

# Neutrino Experiments

## Lecture II

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Fermilab

July 9-11, 2014

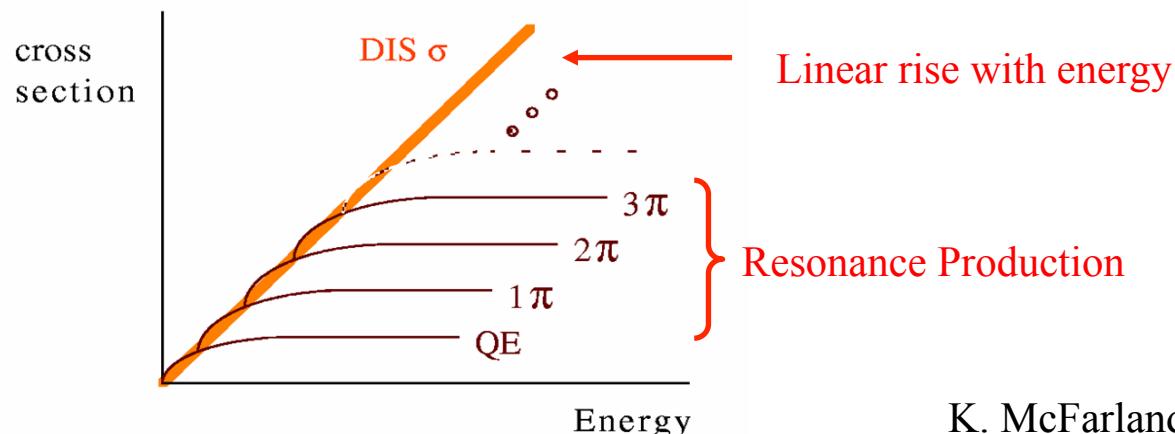
Invisibles School 2014  
Gif-sur-Yvette, FRANCE

9-11 July 2014

Deborah Harris, Fermilab: Neutrino Experiments

# Neutrino-Nucleon Scattering

- Charged - Current:  $W^\pm$  exchange
  - Quasi-elastic Scattering:  
**(Target changes but no break up)**  
 $\nu_\mu + n \rightarrow \mu^- + p$
  - Nuclear Resonance Production:  
**(Target goes to excited state)**  
 $\nu_\mu + n \rightarrow \mu^- + p + \pi^0$  ( $N^*$  or  $\Delta$ )  
 $n + \pi^+$
  - Deep-Inelastic Scattering:  
**(Nucleon broken up)**  
 $\nu_\mu + \text{quark} \rightarrow \mu^- + \text{quark}'$
- Neutral - Current:  $Z^0$  exchange
  - Elastic Scattering:  
**(Target unchanged)**  
 $\nu_\mu + N \rightarrow \nu_\mu + N$
  - Nuclear Resonance Production:  
**(Target goes to excited state)**  
 $\nu_\mu + N \rightarrow \nu_\mu + N + \pi$  ( $N^*$  or  $\Delta$ )
  - Deep-Inelastic Scattering  
**(Nucleon broken up)**  
 $\nu_\mu + \text{quark} \rightarrow \nu_\mu + \text{quark}'$

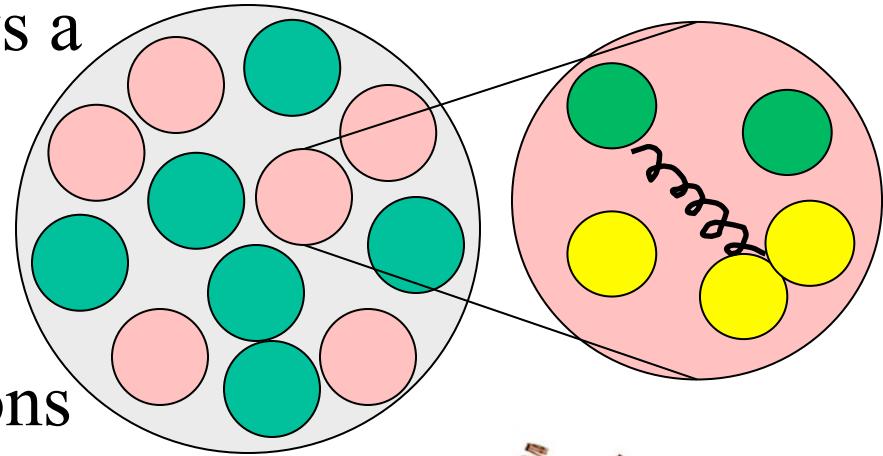


K. McFarland, INSS 2013

# Scattering off Nuclei

- The fundamental theory allows a complete calculation of neutrino scattering from quarks
- But those quarks are in nucleons (PDFs), and those nucleons are in a strongly interacting tangle
- Imagine calculating the excitations of a pile of coupled springs. Very hard in general.

To be discussed in 3<sup>rd</sup> lecture...



# Summary for Neutrino Interactions

- Total cross section proportional to neutrino energy
- Angular dependence because of  $\nu$  helicity and conservation of spin
  - Consequence: neutrinos have higher cross section on matter than anti- $\nu$ 's
- $\nu$ -e scattering is the ONLY perfectly known cross section
  - Everything else is more complicated: **NEED BETTER THEORY PREDICTIONS!**
- The higher the  $\nu$  energy, the more final state particles produced
  - Those particles can produce backgrounds to your oscillation analysis!

Source	$\nu$ Energy	Composition	Reactions
Sun	0.1-10MeV	$\nu_e$ ( $\nu_2$ )	$\nu$ -e or CCQE
Reactor	0.1-10MeV	Anti- $\nu_e$	CCQE
Atmosphere	0.1-1000GeV	$\nu_e + \nu_\mu$	CCQE+RES+DIS
Accelerator	0.1-100GeV	$\nu_\mu + \% \nu_e$ or anti- $\nu_\mu + \% \nu_e$	CCQE+RES+DIS

# Lecture II: Neutrino Detectors



- Introduction
  - What are neutrino detector goals?
- 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 ( $e, \mu, \tau$ )
  - Measure neutrino energy
    - Charged Current Quasi-elastic Events
      - In principle, all you need is the lepton angle and energy (*derive*)
    - 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..

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

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

$$\nu N \rightarrow l X$$

# Neutrino Oscillation Goals vs ν Sources

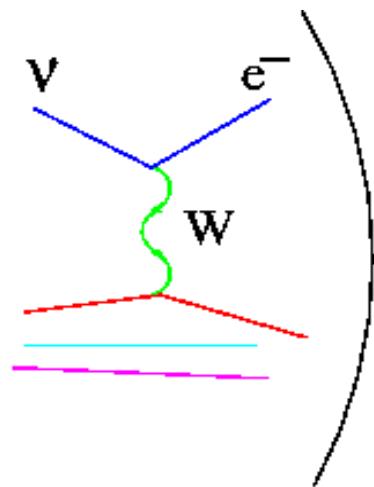


- Sun (all  $\nu_e$ )
  - Neutrino energy too low to make  $\mu$  or  $\tau$
  - For electron scattering, can use direction to the sun
- Reactors (all anti- $\nu_e$ )
  - Neutrino energy too low to make  $\mu$  or  $\tau$
  - Need to identify anti- $\nu_e$  only, can only get e energy
- Atmosphere ( $\nu_\mu$ ,  $\nu_e$  and anti- $\nu_\mu$ , anti- $\nu_e$ )
  - Need to identify at least muons
  - Get baseline from direction of outgoing e or  $\mu$
- Conventional Beams ( $\nu_\mu$ , % $\nu_e$ )
  - Identify muon in final state

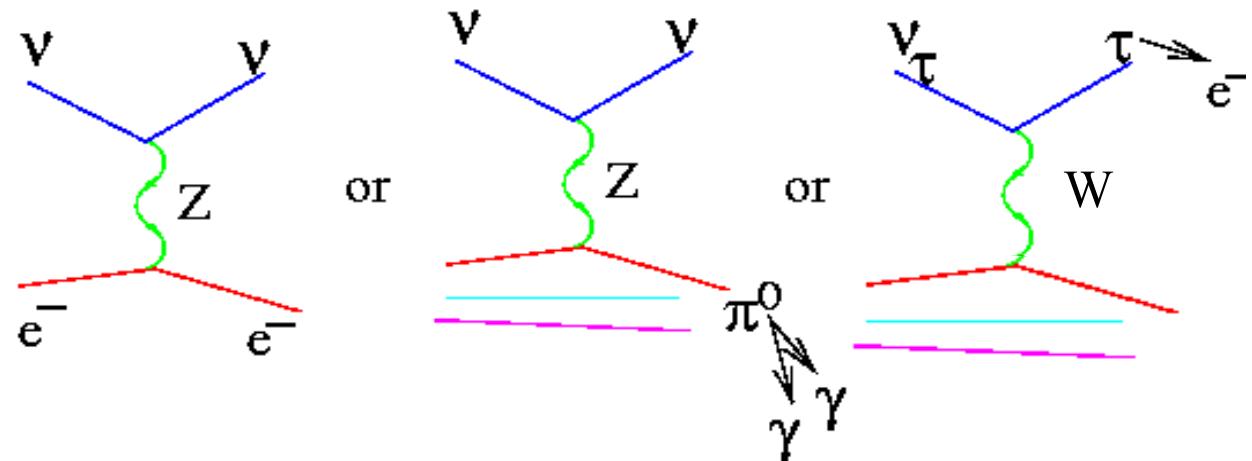
# Detectors and Backgrounds...

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

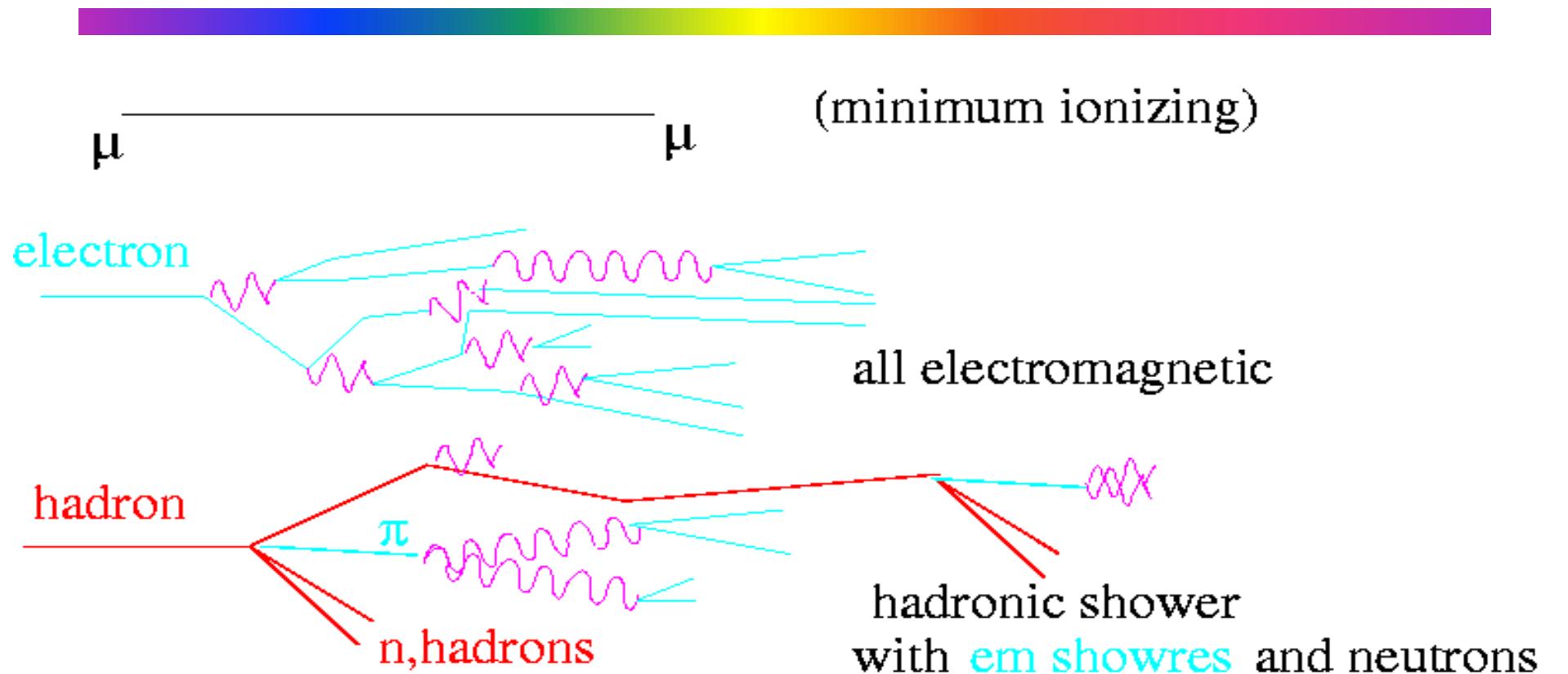
Charged Current



Neutral Currents



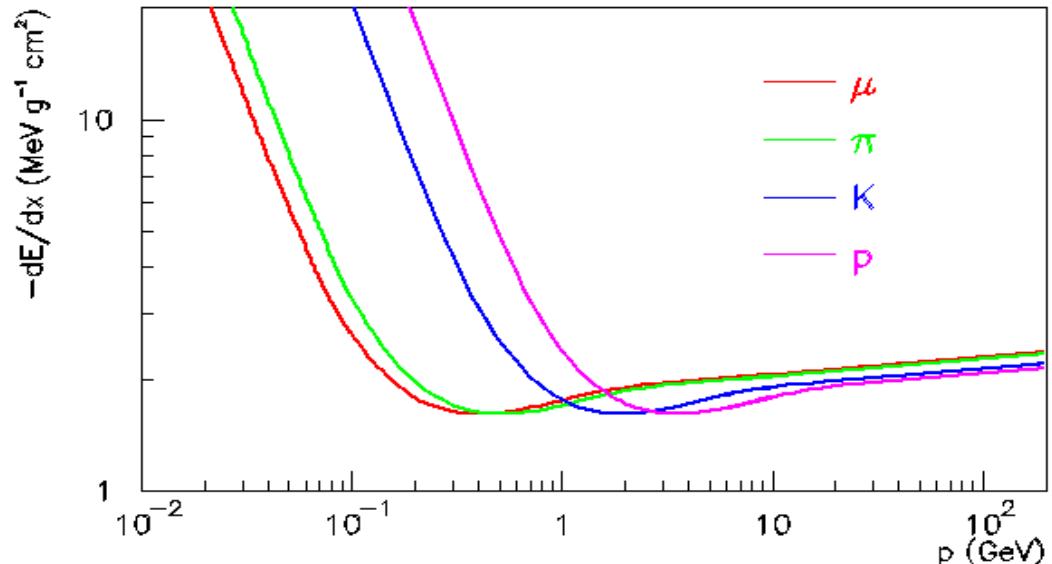
# Three kinds of particle signatures



- 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 lose energy through ionization
  - For Hadron:  $\text{range} < \lambda_{\text{INT}}$
  - For Electron:  $\text{range} < X_0$
- Bethe-Bloch Equation
- Typical value:  $2 \text{ MeV} \cdot \text{cm}^2/\text{g}$
- $x$  in units of  $\text{g}/\text{cm}^2$
- Energy Loss Only  $f(\beta)$



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

- Can be used for Particle ID in range of momentum

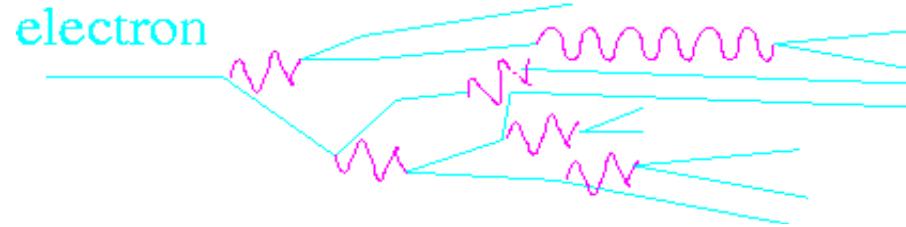
# $dE/dx$ in common detector materials



- 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

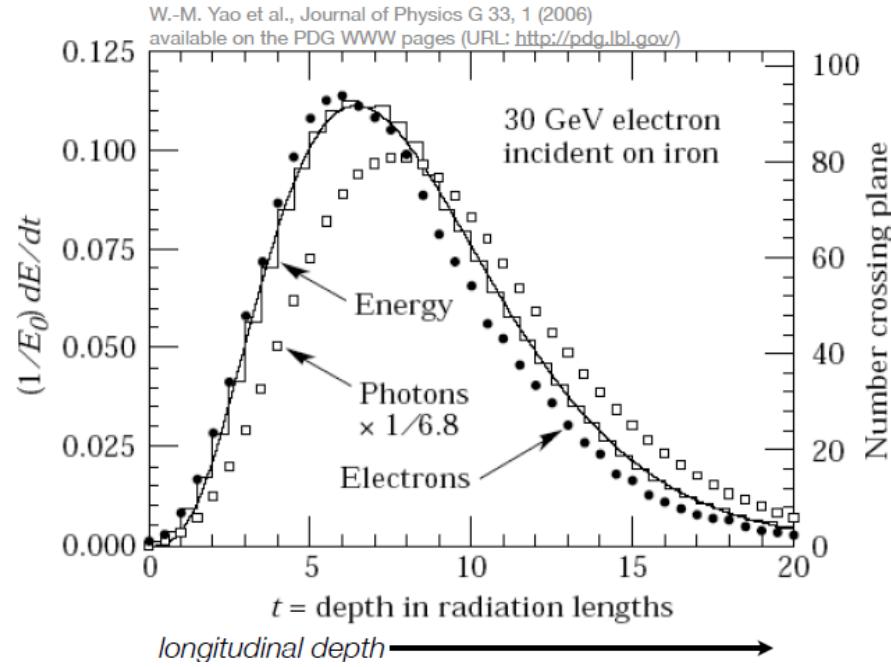
Material	Minimum Ionizing $dE/dx$ (MeV/cm)
Liquid Argon	2.1
Water	2.0
Steel	11.4
Scintillator (CH)	1.9
Lead	12.7

# 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

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



Shower Maximum:

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

$$C_e = -0.5, C_\gamma = 0.5$$

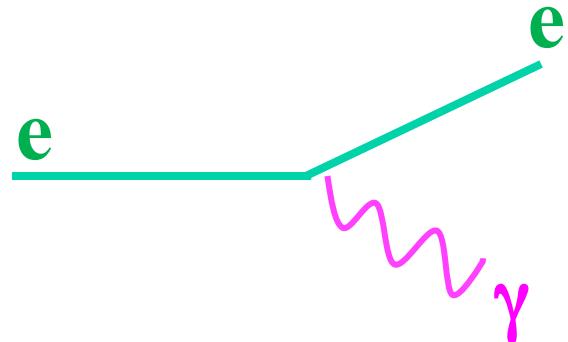
# Radiation Length

- 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 bremsstrahlung
- Distance over which photons will  
pair produce is related:  $\lambda = 9/7 X_0$

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

- Transverse EM shower development:  
determined by Moliere radius

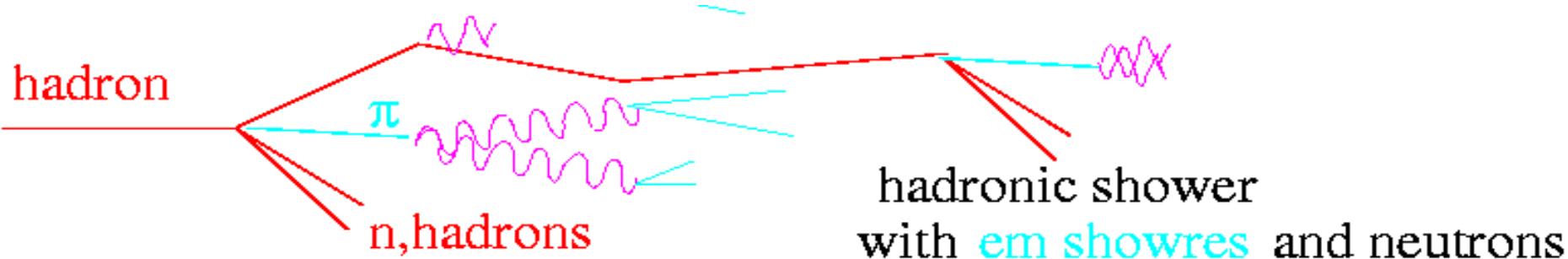
$$R_M = X_0 \frac{21.2 \text{ MeV}}{E_C}$$



Material	$X_0$ (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

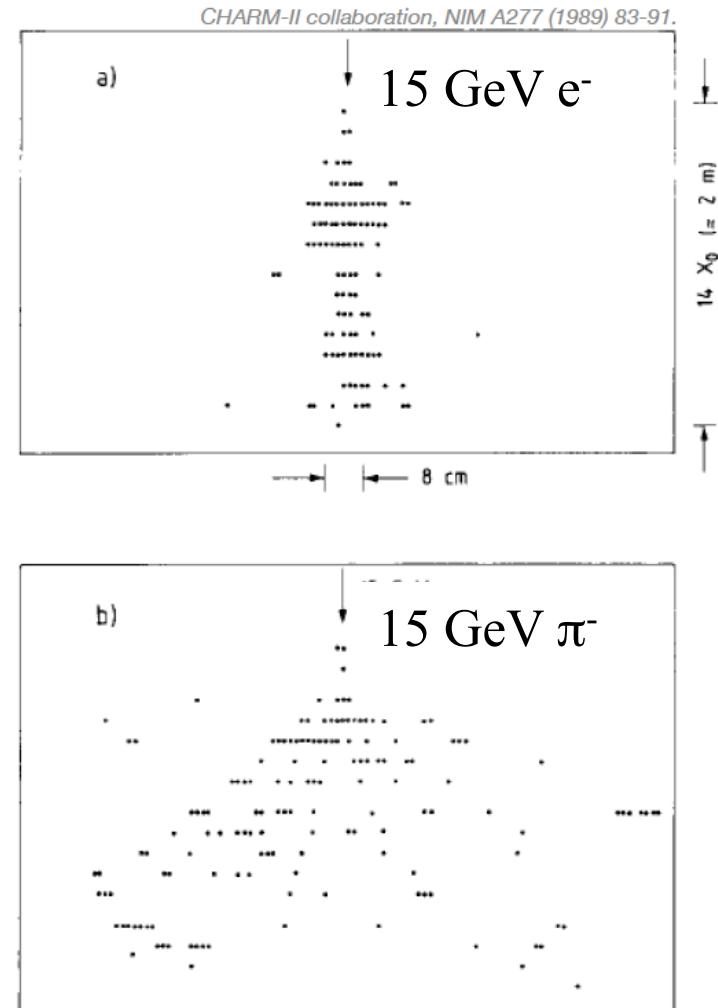


- Instead of a radiation length, now there is an interaction length,  $\lambda_I$ , defined by the average distance a hadron travels before it undergoes a strong (nuclear) interaction
- The catch: sometimes  $\pi^0$ 's are produced which decay to photons which then proceed electromagnetically
- Another 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  $f(\sim A/Z^2)$

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



# Particles passing through material



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

Material	$X_o$ (cm)	$\lambda_{\text{INT}}$ (cm)	$dE/dx$ (MeV/cm)	Density (g/cm <sup>3</sup> )
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



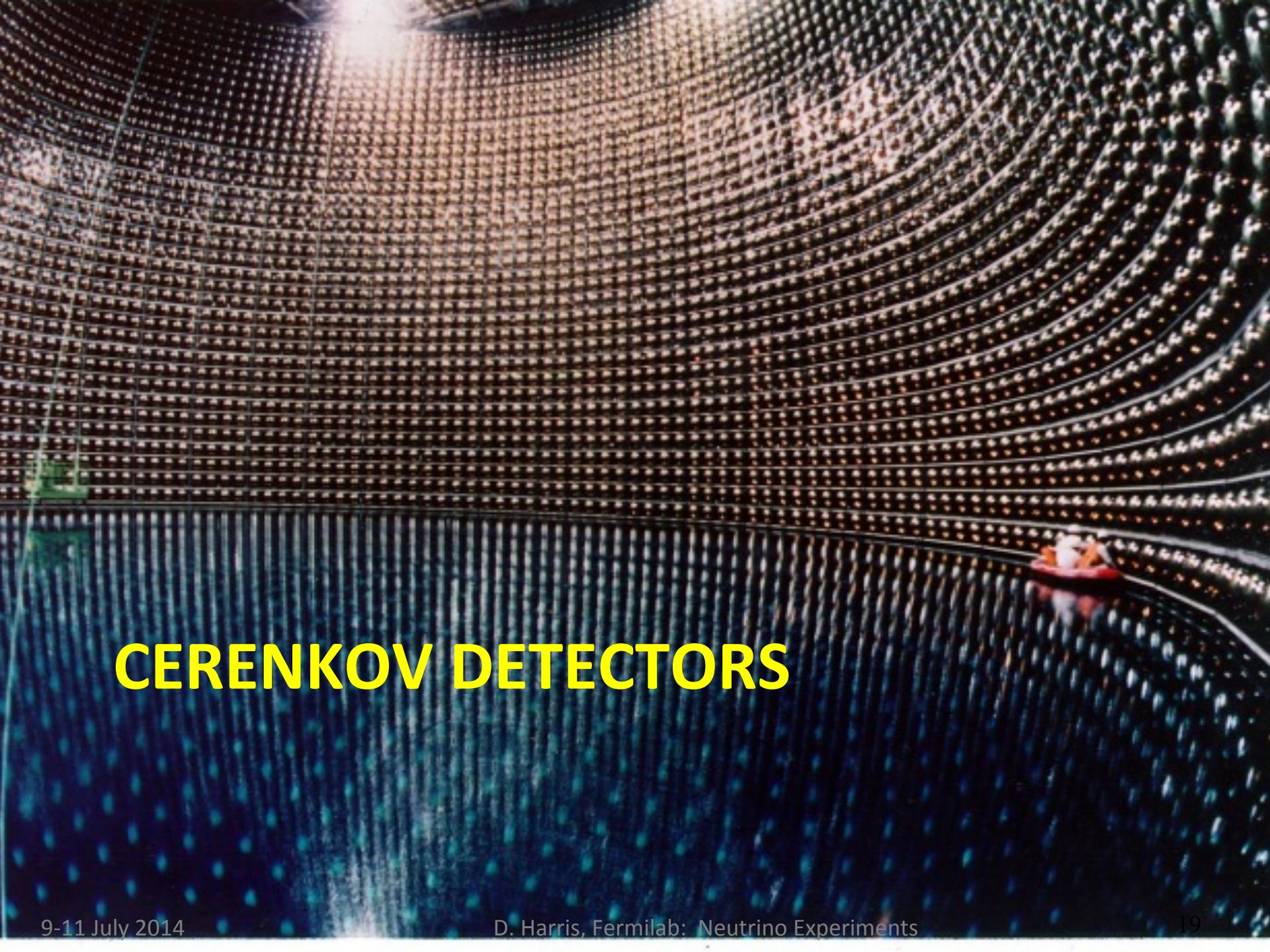
- Cerenkov Detectors
  - Water Cerenkov
  - Heavy Water Cerenkov
- Scintillator Detectors
  - Liquid Scintillator (Reactor Energies)
  - Segmented scintillator
- Active/Passive Detectors
  - Steel plus tracker
  - Emulsion
  - Ice
- Liquid Argon TPC

# For Each Detector



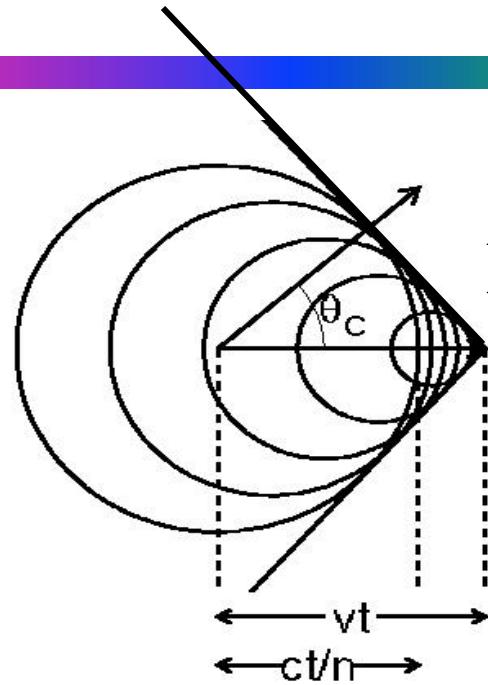
- Underlying principle
- Example from real life
- What do  $\nu$  events look like?
  - Neutrino-electron scattering
  - Quasi-elastic Charged Current
  - Inelastic Charged Current
  - Neutral Currents
- Backgrounds
- Neutrino Energy Reconstruction
- What else do we want to know?

All detector questions are far from  
answered!



# CERENKOV DETECTORS

# Cerenkov Light



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

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

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

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

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

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

# Cerenkov Analogy with Sound

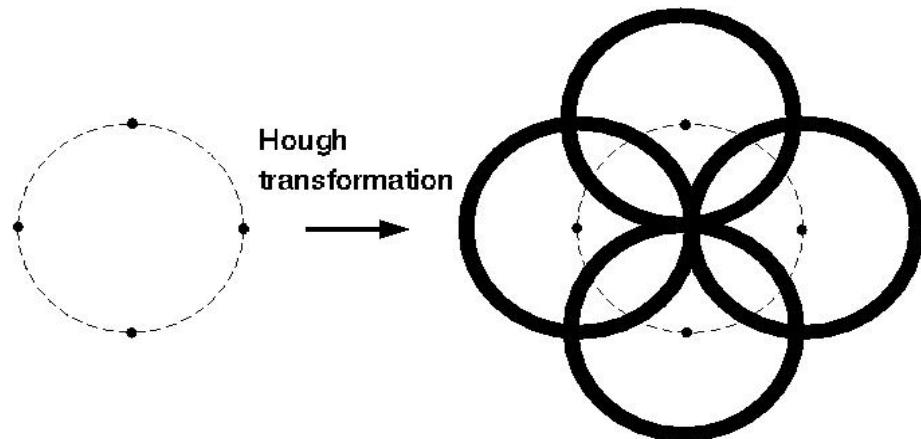
LINENY

- What is a sonic boom?
  - Bang supersonique, boom sonico, estampido sónico
  - The noise that gets made when something goes faster than sound

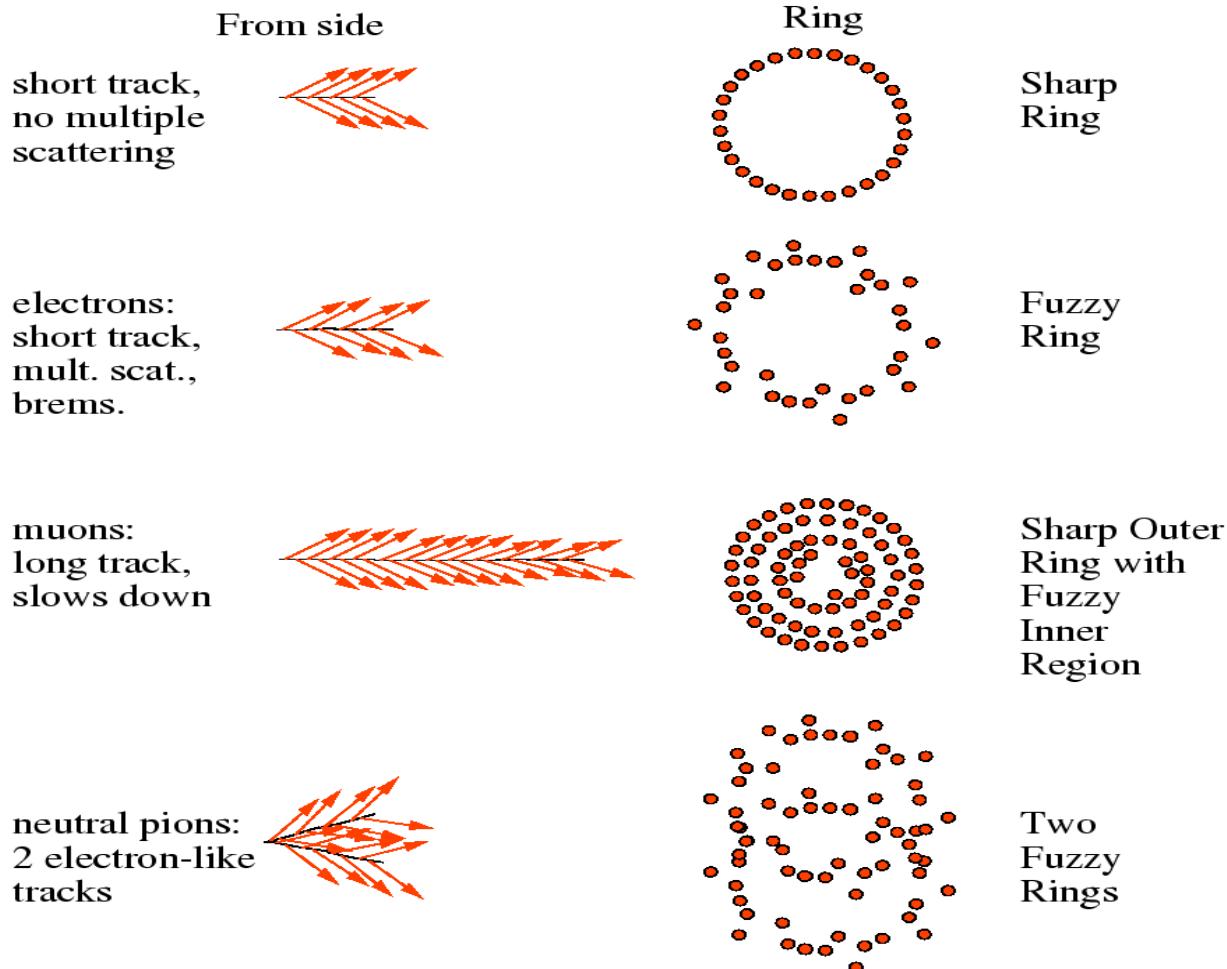


# Event Reconstruction in Cerenkov Detector

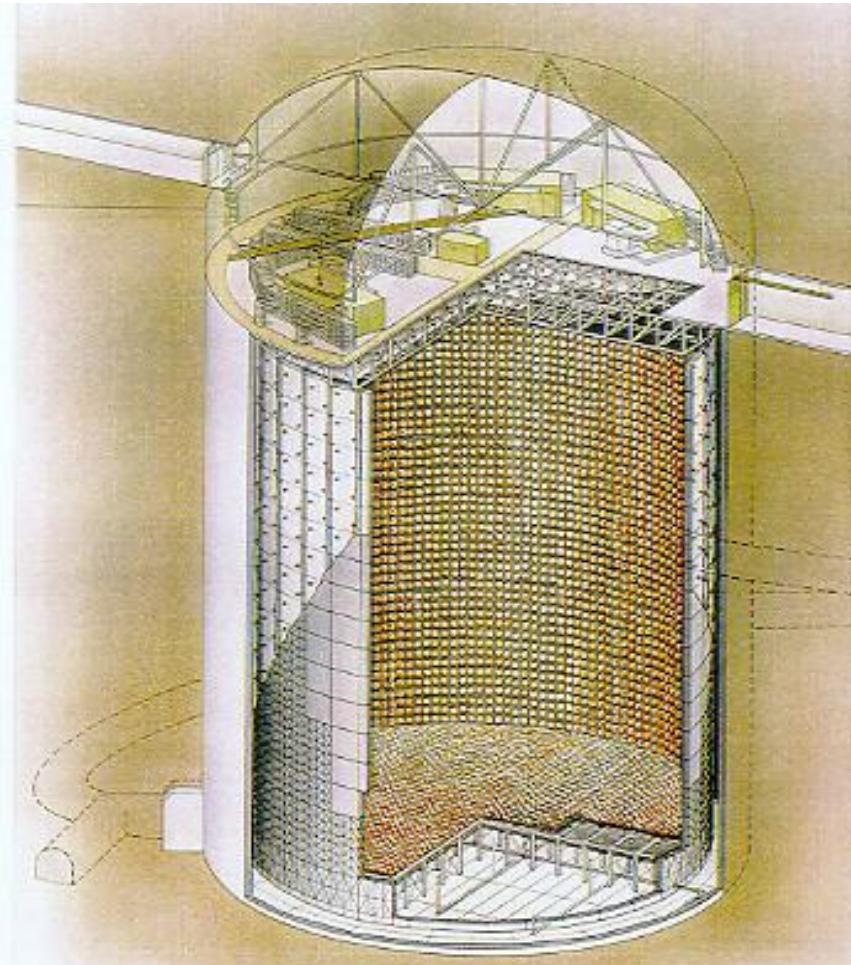
- Vertex Point fit: time of flight should be as sharp as possible
- Define set of **in-time** tubes
- Use Hough Transform to find rings
- Look for rings until you're done
- **Particle ID**
- Corrections to Vertex
- Energy Reconstruction
- Decay Electron Finding



# Particle ID Using Cerenkov Light



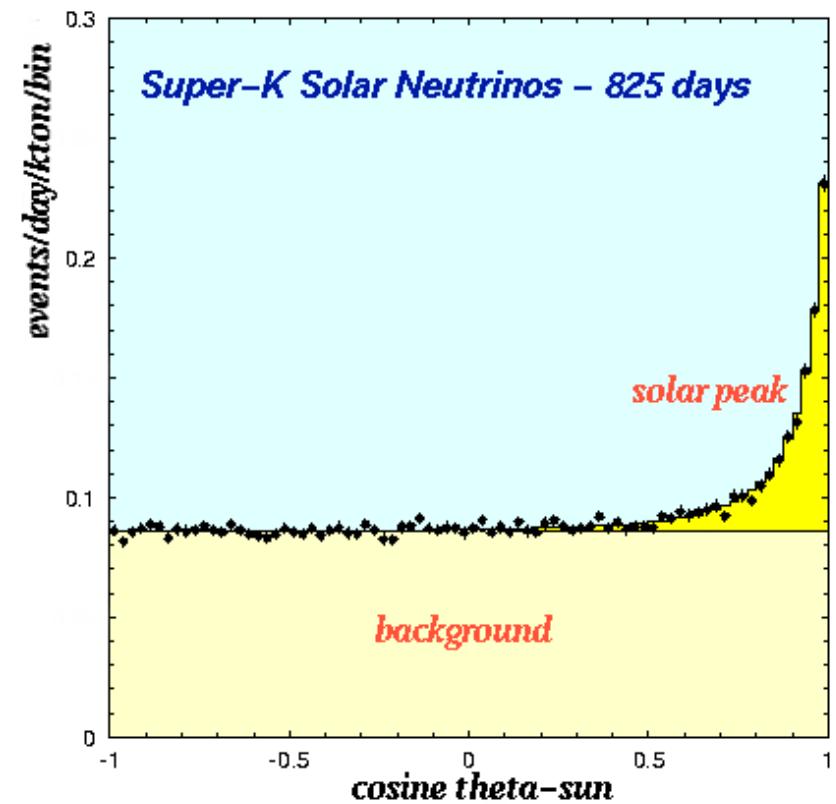
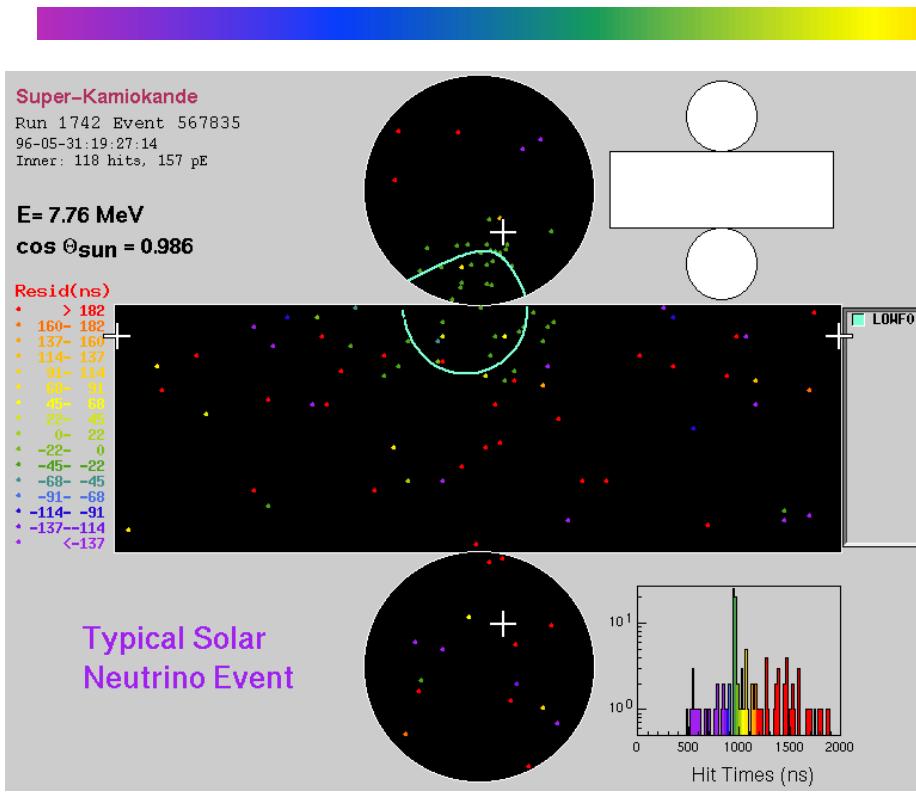
# Super-Kamiokande detector



**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**



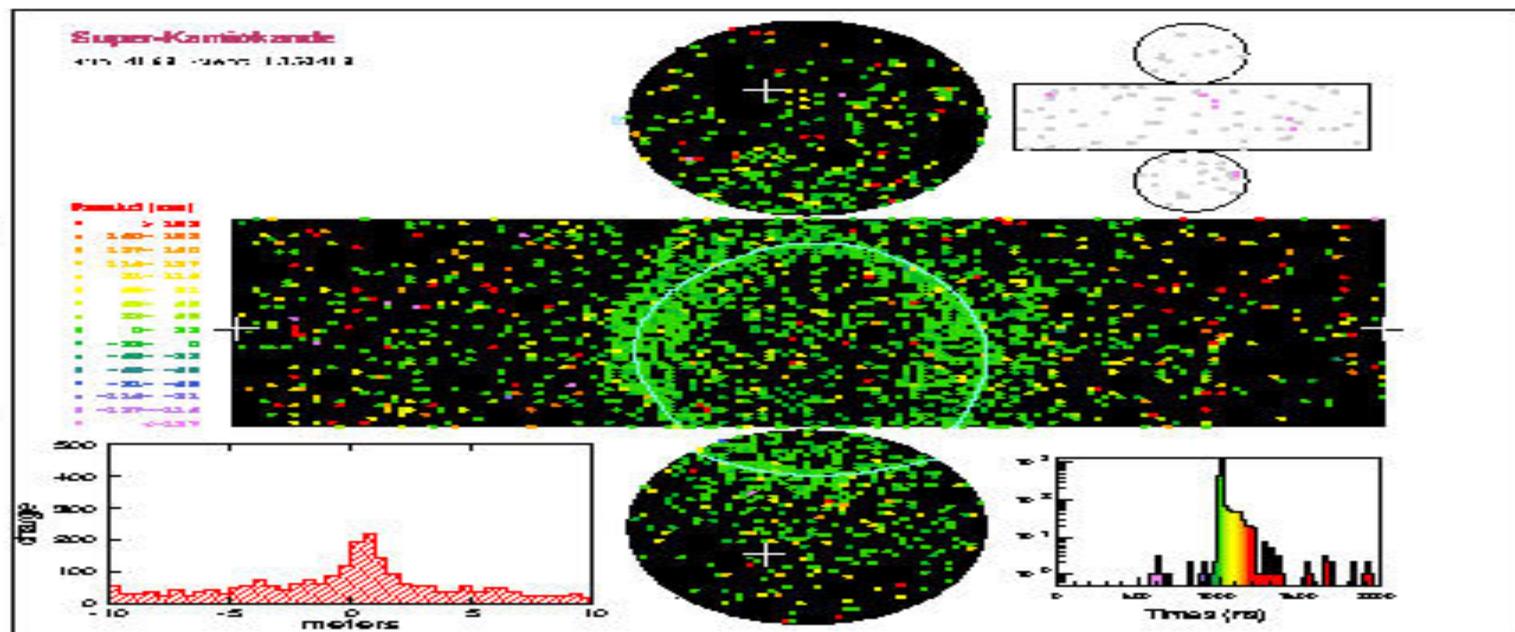
# Solar Neutrinos in Super-K



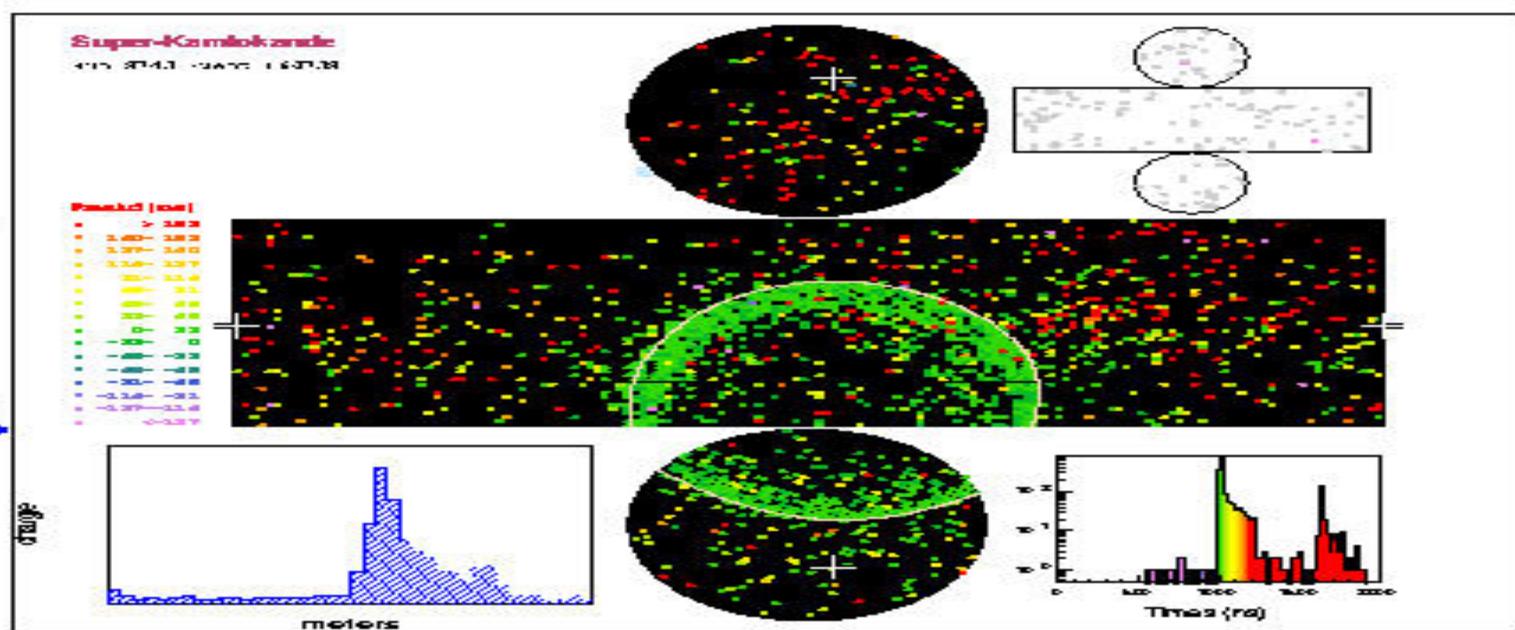
Recall that the  $\nu_e$ -e cross section is much larger than the  $\nu_{\mu,\tau}$ -e cross section!

e-like

2GeV  
neutrino  
interaction



$\mu$ -like



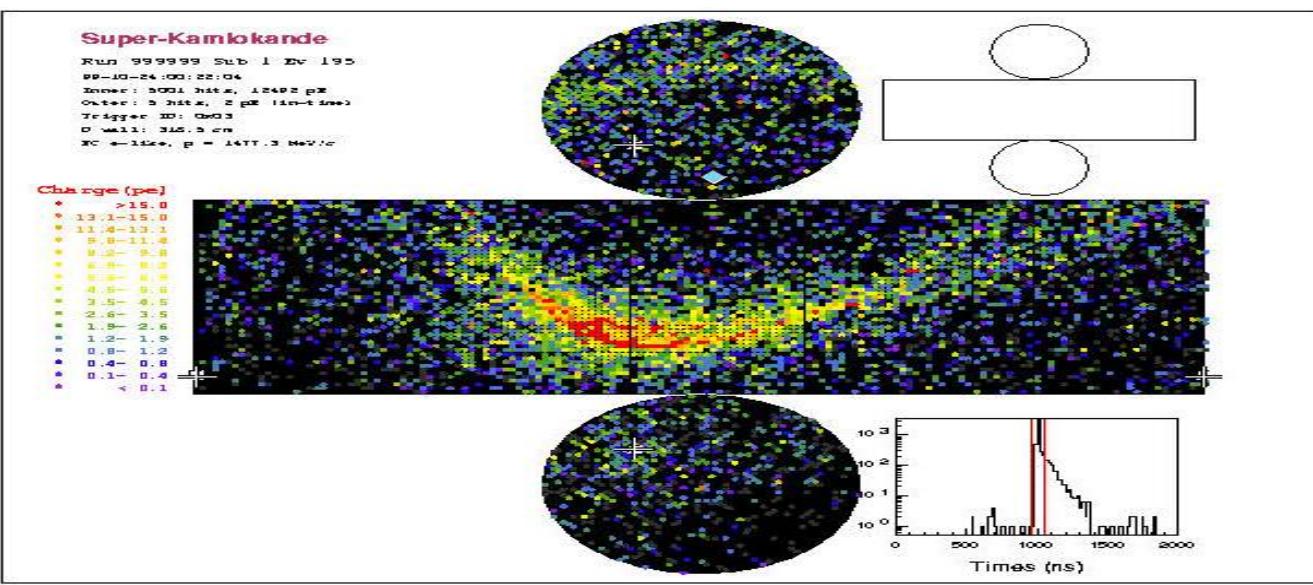
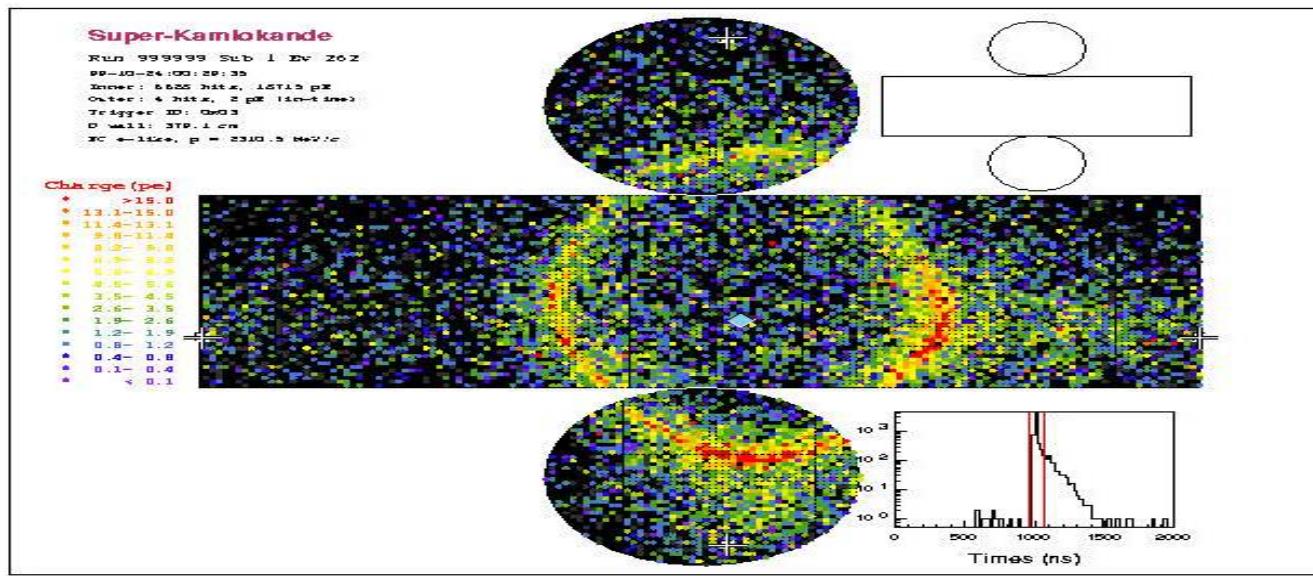
# Neutrino Energy Reconstruction



- Given the quasi-elastic hypothesis, derive an equation for the initial state neutrino energy given only the final state lepton's momentum and direction with respect to the incoming neutrino
- This is how Cerenkov detectors can reconstruct quasi-elastic neutrino interactions
- Question: what happens for other final states?

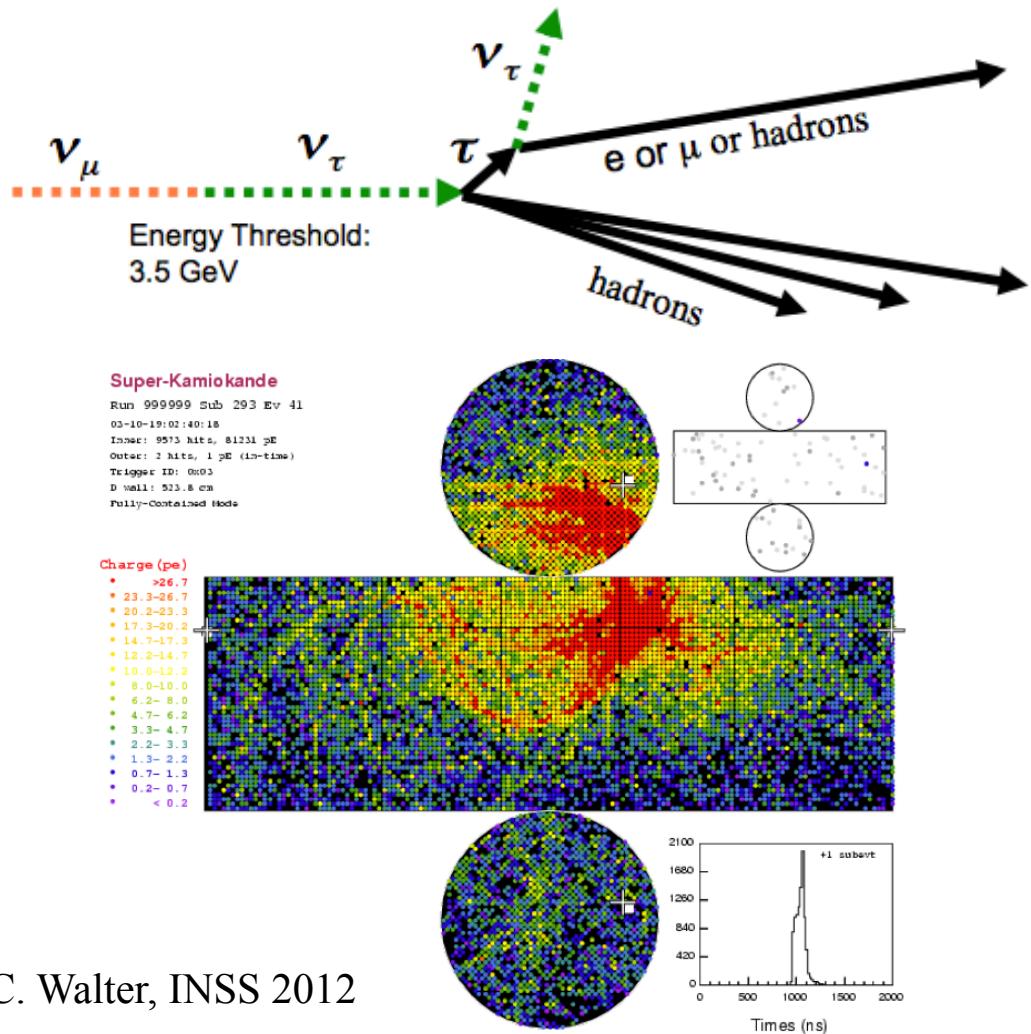
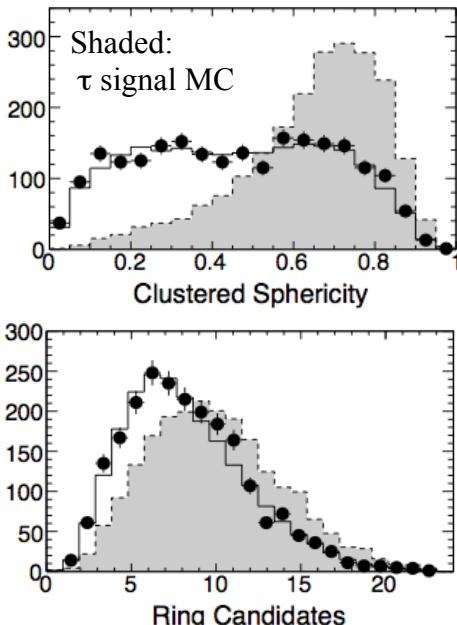
# Backgrounds to Electron Neutrinos in water Cerenkov

Courtesy Mark Messier: one is  $\nu_e$  signal, one is  $\pi^0$  background



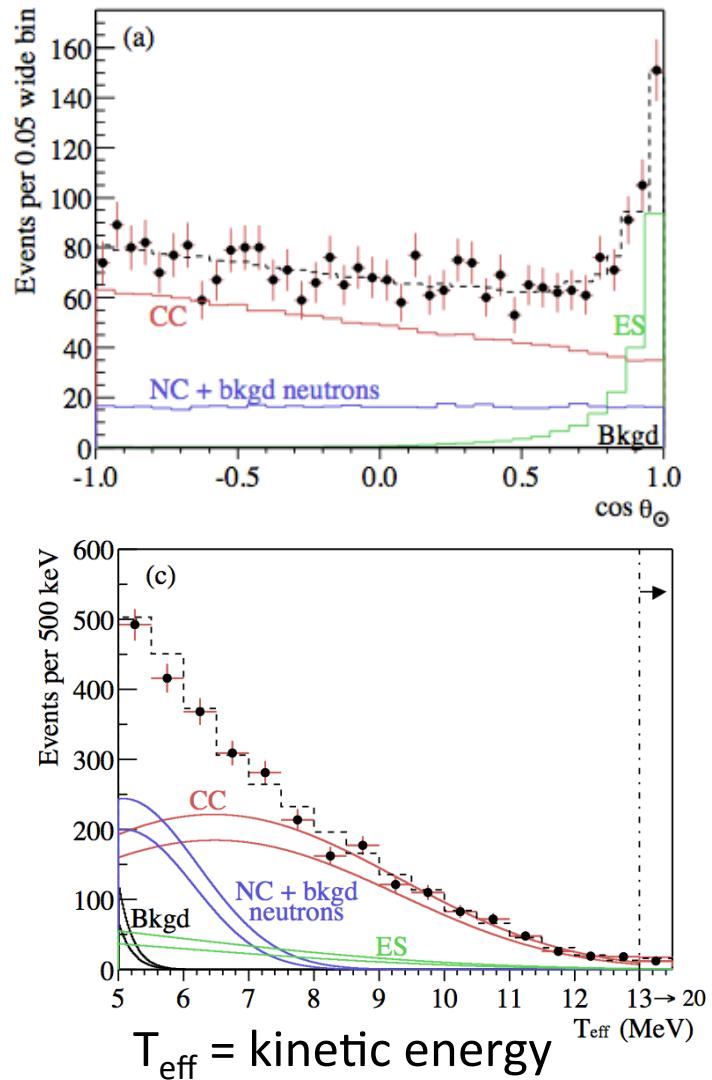
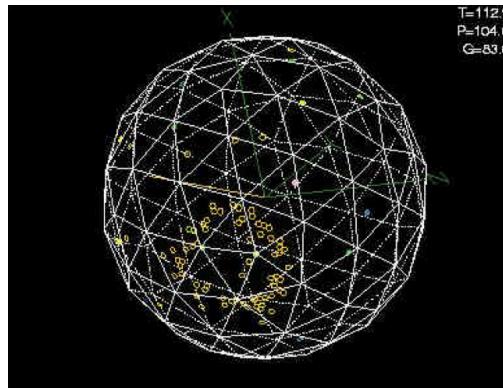
# $\tau$ neutrinos in Super-K

- Signal characteristics:
  - high energy
  - extra pions
  - more spherically symmetric due to decay of heavy  $\tau$



# Heavy Water Cerenkov

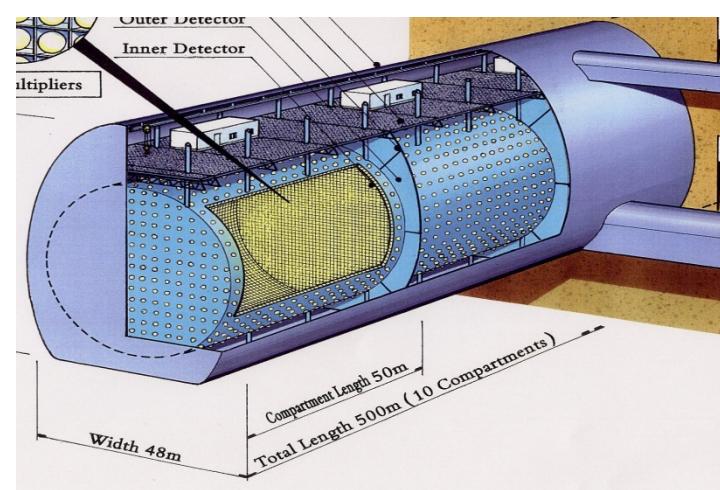
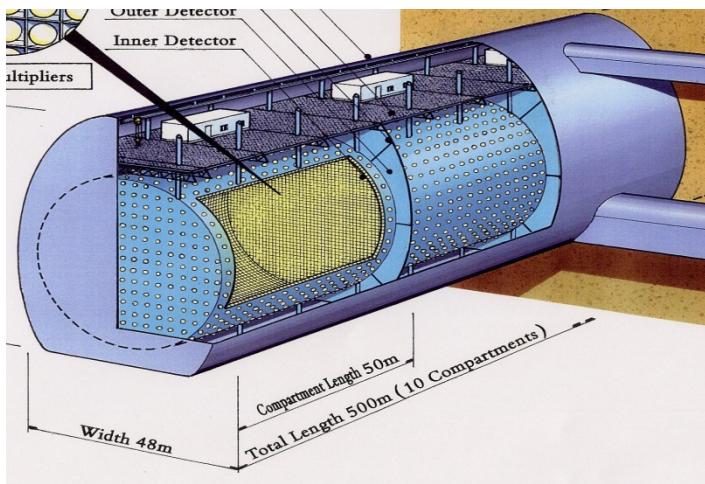
- SNO detector:  
1kton of D<sub>2</sub>O
- Deuterium allows 3 reactions
  - Charged Current:  
 $\nu_e + d \rightarrow p + p + e^-$ 
    - Only  $\nu_e$ 's can do this
    - Threshold: 2.2MeV
  - Neutral Current:  
 $\nu + d \rightarrow p + n$ 
    - All neutrinos contribute equally
    - Threshold: 2.2MeV
  - Elastic Scattering:  
 $\nu_x + e^- \rightarrow \nu_x + e^-$ 
    - More  $\nu_e$ 's than  $\nu_{\mu,\tau}$
    - Threshold: 0MeV



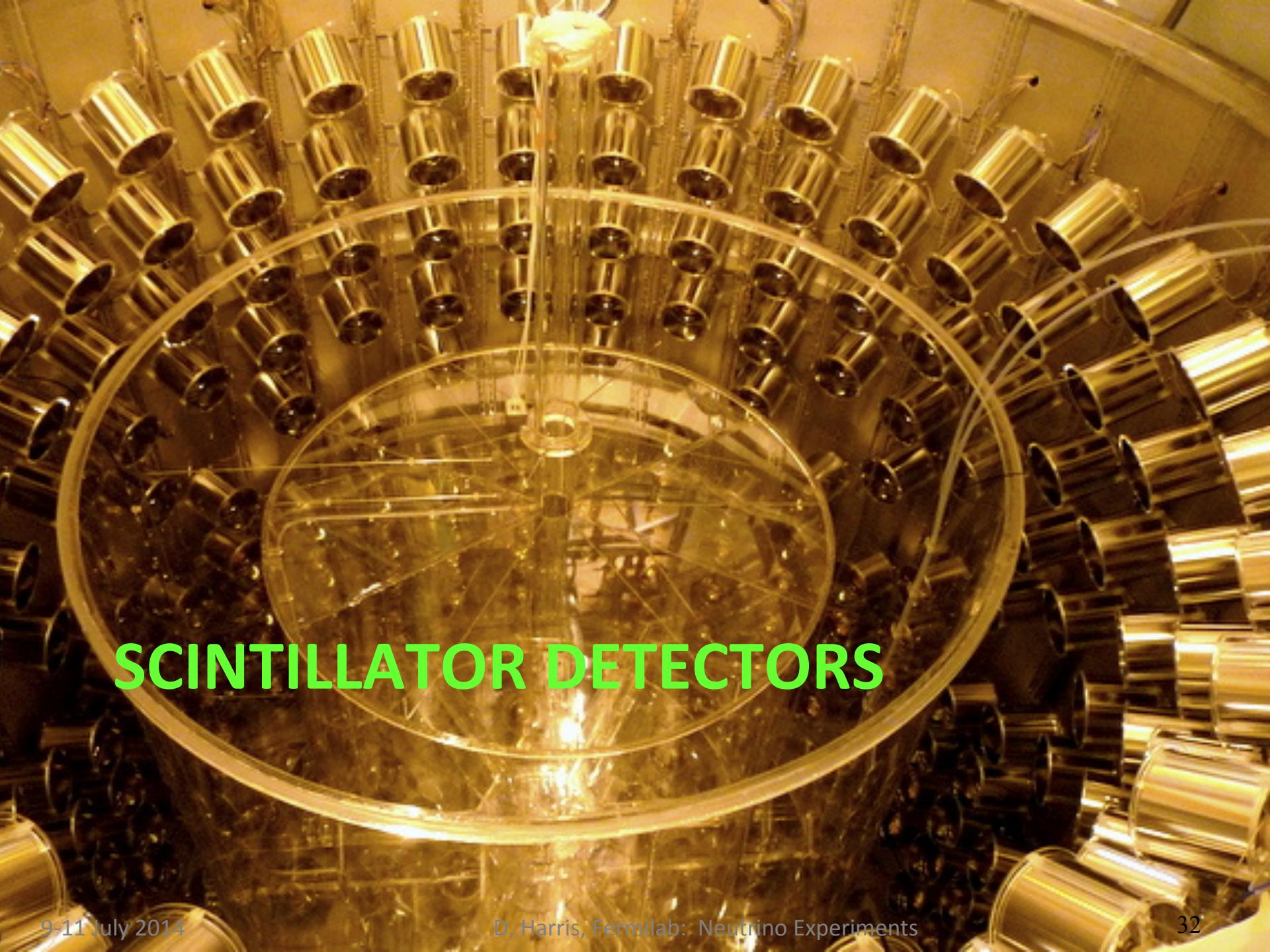
# Oustanding Issues

## Cerenkov Detectors

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

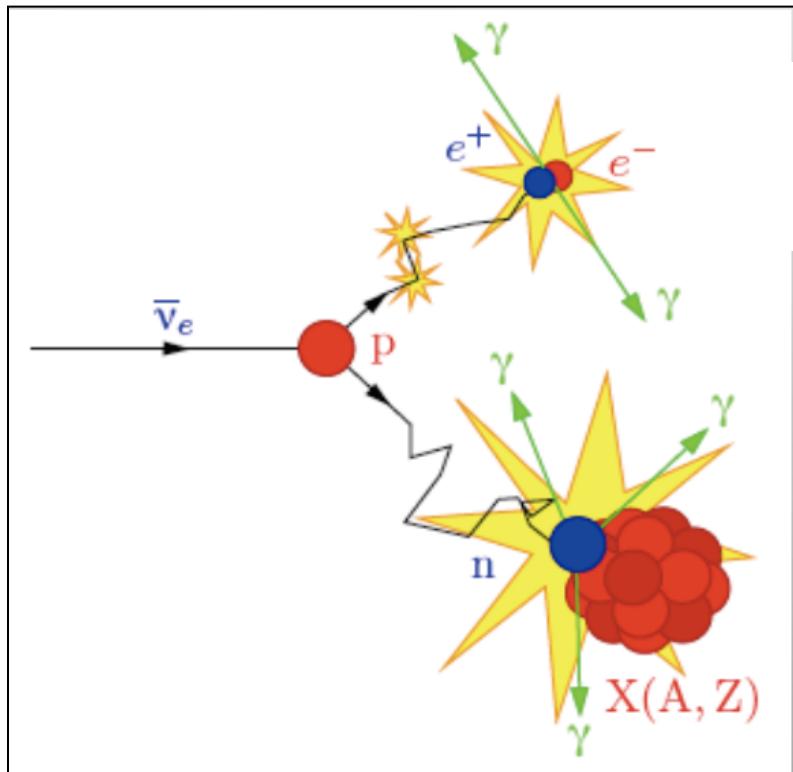
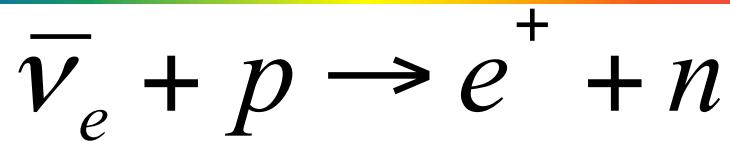


- What is highest energy regime that is possible, with better electronics, photo-detectors, etc?
- Water Cerenkov clearly the cheapest per kton



# SCINTILLATOR DETECTORS

# Anti-neutrinos in Scintillator



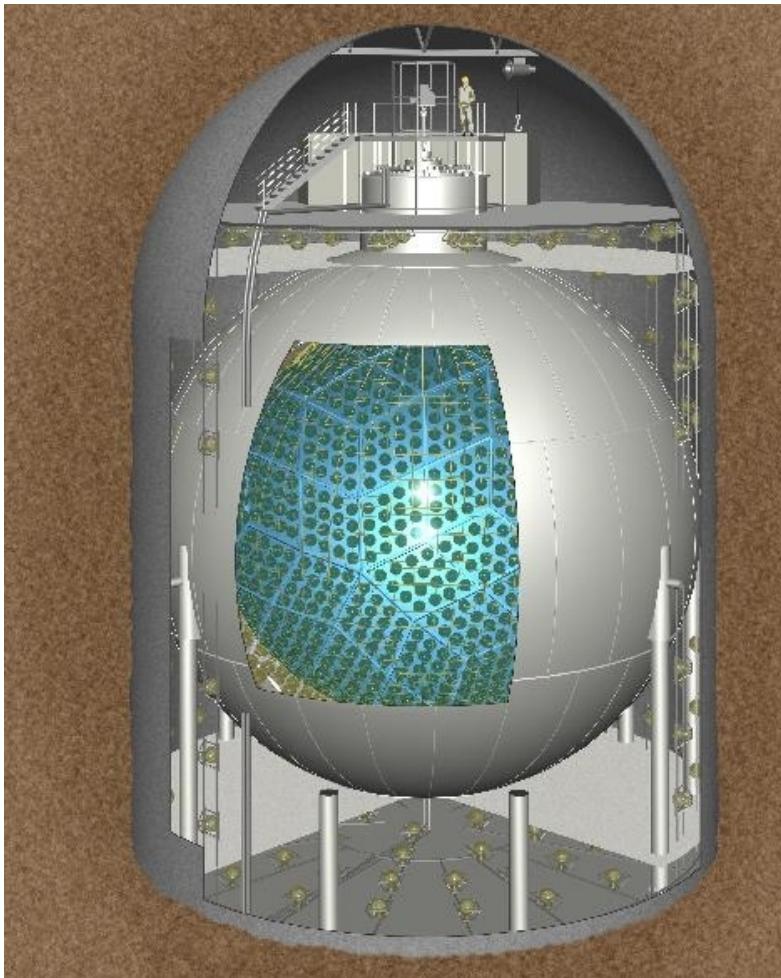
Neutron capture time  $\sim 30\mu\text{sec}$   
for typical  $\theta_{13}$  experiments

Scintillator Oil alone: capture the neutron on Hydrogen, make 2.2MeV gamma

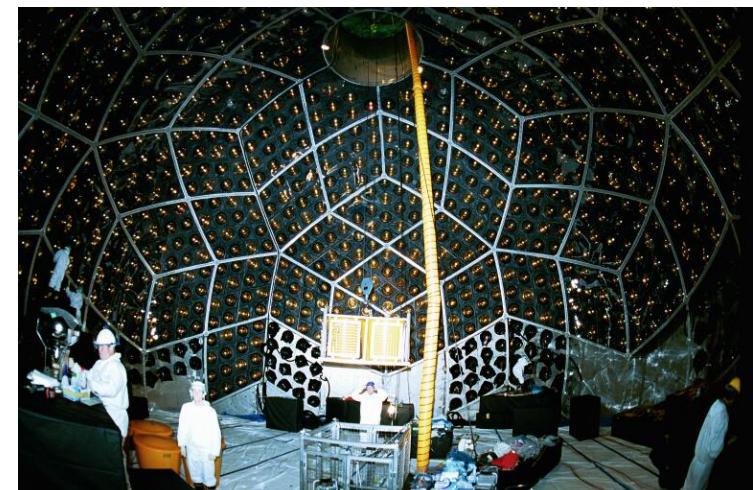
Neutrino capture on Gd has advantages (compared with that on hydrogen):

- ✓ Higher total gamma ray energy (8 MeV)
- ✓ Shorter neutron capture time ( $\sim 30\mu\text{sec}$  vs.  $\sim 200\mu\text{sec}$ )
- ➔ Better signal to noise ratio

# Example: KAMLAND



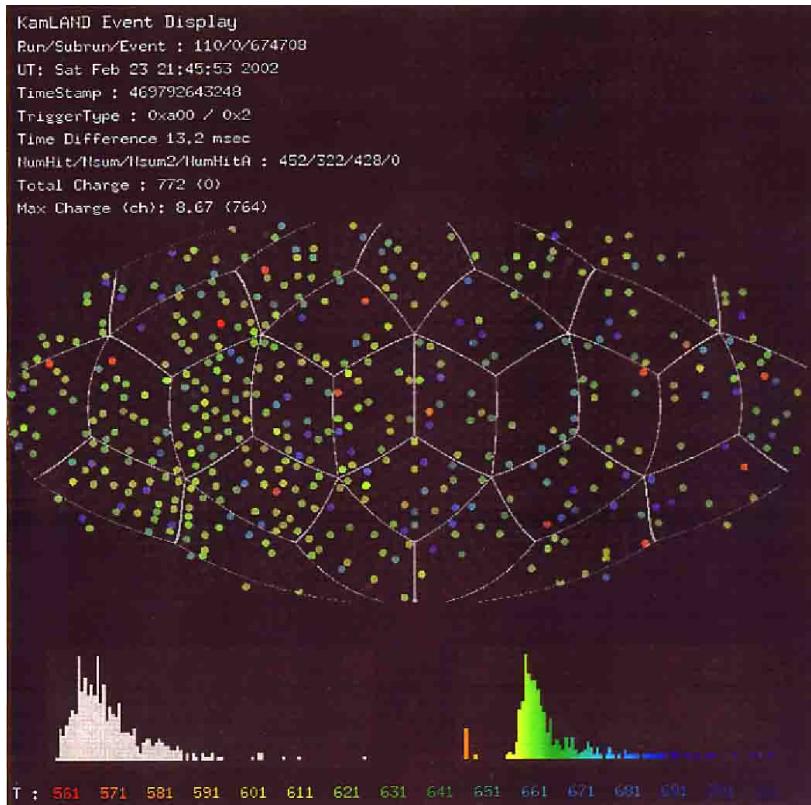
1kton liquid scintillator  
Viewed by 17inch PMTs (22% coverage)  
→ 300 photo-electrons /MeV  
→ Energy resolution = 6-7% /  
 $\sqrt{E(\text{MeV})}$



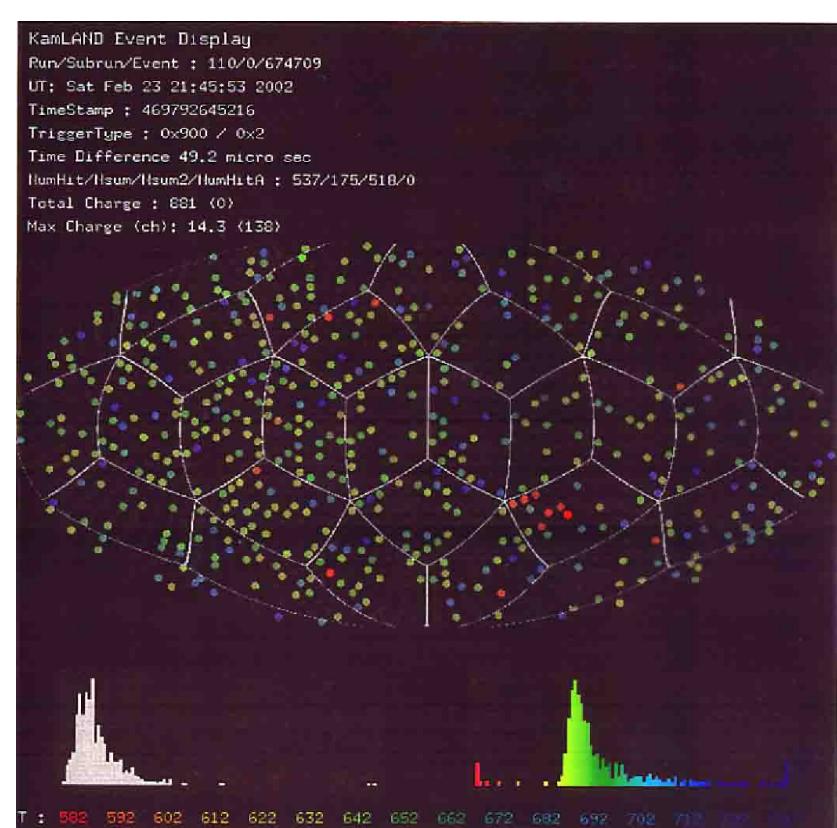
# Events in KAMLAND

- Have to collect all the light for energy measurement, no direction available at these energies

Prompt event



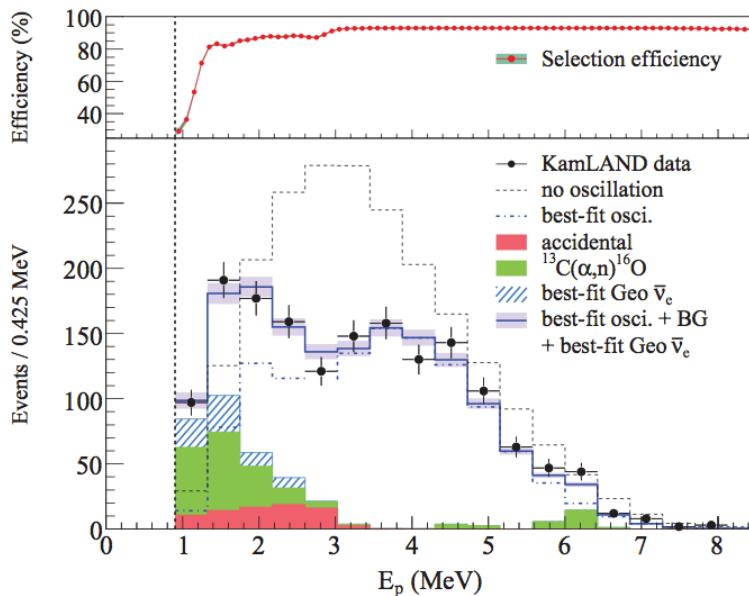
Delayed event



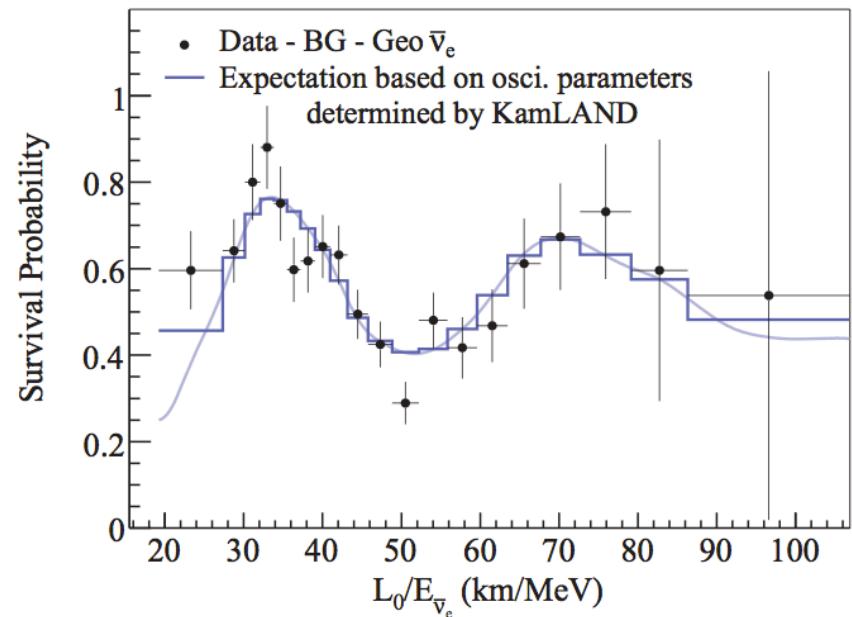
# $\nu$ Energy Measurement in KamLAND

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2 (\Delta m_{31}^2 L / 4E) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 (\Delta m_{21}^2 L / 4E)$$

- $E_\nu = E_p + E_n + 0.8 \text{ MeV}$ 
  - $E_p$  is prompt energy (from e+): resolution is  $10\%/\sqrt{E(\text{MeV})}$
  - $E_n$  is average neutron recoil energy (10keV)



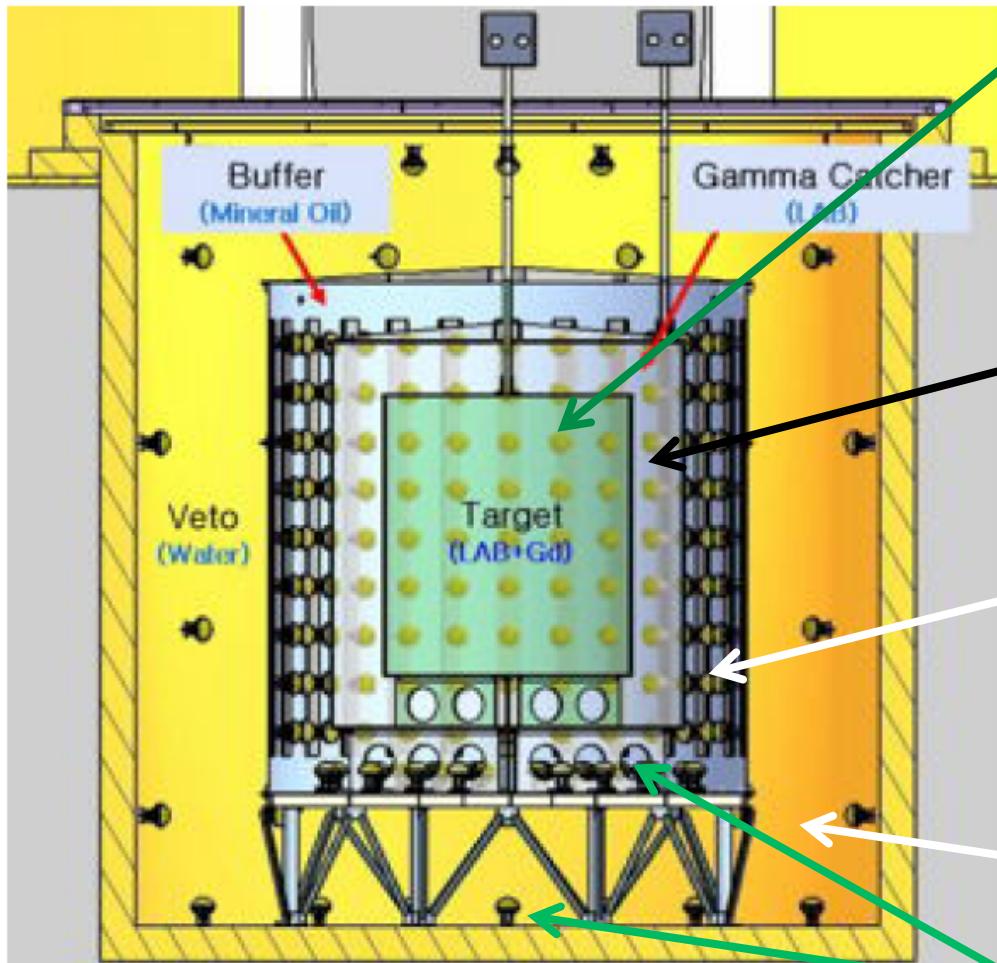
Prompt recoil energy spectrum



Phys. Rev. Lett. 100 (2008) 221803

# “Shorter Baseline” Reactor $\nu$ Detector Design

Example: RENO (Other experiments have the similar designs)



$\nu$ -target: Volume for  $\nu$ -interaction  
0.1% Gd loaded liquid scintillator (to detect neutrons)

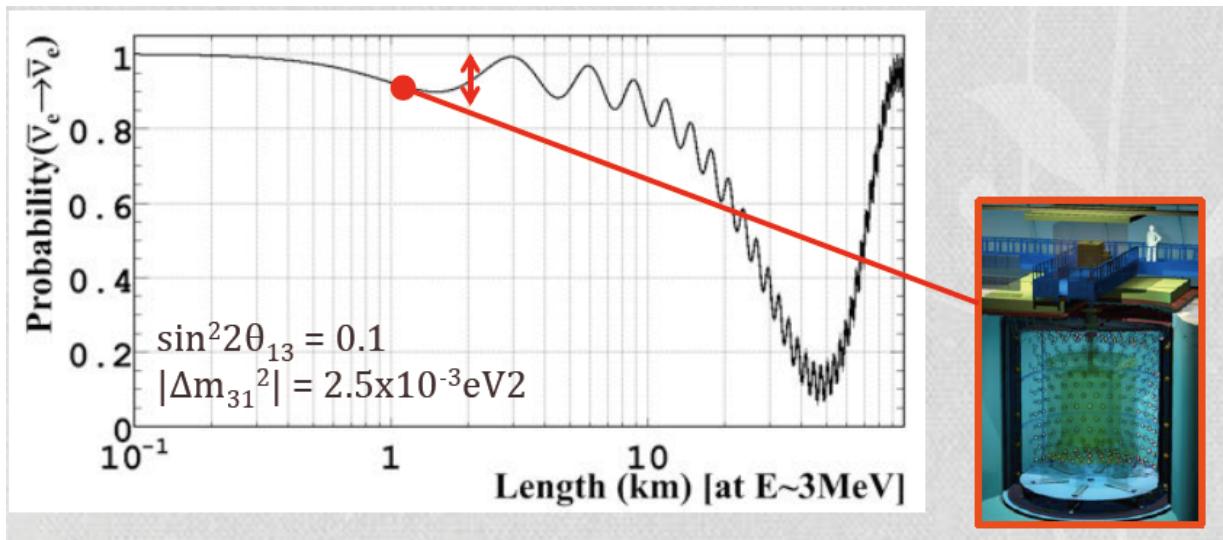
$\gamma$ -catcher: Extra-volume with pure liquid scintillator

Non-scintillating buffer: Mineral Oil to Isolate PMTs from target area

Veto region (water)  
PMTs

# Outstanding Issues for Liquid Scintillator Detectors

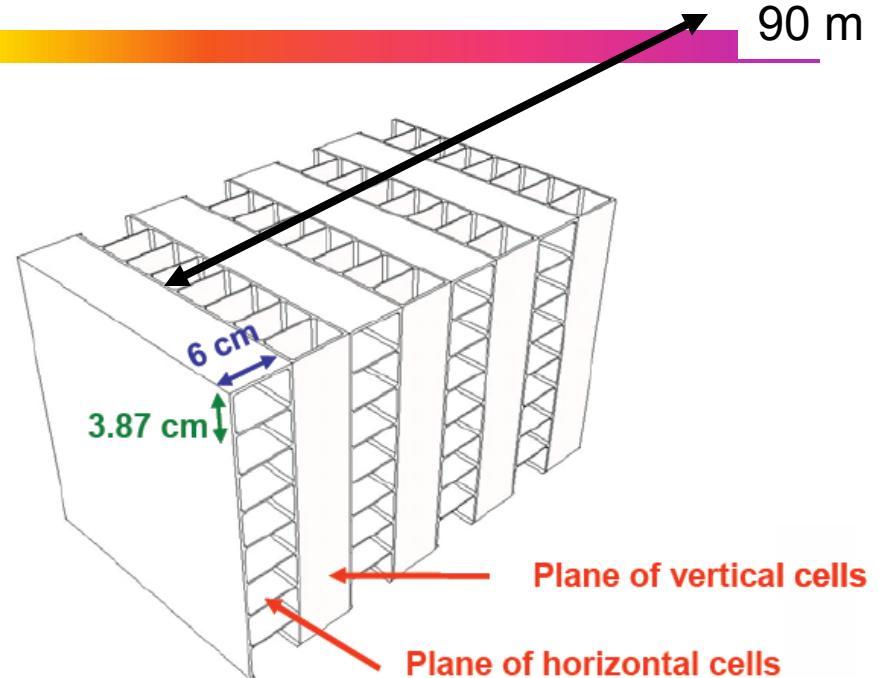
- How large can this kind of detector be made?
- Can the energy resolution for a larger detector size be predicted?
  - Can you really keep as much light as KAMLAND managed to keep?
- Goal: reactor neutrino experiment at high enough baseline to see 2<sup>nd</sup> order effects



# Segmented Scintillator



- 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

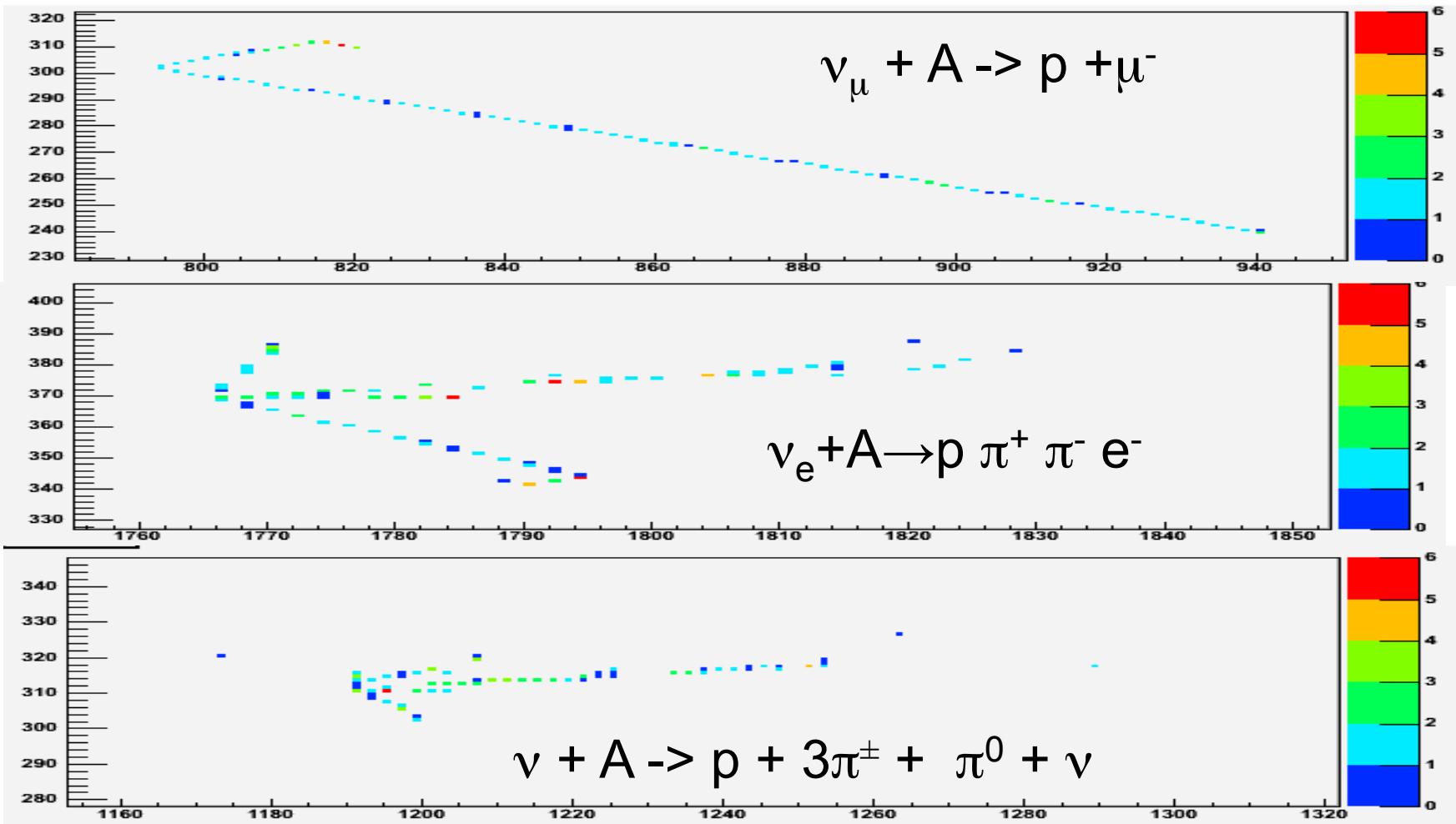


To Build:

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)



Particle ID:

particularly “fuzzy” e’s

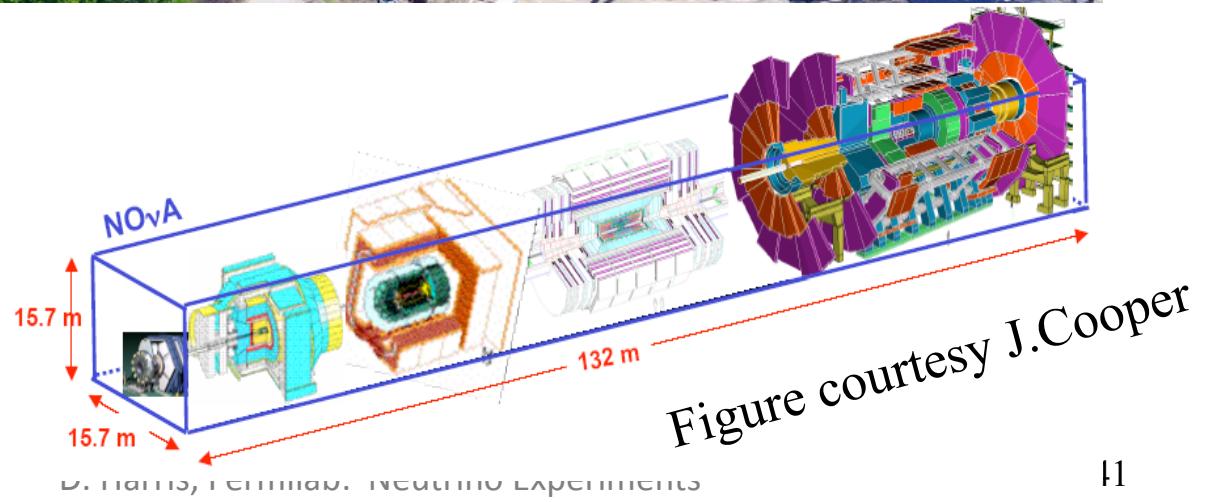
long track, not fuzzy ( $\mu$ )    gaps in tracks ( $\pi^0$ ?)

large energy deposition    (proton?)

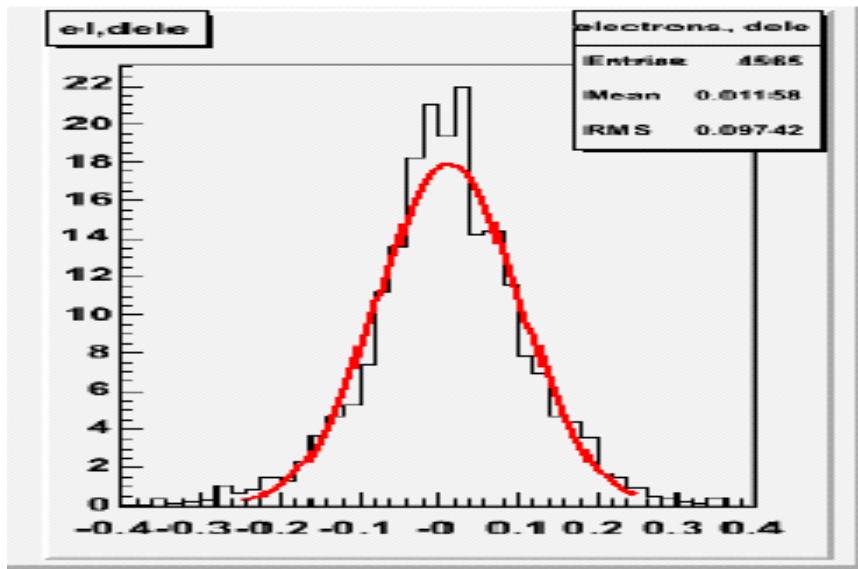
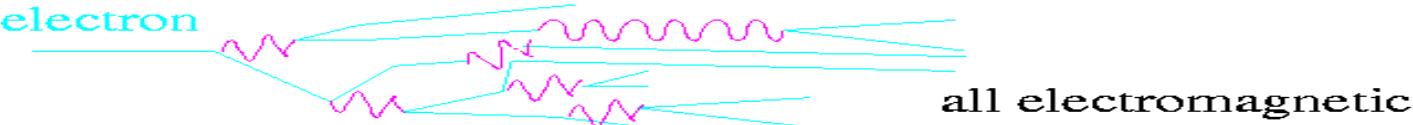
One unit is 4.9 cm (horizontal)  
4.0 cm (vertical)

# Detector Volume

- Scaling detector volume is not trivial



# Energy Resolution



**Measured – true energy  
divided by square root of true energy**

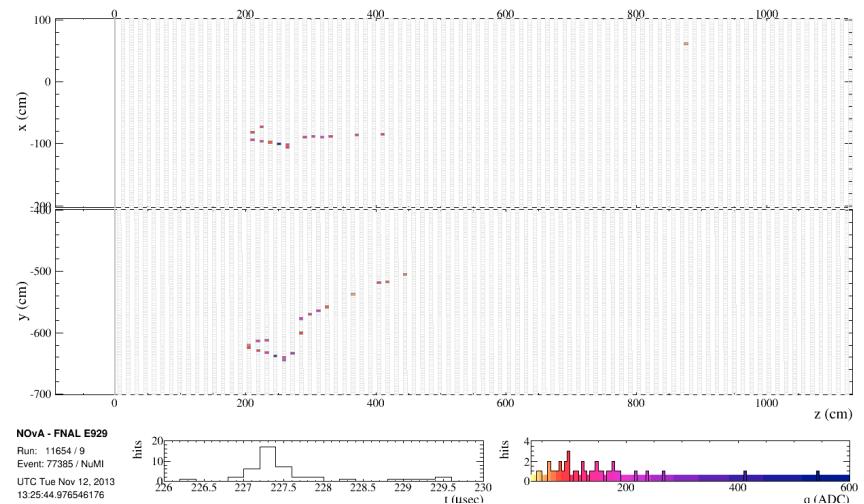
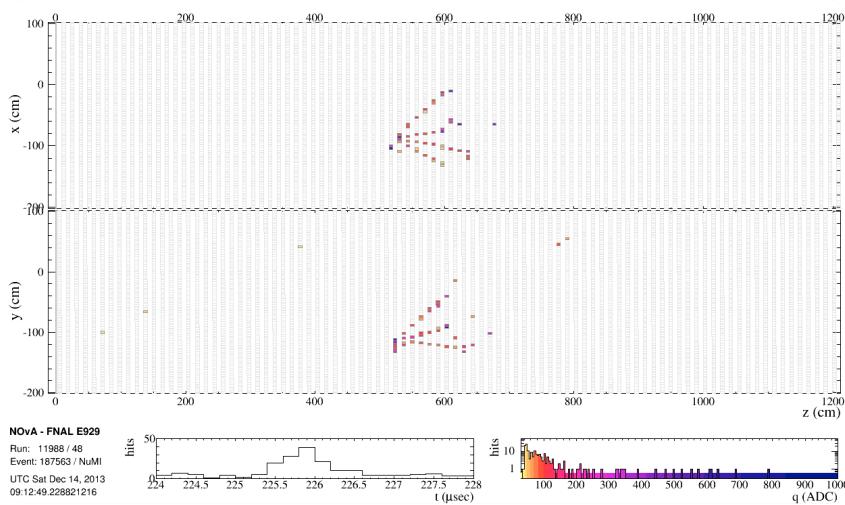
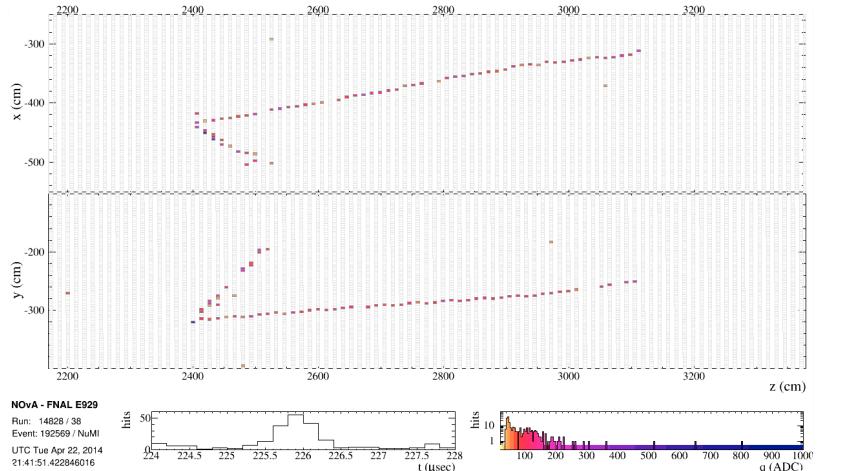
$$\frac{\delta E}{E} \propto \frac{1}{\sqrt{N}}, N = \text{samples}$$

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

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

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

# NO $\nu$ A Data Event Displays



A. Norman, v2014

# Outstanding Issues



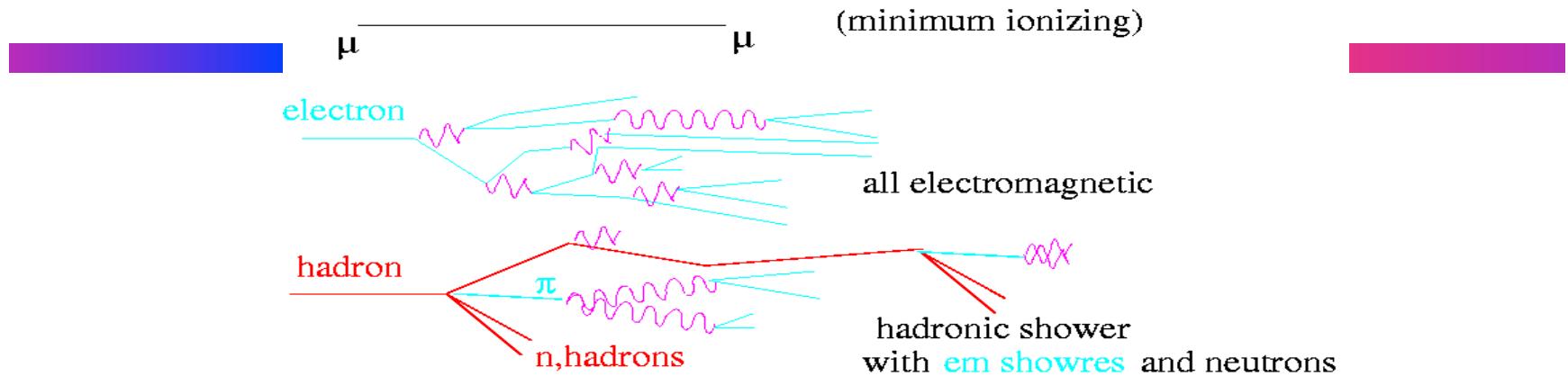
## Segmented Scintillator

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

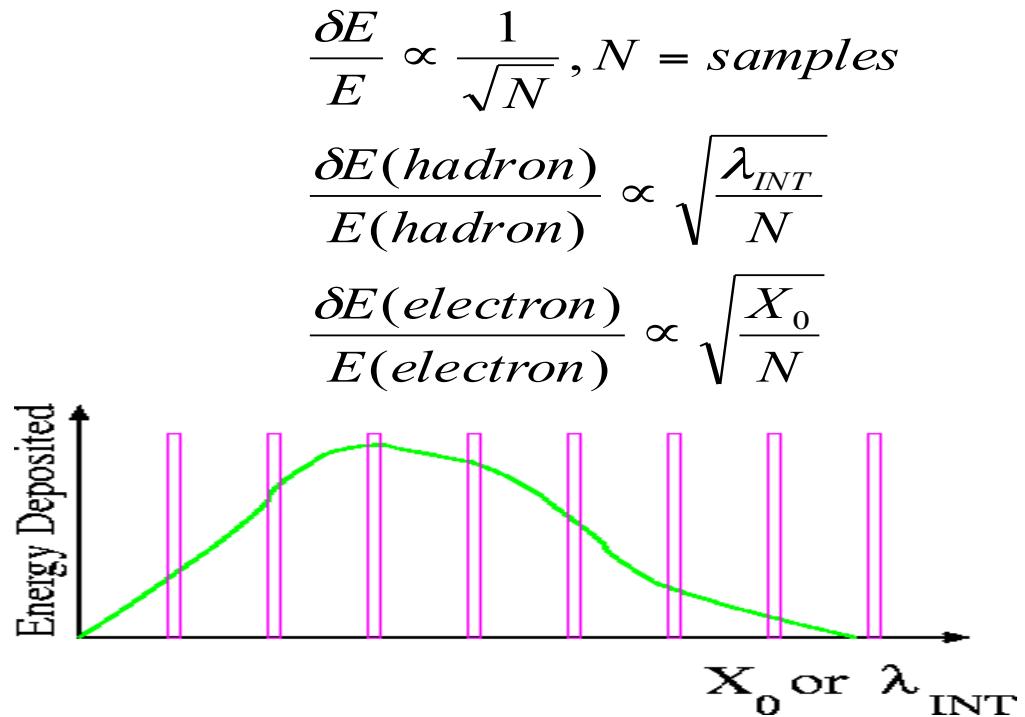
# ACTIVE/PASSIVE DETECTORS



# From Fully Active to Sampling



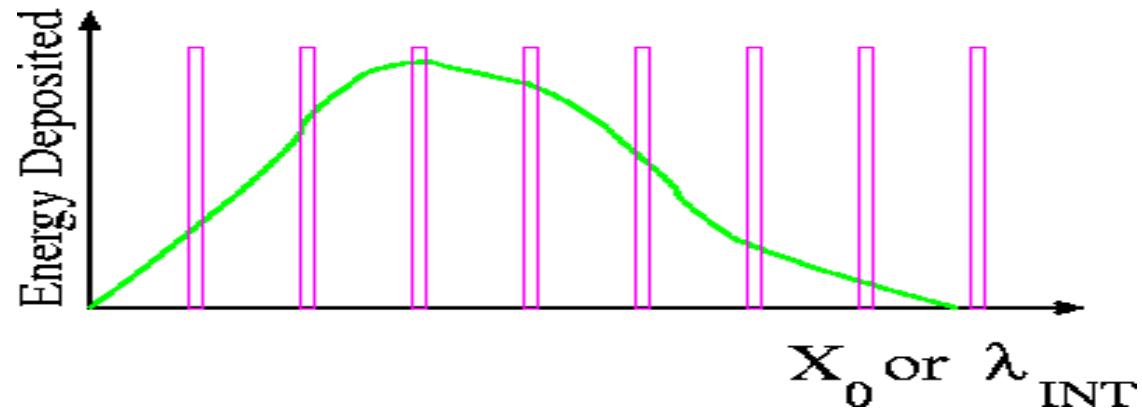
- Advantages to Sampling:
  - Cheaper readout costs
  - Fewer readout channels
  - Denser material can be used
    - More N, more interactions
    - Could combine emulsion with readout
  - Can use magnetized material!
- Disadvantages to Sampling
  - Loss of information
  - Particle ID is harder (except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



# 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)



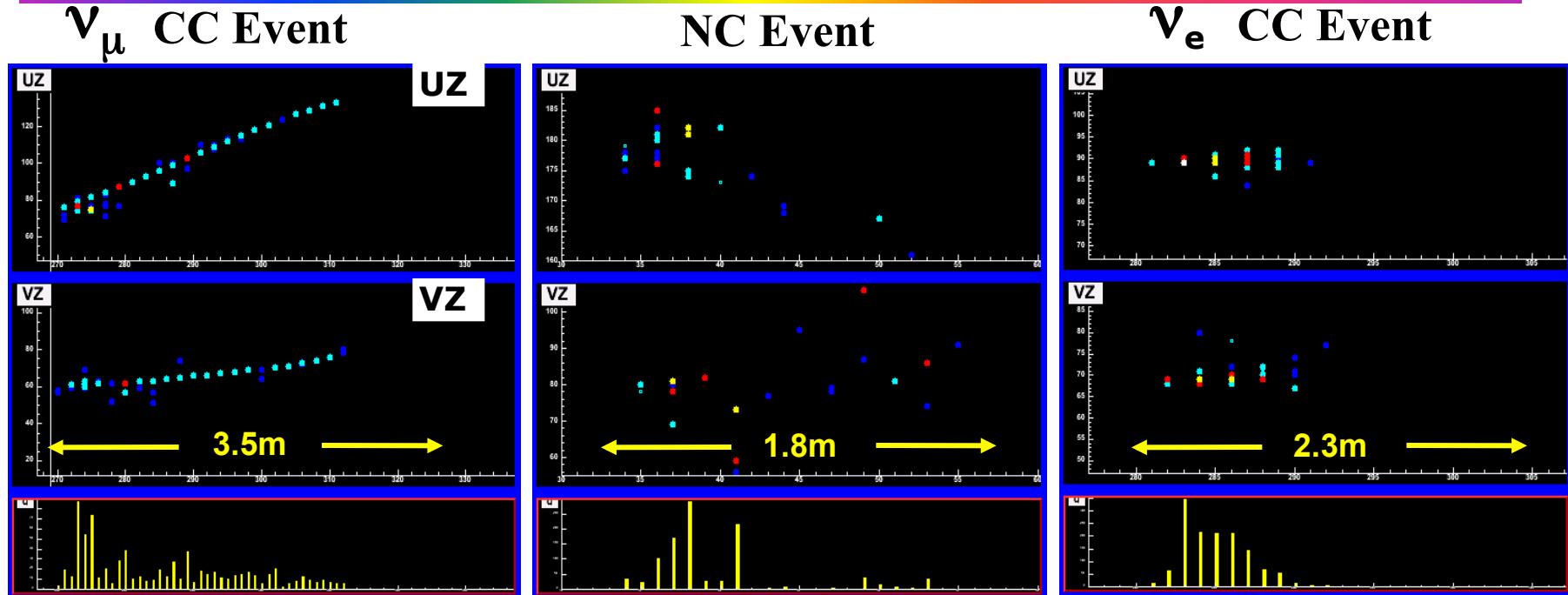
Material	$X_0$ (cm)	$l_{\text{INT}}$ (cm)	Sampling ( $X_0$ )	$X_0$ (g/cm <sup>2</sup> )
L.Argon	14	83.5	0.02 (ICARUS)	20
Steel	1.76	17	1.4 (MINOS)	14
Scintillator	42	~80	0.13 (NOvA)	40
Lead	0.56	17	.2 (OPERA)	6

# 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 Event Topologies



- Long muon track + hadronic activity at vertex

- Short showering event, often diffuse

- Short event with typical EM shower profile

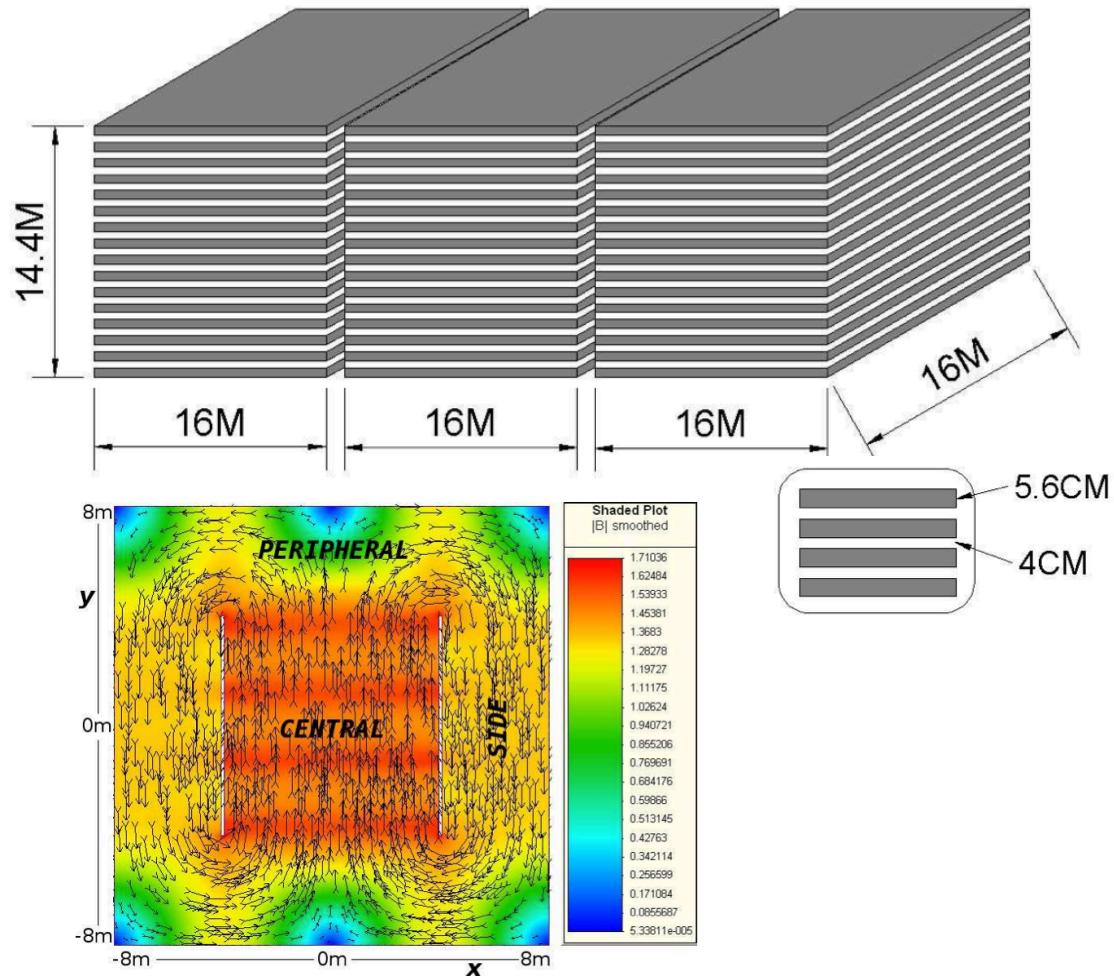
$$E_\nu = E_{\text{shower}} + P_\mu$$

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

Muon momentum resolution: 6% range; 13% curvature

# Indian Neutrino Observatory

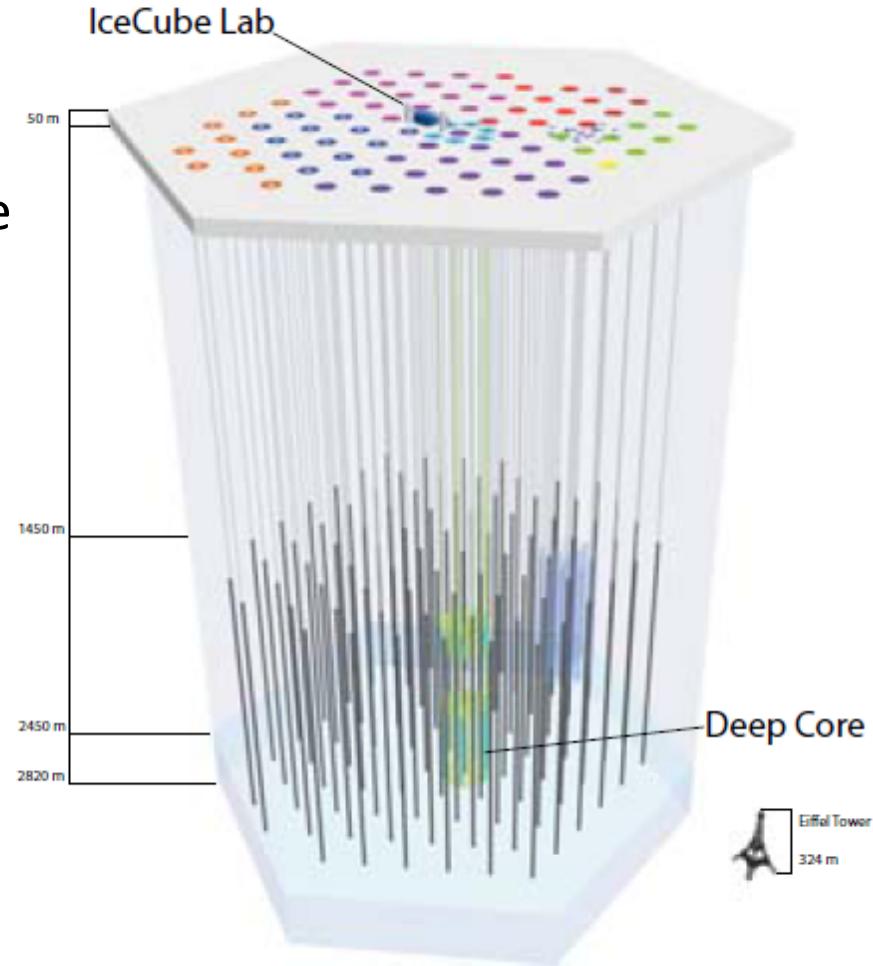
- Largest magnetized detector: need cheaper instrumentation
- Resistive plate chambers (RPC) are answer
- Physics goals
  - Atmospheric neutrinos
  - Neutrino factory neutrinos (high angle)
- 52 kton of steel
  - 151 layers of 5.6cm iron
  - 1.5T B field
  - 30k RPC units (2mx2m)
  - $3.9 \times 10^6$  channels



D. Indumathi, v2014

# Ice as Detector Medium

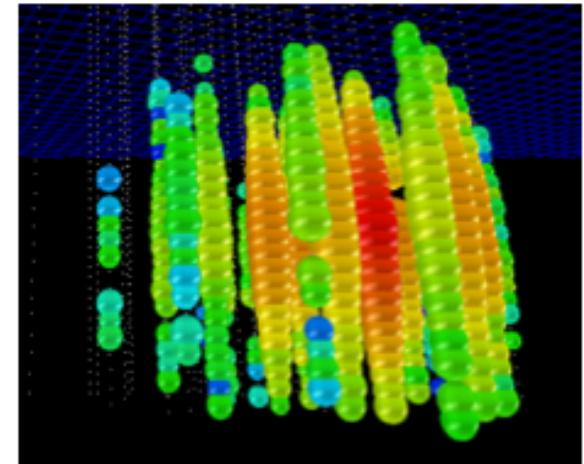
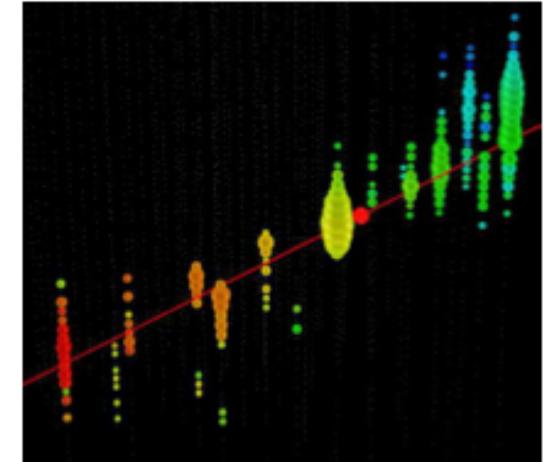
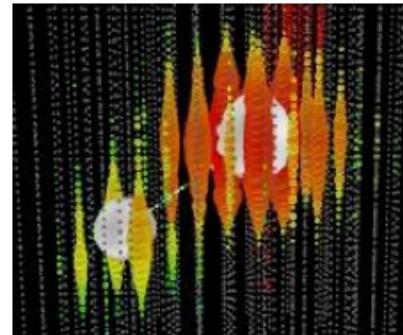
- ICECUBE:
  - 1km<sup>3</sup> volume
  - 86 strings, 5160 PMTs
  - Need to be deep below surface where ice is clear
  - 17m spacing between 2 PMT's on one string
  - Smaller PMT spacing would mean lower energy thresholds



Whitehorn, DPF 2013

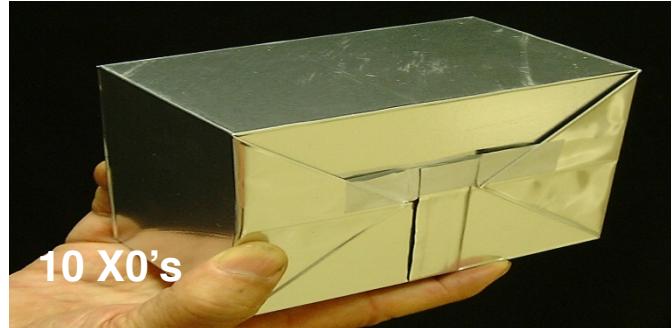
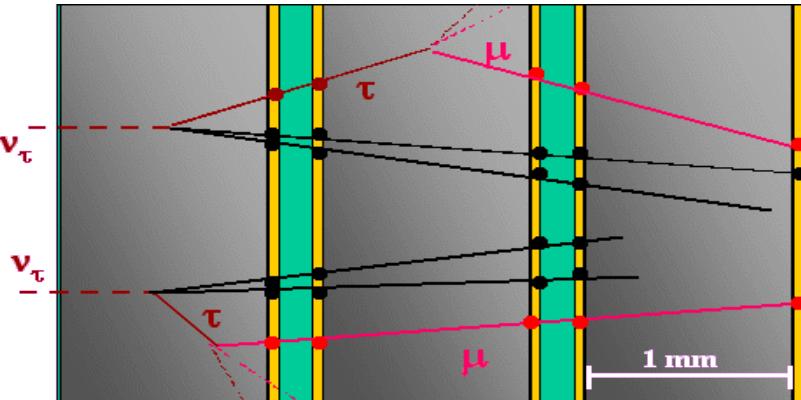
# Event Signatures in Ice

- Muon Neutrino (data)
  - $<1^\circ$  angular resolution
  - Factor of 2 muon energy resolution
- Neutral Current or  $\nu_e$  (data)
  - $10^\circ$  angular resolution (high energy)
  - 15% deposited energy resolution
- $\nu_\tau$  (simulation)

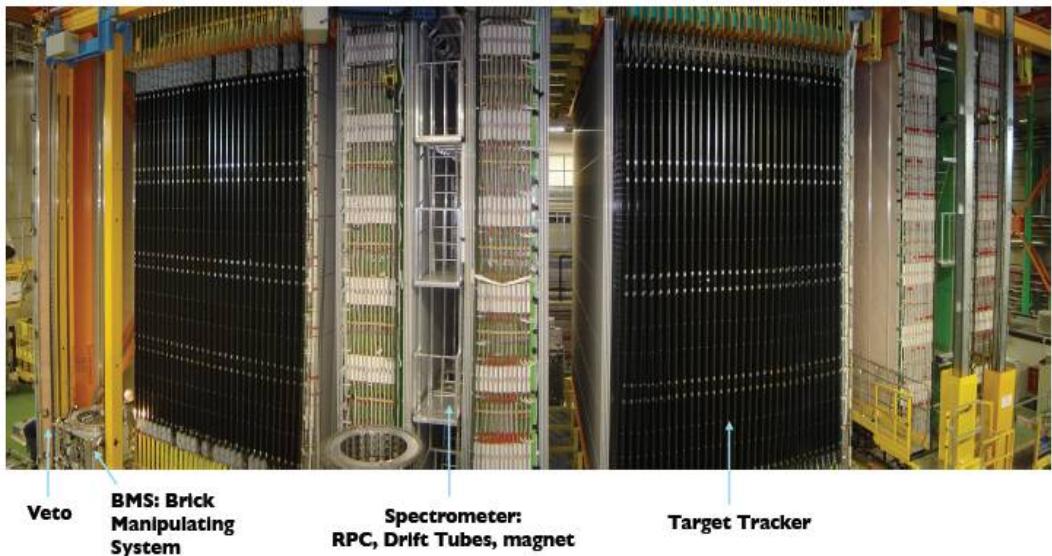


Whitehorn, DPF 2013

# Lead-Emulsion Detector (OPERA)

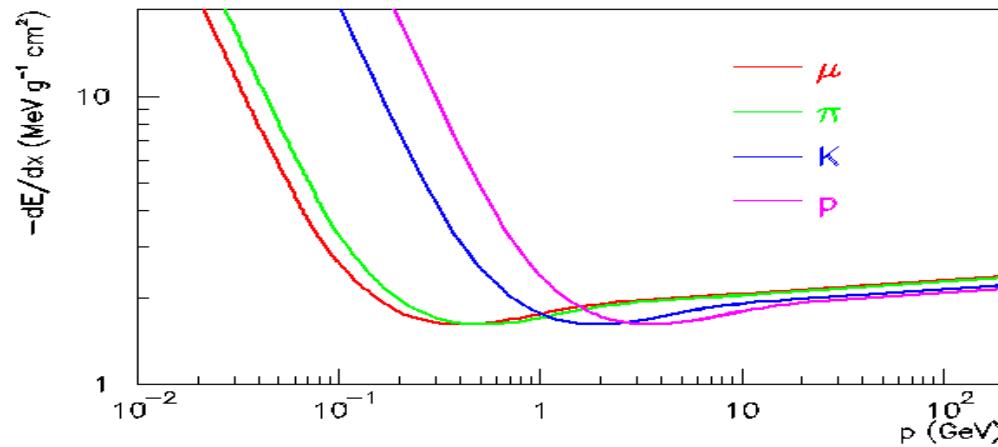


- 1.2kT emulsion detector
  - 146621 bricks, each 8.3kg
  - 56 (1mm) Pb sheets
  - 57 (300mm) FUJI emulsion layers
  - 2 (300mm) changeable sheets (CS)



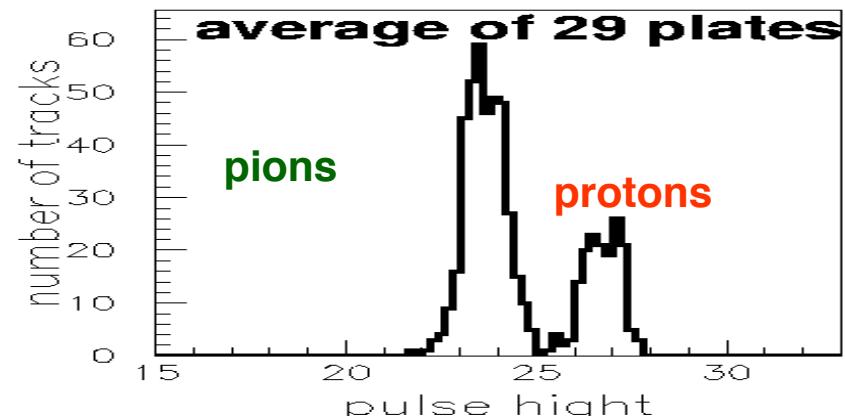
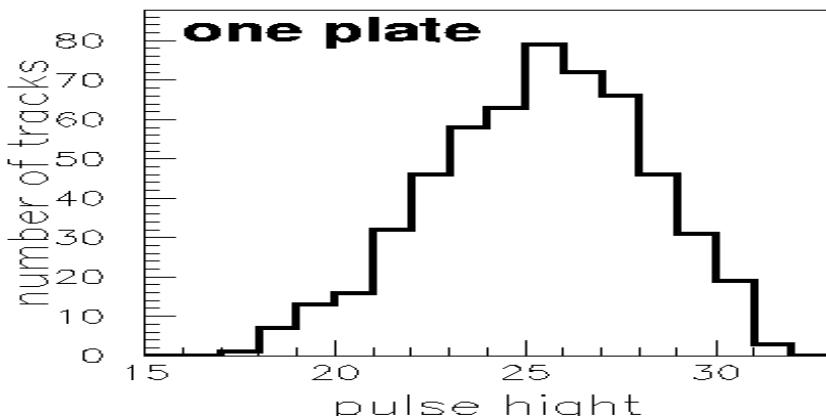
# Particle ID in Emulsion

Grain density in emulsion is proportional to  $dE/dx$

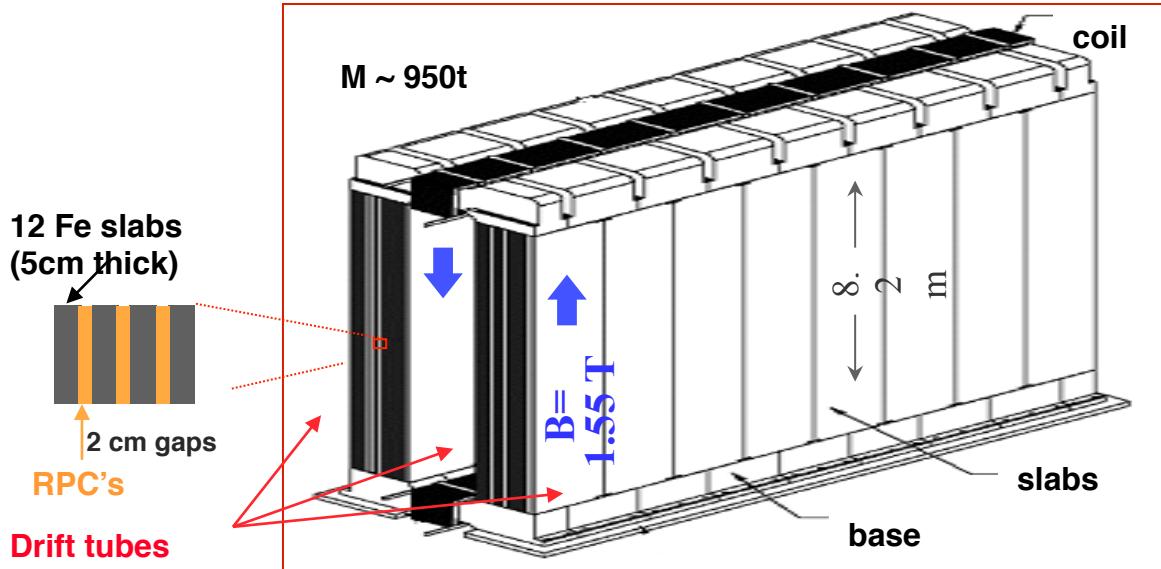


By measuring grain density as a function of the distance from the stopping point, particle identification can be performed.

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



# Muon Spectrometer w/ RPC



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

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

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

**Precision tracker:**  
**6 planes of drift tubes**  
diameter 38mm, length 8m  
efficiency: ~99%  
space resolution: ~300 $\mu\text{m}$

**Inner Tracker:**  
**11 planes of RPC's**  
21 bakelite RPC's ( $2.9 \times 1.1 \text{ m}^2$ ) / plane  
(~1,500 $\text{m}^2$  / 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,  $1.85 \times 10^{19}$  POT)  
Assuming  
 $\Delta m_{32}^2 = 2.5 \times 10^{-3} \text{ eV}^2$  and  
full mixing, expect 0.5  $\nu_\tau$   
events

$100 \mu\text{m}$

9-11 July 2014

D. Harris, Fermilab: Neutrino Experiments

Slide courtesy O. Sato  
v2010

# Outstanding Issues



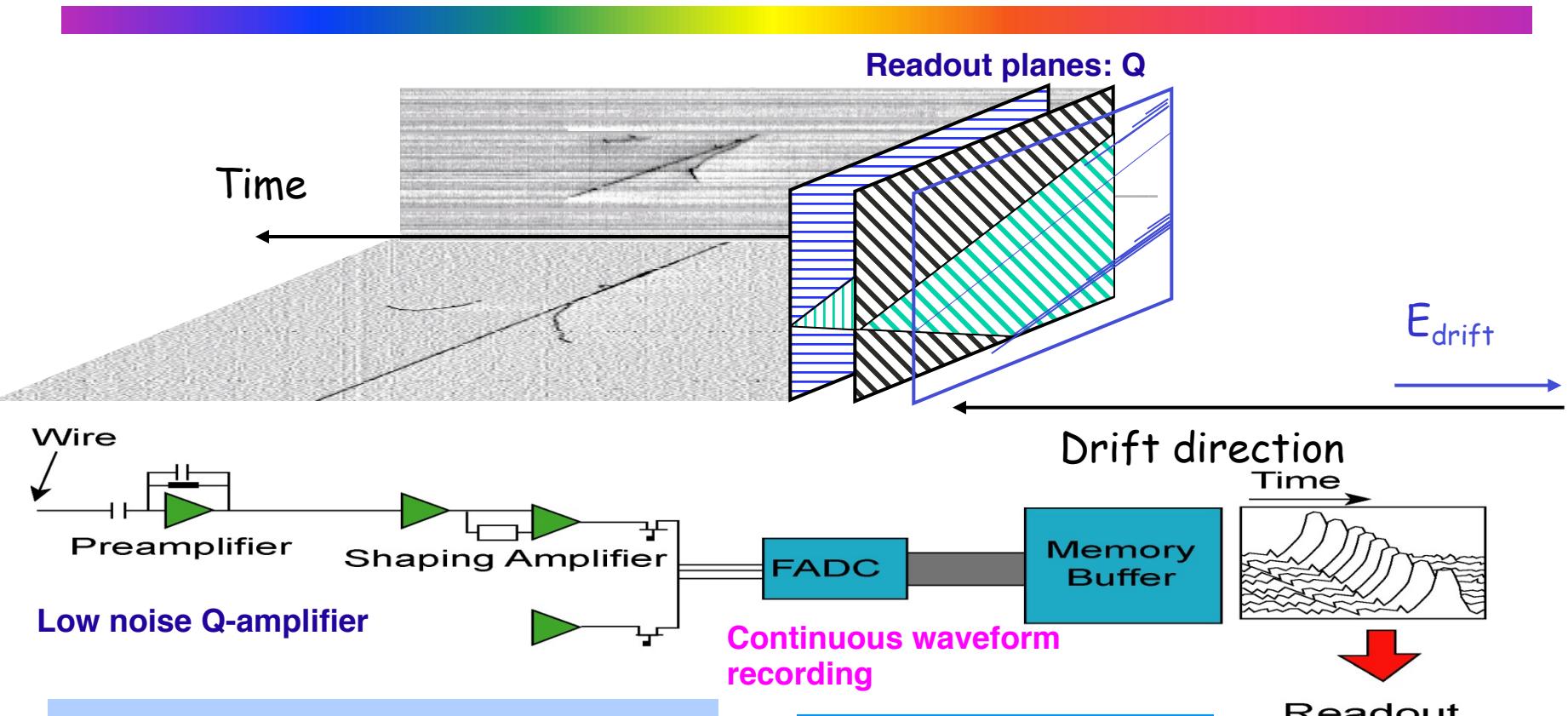
## Sampling Detectors

- Any way to make these detectors cheaper?
  - Cheaper absorber
  - Cheaper readout
  - Less segmentation

# LIQUID ARGON TPC



# Liquid Argon Time Projection Chamber



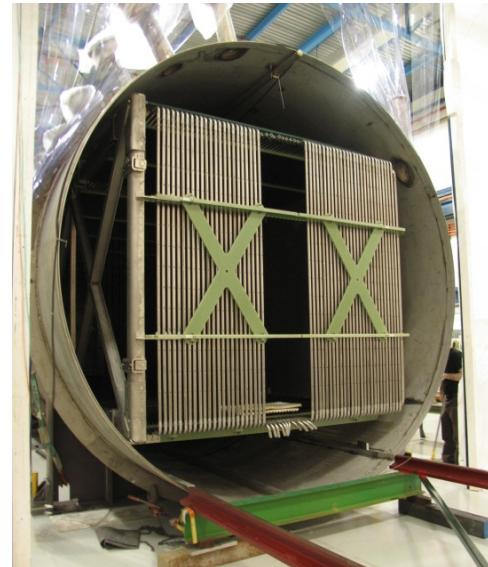
## •INGREDIENTS

- VERY PURE ARGON
- STRONG ELECTRIC FIELD
- SEVERAL PLANES OF WIRES

$dE/dx(mip) = 2.1 \text{ MeV/cm}$   
 $T=88K @ 1 \text{ bar}$   
Density:  $1.4 \text{ g/cm}^3$   
 $X_0=14\text{cm}$   
 $l_{INT}=83\text{cm}$

# ICARUS/MicroBooNE

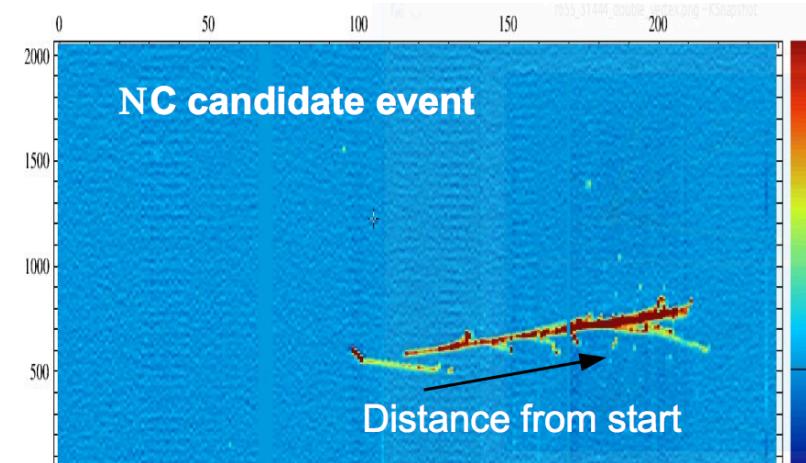
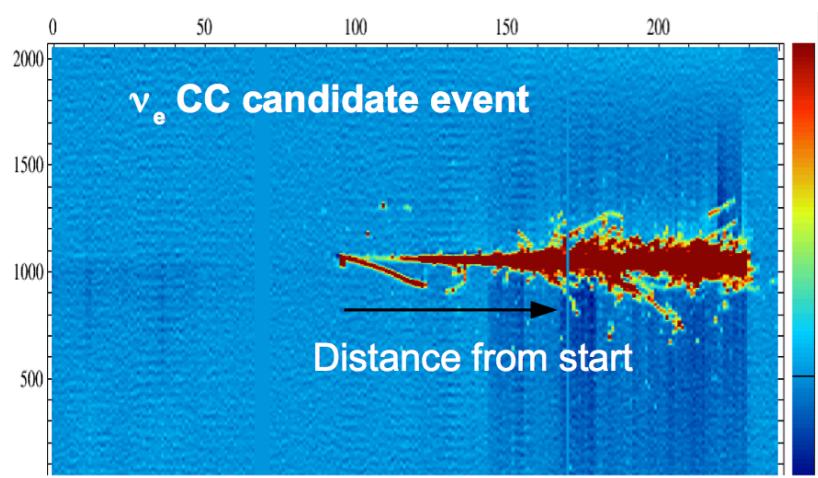
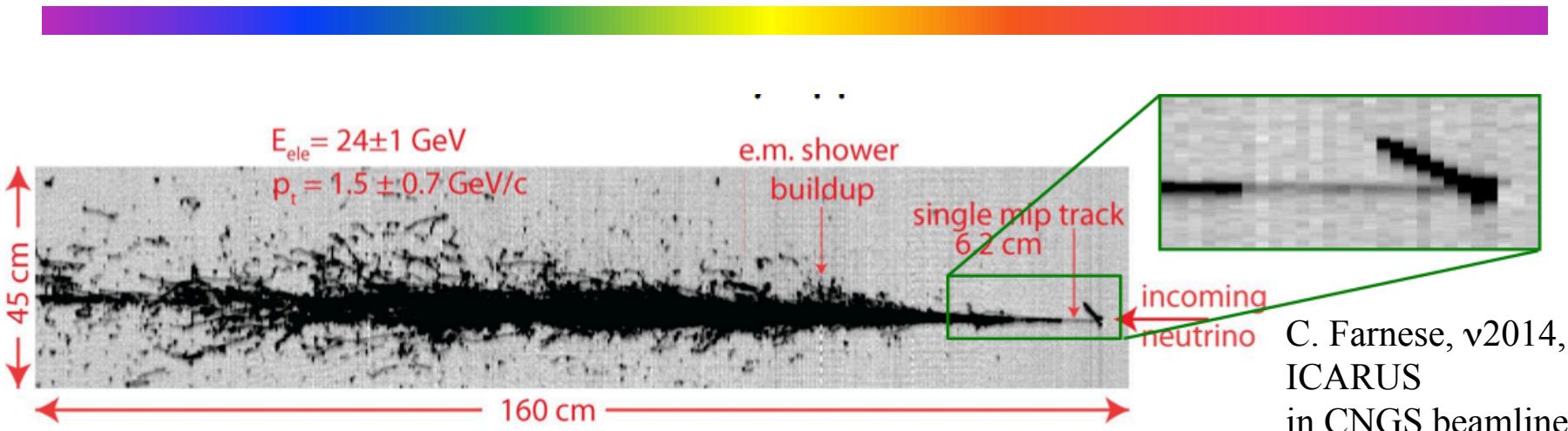
- Active mass: 476 tons / 87 tons
- Wire spacing: 3mm (both)
- Electron drift distance: 1.5m/2.5m
- 54000 wires/10000 wires
- 74 PMT's/ 30 PMT's for scintillation light from pure Argon (timing)
- ICARUS:  $\langle E_\nu \rangle \sim 20\text{GeV}$ , L=730km
  - Took data in CNGS beamline
- MicroBooNE:  $\langle E_\nu \rangle \sim 0.8\text{GeV}$ , L=1km
  - About to take data in MiniBooNE beamline (BNB)



A. Guglielmi, v2010/ A. Szelc, v2014

# Examples of Liquid Argon Events

- Lots of information for every event...



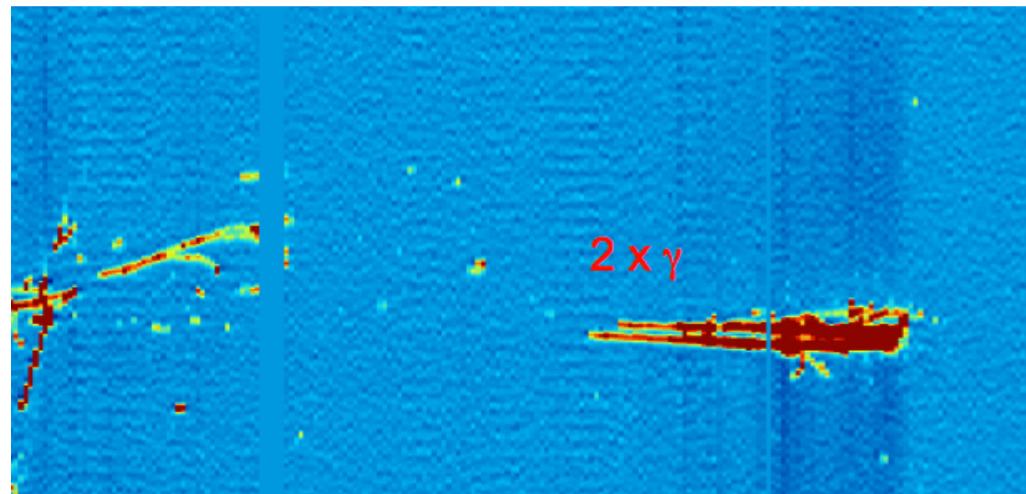
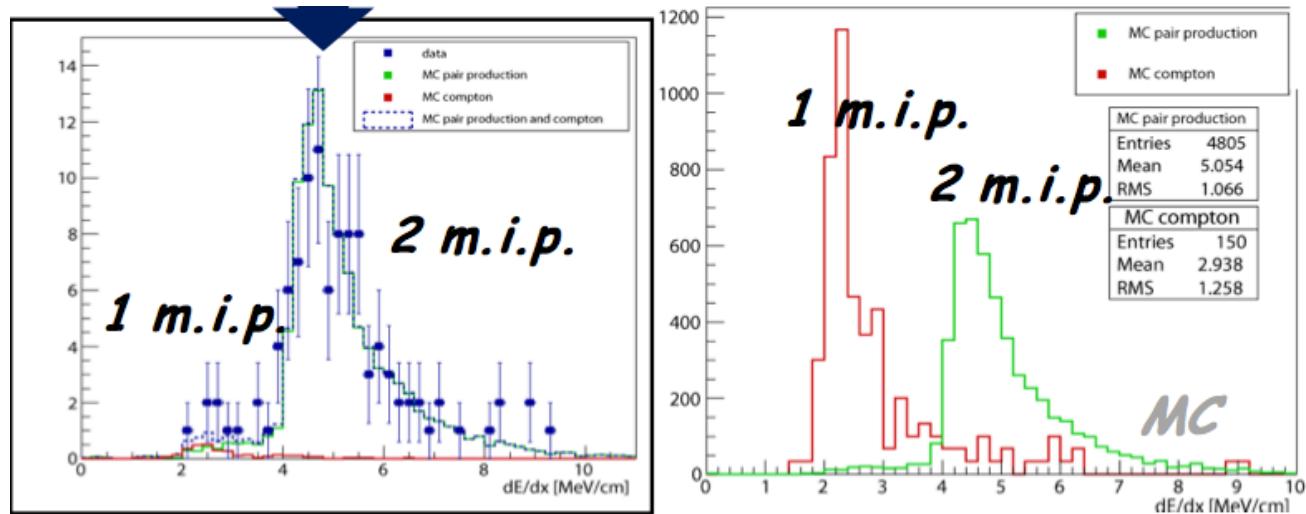
# $\pi^0$ identification in Liquid Argon

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

Questions:

What do you expect for the efficiency of this cut for electrons?

What about the rejection factor for  $\pi^0$ 's?



A. Szelc,  
v2014,  
Argoneut  
in NuMI  
beamline

# Oustanding Issues

## Liquid Argon Time Projection Chamber

- Can a magnetic field be applied
- How well can neutral currents be rejected in practice?
- Can the electronics be put inside the cryostat?
- How does the cost scale with size?
  - 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”

# Detector Summary

Detector Technology	Largest Mass to Date (kton)	Event by Event Identification			+/-?	Ideal ν Energy Range
		ν <sub>e</sub>	ν <sub>μ</sub>	ν <sub>τ</sub>		
LAR TPC	0.6	✓	✓		Not yet	huge
Water Cerenkov	50	✓	✓			<2GeV
Emulsion/Pb/Fe	0.27	✓	✓	✓		>.5GeV
Scintillator++	14	✓	✓			huge
Steel/Scint.	5.4		✓		✓	>.5GeV



# Neutrino Experiments: Detectors past, present, and near future...

Exp't	$\nu$ Energy (GeV)	Detector Technology
MINOS	2-6	Steel Scintillator
MINERvA	1-20	Solid Scintillator
OPERA	15-25	Emulsion-Lead
MicroBooNE	0.2-1.4	Liquid Argon TPC
ICARUS	15-25	Liquid Argon TPC
T2K	0.7	Water Cerenkov
NOvA	2	Segmented Scintillator

