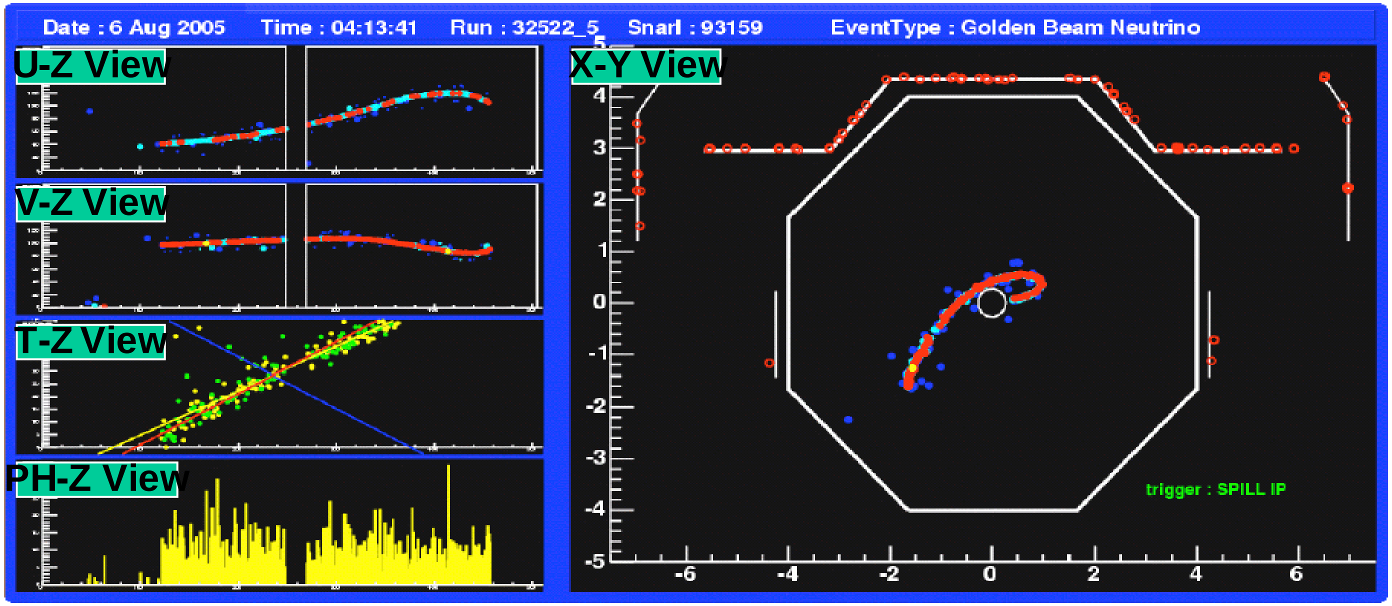
$$E_\nu = E_{\text{shower}} + P_\mu$$

Shower energy resolution: 55%/$\sqrt{E}$

Muon momentum resolution: 6% range; 13% curvature

Courtesy Chris Smith, FNAL Seminar

Beam Events at MINOS (Far)

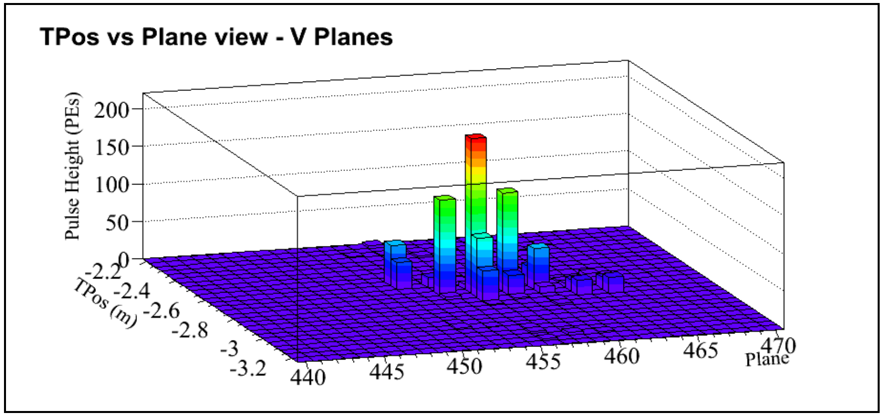


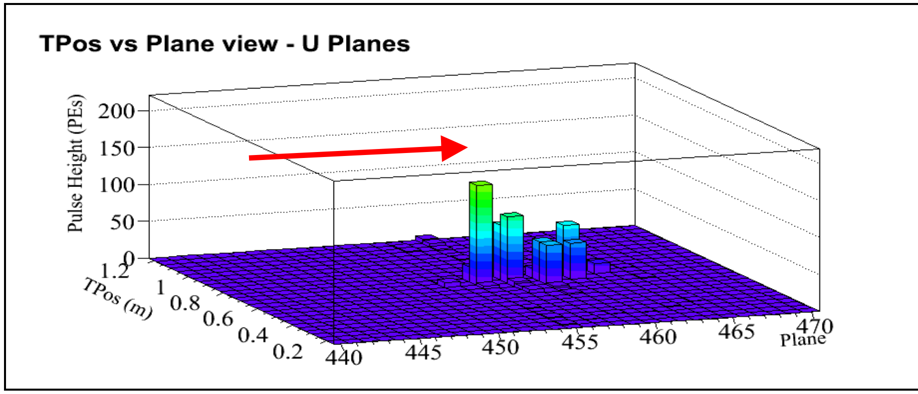
ν_μ CC (left)

ν_e CC candidate (bottom)

Remember: 2.5cm thick steel plates ($\sim 1.5 X_0$)

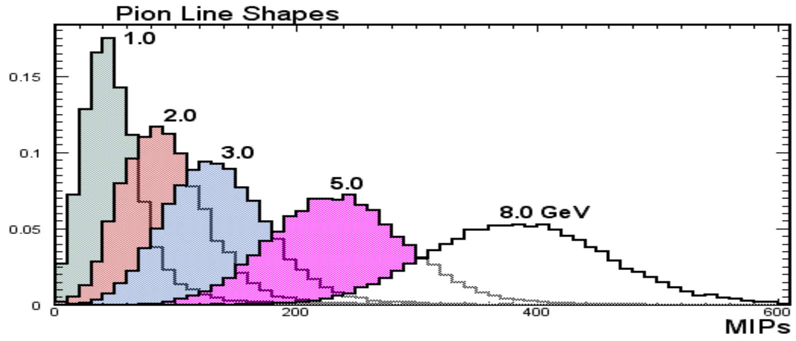
(Courtesy C. Smith, FNAL seminar)

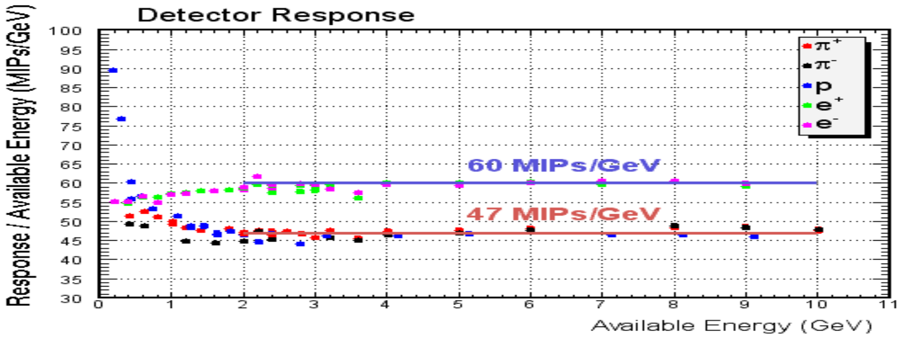


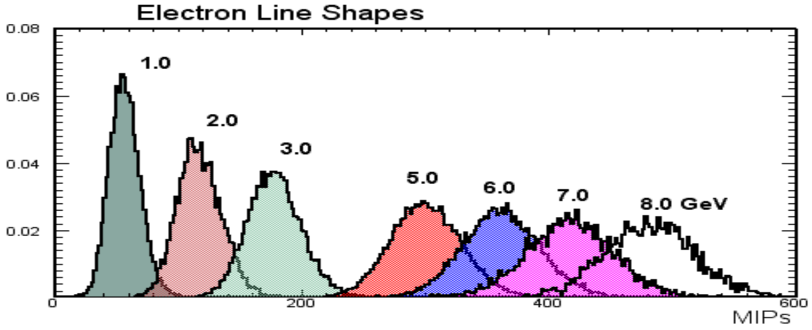


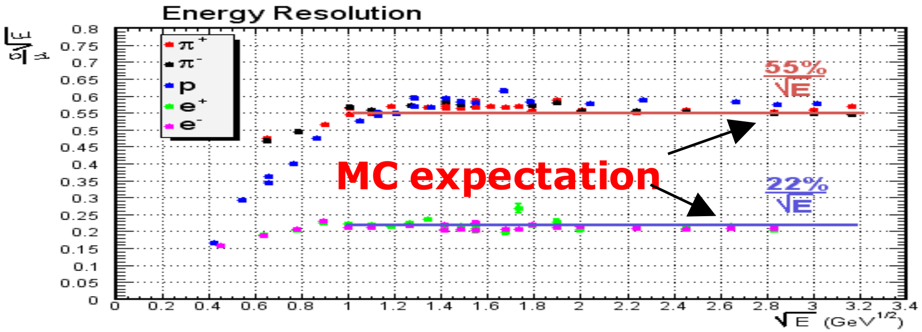
Steel Scintillator Response

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



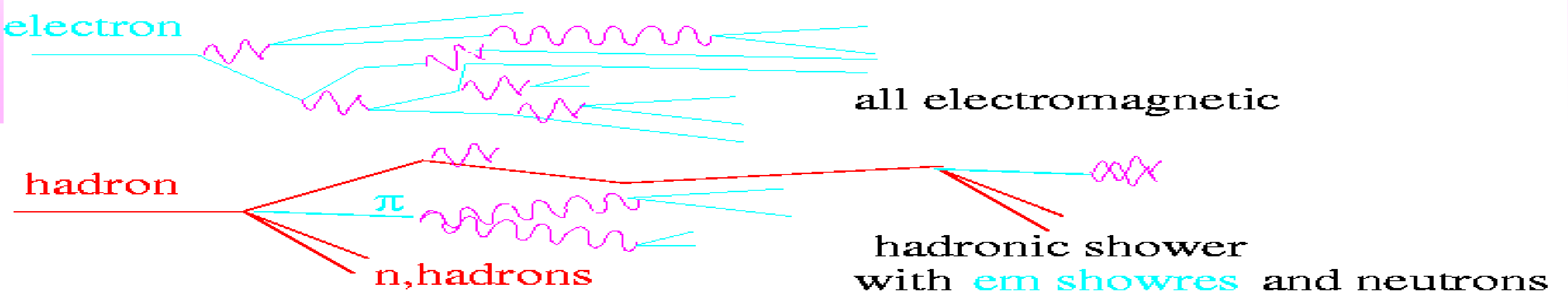




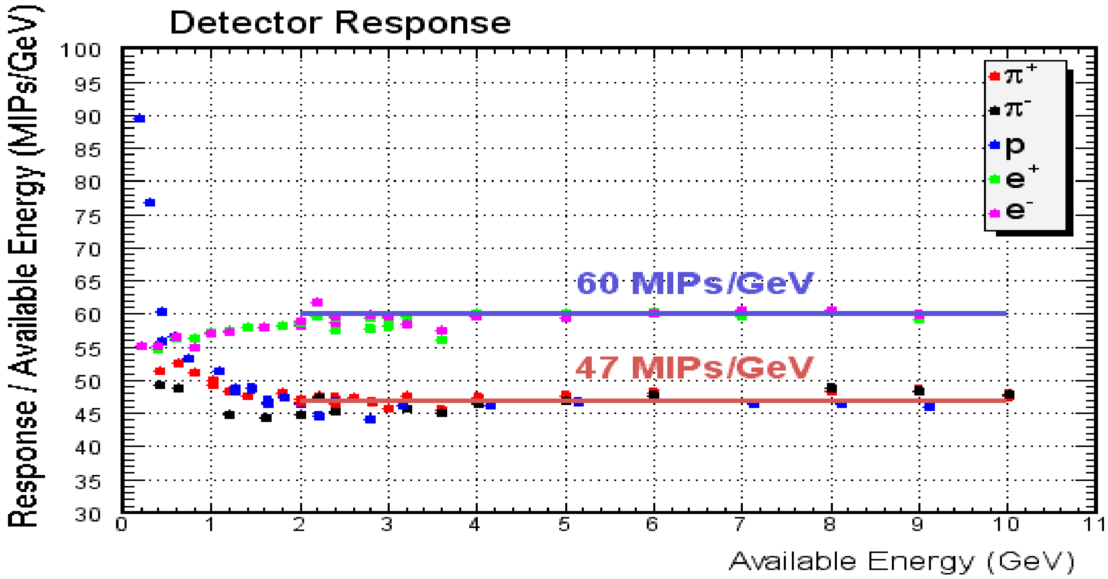


- ★Provides calibration information
- ★Test of MC simulation of low energy hadronic interactions
- ★Question: why might EM response be higher than hadronic response?

Hadron/Electron Comparison



- Electromagnetic response: photons always convert to electrons which deposit all their energy nearby
- Hadronic response: when neutrons are created in the shower, they don’t deposit energy nearby, and often just get absorbed!



Outstanding Issues

Steel/Scintillator

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

Detector Scorecard

Detector Technology	Largest Mass to Date (kton)	Event by Event Identification			+/-?	Ideal ν 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

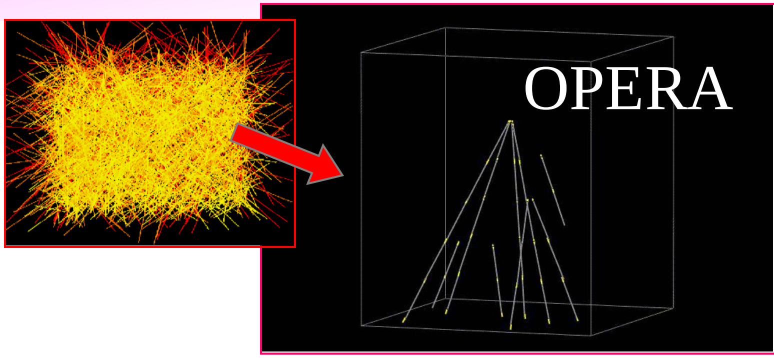
There are huge detector demands on the next generation of detectors

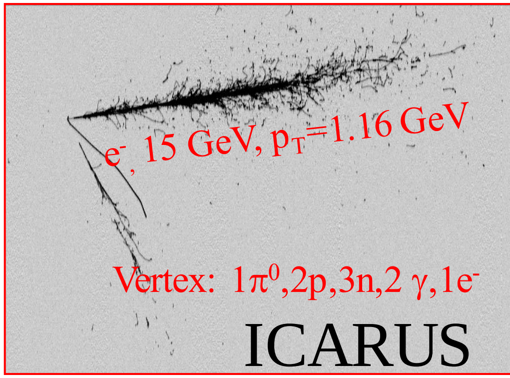
1. Size*signal efficiency
2. Background rejection (NC)
3. "Ability to do other physics"

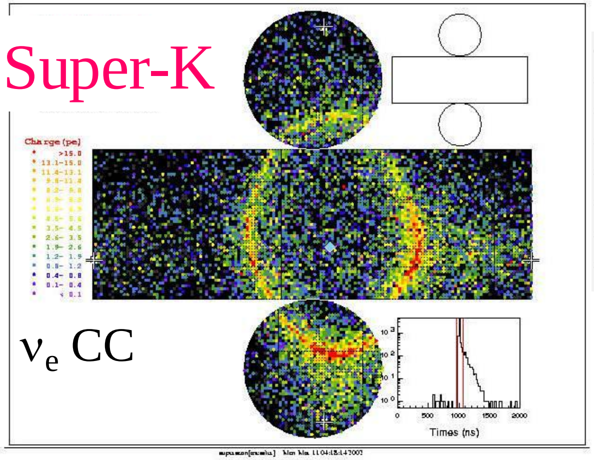
Water Cerenkov the most economical choice, but we need more to get to high energies and matter effects!

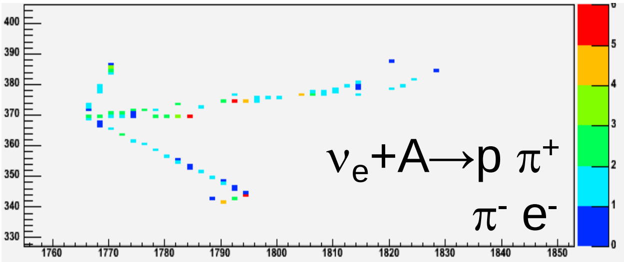
Neutrino Experiments: Detectors past, present, and near future…

Exp’t	**ν Energy (GeV)**	**Detector Technology**
MINOS	2-6	Steel Scintillator
MINERvA	1-20	Solid Scintillator
OPERA	15-25	Emulsion-Lead
ICARUS	15-25	Liquid Argon TPC
T2K	0.7	Water Cerenkov
NOvA	2	Segmented Scintillator

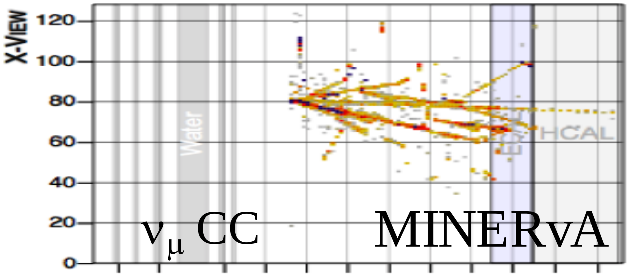




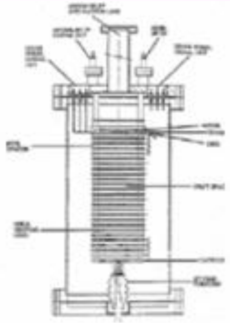




NOvA



The ICARUS steps

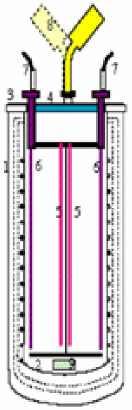


24 cm drift wires chamber

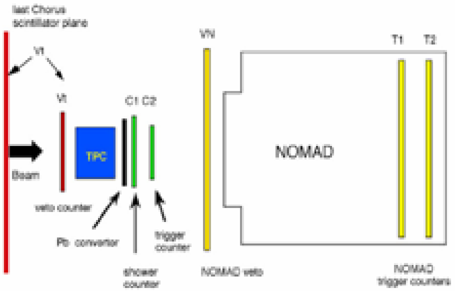
1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

3 ton prototype

1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.



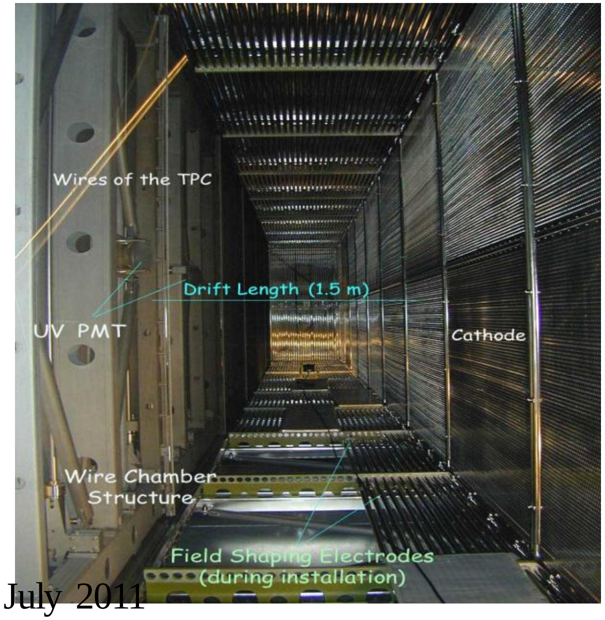
50 litres prototype
1.4 m drift chamber



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.



600 ton detector

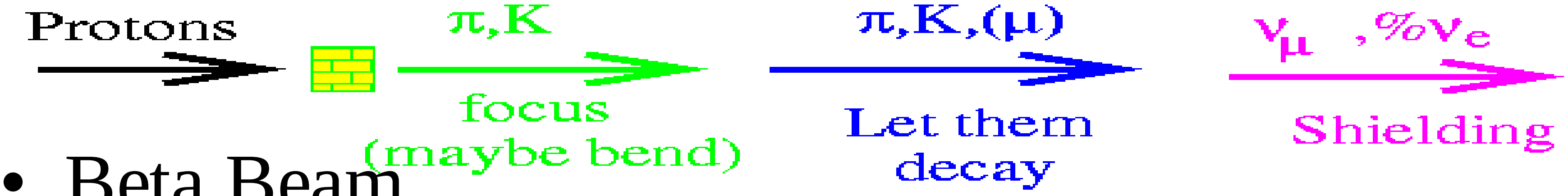
2001: 300 ton detector tested on surface in Pavia. 600 ton

2010: 600 ton detector operational at LNGS.

NIM A 527 (2004) 329

Making a Neutrino Beam

- Conventional Beam



Protons

π,K

focus

(maybe bend)

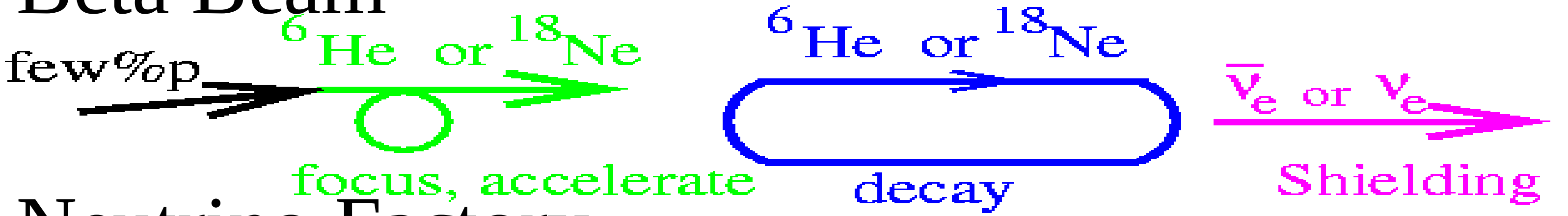
π,K,(μ)

Let them decay

ν_μ ,%ν_e

Shielding

- Beta Beam



few%p

^{6}He or ^{18}Ne

focus, accelerate

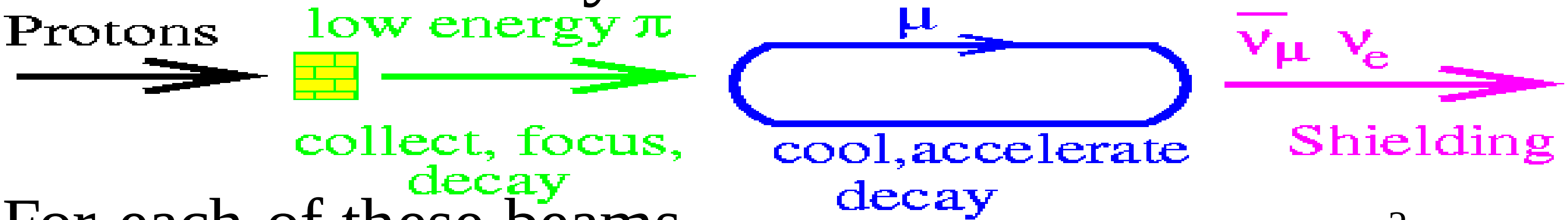
^{6}He or ^{18}Ne

decay

$\bar{\nu}_e$ or ν_e

Shielding

- Neutrino Factory



Protons

low energy π

collect, focus, decay

μ

cool,accelerate decay

$\bar{\nu}_\mu$ ν_e

Shielding

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

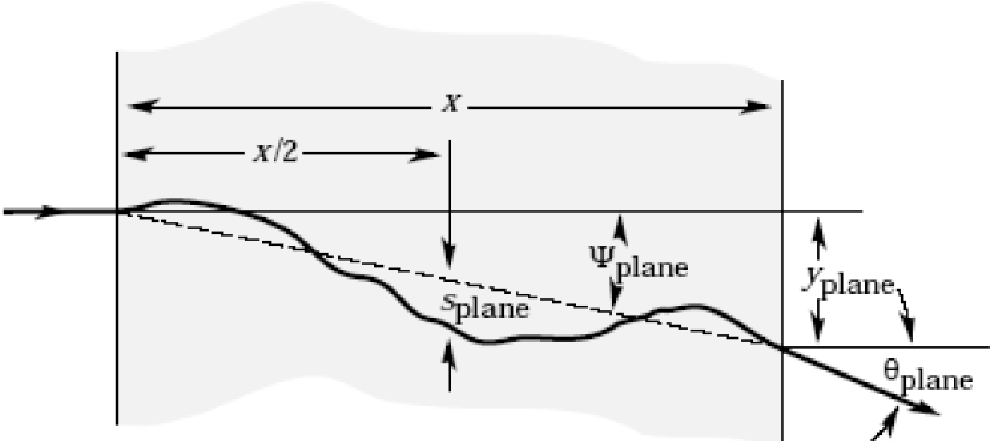
$$\Phi_\upsilon \propto \gamma^2$$

$$\sigma \propto \gamma$$

Multiple Scattering

- While particles move through material, they also will change direction
- Large number of scatters means that the process is statistical, with Gaussian statistics
- This is particularly important in steel, which of course gets used for muon momentum measurements

W.-M. Yao et al., Journal of Physics G 33, 1 (2006)
available on the PDG WWW pages (URL: http://pdg.lbl.gov/)

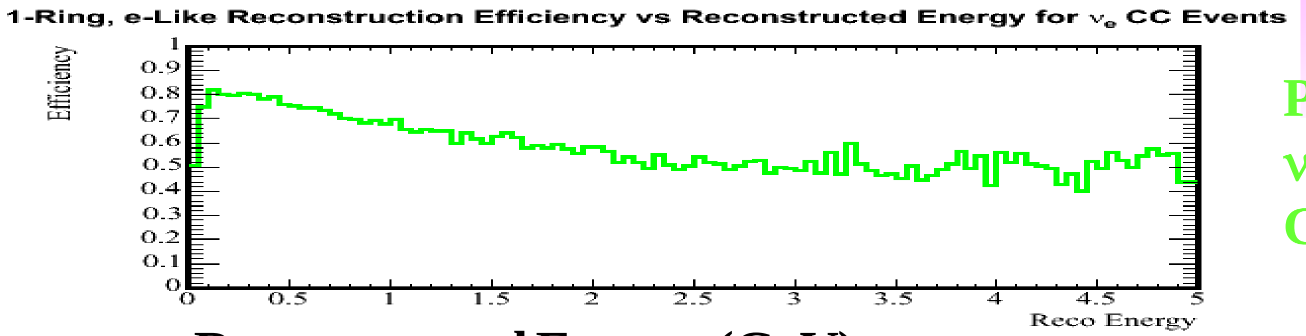


$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]$$

$$\theta_0 = \theta_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{2}}\,\theta_{\text{space}}^{\text{rms}}$$

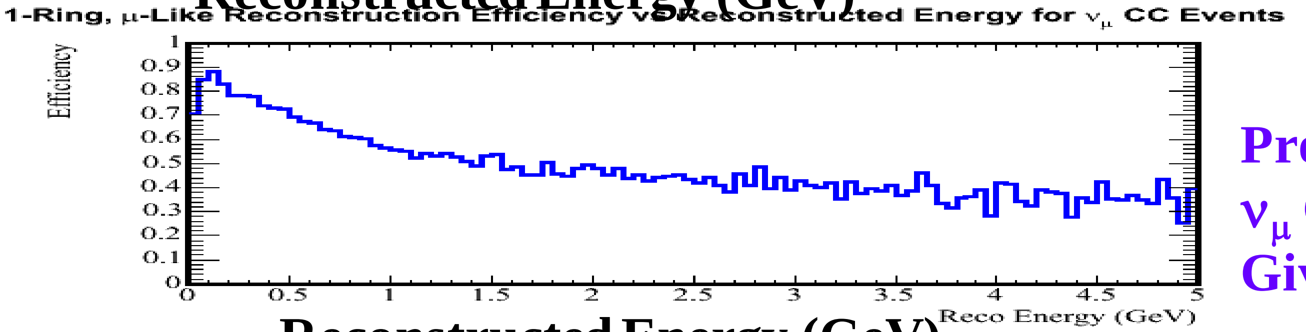
$$\psi_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{3}}\,\theta_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{3}}\,\theta_0\ ,$$

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



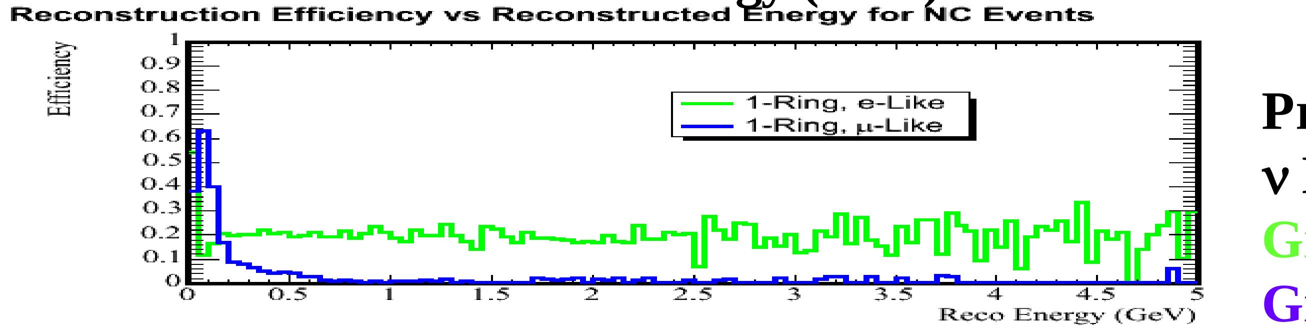
Reconstructed Energy (GeV)

Probability of
ν_e CC
Giving 1 e-like ring



Reconstructed Energy (GeV)

Probability of
ν_μ CC
Giving 1 μ-like ring



Reconstructed Energy (GeV)

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

- Again, courtesy Mark Messier, for Fermilab to Homestake Study